U.S. Department of the Interior
U.S. Geological Survey

PROCESSES OF COASTAL WETLANDS LOSS IN LOUISIANA

Results From a Multi-Year Collaborative Study by the U.S. Geological Survey, National Biological Survey, and Louisiana State University

as presented at

Coastal Zone '93
New Orleans, Louisiana

S. Jeffress Williams[1] and Helana A. Cichon[1]
Editors

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[1] **U.S. Geological Survey, 914 National Center, Reston, VA 22092**

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(Papers are arranged in Session order as they appear in the final program for the Coastal Zone '93 Symposium.)

[1] Paper presented by James Kulpa, U.S. Geological Survey.

[2] Paper not presented and not published.

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[2] Paper not presented and not published.

[3] Paper not published.

[4] Paper presented by Larry Rouse, Louisiana State University.

Introduction

Louisiana is experiencing the greatest amount of wetlands deterioration and loss of any state in the Nation; an estimated 80 percent of the Nation's tidal wetlands loss has occurred in Louisiana, and by current estimates, as much as 75 km^2 are lost each year, primarily in the Mississippi River deltaic plain region of south-central Louisiana. The Louisiana Wetlands Loss Study is a cooperative investigation conducted by the U.S. Geological Survey (USGS) in partnership with the National Biological Survey (formerly the U.S. Fish and Wildlife Service), Louisiana State University, and Argonne National Laboratory. The wetlands study is focused on increasing understanding of the critical geological processes responsible for the creation, maintenance, deterioration, and loss of wetlands, as well as the effects of a wide variety of human activities such as marsh management and forced drainage on wetland environments.

Field investigations have been conducted in the hydrologic basins of two contrasting delta types: an active, accreting delta complex with emergent and vegetated wetlands (Atchafalaya) and an abandoned, eroding delta complex with badly deteriorated wetlands (Teche/Lafourche). Field studies in the sediment-rich Atchafalaya basin and the sediment-starved Terrebonne-basin/Timbalier-Bay/Barataria-basin region compared and contrasted the effects of geological processes and human activities in these vastly different wetland environments. Results of this study, including development of a Louisiana Coastal Geographic Information System Network (LCGISN) which incorporates the major databases, are providing immediate value in implementing project recommendations of the Louisiana Coastal Wetlands Restoration Task Force.

Coastal Zone '93, sponsored in part by the USGS, was a major international meeting held in New Orleans in July 1993. It garnered worldwide attention and the attendance of coastal scientists and managers from numerous countries throughout the world as well as the United States. The conference presented an ideal opportunity to broadly disseminate results from this study, and interest in the three Louisiana Wetlands Sessions was exceptional. The papers included in this report were presented at CZ '93 and published in the Proceedings of the Eighth Symposium on Coastal and Ocean Management, edited by O.T. Magoon, W.S. Wilson, H. Converse, and L.T. Tobin. These papers represent a sampling of final results of the Louisiana Wetlands Loss Study research investigations.

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SESSION 12

Processes of Wetlands Loss in Louisiana I: Sedimentary Processes

Depositional Sediment on Intertidal Marshes
near Terrebonne Bay and Atchafalaya Bay, Louisiana

Flora Chu Wang, F. ASCE, and Menglou Wang[1]

Abstract

The net transport of inorganic sediment through tidal bayous and dispersal into adjacent marsh systems are considered important contribution to marsh accretion. Marsh habitats are dependent upon sedimentation and vertical accretion to maintain a certain elevation within the local tidal range in order to negate the combined effects of subsidence and sea level rise. Marked fluctuations of total suspended sediment concentrations in tidal bayous during each tidal cycle may be related to overall marsh morphology. This paper presents the preliminary results from a study of depositional sediments on marsh surfaces collected at two specific sites near two shallow bays in south Louisiana during spring/neap tides in 1992.

Introduction

Marshes cover some $3.2X10^6$ ha in south Louisiana coast, which contains 40% of all coastal wetlands in the contiguous U.S. (Turner and Gosselink, 1975). The main components of sediment budget include relative sea-level rise, local subsidence, human activities, oxidation and decomposition of surface peat, tides and winds. Recent estimates of relative sea-level rise in Louisiana are 0.65-1.37 cm/year (Turner, 1991). The rate of subsidence, due to the compaction of coastal sediments, has been estimated in the range of 0.3 to 1.0 cm/year (Suhayda, 1987). Human activities (navigation channels and access canals) altered hydrological regimes and increased the degree of saltwater intrusion in inland marsh (Wang, 1988).

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[1] Professor and Graduate Student, respectively, Department of Oceanography and Coastal Sciences, Louisiana State University, Baton Rouge, LA 70803.
Tel (504) 388-6459, Fax (504) 388-6331

The oxidation and decomposition processes in surface peat can annually remove several hundred grams of organic carbon per square meter through carbon dioxide and methane emission to the atmosphere (DeLaune et al. 1983; Smith et al. 1983). Tides and winds can build the marsh up through sediment deposition on the marsh surface. The vertical accretion rates determined by using ^{137}Cs are 0.75-1.35 cm per year in southeast Louisiana coast (DeLaune et al. 1978). The objective of this study is to quantify the spatial and temporary distribution of sedimentation at two different marsh sites adjacent to two shallow bays in south Louisiana, under different tidal and meteorological conditions.

Study Sites

Two different streamside marsh sites in south Louisiana were selected to evaluate the regional influences on vertical accretion. One is influenced by both riverine and marine processes and the other is dominated by marine process (Figures 1a and 1b, respectively). Atchafalaya Bay, receiving relatively high volume of river discharge and sediments from Atchafalaya River and Mississippi

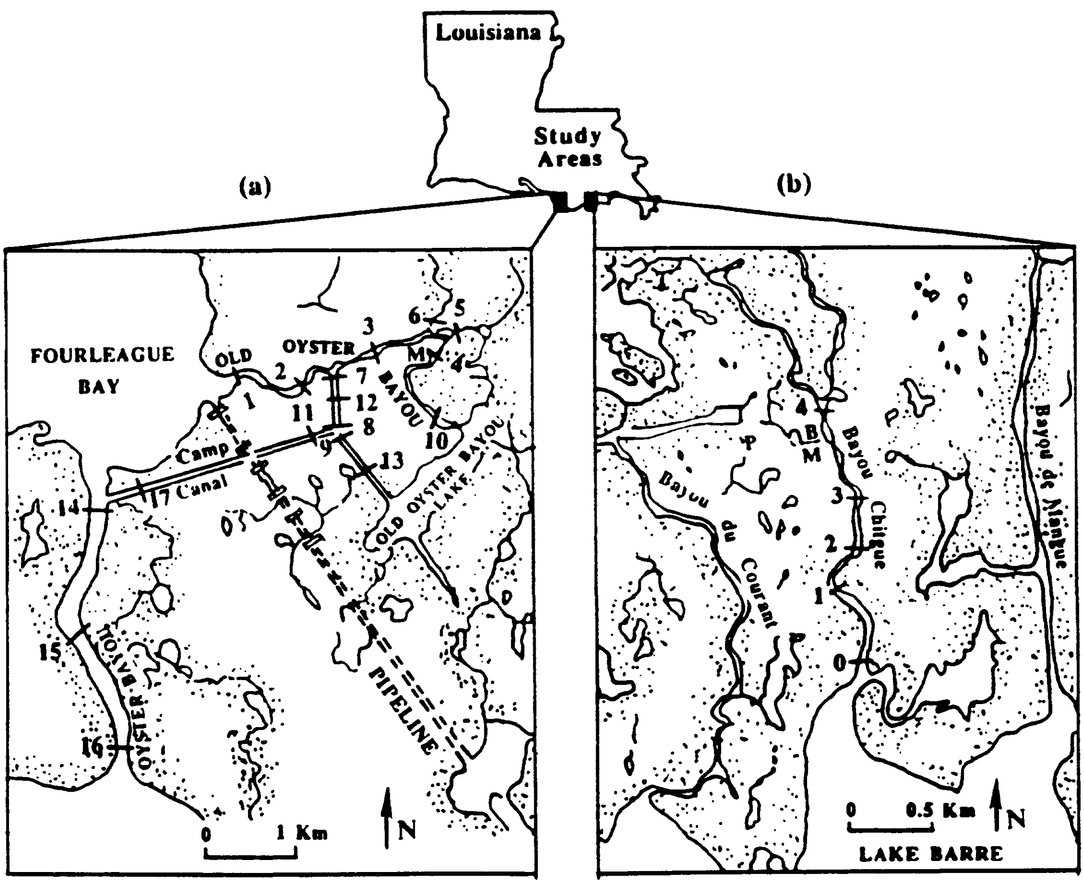

Figure 1. Marsh sites adjacent to (a) Atchafalaya Bay/Marsh Site A and (b) Terrebonne Bay/Marsh Site C in south Louisiana (labelled M).

River, is actively building a new delta in the southcentral Louisiana coast. The surrounding area is flanked by low-lying and healthy marshes. A marsh site (Site A, labelled M in Fig. 1a) adjacent to Fourleague Bay (at the terminus of Atchafalaya Bay) is designated as sediment-rich and riverine-influenced with large amount of freshwater inflow (Wang et al. 1992). A transect, with total length of 47 meters running westerly from the bank of Old Oyster Bayou toward an inland pond, was chosen. A boardwalk was built for pedestrians to walk on it without bogging. The vegetation on this marsh site is primarily *Spartina alterniflora*, with very dense stems.

Terrebonne Bay, located on the southeast Louisiana coast, was formed as old delta lobes of the Mississippi River, the Teche and Lafourche deltas subsided and deteriorated. The surrounding area is now experiencing wetland deterioration, and there are no major fluvial channels in sediment-poor, marine-dominated basin with negligible freshwater inflow (Wang et al. 1993). A marsh site, Site C, (labelled M in Fig. 1b) adjacent to Terrebonne Bay via Lake Barre was selected to study the sedimentation processes. A boardwalk was also built with a length of 120 meters, extending westerly from the bayou bank to a saline pond. The vegetation at this marsh site is dominated by *Juncus roemerianus* and *Spartina alterniflora*. In Louisiana coastal basin, marshes are subject to microtidal fluctuations and irregular floodings (Childers and Day, 1990). The diurnal tidal ranges are small, varying from 30 to 60 cm during spring tides and 10 to 20 cm during neap tides (Wang et al. 1992).

Methods and Materials

A field-sediment collector system was designed to measure the sediment depositing on the marsh surface over a tidal cycle. The sediment collectors were deployed in group of three replicates to each sampling site at low tides on a transect along the boardwalk. Pre-ignited and pre-weighed filter papers (9 cm in diameter) secured by retaining rings in inverted petri dish covers were deployed over a tidal cycle during normal spring/neap tides. The sediment collectors were laid down on the marsh surface before the marsh was inundated and collected after the marsh was exposed when water in the petri dish covers was nearly evaporated in order to avoid spilling.

Sediment deposition analysis was conducted in the laboratory. The salt in each sample was removed by filtering through a pre-ignited and pre-weighed GF/C filter paper with diameter of 4.7 cm and pore size of 1.2 μm. The total amount of sediment deposited on each filter paper was obtained by subtracting the weights of the two filter papers (9.0 and 4.7 cm) from the total weight after dried. The inorganic and organic sediment weights were also measured and calculated through burning the samples at 550 ± 50°C for one hour.

A schematic diagram for the field-sediment collector system and the field deployment carrying box is shown in Figure 2.

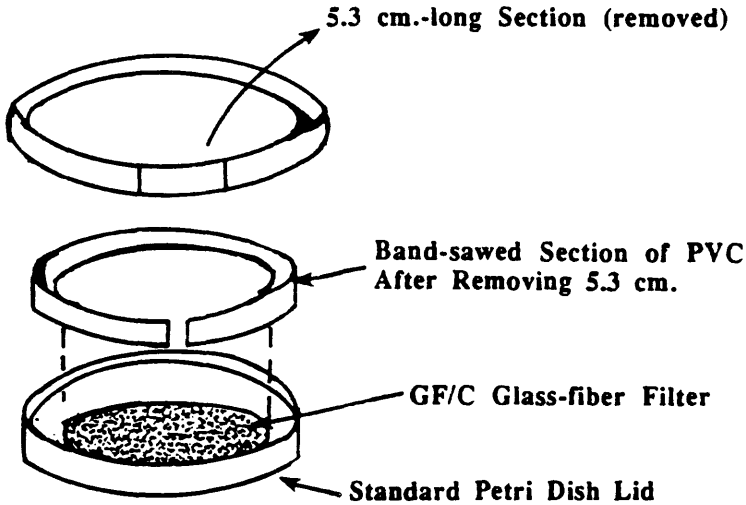

Figure 2a. Schematic diagram of the field-sediment collector system.

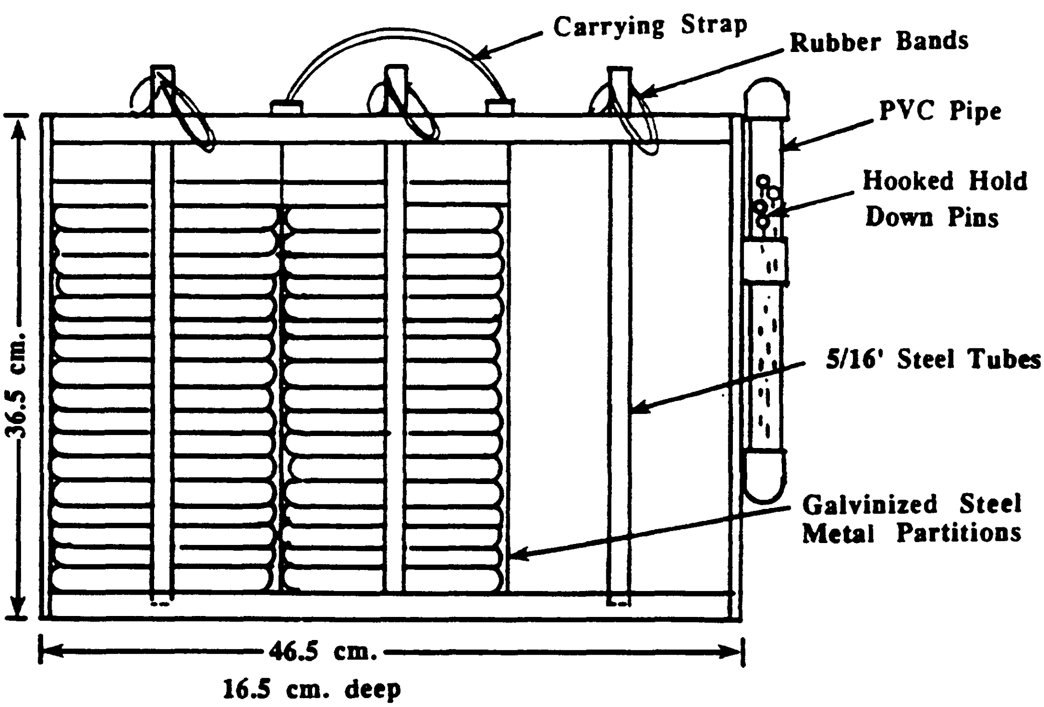

Figure 2b. Carrying box for field deployment of sediment collectors.

During tidal inundations, relative water levels were measured from the staff gauges temporarily installed at the marsh site during sampling periods, supplement with readings directly recorded from the automatic water-level gauges permanently installed at each marsh site. Water samples were taken at each sampling site at one to two hours intervals with minimum disturbance to the marsh surface for sediment concentration analysis. When water depth on the marsh surface was too shallow, a culture bottle was used for sampling. The marsh surface flow velocity was estimated from in-situ, dye-plume experiments (Wang et al., 1992).

Sediment cores at the marsh surface along the boardwalk at marsh Site C, Bayou Chitique marsh, were taken to measure the bulk density and organic matter concentration in the marsh surface soil. The cores were 6.0 cm in diameter and 3.6 cm in height. In laboratory, these core samples were dried at 103-105°C for more than 24 hours to constant weights and weighed for bulk density calculation. The samples were then ground, and ignited at 550±50°C and re-weighed for organic matter content calculation. At marsh Site A, Old Oyster Bayou marsh, coring was very difficult due to the deposition of stems. Only Organic matter concentration was measured.

Five field sampling trips were carried out on February 20-23, March 24-27, May 4-7, October 22-25 and December 19-23, 1992 at Bayou Chitique marsh site. Only two field trips were successfully conducted at Old Oyster Bayou marsh site on May 18-22 and December 22, 1992 due to its low flooding frequency. Old Oyster Bayou marshes were rarely inundated during 1992 (Wang et al., 1992).

Results and Discussion

Sediment deposition during a individual tidal cycle can be estimated by the following equation:

$$q(x) = \int_0^T (-\partial C/\partial x)\, hv\,dt \qquad (1)$$

where q(x) is sediment deposition in a unit area during one tidal cycle (g/m^2), x is the distance (m) starting from the bayou bank toward a saline pond, C is the total suspended sediment concentration (ppm) which varies both spatially and temporally, h is water depth on the marsh surface (m) which changes with time and varies only slightly with distance, v is marsh overland flow velocity (m/min) positive when water flows from the bayou bank to the pond (east to west) and negative the opposite direction, and t represents the time (min) where $t=0$ at the beginning of marsh inundation and $t=T$ at the end of marsh inundation. With the measurements of total suspended sediment concentration, water depth, and flow velocity, the amount of sediment deposition over one tidal cycle can be computed from Eq (1). The estimated results from Eq (1) can be used to compare with the direct measurement of sediment deposition on the traps during the tidal cycle.

However, the estimates from Eq (1) became less accurate when the direction of marsh overland flow was not closely parallel to the transect where the sediment collectors were deployed, due to the complications of marsh topography, the density of vegetation, and the effects of tides and winds.

1. Total suspended sediment concentration and deposition at marsh Site C

Sedimentation rates depend on the total suspended sediment concentration gradient $\partial C/\partial x$, water depth h, marsh flow velocity v, and the duration of marsh inundation T. Measured sediment deposition and the total suspended sediment concentration C at Bayou Chitique marsh site, Site C, were shown in Figures 3 and 4, respectively. In these figures, sediment deposition patterns at Site C, the Bayou Chitique marsh site, were divided into four sections: (1) bayou-affected section, (b) stream-side section, (3) inland section, and (4) pond-affected section.

1.1 Bayou-affected section (x = 0 - 28 m)

In bayou-affected section, about 28 meters long from the bayou bank, both total suspended sediment concentration and its gradient along the transect were greater than other sections (Figure 4). However, there were less sediments deposited on the traps (Figure 3). Field observation showed that, during flooding and ebbing period, marsh flow in this section was perpendicular to the transect and parallel to the bayou. This kind of flow pattern is partially due to the curved path of the Bayou Chitique channel at our study site and the stressed vegetation near the bayou edge. Measured flow velocity in this section was as high as 10-25 cm/sec which was close to the Shields stress threshold. When water in the bayou enters this section, some coarser suspended sediments change into the bed load because of water flow slowing down. Further from the bayou, the more sediments change into the bed load due to the further decreasing in flow velocity with the distance away from the bayou. As the result, the sediment concentration gradient was high but the sediment deposition was low in this section. Figure 5 shows the organic matter content in the water on the marsh, from x=0 in the open water in Bayou Chitique to x=120 m in the pond. Organic matter content in the bayou-affected section is slightly lower than other sections due to coarser suspended sediments changing into the bed load.

1.2 Stream-side section (x = 28 - 48 m)

Water and sediment entering into the Bayou Chitique marsh interior are mainly through a small stream (about 28 m from the west of the bayou bank) during the flooding period. During ebbing period water and sediment return back into Bayou Chitique by the same stream. After water arrives at stream-side section, sedimentation occurs due to reduction of flow velocity. Large sediment gradient (Figure 4) and sedimentation (Figure 3) were measured in this section,

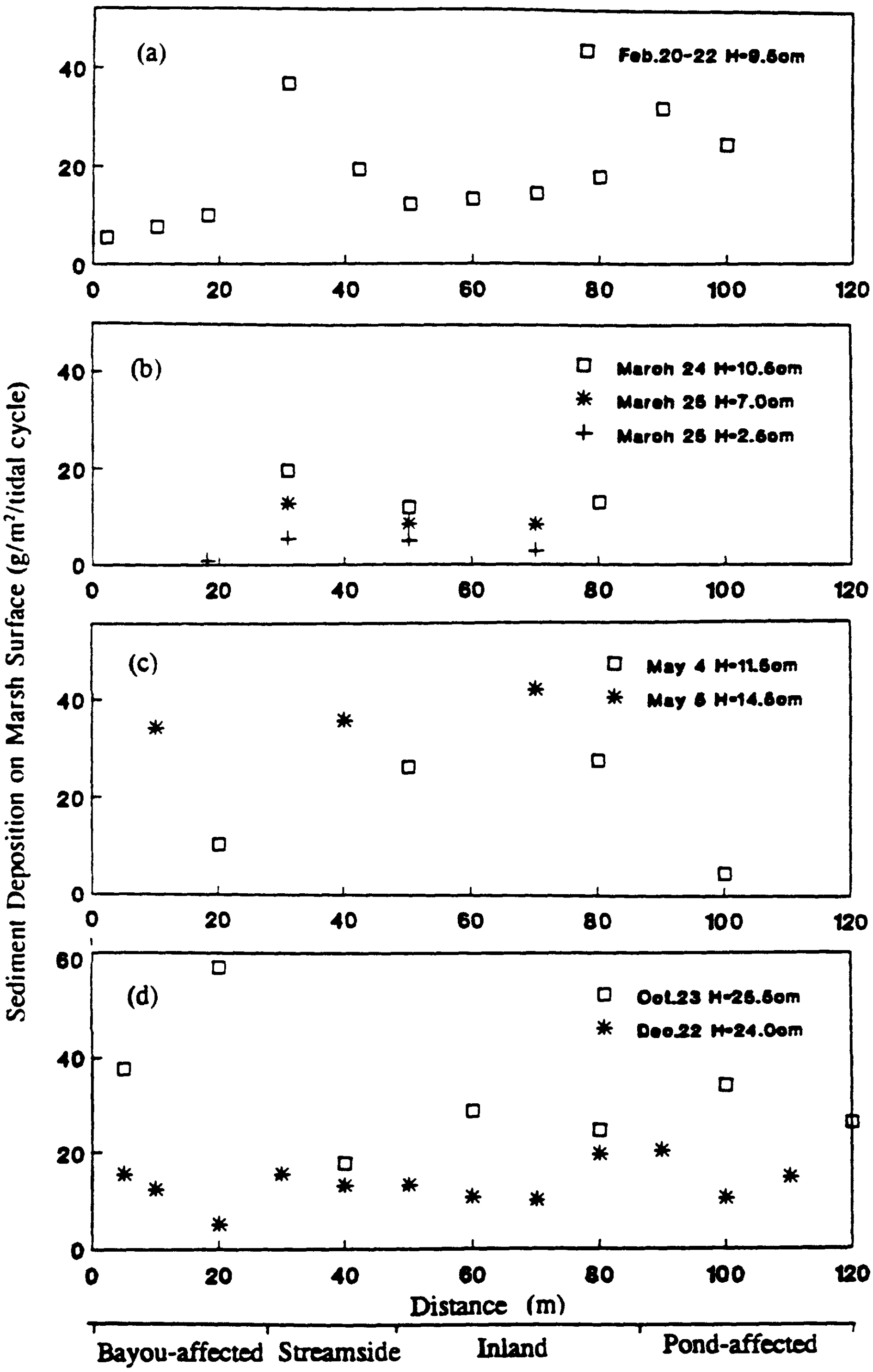

Figure 3. Sediment deposition on marsh surface per tidal cycle at Site C, along 100 m transect from the bank of Bayou Chitique to a saline pond, during (a) February 20 - 22, (b) March 24 - 26, (c) May 4 - 5, and (d) October 23 - 24 and December 22, 1992.

which can be explained by Eq (1). A gradient of sedimentation rate exists in the stream-side section, in which the maximum sediment deposition was measured at the sampling site just 2 meters from the stream (x=30 m). This is because the closer to the stream, the more coarser sediments deposit. Figure 6 shows the surface soil bulk density and the organic matter content in the stream-side section which is larger and less than that in the inland section, respectively. Field observation showed that the vegetation density in stream-side section is higher than that in the other three sections of the marsh.

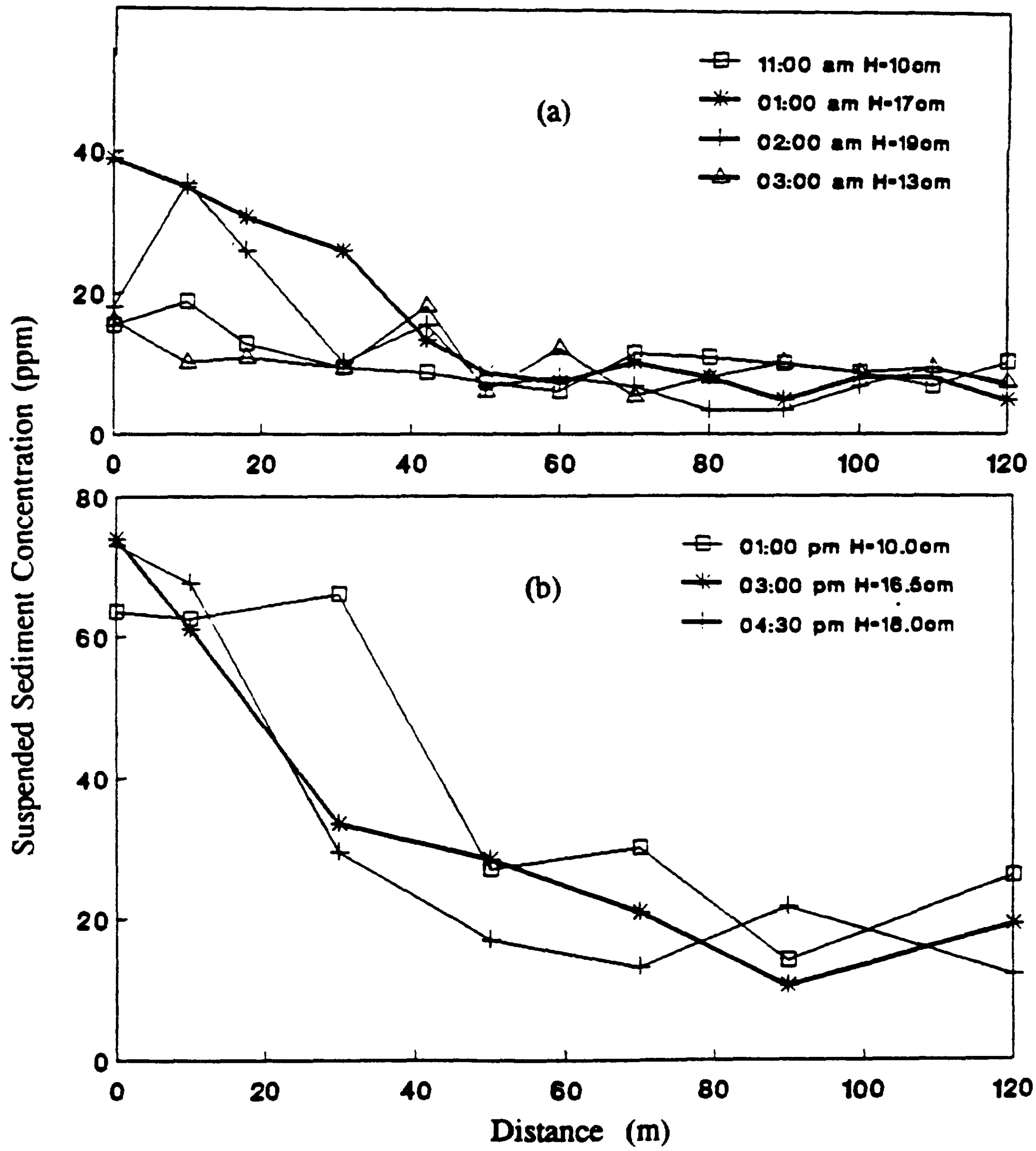

Figure 4. Total suspended sediment concentration at Site C, along Bayou Chitique marsh transect collected during field sampling trips on (a) February 22, and (b) March 24 - 26, 1992.

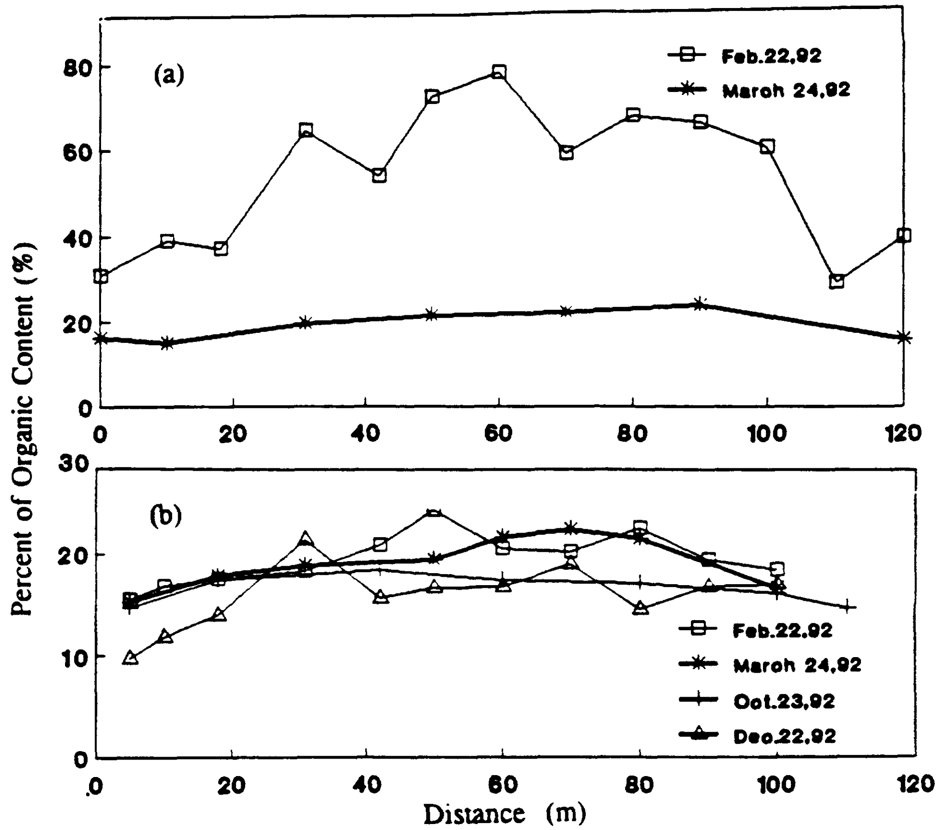

Figure 5. Organic matter content in (a) the suspended sediments, and (b) the deposited sediments in the traps on Bayou Chitique marsh site, Site C.

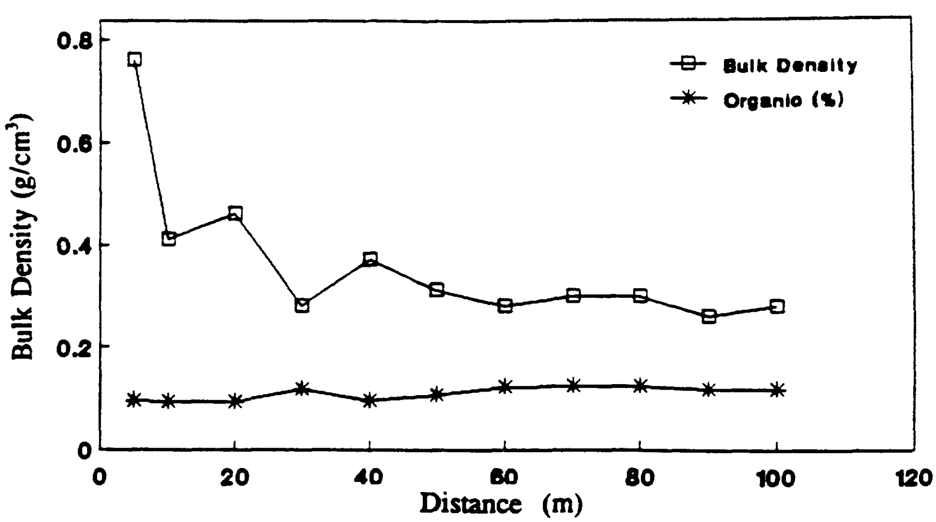

Figure 6. Bulk density and organic matter content in the surface soil on Bayou Chtique marsh site, Site C.

1.3 Inland section (x = 48 - 86 m)

In the inland section measured sedimentation rate is relatively low (Figure 3), surface soil bulk density is below 0.30 g/cm^3 (Figure 6), and the organic matter content in the deposited sediment is high (Figure 5). Organic matter content in the suspended sediment was high probably because of the deposition of mineral sediment and the residual of organic matters in the soil and on the vegetation stems. Marsh in the inland section is in the process of deterioration, since its low sedimentation rate is not able to compensate for subsidence and relative sea-level rise. In some places in the inland section, the formation of permanent open water bodies reduced the opportunities for surface soil to consolidate, which enhanced the erodability of the marsh surface. When bulk density of the root zone falls below 0.2 g/cm^3, salt marsh will not be able to support appreciable growth of *Spartina alterniflora* (DeLaune et al. 1979). The deterioration of vegetation reduces the resistance to marsh flow and subsequently reduces the ability to entrap sediments, which in turn accelerates the deterioration of the marsh.

1.4 Pond-affected section (x = 86 - 100 m)

Sediment deposition in pond-affected section at Bayou Chitique marsh site, Site C, is relatively unpredictable because of the complication of the flow field in this section. The lack of topographic features prohibits well-defined flow patterns whether water flows from tidal bayou to adjacent marshes during flood tide will follow the same path during the ebb tide. Figure 3 shows that measured sediment deposition rate in pond-affected section is, in general, more than that in the inland section. In this section, the deposited sediments are likely from the pond through the processes of advection and diffusion.

2. Sediment deposition at the marsh Site A

Old Oyster Bayou marsh site, Site A, was divided into 3 sections only: (1) bayou-affected section, (2) inland section, and (3) pond-affected section (Figure 7). The sedimentation distributions at Site A are similar to those at Bayou Chitique marsh site, Site C. Both the lengths of bayou-affected section and pond-affected section are less than 10 meters long. The vegetation was very dense and uniform without any small streams on the marsh surface. During the period of inundation, marsh flow is almost parallel to the transect. Higher sediment deposition rate was obtained in the bayou-affected section than in the inland section. Sedimentation rate in the pond-affected section was also higher than that in inland section. This suggests that sediments deposited in the pond-affected section were both from the bayou and the pond through advection and diffusion processes. Similar low organic matter contents in the deposited sediments at both bayou- and pond-affected sections were observed at Site A (Figure 8).

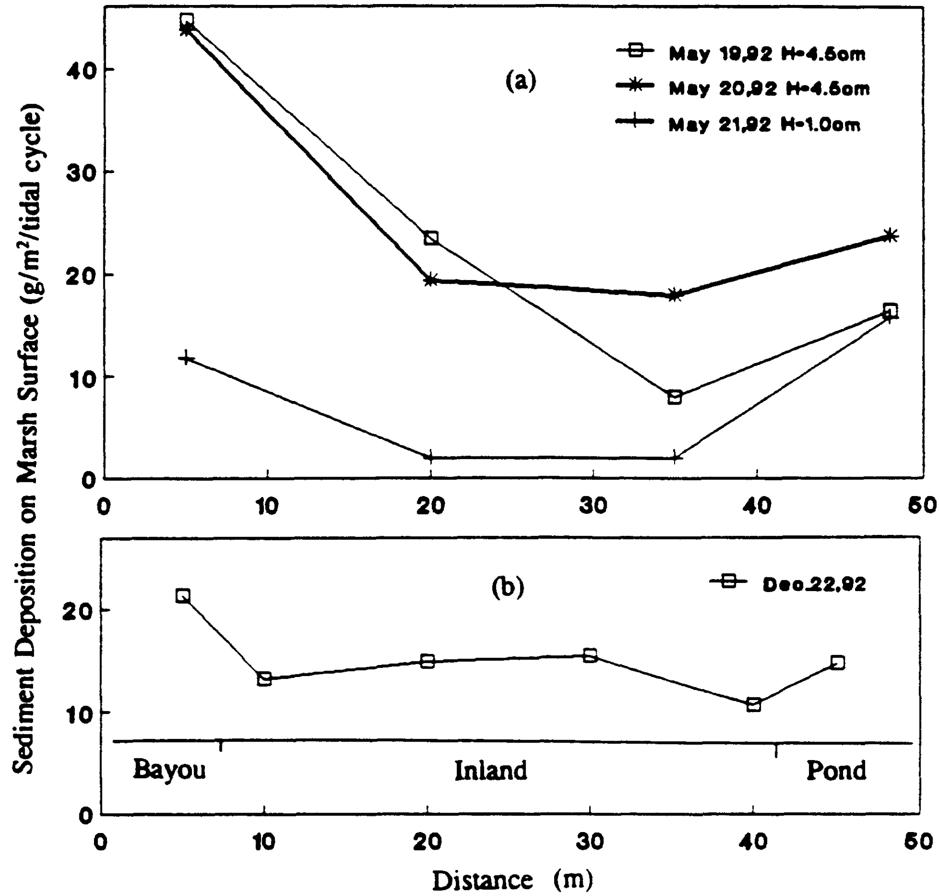

Figure 7. Sediment deposition on marsh surface per tidal cycle at Site A, along 50 m transect from the bank of Old Oyster Bayou to a saline pond, during (a) May 19 - 21, and (b) December 22, 1992.

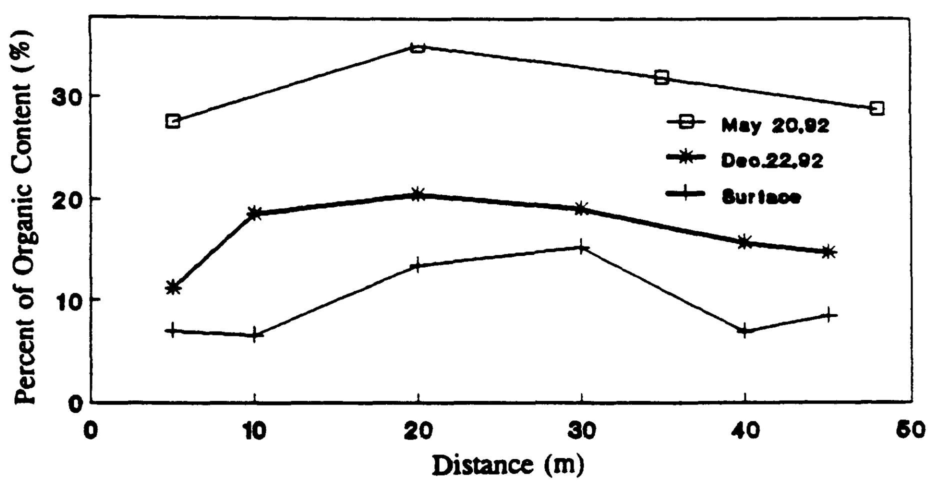

Figure 8. Organic matter content in the deposited sediments in the traps and in the surface soil on Old Oyster Bayou marsh site, Site A.

3. Water depth on the marsh surface at Site A and Site C

Eq (1) expresses that sediment deposition increases with water depth on the marsh surface. This was confirmed by our field monitoring program. A high tide not only brings more sediments, but also provides longer flooding duration. During March 24-26, 1992 sampling trip at Bayou Chitique marsh site, Site C, water depths on the marsh surface reached 10.5 cm, 7.0 cm, and 2.5 cm over the three tidal cycles, respectively as shown in Figure 3b. In the figure, it indicates that the maximum sediment deposition reached 20 g/m^2 at the highest water depth at 10.5 cm. The minimum deposition was less than 5 g/m^2 at the lowest water depth at 2.5 cm. Similar results were observed for Old Oyster Bayou marsh site, Site A, 45 g/m^2 at the water depth 4.5 cm and 16 g/m^2 at 1.0 cm water depth, during May 19-21, 1992 sampling trip (Figure 7a).

Field measurements also showed that high tides can increase suspended sediment concentration in the bayou, which acts as the sediment source for marsh deposition. During flooding period over each tidal cycle, the total suspended sediment measured along the board walk at Bayou Chitique were 65-75 ppm, 30-40 ppm, 20-30 ppm corresponding to the water depth 16.5 cm, 14.5 cm, and 12.0 cm, on March 24, 25, and 26, respectively (Figure 4b). Very steep sediment gradient was observed along the transect at Bayou Chitique on March 24, which enhanced sediment deposition (Figure 3b).

4. Sediment dispersal in shallow bays

It has been suggested that, in south Louisiana coast, strong southerly winds may mobilize sediments in shallow bays, which are then transported through tidal bayous and dispersed onto adjacent marshes (Reed, 1989; Wang et al., 1992). The seasonal changes in sediment concentrations in bays contribute to different sedimentation rates on the marsh. During the flood season, Fourleague Bay receives large volume of water and sediments from both the Atchafalaya River and Mississippi River.

Table 1 displays the observed maximum flood and ebb currents and the measured total suspended sediments during spring tides in May, 1992 (high river flow season) and October, 1992 (low river flow season) in Oyster Bayou, which links Fourleague Bay to the Gulf of Mexico (Figure 1). In the table, it shows that during the high river flow season, the sediment concentration (160-184 ppm) is one order of magnitude higher than that in the low river flow season (32-47 ppm). Similar results were also observed at Bayou Chitique site. In Figures 3c and 3d, the sediment deposition in May, 1992 was more than that in October, 1992, even though water depths on the marsh surface were 11.5-14.5 cm in May, much lower than those in October, 25.5 cm.

TABLE 1. Observed Maximum Flood and Ebb Currents and Measured Total Suspended Sediment Concentrations in Oyster Bayou/Fourleague Bay during May 4-5 and October 23-24, 1992 Sampling Trips

Sampling date	Tidal period	Tidal current (m/sec)	Sediment concentration (ppm)
May 18-19, 1992	Flooding	0.47	184
	Ebbing	0.56	160
Oct 23-24, 1992	Flooding	0.38	47
	Ebbing	0.84	32

5. Marsh surface elevation at marsh Site A and Site B

In general, more sedimentation rates were observed in bayou-affected section (stream-side effect) than the inland section of the marsh. Relative marsh surface elevations along the transects at two marsh sites, Site A and Site C, are plotted in Figure 9. An elevated profile was observed at Old Oyster Bayou marsh site, Site A. The elevation of marsh surface at the midway, about 30 m from the bayou bank, is higher than the elevation near the bayou and the pond. This sloping downward toward either side may wash down more sediments to the pond and the bayou during a rainfall/storm event at low tide (Figure 7).

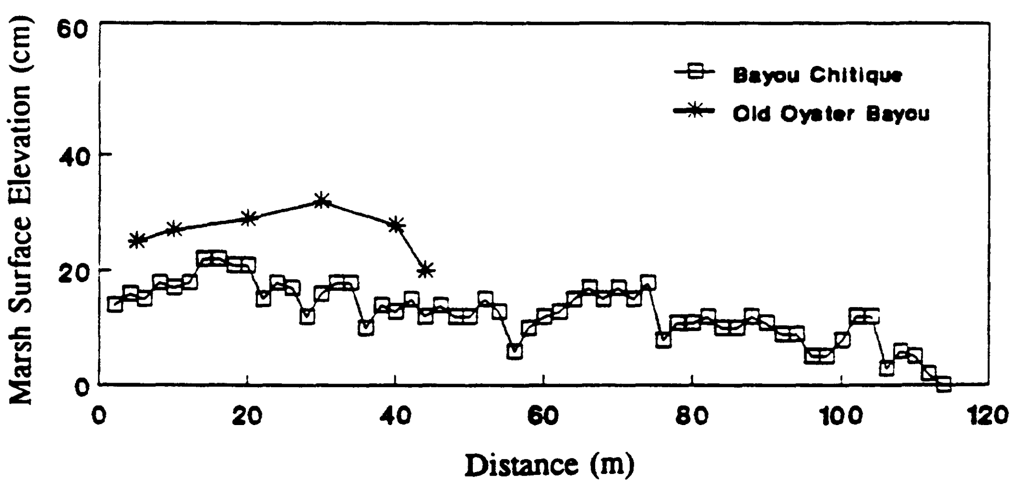

Figure 9. Relative marsh surface elevations along the transects of Old Oyster Bayou marsh site, Site A, and Bayou Chitique marsh site, Site C, measured from the bayou bank toward the saline pond.

The topography of Bayou Chitique marsh site is more complicated than that of Old Oyster Bayou marsh site. Several streams of different sizes exist on Bayou Chitique marsh site, Site C, oriented roughly perpendicular to the transect. At the stream crossing, the elevation was lowered as depicted in Figure 9. During low-tide storms, most storm runoff will flow along the stream axis and perpendicular to the transect. No stream runoff will be accumulated near the bayou and the pond (Figure 3).

Summary

A field monitoring program was carried out in 1992 for the study of the depositional sediments on marsh surface at two specific sites, adjacent to two shallow bays in south Louisiana. Marsh Site A, adjacent to Fourleague Bay is designated as a sediment-rich and healthy marsh site, and Site C, adjacent to Terrebonne Bay, is considered as a sediment-poor and stressed site (Figure 1).

A field-sediment collector system was designed to deploy and retrieve the sediment traps along the transects, from the bayou bank to the pond, during each tidal cycle at each site (Figure 2). Five field sampling trips were carried out at the Bayou Chitique site, Site C, and only two trips were conducted at Site A, the Old Oyster Bayou marsh site. The results of sediment depositions, suspended sediment concentrations, organic matter contents, and bulk density at Site C are displayed respectively in Figures 3, 4, 5, and 6. At Site A, only the deposited sediment and its organic matter content are shown in Figures 7, and 8, separately. Figure 9 plots the relative marsh surface elevation at both sites.

The preliminary results show that the amount of deposited sediments on the marsh are correlated with the water depth on the marsh surface during each tidal cycle at each site. The higher the water depth, more sediments are deposited on the marsh surface (Figures 3 and 7). In December trip, two sites were conducted at nearly the same time period. The results show that at Site A, 10 - 46 g/m^2 at the water depth 4.5 cm were deposited per tidal cycle; and at Site C, water depth reached 24 cm, 10 - 20 g/m^2 sediments were deposited. This suggests that the difference in marsh elevation (Figure 9) may affected the rate of sedimentation. Finally, the seasonal river discharge may play an important role in sedimentation processes. During high river flow season in May, sediment concentrations were one order magnitude larger than in October, the low river flow season (Table 1).

Acknowledgements

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PROCESSES AFFECTING COASTAL WETLAND LOSS IN THE LOUISIANA DELTAIC PLAIN

S. Jeffress Williams[1], Shea Penland[2], and Harry H. Roberts[3]

Abstract

Approximately one-half of the Nation's original wetland habitats have been lost over the past 200 years due in part to natural evolutionary processes, but human activities, such as filling wetlands for agriculture or development and dredging for canals, are largely responsible for much of the marsh habitat alternation and destruction. With increased environmental awareness and recent legislation, wetland losses have slowed, but deterioration of valuable coastal resources continues at alarming rates. Nowhere are the problems of coastal wetland loss more serious and dramatic than in the Mississippi River deltaic plain region of south-central Louisiana. In that area, rates of shoreline erosion of 20 m/yr and loss of land area of up to 75 km^2/yr result from a complex combination of natural (delta switching, subsidence, sea-level rise, storms) and human (flood control, navigation, oil and gas development, land reclamation) factors.

The U.S. Geological Survey (USGS), as part of the National Coastal Geology Program, has undertaken joint field investigations with Federal, State, and university partners. The objective of these long-term studies is to gather and interpret baseline information in order to improve our scientific understanding of the critical processes and responses responsible for creation, maintenance, and deterioration of coastal wetlands. To date, large data sets on topics such as storm effects, flux and dispersal of water and fine-grained sediments, soils development, marsh disintegration, and subsidence/sea-level rise have been systematically collected since 1989 from representative sediment-starved (Terrebonne/Barataria) and sediment-rich (Atchafalaya) basins in

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[1] U.S. Geological Survey, 914 National Center, Reston, VA 22092

[2] Center for Coastal, Energy, and Environmental Resources, Louisiana State University, Baton Rouge, LA 70803

[3] Coastal Studies Institute, Louisiana State University, Baton Rouge, LA 70803

Louisiana. Synthesis and comparisons of these data sets are enhancing our knowledge of how wetlands function and the critical processes responsible. Computer-based GIS technology is being used to store data and develop process-response classification systems for quantifying natural and human causes of land loss. Following Hurricane Andrew, additional studies were initiated to delineate the storm's effects.

Results of these studies are finding immediate application in managing and conserving Louisiana's coastal resources and in mitigating losses through projects supported by the Coastal Wetlands Planning, Protection, and Restoration Act (CWPPRA).

Introduction

The negative environmental and economic effects of the degradation and loss, over the past 200 years, of approximately one-half of the Nation's coastal wetlands has led to the realization that coastal wetlands are among the most valuable and productive ecosystems in the world. In addition to providing critical habitats for fish and wildlife, other important benefits include flood-effects mitigation, storm protection, and water quality improvement. While natural evolutionary processes play a role in the loss of wetlands, man has been largely responsible for widespread habitat alteration and destruction.

Wetland losses have slowed with enhanced environmental awareness and recent legislation, but deterioration of valuable coastal resources still continues at alarming rates. Of the 48 conterminous States, Louisiana has 25 percent of the vegetated wetlands and 40 percent of the tidal wetlands (Penland and others, 1990). These coastal wetlands, including the associated bay and estuary environments (Figure 1), support renewable natural resources valued at over $1 billion per year. Nowhere in the Nation are the problems of wetland loss more serious and dramatic than in the Mississippi River deltaic plain of south-central Louisiana, in which 80 percent of the Nation's tidal wetland area loss has occurred. Within this area, the greatest losses are in the modern Mississippi River Delta and the Barataria and Terrebonne Basins to the west. Map comparisons show that wetland loss had steadily increased during the 20th century to an estimated 75 km^2/yr as a result of a combination of natural (delta switching, subsidence, sea-level rise, storms) and human (flood control, navigation, oil and gas development, land reclamation) factors (Williams and others, 1991a). Recent mapping suggests that wetland losses are continuing, but at slightly reduced rates (Britsch and Kemp, 1990).

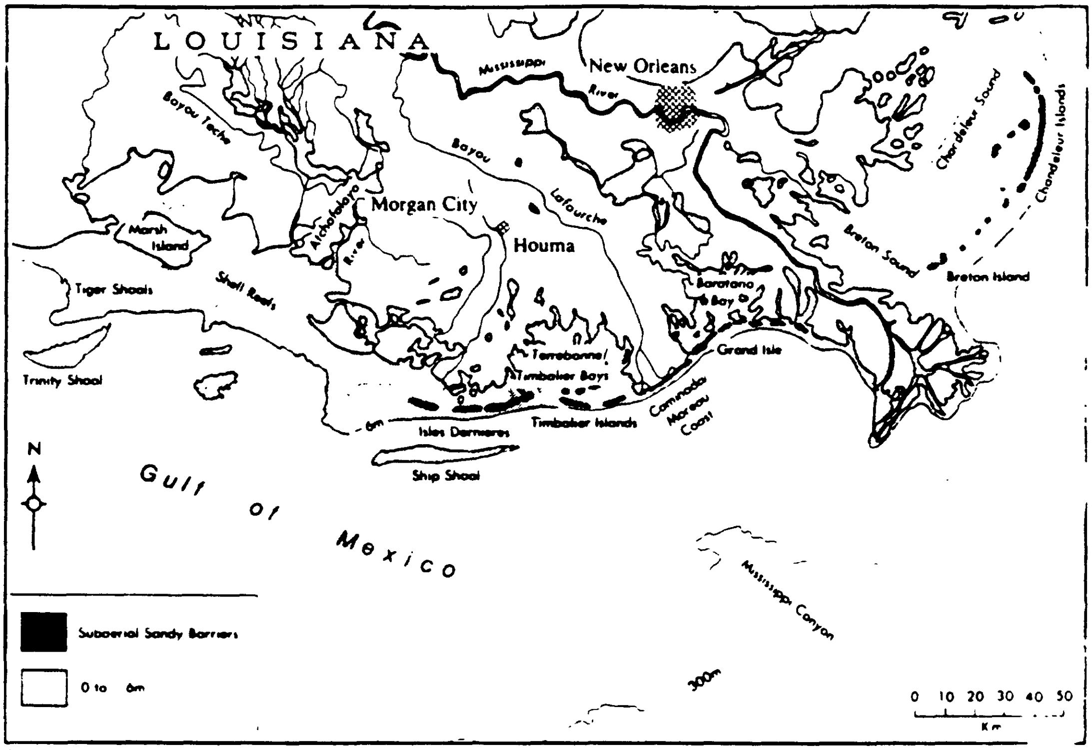

Figure 1. - *Mississippi River deltaic plain region.*

Origin, Evolution, and Degradation of the Wetlands

The 300 km-wide Mississippi River deltaic plain and associated wetlands are the product of the continuous accumulation of sediments deposited by the Mississippi River and its distributaries during the past 7,000 years (Coleman, 1988; Penland and others, 1990). Major shifts in the River's course have resulted in four ancestral (Teche, Maringouin, Lafourche, St. Bernard) and two active (Atchafalaya and Modern) delta lobe complexes which accumulated as overlapping, stacked sequences of unconsolidated sands and muddy sediments (Williams and others, 1991b). Since each of the ancestral complexes was abandoned by the Mississippi River, their main source of sediment, the deltas have experienced erosion and degradation, primarily due to subsidence by compaction of the unconsolidated sediments; the rate of subsidence, mostly a function of sediment composition and thickness, combined with the rate of eustatic sea-level rise often exceeds 1 cm/yr (Penland and Ramsey, 1990). Marine coastal processes eroded and reworked the seaward margins of the delta complexes, forming sandy headlands and barrier beaches and spits, and continued transgressive submergence resulted in segmented barrier, low-relief islands separated by tidal inlets and backed by shallow bays and lagoons (Penland and others, 1988; Williams and others, 1991b).

Barrier islands fronting wetlands in the Mississippi River deltaic plain act as a buffer, reducing the effects of ocean waves and currents on back-barrier estuaries and wetlands. The barriers are eroding rapidly, however, at rates up to 20 m/yr, due to continued subsidence, lack of adequate coastal sediment, and frequent storm events. Ultimately, they are unable to maintain their subaerial geomorphology and become submerged sand bodies. The unprotected wetlands and estuaries are then subject to the full force and effects of open marine processes.

Natural processes alone are not responsible for the degradation and loss of wetlands in the Mississippi River deltaic plain. Human activities during the past century, and especially within the past 50 years, have drastically impacted wetlands. The seasonal flooding that previously provided sediments critical to building and maintaining the wetlands has been eliminated by construction of massive levees that channel the flow of the Mississippi River for more than 1500 km; sediment that is carried by the River is now discharged far from the coast out near the edge of the continental shelf. The volume of sediment being transported by the Mississippi River and its tributaries to the wetlands has been reduced by as much as 50 percent because of the construction of dams and flood control engineering structures over the past century (Meade and Parker, 1985). Throughout the wetlands, an extensive system of dredged canals and waterways, constructed to facilitate hydrocarbon exploration and production as well as commercial and recreational boat traffic, has enabled saltwater from the Gulf of Mexico to intrude brackish and freshwater wetlands, accelerating their deterioration; dredging and maintenance of this system of canals and channels also impact the wetlands. Localized increases in subsidence associated with the extraction of minerals and fluids in the shallow subsurface and forced drainage to accommodate agriculture and development also contribute to wetland loss throughout the Louisiana deltaic plain (Hunt, 1990). Factors of greatest influence, both natural and anthropogenic, are shown in the table on the next page.

USGS Wetland Studies

In late 1988, the USGS, as part of the National Coastal Geology Program, began a study of wetland processes in cooperation with the U.S. Fish and Wildlife Service (USFWS) and Louisiana State University (LSU) (Williams and others, 1991a). As an extension of the completed Louisiana Barrier Island Erosion Study, conducted to document historical changes in the barriers fronting the wetlands and to increase understanding about the processes responsible for the changes, the Louisiana Wetlands Loss Study focuses on understanding the critical physical processes that cause the extreme rates of

PRIMARY FACTORS AFFECTING LOUISIANA COASTAL WETLANDS

Origin and Evolutionary Development

- Channel switching cycles and high rates of riverine sediment deposition
- Slow-to-modest rates of relative sea-level rise
- Sheltered low-energy environment
- Low-to-modest storm activity
- High biological productivity

Degradation and Loss

Natural Processes

- Sediment starvation due to channel switching
- High rates of subsidence (sediment compact/consolidation)
- High rates of eustatic sea-level rise
- High storm activity
- Erosion of protective barrier islands

Human Activities

- Sediment starvation due to building dams, levees, flood control engineering structures
- Canal and waterway dredging; saltwater intrusion
- Introduced species increasing herbivory activity
- Local subsidence due to extraction of minerals and fluids
- Forced drainage, land reclamation

wetland loss in coastal Louisiana and on evaluating the best management practices to address the losses. The study includes six main elements:

- o Field investigations are being conducted on a basin-wide scale to understand the critical processes causing wetland loss,
- o At specific sites, research is being conducted on the effects and long term utility of various wetlands management activities on the processes,
- o Existing and new baseline data are being compiled and assembled into the Louisiana Coastal Geographic Information System Network (LCGISN),
- o A classification system is being developed to consider geomorphology and process in delineating coastal wetland loss,
- o Effects of Hurricane Andrew striking the Louisiana barrier coast and wetlands on 26 August 1992 are being assessed and quantitatively evaluated,
- o The information and results from these studies are being passed to the user community by means of atlases, reports, maps, newsletters, and workshops.

An ongoing comparative investigation of the effects of critical physical processes and responses in wetlands consists of studies in two separate hydrologic basins that typify two extremes: sediment deficient with badly deteriorated wetlands (Terrebonne Basin-Timbalier Bay and parts of the Barataria Basin) and sediment rich with an emergent and vegetated delta and healthy wetlands (Atchafalaya Basin). Many of the processes and responses being investigated, in relation to widely varying spacial and temporal scales, are shown in Figure 2. Numerous field investigations by the USGS and LSU scientists have been completed along with a study by Roberts and others (1992) which examined the effects of small-scale freshwater diversions from the Mississippi River on brackish marshes adjacent to the levees. Baseline data on meteorological forcing effects, freshwater and saltwater dispersal, fine-grained sediment dispersal, wetland soils development, physical processes of marsh deterioration, and subsidence/soil compaction and sea-level rise continue to be analyzed and synthesized and compiled into the LCGISN for use by coastal resource planning and management agencies.

LCGISN was created to facilitate the identification and exchange of geographic data pertinent to research, planning, and management in the Louisiana coastal zone. To accomplish this mission, LCGISN is developing a spatially indexed cataloging system that will include a framework, procedures, and guidelines for documenting hard copy and digital data such as maps, aerial photography, satellite imagery, videotape surveys, reports, and other coastal-related data.

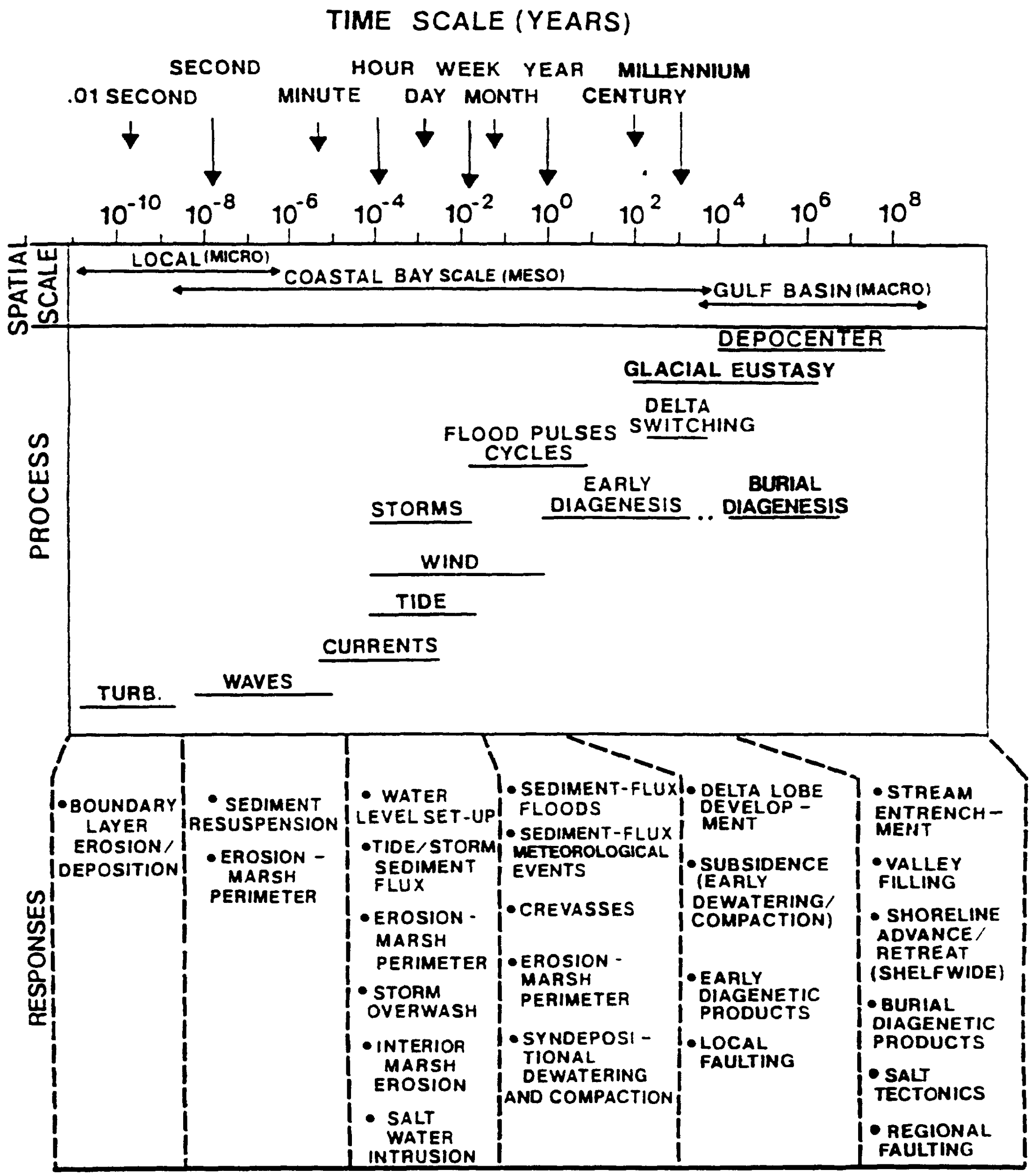

Figure 2. - ***Temporal and spatial relationships of wetland-related processes and responses.***

Since the turn of the century and through the late 1970's, coastal loss in the deltaic plain accelerated to rates of 75 km²/yr. Recently, the U.S. Army Corps of Engineers (USACE) completed a regional analysis of the coastal land loss for the time periods of 1930-1950, 1950-1970, 1970-1980, and 1980-1990. Results suggest rates have decreased in the early 1990's to 50 km²/yr. The USGS with the USACE, LSU, and Argonne National Laboratory is undertaking a further analysis of the just completed delta plain land loss study by

developing a form and process classification system for delineating the causes of coastal land loss. The intent is to develop a spread sheet inventory for each classification scheme to quantify the types and processes of loss. Through this process, the primary causes of loss will be identified and quantified.

Hurricane Andrew directly impacted south-central Louisiana on August 26, 1992, with sustained winds of nearly 200 km/hr and additional studies were immediately initiated to quantify and evaluate the storm's effects. A storm surge of 3.5 m inundated the coast for more than 40 km inland. The barrier islands were hardest hit; more than 40 m of beach erosion occurred in two days. The storm surge completely inundated the islands, stripping nearly 70 percent of the sand from them and cutting more than 25 breaches. The coastal wetlands behind the barrier islands experienced extensive physical destruction as a consequence of the high wave energy superimposed on the storm surge as it flooded the marshes. Wetlands were stripped of vegetation, producing balls and rolled mats of marsh vegetation scattered throughout the storm surge zone. Within the area inundated, a blanket of mud up to 45 cm thick was deposited over tens of thousands of hectares of marsh and shallow bays. This mud blanked will help to nourish the deteriorating wetlands; however, in contrast, it also smothered more than 70 percent of the oyster reefs in the Barataria-Terrebonne Estuary. These studies of the effects of Andrew will continue for another year.

Most immediately, results from the USGS wetland studies are being used to set priorities and design projects by State, Parish, and Federal agencies as part of the CWPPRA activities, currently funded at about $40 million per year.

Summary

Coastal erosion and the deterioration and loss of valuable wetlands are widespread problems of national concern. The delta plain region of south-central Louisiana, however, leads all other regions in land loss due to a combination of natural processes and a long history of human intervention and development. To provide the high quality scientific information necessary to understand and quantify the processes responsible, the USGS, working jointly with Federal, State, and parish governments as well as LSU scientists, has undertaken studies of the coastal wetlands west of the Mississippi River delta. Results of field investigations in the wetlands of the sediment-starved Terrebonne and Barataria basins are being compared with results from similar field studies in the sediment-rich Atchafalaya basin. As interim and final results are obtained, they are published and made available to the coastal scientific, planning, and management community.

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SHORT-TERM WATER AND SUSPENDED-SEDIMENT FLUCTUATIONS IN A LOUISIANA MARSH

John R. Dingler[1]

ABSTRACT

Because the extensive marsh system in southern Louisiana is ecologically and economically important, a high rate of marsh disappearance has generated great concern amongst various local, state, and federal agencies. In general terms, marsh disappearance occurs when the combined rate of regional subsidence and sea-level rise exceeds the rate of inorganic and organic sedimentation. However, the factors that control the rate and timing of marsh sedimentation are not well understood. Of specific interest is whether marsh impoundment, a common marsh-management practice in Louisiana, has any effect on marsh loss.

To determine the timing of and driving forces for sediment suspension and deposition and the effect of impoundment, three self-recording instrument packages were deployed in a section of Louisiana marsh. Two of the packages went into an impoundment and one into an adjacent open, or control, area. A data logger in the package controlled sensors to measure water level, velocity, salinity, and temperature and suspended sediment concentration. At one impoundment site and the control site, weather stations recorded wind speed and direction.

The data loggers ran for at least 15 min, either hourly or 4-times per day, at a 4-Hz sample rate during late May and early June 1992. The package at the control station stopped working after 7 days, but the other two packages ran for 27 days. Data show small temporal and spatial variations in most of the parameters. At the control site, water level had a tidal signature with a range of about 15 cm; at the impoundment sites, there was a non-periodic variation in water level because the flap gate was closed to create a draw-down effect within the impoundment. Conversely, currents were greater at the impoundment sites than at the control site, and greatest at the site adjacent to the flap gate. The current direction at the flap-gate site was toward the flap gate and, thence, out of the impoundment. Suspended-sediment concentration, as measured with optical back scatter sensors, was generally low, indicating that the currents were too weak to put material into suspension. Salinity, which varied only

[1] Scientist, U.S. Geological Survey, 345 Middlefield Road, Menlo Park, CA 94025

slightly over time at all the sites, was highest at the control site, reaching a maximum value of 2.4 ppt.

INTRODUCTION

The wetlands of southern Louisiana, which bound the entire coast and extend inland as much as 80 km, cover almost 10,000 km^2 (Chabreck, 1988). Based on water salinity and associated plant communities, four environmental zones extend inland from the Gulf of Mexico—saline, brackish, intermediate, and fresh—exist within Louisiana's coastal wetlands. Recent estimates of the rate of wetlands loss in Louisiana (Salinas et al., 1986), mostly through the conversion of vegetated land to open water, are as high as 150 km^2/ yr. This conversion results from a complex mix of natural processes and human activities including: regional subsidence (Dozier et al., 1983), a rise in eustatic sea level (Barnett, 1984), and the curtailment of alluvial sediment deposition by levee construction along the Mississippi River (Templet and Meyer-Arendt, 1988). For a marsh to retain its elevation relative to local water levels, the rate of regional subsidence, sea-level rise, and sediment transport out of the area can not be greater than the depositional rate of inorganic silts and organic detritus. Because the volume of inorganic material reaching Louisiana's coastal marshes has been reduced substantially by the Mississippi River levees, the rate of organic accumulation and, subsequently, decay becomes relatively more important in maintaining marshland, particularly the extensive, organic floating mats of vegetation called "flotant" (Russel, 1942) that are common in all but the saline zone. Consequently, processes that disrupt marsh growth can accelerate the formation of open water.

Because the density and type of wildlife species in a marsh largely depend on the quality and quantity of available habitat (Chabreck, 1988), some sections of marsh are managed to improve habitat. The high rate of freshwater marsh deterioration in coastal Louisiana has recently resulted in marsh management procedures being implemented for habitat restoration. The usual management technique is to impound the managed area by surrounding it with a levee and installing a water control structure. However, the effects of impoundments on marsh deterioration are not fully understood. Proponents contend that protection from tidal effects reduces net loss of sediment and organic material (Gagliano and Wicker, 1989). Opponents contend that impoundments have failed to improve growing conditions (Herke, 1979; Cowan et al., 1988). In the simple case, some type of passive control structure, like a fixed-crest weir, restricts water flow into and out of the impoundment to reduce the intrusion of saline water, which is destructive to the vegetation of freshwater marshes, and to maximize the entry of sediment-laden water (Foote, written comm., 1990). A more involved management technique consists of opening and closing a flap gate in the levee following a schedule designed to minimize the entry of saline water and maximize the entry of sediment-laden water. This paper presents a preliminary analysis of measurements taken inside and outside an impoundment during the draw down phase of an experiment to evaluate the flap-gate-control marsh management technique in a section of brackish marsh in coastal Louisiana (Fig. 1).

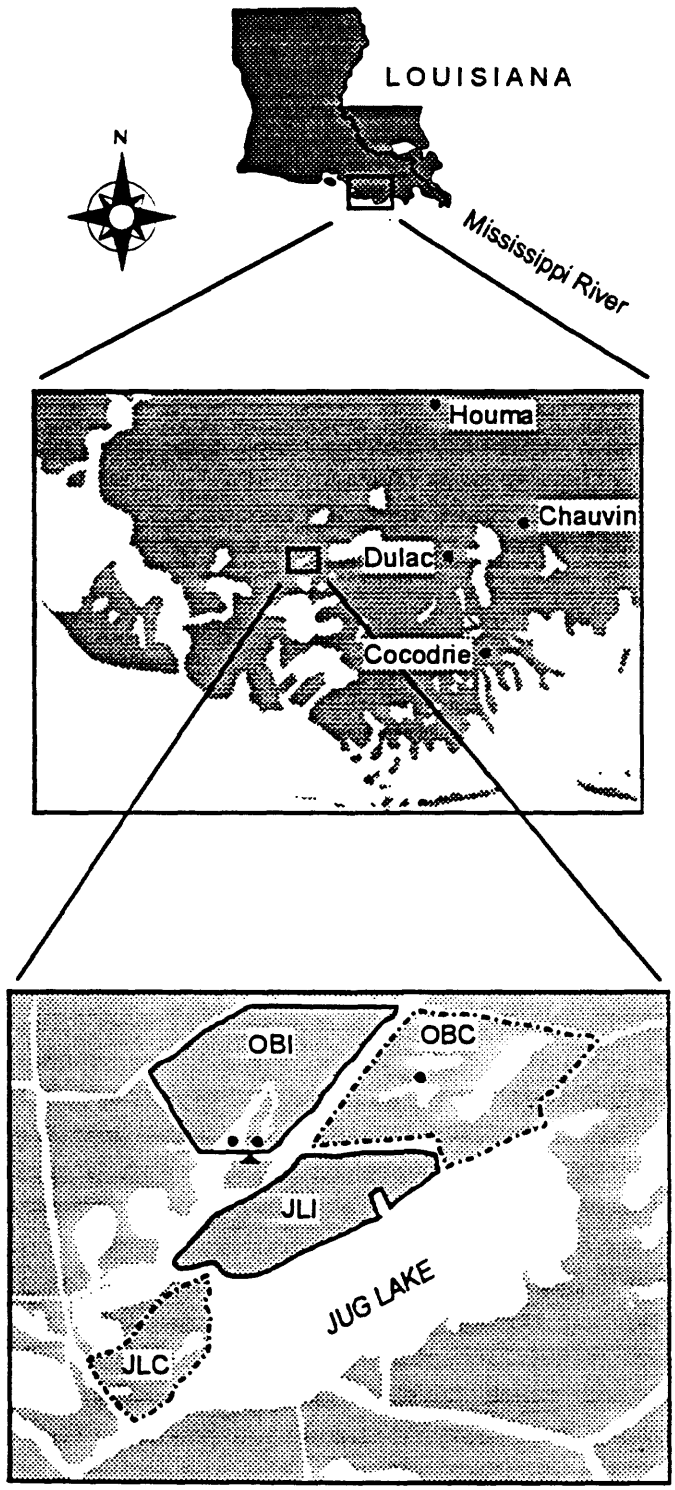

Figure 1. Study area location in the wetlands of coastal Louisiana. OBC, Otter Bayou Control; OBI, Otter Bayou Impoundment; JLC, Jug Lake Control; JLI, Jug Lake Impoundment. In bottom enlargement, solid circles, sampling sites; solid triangle, flap gate; solid lines, levees; broken lines, control boundaries.

Draw down refers to the closing of the flap gate so that water can flow out of the impoundment but not into it. When the water level is higher inside the impoundment than outside, water flows out the flap gate; when the water is lower inside the impoundment, there is no flow through the flap gate. When the flap gate works properly during draw down, the water can only enter the impoundment as rain or as seepage through the levee. The goal of drawing down the water inside the impoundment is to increase plant growth by improving the oxidation-reduction potential of the sediment in hopes of lowering sulfide concentrations and by stimulating sunlight-induced germination and tillering. For that reason, draw down takes place in the spring to coincide with emergent plant germination, growth, and re-establishment (Foote, written comm., 1990).

SETTING

As part of a joint U. S. Fish and Wildlife Service and U. S. Geological Survey study of sedimentation patterns in open and impounded marsh, three sampling stations were installed just north of Jug Lake, which is west of Lake de Cade (Fig. 1) in the Terrebonne Basin of southern Louisiana. The study area is 22 km north of the Gulf of Mexico. In that area the marsh is brackish to intermediate and mostly consists of partially rooted, densely vegetated mats that either rest upon or float above the underlying organic-rich sediments. There is a small tidal signature of approximately ten centimeters in the area, but the primary changes in water level result from wind-driven surges, flooding, and, in the impoundment, controlled draw down. Except along spoil banks where trees and bushes appear, the marsh in the vicinity of the study area is dominated by *Spartina patens* (wiregrass), a low-lying grass that grows in dense clumps and, thus, gives the marsh a hummocky appearance, and *Scirpus olneyi* (Olney's bulrush).

The study area was subdivided into two sets of tracts—Jug Lake and Otter Bayou—each with an impounded and an open, or control, tract (Fig. 1). The Otter Bayou impoundment has a maximum east-west length of 1500 m, a maximum north-south length of 900 m, and an area of 0.7 km^2. Two of our sampling stations were located in the Otter Bayou impoundment (from east to west they were named OBI1 and OBI2) and one in the Otter Bayou control tract (OBC). Each of the three sampling stations consisted of an open platform situated in shallow water amidst the vegetation. The impoundment stations were situated 50 to 100 m north of the south levee with OBI1 being directly opposite the flap gate in the south levee. Although the two impoundment stations were only a couple of hundred meters apart, the open-water areas they were in were only connected by a long, circuitous, shallow channel that ran through the center of the impoundment. The control station was located in the center of its tract in a channel connecting two small open-water areas.

The primary purpose of the sampling program was to collect data to relate water level, salinity, currents, temperature, and suspended-sediment concentration to changes in meteorological conditions, which were continuously monitored at OBI2 and OBC. Each station had a data logger that controlled an absolute pressure sensor to measure water level, a two-axis electromagnetic current meter to measure water motion, a conductivity probe to measure salinity, and an optical backscatter (OBS) sensor to measure turbidity. OBC also had a high-frequency acoustic water-level sensor, and OBI2 an acoustic water-level sensor and a water-temperature sensor. OBC and OBI2 had weather stations consisting of cup anemometers mounted 2 and 6 m above the normal water level and one direction vane. Each data logger sampled at a frequency of 4 Hz for about 15-minutes every hour for the first day and a half and every 6 hours for the remainder of the experiment.

RESULTS AND DISCUSSION

The data loggers were programmed to operate hourly from 0000 CDT on 20 May 1992 until 1200 CDT on 21 May and daily at 0000, 0600, 1200, and 1800 CDT thereafter. OBC malfunctioned between 1200 and 2000 CDT on 20 May and failed after 1200 CDT on 26 May. The impoundment stations operated until their removal on 25 June, although one axis of the current meter at OBI2 failed in early June. Consequently, conditions in- and outside of the impoundment can only be compared over a short time period (Fig. 2), but impoundment variability can be assessed for a period of more than one month (Fig. 3). Records taken at 1200 CDT (noon) every day are used herein to show long-term variations.

Continuous recording of wind speed and direction commenced on 19 August 1992. One Hertz samples were averaged over 10 minutes, and the mean value and its standard deviation recorded. Throughout the study period, winds were gentle and variable. For example, the average 10-minute-average wind speed at the upper anemometer at OBI1 was 3.3 m/s with a standard deviation of 1.6 m/s, and the maximum speed was 9.2 m/s. The wind mostly blew from the south with the average direction being ~170 ±80°.

Both pressure sensors and acoustic water-level sensors respond to changes in water level, but the pressure sensors also detect changes in atmospheric pressure. The hourly pressure and acoustic water-level records for OBI2 (Fig. 2A,B) show an example of this response. The pressure record shows a large drop in water depth between 1100 and 1200 CDT on 20 May, but the acoustic water-level record shows no change. That change, which also shows up on the pressure record from OBI1, reflects the passage of a weather front through the area. The associated change in barometric pressure produced a change in the pressure signal without a change in water level.

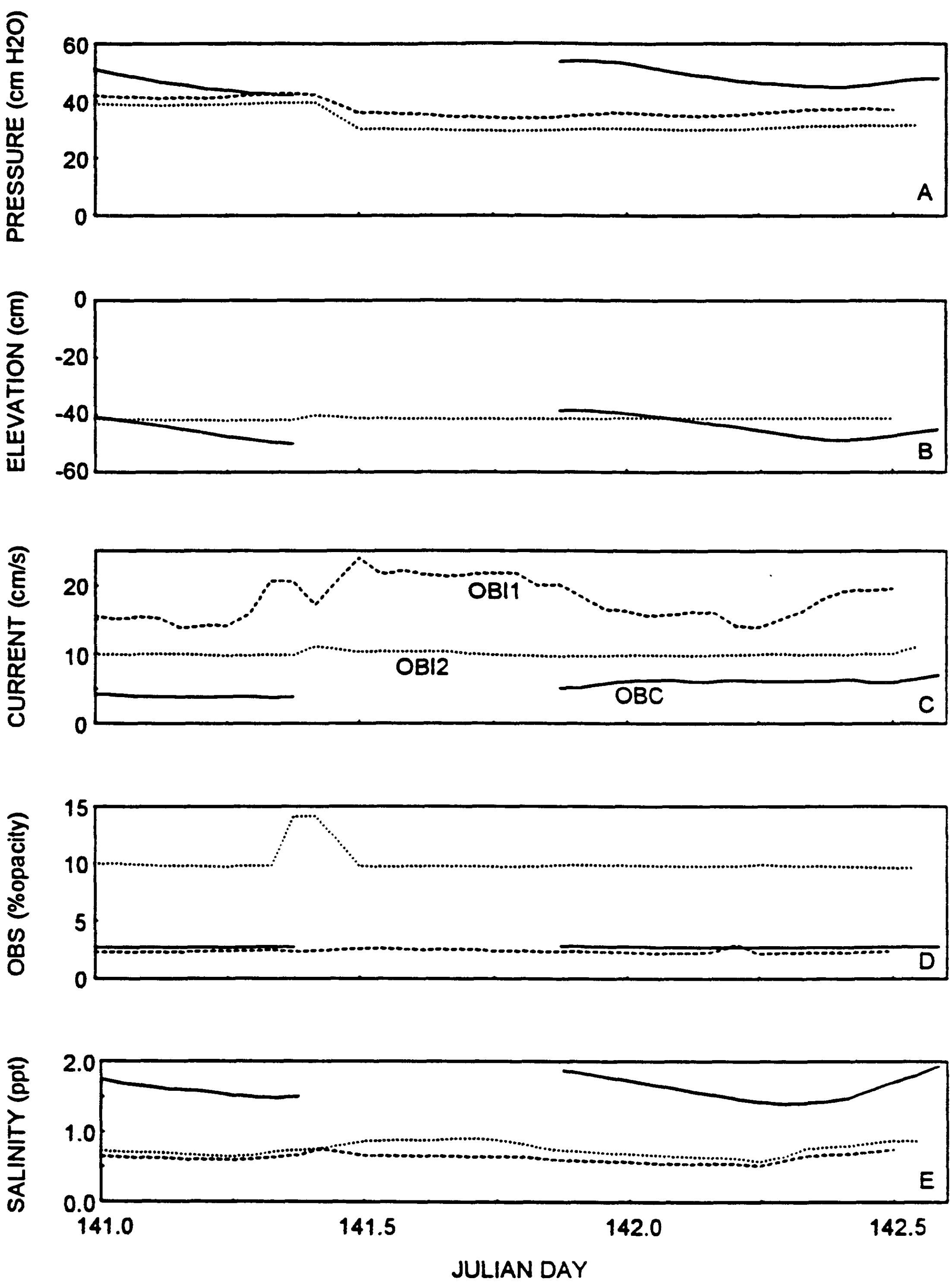

Figure 2. Summary plots of hourly data from Otter Bayou sites OBC (control), OBI1 (impoundment near flap gate), OBI2 (impoundment west). OBC line broken where data missing. Julian Day 141 is 20 May 1992. Elevation in (B) refers to water height relative to acoustic water-level sensor.

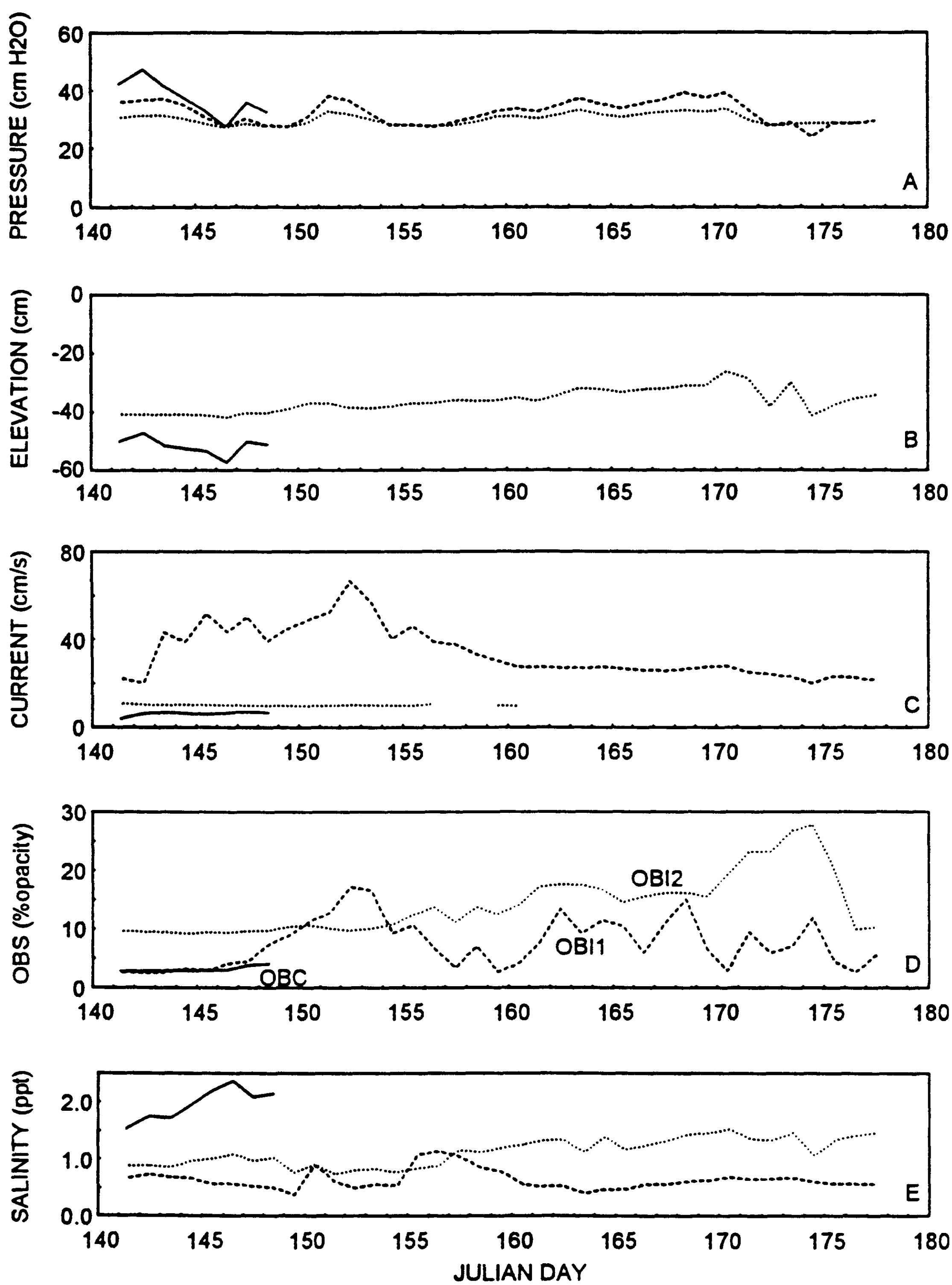

Figure 3. Summary plots of noon data from Otter Bayou sites OBC (control), OBI1 (impoundment near flap gate), OBI2 (impoundment west). OBI2 line broken where data missing. Julian Day 140 is 19 May 1992. Elevation in (B) refers to water height relative to acoustic water-level sensor.

Comparing the noon pressure and acoustic water-level records from OBI1 and OBI2 (Fig. 3A,B) further demonstrates the large effect of atmospheric pressure on water-level measurements by absolute pressure sensors in shallow water. The two pressure records have the same pattern, which shows that pressure was changing in the same manner at both sites. However, the acoustic water-level record shows a different, less variable response. The result is that the slight rise in water level in the impoundment (the acoustic water-level sensor measures its elevation relative to the water surface so that a decrease in elevation represents a rise in water level) during the first 30 days of the study is masked on the pressure record by atmospheric pressure fluctuations that mimic long term water-level oscillations.

Currents were always stronger in the impoundment than at the control station, and strongest at OBI1, which was adjacent to the flap gate (Figs. 2C and 3C). The direction of the current at OBI1 was toward the flap gate, indicating that water was continually flowing outward. This is puzzling because the flap gate should have only let water out when the water level was higher in the impoundment than outside of it. Because of the tidal fluctuations outside, there should have been times when the water level in the impoundment was lower than the outside level, and flow should have ceased. Because the acoustic water-level sensor showed that the impoundment water level increased slightly during most of the study, water must have been continually entering the impoundment as seepage through the levee or as rain or both.

Flow at OBI2 was much lower than at OBI1 and much less variable (Figs. 2C and 3C). This difference was probably due to two factors: (1) OBI2 was in the center of a large, shallow open-water area while OBI1 was at one end of a channel leading from the flap gate, and (2) the two sites were only connected by a shallow, circuitous channel so that water could only move slowly from one area to the other.

Turbidity was measured optically (Figs. 2D and 3D), which meant that anything in the water column or covering the sensor window would affect the sensor readings. During the day and a half of hourly measurements, the water opacity remained constant at each site, but the values varied from site to site. The opacity level was ~10% at OBI2 and ~3% at OBC and OBI1. The higher value at OBI2 could reflect a difference in siting because it is located in the middle of a large open-water area while OBI1 and OBC are located in more constricted areas. During station deployment, we observed high concentrations of lightly rooted vegetation at OBI2 but not at the other two sites. If that vegetation grew thicker or started to drift, it could cover the sensor and, thus, increase the opacity.

The long-term fluctuations in opacity at the two impoundment stations are not understood. Except for the opacity peak at OBI1 at noon of Julian Day 152 (Fig. 3D), there does not seem to be a correlation between opacity and current. Again, one possibility is interference from drifting vegetation.

Salinity was higher at OBC than at either impoundment station (Figs. 2E and 3E). During the first day and a half, salinity was positively correlated with water level at OBC meaning that salinity increased when the tide rose (Fig. 2B). However, during the rest of the 7 days that OBC functioned, the two were negatively correlated meaning that salinity increased when water level fell (Fig. 3B). At OBI2 salinity and water level were positively correlated, which could indicate that the water-level rise in the impoundment was caused by the seepage of more saline water from outside the impoundment.

CONCLUSIONS

The purpose of this study is to understand the relationship between driving forces and water response in a Louisiana marsh. Preliminary analysis of a variety of water measurements inside and outside of an impoundment during a period of draw down indicates that:

- The levees and flap gate are able to maintain less saline water inside the impoundment, which is one of the major purposes of the flap-gate-control system.
- Currents are stronger inside the impoundment, especially near the flap gate because water is continually flowing out of the impoundment. Consequently, water must be continually entering the impoundment as seepage through the levee and rain or eventually the water level in the impoundment would equilibrate with the outside water level and flow would stop. Instead, water level rose slightly during the study period.
- Water-level measurements using absolute pressure sensors can have a significant atmospheric pressure component. Independent measurements of atmospheric pressure, use of differential pressure sensors, or use of other types of water-level sensors are required to accurately determine water-level changes. If salinity varies significantly, its effect on water density would also have to be considered when determining water level.
- Turbidity varied in a not understood manner, although drifting vegetation could be responsible for some of the observed variation in opacity.

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Impacts of Winter Storms on Sediment Transport within the Terrebonne Bay Marsh Complex

Stephen P. Murray, Nan D. Walker and Charles E. Adams, Jr.[1]

Abstract

Winter storms provide important controls on erosion and deposition in coastal Louisiana. An unanswered question of the Louisiana land loss problem is how these storms impact sediment flux within the numerous marsh-bay systems. In an attempt to improve our knowledge in this area, a major data collection exercise was launched during the 1990, 1991 and 1992 winter seasons. This paper discusses the results of two field experiments in the Bayou Chitigue/Lake Barre region, where deteriorating marshland is connected, via a major bayou, to an embayment of Terrebonne Bay. Four sites were instrumented with electromagnetic current meters and Downing OBS^{tm} nephelometers for measuring suspended sediment. During the first experiment in December 1990, sediment was resuspended in the bay by strong winds before, during and after a weak frontal passage, then carried into the bayou by strong flood tidal currents, yielding a net sediment *import* to the marsh of $\sim 3.6 \times 10^6$ kg. Computations with a wave-current interaction model confirmed that waves and currents present in Lake Barre both prior to and during frontal passage were adequate to resuspend the entire range of sediments found there. During the November 1991 experiment, strong northerly winds from 3 successive winter storms caused erosion and resuspension of sediments in the bayou, which were transported to the bay by strong ebb tidal currents. In contrast to the first experiment, $\sim 3.8 \times 10^6$ kg of sediment was *exported* from the marsh environment into the bay. Our results demonstrate that sediment flux events in marsh-coastal bay systems are highly episodic and controlled by complex interactions between wind speed, wind direction and fetch, bathymetry, tidal currents, water level and sediment availability.

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[1]Coastal Studies Institute, Louisiana State University, Baton Rouge, Louisiana 70803.

Introduction

The subsidence of Louisiana's wetlands in conjunction with a decrease in sedimentation has caused the greatest persistent land loss problem in the United States. Louisiana contains 41% of the U.S. wetlands and, since 1955, these wetlands have been converting to open waters at a rate exceeding 50 mi^2/year (Craig et al, 1980; Gagliano et al, 1981; Walker et al, 1987). Most studies of wetland loss focus on changes over relatively long time scales of months or years such as mapping shoreline retreat rates or studying changes in open water areas from aerial photographs or satellite images. These morphological changes should be related to changes in particulate sediment flux in the channels and embayments which exchange water, salt and sediment between the bays and the marshlands. Thus, we consider it of fundamental importance to understand the hydro- and sediment dynamics of the marsh-bay boundary region and within the channels that serve as arteries into the marsh. Relatively few quantitative studies of this problem are available for guidance (e.g. Orson et al, 1990; Boone, 1978). Terrebonne Bay, 60 km west of the Mississippi delta, is one of those areas experiencing serious wetland deterioration (for a map of Terrebonne Bay see Figure 1 in Kuecher et al, this volume). This deterioration is consistent with tide gauge records which indicate a relative sea level rise of 1.09 cm/year at Houma in the central Terrebonne basin (Penland et al, 1989).

Our objectives in this paper are (a) to assess the importance of tidal and storm driven events in transporting sediment in the marsh channels and (b) to assess the resuspension of sediment by wind driven waves in this type of shallow bay environment. The study area for the sediment flux experiments is located along the northern shore of Terrebonne Bay, a shallow (2m) estuary of the bar built type. Exchanges between Terrebonne Bay and the Gulf of Mexico are vigorous despite the narrow passes through the barrier islands which act to maintain salinities of 10 to 25 ppt in the bay. An embayment of Terrebonne Bay (Lake Barre) and a contiguous channel into the marsh (Bayou Chitigue) were instrumented for this study (Figure 1). Site 1 was located in Bayou Chitigue and Sites 2 through 4 were located within Lake Barre in water depths less than 2 meters. The four sites were instrumented with arrays of Marsh-McBirney electromagnetic current meters and Downing optical back-scatter sensors, for the estimation of suspended sediment concentrations. In addition; conductivity, salinity, pressure (water level), and water temperature measurements were obtained to further quantify the critical physical processes. For this paper, the results from two early winter deployments will be discussed as they reveal the major processes controlling sediment transport in this wetland environment. Our analysis here will be restricted to sites 1 and 2. A schematic layout of the instrumention at these sites is shown in Figure 2.

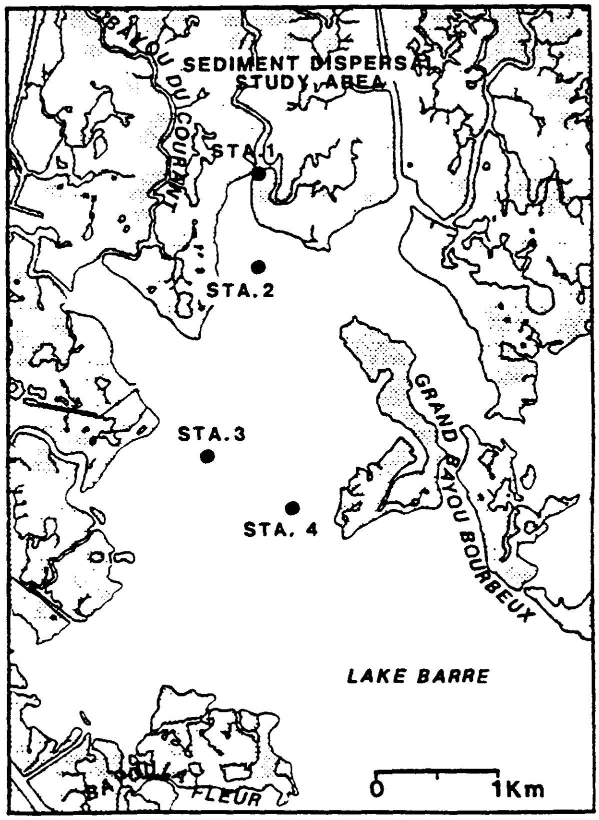

Figure 1. Location map of instrumented sites in Lake Barre and Bayou Chitigue.

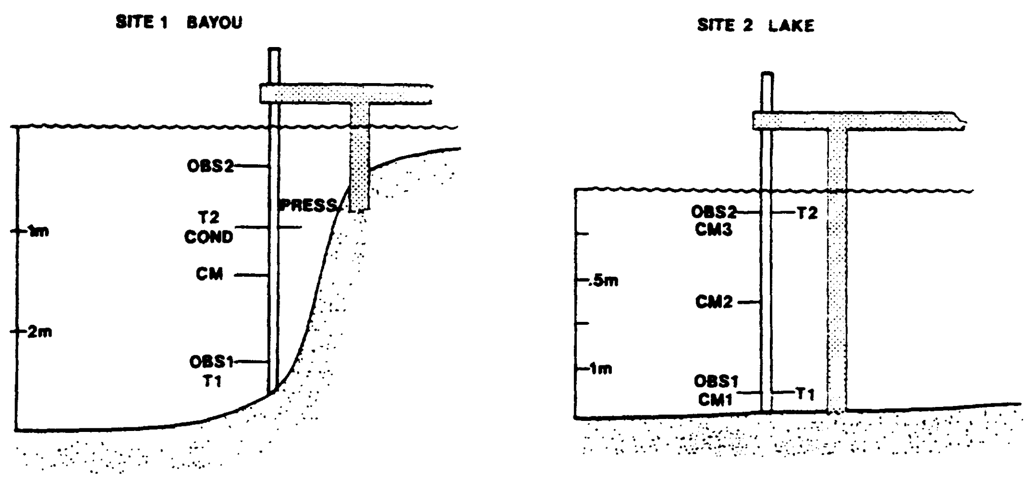

Figure 2. Schematic diagram of instrumentation at sites 1 and 2.

The Experiment of December 11-21, 1990

Figure 3 shows the north-south component of the current at sites 1 and 2 over the 10-day experiment. Positive currents are northward or directed into the marsh. A remarkably strong diurnal tidal periodicity was a dominant feature with flood currents reaching 40 cm/sec and ebb currents reaching 60 cm/sec in Bayou Chitigue. At site 2, in Lake Barre, currents decelerated rapidly to ± 15 cm/sec.

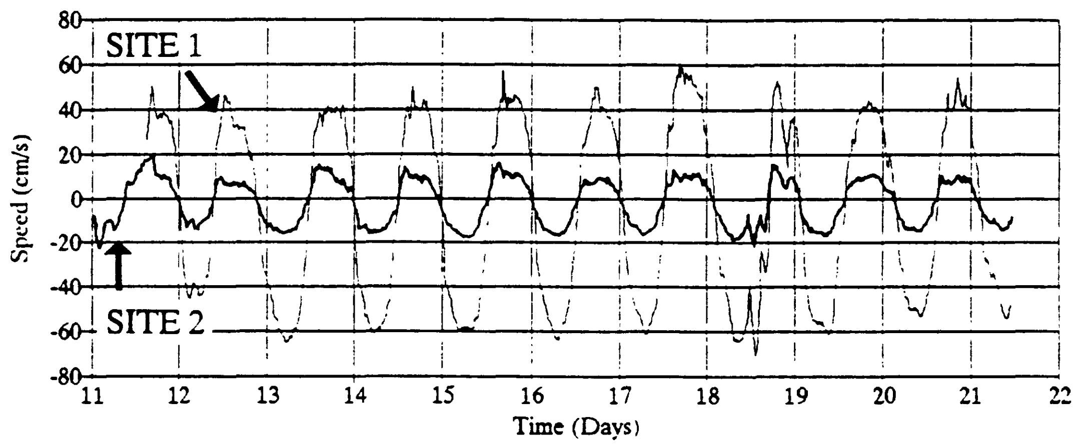

Figure 3. North-south component of currents measured at sites 1 and 2 during the December 11-21, 1990 experiment. Positive currents are northward or into the marsh.

To determine the subtidal or residual flow these time series were passed through a 40 hour digital filter (de-tiding) and several strong net outflow events became evident (Figure 4a). It is instructive to compare this outflow curve with the local water level. Unfortunately, our on-site pressure (water level) data was not available and we used the Cocodrie gauge data (Figure 4b) which is located 12 km to the southwest. Nonetheless, a comparison of Figures 4a and 4b shows, as expected, a strong qualitative correlation between subtidal currents at Bayou Chitigue and subtidal water level fluctuations at Cocodrie. A progressive wave type of relationship exists between bay water levels and bayou channel currents; i.e. high water level in the bay produces strongest inflow currents and low water levels produce strong outflow currents. Note the inflow events labelled A, B, and C on Figure 4a all occurred within 6 to 12 hours of high water events A', B', C' in Figure 4b. Outflow events marked D and E on Figure 4a occurred almost simultaneously with low water levels D' and E' on Figure 4b. The marked strength of outflow event E could be explained by rainfall in the marsh water shed or a local difference in water level between Cocodrie and Bayou Chitigue. The secondary events labelled a', b', and c' were not well correlated and may be explained by small scale differences in water level between Lake Barre and

Cocodrie. It appears reasonable to conclude that the currents measured at site 1 are proportional to transport fluctuations across the entire channel, as the transport fluctuations must result from the sea level fluctuations which do correlate well with site 1 currents.

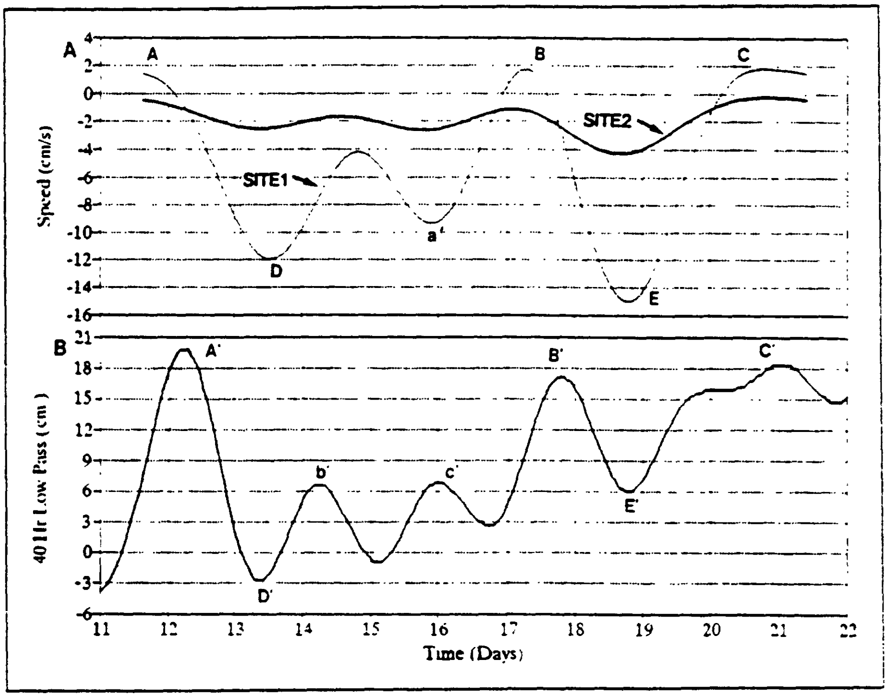

Figure 4a. Subtidal north-south currents (40 hour low pass filtered) at sites 1 and 2 from December 11-21, 1990. 4b. Subtidal water level at Cocodrie over the same interval.

Suspended sediment concentrations (inorganic and organic material) were obtained by calibrating the optical back-scatter sensor (OBS) data with field measurements of concentrations of suspended particulates. One-liter water samples were collected in the field simultaneously with OBS instrument measurements. The concentrations of suspended solids in the field samples were determined in the laboratory by filtering through a 1.2 μm glass fiber filter. The filters were dried at 60°C for 12 hours and reweighed. These values were used in combination with the field OBS values to develop a calibration equation for suspended solids. An acceptable linear correlation (r^2 = 0.81, 114 degrees of freedom) was obtained with a 95% confidence interval of $\pm$ 50 mg/l.

Figure 5b shows the time series of suspended sediment (C_S) during the December 1990 experiment at sites 1 and 2. The interval December 11-14 was characterized by consistently low values of C_S at both sites. It is notable that these low values persisted despite the fact that current speeds reached 60 cm/sec in the channel and 15 cm/sec at site 2 (Figure 3). Elevated levels of C_S appeared

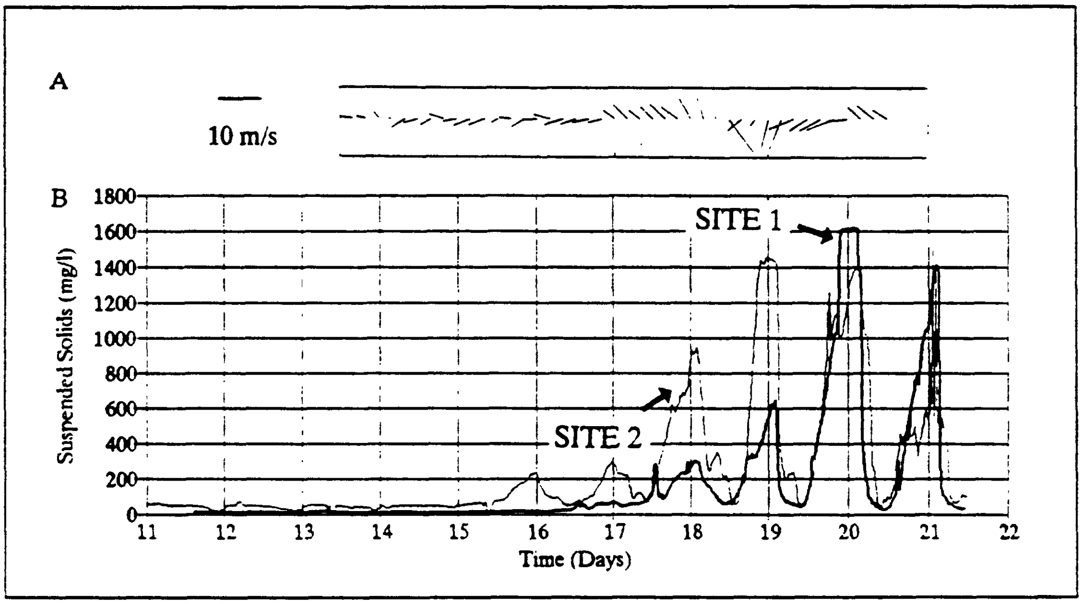

Figure 5a. Wind vectors in Terrebonne Bay over the same interval. 5b. Suspended sediment (C_S) at sites 1 and 2.

first at site 2 by mid-day on December 15 followed by elevated levels at site 1 in the channel more than a day later. This suggests that the bay, rather than the marsh, was the source of sediment. Pulses of high C_S continued with an obvious daily periodicity such that high C_S pulses were associated with flooding currents. Ebb currents from the marsh brought very low turbidity water passed sites 1 and 2, as seen by comparison with the tidal currents shown in Figure 3.

What caused the abrupt change in the regime of suspended sediment? The answer apparently lies in a subtle interplay between wind speed, wind direction, the local topography, and the tidal currents. Figure 5a shows the wind velocity vectors measured over Terrebonne Bay (data courtesy of S.A. Hsu). Wind behavior from December 11-13 is inferred from another station at Isles Dernieres. Winds from December 11-14 were not only weak but were from the east and east- northeast making the fetch at site 1 essentially zero, and only 0.5 km at site 2. Short period wind-driven waves capable of resuspending bottom sediment were absent. On-site observations by our technicians during this period noted 'an essentially flat water surface with water clarity that had not been seen in many years.' Fortunately, for our brief experiment, winds began to shift occasionally to ESE late on December 15 apparently generating the short waves necessary to initiate sediment resuspension.

Late on December 16 winds began to blow more steadily from the southeast and south-southeast extending the effective wave fetch at site 2 to at least 3-5 km. This set-up favorable wind event is clearly seen in the 13 cm rise in the de-tided water level on December 17 (Figure 4b). Sediment concentrations (Figure 5b) rose to over 900 mg/l at site 2 by 0200 hours on December 18. This sediment rich water was then advected by the flood tidal currents into the bayou channel where high C_s values were recorded at site 1. Inspection of Figures 3 and 5b indicates that the ebb tidal current carried water of comparatively low C_s back into the bay, implying a net gain of sediment for the marsh complex during this SE wind episode.

A weak cold front pushed rapidly through the area around noon on December 18 . Local winds shifted and blew from the north at -8 m/sec for about 10 hours (Figure 5a). The ebb tidal current was prolonged (Figure 3) and the mean current (Figure 4a) showed a strong outflow pulse that lasted for 2 days, while sea level dropped 10 cm (Figure 4b). Despite the strong north winds, sediment concentrations remained low on the ebb tide as relatively clear marsh water was advected past the OBS sensors at sites 1 and 2. However during the flood tide current (about midnight of December 18) turbid water, resulting from strong winds in Lake Barre, were advected north towards the marsh past the sensors. Continued strong winds (even though from the NE) on December 19 agitated Lake Barre enough to cause very high C_s values (1600 mg/l) at both sites 1 and 2 again during the flood tidal current late on December 19. During the ensuing ebb tide outflow, current suspended sediment values decreased dramatically again.

This persistent pattern of high C_s during flood currents and low C_s during ebb currents, independent of wind direction, implies a net transfer of sediment from the bay (Lake Barre) into the marsh complex.

Sediment Flux into the Marsh

To quantify sediment flux, Q_s, through the channel cross-section at site 1 we compute $Q_s = v\ C_s\ A$ with the current speed v in m/sec, C_s expressed in kg/m^3, and the channel cross-sectional area at site 1, $A = 134m^2$. Figure 6 shows the time series of sediment flux plotted together with the along channel current speed. The episodic nature of the sediment flux associated with the flood tidal current is noteworthy. Sediment fluxes into the marsh peaked at 90 and 60 kg/sec on December 20 and 21. Smaller, short duration, sediment fluxes out into the bay were only 10-15 kg/sec. Integrating over the 10-day experiment there was a net flux into the marsh of 3.5×10^6 kg of sediment. Of this amount 2.02×10^6 kg or 56% occurred in the 13-hour interval from 14:00 hrs on December 19 to 03:00 hrs on December 20. It is fundamental to note that there was a consistent net outflow of water from the marsh over the period but a large net influx of sediment. Net sediment flux must be computed from the covariance of speed and sediment concentration. The product of the mean current, over a tidal cycle, and the tidal average of C_s would give completely erroneous results.

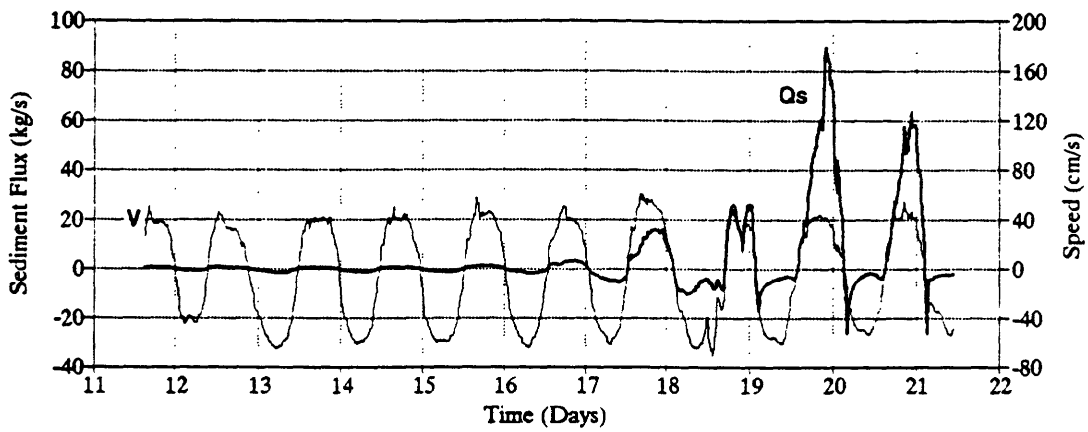

Figure 6. Sediment flux (Q_S) through the channel cross-section at site 1 - Bayou Chitigue. Also plotted is the north-south current component (v) for comparison.

The November 1991 Experiment

Three winter storms passed over the study site during the November 1991 experiment bringing strong northerly winds of 10-15 m/s which, in each event, lasted one to two days (Figure 7a). In response, a net outflow of water was experienced in the bayou, with episodic outflow events occurring on November 8, 20 and 23 (Figure 7b). Maximum current speeds of 100-125 cm/s resulted from the first two winter storms, twice the values observed in the earlier experiment. As during the December 1990 experiment, currents were similar in character but much weaker in Lake Barre (see site 2). The subtidal Cocodrie water levels (Figure 8) were well correlated with the subtidal currents in the bayou, lowest water levels coinciding with strongest outflows in the bayou. During the first and second outflow episodes, outgoing tidal currents were augmented by strong northerly winds accompanying the winter storm events (Figure 7a). In the third case, the onset of northwesterly winds of 10-15 m/s occurred on an incoming tide. The current meter record suggests that the northerly winds efficiently inhibited flood tidal currents in the bayou and, in fact, resulted in premature ebb tidal currents, essentially reversing the flow within the bayou! The subtidal outflow was maximized on November 23 as a result of the abnormally prolonged period during which ebbing currents drained the bayou. Not surprisingly, water levels at Cocodrie reached a minimum during the third storm event (Figure 8).

Extremely high concentrations of suspended sediment occurred at site 1 on November 8 (after passage of the first cold front), with peak values reaching 2000 mg/l for a short period of time (Figure 9b). There was a six-hour lag

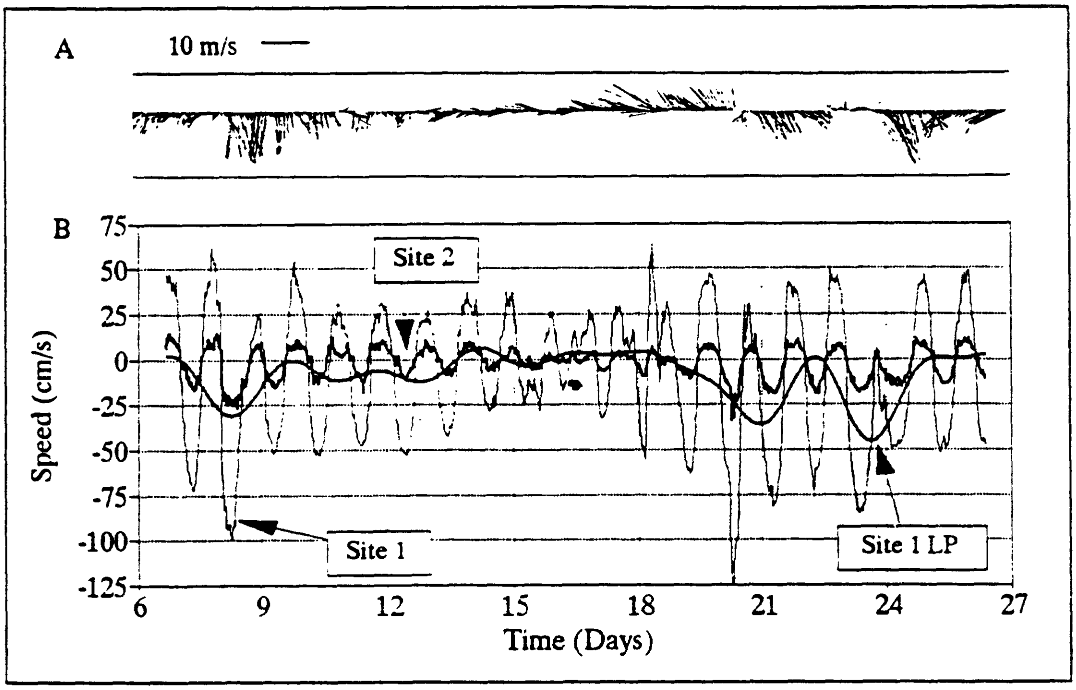

Figure 7a. Wind vectors at Grand Isle, Louisiana during the November 1991 experiment. 7b. North-south component of currents at site 1 and 2 from November 6-27, 1991 and the subtidal (40 hour low pass filtered) currents at site 1. Negative values indicate flow out of the bayou into Lake Barre.

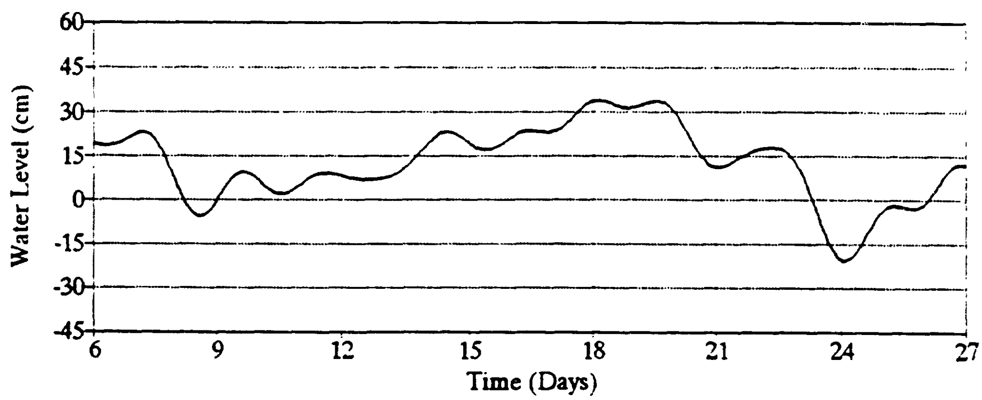

Figure 8. Subtidal water levels at Cocodrie from November 6-27, 1991.

between initiation of the strong northerly winds and the precipitous jump in suspended sediment concentrations which, in sharp contrast to the earlier experiment, coincided closely in time with the strongest outflow from the bayou (80-100 cm/sec). The field team observed that resuspension of sediment along the almost subaerial channel flanks by small wind-waves played an important role in sediment resuspension within the bayou. This high sediment flux event lasted eight hours, with turbidity levels returning to pre-event levels with the next incoming tide. On the following ebbing tide, suspended sediment levels again increased as the strong northerly winds persisted. Turbidity at site 2 was an order of magnitude lower than that measured in the bayou suggesting that considerable sediment dispersal and/or deposition was occurring in the lake.

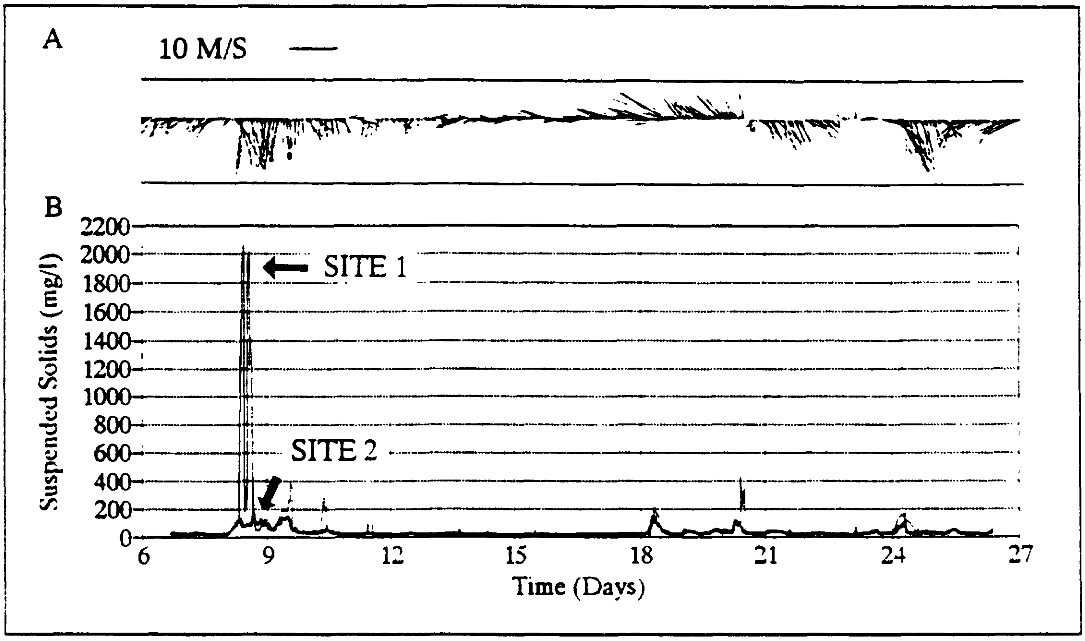

Figure 9a. Wind vectors at Grand Isle, Louisiana, November 6-27, 1991.
9b. Suspended sediment (C_S) at sites 1 and 2.

Under the influence of relatively weak easterly winds from November 12 through 17, sediment concentrations were negligible both in the bayou and lake (Figure 9b). As the wind shifted to southeast on November 18 (Figure 9a), sediments were resuspended from the lake bottom for a short period of time and transported via unusually strong flood-tidal currents pass the site 1 sensor (Figure 9b). With the passage of the next winter storm on the 20th, turbidity levels increased in the lake and in the bayou. As during the first event, northerly winds caused resuspension of sediments within the channel and relatively high turbidity levels were experienced at Site 1 during the strongest wind-augmented ebb-tidal current period on the 20th. Then again on the 24th, movement of a frontal system over the study site brought strong northwesterly winds similar to those experienced on the 8th (Figure 9a) and turbidity of both bayou and bay waters increased somewhat. Although the wind speeds on this occasion were similar in strength to those on the 8th, the directions were northwesterly rather than northerly and perhaps this direction shift was less favorable to sediment resuspension within the bayou.

Sediment Flux out of the Marsh

Figure 10 depicts sediment flux during the three-week experiment. The first winter storm caused a major pulse of sediment to exit Bayou Chitigue with fluxes greater than 100 kg/s lasting for several hours. For 15 hours, sediment exited the channel, resulting in an export from the marsh environment to the lake of 2.5×10^6 kg. Over the three-week period, the net sediment flux was 3.8×10^6 kg, most of which was exported from the bayou during the first winter storm event. The two storms later in the month, on the 20th and 24th, were

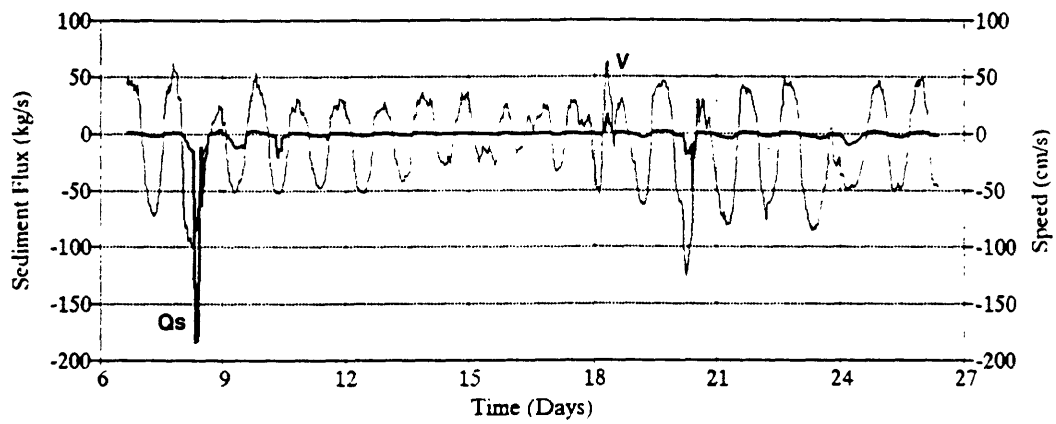

Figure 10. Sediment flux (Q_s) through the Bayou Chitigue channel cross-section. Also plotted is the north-south current component (v) for comparison.

insignificant in comparison. Several explanations are proposed to account for these results. Winds during the first event were primarily out of the north, aligning well with the north-south oriented bayou. Wind-waves, generated along both channel flanks, efficiently resuspended sediments from the channel's banks. Another consideration is the cohesiveness of the sediment which affects its susceptibility to erosion and resuspension. The observations suggest that sediment was either more available during the first storm or more easily eroded. It is notable that prior to this experiment a prolonged winter storm influenced the region from November 2 through November 5. It is plausible that this event had an impact on the amount of sediment and/or erodability of sediments in Bayou Chitigue during the first winter storm of our experiment. Perhaps the strong wind-augmented ebb-tidal currents on November 8 and 9 transported most of the easily erodable material into the lake, leaving less loose material for the later storms. In addition, during the six-day calm period between the first and second storm, some algal binding of the sediments may have occurred, making sediments less susceptible to resuspension.

Sediment Resuspension Processes

The two experiments discussed above clearly point out the important role of sediment resuspension in the marsh-bay environment. The level of bottom stress needed to resuspend fine-grained sediment is dependent upon a number of obvious physical properties including grain size, mineral and organic composition, water content, and depositional history (Young and Southard, 1978). Numerous laboratory studies have been conducted to determine sediment resuspension thresholds under a variety of site-specific conditions (Partheniades, 1965; Einsele et al, 1974; Lonsdale and Southard, 1974; and others). Difficulties remain, however, as Young and Southard (1978) found that laboratory experiments yielded critical erosion velocities that were greater by a factor of two than those determined from the same sediments in situ. Moreover, the spatial variability of natural sediments in wetland environments suggests that extrapolation of critical parameters determined at a site to others in the general area could lead to significant errors in calculations of transport rates. In this context the role of waves and currents in the resuspension process is examined in a limited time frame.

Bathymetric and sediment surveys were conducted in Lake Barre in January 1992. Thirty-one samples, representing the uppermost 1 cm of the sediment column, were analyzed in the laboratory to provide measures of the sand, silt, and clay sediment fractions. The sand component was further analyzed for quantities of sand in the various size fractions as represented by whole phi units. The laboratory analyses indicate a sediment cover within Lake Barre that is rich in the sand component and deficient in the finest materials (clay) (Figure 11). The relative proportions of sand (46.4%), silt (37%), and clay (16.6%), suggest that the sediment would be classified, for the most part, as non-cohesive. Therefore, standard analytical techniques available for non-cohesive sediments should be adequate for establishing criteria for its resuspension.

To examine sediment resuspension processes in Lake Barre under a variety of forcing conditions, water turbidity data were examined for the period December 17-21, 1990. These data were normalized with the station maximum, and thus give only relative measures of turbidity. The turbidity information (Figure 12) represents conditions typical of a frontal event consisting of several days of moderate pre-frontal winds from an easterly direction followed by strong winds from the northwest. Superimposed on the turbidity data are outputs of a wave-current interaction model (Grant and Madsen, 1979). Model inputs included observed currents at the four stations plus surface gravity wave hindcasts based on observed wind patterns during the period and small amplitude wave theory. Horizontal lines in Figure 12 represent critical erosion velocities for fine sand (upper line) and coarse silt as determined by the Shields criterion.

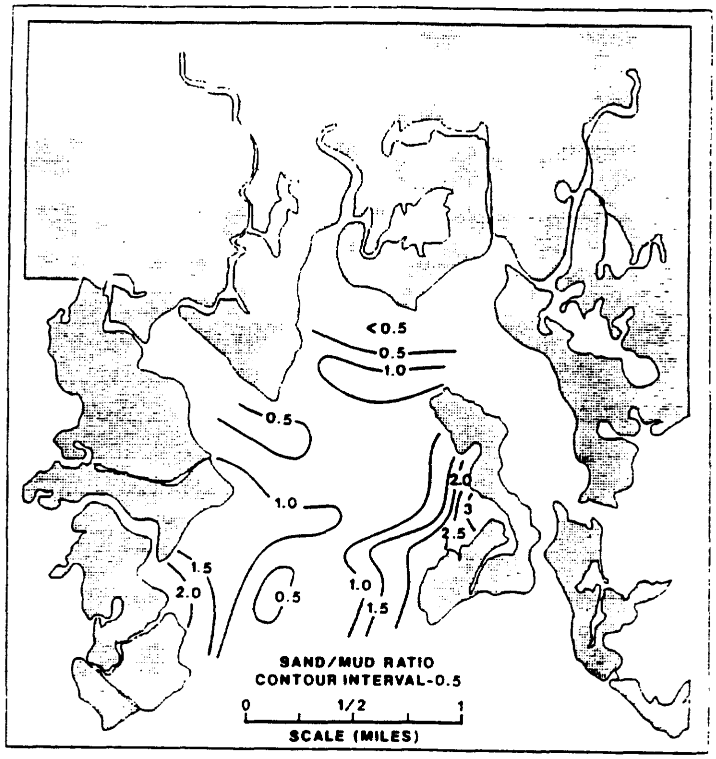

Figure 11. The sand/mud ratio of the upper 1 cm of Lake Barre sediments in January 1992.

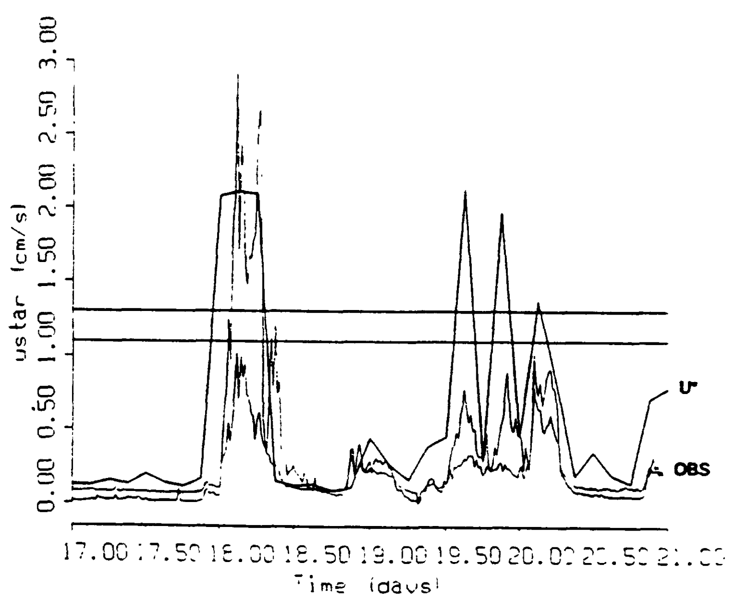

Figure 12. The friction velocity u^* predicted by a wave-current interaction model for site 2, December 17-21, 1990. The horizontal lines are the shields critera for critical erosion velocities of fine sand and coarse silt. The lowest lines are proportional to the OBS 1 and OBS 2 readings at this site.

This lake site showed significant resuspension events on December 18 and 19 during strong wind events from the north and northeast (Figure 5a). Turbidity maxima coincided with bottom shear stress (represented by friction velocity, u^*, in Figure 12) maxima. Model results demonstrate that waves and currents present in Lake Barre both prior to and during a frontal passage are adequate to resuspend the entire range of sediments found there. This is significant in that fetch lengths vary over at least an order of magnitude during the sequence.

Summary and Conclusions

Instrumentation of a small embayment (Lake Barre) and a tidal channel (Bayou Chitigue) connecting Terrebonne Bay and its contiguous marshlands has shed considerable light on the processes controlling sediment flux in this region. An experiment during December 1990 began with a four day period with negligible wind speeds and limited fetch. Despite strong currents of 60 cm/sec in the bayou and 15-20 cm/sec in the lake, suspended sediment concentrations were minimal. A period of set-up favorable winds raised the suspended sediment concentration but only the flood tidal current carried sediment. Ebb tidal currents draining the marsh were consistently low in suspended sediment. A weak frontal passage with northerly winds also produced increased turbidity levels, leading to a net sediment flux into the marsh of 3.6×10^6 kg over the 10-day period. It is notable that this net sediment flux into the marsh occurred in conjunction with a net water mass flux out of the marsh over the experimental period. Computation with a wave-current interaction model showed that the local wind and currents during the December experiment did indeed provide the conditions necessary to resuspend sediments in the lake. In a second experiment at this site in November 1991, three strong frontal passages produced a large export of sediment from the marsh. Strong northerly wind effects (waves and wind-augmented tidal currents) entrained sediment in the marsh complex and there was a large net sediment flux out of the marsh totalling 3.8×10^6 kg over the three week period. Most of this sediment flux took place during the first northerly wind event.

Our measurements show that sediment flux events are highly episodic and distinctly wind-related. The direction and magnitude of sediment flux is controlled by complex interactions between wind speed, wind direction and fetch, tidal currents, water level, bathymetry, and sediment availability.

Acknowledgment

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METEOROLOGICAL FORCING ON LOUISIANA WETLANDS

Shih-Ang Hsu and Brian William Blanchard[1]

Abstract

The open wetland areas of southern Louisiana are vulnerable to meteorological forcing. On the basis of over one year U.S.G.S.-funded measurements of atmospheric pressure, air-sea temperature difference, wind speed and direction, and the momentum flux in the wetland system comprising the Terrebonne and Four League Bays and a U.S.G.S. site on the marsh, a characterization of these meteorological forcings is discussed. Two important atmospheric stresses are temperature (thermal) and the wind (mechanical). It will be shown that the response of the sea-surface temperature to the atmospheric temperature forcing at a shallow (less than 4 m) bay is direct and nearly instantaneous. The effect of the wind stress is investigated from three sites in the wetlands via the two-level wind speed measurement system. The results indicate that the deep water drag coefficient formulation as often used by researchers can not be applied to the wetland environment.

Introduction

Louisiana wetlands are vulnerable to meteorological forcing. Two of the most important atmospheric stresses are discussed in this presentation. One is the temperature (thermal) and the other is the wind (mechanical). In winter, the passage of many cold fronts over our study area can chill the water; while in summer tropical storms such as hurricanes can alter the wetlands.

[1]Dr. S. A. Hsu is a Professor of Oceanography and Coastal Sciences and Brian Blanchard is a research meteorologist, both with Coastal Studies Institute, Louisiana State University, Baton Rouge, Louisiana, 70803.

Since results from systematic measurements of air-sea temperature difference and wind stress over at least a one-year period are not available in the literature, we have investigated these stresses in the Terrebonne Bay area since 1991 (Fig. 1). It is the purpose of this presentation to discuss the results of these measurements. Additionally, with the passage of Hurricane Andrew in 1992 a unique wind forcing on the wetlands was made available through a U.S. Geological Survey monitoring station in our study area.

Thermal Forcing

Depending on the local conditions, the water temperature can respond to atmospheric forcing directly. An example is shown in Figs. 2 and 3. Around October 6, 1991, a cold front passed over our meteorological station located in Four League Bay, Louisiana (see Figs. 1, 2, and 3). The air temperature dropped approximately 11°C from 28°C to 17°C. Almost simultaneously the water temperature (located 1 m from the sea surface) dropped 13°C from approximately 29°C to 16°C. Thus, the response of the sea-surface temperature to the atmospheric temperature forcing at this shallow (less than 4 m) bay can be direct and nearly simultaneous.

Mechanical Forcing

The momentum flux or wind stress, τ, is defined as

$$\tau = \rho u_*^2 = \rho C_d u_{10}^2 \qquad (1)$$

where ρ is the air density, u_* is the shear (or friction) velocity, $C_d = (u_*/u_{10})^2$ is the drag coefficient, and u_{10} is the wind speed at 10 m above the sea surface.

In the atmospheric surface boundary layer we have (see, e.g., Hsu, 1988)

$$\frac{\kappa Z}{u_*}\left(\frac{\partial u}{\partial Z}\right) = \phi_m\left(\frac{Z}{L}\right) \qquad (2)$$

or

$$u_z = \frac{u_*}{\kappa}\left[\ln\frac{z}{z_0} - \psi_m\left(\frac{Z}{L}\right)\right] \qquad (3)$$

where κ (=0.4) is the von Karman constant, Z is the height and Z/L is the stability parameter such that

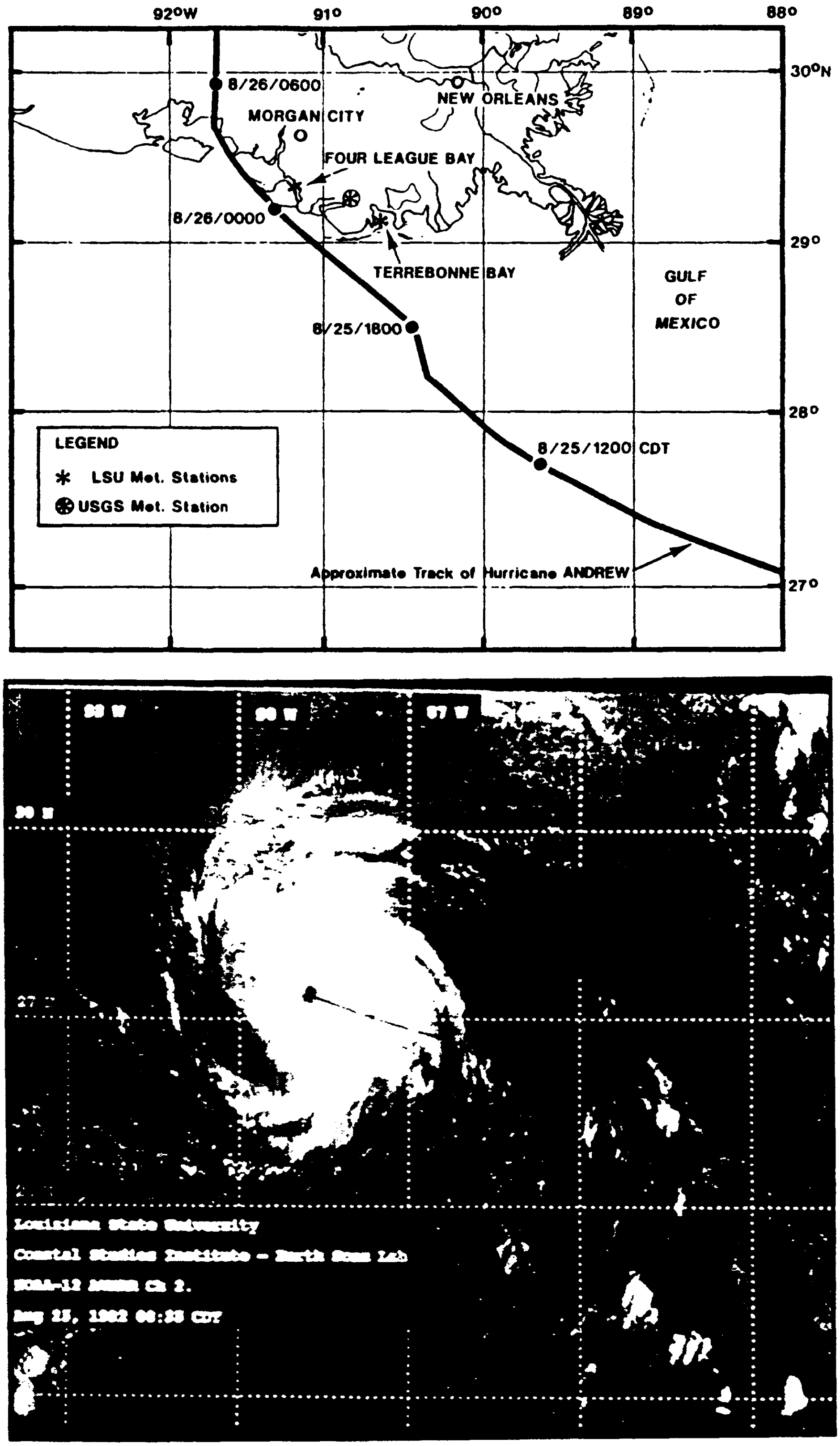


Fig. 1. The study area and approximate track of Hurricane Andrew in August 1992.

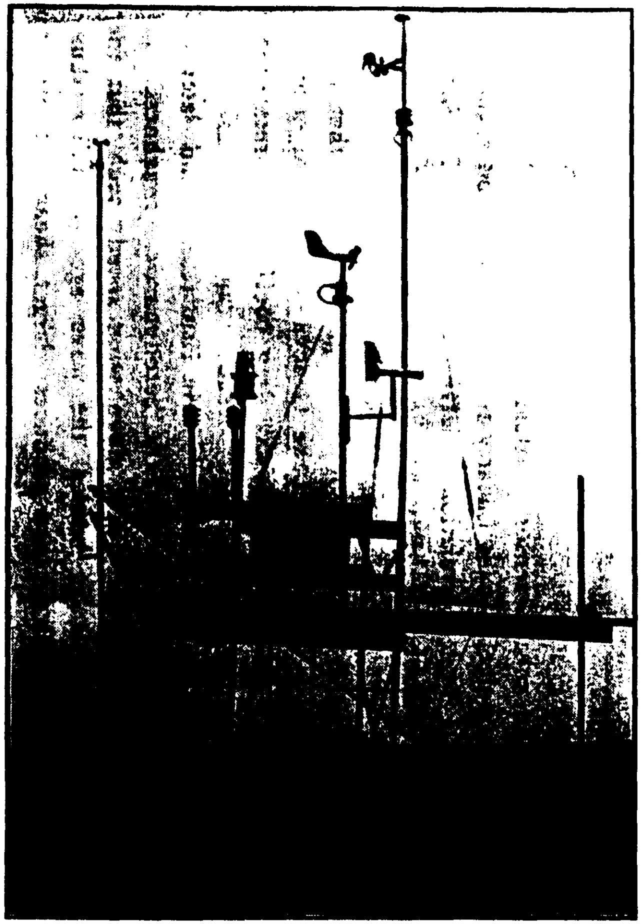


Fig. 2. The meteorological station in Four League Bay. For this study we used the top and bottom cup anemometers attached to the pipe to left of the platform.

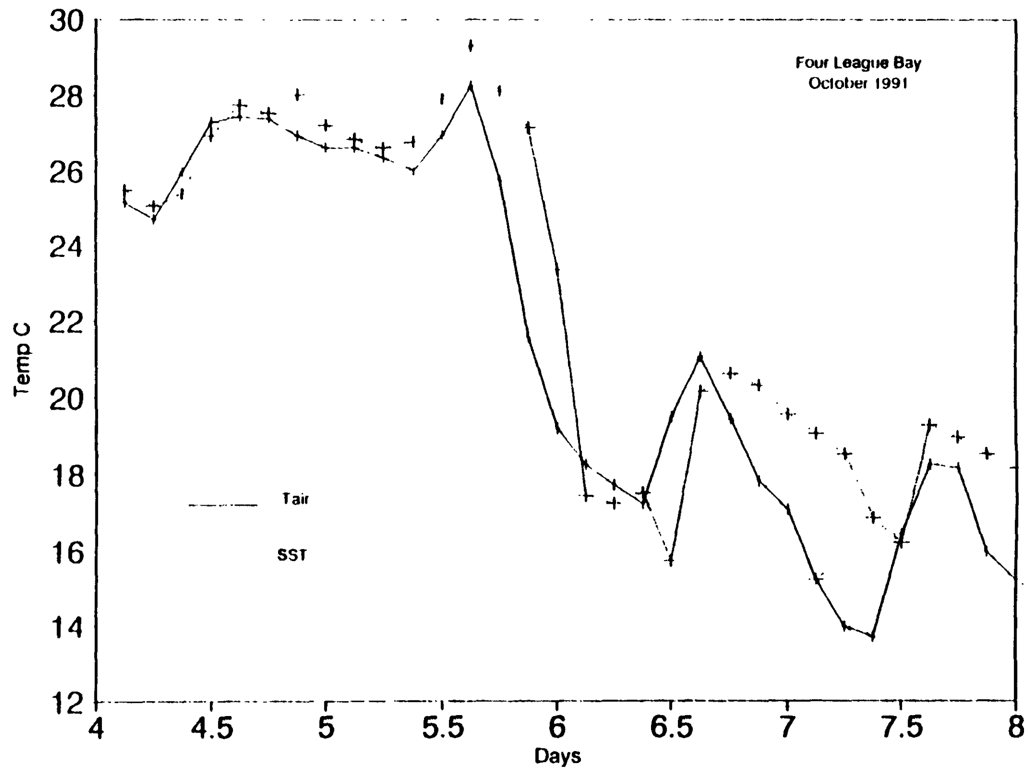


Fig. 3. An example of the response of the sea-surface temperature to the passage of a cold front over Four League Bay (see Fig. 2).

$$\frac{Z}{L} = -\frac{g\kappa Z\overline{\theta_v' w'}}{u_*^3 T_{v0}} \tag{4}$$

where $\overline{\theta_v' w'}$ is the heat flux and T_{v0} is the virtual temperature.

From Eq.(3) the difference between level 1 (lower elevation) and level 2 (upper elevation) is

$$u_2 - u_1 = \frac{u_*}{\kappa}\left[\ln\left(\frac{Z_2}{Z_1}\right) + \psi_m(\zeta_1) - \psi_m(\zeta_2)\right] \tag{5}$$

$$u_* = \frac{\kappa(u_2 - u_1)}{\ln\left(\frac{Z_2}{Z_1}\right) + \psi_M\left(\frac{Z}{L}\right)} \tag{6}$$

$$\text{where } \psi_M\left(\frac{Z}{L}\right) = \psi_m(\zeta_1) - \psi_m(\zeta_2) \tag{7}$$

Eq.(6) states that under neutral atmospheric stability conditions where mechanical turbulence dominates the heat flux or the denominator >> numerator in Eq.(4), $Z/L \to 0$ which makes $\psi_M(Z/L) \to 0$ by definition (see, e.g., Hsu, 1988 and 1992). Therefore, under neutral conditions, Eq.(6) becomes

$$u_* = \frac{\kappa(u_2 - u_1)}{\ln\left(\frac{Z_2}{Z_1}\right)} \tag{8}$$

From a two-level wind speed sensor system as shown in Fig. 2 over Four League Bay, the shear velocity u_* is linearly related to the wind speed at 10 meter height, u_{10}, with a high correlation coefficient R = 0.89. Similar results were obtained from Terrebonne Bay as shown in Figs. 1, 5, and 6.

In order to compare our results with others, Fig. 7 indicates that for a given wind speed, the value of u_* is closer to Lake Geneva than to that of open and deep oceans. Therefore, the commonly used drag coefficient formulation of Large and Pond (1981) for deep and open oceans can not be used for Louisiana bays. The reason has been provided in Hsu (1988) and later in Maat et al. (1991). Briefly, this is because the aerodynamic roughness is inversely proportional to the wave age for a given wind speed such that for younger wind seas over smaller water bodies the wave age is smaller thus making the roughness larger which in turn produces larger shear velocity or

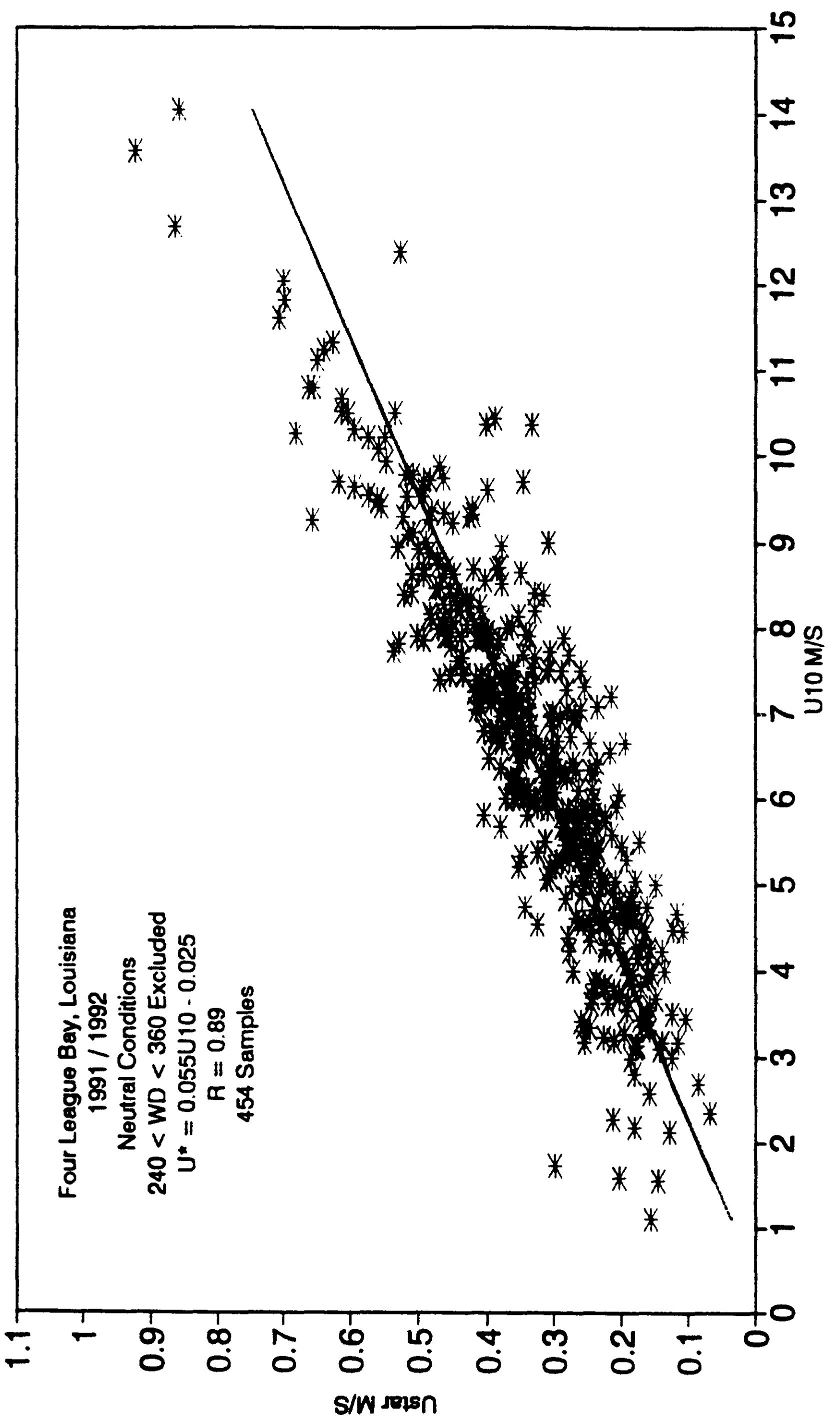
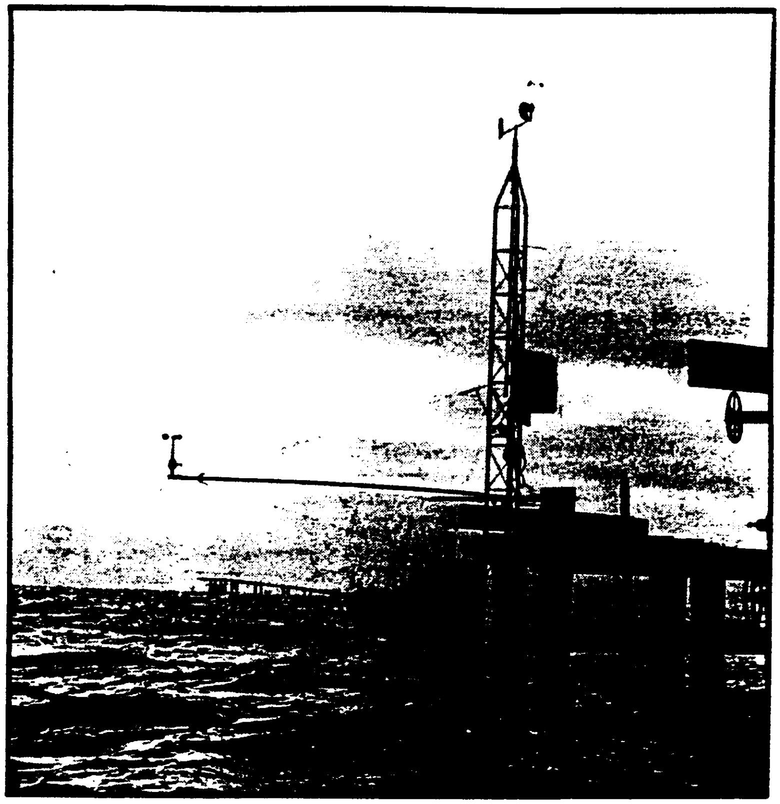
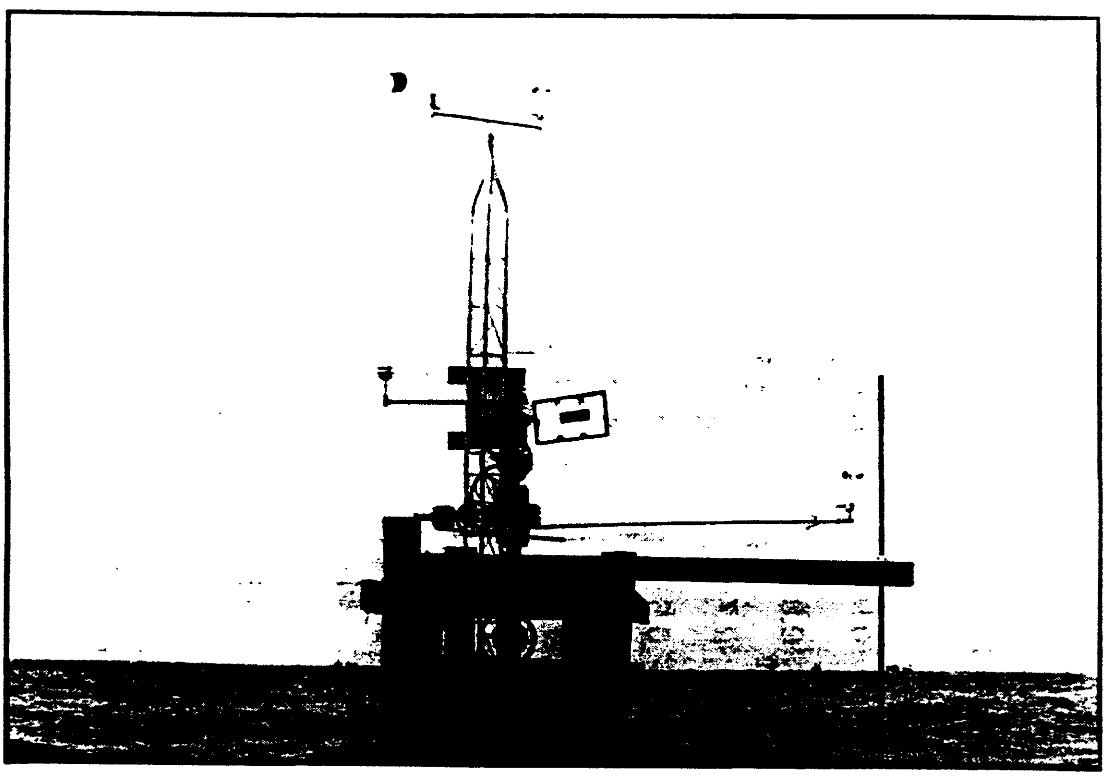


Fig. 4. The relationship between the shear velocity, u_*, and the wind speed, u_{10}, in Four League Bay under neutral conditions.





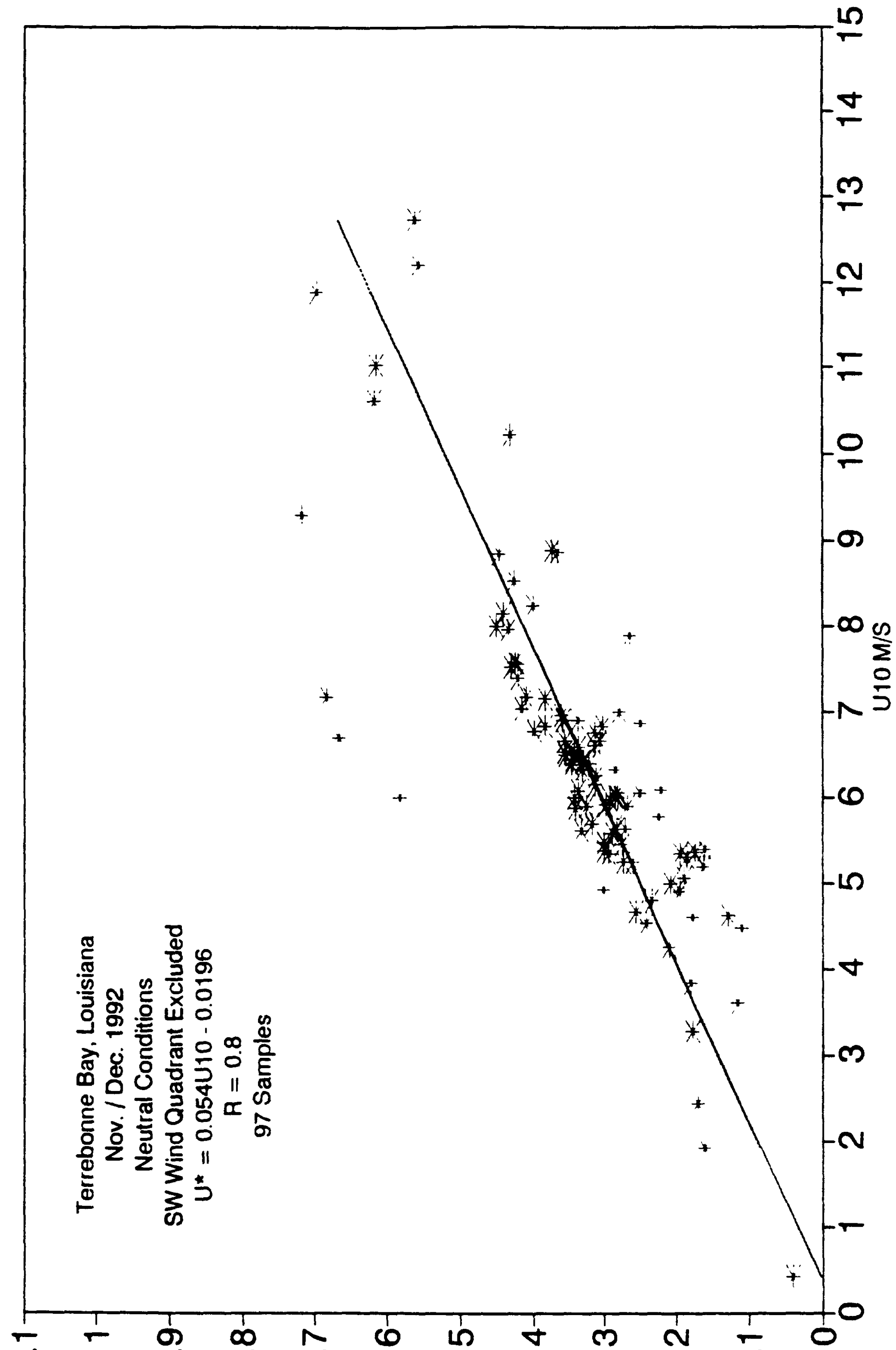


Fig. 6. The relationship between u_* and u_{10} in Terrebonne Bay under neutral conditions.

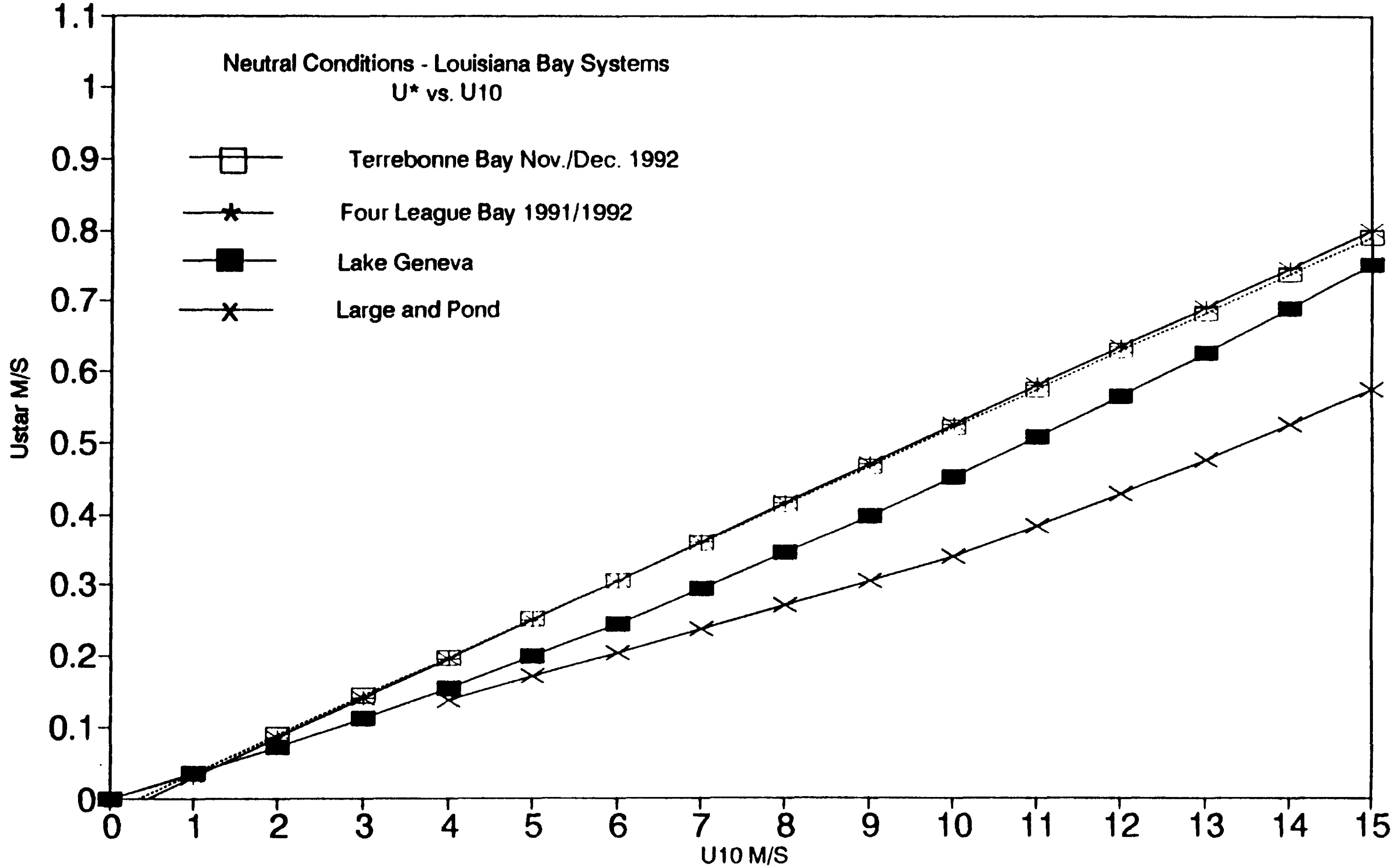


Fig. 7. A comparison of u_* vs. u_{10} amongst Louisiana Bays and other locations such as over Lake Geneva from Graf et al. (1984) and over open, deep oceans (Large and Pond, 1981).

drag values.

Under hurricane conditions, the momentum flux undergoes another level of alteration. Figs. 1 and 8 give an example during the passage of Hurricane Andrew in August 1992 through our general study area. The two-level wind speed measurements at the U.S.G.S. site between Terrebonne Bay and Four League Bay (Fig. 1) show that before the water level (storm surge) affected the site, the wind stress experienced a "jump" from less than 0.5 N/m^2 to over 2 N/m^2 around the wind speed of 22 to 23 m/s which corresponds to a increase in drag coefficient from less than 1×10^{-3} to over 4×10^{-3}. For more detail see Dingler et al. (1993). Because by hurricane classification the wind speed for Class 1 is greater than 33 m/s, the wind stress of 5 N/m^2 or higher should exist near the hurricane track. Since from 1900 through 1992 we have had 38 hurricanes hit the Louisiana coast including 9 out of these 38 having the strength of Andrew (Class 4), the hurricanes must have a "devastating" effect on the marsh environments similar to the U.S.G.S. site.

Conclusions

On the basis of the foregoing discussions we can conclude that

1. During cold frontal passages and depending on the location in a shallow bay, the response of the sea-surface temperature to the atmospheric temperature forcing can be direct and nearly simultaneous at a site having a water depth of 4 m or less.

2. During the passage of Hurricane Andrew in 1992 through a Louisiana marsh but before the storm surge occurred, the drag coefficient "jumped" from less than 1×10^{-3} to around 5×10^{-3}.

3. The drag coefficient formulation for the open ocean as commonly used in the oceanographic community can not be applied in the wetland environment. The approximate formula based on in situ measurements is provided for modeling purposes.

Acknowledgements

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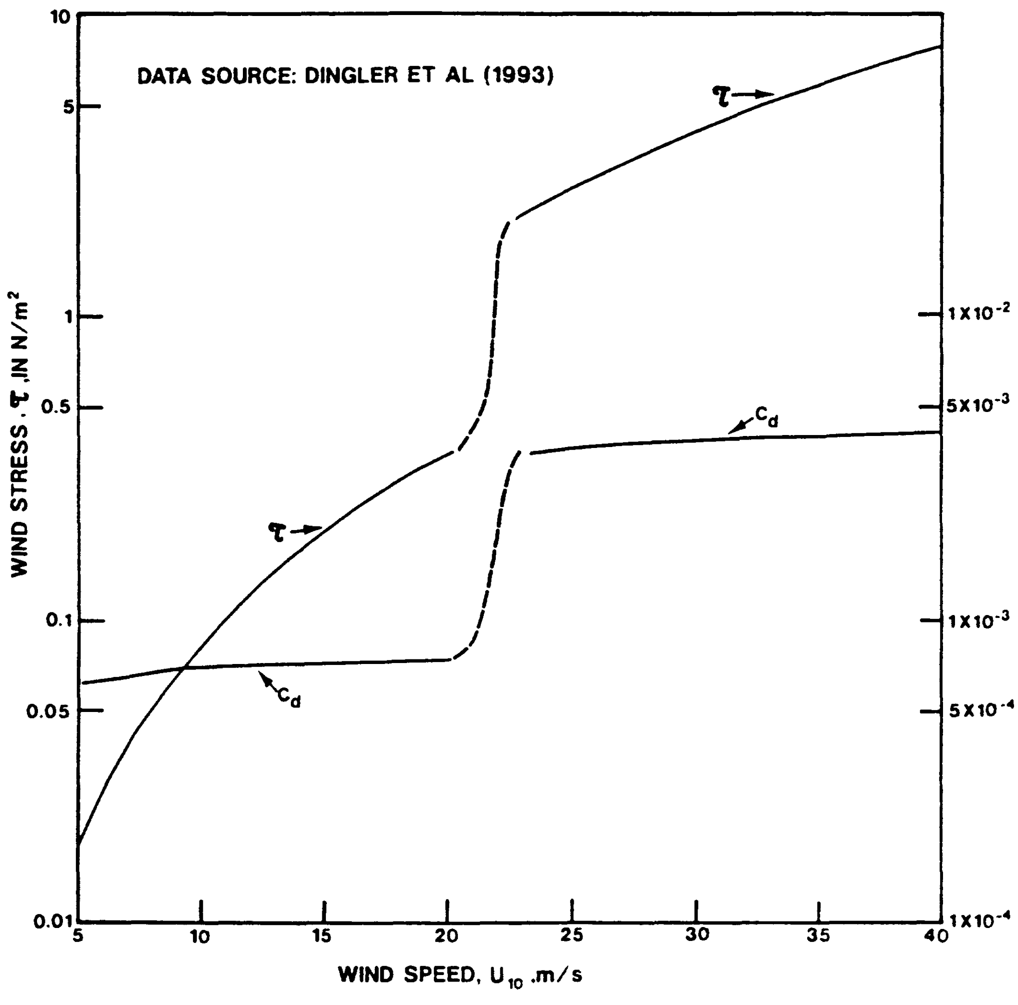

Fig. 8. Variations of the wind stress and the drag coefficient as a function of u_{10} on a march during Hurricane Andrew, August 1992.

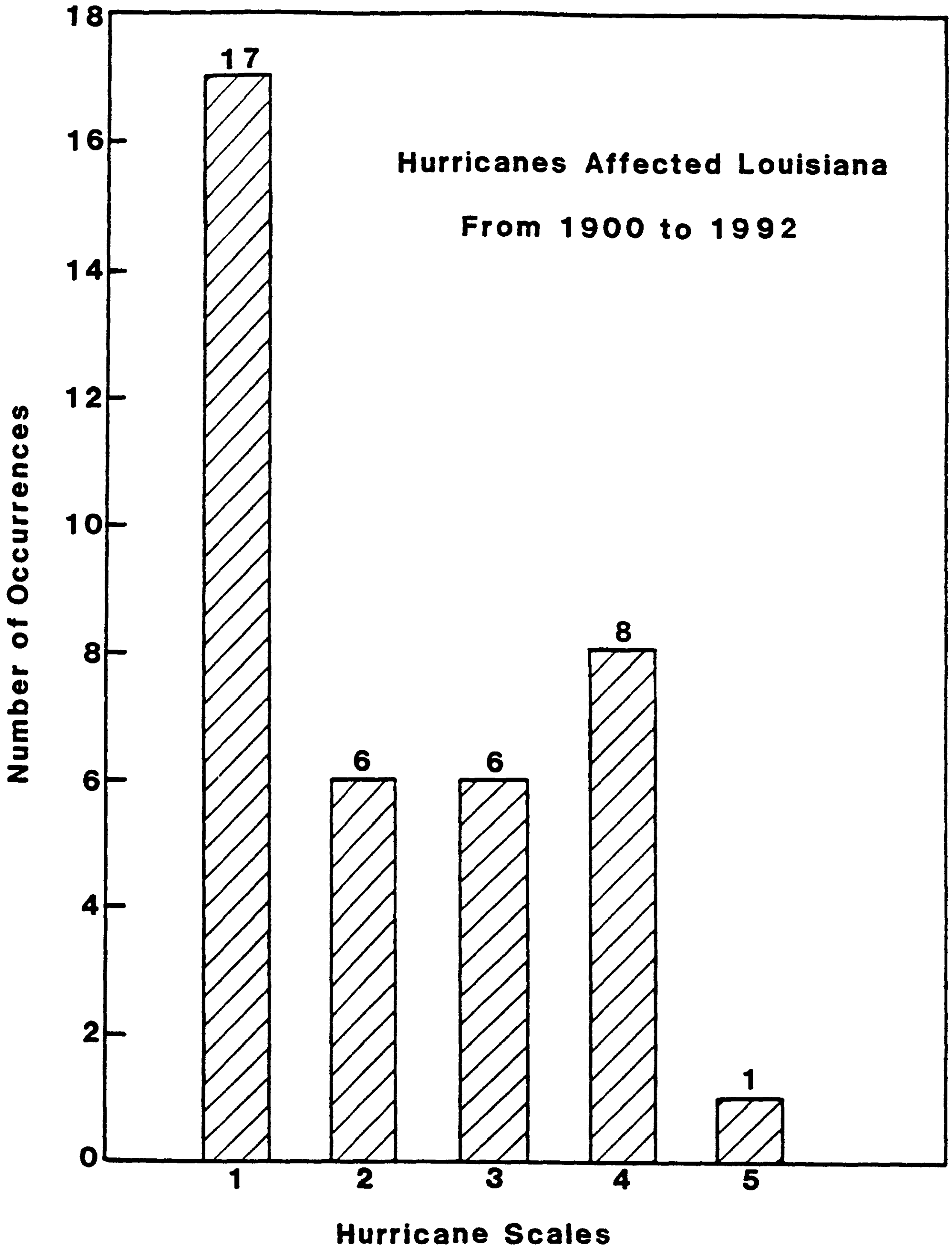

Fig. 9. Number of occurrences vs. hurricane scales for hurricanes which have affected Louisiana from 1900 through 1992.

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Marsh Submergence vs. Marsh Accretion: Interpreting Accretion Deficit Data in Coastal Louisiana

Denise J. Reed[1]

Donald R. Cahoon[2]

Abstract

The apparent imbalance between relative sea-level rise and vertical marsh accretion is frequently cited as a major factor in the problem of wetland loss in Louisiana. Rates of relative sea-level rise are high in Louisiana due to high rates of subsidence. Although marsh accretion rates are also high, they are usually insufficient to maintain the relative elevation of the marsh surface. This situation is commonly referred to as an accretion deficit. The interpretation of subsidence and accretion data, and therefore accretion deficit data, is confounded by the numerous geologic, biologic, and sedimentologic processes influencing coastal marshes in Louisiana. Therefore, calculation of accretion deficits can be influenced by the techniques used to measure subsidence and accretion. The concept of accretion deficit is based on the assumption that accretion rates are equivalent to elevation change rates, but this assumption may not necessarily be correct. We suggest that direct measurements of elevation change in marsh surface can provide better indications of the status of the marsh surface with respect to subsidence and accretion.

Introduction

There are approximately 2.7×10^6 ha of coastal marshes in Louisiana (Field et al. 1991). During this century, Louisiana marshes have been disappearing at an increasingly rapid rate (Gagliano et al. 1981) although the rate of loss has slowed

[1]Louisiana Universities Marine Consortium, 8124 Hwy 56, Chauvin, LA 70344, USA.

[2]U.S. Fish and Wildlife Service, National Wetlands Research Center, 700 Cajundome Blvd., Lafayette, LA 70506, USA.

during the past decade (Britsch and Kemp 1990). The mechanisms of wetland loss include marginal erosion (Reed 1989), dredge-fill activities, and deterioration of interior marshes (see Turner and Cahoon 1988 for review). Widespread deterioration of interior marshes is generally attributed to high rates of subsidence-induced relative sea-level rise (a combination of subsidence and eustatic sea-level rise, which in Louisiana is often $\geq$1.0 cm/yr; Penland and Ramsey (1990)) and insufficient accretion rates. This imbalance between land-sinking and land-building processes has been variously described as aggradation deficit (DeLaune et al. 1983; Hatton et al. 1983), sedimentation deficit (Turner 1991), or accretion deficit (Templet and Meyer-Arendt 1988). The deficit is due to lowered sediment concentrations in the Mississippi River (Kesel 1988), lowered opportunity for sediment delivery to the marshes because of levees along the Mississippi River (Templet and Meyer-Arendt 1988), and lowered plant productivity related to saltwater and submergence effects (e.g., Pezeshki et al. 1987; McKee and Mendelssohn 1989; Reed and Cahoon 1992) caused by sea-level rise and human alterations of local hydrology (e.g., Swenson and Turner 1987).

The deficit is usually calculated by comparing measures of marsh accretion (e.g., DeLaune et al. 1983; Hatton et al. 1983) or matter accumulation (e.g., Day and Templet 1989; Nyman et al. 1990) with estimates of sea-level rise or land subsidence. However, measurements of subsidence and accretion are not necessarily compatible and use of the accretion deficit concept can be misleading. The deficit concept is commonly used by researchers who use a wide range of techniques to measure accretion, each technique with its own time scale that is often different from the time scales by which subsidence is measured. This paper evaluates the techniques used to measure accretion and subsidence and describes alternative approaches to assessing the sustainability of coastal marshes in the face of subsidence and sea-level rise. We will focus our attention on the measurement of marsh accretion rather than accumulation as the latter is usually calculated from measured accretion rates.

Causes of Subsidence in Coastal Louisiana

The interpretation of subsidence data, especially in comparison to vertical soil development, is confounded by the large number of contributing geologic processes. Subsidence may be defined as the negative change in land surface elevation with respect to local water levels; as such it integrates geologic processes occurring within the crust, which can range from diastrophic processes (orogenic, epierogenic, or isostatic movements), through localized consolidation of recent deposits, to collapse or compaction associated with subsurface fluid withdrawal. Within the Mississippi deltaic plain the main factors contributing to subsidence have been identified by Penland et al. (1988) as geosynclinal downwarping, compaction of Tertiary and Pleistocene deposits, compaction of Holocene deposits, localized consolidation, tectonic activity, and subsurface fluid withdrawal.

Downwarping of the gulf coast geosyncline is caused by the 12,000 m sequence of shallow water sediments that have been deposited during the Tertiary, Pleistocene, and Holocene. Kolb and Van Lopik (1958) estimated the average rate of downwarping for the last 60 million years at 0.02 cm/yr, but this figure is highly variable, with downwarping maximized during periods of maximum sedimentation. Consolidation of Tertiary and Pleistocene deposits is also variable because of differences in dewatering, compaction, and loading. The greatest amount of subsidence associated with this consolidation was estimated by Fisk and McFarlan (1955) to be along the axis of an infilled alluvial valley in the Timbalier Bay area. Compaction of Holocene deposits is considered by Penland et al. (1988) to be the primary cause of widespread subsidence in the Mississippi deltaic plain. This compaction decreases with time after deposition (Morgan 1973), and so younger deltas are more prone to compaction and subsidence than older deltas. Within individual deltas, localized consolidation of different deposits (e.g., sand vs. silts) will lead to variations in subsidence rates. Consolidation can also be caused by the weight of minor landforms and structures. Suhayda (1988) calculated the local compaction of marsh soils caused by the placement of dredged material on the marsh adjacent to a canal. He found that subsidence occurs but is restricted to the immediate vicinity of the levee, and is not considered to be a major contributor to general subsidence of the marsh plain.

In Louisiana, where oil and gas extraction activities are the dominant industries of the coastal zone, subsurface fluid withdrawal is seen as the major anthropogenic contribution to subsidence and is therefore frequently viewed as preventable. Subsidence associated with oil and gas extraction from shallow reservoirs is well documented in California and East Texas, and Suhayda's (1988) analysis of shallow fields in Louisiana using Martin and Serdengecti's (1984) model shows that there were 19 fields with a subsidence potential of greater than 10 cm. Trahan (1982) investigated the relationship between reservoir-defining growth faults and subsidence anomalies in several southwestern Louisiana geopressured prospects. In some areas no correlations existed between subsidence and lineations or fault projections, but in other areas a clear relationship existed between subsidence profiles and the extrapolated updip extensions of mapped subsurface faults. Such subsidence cannot be measured independently from other forms, but it is likely to be spatially and temporally variable across the Louisiana coastal zone. In addition, fluid withdrawal is unlikely to have been a factor contributing to coastal subsidence before the 1940's, when oil and gas extraction in this area expanded (Lindstedt et al., 1991).

Another localized, and perhaps better documented, human-induced factor in subsidence is that associated with groundwater withdrawals (Davis 1987). Withdrawal of ground water is usually associated with urban or industrial uses, such as in Baton Rouge (Davis and Rollo 1969), Houston (Gabrysch 1969) and New Orleans (Kazmann and Heath 1968), but can impact surrounding wetland and coastal areas depending on aquifer configuration.

Measuring Subsidence

The relative contributions of the above factors to subsidence can rarely be identified because measurement techniques focus on changing land surface elevations relative to a specific datum. There are four techniques that have been used to measure subsidence in Louisiana: (1) analysis of tide gauge records, (2) repeated geodetic leveling, (3) dating of buried horizons, and (4) extensometers.

Tide-gauge records have been used to measure relative sea-level rise (subsidence combined with eustatic sea-level changes) across the Louisiana coastal zone (Penland and Ramsey 1990). Regression analysis of the rise in water levels between different lunar epochs (Penland and Ramsey 1990) showed an increase in relative sea-level rise from 01.14 cm/yr (1942-1962) to 1.80 cm/yr (1962-1980) for the tide gauge at Grand Isle, Louisiana. Subsidence estimates are obtained by subtracting the eustatic rate of sea-level rise for the Gulf of Mexico from the records. Turner (1991) warned against the use of tide-gauge records to estimate either sea-level rise or subsidence. He considered that short-term trends (on the scale of decades) in tide-gauge records are frequently no more than minor perturbations in longer-term (on the scale of centuries) trends. He also noted that gauges are frequently located on structures that are themselves subjected to localized subsidence (e.g., piers) and that such records should not be used to infer water level changes in areas other than the immediate vicinity of the gauge. Despite these criticisms, tide-gauge records remain the most readily available from of data that can be used to estimate sea-level rise and subsidence and the technique has been widely used around the world (Gornitz et al. 1982; Emery and Aubrey 1989). The time scale over which the subsidence estimate is taken is rarely more than 100 years because of the scarcity of long-term tide-gauge stations.

The use of repeated geodetic leveling to evaluate subsidence is restricted to areas where benchmark networks have been maintained. Penland et al. (1988) used part of the National Ocean Service network of high-resolution geodetic leveling transects to evaluate subsidence in the Terrebonne basin of coastal Louisiana. Successive surveys of replicate bench marks were used with screening of each bench mark to ensure monument quality and stability. Comparisons of surveys conducted in 1965 and 1982 showed a subsidence rate of 1.03 cm/yr at the master bench mark on Grand Isle (Penland et al. 1988) with rates from other marks ranging between 0.83 cm/yr and 0.92 cm/yr. Overall, Penland et al. (1988) found subsidence rates based on geodetic leveling to be highly variable and to show generalized trends east to west and from the coast inland. Within Louisiana these bench-mark networks are usually located along bayou ridges rather than in channels or marsh areas. Consequently, the data are subject to some of the same problems of interpretation that Turner (1991) identified for tide gauge records. In addition, the period of measurement is short, perhaps 50 yr, and in Louisiana coincides with the period of major oil and gas extraction activities.

Integrated measures of subsidence over longer periods can be obtained by dating buried horizons. Specific index points, usually including datable material, e.g., peat or shell fragments, can be used to determine rates of sediment accumulation (depth of sample/age of sample), which are then used as surrogates for the rate of subsidence or sea-level rise (Shennan 1982; Plassche 1986). This technique has received some criticism (Kearney and Ward 1986; Allen 1990) because the accuracy of the resulting sea-level reconstruction depends upon the relationship of the local environment in which the sample was accumulated to a contemporaneous reference tide level. Estimating this relationship involves considerable error terms for different materials as well as the errors involved in measuring the altitude of the sample or stratigraphic boundary (Shennan 1982). However, in Louisiana the rapid accumulation of deltaic deposits and the abundance of marsh-peat strata minimize many of these errors. Where several datable horizons are available at different elevations this technique can be used to evaluate changes in subsidence over different periods. Within the Terrebonne deltaic plain Penland et al. (1988) used this technique to show that, assuming a stable eustatic regime, the rate of compactional subsidence decreases with time after deltaic deposition and abandonment by the Mississippi River. Rates of subsidence from dating *in situ* organic horizons less than 300 yr old are as high as 1.5 cm/yr while dates from older horizons (300-1500 BP) show subsidence rates of less than 0.5 cm/yr (Penland et al., 1988). Such rates are based on the assumption that subsidence is constant over the period of deposition above the horizon; accordingly any modern-day enhancement of subsidence would be averaged over a much longer period.

More direct, site-specific measurement of contemporary subsidence is possible. Vertical extensometers are used to monitor aquifer compaction caused by withdrawal of groundwater. They consist of a well with a casing installed to a chosen depth. A pipe is placed inside the casing and anchored outside the bottom of the casing. If the formation above the base of the casing compacts, the pipe appears to rise above the ground because it is free to move. Nests of three extensometers completed at different depths can be used to determine the amount of shallow compaction (or subsidence) and its vertical distribution. This technique provides real-time estimates of subsidence, independent of eustatic sea-level considerations, and can be installed in areas where subsidence rates are important for coastal management decisions.

Factors Influencing Marsh Accretion

The interpretation of accretion data, especially in comparison to subsidence and sea-level rise, is confounded by the numerous contributing biologic and sedimentologic processes that occur at different time scales. Marsh accretion may be defined as the vertical dimension of marsh soil development, and as such integrates the biologic and sedimentologic processes occurring on and within the uppermost part of the marsh substrate. These processes include sediment deposition, sediment erosion, plant production (aboveground and belowground), and plant decomposition. In the sediment-poor regions of the Louisiana coast, the contribution of biologic components to marsh accretion is likely to be relatively more important than it would be in a sediment-rich environment. The sources of matter accumulating on marsh surfaces in Louisiana are net tidal and storm-related import of suspended sediments, net plant litter fall, and net plant belowground production.

Rates of sediment deposition in the microtidal marshes of Louisiana (astronomical mean tidal range approximately 30 cm) are influenced by sediment availability (e.g., distance from sediment supply and initial sediment concentration) and the opportunity for sediment deposition (e.g., the frequency at which sediment is delivered to the marsh surface). In Louisiana, sediment deposition rates are high near the Atchafalaya River but low in the distributary basins of the Mississippi River (Baumann et al. 1984) because flood control levees have eliminated overbank flooding. Storm events deliver more sediment to the marsh surface than regular tidal events (Baumann et al. 1984; Rejmanek et al. 1988; Reed 1989a). Hydroperiod (i.e., the frequency and duration of flooding events) directly influences sediment deposition rates (Reed 1989b), with greater hydroperiod resulting in greater deposition.

Rates of marsh surface erosion (i.e., a decrease in marsh elevation as opposed to lateral erosion of the marsh substrate at the marsh-water boundary) have not been reported for Louisiana marshes, but surface erosion occurred (Cahoon and Turner 1989) in marshes influenced by boat wakes as well as in interior marsh areas. The potential for marsh surface erosion exists in marshes with low stem densities, e.g., deteriorating marshes, where sediments may be more readily entrained by tidal waters than in marsh areas with high stem densities (Gleason et al. 1979). The magnitude of overwash flows (e.g., boat wakes) will also influence the rates of surface erosion.

Plant production and decomposition rates vary with vegetation type, soil nutrients, and the hydrologic setting. Increases in sea-level and associated salinity concentrations have been reported to decrease plant growth (Pezeshki et al. 1987; McKee and Mendelssohn 1989; and Cahoon and Reed 1992), both aboveground and belowground. The primary source of organic matter in the marsh substrate is belowground plant production, but no estimates of belowground productivity have been reported for Louisiana. However, amounts of belowground biomass in a Louisiana salt marsh have been found to be negatively correlated with frequency and duration of inundation (Reed and Cahoon 1992). The extent to which litterfall of aboveground plant parts contributes directly to marsh accretion has not been reported but is apparently limited (Cahoon and Reed unpublished). However, plant litter apparently may enhance inorganic sedimentation by trapping sediments on the marsh surface (Cahoon and Reed unpublished).

Measuring Accretion

Accretion is measured by use of marker horizons incorporated in the soil (Table 1), including those present in the soil worldwide (e.g., ^{234}Th, ^{137}Cs, and ^{210}Pb) and those added at specific locales (e.g., visible markers such as feldspar and stable isotopes). There are two reasons why the interpretation of accretion deficit data can be influenced by the method used to measure accretion. First, each technique has an inherent bias for or against one or more of the processes described in Table 1, yet the influence of that bias on the measure of accretion is difficult to quantify. The relative contribution of the processes to accretion can rarely be determined because the processes occur simultaneously and the accretion techniques are usually not sensitive to the different rates at which the processes occur. Secondly, the accuracy of results of the techniques described in Table 1 varies.

Soil-marker studies measure sediment accretion over varying time periods, depending on the type of marker employed (Table 1). The use of a horizon showing peak ^{137}Cs activity, which occurred in 1963 (DeLaune et al. 1978; Hatton et al. 1983), measures sediment accumulation over a period of nearly 30 yr. As this horizon, in Louisiana marshes, is presently up to 30 cm below the marsh surface, material has accumulated above the horizon from both deposition on the marsh surface and net belowground production. The rate of accretion measured by using this technique is averaged over a period of nearly 30 years and provides no information about the processes contributing to the accumulation of matter (e.g., deposition and erosion), including temporal variability of the processes.

The ^{210}Pb method of measuring accretion is based upon a profile of ^{210}Po activity down-core, and a best-fit line is used to derive the average rate of accretion (Lynch et al. 1989). As the accretion rate is calculated from the slope of a line, it is determined by the distribution of many data points rather than the depth of one specific peak, as in ^{137}Cs. ^{210}Pb provides a better estimate of average accretion rate over the period of measurement than ^{137}Cs, but ^{210}Pb still provides little information about the accumulation process.

Table 1. Methods used to measure marsh accretion in Louisiana.

Method	Time Scale	Reference
Short-lived radioisotope soil marker		
^{234}Thorium	Months	McKee and Twilley unpublished
^{7}Beryllium	Months	"
Visible soil marker (e.g., feldspar)	Months to years	Baumann et al. 1984 Cahoon and Turner 1989
Stable isotope soil marker	Months to years	Knaus and van Gent 1989
Long-lived radioisotope soil marker		
^{137}Cs	30 years	DeLaune et al. 1978
^{210}Pb	$\geq$100 years	DeLaune et al. 1987

Marker horizons such as feldspar are frequently deployed specifically for marsh-accretion studies (e.g., Baumann et al. 1984; Cahoon and Turner 1989; Knaus and Van Gent 1989), and measurements are taken seasonally. Feldspar studies provide more information about the nature of depositional processes because of their shorter measurement period and repeated measurements at the same site. For example, Baumann et al. (1984), using seasonal sampling, noted increased accretion during a period of tropical storm activity. However, the short life span of marker horizons deployed in a specific locale, usually several years, and small

depth measurements of several centimeters indicate that the technique initially measures only net deposition at the marsh surface. Because the marker becomes buried deeper and plant roots occur above it, the accretion above the marker is a result of both surface deposition and belowground production. Measurements above marker horizons, therefore, provide an integrated measure of several processes contributing to accretion, but the contributing processes vary through time.

Accretion is expressed as a yearly rate, but as seen in Table 1, it is actually measured on time scales ranging from months to decades. When short- and long-term techniques are compared, the annual rates of accretion are generally lower for techniques measuring a long-time scale because of compaction of sediments and decomposition of organic matter over time. The importance of individual depositional events or episodes diminishes, as well as the level of variability, as the time scale of measurement increases. It is advisable to use two or more accretion techniques simultaneously to provide an estimate of the range of variation and to corroborate results.

Comparing Accretion and Subsidence Measures

We define the difference between accretion and relative sea-level measures as an accretion deficit, rather than aggradation or sedimentation deficit, because we want to emphasize the vertical dimension of the accretionary process. Two important factors influencing the accretion deficit are (a) the technique used to measure accretion or subsidence, and (b) the different time scales of accretion and subsidence measurements.

The short time-scale methods (e.g., ^{234}Thorium, pins, feldspar, and stable isotopes), allow measurement of seasonal and annual variation in accretion. Long-lived radioisotope techniques (e.g., ^{137}Cs and ^{210}Pb) are not suited to these two uses because they provide an average annual rate of accretion integrated over several decades. However, they measure accretion on a time scale closer to that used to measure subsidence (tide gauge and leveling techniques). Long time-scale methods are better suited to estimate sediment deficits than short time-scale methods because they account for erosional processes and compaction.

Widely different time scales in accretion and subsidence measures can result in misleading estimates of sediment deficit because of potential overestimates of accretion by some techniques and underestimation of subsidence by ^{14}C-dating of only a part of the Holocene sequence. When compared with long-term subsidence estimates, accretion measured over short time scales may tend to overestimate because the accretion measure fails to adequately include compaction, resulting in the interpretation that the accretion deficit is not as great as it really is. On the other hand, subsidence estimates that do not account for all components of subsidence (e.g., deep Holocene sediments) will also underestimate the accretion deficit. The best estimates of accretion deficit will come from comparisons of accretion and subsidence rates measured over the most similar time scales.

Another factor to be considered is the sample size of both the subsidence and accretion data sets. Usually sampling density differs substantially between accretion and subsidence measures as well as short- and long-term accretion methods with fewer subsidence samples collected because cores are logistically more difficult to collect and more time consuming to analyze, and because tide gauges are widely spaced across the coastal zone. This difference in sample size can influence sampling variability and may influence the ability to accurately estimate the relationship between accretion and subsidence.

Marsh Surface Elevation Change

The concept of accretion deficit is based on the assumption that marsh accretion is the equivalent of marsh surface elevation change. Thus, when the rate of marsh accretion (assumed to represent positive elevation change) is the same as the rate of subsidence (negative elevation change), the marsh surface is considered to be in equilibrium. If the rates are not the same then the accretion deficit is measured as the difference between the rate of accretion and the rate of subsidence. For example, an accretion rate of 7 mm/yr and a subsidence rate of 10 mm/yr would yield an accretion deficit of 3 mm/yr. This would mean that the marsh surface is becoming progressively lower at a rate of 3 mm/yr. The consequences of such an assumed lowering are increased hydroperiod, waterlogging of the marsh substrate, and the accumulation of toxic sulfides in the soil (e.g., Koch et al. 1990).

However, the difficulties and inconsistencies encountered in comparing accretion and subsidence measurements outlined in this paper show that assuming accretion and elevation change are equivalent may result in an oversimplified view of the vertical development of marsh. It is the deficit in elevation rather than accretion that has important consequences for marsh deterioration, and the ratio of accretion to elevation change may not be 1:1. The value of using measured accretion deficits as surrogates for elevation change can only be verified by measuring elevation change directly.

Changes in elevation of marsh surface relative to a sub-soil datum can be measured directly by a sediment erosion table (SET). This technique was developed for measuring small changes on tidal flats in The Netherlands (van Erdt, 1985) and has been adapted for the study of coastal marshes (Boumans and Day in press). A 7.5 cm diameter aluminum pipe is driven into the marsh substrate until it will penetrate no farther and is trimmed to within 30 cm of the marsh surface. The base of the pipe is the datum against which marsh surface elevation is measured. A smaller notched pipe is cemented into the top of the aluminum pipe and becomes the base for the SET. The SET is placed in fixed positions on the notched pipe and levelled during measurement. The distance between the table and the marsh surface is measured with thin aluminum rods. Changes in the distance between the marsh and the table represent changes in the elevation of the marsh surface.

In the Mississippi deltaic plain the base of the pipe usually is too shallow (approximately 5-10 m) to encompass the entire thickness of subsiding sediments (Penland et al. 1988). However, it may penetrate the most recent deltaic deposits that are thought to contribute most of the subsidence experienced in the deltaic plain (see earlier discussion of subsidence). In the chenier plain in southwestern Louisiana, where the thickness of Holocene sediments is frequently less than 10 m, it is likely that SET pipes can reach into Pleistocene deposits. In this case, measures of change in marsh surface elevation would represent the balance between contemporary marsh accretion and Holocene subsidence processes.

Measuring change in marsh surface elevation is a way of integrating the net result of all the processes contributing to subsidence and marsh accretion. This measurement can be a useful tool for managers and land owners to assess the current status of coastal marshes and their susceptibility to the problems associated with waterlogging. Should such an evaluation reveal a loss of elevation, the development of management strategies to address the problem requires a more detailed understanding of the contributing processes. Because managers can do little to alter subsidence (except locally, where it is associated with the placement of levees or structures), efforts are normally focused on enhancing marsh accretion or increasing marsh-surface elevation.

Conclusions

Although the concept of accretion deficit has been widely applied to Louisiana coastal marshes as a method for evaluating their sustainability in the face of rapid subsidence, the problems associated with directly comparing accretion and subsidence measures are many and the results may be misleading. We suggest that new techniques that allow direct measurements of changes in marsh surface elevation can provide better indications of the status of the marsh surface with respect to subsidence and accretion. Where change in marsh surface elevation is negative, an elevation deficit can be quantified and used as a basis for management decisions.

However, because change in marsh-surface elevation is measured against a sub-surface datum, marshes with no elevation deficit can still be subjected to increased hydroperiod and waterlogging through eustatic sea-level rise. In Louisiana, because subsidence rather than eustacy is the main factor in relative sea-level rise, this effect may be assumed to be negligible. In other areas where subsidence is less of a problem, or under future global change scenarios where eustatic sea-level changes become significant in Louisiana, further refinements of the techniques for measuring the response of marsh to subsidence and sea-level rise may be necessary.

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Natural Resource Problem Solving: an Interdisciplinary Approach in Coastal Louisiana.

A. Lee Foote[1], Virginia Burkett[1], and S. Jeffress Williams[2]

Abstract

Ecological issues such as coastal wetland loss cannot be adequately addressed by experts in any one particular discipline. After extensive consultation with wetland users and regulators, the U. S. Fish and Wildlife Service and the U. S. Geological Survey assembled an interdisciplinary team of researchers to conduct a detailed field study of wetland processes, dynamics, and management on four pairs of coastal wetlands. The study serves as an example of cooperation in accumulating information to be applied to large-scale problem solving by using interdisciplinary expertise, incorporating multiple managed and unmanaged areas into the study design, and studying annual variation in processes.

Introduction

Research on U. S. coastal wetland loss during the last decade has clearly described the magnitude of loss and has identified many of the causes of loss (Evers et al. 1992). In theory, the role of applied wetlands research is to understand the mechanisms and extent of wetland loss as well as to develop effective techniques for restoring and protecting these important habitats. Research in coastal Louisiana, a zone of extreme wetland loss, has recently matured to the point of empirically testing proposed landscape-level solutions to wetland loss. Those who restore wetlands must operate with inadequate information. Ecosystem-wide alterations to the most basic hydrologic and sedimentologic processes to improve wetland sustainability are only now being tested.

Researchers have demonstrated that coastal Louisiana wetlands are converting to open-water, estuarine systems of the Gulf of Mexico because of increases in relative sea level (Penland et al. 1987), deprivation of sediments (Bauman et al. 1984, Cahoon and

[1]U.S. Fish and Wildlife Service, 700 Cajundome, Lafayette, LA 70506

[2]U.S. Geological Survey, 914 National Center, Reston, VA 22090

Turner 1989), hydrologic alteration (Day et al. 1986, Swenson and Turner 1987), changes in salinity regime (Van Sickle et al. 1976, Wiseman et al. 1990), introduction of exotic species (Linscombe et al. 1981), and direct development of marsh surfaces (Scaife et al. 1983).

Cahoon and Groat (1990) reported that as of 1989, 165 applications had been made to the State of Louisiana to manage 203,500 ha of coastal marsh, which make up about 12% of all coastal marsh habitats. The primary purpose stated for management was to mitigate land loss, and the second and third most commonly stated goals of management were to improve waterfowl habitats and furbearer habitats, respectively. The high level of interest in marsh management provides a strong justification for continuing research efforts.

The scale of research programs conducted to date in this rapidly deteriorating ecosystem has generally been limited to areas that are less than 20% of a watershed and have focused on several critical elements of the functioning ecosystem (e.g., sediments, salinity, and herbivory). Consequently, most restoration efforts have been directed toward only a small portion of a hydrologic unit, with objectives confined to mitigating only one factor or mechanism, such as saltwater intrusion.

From a stewardship perspective, the next phase of research is to measure and analyze the effects of restitutive actions or management options designed to reduce wetland degradation and loss. To be useful and applicable beyond the boundaries of a traditional study area, research must offer explanations of the mechanisms and processes of wetland alteration and the interactions of these processes at a regional scale.

Joint Study

In 1990 the U. S. Fish and Wildlife Service (USFWS) and the U. S. Geological Survey (USGS) began an interdisciplinary study of the effects of marsh management in threatened wetlands along the Louisiana coast. For this study, marsh management is rather narrowly defined as exerting control over a wetland's hydrologic regime through the use of levees and water control structures. Marsh management continues to be a controversial topic, largely because of the various practices, needs, and economic perceptions of diverse interest groups, and insufficient scientific data to accept or reject hypotheses about marsh responses to manipulation. To obtain reliable, field-applicable knowledge of marsh processes in response to manipulation, we developed a program of research incorporating the following premises and objectives:

(1) There needs to be an integrated understanding of the physical, chemical, and biological processes that affect the sustainability of marshes in this region. Each manipulated marsh unit is being contrasted with a comparable "control" wetland unit that remains unmanipulated.

(2) Research is conducted as impartially as possible. Public acceptance and objectivity dictate that the study be controlled by Federal agencies which are perceived as the least-easily influenced by local interest groups. The study focuses on effects, processes, and causative linkages and not on user-defined values, although after analyses are completed and results are published, subsequent work may address effects on users.

(3) Issues and utility of the study receive extensive prestudy review and input from a 12-person steering committee with representatives from Federal agencies (USFWS, Army Corps of Engineers (USACOE), National Marine Fisheries Service (NMFS), and Soil Conservation Service (SCS)), two large oil companies (Fina Laterre Inc. and Louisiana Land and Exploration), the State regulatory agency (Louisiana Division of Natural Resources (DNR)), and one private wildlife biologist (Table 1). The steering committee reflects the ultimate end users of knowledge accumulated from this study, and they are a crucial link to implementation of the findings. The committee's involvement and understanding of the work at the start of the study were important and helpful. Committee members helped to refine questions, select study areas, and define critical knowledge gaps.

(4) Research is conducted by an interdisciplinary team of scientists (Table 2), each of which is primarily responsible for their area of expertise while working cooperatively with overlapping projects. The USFWS and USGS provide research support in the form of grants, cooperative agreements, technicians, airboats, site access, and materials.

(5) Overall design of the project received extensive statistical review from consulting statisticians (years 1-2); preliminary results and progress reports are presented at national and regional symposia (years 2-4); final results will be published in peer-reviewed journals (years 4-6).

Table 1. Cooperating landowners, consultants, and steering committee members involved with the Louisiana marsh management study.

•	William Berry, Manager, Louisiana Land and Exploration
•	Donald R. Cahoon, Geologist (USFWS)
•	Daryl Clark, Marsh manager, Louisiana (DNR)
	Alan Ensminger, Private wetland wildlife biologist
	Larry Handley, Geographer (USFWS)
•	Noel Kinler, Furbearer biologist, Louisiana Department of Wildlife and Fisheries (LDWF)
•	Greg Linscombe, Furbearer biologist (LDWF)
•	Irv Mendelssohn, Ecologist, Center for Wetland Resources (LSU)
•	Ronnie Paille, Wetland biologist, USFWS Ecological Services
	Edward Pendelton, Wetland ecologist (USFWS)
•	Bruce Pugesek, Statistician, (USFWS)
•	John Reddoch, Permitting division (USACOE)
•	Dave Reece, Permitting division (USACOE)
•	Mr. Rick Ruebsamen, Program manager (NMFS)
•	Mr. James Winston, District Conservationist (SCS)
•	Mr. John Woodard, Manager, Fina Laterre Oil and Chemical Company Inc.
	Mr. Robert Zurfluh, Surveyor, National Oceanic and Atmospheric Administration (NOAA)

• denotes steering committee members for this study

Table 2. Scientists associated with the Louisiana marsh management study, their affiliation, and research responsibility.

U. S. Fish and Wildlife Service	
Virginia Burkett	USFWS program administrator
Donald R. Cahoon, PhD	Sedimentation rates (horizon markers)
A. Lee Foote, PhD	Research project manager-scientist
Jim Grace, PhD	Fire/herbivory interaction
Glenn R. Guntenspergen, PhD	Vegetation productivity, storm effects
Lori A. Johnson	Plant turnover rate and herbivory effects
Thomas C. Michot, PhD	Waterbird use of managed vs unmanaged marshes
Elijah Ramsey, PhD	Leaf area index, area-wide spectral reflectance measurements
Kathy A. Reynolds	Biomass and decomposition rates
Eric Seeger	Photointerpretation and rectification
Katherine Taylor, PhD	Fire/herbivory interaction
U. S. Geological Survey	
Laurie Balistrieri, PhD	Radioisotope sediment dating
John Dingler, PhD	Meteorological effects and sediment suspension
Larry Jackson, PhD	Short-term sedimentation, pore water chemistry
Joel Leventhal, PhD	Methane production, seasonal and area wide measurements
Tom Reiss	Subsidence surveys
Kathleen Smith	Water column nutrient flux
Jeff Williams, PhD	USGS Research project manager, geologic framework
University of Southwestern Louisiana (USL)	
Tom Hargis	Pore water dynamics, interstitial salinity
Patricia Rafferty	Nutrient fluxes
Robert Twilley, PhD	USL coordination, nutrient dynamics, hypsometry
Louisiana State University (LSU)	
Shea Penland, PhD	Deltaic plain geology, storm effects
Paul Conner	Soil core analyses
Louisiana Universities Marine Consortium (LUMCON)	
Denise Reed, PhD	Sedimentary processes, storm effects

Research that integrates multiple ecological functions and processes requires both scientific expertise and collaboration. Below we elaborate on three general themes and justifications for the interagency team approach to research; comprehensiveness, efficiency, and effectiveness.

With greater cooperation between agencies, public research dollars can yield a more extensive explanation of the main effects and overriding influences within an ecological setting. While no single research group contains all of the necessary expertise or resources to carry out a large wetland study that spans topics from geological processes to human dimensions, a combination of research groups can share questions, methods, and build upon each other's findings to enhance the scientific knowledge base on wetland changes (see Table 3). Cooperative research on complex and interactive ecological processes provides an internal series of checks and balances on research procedure, thoroughness, and rational interpretation of results.

Public understanding and acceptance of research findings is often a weak link in applied research. However, acceptance of results is critical to effecting changes in the ways humans use and manage resources. Interagency research results that have been developed and published in collaboration with university scientists are likely to be more credible to the scientific community and the public in general.

Most questions addressed in this study are not new. Several dozen studies have addressed the individual factors considered to be responsible for most coastal wetland loss in this region. We are indebted to these researchers for establishing techniques, baseline data, and providing enough information to develop and extend our research hypotheses.

Four design factors help make this study comprehensive and applicable to a wide variety of areas: (1) multiple study areas, (2) temporal and spatial controls within areas, (3) teamwork among agencies and landowners (Table 1), and (4) simultaneous measurement of a wide array of wetland processes, which allows us to measure interactions between variables (Table 3).

Efficiency of the USFWS and USGS marsh management research is greatly improved in joint studies of this type. Experimental manipulation of ecosystems is usually very expensive and once such an investment has been made, Federal agencies have a fiscal responsibility to maximize the knowledge gain from this investment. Additionally, basic data such as water levels, water salinity, and weather data may be shared.

Table 3. Factors examined in managed and unmanaged marshes over 4 years in the USFWS-USGS marsh management study.

Abiotic Factors	Geological structure and history Shallow (recent) sedimentary record Amount and change in land area versus water area Hydrology Sedimentation and accretionary processes Porewater and nutrient flux, redox status Water quality Meteorological effects (wind and waves) Storm effects
Biotic Factors	Plant community change Organic matter decomposition Seed bank constituency changes Aboveground and belowground plant productivity Herbivory effects on turnover of plant materials Use of sites by wetland-dependent birds

Effectiveness of the study is enhanced by corroboration of results and by the presentation of a more complete description of effects. Explaining research findings in a way that satisfies a diverse suite of scientists, such as those working on this project, functions as a checks-and-balance screening of results. The knowledge gained in this study will be in a format that is more interpretable to a wide spectrum of wetland managers and investigators. We seek to make this research useful and applicable to the problems along the coast.

The primary research questions of this study include:

1. How does traditional wetland management affect long term marsh sustainability?
2. What effects do levees and structures have on sedimentation?
3. How do individual plants and plant stands respond to management?
4. What is the fate of organic material produced on wetland sites?
5. How is seasonal hydrology affected by marsh management.
6. What influence does hydrologic manipulation have on ambient salinity?
7. How does management affect the chemical and nutrient status of marsh soils?

8. What is the absolute rate of subsidence in managed versus unmanaged coastal marshes?
9. What are the components of subsidence: surface, upper sediments, or deep bedding compaction?
10. How do waterbirds respond to the availability of managed marsh?
11. What is the role of herbivory in coastal marsh management?
12. In what ways do storms directly affect marsh surfaces?

There are many additional questions that relate to specific processes, rates of alteration, and future conditions resulting from management actions.
Where possible, we are making direct measurements of the phenomena and processes of marsh loss. Many ecological phenomena operate at rates not detectable by short studies and because this study is planned as a 5-year investigation, we expect data records of subsidence, plant-species change, and marsh area loss to be more clearly measured and more interpretable.

As with any study of this scope and duration, many questions are being raised and brought into focus. In addition to addressing specific research hypotheses, resources made available through this study have generated new field techniques and findings of a "survey" nature which describe ecosystems in coastal Louisiana. Thus far, during the first 2 years of fieldwork, researchers have produced 5 scientific papers, 6 posters at scientific meetings, 15 formal presentations at professional meetings, and many non-technical and community presentations. The study has partially supported two M.S. theses and one Ph.D. thesis as well as provided cooperation and work contracts to two university departments. The study is currently in the third year of five, and if previous trends continue, a great deal more information will be contributed to the scientific knowledge pool as a result of this cooperative wetlands research.

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SESSION 17

Processes of Wetlands Loss in Louisiana II: Identifying Land Loss Mechanisms and Mapping Land Loss

Are Landscape Patterns Related to Marsh Loss Processes?

J.A. Nyman[1], M. Carloss[2], R.D. DeLaune[3] and W.H. Patrick, Jr.[4]

Abstract

Marsh loss that occurs in Louisiana is seldom associated with shoreline erosion of lakes and bayous; instead, marshes break up internally. Marsh loss is attributed to processes that stress vegetation, such as salt-water intrusion or excessive flooding, and occurs in two landscape patterns. Previous workers classified marsh loss as either concentrated in "hotspots" or scattered in the marsh interior. Those workers found that although hotspots accounted for only 12% of all marsh in their study areas, they accounted for 43% of all marsh loss. We recently studied marsh loss processes where it occurred in a hotspot pattern and in a scattered pattern. Marsh loss at the hotspot proceeded by the previously recognized process of inadequate vertical accretion, which led to excessive flooding of the marsh surface, and subsequent plant stress followed by collapse of the marsh surface and ponding. Marsh loss at the scattered site proceeded by erosion of soil below the living root zone, which is a process that has not previously been recognized as important in Louisiana. Additional study is

[1]Research Associate, Wetland Biogeochemistry Institute, LSU, Baton Rouge LA 70803-7511. phone: 504 388-6422

[2]Biologist, New Iberia Field Office, Louisiana Department of Wildlife and Fisheries, Rt. 4, Box 78 Darnell Rd., New Iberia, LA 70560. phone: 318 369-3807

[3]Professor, Wetland Biogeochemistry Institute, LSU, Baton Rouge LA 70803-7511. phone: 504 388-6421

[4]Director and Boyd Professor, ibid., phone: 504 388-8806

needed to determine if such internal erosion is important elsewhere in Louisiana, and if landscape patterns can be associated with marsh loss mechanisms.

Introduction

The conversion of coastal marsh to open water causes the loss of valuable wildlife and fisheries habitat throughout the world (Coleman and Roberts 1989). Most documented cases are from the Atlantic and Gulf coasts of the United States (Gagliano et al., 1981, Hackney and Cleary 1987, Kearney and Stevenson 1991, Phillips 1986, Morton and Paine 1990). Marsh loss is particularly severe in Louisiana where on average, 2,278 ha of marsh convert to open water each year (Gagliano et al. 1981).

Lateral erosion of water bodies is the most often cited mechanism of marsh loss outside Louisiana (Kearney and Stevenson 1991, Morton and Paine 1990, Phillips 1986). In Louisiana however, vegetation stress followed by plant dieback and pond formation is believed to be the primary mechanism of marsh loss (Gagliano et al. 1981, Turner 1990). Plant stress is commonly assumed to originate from one of two sources in Louisiana. The earliest recognized plant stress was saltwater intrusion into non-saline marshes caused an absence of overbank flooding by the Mississippi River, and the presence of a network of canals throughout the marsh zone (Viosca 1928). The resulting conversion from less saline conditions to more saline conditions has been associated with rapid marsh loss (Sasser et al. 1986). Later, it was recognized that rapid subsidence also contributes to marsh loss (Gagliano and van Beek 1973). In some marshes, vertical accretion is slower than submergence. Such marshes are slowly sinking lower and lower relative to mean water levels, which results in flooding stress on vegetation and subsequent marsh loss (DeLaune et al. 1983). Regardless of what causes marsh loss, the resulting water bodies might provide avenues for subsequent salt water intrusion. Thus, the mere documentation of marsh types converting from fresher to more saline conditions following marsh loss is not necessarily indicative of saltwater intrusion causing marsh loss.

Leibowitz and Hill (1987) recently discovered that marsh loss occurs in two landscape patterns in coastal Louisiana. Marsh loss was scattered throughout the marsh interior in the most common landscape pattern. Marsh loss rates in these areas averaged less than 0.5%/yr. Less common were areas where marsh loss was concentrated in large hotspots. Marsh loss rates in these areas averaged just over 2.7%/yr. Hotspots occupied less than 12% of all marsh, but accounted for almost 43% of all the marsh loss in that previous study (Leibowitz and Hill 1987).

We recently completed studies of marsh loss processes in a hotspot landscape and a scattered landscape in coastal Louisiana. The details of those studies are contained elsewhere (unpublished manuscripts in review). The purpose of this paper is to contrast the findings of those two field studies. Those studies were designed as detailed examinations of marshloss processes, rather than as test of hypotheses regarding landscape patterns. Thus the findings presented in this paper do not constitute a rigorous comparison of the processes occurring in the two landscapes. Rigorous, statistically valid comparisons would require that more than one site be studied in each landscape pattern. However, the findings presented in this paper may suggest avenues for such future research.

Study Areas

The study site that contained the hotspot was near Lake Barre, Louisiana (Figure 1). This site was selected because this area of Louisiana is sediment poor, and is in the delta lobe abandonment phase of the delta lobe cycle (Coleman and Gagliano 1964, Coleman 1988). During this phase of the delta cycle, marshes do not receive river borne sediments, but subsidence continues. This leads to increased flooding and saltwater intrusion. There were also a few oil and gas canals in the area, but their role in increasing wetland loss is unknown. Vegetation type maps indicate that the border between saline and brackish marsh migrated 4-5 km inland between the 1940's and 1988 (O'Neil 1949, Chabreck and Linscombe 1978, Chabreck and Linscombe 1988). Small places where marsh converted to open water were scattered throughout the marsh interior. Additionally, a large hotspot formed after 1974 (Britsch and

Kemp 1990). Much of it coincides with an area that converted from brackish to saline. Broken marsh, solid marsh, and irregular shaped lakes all existed in the hotspot area before 1974. Thus, the landscape pattern at this site consisted of a large hotspot imbedded in the typical pattern of interior broken marsh surrounded by solid marsh. Marsh loss rates for the 15 minute map containing this site increased since 1974, and averaged 515 ha/yr between 1974 and 1983 (Britsch and Kemp 1991).

The other study site was at Marsh Island, Louisiana (Figure 1). Marsh Island was selected because it has slower subsidence than the Lake Barre site, and because it is closer to the sediment rich waters of the Atchafalaya River than the Lake Barre site is. Limited oil and gas exploration also occurred at Marsh Island. Vegetation type maps indicated that vegetation

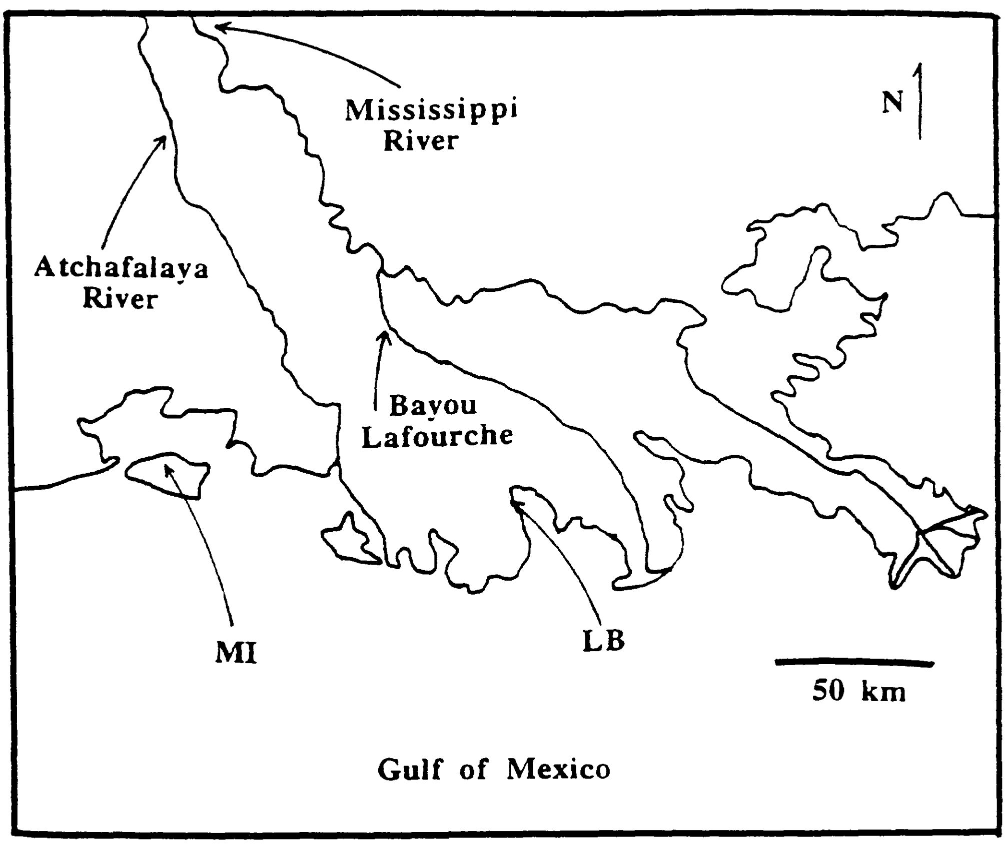

Figure 1. Location of Lake Barre (LB) and Marsh Island (MI) marshes studied in southeast Louisiana, USA.

has been brackish since at least the 1940's (O'Neil 1949, Chabreck and Linscombe 1988). The landscape at this site followed the typical pattern of internal broken marsh where marsh loss occurs, surrounded by solid marsh adjacent to bayous and large lakes. Marsh loss rates for the 15 minute map containing this site decreased since 1974, and averaged 62 ha/yr (Britsch and Kemp 1991).

Results and Discussion

Hotspot Marsh Loss. Vertical accretion in the Lake Barre study area was extremely rapid relative to other marshes, which we did not expect. Vertical accretion averaged almost 1 cm/yr, which was substantially greater than the average for southeast Louisiana, which is 0.72 cm/yr (Nyman et al. 1990).

Although vertical accretion was extremely rapid, it was inadequate to counter submergence in the area. Submergence was estimated to be greater than 1.3 cm/yr. Thus inadequate vertical accretion leading to excessive flooding stress on marsh vegetation, and subsequent plant die-back and pond formation was indicated as the marsh loss mechanism at this site.

Plant production was lower in this study site than in other Louisiana marshes. There was therefore less organic matter available for soil formation and for export to the surrounding estuary at this site than at other marshes. Aboveground, belowground biomass ratios and soil Eh indicated that flooding stress on vegetation was high. Thus the poor production was attributed to flooding stress, as would be expected if there was a vertical accretion deficit.

Conversion of marsh to open water was monitored at the hotspot. There was no distinct border between marsh and open water (Figure 2). Instead, hummocked vegetation gradually gave way to open water. As hummocks died, which was attributed to flooding stress, elevation of the marsh surface decreased over 10 cm within the following 2 years (unpublished data). This caused the conversion of marsh to open water, and was attributed to a collapse of the living root network in the upper layers of the soil. Plant stubble was still rooted in place beneath the water, and no evidence of surface erosion was noted until long after marsh converted to open water.

It was concluded that marsh loss could be countered in this study area with extremely large mineral sediment additions, which do not seem feasible. At least 11 cm of mineral sediments would have to be pumped onto the marsh surface just to restore marsh elevation to normal. Assuming that such a mineral deposit would have a bulk density of 0.80 g/cm^3, then

Figure 2. View from bayou edge, looking inland, to area where marsh loss occurs near Lake Barre, Louisiana; early May 1992.

88 kg/m^2 of sediment would be required. Furthermore, additional sediments would be needed each year to counter on-going submergence. We used the sediment requirements for brackish and saline marsh estimated by Nyman et al. (1990) and the amount of mineral sediments actually deposited in the study area to estimate the amount of mineral sediments required each year in addition to those naturally deposited. We estimated that mineral sedimentation in saline marsh would have to increase by 0.5 kg m^{-2} yr^{-1} so that it was 2.5 g m^{-2} yr^{-1}. Mineral sedimentation in brackish marsh would have to increase even more, by 0.7 kg m^{-2} yr^{-1} so that it was 1.4 kg m^{-2} yr^{-1}.

Interior Breakup. Conditions were very different at the study area where marshloss was scattered throughout the marsh interior. Vertical accretion averaged 0.55 cm/yr, which was much slower than at the Lake Barre site. However, vertical accretion was adequate to counter the moderate submergence rate in this area, which was estimated at only 0.31 cm/yr. Vertical accretion was actually greater in broken marsh (0.60 cm/yr) where marsh loss occurred, than in solid marsh (0.50 cm/yr) where marsh loss did not occur. Contrary to our initial expectations, there was no difference in soil Eh between solid marsh and broken marsh, and broken marsh soil was well drained. End-of-season, standing-crop plant biomass at this study site was typical of healthy brackish marshes, and did not differ between broken marsh and solid marsh. These data indicated that marsh loss at this site was unrelated to either salinity stress or flooding stress.

The mechanism of marsh loss appeared to be soil erosion below the living root zone, as indicated by the vertical and often undercut marsh water interface, and by the separation of sod clasts (Figure 3). We were unaware that the marsh water interface was undercut until we were caught in the middle of a field trip by a winter weather front that produced extremely low water levels. This also appears similar to the erosion of floating, fresh marsh in Louisiana described by Gagliano and Wicker (1989), except that erosion at Marsh Island does not seem to be related to tidal action (unpublished manuscript in review). Thus, some marsh loss in Louisiana is not associated with plant stress as is currently believed, but is similar to the internal erosion reported in a Chesapeake Bay brackish marsh (Stevenson et al. 1985).

It was concluded that marsh loss in this study area could be countered only by increasing the elevation of the pond bottoms so that the loosely consolidated soil below the living root zone at the marsh/water interface would not be exposed to open water (Figure 4). This may be possible without pumping sediments. If the broken marsh areas could be drained for a short time each year for several years, perhaps emergent vegetation could grow in the pond areas and build up the elevation of the pond bottoms by the production of a thick root mat. It might be possible to achieve this goal with modification

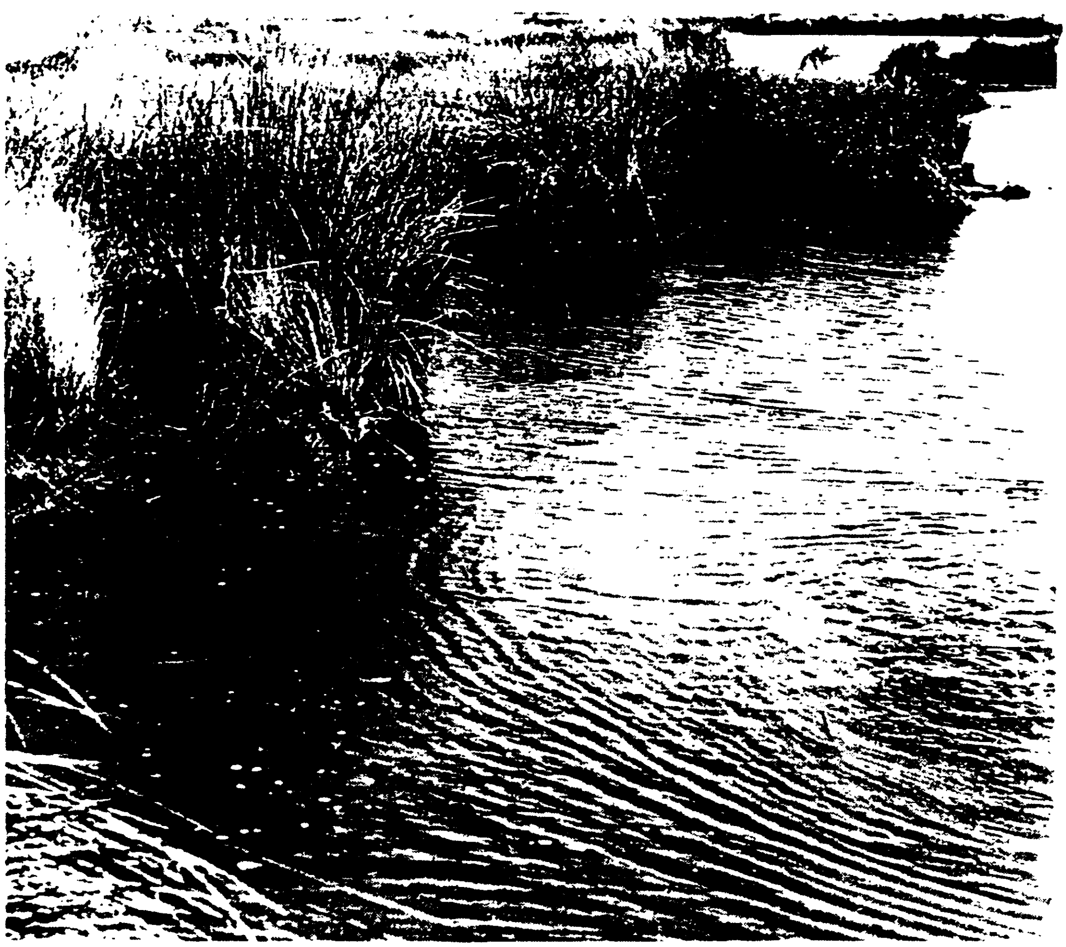

Figure 3. View of the broken marsh interior where marsh loss occurs at Marsh Island, Louisiana; early October, 1990.

of current Louisiana marsh management techniques, which are usually directed at improving wildlife habitat by producing favorable plant communities.

Conclusions

Some marsh loss was caused by the previously recognized process of inadequate vertical accretion, followed by plant stress, plant die-back, which was followed by collapse of the surface peats that caused ponding. This mechanism was important in a area experiencing rapid marsh loss in a hotspot pattern. Other marsh loss was caused by erosion of soil below

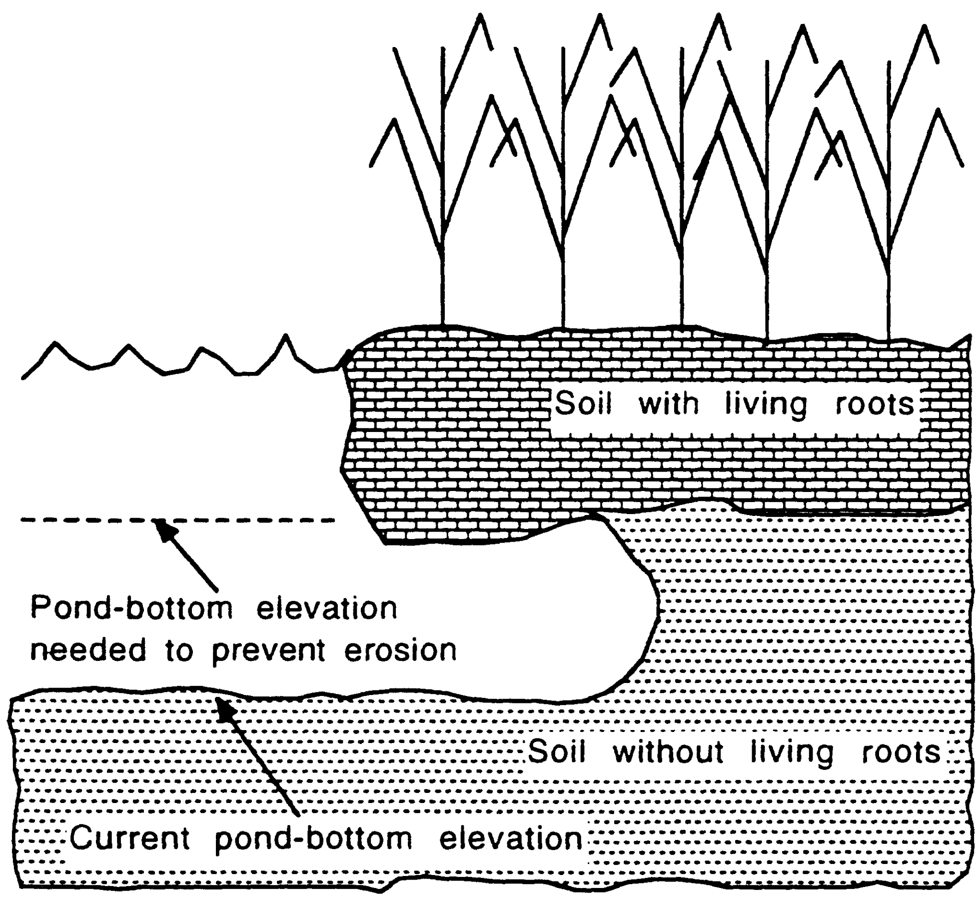

Figure 4. Cross sectional diagram of eroding marsh/water interface in interior marsh showing pond bottom elevation needed to prevent erosion.

the living root zone at the edges of irregularly shaped, interior marsh ponds. This was found to occur in an area where marsh loss occurred only in the internal breakup pattern, which is much more widespread in Louisiana than hotspots, but slower than in hotspots. Internal erosion has been documented in a Chesapeake Bay brackish marsh and appears to have occurred in a Louisiana floating, fresh marsh (Gagliano and Wicker 1989), but has not generally been considered important in Louisiana. It is not yet known if internal erosion is as widespread in Louisiana as the broken marsh interior landscape pattern is, or if hotspots result from plant stress. These are important points because marsh restoration in Louisiana generally seeks to prevent marsh loss by preventing plant stress, but hotspots are relatively rare.

Acknowledgments

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An Analysis of Wetland Change Mapping for the Mississippi River Deltaic Plain, Louisiana

M.R. Byrnes, R.A. McBride, Q. Tao[1]

ABSTRACT

Louisiana contains 41 percent of the coastal wetlands in the United States and derives considerable economic, social, and ecologic benefit from them. However, Louisiana is experiencing extensive and rapid land loss when considered on a historical time scale. As of 1990, about 66 km^2 of coastal wetland habitat is disappearing each year when estimates for the Mississippi River delta plain (52 km^2) and chenier plain (14 km^2) are combined (Britsch and Dunbar, 1993). Because land loss greatly reduces renewable resource benefits to humans (e.g., fish, wildlife, waterfowl) and wetland ecosystem values (e.g., buffering torm impacts, enhancing water quality) as well as diminishing human social values such as recreation and aesthetic enjoyment, there is considerable motivation for users and managers of wetlands to understand the causes and processes of wetland loss in order to determine effective management solutions). Based on a project funded by Argonne National Laboratory and the U.S. Geological Survey (USGS), a strategy for wetland change mapping, including evaluation of data sources, data compilation techniques, computer mapping procedures, and geographic information system (GIS) analyses, is presented. A primary component of the strategy is examination of potential errors associated with wetland change mapping. A comparison between this study and previous studies was made to assess the accuracy and variability of wetland change results.

A comprehensive analysis of land loss for the coastal zone of Louisiana for the period 1932 to 1990 was recently completed by the U.S. Army Corps of Engineers (USACE) to document regional patterns of change and its history of evolution (Britsch and Dunbar, 1993). Data used in their study included 1932/33 topographic sheets (scale equals 1:20,000) from the National Ocean Service (NOS), 1956/58 Tobin black-and-white aerial photography (scale equals 1:24,000), 1974 National Aeronautics and Space Administration (NASA) color infrared aerial photography (scale equals 1:120,000), 1983 color infrared photography at a scale of 1:58,000, and 1990 color infrared photography (scale equals 1:62,5000> The study used USGS 15-minute topographic quadrangles as base maps and converted all data to that scale. In order to assess the sensitivity of USACE results to scale and interpretation, the 15-minute Dulac Quadrangle for Terrebonne Parish was used as a test area. The area consists of four marsh types: fresh, intermediate, brackish, and saline. Data used for comparison with the

[1] Coastal Studies Institute, Louisiana State University, Baton Rouge, LA 70803

USACE results include the 1932 NOS topographic sheets, 1953 black-and-white aerial photography flown at a scale of 1:20,000 by the American SoilConservation Service (ASCS), 1963 USGS 7.5-minute topographic quadrangles (scale equals 1:24,000), and 1989 NASA color infrared aerial photography (scale equals 1:65,00). The 1932 NOS topographic sheets were digitized as base maps for the study area. Because these maps contain undetermined shoreline (dashed lines on the map), 1942 ASCS black-and-white aerial photographs were used as control for undetermined portions of the maps. The 1942, 1953, and 1989 photographs were rectified to USGS 7.5-minute topographic quadrangles and interpreted using a Stereo Zoom Transfer Scope. The interpreted shorelines were then digitized using Intergraph hardware and software platforms with attribute data stored in a relational database. Topological relationships with the three shorelines were constructed to perform GIS analyses. Three time periods for evaluating land change (1932-1953, 1953-1963, 1963-1989) were analyzed and associated rates of change were calculated using Intergraph Modular GIS Environment (MGE) and Modular GIS Analyst (MGA).

Based on the land loss analysis for the Dulac Quadrangle, variability in wetland change mapping results are introduced in two primary ways: 1) inaccuracies inherent with data sources and 2) errors associated with compilation techniques. Factors related to potential errors in data sources include data quality, data scale and resolution, and data surveying standards. Mapping errors introduced by compilation techniques include data interpretation, digitization, and control point selection for georeferencing. Preliminary results suggest that mapping variability associated with compilation techniques is the primary factor affecting comparisons of wetland loss. Between 1932 and 1963, the magnitude of change for each study was not significantly different. However, by 1989/90, when the marsh showed greater fragmentation, a substantial difference in land loss estimates was indicated. Currently, we are investigating the cause and magnitude of this difference.

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Production and Decomposition of *Spartina patens* in a Degrading Coastal Marsh

Lori A. Johnson, Kathleen A. Reynolds, and A. Lee Foote[1]

Abstract

Production and decomposition rates were calculated for *Spartina patens* in a mesohaline coastal marsh in Louisiana. Production was estimated to be 800 g m^{-2} yr^{-1} during 1991 and 1,696 g m^{-1} yr^{-1} during 1992. The relative decomposition rate of *S. patens* stems was -0.001152 g g^{-1} d^{-1} which may be restated as a half life of 395 days. Both production and decomposition rates for this area are low relative to most other studies in coastal areas. These data contribute to our understanding of the dynamics of organic matter in degrading coastal wetlands.

Introduction

Most emergent wetlands in temperate climates appear to be unchanging landscapes of wetland grasses; however, this is rarely the case. Unlike forests, virtually the entire standing crop of emergent wetland plants turns over on a time frame from weeks to several years, and fallen stems are incorporated into the wetland substrate. Plant-stem replacement requires rapid growth if the area is to remain vegetated, and similarly fast stem decomposition lest the wetland completely fill with undecomposed plant litter.

The inputs of detritus and sediments and the change in vegetated marsh area are particularly important considerations in the rapidly subsiding coastal wetlands of Louisiana, yet these relationships . Large reductions in terrigenous sediments have resulted in a sediment

[1]U.S. Fish and Wildlife Service, National Wetlands Research Center, 700 Cajundome Blvd., Lafayette, LA 70506

deficit (D.R. Cahoon, U.S. Fish and Wildlife Service, National Wetlands Research Center, Lafayette, Louisiana; personal communication) which has, in part, caused deltaic wetlands to convert to open water at rates estimated up to 60 km^2 per year (Gagliano 1981). In addition to sediments, plant matter adds to the vertical accretion of the marsh surface. Plant growth and survival have been shown to decrease in relation to increased mean water level in fresh marshes (McKee and Mendelssohn 1989). Researchers have suggested that plant production alone cannot provide sufficient material to maintain marsh surface elevations above the elevated water levels caused by the combined effects of subsidence and sea-level rise (Bauman et al. 1984); however, decomposing vegetation and mineralized plant components remain important elements of the marsh- soil matrix.

The contribution of plant materials to vertical accretion is difficult to generalize because production rates differ between marshes, detrital inputs vary seasonally, rates of decay vary over time (Valiela et al. 1985), and the physical-chemical microenvironment of the marsh surface affects stem residence time (Howarth and Hobbie 1982). Local sediments are primarily composed of organic material (Foote, unpublished data). Because below ground cores from the Spartina patens marsh we studied revealed recognizable S. patens plant parts throughout the upper 30 cm, it appears that much of the organic matter accretion is autochthonous.

The objective of this study was to establish simultaneous baseline estimates of S. patens production and decomposition in 4 degrading wetlands.

Study Area

Research was conducted in the northern part of Barataria basin, which is located about 35 km south of New Orleans, LA (29°36'N, 90°12'W, see figure 1). The study site is comprised of 4 tidally influenced, mesohaline, emergent wetlands dominated by S. patens and Scirpus olneyi. All 4 wetlands are within 1 km of each other. The region is one of rapid subsidence, and emergent marsh has been converting to open water at a rate of approximately 2% yr^{-1}, which we estimated from planimetric measurements of aerial photos from 1975, 1985, and 1989 (Foote, unpublished data).

This paper presents two concurrent field experiments that contribute to the understanding of the biological processes of stem production and decomposition of S. patens, an important wetland grass species in many deteriorating marshes in coastal Louisiana.

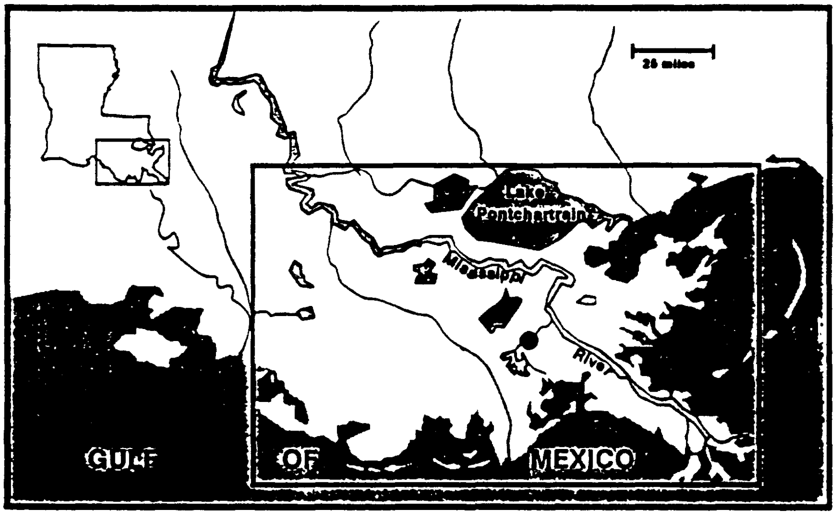

Figure 1. The study site was located 35 km south of Lake Pontchartrain.

Methods

Twenty sampling stations were selected by using a stratified random sample design. One 9-m^2 plot containing two permanent 0.0625-m^2 subplots was installed at each sampling station. Beginning in March 1991, all living S. patens stems in each subplot were tagged with colored tape. The following month, all tagged stems were counted, new emerging stems were tagged with a new color of tape, and all stems were measured for total height (Smith and Kadlec 1985, Morris and Haskin 1990). Stem counts and color tagging were repeated bimonthly until December 1992.

Phenometric techniques were used to estimate the aboveground biomass of tagged stems (Hopkinson et al. 1980). During each sampling period, we randomly selected around 100 S. patens stems from areas within 200 m of the plots, clipped them at the sediment surface, and returned them to the laboratory for subsequent measurements. The stems were dried at 70°C to a constant weight, measured for total length, and weighed.

Regression equations were derived from the height-mass relationship and were used to estimate the aboveground live biomass of tagged stems. Because the height-mass relationship changed throughout the growing season, a separate equation was calculated for each sampling period. To account for stem shrinkage during oven-drying, we applied a correction factor to biomass estimates. Stem mortality was estimated from the loss of tagged stems during each sampling interval and was converted to a biomass loss estimate by using the appropriate regression equation.

Annual production, P, of S. patens was calculated by applying the following formula:

$$P = \frac{[(B_{max} - B_{min}) + L]}{D} * 365$$

where B_{max} was the peak standing crop estimate, B_{min} was the initial biomass estimate of the growing season, L was the biomass loss for each sampling period summed over the growing season, and D was the total number of days sampled in one year.

For the decomposition study, standing dead S. patens material was collected from areas near the study site in April 1991. We prepared the material by clipping the intact plant stems into 12-15 cm lengths. Litter bags were constructed out of 1-mm^2 nylon screening and filled with approximately 5 g of the plant material. Because oven-drying could have affected the chemical composition of the stems, hence the decomposition rate, we estimated oven-dried initial weights by using a correction factor calculated from oven-dried samples taken throughout the processing period.

Fifty bags were placed at each of the 20 sampling stations in May 1991. Eight randomly selected bags were collected from each sampling station after 66, 159, 250, and 320 days in the field. Bag contents were carefully rinsed and foreign material was removed. Samples were oven-dried at 70°C to a constant weight and weighed to the nearest 0.01 g.

The relative decomposition rate k was calculated by the single exponential model:

$$x_t/x_0 = e^{-kt}$$

where x_t was the oven-dried weight of the plant material at time of collection, x_0 was the oven-dried initial weight of the plant material, e was the natural log, and t was the number of days in the field (Wieder and Lang 1982).

Results

Primary production. The total standing crop of S. patens varied seasonally and annually. During the 1991 growing season aboveground biomass estimates ranged from a low of 189 g/m^2 in April to a peak standing crop of 414 g/m^2 in October. Production declined over the winter, resulting in an annual minimum standing crop of 229 g/m^2 in January 1992. Growth rates increased throughout the 1992 growing season and reached a peak standing crop of 929 g/m^2 in December (figure 2).

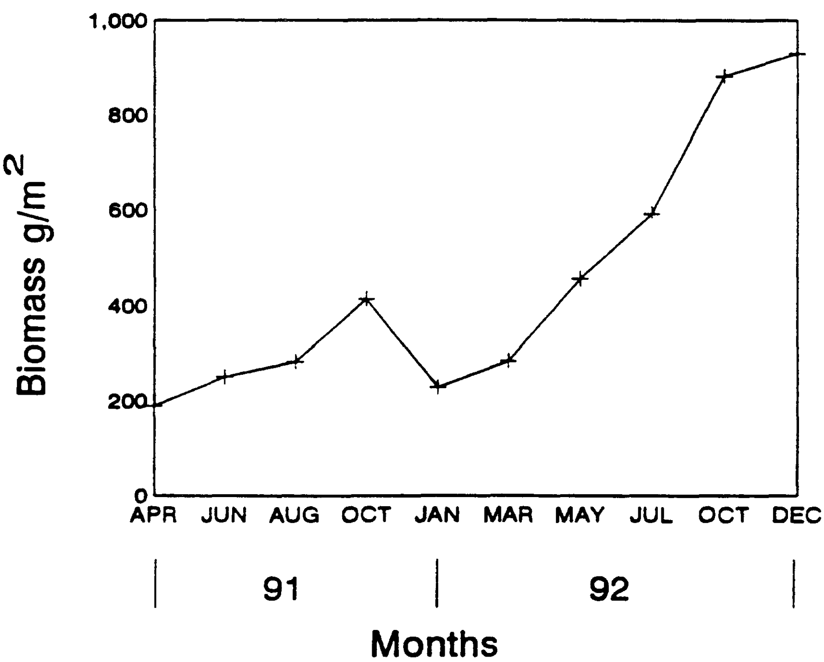

Figure 2. Aboveground biomass estimates for Spartina patens.

Peak standing crop estimates have been used in the past to estimate annual production; however, these estimates fail to consider losses throughout the growing season and provide a much lower and less accurate estimate of annual biomass production. After including stem mortality, S. patens production for the 1991 growing season was calculated to be 800 g m^{-2} yr^{-1}. Annual production in 1992, calculated to be 1,696 g m^{-2} yr^{-1}, was more than twice that of 1991.

Decomposition. The relative decomposition rate, k, for S. patens was -0.001152 g g^{-1} d^{-1}. We found 56% of the initial plant material remaining after 320 days of exposure (figure 3). Using the decay constant (k), we calculated that 50% would remain after 13 months (395 days).

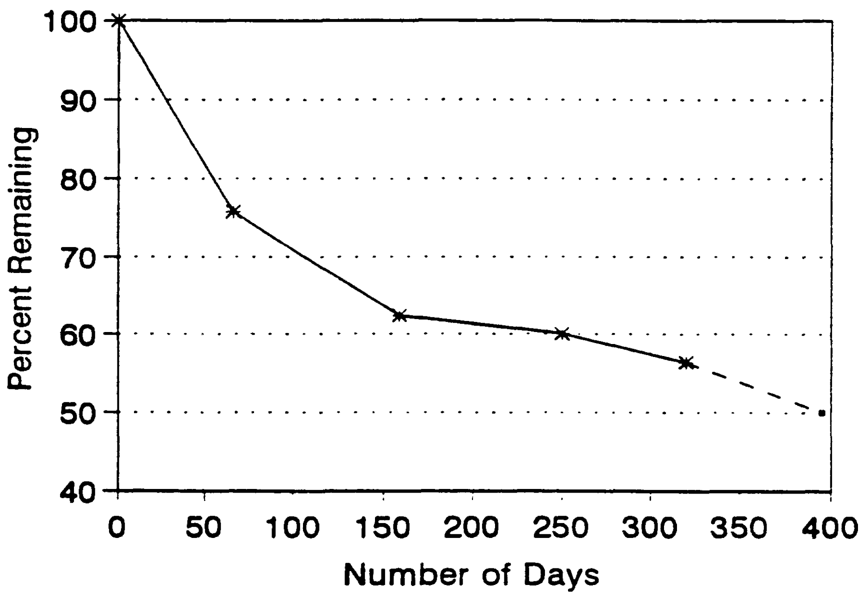

Figure 3. Percent of oven-dried Spartina patens litter remaining in Barataria basin study area. The line from day 320 to day 395 is projected.

Discussion

Production and decomposition of aboveground biomass are critical to the marsh-building process, and a change in either cycle is likely to alter the rate of vertical accretion. Inputs of autochthonous plant matter are though to be especially important in coastal Louisiana marshes where, as a result of sediment deprivation, subsidence and sea-level rise, the marsh surface elevation remains close to the mean water surface elevation. Even slight changes in rates of either production or decomposition may result in a submersed marsh surface.

The methods for measuring live standing crop and annual production vary among researchers (Wiegert and Evans 1964, Williams and Murdoch 1972, Hopkinson et al. 1980, Morris and Haskin 1990, Pezeshki and DeLaune 1991); thus it is difficult to compare the results from different studies (de la Cruz 1978). For example, the methods described by Wiegert and Evans (1964) generate high estimates, while the Smalley method is consistently conservative (Hopkinson et al. 1980). The stems of S. patens have a life span that exceeds one growing season; therefore a multi-year study that incorporates the life history and mortality rate of this species is essential for accurate productivity calculations (Bernard and Gorham 1978). Our productivity estimates are lower than most for Louisiana (Hopkinson et al. 1980, Pezeshki and DeLaune 1991); however, they are reasonable because we used nondestructive methods to measure permanent plots over two growing seasons, which accounted for over-wintering green stems and incorporated mortality throughout the year.

The lack of a clear, seasonal trend in the live standing crop of S. patens reflects the year-round growth, mortality, and disappearance of stems. Similar results have been reported for S. patens stands in the Terrebonne basin (Hopkinson et al. 1980). What is most apparent from the comparisons between our sites and results from other studies is the low estimates for peak standing crop and annual production. The peak standing crop on our site ranged from 437 g/m^2 to 960 g/m^2 lower than biomass estimates for nearby brackish marshes in the Terrebonne basin (Hopkinson et al. 1978, 1980).

Annual production estimates for S. patens in other Louisiana brackish marshes range from 2,500 $g\ m^{-2}\ yr^{-1}$ to 6043 $g\ m^{-2}\ yr^{-1}$ (Hopkinson et al. 1980, Pezeshki and DeLaune 1991). Annual production on our sites in 1991 was well below these estimates; however, production in 1992 was comparable to previous studies. We speculate that the large interannual difference we detected resulted from the extremely wet growing season in 1991 which may have caused greater waterlogging of roots, and the dry fall in 1992 which allowed a longer accumulation of plant matter.

By measuring vegetated and open-water areas from current and historical aerial photographs, we estimated a 2-5% areal conversion to open water since 1975 (Foote, unpublished data). These marshes are degrading and the growth and expansion of vegetation are not keeping pace with stem-mortality rates. This condition, though circumstantial, is consistent with low production values.

A very low ratio of live to dead S. patens biomass has been found in Louisiana brackish marshes (Pezeshki and DeLaune 1991). The ratio is lower than what has been reported for Atlantic coast marshes but is comparable to results from Texas marshes (Hopkinson et al. 1978). The fragmented nature of these plant stands precludes large areas from being burned and allows standing dead material to accumulate. Cores taken at 20 vegetated locations in the study area showed annual layers of horizontal stems, many of which were still rooted, therefore we think that most plant material remains near where it grew. This large volume of dead biomass is eventually incorporated into the fine organic material in the substrate through decomposition. These marshes have very little tidal energy due to a mean tidal range of only 15 cm, therefore we do not think that tidal export was an important factor in removing stems and leaves, however, losses of fine particulate organic matter would not have been easy to detect and were not measured in this study.

Relatively few studies have been done on S. patens decomposition, and the rates that have been determined vary widely. Our estimate of 50% remaining after 13 months is a much slower rate of decomposition than that reported by White et al. (1978), which was 50% remaining after 5 months with 38% remaining after one year of exposure in a Louisiana tidal salt marsh. Our results were similar, however, to a study done by Cramer et al. (1981) who reported a 34-40% loss of S. patens after 6 months in areas around oligohaline Lake Pontchartrain, Louisiana. We show approximately 38% loss for the same amount of time (figure 3). An even slower loss rate of 36% per year has been reported for S. patens in marshes of the Mississippi sound (Stout and de la Cruz 1978, referenced in Stout 1984.) Variation in loss rates for S. patens may be due to differences in tidal flushing and nutrient levels (Cramer et al. 1981), and period of inundation (Kruczynski et al. 1978, Valiela et al. 1985).

Cramer et al. (1981) did not find salinity to be a factor in decomposition rate.

Elevation in marshes such as the one we studied may depend both on the amount of plant biomass produced and on the residence time of that biomass on the marsh. A slow rate of decomposition allows organic matter to accumulate and increase marsh elevation, an important factor for marshes isolated from sediment input. Cores taken from the study site contain horizontal layers of S. patens alternating with mineral sediment layers, which indicates that plant matter plays an important role in the formation of these marshes. The slow rate of decomposition contributes to the continued existence of these wetlands. Despite the relatively low rates of decomposition, plant production on these sites appears to be inadequate to maintain the subaerial character of these wetlands.

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A Method for Classifying Land Loss by Geomorphology and Process

Lynda D. Wayne[1], Mark R. Byrnes[1], L. D. Britsch[2], Shea Penland[1], Patrick L. Wilkey[3], Ted A. Williams[4], and S. Jeffress Williams[5]

Abstract

There is great debate as to the causes of land loss in Louisiana and the restoration/preservation solutions that should be implemented. Much of the controversy can be attributed to a lack of quantitative information about the geomorphological character of land loss areas and the processes that formed them. The purpose of this paper is to present the results of research to develop a classification scheme capable of capturing this information.

Louisiana land loss data provided by the US Army Corps of Engineers were used to formulate the classification scheme. Geomorphology and process were identified as key elements for characterizing areas of land loss. Parameters of geomorphology and process were generated by a systematic review of distinct land loss areas. Separate hierarchical classification schemes were then devised to organize and relate the parameters of geomorphology and process. Once refined, this classification method will be applied to the Mississippi River delta plain and used to investigate the physiographic association between land loss geomorphology and process.

[1]Center for Coastal, Energy, and Environmental Resources, Louisiana State University, Baton Rouge, LA, 70803; [2]US Army Corps of Engineers, PO Box 60267, New Orleans, LA 70160-0267; [3]Argonne National Laboratory, 9700 Cass Avenue, Argonne, IL 60439-4815; [4]Gas Research Institute 8600 West Bryn Mawr Avenue, Chicago, IL 60631; [5]US Geological Survey, National Center, 12201 Sunrise Valley Drive, Reston, VA 22092.

Introduction

Land loss is a critical issue facing south Louisiana (Penland et al 1990). The rate of loss for 1990 is estimated to be 25 miles^2 (65 km^2) per year (Dunbar et al 1992). Most of this loss occurs in the biologically rich wetland areas of the Mississippi River delta plain (Sallenger et al 1992). These areas provide critical habitat for fish and wildlife, serve important ecological functions such as filtration and buffering of storm energy, and support a variety of recreational activities (Turner and Cahoon 1987). Preservation and restoration of valuable wetlands is dependent upon improved understanding of the land loss processes affecting coastal Louisiana (Penland et al 1992).

Researchers have endeavored to gain insight into the factors affecting land loss in coastal Louisiana. Numerous studies have been performed in an attempt to identify land loss effects of various natural and cultural activities. Most of these studies have focused either upon the impacts of an individual activity such as canal dredging (Scaife et al 1983), or a particular region of the coastal zone such as the Barataria Basin (Dozier et al 1983). As a result, study findings are typically too site or event specific to compile into a composite assessment of land loss in coastal Louisiana. In contrast, those studies which have attempted to address the full range of Louisiana's land loss character are usually too general in character to apply to the analysis of specific land loss incidents (Leibowitz and Hill 1988). This situation has lead to debate as to the causes of land loss in coastal Louisiana and the preservation/restoration measures that would best address the problem.

Much of this controversy can be attributed to a lack of regional quantitative land loss data. Recent land loss data collection efforts undertaken by the US Army Corps of Engineers (USACE) and the US Fish and Wildlife Service (USFWS) have served to address this need for information by providing maps and statistics which can be used to characterize baseline conditions of land loss in Louisiana. The US Geological Survey's (USGS) *National Coastal Geology Program* supports a range of Louisiana land loss studies which address issues such as barrier island erosion and wetland loss (Sallenger et al 1992). Collectively, these programs provide needed resources for the development of a Louisiana land loss data set.

The purpose of the Louisiana land loss classification study is to expand upon baseline data collection efforts by providing quantitative information about land loss geomorphology and process. Researchers are developing individual classification schemes capable of isolating 1) geomorphologically distinct forms of land loss and 2) the land loss processes associated with areas of loss. The schemes will be used to classify existing land loss data and investigate potential relations among the physical expression of land loss and the cultural and natural activities associated with the loss.

Data

The land loss data used within this study were provided by the US Army Corps of Engineers, New Orleans District (USACE-NO). The data were first published in an atlas entitled "Geologic Investigation of the Mississippi River Deltaic Plain: Land Loss and Land Accretion" (May and Britsch 1987) and later used to establish rates of land loss in two subsequent technical reports (Britsch and Kemp 1990, and Dunbar et al 1992). The data was provided to the classification research team in digital format and includes the following information for the Mississippi River deltaic plain (Figure 1):

- 1932 land/water interface base map compiled from National Ocean Service (formerly US Coast and Geodetic Survey) topographic sheets (NOS T-sheets) and 1:62,500 USGS topographic quadrangle maps,
- areas that converted from land to water in each of three time periods, 1932-1956/8, 1956/8-1974, and 1974-1983, and
- coding which discriminates man-made channels for each time period.

The data were originally developed by the USACE-NO to:

1) map the location of land loss in coastal Louisiana,
2) quantify the spatial and temporal magnitude of land loss between 1932 and 1983,
3) identify significant historical trends in Louisiana land loss rates.

The mapping was accomplished by comparing 1:62,500 scale aerial photography from each study period with the land loss base developed for the previous time period. Land loss was defined as the convergence of land on the base map to water on the photography. NOS T-sheets served as the primary base, however, early USGS 1:62,500 topographic maps were used for those areas where T-sheet coverage was unavailable. Mapping was performed for each quadrangle map unit within the Mississippi River delta plain. Land loss statistics were generated for each map then compiled to produce a land loss rate curve for the entire deltaic plain (Dunbar et al 1992).

The USACE study of land loss rates resulted in the generation of a large, detailed land loss data set. To achieve the objectives of the land loss classification study within project time and budget limits, it was necessary to select a single time period of data for classification. The cumulative time period (1932-1983) was selected for two primary reasons:

1) it contained the most diverse land loss conditions and therefore provided the best means of evaluating the range of applicability of the classification schemes, and
2) the interim data could be used to understand the processes affecting the loss and enable researchers to better refine the classification for complex loss scenarios.

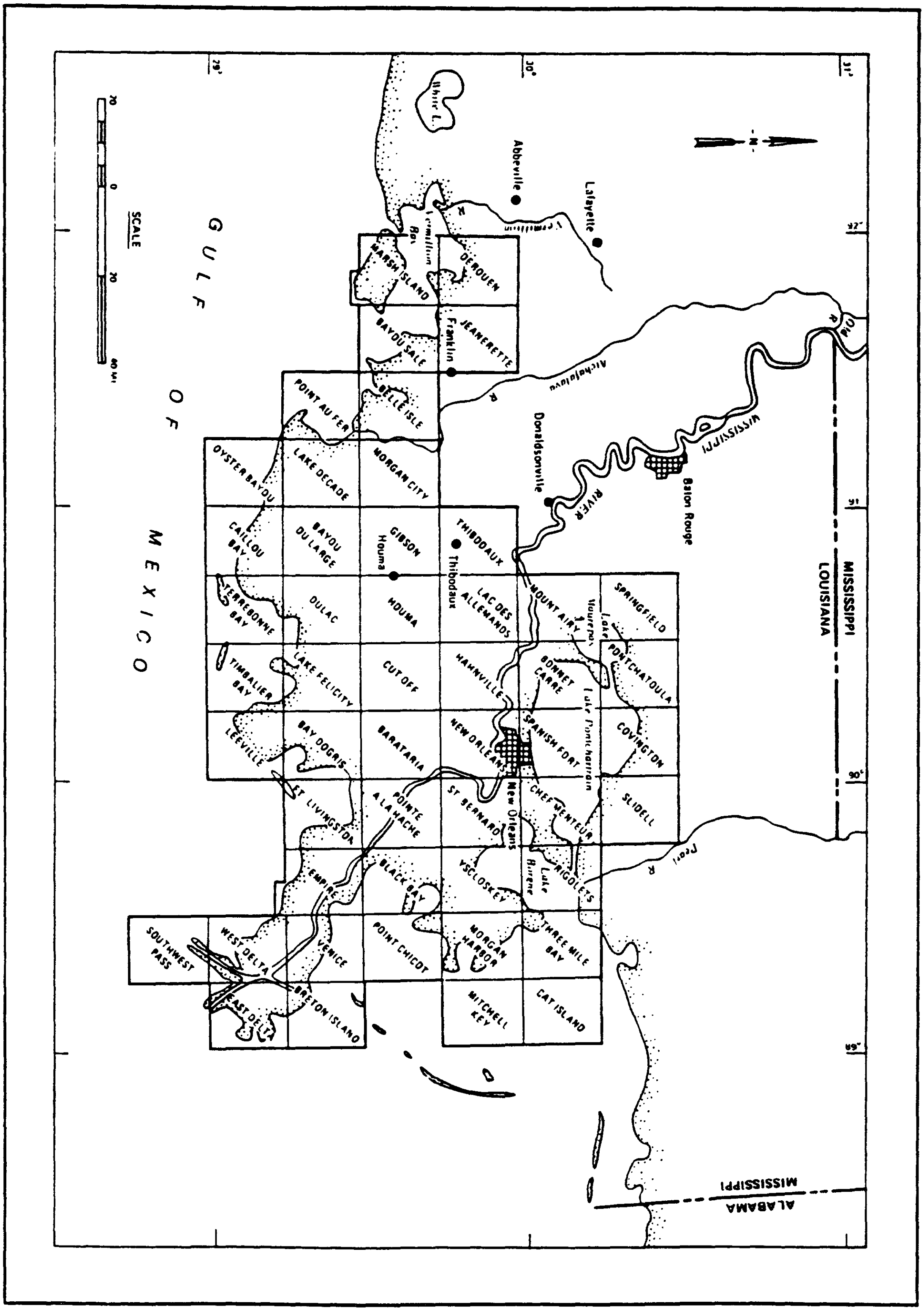

Figure 1 Project study area (from Britsch and Kemp, 1990)

Method

Researchers carefully reviewed the USACE land loss data set and derived initial concepts of loss geomorphology and processes. A mosaic of the fifty maps was created on a single wall of the laboratory and used as reference during a series of open discussions in which similarities in land loss configurations were identified and evaluated. Additional information was compiled about land loss processes and landscape activities (cultural and natural) associated with individual areas of loss. This information was used to generate process scenarios for highly expressive land loss formations. Once a familiarity with the regional data set was acquired, a series of examples were extracted to illustrate rough concepts of similarity and disparity with regard to land loss geomorphology and process.

These basic concepts were presented to an advisory committee of land loss experts from Louisiana. The committee was created as part of the classification study and is comprised of scientists from the university community, state and federal government, and private business, with backgrounds in sedimentology, marsh ecology, coastal geology, wildlife biology, vegetative dynamics, and coastal management. The advisory committee provided regional and disciplinary insight and responded to the conceptual presentation by generating a list of terms which more specifically characterized differences in form and process. The terms were organized into logical groups of process and geomorphology, and the groups were refined into initial classification schemes.

Once the initial classification schemes were derived, the advisory committee reviewed the schemes and provided critical comments. These comments were used to refine the classification schemes. Several land loss committee meetings were held prior to establishing the final land loss geomorphology and process classification schemes.

Geomorphological Classification

The geomorphological classification is intended to capture information about the physical form of land loss areas. Development of the geomorphological classification scheme was based upon two fundamental observations: 1) areas of land loss are, by definition, water, and 2) morphology cannot imply action or process. As a result, the derived scheme employs morphological parameters commonly associated with the description of waterbodies while avoiding process-oriented qualifiers. For example, the term "erosional shadow" aptly describes the linear loss patterns that occur in the lee of engineering structures. However, the term also imparts specific information about the process that may have caused the land loss and therefore is not appropriate for the geomorphological classification.

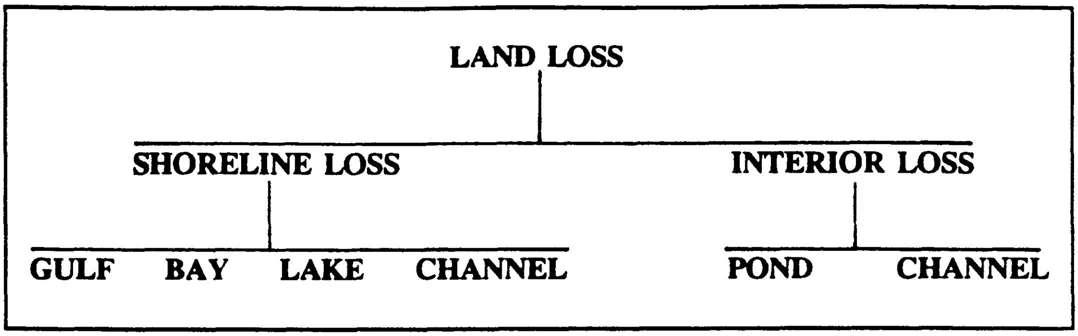

Figure 2 Geomorphological classification scheme

There are two levels to the geomorphological classification hierarchy as illustrated in Figure 2.

The first level addresses the physical relation of the loss relative to existing waterbodies. The first class, *shoreline*, applies to loss areas that occur relative to existing waterbodies. The second class, *interior*, applies to loss areas that occur independent of existing waterbodies. Shoreline loss areas are typically curvalinear, mirror the morphology of the previous shoreline, and have a large ratio of shoreline length to total area. Interior loss areas are new waterbodies that develop within the land mass and may vary in form from linear to rounded. Interior areas may also occur adjacent to existing waterbodies, but the ratio of shoreline length to total area is smaller than that of shoreline areas.

The next level of the hierarchy addresses the waterbody type most closely related to loss. For shoreline areas, this level depicts the type of waterbody physically related to the loss. Four classes of shoreline loss were established:

1) *gulf* - the outer shoreline facing the Gulf of Mexico,
2) *bay* - semi-enclosed waterbody with direct contact to the Gulf of Mexico,
3) *lake* - enclosed or semi-enclosed waterbody with no direct contact to the Gulf of Mexico, and
4) *channel* - linear waterbody that commonly connects other waterbodies.

For interior areas, this level of the classification depicts the waterbody type that is most similar new interior loss. Two interior classes were established:

1) *pond* - enclosed or semi-enclosed waterbody with minor connections to the existing drainage network, and
2) *channel* - narrow, linear waterbody.

Process Classification

Land loss is typically the result of complex interactions among natural and human activities upon the landscape. Therefore, it is difficult to isolate an activity as the singular cause of a specific area of land loss. However, general assumptions can be made for most areas regarding the primary physical process that removed or submerged the land, as well as the primary actions and catalysts that initiated the process. By employing a hierarchical classification scheme which graduates from general land loss process to specific cultural and natural landscape activities, the research team is able to classify each loss area as specifically as available information and scientific consensus allow. The process classification scheme is illustrated in Figure 3.

The first level of the classification hierarchy addresses the basic processes of land loss. For purposes of this classification scheme, the term land is defined as all subaerial materials including surface vegetation, sediments, and organic soils. Three primary land loss processes were identified:

1) *erosion* - mechanical removal and transport of land by water action,
2) *submergence* - increase of water level relative to ground surface elevation, and
3) *direct removal* - physical removal of land by actions other than water.

A fourth category, *undetermined*, is included for those areas to which no assignment can be made.

The second level of the process classification scheme identifies the primary physical actions that are associated with each loss process. This level of the classification includes both natural and cultural actions.

The actions of erosion include:

1) *scour* - mechanical removal of land by water, and
2) *transport* - suspension and conveyance of land by water.

The actions of submergence include:

1) *flooding* - short-term increase in water level,
2) *substrate collapse* - reduction in substrate thickness, and
3) *subsidence* - reduction in land surface elevation.

The actions of direct removal include:

1) *excavation* - extraction and transport of land to another location, and
2) *burning* - oxidation of the organic component of land.

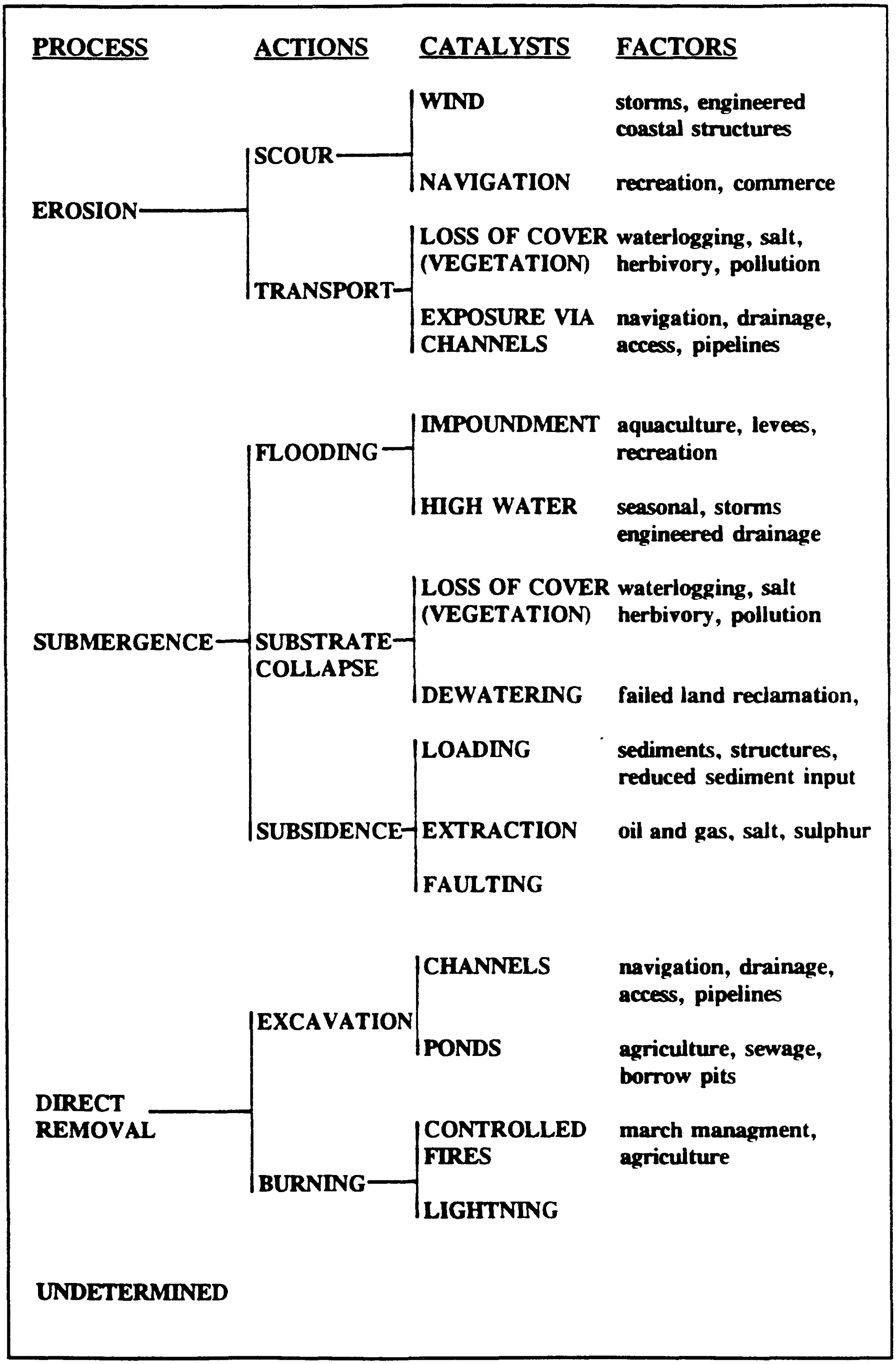

Figure 3 Process classification scheme

At the third level of the process classification scheme issues of cause emerge. This level identifies the natural and cultural catalysts to the physical actions. Natural catalysts include phenomena such as wind, loss of vegetation, high water, loading, and faulting. Cultural catalysts include human activities such as navigation, channel cutting, building of impoundments, resource extraction, excavation of ponds, and controlled fires.

The fourth level of the process classification identifies the factors known to stimulate natural and cultural land loss catalysts. This is a diverse category of information which includes natural and cultural events, activities, and structures. Factors included at this level of the classification scheme include storms, herbivory, sediment transport, recreation, agriculture, commerce, levees, and engineered coastal preservation/restoration structures.

Additional levels of factors are expected to evolve as the classification scheme is implemented. For example, engineered coastal structures can be further segregated into jetties, groins, and weirs. Levees can be designated by their use or origin, e.g., transportation, industry, flood control, or natural. This level of the classification scheme, however, will only be utilized for those areas where distinct assignments of loss can be made, e.g., pipeline canals, failed reclamation projects, animal eatouts.

Conclusions

The land loss classification schemes presented here are intended to provide researchers with a method for generating quantitative data about the character and processes of land loss in coastal Louisiana. Geographic information system (GIS) technology will be used to apply the schemes to the USACE-NO land loss data set and to create digital geomorphological and process classification maps and statistics. Because the diversity of opinions regarding specific causes of land loss, the study will continue to depend upon the resources of the advisory committee to review results. The hierarchical nature of the classification schemes and the numerical capabilities of the GIS provide a method for extracting values and statistics based upon the level of confidence associated with each classification level.

The results produced by the land loss classification study are intended to:

1) identify regional trends in land loss character,
2) identify the primary land loss processes and activities affecting coastal Louisiana, and
3) provide the quantitative data needed by related research projects to form specific hypothesis about causal relationships.

Acknowledgements

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Crevasses on the Lower Course of the Mississippi River

Donald W. Davis[1]

Abstract

Before construction of artificial levees, crevasses were a common event along the Mississippi River. They directed sediment out of the main channel and reduced flood stage down river. Archaeological evidence suggests these geomorphic features were a natural phenomenon that often remained open and functional for several hundred years. For example, in 1849 a crevasse flooded the upper Barataria basin to a depth of 1.2 m depositing a thin layer of new sediment onto impacted sugar and rice plantations. In that same year, Sauve's crevasse submerged New Orleans for 48 days. Breaches connected with these crevasses and others could not be repaired easily. Closure procedures began only when flow through a break was no longer a raging torrent. Crevasses were so dangerous the utmost precautions were taken to prevent them. Once present, they flowed at will.

Natural processes, defective rice flumes, saw mill raceways, crawfish (*Astacidae*), and muskrats (*Ondatra zibethicus rivalicius*) damaged the earthen levees to such an extent that their structural integrity was weakened and a crevasse was created. These early earthen embankments were narrow—scarcely wide enough for a foot or bridle path. When water came to within a few centimeters of the top of the embankment, they caved in to create a crevasse that could lower surface waters from 0.6 to 0.9 m (Humphreys and Abbot 1861). Many levee breaks were frequently less than 152 m wide but scoured a channel from 2.7 m to 3.0 m below the top of the levee.

Consequently, between 1850 and 1927, more than 1,000 crevasses punctured the lower Mississippi's levee. These fissures served as natural safety valves in directing flood waters away from the main channel. Many engineers advocated that these natural outlets should be emulated by constructing artificial outfalls that would

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[1] Research Professor, Louisiana State University, Center for Coastal, Energy, & Environmental Resources, Room E302, Howe-Russell Geoscience Complex, Baton Rouge, LA 70803

act as conduits to move flood waters into the coastal lowlands, depositing after each a veneer of delta-building sediment. This process would renourish the wetlands flood annually. In retrospect, an active system of artificial diversions would have replenished the marshes and offset the accumulated damage caused by leveeing the Mississippi River. Even though contemplated in 1829, 1850, 1866, and 1874, a comparable plan is being proposed for Louisiana's disappearing wetlands. Crevasse history provides guidelines for current discussions concerning controlled deposition through artificial channels and provides significant baseline information on a crevasse's role in building new land.

Introduction

On contemporary maps of delta switching more than 10,000 years of geomorphic history are recorded. Superimposed on this natural sequence of deltaic events are the engineered structures that harnessed and trained the Mississippi River's 54 tributaries to follow a designated route. No longer can the river overflow at random; it must follow a course outlined by earthen mounds constructed to control spring floods. Crevasses through these embankments allowed water to submerge the country "with the force of a torrent, carrying ruin and destruction in its course." (Wilson 1850:4) Humans have been directly responsible for most crevasse events.

Flooding From Crevasses

Early Louisiana records attest to the connectivity between floods and crevasses, and the interval from 1750 to 1927 is known as the "crevasse period" in Louisiana's fluvial history. It was a period when gaps in the east bank levees discharged into Lake Pontchartrain, Lake Borgne, Breton Sound or Mississippi Sound. Water escaping through breaks in the west bank emptied into Barataria Bay. These crevasses, some of which were 0.8 km wide and 21.3 m deep, created an enormous eddy. "Into this maelstrom flat-boats, rafts, barges, trading boats, are constantly drawn and destroyed." (Ellis 1876:5)

In the fall, winter, and spring of 1858 and 1859, "the worst flood in the history of the Mississippi valley occurred" (Frank 1930:27). Numerous crevasses ripped through the levees and devastated the Mississippi's bottom lands. Over 40.2 km of cumulative crevasse breaks submerged this valuable agricultural real estate (Frank 1930). The magnitude of these floods convinced levee builders their construction design was inadequate. Further, waves created by passing steamboats often weakened levees and were a recognized component in crevasse creation. "The lateral wave of one single steamboat is liable ... to wash over and dissolve the levee." (Warfield 1876:7)

When natural levees are overtopped, the water moves gently across the landscape. This sheet flow does not cut crevasses. In general, a crevasse is a product of artificial levees that prevents normal overflow. However, there are natural crevasses that cut through the natural levees. When a crevasse occurs, a channel is scoured to allow the outlet to function during high water. A break usually silts up in a few years and is generally associated with a river's cut bank side—a natural erosion point and ideal place for a crevasse.

When a levee was breached, a crevasse furnished a pathway, or vent, for water and sediment to be discharged into the backswamps and interdistributary basins (Kesel 1989). Deposition connected with a crevasse was an important sedimentary source and helped to form the lower-Mississippi-River-Delta's subaerial land (Coleman 1988). Much of the coastal area benefitted through sequential flooding and sedimentation.

Before construction of artificial levees, crevasse splays were a common occurrence that directed sediment out of the main channel and reduced flood stage down river. Archaeological evidence suggests these geomorphic features are a natural phenomenon that often remained open and functional for several hundred years (Gagliano and Van Beek 1970). Vogel (1930) shows a crevasse splay will encompass an average of about 1675 km^2---the largest involved 5,600 km^2, while the smallest was about 550 km^2. Regardless, a large crevasse can discharge water and sediment over several 100 km^2.

Once a large crevasse opens, closure is difficult. The breach cannot be repaired until the flooded areas influenced by the crevasse splay are sufficiently sediment filled to materially reduce current flow through the break. Once the flow is no longer a raging torrent, usually during the next low-water period, closure procedures can be initiated to seal the fissure. Closing a crevasse is such an acute problem precautions must be taken to prevent it from forming. Once formed, they flow at will. A crevasse at Fortier's Plantation in 1849—about 24 km above New Orleans on the Mississippi's west bank—flooded the upper Barataria basin between the river and Bayou Lafourche to a depth of 1.2 m. That same year Sauve's crevasse submerged New Orleans for 48 days and did an "immense amount of damage." (Humphreys and Abbot 1861:174).

Bonnet Carre Crevasses

In 1850, a 2-km-wide crevasse broke through the Bonnet Carre levee (also in 1849, 1871, and 1874) and flowed for more than six months at an estimated rate of 4,236.2 m^3/sec (Ellet 1852, Elliott 1932a). As long as water passed through the gap with sufficient velocity, the opening continued to widen, but the accumulated discharge did not destroy the natural landscape. "No channel was excavated. The furrows left by the plough and the roots of the crops remained on the field where it had been swept by the water, after the flood had subsided." (Ellet 1852:67) With an estimated discharge between 8,676 m^3/sec and 15,523 m^3/sec, many other crevasses were actively removing water from the Mississippi during the winter and spring of 1849/1850 (Ellet 1852).

From 1849 to 1874 this crevasse overflowed four times. The 1874 break remained open until 1883—ten years and raised the level of Lake Pontchartrain by 0.6 m (Gunter 1950). Water flowed through a gap 417.5 m wide, with an average channel depth of 6.8 m (Warfield 1876, Millis 1894). The rupture was caused by a muskrat (*Ondatra zibethicus rivalicius*) hole or burrow in the levee. Unlike the 1850 break, flood waters estimated at between 2,024 m^3/sec and 6,507 m^3/sec swept away "dwellings, sugar-houses, crops, and fences, like chaff before the wind, tearing out railroad embankments for many miles [km], interrupting railroad communication from the north with New Orleans, and even threatening the safety of the city itself." (Morey 1872:7) The steamer, "Katie, one of the largest and finest steamers on the western waters, was drawn into the vortex of Bonnet Carre ... and was only pulled from her peril by tugs." (Warfield 1876:6) Destruction of the New Orleans, St. Louis and Chicago railroad tracks had resulted in a $2,000,000 loss in business (Warfield 1876). Because the opening functioned for 10 years, hundreds of fishermen were unable to harvest Lake Pontchartrain's oyster beds and saltwater species.

Rice Flumes, Burrowing Critters, and the Crevasse Process

Newspaper accounts note many crevasses were a product of defective rice flumes placed in the levee. State and parish officials were charged with the responsibility to insure these rice flumes were safe. Supposedly inspected regularly, rice flumes repeatedly served as break points for crevasse formation. An 1882 crevasse at Live Oak Plantation in Plaquemines Parish was attributed to a derelict rice flume. The plantation's levees were "absolutely rotten, [collapsed] in places for more than a mile [km] and letting in a flood which overflowed ... the towns of Algiers and Gretna." (Daily States 1884:p 4, c. 3). Two years later, Davis crevasse (on the west bank at the railroad station of the same name, in St. Charles Parish, approximately 32 km north of New Orleans) was directly attributed to an old rice flume that was abandoned "and removed a few months previous to the high water" (Ewens 1885:107); although, a muskrat hole also may have been responsible for the break. The crevasse was by far the single most destructive crevasse known in the history of overflows in Louisiana (Britsch and Dunbar 1990). Its destruction extended for more than a 160 km along the west bank of the Mississippi River. Much of the region was under 0.6-2.4 m of water. (Daily States 1884:p 4, c. 3)

From his experience it was concluded "rice flumes are the great crevasse makers, and ... should be abolished." (Ewens 1885:108) South of New Orleans the levee was small and quite vulnerable to crevassing. Although easily breached, local residents were accustomed to dealing with high water. Nevertheless, in the 1897 flood rice flumes were responsible for more than a dozen breaks (Gillespie et al. 1897). Levees south of New Orleans were like the earliest structures built along the Mississippi—small, low, and frequently overtopped.

The warning of 1884 was not heeded. Rice flumes continued to initiate crevasses in the late 1800s and early 1900s. Further, crayfish (*Astacidae*) and muskrats sometimes damaged the protective levees to such an extent as to weaken their structural integrity and cause crevasses (Ewens 1885). Borrow pits and other excavations on the land side of the levee were also unstable points that had to be monitored during a flood, as they were potential sites for the formation of a crevasse.

Ewens (1885) reports on the 1884 flood and notes several crevasses from Red River Landing to New Orleans. At Batchelor, the break was so small little or no damage was reported. A sand boil or blow out—natural breaks in the levee—in one of the barrow pits used to repair the levee was destroyed in the 1874 flood. It was the first indication that a break at Morganza may be imminent. The levee broke a month after the levee was repaired and for all practical purposes the crevasse functioned from the flood of 1874 up to 1887, when the "new" levee was completed (Millis 1894). The March 1884 crevasse flooded parts of Pointe Coupee, Iberville, West Baton Rouge, and St. Landry parishes. It broke again in 1890 with an average depth of 4.7 m and discharged 4,251 m^3/sec. South of Bayou Sara at Waterloo a break in a 40-m-high levee caused by a defective rice flume resulted in a crevasse. Belle Air Plantation was submerged from a break associated with a crawfish hole. Opposite Convent, a derelict rice flume caused a crevasse on the Guidry Plantation (Ewens 1885). These events were repeated with every flood.

Crevasses on the Mississippi: A Representative Sample

Between 1735 and 1927 more than 1000 crevasses punctured a levee built for an effective life "of at least 20 years." (Waddill 1945:6) After these flooding events many citizens contemplated moving out of the flood zone. They were afraid the levees would be abandoned and not repaired; however, their concerns were appeased when the Mississippi River Commission began closing the crevasses (Richardson 1901).

The water was so high in 1735 and 1775 crevasse waters inundated New Orleans (Humphreys and Abbot 1861). Seven years later the water "rose to a greater height than was remembered by the oldest inhabitants ... the inundation was extreme." (Humphreys and Abbot 1861:168) New Orleans was flooded from December to June (Morey 1872).

In 1785, 1791, 1799, and 1816, New Orleans was submerged by high water from various crevasses (Humphreys and Abbot 1861). Although most damage was reported along the Mississippi, Bayou Teche overflowed its banks in 1796 and poured a sheet of water into Grand Lake (Humphreys and Abbot 1861).

Several crevasses developed between Baton Rouge and New Orleans from the 1823 flood. One of these, 32.1 km up river from New Orleans, increased flooding within the city (Elliott 1932a). Across the river at Algiers, an 1847 crevasse caused extensive damage to the communities on the river's west bank (Humphreys and Abbot

1861).

Humphreys and Abbot (1861) described the flood of 1849 as among the most destructive known. The first great crevasse occurred in March a few km south of Red River Landing on the Mississippi's west bank. Others occurred throughout the drainage basin. These breaks remained open and submerged much of the Atchafalaya basin. At Brashear City (now Patterson) water was over the banks for eight days.

On Bayou Lafourche a crevasse north of Lockport in 1851, remained open for months, reducing flow in lower Bayou Lafourche by about 0.9 m (Humphreys and Abbot 1861). Five additional crevasses were reported south of Lockport (Thibodaux Minerva 1854a). Local citizens believed this problem was directly related to the obstructions placed in Bayou Lafourche by General Andrew Jackson during the War of 1812. They believed this barricade needed to be removed. South of the termination point of these levees, Bayou Lafourche flowed freely into the surrounding swamps and marshes. This lateral discharge was calculated by Humphreys and Abbot (1861) to extend from 32 km to 48 km adding valuable sediment to the alluvial wetlands—contributing substantially to the accretion process. Ellet (1852) calculated that discharges associated with the 1851 crevasses equaled 2,915 m^3/sec—representing about 10% of the total discharge of the Mississippi at New Orleans—that escaped from the channel through crevasses. These crevasses reduced flood heights by about 0.6 m.

This flood height reduction also was evident in 1854 when a levee in front of an old rice mill at Lockport created a crevasse that submerged the surrounding property and remained open for five months (Thibodaux Minerva 1854a, 1854b, 1854c). This breach inundated a substantial portion of the interdistributary basin between Bayou Lafourche and Bayou Blue—a situation that prevented planters from shipping their crops to market because the preferred water route was flooded.

In 1874, fourteen plantations were flooded by a crevasse 45 m wide and 1.2 m deep, with water running "through like a mill race" displacing more than 200 families in the settlements of "Chupeck, Shack Bay [Chegby], Bayou Deron, and Baton Pilon." (The Daily Picayune 1874:1) Ironically, the year before a levee ordinance was passed by the Lafourche Parish Police Jury mandating levees be constructed according to a strict height-to-base ratio (0.3 m to 1.5 m; 0.3 m to 1.8 m; 0.3 m to 2.1 m) (Thibodaux Minerva 1853a). Newspapers reported this "Grand Levee" was not going to be constructed because of the expense, labor problems, and an unwillingness of some planters to participate in the project (Thibodaux Minerva 1853b:2).

The flood of 1866 was considered as belonging to "the class of ordinary high waters," while the floods of 1862, 1865, and 1867 were considered great flood years (Abbot 1870:10). Humphreys counted 59 crevasses after the flood of 1865, one of which was 3.2 km long and flooded thousands of ha (Cowdrey 1977). In the flood of 1865, Bayou Teche overflowed its banks in several places between Franklin and Brashear City (now Patterson). This flood was only 0.3 lower than the flood of 1828 (Abbot 1870).

Between the Louisiana-Arkansas border and Red River there were as a result of the 1867 flood ten levee breaks with widths ranging from 91 m to 457 m—depths varied from 0.76 m to 2.7 m (Abbot 1870). Crevasses in conjunction with the 1874 flood had an aggregate length of 230 km, 7.56 km in Louisiana.

The most destructive flood to be recorded on the Mississippi River—up to that time—occurred in 1882. Crevasses associated with this flood "left the people of the valley prostrate." (Levees of the ... 1891:12) At New Orleans, the flood stage lasted 91 days. In 1882 there were 284 crevasses reported in the Mississippi system. In 1883 the number was 224 (Levees of the ... 1891). This flood and the flood of 1927 submerged 149,184 km^2 through 226 crevasses (Elliott 1932a, Elliott 1932b)—an area larger than Delaware, Connecticut, Hawaii, Massachusetts, Maryland, New Hampshire, New Jersey, Rhode Island, and Vermont combined. Even so, the 1882 flood inundated an estimated 89,614 km^2, while the flood of 1927 (the greatest gaged flood of record) submerged approximately 59,570 km^2 (Elliott 1932a).

The flood of 1890 was adopted as the standard project flood on which all levee grades were to be referenced. Fifty-three crevasses were reported with a combined length of 10.9 km (Elliott 1932a, Elliott 1932b). The Nita crevasse flowed through a 946-m gap for 122 days, with a maximum discharge rate of 11,568 m^3/sec (Millis 1894).

In 1897, a destructive flood caused 37 crevasses (Levees, 1912 reports 38), with a combined length of 14 km. These levee gaps flooded 3,863 km^2 (Waddill 1945). Seven crevasses were reported in 1903, 12 in 1912. Of these, ten were in Louisiana. It was clear the levee system was beginning to control the Mississippi's flood waters.

In 1915, a hurricane made land fall in Louisiana when the Mississippi was bank full. The storm raised the river's water by 1.5 m. Waves broke over the levee with sufficient force to carry boats over them. In many places the levee was destroyed; 29 km of levee were obliterated and nearly 161 km of additional levees were more or less damaged. There is no previous record of a hurricane coinciding with a high river state (Waddill 1945).

In 1920, levees constructed by the federal government sustained little damage. The only problems were two breaks south of New Orleans, totaling 144.7 m (Elliott 1932a). In 1922, at Ferriday, Louisiana, a 1,127-m-wide crevasse in 1922 flooded parts of north Louisiana. A crevasse at Myrtle Grove, south of New Orleans was attributed to a muskrat hole (Russell et al. 1936) and reached 304 m wide. At Poydras (also called Caernarvon), a 335-m break resulted in a discharge of 13,014

m^3/sec.

Most of the crevasses reported in the period from 1850 to 1920 were a result of the abandonment and neglect of the levees designed to protect the population. Breaks were the result of 1) paths worn across the levee by lumber interests or livestock; 2) poor maintenance where, in some cases, a shovel or two of dirt could have prevented the break; 3) defective rice flumes; 4) crawfish and muskrat holes; and 5) sand boils or blow outs. Crevasses associated with these elements could, in most cases, have been stopped if proper defensive measures (sacks of sand, lumber, and repair crews) and surveillance techniques were utilized.

In the great flood of 1927 press accounts reported 226 crevasses, but most of these were minor and of little consequence. Fifty-two, however, were considered major. This flood inundated 74,000 km^2 (McDaniel 1930). The unprecedented number of crevasses associated with this flood precipitated renewed interest in levee construction. The problem was serious in New Orleans.

Within the walled confines of the city, the population began to demand action to reduce the flooding. They wanted the levee cut. On April 26, Louisiana's governor, O.H. Simpson, signed a proclamation giving permission to dynamite the levee (Dabney 1944). To reduce the flood water's height, 680 kgs of explosives were required to blow up the levee at Caernarvon. This action created a 979.3-m wide artificial crevasse that removed 9,202.9 m^3/sec from the main flow of the channel and thus relieved the hydrostatic pressure on New Orleans' levees (Simpich 1927, Elliott 1932b).

In reality, the dynamited crevasse reopened one of the Mississippi's "ancient lines of discharge although the water did not follow the old bayou but flowed away from it toward the swamps on either side." (Trowbridge 1922:13)

The severity of the 1927 flood resulted in passage of the 1928 Flood Control Act. This comprehensive legislation began the process of locking the Mississippi into a conduit, with spillways constructed along its course to protect against severe flooding. Therefore, an undisturbed natural levee cannot be found. These spillways proved their worth during the 1937 flood.

Spillways Serve as Artificial Crevasses

As a result of the 1922 flood and to diminish the threat to New Orleans, a relief outlet was constructed at Pointe-a-la-Hache 72.4 km south of New Orleans—initiating the first of many spillways. To guard against flooding, the U.S. Army Corps of Engineers built two major floodways that are, in effect, artificial and controlled crevasses. The Bonnet Carre Spillway diverts Mississippi River water through Lake Pontchartrain, and the Morganza structure diverts about 25% of the Mississippi's discharge into the Atchafalaya River. At these sites, large dams and gates were constructed that could be opened during floods.

Begun in 1932 and completed in 1937, the Bonnet Carre Spillway has been opened six times (1937, 1945, 1950,1973,1979, 1983) to cause short-term environmental changes in Lake Pontchartrain as fresh water is mixed with the lake's saline-brackish water. Some effects are beneficial such as an increase in fish production because of increased nutrient supply two to three years after the structure is activated.

The Morganza Spillway, on the other hand, has been opened only once. The portion of flow that enters the Atchafalaya River from the Mississippi has been maintained at a constant level since the Old River control structure was completed in 1963. Prior to 1963, Mississippi flow into the Atchafalaya was increasing, and total diversion down the Atchafalaya was a distinct possibility. The Old River control structure eliminated this danger and restricted Mississippi flow to 25-30%.

Through this system an enormous sediment load is introduced into the basin annually. From 1951-1967 an average of 135 million tons of suspended sediment entered the system yearly—approximately 75% is carried during high water of the 55 million m^3 of sediment entering the system annually. Thirty-seven million m^3 exit the floodways via the Lower Atchafalaya, with over 30 million m^3 of this material deposited in Atchafalaya Bay—often called "the world's fastest building delta."

Early Alternate Solutions to Flooding

Although recognized as significant, crevasses acted as natural safety valves that redirected flood waters away from the main channel—an event that, in many cases, reduced the high-water-potential downstream. Graham (1829) and Wilson (1850) suggested these natural outlets should be emulated by human-made canals. These structures, once properly leveed, would prohibit water constricted within their channels from inundating the surrounding property. The recommendation was that the proposed canals should be cut "through the lowest parts of the swamps between the streams, and ... be controlled and directed, so that large bodies of land, now swampy or overflowed even at dry seasons, would be reclaimed." (Wilson 1850:7)

Roberts (1866) advocated a system of weirs was necessary to preserve the plantations and their associated cultivated fields from floods. These weirs "should be constructed in the levees, so as to carry off the flood waters into the swamps, marshes, and lagoons, depositing in them the delta-making material of every flood." (Roberts 1866:3) Morse (1874) reported that to prevent flooding planters and engineers constructed levees. Unfortunately, these levees deprive the coastal low lands of the sediment that "if deposited ... in the natural way, would reclaim [the] worthless marshes" (Morse 1874:2)

Deltaic Crevasses: Modern Examples of Building New Land

Constructing this network of artificial distributaries would have been an expensive undertaking. Nevertheless, the results would have successfully redirected Mississippi sediment into the swamps and marshes, reduced flood heights downstream, and relieved pressure on the levee system.

There is little data on the importance of crevasses in adding sediment to the coastal lowlands, but within the delta the sequence is well documented (Coleman and Roberts 1989). Throughout the delta numerous crevasses were recorded in historic times. Cubit's Gap, Pass a Loutre, The Jump, Baptiste Collette, Grand Bayou, Joseph Bayou, and probably many other points within the delta initially opened into the Mississippi's main channel as a crevasse. In several instances, Cubit's Gap, Grand Bayou, and The Jump, were dammed. Generally, these protective dams were lost during a flood (Russell et al. 1936). For example, The Jump south of Venice originated as a crevasse in 1839. By 1840 the siphon was 0.8 km wide and 18 m deep, serving as a sediment conduit (Russell et al. 1936). From the late 1860s into the 1980s, deltaic crevasse evolved into a progressive chain of distributary channels. Each channel served as a sediment conduit prograding through a series of subdeltas into the shallow bays. These subdeltas are responsible for more than 80% of the new land built around the modern Balize delta complex (Gagliano et al. 1981) .

Sometime in the 1860s, Cubit's crevasse formed north of Head of Passes—the apex of the Mississippi Delta. Some speculate that it "originated ... from a cut made by the Navy through the bulkhead of a fisherman's canal to provide a boat passage to oyster." (Mitchell 1883:2304) Sediment moving through this outlet and deposited into Bay Rondo is responsible for creating a subdelta complex of more than 259 km^2 (Welder 1959). The gap was originally quite small but enlarged to 914 m. The break carried about 12% of the river's flow.

Cubit's Gap is in many ways a deltaic anomaly because it continues to distribute sediments into the interdistributary basin. Overbank flooding is not an annual occurrence, but normally is associated with flooding events. Deltaic crevasse splays, when open, scour a channel into an interdistributary bay and within 10-15 years fills in the bay. This was quite fast because some take well over 100 years to fill in a bay. While active, a 3-m thick cover of sediment will be added to the bay, and the system will cover 12-15 km^2. Thus, in a relatively short period of time the depositional unit will cover a considerable area (Coleman 1988). In fact, sedimentation rates were not uniform across the Cubit's Gap crevasse splay. Some areas were deprived of sediment, subsided, and reverted to open water experienced regular inundations of sea water.

Between 1872 and 1891, the Pass a Loutre crevasse enlarged from a 0.9-m channel to 262 m. By 1896 the break was 680 m wide. From 1891 to 1921, the distributary network prograded 8.8 m into Garden Island Bay (Russell et al. 1936; Welder 1959). A dam was built to close the crevasse, but it failed during a 1893 storm, allowing the break to remain open in-filling Garden Island Bay at a rate of

385 m/yr (Russell et al. 1936). In the process of in-filling the bay, sediment-laden water submerged the remains of the old community of Spanish Balize to hide it from various treasure hunters (Russell et al. 1936). Throughout the delta, small unnamed crevasses are responsible for creating minor subdeltas.

These outlets caused adjacent waters to shoal and subsequently were colonized by marsh vegetation. Their braided streams and distributaries contributed to the region's general pattern of drainage. The process of in-filling the bays is directly related to the delta's system of overlying crevasse splays. Each crevasse breaks off the main channel and in-fills the adjacent interdistributary bays. The process is not immediate but the result of repetitive flooding events through the crevasse over a period of 100–150 years. The end result is a new subdelta, involving an area from 300–400 km^2 containing 10–15 m of bay fill (Coleman 1988, Coleman and Roberts 1989). Thus the process can be documented and evaluated historically. The deltaic crevasse cycle revolves around a crevasse, rapid sedimentation, bay in-fill, vegetation growth, sediment depletion, subsidence, and eventual deterioration (Coleman and Roberts 1989) and is currently being replicated.

Current Solutions: Controlled crevassing

In retrospect, an active system of artificial diversions, as proposed in 1829, 1850, 1866, and 1874, would have replenished the marshes and offset the accumulated damage caused by leveeing the Mississippi River. A comparable plan is currently being proposed for renourishing Louisiana's disappearing wetlands (Roberts et al. 1992). However, it was not until the 1970s that Louisiana's wetland loss problem began to receive special attention from the research and public community. Over the last two decades interest and research increased dramatically. State officials began to take action in the design of a plan to reduce land loss and its immediate impacts. These actions included construction of controlled fresh water diversions, regulating dredge and fill activities, promoting the beneficial use of dredge material, and promoting land building in the Atchafalaya delta (Cowan, Turner, and Cahoon 1989).

Currently, siphons are being designed to imitate and mimic natural crevasses, while diversions will supply the freshwater to the wetlands from the Mississippi to restore and maintain wetlands (Britsch and Dunbar 1990; Roberts et al. 1992). Diversions projects at ten points along the Mississippi—Bonnet Carre, Davis Pond, Violet Caernarvon, Hero Canal, White's Ditch, Naomi, West Pointe-a-la-Hache, Bohemia, Bayou La Moque—will emphasize freshwater introduction into the wetlands (Table 1). It should be noted these are not sediment projects. Yet, all large-scale projects are at sites of historic crevasse activity and will help create aquatic habitats for fish and wildlife resources. Caernarvon's 243-cm discharge is designed to control water salinities in Breton Sound oyster beds (Roberts et al. 1992). Not as large as the freshwater diversion systems, small-scale diversions are also like a crevasse—sediment flows through a cut deigned to promote accretion in marsh areas under erosional stress. These projects augment the Mississippi River's ability to replace the wetlands being lost.

Table 1. Large- and small-scale Restoration Activities along the Mississippi 1992 (from Louisiana Department of Natural Resources 1992)

Location	Approx. Area Benefitted in ha
Violet Siphon Diversion	2,830
Violet Freshwater Diversion, Central Wetlands	1,010
Violet Freshwater Distribution, Lake Lery	200
Bonnet Carre Freshwater Diversion	4,250
Davis Pond Freshwater Diversion	33,590
Davis Pond Diversion Outfall Management	1,620
Caernarvon Diversion Outfall Site 1A	10,280
Caernarvon Diversion Outfall Site 1B	9,710
White's Ditch Diversion Siphon	2,530
Bohemia Diversion Structure	565
Bayou LaMoque Diversion Outfall	970
Tiger/Red Pass Diversion and Outfall Management	650
Grand/Spanish Pass Diversion	1,620
City Price Diversion	1,300
West Pointe-a-la-Hache Diversion Siphon	3,725
Naomi Diversion Siphon	3,320
Hero Canal Diversion	3,235
Small Sediment Diversions	
Pass-A-Loutre Management Area	2,265*
Small Diversions Delta National Wildlife Refuge	——
Pass a Loutre Sediment Fencing	24

* Combined benefits for the Pass a Loutre Management Area and the Delta National Wildlife Refuge

Within the delta, small-scale diversion projects are emulating the crevasse process within the Mississippi Delta. Roberts et al. (1992) believe these small-scale endeavors will achieve substantial benefits because they are relatively inexpensive, easy to build, and results are quickly realized. With an average depth of 4.5 m, across a 30-m wide break, these controlled crevasses introduce river-borne sediment into a number of the Delta's shallow bays. The objective is to stimulate land building processes by encouraging the formation of emergent deltas. In 1992, Louisiana's Department of Natural Resources proposed to construct, at an estimated cost of $770,000, 20 sediment diversion projects.

By early 1992 nine projects were completed; 11 remain on either the Delta National Wildlife Refuge, Pass a Loutre Wildlife Management area, or at South Pass. Project engineers estimate these cuts will be completed in early 1993—seven on Delta National Wildlife Refuge and four within the Pass a Loutre Wildlife Management area. If successful, these sediment diversion efforts will create in the next 50 years approximately 2,050 ha (20.4 km^2) of marsh habitat, particularly valuable for the estimated 250,00 ducks and 60,000 snow geese that annually migrate to these marshes.

In conjunction with funding provided under the Coastal Wetlands Planning, Protection, and Restoration Act (Public Law 101-646 also called the Breaux-Johnston Bill) and Louisiana's Coastal Wetlands Conservation and Restoration Plan state planners are implementing guidelines to restore, preserve, and enhance the state's eroding wetlands. Both endeavors include projects designed to counteract site-specific erosional problems. Each project is designed to address a specific land loss issue within the narrow limits of a specific geographical area. No single solution will solve Louisiana's land loss problem. It will take a multiple approach based on creative and innovative ideas and engineering methods.

These programs also encourage developing marsh management plans that have caused considerable discussions individually, collectively, and between federal and state agencies. Discussions generally focus on impounding marsh areas or designing projects that promote tidal exchange. The debate continues on the structural modifications required to maintain and/or regulate wetland habitat quality and quantity (Cowan, Turner, and Cahoon 1989; Day, Holz, and Day 1990). The problem is that impoundments tend to 1) limit some species of vegetation, and fish and wildlife 2) alter hydrologic regimes and nutrient cycles 3) eliminate sediment 4) reduce public access and 5) restrict movement of estuarine organisms. Although considerable discussions center around the merits of impoundments, there are other techniques being implemented. Current restoration techniques include marsh management, shallow-bay terracing, sediment capture, structural shoreline protection against erosion and emulating crevassing through diversion projects that promote sedimentation within the wetlands. Regardless of the technique employed, sediment is considered critical. Historically, the crevasse process can provide valuable information on evaluating the significance of crevasses in mimicking nature's delta-building processes. These former crevasses also can serve as the control in the analysis of the success or failure of the small-scale siphons.

Summary and Conclusions

After the devastating 1927 flood, the U.S. Army Corps of Engineers began to construct the Mississippi's "guide levees." Today this levee network protects cities, towns, villages, farmlands, and industrial complexes. In retrospect, the levees had a dramatic impact on the general ecology of the wetlands and modified the orderly distribution of fresh water out of the river into the marsh-estuary complexes. Natural wetland processes, interlevee basin drainage regimes, and vegetation patterns were altered permanently. Engineers brought about these changes through their use of levees, internal drains, and pumps. Through time, the Mississippi's levees were strengthened, eliminating overbank flooding and the systematic sediment recharge to Louisiana's subsiding coastal lowlands through crevasses. Sediment flow was effectively shut off. Natural accretion, derived from overbank flooding was terminated. An artificial levee system is responsible. Engineered to protect the population living within the river's alluvial valley, this levee also altered the region's natural topography.

Long-term protection, preservation, and restoration of Louisiana's wetland resource base cannot be accomplished without diverting sediment-laden water from the Mississippi River. Historically, crevasses and overbank flooding renourished the wetlands. Crevasses served as conduits to direct sediment-laden water throughout the corridor affected by the break. Sediment is critical in rebuilding the wetlands, helping to offset accretion deficits partially induced by channelizing the river. Mississippi Delta projects that emulate crevasses will provide valuable baseline data in the analysis of the success of small-scale diversion efforts. These controlled crevasses should be monitored carefully because they represent a cost-effective way to maximize movement of sediment-laden waters into sediment-starved areas. If projects are to be placed along the Mississippi's lower course, the historical sequence of crevasses along the river needs to be fully understood to design sediment siphons that emulate these historic events.

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Changes in Louisiana Coastal Wetlands Since 1978

L.R. Handley[1]

ABSTRACT

Wetlands along the Gulf Coast of the United States have seen remarkable reductions in area over the past fifty years. Louisiana, which has more wetlands than any other State in the country, lost approximately 700,000 acres of wetlands over a twenty-two year period between 1956 and 1978. The infamous wetland loss rate for coastal Louisiana of 48 square miles per year was derived from a series of 256 1:24,000-scale wetland habitat maps produced by the U.S. Fish and Wildlife Service (USFWS) for both 1956 and 1978. In 1988, the USFWS began to remap the wetlands of the Louisiana coast with another series of 1:24,000-scale habitat maps; this mapping effort produced 330 maps. Between 1978 and 1988, the USFWS produced, for the U.S. Army Corps of Engineers, wetland habitat maps for 15 1:24,000 quadrangles of the Lower Mississippi River Delta from 1983 aerial photography and, for the Louisiana Department of Natural Resources, 11 quads scattered in Barataria Bay and the Terrebonne Marsh from 1985 aerial photography. The results of the 1983 and 1985 mapping have shown that the rate of wetland loss for coastal Louisiana had decreased to around 37 square miles per year. Analysis of the 1988 habitat mapping has not been completed since all of the maps have not been produced. However, preliminary GIS analysis indicates that the trend of wetland loss may have increased slightly to around 40 square miles per year. Although marsh acreage may be decreasing, habitats such as forested wetlands and scrub-shrub may be increasing dramatically.

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[1] National Wetlands Research Center, National Biological Survey, Lafayette, LA 70506

Critical Small-Scale Physical Processes that Contribute to Marsh Loss on Louisiana's Subsiding Coastal Plain

J.N. Suhayda[1], D.J. Reed[2], R.M.H. Boumans[3], J.W. Day, Jr.[3], G.P. Kemp[3], D.R. Cahoon[4], N. Latif[3], S.J. Williams[5]

ABSTRACT

Measurements of waves, currents, suspended sediments, and morphodynamic responses have been made in sediment-rich and sediment-poor marsh pond systems in Louisiana as part of an ongoing regional study jointly sponsored by the U.S. Geological Survey and the Louisiana State University. The process of pond formation, expansion, and joining accounts for a significant portion of coastal marsh loss each year; however, detailed synoptic measurements of winds, waves, currents, and suspended sediment dynamics in small shallow marsh waterbodies and on the marsh surface awaited the development of sensor arrays designed specifically to function in this environment. This instrumentation is now available, and these marsh systems have been monitored on a variety of time scales including those of wave frequency, tidal cycle, multi-day storm events, and seasonal. We report here on the gradients in suspended sediment and wave energy observed from channel to pond center and on to the marsh surface and on the effects of water levels on circulation, channel dynamics, and pond margin reworking. These factors are related to sedimentation and erosion rates observed in different parts of the two pond-marsh systems. Detailed survey data permits documentation of a pond edge failure sequence that results in local acceleration of the subsidence process through undermining of the root mat and creation of a vegetated terrace approximately 10 cm below normal marsh elevation. Vegetation on this terrace feature dies off, and the shear strength of the root mat drops from 0.4 to 0.1 kg-cm^{-2}. The terrace then quickly loses definition as it is eroded to the level of the pond bottom, approximately 50 cm lower.

[1] Department of Civil Engineering, Louisiana State University, Baton Rouge, LA

[2] Louisiana Universities Marine Consortium, Chauvin, LA

[3] Center for Coastal, Energy, and Environmental Resources, Louisiana State University, Baton Rouge, LA

[4] National Biological Survey, National Wetlands Research Center, Lafayette, LA

[5] U.S. Geological Survey, Reston, VA

Managing the Mississippi River to Ensure Long-Term Restoration and Creation of Wetlands in Coastal Louisiana

Ivor L. van Heerden[1]

ABSTRACT

Prior to the early 1900's, the Mississippi River overtopped its banks for approximately 90 days a year, introducing sediment and fresh water into adjoining wetlands, aiding in their maintenance. Additionally, distributaries delivered sediment and fresh water to more distant wetlands. Subsequent development in Louisiana focussed on eliminating flooding and extending navigation. As a consequence, sediment and fresh water delivery to the wetlands was dramatically reduced. Associated with oil and gas field development, Louisiana has, since the 1950's, experienced a wetland loss in excess of 25,000 acres per year.

Recognizing the seriousness of the wetland loss problem - in terms of real estate, diminishing wildlife and fish resources, and jobs - a number of Federal and State programs have been initiated to attempt to address the problem. Unfortunately, most of these projects do not take into account the long-term solution of the wetland loss problem, and the majority address reductions in the wetland loss rate, rather than wetland creation.

The plan herein proposed has as its central theme getting sediments and fresh water from the Mississippi. It attempts to stimulate natural delta growth processes by creating and re-establishing former distributaries. The plan has four major points:

1. Divert the Mississippi River into Breton/Chandeleur Sound through the Bohemia Wildlife Management Area. As a consequence of this action, approximately 10,000 acres of new wetland will be created every year in this stable basin. Increased sediment and fresh water input will greatly aid the whole St. Bernard Marsh complex and freshen up Lake Pontchartrain.

[1] Center for Coastal, Energy, and Environmental Resources, Louisiana State University, Baton Rouge, LA 70803

2. Reconnect Bayou Lafourche to the Mississippi River and divert about 10-12 percent of the Mississippi River down the Bayou. To accommodate this discharge, parts of the Bayou will have to be dredged and the sediment used to create or restore wetlands. Communities along the Bayou have a major fresh water problem which will be alleviated by this action. Secondly, the oil industry job pool is rapidly disappearing; restoring the Bayou to a navigable waterway and associated marsh creation opens up many opportunities for job creation through the development of an eco-tourism industry.

3. Increase the discharge down the Atchafalaya River from 30 percent to 40 percent of the Mississippi discharge.

4. At a point north of Morgan City, feed this extra 10 percent of flow eastward to Houma and then distribute the discharge through numerous bayous that radiate from Houma, thus benefitting large portions of Terrebonne parish.

The long-term restoration of Louisiana's wetlands is also dependent upon the restoration of Louisiana's barrier islands. Thus, management of the Mississippi River for wetland restoration should go hand-in-hand with barrier island restoration.

The above 4-point plan will not be cheap. If the projects were undertaken by the U.S. Army Corps of Engineers, with funding from the Military Budget, it would amount to 0.2 percent of this budget for 8 years.

SESSION 46

Processes of Wetlands Loss in Louisiana III: Geomorphology and Land Loss

Anthropogenic Modification and the Induced Hydrologic Changes in a Small Bayou and Adjacent Salt Marshes in a Sediment-Rich Coastal Basin

Water B. Sikora[1], and Flora C. Wang[2], F. ASCE

Abstract

A hydrologic and hydrodynamic study of a meandering bayou and its adjacent marshes on the southcentral Louisiana coast (5 km from the Gulf of Mexico) has revealed an interesting flow pattern. A sequence of channel construction ranging from small trapper's channels (called trainasses) to 30-m wide oil-access canals has significantly modified the hydrology of the natural bayou and the tidal flooding regime of the adjacent marshes along the upper reaches of the bayou. Hourly water-level data recorded at a marsh site in the upper reaches of the bayou shows that pattern of marsh inundation is characterized by sporadic flooding interspersed by longer drained periods. This paper attempts to explain the reason for the different flow circulation patterns observed in the bayou during two field trips conducted in September and October 1991, and to show the effect of anthropogenic modifications on flow regime in the area.

Introduction

Louisiana Gulf coast is rapidly subsiding with subsequent wetland erosion and loss (Gagliano et al., 1981). Many factors influence wetland loss. Through the natural processes, wetlands are converted into open waters by storms and hurricanes (Turner, 1990). Other factors are related to human activities. Coastal subsidence is caused by the compaction of recent sediment for fluid withdraw and mineral extractions (Baumann et al., 1984). Wetlands are replaced by the construction of flood protection levees, navigation channels, and oil and gas access canals (Wang, 1988).

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[1] Assistant Professor-Research, Coastal Ecology Institute, Louisiana State Univ.;
[2] Professor, Department of Oceanography and Coastal Sciences, Louisiana State University, Baton Rouge, LA 70803. Tel (504) 388-6459, Fax (504) 388-6331

Many coastal basins in south Louisiana are depressional watersheds. They are primarily river-bay-bayou-lake systems, characterized by large areas of marshes and swamps and slow natural drainage through meandering bayous (Wang, 1987). These coastal marshes are inundated by regular diurnal and semi-diurnal tides and irregular tropical and winter storms (Childers and Day, 1988). This paper examines the behavior of flow patterns in a decouple system resulting from the construction of a series of man-made canals adjacent to a natural bayou.

Study Area Description

Atchafalaya coastal basin has been designated as sediment-rich and riverine-dominated basin with large amount of freshwater inflow (Wang et al., 1992). Atchafalaya Bay, receiving a relatively high volume of river discharge and sediment load from the Mississippi River, has been building an extensive delta at its mouth in the south central Louisiana coast since late 1970. Fourleague Bay, a large (100 km^2) and shallow (2 m deep) bay, opens to the eastern side of Atchafalaya Bay. The upper portion of Fourleague Bay connects with Atchafalaya Bay via a 2.5 km wide passage, and the lower portion of the bay communicates with the Gulf of Mexico at its south end through a 250 meters wide and 8 meters deep tidal inlet, the Oyster Bayou.

Old Oyster Bayou, a relatively small natural meandering channel, running west to east and opening into Fourleague Bay, was chosen as a specific study site within this coastal basin (Figure 1). The surrounding area is flanked by low-lying and healthy marshes. Old Oyster Bayou is intersected by a series of man-made canals, Camp Canal running west to east, with a second canal running north to Old Oyster Bayou and a third canal running south to Old Oyster Bayou Lake (Figure 1).

Methods and Materials

Originally, four stations (labelled S-1, S-2, S-3, and S-4 in Figure 1) along Old Oyster Bayou were chosen for intensive field measurement. Sampling periods were designed to coincide with predicted equatorial tides in September 1991 and predicted tropic tides in October 1991. Prior to each field trip, tidal heights at Eugene Island (24 km west of our sampling stations) were predicted according to the methods described by the National Oceanographic and Administration (NOAA, 1991). Temporary staff gauges were set near Stations S-1 and S-4 and relative water levels were recorded hourly. Hourly measurements of flow velocity at each station were taken simultaneously at 0.5 m increments from 20 cm below the surface to near the channel bottom (20 cm above the bottom). Current velocities were measured using Montedoro Whitney PVM-2A current meters.

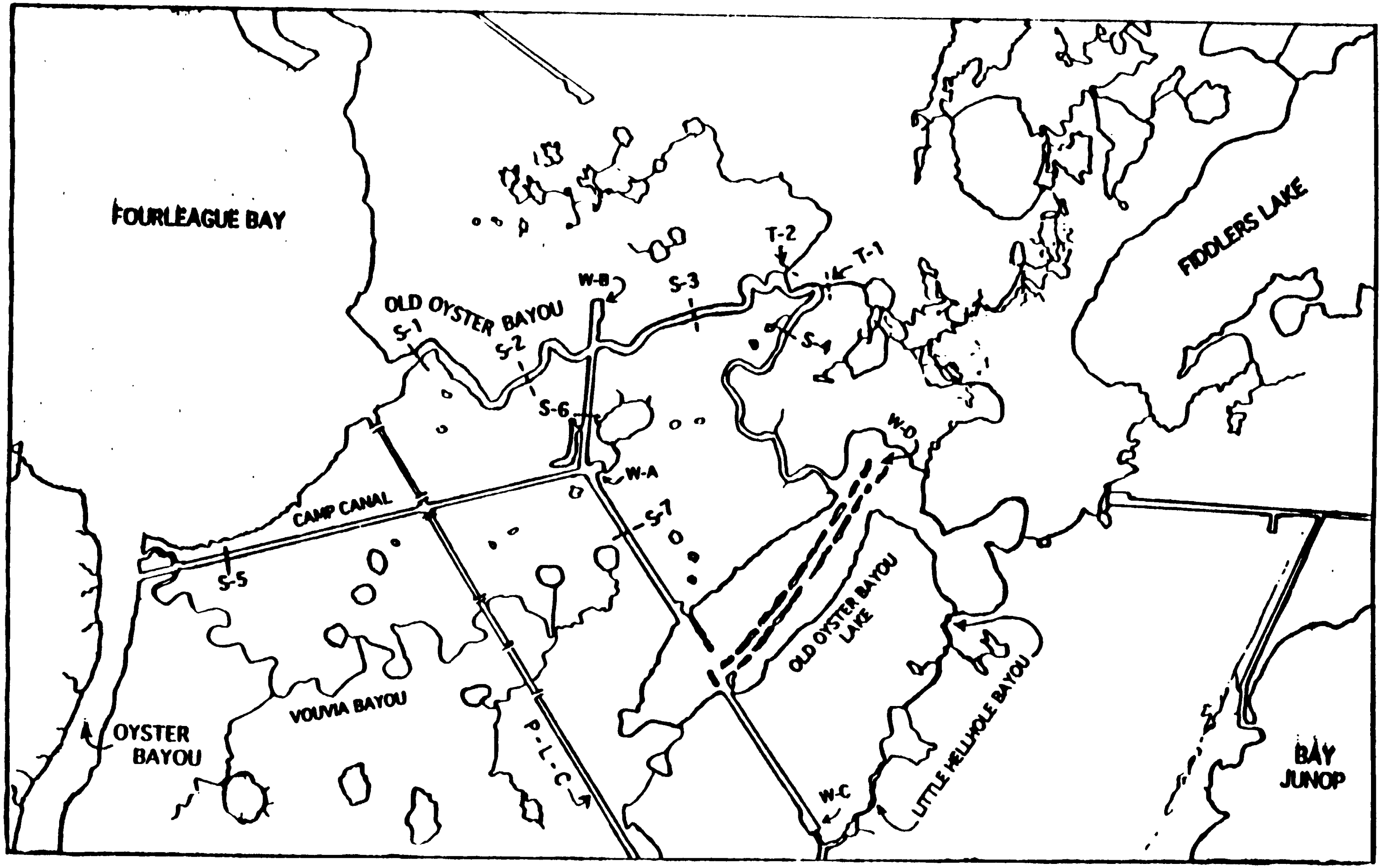


Figure 1. Location map of study area and sampling stations.

Subsequently, additional stations were selected in the study area to facilitate the explanation of changes in flow circulation patterns in Old Oyster Bayou induced by man-made canals, the Camp Canal (an oil and gas access canal) and the Trainasses (the trappers watercourses). Three Camp Canal stations, Station S-5 (western end of Camp Canal), S-6 (north folk to Old Oyster Bayou), and S-7 (south folk to Old Oyster Bayou Lake); and two Trainasses stations, Station T-1 (near Old Oyster Bayou Station S-4), and T-2 (near Old Oyster Bayou Station S-3) were added (Figure 1).

Channel profile tracings at each station were determined from echo-sounding using Raytheon Fathometer during sampling trips. At Station S-2, channel cross-section was also measured manually by taking depth measurements at 4-meter intervals across the channel width, to check with the results of Fathometer tracings in this shallow bayou. The cross-sectional area was calculated as a function of water depth at each station. Each cross-sectional area was then divided into a number of 0.5 m layers for the computation of total water discharge at each station. Finally, average flow velocity was calculated by dividing total discharge by the respective cross-sectional area. Positive values indicate flood tides, whereas negative values indicate ebb tides.

Wind speed and direction, recorded at the Golden Meadow about 80 km east of the study area, were available upon request from Corps of Engineers, New Orleans District. These data provide valuable information to examine the response of water levels and flow circulations to surface wind forcing in a shallow estuary.

Results and Discussion

1. Channel flow cross-sectional areas

Figure 2 displays the channel cross-sectional areas for both natural and man-made channels. In a natural, unaltered bayou system, one would expect that the cross section at the mouth would be the largest and each cross section further inland would be progressively smaller by its aspect ratio (ratio of width to depth). From Figure 2, it shows that the cross-sectional areas at Stations S-1, S-2, and S-3 are nearly equal (around 50 m^2), the cross-sectional area at Station S-4 is less than half (25 m^2), suggesting an altered flow pattern in Old Oyster Bayou.

The data from Old Oyster Bayou also indicates that S-1 has probably been filled in slightly, S-2 has probably retained its original cross-sectional area, while S-3 has been enlarged somewhat. The cross-sectional areas of man-made canals (S-5 and S-7) are comparable to the natural bayou. It is interesting to note that the cross-sectional area of trainasses (T-1) is actually greater than S-4.

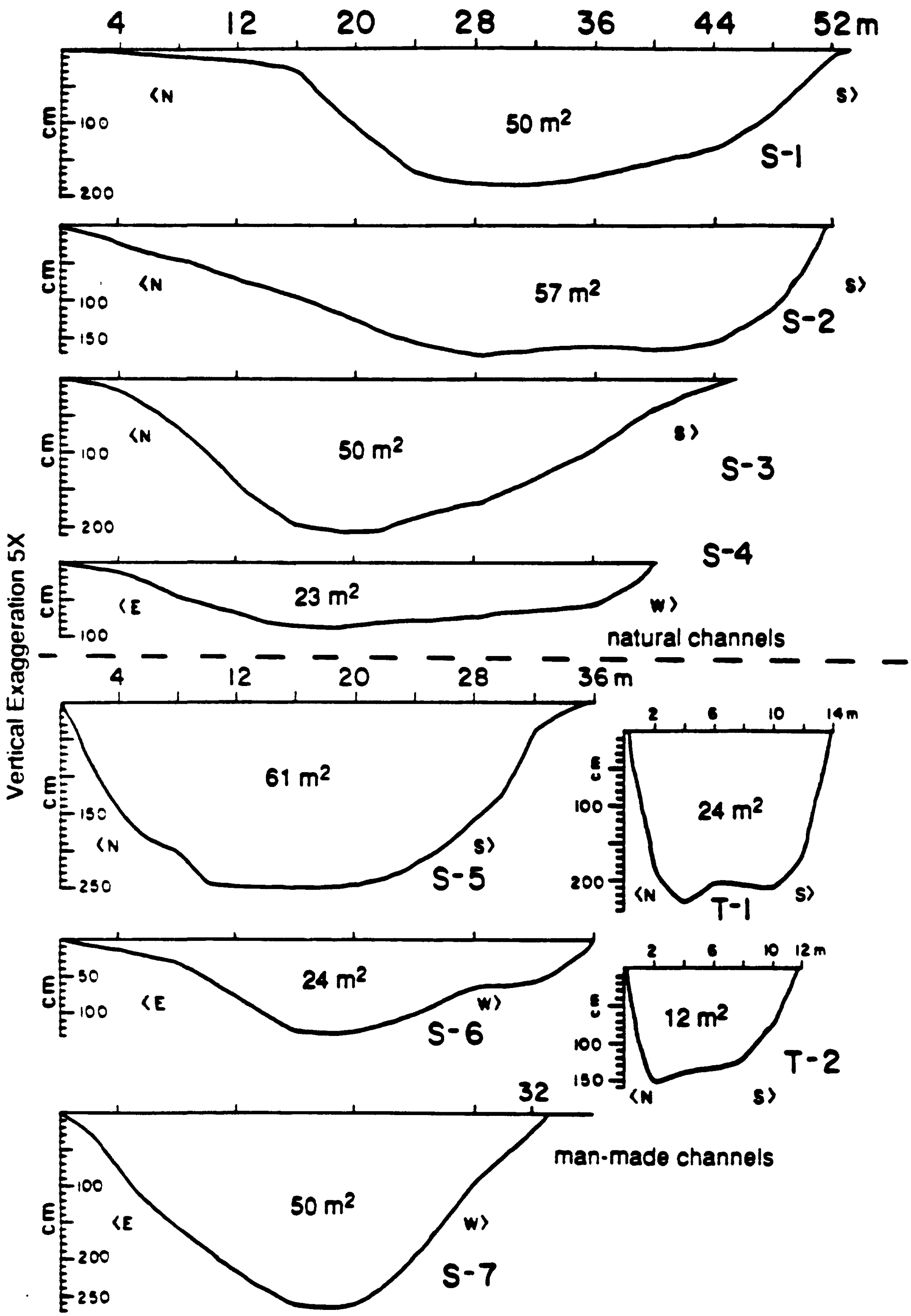


Figure 2. Channel cross sections scanned by Raytheon Fathometer.

2. September 1991 data results

Figure 3a plots the predicted (solid line) and observed (broken line) tidal heights (NGVD) at Eugene Island in Atchafalaya Bay during September 19-21, 1991 sampling period (from 0100 September 20 to 0800 September 21, 1991). The observed tidal patterns resembled closely to the predicted one. However, the range of observed values was smaller than the range of predicted ones. The reduced tidal range (from 55 cm to 35 cm) produced much weaker tidal forcing to the system as predicted.

Consequently, the current velocities flow through Stations S-1, S-2, S-3, and S-4 along Old Oyster Bayou were relatively slow. It is noted that the flow circulation patterns at Station S-1 and S-2 resembled closely as did those at Stations S-3 and S-4 (Figure 3b). However, the peak velocities at Stations S-1 and S-2 (±60 cm/sec) were greater than those at Stations S-3 and S-4 (±20 cm/sec).

3. October 1991 data results

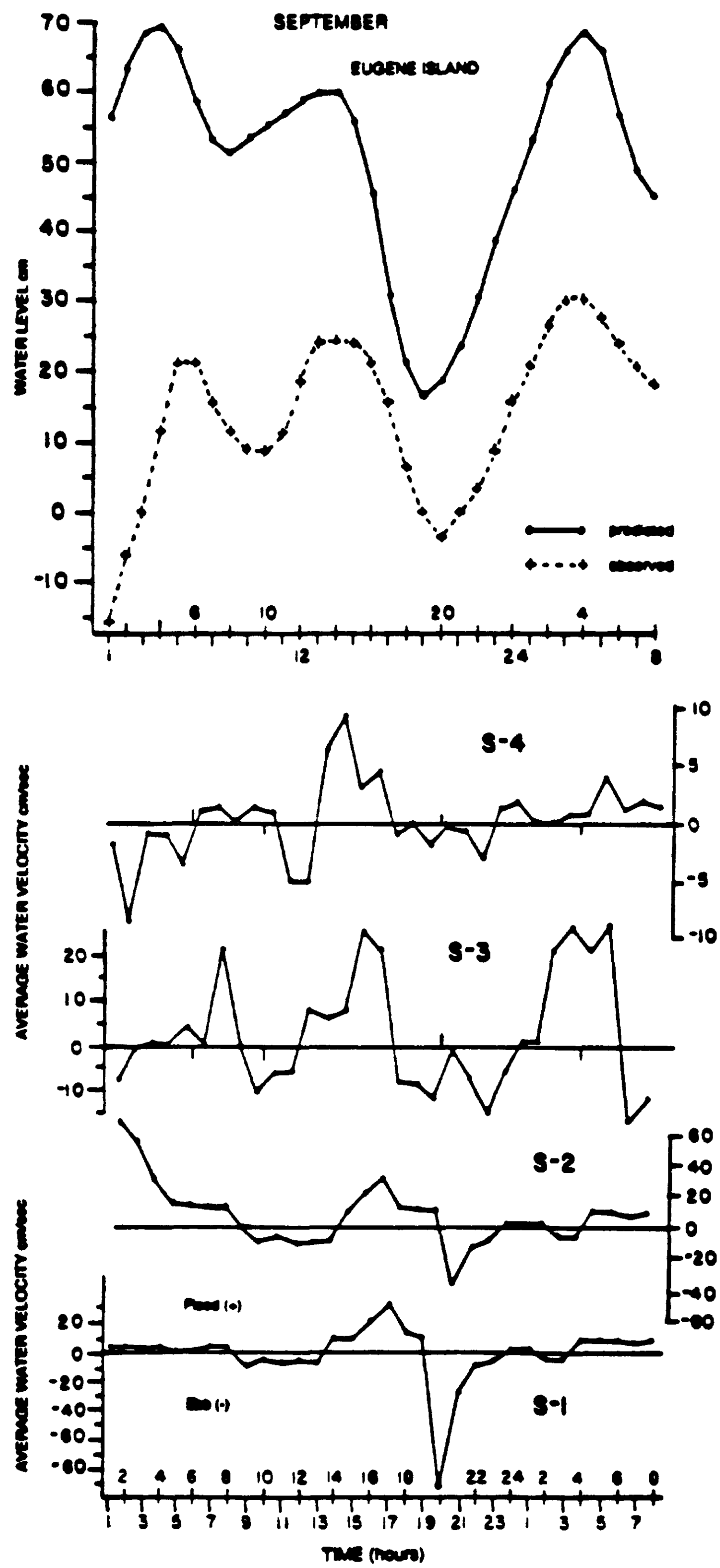
During October 24-26, 1991 sampling period (from 2000 October 24 to 0800 October 26, 1991) the observed high tides were lower than the predicted ones, and the observed low tides were nearly the same as the predicted one (Figure 4a). The high tidal range (60 cm) in October 1991 provided much stronger tidal forcing to the system than in September 1991.

In October 1991, the flow patterns at Stations S-1 and S-2 also behaved similarly to each other; but at Stations S-3 and S-4, a different flow pattern was observed (Figure 4b). Especially, during the time period from 1400 to 2200 October 25, S-3 exhibited a positive (flood) flow and S-4 a negative (ebb) flow, or vice versa. Average current velocities recorded at Stations S-1 and S-2 were greater than those at Stations S-3 and S-4. The peak velocities reached ±160 cm/sec at Stations S-1 and S-2, ±40 cm/sec at Station S-3, and ±25 cm/sec at Station S-4. All stations, exhibited stronger current velocities on the flood tides than on the ebb tides.

From these data sets, the effect of anthropogenic modifications on flow regime in the study area can been seen. It is noted that the flow circulation patterns at Stations S-3 and S-4 are uncoupled from Stations S-1 and S-2, largely due to the flow interception by the north folk of Camp Canal (Figure 1).

Furthermore, it appears that Trainasses T-1 is shunting water flow from Old Oyster Bayou before the water gets to Stations S-4. This means that Old Oyster Bayou Lake has been uncoupled from Old Oyster Bayou, and is now flooded and drained by the south folk of Camp Canal (Figure 1).

(a)



(b)

Figure 3. September 19-21, 1991 data sets:
(a) Predicted and observed tidal heights (NGVD) at Eugene Island; and
(b) Average flow velocities measured at Station S-1, S-2, S-3, and S-4.

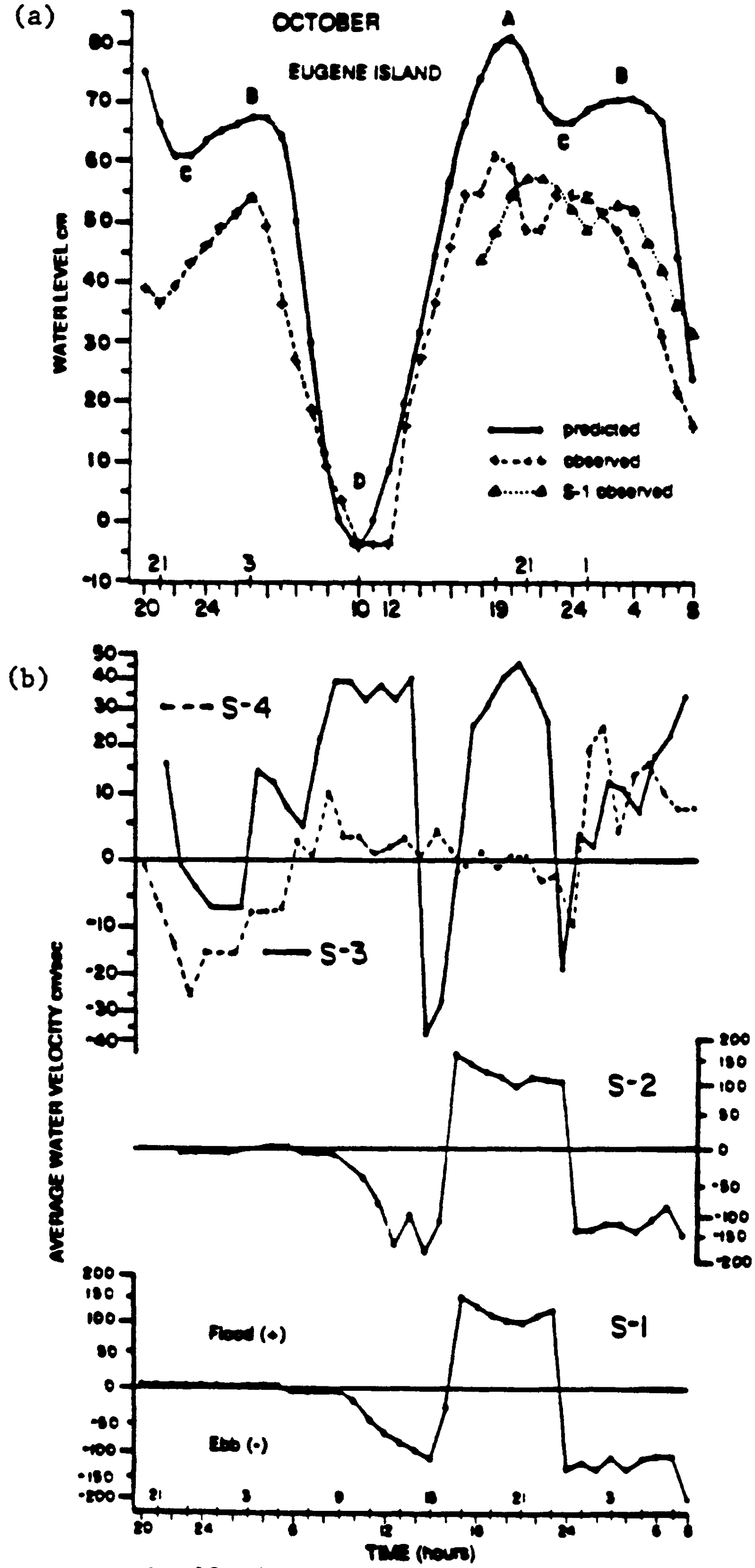


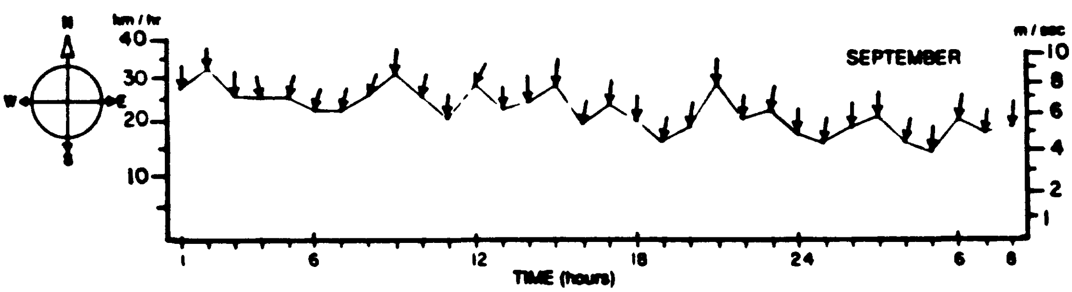
Figure 4. October 24-26, 1991 data sets:
(a) Predicted and observed tidal heights (NGVD) at Eugene Island; and
(b) Average flow velocities measured at Station S-1, S-2, S-3, and S-4.

4. Effect of winds on flow regimes

Figure 5 shows wind speed and direction recorded at Golden Meadow near our study area during September 19-21 and October 24-26, 1991 sampling periods. In September, relatively strong steady winds, varied from 4 m/sec to 9 m/sec, predominantly from the north were observed. In October, east to southeast wind, ranged from 2 m/sec to 8 m/sec, were recorded.

The steady north wind in September decreased both the high tide and the low tide as compared to the predicted one (Figure 3a). In October, east wind depressed moderately the high tide, and the low tide was not affected (Figure 4a). Therefore, under north wind conditions, it is expected that slower flow velocities will prevail, because the difference between high and low water is less than under east wind conditions. The velocities in October were twice higher than in September (Figures 3b and 4b).

(a)



(b)

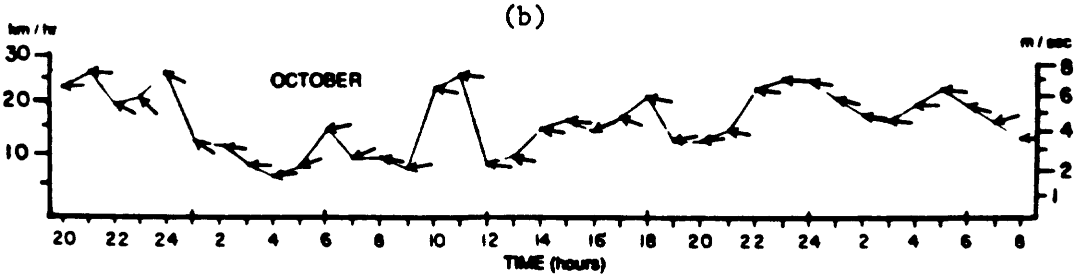


Figure 5. Wind speed and direction recorded at Golden Meadow during:
(a) September 19-21, 1991 sampling period; and
(b) October 24-26, 1991 sampling period.

5. Induced hydrologic changes in the area

From the limited field measurements, supported by additional field observations, it appears that the south folk of Camp Canal (via Station S-7) is draining Old Oyster Bayou Lake and the area to the south of Station S-4. The trainasses (in particular, T-1) are draining the area east of Station S-4 (Figure 1). The combined results are that water flow past Station S-4 is drastically reduced (Figures 3a and 3b). Gradually, S-4 will be filled in with sediment due to decreased water velocity (Figures 3b and 4b). This is also evident from the small cross-sectional area (23 m^2) at Station S-4 (Figure 2). Eventually, S-4 will be closed off resulting from the induced hydrologic changes in the area. This shows that the anthropogenic modifications have affected surface flow regime in Old Oyster Bayou by short-circuiting the flow of head waters and the surface overland flow across the adjacent marshes.

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Processes of Coastal Geomorphic Development: Land Building and Land Loss Along the Louisiana Deltaic Coastline

O.K. Huh[1], H.H. Roberts[1], C. Moeller[2], and W.P. Menzel[2]

ABSTRACT

The geomorphology of deltas is inherently complex and dynamic as their huge depositional rates have been sufficient to overwhelm the recent sea-level rise of 130 m. in the last 18,000 years. The complex, deltaic geomorphology of the Louisiana coast has its origins in the development of multiple delta lobes; annual floods of clay, silt, and sand; levees (natural and man-made); cold front passages; hurricanes; regional subsidence; and shifting domains of fresh water, brackish water, and salt water zones. All of these processes leave geomorphic imprints on the coast, extensively recorded in aerial and satellite imagery.

The low relief environments including the intertidal zone and shallow subtitle zones of high river runoff and suspended sediment rich areas are detectable only during unusually low stands of water. Cold front passages, with strong northerly winds and clear skies, synchronous with low astronomical tide provide the best views of the results of coastal erosion and depositional processes. The clear water sediment starved regions such as the Chandeleur Island chain are mappable under most conditions due to clear water and visibility of the predominant sandy shoals. Sea-level rise, breakup of the marsh, pond expansion, shoreface erosion, and subsidence deteriorate the sediment starved coastal environments, and results are readily detectable from the air. Formation of bay head deltas, crevasse splays/subdeltas, river channel overflow, and muddy chenier plain progradation actively build new land. Some 16 NASA color, high altitude aerial photographic missions have been overflown at low water since 1987. They provide critical information on the processes of coastal geomorphic evolution. This kind of information is crucial to coastal zone management.

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[1] Coastal Studies Institute, Louisiana State University, Baton Rouge, LA 70803

[2] Cooperative Institute for Meteorological Satellite Studies, University of Wisconsin, 1225 W. Dayton Street, Madison, WI 536706

Consolidation Settlement Potential in South Louisiana

Kuecher, G.J.[1], Chandra, N.[2], Roberts, H.H.[3], Suhayda, J.H.[2], Williams, S.J.[4], Penland, S.P.[5], and Autin, W.J.[5]

Abstract

Primary consolidation is an important cause of wetland loss in active and recently abandoned deltaic plains in south Louisiana. Argillaceous and organic facies are most subject to reduction in volume, and experience great changes with minimal loading. Sampling with traditional vibracores, which induce compaction in the near-surface, has proven inadequate to obtain a baseline on the zero consolidation point in these critically sensitive soils. For this reason, a liquid nitrogen annulus core method was developed for obtaining in-situ samples within the consolidometer trim ring.

Four facies types were selected for consolidometer modeling in the greater Mississippi River deltaic plain at the time of this publication. Although testing is incomplete (four facies types remain to be tested), two end-members of the consolidation spectra have been identified: sands and organic fat clays (i.e. SP and CH soils in the Unified Classification, respectfully). Results indicate that sand facies accumulate rapidly, do not readily consolidate, and form elongate loads which deform underlying, sensitive clays. Conversely, clay and organic soils accumulate in broad, inter-distributary basins, and are subject to drastic volume changes upon loading. The uppermost 10 meters (the Lafourche Delta in our study area) is most subject to further consolidation settlement.

[1]Basin Research Institute, Louisiana State University, Baton Rouge, LA 70803.
[2]Department of Civil Engineering, Louisiana State University, Baton Rouge, LA 70803.
[3]Director, Coastal Studies Institute, Louisiana State University, Baton Rouge, LA 70803.
[4]United States Department of the Interior, Geological Survey, Reston, VA 22092.
[5]Louisiana Geological Survey, Louisiana State University, Baton Rouge, LA 70803.

Previous studies

The relationship of deltaic soil consolidation to subsidence and apparent sea level rise in coastal Louisiana was first addressed by Fisk et al.(1954) when he observed pronounced effects of compaction beneath bar finger sands on prodelta muds at Southwest Pass. He additionally noted the subsidence of thick natural levee systems at the mouth of the river. Morgan and Larimore (1957) suggested that subsidence rates of deltaic plains following abandonment are initially high then decrease with time, and proposed the rate of compaction varies with the thickness of a delta, i.e. thin deltas subside slowly whereas thick deltas subside rapidly. This work was followed by a U.S. Army Corps of Engineers study (1958) in which consolidation beneath natural and man-made landforms was illustrated. In the same year, Kolb and Van Lopik (1958) published a report which summarized the factors contributing to subsidence in the Mississippi deltaic plain. Roberts (1985) proposed that high subsidence rates in the Mississippi deltaic plain coincide with thick Holocene valley fill, while low rates coincide with Holocene thins. Penland et al. (1988) synthesized several of these previous studies in addressing relative sea level rise in Terrebonne Parish, LA.

Engineering reports on the properties of Mississippi River alluvial soils were produced by the U.S. Army Corps of Engineers Waterways Experiment Station in 1962 and 1974, the latter correlating geologic facies to engineering properties. Kosters and Bailey (1983) published measurements on the low in-situ bulk density for organic soils and peats in the adjacent Barataria Basin; results pointing to a need for developing better techniques to sample such soils.

A recent, pertinent paper by Lundegard (1991) concludes that sands will not appreciably reduce their volume with shallow burial, and thus are not subject to rapid consolidation settlement. This work is consistent with a study by Atkins and McBride (1992) in which the average depositional porosity of surficial beach and river point bar sands (47 and 48 percent, respectively) was found to undergo only minor reduction with burial to 17 meters. Sands, therefore, do not contribute to massive volume loss associated with consolidation, although such loss could be caused by the loading of a sand body on a deformable substrate. The present authors believe that certain surficial soils, eg. organic soils, and mixed organic and fat clay systems (peats and bay muds, respectively), are the principal units on the deltaic plain which consolidate rapidly. An understanding of the consolidation settlement characteristics of each facies constituting individual deltaic cycles allows us to model the sum of these effects when dealing with a stack of such lobes, as in the case of the shallow subsurface Lafourche Delta. This paper will attempt to address these hypotheses using a cross-disciplinary approach of soils engineering and subsurface stratigraphic modeling within the greater framework of the Topstratum cyclic sequence.

Geologic Setting

Fisk (1944) recognized that incised valleys occur beneath Louisiana bays and estuaries. He suggested the valleys resulted from sea level lowstand and proposed they probably extend offshore. Fisk identified two so-called formations in the course of this, and later studies: 1) a fine grained Topstratum, deposited during the most recent sea level highstand (0-16 ka); and 2) a coarse grained Substratum, deposited immediately following the sea level lowstand which incised the valley (>18 ka < 35 ka). The problem with this nomenclature is that formational distinction is based solely on grain size.

A cross section across the now-filled valley illustrates the coarse grained Substratum, presumably deposited by high-gradient braided streams, occupying the base of the valley, while fine grained Topstratum, deposited by low-gradient meandering streams, occupies the upper part (Figure 1). From a soils strength

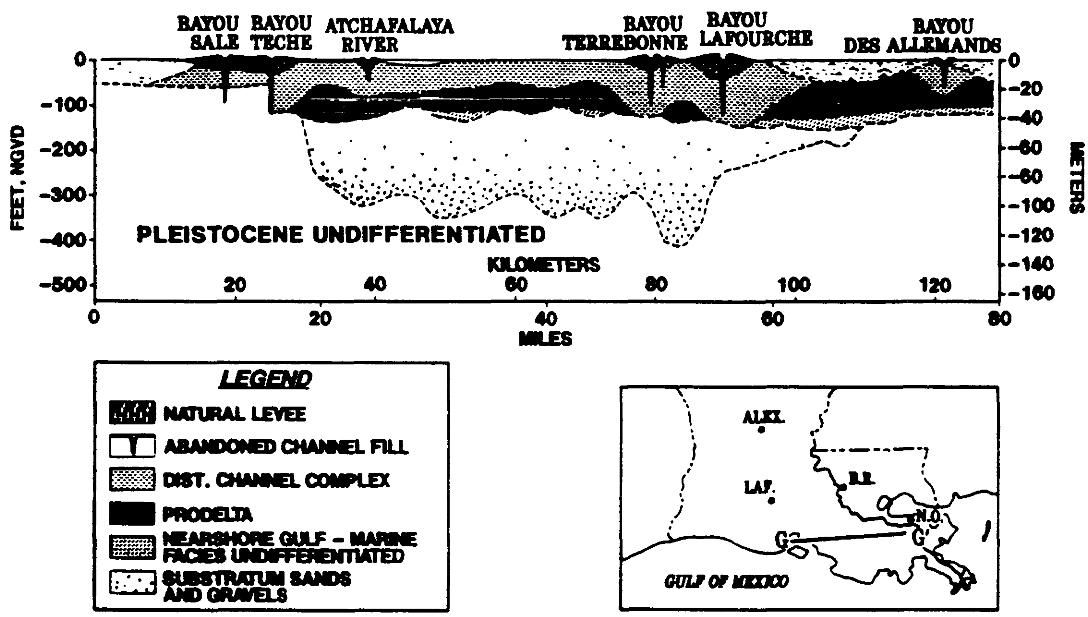

Figure 1. Substratum and Topstratum valley fill, south Louisiana. Modified from the GSA Quaternary Nonglacial Geology, vol. K-2, 1991. Reprinted with permission of author.

standpoint, the net result was the removal of a great wedge of consolidated Pleistocene soils and its replacement by a younger mixed sequence, the uppermost part of which is subject to rapid consolidation settlement.

Roberts (1985) referred to this wedge as the Holocene valley fill and reported on a relationship between the thickness of this wedge and the rate of radiocarbon age vs depth- determined subsidence, i.e. the thicker the valley fill, the greater the subsidence rate, and vice versa (see Figure 2). The Roberts

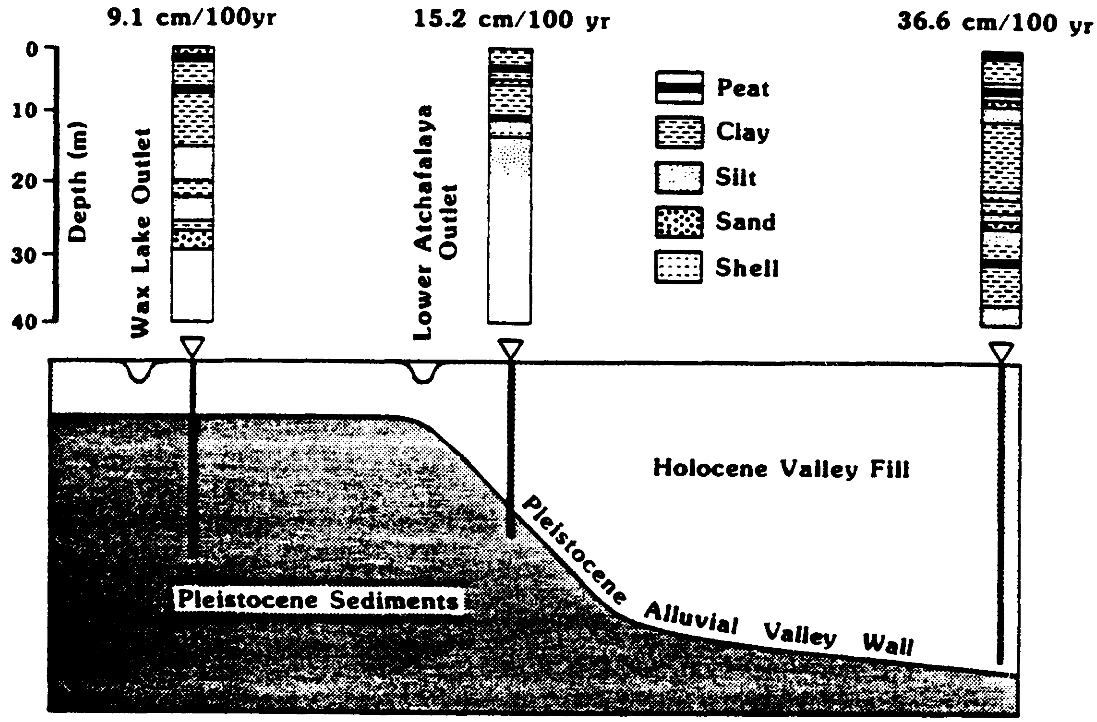

Figure 2. Stratigraphic subsidence rates, determined from radiocarbon-dated peat samples at three coastal sites across the western wall of the Pleistocene alluvial valley. Reprinted with permission of author.

(1985) paper, therefore, signaled a first-order subsurface control for wetland loss in south Louisiana. This first order relationship explains some, but not all of the curious surficial patterns of wetland loss. The identification of second and third order subsurface controls is the objective of this paper. In order to gain this information, two key deep borings were acquired as part of a joint USGS-Basin Research Institute- Louisiana Geological Survey project investigating subsidence in south Louisiana; P-1-90 and P-2-91.

Deep borings

Central to this study are two deep (>50 meters, <100 meters) boreholes; the P-1-90 boring, located at the Louisiana Universities Marine Consortium (LUMCON) facility in Cocodrie, LA, and the P-2-91 boring, located 22 kilometers to the NNW, in Grand Caillou, LA (see Figure 3). Both borings penetrated the entire Topstratum valley fill. The purpose for their acquisition was largely to model the subsurface facies stack at their respective localities, to characterize the Topstratum- Substratum boundary, and to gain velocity and geotechnical control by offsetting logged holes.

The region penetrated by these boreholes is locally called the Terrebonne Basin. Wetland loss is a major problem in this region.

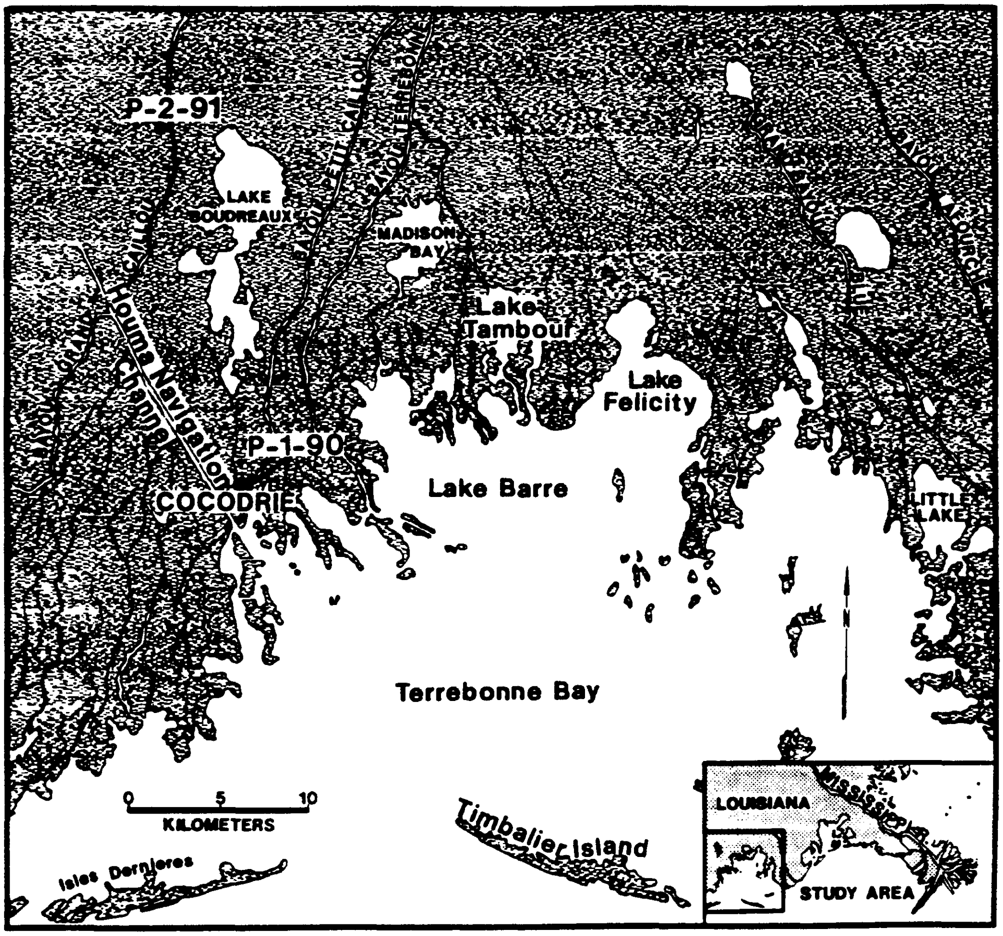

Figure 3. Location of two deep borings, Terrebonne Parish, south LA.

Defining the Topstratum-Substratum Contact

This paper is concerned with Topstratum cyclic sequences, so it follows that a definition of the base of the Topstratum must be proposed. Like all boundary sections, the definition must be clear, scientifically rigorous, and mappable. In Figure 4, a montage of data is presented which justifies the pick. In this presentation, the sonic log exhibits a marked increase in velocity (i.e. a decrease in sonic travel time) at 47 meters, and the character of the sonic profile is different above and below this depth. The density log shows a corresponding increase in bulk densities at 47 meters, and the reflection coefficient (RC) calculated for 47 meters is greater than any other boundary in the section. This gives us confidence this boundary is mappable. A cone penetrometer tip resistance profile (TR) illustrates the markedly different response of massive Substratum sands to the thinner, lower resistance sands characterizing the Topstratum, above. Finally, a most convincing data set is the

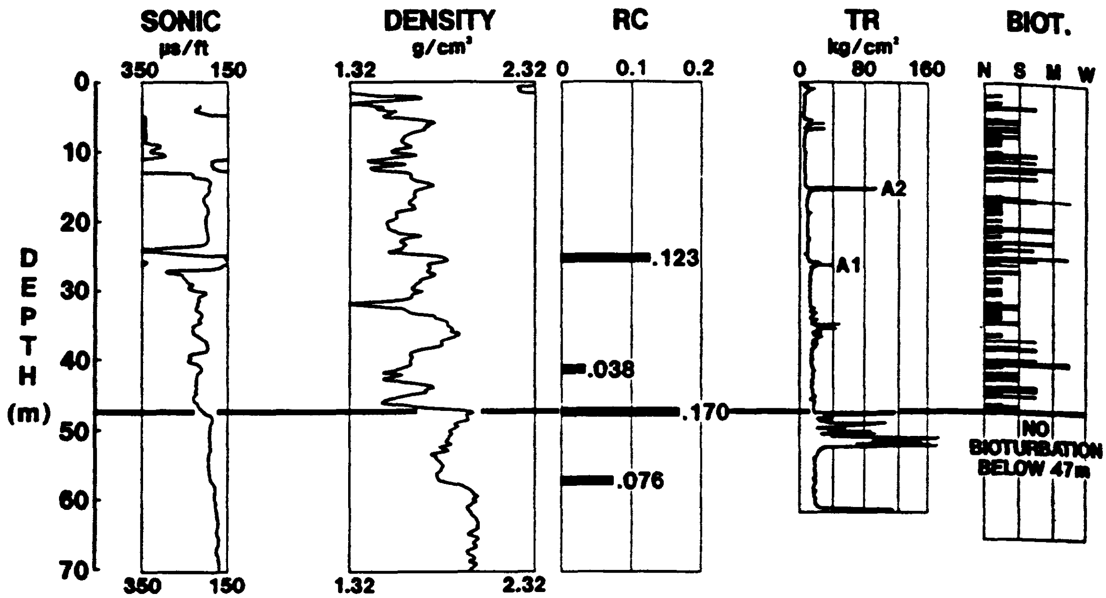

Figure 4. Base Topstratum-Top Substratum pick in P-1-90 at 47 m.

record of bioturbation (BIOT). Whereas Topstratum sands are variably bioturbated (i.e. N=none; S=slight; M=moderate; and W=well), no bioturbation was found beneath 47 meters, an indication that a fundamentally different unit had been encountered.

In the P-2-91 boring, the same exercise was followed in determining the boundary between Topstratum and Substratum (see Figure 5). The sonic log's first meaningful departure towards higher velocities occurs at 69 meters. The density log exhibits a corresponding increase in bulk densities at the same depth, and the reflection coefficient (RC) calculated at this boundary was greater than any other boundary in the section. The authors of this paper believe this acoustic boundary is the same boundary picked in P-1-90 at 47 meters. The tip resistance (TR) profile reveals a Topstratum-like character (i.e. thin, low resistance) for all sands encountered, but results are inconclusive since the tool was lost in the hole as hard Substratum sands were being penetrated. As with P-1-91, no bioturbation was encountered in Substratum sands.

Previously, workers distinguished Topstratum from Substratum solely on grain size. Textural analyses of all sand bodies in the P-1-90 and the P-2-91 borings are coded in Figure 6, Substratum or Topstratum, on a Passega C-M chart (1957). Topstratum sands in these two borings are very fine to fine grained, and are well sorted. Substratum sands, this chart indicates, can also be very fine and fine grained, but only Substratum sands have median grain size values

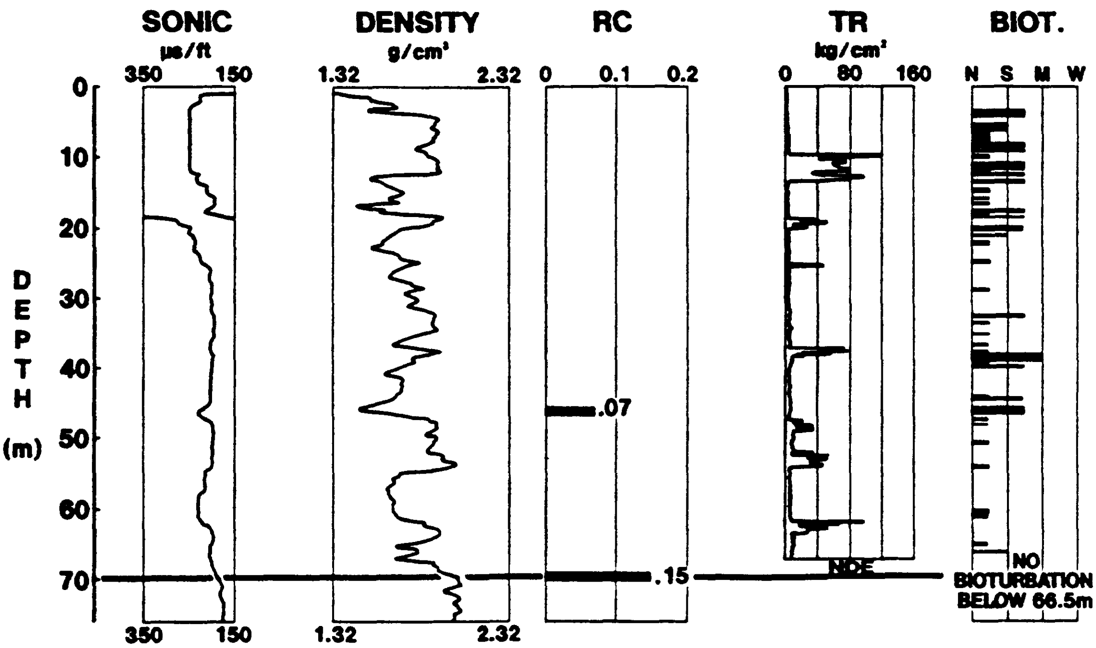

Figure 5. Base Topstratum-Top Substratum pick in P-2-91 at 69 m.

coarser than fine grained upper (>185 microns). This data suggests Upper Substratum has likely been mis-identified as Topstratum in previous studies. A re-examination of previous picks, in lieu of this work, should be undertaken, and the valley fill re-interpreted (Kuecher, 1992). C-M data on a modern Mississippi River point bar at Plaquemine Point, is included for reference.

Cyclicity in the Topstratum Sequence

"The initiation, growth, and abandonment of various delta lobes results in cyclic alternations of detrital and non-detrital deposits. Each major lobe is comprised of a detrital lens, or complex of lenses, and generally bounded on all sides by essentially non-detrital sediments indigenous to the basin of deposition." (Coleman and Gagliano, 1964). These authors add, "recognizable cycles occur on many scales... with thicknesses of 50 to 250 feet and an aerial extent of 2500 square miles, to small crevasses which fill interdistributary depressions."

Deltaic cyclicity was the dominant theme which recurred during description of the P-1-90 and P-2-91 boreholes. Peat deposits typically cap each deltaic cycle, thus successive peats in a section, or the uppermost peat in a successive series of peats represent the limits of individual cycles (see Figure 7). As active deltas are abandoned, the vertical accretion rate of the capping marsh deposit (FGC= fine grained cap) is overtaken by a relative sea level rise (attributed to the consolidation of itself and its underlying delta lobes), and this

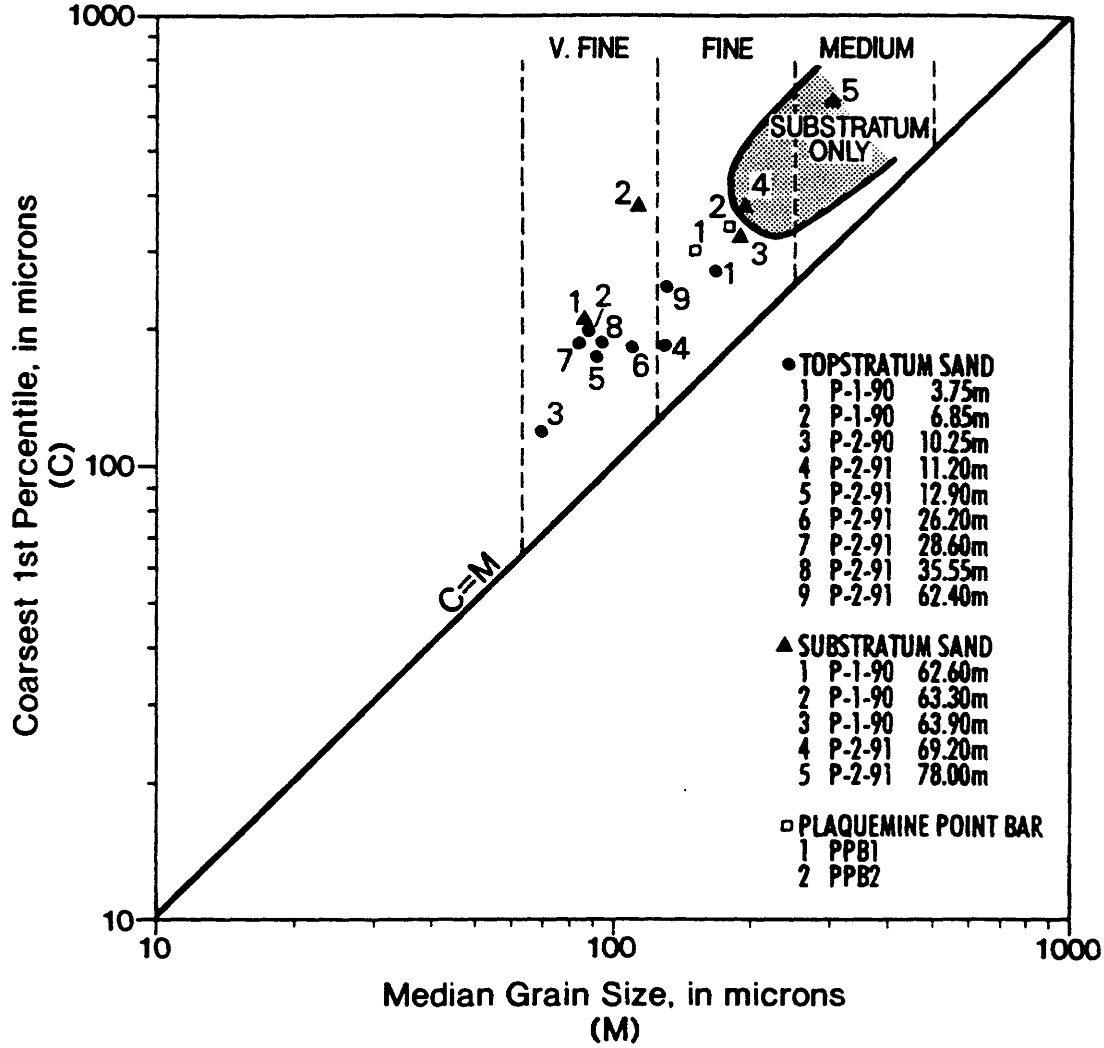

Figure 6. Coarsest 1 percentile (C) vs median grain size (M) for Topstratum and Substratum sands, P-1-90 and P-2-91 borings, vs Plaquemine Point Bar.

results in a thin transgressive silt deposited non-conformably atop an eroded peat sequence. Shelly, dark gray to olive gray bay muds follow, and these represent the maximum flooding event in the new cycle. At some time, thereafter, an active, prograding delta begins discharging into the bay, and a coarsening-upward sequence is initiated. Detrital sands are found near the middle of these cycles, but channelization can locally scour through the base of a cycle into an underlying cycle. Once the active distributary wanes, a fining-upward sequence characterizes the deposition until this deltaic lobe subsides, peat marsh re-occupies the delta plain, and a new cycle is initiated. Based on peat to peat lithic correlations, four (4) deltaic cycles were recognized in the P-1-90 boring in 10.3 ka (2.6 ka/cycle). In the P-2-91 boring, six (6) deltaic cycles were recognized in

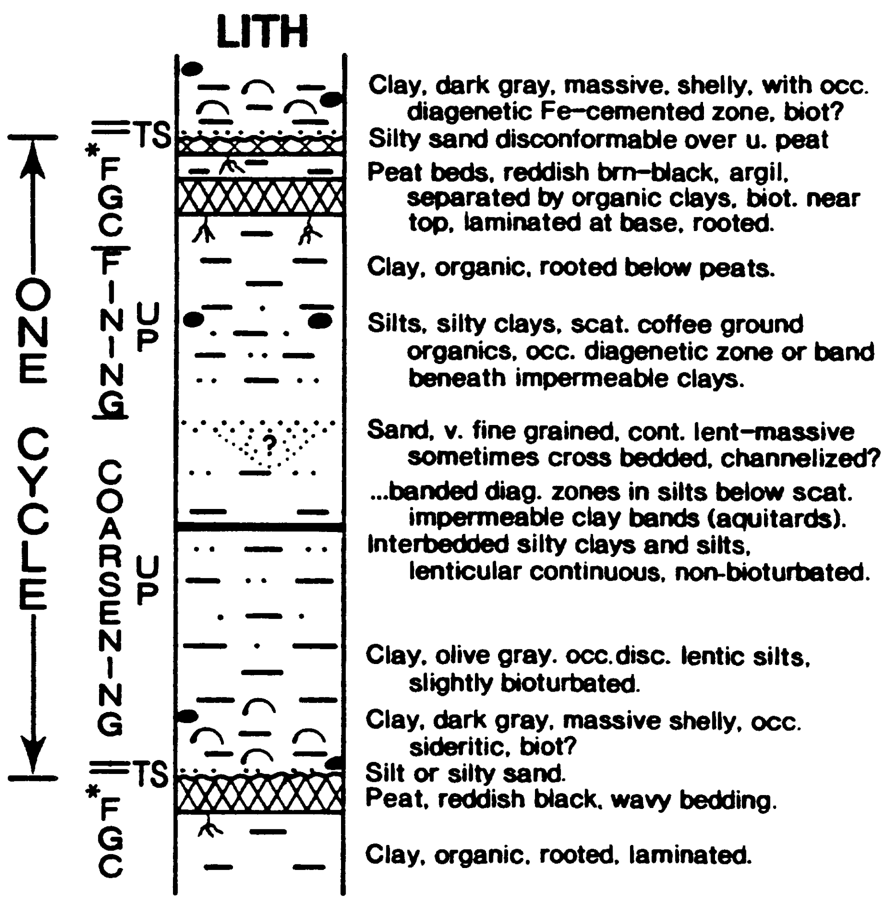

Figure 7. Typical Topstratum deltaic cycle, as gleaned from the description logs of P-1-90 and P-2-91.

15.1 ka (2.5 ka/cycle). The average compacted thickness of a deltaic cycle in the P-1-90 boring was 10.5 meters/cycle; at P-2-91 it was 11.2 meters/cycle (both values on the low side of Coleman and Gagliano's (1964) range of 15.2 to 76.2 meters/cycle). The delta cycle is important to this study because it is tied to predictability; only a limited number of facies recur in a Waltherian facies stack, and these facies have distinct consolidation characteristics.

Geotechnical Modeling of Facies

The old field adage, "No matter how you take a sample, you disturb it" is true, but some methods disturb more than others. Experience in push-coring argillaceous sediments in the P-2-91 boring (see Figure 8) illustrates the magnitude of near-surface compaction induced by this sampling method. In the first two (2) meters of depth, a 1.0 meter sampling attempt yielded only about 0.45 meters of core, thus it had a 45% recovery percentile. At depths of 7.0-8.0 meters, core recovery had increased to about 85%, and after 12.0 meters, a full

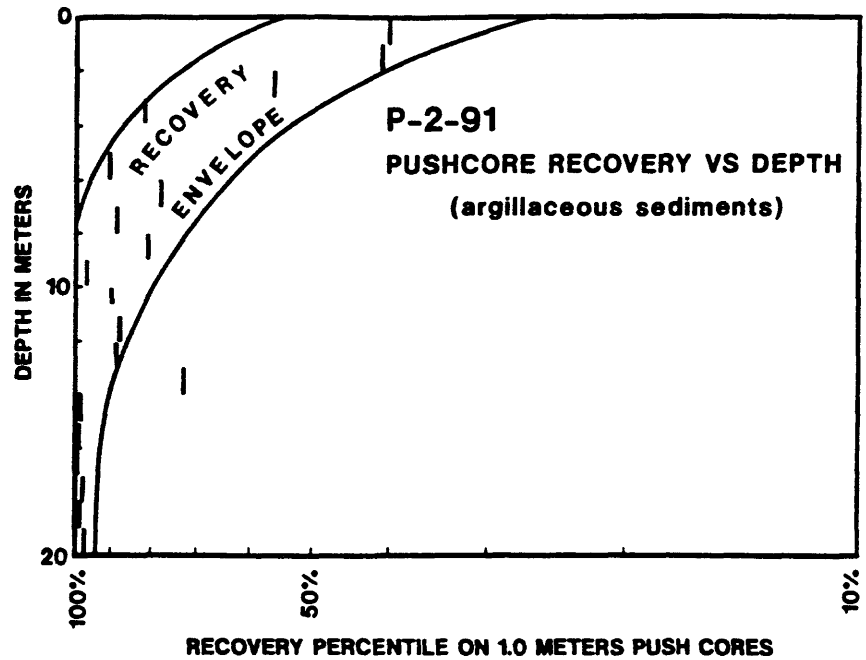

Figure 8. Push core recovery vs depth for argillaceous sediments, P-2-91.

recovery is likely. Researchers must be aware that push cores reduce the volume (i.e. length), increase the bulk density, and shift the zero consolidation point of a soil during sampling. Cores thus obtained represent a distortion of in-situ conditions and are not representative of the section.

To minimize problems of compactional deformation, the authors present a method used successfully in the field. Our sampling procedure utilizes what we call a liquid nitrogen (LN_2) annulus coring device (see Figure 9). The soil is sampled in a modern, active depositional setting. Best results are obtained when the sampling site is directly at water's edge. In this way, the consolidometer trim ring (a bushing-like ring which holds the sample during soil consolidation testing), can be inserted into a water-saturated, or 'quick', soil, with little or no deformation. Procedure then involves trimming excess soil from the top of the ring, excavating soil to a depth of 1/2 the width of the ring, and placing the containment vessel around the trim ring core. The ring stand apparatus is then set up to facilitate transfer of liquid nitrogen into the containment vessel; a procedure which freezes the core in the trim ring. At this point, the trim ring and sample are extracted from the soil and the base is trimmed flush with the ring. The sample core is packed in dry ice for transport back to the lab. The authors recognize a 2-3% increase in volume upon freezing, which at worst case involves minimal remolding, but point to the technique's advantages over the push core in obtaining cores with minimal disturbance.

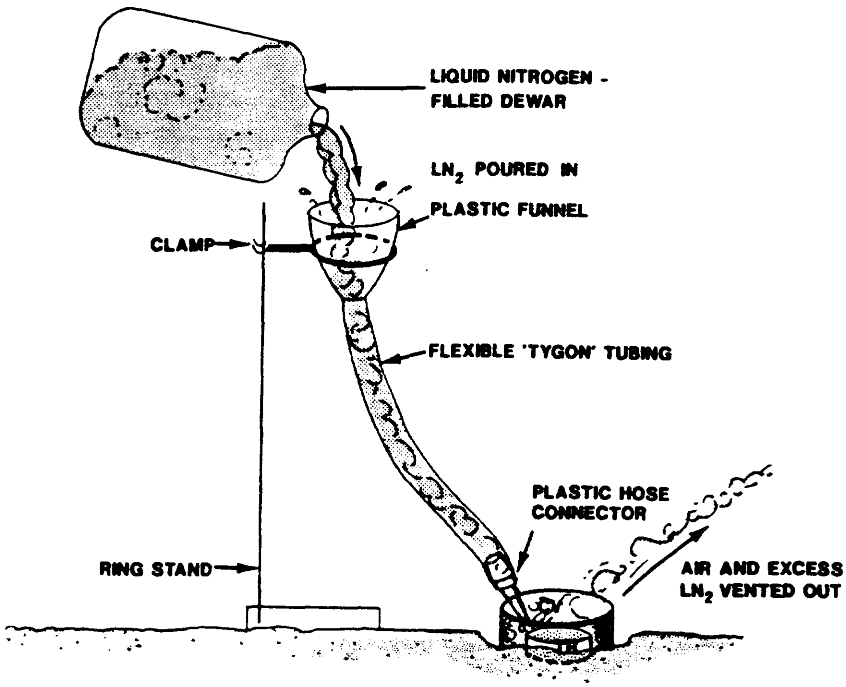

Figure 9. Liquid nitrogen (LN_2) annulus coring device used to sample modern surficial soils with minimum deformation. Note: CV= containment vessel; TR= consolidometer trim ring. Method a modification by Kuecher (this paper) of a device pioneered by Knaus (1986).

In the lab, frozen samples are placed directly into the consolidometer (see Figure 10) and thawed for 24 hours in-place. Once thawed, the upper surface is evened with a straight edge. Filter paper and porous stones are placed at top and bottom for drainage. Loading is scheduled in the following increments: 0.5 kg/cm^2, 1.0 kg/cm^2, 2.0 kg/cm^2, 4.0 kg/cm^2, 8.0 kg/cm^2, 16.0 kg/cm^2, 32 kg/cm^2, and 64 kg/cm^2. Each loading compacts the soil sample, and a scheduled record of deformation versus time is obtained. A decision is made to increase a load when deformation has ceased.

Consolidation is commonly measured in terms of its changing voids ratio at the termination of successive loads. Void ratio is the ratio of the volume of voids divided by the volume of solids in the trim ring, as follows:

$$e = V_V/V_S$$

This study will present data in the format of e versus the log of pressure, p.

Sands were the first soil type examined. Samples were obtained from various locations in the greater Mississippi River deltaic plain. All are fine grained and well-sorted. A plot of e versus log p for these sands is shown (see Figure 11). Despite differences in initial void ratio (which may be due to differences in packing or sorting), the Grand Isle beach sand, the Plaquemine

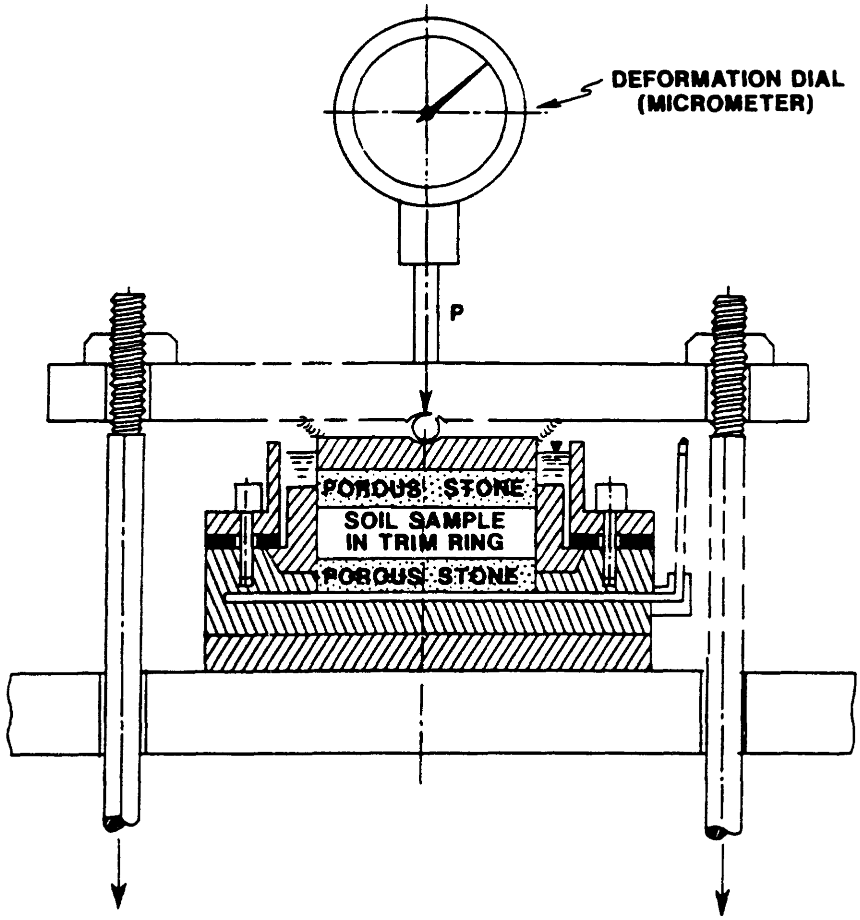

Figure 10. Diagram of a typical consolidometer. Soil sample is housed in trim ring between two porous plates. Load is applied from above (P), and deformation is measured by a spring-type micrometer.

point bar sand, and the South Pass distributary mouth bar sand all exhibit similar consolidation characteristics; all plots run parallel and all exhibit limited consolidation settlement upon loading. The exception lies in sample MBSO, which represents the South Pass distributary mouth bar with 50 volume percent woody organics included. Interestingly, this sample has a high initial void ratio, but consolidates to a void ratio at 64 kg/cm^2 load which approximates the mouth bar sand without organics. These data suggest that sands from a variety of modern environments behave similarly under consolidation, and have been grouped as one geotechnical soil type, SP (Unified Classification), when modeling settlement potential. Initial wet unit weights ranged between 5.8 and 8.2 kg/cm^3.

The compression index of soils, a useful parameter for reviewing the potential of various soil types to deformation upon loading, is expressed as:

$$C_c = \frac{e_1 - e_2}{\log p_2 - \log p_1}$$

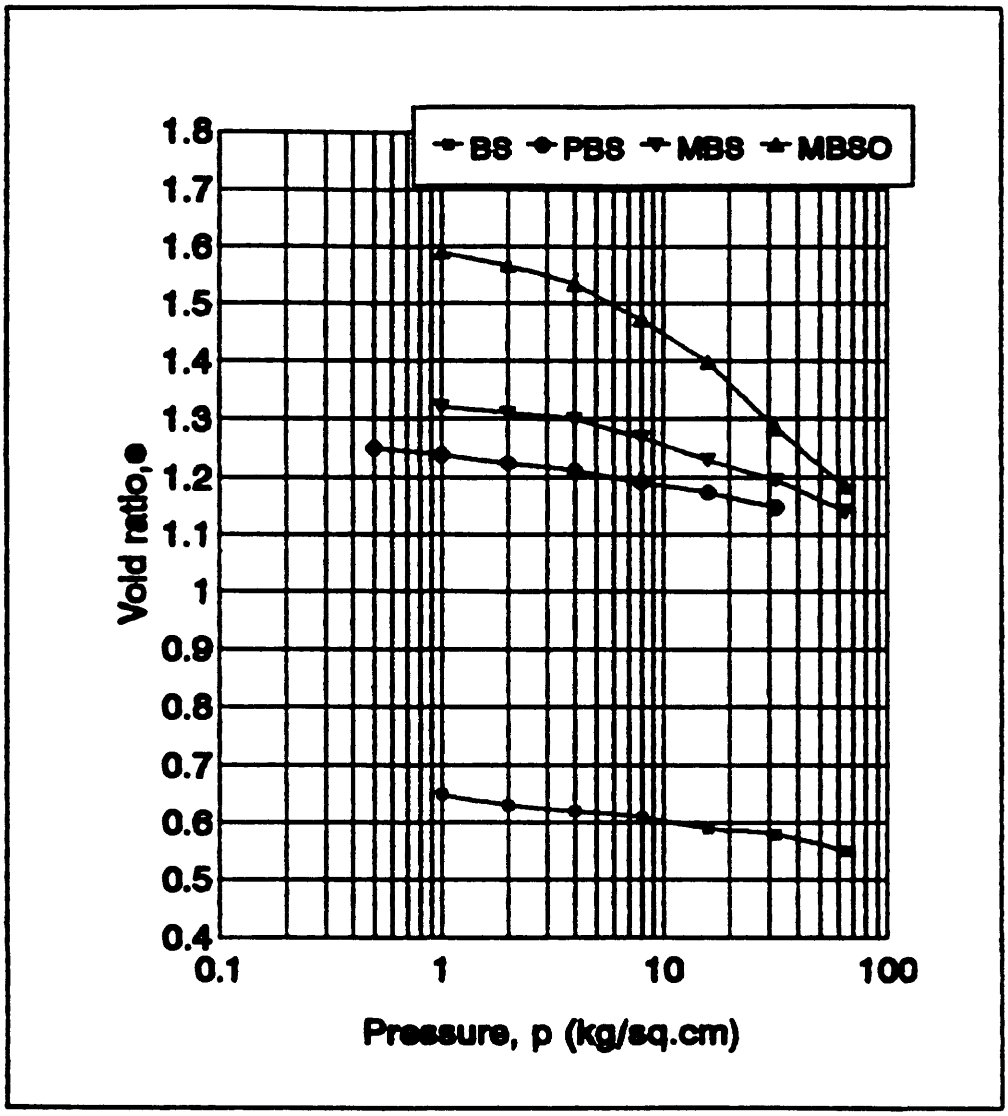

Figure 11. Void ratio (e) versus log of pressure (p) plot for various sand facies within the study area. Legend: BS = Grand Isle beach sand; PBS = Plaquemine point bar sand; MBS = South Pass distributary mouth bar sand; and MBSO = South Pass distributary mouth bar sand with 50 volume percent woody, "coffee ground" organics.

The sands in Figure 11 have the following C_c values:BS = 0.047; PBS = 0.063; MBS = 0.115; and MBSO = 0.227. High values of C_c correspond to high values of settlement, S, as follows:

$$S = \frac{C_c H}{1 + e_0} \log \frac{(p_0 + \text{delta } p)}{(p_0)}$$

where H is the thickness of a particular facies unit; and p_0 is the overburden pressure. Sands experience very little consolidation settlement, largely because the C_c for sand is so low.

By contrast, the bay/swamp mud from Cocodrie, Louisiana, is subject to drastic changes in consolidation settlement (Figure 12) and represents the

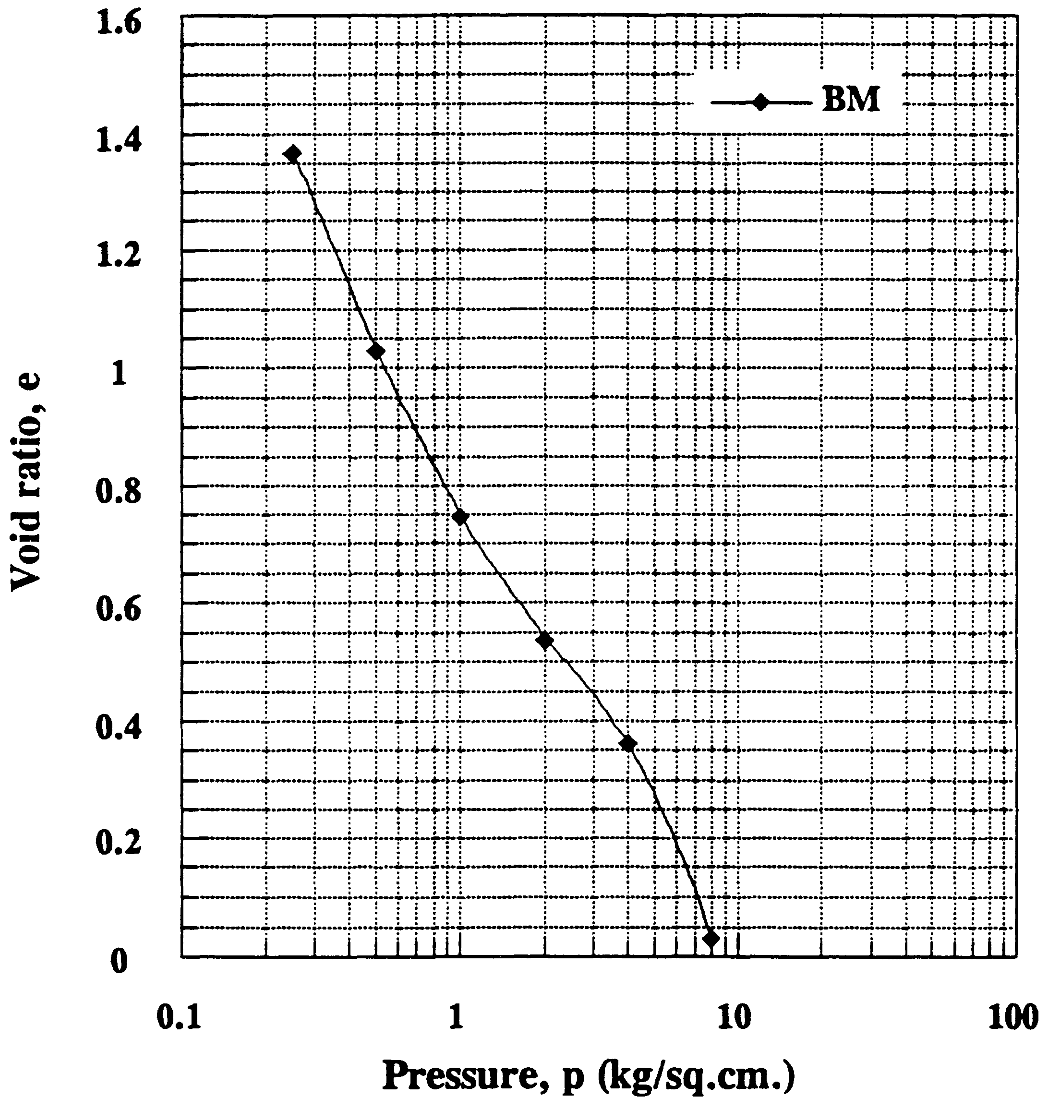

Figure 12. Void ratio (e) versus log of pressure (p) plot for bay/swamp mud sample from Cocodrie, Louisiana.

opposite end-member to our previously studied sands, exhibiting a compression index of 0.8172. Initial void ratio in this sample is high, and the sample contains 150 weight percent water (n=2). The liquid limit is reached at 125 weight percent water (n=2) and the plastic limit is reached at 49 weight percent water (n=2). This soil has a plasticity index of 76, and is categorized as a CH soil, or "fat clay" in the Unified Classification scheme.

Calculations indicate this soil would consolidate from an initial wet unit weight of 0.00139 kg/cm³ (87 lbf/ft³) to 0.0024 kg/cm³ (150 lbf/ft³) with burial from the surface to a depth of 8.31 meters. With such rapid consolidation, it is no wonder why the uppermost Topstratum deltaic wedge in this study area (i.e. the Lafourche Delta) is suspected of being the terrane most subject to further consolidation settlement.

Results and Discussion

The Lafourche Delta subcrops the surface in the area of south Louisiana experiencing the most dramatic rates of wetland loss. It is a lens shaped deposit consisting of four distinct lobes (Figure 13). Bayou du Large was deposited atop

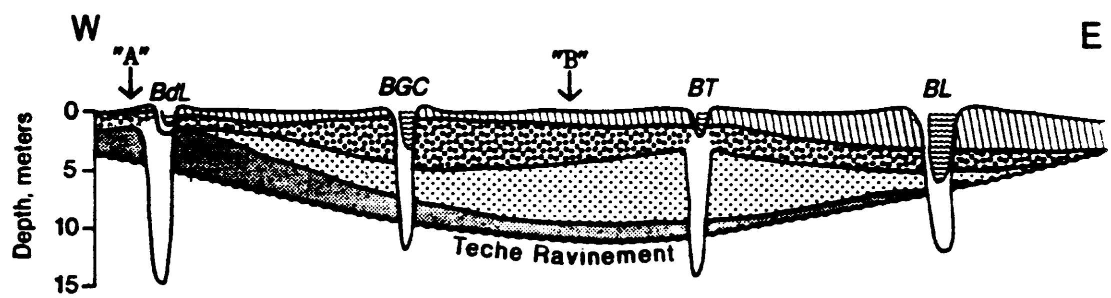

Figure 13. Schematic strike section across the Lafourche Delta, Terrebonne and Lafourche Parishes, Louisiana. Legend: BdL = Bayou du Large; BGC = Bayou Grand Caillou; BT = Bayou Terrebonne; and BL = Bayou Lafourche.

a marine ravinement surface between 2.6 and 1.3 ka. Bayou Terrebonne was the major distributary between 1.3 and 0.8 ka; Bayou Grand Caillou was active between 0.9 and 0.5 ka; and Bayou Lafourche occupied the eastern edge of the basin between 0.7 and 0.3 ka.

If our first order control to wetland loss is the thickness of the valley fill (refer to p. 4), then the second order control is the thickness of the Lafourche Delta, which rides piggy-back atop the valley. In areas where the Lafourche is thick (see "B" on Figure 13), consolidation settlement is great and the wetland loss problem is magnified. In areas where the Lafourche is thin (see "A" on Figure 13), consolidation settlement is reduced and wetland loss is attenuated.

Within the Lafourche Delta lies a complex stack of facies, some of which are consolidation-prone (e.g. bay muds and peats), some are not (e.g. beach sands, distributary mouth bar sands, and channel or point bar sands), and some are intermediate (e.g. levee and prodelta silts). Figure 14 addresses such a case

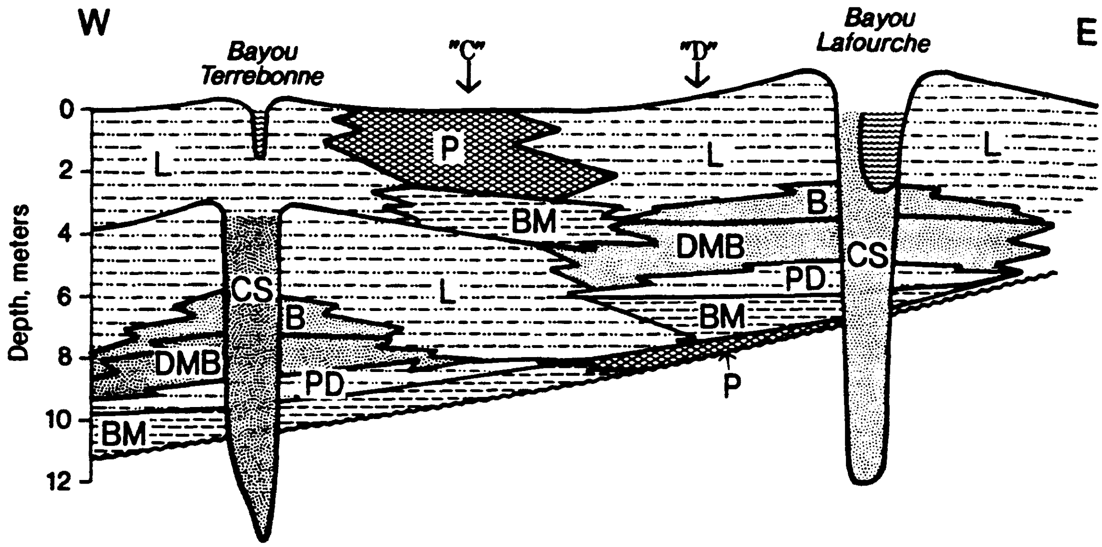

Figure 14. Schematic cross section of the eastern side of the Lafourche Delta illustrating the facies relationships which may exist. Legend: BM = bay mud; P = peat; PD = prodelta; DMB = distributary mouth bar; B = beach; CS = channel sand; and L = levee.

from the eastern side of the delta. In position "C", low density peat deposits subcrop the surface, and this is underlain by a consolidation-prone bay mud in the shallow subsurface. Areas like "C" are presently experiencing the greatest surficial rates of wetland loss. At position "D", however, silty levee deposits are anchored below by sands, and such areas are presently more stable.

In conclusion, the consolidation characteristics of individual facies types represents the third order subsurface control which governs wetland loss in the Terrebonne Basin, south Louisiana. Additional work needs to be done to refine this model.

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SUBSIDENCE PROPERTIES OF HOLOCENE SEDIMENTS: S. LA.

J. N. Suhayda[1], A. Bailey[2], H. H. Roberts[3], S. Penland[4], and G. Kuecher[5]

Abstract

As part of a comprehensive USGS-sponsored study of processes that drive subsidence and wetland loss in south Louisiana, two continuously cored deep borings (60 m and 72 m) were acquired in south Terrebonne Parish marshlands. Both borings were supported with in-situ geotechnical data acquired by cone penetration testing. Additional laboratory testing included X-ray radiography, lithologic description, radiocarbon dating, selected shear strength and consolidation tests, pore water geochemistry, and solid phase diagenetic properties examination (X-ray diffraction for mineralogy, thin-section petrology, and scanning electron microscopy).

Boring 1 was taken at Cocodrie, Louisiana, currently in a salt marsh environment. Boring 2 was taken in the same interdistributary basin approximately 22 km to the north in a freshwater marsh setting. Both borings penetrated the entire Holocene alluvial valley fill. Initial results suggest that dewatering and compaction of thick sections of recently deposited Holocene sediment are largely responsible for regional subsidence and wetland loss. Radiocarbon dating indicates that a linear relationship exists between age and

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[1]Dept. of Civil Engineering, Louisiana State Univ., Baton Rouge, LA 70803

[2]Dept. of Geology, Univ. of Southwestern Louisiana, Lafayette, LA 70504

[3]Coastal Studies Institute and Dept. of Oceanography, Louisiana State Univ., Baton Rouge, LA 70803

[4]Center for Coastal, Energy and Environmental Resources, Louisiana State Univ., Baton Rouge, LA 70803

[5]Basin Research Institute, Louisiana State Univ., Baton Rouge, LA 70803

depth at Boring 1, suggesting a constant depositional rate with age. The sediment columns at both boring sites are characterized by at least 5 cyclic coarsening upward sequences and in some cases, thick shales associated with the lower parts of given cycles. Variations in geotechnical properties of each cycle are directly correlated with distinct lithologies. The base of a typical cycle is a relatively massive, low strength, underconsolidated clay. These sediments are interpreted as rapidly deposited units that precede coarser deposition. In contrast, the sands at the top of each cycle exhibit high strength and normal consolidation. A column of these cyclic sequences typically contains alternating highly consolidated and underconsolidated units.

While the sediments are dominantly quartz, feldspars and clays, sedimentologic and geochemical analyses indicate the presence of abundant diagenetic products (siderite, calcite, and pyrite) in the very lowest clay-rich parts of each cycle and in the high organic units at the top of each cycle. Initial results indicate that the shear strength and consolidation of sediments within the zones of diagenetic change are much higher than in comparable zones with diagenetic products.

Results from this study suggest that the consolidation of sediments in the Terrebonne Basin is largely controlled by the thickness of the Holocene section, a first order effect. Within an area of given thickness, a second order effect is the actual consolidation related to variations in lithology. A third order effect appears to be controlled by diagenetic processes.

Introduction

Subsidence is an important and major process affecting the stability of Louisiana's coastal wetlands. Subsidence and land loss involve numerous processes, both local and regional (Coleman and Roberts, 1989). However, rapid deposition, dewatering, and compaction of sediments comprising the Holocene Mississippi River delta complex are certainly major factors. Complexity of the present Louisiana coastal plain is inherited from rather abrupt diversions of Mississippi River water and sediment to form off-set, overlapping, rapidly deposited delta lobes. Kolb and van Lopik (1958) described this process of delta-switching and indicated that at least seven major switching events and their associated delta lobes have occurred since sea level approached its present position approximately 7000-8000 years ago. The present coastal plain is composed of remnants of these delta lobes and their fluvial feeder systems in various stages of deterioration. Much of the dramatic coastal land loss reported by Morgan and Larimore (1953), Gagliano and van Beek (1970), Gagliano et al. (1981), and Craig and others (1979), can be attributed to processes of compaction and dewatering. Initial data indicate that subsidence rates are highest where the Holocene sediment thickness is greatest (Roberts, 1985), suggesting that consolidation and settlement of Holocene sediments are major factors.

The purpose of this study, funded by the U.S. Geological Survey, is to acquire geologic, geotechnical, and geochemical data which can provide a better understanding of the role of consolidation and settlement in Louisiana's coastal land loss problem. The approach combines in-situ and laboratory testing methods. Consolidation and settlement are processes involving the change in volume of sediments resulting from the expulsion of pore water due to excess pore water pressure under a given overburden load. In southern Louisiana, the deltaic sediments frequently consist of alternating sands and clays. Hence, clays are consolidating due to the weight of the overlying sedimentary units, as a result of dissipation of excess pore water pressure from clay units into sands. The various factors involved in this process of consolidation and settlement are thickness of each clay layer and its drainage conditions, stress history, excess pore water pressures, and sediment properties such as consolidation coefficient, specific gravity, unit weight, permeability, and void ratio. The actual conditions of the sediments at a site depend upon the geologic history of deposition and erosion, as well as early diagenetic changes. Hence, to understand, and eventually predict subsidence magnitudes, detailed correlations need to be made between geologic and geochemical properties of the sediment and its geotechnical properties.

It is the objective of this paper to provide new information concerning the consolidation state and geochemical properties of Louisiana's coastal plain deposits and the importance of these factors to subsidence. The study presents the following new elements of understanding in the subsidence problem:

1. Detailed site-specific information about stratification (facies stacking) of the entire Holocene sediment column.

2. Continuous piezocone penetrometer profiles of the Holocene sediment column for in-situ geotechnical properties.

3. Additional geotechnical properties from laboratory testing not obtainable from in-situ penetrometer data.

4. Estimates of early digenetic alteration of sediment properties by precipitation of cements (siderite, dolomite, other iron-rich calcium carbonates, iron oxides, and pyrite are the most common).

5. A first-approximation quantitative model of consolidation-settlement rate using a finite difference computer program.

Description of the Study Area

Subsidence of recently deposited, unconsolidated, deltaic materials in south Louisiana, combined with an insufficient soil accretion, drives the greatest coastal land loss problem in the United States. Louisiana contains 41% of the nation's wetlands, and in the period 1974-1983, these wetlands have been converted to open water at a rate of 30.71 mi^2/yr (80 km^2/yr) (Britsch and Kemp, 1991).

The study area for this paper (Figure 1) is a part of the Louisiana coastal plain severely impacted by coastal land loss. As recently as 1853, this setting was characterized by a nearly continuous land connection to its barrier islands. Today, this region is in a state of rapid coastline retreat.

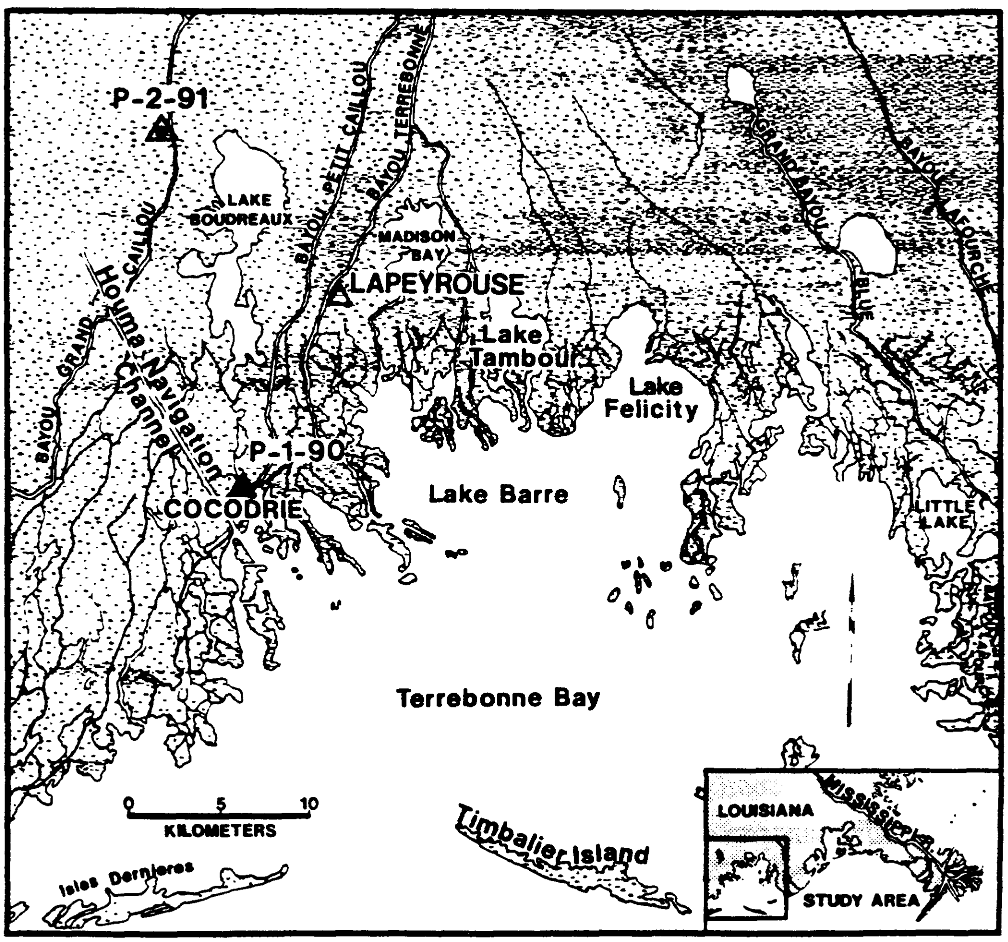

Figure 1. Study area, Terrebonne Bay regon, south-central Louisiana. Legend: filled circles = boring sites; triangles = cone penetrometer sites.

Two deep borings, P-1-90 and P-2-91, were taken by cooperative efforts (U.S. Geological Survey, Basin Research Institute, and the Center for Coastal, Energy, and Environmental Resources) in an attempt to understand subsurface controls on wetland loss. These boring sites were twinned by a geotechnical cone penetrometer, and a third site, Laperouse, and was investigated by cone penetrometer profiling, alone.

Knowledge of subsidence rates is essential before effective federal, state, or parish land loss plans can be formulated. Coleman and Smith (1964) and Roberts (1985) quantified rates of compactional subsidence with radiocarbon data, the latter documenting ranges between 0.09 and 0.37 cm/yr. Zilkoski and Reese (1986) analyzed geodetic leveling in the Gulf coastal states and reported subsidence rates in coastal Louisiana to be about 0.5 cm/yr. This study will investigate subsidence based on geotechnical data and predictive models.

Methods

At the sites treated in this paper, one or both of two types of data collection were utilized: cone penetrometer measurements and direct examination and testing of sediment borings. Two types of borings were collected: short (3-6 m) vibracores for compressibility tests and long borings for general sediment characterization and discrete sample testing for geotechnical and geochemical properties.

Cone Penetration Tests

In-situ soil testing was conducted using a dual piezocone penetrometer (DPCP) (Tumay and Juran, 1989). The cone had an apex angle of 60° and a cross-sectional area of 15 cm^2. This technique offers the advantages of minimal disturbance, retention of in-situ soil conditions (stress, temperature, etc.), and reduction of cost and time of testing. The dual piezocone penetrometer allows for a simultaneous measurement of the pore pressures at the tip and along the penetrometer shaft behind the friction sleeve, together with tip resistance and sleeve friction.

A major application of cone penetration testing is soil classification. Classification schemes are based upon tip resistance and the ratio of the friction resistance to the tip resistance, called the friction ratio. The classification scheme proposed by Tumay (1985) has been used to classify the soils profiled in this study. Pore pressure dissipation tests with the piezocone provide a useful means of evaluating approximate consolidation and hydraulic conductivity properties. The rate of pore pressure dissipation depends on the coefficient of consolidation in the horizontal direction and the drainage conditions. Many approaches have been used to determine the coefficient of consolidation and hydraulic conductivity using dissipation tests, in which the time rate of dissipation of excess pore pressure around the cone is recorded after penetration is stopped. The method proposed by Baligh and Levadoux (1980), based upon a finite element analysis to predict the pore pressure dissipation, was used in this study. Dissipation curves at various locations on cone for a 60° cone presented from which the coefficient of consolidation can be calculated.

The geotechnical testing was accomplished in three steps. The first step was profiling using the cone penetrometer at rate of 2 cm/sec. Depths of penetration of 30 m were routinely obtained. Dissipation tests were then conducted within the massive clay layers to determine the static excess pore pressure and compressibility characteristics. Finally, soil samples were obtained and subjected to laboratory analysis. The soil samples were obtained using the Mostap soil sampler. The sampler consists of a 1 in. long steel pipe (66 mm diameter) with one conical end and the other hollow. From the cores, soil samples were taken at required depths for conducting consolidation tests. The consolidation ring and the test was performed according to ASTM D2435-90 standards.

Acquisition of Deep Borings

The P-1-90 and P-2-91 borings (Figure 1) were acquired as part of the U.S. Geological Survey supported research project concerning physical processes of wetland loss in Louisiana. The objective of both borings was to recover continuous push core from the surface to a total depth of 75 m, or point of core barrel rejection in the Pleistocene substratum sands, whichever came first. The contract, at this point, specified that the existing borehole was to be reamed to 18 cm diameter to accommodate logging tools, then deepened to around 85 m to provide a 'rathole' for resolving the top of the Substratum sands.

The P-1-90 boring was spudded on June 27, 1990, and abandoned in June 30, 1990, after reaching a log total depth of 78.2 m. The P-2-90 boring (located 22 km to the north) was spudded on July 24, 1991, and abandoned in July 30, 1991, after reaching a log total depth of 80 m. Eustis Engineering Company, of Metairie, Louisiana, was contracted to take the core, and in both cases utilized a water well-type mobile rig.

Core sampling at shallow depths (0 to 20 m) was accomplished by utilizing a short length of aluminum pipe attached to the drill string by allen screws. These 'barrels' (1.5 m in length for P-1-90, 1 m for P-2-91) were pushed into the sediment hydraulically, using the weight of the rig. Sampling at intermediate depths (20 to 40 m) was largely accomplished with a steel, 1.5 m split barrel core device. Deep core sampling (40 to 70 m) proved most successful with a device called the 'Eustis tube', which consists of a stiff outer barrel, 1 m in length, and no inner aluminum core tube. Samples from this device are extruded hydraulically at the surface. Full circulation rotary wiper trips followed each core barrel retrieval.

Core was geochemically sampled on-site, then wrapped and labeled for transport back to the laboratory. Subsequent operations involved the following schedule: (l) x-radiography, (2) core description and photograph, (3) sampling of peats for C dating, (4) sampling for forams and ostracodes, (5) sampling for ROCKEVAL pyrolysis and C isotopes, (6) performing grain size analyses on all sands, and (7) re-wrapping for storage.

Schlumberger, Inc., was contracted to perform logging services on both deep borings. Two logging suites were used: (1) GR-DIL-SONIC, and (2) GR-CAL-NEUTRON-DENSITY. These logs provided a continuous record to total depth, and calibrated the core.

Deep Boring Data Acquisition

Two types of data were collected for deep borings: X-ray radiographs and geochemical.

X-ray Radiography

The nondestructive application of X-ray radiography testing to core samples from the borings proved extremely valuable for studying sediment structure and identifying organic and inorganic inclusions. Radiographs also provided a means for identifying and precisely sampling diagenetic zones as well as discrete nodules. The X-ray radiography technique consists of preparing a uniform slab of sediment 1 cm thick and exposing it to x-radiation. The image is recorded on Kodak Type-M industrial X-ray film. A Norelco 150 industrial X-ray unit was used at power settings of 20 ms and 28 kv. Exposure times ranged to 2 to 4 min. depending on sediment type and degree of compaction.

Geochemical Data

Samples were collected while each boring was being taken. Two plugs (2.5 x 10 cm) of fresh sediment were taken from the interior of the bottom end of each 1 m core before it was sealed. These were then stored in ice chests and transported back to the laboratory where one plug was frozen for possible later use and the other was treated with a gas-pressured squeezer to remove several mililiters of pore solution. Pore solutions were then filtered through 0.45 μ membrane filters and separated into four portions. One of these was fixed for later determination of metals by inductively coupled plasma emission spectroscopy (ICP). Another was fixed for sulfide determination by the Gilboa-Garber method. The third portion was analyzed for pH and alkalinity (immediately after separation). Chloride was determined in 1 ml of the remaining solution by titration. Steps are summarized in Figure 2.

In addition to pore solutions, individual inclusions of diagenetic cement, located using X-ray radiographs of the cores, were extracted for examination. Portions of these to maintain the structure and thin sections produced to examine microscopically. Subsamples of uninfiltered inclusion adjacent to each thin section were powdered and X-ray diffraction patterns collected for further mineral identification (Figure 2).

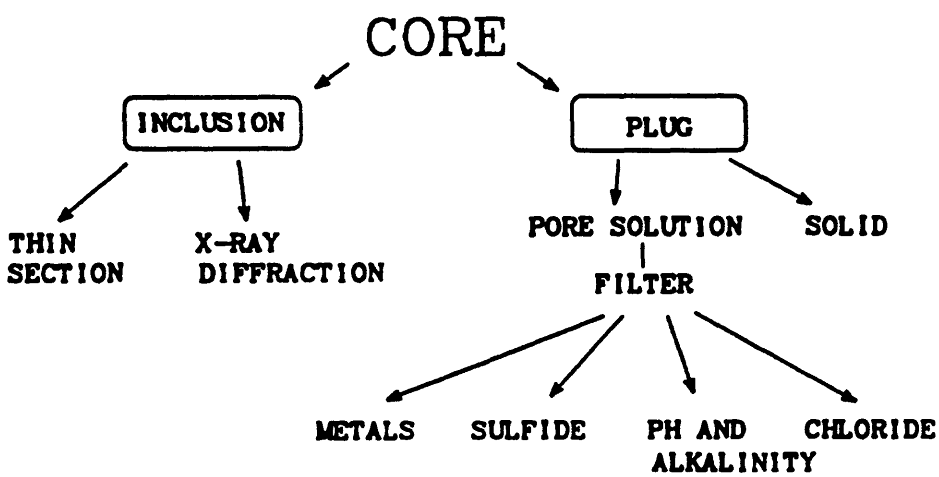

Figure 2. Steps in analysis of geochemical data.

Results

Lithic Framework

The borings were collected within the Lafourche delta complex which was actively building between approximately 2000 to 800 years ago. They penetrate sediments of the entire Lafourche delta complex and older Holocene deposits that comprise a thick top stratum section above the substratum sands and gravels of the basal Mississippi River Valley fill (Fisk, 1944). One boring was acquired from the natural levee of the abandoned Bayou Du Large distributary in western Terrebonne Parish and the other was taken on the natural levee of the once active Bayou Peti Caillou distributary in eastern Terrebonne Parish (Figure 1). These distributaries have been abandoned for nearly 1000 years. A decrease in sediment input coupled with subsidence has caused them to be onlapped by brackish bay waters and sediment, the beginnings of a marine flooding surface.

Lithology and radiocarbon dating suggest that both borings penetrated the entire Holocene alluvial valley fill at each site. Cyclic depositional events are recorded throughout the top stratum sediments in each boring. In contrast to the repeated and stacked depositional units described from the freshwater Atchafalaya Basin by Coleman (1966), these borings contain repeated sedimentary units from a lower deltaic plain setting which are periodically intruded by brackish to marine waters. Alternating bay, lake, thin bay-fill or subdelta, and marsh environments are represented in the stacked deposits at each boring site. Many of the depositional cycles consist of a coarsening upward unit which may or may not culminate in marsh followed by a marine flooding event or local transgression. In the Terrebonne region of the Lafourche delta complex, the upper cycles of the Holocene alluvial valley fill describe a series of individual delta plains related to pauses in Holocene sea level rise. Each cyclic depositional event is separated by a transgressive surface of erosion which is interpreted as the result of a rapid rise in sea level after minor stillstand. Presently, data are being collected to determine the lithostratigraphic relationships between sedimentary cycles within and between the two borings. These data will then be placed into a more regional appraisal of Holocene delta complex development.

Figure 3 illustrates the lithologies that are deposited in discrete cycles and specific data sets associated with each boring. Analysis of the X-ray radiographs indicates that the fine-grained facies have a tendency toward abundant and sometimes diverse types of early diagenetic products of which pyrite and iron-rich carbonates, particularly siderite, are the most abundant.

Geotechnical Properties

Results of DPCP tests conducted at the Lumcon facility near Boring 1 are shown in Figure 3. Data are displayed as profiles of tip resistance, friction and friction ratio. The geotechnical profiles indicate that Holocene sediments at the boring site can be subdivided into massive units of weak material separated by thin beds of substantially stronger material organized into numerous thin layers. The soil classification indicates the massive units are sandy clay, clayey sand, and clayey sand and silt. The thinner and more resistant units are classified as loose sand, sand, and dense or cemented sand. Similar units are found at the Boring 2 site and at the Laperouse site.

The coefficient of consolidation was determined from the cone profile data. A recommended value of 3.75 was taken as the value of T for a 60° cone that was used in this study. The value of R was taken as 2.2 cm. In Table 1, the coefficient of consolidation in horizontal direction are presented for both Lumcon and Laperouse sites. Table 1 also shows the sediment permeabilities.

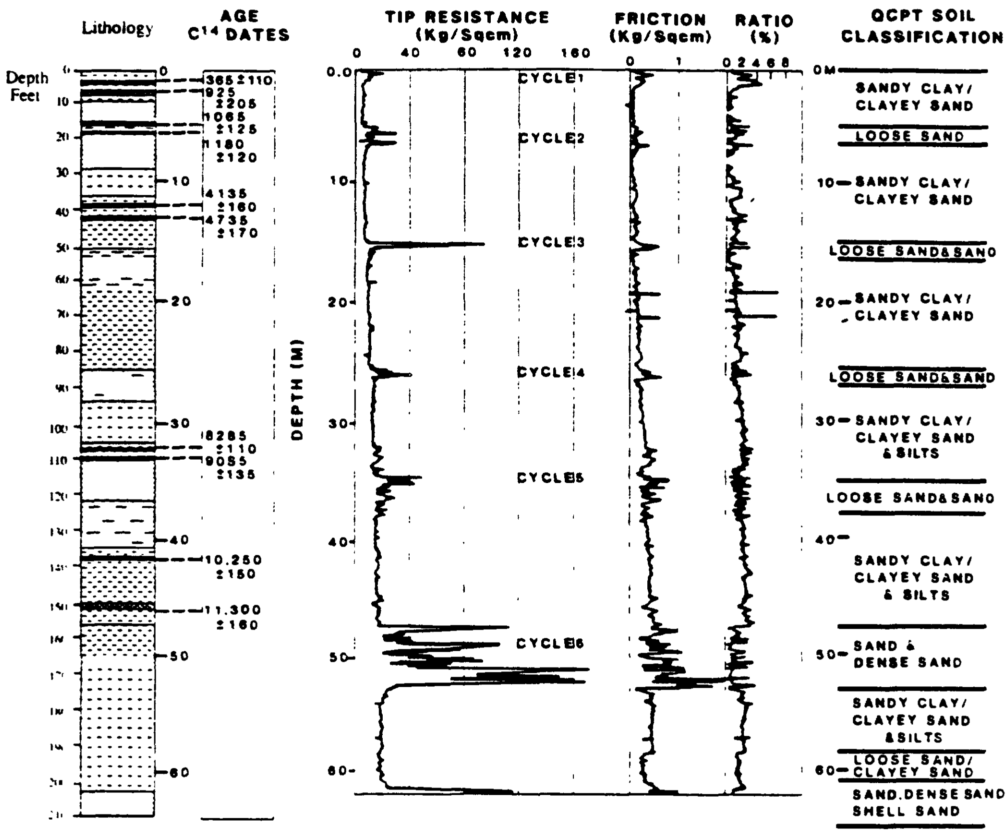

Figure 3. Lithology, radiocarbon dates, profiles of geotechnical data from cone penetrometer testing, and soils classification for the boring 1 site.

Table 1. Geotechnical Data.

Site	Depth (m)	Unit Weight (g/cc)	Void Ratio	Coefficient of Consolidation (cm^2/s)	Permeability (cm/s)
Lumcon	11.0	1.42	1.55	.001210	4.47×10^{-8}
	18.7	1.62	1.47	.000104	2.52×10^{-9}
Laperouse	5.4	1.53	1.95	.000165	4.84×10^{-10}
	12.1	1.72	1.34	.0000403	8.38×10^{-10}
	17.3	1.67	2.08	.000130	6.52×10^{-10}

Pore pressure dissipation test results indicated the time decay of the pore water pressure after penetration had been stopped. Excess pore pressure was determined by subtracting the hydrostatic pressure from the estimated static pore pressure. Excess pore pressures are found at the middle of each clay layer. Once the excess pore pressure at the middle of each clay layer is known, an estimation of excess pore pressure at various intervals within that particular clay layer can be calculated using a linear interpolation to zero excess pressure at the top and base of a bed. The values of these excess pore pressures for all the clay layers from both the test sites ranged from 0.2 to 2 kg/cm^2.

Laboratory consolidation test data indicate that the laboratory results are about 1% of the cone results. The effect of cementation was examined by artificially cementing clays and repeating the consolidation test. The effect of the cements is to introduce a preconsolidation stress condition, which reduces the coefficient of consolidation up to this stress level. After the pre-consolidation stress is exceeded the cemented sediment displays a much larger coefficient of consolidation than the uncemented sediment.

Geochemical Properties

Important pore water parameters are chloride and dissolved Fe. Chloride concentrations range from 655 to 4,643 mg/l for P2, and from 215 to 13,440 mg/l for P1. They generally decrease with depth (Figure 4a).

Dissolved Fe ranges from 0 to 47.7 mg/l for P2 and from 0 to 2.7 mg/l for P1. There is a general vertical concentration pattern in each boring of low

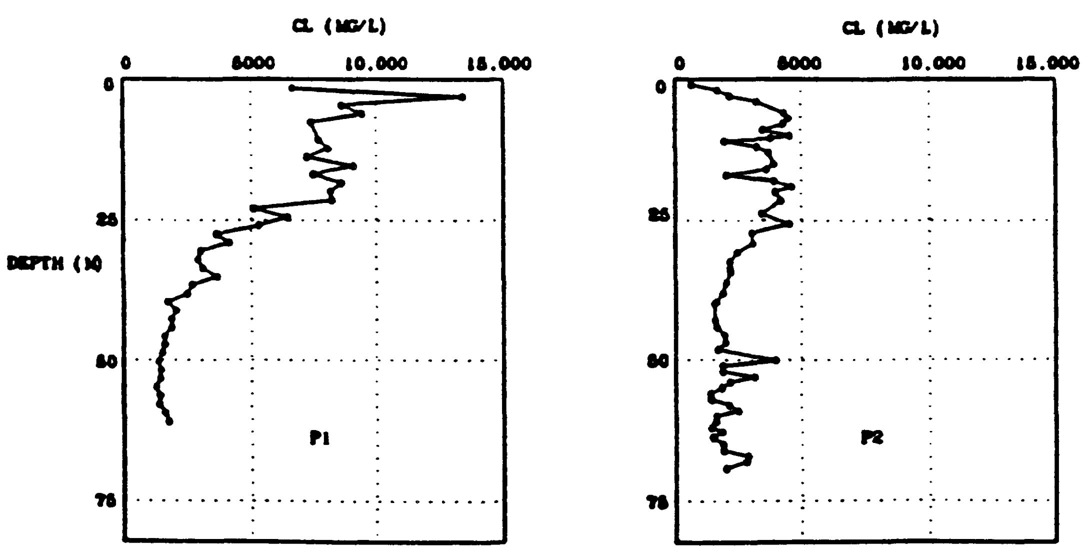

Figure 4a. Chloride concentration profiles for boring sites P1 and P2.

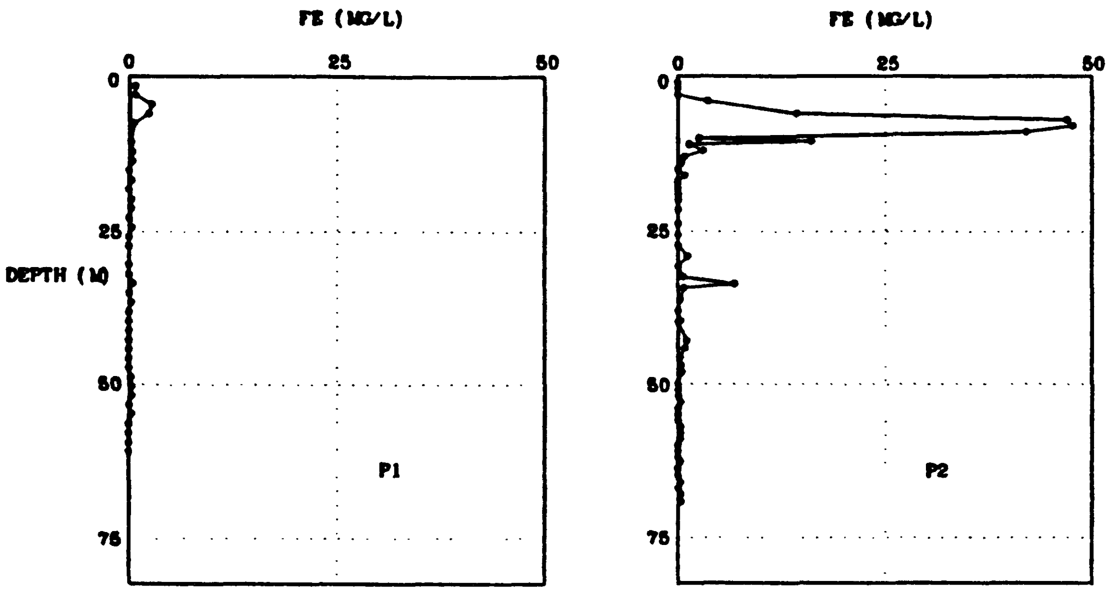

Figure 4b. Dissolved Fe concentration profiles for boring sites P1 and P2.

values at the surface, followed by relatively high values. Below depths of a few meters, dissolved Fe values are again very low (Figure 4b).

Inclusion data consist of micrographs of thin sections and X-ray diffraction patterns. Diffraction patterns are shown in Figure 5. The dominant mineral is impure siderite, but pyrite is also fairly common. Siderite occurs as cement filling interstices between elastic grains, while pyrite occurs as disseminated grains and framboidal aggregates associated with rootlets and organic fragments distributed throughout the detrital muds.

Implications of Results

Coastal subsidence is mainly due to the consolidation of certain underconsolidated clay deposits and the consolidation process can be documented geotechnically with the help of in-situ soil testing. The land subsidence rates differ from place to place and these rates mainly depend on the magnitudes of excess pore pressures as well as to the soil deformation characteristics such as consolidation and permeability. Excess pore pressures within a clay layer are a function of the overburden pressure as can be seen from the excess pore pressure results of Laperouse site, where the increase in excess pore pressure can be noticed clearly from layer 1 to layer 2 to layer 3 (Figure 3). At the same time, excess pore pressures at Lumcon site decreased from layer 1 to layer 2. This result is related to the difference in the soil properties between the two layers.

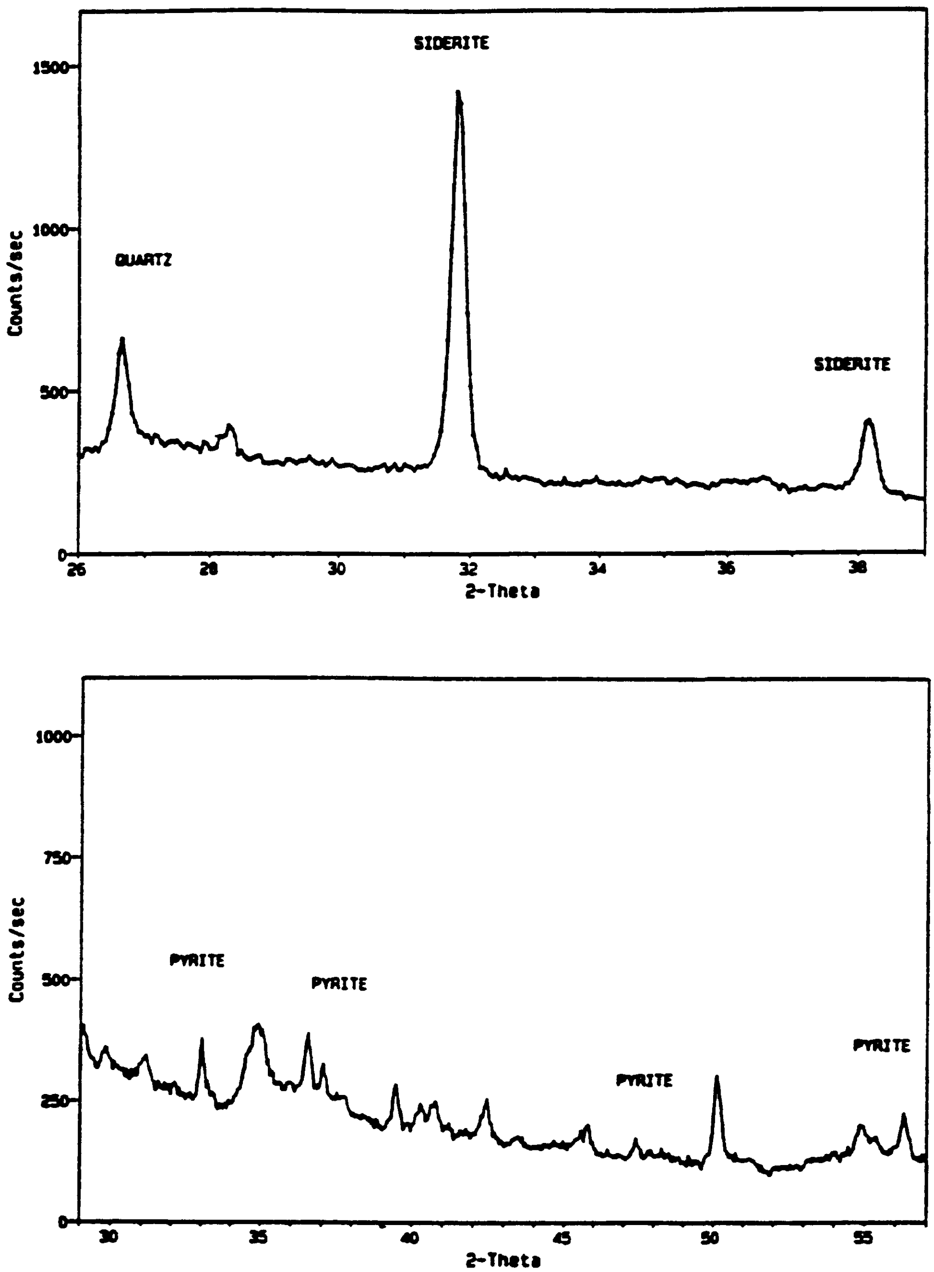

Figure 5. X-ray diffraction patterns of diagenetic inclusions from boring P2.

These excess pore pressures also depend on the soil properties such as its classification and consolidation characteristics, permeability, and void ratio.

The field determined consolidation coefficients are two orders of magnitude higher than the laboratory determined ones. The reason for this discrepancy is attributed mainly to the difference in the testing conditions. In the field, the sample would be tested under the actual soil conditions such as its fabric, soil anisotropy, soil sensitivity, etc.

Discussion

The geochemical data suggest that chemical variations affect recent coastal subsidence and physical properties of the sediment. They therefore play a role in subsidence. Increased chloride concentrations towards the tops of both borings may reflect marine incursion related to subsidence. Higher concentrations in P1 than P2 indicate greater marine influence in the southerly boring, a trend to be expected.

With respect to mechanical properties, changing salinities of pore water in contact with abundant smectitic clays in the sediment may change properties of the clays through exchange of Na^{+1} for Ca^{+2}. The material may be rendered more expansive and less permeable and this may affect excess pore pressure.

Vertical variation of dissolved Fe reflects early solubilization of ferric hydroxides in the sediment as they are subjected to reducing conditions, followed by precipitation as carbonates and sulfides at depths of a few meters and greater.

Examination of thin sections verifies the presence of siderite and pyrite. As a factor in stress-strain relationships, a role for these cements in subsidence is strongly indicated. X-ray diffraction verifies the presence of these minerals.

Acknowledgment

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Salinity Variations in Two Louisiana Estuaries

Wm. J. Wiseman, Jr.[1] and Masamichi Inoue[1]

Abstract

Salinity variations, on a variety of time scales, are described for two shallow bar-built estuaries of the Louisiana coast. Tidal, sub-tidal, and seasonal scale variations are important in both estuaries, but the response to similar forcing in these neighboring estuaries is significantly different because of the local morphology and site of major boundary salinity variation - the head of the estuary or the coastal ocean.

Introduction

Coastal Louisiana is losing land at a rapid rate (Gosselink, 1984). While decreasing in recent years (R. E. Turner, personal Communication), the rate of land loss is still the highest in the United States. The processes suggested as being responsible for this loss are many. Some, such as canal building, fluid withdrawal from the underlying sediments, and levee building, are man-induced. Others, such as consolidation of the sediments, wave-induced erosion, and sea level rise, are natural. One natural phenomenon suggested to be responsible for land loss is salt water intrusion. It is argued that, as it intrudes into the estuaries, salt water stresses the marsh plants. As these plants die, their root systems are no longer available to protect the unconsolidated marsh sediments from the erosive action of waves and currents. The data to be presented in this paper were collected as part of a larger program designed to study the natural processes responsible for land loss in the Mississippi

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[1]Coastal Studies Institute and Department of Oceanography and Coastal Sciences, Louisiana State University, Baton Rouge, LA 70803

River Delta Plain region of coastal Louisiana. These data are meant to define the processes controlling the variability of salinity in the coastal marshes of the region.

Two estuaries were sampled: Terrebonne Bay and Four League Bay (Figure 1a). The former is a broad shallow estuary forming the western half of a larger complex which includes Timbalier Bay. Depths are typically less than 2.25 m except in a dredged ship channel where depths may exceed 5 m. The system resulted from subsidence, erosion and reworking of sediments from the old LaFourche Delta lobe of the Mississippi River (Penland, 1990). Monthly excess precipitation over the catchment basin is small, generally less than 0.05 m (Prager, 1992). Much of this occurs in short-lived events. Sediment supply to the estuary is also small. Terrebonne Bay connects to the Gulf of Mexico through Cat Island Pass and Whiskey Pass. It also has connection to Timbalier Bay which is connected to the Gulf through Little Pass Timbalier.

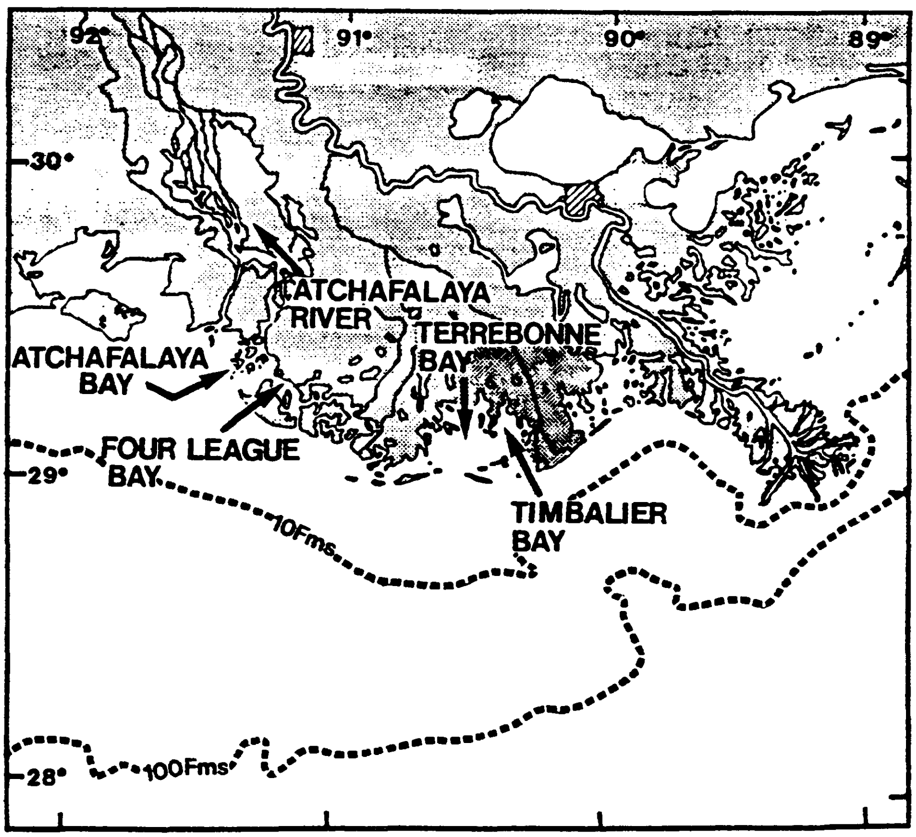


Figure 1a. Location map of study sites.

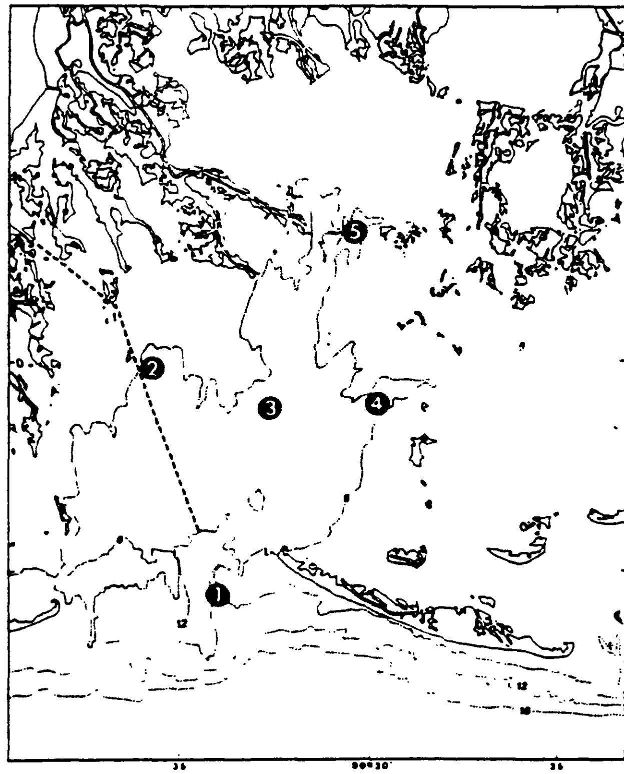


Figure 1b. Chart of Terrebonne Bay study site. Numbered dots indicate mooring locations. Dashed line is location of dredged ship channel. (Depth contours in feet.)

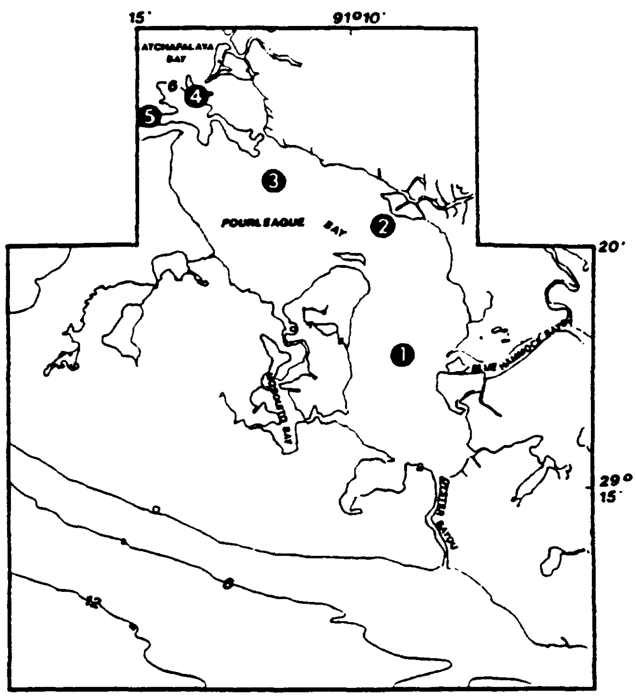


Figure 1c. Chart of Four League Bay study site. Numbered dots indicate mooring locations. (Depth contours in feet.)

Four League Bay is a smaller bay immediately west of Terrebonne Bay. It is the easternmost bay in the Vermillion-Cote Blanche-Atchafalaya Bay system, which has developed over the site of the former Sale-Cypremort lobe of the Mississippi Delta (Kolb and Van Lopik, 1958). The estuary connects to Atchafalaya Bay at its northern end and to the Gulf of Mexico through the narrow Oyster Bayou at its southern end. It also connects to marshes further east through a variety of small bayous of which Blue Hammock Bayou is the most important. Depths are generally less than 2 m within the bay. While direct discharge of fresh water and sediment to the bay is small, during certain times of the year the Atchafalaya discharge flows through the bay and provides a significant source of both fresh water and sediment.

The dominant oceanographic feature of the inner shelf in this region is the Louisiana Coastal Current (Wiseman et al., 1986). This low salinity current is separated from the mid-shelf water by a strong haline front. It carries much of the fresh water discharged by the Mississippi River westward along the coast in front of the tidal passes connecting the local estuaries with the Gulf of Mexico. Tides in the region are small (ranges less than 60 cm) and diurnal (Marmer, 1954). Winds are dominated by the Bermuda High Pressure System. In summer gentle southeasterly breezes, with dominant time scales of a few weeks, are characteristic. Strong diurnal sea breeze systems develop along the coast. Occasional squalls, thunderstorms, tropical storms, and hurricanes interrupt the less energetic system of winds. Winter is a period of cold air outbreaks with brief, but strong, events during which cold, dry air blows intensely from the north. These events are interspersed with periods of southerly return flow of warm, moist air. The characteristic time scales involved are three to ten days (DiMego et al., 1976).

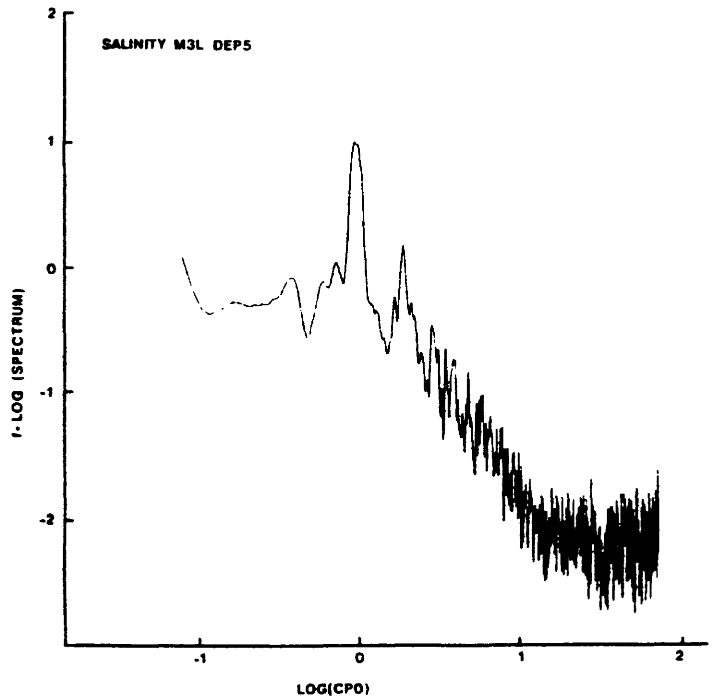
Examination of long term salinity records from the estuaries of coastal Louisiana has failed to determine the existence of a consistent, coast-wide, long-term salinity trend (Wiseman et al., 1990a). Statistically significant trends, though, exist in the records from individual stations. Furthermore, in many estuaries, the salinity variability at time scales of a few months and longer are well represented by an auto-regressive moving-average (ARMA) model which depends on lagged Mississippi River discharge, even though the Mississippi River does not discharge directly into the estuaries in question. The dependency of the estuarine salinities on Mississippi River discharge is assumed to result from the Mississippi's control of the salinity of the Louisiana Coastal Current whose waters exchange with those of the local estuaries (Wiseman et al., 1990b). The ARMA models are purely statistical and their coefficients have not been directly related to a simple physical phenomenon. Hence, the present study was designed to better delineate the physical processes responsible for the salinity variability within the coastal estuaries of the Mississippi River Delta Plain.

Data Collection and Processing

Data were collected from five sites in Terrebonne Bay (Figure 1b). Most sites were occupied from early 1990 until the end of the year. The record from one site extended into early 1991. All records were not of equal quality. There were breaks in the data due to instrument failure and damage due to local ship traffic. At the mid-bay site in Terrebonne Bay, site 3, two current meters were located roughly 0.5 m above the bottom and 1 m above the bottom in 2 m of water. Although some stratification was observed, the bottom salinity record was generally representative of this station. All other sites involved a single meter at mid-depth in roughly 2 m of water. Five other sites were occupied within Four League Bay from early 1991 until summer 1992 (Figure 1c). All measurement sites in Four League Bay involved a single meter at mid-depth in waters generally less than 2 m deep.

The instruments used in this study were Endeco 174 current meters. They recorded average current speed and instantaneous current direction as well as temperature and conductivity, which were later converted to salinity. The conductivity sensors were calibrated before and after each instrument deployment. Instruments were serviced every 6 to 8 weeks. The conductivity cutoff was 5 millimhos per centimeter, so we were unable to record the very lowest salinities which actually occurred within Four League Bay. Wind records were acquired from the NOAA C-MAN site at Grand Isle, LA.

Both raw data records and forty-hour low-passed versions were analyzed. This filtering was accomplished by fast Fourier transforming the data and setting all coefficients at unwanted frequencies to zero and inverse transforming the data. Gaps between low-passed records were filled by linear interpolation to create longer records. Principal axes of the currents were computed both with and without inclusion of the tidal components. Spectra were estimated using the fast Fourier transform and smoothing in the frequency domain. Coherence between various time series was estimated in a similar fashion.



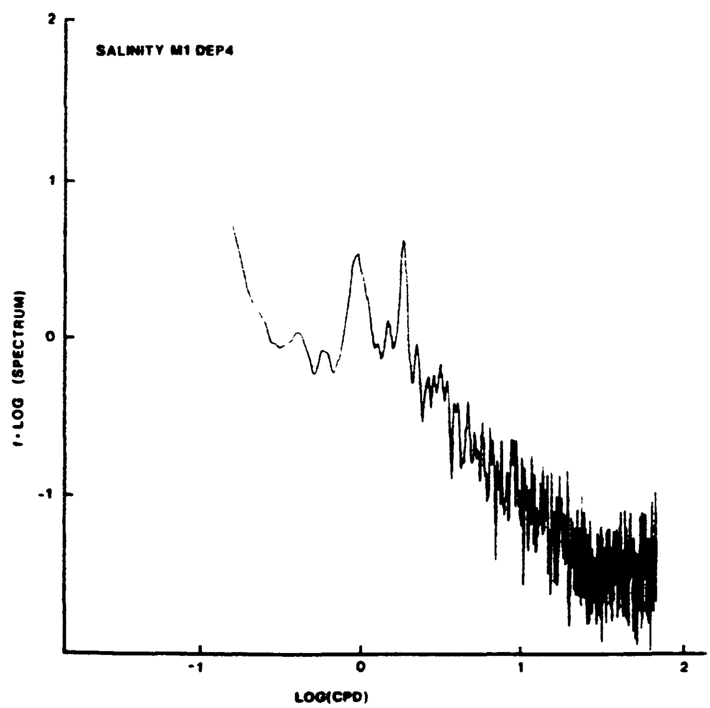


Figure 2. Upper: Salinity spectrum for a 77-day record from mid-Terrebonne Bay (site 3). Lower: Salinity spectrum for a 46-day record from lower Four League Bay (Site 1). Spectra were estimated by smoothing the periodogram with an 11-point triangular running filter.

Results and Discussion

The scales of variability recorded in the time series are best seen in the salinity spectra (Figure 2). Both sites are strongly dominated by the diurnal tidal signal, but a significant semi-diurnal signal is also present. The semi-diurnal signal is stronger at the Four League Bay site than at the Terrebonne Bay site. It is not clear whether this increased amplitude of the semi-diurnal signal is due to overtides or to the broader continental shelf offshore of the Atchafalaya River Delta. Both sites also exhibit increased variance levels within the weather band. Current spectra exhibit similar spectra.

The principle axes of the currents are consistent from record to record at both sites. They also indicate strong association with the bathymetry. The principal axes of the forty-hour low-passed currents, though, while nearly parallel to those of the higher frequency currents in Four League Bay, show significant variability in direction from deployment to deployment within Terrebonne Bay.

The importance of the tidal frequencies in both estuaries is indicative of their small size with respect to the tidal excursion. A characteristic tidal current amplitude of 0.2 m/s for the diurnal tide corresponds to a tidal excursion of 6 km, a significant fraction of the total length of either bay. Advection of salinity gradients past the measurement sensors by these currents results in strong tidal signals in the salinity records.

A number of different processes contribute to the importance of the weather band frequencies in the two bays. Ekman set-up and set-down at the coast will force water exchange between the bays and adjacent water bodies. Both bays communicate directly with the Gulf of Mexico, but both also communicate with the Gulf through adjacent bays: Timbalier Bay in the case of Terrebonne Bay and Atchafalaya Bay in the case of Four League Bay. Thus the path that exchange will take in response to a given wind stress is not intuitively obvious. Both bays are shallow and frictionally driven flows within the bays may be important. Indeed, the highly variable direction of the forty-hour low-passed currents within the open regions of Terrebonne Bay are coherent with the wind.

Coherence between processes was variable from site to site within Terrebonne Bay. Salinity was coherent with the eastward currents and water level at site 4 at very low frequencies and at frequencies of roughly 0.2 cpd. At site 2, though, the salinity was coherent with the northerly

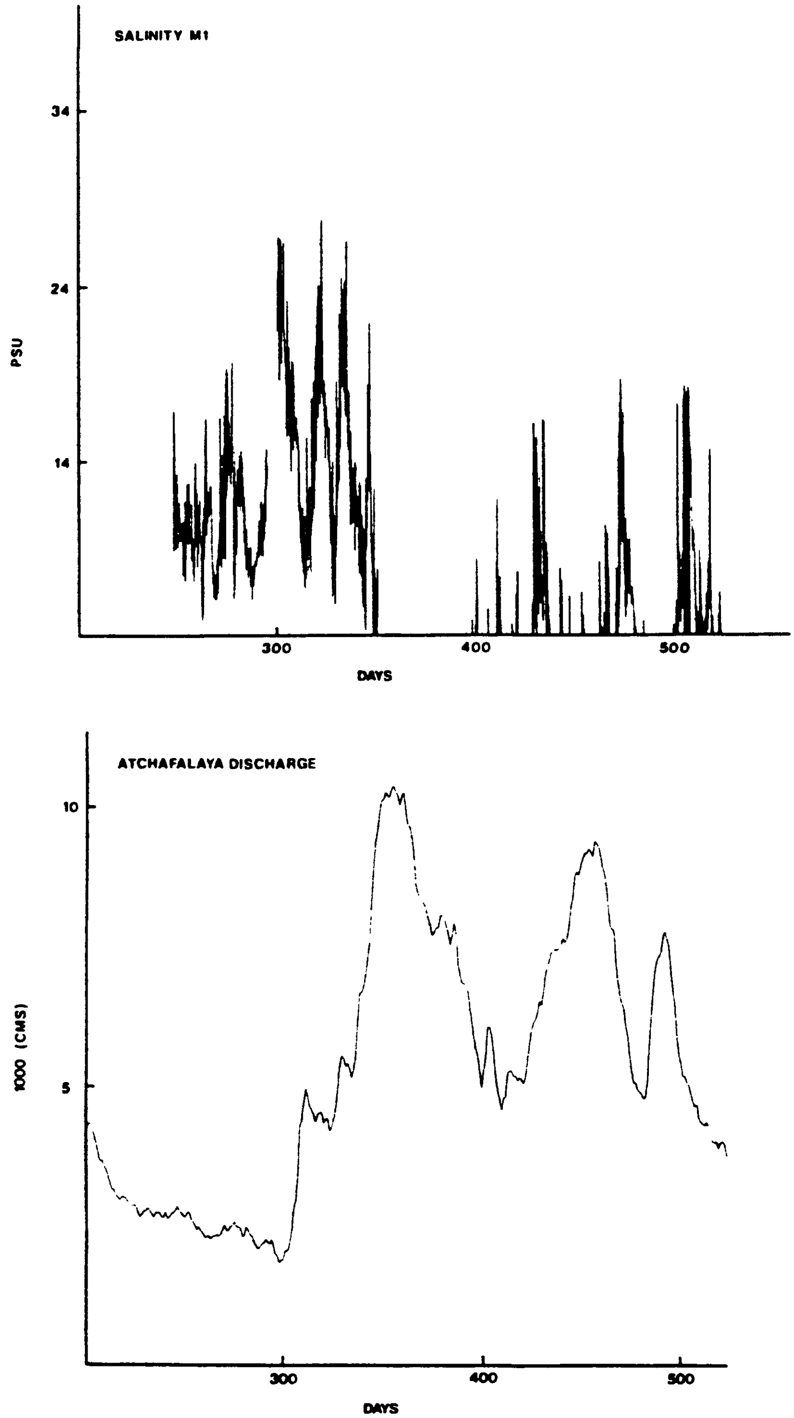


Figure 3. Upper: Salinity time series from lower Four League Bay (site 1). Lower: Time series of Atchafalaya River discharge at Simmsport, LA. The time origin (day 0) for these plots is 1 January 1991.

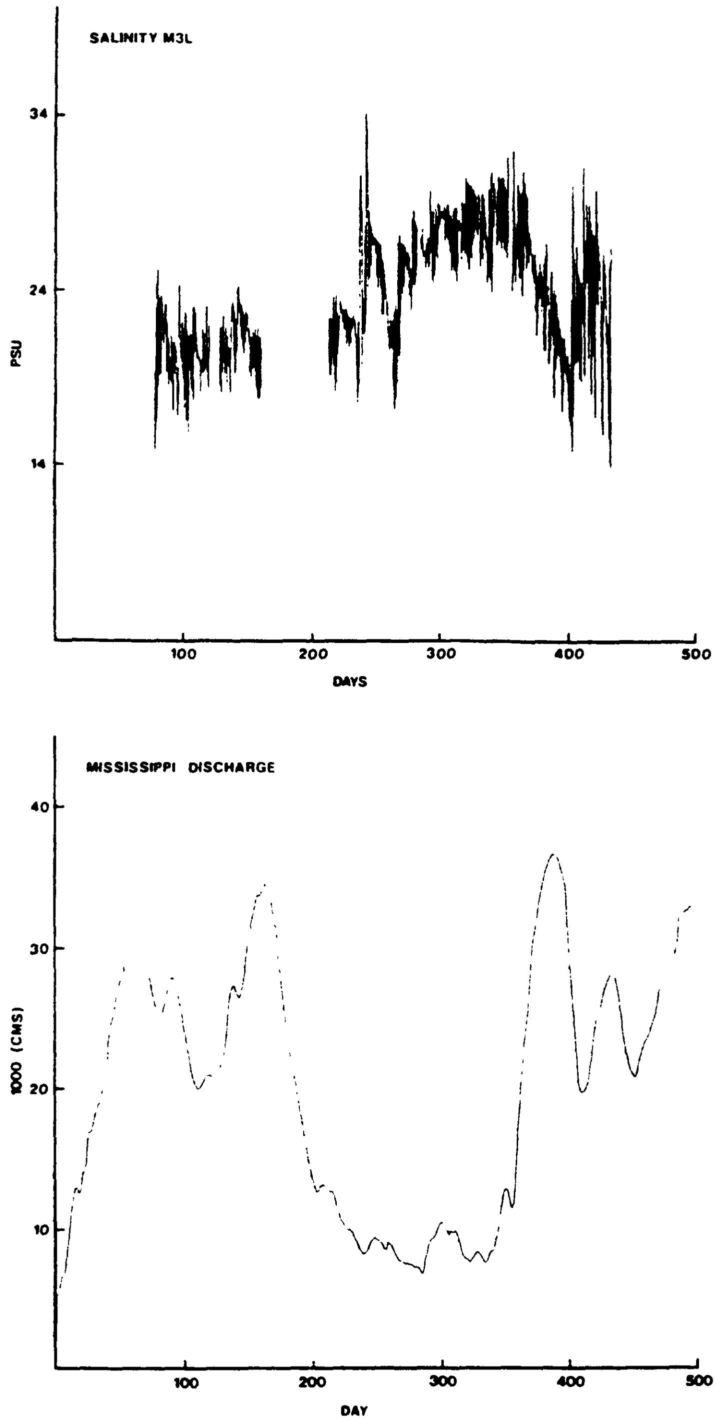


Figure 4. Upper: Salinity time series from mid-Terrebonne Bay (site 3). Lower: Time series of Mississippi River discharge at Tarbert Landing, LA. The time origin (day 0) for these plots is 1 January 1990.

currents at 0.2 cpd, probably reflecting proximity of the site to both a dredged ship channel and the western edge of the bay.

Within Four League Bay, the response of the salinity to winds is somewhat different. Under conditions of low flow from the Atchafalaya River, the river plume is forced by the wind stress. Under typical winds from the east, the plume is pushed away from the head of Four League Bay. Under winds from the west, the plume is pushed towards the head of the bay. If the winds then swing around to blow from the north or northwest, fresh water is blown down the bay. Furthermore, northerly or westerly winds will cause a coastal set-down and the resultant sea surface slope will accelerate the flow of water from the head of the bay towards Oyster Bayou. Three large oscillations of salinity are seen within Four League Bay towards the end of 1991 (Figure 3). The associated winds follow the scenario outlined above and the coherence between wind stress, current and salinity is significant at frequencies below approximately 0.2 cpd.

At the lowest frequencies observed, the salinity signal in Terrebonne Bay appears correlated with Mississippi River discharge (Figure 4). The highest salinities are associated with what we believe is an intrusion of shelf water associated with a breakdown of the LCC. Following this event, the high salinity water was gradually flushed from the bay by tidal and wind-driven exchange processes. The high salinities observed for roughly 100 days at the end of 1990 are associated with a period of low discharge from day 200 to day 365. A rapid rise in discharge at the beginning of 1991 (day 366 to day 400) is followed within approximately one month by a drop in salinity. As the runoff decreases, though, the salinity begins to increase. The lag between discharge and bay salinity reflects the time required by the fresh water to flow from the gauging station to the mouth of the river, to flow along the coast to the tidal passes entering the estuary and to disperse into the estuary.

Since the waters of the Louisiana Coastal Current are those which exchange with the estuarine waters, any process which alters the salinity of the coastal waters will be very important in determining the salinity of the adjacent estuaries, particularly those estuaries which receive little local runoff, such as Terrebonne Bay. Upwelling, mixing, and mesoscale eddies are three such processes. Vertical mixing is important under strong wind conditions such as might be found during cold-air outbreaks (Huh et al., 1984) or hurricane conditions (Forristall et al., 1977). Upwelling along the inside edge of the LCC has been observed (Dagg, 1988). The process is presumably very similar to upwelling onshore of the coastal jet as seen in the Great Lakes (Csanady, 1972). Mesoscale eddies have been seen on satellite images of the Louisiana shelf and concurrent velocity measurements appear to confirm that they can reverse the flow of the LCC (A. C. Vastano, personal communication). Such events may contribute to the aperiodic intrusions of high salinity water observed in Terrebonne Bay.

Flow from the Atchafalaya River, as mentioned above, is easily pushed to the head of Four League Bay by westerly winds. This situation occurs under low flow conditions. Under discharges in excess of approximately 10,000 cms, we did not observe any salt within Four League Bay. Presumably, the discharge from the Atchafalaya River filled the upper Atchafalaya Bay and flowed into Four League Bay, flushing salt from the latter.

Thus, as in most coastal plain estuaries, salinity variability in Four League Bay is dominated by the inflow of fresh water at the upstream end (that which connects to Atchafalaya Bay) and modified by tidal and sub-tidal, wind-driven exchanges with the coastal ocean. In those estuaries without any significant runoff entering their upstream end, tidal and sub-tidal exchange with the coastal ocean are still important sources of salinity variability, as are those processes which alter the coastal ocean salinity at the mouth of the estuary. These latter processes, as well as those occurring within the weather band, are stochastic. Thus, a simple, meaningful, deterministic model of low-frequency salinity variations in such estuaries may still be many years in the future.

Acknowledgements

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Jump Starting the Atchafalaya Delta: A Management Plan to Reinstate Delta Growth

Ivor L. van Heerden[1]

ABSTRACT

Sediment delivery to the Atchafalaya delta averages 61,000,000 tons every year. The subaqueous phase of delta growth was initiated in 1962, and the delta became a subaerial feature in 1973. Initial subaerial growth amounted to 1177 acres per year, but since the late 1970's, the growth rate has dramatically diminished to 253 acres per year. Volumetric calculations and comparisons to the Atchafalaya's sister delta, the Wax Lake delta, reveal that the growth rate of the Atchafalaya should be 1593 acres per year.

Lack of delta development reflects that the Atchafalaya delta is bisected by a navigation channel. This channel is maintained at a depth deeper than would exist in totally natural conditions and is bounded almost continuously down its west bank by high dredge spoil piles and, to a lesser extent, by spoil deposits along its east bank. The consequence of this configuration is that the channel is a very efficient conduit for river sediment to the Gulf of Mexico. Additionally, placement of dredge material in the eastern half of the delta has aided in the shut down of the natural distributary system.

A long term management plan has not been formulated for the delta. However, restoration/creation projects to be funded by the Coastal Wetlands Planning, Protection, and Restoration Act (CWPPRA) as well as beneficial use of dredge material by the Corps of Engineers should see a dramatic increase in delta growth in the short term. The projects are designed to simulate the natural environment.

The CWPPRA projects relate to distributary channel development. One project entails reopening distributary channels using a spray disposal dredge, while the other, more ambitious project calls for creation of a distributary channel through a large spoil pile. The beneficial use of dredge material projects will result in the creation of crescentic shaped delta lobes.

The above combination of projects should stimulate natural delta growth, and estimates are for the 1993-1996 period, subaerial delta growth should exceed 920 acres per year, a 350 percent increase over the present rate.

[1] Center for Coastal, Energy, and Environmental Resources, Louisiana State University, Baton Rouge, LA 70803

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