SEDIMENTATION IN FLUVIAL-DELTAIC WETLANDS AND ESTUARINE AREAS TEXAS GULF COAST

SUMMARY

by

William A. White and Thomas R. Calnan

Prepared for

Texas Parks and Wildlife Department
Resource Protection Division
In accordance with Interagency Contracts (88-89) 820 and 1423

Bureau of Economic Geology
W. L. Fisher, Director
The University of Texas at Austin
Austin, Texas 78713

1990

QAe7625

FIGURES

CONTENTS

TABLES

SEDIMENTATION IN FLUVIAL-DELTAIC WETLANDS AND ESTUARINE AREAS TEXAS GULF COAST

SUMMARY

INTRODUCTION

Deltaic and associated riverine deposits near the mouths of rivers that discharge into estuaries along the Texas coast are the sites of extensive salt-, brackish-, and fresh-water marshes that are essential components of biologically productive estuarine systems. These bay-head depositional features are constructed primarily by fluvial sediments, sediments transported and deposited by the major rivers that enter estuarine waters. The loss of over 10,000 acres of wetlands in alluvial and deltaic areas of the Neches (White and others, 1987) and San Jacinto Rivers (White and others, 1985) emphasized the need to examine in more detail the processes that establish and maintain, as well as degrade, these important natural resources along the Texas coast.

Background and Scope of Study

This summary is derived from (1) a literature synthesis report (White and Calnan, 1990a) and (2) a field and historical investigation (White and Calnan, 1990b) that focus on fluvial-deltaic and estuarine sedimentation, and associated interactive processes along the Texas Gulf Coast. These studies were funded by the Texas Parks and Wildlife Department and Texas Water Development Board with funds allocated by the Texas Legislature for comprehensive studies of the effects of freshwater inflows on the bays and estuaries of Texas.[1]

Most of the Texas freshwater inflow studies, past and ongoing, have focused on inundation, cycling and exchange of nutrients, salinity patterns, and fisheries production (TDWR, 1982). A significant part of the past research effort has dealt with the need to inundate deltaic wetlands (through freshwater inflows) in order to export nutrients into the estuarine system. Although habitat maintenance was one of the objectives of the investigations, little emphasis was placed on the geological processes that play a critical role in the construction of the deltaic and alluvial systems on which the biologically productive wetlands develop.

Among the objectives of this study was to focus on the sedimentary and associated interactive processes that develop, maintain, and/or degrade the environments. Information is provided on the present and historical role of fluvial sediments--sediments carried by rivers--in developing and maintaining estuarine habitats, with emphasis on wetlands. Interactive processes that are presented include: subsidence (both natural and human-induced), sea-level rise, riverine discharge and associated

---

1 **In response to House Bill 2 (1985) and Senate Bill 683 (1987), as enacted by the Texas Legislature, the Texas Parks and Wildlife Department and the Texas Water Development Board must maintain a continuous data collection and analytical study program on the effects of and needs for freshwater inflow to the State's bays and estuaries. As part of the mandated study program, this research project was funded through the Board's Water Research and Planning Fund, Authorized under Texas Water Code Sections 15.402 and 16.058 (e), and administered by the Department under interagency cooperative contracts No. IAC (86-87)1590, IAC(88-89)0821, and IAC(88-89)1457.**

sediment loads, fluvial-deltaic-wetland sedimentation, bay-estuary-lagoon sedimentation, and biodeposition.

FLUVIAL (RIVERINE) SEDIMENTS IN THE ESTUARINE SYSTEM

Deposition of sediments along the coastal river valleys and at the river mouths has produced extensive fluvial-deltaic deposits (Fig. 1) on which marshes and other wetlands have developed. The primary sources of sediments delivered to the estuaries and associated deltas are the rivers that cross the coastal plain. Sediments delivered to the marshlands not only provide a source of nutrients for sustained plant growth, but they also provide an inorganic foundation necessary to maintain the substrate above a rising sea level. The submergence of more than 10,000 acres of fluvial-deltaic wetlands between the mid-1950's and the late-1970's in two areas along the Texas coast (see Fig. 2 for one of the areas) signifies that sediments in these areas are not accumulating at rates sufficient to keep pace with relative sea-level rise. A similar conclusion has been reached in Louisiana where wetlands are being lost at a dramatic rate on the Mississippi River delta. In fact, land-loss rates have accelerated geometrically during the 20th century, largely as a result of natural factors, of harnessing the Mississippi River deltaic-sedimentation processes, and of accelerated subsidence (natural and possibly human induced) (Gagliano and others, 1981; Boesch and others, 1983; Wells and Coleman, 1987). Results of several investigations on Louisiana marshes indicate that marsh sedimentation (vertical accretion) rates are not keeping pace with relative sea-level rise.

The delivery of fluvial sediments to the bay-estuary-lagoon systems has been a process operating through much of recent geologic past, and of course continues today. Of the total volume of sediments that settle in Texas coastal estuaries, it is estimated that 75 to 90 percent are from fluvial, or riverine, sources. Much smaller volumes are contributed from shoreline erosion and from the Gulf of Mexico. The most extensive look at the accumulation of sediments in the bays and estuaries of Texas was done by Shepard (1953); the most thorough investigation of a single bay system (Lavaca Bay) was accomplished by Wilkinson and Byrne (1977). In general, Shepard (1953) concluded, on the basis of bathymetric surveys made in the latter half of 1800's and mid-1930's, that Texas bays and estuaries were shoaling (becoming shallower) at an average rate of 3.8 mm/yr (0.15 in/yr).[2] The highest rates of shoaling occurred at the heads of bays where deposition of fluvial sediments was at a maximum. In bays located away from fluvial input, shoaling rates were much lower and in some areas deepening of the bay floors had occurred. Wilkinson and Byrne (1977) concluded that historical rates of sedimentation in Lavaca Bay are higher than rates over a geologic time frame (past 8,000 to 10,000 years) and suggested the higher historic rate may be related to land-use practices (cropland) in the drainage basin.

Much of the sediment carried by rivers discharging into bays and estuaries is deposited near river mouths forming deltas. Two rivers discharging into Texas estuaries have significantly extended their deltas since the mid-1800's, the Colorado and Trinity Rivers. The Colorado River delta has a unique history of very rapid progradation across the eastern arm of Matagorda Bay following the removal of a log raft upstream that had blocked sediment along the lower reaches of the river channel. Shepard (1953) estimated that the Trinity River had extended its delta about 0.3 mi since the mid-1800's. On the Guadalupe River delta a small subdelta has formed in Mission Lake as a result of the artificial diversion of river discharge and sediment load into the shallow lake.

---

2 Because rates of sedimentation are so small, it is more convenient and meaningful to present them in metric units. For reference purposes, 1 inch (in) equals 2.54 centimeters (cm) or 25.4 millimeters (mm); 1 foot equals approximately 30.5 cm; 10 cm, or 100 mm, equals about 4 in, and 10 mm about 0.4 in.

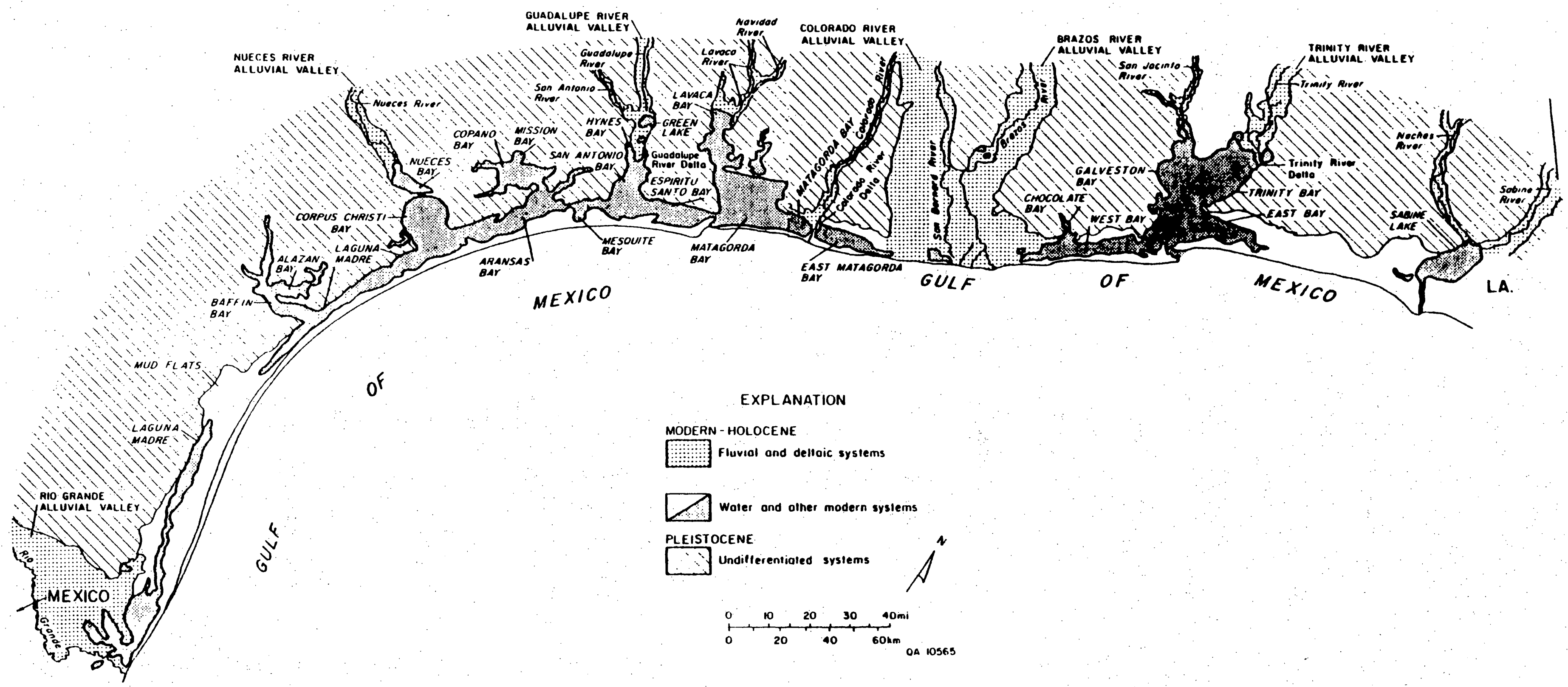
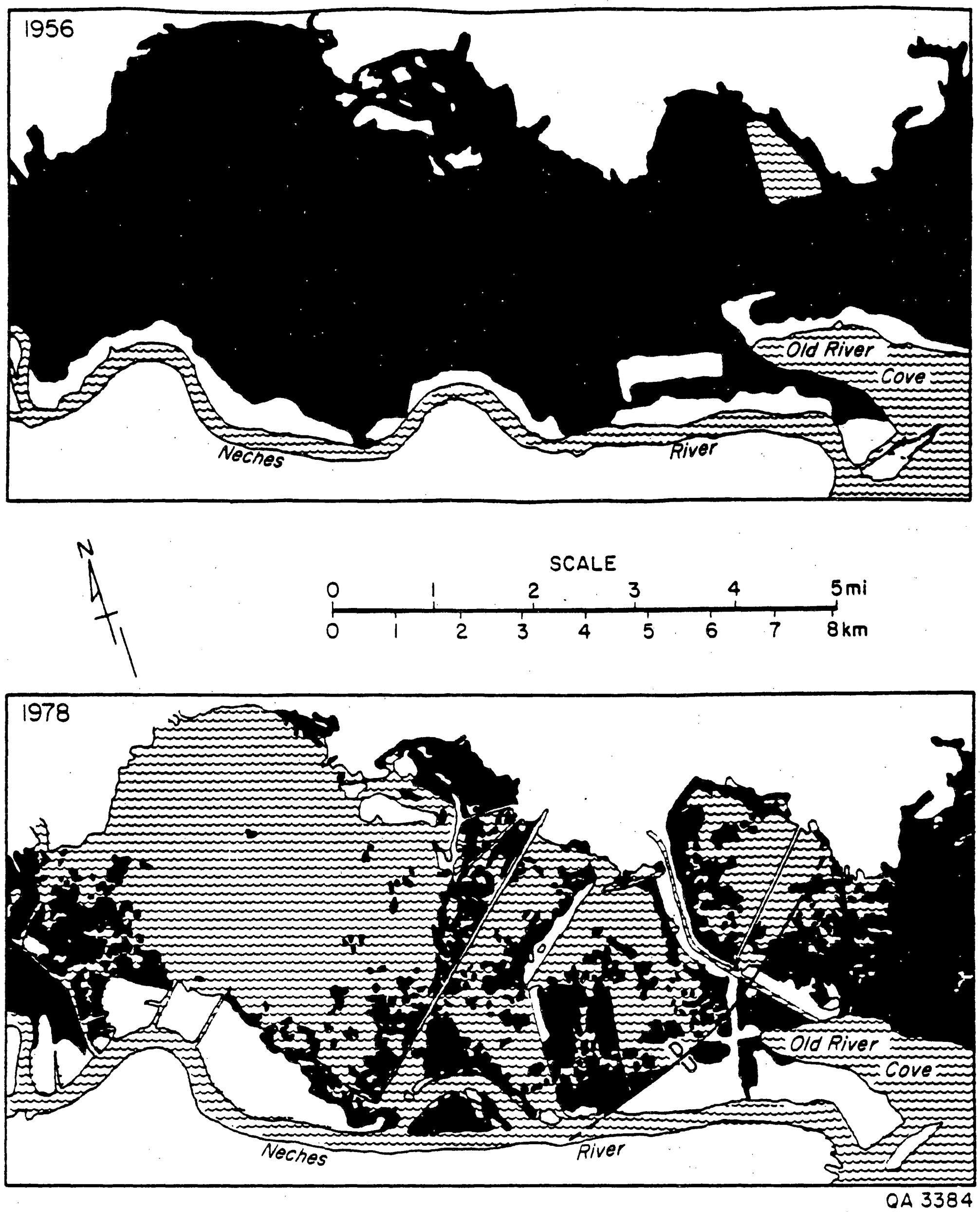


Figure 1. Bay-estuary-lagoon and major fluvial-deltaic systems along the Texas Gulf Coast. Fluvial-deltaic areas are located in stream valleys and near the mouths of the rivers, and are the sites of extensive wetlands. (Modified from LeBlanc and Hodgson, 1959.)



Map Unit	1956		1978		Net Change*	
	Acres	Hectares	Acres	Hectares	Acres	Hectares
Water	2,560	1,037	11,070	4,483	+8,510	+3,446
Marsh	15,740	6,375	6,330	2,564	−9,410	−3,811

* Loss of additional 900 acres (365 hectares) of marsh primarily due to spoil disposal.

Figure 2. Changes in the distribution of wetlands between 1956 and 1978 in the lower Neches River valley near the head of Sabine Lake. Loss of more than 9,000 acres of marshes was apparently caused by several interactive factors including a reduction of fluvial sediments delivered to the marsh, as well as subsidence, faulting, channelization, and disposal of dredged material along levees. (From White and others, 1987.)

Although other rivers have not significantly extended their deltas into their estuaries, they have filled the lower reaches of their valleys with sediments on which wetlands have developed. During each river flood event additional sediments are deposited on wetland surfaces, nourishing and sustaining plant growth, and maintaining wetland habitats that are essential to the overall biological productivity of the estuarine system.

Invertebrates that live on or in the sediments, and vegetation, such as marine grasses, help in the development and maintainence of a productive estuary. Biologically mediated sedimentation processes may be as important as the physical processes that lead to deposition of fine sediments. Smith and Frey (1985) have proposed that invertebrates which actively filter suspended particles from flood waters and bind and deposit the particles on the marsh surface, may be responsible for much of the net sedimentation in the marsh. Feces and pseudofeces of these invertebrates are important in stabilizing the sediment surface by forming large aggregates of silt and clay-size particles, providing the marsh with a means of retaining nitrogen, phosphorus, and trace elements, and organic materials. Many invertebrates, such as oysters, barnacles, tunicates, and copepods, ingest large quantities of small particles and after passage through the digestive tract, the particles are voided into the water as fecal pellets. Feces and pseudofeces that settle to the bottom are termed biodeposits. The entire complex process, involving many groups of animals and physical and chemical factors, is termed biodeposition. Invertebrates may produce large quantities of biodeposits. Lund (1957) calculated that if oysters covered 1 acre (0.405 hectares) of bottom, they would deposit 8.36 tons (7,584 kg) of fecal material (dry weight) or 6 tons (5,443 kg) of dry mineral matter in 11 days.

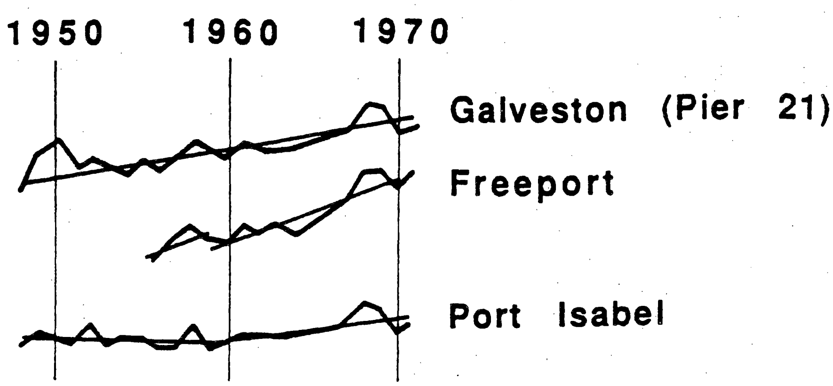
Vegetation also affects sedimentation. For example, marine grasses alter sedimentation processes by increasing sedimentation rates, by concentrating preferentially finer particle sizes, by increasing organic carbon in the sediments, and by stabilizing deposited sediments. Leaf and root structures effectively attenuate waves and baffle tidal currents, leading to increased deposition and consolidation of sediments and reduced resuspension. Ward and others (1984) estimated that sediment accumulated in seagrass beds at 2-3 mm/mo (0.08 to 0.12 inches/mo) over a 6-month growing season, thus increasing water clarity during the most productive part of the year. The efficiency of seagrasses in baffling the current flow and removing fine suspended particles depends primarily upon the leaf structure of the species and upon plant density (Burrell and Schubel, 1977).

SOME MAJOR PROCESSES AFFECTING ESTUARIES AND COASTAL WETLANDS

Relative Sea-level Rise

The bay-estuary-lagoon system is affected by many interacting physical processes including river flooding, waves and currents, tides, storms, subsidence, sea-level rise, and human activities. A major process is relative sea-level rise. Relative sea-level rise, as used here, refers to a rise in sea level with respect to the surface of the land, whether it is caused by actual sea-level rise or land-surface subsidence. Relative sea-level rise is generally composed of two components, a lesser component of eustatic (global) sea-level rise that is estimated to be about 1.2 mm/yr (2.3 mm/yr in Gulf of Mexico; Gornitz and others, 1982), and a more significant component of land-surface subsidence, which varies along the Texas coast from approximately 5 to 13 mm/yr (Fig. 3). Tide gauges are the principal method for determining changes in water levels, and gauges with the longest period of record provide the most reliable data. In Texas, the gauge with the longest continuous record is located at Galveston (Pier 21). The records from this gauge indicate an increase in the rate of water-level rise through time from 3.2 mm/yr for the period 1942 to 1962 to 11.5 mm/yr for the period 1962 and 1982 (Fig. 3). The long-term mean water-level rise is 6.2 mm/yr. Rates of relative-sea level rise are considerably higher than this in areas undergoing human-induced subsidence due to underground fluid withdrawal (ground water and oil and gas) such as in the Houston area. Subsidence rates in the area of maximum subsidence near Houston have exceeded 75 mm/yr.

A)



Location	Time period	Rate (mm/yr)
Sabine Pass	1960-1969	12.5
Galveston (Pier 21)	1959-1971	6.0
Galveston (PP)	1959-1970	8.6
Freeport	1959-1971	11.2
Port Aransas	1959-1969	12.8
Port Isabel	1959-1971	4.9

B)

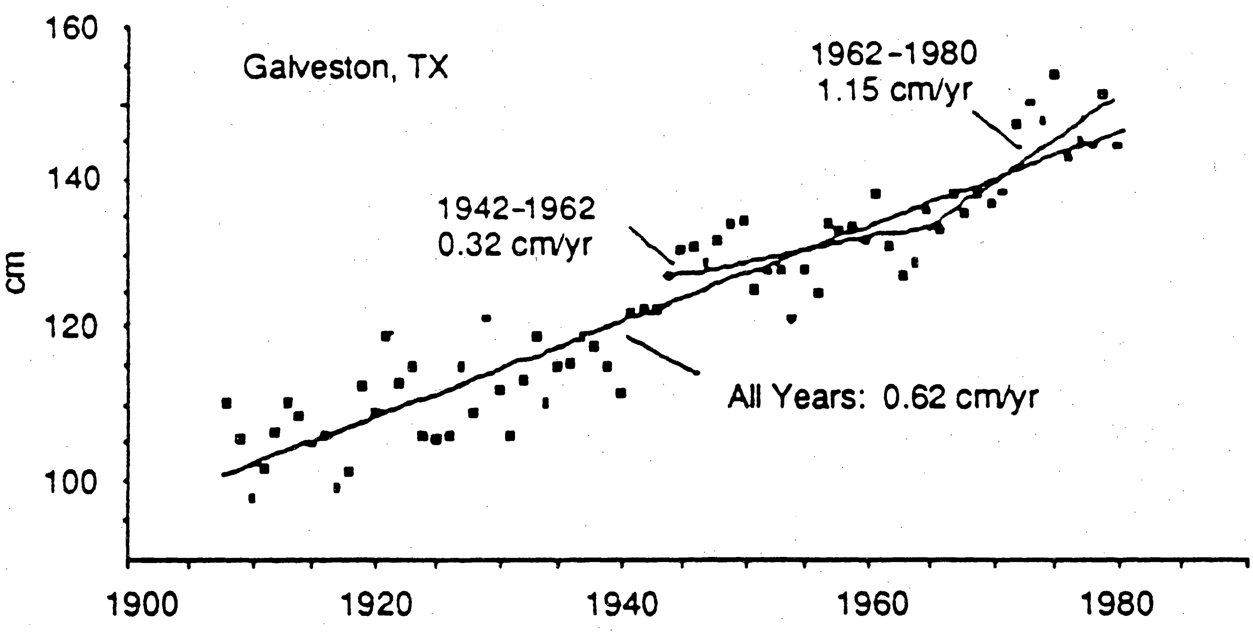


Figure 3. Subsidence and water-level changes at selected sites along the Texas coast based on tide-gauge records. (A) Estimated subsidence at various locations (from Swanson and Thurlow, 1973) (PP = Pleasure Pier). (B) Annual changes in water level at Galveston, with variations in rates of rise indicated for different periods (from Turner, 1987).

Sediment Load Delivered by Coastal Rivers

Another important process that can affect sedimentation in coastal wetlands and estuaries is river sediment load. Over the past 3 to 4 decades, there has been a marked decline in fluvial sediments delivered by many coastal rivers. Among the rivers are the Trinity (Fig. 4), San Jacinto, Brazos, Colorado (Figs. 5 and 6), and Nueces. The sediment loads of other rivers have also possibly diminished, but in many instances sediment-load measuring stations are not located close enough to the coast to adequately reflect the decline. Sediment load in several rivers, for which there is data, is less than half the previous load measured before the 1950's, and in some cases the load is less than 15 percent of previous amounts. Decreases in stream sediment load are related to different factors including implementation of soil conservation measures, which reduce the amount of sediment reaching rivers. But comparisons of reservoir development in the drainage basins with reductions in stream sediment load indicate reservoirs are probably the major factor (Fig. 7). Large reservoirs can trap from 95 to 100 percent of the sediment delivered to them, and reduction in peak flows below the dams decreases the ability of the stream to transport sediments accumulating downstream at the mouths of tributaries. The largest quantities of sediment are delivered to the estuaries during major flood events, which are controlled along streams with large reservoirs.

Channel degradation downstream from reservoirs can contribute sediment to estuarine areas, but the amounts are difficult to quantify becauses of numerous variables involved. Isphording (1986) reported an increase in sand and clay deposition in Apalachicola Bay, Florida, after reservoir development, but he also reported a striking reduction in silt. Silt, which had been previously supplied under natural conditions, was trapped along with sand by the reservoir. He suggested that clay was washed over the spillways and continued downstream to the bay, and he attributed increases in sand to channel erosion downstream from the reservoirs. Studies by Williams and Wolman (1984) of effects downstream from reservoirs generally indicate substantial decreases in average annual peak discharges with marked reductions in suspended sediment load for hundreds of kilometers downstream. In some major rivers, annual sediment loads did not equal pre-dam values for hundreds or thousands of kilometers. Degradation of channel beds generally occurred during the first decade or two after dam completion.

Other Processes Affecting Sedimentation near River Mouths

The environments at the mouths of many rivers along the Texas coast have been significantly modified through canal dredging and associated sediment disposal activities, and construction of dikes and artificial levees. These modifications have altered the hydrologic regime and sediment dispersal pathways in some areas, which can hinder natural sedimentary processes and promote erosion.

WETLAND SEDIMENTATION RATES IN TEXAS: FIELD INVESTIGATION

Purpose

There have been few studies of sedimentation in Texas marshes. Investigations have principally focused on shoreline changes to document retreat (erosion) and advancement (accretion) of the shoreline. The loss of interior marshes in fluvial-deltaic areas has only recently been systematically investigated as part of this study (White and Calnan, 1990b) to determine the historical trends in marsh transformation to open water, a process that has been previously documented only in selected areas. This field investigation, which had as a primary objective to document local marsh sedimentation (vertical accretion, or aggradation) rates, is apparently the first of its type in Texas coastal marshes.

Rivers discharging into the bays and estuaries along the Texas coast have constructed deltas that are the sites of extensive marshlands and forested wetlands. Fluvial sediments delivered by the

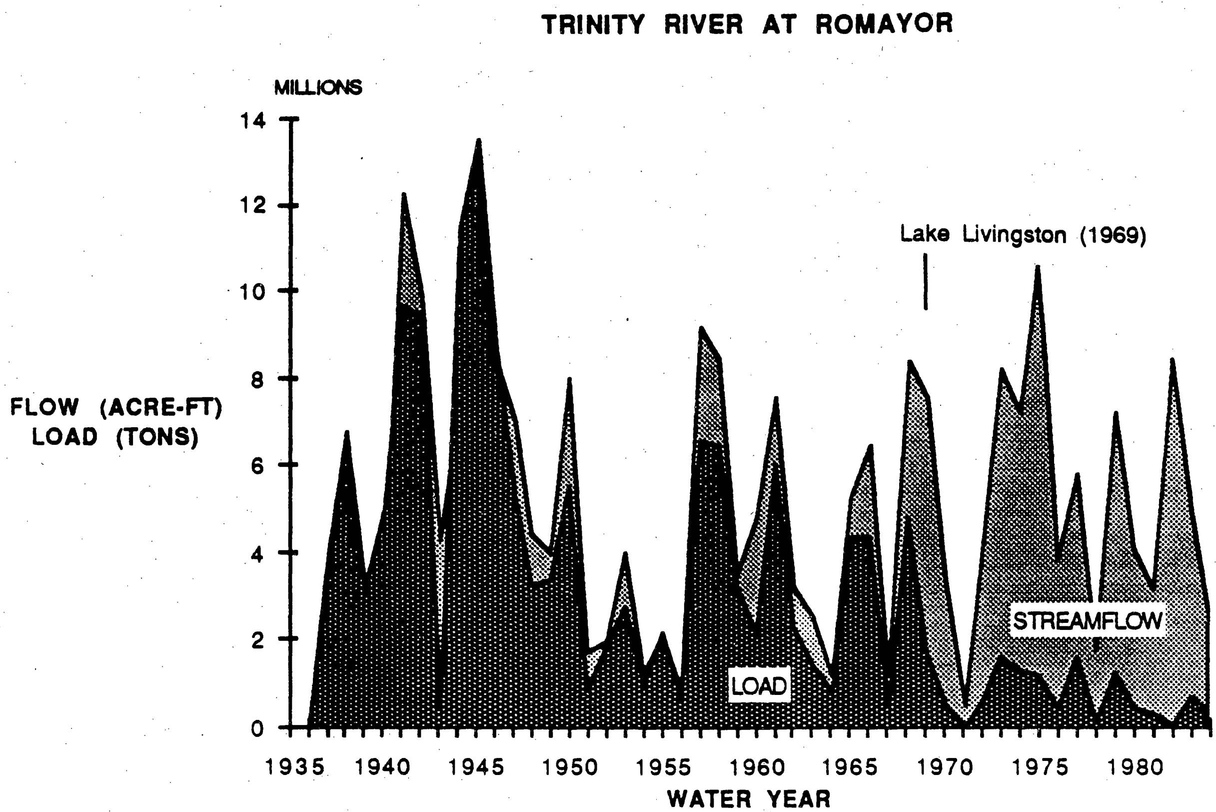


Figure 4. Annual streamflow and suspended sediment load of the Trinity River. (Compiled from Texas Water Development Board reports.)

COLORADO RIVER AT AUSTIN

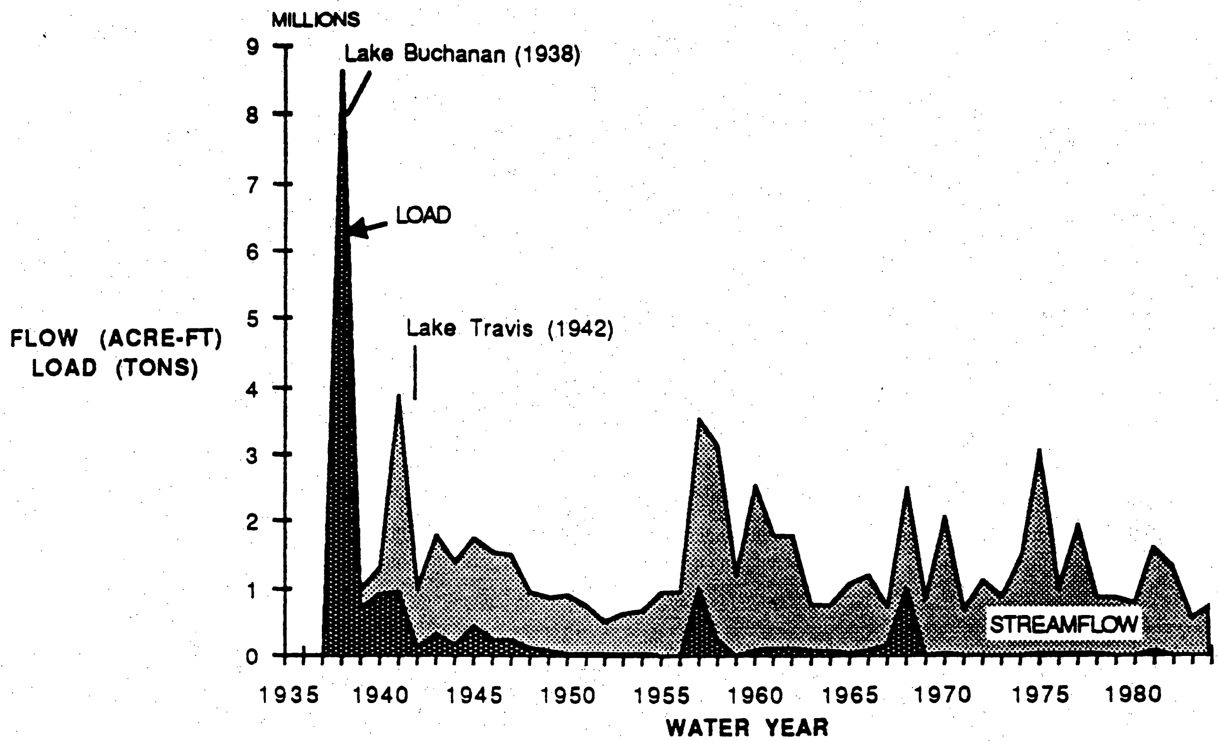


Figure 5. Annual streamflow and suspended load of the Colorado River. Data were not available for the following years: streamflow for 1962 and 1963, and suspended load for 1962, 1963, 1976, and 1977. (Compiled from Texas Water Development Board Reports.)

COLORADO RIVER AT AUSTIN/COLUMBUS

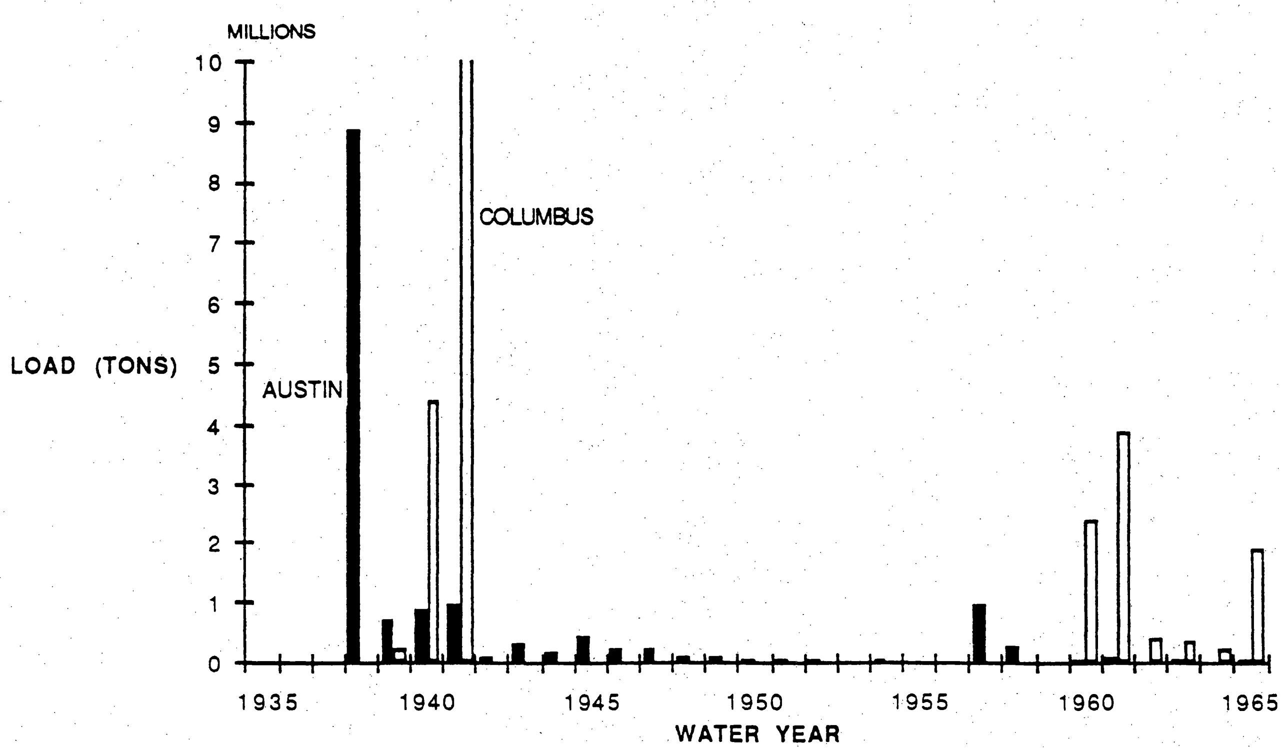


Figure 6. Annual suspended load of the Colorado River at Austin and Columbus. (Compiled from Texas Water Development Board Reports.)

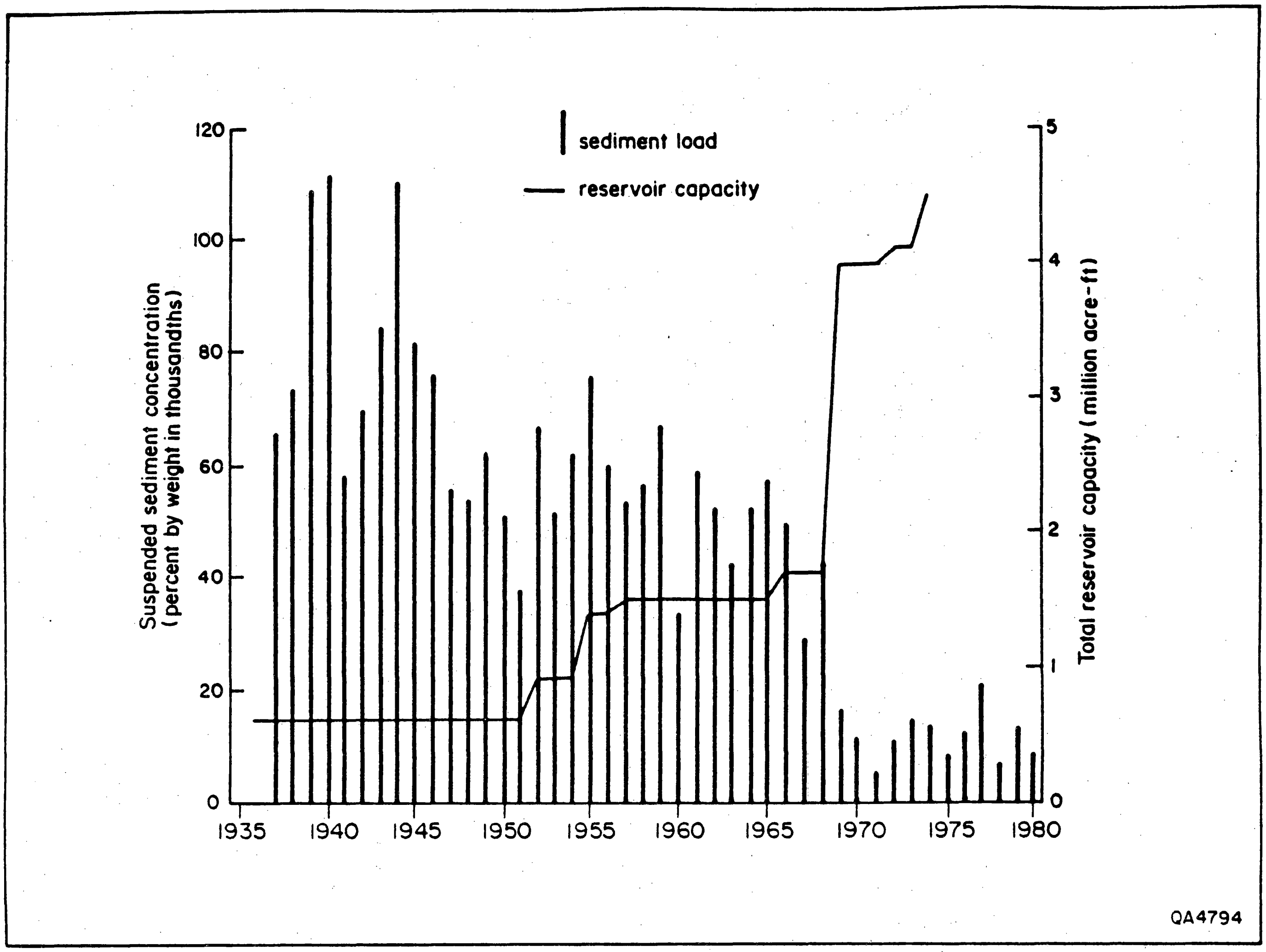


Figure 7. Suspended-sediment load (percent by weight) of the Trinity River at Romayor, and cumulative authorized water storage in reservoirs of the Trinity River basin. (From Paine and Morton, 1986.)

rivers help maintain these valuable natural resources. Marshes are dependent upon sediment deposition not only for nutrient supply, or fertilization, but also in order to maintain their intertidal position. Accordingly, comparisons of marsh sedimentation rates with rates of relative sea-level rise provide critical information for predicting marsh vegetation survival. If sediment deposition is such that marsh sedimentation rates can keep pace with rates of relative sea-level rise, the marsh can survive and even flourish, but if sedimentation rates fall behind, the marsh will drown and be replaced by open water. A major objective of the field investigation on sedimentation was to document sedimentation rates using artificial-marker horizons placed at strategic locations on the wetland surface. In addition, sediments from a few cores collected in wetlands were radiochemically dated using ^{210}Pb (an isotope of lead) to determine long-term (approximately 80 to 100 years) sedimentation rates. Two deltaic areas were selected for the field study: the Colorado River delta and the Trinity River delta. Both areas have significantly extended their deltas within historic times, and both are fed by rivers whose sediment loads have, more recently, been significantly reduced (Figs. 4 and 5).

Methods

Salt-water marshes in the Colorado River delta, and brackish-water marshes and other wetlands in the Trinity River delta were monitored over a period of 18 to 24 months to document sediment accumulation rates. Vegetation types, vegetation heights, elevations, and sediment composition were among the other types of information collected during periodic surveys. Short-term marsh sedimentation rates were determined primarily by using artificial-marker horizons of white clay established on the wetland surface at selected sites along marsh transects. The marker horizons were periodically examined to determine the thickness of sediment that had accumulated above them (Fig. 8). Eleven artificial-marker horizons were initially placed in wetlands in the Trinity River delta study area, and nine in the Colorado River delta study area. Long-term sedimentation rates (representing approximately the past 80 to 100 years) were determined by radiochemically dating sediment layers in cores from marshes using the isotope, lead-210 (^{210}Pb). This isotope occurs naturally in the atmosphere and theoretically accumulates at a constant rate at the earth's (and wetland's) surface, where it is incorporated into the sediment and continuously buried through sedimentary processes. Like other radioactive materials, the lead isotope decays into another element (bismuth) at a constant rate (^{210}Pb has a half-life of about 22.2 yrs, which means that half of a given sample will have decayed to the new element in that period). By measuring the amount of lead, or its daughter product bismuth, in sediments taken from different depths in a core, the burial rate (sedimentation rate) can be inferred. A total of five sediment cores ranging in length from 2 to 3.3 ft (0.6 to 1 m) were collected along selected marsh transects; 3 cores were from the Trinity River delta and 2 from the Colorado River delta.

Salt-Marsh Sedimentation Rates: Colorado River Delta

Salt-marsh sedimentation rates on the Colorado River delta are similar to those in salt marshes reported for other areas of the Gulf Coast (tables 1 and 2). These rates, which are commonly higher than those recorded along the Atlantic Coast, are apparently related to higher rates of relative sea-level rise that characterize the Gulf Coast in Louisiana and Texas (table 1). (Higher rates of relative sea-level rise would tend to raise sedimentation rates due to the increasing frequency of inundation of the marshes through time, assuming there is an adequate sediment supply for deposition during the inundations). In the Colorado River delta, the highest short-term rates (based on sediment accumulations above artificial-marker horizons) were about 12 mm/yr and occurred in bay margin-distributary influenced and levee environments (table 2). These sites are comparable to the streamside saline marshes of the Louisiana Deltaic Plain where the reported rate is 13.5 mm/yr (table 1). Short-term sedimentation rates (based on marker horizons) in backmarsh-distributary influenced environments in the Colorado River delta were very consistent, with four sites varying less than 1 mm/yr; sedimentation rates range from 8.5 to 9.3 mm/yr and average 9.0 mm/yr. These sites are intertidal marshes. Sediment deposition at these sites prior to September 1988 when Hurricane Gilbert made landfall, was apparently related to normal estuarine intertidal processes. The location of these

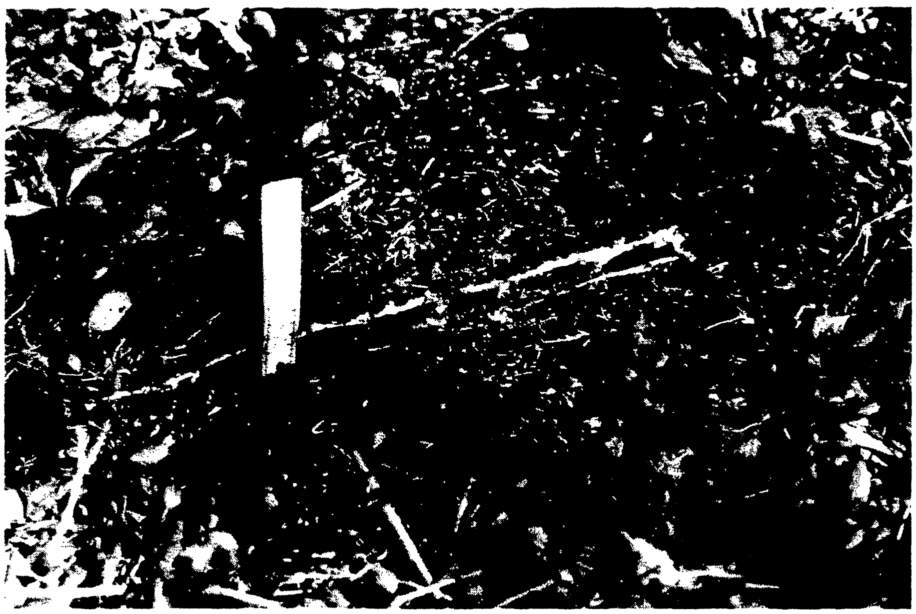


Figure 8. Vertical trench intersecting an artificial-marker horizon of white clay. The ruler in the trench is 15 cm (6 in) long.

Table 1. Marsh aggradation (vertical accretion) rates measured in coastal Louisiana and along the U. S. Atlantic coast (from Boesch and others, 1983).

Location	Marsh type	Marsh accretion rate (mm/yr)	Mean sea-level rise (mm/yr)	Source
Louisiana Deltaic Plain	Freshwater		11.0	Hatton and others (1983)
	streamside	10.6		
	backmarsh	6.5		
	Intermediate (Spartina patens)			" "
	streamside	13.5		
	backmarsh	6.4		
	Brackish (S. patens			" "
	streamside	14.0		
	backmarsh	5.9		
	Saline (S. alterniflora)		13.0	DeLaune and others (1978); Baumann (1980)
	streamside	13.5		
	backmarsh	7.5		
Chenier Plain	Salt-brackish (S. patens)	7.0	12.0	Baumann and and DeLaune (1982)
Georgia	S. alterniflora	3-5		Summarized by Hatton and others (1983)
Delaware	S. alterniflora	5.0-6.3	3.8	" "
New York	S. alterniflora	2.5-6.3	2.9	" "
Conn.	S. alterniflora	8-10	2.5	" "
	S. patens	2-5		
Mass.	S. alterniflora	2-18	3.4	Redfield (1972)

Table 2. Salt marsh environments and sedimentation rates in the Colorado River delta. (Numbers in parenthesis are station numbers.)

MARSH ENVIRONMENT	MARSH SEDIMENTATION RATE (mm/yr)
LEVEE	
Borrichia, Batis, Distichlis (3-1)	11.9
Borrichia, S. patens, Batis (1-14)	5.4
BARRIER FLAT	
Monanthochloe (2-9)	1.9
BAY MARGIN-DISTRIBUTARY INFLUENCED	
Spartina alterniflora (2-4)	11.7
BACKMARSH-DISTRIBUTARY INFLUENCED	
Spartina alterniflora (3-3)	9.3
Spartina alterniflora, Scirpus maritimus (1-3)	9.2
Distichlis, Scirpus maritimus (1-2)	8.9
Spartina alterniflora, Distichlis (3-2)	8.5
BACKMARSH/BAY MARGIN	
Spartina alterniflora (4-10)	5.7

marshes in the intertidal zone contributed to the higher sedimentation rate by increasing the frequency of inundations and the period of time during which deposition occurred. Processes and conditions affecting sedimentation rates are presented in table 3.

Sediment in Colorado River delta low backmarsh areas are composed predominantly of clay and silt, averaging 65 and 30 percent, respectively, with a sand content of about 5 percent. Sediments in high marshes on levees along distributary channels have a higher percentage of silt (55 percent) than clay (40 percent). Organic carbon in sediments ranges from less than 1 percent to more than 5 percent.

Variations of Rates Seasonally and in Response to Hurricanes

Seasonal variations in sedimentation were recorded by most marker horizons in the Colorado River delta even though no river flood events occurred during the monitoring period. The least amount of deposition occurred during winter months (Fig. 9). Sediment accumulation during each of two winter periods (December 1987-March 1988 and November 1988-March 1989) represented an average of only 2.5 to 3 percent of the total deposition at the various sites (table 4). The months registering the highest amount of deposition were July to November 1988, a period that includes Hurricane Gilbert. About 50 percent of the total sediment that accumulated on marker horizons was deposited during this period. A high of almost 80 percent was deposited at a levee site along the margin of Tiger Island Cut. This deposition can be attributed to Hurricane Gilbert, and indicates that over an 18-month period this levee site received most of its sediment during a single depositional event. The insignificant sediment deposition (< 1 mm) on levee marshes before Hurricane Gilbert made landfall in September 1988, supported the fact that no flood events with a magnitude sufficient to inundate these marshes occurred during the pre-Gilbert monitoring period.

Seasonal and storm-related deposition of sediments have been reported in other marsh systems. Researchers in Georgia (Letzsch and Frey, 1980) found a seasonal variation in marsh sediment accumulation with minimum deposition occurring in autumn, through winter and spring, and maximum deposition occurring in summer. The differences apparently correlate, to some degree, with the seasonality of storm-wind incidence. In a study of marsh sedimentation in the Mississippi Deltaic Plain, investigators (Baumann and others, 1984) also concluded that there is a seasonal component to sediment deposition but it varied depending on sediment sources. In marshes receiving fluvial sediment, spring river flooding contributed from 91 to 69 percent of sediments in streamside and inland marshes, respectively. Marshes away from a fluvial input received the largest percentage of sediments (36 to 40 percent) from hurricanes and tropical storms. During periods without hurricanes, rates of sedimentation were highest during winter when winter storms were the primary depositional event. Some scientists (Stevenson and others, 1986) have postulated that hurricanes and storms may play a critical role in sediment budgets in areas where tides are weak and irregular and sediment inputs are low or reduced relative to past levels. This is in agreement with other conclusions (Stumpf, 1983) that storms control marsh sediment supply in microtidal areas (areas that have low tidal range such as along the Gulf coast), and that sedimentation depends directly on storm frequency and sediment availability.

Sedimentation vs. Relative Elevation of Marshes

Analysis of sediment accumulation with respect to relative elevation in the Colorado River delta indicates an inverse relationship between elevations of most marker horizons and sedimentation rates (Fig. 10). The topographically higher marker horizons received less sediment than lower horizons, supporting another researcher's conclusions (Pethick, 1981) of a statistical relationship between marsh elevation/age and vertical accretion rates. The concept is that younger marshes are lower in elevation, which amplifies the depth and frequency of inundations and sediment accumulation compared to older, topographically higher marshes. However, as shown in this study the statistical relationship may be reduced by major storms or floods when sediment is deposited at higher elevations, such as on natural levees.

Table 3. Processes and conditions influencing salt marsh aggradation rates. (Compiled by Oenema and DeLaune, 1988.)

FREQUENCY AND DURATION OF FLOODING

SUSPENSION CONCENTRATION

TIDE RANGE

STORM FREQUENCY

EXPOSURE TO WAVE ATTACK

VEGETATION CHARACTERISTICS

BIODEGRADATION

COMPACTION OF SURFACE SEDIMENTS

SUBSIDENCE

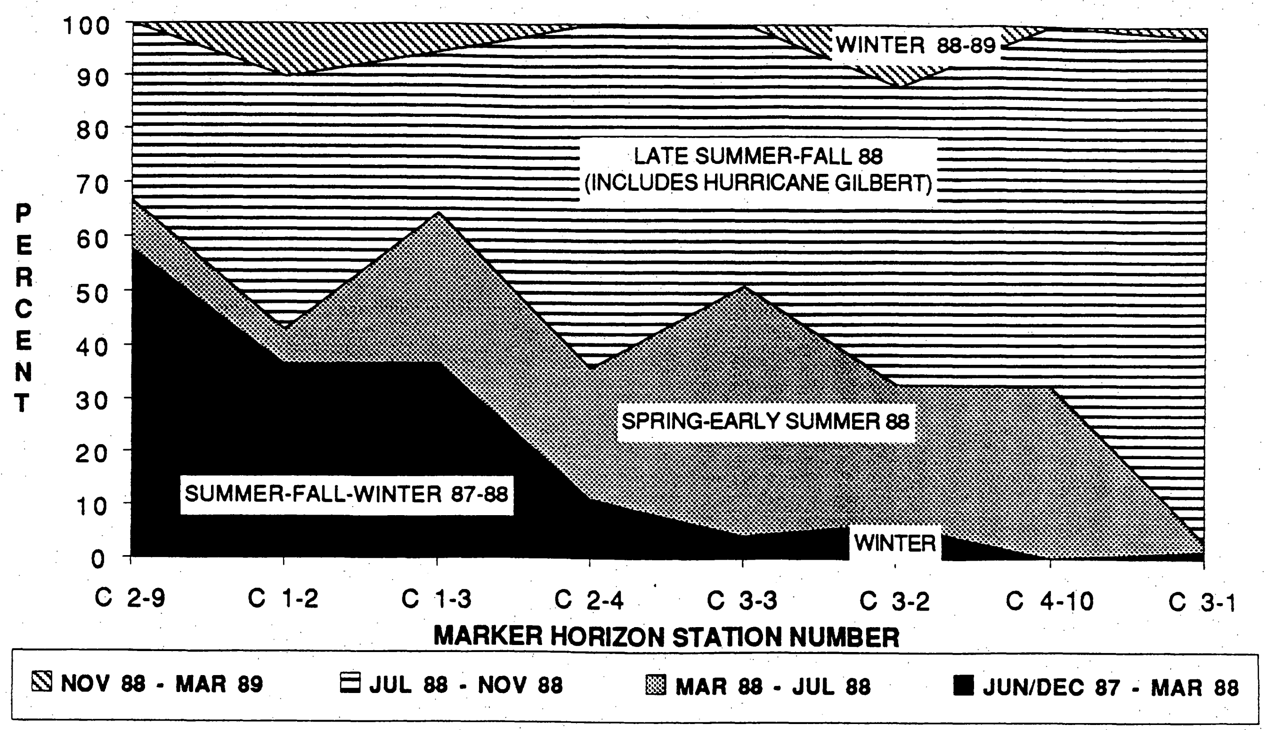


Figure 9. Seasonal sedimentation in percent as measured above eight marker horizons located in the Colorado River delta. Highest percentages of sedimentation generally occurred during the period that included Hurricane Gilbert, and lowest occurred during winter months.

Table 4. Percentage of the total aggregation above artificial-marker horizons that occurred during specified periods, Colorado River delta.

MARKER HORIZON	SUMMER, FALL, AND/OR WINTER (Percent)	SPRING AND SUMMER (Percent)	LATE SUMMER AND FALL (Percent)	WINTER (Percent)
C 2-9	58	9	33	0
C 1-3	37	28	30	5
C 2-4	11	25	64	0
C 3-3	4	47	49	0
C 3-2	7	26	55	12
C 4-10	0	33	67	0
C 1-14	0	16	81	3
C 3-1	2	2	95	2
AVERAGE	15	23	59	3

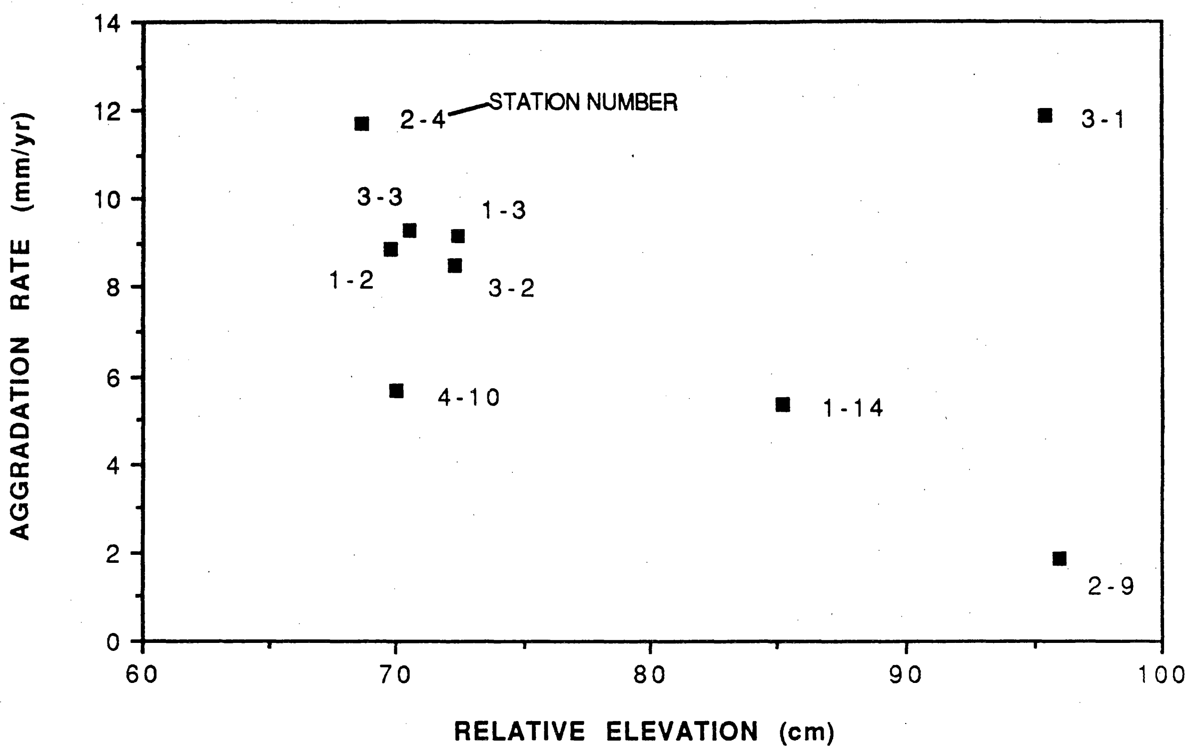


Figure 10. Comparison of sedimentation rates at stations in the Colorado River Delta with relative elevations of marshes at those stations. In general, marshes at lower elevations had higher sedimentation rates than those at higher elevations. This indicates that there is an inverse relationship between elevation and sedimentation, at least during storm-free periods. Storms and flood events can deposit sediments at the higher elevations, nullifying this relationship.

Long-Term Sedimentation Rates in Salt Marshes

Long-term sedimentation rates (past 80 to 100 yrs), based on ^{210}Pb dating of cores from two backmarsh sites in the Colorado delta, are 7.6 and 7.4 mm/yr. The higher short-term rates (average of 9 mm/yr) determined by the artificial-marker horizons in backmarshes are probably due in large part to lower amounts of compaction and organic decomposition in the surface sediments compared to deeper sediments in the cores. The long-term sedimentation rates are similar to the rate of 7.5 mm/yr in saline backmarshes (table 1) reported in Louisiana.

Sedimentation in Brackish-Water Wetlands: Trinity River Delta

Rates of sedimentation in the Trinity River delta (table 5) were more variable and less predictable than in the Colorado River delta, in part reflecting the more complex setting of the Trinity delta brackish-water wetland system, which includes marshes and forested wetlands. In addition, the field investigation in the Trinity delta was begun later in the year (December 1987), which provided a monitoring period of about 20 months compared to two years at some sites in the Colorado delta. During the first 15 months of study in the Trinity delta, variations in sediment accumulation ranged from erosion at bay-margin sites to deposition of more than 28 mm in less than 8 months at a site farther inland. The estuarine shoreline near one of the eroded marker horizons, retreated (moved landward) approximately 3 ft (1 m) during a 3.5-month winter period (December 1987 to March 1988) indicating both vertical and lateral erosion of this area. Erosion did not occur during the succeeding two periods (March to July and July to November), but the shoreline retreated another 3 ft (1 m) during the following winter (November 1988 to March 1989), indicating, as in the Colorado River delta, that there is a seasonal factor in the deposition and erosion of marsh sediments. Minimum deposition occurs in winter, and maximum in late spring to early fall when major flood events (hurricanes, tropical storms, and river flooding) are more likely to occur.

Sedimentation Associated with Major Flood Events

Near record flooding along the Trinity River during the spring and early summer of 1989 had a major effect on sediment deposition at levee and bay/channel margin sites. Maximum flooding at Liberty, which coincided with release rates from Lake Livingston exceeding 70,000 ft^3/sec (Fig. 11), almost equaled the record set in 1942. In addition to this peak flood event, the frequency and duration of flooding was excessive from May through mid-July of 1989 during which daily release rates from Lake Livingston exceeded 30,000 ft^3/sec on 45 occasions. The major flood event produced abnomally high amounts of sediment accumulation on levees along the Trinity River. One levee marker located less than 12 ft from the channel cut bank recorded the most deposition. Between March and August 1989, approximately 6.7 cm of sediment accumulated, which is more than 95 percent of the total deposition at this site over a 20 month period. In fact, between June and August 1989, more than 5 cm of sediment was deposited at this site, which probably can be attributed to the near record flood in early July. On another levee several miles downstream along Anahuac channel, sedimentation during this same two-month period (June-August 1989) was less than 2 cm. However, this represented about 95 percent of the sediment that had accumulated at this location since March 1989, when the artificial marker was established.

The importance of river flooding on sediment deposition is illustrated in figure 12, which shows that a high percentage of deposition occurred at most markers (those that had not been previously eroded) during the spring and summer of 1989. The effect of the flood events on sedimentation is also reflected in table 5, which indicates a sizable increase in sedimentation rates after flooding occurred (compare the rates based on data collected until March 1989 with rates based on data collected until August 1989 in table 5).

Table 5. **Brackish wetland environments and sedimentation** rates in the Trinity River delta.

WETLAND ENVIRONMENT	VEGETATION	STATION NO.	SEDIMENTATION RATE (mm/yr)	
			To Mar 89	To Aug 89
BAY/CHANNEL MARGIN	ANNUAL	T 1-4	0 (eroded)	--
BAY/CHANNEL MARGIN	ANNUAL	T 1-3	0 (eroded)	--
BAY/CHANNEL MARGIN	ANNUAL	T 6-1	0 (eroded)	--
FLUVIAL CHANNEL LEVEE	WOODLAND	T 5-1	1.8	42.3
DISTRIBUTARY CHANNEL LEVEE	WOODLAND/PERENNIAL	T 3-2	1.9	8.3
BAY/CHANNEL MARGIN	PERENNIAL	T 6-2A	4.8	13
BACKMARSH/TIDAL CHANNEL	PERENNIAL	T 2-2	8.8	11.6
BACKMARSH	PERENNIAL/ANNUAL	T 3-4	12.5	9.5
BAY MARGIN (SALT MARSH)	PERENNIAL	T 7	12.6	16.8*
LEVEE FLANK/POND MARGIN	PERENNIAL/ANNUAL	T 4-3	39	Not measured

* Measured from brass rod

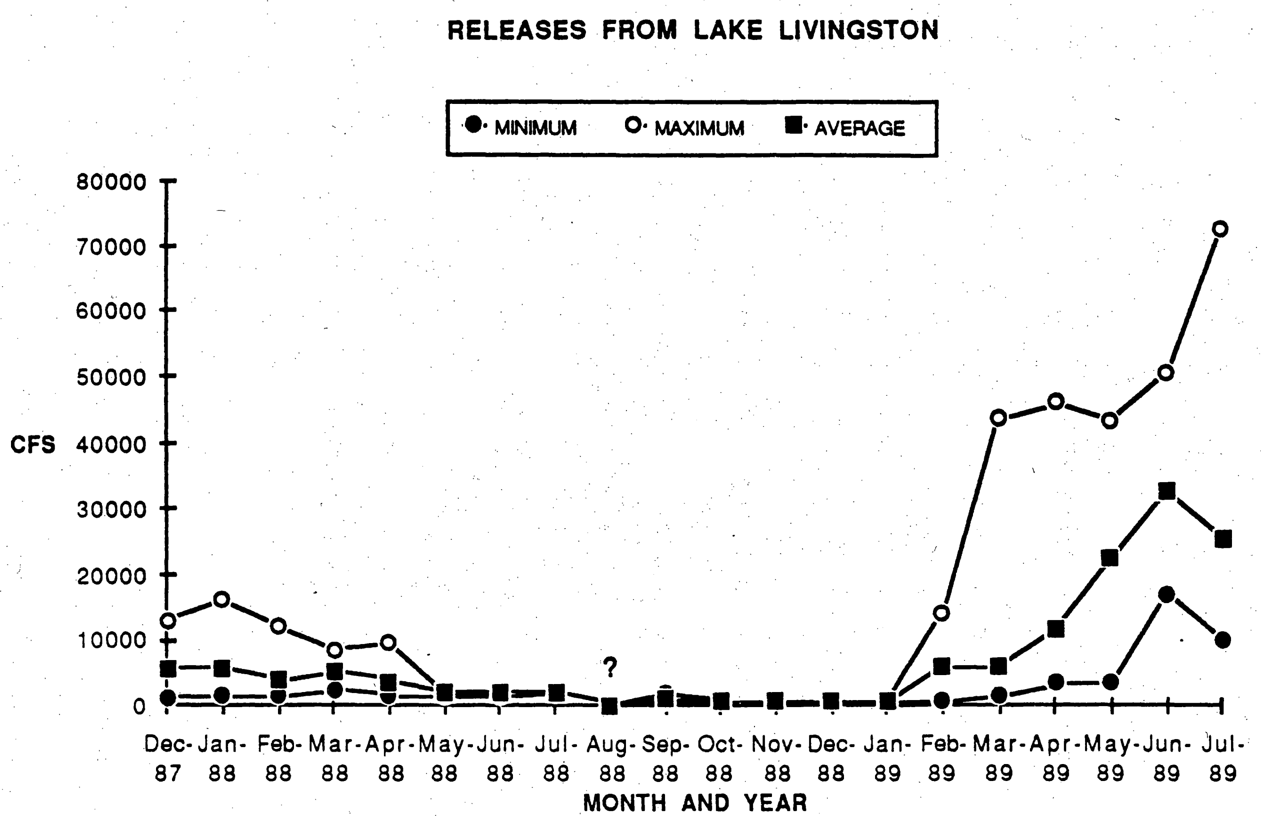


Figure 11. Water releases from Lake Livingston in ft^3/sec (CFS) from December 1987 through July 1989. It has been estimated that all of the Trinity River delta is completely flooded at river discharges exceeding 30,000 ft^3/sec during high tide. Near record flooding occurred during July 1989. (Data from Trinity River Authority.)

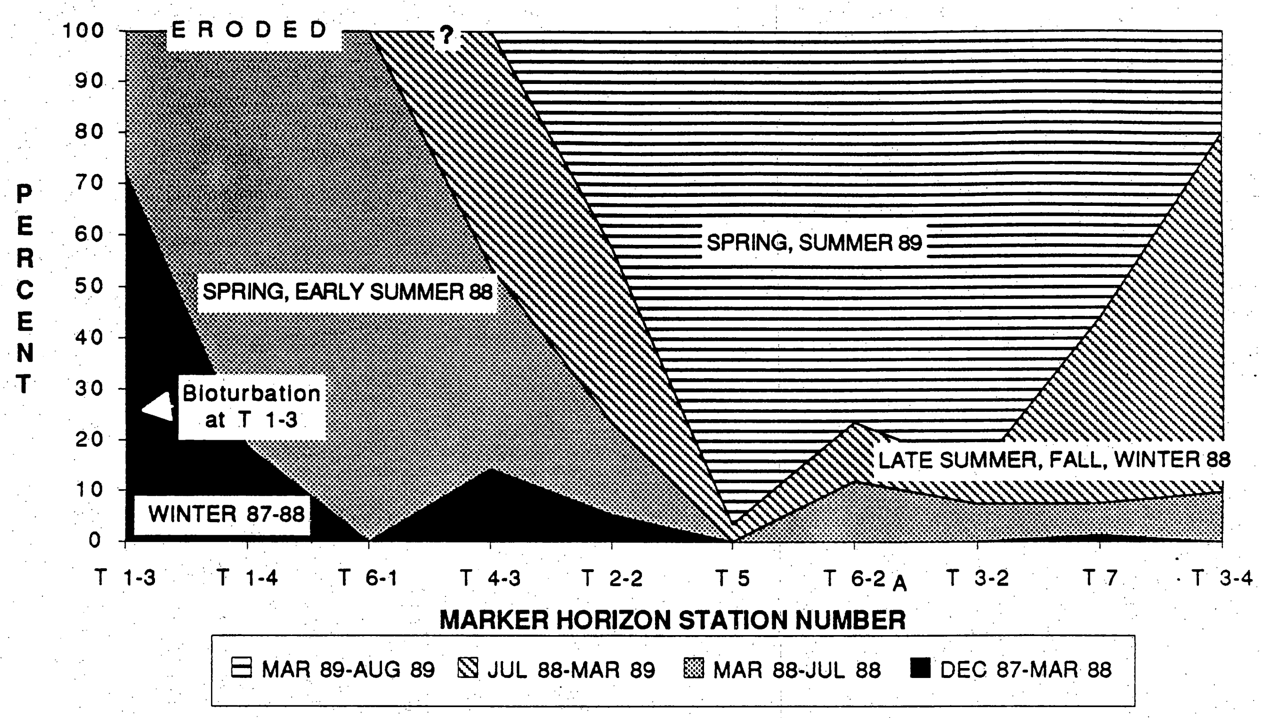


Figure 12. Seasonal sedimentation in percent as measured above ten marker horizons located in the Trinity River delta. Highest percentages of sedimentation generally occurred during the spring and summer 1989, a period that included major flooding along the Trinity River.

Surveys along the Trinity River in August 1989 after the major flood event disclosed relatively thick deposits of clean, very fine-grained sand deposited on levees. A few measurements revealed that the recently deposited sand was as thick as 25 cm locally near the channel, but thinned rapidly away from the river toward backmarsh environments and downstream. The fine sand was apparently carried in suspension and deposited as flood-water velocities diminished across the levee. Deposition of silt and clay in backmarsh areas did not appear to be nearly as significant as sand deposition on the levees. This supports streamflow records that show a large reduction in suspended load (primarily silt and clay) since Lake Livingston was constructed in 1969. The deposited sand was apparently derived from scouring of the channel floor and erosion of point-bar sands downstream from the reservoir.

Delivery of large amounts of suspended sediments during flood events is supported by studies of Trinity River's suspended load. Rice (1967) determined that approximately 80 percent of the sediment discharged by the Trinity River in 1965 occurred during two major floods. The larger flood accounted for 59 percent of the year's total load. Significant deposition can take place on levees during flood events if river flood waters are carrying large sediment supplies. Sedimentation rates of levee environments along the Atchafalaya delta, Louisiana, were correlated with annual flood events by van Heerden and others (1981), whose designations indicated that high rates of sedimentation exceeded 30 cm, medium rates ranged from 15 to 30 cm, and low rates were less than 15 cm per annual flood.

Long-Term Sedimentation Rates in Brackish-Water Marshes

Analyses of ^{210}Pb in cores taken in three marsh areas in the Trinity delta were conducted to determine longer-term rates of sedimentation. Sedimentation rates inferred from core analyses are 6.8, 5.2, and 4.2 mm/yr. These rates are lower than in the Colorado River delta, which averaged 7.5 mm/yr. In addition, the short-term rates measured from artificial-marker horizons are higher than the long-term rates, which probably, as suggested for the Colorado delta marshes, reflects lower amounts of compaction and organic decomposition in surface sediments measured above the marker horizons compared to buried sediments in cores.

Seasonal Changes in Trinity Delta Marshes

A seasonal change in vegetation type and cover is a significant process in some brackish marsh areas in the Trinity River delta. Relatively barren intertidal flats observed in December at one site, had become thickly vegetated with a seasonal bullrush by July. At another site, a seasonal plant that is dominant during the fall (fall panic), had declined and almost disappeared by March and was totally replaced by other species by midsummer. This seasonal variation can affect both organic and inorganic erosion, transport, and deposition. For example, the dieback of vegetation in winter increases the chances of erosion in delta-front environments during winter storms. Organic matter from the dead, annual vegetation may be exported into the bay, or it may be transported into more inland parts of the delta where it is trapped by perennial vegetation. During the spring and summer, thick stands of annual bullrush or other annual species help trap sediment and increase sedimentation.

Marsh environments that were especially affected on a seasonal basis were those along the bay margin at the front of the delta. These dynamic environments were subjected to large amounts of physical energy, especially during storms and flood events. Although sediment accumulated above markers in this environment during the first spring, the markers were eroded during the second winter indicating net erosion of the marsh surface and no deposition. These relatively high-energy environments are characterized by sandy substrates and annual vegetation. The dieback of vegetation in winter, coupled with extensive nutria bioturbation, intensify the impact of winter storms and produce a dynamic environment in which sediment is vigorously reworked by waves and currents. The delta front environments are near distributary channels and are modified by a combination of fluvial and estuarine processes, which can result in erosion or deposition as existing deltaic sediment is reworked during flood events. If enough new sediment is added to these delta-front environments to counter wave and current attack, the delta will build farther into the bay allowing new marshland with more permanent vegetation to develop. However, if sediment is not supplied to these areas, they will begin to erode and retreat landward.

Importance of Organics in Brackish-Water Marsh Systems

Organics were a more significant component of the marsh sediments in the brackish-water marshes of the Trinity River delta than the salt-water marshes of the Colorado River delta. Organic carbon makes up more than 5 percent of the sediment in low backmarsh areas. When plant roots and organic debris are considered, organic matterial may exceed 20 percent at some sites. It appears that organic sediments are important constituents of marsh soils, especially over the short term. Organics from plant debris make up an integral part of the top few centimeters of marsh substrate in many areas. However, organic material decreases at depth, and thick peat deposits that characterize marshes in the Mississippi River delta are apparently not a part of the Trinity River delta or other Texas deltas, probably for several reasons. Among them are those noted by other researchers (Frey and Basan, 1985) and include tidal flushing and rapid degradation of plant material by intense biologic activity and oxidation. Deltaic marsh sediments in Texas are similar to those of the southeastern Atlantic coast such as in Georgia, which are described as dominantly inorganic with an insignificant amount of peat.

Inorganic sediment in the Trinity River delta marshes are similar in composition to that in the Colorado River delta. Sediments in low backmarsh environments are composed predominantly of clay (average 67 percent) and silt (28 percent), with a small amount of sand (less than 5 percent). Sand and silt become more prominent than clay on levees and in high-energy delta front areas where waves and currents concentrate the larger particles (sand) and remove the smaller ones (clay).

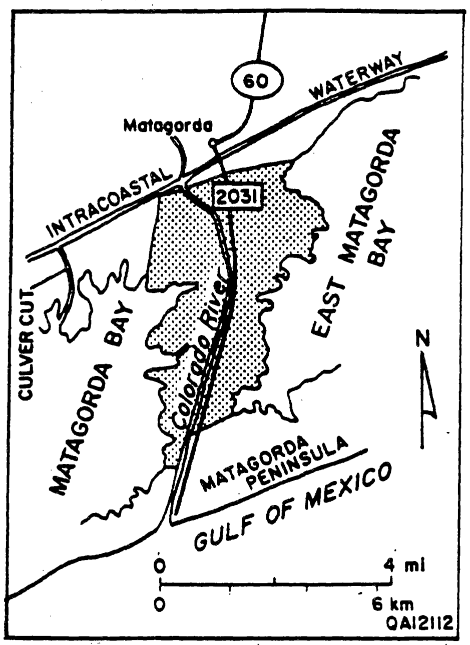
Sedimentation Rates vs. Rates of Relative Sea-level Rise

Based on subsidence rates reported by Swanson and Thurlow (1973) and Gabrysch (1984), marsh sedimentation rates in Texas deltaic areas may have to average from 5 mm to more than 13 mm/yr to remain emergent in most areas (Fig. 3). Predicted increases in global sea-level rise (Barth and Titus, 1984) may increase these minimal rates for marsh survival in the more distant future. Although short-term sedimentation rates determined during the field investigation generally exceeded 11 mm/yr in levee and streamside marshes, long-term rates in backmarshes range from a low of 4.2 mm/yr in the Trinity delta to 7.6 mm/yr in the Colorado River delta. This latter rate, which applies to the southwest half of the Colorado River delta, appears to equal or exceed relative sea-level rise because marshes are remaining stable or expanding. In the Trinity River delta, the estimated subsidence rate is approximately 6.5 mm/yr (Gabrysch, 1984), but the long-term sedimentation rates in the delta average only 5.4 mm/yr, which indicates that sedimentation is not keeping pace with subsidence. As noted in the following section on historical changes, marsh area in the Trinity delta is declining.

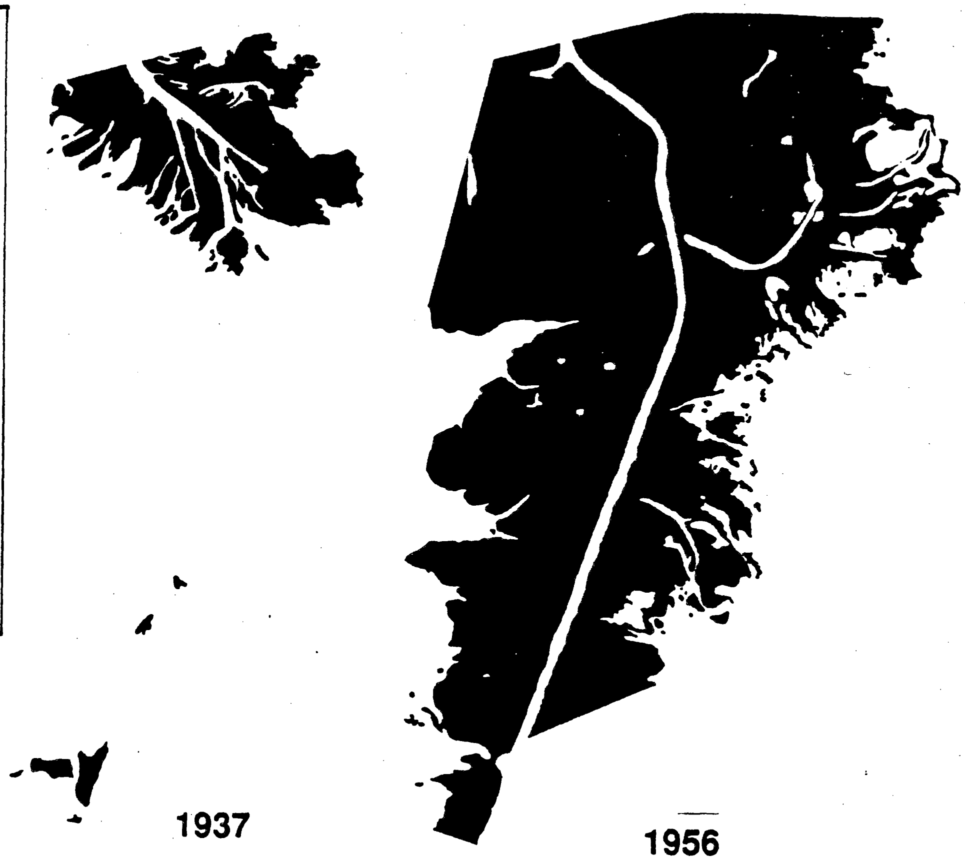
HISTORICAL ANALYSES OF CHANGES IN FLUVIAL-DELTAIC WETLANDS

Purpose and Methods

Historical changes in vegetation and water/barren flats were analyzed in deltaic and alluvial-valley wetlands near the mouths of seven rivers (Colorado, Guadalupe, Lavaca, Neches, Nueces, San Jacinto, and Trinity). Historical analyses are based on aerial photographs taken in the 1930's to the 1980's (Figs. 13 and 14). The principal focus of the historical investigation was to document changes in emergent vegetation in fluvial-deltaic wetlands to determine the extent to which the vegetated areas are being replaced by open water or barren flats. This kind of transformation, from vegetated to non-vegetated flats, would be expected if sediment accumulation rates are not keeping pace with rates of relative lea-level rise.



Colorado River delta index map and historical sequence of vegetated areas (in black) for the years 1937, 1956, 1974, and 1982.



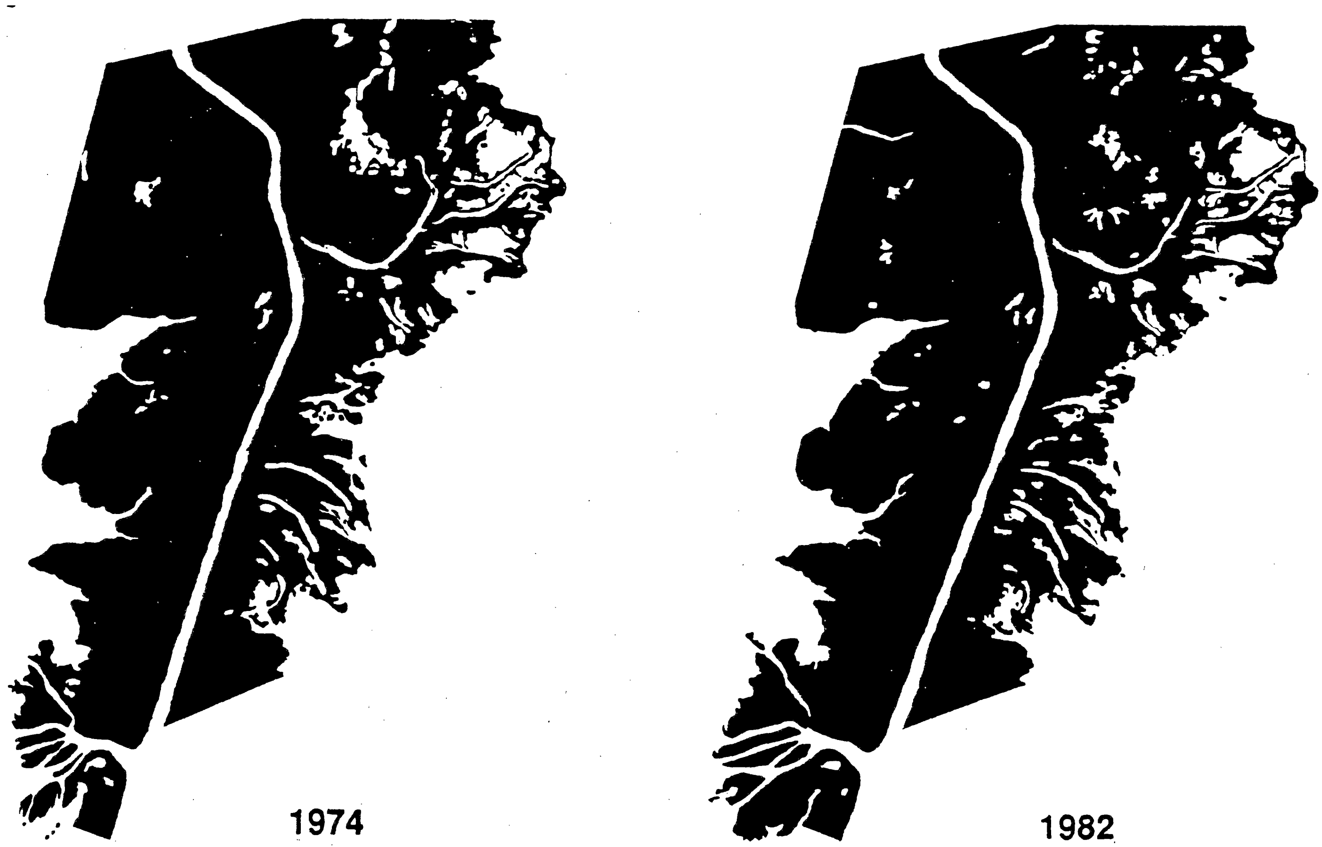
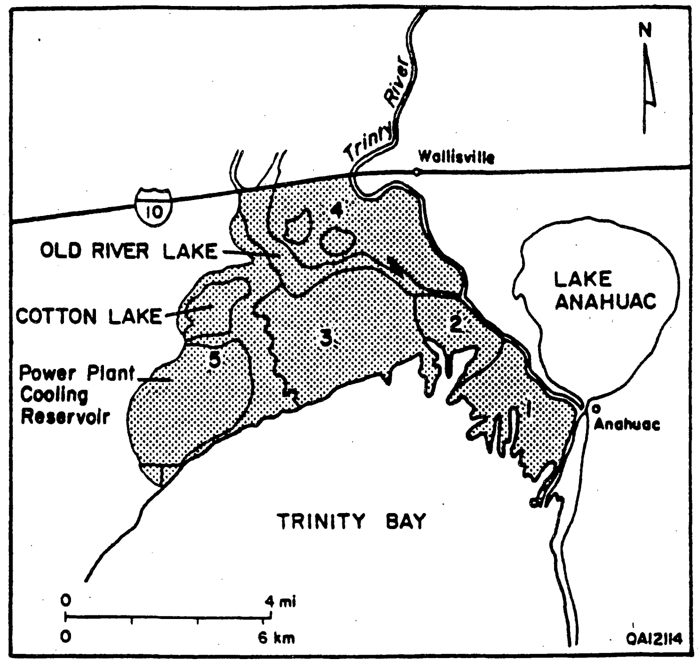


Figure 13. Historical changes in vegetated wetlands in the Colorado River delta.



Trinity River delta index map and historical sequence of vegetated areas (in black) for the years 1930, 1956, 1974, and 1988.

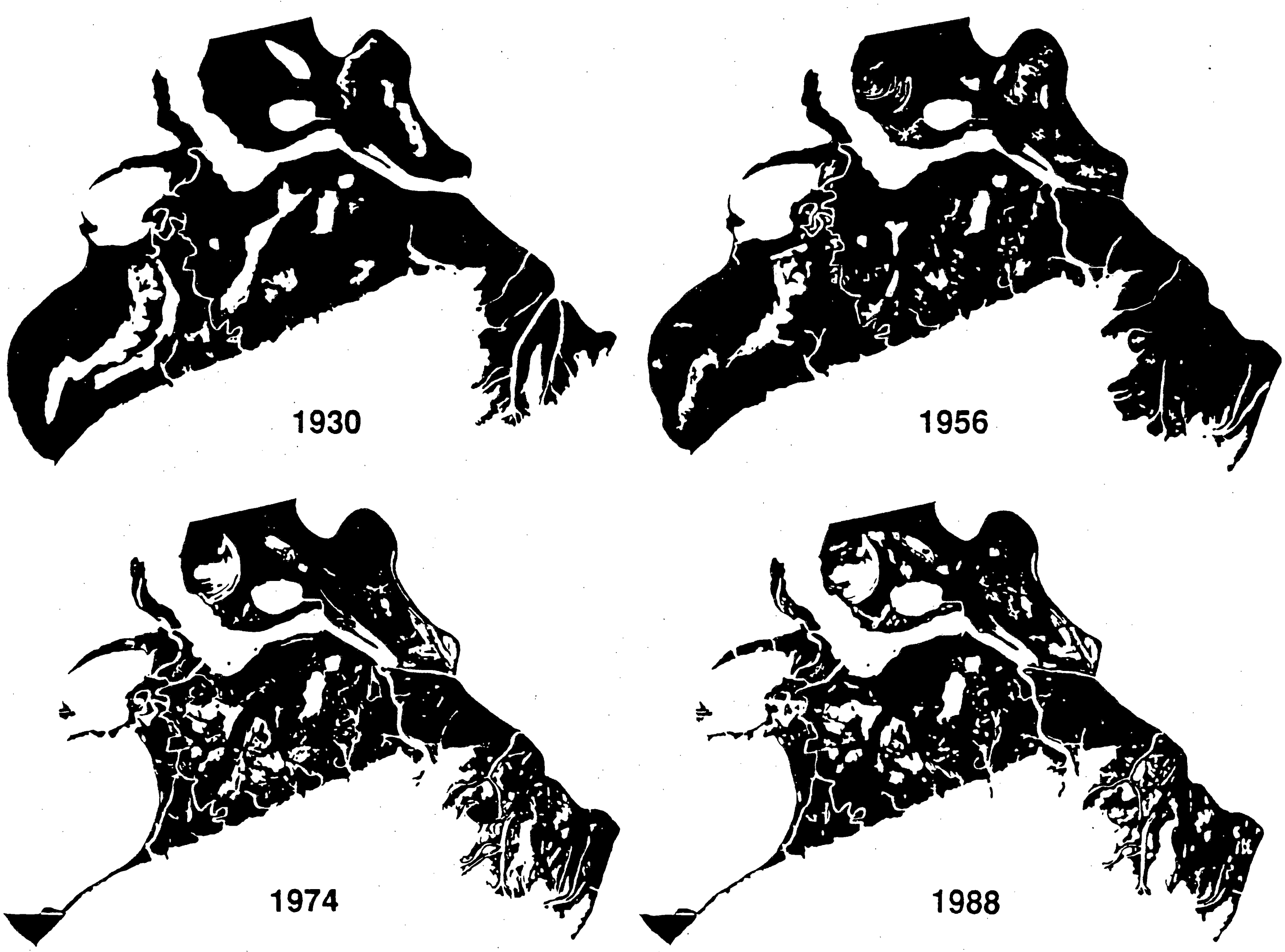


Figure 14. Historical changes in vegetated wetlands in the Trinity River delta.

The distribution of (1) vegetated wetlands (which includes marshes, swamps, and fluvial woodlands) and (2) water/barren flats were mapped on sequential aerial photographs dating from the 1930's to the late 1970's or 1980's. Units delineated on aerial photographs were digitized, plotted on maps, and the areal distribution of wetland vegetation and water/barren flats computed and graphed to determine trends and magnitudes of historical changes. Map areas in each delta and valley are generally restricted to regions in the lower alluvial valley, and do not encompass the entire wetland system.

Changes in Fluvial-Deltaic Wetlands

Analysis of historical changes in fluvial-deltaic and alluvial valley wetlands along the Texas coast indicates that vegetated wetlands are being replaced by water and barren flats in all of the deltas. The rate of replacement varies from less than 5 percent to about 50 percent for the period of analysis (generally from the mid-1930's to 1979 or later). Both the Colorado and Trinity deltas increased in size between the mid-1930's and mid-1950's, but the Colorado River delta is the only one of the seven analyzed that increased in total vegetated area after the mid-1950's (vegetation increased by about 2 percent between 1956 and 1982) (Figs. 15 and 16). Although the eastern half of the Colorado delta is undergoing slow deterioration in which vegetated wetlands are being replaced by water and barren flats, the western half has increased in size due primarily to delta growth apparently as a result of marine, estuarine, and to a lesser extent, riverine processes. Other deltas had a reduction in total vegetated wetland area after the 1950's with the greatest losses occurring along the San Jacinto (40 percent reduction) and Neches (40 percent) Rivers, and smaller losses occurring along the Trinity (30 percent), Lavaca (15 percent), Guadalupe (6 percent), and Nueces (3 percent) Rivers (Fig. 15).

The total area of vegetated wetland loss in all areas studied amounts to about 20,000 acres, with more than half occurring in the Neches River valley.[3] Among the factors contributing to the losses are subsidence and associated relative sea-level rise, and reductions in sediments supplied to the wetlands not only as a result of reservoir development in river drainage basins, but also as a result of channelization and spoil disposal, which can alter streamflow patterns and prevent overbank flooding. Man-induced subsidence plays a major role along the San Jacinto River and possibly along the Neches River.

Relationship between Decreasing Fluvial Sediments and Wetland Loss

Reductions in sediment supplied to deltaic areas as a result of dams and water diversion upstream apparently contributes to wetland losses, but there does not appear to be a one to one correlation between decreasing suspended sediment load along rivers and decreasing wetlands. Rivers with the largest reduction in suspended load are the Nueces, Colorado (based on measurements at Austin), Trinity, and probably San Jacinto and Neches. Although the Nueces River delta ceased its progradation (extension) into Nueces Bay sometime before 1959 (Morton and Paine, 1984), transformation of vegetated wetlands to nonvegetated wetlands is taking place very slowly (about 0.1 percent a year). The Colorado River delta has shown an overall gain in vegetated wetlands, although there have been losses in selected areas, since the mid-1950's. Diversion of the Colorado River into Matagorda Bay, a project presently underway, should increase the rate of marsh expansion. About 65 percent of the loss in the Trinity River delta marshes is due to a power plant cooling pond constructed after 1956. Still, vegetated areas in the Trinity delta are undergoing a gradual transformation to open water and barren flats. This trend is supported by analyses that show long-term marsh sedimentation rates (average of 5.4 mm/yr) are lower than estimated subsidence rates (average 6.5 mm/yr for the years 1943 to 1978, Gabrysch, 1984). San Jacinto and Neches River alluvial valleys are undergoing the most rapid changes. Subsidence is the overriding factor in the San Jacinto area, which is near the center of maximum subsidence due to groundwater withdrawal in the Houston area (Gabrysch, 1984). In the

---

3 This total area includes losses along the Neches River shown in figure 2.

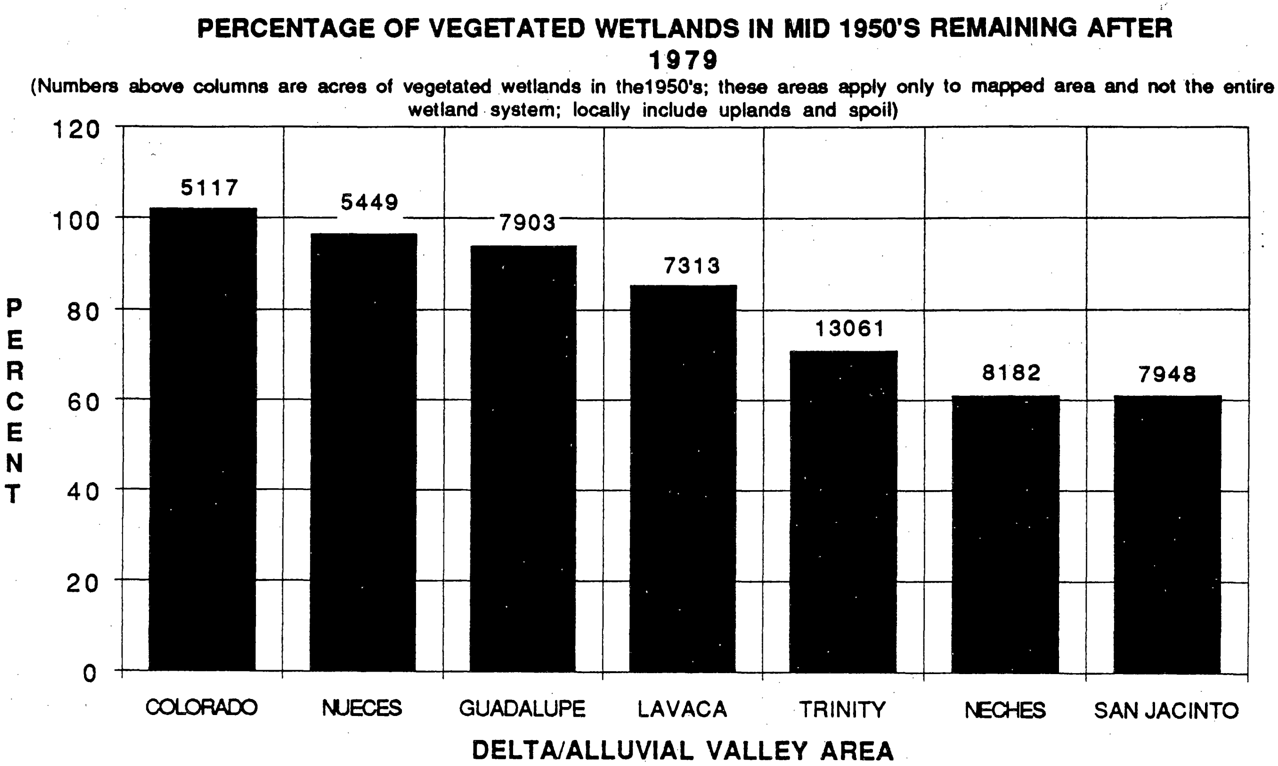


Figure 15. Comparison of mid-1950's vegetated wetlands with post-1979 wetlands in the seven fluvial-deltaic areas investigated.

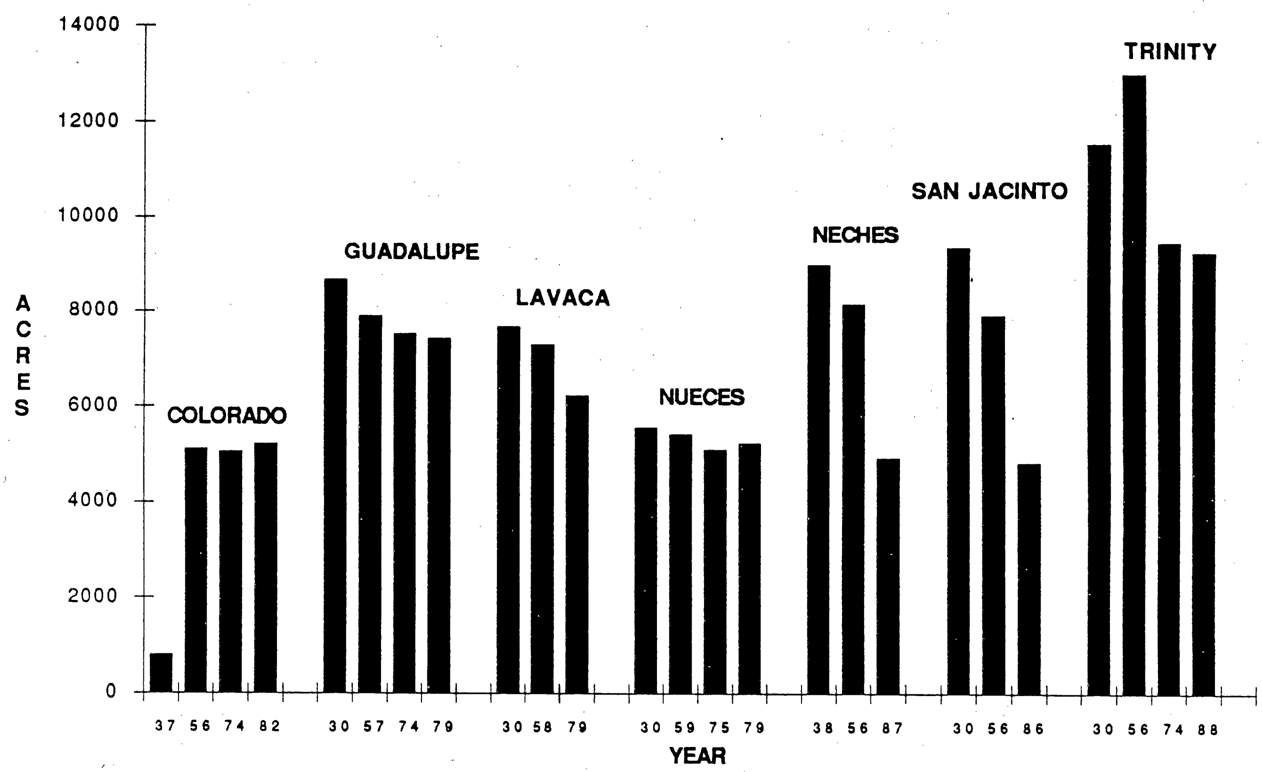


Figure 16. Summary of historical changes in vegetated wetlands in the seven fluvial-deltaic areas investigated.

Neches River valley, several factors, including subsidence, dredged channels, spoil disposal on levees, and reduction in sediments transported by the Neches River, are apparently contributing to wetland losses.

CONCLUSIONS

Transportation and deposition of fluvial (riverine) sediments in coastal waters of Texas are important natural processes. Extensive wetlands, which are vital components in a healthy estuarine system, have developed on the resulting sedimentary deposits at the river mouths and upstream in the river valleys. The deposition of sediments on wetland surfaces not only provides a source of nutrients to sustain plant growth, but it also provides the foundation necessary to maintain the substrate above a rising sea level.

Sedimentation rates in the Colorado River delta salt-water marshes are similar to rates in other Gulf coast salt marshes, where the highest rates (approximately 12 mm/yr) occur in streamside areas (levee and bay margin) and lowest rates (approximately 6 to 9 mm/yr) occur in backmarsh environments.

Sedimentation rates in the Trinity River delta, while also displaying the general trend of higher rates on levees (streamside environments) than in backmarsh areas, are more variable than in the Colorado River delta. Sites monitored ranged from deposition at rates exceeding 12mm/yr at several sites, to erosion. In addition, delta front/bay-margin areas are dynamic environments characterized by seasonal changes in vegetation, intense bioturbation, and episodes of extensive, and apparently rapid, deposition and erosion as storm waters rework surface sediments.

There is a seasonal variation in marsh sedimentation, with highest rates occurring in spring, summer, and fall, and lowest in winter when erosion may be associated with winter storms (frontal passage) and loss of vegetation.

Hurricanes can be major depositional events as demonstrated by Hurricane Gilbert, which during one year of the study accounted for more than 95 percent of the annual sediment deposition at a levee site, and an average of about 60 percent at other sites in the Colorado River delta.

Hurricane Gilbert was also an important depositional event in the Trinity delta, but it was overshadowed by near-record flooding along the Trinity River during the spring and summer of 1989. The river floods shifted the depositional pattern by accounting for more than 95 percent of the total sediment that accumulated on river levee sites, and a significant although lesser percentage (about 20 to 40 percent) in backmarsh environments. These depositional patterns re-emphasize the importance of river flooding to the wetland system.

Sedimentation rates in both the Colorado and Trinity deltas were inversely related to marsh elevations during storm-free periods. Topographically low, backmarsh environments had higher sedimentation rates than levee environments because the lower elevations increased the frequency and duration of flooding. However, deposition on topographically higher levees during major flood events (hurricanes and river floods) essentially nullified the correlation between marsh elevation and sedimentation.

Long-term sedimentation rates in the Colorado River delta are higher (approximately 7.5 mm/yr) than in the Trinity River delta (approximately 5.4 mm/yr). In the Colorado delta, these rates are apparently equal to or higher than rates of relative sea-level rise, but in the Trinity River delta relative sea-level rise (the major component of which is subsidence) appears to be surpassing sedimentation. These conclusions are consistent with historical analyses of trends in the deltaic wetlands, which indicate an overall increase in marsh area in the Colorado River delta, and an overall decrease in the Trinity River delta.

The general trend in fluvial-deltaic wetlands along the Texas coast is one in which vegetated wetlands are being replaced by water and barren flats. The most extensive losses of vegetated wetlands have occurred along the San Jacinto and Neches Rivers, which, together, account for more than 70 percent of the total losses documented. Losses of vegetated wetlands are significantly less along other rivers, including the Nueces, Guadalupe, and Lavaca. Factors contributing to losses include (1) those processes that result in a rise in water level relative to the land's surface, including man-induced subsidence, natural regional compactional subsidence, and global sea-level rise, and (2) those processes that tend to reduce sediment input into marshes including (a) reservoir development in river drainage basins, which reduces river sediment loads, and (b) channelization and disposal of spoil on natural levees, which can alter water circulation patterns and prevent overbank flooding.

With relative sea-level rise along the Texas coast matching rates reported in some areas of the Gulf coast of Louisiana, and with marked declines in fluvial sediments delivered to many Texas coastal fluvial-deltaic and estuarine systems, it is probable that marsh sedimentation rates and bay floor sedimentation rates are no longer keeping pace with rates of relative sea-level rise in many areas. This conclusion is supported by observations in selected areas, including the systematic investigation of historical changes in interior marshes in fluvial-deltaic areas, and measurements of marsh sedimentation rates in two areas along the Texas coast. Relatively recent comparisons of bathymetric data in the Galveston-Trinity bay system indicate that water depths have increased as a result of subsidence (Morton and McGowen, 1980). More up-to-date comparisons of bathymetric data in all Texas bay-estuary-lagoon systems would provide current information on shoaling or submergence/erosion rates to compare with earlier studies.

Many questions remain with regard to fluvial-deltaic sedimentation and the processes that affect it, such as river sediment load and subsidence. Establishment and operation of stream-discharge and sediment-load (including bed load) measuring stations on many streams at locations closer to the coast would allow a better estimation of the quantities of fluvial sediments delivered to the bay-estuary-lagoon systems. In addition, more extensive and detailed investigations of sedimentation and its relationship to river flooding, sediment load, and tide levels would help provide a more complete picture of the role of riverine discharge in marsh and estuarine sedimentation along the Texas coast.

ACKNOWLEDGMENTS

Funding for this study was provided by the Texas Parks and Wildlife Department and Water Development Board through the Board's Water Research and Planning Fund, authorized under Texas Water Code Sections 15.402 and 16.058 (e), and administered (1) by the Department under interagency cooperative contract No. IAC(88-89)1457, and (2) by the Texas Parks and Wildlife deparment under IAC (88-89) 0820 and 1423.

REFERENCES

Barth, M. C., and Titus, J. G., 1984, Greenhouse effect and sea level rise - a challenge for this generation: New York, Van Nostrand Reinhold Company, 325 p.

Baumann, R. H., 1980, Mechanisms of maintaining marsh elevation in a subsiding environment: Louisiana State University, Master's thesis, 92 p.

Baumann, R. H., Day, J. W., Jr., and Miller, C. A., 1984, Mississippi deltaic wetland survival: sedimentation versus coastal submergence: Science, v. 224, no. 4653, p. 1093-1095.

Baumann, R. H., and DeLaune, R. D., 1982, Sedimentation and apparent sea-level rise as factors affecting land loss in coastal Louisiana, in Boesch, D. F., ed., Proceedings of the conference on coastal erosion and wetland modification in Louisiana: causes, consequences, and options: U.S. Fish and Wildlife Service, Biological Services Program, FWS/OBS-82/59, p. 2-13.

Boesch, D. F., Levin, D., Nummedal, D., and Bowles, K., 1983, Subsidence in coastal Louisiana: causes, rates, and effects on wetlands: U.S. Fish and Wildlife Service, Division of Biological Services, Washington, D.C., FWS/OBS-83/26, 30 p.

Burrell, D. C., and Schubel, J. R., 1977, Seagrass ecosystem oceanography, in McRoy, C. P., and Helfferich, C., eds., Seagrass ecosystems: New York, Marcel Dekker Inc., p. 195-232.

DeLaune, R. D., Patrick, W. H., Jr., and Buresh, R. J., 1978, Sedimentation rates determined by 137-Cs dating in a rapidly accreting salt marsh: Nature, v. 275, p. 401-412.

Frey, R. W., and Basan, P. B., 1985, Coastal salt marshes, in Davis, R. A., Jr., ed., Coastal sedimentary environments, second revised, expanded edition: New York, Springer-Verlag, p. 225-301.

Gabrysch, R. K., 1984, Ground-water withdrawals and land-surface subsidence in the Houston-Galveston region, Texas, 1906-1980: Texas Department of Water Resources Report 287, 64 p.

Gagliano, S. M., Meyer-Arendt, K. J., and Wicker, K. M., 1981, Land loss in the Mississippi River deltaic plain: Gulf Coast Association of Geological Societies Transactions, v. 31, p. 271-273.

Gornitz, V., Lebedeff, S., and Hansen, J., 1982, Global sea level trend in the past century: Science, v. 215, p. 1611-1614.

Hatton, R. S., DeLaune, R. D., and Patrick, W. H., Jr., 1983, Sedimentation, accretion, and subsidence in marshes of the Barataria Basin, Louisiana: Limnology and Oceanography, v. 28, no. 3, p. 494-502.

Isphording, W. C., 1986, Apalachicola Bay: dynamic sedimentation in a Gulf Coast estuary: Gulf Coast Association of Geological Societies Transactions, v. 36, p. 471-488.

LeBlanc, R. J., and Hodgson, W. D., 1959, Origin and development of the Texas shoreline, in Russell, R. J., chm., Coastal geography conference, 2nd: Baton Rouge, Louisiana State University, Coastal Studies Institute, p. 57-101.

Letzsch, W. S., and Frey, R. W., 1980, Deposition and erosion in a Holocene salt marsh, Sapelo Island, Georgia: Journal of Sedimentary Petrology, v. 50, no. 2, p. 529-542.

Lund, E. J., 1957, Self-silting by the oyster and its significance for sedimentation geology: University of Texas, Publications of the Institute of Marine Science, v. 4, no. 2, p. 320-327.

Morton, R. A., and McGowen, J. H., 1980, Modern Depositional Environments of the Texas Coast: The University of Texas at Austin, Bureau of Economic Geology, Guidebook 20, 167 p.

Morton, R. A., and Paine, J. G., 1984, Historical shoreline changes in Corpus Christi, Oso, and Nueces Bays, Texas Gulf Coast: The University of Texas at Austin, Bureau of Economic Geology Geological Circular 84-6, 66 p.

Oenema, Oene, and DeLaune, R. D., 1988, Accretion rates in salt marshes in the Eastern Scheldt, Southwest Netherlands: Estuarine, Coastal and Shelf Science, v. 26, p. 379-394.

Paine, J. G., and Morton, R. A., 1986, Historical shoreline changes in Trinity, Galveston, West, and East Bays, Texas Gulf Coast: The University of Texas at Austin, Bureau of Economic Geology Geological Circular 86-3, 58 p.

Pethick, J. S., 1981, Long-term accretion rates on tidal marshes: Journal of Sedimentary Petrology, v. 51, no. 2, p. 571-577.

Redfield, A. C., 1972, Development of a New England salt marsh: Ecological Monographs, v. 42, no. 2, p. 201-237.

Rice, R. H., 1967, A study of the suspended load of the Trinity River, Texas: Rice University, Houston, Texas, Master's thesis, 47 p.

Shepard, F. P., 1953, Sedimentation rates in Texas estuaries and lagoons: American Association of Petroleum Geology Bulletin, v. 37, no. 8, p. 1919-1934.

Smith, J. M., and Frey, R. W., 1985, Biodeposition by ribbed mussel, Geukensia demissa, in a salt marsh, Sapelo Island, Georgia: Journal of Sedimentary Petrology, v. 55, no. 6, p. 817-828.

Stevenson, J. C., Ward, L. G., and Kearney, M. S., 1986, Vertical accretion in marshes with varying rates of sea level rise, in Wolfe, D. A., ed., Estuarine variability: New York, Academic Press, p. 241-259.

Stumpf, R. P., 1983, The process of sedimentation on the surface of a salt marsh: Estuarine, Coastal and Shelf Science, v. 17, no. 5, p. 495-508.

Swanson, R. L., and Thurlow, C. I., 1973, Recent subsidence rates along the Texas and Louisiana coasts as determined from tide measurements: Journal of Geophysical Research, v. 78, no. 5, p. 2665-2671.

Texas Department of Water Resources, 1982, The influence of freshwater inflows upon the major bays and estuaries of the Texas Gulf coast: Texas Department of Water Resources, Executive Summary, LP-115, 53 p.

Texas Water Development Board, 1973, Engineering data on dams and reservoirs in Texas, part II: Texas Water Development Board Report 126, unpaginated.

Turner, R. E., 1987, Tide gage records, geological subsidence and sedimentation patterns in the northern Gulf of Mexico marshes, in Turner, R. E., and Cahoon, D. R., eds., Causes of wetland loss in the coastal central Gulf of Mexico: volume II: technical narrative, final report submitted to Minerals Management Service, New Orleans, Louisiana, contract no. 14-12-0001-30252, OCS study/MMS 87-0120, 400 p.

Van Heerden, I. Li., Wells, J. T., and Roberts, H. H., 1981, Evolution and morphology of sedimentary environments, Atchafalaya Delta, Louisiana: Gulf Coast Association of Geological Societies Transactions, v. 31, p. 399-408.

Ward, L. G., Kemp, W. M., and Boynton, W. R., 1984, The influence of waves and seagrass communities on suspended particulates in an estuarine embayment: Marine Geology, v. 59, p. 85-103.

Wells, J. T., and Coleman, J. M., 1987, Wetland loss and the subdelta life cycle: Estuarine, Coastal and Shelf Science, v. 25, p. 111-125.

White W. A., and Calnan, T. R., 1990a, Sedimentation in fluvial-deltaic wetlands and estuarine areas, Texas Gulf Coast, literature synthesis: The University of Texas at Austin, Bureau of Economic Geology, Report prepared for the Texas Parks and Wildlife Department under IAC (88-89) 0820 and 1423, 261 p.

White W. A., and Calnan, T. R., 1990b, Sedimentation and historical changes in fluvial-deltaic wetlands along the Texas coast with emphasis on the Colorado and Trinity River deltas: The University of Texas at Austin, Bureau of Economic Geology, Report prepared for the Texas Parks and Wildlife Department under IAC (88-89) 1423, 124 p. and 7 appendices.

White, W. A., Calnan, T. R., Morton, R. A., Kimble, R. S., Littleton, T. G., McGowen, J. H., and Nance, H. S., 1987, Submerged lands of Texas, Beaumont-Port Arthur area: sediments, geochemistry, benthic macroinvertebrates, and associated wetlands: The University of Texas at Austin, Bureau of Economic Geology Special Publication, 110 p., 6 plates.

White, W. A., Calnan, T. R., Morton, R. A., Kimble, R. S., Littleton, T. G., McGowen, J. H., Nance, H. S., and Schmedes, K. E., 1985, Submerged lands of Texas, Galveston-Houston area: sediments, geochemistry, benthic macroinvertebrates, and associated wetlands: The University of Texas at Austin, Bureau of Economic Geology Special Publication, 145 p., 6 plates.

Wilkinson, B. H., and Byrne, J. R., 1977, Lavaca Bay transgressive deltaic sedimentation in central Texas USA estuary: American Association of Petroleum Geologists Bulletin, v. 61, no. 4, p. 527-545.

Williams, G. P., and Wolman, G. M., 1984, Downstream effects of dams on alluvial rivers: U.S. Geological Survey Professional Paper 1286, 64 p.