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Submergence of Wetlands as a Result of Human-Induced Subsidence and Faulting along the upper Texas Gulf Coast

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ABSTRACT

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Loss of wetlands in the northern Gulf of Mexico has been attributed to numerous processes and is of continuing concern. This paper synthesizes and examines the distribution and extent of wetland losses along the upper Texas coast in relation to subsidence and faulting associated with underground fluid production. Since the 1930's, these processes have been of primary importance along the upper Texas coast, contributing to the conversion of thousands of hectares of vegetated coastal wetlands to either open water or shallow subaqueous flats. Relatively large wetland losses have occurred in salt, brackish, and fresh marshes and woodlands in the Galveston Bay and Sabine Lake estuarine systems on the upper Texas coast. Throughout Galveston Bay, approximately 10,700 ha of wetland habitat has been permanently inundated, with major losses occurring on the north and west sides of the bay system, including 3,600 ha in fluvial-deltaic areas along the San Jacinto and Trinity Rivers. More than 5,000 ha of vegetated wetlands have been submerged along the lower reaches of the Neches River since the 1950's. Although many processes or activities can lead to loss of wetlands, there is evidence that the major contributing factor in this change along the upper Texas coast is human-induced subsidence caused by ground-water withdrawal. In addition, submergence of wetlands in some areas is associated with more localized faulting and subsidence apparently related to hydrocarbon production. Human-induced subsidence and faulting accelerate rates of relative sea-level rise so they greatly exceed rates of wetland vertical accretion. In fluvial-deltaic areas, where there is the potential for fluvial sediment deposition to offset submergence, upstream dams and reservoirs trap sediments and prevent their delivery to coastal wetlands. Although rates of submergence and wetland loss generally increased from the 1930's to 1980's, rates have declined in some areas since the 1970's, a trend that possibly tracks diminishing rates of human-induced subsidence.

ADDITIONAL INDEX WORDS: *Faults, Galveston Bay, marsh loss, marsh sedimentation, relative sea-level rise, Sabine Lake, subsidence rates.*

INTRODUCTION

The most extensive losses of coastal wetlands in the United States over the past two decades have occurred along the coast of the northern Gulf of Mexico. Almost 60 percent of the wetland losses are due to conversion of salt and brackish marshes to open water (DAHL *et al.*, 1991). Extreme loss of coastal wetlands have been reported in Louisiana (GAGLIANO *et al.*, 1981; BRITSCH and DUNBAR, 1993) and in Texas (WHITE *et al.*, 1985, 1987, 1993), where approximately 58 percent of the Nation's salt and brackish marshes are located (FIELD *et al.*, 1991).

Wetland losses in Louisiana have been severe (BRITSCH and DUNBAR, 1993), with their extent and causes reasonably well known (TURNER and CAHOON, 1988; PENLAND *et al.*, 1990; WILLIAMS *et al.*, 1993). Such is not the case in Texas. Only recently through comprehensive studies of wetlands along the Texas coast (WHITE and CALNAN, 1991; WHITE *et al.*, 1993) has a more quantitative understanding of wetland losses been determined on a regional scale. In Louisiana, a combination of natural and artificial causes of wetland loss have been identified, including compactional subsidence, delta abandonment, sea-level rise, severe storms, geosynclinal downwarping, long-term climate change, construction of dams and levees for flood control, dredging of canals, mineral extraction, and subsurface fluid withdrawal (PENLAND *et al.*, 1990; WILLIAMS *et al.*, 1993). Most of these processes have also affected Texas coastal wetlands, but one process is of primary importance—subsurface fluid withdrawal. In Louisiana, this process is considered of local importance (TURNER and CAHOON, 1988), but along the upper Texas coast, subsurface fluid withdrawal, a process that has accelerated subsidence, is considered a primary cause of wetland submergence and loss of

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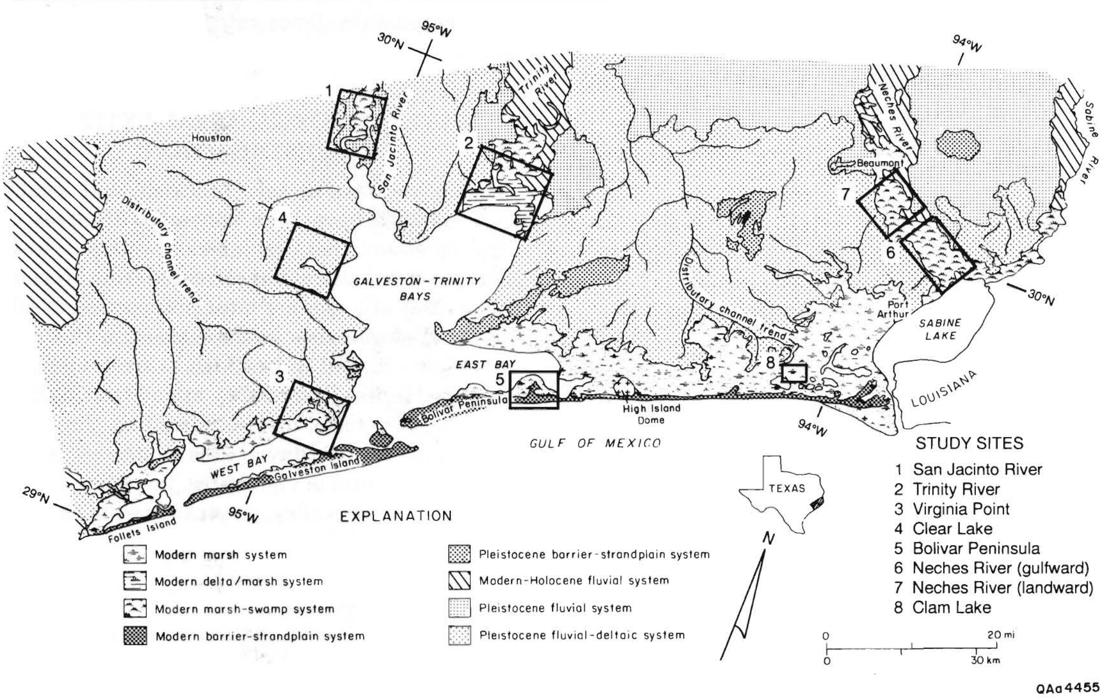


Figure 1. Study sites in relation to upper Quaternary depositional systems. Modified from FISHER *et al.* (1972, 1973).

emergent vegetation (WHITE *et al.*, 1993). This paper examines the relationship between wetland loss and accelerated relative sea-level rise resulting from human-induced subsidence and faulting along the upper Texas coast.

Geologic Setting

The regional geologic framework of the upper Texas coast consists of two major estuaries, Sabine Lake and Galveston Bay, and a complex array of Holocene and Pleistocene depositional systems (FISHER *et al.*, 1972, 1973) (Figure 1). The estuaries formed when valleys entrenched by major rivers during Wisconsinan glaciation and sea-level lowstand were flooded during the post-glacial sea-level rise (LEBLANC and HODGSON, 1959). The shallowness of the estuaries (< 3 m) indicates that the entrenched valleys, incised to depths locally exceeding 30 m (KANE, 1959; REHKEMPER, 1969), have been largely filled with Holocene sediment. Inland parts of the various river valleys, where entrenchment was not as deep and fluvial sediment supply is abundant, have been completely filled. In the case of the Trinity River, a bayhead delta has prograded over estuarine muds at the head of Trinity Bay.

Prominent depositional features along the upper Texas coast include a modern strandplain-chenier system (FISHER *et al.*, 1973) in an interfluvial area southwest of Sabine Lake, and an extensive barrier island and peninsula complex that separates the bays and lagoons of Galveston Bay from the Gulf of Mexico (Figure 1). Major fluvial systems include the San Jacinto and Trinity Rivers in the Galveston Bay system and the Neches and Sabine Rivers that flow into Sabine Lake (Figure 1).

Distribution of Wetlands

Brackish and salt marshes are extensive along the upper Texas coast (WHITE *et al.*, 1985, 1987). Brackish marshes, which commonly include *Spartina patens, Distichlis spicata, Spartina spartinae, Alternanthera philoxeroides, Phragmites australis, Scirpus maritimus,* and *Scirpus,* cover broad areas between Sabine Lake Americanus and Galveston Bay landward of the barrier-strand-plain-chenier system. Other occurrences are along the lower alluvial valleys and deltas of the Trinity and Neches Rivers, and on landward margins of East and West Bays (Figure 1). Salt marshes, which are composed of *Spartina alterniflora, Batis maritima, Salicornia* spp., *Distichlis spicata, Monanthochloe littoralis, Scirpus maritimus, Juncus roemerianus,* and at higher elevations *Spartina patens,* fringe the Galveston Bay system principally along the mainland and back-island shores of West Bay and the shores of Bolivar Peninsula in East Bay (WHITE and PAINE, 1992). Fresh marshes, fluvial woodlands and swamps occur along more inland reaches of the Sabine, Neches, Trinity, and San Jacinto Rivers (Figure 1).

Wetlands have developed on various Holocene and Pleistocene land forms. Thicknesses of Holocene sediments underlying wetlands range from more than 40 m at the southwest end of Bolivar Peninsula, which lies above the entrenched Pleistocene valley, to less than 1 m where marshes have developed on flooded Pleistocene surfaces along the inland margins of the marsh system. Thickness of Holocene sediments in the major fluvial-deltaic areas is generally less than 15 to 20 m, and in the interfluvial area between Sabine Lake and Galveston Bay, it is generally less than 10 m (based on unpublished soils borings).

Methods of Documenting Wetland Losses and Relationships to Subsidence

In studies of wetland losses from which this synthesis is derived, aerial photographs taken in the 1930's, 1950's, 1970's, and 1980's, supported by field surveys, were used to determine changes in wetland distribution. Two major map units were used in the analysis (1) vegetated areas and (2) open water and unvegetated flats. Units delineated on photographs were transferred to base maps from which spatial and temporal changes were determined primarily through digitization and entry of data into a geographic information system (WHITE *et al.*, 1993) and secondarily with a grid system used to measure mapped areas (WHITE *et al.*, 1985, 1987). Losses throughout the entire Galveston Bay system have been documented (Figure 2), but only major losses have been quantified in the Sabine Lake estuarine system and in the interfluvial area between Sabine Lake and Galveston Bay (Figure 1). Wetland areas undergoing submergence were examined with respect to subsidence patterns (GABRYSCH, 1984; GABRYSCH and BONNET, 1975; GABRYSCH and COPLIN, 1990) to define spatial and temporal relationships between submergence and subsidence and to identify significant differences between documented subsidence rates and possible wetland vertical accretion rates.

WETLAND LOSSES, AREAL EXTENT AND DISTRIBUTION

Extensive areas of salt, brackish, and locally fresh marshes have been converted to areas of open water and flats as interior wetlands were submerged and shorelines retreated from erosion. These kinds of losses are most pronounced in salt and brackish marshes in the Galveston Bay system (Figure 2) and in brackish to fresh marshes along the Neches River valley inland from Sabine Lake. Losses have also occurred in brackish marshes in the interfluvial area southwest of Sabine Lake. A total of eight sites, including two in the Neches River valley, are examined in this paper (Figure 1).

Galveston Bay System

The Galveston Bay System ranks as the seventh largest estuary in the United States (MCKINNEY *et al.*, 1989), encompassing almost 163,000 ha of estuarine open water and an additional 52,800 ha of marsh (WHITE *et al.*, 1993). Brackish and salt marshes compose about 83 percent of the marsh system, with fresh marshes making up the remaining 17 percent. From the 1950's to 1989, approximately 10,700 ha of marsh was converted to open water and flats (WHITE *et al.*, 1993). Major areas impacted include wetlands in the San Jacinto and Trinity River valleys, Virginia Point (an area south of Texas City), Bolivar Peninsula, and nearshore areas along west Galveston Bay (Figure 2 and Table 1).

San Jacinto River

In the lower San Jacinto River valley at the head of Galveston Bay, more than 570 ha of fluvial woodlands, swamps, and fresh to brackish marshes were replaced by open water between 1956 and 1979 (WHITE *et al.*, 1985; Figure 3). Aerial photographs taken in the 1930's, 1950's, and 1980's show that water progressed up the San Jacinto River valley, displacing wetlands and uplands (WHITE and CALNAN, 1991). During the 26-year period between 1930 and 1956, emergent areas decreased by 590 ha, and between 1956 and 1986, by 1,259 ha (Table 1). The rate of vegetated-area loss (fluvial woodlands, swamps, and marshes) in-

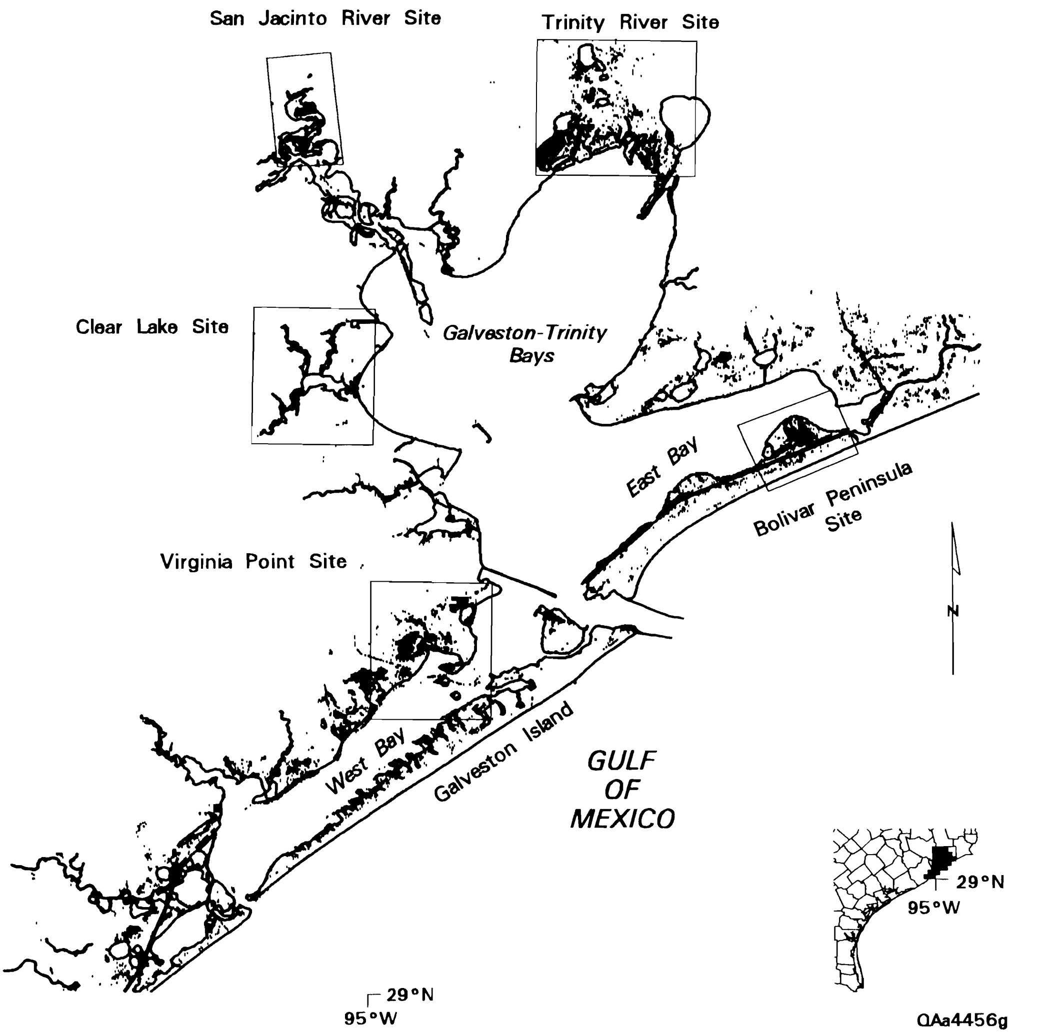


Figure 2. Study sites in the Galveston Bay system in relation to marsh areas (in black) that were converted to open water and flats between the 1950's and 1989. Modified from WHITE *et al.* (1993).

creased from about 23 ha yr^{-1} to more than 40 ha yr^{-1} during these two periods.

Trinity River

The Trinity River delta, at the head of Trinity Bay, is the only natural bay-head delta in Texas that has undergone significant progradation in recent historic times. Historical analysis of the Trinity River delta using aerial photographs taken in 1930, 1956, 1974, and 1988 (WHITE and CALNAN, 1991) shows that delta progradation continued from 1930 to 1956, when approximately 600 ha of marsh was added to the delta. This trend in marsh gain was reversed between 1956 and 1974, when 1,445 ha of mostly marshland was converted to open water and unvegetated flat. Vegetated wetlands continued to shrink by an additional 90 ha between 1974 and 1988. Although some wetland losses around the Trinity River delta have resulted from bay shoreline erosion (PAINE and MORTON, 1986), the most extensive losses have occurred in interior marshes. From 1953 to 1989, wetland losses exceeded 1,742 ha in the delta and

Table 1. *Submergence of vegetated wetlands along the upper Texas coast. See Figure 1 for site locations. All but interfluvial area compiled from* WHITE et al. *(1985, 1987, and 1993), and* WHITE *and* CALNAN *(1991).*

Location	Period	Gain or Loss (hectares)
Galveston Bay System		
San Jacinto River	1930–1956	−590
	1956–1986	−1,259
Trinity River	1930–1956	+596
	1956–1974	−1,445[1]
	1974–1988	−89
Trinity River	1953–1989	−1,742[2]
Virginia Point	1952–1989	−1,470
Clear Lake	1952–1989	−355
Bolivar Peninsula	1952–1989	−600
Sabine Lake Estuarine System		
Neches River		
Site 6 (see Figure 1)	1956–1978	−3,811
Site 7 (see Figure 1)	1938–1956	−340
	1956–1987	−1,306
Interfluvial area (Clam Lake)	1930–1956	0
	1956–1987	−277
Total losses (Trinity River data includes only 1953–1989)		−11,750

[1] Includes approximately 600 ha of marsh submerged by a power plant cooling reservoir

[2] This area (from WHITE *et al.*, 1993) includes more alluvial valley than the preceding site along the Trinity River. It also includes the power plant cooling reservoir, which accounts for 600 ha of marsh loss

lower reaches of the Trinity River alluvial valley (WHITE *et al.*, 1993, Figure 2).

Virginia Point

Wetland losses near Virginia Point, located on the inland margin of West Bay south of Texas City (Figure 2), are among the most extensive in the Galveston Bay system. Approximately 1,470 ha of primarily regularly flooded salt marsh was replaced by open water and mud flats between the early 1950's and 1989 (WHITE *et al.*, 1993). Wetland losses in the Virginia Point area have previously been reported by JOHNSTON and ADER (1983), and WHITE *et al.*, (1985).

Western Margins of Galveston Bay (Clear Lake)

The Clear Lake study site, which encompasses the lake and tributaries on the western margin of Galveston Bay (Figure 2), is an example of wetland submergence along bayous and creeks connecting to Galveston Bay. In the Clear Lake area, approximately 355 ha of vegetated wetland habitat was converted to open water and flats between the 1950's and 1980's (WHITE *et al.*, 1993). Ninety-one percent of the emergent wetlands located along Armand Bayou, which discharges into Clear Lake, disappeared between the early 1950's and 1979 (MCFARLANE, 1991).

Bolivar Peninsula

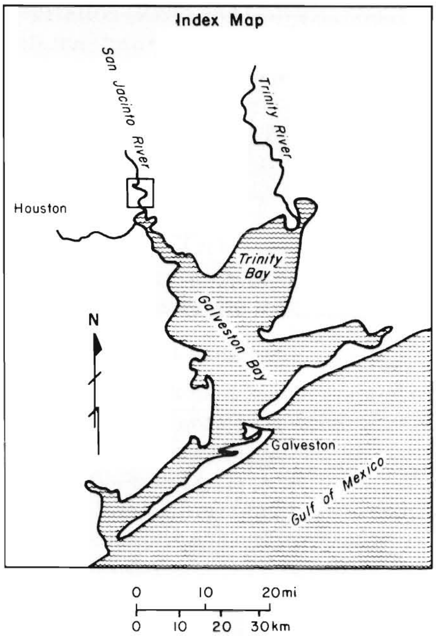
A relatively large salt marsh occurs on the relict tidal inlet/washover fan complex on the bayward side of Bolivar Peninsula in East Bay (Figure 2). Aerial photographs taken in 1930 indicate that the marsh system was well vegetated and interior marshes had not yet begun to deteriorate. By 1956 open water had begun to replace vegetated areas, and between 1956 and 1979, approximately 600 ha of emergent vegetation was replaced primarily by shallow subaqueous flats and open water (Figure 4).

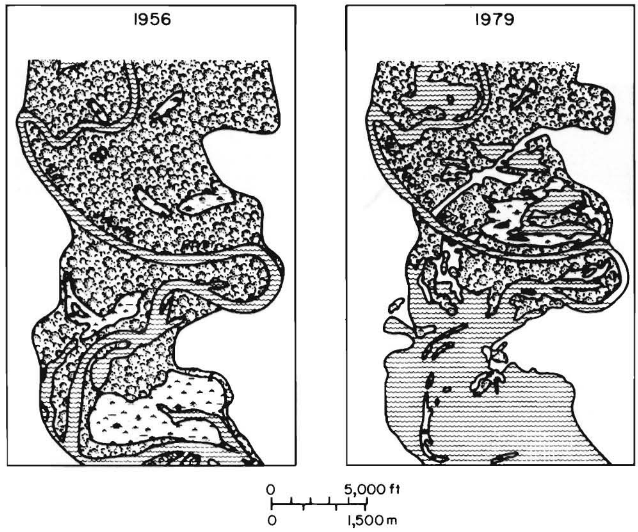
Sabine Lake Estuarine System and Interfluvial Area

Sabine Lake is about one-eighth of the size of Galveston Bay in terms of area of estuarine open water (DIENER, 1975), but an extensive marsh complex occurs in the strandplain-chenier system southwest of the lake extending westward in the interfluvial area that separates the two bay systems. Additional wetlands are located inland from the lake along the modern rivers (Figure 1).

Neches River

The Neches River, which discharges at the head of Sabine Lake, is the site of a large marsh-swamp complex that has developed on fluvial and fluvial-deltaic deposits within the entrenched valley (FISHER *et al.*, 1973). The most extensive loss of contiguous wetlands on the Texas coast has occurred within the Neches River valley (WHITE *et al.*, 1987; WHITE and CALNAN, 1991). Two areas along a 25-km reach of the Neches lower valley have been investigated (Figure 1). Vegetated wetlands in both areas underwent substantial losses after the 1950's. Between the mid-1950's and 1978, 3,810 ha of marsh was displaced primarily by open water along an approximately 16-km stretch of the lower Neches River valley (Figure 5). The rate of loss was almost 160 ha yr^{-1}. Additional losses in fresh-water marshes, woodlands, and swamps have occurred upstream from this site (WHITE and CALNAN, 1991). At the upstream site, emer-





Wetland Map Unit	1956		1979		Net Change	
	Acres	Hectares	Acres	Hectares	Acres	Hectares
Water	875	355	2,295	930	+1,420	+ 575
Fluvial Woodlands & Swamps	3,480	1,410	2,090	845	−1,390	− 565
Fresh to Brackish Marsh	650	265	300	120	−350	−145

QA 937

Figure 3. Changes in the distribution of wetlands between 1956 and 1979 within a subsiding segment of the San Jacinto River near Houston, Texas. The difference in net changes in water and vegetated wetlands is due principally to devegetation of wetlands from other processes such as pipeline construction and mining of sand resources. From WHITE *et al.* (1985).

gent vegetation decreased by about 340 ha between 1938 and 1956, and by approximately 1,300 ha between 1956 and 1987. These losses translate into averages rates of 19 ha yr^{-1} for the earlier period and 42 ha yr^{-1} for the latter period.

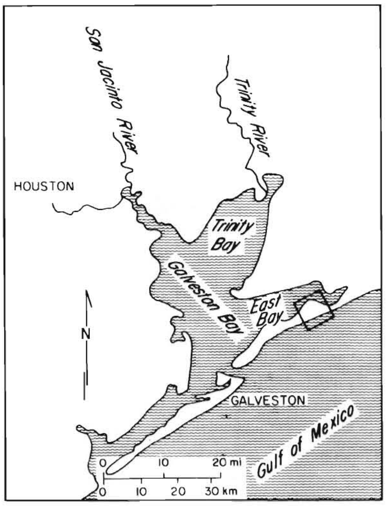
Interfluvial Area (Clam Lake)

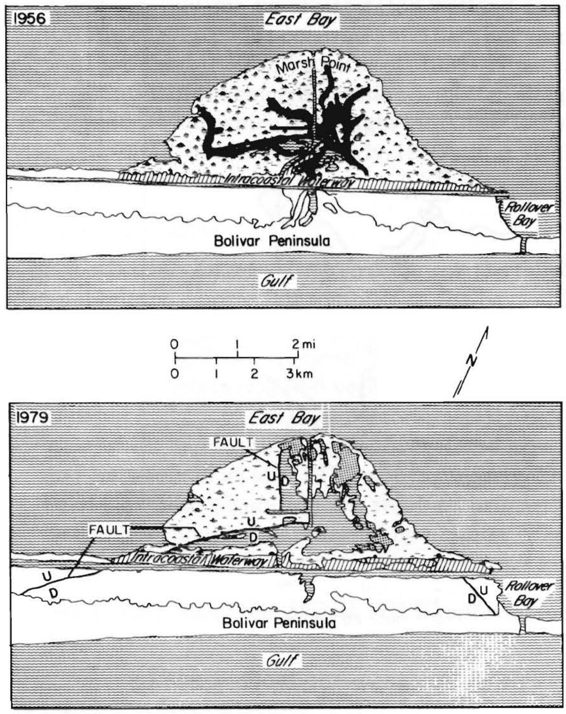
Losses in vegetated wetlands are not restricted to estuaries and fluvial-deltaic systems. In the interfluvial area southwest of Sabine Lake, conversion of emergent vegetation to open water occurred in the broad brackish-marsh complex. This marsh complex has developed on a relatively thin wedge of Holocene sediments (generally < 10 m thick; unpublished Bureau of Economic Geology soil borings) landward of the modern barrier/strandplain system (Figure 1). The area of marsh loss investigated is near Clam Lake, which is about 19 km southwest of Sabine Lake and approximately 4 km inland from the Gulf shoreline. Additional marsh loss has occurred within this interfluvial area nearer to Sabine Lake, but these losses have not been quantified.

Almost 280 ha of brackish marsh was converted to open water between the mid 1950's and 1987 in the area immediately northeast of Clam Lake. In fact, most of the conversion had occurred by 1978. Coalescing ponds formed landward of a northeast-southwest-oriented lineament (WHITE *et al.*, 1987).

MAJOR CAUSES OF WETLAND LOSS

Conversion of vegetated wetlands to water and barren flats may result from several interactive





Wetland Map Unit	1956		1979		Net Change	
	Acres	Hectares	Acres	Hectares	Acres	Hectares
Water	140	57	1130	458	+990	+401
Marsh	3480	1409	2560	1037		
Marsh-covered tidal channels	640	259				
TOTAL MARSH	4120	1669	2560	1037	-1560	-632
Barren tidal flats			270	109	+270	+109
Dredged spoil/uplands	520	211	720	292	+200	+81
TOTAL	4780	1936	4680	1896	-100*	-40*

*Most of the loss in total area is probably due to erosion of marsh along the margins of East Bay. Historical monitoring indicates that this shoreline is undergoing erosion at rates of up to 3ft (1m) per year (Paine and Morton, 1986)

(Areas were calculated using a square-count method; smallest squares used were equivalent to 6.4 acres or 2.6 hectares).

QA 1774

Figure 4. Changes in distribution of wetlands between 1956 and 1979 near Marsh Point on the bayward side of Bolivar Peninsula. Increases in the areal extent of open water and decreases in the areal extent of marsh are apparently related to localized subsidence and active faults (D = downthrown side of fault, U = upthrown side). From WHITE *et al.* (1985).

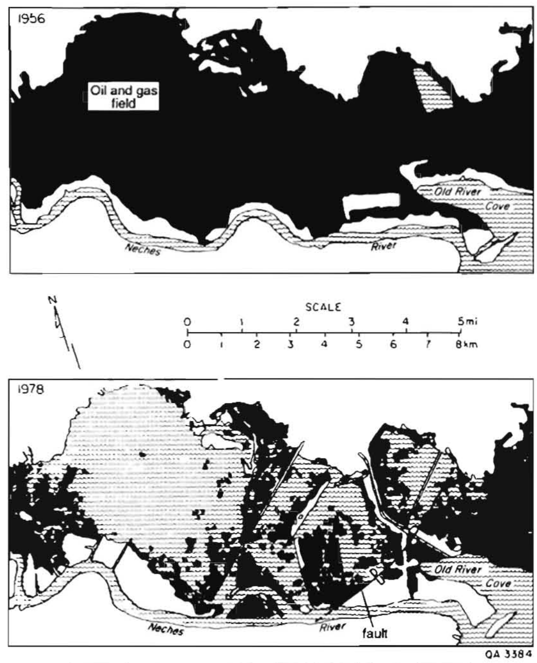
processes, including natural and artificial changes in hydrology, intrusion of salt water into fresh areas, reductions or alterations in sediment supply and dispersal, dredging of canals, climatic changes, subsidence, and high rates of relative sea-level rise (TURNER and CAHOON, 1988; PENLAND *et al.*, 1990; WILLIAMS *et al.*, 1993). Submergence of wetlands in many areas indicates that wetland vertical accretion rates are not sufficient to offset rates of relative sea-level rise (BAUMANN and DELAUNE, 1982). Although marsh vertical accretion rates tend to track rates of relative sea-level rise (NIXON, 1980; STEVENSON *et al.*, 1985), the upper limit, based on organic matter production, is estimated to be 14 to 16 mm yr^{-1} (BRICKER-URSO *et al.*, 1989). In Louisiana, marsh vertical accretion rates, which are among the highest on the Gulf Coast, range from about 13 mm yr^{-1} in levee areas to less than 8 mm yr^{-1} in backmarshes (HATTON *et al.*, 1983). Rates of relative sea-level rise exceed vertical accretion rates in many areas, and marshes are being replaced by open water (DELAUNE *et al.*, 1983; HATTON *et al.*, 1983; BAUMANN *et al.*, 1984). Although the imbalance between rates of vertical accretion and relative sea-level rise can be expressed as an accretion deficit and corresponding loss in elevation, REED and CAHOON (1993) suggest that direct determinations of elevation provides a better measure of the elevation change and the relationship between subsidence and accretion. Low elevations, which lead to increased frequency and duration of flooding, can result in deterioration and eventual loss of vegetation (REED and CAHOON, 1992). Vegetation loss may be a result of plant dieback or soil erosion below the living root zone (NYMAN *et al.*, 1993).

Along the upper Texas coast numerous interactive processes of natural and artificial origin are undoubtedly involved in the submergence and deterioration of wetlands. Regional human-induced subsidence and faulting, which have greatly accelerated rates of relative sea-level rise, appear to be the primary processes affecting wetlands in areas where losses are most pronounced.

Human-Induced Subsidence

Holocene sediment sequences underlying wetlands in Texas are not as thick as in Louisiana, and therefore coastwide natural compactional subsidence is not as high (RAMSEY and PENLAND, 1989). However, regional human-induced subsidence caused by subsurface fluid production has been extensive and has affected a relatively large area in the Galveston Bay system (Figure 6). Rates of "natural" compactional subsidence and eustatic sea-level rise, which together may range up to 13 mm yr^{-1} along the upper Texas coast (SWANSON and THURLOW, 1973; LYLES *et al.*, 1988), are greatly exceeded by human-induced subsidence with rates of up to almost 120 mm yr^{-1} from 1964 to 1973 (GABRYSCH and BONNET, 1975). The major cause of human-induced subsidence is the withdrawal of underground fluids, principally ground water, oil, and gas (PRATT and JOHNSON, 1926; WINSLOW and DOYEL, 1954; GABRYSCH, 1969; YERKES and CASTLE, 1969; KREITLER, 1977; PAINE, 1993).

In the Houston-Galveston area, there has been up to 3 m of land-surface subsidence from large-scale ground-water withdrawal since 1906 (GABRYSCH and COPLIN, 1990). The subsidence "bowl" encompasses an area of approximately 943,500 ha where a minimum of 30 cm of subsidence has occurred (Figure 6). The large Houston subsidence bowl merges with a secondary depression bowl centered on Texas City (Figure 6). From the early 1940's to late 1970's, rates of subsidence were exceptionally high, more than 75 mm yr^{-1} in the area of maximum subsidence (GABRYSCH and COPLIN, 1990). Since the late 1970's rates in some areas, notably the eastern part of the subsidence bowl and Texas City, have declined substantially due to the curtailment of ground-water pumpage (GABRYSCH and COPLIN, 1990).



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 5. Changes in the distribution of wetlands between 1956 and 1978 in the lower Neches River Valley at the head of Sabine Lake. Site 6 on the Neches River shown in Figure 1. The fault crossing this area has apparently contributed to the changes (D = downthrown side, U = upthrown side). From WHITE *et al.* (1987).

Faulting

Subsidence in some areas has occurred along active faults that intersect wetlands. The major zone of surface faulting along the Texas coast is in the Houston-Galveston area where 150 linear km of faulting has been reported (BROWN *et al.*, 1974). Surface faults correlate with, and appear to be extensions of, subsurface faults in many areas (WEAVER and SHEETS, 1962; VAN SICLEN, 1967; KREITLER, 1977). Most of the surface faulting in the Houston metropolitan area has apparently taken place during the last few decades, largely due to fluid withdrawal (water, oil, and gas), which has reinitiated and accelerated fault activity (REID, 1973; KREITLER, 1977; VERBEEK and CLANTON, 1981).

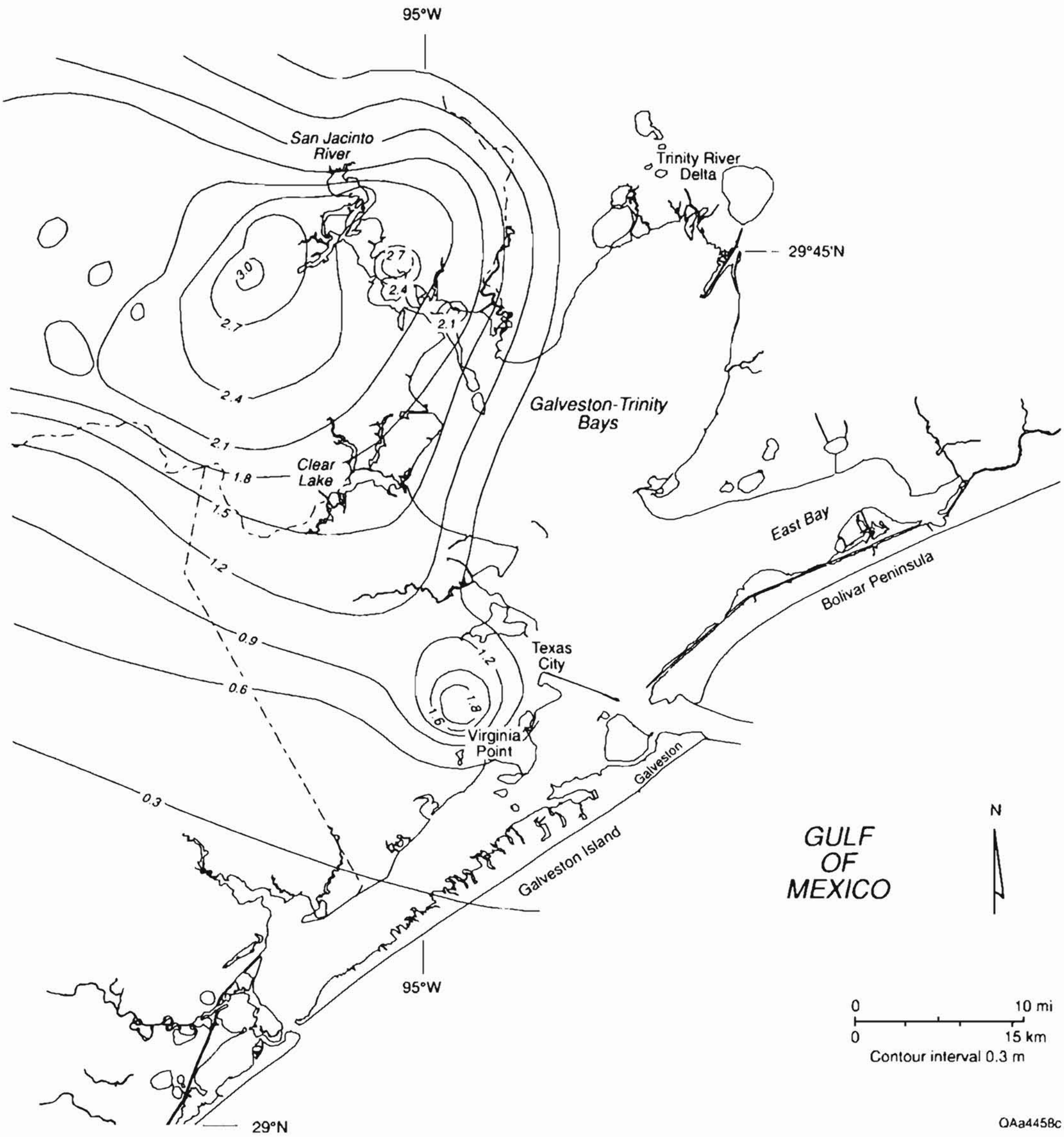


Figure 6. Land-surface subsidence in the Galveston Bay area, 1906 to 1987. Subsidence contours in meters are from GABRYSCH and COPLIN (1990).

The range in measurable vertical displacement of surface traces of faults is from 0 to 3.9 m (REID, 1973). Rates of fault movement commonly range between 5 mm yr^{-1} and 20 mm yr^{-1} (VERBEEK and CLANTON, 1981) but may exceed 40 mm yr^{-1} (VAN SICLEN, 1967; REID, 1973). Movement along surface faults apparently occurs episodically (REID, 1973). Highways, railroads, industrial complexes, airports, homes, and other structures placed on active faults in the Houston area have undergone millions of dollars worth of damage annually (VERBEEK and CLANTON, 1981).

As vertical displacement occurs along a fault that intersects a marsh, more frequent and eventually permanent inundation of the surface on the downthrown side of the fault can lead to replace-

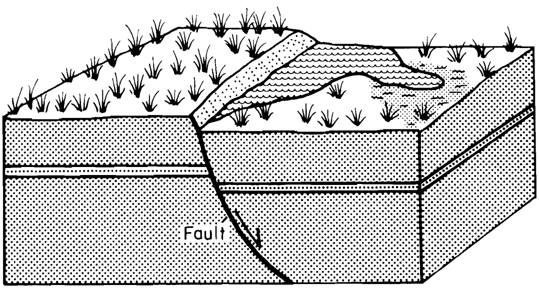


FIGURE 7. Block diagram of changes in wetlands that may occur along an active surface fault. There is generally an increase in low marshes, shallow subaqueous flats, and open water on the downthrown side of the fault relative to the upthrown side. From WHITE *et al.* (1993).

Table 2. *Estimated rates of subsidence in wetlands undergoing submergence in the Galveston Bay system. Based on land-surface subsidence maps published by* GABRYSCH, *1984,* GABRYSCH *and* BONNET, *1975, and* GABRYSCH *and* COPLIN, *1990.*

Site	Subsidence for Selected Periods (mm/yr) 1906–1943	1964–1973	1973–1978	1978–1987
San Jacinto River	5	67	46	8
Trinity River	?	10–14	8	?
Clear Lake	3	60	61	17
Virginia Point	2–5	14–34	12–30	8

ment of marsh vegetation by open water (Figure 7). The loss of vegetation on the downthrown side of the fault but not the upthrown side indicates that the rate of relative sea-level rise exceeds the rate of marsh sedimentation on the downthrown side. More than 25 active faults that cross wetlands along the upper Texas coast (Freeport area to Sabine Pass) have been identified on aerial photographs. Most of the identified faults are in the Galveston Bay area (WHITE *et al.*, 1985). Not all the active faults are associated directly with oil and gas production.

Relationship Between Wetland Submergence and Subsidence and Faulting

Galveston Bay System

San Jacinto River. Although some wetland losses can be attributed to mining of sand in the San Jacinto River alluvial valley, most of the loss in marshes and fluvial woodlands is due to subsidence caused by ground-water withdrawal (GABRYSCH, 1984). Submergence along the San Jacinto River valley is pronounced because of its proximity to the center of maximum subsidence (Figure 6). Between 1964 and 1973, approximately 0.6 m of subsidence occurred in this area, which translates into rates as high as 67 mm yr^{-1} (Table 2). As subsidence occurs, submergence of wetlands and uplands progresses inland along the axis of the entrenched valley (Figure 3).

Lake Houston, with a sediment trapping efficiency of 87 percent (U.S. DEPARTMENT OF AGRICULTURE, 1959) and located only 16 km upstream from the mouth of the San Jacinto River, has undoubtedly reduced the amount of fluvial sediments reaching coastal wetlands. Nevertheless, the magnitude of land-surface subsidence in the river valley has been so great that it is unlikely aggradation rates could keep pace with past subsidence rates even if Lake Houston and other lakes had not been constructed. More recent subsidence rates are dramatically lower (GABRYSCH and COPLIN, 1990), however, and reductions in fluvial sediment supply may become a more significant factor in wetland loss in the future.

Trinity River. Approximately 40 percent of the submergence of wetlands in the Trinity River delta and alluvial valley (Figure 2) resulted from construction of a power plant cooling reservoir (more than 1,010 ha in size) in the southwestern part of the delta. Most of the remaining 60 percent of marsh loss, however, was due to submergence apparently associated with subsidence and declining river sediment loads (Figure 8). Benchmark releveling surveys across the Trinity River alluvial valley (BALAZS, 1980) indicate that subsidence rates from 1973 to 1978 approached 8 mm yr^{-1}. A similar rate was estimated for the period 1943–1973 (Table 2), and adding the Gulf of Mexico regional sea-level rise of 2.4 mm yr^{-1} (GORNITZ and LEBEDEFF, 1987) yields a relative sea-level rise of more than 10 mm yr^{-1} at this Trinity River site. Estimated rates of marsh sedimentation over the past 50 years, based on ^{210}Pb analysis in three cores from marshes in the Trinity River delta, average 5.4 mm yr^{-1} and range as low as 4.2 mm yr^{-1} (WHITE and CALNAN, 1990). The rate of relative sea-level rise is almost two times the average rate of sedimentation, or vertical accretion.

Even though the dramatic reduction in fluvial sediments (Figure 8) has likely contributed to marsh loss, subsidence appears to be the controlling factor. Excluding losses resulting from the

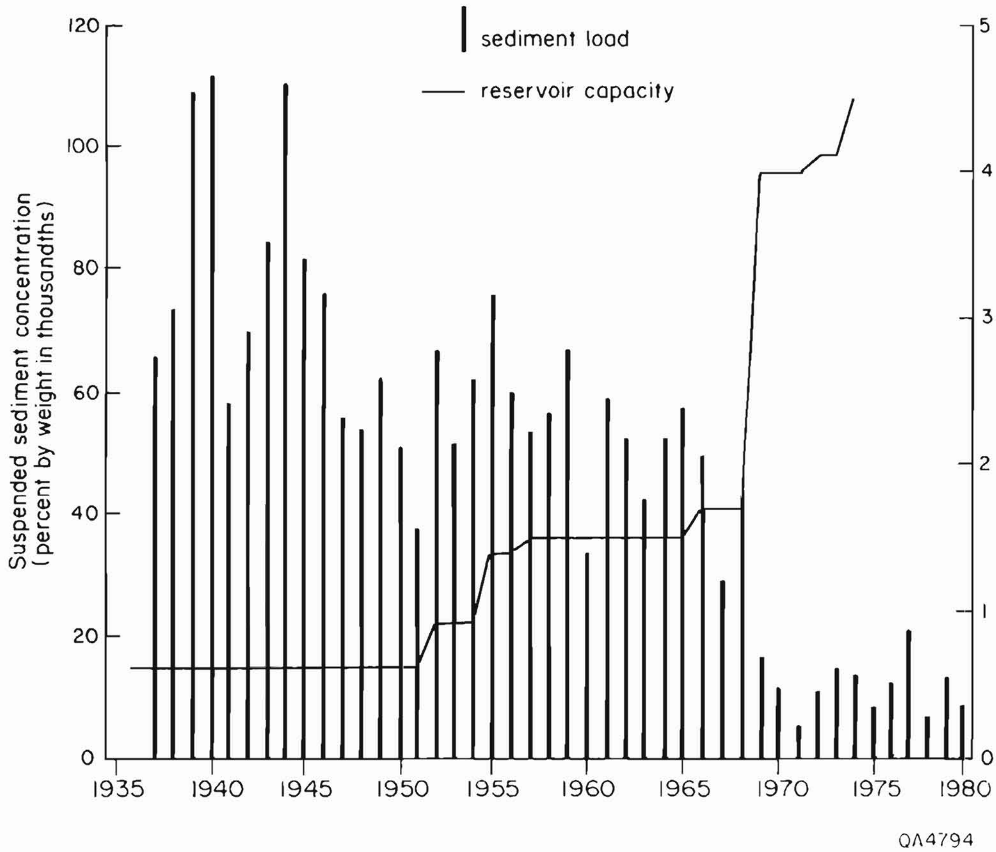


Figure 8. Suspended-sediment load (percent by weight) of the Trinity River at Romayor, and cumulative authorized water storage in reservoirs of the Trinity River basin. Note the dramatic decline in sediments after 1968 when Lake Livingston was completed on the Trinity River above the Romayor gaging station. From Paine and Morton (1986).

power plant cooling reservoir mentioned previously, the rate of marsh loss during the period 1974–1988 was approximately 70 percent lower than the rate in 1956–1974 (White and Calnan, 1990). This diminishing marsh-loss rate may be due to the sharp declines in subsidence rates on the east side of the Houston-Galveston subsidence bowl (Figure 6) after 1978. Subsidence rates declined in some areas by as much as 90 percent as a result of reductions in ground-water pumpage (Gabrysch and Coplin, 1990).

Virginia Point. Although some of the wetland loss near Virginia Point (Figure 2) can be attributed to dredging of channels and construction of industrial ponds near Texas City, the major cause is human-induced subsidence (Figure 9). The largest area of change is northwest of Jones Bay where salt marsh vegetation was replaced by open water in an area unaffected by dredged channels and reservoirs. The Virginia Point area is partly encompassed by a subsidence "bowl" centered on Texas City (Figure 6). Land-surface subsidence from 1906 to 1987 ranged from slightly less than 0.6 to 1.8 m (Figure 9). In the area northwest of Jones Bay, estimated rates of subsidence exceeded 14 mm yr^{-1} for the period of 1943 to 1987 (Gabrysch and Coplin, 1990). With the inclusion of the Gulf of Mexico regional sea-level rise of 2.4 mm yr^{-1} (Gornitz and Lebedeff, 1987), the rate of relative sea-level rise is more than 16 mm yr^{-1}, which apparently was higher than marsh vertical accretion rates. Emergent vegetation did not continue its decline from 1979 to 1989 (White *et al.*, 1993), perhaps reflecting a diminishing rate of

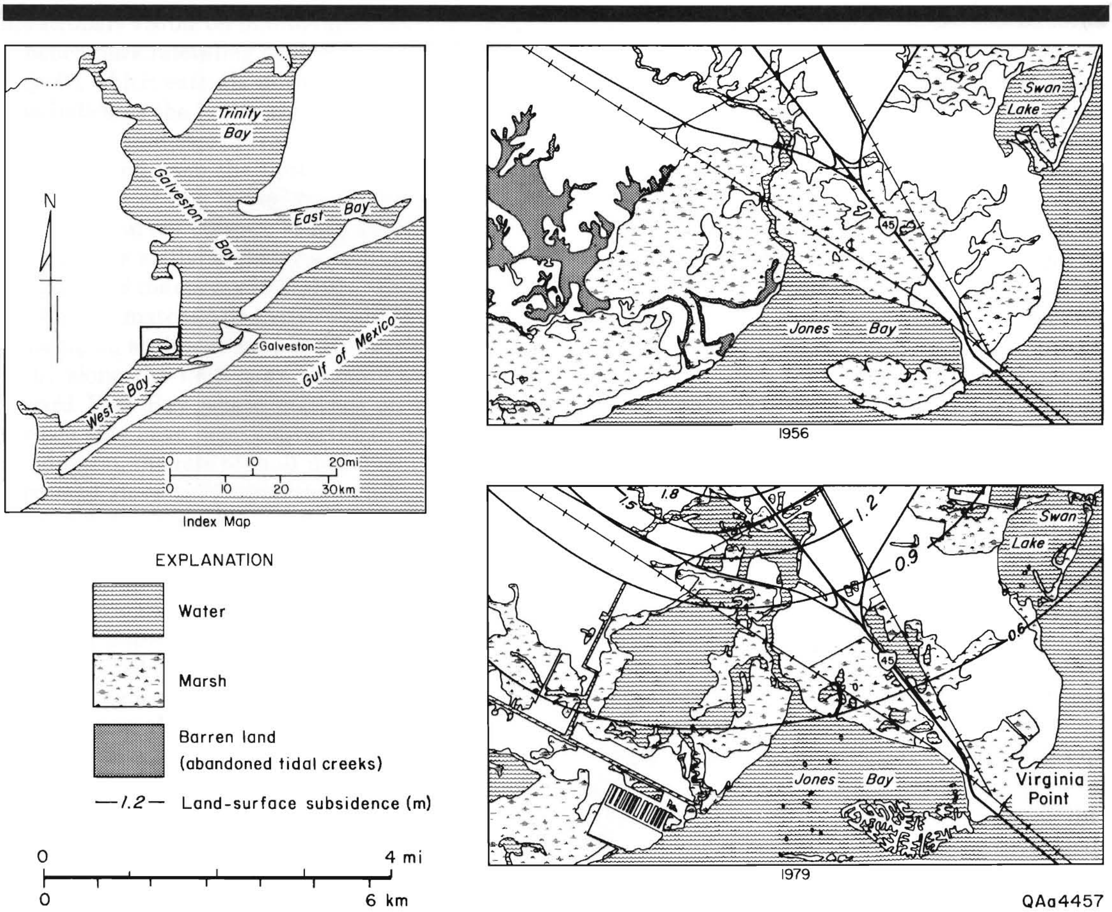


Figure 9. Changes in the distribution of wetlands between 1956 and 1979 in relation to subsidence in the Virginia Point quadrangle south of Texas City. Note the increase in open water in 1979. Contours show the amount of subsidence (in meters) that occurred between 1906 and 1987 based on maps from GABRYSCH and COPLIN (1990). Modified from WHITE *et al.* (1985).

subsidence (Table 2) as a result of reductions in ground-water pumpage in Texas City (GABRYSCH and COPLIN, 1990).

Western Margins of Galveston Bay (Clear Lake). Conversion of wetlands to water and flats in the Clear Lake area (League City 7.5-minute quadrangle) represents the trend occurring along the bayous and creeks located on the north and west sides of Galveston Bay, an area affected most by subsidence (Figure 6). The Clear Lake area had subsided between 1.5 and 2 m by 1987 (Figure 10). Rates of subsidence near the mouth of Clear Lake increased from less than 3 mm yr^{-1} in 1906–1943 to about 35 mm yr^{-1} in 1943–1973 to almost 60 mm yr^{-1} in 1964–1973 (PULICH and WHITE, 1991). The trend in this area has been one of expansion of open water and shallow flats at the expense of marshes and woodlands as subsidence promoted the encroachment of estuarine water up the valleys.

Bolivar Peninsula. The Bolivar Peninsula site is outside of the Houston subsidence bowl (Figures 2 and 6). Submergence of marshes on this relict tidal inlet/washover fan complex on the margins of East Bay are related to faulting and more localized subsidence (WHITE *et al.*, 1985). The location and orientation of two faults in this area (Figure 4) correlate with normal faults that have been mapped in the subsurface (Figure 11) (EWING, 1985; MORTON and PAINE, 1990). Analysis of aerial photographs indicates that the faults are active. Fault traces do not appear on aerial photographs taken in the 1930's, they are faintly visible on photographs taken in 1956, and they

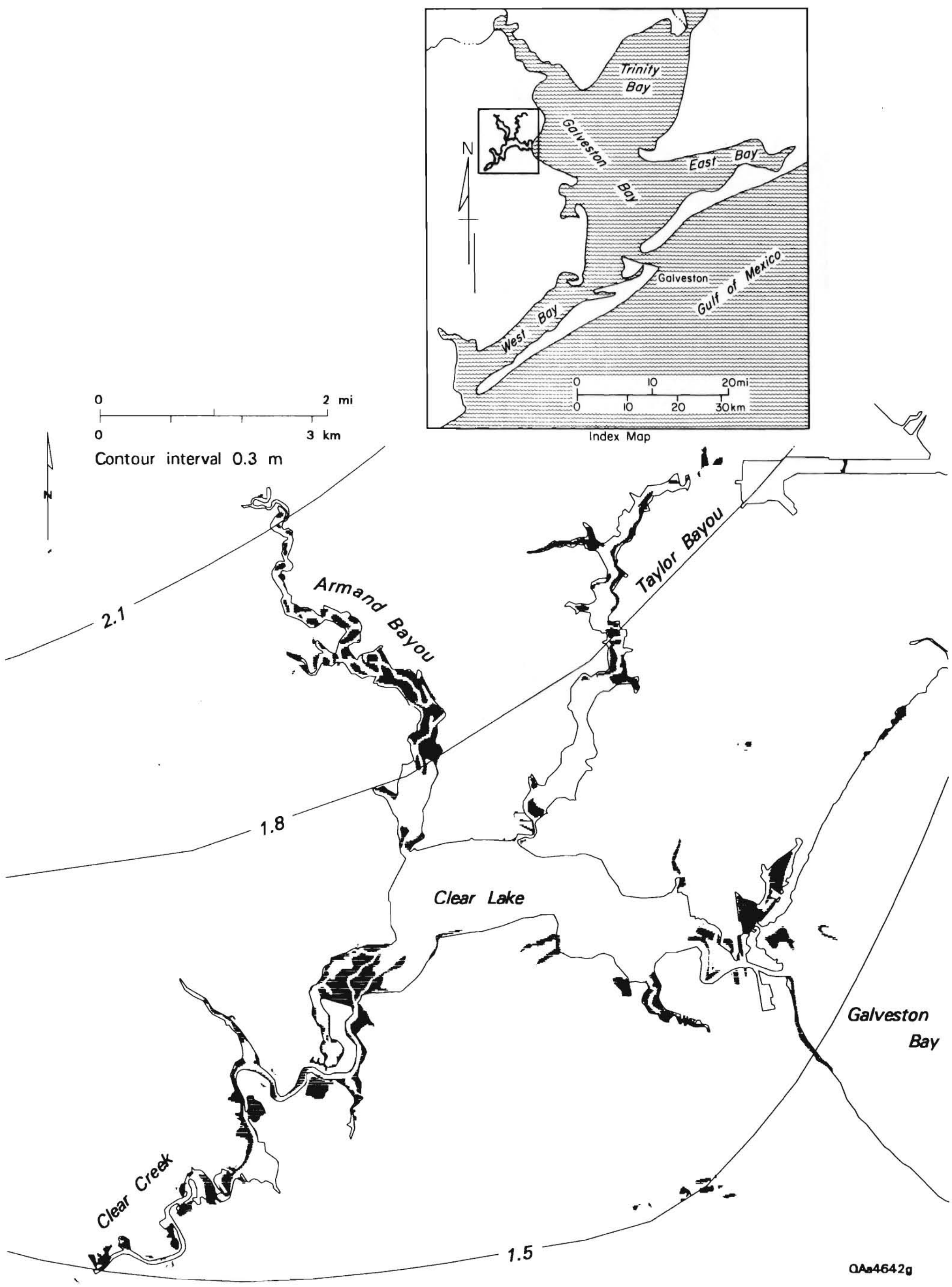


Figure 10. Relationship between subsidence and marsh submergence in the Clear Lake area. Marsh areas that were converted to open water and flats are shown in black. Modified from WHITE *et al.* (1993).

are strongly visible on photographs taken in 1979. A benchmark releveling profile along State Highway 87, which extends down Bolivar Peninsula, also indicates the faults are active; a marked increase in subsidence of from 6 mm yr^{-1} to 10 mm yr^{-1} occurred from the upthrown side to downthrown side of one of the faults crossed by the releveling survey (WHITE *et al.*, 1993). The subsidence rate at the highway was 10 mm yr^{-1} for the period of the survey 1936–1954. This rate could possibly be matched by marsh sedimentation, depending on sediment supply. However, displacement along the fault may be more pronounced toward East Bay where marshes on the downthrown side have been converted to open water. In addition, the rate of fault movement may have increased since 1954 when the benchmarks were releveled. Fault activation and subsidence at this site appear to be associated with hydrocarbon production and regional depressurization of subsurface formations by large-scale fluid withdrawal from the Caplen oil and gas field (EWING, 1985; KREITLER, *et al.*, 1988). Total fluid withdrawal (oil, gas, and formation water) from the Caplen field since its discovery in 1939 is approximately 30–40 million barrels to 1985, with most production from lower Miocene reservoirs at depths of 2,100 to 2,200 m (EWING, 1985). EWING (1985) noted that the association of oil and gas production and fault movement since the 1930's suggests a causal relationship.

Sabine Lake Estuary System and Interfluvial Area

Neches River. Reasons for submergence of marshes in the Neches River valley (Figure 5) are more complex than those for marsh submergence in the Galveston Bay area where the magnitude of subsidence has been so great. Although human-induced subsidence associated with ground-water and oil and gas production has been documented in the Sabine Lake area (RATZLAFF, 1980), it is more localized than around Galveston Bay. Unfortunately, benchmark releveling surveys do not cross the Neches River valley where the most extensive marsh loss has occurred. Additionally, numerous human alterations of the marsh system complicate the analysis. The river, which is located on the south side of the valley, was dredged for navigation purposes in the early 1900's. Since then, the channel has been straightened, deepened, and maintained as a deep-draft shipping route. Dredged material has been dumped on natural levees along the channel. Two oil and gas fields with access channels and levees have been developed in the valley, and canals have been dredged across the valley for pipeline installation. In addition, intake and discharge canals for a power plant located on the north side of the valley cross the marsh system.

Displacement of marshes by open water and shallow subaqueous flats appears to be related to a combination of factors in addition to subsidence and faulting (WHITE *et al.*, 1987). Other factors include dredged canals, which can cause direct and indirect losses (SCAIFE *et al.*, 1983; TURNER and CAHOON, 1988), changes in hydrologic regime due to artificial channels and spoil disposal (SWENSON and TURNER, 1987), a decline in fluvial sediments supplied to this alluvial area as a result of reservoir development in the Neches River basin, and artificial levees (dredged spoil) that inhibit overbank flooding along the dredged portion of the river. GOSSELINK *et al.* (1979) attributed some of the habitat loss in the Sabine basin to a number of causes, including hydrologic and salinity modifications resulting from canals and upstream reservoirs.

Although factors contributing to marsh loss in the Neches River valley are complex and difficult to quantify adequately with existing data, the conversion of marsh to open water suggests that marsh aggradation rates are not keeping pace with the rate of relative sea-level rise. A similar conclusion was reached by DELAUNE *et al.* (1983) in a study of a brackish marsh in the Chenier Plain near Calcasieu Lake, Louisiana, about 50 km east of Sabine Lake. DELAUNE *et al.* (1983) reported that marsh area was being replaced by water at an increasing rate because marsh vertical accretion rates averaging 0.8 cm yr^{-1} were surpassed by submergence rates averaging 1.2 cm yr^{-1}. Among the human activities that possibly contributed to the transformation to open water were (1) ship channel construction (promoting salt intrusion and possibly sediment diversion) and (2) oil, gas, and groundwater withdrawals (accelerating subsidence) (DELAUNE *et al.*, 1983).

Subsidence rates in the Neches River valley are not known, but tide gage records at Sabine Pass, about 35 km gulfward of the Neches River valley, indicate a relative sea-level rise of 13.2 ± 3.2 mm yr^{-1} for the period 1960 to 1978 (LYLES *et al.*, 1988). Benchmark releveling surveys near the northernmost site indicate that at least 20 cm of subsidence has occurred in association with with-

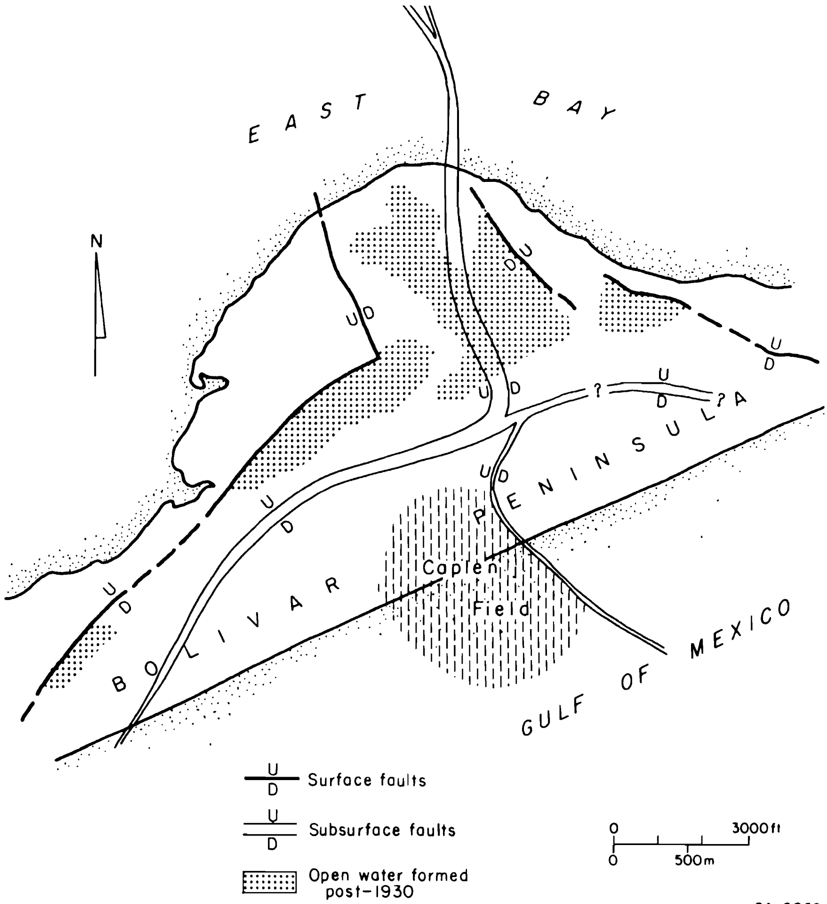


Figure 11. Relationship between subsurface and surface traces of faults at the Caplen Field on Bolivar Peninsula. Compare with Figure 4, which illustrates the marsh loss along faults in this area. Modified from EWING (1985).

drawal of underground fluids (RATZLAFF, 1980). Interpretation of marsh losses on aerial photographs shows that the most extensive submergence has occurred above oil and gas fields located in the Neches River valley. Oil production from the Port Neches field (Figure 5), most of which are from depths of about 1,800 m, has exceeded 30 million barrels since the field's discovery in 1928 (TEXAS RAILROAD COMMISSION, 1993). The field is associated with a moderate to deep-seated piercement salt dome with no surface expression (FISHER *et al.*, 1973). A fault, downthrown toward the field, bounds the southern margin of the most impacted area (Figure 5). Submergence of marshland has occurred more extensively on the downthrown side of the fault than on the upthrown side, suggesting that submergence rates exceed vertical accretion rates on the downthrown side.

Interfluvial Area (Clam Lake). Submergence of marsh vegetation near Clam Lake has occurred on the northwest side of a lineament interpreted as a fault (Figure 12). Coalescing ponds have formed since 1956 on the fault's downthrown side. The fault could not be located on aerial photographs taken in the 1930's or in 1956. However, it is distinct on 1978 and 1989 photographs (Figure 12). The appearance (configuration, alignment, and contrasting tones on each side) of this lineament is similar to that of surface faults reported by VERBEEK and CLANTON (1981) and WHITE *et al.* (1985). The fact that the fault does not appear on photographs taken in the 1930's

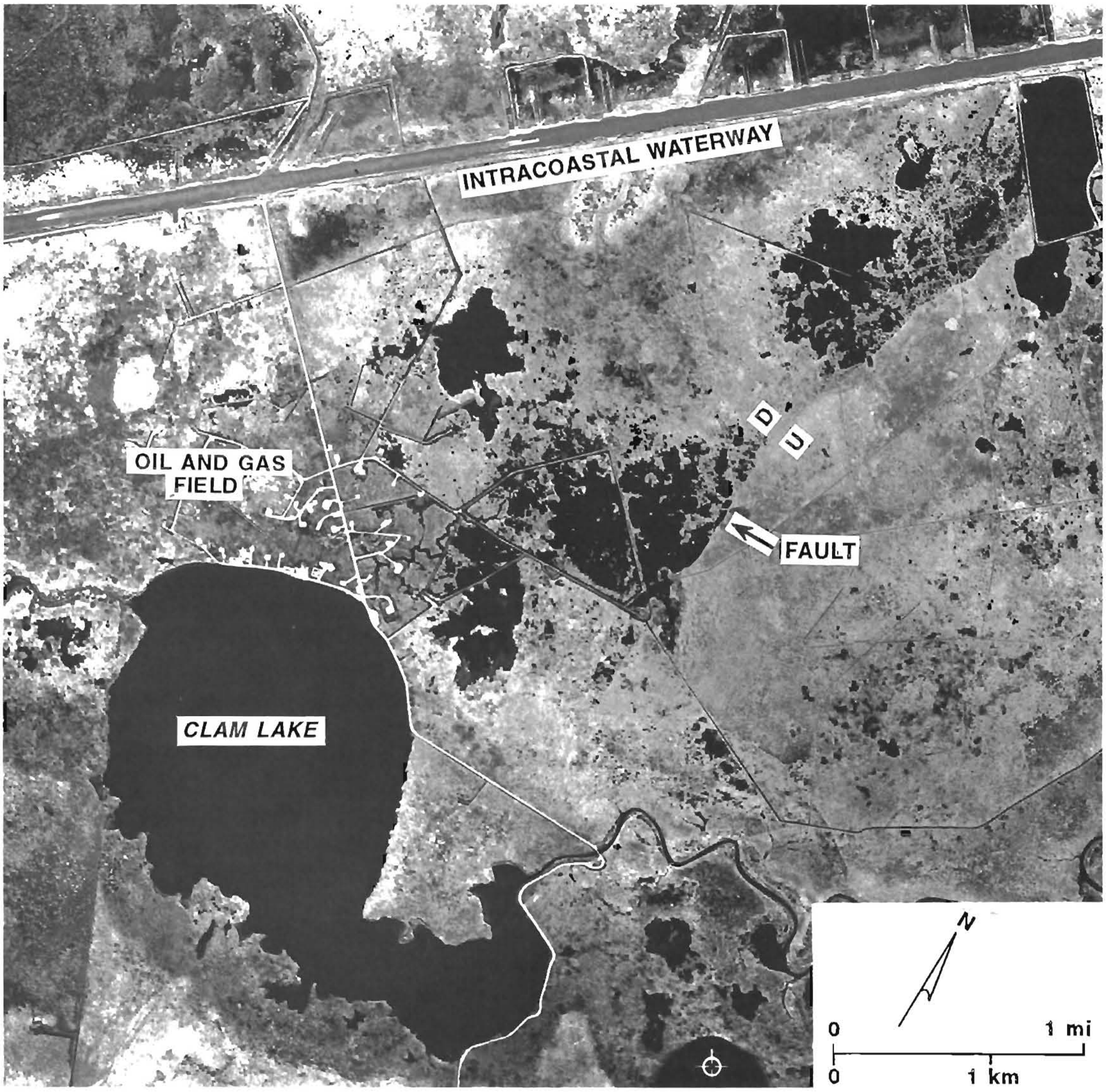


Figure 12. Aerial photograph of fault near Clam Lake. Topographically low marshes and open water increase in area on the downthrown side (D) of the fault relative to the upthrown side (U). Photograph taken by NASA in 1989. Location in Figure 1.

and 1950's but is distinct on later photographs indicates that the fault has been activated. The fault is downthrown to the northwest toward an oil and gas field north of Clam Lake. It is probable that the fault is the surface extension of a deep-seated fault that has been activated by hydrocarbon production similar to the Bolivar Peninsula site (Figure 11). Oil production from the Clam Lake field has exceeded 21 million barrels since its discovery in 1937 (TEXAS RAILROAD COMMISSION, 1993). Production is from a depth of approximately 700 m, and similar to the Port Neches field; it is associated with a moderate to deep-seated piercement salt dome (FISHER *et al.*, 1973). Some of the wetland loss near Clam Lake can be attributed to levees constructed across the marsh, but canals, except for those formed in borrow areas that parallel the levees, have not been dredged through the marsh and have not contributed to the marsh loss.

SUMMARY AND CONCLUSIONS

Synthesis of data on wetland losses documented from aerial photographic analysis of selected sites on the upper Texas coast indicates that thousands of hectares of vegetated coastal wetlands have been converted to open water and shallow subaqueous flats. Major areas affected include brackish to fresh marshes and woodlands in fluvial-deltaic areas along the San Jacinto, Trinity, and Neches Rivers, brackish and salt marshes in the Galveston Bay estuarine system, and brackish marshes in the interfluvial area between Sabine Lake and Galveston Bay.

More than 10,000 ha of wetlands throughout the Galveston Bay estuarine system have been affected by submergence. Losses are pronounced on the north and west side of the bay, including the San Jacinto and Trinity River fluvial-deltaic areas where together almost 3,600 ha of vegetated area has been replaced by open water and flats since the 1930's. Locally on the west side of Galveston Bay at Virginia Point, approximately 1,470 ha of salt marsh was converted to open water and flat between 1952 and 1989. In the Neches River fluvial-deltaic area near the head of Sabine Lake, more than 5,000 ha of emergent vegetation has been lost since the 1950's. Submergence of salt and brackish marshes also occurred on the bayward side of Bolivar Peninsula and in the interfluvial area between Sabine Lake and Galveston Bay.

As exemplified in Louisiana where causes for wetland loss are relatively well known, many processes may lead to the conversion of vegetated wetlands to open water and shallow flats: compactional subsidence and sea-level rise, delta abandonment, erosion from severe storms, dredging of canals, construction of levees and dams that alter hydrology and sediment supply, saltwater intrusion, and underground fluid withdrawal, among others. Whereas these processes also affect Texas coastal wetlands, there is evidence that the major contributing factors in wetland submergence on the upper Texas coast are subsidence and faulting associated with underground fluid production. Rates of "natural" subsidence and eustatic sea-level rise are greatly exceeded by rates of human-induced subsidence in the Galveston-Houston area where a subsidence "bowl" formed primarily from ground-water withdrawal encompasses more than 1×10^6 ha. In wetland areas undergoing submergence, rates of relative sea-level rise due primarily to human-induced subsidence range from 10 to more than 60 mm yr^{-1}. For comparison, maximum rates of marsh vertical accretion documented along the Gulf Coast in Louisiana, where the highest rates have been reported, are near 13 mm yr^{-1} in streamside marshes and less than 8 mm yr^{-1} in backmarshes. Rates of vertical accretion in backmarshes in the Trinity River fluvial-deltaic system in Texas average less than 6 mm yr^{-1}.

Wetland loss associated with faulting and subsidence has occurred in several locations, including Bolivar Peninsula in East Galveston Bay, the Neches River Valley at the head of Sabine Lake, and the interfluvial area between Sabine Lake and Galveston Bay. Emergent vegetation is converted to open water and shallow subaqueous flats on the downthrown side of faults where the rate of downward vertical movement and sea-level rise apparently exceeds marsh vertical accretion rates. There is evidence that fault movement in the areas investigated is related to hydrocarbon production.

Near the mouths of coastal rivers where there is the potential for sediment deposition to offset submergence, upstream dams and reservoirs trap a large percentage of sediment and prevent its delivery to coastal wetlands. Artificial channels and levees further inhibit available sediment from reaching wetlands.

Although rates of wetland loss doubled locally from the 1930's–1950's compared to the 1950's–1970/80's, rates declined in some areas after the 1970's. These reductions in wetland loss in the Galveston Bay system may be related to dramatic reductions in rates of human-induced subsidence as a result of curtailment of ground-water pumpage after the 1970's.

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LITERATURE CITED

BALAZS, E.I.M. 1980. The 1978 Houston-Galveston and Texas Gulf Coast vertical control surveys. *NOAA Technical Memorandum NOS NGS 27.* Rockville, Maryland, 61 p.

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.* Washington, D.C.: U.S. Fish and Wildlife Service, Biological Services Program, FWS/OBS-82/59, pp. 2–13.

BAUMANN, R.H.; DAY, J.W., JR., and MILLER, C.A., 1984. Mississippi deltaic wetland survival: Sedimentation versus coastal submergence. *Science,* 224, 1093–1095.

BRICKER-URSO, S.; NIXON, S.W.; COCHRAN, J.K.; HIRSCHBERG, D.J., and HUNT, C., 1989. Accretion rates and sediment accumulation in Rhode Island salt marshes. *Estuaries,* 12, 300–317.

BRITSCH, L.D. and DUNBAR, J.B., 1993. Land loss rates: Louisiana coastal plain. *Journal of Coastal Research,* 9, 324–338.

BROWN, L.F., JR.; MORTON, R.A.; MCGOWEN, J.H.; KREITLER, C.W., and FISHER, W.L., 1974. *Natural Hazards of the Texas Coastal Zone.* Austin, Texas: The University of Texas at Austin, Bureau of Economic Geology, 13p., 7 maps.

DAHL, T.E.; JOHNSON, C.E., and FRAYER, W.E., 1991. *Wetlands, Status and Trends in the Conterminous United States Mid-1970's to Mid-1980's.* Washington, D.C.: U.S. Department of the Interior, U.S. Fish and Wildlife Service, 23p.

DELAUNE, R.D.; BAUMANN, R.H., and GOSSELINK, J.G., 1983. Relationships among vertical accretion, coastal submergence, and erosion in a Louisiana Gulf Coast marsh. *Journal of Sedimentary Petrology,* 53, 147–157.

DIENER, R.A., 1975. *Cooperative Gulf of Mexico Estuarine Inventory and Study—Texas*: Area description. Seattle, Washington: National Oceanic and Atmospheric Administration, Technical Report, National Marine Fisheries Service Circular 393, 129p.

EWING, T.E., 1985. Subsidence and surface faulting in the Houston-Galveston area, Texas—Related to deep fluid withdrawal?. *In*: DORFMAN, M.H. and MORTON, R.A (eds.), *Geopressured-Geothermal Energy: Proceedings of the 6th U.S. Gulf Coast Geopressured-Geothermal Energy Conference.* New York: Pergamon, pp. 289–298.

FIELD, D.W.; REYER, A.J.; GENOVESE, P.V., and SHEARER, B.D., 1991. *Coastal Wetlands of the United States, An Accounting of a Valuable National Resource.* Rockville, Maryland: National Oceanic and Atmospheric Administration in Cooperation with the U.S. Fish and Wildlife Service, A special NOAA 20th anniversary report, 59p.

FISHER, W.L.; BROWN, L.F., JR.; MCGOWEN, J.H., and GROAT, C.G., 1973. *Environmental Geologic Atlas of the Texas Coastal Zone—Beaumont-Port Arthur Area.* Austin, Texas: The University of Texas at Austin, Bureau of Economic Geology, 93p., 9 maps.

FISHER, W.L.; MCGOWEN, J.H.; BROWN, L.F., JR., and GROAT, C.G., 1972. *Environmental Geologic Atlas of the Texas Coastal Zone—Galveston-Houston Area.* Austin, Texas: The University of Texas at Austin, Bureau of Economic Geology, 91p., 9 maps.

GABRYSCH, R.K., 1969. Land-surface subsidence in the Houston-Galveston region, Texas. *Proceedings, International Symposium on Land Subsidence, Publication No. 88,* Tokyo, Japan, AIHS, pp. 43–54.

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,* Austin, Texas, 64p.

GABRYSCH, R.K. and BONNET C.W., 1975. Land-surface subsidence in the Houston-Galveston region, Texas. *Texas Water Development Board Report 188,* Austin, Texas, 19p.

GABRYSCH, R.K. and COPLIN, L.S., 1990. Land-surface subsidence resulting from ground-water withdrawals in the Houston-Galveston region, Texas, through 1987. *U.S. Geological Survey Report of Investigations No. 90-01,* Washington, D.C., 53p.

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,* 31, 271–273.

GORNITZ, V. and LEBEDEFF, S., 1987. Global sea-level changes during the past century. *Society of Economic Paleontologists and Mineralogists, Special Publication No. 41,* 3–16.

GOSSELINK, J.G.; CORDES, C.L., and PARSONS, J.W., 1979. *An Ecological Characterization Study of the Chenier Plain Coastal Ecosystem of Louisiana and Texas.* Washington, D.C.: U. S. Fish and Wildlife Service, Office of Biological Services, FWS/OBS-78/9 through 78/11, 3 vols.

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,* 28, 494–502.

JOHNSTON, J.B. and ADER, R.A., 1983. The use of a GIS for Gulf of Mexico wetland change. *In*: MAGOON, O. T. and CONVERSE, H. (eds.), *Coastal Zone '83,* Volume I. New York: American Society of Civil Engineers, pp. 362–371.

KANE, H.E., 1959. Late Quaternary geology of Sabine Lake and vicinity, Texas and Louisiana. *Gulf Coast*

Association of Geological Societies Transactions, 9, 225–235.

KREITLER, C.W., 1977. Faulting and land subsidence from ground-water and hydrocarbon production, Houston-Galveston, Texas. *Bureau of Economic Geology Research Note 8,* The University of Texas at Austin, Austin, Texas, 22p.

KREITLER, C.W.; WHITE, W.A., and AKHTER, M.S., 1988. Land subsidence associated with hydrocarbon production, Texas Gulf Coast (abs.). *American Association of Petroleum Geologists Bulletin,* 72, 208.

LEBLANC, R.J. and HODGSON, W.D., 1959. Origin and development of the Texas shoreline. *In:* RUSSELL, R.J., (chm.), *Second Coastal Geography Conference.* Louisiana State University, Coastal Studies Institute, Baton Rouge, Louisiana, pp. 57–101.

LYLES, S.D.; HICKMAN, L.E., JR., AND DEBAUGH, H.A., JR., 1988. *Sea Level Variations for the United States.* Rockville, Maryland: National Oceanic and Atmospheric Administration, National Ocean Service, 182p.

MCFARLANE, R.W., 1991. An environmental inventory of the Armand Bayou Coastal Preserve. *Galveston Bay National Estuary Program, GBNEP-6,* Webster, Texas, 66p.

MCKINNEY, L.D.; HIGHTOWER, M.; SMITH, B.; BECKETT, D., and GREEN A., 1989. Management issues: Galveston Bay. *In:* Galveston Bay: Issues, Resources, Status, and Management. U.S. Department of Commerce, National Oceanic and Atmospheric Administration, *Estuary-of-the Month Seminar Series No. 13,* Washington, D.C., pp. 79–87.

MORTON, R.A. and PAINE, J.G., 1990. Coastal land loss in Texas—An overview. *Gulf Coast Association of Geological Societies Transactions,* 40, 625–634.

NIXON, S.W., 1980. Between coastal marshes and coastal waters—A review of twenty years of speculation and research on the role of salt marshes in estuarine productivity and water chemistry. *In:* HAMILTON, PETER and MACDONALD, K.B. (eds.), *Estuarine and Wetland Processes.* New York: Plenum Press, 437–525.

NYMAN, J.A.; CARLOSS, M.; DELAUNE, R.D., and PATRICK, W.H., JR., 1993. Are landscape patterns related to marsh loss processes. *In:* MAGOON, O.T.; WILSON, W.S.; CONVERSE, H., and TOBIN, L.T. (eds.), *Coastal Zone '93, Proceedings of the Eighth Symposium on Coastal and Ocean Management.* New York: American Society of Civil Engineers, 337–348.

PAINE, J.G., 1993. Subsidence of the Texas coast: Inferences from historical and late Pleistocene sea levels. *Tectonophysics,* 222, 445–458.

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

PENLAND, S.; ROBERTS, H.H.; WILLIAMS, S.J.; SALLENGER, A.H., JR.; CAHOON, D.R.; DAVIS, D.W., and GROAT, C.G., 1990. Coastal land loss in Louisiana. *Gulf Coast Association of Geological Societies Transactions,* 40, 685–699.

PRATT, W.E. and JOHNSON, D.W., 1926. Local subsidence of the Goose Creek oil field. *Journal of Geology,* 34, 577–590.

PULICH, W.M. and WHITE, W.A., 1991. Decline of submerged vegetation in the Galveston Bay system: Chronology and relationships to physical processes. *Journal of Coastal Research,* 7, 1125–1138.

RAMSEY, K.E. and PENLAND, S., 1989. Sea-level rise and subsidence in Louisiana and the Gulf of Mexico. *Gulf Coast Association of Geological Societies Transactions,* 39, 491–500.

RATZLAFF, K.W., 1980. Land-surface subsidence in the Texas coastal region. Washington, D.C. *U.S. Geological Survey Open-File Report 80-969,* 19p.

REED, D.J. and CAHOON, D.R., 1992. The relationship between marsh surface topography, hydroperiod, and growth of *Spartina alterniflora* in a deteriorating Louisiana salt marsh. *Journal of Coastal Research,* 8, 77–87.

REED, D.J. and CAHOON, D.R., 1993. Marsh submergence vs. marsh accretion: Interpreting accretion deficit data in coastal Louisiana. *In:* MAGOON, O.T.; WILSON, W.S.; CONVERSE, H., and TOBIN, L.T. (eds.), *Coastal Zone '93, Proceedings of the Eighth Symposium on Coastal and Ocean Management.* New York: American Society of Civil Engineers, pp. 243–257.

REHKEMPER, L.J., 1969. Sedimentology of Holocene estuarine deposits, Galveston Bay. *In:* LANKFORD, R.R. and ROGERS, J.J.W. (eds.), *Holocene Geology of the Galveston Bay Area.* Houston, Texas: Houston Geological Society, pp. 12–52.

REID, W.M, 1973. Active Faults in Houston, Texas. Unpublished Ph.D. Dissertation, The University of Texas at Austin, Austin, Texas, 122p.

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

STEVENSON, J.C.; WARD, L.G., and KEARNEY, M.S., 1985. Vertical accretion in marshes with varying rates of sea level rise. *In:* WOLFE, T.A. (ed.), *Estuarine Variability.* Orlando, Florida: Academic Press, Inc., 241–259.

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,* 78, 2665–2671.

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

TEXAS RAILROAD COMMISSION, 1993. *Oil and Gas Division Annual Report, 1992, Volume 1.* Austin, Texas: Railroad Commission of Texas, 440p.

TURNER, R.E. and CAHOON, D.R. (eds.), 1988. *Causes of Wetland Loss in the Coastal Central Gulf of Mexico, Volume II: Technical Narrative.* New Orleans, Louisiana: U.S. Department of the Interior, Minerals Management Service, OCS Study/MMS 87-0120, 400p.

U.S. DEPARTMENT OF AGRICULTURE, 1959. Inventory and use of sedimentation data in Texas. Austin, Texas: *Texas Board of Water Engineers, Bulletin 5912,* 85p.

VAN SICLEN, D., 1967. The Houston fault problem. *Proceedings of the American Institute of Professional Geologists,* 3rd Annual Meeting, Texas Section, pp. 9–31.

VERBEEK, E.R., and CLANTON, U.S., 1981. Historically active faults in the Houston metropolitan area. Texas. *In:* ETTER, E. M. (ed.), *Houston Area Environmental Geology: Surface Faulting, Ground Subsidence, Haz-*

ard Liability. Houston, Texas: Houston Geological Society, pp. 28–68.

WEAVER, P. and SHEETS, M., 1962. Active faults, subsidence and foundation problems in the Houston, Texas, area. *Geology of the Gulf Coast and Central Texas, Houston Geological Society Guidebook*, Houston, Texas, pp. 254–265.

WHITE, W.A., and CALNAN, T.R., 1990. *Sedimentation and Historical Changes in Fluvial-Deltaic Wetlands along the Texas Gulf Coast with Emphasis on the Colorado and Trinity River Deltas*. The University of Texas at Austin, Bureau of Economic Geology, final report prepared for the Texas Parks and Wildlife Department, Austin, Texas, 124p., 7 Appendices.

WHITE, W.A., and CALNAN, T.R., 1991. Submergence of vegetated wetlands in fluvial-deltaic areas, Texas Gulf Coast. *In*: *Coastal Depositional Systems, Gulf of Mexico*. Society of Economic Paleontologists and Mineralogists, Gulf Coast Section, Twelfth Annual Research Conference, Houston, Texas, pp. 278–279.

WHITE, W.A. and PAINE, J.G., 1992. Wetland plant communities, Galveston Bay system. *Galveston Bay National Estuary Program, GBNEP-16*, Webster, Texas, 124p.

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*. Austin, Texas: The University of Texas at Austin, Bureau of Economic Geology, Special publication, 145p.

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*. Austin, Texas: The University of Texas at Austin, Bureau Economic Geology Special Publication, 110p.

WHITE, W.A.; TREMBLAY, T.A.; WERMUND, E.G., JR., and HANDLEY, L.R., 1993. Trends and status of wetland and aquatic habitats in the Galveston Bay system, Texas. *Galveston Bay National Estuary Program, GBNEP-31*, Webster, Texas, 225p.

WILLIAMS, S.J.; PENLAND, S., and ROBERTS, H.H., 1993. Processes affecting coastal wetland loss in Louisiana deltaic plain: *In*: MAGOON, O.T.; WILSON, W.S.; CONVERSE, H., and TOBIN, L.T. (eds.), *Coastal Zone '93, Proceedings of the Eighth Symposium on Coastal and Ocean Management*. New York: American Society of Civil Engineers, pp. 211–219.

WINSLOW, A.G. and DOYEL, W.W., 1954. Land-surface subsidence and its relation to the withdrawal of ground water in the Houston-Galveston region, Texas. *Economic Geology*, 49, pp. 413–422.

YERKES, R.F. and CASTLE, R.O., 1969. Surface deformation associated with oil and gas field operations in the United States. *Proceedings, International Symposium on Land Subsidence, Publication No. 88*, Tokyo, Japan, AIHS, 1, pp. 55–66.