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# **STATUS AND TRENDS OF WETLAND AND AQUATIC HABITATS ON BARRIER ISLANDS, UPPER TEXAS COAST, GALVESTON AND CHRISTMAS BAYS**

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**William A. White, Thomas A. Tremblay, Rachel L. Waldinger,  
and Thomas R. Calnan\***

\*Coastal Coordination Division, Texas General Land Office

Final Report  
Prepared for the

Texas General Land Office  
and  
National Oceanic and Atmospheric Administration  
under GLO Contract No. 03-057

A report of the Coastal Coordination Council pursuant to National Oceanic and  
Atmospheric Administration Award No. NA17OZ2353

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Bureau of Economic Geology  
Scott W. Tinker, Director  
John A. and Katherine G. Jackson School of Geosciences  
The University of Texas at Austin  
University Station Box X  
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ON BARRIER ISLANDS, UPPER TEXAS COAST,  
GALVESTON AND CHRISTMAS BAYS**

**EXECUTIVE SUMMARY**

William A. White,<sup>1</sup> Thomas A. Tremblay,<sup>1</sup> Rachel L. Waldinger,<sup>1</sup>  
and Thomas R. Calnan<sup>2</sup>

<sup>1</sup>Bureau of Economic Geology  
John A. and Katherine G. Jackson School of Geosciences  
The University of Texas at Austin

<sup>2</sup>Texas General Land Office  
Coastal Coordination Division

**Introduction**

Wetland and aquatic habitats are essential components of barrier islands along the Texas coast. These valuable resources are highly productive both biologically and chemically and are part of an ecosystem on which a variety of flora and fauna depend. Scientific investigations of wetland distribution and abundance through time are prerequisites to effective habitat management, thereby ensuring their protection and preservation and directly promoting long-term biological productivity and public use. This report presents results of an investigation to determine current status and historical trends of wetlands and associated aquatic habitats along the upper coast of Texas' barrier island system from the northeastern corner of Galveston's East Bay to the southwestern corner of Christmas Bay. The study area encompasses Bolivar Peninsula, Galveston Island, and Follet's Island, an area that is located within Galveston and Brazoria Counties along the upper Texas coast (Fig. 1). Galveston Island and Bolivar Peninsula are broad accretionary barriers with low fore-island dunes, extensive back-island estuarine marshes, and numerous relict beach ridges and intervening swales that are the sites of palustrine marshes in the central part of the island. Development is extensive on Galveston Island and Bolivar Peninsula. Follet's Island, a much narrower barrier that is undergoing erosion along much of its length, is characterized by low fore-island dunes, productive back-island estuarine marshes, and in adjacent Christmas Bay, ecologically important seagrass beds.

**Methods**

This study of status and trends is based on wetlands interpreted and mapped on recent and historical aerial photographs. Current distribution (status) of wetlands was determined using color-infrared (CIR) photographs taken in February 2002. Historical distribution is based on 1950's black-and-white and 1979 CIR photographs. Mapped wetlands for each period were digitized and entered into a GIS for analysis. The historical



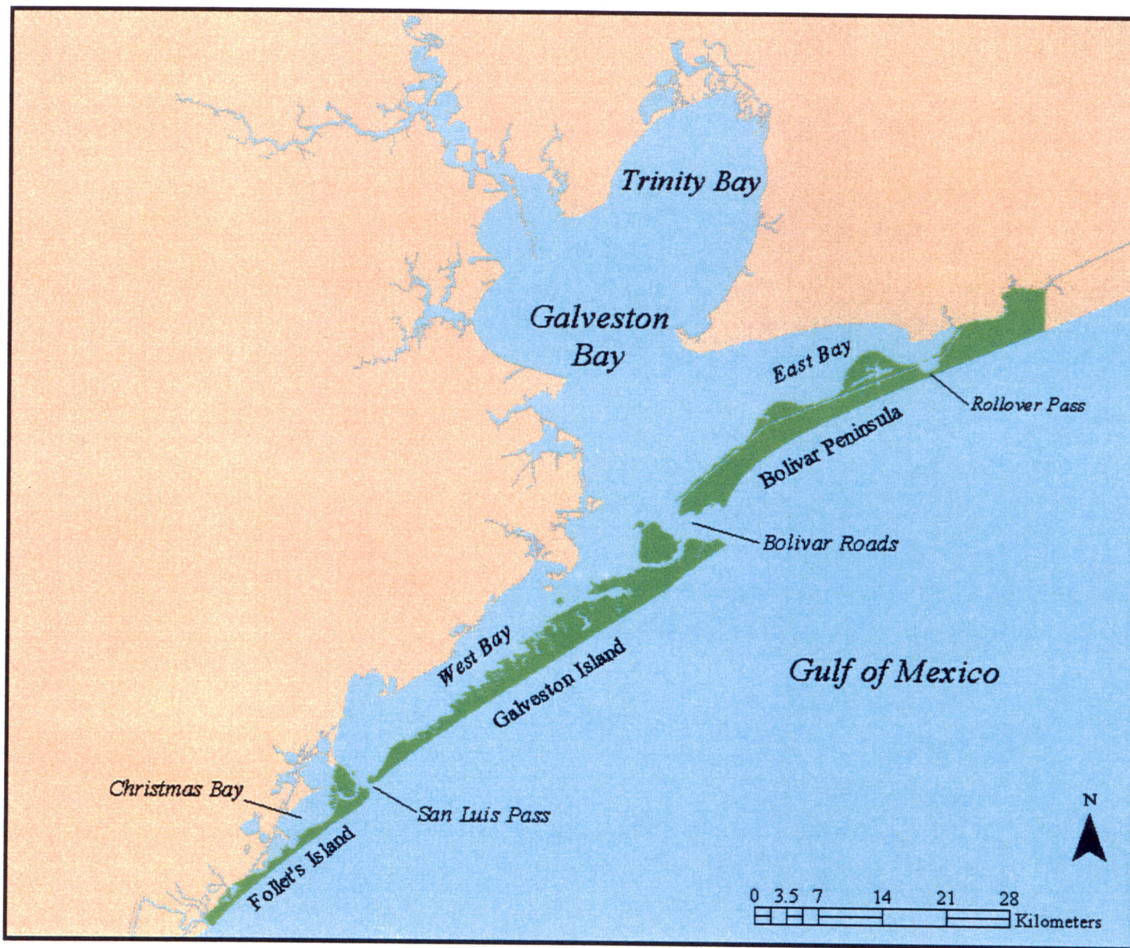


Figure I. Index map of study area.

GIS maps were obtained from the U.S. Fish and Wildlife Service (USFWS), who mapped the wetlands using methods established as part of the National Wetlands Inventory program. Methods included interpreting and delineating habitats on aerial photographs, field checking delineations, and transferring delineations to 1:24,000-scale base maps using a zoom transfer scope. The resulting maps were digitized and entered into a GIS, producing GIS maps for the two time periods. Both the 1950's and 1979 series USFWS maps, which are in digital format, were partially revised in this project to be more consistent with wetlands interpreted and delineated on the 2002 photographs.

Methods used to delineate 2002 habitats differed from the earlier methods. The 2002 photographs were digital images with a pixel resolution of 1 meter, and registered to USGS Digital Orthophoto Quadrangles (DOQ's). Mapping of wetlands and aquatic habitats was accomplished through interpretation and delineation of habitats on screen in a GIS at a scale of 1:6,000. The resulting current-status GIS maps were used to make direct comparisons with the historical GIS maps to determine habitat trends and probable causes of trends.

Wetlands were mapped in accordance with the classification by Cowardin et al. (1979), in which wetlands are classified by system (marine, estuarine, riverine, palustrine, lacustrine), subsystem (reflective of hydrologic conditions), and class (descriptive of vegetation and substrate). Maps for 1979 and 2002 were additionally classified by subclass (subdivisions of vegetated classes only), water regime, and special modifiers. Field sites were examined to characterize wetland plant communities, define wetland map units, and ground-truth delineations. Topographic surveys conducted at several field sites provided data on relative elevation that helped define habitat boundaries and potential frequency of flooding, or water regimes.

### **Current Status, 2002**

Major estuarine and palustrine habitats in the study area include salt, brackish, and fresh marshes, tidal flats, and seagrass beds. Areas of estuarine open water are also important components of the salt and brackish marsh complex. The primary habitat mapped in the marine system is the Gulf beach, which consists of a topographically lower forebeach and a higher, less frequently flooded backbeach.

In 2002, wetland and aquatic habitats (excluding open water) were dominated by estuarine marshes, with a total area of 7,715 ha (19,048 acres), followed by tidal flats totaling 771 ha (1,904 acres), and palustrine marshes at 607 ha (1,499 acres) (Fig. II). Palustrine flats and water bodies had a total area of 381 ha (941 acres), and wetland scrub/shrub wetlands 39 ha (96 acres). Along the Gulf shoreline, the area of mapped beaches totaled 556 ha (1,373 acres). Lacustrine habitats, consisting primarily of impounded water and barren flats, had a total area of 797 ha (1,968 acres).

The study area was subdivided into geographic areas—Bolivar Peninsula, Galveston Island, and Follet's Island—to allow a more site-specific analysis of status and trends (Fig. III). Included in the Bolivar Peninsula subarea is an area of marsh on its northeastern end (Fig. I). The modified flood-tidal delta, Pelican Island, at the northeast end of Galveston Island was included in the Galveston Island subarea, and the flood-tidal delta, Mud Island, at the northwest corner of Follet's Island was included in Follet's Island (Fig. I).

The most extensive estuarine emergent wetlands (salt and brackish marshes) occur on Bolivar Peninsula (4,734 ha; 11,689 acres), followed by Galveston Island (1,519 ha; 3,750 acres), and Follet's Island (1,459 ha; 3,602 acres) (Fig. III). Although marshes are much less extensive on Galveston Island and Follet's Island compared with Bolivar Peninsula, these marshes are critical habitats that fringe West and Christmas Bays, respectively. Seagrass beds are most abundant in Christmas Bay adjacent to Follet's Island (Fig. III), where their mapped areal extent is 67 ha (165 acres). Almost 50 ha (123 acres) of seagrass beds were mapped in West Bay. The areas of palustrine marshes total 322 ha (795 acres) on Bolivar Peninsula, 276 ha (681 acres) on Galveston Island, and 9 ha (22 acres) on Follet's Island. Scrub-shrub wetlands are most extensive on Galveston Island where 12 ha (30 acres) of estuarine scrub-shrub and 18 ha (44 acres) of palustrine scrub-shrub were mapped. The scrub-shrub habitat on Bolivar Peninsula consists of 2 ha



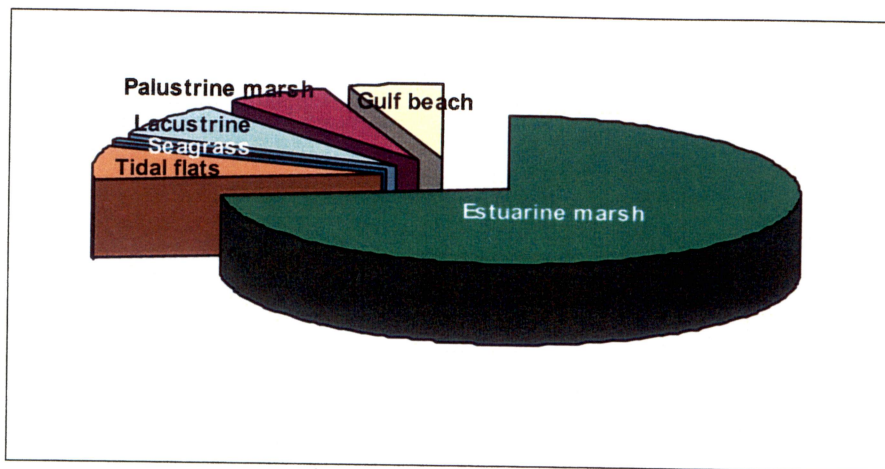


Figure II. Areal extent of selected habitats in the study area in 2002.

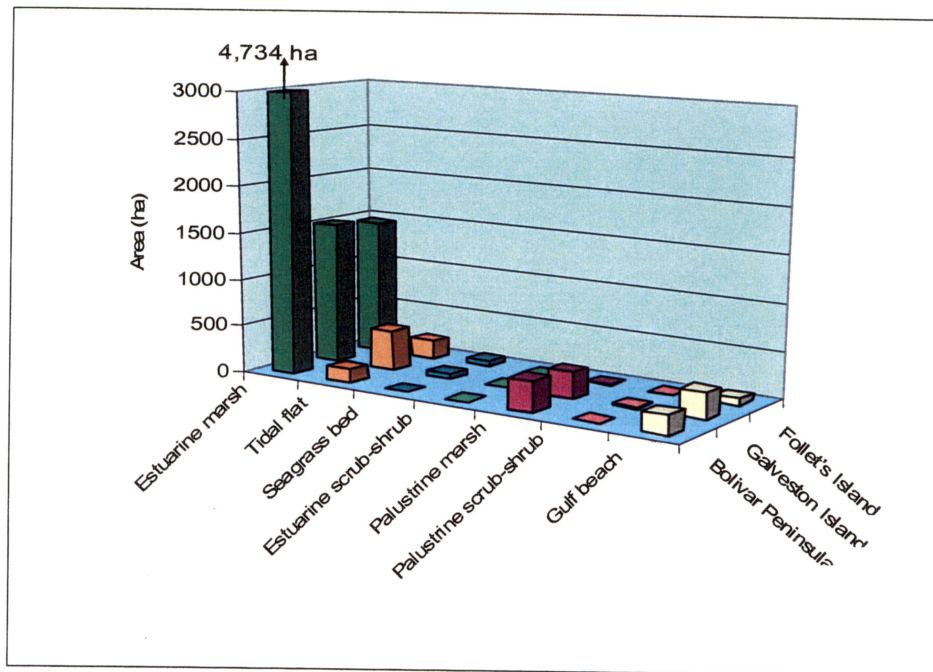


Figure III. Distribution of selected habitats by geographic area in 2002. The most extensive distribution of salt and brackish marsh (4,734 ha; 11,689 acres) is on Bolivar Peninsula.

(5 acres) of estuarine scrub-shrub, and 8 ha (20 acres) of palustrine scrub-shrub. The largest area of Gulf beach (278 ha; 686 acres) is along Galveston Island, with the smallest area occurring on Follet's Island (76 ha; 188 acres) (Fig. III).

## Wetland Trends and Probable Causes, 1950's–2002

In analyzing trends, wetland classes were emphasized over water regimes and special modifiers because habitats were mapped only down to class on 1950's photographs. It should be noted that there is a cumulative error that arises from interpreting and delineating wetlands on aerial photographs, transferring delineations to base maps, and georeferencing the different vintages of maps to a common base for comparison. Accordingly, we have more confidence in direction of trends than absolute magnitudes. Probable causes of historical changes are discussed by geographic area toward the end of this summary.

From the 1950's through 2002 within the study area, all wetland classes, with the exception of scrub-shrub, underwent net losses (Fig. IV; Table I). In general, estuarine marshes decreased in total area during each period (1950's–1979 and 1979–2002), with a total net loss of 1,552 ha (3,833 acres) from the 1950's to 2002. Approximately 70% of this loss occurred from the 1950's through 1979, indicating that the rate of loss decreased from 1979 to 2002. The average rate of marsh loss during the earlier period was about 48 ha/yr (119 acres/yr), and for the more recent period, about 19 ha/yr (47 acres/yr). Losses were also extensive in tidal-flat habitats, which had a net decline from the 1950's to 2002 of 1,600 ha (3,950 acres), with most of the loss, 1,162 ha (2,869 acres), occurring during the later period (Fig. IV). The rates of tidal-flat loss were 19 ha/yr (47 acres/yr) during the earlier period (1950's–1979) and 51 ha/yr (126 acres/yr) during the later period (1979–2002), which are rates that are opposite to the rates of marsh loss for the two periods. Seagrass beds decreased in total area by about 1,000 ha (2,470 acres) from the 1950's through 1979, a year in which none were mapped, although seagrasses were in Christmas Bay at that time. A total of 116 ha (286 acres) were mapped in 2002 in Christmas and West Bays. Palustrine marshes had their largest distribution in the 1950's, at 1,045 ha (2,580 acres), and lowest in 2002, at 607 ha (1,499 acres) (Table I). The total area of mapped scrub-shrub was slightly larger in 1979 than in the 1950's and 2002 (Table I). Finally, there was a net decline in the mapped area of Gulf beaches, decreasing in total area by 384 ha (948 acres) from the 1950's through 1979 and 74 ha (182 acres) from 1979 to 2002, a net change of almost 45% since the 1950's.

An analysis of habitat changes within the different geographic areas reveals some interesting trends and helps elucidate some of the probable causes. At the northeastern part of the study area at **Bolivar Peninsula**, there was a systematic decline in estuarine marshes from the 1950's through 1979 to 2002, ending in a net loss of about 536 ha (1,323 acres), or about 10% of the 1950's area (1950's area = 5,269 ha; 13,010 acres). Losses were primarily the result of active surface faults that intersect wetlands on the peninsula, and secondarily to bay shoreline erosion, local development including draining and filling of marshes, and differences in classification of marsh types. Two active faults cross a large relict flood-tidal delta/washover fan complex that extends into West Bay. Losses have occurred on the downthrown side of the faults where subsidence has promoted flooding and erosion of the marshes. Loss of marsh in this area since the 1950's has exceeded 400 ha. The rate of subsidence and relative sea-level rise on the Gulfward side of the fault apparently exceeded the rate of marsh vertical accretion, and the marsh



was replaced primarily by open water. Similar losses along active surface faults, including these, were reported by White et al. (1993) and White and Tremblay (1995) along the upper Texas coast. Losses in this area occurred from the 1950's through 1979. The timing of wetland loss coincides with the period in which annual gas production peaked at the Clam Lake Oil and Gas Field in the late 1960's to early 1980's. The spatial and temporal relationships between oil and gas production, faulting, and marsh loss support Ewing's (1985) conclusion of a causal relationship between fluid production and fault movement.

An example of additional losses due to relative sea-level rise and erosion occurred at the southwest end of Bolivar Peninsula in the central part of the peninsula where marshes in an estuarine lagoon underwent a net loss.

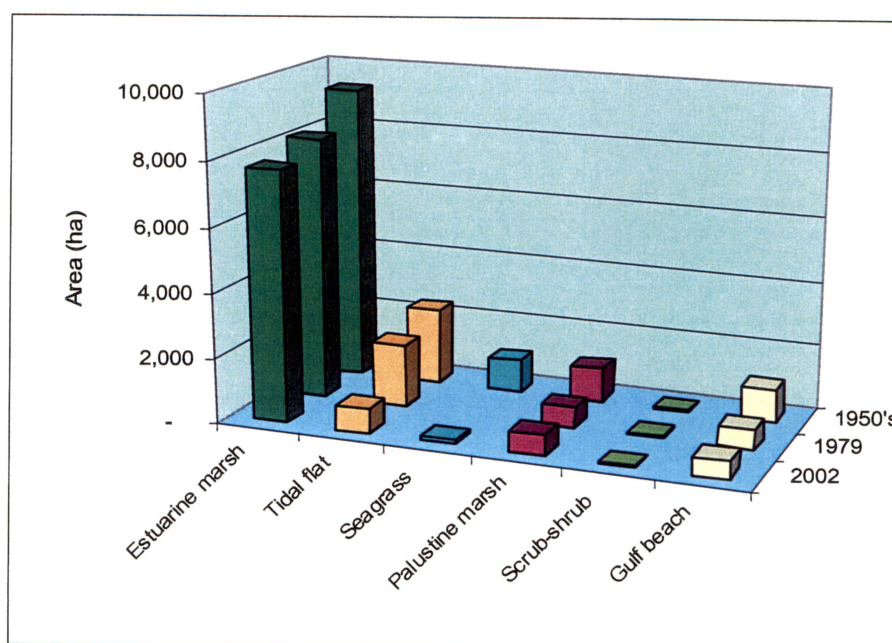


Figure IV. Areal distribution of major habitats in the study area in the 1950's, 1979, and 2002.

Table I. Total area of major habitats in the 1950's, 1979, and 2002 in study area.

Habitat	1950's		1979		2002	
	(ha)	(acres)	(ha)	(acres)	(ha)	(acres)
Estuarine marsh	9,267	22,880	8,375	20,678	7,715	19,048
Tidal flat	2,371	5,854	1,933	4,774	771	1,904
Seagrass	1,009	2,491	?	?	116	286
Palustine marsh	1,045	2,580	618	1,525	607	1,498
Scrub-shrub	34	84	45	111	39	96
Gulf beach	1,013	2,501	629	1,553	556	1,373

In contrast to a loss of estuarine marshes due to faulting, subsidence, and erosion, was a gain in salt and brackish marshes at the southwest end of Bolivar Peninsula near the north jetty at Bolivar Roads due to sediment accretion. Marsh expansion in this area from the 1950's to 1979 was 140 ha (346 acres), and from 1979 to 2002, 50 ha (123 acres). Local rates of accretion in this area have exceeded 10 m/yr (33 ft/yr) (Gibeaut et al., 2002). Mapped palustrine marshes on Bolivar are limited in areal extent, although having a larger distribution than the other barriers, with 495 ha (1,222 acres) in the 1950's, 164 ha (405 acres) in 1979, and 322 ha (795 acres) in 2002. Changes are in part due to differences in interpretation and classification on the different vintages of photographs. The total area of Gulf beach mapped decreased systematically from the 1950's through 2002, for a net loss of 251 ha (620 acres). Much of this change was due to a narrowing through time of the area mapped as beach because of a spread of vegetation and vegetated dunes along the backbeach and shoreline erosion. Much of the change occurred near the jetties at Bolivar Roads where broad accretionary beaches and flats in the 1950's became vegetated by 1979 and 2002.

Wetland habitats decreased on **Galveston Island**. Estuarine marsh was reduced by 32%, from 2,228 ha (5,501 acres) in the mid-1950's to 1,519 ha (3,750 acres) in 2002, tidal flats were reduced by 61%, from 1,102 ha (2,721 acres) in the mid-1950's to 426 ha (1,052 acres) in 2002, and palustrine marshes were reduced by 50%, from 556 ha (1,373 acres) in the mid-1950's to 276 ha (681 acres) in 2002. Seagrasses, which were not observed at all in 1979, increased to 49 ha (121 acres) in 2002. In the mid-1950's 882 ha (2,178 acres) of seagrasses were mapped. Gulf beaches declined by 30%, from 396 ha (978 acres) in the mid-1950's to 276 ha (681 acres) in 2002. The losses in wetlands are caused primarily by subsidence. Subsidence causes relative sea-level rise, which replaces marshes and tidal flats with open water over time. Development and cattle trails also contribute to marsh loss on Galveston Island. Restoration projects are being used in an effort to counteract some of the losses. The San Luis Pass area has undergone a large amount of change over time. Deep-water channels and shifting sands in the Pass largely shape the area's dynamic character. The northeastern tip of Galveston Island has lost a large amount of marsh from the mid-1950's to 1979. This loss can be explained by the impoundment of the area during that time. The island's interior marshes changed in size and character during both time periods. This is most likely caused by the unusually dry ground conditions in the mid-1950's and the unusually wet ground condition of 1979. The decline of the Gulf beach is due to the loss of sand and narrowing of the beach over time.

**Follet's Island** underwent a systematic loss of estuarine intertidal marsh between the mid-1950's and 2002. An original 1,771 ha (4,373 acres) of E2EM was reduced to 1,606 ha (3,965 acres) by 1979 and further reduced to 1,459 ha (3,602 acres) by 2002. Each subsequent time interval shows a 9% loss. Initial loss was owing to residential development and dredged material disposal. Over time relative sea-level rise compounded by subsidence along active faults on Mud Island became a more significant cause of marsh loss. By 2002, open water and intertidal flats had replaced large amounts of marsh in areas adjacent to the faults. The island also underwent a significant amount of marsh erosion where high-energy currents flow through San Luis Pass. Adjusting for

photointerpretation differences reduces the 1979–2002 E2EM loss to ~7%. The trend in marsh loss on Follet's Island continues but at a lower rate. Estuarine intertidal flats (E2US) in the 1950's occupied an area of 409 ha (1,010 acres). That number dropped by more than half to 195 ha (481 acres) by 1979. Most flats are lost owing to marsh encroachment. This occurs where washover fans are revegetated and where sea-level rise inundates flat areas on the bay side of the island. In the later time interval, estuarine flats rebounded somewhat with a 7% increase in area. Seagrass beds (E1AB) were most extensive in the Follet's Island barrier system in the mid-1950's. Although present, water turbidity at the time of the 1979 photography precluded mapping of seagrasses. Comparing the 1956 total (127 ha; 314 acres) with the area of seagrass present in 2002 (67 ha; 165 acres) shows a 47% loss of the original resource. The 2002 aerial photographs, however, were taken in February, and the apparent decline in seagrasses may have been a seasonal response. Gain and subsequent loss of palustrine emergent marsh (PEM) and palustrine unconsolidated bottom (PUB) over the length of the study are due to drier conditions in 1956 (0.6 ha; 1.5 acres PEM and 1 ha; 2.5 acres PUB) and 2002 (9 ha; 22 acres PEM and 2 ha; 4.9 acres PUB) than the unusually wet 1979 period (13 ha; 32 acres PEM and 3 ha; 7.4 acres PUB). A systematic loss of marine intertidal unconsolidated shore (M2US) is due to erosion along the dynamic tidal inlet at San Luis Pass. The Gulf beach diminished in area from the mid-1950's total of 163 ha (402 acres) to 147 ha (363 acres) in 1979, a 10% loss. The area of beach declined an additional 49% to 76 ha (188 acres) by 2002.





Figure 1. Salt-water marsh on the bayward side of Galveston Island near San Luis Pass.

## INTRODUCTION

Coastal wetlands on barrier islands are essential natural resources that are highly productive biologically and chemically and are part of an ecosystem in which a variety of flora and fauna depend (Fig. 1). Scientific investigations to determine status and trends of wetlands assist in their protection and preservation, directly benefiting long-term productivity and public use. This report presents results of an investigation to determine the current status and historical trends of wetlands and associated aquatic habitats along the upper Texas barrier island system from East Galveston Bay to Christmas Bay. Previous studies by the Bureau of Economic Geology (BEG) of Galveston Bay (White et al. 1993) indicate substantial losses in wetlands due to subsidence and associated relative sea-level rise. Some of the losses on Galveston Bay barriers have occurred along surface faults that have become active as a result of underground fluid production. In contrast to the Galveston Bay system, studies of wetlands on barrier islands in the Corpus Christi Bay area by BEG, Texas Parks and Wildlife Department, and Texas A&M University at Corpus Christi (White et al. 1998) show that marshes have expanded as a result of relative sea-level rise. Between these two bay systems is the Matagorda Bay/San Antonio Bay complex where extensive wetlands on barrier islands and peninsulas have also



undergone changes, including the Colorado River Delta and associated diversion channel, which were investigated by White et al. (2002). Results of these kinds of studies improve our understanding of marsh changes on Texas barriers and pinpoint wetlands threatened from erosion, faulting, subsidence, and other processes. These data provide site-specific information for implementing marsh protection and restoration programs.

The study is based on wetlands interpreted and mapped using aerial photographs taken in February 2002, and on historical wetlands mapped on photographs taken in the 1950's and November 1979 by the U.S. Fish and Wildlife Service (USFWS). The 1979 series maps were prepared under the USFWS National Wetlands Inventory (NWI) program and the 1950's series under a special project administered by USFWS (Shew et al. 1981). Both the 1950's and 1979 series USFWS maps, which are in digital format, were partially revised in this project to be more consistent with wetlands interpreted and delineated on the 2002 photographs. The revisions are discussed in more detail in the methods section. The USFWS NWI maps based on 1992 photographs were used as collateral data in the delineation and analysis of wetlands, and in investigating trends.

### **Study Area**

The study area includes the barrier and peninsula system stretching from East Galveston Bay to Christmas Bay (Fig. 2). Included are Bolivar Peninsula, Galveston Island, and Follet's Island. The estuarine system in this area includes Galveston Bay, East and West Bays, and to the southwest, Christmas Bay. The study area is located in Galveston and Brazoria counties.

### **General Setting of Barriers**

Geologically, Galveston Island is a modern progradational (accretionary) barrier island (Bernard et al. 1970; Fisher et al. 1972) with well-preserved ridge-and-swale topography (Fig. 3). Relict beach ridges and intervening swales have an orientation roughly parallel to the present island shoreline marked by the Gulf beach. The swales are the sites of extensive linear estuarine and palustrine wetlands. Bayward of the ridge and swale features on Galveston Island are numerous truncated channels, the remnants of past tidal inlets and storm washover channels along which there are extensive marshes. Galveston Island is relatively wide along its northeastern half and tapers and narrows toward San Luis Pass to the southwest. To the northeast is Bolivar Peninsula, which also has accretionary topography and is characterized by two large fan complexes extending into East Bay, which are the remnants of relict flood-tidal delta and washover fan deposits (Fig. 2). These fans are the sites of extensive salt and brackish marshes. The Gulf Intracoastal Waterway separates the fans from the island proper. At the southwest end of Bolivar Peninsula, recent accretionary beach ridges and swales have formed where sediments are deposited near the jetties at Bolivar Roads, a tidal inlet and ship channel. To the southwest of Galveston Island and separated by the tidal inlet, San Luis Pass, is Follet's Island, a very narrow barrier but the site of extensive marshes and, in adjacent Christmas Bay, productive seagrass beds. A flood-tidal delta at San Luis Pass, known as Mud Island, is part of the wetland system mapped with Follet's Island.

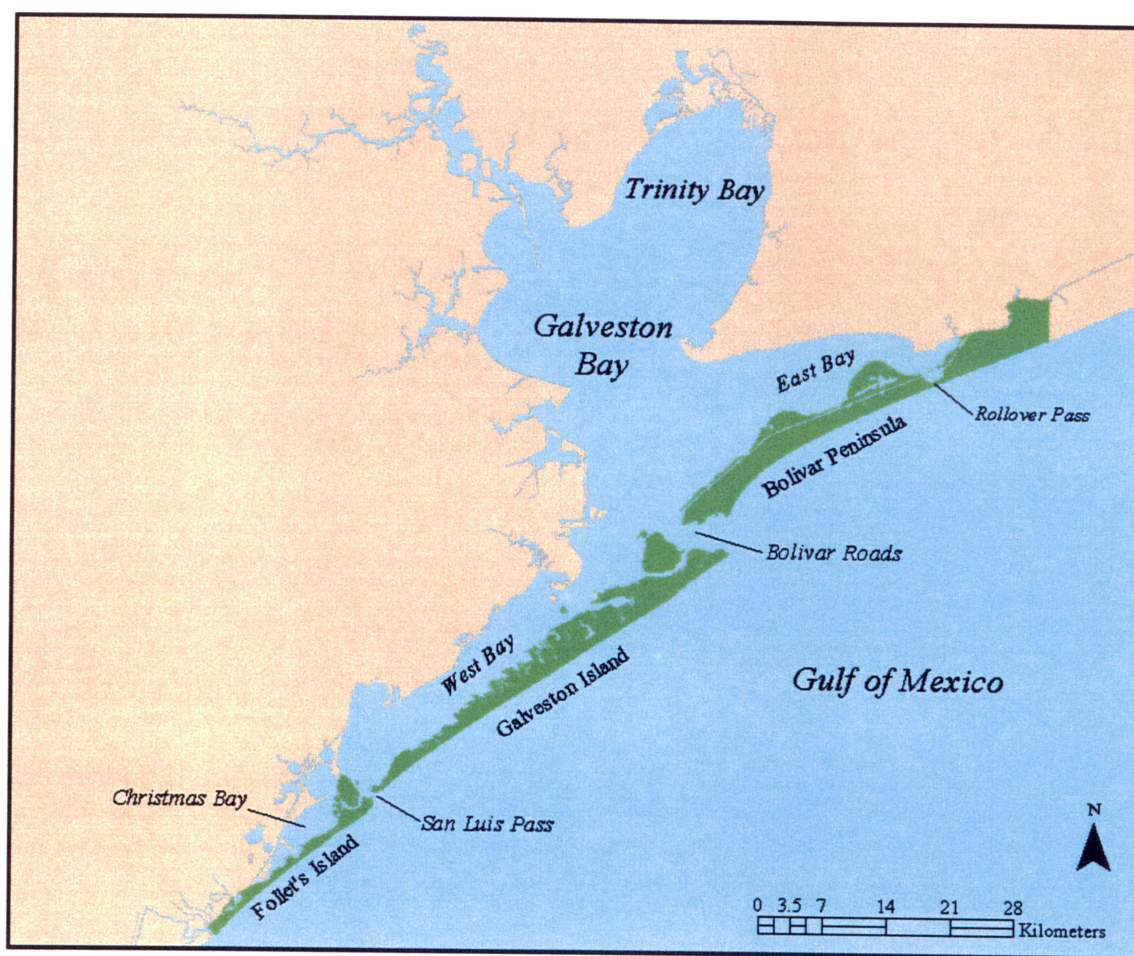
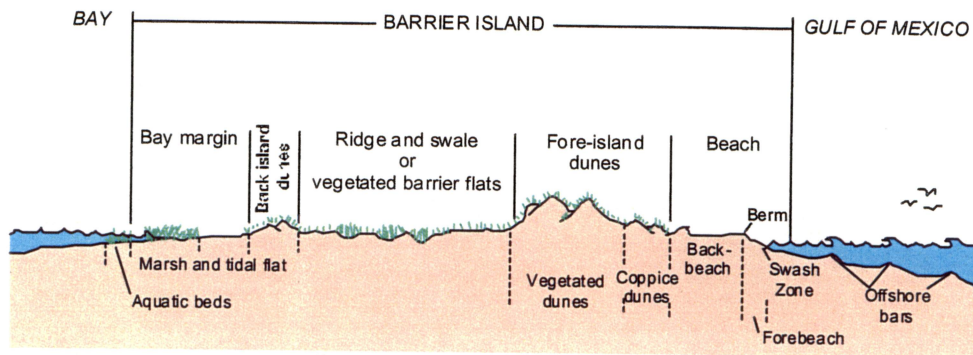
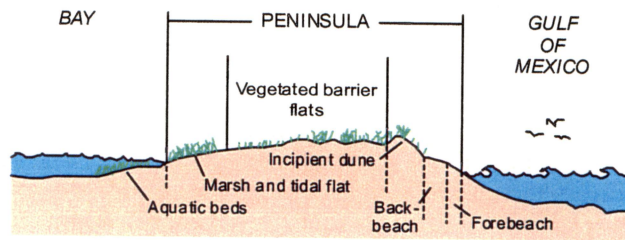


Figure 2. Index map of study area.

(a)



(b)



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Figure 3. Schematic profile illustrating major environments across a broad accretionary Texas barrier island with ridge and swale topography, such as Galveston Island (a), and a more narrow barrier peninsula or island, such as Follet's island (b).

Geomorphic features on which various types of barrier island wetlands have developed are the result of numerous interacting processes. Physical processes that influence wetlands include astronomical and wind tides, waves and longshore currents, storms and hurricanes, river flow, deposition and erosion, subsidence, faulting, sea-level rise, precipitation, water table fluctuations, and evapotranspiration. These processes have contributed to development of a gradational array of permanently inundated to infrequently inundated environments ranging in elevation from estuarine subtidal areas to topographically higher inter-tidal wetlands that grade upward from the astronomical-tidal zone through the wind-tidal zone to the storm-tidal zone.

### **Bay-Estuary-Lagoon Setting**

Exchange of marine waters with waters of the estuarine system occurs primarily through (1) the tidal inlet San Luis Pass that connects to West Bay and separates Galveston Island from Follet's Island, (2) Bolivar Roads, a dredged ship channel that connects to Galveston Bay and separates Galveston Island and Bolivar Peninsula, and (3) a narrow dredged channel at the northeast end of Bolivar Peninsula called Rollover Pass that connects to East Bay (Fig. 2). The main sources of fresh-water inflow into the estuarine system of the study area are the Trinity River that discharges into Trinity Bay, the San Jacinto River that discharges at the head of Galveston Bay, and Chocolate Bayou that discharges into Chocolate Bay and then West Bay (Fig. 2). Average tidal range is approximately 0.5 m in the Gulf and 0.2 m in the bays (U.S. Department of Commerce, 1979), although wind-generated tides in the bays can be substantially higher. Estuarine salinities are generally highest in West Bay, followed in order of decreasing average salinities by Galveston, East, and Trinity Bays. Average salinities in West Bay are generally more than 15 ppt and range into the 30's. Salinities increase near the tidal inlets of San Luis Pass and Bolivar Roads reflecting the influence of marine water in tidally influenced areas (White et al. 1985). Salinities decrease toward the heads of the bays where they are moderated by fresh-water inflows. Near the head of Trinity Bay average salinities range from less than 5 to about 10 ppt, but can be higher or lower depending on fresh-water inflows from the Trinity River.

### **Relative Sea-level Rise**

Another important process affecting wetland and aquatic habitats is relative sea-level rise, which is the relative vertical rise in water level with respect to a datum at the land surface. This change in relative sea level can be caused by a rise in mean-water level or subsidence of the land surface. Along the Texas coast both processes, eustatic sea-level rise and subsidence, are part of the relative sea-level rise equation. Subsidence, especially associated with withdrawal of ground water and oil and gas, is the overriding component.

Over the past century, sea level has risen on a worldwide (eustatic) basis at about 0.12 cm/yr, with a rate in the Gulf of Mexico and Caribbean region of 0.24 cm/yr (Gornitz et al. 1982, Gornitz and Lebedeff, 1987). Adding compactional subsidence to these rates yields a relative sea-level rise that locally exceeds 1.2 cm/yr (Swanson and Thurlow,



1973, Penland et al. 1988). The tide gauge at Pier 21 at Galveston Island provides the longest continuous record of sea-level variations along the Texas coast. The average rate of sea-level rise from 1909 to 2003 was 0.65 cm/yr (Fig. 4). Rates of sea-level rise recorded by the tide gauge reached a high of 1.9 cm/yr from 1963 to mid 1975. Short-term rates of sea-level rise at Freeport, southwest of Follet's Island, exceeded 1.1 cm/yr from 1959 to 1971, (Swanson and Thurlow, 1973), and 1.4 cm/yr from 1954 to 1986 (records were incomplete for the years 1954, 1966, and 1984) (Lyles et al. 1988). These short-term rates can be affected by secular variations in sea level caused by climatic factors, such as droughts and periods of higher than normal precipitation and riverine discharge. Short-term sea-level variations produce temporary adjustments in the longer term trends related to eustatic sea level rise and subsidence. The period of rapid relative sea-level rise from the mid-1960's to mid-1970's is time coincident with a maximum change in some habitats such as wind-tidal flats (White et al. 1998).

### **Subsidence**

Subsidence of varying amounts has occurred along the entire Texas coast, but the most significant subsidence is in the Houston-Galveston area where a large subsidence "bowl", with over 3 meters of subsidence near its center, has formed (Fig. 5) (Gabrysch, 1984; Gabrysch and Coplin, 1990). In this area, the amount of land undergoing at least 30 cm of subsidence, including the area around Texas City, has grown from about 360 km<sup>2</sup> in the 1940's to more than 10,000 km<sup>2</sup> in the 1980's. Average maximum rates of subsidence at the center of the "bowl" were as high as 12 cm/yr for the period 1964 to 1973 (Gabrysch and Bonnet, 1975). The subsidence bowl centered on Texas City encompasses much of Galveston Island.

There are many causes of subsidence, including regional downwarping or tilting of the earth's crust due to loading, which is significant over a geologic time frame along the Texas coast but not over an historic time frame (Winker, 1979). Within an historic time frame, the cause of subsidence in the Houston-Galveston area is primarily due to ground-water withdrawal and secondarily oil and gas production that began in the early part of this century. On the eastern side of the subsidence bowl in the Houston-Galveston region including Texas City, rates of subsidence have decreased dramatically in some areas due to curtailment of ground-water pumpage (Gabrysch and Coplin, 1990).

### **Faulting**

Geologically, active surface faults along the Texas coast are fractures in the earth's crust along which movement has occurred within the past few thousand years. Generally, the earth's surface moves downward or subsides at a faster rate on one side (downthrown side) of the fault than on the other side. This produces a fault scarp or sharp change in elevation at the surface along the trace of the fault. Active faults are significant geologic hazards because their movement at the surface breaks and bows structures such as highways, railroads, foundations of residential and commercial developments, pipelines,

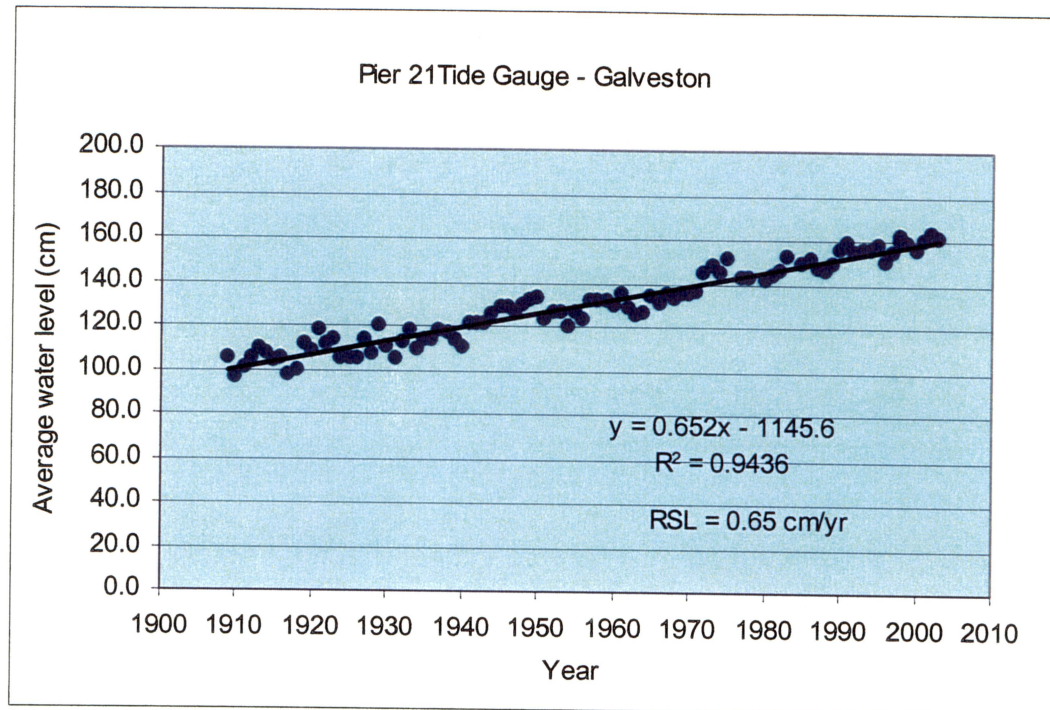


Figure 4. Tide gauge record at Pier 21, Galveston. The average rate of sea-level rise from 1909 to 2003 was 0.65 cm/yr. The highest short-term rate (1963-1975) was 1.92 cm/yr. Data from NOAA National Ocean Service.

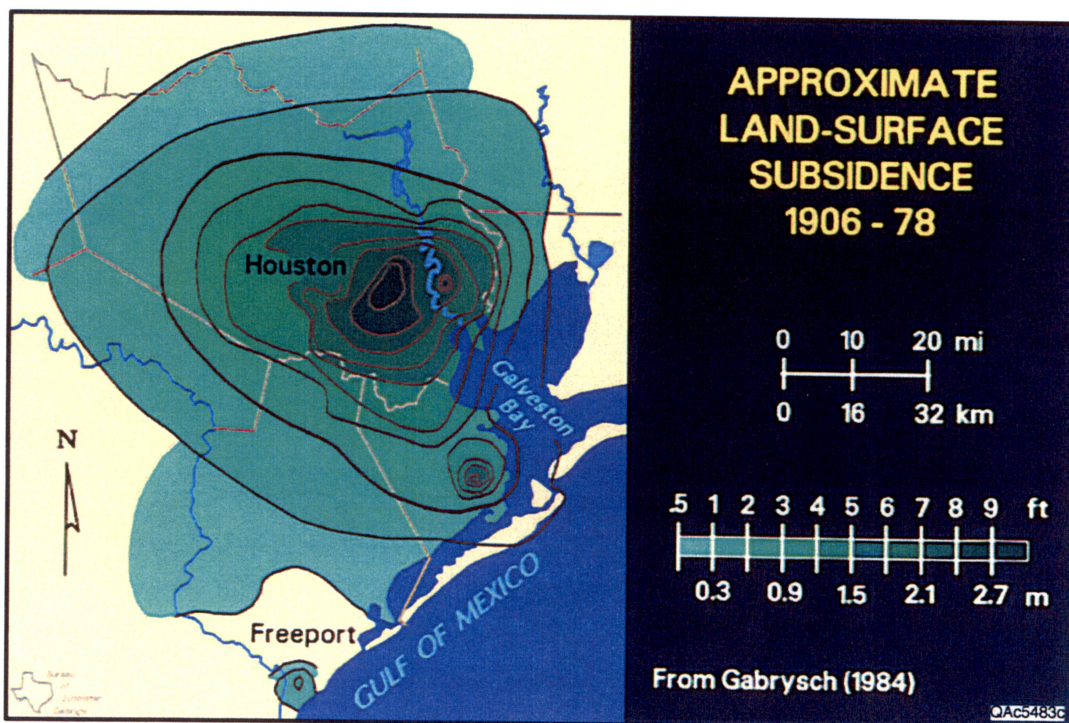


Figure 5. Houston-Galveston area subsidence from 1906 to 1978 caused primarily by ground-water withdrawal. Maximum subsidence in 1978 was near 9 ft at the center of the major subsidence bowl northwest of Galveston Bay. A secondary subsidence bowl is centered on Texas City across the bay from Galveston.



airfield runways, and other features. Millions of dollars of damage are caused annually by faults (Verbeek and Clanton, 1981). Natural resources such as wetlands are also affected by faulting. As the land surface moves downward along a fault that intersects a wetland, more frequent and eventually permanent inundation can lead to replacement of marsh vegetation by open water (Fig. 6) (White and Tremblay, 1995; White and Morton, 1997). Forty faults, together measuring about 150 km have been identified and mapped in marsh areas along the upper coast (Fig. 7) (White and Morton, 1997). The lengths of individual fault traces range from less than 1 km to more than 13 km. Surface faults correlate with, and appear to be natural extensions of subsurface faults in many areas (Weaver and Sheets, 1962; Van Siclen, 1967; Kreitler, 1977; Verbeek and Clanton, 1981; White and Morton, 1997). Although movement of the earth's surface along some faults is related to natural processes, there is evidence that most of the surface faulting in the Houston metropolitan area and the upper Texas coast has taken place during the last few decades, and is largely due to the withdrawal of water, oil, and gas, which has reinitiated and accelerated fault activity (Reid, 1973; Kreitler, 1977; Verbeek and Clanton, 1981; White and Morton, 1997). Most of the faults in the Houston-Galveston area occur within the subsidence bowl caused by ground-water withdrawal, but at some locations there is a close association between the faults and oil and gas production (Gustavson and Kreitler, 1976; Hillenbrand, 1985; White and Morton, 1997).

Many faults are not visible on historical photographs but are visible on more recent photographs, which indicates that they have become active recently. Other lines of evidence of fault activity are (1) reoccurring breaks and repairs in pavements, buildings, and other structures, (2) abrupt changes in elevations as shown on topographic maps, and (3) sharp changes in the rates of subsidence along benchmark releveing profiles.

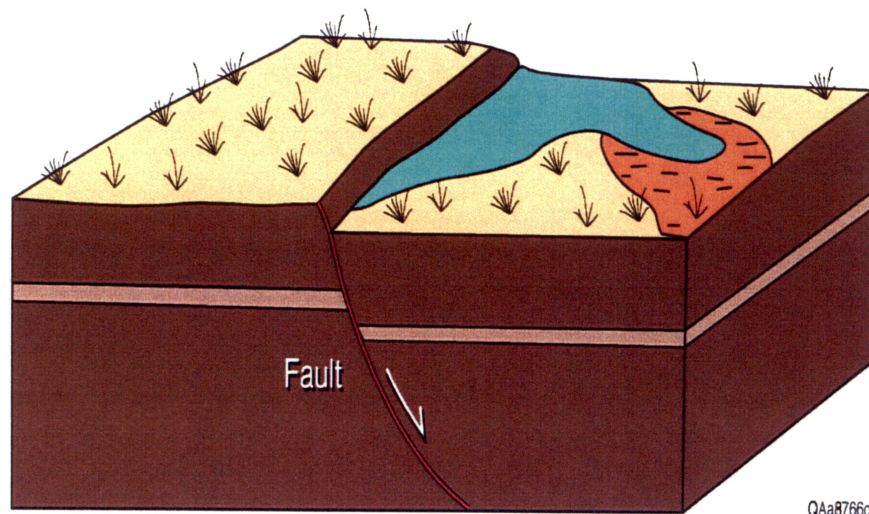


Figure 6. Diagram illustrating changes in wetlands along an active surface fault. There is generally an increase in low marshes and ponded water on the side of the fault that is moving downward. From White and Tremblay (1995).



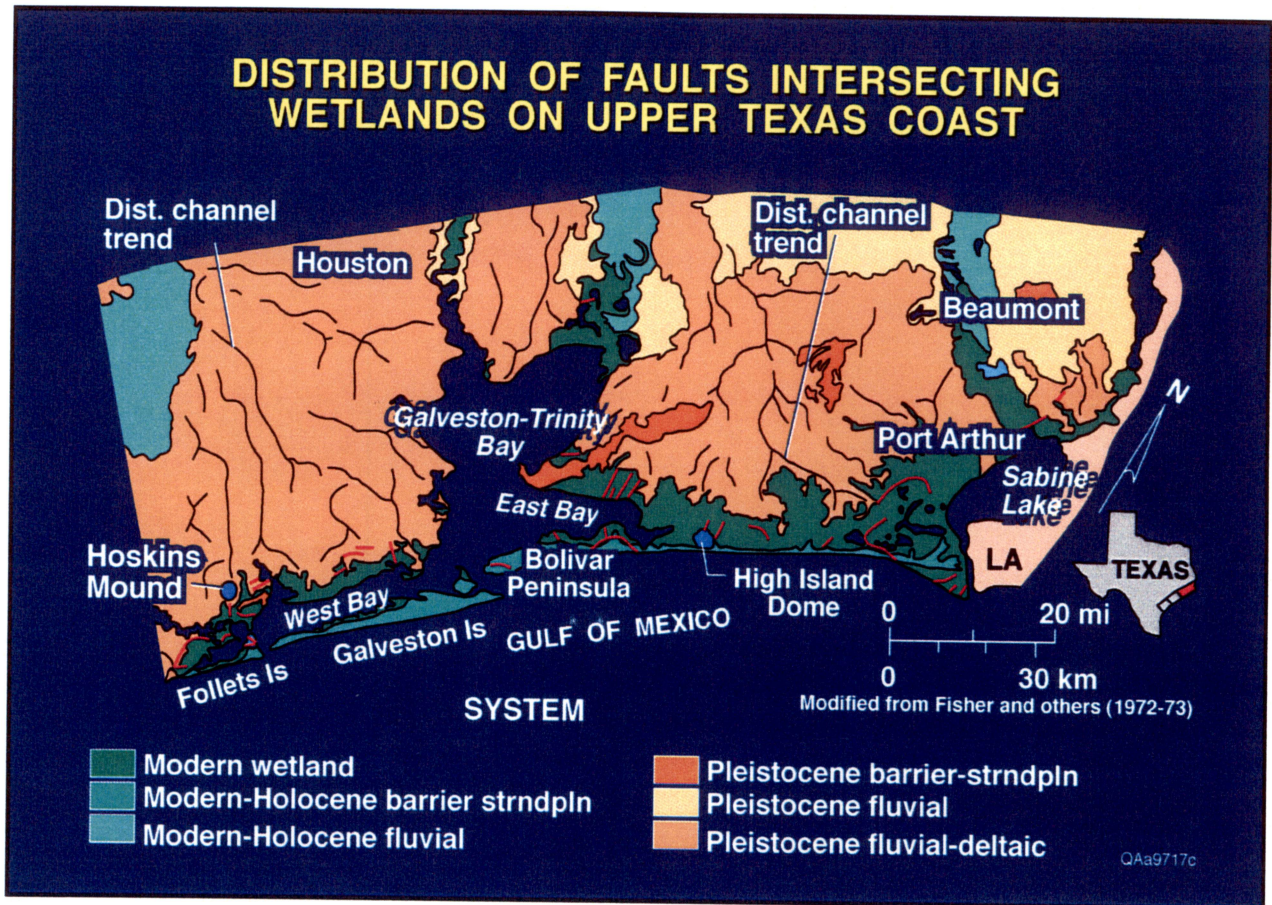


Figure 7. Surface faults, shown in red, that intersect marshes between Follet's Island and the Louisiana border. The faults were mapped from sequential aerial photographs. Only about 25 % of the faults were visible on photographs taken in the 1930's, but the remaining 75 % could be seen on later photographs indicating that they have become active since the 1930's. From White and Morton (1997).

Differences in plant communities across faults in some areas appear to be related to a successional change in vegetation as subsidence and associated relative sea-level rise increase the depth, frequency, and duration of flooding on the downthrown sides of faults. Because *Spartina alterniflora* can withstand more frequent flooding than *Spartina patens* and *Distichlis spicata* (Adams, 1963; Chabreck, 1972; Webb And Dodd, 1978; Gleason and Zieman, 1981; Mendelssohn and McKee, 1988a; Naidoo et al. 1992), a gradual replacement of these higher marsh species by *Spartina alterniflora* is expected. In a salt marsh in North Carolina, Adams (1963) attributed the replacement of portions of a maritime forest (*Juniperus virginiana*) by *Spartina alterniflora* to a relative rise in sea level. If fault-related subsidence and relative sea-level rise continue at rates that surpass rates of marsh sedimentation, eventually water depths and frequency of inundation will exceed even that which *Spartina alterniflora* can tolerate (Mendelssohn and McKee, 1988b) and all emergent vegetation will be replaced by open water.



## METHODS

### Mapping and Analyzing Status and Trends

Status and trends of wetlands in the study area were determined by analyzing the distribution of wetlands mapped on aerial photographs taken in the 1950's, 1979, and 2002. Maps of the 1950's and 1979 were prepared as part of the USFWS-sponsored Texas Barrier Island Ecological Characterization study (Shew et al. 1981) by Texas A&M University and the National Coastal Ecosystems Team of the USFWS. Final maps of the 1979 series were prepared under the NWI program. Maps of the 1950's and 1979 series were digitized and initially analyzed in 1983 (USFWS, 1983). Current USFWS NWI maps and digital data for the Texas coast were prepared using 1992 aerial photographs. The current status of wetlands in this study is based on photographs taken in February 2002 by Kucera International, Inc., contracted by GLO.

### Wetland Classification and Definition

For purposes of this investigation, wetlands were classified in accordance with *The Classification of Wetlands and Deepwater Habitats of the United States* by Cowardin et al. (1979). This is the classification used by the USFWS in delineating wetlands as part of the NWI.

Definitions of wetlands and deepwater habitats according to Cowardin et al. (1979) are:

Wetlands are lands transitional between terrestrial and aquatic systems where the water table is usually at or near the surface or the land is covered by shallow water. For purposes of this classification wetlands must have one or more of the following three attributes: (1) at least periodically, the land supports predominantly hydrophytes<sup>1</sup>; (2) the substrate is predominantly undrained hydric soil<sup>2</sup>; and (3) the substrate is nonsoil and is saturated with water or covered by shallow water at some time during the growing season of each year.

Deepwater habitats are permanently flooded lands lying below the deepwater boundary of wetlands. Deepwater habitats include environments where surface water is permanent and often deep, so that water, rather than air, is the principal medium within which the dominant organisms live, whether or not they are attached to the substrate. As in wetlands, the dominant plants are hydrophytes; however, the substrates are considered nonsoil because the water is too deep to support emergent vegetation (U.S. Soil Conservation Service, Soil Survey Staff, 1975).

Because the fundamental objective of this project was to determine status and trends of wetlands using aerial photographs, classification and definition of wetlands are integrally connected to the photographs and the interpretation of wetland signatures. Wetlands were

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<sup>1</sup>The USFWS has prepared a list of hydrophytes and other plants occurring in wetlands of the United States.

<sup>2</sup>The NRCS has prepared a list of hydric soils for use in this classification system.

not defined nor mapped in accordance with the USACE wetlands delineation manual for jurisdictional wetlands (U.S. Army Corps of Engineers, 1987).

## **Interpretation of Wetlands**

### **Historical Wetland Distribution**

Historical distribution of wetlands is based on the 1950's and 1979 USFWS wetland maps. Methods used by the USFWS include interpretation and delineation of wetlands and aquatic habitats on aerial photographs through stereoscopic interpretation. Field reconnaissance is an integral part of interpretation. Photographic signatures are compared to the appearance of wetlands in the field by observing vegetation, soil, hydrology, and topography. This information is weighted for seasonality and conditions existing at the time of photography and ground-truthing. Still, field-surveyed sites represent only a small percentage of the thousands of areas (polygons) delineated. Most areas are delineated on the basis of photointerpretation alone, and mis-classifications may occur. The 1950's photographs are black-and-white stereo-pair, scale 1:24,000, most of which along the Texas coast were taken in the mid-1950's, (Larry Handley, USGS, Personal Communication, 1997). The 1979 aerial photographs are NASA color-infrared stereo-pair, scale 1:65,000, that were taken in November.

The USFWS NWI maps were prepared by transferring wetlands mapped on aerial photographs to USGS 7.5-minute quadrangle base maps, scale 1:24,000, using zoom-transfer scopes. Wetlands on the completed maps were then digitized and the data entered into a GIS. As in the photointerpretation process, there is a margin of error involved in the transfer and digitization process.

Photographs used are generally of high quality. Abnormally high precipitation in 1979, however, raised water levels on tidal flats, and in many island fresh to brackish wetlands, produced more standing water than in the 2002 photographs that were taken during much lower tides and generally drier conditions. The low tides captured in the 2002 photographs exposed many flats that are typically submerged. Although the 1950's photographs are black and white, they are large scale (1:24,000), which aids in the photointerpretation and delineation process. The 1950's photographs may have been taken before the severe drought that peaked in 1956 in Texas (Riggio et al. 1987), which possibly accounts for extensive palustrine marshes on Bolivar Peninsula on the 1950's maps. These differences in wet and dry conditions during the various years affected habitats, especially palustrine, and their interpreted, or mapped, water regimes.

The following explanation is printed on all USFWS wetland maps that were used in this project to determine trends of wetlands:

This document (map) was prepared primarily by stereoscopic analysis of high-altitude aerial photographs. Wetlands were identified on the photographs based on vegetation, visible hydrology, and geography in accordance with "Classification of Wetlands and Deepwater Habitats of the United States" (FWS/OBS-79/31 December 1979). The aerial photographs typically reflect conditions during the specific year and season when they

were taken. In addition, there is a margin of error inherent in the use of the aerial photographs. Thus, a detailed on-the-ground and historical analysis of a single site may result in a revision of the wetland boundaries established through photographic interpretation. In addition, some small wetlands and those obscured by dense forest cover may not be included on this document.

Federal, State, and local regulatory agencies with jurisdiction over wetlands may define and describe wetlands in a different manner than that used in this inventory. There is no attempt in either the design or products of this inventory to define the limits of proprietary jurisdiction of any Federal, State or local government or to establish the geographical scope of the regulatory programs of government agencies. . .

## **Revision of Historical Wetland Maps**

As part of this study, researchers at BEG revised USFWS historical wetland maps (1950's and 1979) so there would be closer agreement between the historical map units and the current (2002) wetland map units. Revisions of the USFWS data are restricted primarily to the estuarine marshes, tidal flats, and areas of open water. The principal reason for the revisions was that in many areas on the historical maps, estuarine intertidal emergent wetlands (E2EM) were combined with intertidal flats (E2FL) or open water (E1OW) as a single map unit (E2EM/E2FL and E2EM/E1OW). In our revisions, many of these areas were subdivided into E2EM and E2FL or E1OW where possible at the mapping scale. In addition, because of the larger scale of the 1950's aerial photographs (1:24,000) compared to the 1979 photographs (~1:65,000), smaller wetlands, particularly water features, were mapped on the 1950's photographs. As part of the revisions, many of these smaller water bodies were added to the 1979 wetland maps.

To accomplish the revisions, USFWS maps for the 1950's and 1979 were plotted on a quadrangle by quadrangle basis, and wetlands were analyzed and revised at a scale of 1:24,000 by optically rectifying the aerial photographs (1950's and 1979) to the wetland maps using Zoom Transfer Scopes (ZTS). Wetlands on the aerial photographs were interpreted and changes mapped directly on the plotted wetland maps. Changes were digitized, and the revised data were entered into our GIS. Revised maps were then plotted in color on a quadrangle by quadrangle basis and the revision checked for accuracy and completeness. Problem areas were marked, and the digital data were revised accordingly.

## **Current Wetland Distribution**

The current distribution of wetlands is based on digital, Color Infrared (CIR), 1-meter resolution aerial photographs, taken in February 2002 by Kucera International, Inc. The digital images were registered to USGS orthophoto quarter quadrangles (DOQQ's). Interpretation and mapping of wetlands and aquatic habitats were completed by BEG researchers through interactive digitization of habitats on screen in a GIS (ArcInfo and ArcView) at a scale of 1:6,000. An attempt was made to show about the same amount of detail as the historical maps in order to make accurate comparisons of wetland changes through time. Still, because of the method used, the current wetland maps show more detail than the historical maps.

## Field Investigations

Field investigations (Fig. 8) were conducted for two purposes: (1) to characterize wetland plant communities through representative field surveys and (2) to compare various wetland plant communities in the field with corresponding “signatures” on aerial photographs used to define wetland classes, including water regimes, for mapping purposes. Characterization of prevalent plant associations provided vital plant community information for defining mapped wetland classes in terms of typical vegetation associations. Interpretations of wetlands were supported by Light Detection and Ranging (LIDAR) data acquired by BEG in the spring of 2002 (Fig. 9). The LIDAR images provide detailed elevation data that help differentiate between high and low marshes and flats, and areas that are transitional between uplands and wetlands.

## Variations in Classification

Classification of wetlands varied somewhat for the different years. On 1979 and 2002 maps, wetlands were classified by system, subsystem, class, subclass (for vegetated classes), water-regime, and special modifier in accordance with Cowardin et al. (1979) (Figs. 10-12). For the 1950's maps, wetlands were classified by system, subsystem, and class. On 1979 maps, upland areas were also mapped and classified by upland habitats using a modified Anderson et al. (1976) land-use classification system (Fig. 12). Flats and beach/bar classes designated separately on 1950's and 1979 maps were combined into a single class, unconsolidated shore, on 2002 maps, in accordance with updated NWI procedures as exemplified on 1992 NWI wetland maps (Fig. 12). USFWS data for the study area was selected from fifteen 7.5-minute quadrangles (Table 1, Fig. 13) from files previously digitized and maintained by the USFWS for the 1950's and 1979 wetland maps.

Table 1. Names of USGS quadrangles in the study area.

Quadrangle Name	
Caplen	High Island
Christmas Point	Lake Como
Christmas Point OE S	Point Bolivar
Flake	San Luis Pass
Freeport	Sea Isle
Frozen Point	The Jetties
Galveston	Virginia Point
Galveston OE S	



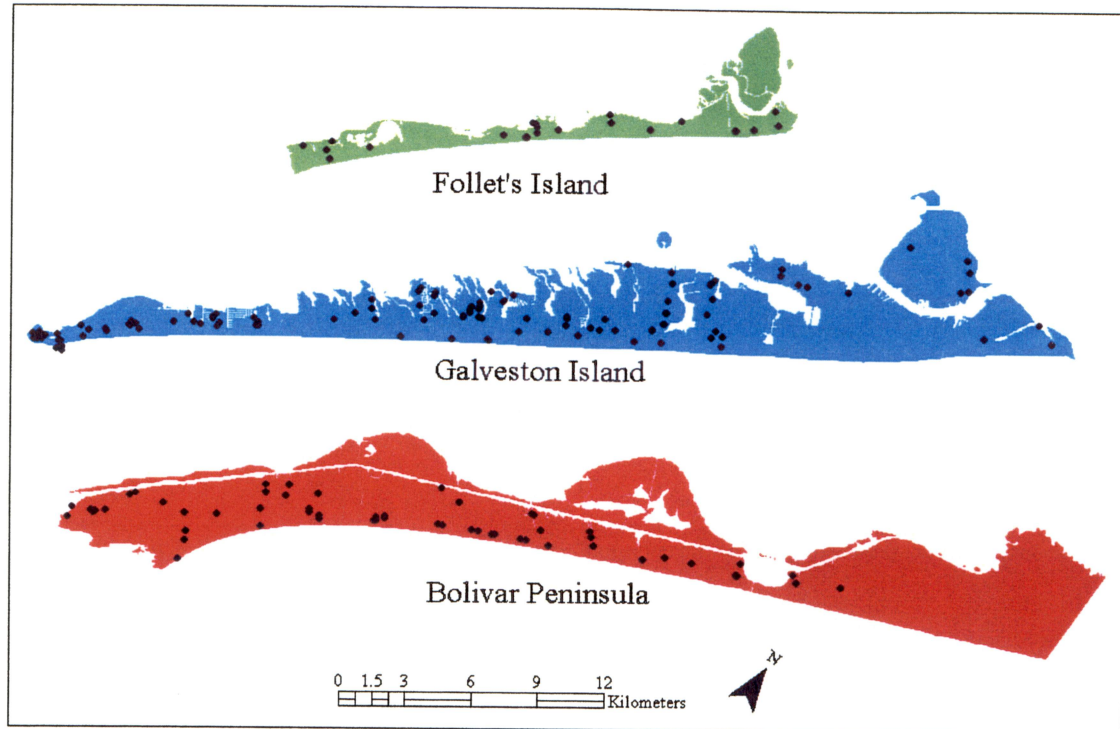


Figure 8. Index map of field-survey sites used for ground-truthing aerial photo delineations, and recording vegetation composition and water regimes.

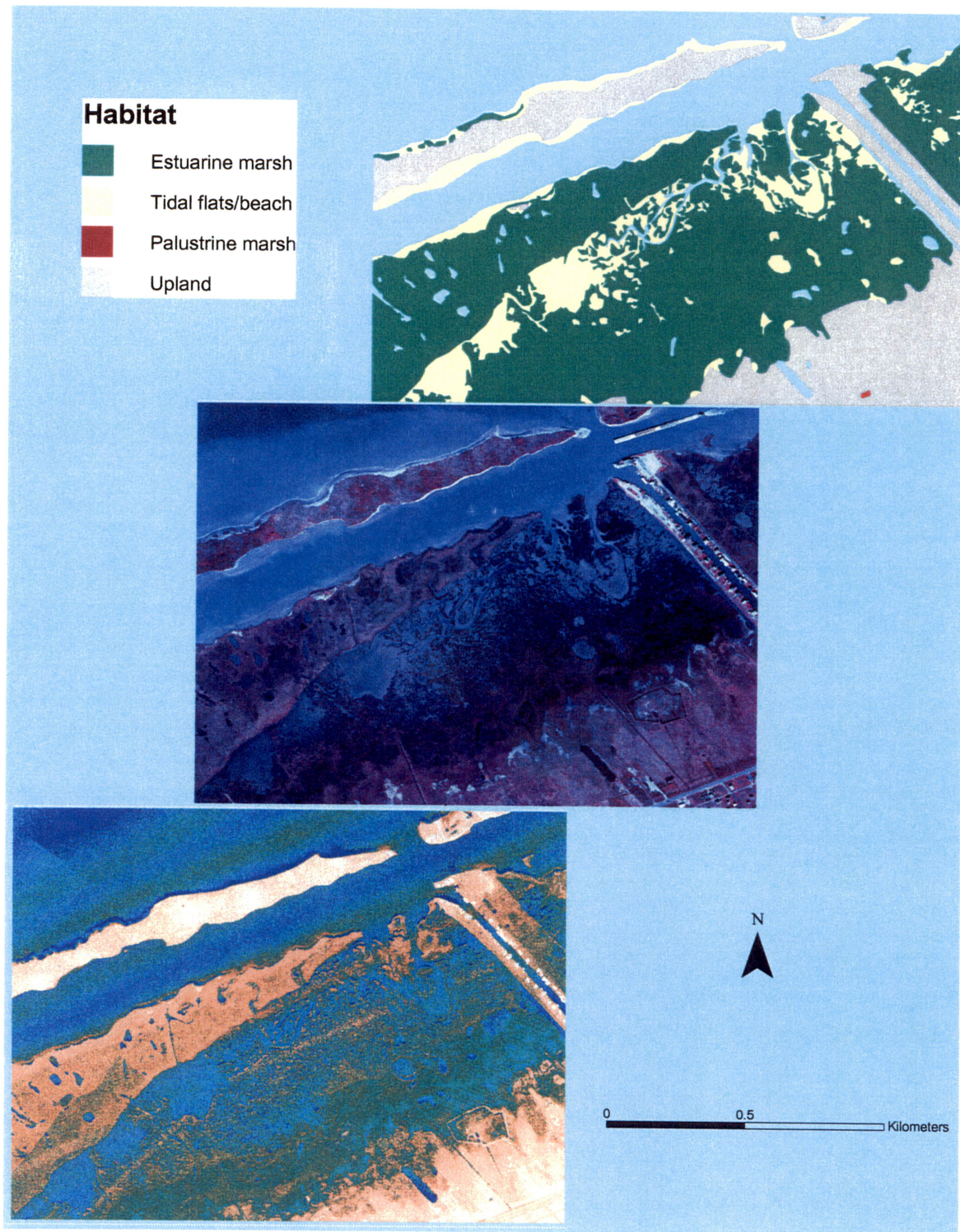


Figure 9. Wetland map (top), 2002 aerial photo (center) and LIDAR image (bottom) of marshes affected by an active fault on Bolivar Peninsula. The fault orientation is northeast-southwest and is downthrown to the southeast. Water and tidal flats have replaced marshes on the downthrown side. LIDAR from Smyth et al., 2003.

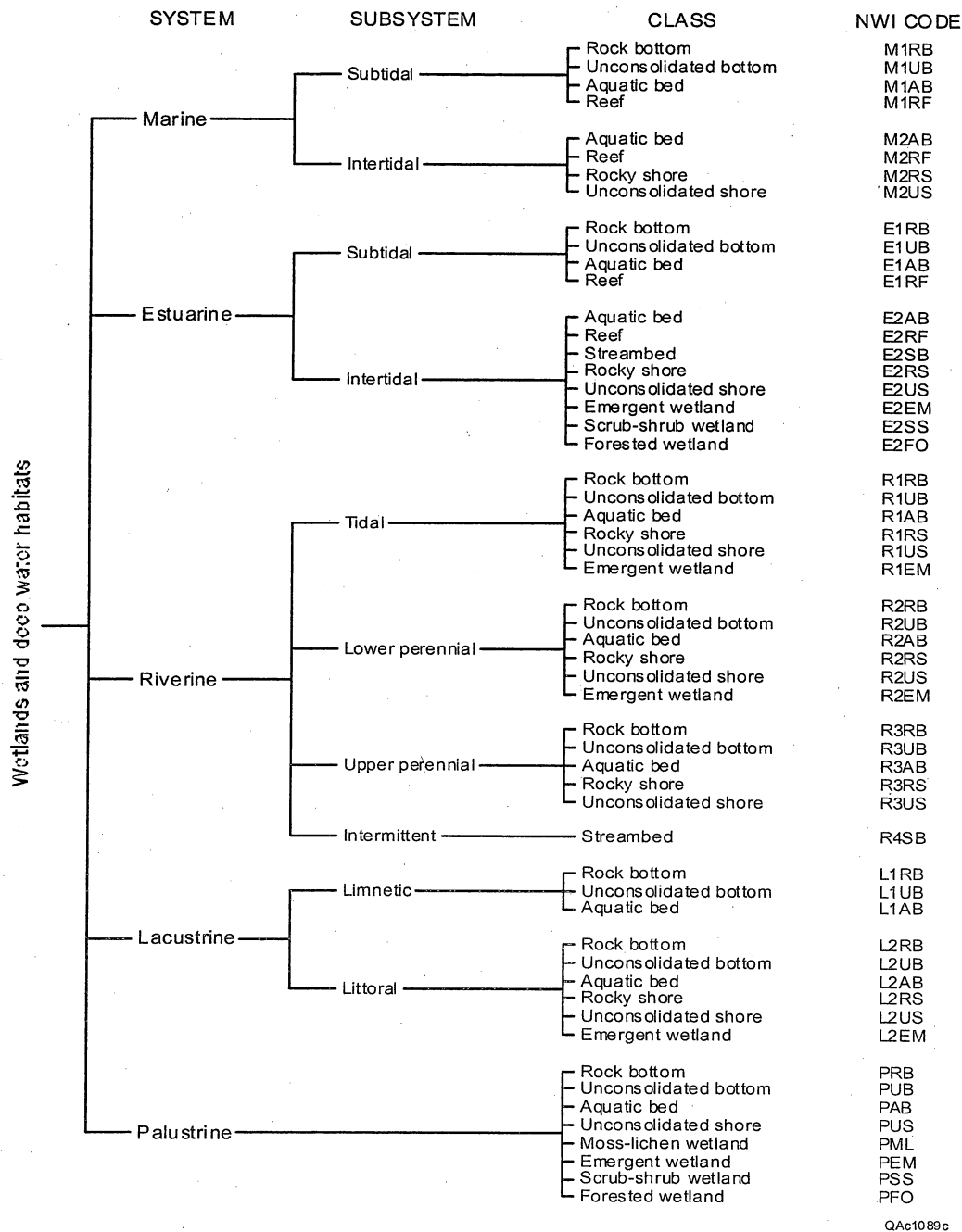


Figure 10. Classification hierarchy of wetlands and deepwater habitats showing systems, subsystems, and classes. From Cowardin et al. (1979).



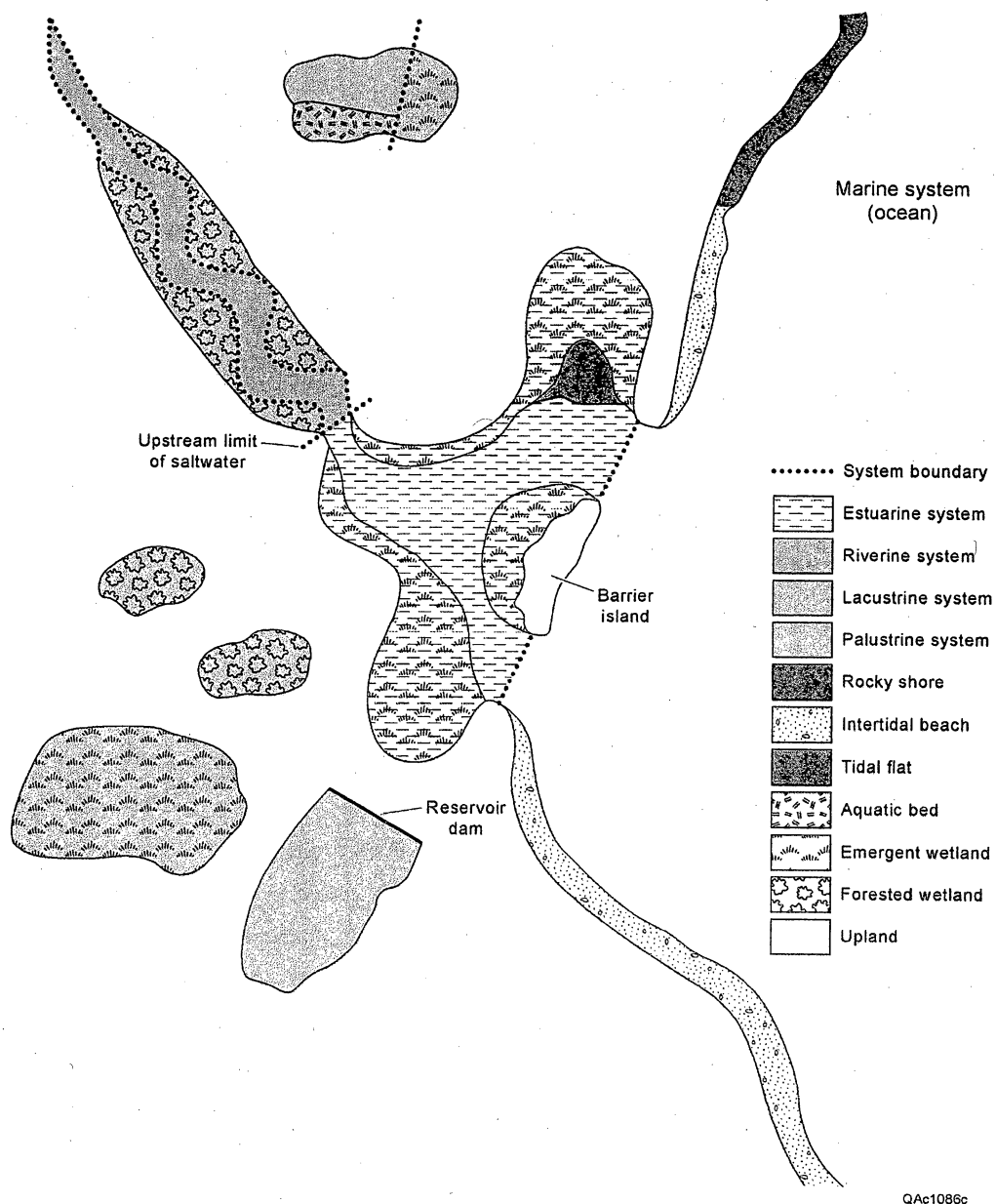
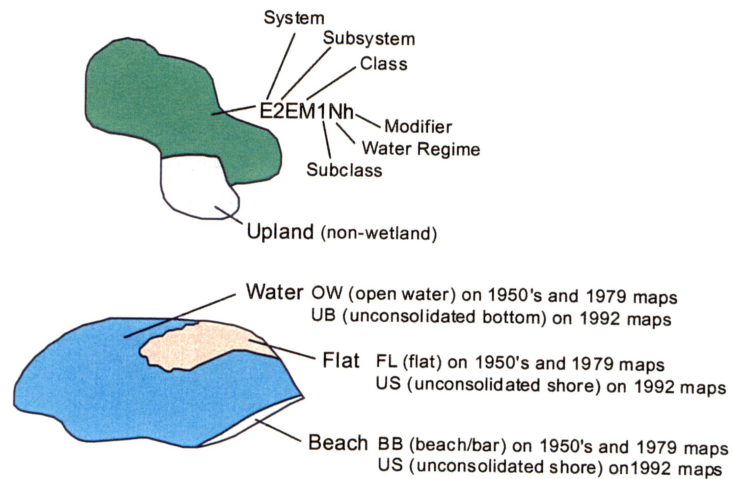


Figure 11. Schematic diagram showing major wetland and deepwater habitat systems. From Tiner (1984).



#### Upland Legend for 1979 maps only

Upland Classes	Modifying Terms
U = Urban or developed	o = oil and gas
A = Agricultural	r = rice field
F = Forest	6 = deciduous
SS = Scrub/shrub	7 = evergreen
R = Range	8 = mixed
B = Barren	s = spoil

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Figure 12. Example of symbology used to define wetland and upland habitats on NWI maps.

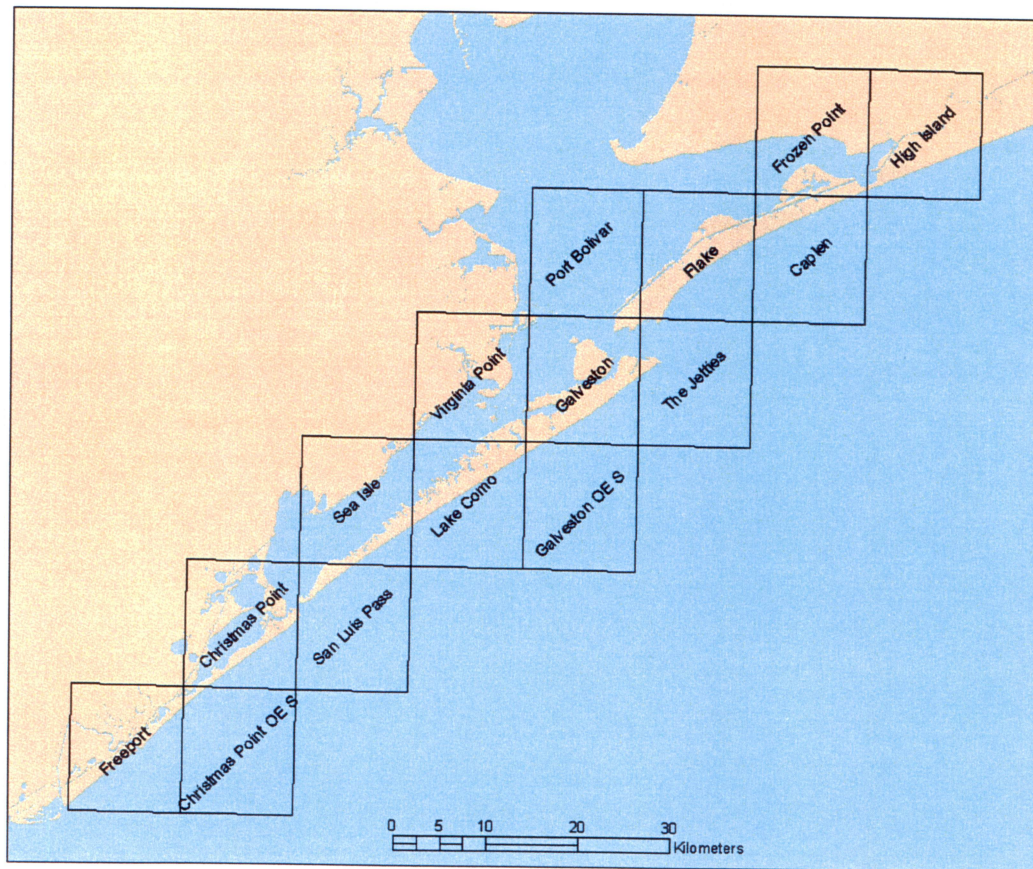


Figure 13. Index map of USGS 7.5 minute quadrangles that encompass the study area.

Results include GIS data sets consisting of electronic-information overlays corresponding to mapped habitat features for the 1950's, 1979, and 2002. Data can be manipulated as information overlays, whereby scaling and selection features allow portions of the estuary to be electronically selected for specific analysis.

Among the objectives of GIS are to: (1) allow direct historical comparisons of wetland types to gauge historical trends and status of habitats, (2) allow novel comparisons of feature overlays to suggest probable causes of wetland changes, (3) make information on wetlands directly available to managers in a convenient and readily assimilated form, and (4) allow overlays to be combined from wetland studies and other topical studies in a single system that integrates disparate environmental features for planning and management purposes. The GIS is a flexible and valuable management tool for use by resource managers. Still, users must be aware of potential errors, for example from registration differences, which can arise from direct analysis of GIS overlays.

### **Map Registration Differences**

There are map registration differences in the historical and recent digital data. This causes errors when the data sets are overlain and analyzed in a GIS. The 2002 aerial photographs are georeferenced to USGS DOQQ's. There is good agreement in registration with these base photographs. However, the historical data sets are not as well registered, and there is an offset in wetland boundaries between the historical and the 2002 data. When the two data sets are superimposed in a GIS, the offset creates apparent wetland changes that are in reality cartographic errors due to a lack of precision in registration. Re-registration of the USFWS digital data sets was done by georeferencing them to the USGS DOQQ's which improved the agreement of the historical maps with the 2002 maps. Still, there is not "perfect" agreement in registration between the different maps. Thus, caution must be used in interpreting changes from direct projection of the different data sets as layers in a GIS. We tabulated wetland totals separately for each year to determine wetland changes within the given study area. Projection of the data sets with respect to each other was done primarily to identify significant wetland changes that could be verified by analyzing and comparing aerial photographs.

### **CLASSIFICATION OF WETLAND AND DEEPWATER HABITATS IN THE STUDY AREA**

Cowardin et al. (1979) defined five major systems of wetlands and deepwater habitats: Marine, Estuarine, Riverine, Lacustrine, and Palustrine (Fig. 10). Systems are divided into subsystems, which reflect hydrologic conditions, such as intertidal and subtidal for marine and estuarine systems. Subsystems are further divided into class, which describes



the appearance of the wetland in terms of vegetation or substrate. Classes are divided into subclasses. Only vegetated classes were divided into subclasses for this project, and only for 1979 and 2002. In addition, water-regime modifiers (Table 2) and special modifiers were used for these years.

Table 2. Water-regime descriptions defined by Cowardin et al. (1979).

Water-Regime Symbols and Description	
<b>Nontidal</b>	
(A)	Temporarily flooded—Surface water present for brief periods during growing season, but water table usually lies well below soil surface. Plants that grow both in uplands and wetlands are characteristic of this water regime.
(C)	Seasonally flooded—Surface water is present for extended periods, especially early in the growing season, but is absent by the end of the growing season in most years. The water table is extremely variable after flooding ceases, extending from saturated to well below the ground surface.
(F)	Semipermanently flooded—Surface water persists throughout the growing season in most years. When surface water is absent, the water table is usually at or very near the land's surface.
(H)	Permanently flooded—Water covers land surface throughout the year in all years.
(K)	Artificially flooded
<b>Tidal</b>	
(K)	Artificially flooded
(L)	Subtidal—Substrate is permanently flooded with tidal water.
(M)	Irregularly exposed—Land surface is exposed by tides less often than daily.
(N)	Regularly flooded—Tidal water alternately floods and exposes the land surface at least once daily.
(P)	Irregularly flooded—Tidal water floods the land surface less often than daily.
(S)*	Temporarily flooded—Tidal
(R)*	Seasonally flooded—Tidal
(T)*	Semipermanently flooded—Tidal
(V)*	Permanently flooded—Tidal

\*These water regimes are only used in tidally influenced, fresh-water systems.

The USFWS-NWI program established criteria for mapping wetlands on aerial photographs using the Cowardin et al. (1979) classification. Alphanumeric abbreviations are used to denote systems, subsystems, classes, subclasses, water regimes, and special modifiers (Table 3, Fig. 12). Symbols for certain habitats changed after 1979; these changes are shown in Figure 12 and are noted in the section on trends in wetland and aquatic habitats. Examples of alphanumeric abbreviations used in the section on status of wetlands apply only to 2002 maps. Much of the following discussion of wetland systems as defined by Cowardin et al. (1979) is modified from White et al. (1993, 1998, and 2002). Nomenclature and symbols (Appendix) in this discussion are based primarily on 1992 NWI maps.



Table 3. Wetland codes and descriptions from Cowardin et al. (1979). Codes listed below were used in mapping wetlands on the 2002 delineations, which varied in some cases from 1950's and 1979 maps (see Fig. 12).

NWI code (water regime)	NWI description	Common description	Characteristic vegetation
M1UB (L)	Marine, subtidal unconsolidated bottom	Gulf of Mexico	Unconsolidated bottom
M2US (P, N, M)	Marine, intertidal unconsolidated shore	Marine beaches, barrier islands	Unconsolidated shore
M2RS (P)	Marine, intertidal rocky shore	Marine breakwaters, beach stabilizers	Jetties
E1UBL (L)	Estuarine, subtidal unconsolidated bottom	Estuarine bays	Unconsolidated bottom
E1AB (L)	Estuarine, subtidal aquatic bed	Estuarine seagrass or algae bed	<i>Halodule wrightii</i> <i>Halophila engelmannii</i> <i>Ruppia maritima</i> Unconsolidated shore
E2US (P, N, M)	Estuarine, intertidal unconsolidated shore	Estuarine bay, tidal flats, beaches	Unconsolidated shore
E2EM (P, N)	Estuarine, intertidal emergent	Estuarine bay marshes, salt and brackish water	<i>Spartina alterniflora</i> <i>Spartina patens</i> <i>Distichlis spicata</i>
E2SS (P)	Estuarine, intertidal scrub-shrub	Estuarine shrubs	<i>Iva frutescens</i> <i>Baccharis halimifolia</i> Unconsolidated bottom
R1UB (V)	Riverine, tidal, unconsolidated bottom	Rivers	Unconsolidated bottom
R1SB (T)	Riverine, tidal, streambed	Rivers	Streambed
R2UB (H)	Riverine, lower perennial, unconsolidated bottom	Rivers	Unconsolidated bottom
R4SB (A, C)	Riverine, intermittent streambed	Streams, creeks	Streambed
L1UB (H, V)	Lacustrine, limnetic, unconsolidated bottom	Lakes	Unconsolidated bottom
L2UB (H, V)	Lacustrine, littoral, unconsolidated bottom	Lakes	Unconsolidated bottom
L2AB (H, V)	Lacustrine, littoral, aquatic bed	Lake aquatic vegetation	<i>Nelumbo lutea</i> <i>Ruppia maritima</i> Unconsolidated bottom
PUB (F, H, K)	Palustrine, unconsolidated bottom	Pond	Unconsolidated bottom
PAB (F, H)	Palustrine, aquatic bed	Pond, aquatic beds	<i>Nelumbo lutea</i>
PEM (A, C, F, S, R, T)	Palustrine emergent	Fresh-water marshes, meadows, depressions, or drainage areas	<i>Schoenoplectus californicus</i> <i>Typha spp.</i>
PSS (A, C, F, S, R, T)	Palustrine scrub-shrub	Willow thicket, river banks	<i>Salix nigra</i> <i>Parkinsonia aculeata</i> <i>Sesbania drummondii</i>
PFO (A, C, F, S, R, T)	Palustrine forested	Swamps, woodlands in floodplains depressions, meadow rims	<i>Salix nigra</i> <i>Fraxinus spp.</i> <i>Ulmus crassifolia</i> <i>Celtis spp.</i>

## Marine System

Marine areas include unconsolidated bottom (open water), unconsolidated shore (beaches) and rocky shore (jetties). Mean range of Gulf tides is about 0.5 m. Nonvegetated open water overlying the Texas Continental Shelf is classified as marine subtidal unconsolidated bottom (M1UBL) (Table 3). Unconsolidated shore is mostly irregularly flooded shore or beach (M2USP) with a narrow zone of regularly flooded shore (M2USN) (Fig. 14). Composition of these areas is primarily sand and shell. Granite placed along shore and in jetties along the coast in the marine system are classified as marine intertidal, rocky shore, irregularly flooded, rubble, artificial (M2RS2Pr) (Fig. 15).

## Estuarine System

The estuarine system consists of many types of wetland habitats. Estuarine subtidal unconsolidated bottom (E1UBL), or open water, occurs in the numerous bays and in adjacent salt and brackish marshes. Unconsolidated shore (E2US) includes intertidal sand and mud flats (wind-tidal flats) and estuarine beaches and bars. Water regimes for this habitat range primarily from regularly flooded (E2USN) to irregularly flooded (E2USP) (Fig. 16).

Aquatic beds observed in this system are at some locations made up of submerged rooted vascular plants (E1AB3L) that include predominantly *Halodule wrightii* (shoalgrass), but in Christmas Bay (Fig. 17) also include *Ruppia maritima* (widgeongrass), *Halophila engelmannii* (clover grass), and *Thalassia testudinum* (turtlegrass) (Pulich and White, 1991). In some areas of West Bay submerged brown algae occurs and is mapped as E1AB1L (Fig. 18).

Emergent areas closest to estuarine waters consist of regularly flooded salt-tolerant grasses (low salt and brackish marshes) (E2EM1N) (Figs. 19 and 20). These communities are mainly composed of *Spartina alterniflora* (smooth cordgrass), *Batis maritima* (saltwort), *Distichlis spicata* (seashore saltgrass), *Salicornia* spp. (glasswort), *Monanthochloe littoralis* (shoregrass), *Suaeda linearis* (annual seepweed), and *Sesuvium portulacastrum* (sea-purslane) in more saline areas. In brackish areas, species composition changes to a salt to brackish-water assemblage including *Schoenoplectus* (formerly *Scirpus*) spp. (bulrush), *Paspalum vaginatum* (seashore paspalum), *Juncus roemerianus* (black needle rush), *Spartina patens* (saltmeadow cordgrass), and *Phyla* sp. (frog fruit). At slightly higher elevations irregularly flooded estuarine emergent wetlands (E2EM1P) (high salt and brackish marshes) include *Borrchia frutescens* (sea oxeye), *Spartina patens*, *Spartina spartinae* (gulf cordgrass), *Distichlis spicata*, *Fimbristylis castanea* (marsh fimbry), *Aster* spp. (aster), and many others.

Estuarine scrub-shrub wetlands (E2SS) are much less extensive than estuarine emergent wetlands. Representative plant species in irregularly flooded zones (E2SS1P) between





Figure 14. Marine beach along the Gulf shoreline. The forebeach (lower beach along the Gulf margin) was mapped as M2USN (marine intertidal unconsolidated shore, regularly flooded), and the backbeach as M2USP (marine intertidal unconsolidated shore, irregularly flooded).



Figure 15. Rocky shore (rip-rap) along the southwest end of the Galveston seawall. Where areas like this one are large enough to map, they are mapped as marine intertidal, rocky shore, irregularly flooded, rubble, artificial (M2RS2Pr).





Figure 16. Example of a regularly flooded tidal flat on the bayward side of Galveston Island. These typically sandy flats were mapped as estuarine intertidal unconsolidated shore, regularly flooded (E2USN).





Figure 17. Seagrass beds (dark area) on the bayward side of Follet's Island in Christmas Bay. Areas like these were mapped as E1AB3L (estuarine subtidal aquatic bed, rooted vascular, subtidal water regime).



Figure 18. Submerged brown algae in Galveston Bay. Where we could confirm the locations of these areas they were mapped as E1AB1L (estuarine subtidal aquatic bed, algal, subtidal water regime).





Figure 19. Estuarine intertidal low marsh (E2EM1N) on Galveston Island characterized by *Spartina alterniflora* along the water's edge, and in higher, irregularly flooded marshes (E2EM1P) *Spartina patens* with scattered *Fimbristylis castanea*. Small shrubs are *Avicennia germinans* (black mangroves).

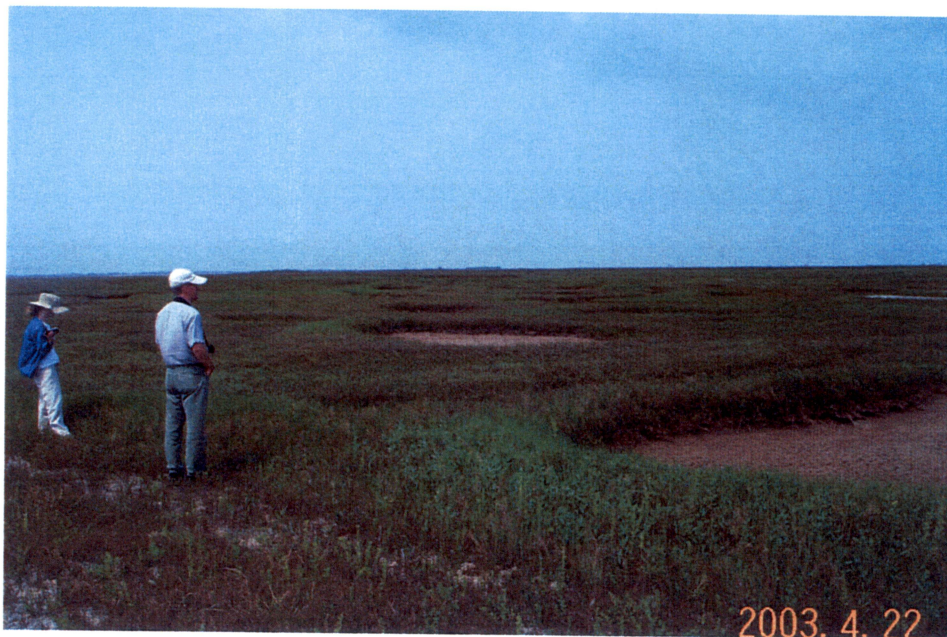


Figure 20. Estuarine intertidal low marsh on Follet's Island characterized by *Salicornia virginica*, *Batis maritima*, *Distichlis spicata*, and *Lycium carolinianum*.

emergent wetland communities and upland habitats, include, *Tamarix* spp. (salt cedar) (Fig. 21), *Iva frutescens* (big-leaf sumpweed), *Baccharis halimifolia* (sea-myrtle, or eastern false-willow), and *Sesbania drummondii* (drummond's rattle-bush). In regularly flooded zones, *Avicennia germinans* (black mangrove) (Fig. 19) occurs scattered with salt marsh vegetation but its concentration is too sparse to map separately as a scrub-shrub wetland, so it is included in the marsh class.

Mapping criteria allow classes to be mixed in complex areas where individual classes could not be separated. Most commonly used combinations include the estuarine emergent class and estuarine intertidal flat (E2EM/FL) and estuarine open water (E2EM/OW). The classes E2EM/FL and E2EM/OW were only used on 1956 and 1979 maps. In such combinations, each class must compose at least 30 % of the mapped area (polygon); on the 1950's and 1979 maps the wetland class was always listed first (E2EM/OW) whether or not it was most abundant. For our purposes, we subdivided these classes into 50-50 components so that 50 % was combined with the marsh (E2EM) and 50 % with the water (E1OW).

The estuarine system extends landward to the point where ocean-derived salts are less than 0.5 ppt (during average annual low flow) (Cowardin et al. 1979). Mapping these boundaries is subjective in the absence of detailed long-term salinity data characterizing water and marsh features. Vegetation types, proximity and connection to estuarine water bodies, salinities of water bodies, and location of artificial levees and dikes are frequently used as evidence to determine the boundary between estuarine and adjacent palustrine systems. In general, a pond or emergent wetland was placed in the palustrine system if there was an upland break that separated it from the estuarine system.

### **Palustrine System**

Palustrine areas include the following classes: unconsolidated bottom (open water), unconsolidated shore (including flats), aquatic bed, emergent (fresh or inland marsh), scrub-shrub, and forested. Naturally occurring ponds are identified as unconsolidated bottom permanently or semipermanently flooded (PUBH or PUBF). Excavated or impounded ponds and borrow pits are labeled with their respective modifiers (PUBHx or PUBHh), and artificially flooded areas by PUBK.

Palustrine emergent wetlands are generally equivalent to fresh, or inland marshes that are not inundated by estuarine tides. Semipermanently flooded emergent wetlands (PEM1F) are low fresh marshes; seasonally flooded (PEM1C) and temporarily flooded (PEM1A) palustrine emergent wetlands are high fresh marshes. Artificially flooded areas are designated PEM1K.





Figure 21. Estuarine scrub-shrub wetland composed of *Tamarix* sp. (salt cedar) on Galveston Island.

Vegetation communities typically characterizing areas mapped as low emergent wetlands (PEM1F) include *Paspalum vaginatum* (seashore paspalum), *Schoenoplectus* (formerly *Scirpus*) *californicus*, *Typha domingensis* (southern cattail), *Schoenoplectus pungens* (formerly *Scirpus americanus*) (three-square bulrush), *Eleocharis* spp. (spikerush), *Bacopa monnieri* (coastal water-hyssop), *Juncus* sp., and others (Figs. 22 and 23). Areas mapped as topographically higher and less frequently flooded emergent wetlands (PEM1A) include *Spartina spartinae*, *Borrichia frutescens*, *S. patens*, *Cyperus* spp. (flatsedge), *Hydrocotyle bonariensis* (coastal plain penny-wort), *Phyla* sp. (frog fruit), *Aster spinosus* (spiny aster), *Paspalum* spp. (paspalum), *Panicum* spp. (panic), *Polygonum* sp. (smartweed) and scattered *Andropogon glomeratus* (bushy bluestem) to mention a few. A common location of some palustrine wetlands on Galveston Island and Bolivar Peninsula are in swales between relict beach ridges (Fig. 24).

It should be noted that in many areas, field observations revealed the existence of small depressions or mounds with plant communities and moisture regimes that varied from that which could be resolved on photographs. Thus, some plant species that may typify a low regularly flooded marsh, for example, may be included in a high marsh map unit. LIDAR data, which provided elevation measurements, helped to differentiate high and low marsh communities in some areas (Fig. 9).

Palustrine scrub-shrub wetlands that were mapped are typically seasonally (PSS1C) or temporarily flooded (PSS1A) and may include *Tamarix* spp., *Baccharis* sp., and *Iva frutescens*.





Figure 22. Palustrine marsh in swale between relict beach ridges on Bolivar Peninsula. The dominant vegetation is *Schoenoplectus* (formerly *Scirpus*) *californicus*.



Figure 23. Palustrine marsh in depression on Galveston Island. The dominant vegetation in this area is *Typha* sp. (cattail).



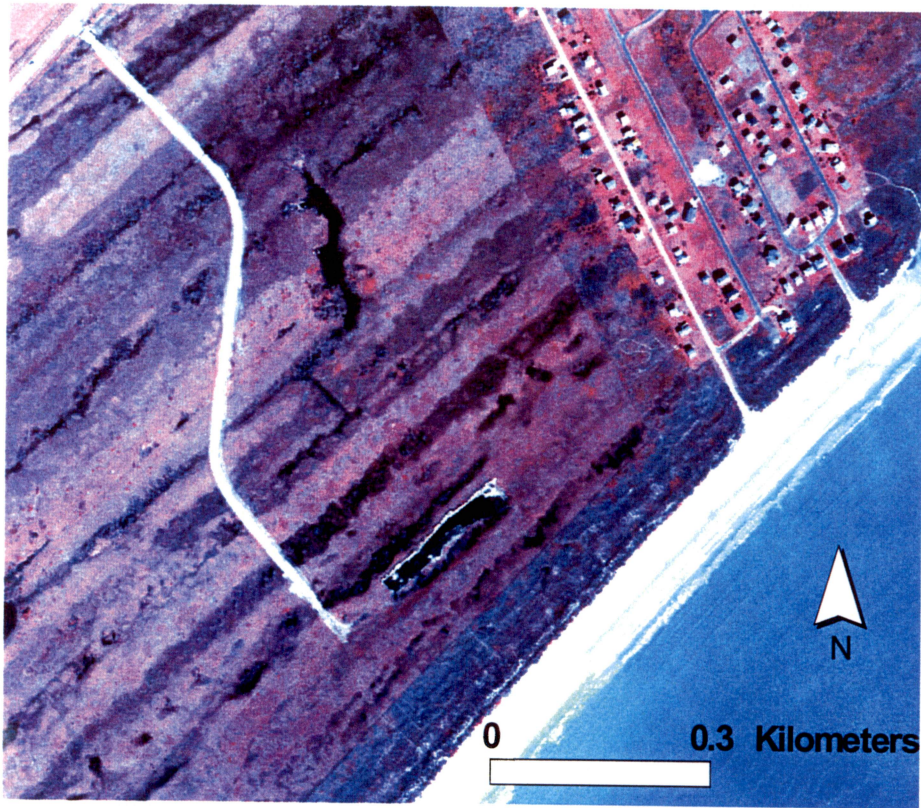


Figure 24. Aerial photograph taken in 2002 showing ridge and swale topography on Bolivar Peninsula. Dark areas are wet zones supporting emergent vegetation in swales between relict beach ridges. The dark area with the white border has been excavated.

### **Lacustrine System**

Water bodies greater than 8 ha are included in this system with both limnetic and littoral subsystems represented. Few areas were classified as lacustrine in 1979 and in 2002. Nonvegetated water bodies are labeled limnetic or littoral unconsolidated bottom (L1UB or L2UB) (L1OW or L2OW in 1950's and 1979 data sets) depending on water depth. Bodies of water with vegetation are classified with the subclass of rooted (L1AB3 and L2AB3) or floating (L1AB4 and L2AB4) aquatic bed. The impounded modifier (h) is used for bodies of water impounded by levees or artificial means. The artificially flooded modifier (K) is used in situations where water is controlled by pumps and siphons, and in this study where water features or diked or leveed and water levels are affected by water associated with pumped, disposed sediments.

### **Riverine System**

No areas were classified in the Riverine System in the study area.

## **STATUS OF WETLANDS AND AQUATIC HABITATS IN 2002**

In February 2002, wetland and aquatic habitats covered about 42,017 ha within the study area (Table 4). This area includes a buffer zone of open water about 1 km wide that parallels the shoreline in the bays and the Gulf. Within the study area, 13,263 ha was classified as uplands. Of the three wetland systems mapped, the estuarine system is by far the largest (Fig. 25; Table 4). Emergent vegetated wetlands (E2EM, E2SS, PEM, and PSS areas) cover 8,361 ha, 92 % of which is estuarine marsh. The extent of all mapped wetlands, deepwater habitats, and uplands for 2002 and earlier periods is presented in the appendix.

### **Estuarine System**

#### **Marshes (Estuarine Intertidal Emergent Wetlands)**

The estuarine intertidal emergent wetland habitat (E2EM) consists of 7,715 ha of salt and brackish marshes. The regularly flooded estuarine marsh, or low marsh, is most abundant, at 4,204 ha (Fig. 25; Table 4). The irregularly flooded estuarine marsh (high marsh) covers about 3,511 ha. The most extensive estuarine marshes occur on (1) Bolivar Peninsula, where 4,734 ha were mapped including a large estuarine marsh at the northeast end of the peninsula, (2) Galveston Island, where 1,519 ha were mapped including the human-modified flood-tidal delta, Pelican Island, and (3) Follet's Island, where 1,459 ha were mapped including the relict flood-tidal delta/washover fan complex of Mud Island (Figs. 26 and 27; Table 5). Marshes along Galveston Island and Follet's Island are relatively narrow and not nearly as extensive as the marshes on Bolivar Peninsula, but these marshes are very important habitats fringing West Bay and Christmas Bay (Fig. 1).

#### **Tidal Flats (Estuarine Intertidal Unconsolidated Shores)**

Estuarine intertidal unconsolidated shores (E2US) include wind-tidal flats, bay beaches, and algal flats. Because of the low astronomical tidal range, many flats are flooded or exposed only by wind-driven tides and are, thus, designated as wind-tidal flats (Fisher et al. 1972). The mapped extent of the tidal flats can be substantially affected by tidal levels at the time aerial photographs were taken. Accordingly, absolute areal extent of flats may vary from that determined using aerial photographs.

Approximately 1,807 ha of E2US was mapped in the study area, however, the 2002 aerial photographs were taken during very low tides apparently following passage of a polar air mass with north winds that lowered bay water levels exposing flats that are usually submerged. The water regime assigned to these flats was "M", irregularly exposed. Because these flats are normally under water, for purposes of comparison with historical distribution we can assign these flats, an area of 1,035 ha (Table 4), to the open water class (E1UB). The remaining tidal flat class is then approximately 760 ha in total area. Tidal flats are most extensive on Galveston Island, followed by Follet's Island (Fig. 26;



Table 4. Areal extent of mapped wetland and aquatic habitats in 2002.

National Wetlands Inventory Description		Hectares	Acres	%
NWI Code				
E2EM1N	Estuarine Intertidal Emergent Wetland, Regularly Flooded	4,204	10,380	7.60
E2EM1P	Estuarine Intertidal Emergent Wetland, Irregularly Flooded	3,511	8,669	6.35
E1AB1, 5	Estuarine Subtidal Aquatic Bed, Algae or Unknown	161	398	0.29
E1AB3	Estuarine Subtidal Aquatic Bed, Seagrasses	116	286	0.21
E2USN	Estuarine Intertidal Flat, Regularly Flooded	341	839	0.62
E2USM	Estuarine Intertidal Flat, Irregularly Exposed	1,035	2,555	1.87
E2USP	Estuarine Intertidal Flat, Irregularly Flooded	431	842	0.62
E2RF2M	Estuarine Intertidal Reef, Mollusk	6	15	0.01
E2SS	Estuarine Intertidal Emergent Scrub Shrub	14	35	0.03
E1UB	Estuarine Subtidal Unconsolidated Bottom	18,540	45,775	33.54
<b>Subtotal</b>		<b>28,268</b>	<b>69,794</b>	<b>51.14</b>
L2UB	Lacustrine Unconsolidated Bottom	253	625	0.46
L2US	Lacustrine Unconsolidated Shore	544	1,343	0.98
<b>Subtotal</b>		<b>797</b>	<b>1,968</b>	<b>1.44</b>
PEM1A	Palustrine Emergent Wetland, Temporarily Flooded	403	995	0.73
PEM1C	Palustrine Emergent Wetland, Seasonally Flooded	111	274	0.20
PEM1F	Palustrine Emergent Wetland, Semi-Permanently Flooded	93	230	0.17
PSS	Palustrine Scrub Shrub	25	62	0.05
PUS	Palustrine Unconsolidated Shore	127	314	0.23
PUB	Palustrine Unconsolidated Bottom	255	630	0.46
<b>Subtotal</b>		<b>1,014</b>	<b>2,504</b>	<b>1.83</b>
M2USN	Marine Intertidal Unconsolidated Shore, Regularly Flooded)	171	422	0.31
M2USP	Marine Intertidal Unconsolidated Shore, Irregularly Flooded)	385	951	0.70
M1UB	Marine Subtidal Unconsolidated Bottom	11,382	28,102	20.59
<b>Subtotal</b>		<b>11,938</b>	<b>29,475</b>	<b>21.60</b>
U	Upland	13,263	32,746	23.99
<b>Total</b>		<b>55,280</b>	<b>136,486</b>	<b>100.00</b>

Table 5). High, irregularly flooded tidal flats are slightly more extensive than low flats (Table 4). These tidal habitats represent about 22% of the intertidal wetland system (excluding subtidal habitats in the E1 and M1 subsystems). Excluding E2USM areas, tidal flats compose about 11% of the intertidal habitats.

### Shrubs and Trees (Estuarine Intertidal Scrub/Shrub)

Estuarine scrub/shrub wetlands (E2SS) (mostly salt cedar habitat) have a total area of 14 ha, or about 0.2% of the estuarine intertidal vegetated classes. It should be noted that scattered black mangrove (*Avicennia germinans*) shrubs occur in some estuarine marshes, typically mixed with *Spartina*, *Batis*, and *Salicornia*, but they are not concentrated enough to map separately from salt marshes. The E2SS habitat has its broadest distribution on Galveston Island. (Fig. 21; Table 5).

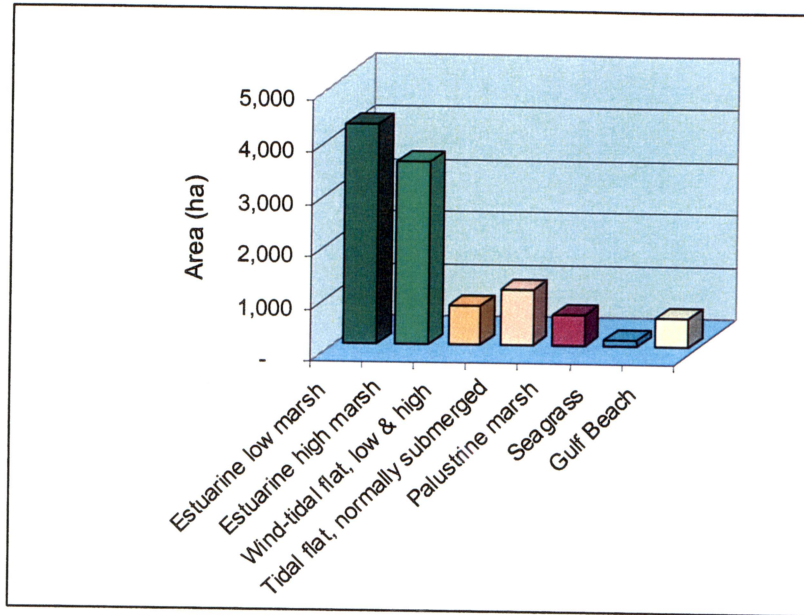


Figure 25. Graph illustrating the extent of selected habitats in the study area in 2002. The unit mapped as tidal flat, normally flooded, was subaerially exposed because of abnormally low tides at the time the 2002 photographs were taken. This habitat (E2USM) is typically subtidal, or open water, and was combined with the estuarine subtidal unconsolidated bottom for comparison with historical habitats.

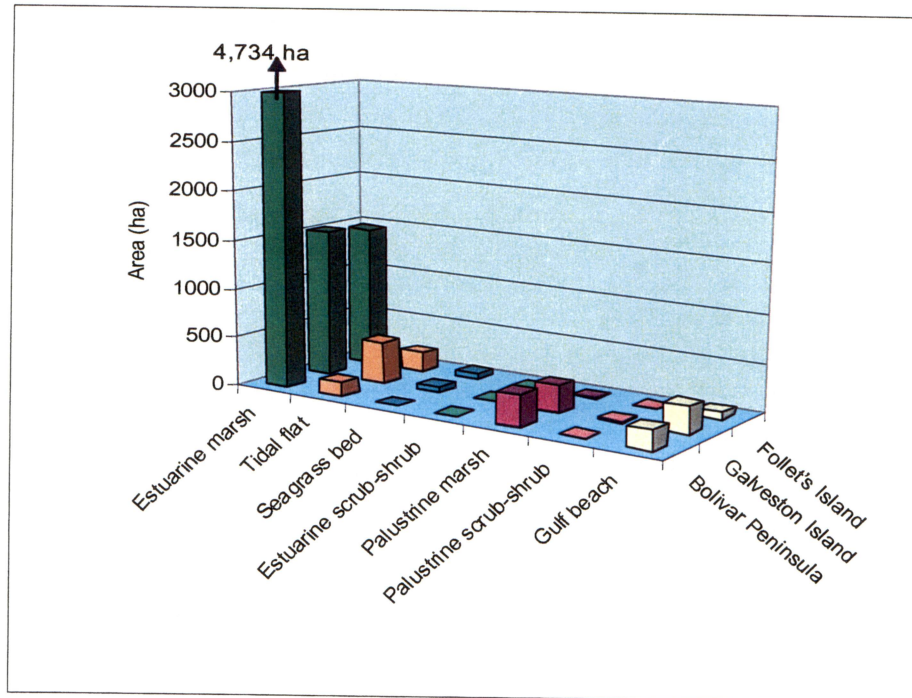


Figure 26. Graph showing areal extent of wetland habitats in 2002 for different geographic areas.



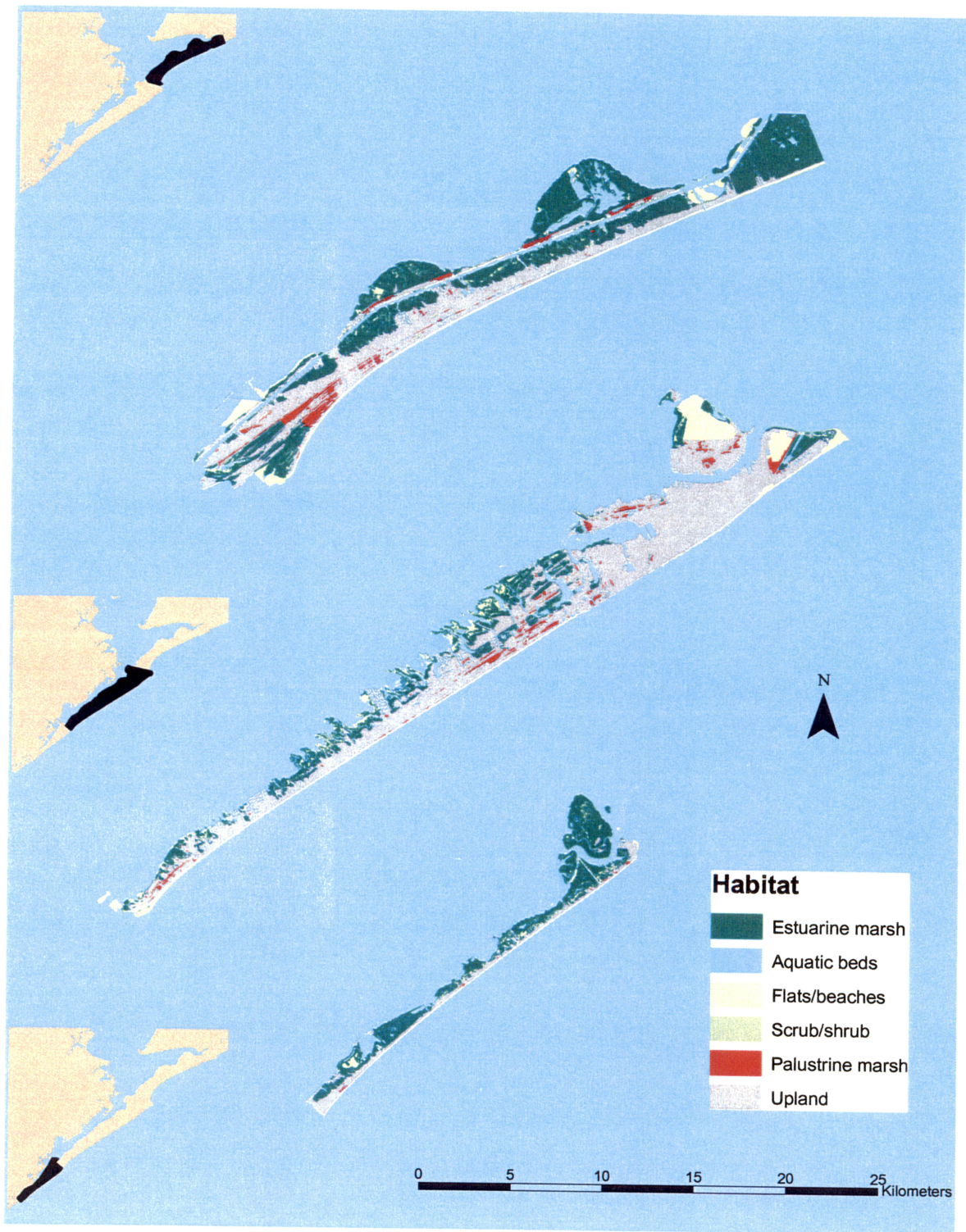


Figure 27. Maps of habitats in 2002 for different geographic areas.



Table 5. Areal extent (in hectares) of selected habitats by geographic area in 2002.

<i>Habitat</i>	<i>Bolivar Peninsula</i>	<i>Galveston Island</i>	<i>Follet's Island</i>
Estuarine marsh	4,734	1,519	1,459
Tidal flat	140	426	208
Seagrass bed	-	49	67
Estuarine scrub-shrub	2	12	-
Palustrine marsh	322	276	9
Palustrine scrub-shrub	8	18	-
Gulf beach	202	278	76

### **Seagrass Beds (Estuarine Subtidal Aquatic Beds)**

Estuarine subtidal rooted vascular aquatic beds (E1AB3L) represent areas of submerged vascular vegetation, or seagrasses. Accurate delineation of seagrasses on aerial photographs is dependent on the season in which the photographs were taken and water turbidities, which can obscure seagrass areas. Seagrasses are quite visible in most areas on the 2002 imagery but are obscured by turbidities in some areas and could not be mapped in total. Densities of the mapped seagrass ranged from very dense to patchy. Seagrass beds throughout the study area covered 116 ha in 2002. The largest distribution of seagrasses is along the margins of Follet's Island in Christmas Bay and Galveston Island in areas adjacent to Galveston Island State Park. Seagrass beds mapped along Follet's Island have an area of approximately 67 ha and account for almost 60% of this habitat in the study area (Table 5; Fig. 17).

### **Open Water (Estuarine Subtidal Unconsolidated Bottom)**

In addition to the shallow lagoons and ponds within the marsh complexes, estuarine subtidal unconsolidated bottom (E1UBL), or open water, in the study area includes a strip of estuarine water about 1 km wide paralleling the bay shoreline. This area was included primarily for cartographic purposes to help standardize the study area for each time period. Including this zone, the total area of estuarine open water mapped in the study area is 18,540 ha. If the irregularly exposed tidal flat (E2USM) class is included, then the total open water in the study area is about 19,575 ha.

### **Oyster Reefs (Estuarine Reefs)**

Oyster reefs (E2RF2M) mapped on the 2002 photographs amounted to just 5.7 ha and are mostly in Christmas Bay along the shores of Follet's Island. Only those that were very near the water's surface and were clearly visible were mapped.

## **Palustrine System**

### **Marshes (Palustrine Emergent Wetlands)**

Palustrine emergent wetlands (PEM), or inland "freshwater marshes," cover 607 ha (Fig. 25) and represent only 7 % of emergent vegetated wetlands. The broadest distribution of palustrine emergent wetlands is on Bolivar Peninsula (Figs. 26 and 27), where swales between relict beach ridges (Fig. 24) provide topographic lows in which water ponds and supports hydrophytic vegetation. Typically, palustrine marshes were classified into one of three water regimes: (1) temporarily flooded, (2) seasonally flooded, or (3) semi-permanently flooded. Most extensive in the map area were those that were temporarily flooded or seasonally flooded. Palustrine marshes on Bolivar Peninsula account for more than 50 % of this habitat mapped in the study area. As mentioned previously, dry conditions over the years preceding 2002 when the aerial photographs were taken reduced the extent of palustrine marshes.

### **Shrubs and Trees (Palustrine Scrub/Shrub)**

Palustrine scrub/shrub wetlands (PSS) were most extensive on Galveston Island where 18 ha were mapped on 2002 photographs (Table 5). Eight ha were mapped on Bolivar Peninsula.

### **Open Water and Flats (Palustrine Unconsolidated Bottom; Unconsolidated Shore)**

Palustrine unconsolidated bottom habitats (PUB) are generally small-fresh to brackish water ponds. The total mapped area of this habitat is 255 ha, of which about 60 % of this total area was created artificially by excavations or levees. Palustrine unconsolidated shore (PUS), or flats, had an area of 127 ha in 2002. Most PUS habitats were also created by human excavations and impoundments.

## **Marine System**

### **Gulf Beach (Marine Intertidal Unconsolidated Shore)**

The Gulf beach represents the marine intertidal unconsolidated shore (M2US). Two components were mapped, the topographically lower regularly flooded fore beach and irregularly flooded backbeach (Figs. 3 and 14). The total area of this habitat in the study area is 556 ha. This habitat is most extensive on Galveston Island, which is longer than Bolivar Peninsula (Fig. 27). A buffer zone approximately 1 km wide of marine subtidal



unconsolidated bottom (M1UB), or marine open water, was included along the Gulf shoreline, primarily to standardize the size of the map area for each time period analyzed.

## **HISTORICAL TRENDS IN WETLAND HABITATS**

### **Methods Used to Analyze Trends**

Trends in wetland habitats were determined by analyzing habitat distribution as mapped on 1950's, 1979, and 2002 aerial photographs. In analyzing trends, emphasis was placed on wetland classes (for example, E2EM and PEM), with less emphasis on water regimes and special modifiers. This approach was taken because habitats were mapped only down to class level on 1950's photographs and because water regimes can be influenced by local and short-term events such as tidal cycles and precipitation.

### **Geographic Information System**

The GIS-ArcInfo and ArcView were used to analyze trends. This software allowed for direct comparison between years, but also by geographic areas such as the barrier islands and peninsula. Analyses included tabulation of losses and gains in wetland classes for each area for selected periods. The GIS allowed cross classification of habitats in a given area as a means of determining changes and probable cause of such changes. Maps used in this report showing wetland distribution and changes were prepared from digital data using ArcInfo.

### **Possible Photointerpretation Errors**

As mentioned previously, existing maps prepared from photointerpretation as part of the USFWS-NWI program and associated special projects were used to determine trends. Among the shortcomings of the photointerpretation process is that different photointerpreters were involved for different time periods, and interpretation of wetland areas can vary somewhat among interpreters. As a result, some changes in the distribution of wetlands from one period to the next may not be real but rather relicts of the interpretation process. Inconsistencies in interpretation seem to have occurred most frequently in high marsh to transitional areas where uplands and wetlands intergrade.

Some apparent wetland changes were due to different scales of aerial photographs. The 1950's aerial photographs were at a larger scale (1:24,000) than those taken in 1979 (1:65,000), which affected the minimum mapping unit delineated on photographs. Accordingly, a larger number of small wetland areas were mapped on earlier, larger-scale photographs, accounting for some wetland losses between earlier and later periods. In general, wetland changes that seem to have been influenced the most by photointerpretation problems are interior (palustrine), temporarily flooded wetlands bordering on being transitional areas. Apparent losses in palustrine wetlands were documented on barrier islands, but much of this change we believe is due to drier conditions when the 2002 photographs were taken.

In the analysis of trends, wetland areas for different time periods are compared without attempting to factor out all misinterpretations and photo-to-map transfer errors except for major, obvious problems. However, maps and aerial photographs representing each period were visually compared as part of the trend-analysis process and as part of the effort to identify potential problems in interpretation. Numerous comments in the text with respect to apparent changes are based on these comparisons, as well as on knowledge of the investigators of wetland distribution in the study area. Still, users of the data should keep in mind that there is a margin of error inherent in photointerpretation and map preparation.

### **Wetland Codes**

As mentioned in the introduction (Fig. 12), some wetland codes used on 2002 maps are different from those used on the 1950's and 1979 maps. In the following discussion of trends, E2FL (instead of E2US used on the most recent USFWS NWI maps prepared from 1992 photos) is generally used to denote tidal flats, and OW (rather than UB) is used to represent open water.

### **General Trends in Wetlands within the Study Area, 1950's-2002**

Analysis of trends in wetlands and aquatic habitats from the 1950's through 2002 shows that there was a net loss in estuarine marshes during each period. The total area of estuarine marshes<sup>3</sup> decreased from 9,267 ha in the 1950's to 8,162 ha in 1979 to 7,715 in 2002 (Figs. 28 and 29). These decreases amounted to 1,105 ha from the 1950's through 1979, and 447 ha from 1979 through 2002. During the same time, there was a decrease in tidal flats (E2FL or E2US). The area of flats declined from 2,371 ha in the 1950's to 1,933 ha in 1979 to 771 ha in 2002 (the 2002 area excludes the irregularly exposed flats – E2USM) (Fig. 25). These changes reflect losses of 438 ha and 1,162 ha for each period, respectively. Palustrine marshes (PEM) decreased in area from the 1950's through 1979 by 427 ha, but declined by only 11 ha more from 1979 through 2002. There was a major loss of seagrass beds from the 1950's through 1979. Based on the USFWS maps of the 1950's to 1979, there was a decline of more than 1,000 ha. No seagrasses were mapped in 1979 although they were present in Christmas Bay at that time (Pulich and White, 1991). The visibility of seagrass beds was reduced on the 1979 aerial photographs because of turbulence in the bay. Pulich and White (1991) reported that in lower West Bay, mixed beds of *Ruppia maritima* and *Halodule wrightii* declined steadily from the 1950's and disappeared by the early 1980's. West Bay was in contrast with Christmas Bay, however, which contained extensive beds of *Halodule wrightii* and small patches of *Thalassia testudinum* and *Halophila engelmanni*. By 2002, seagrasses, with human assistance, have begun to recover in West Bay as indicated by seagrass beds mapped near Galveston Island State Park. Scrub-shrub wetlands, including both estuarine and palustrine had total areas of 34 ha in the 1950's, 45 ha in 1979, and 39 ha in 2002. Probable causes of changes in habitats are presented in the following sections organized by geographic area.

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<sup>3</sup> Total area of estuarine marsh for the 1950's and 1979 periods includes 50 % of the EM/OW class.



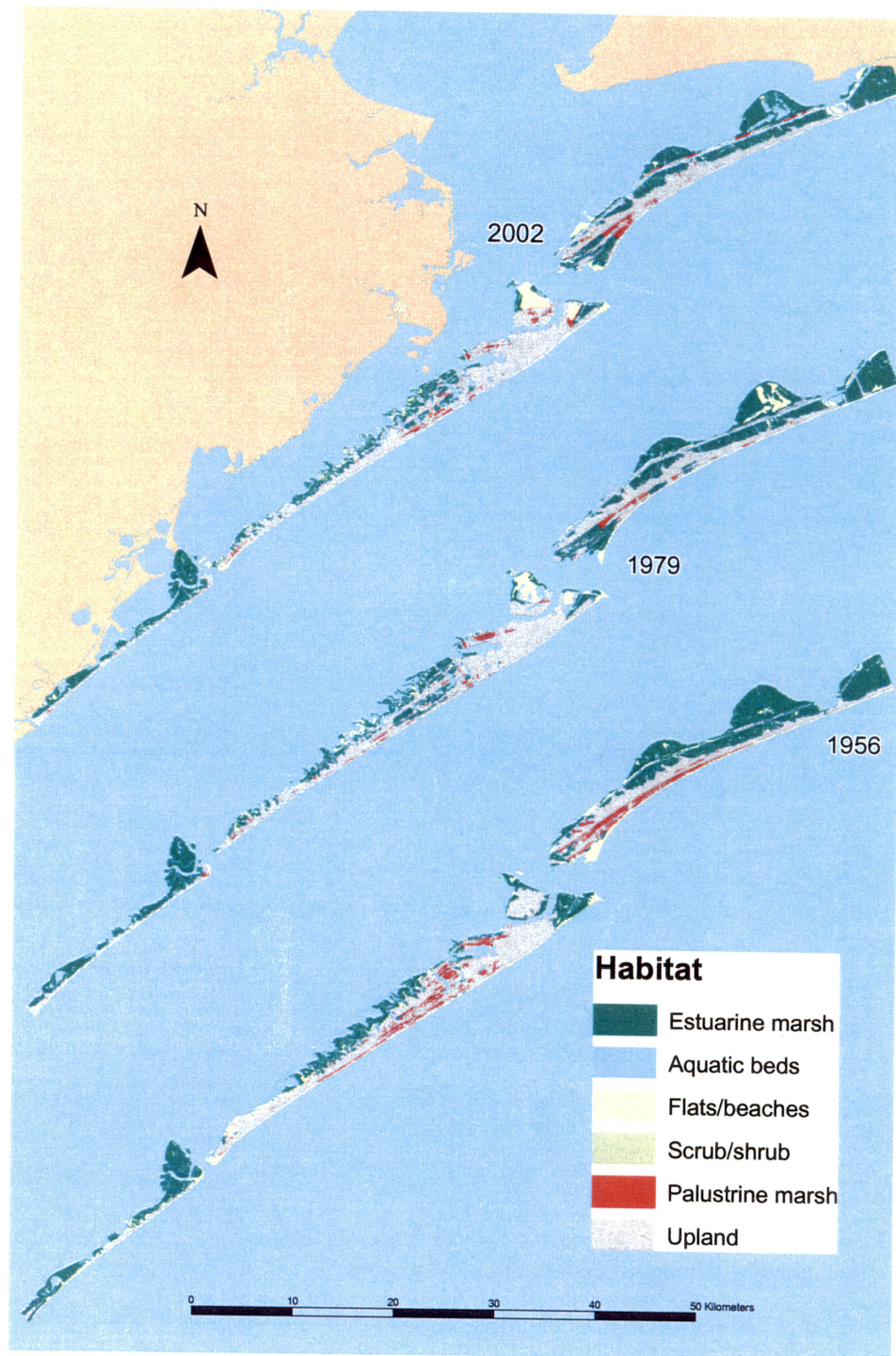


Figure 28. Maps showing distribution of major wetland and aquatic habitats in the study area in 2002, 1979, and the 1950's.

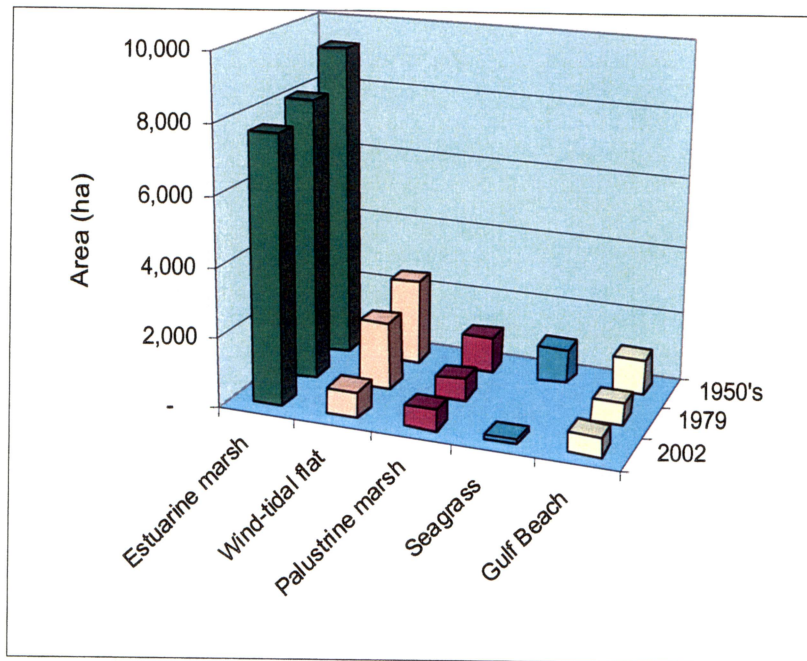


Figure 29. Graph showing extent of selected habitats in the 1950's, 1979, and 2002 in the study area. Note the systematic decrease in estuarine marshes through time.

## Analysis of Wetland Trends by Geographic Area

As in previous sections, the study area was subdivided into major natural areas and geographic components for analysis of historical trends (Fig. 27). The areas are presented from northeast to southwest in the following order (1) Bolivar Peninsula, (2) Galveston Island, (3) Follet's Island. This subdivision allowed a more site-specific analysis of trends and their probable causes. Estuarine and palustrine marshes, tidal flats, seagrass beds, and Gulf beaches are emphasized.

### Bolivar Peninsula

**General Trends.** The most significant trend, or change, on Bolivar Peninsula was a net decline in estuarine marshes. The total area of marsh habitat, which covered about 5,269 ha in the 1950's, decreased in size by 401 ha from the 1950's through 1979, and by 134 ha from 1979 to 2002 (Fig. 30). This decrease represents a 10 % net loss of marsh habitat on Bolivar Peninsula since the 1950's. In contrast to the loss of marshes through time, there was an increase in estuarine open water of about 733 ha from the 1950's to 1979 and 444 ha from 1979 to 2002. The area of Gulf beach decreased in total area by 210 ha and 42 ha for the two periods, respectively. Tidal flats had a slight increase of 127 ha in total area from the 1950's through 1979 and a relatively large decrease of 882 ha from 1979 to 2002. Mapped palustrine marshes decreased in total area during the first period (1950's-1979) and increased during the second period (1979-2002) (Fig. 30). A look at total emergent wetlands for each period indicates a significant net loss from the 1950's to 1979 and little change from 1979 to 2002 (Fig 31). No seagrasses were found nor mapped in this area.

**Probable Cause of Trends.** The largest loss of marsh on Bolivar Peninsula occurred on the large relict fan west of Rollover Pass (Fig. 32). The loss in this area resulted primarily from subsidence and erosion of marshes along active surface faults that cross this large fan (Figs. 6; 32) (White and Morton, 1997; Morton et al. 2001). Field observations in May 1991 (White et al. 1993) indicated that vegetation communities on the topographically higher upthrown sides of the faults were more extensive and contained more *Spartina patens* and *Distichlis spicata* than the downthrown sides, where marshes were lower, less extensive, and supported *Spartina alterniflora* and patchy areas of *Bolboschoenus* (formerly *Scirpus*) *maritimus*, *Distichlis spicata*, and *Spartina patens*. Losses in marshes along the faults in this area occurred primarily between the 1950's and 1979.

Aerial photographs taken in the 1930's do not reveal the faults. Vegetation appears to be primarily that of a topographically high irregularly flooded marsh (E2EM1P) characterized by *Spartina patens* and *Distichlis spicata*. By the 1950's, the faults were visible, and formerly high marshes located on the downthrown sides had become partly replaced by low regularly flooded *Spartina alterniflora* marsh (E2EM1N), and open water. A benchmark releveing survey along Bolivar Peninsula for the period 1936 to 1954 (Fig. 33) indicates differential subsidence across one of the faults where it crosses the highway in this area. The faults are more pronounced on photographs taken in the



1970's and 1980's, as areas of open water expanded at the expense of marshes (White and Tremblay, 1995). The wetland loss in this area coincides with annual gas production at the Clam Lake Oil and Gas Field that peaked in the late 1960's to early 1980's.

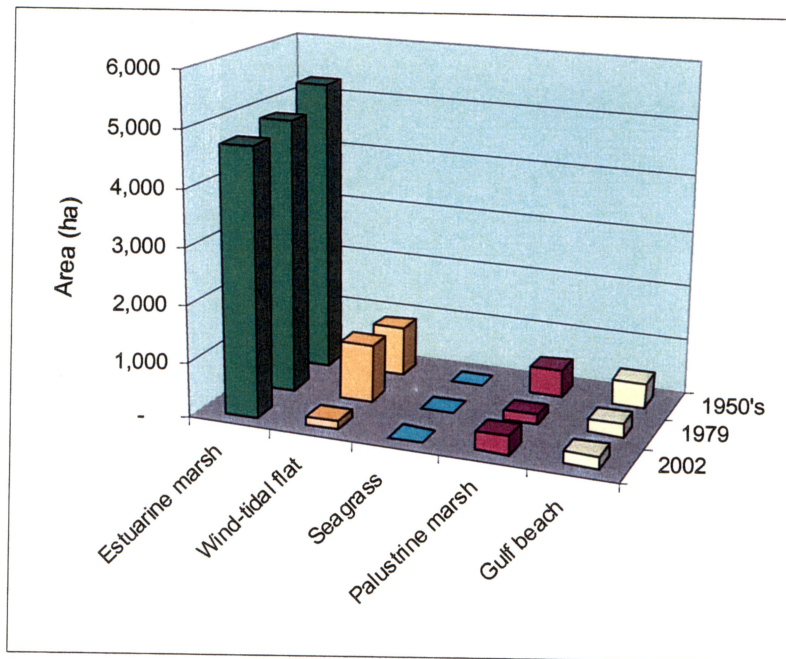


Figure 30. Areal extent of major habitats on Bolivar Peninsula in the 1950's, 1979, and 2002.

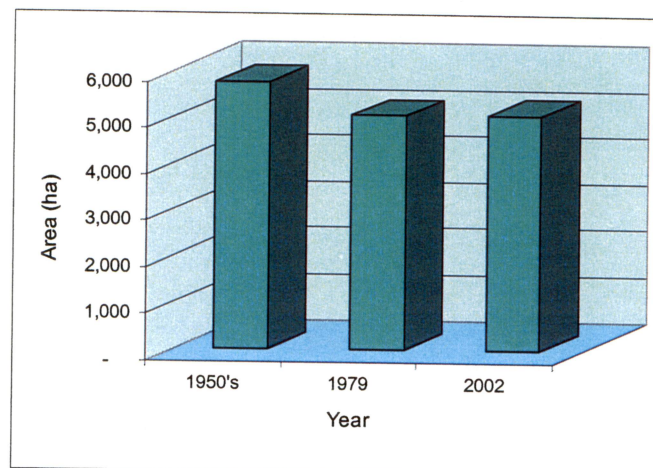


Figure 31. Areal extent of emergent wetland habitats (E2EM, PEM, E2SS, and PSS) on Bolivar Peninsula in the 1950's, 1979, and 2002.

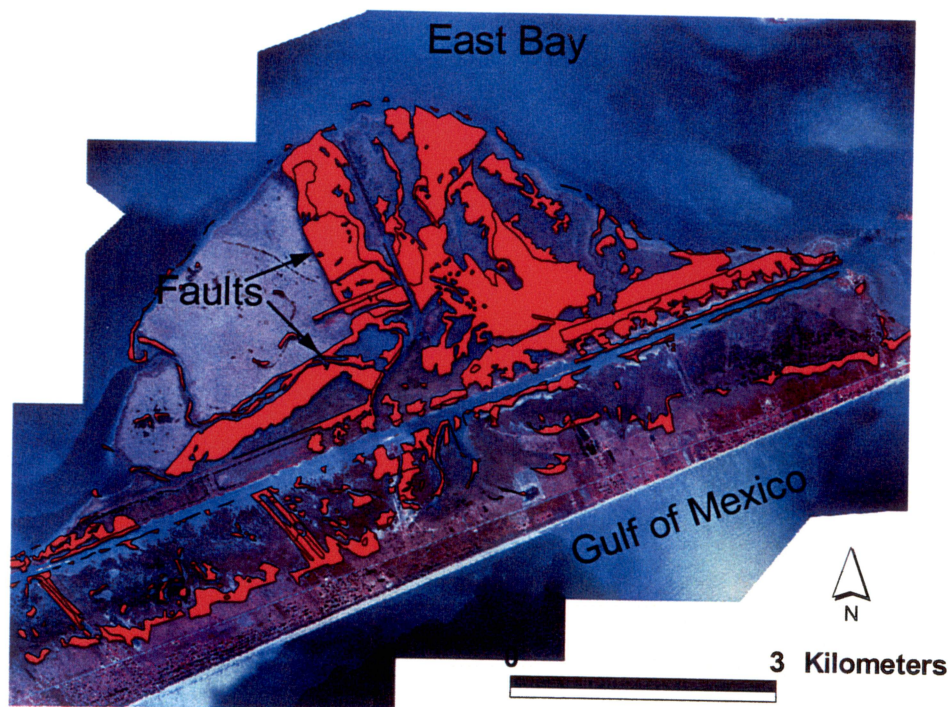


Figure 32. Marsh loss from the 1950's through 1979 along active faults on relict fan on Bolivar Peninsula. Losses, shown in red, principally due to replacement of marsh by open water and shallow flats. Aerial photograph was taken in 2002.

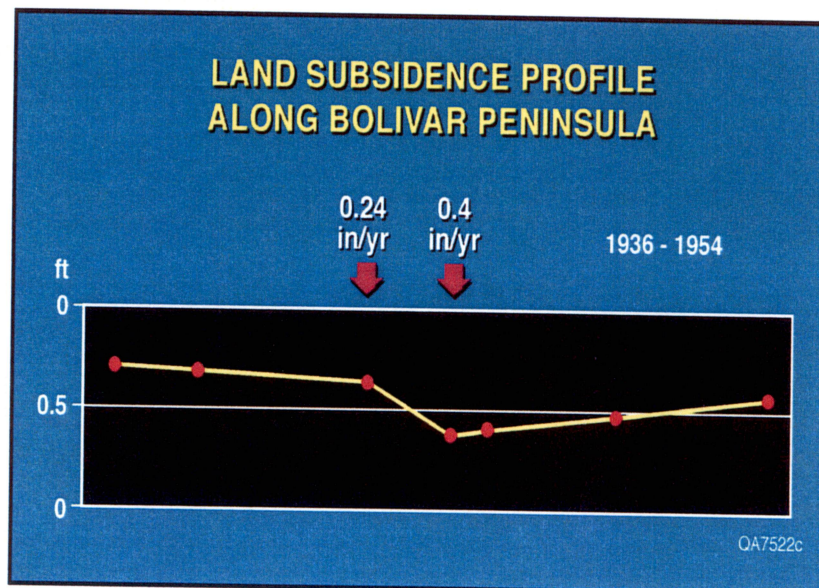


Figure 33. Profile constructed from benchmark releveing surveys that cross a fault along a highway on Bolivar Peninsula (White and Morton, 1997). The increase in subsidence of 0.24 in/yr (6 mm/yr) to 0.4 in/yr (10 mm/yr) shows that the downthrown side of the fault is subsiding at a faster rate than the upthrown side for the period of the surveys, 1936-1954. Fault activation and subsidence at this site appear to be associated with oil and gas production (Ewing 1985).

Total marsh loss from the 1950's to 2002 was about 420 ha. The spatial and temporal relationships between oil and gas production, faulting, and marsh loss support Ewing's (1985) conclusion of a causal relationship between fluid production and fault movement. Much larger fluid volumes produced from reservoirs at High Island salt dome to the northeast may have caused regional depressurization and subsidence that in turn contributed to reactivation of several faults along the northern margin of East Bay (Ewing, 1985). By 1979, there was additional local replacement of high marsh by low marsh, but the most significant and widespread change was that from marsh to open water.

Succession and loss of emergent vegetation in this area are attributed more to inundation and erosion (Morton et al. 2001) than to increases in salinity. Estuarine salinities in East Bay, for example, average approximately 10-15 ppt (Martinez 1973, 1974, 1975), which is within the tolerance range of salinities for most of the above listed species (Penfound and Hathaway, 1938; Chabreck, 1972; Mendelssohn and McKee, 1988a). Salinity may play a role in the succession, however, as *Spartina patens* is less tolerant of increasing salinities than *Spartina alterniflora* (Pezeshki et al. 1987; Mendelssohn and McKee, 1988a; Naidoo et al. 1992). Additional wetland losses totaling almost 900 ha have occurred along faults in salt marshes including Bolivar Peninsula and brackish marshes to the northeast (White and Tremblay, 1995).

A field study of marsh loss due to submergence associated with fault movement and erosion at the Caplen Field and other oil and gas fields on the upper Texas coast was conducted by Morton et al. (2001). At the Caplen field, they concluded that erosion was a significant process in marsh loss on the downthrown side of the fault as subsidence dropped the land surface and flooded the marsh. In other fields to the northeast, subsidence was more significant than erosion in the expansion of open water and loss of marsh.

Losses in estuarine marshes occurred along the bay shoreline of Bolivar Peninsula due to erosion. The average rate of shoreline erosion was approximately 1 m/yr from 1930 to 1982 (Paine and Morton, 1986). Highest rates of erosion at selected locations during this period were about 2 m/yr and lowest 0.3 m/yr. The Bolivar shoreline is approximately 40 km in length. If we use the average rate of erosion of 1m/yr, then about 4 ha of marsh loss occurred each year from 1930 to 1982, for a total loss of over 200 ha.

Local marsh losses were caused by development, and draining and filling of wetlands. But these losses were much less extensive than those due to submergence and erosion along the active faults. Apparent losses in tidal flats from 1979 to 2002 is in part due to low tides in 2002 and the subareal exposure of flats that are normally inundated (E2USM). These flats were included with open water for comparison with 1979.

In contrast to the marsh losses on the bay side of Bolivar Peninsula caused by faulting, subsidence, and erosion, there was an increase in estuarine marsh at the southwest end of Bolivar on the Gulf side due to sediment deposition and accretion near the north jetty at



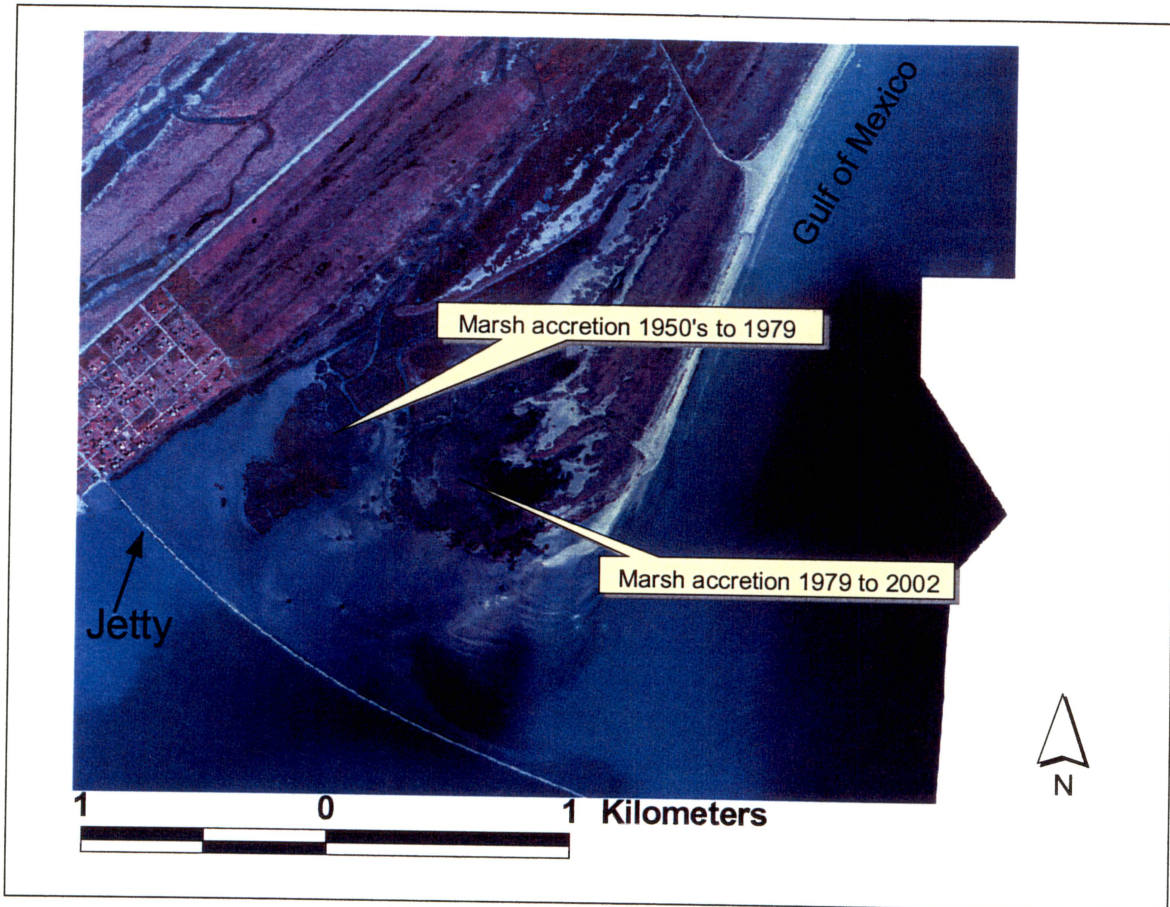


Figure 34. Gain in marshes as a result of accretion near Bolivar Roads. Jetty in this area traps sediments on which marshes develop.

Bolivar Roads. Between the 1950's and 1979 there was a large expansion of marsh of more than 140 ha as *Spartina alterniflora* and other salt-marsh species spread onto flats and unconsolidated shore deposits that had accumulated since the 1950's (Fig. 34). The expansion continued in this area between 1979 and 2002 when an additional  $50 \pm$  ha of marsh formed (Fig. 34). The rate of accretion in this area since 1882 has exceeded 10 m/yr locally (Gibeaut et al. 2002).

Apparent losses and gains of estuarine and palustrine marshes occurred near the southwest end of Bolivar Peninsula from the 1950's to 1979 to 2002. Some of these changes, however, were due to differences in interpretation and classification of estuarine and palustrine marshes and locally, uplands. Combining the estuarine and palustrine marshes together and adding scrub-shrub wetlands offers a more complete view of historical changes in the emergent wetland habitats, a view that is less affected by interpretation of marsh type. Analysis of vegetated wetlands as a whole shows that major changes occurred from the 1950's through 1979 when a net loss of more than 700 ha occurred. From 1979 to 2002, there was little net change (Fig. 31).

## Galveston Island

**General Trends.** There has been a dramatic decrease in the amount of estuarine marsh on Galveston Island from the mid-1950's to 2002. In the mid-1950's, 2,228 ha were mapped, while only 1,519 were mapped in 2002. This represents a 32 % decrease in estuarine marsh. Estuarine tidal flats also declined significantly, from 1,102 ha in the mid-1950's to 426 in 2002, a 61 % loss. Palustrine marshes decreased by 50 %, from 556 in the mid 1950's to 276 in 2002. In the mid-1950's, 882 ha of seagrasses were mapped, but by 1979 they appeared to have been entirely eradicated in West Bay (other sources, however, indicate seagrasses were present in West Bay until the 1980's). The seagrasses in West Bay have been recovering since then. In 2002, 49 ha of seagrasses were mapped. The Gulf beaches showed an overall decrease of 30 % from the mid-1950's to 2002. In the mid-1950's, 396 ha existed; by 1979 the area had declined to 240 ha. The area increased to 278 ha in 2002 (Fig. 35).

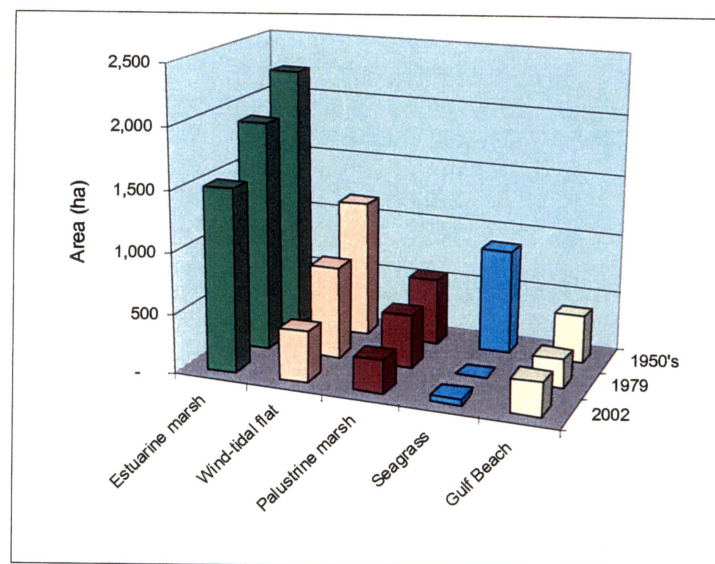


Figure 35. The area (in hectares) of each major habitat type for each year on Galveston Island.



**Probable causes of trends.** Rising relative sea-level caused primarily by subsidence has had a major impact on the wetland habitats of Galveston Island. The trend in estuarine wetland loss is characterized by replacement of marsh and tidal flats by open water. This is the expected result of subsidence, as the land sinks the low-lying areas will be engulfed by water. Another indication of habitat changes due to subsidence is a clear trend in marsh gains moving landward over time. As the land subsides and tidal influence reaches further inland marsh species become established in formerly upland areas (Fig. 36).

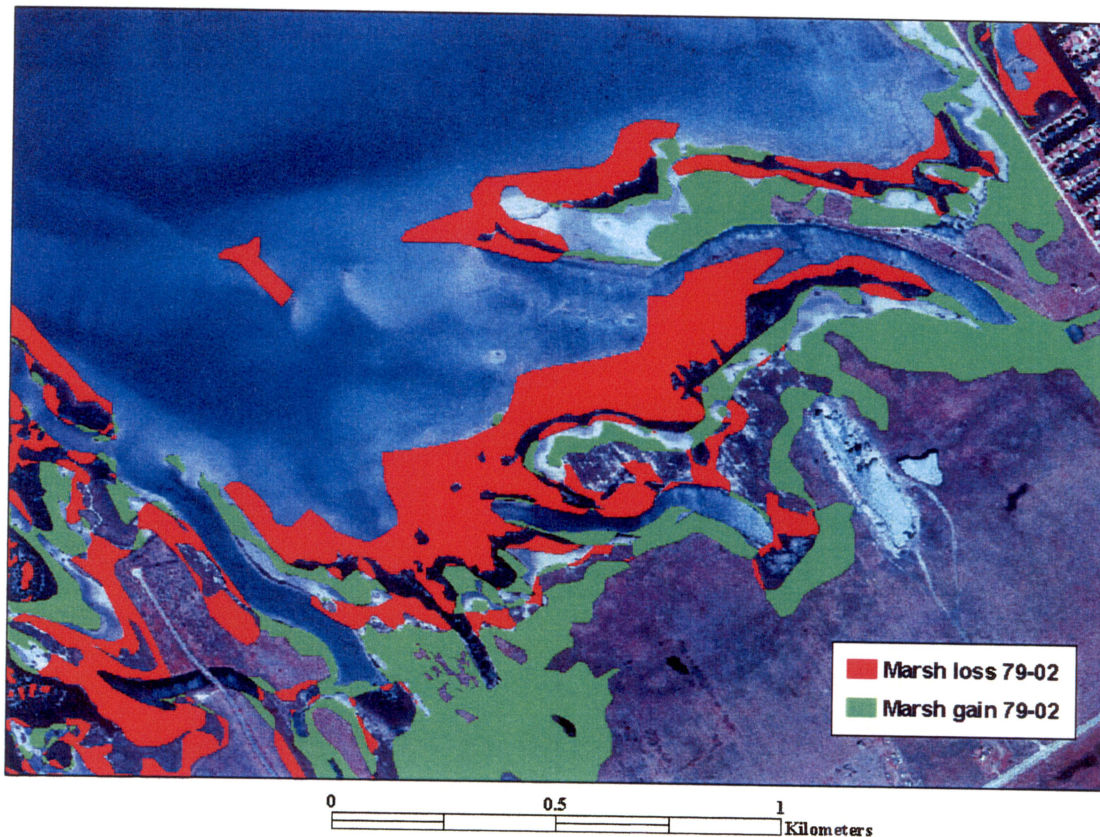


Figure 36. Gains inland of areas where marsh has been lost indicate relative sea level rise. As the water rises marshes are being replaced by low tidal flats and open water, while upland areas and high tidal flats are being colonized by marsh vegetation.

Development has also contributed to wetland loss where projects have replaced habitat (Fig. 37). Restoration projects have been used to mitigate these losses in some areas (Fig. 38). A minor cause of wetland losses in localized areas have been cattle trails. Cattle make trails in the marshes as they graze. They use the same trails repeatedly, preventing the vegetation from recovering. Flowing water during tidal cycles deepens and widens the trails, further preventing recovery (Fig. 39).



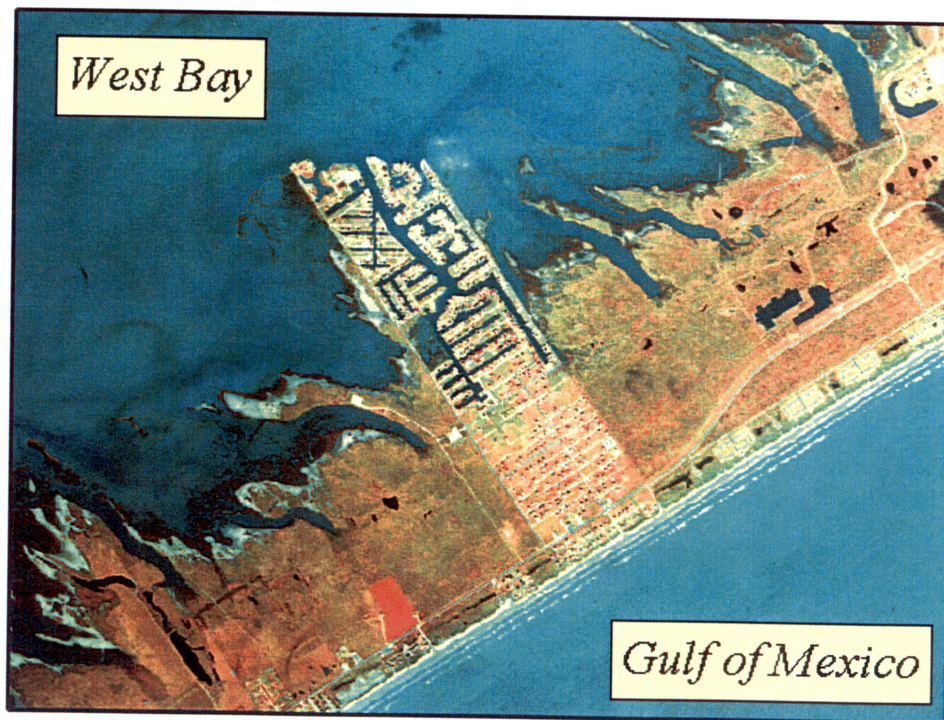
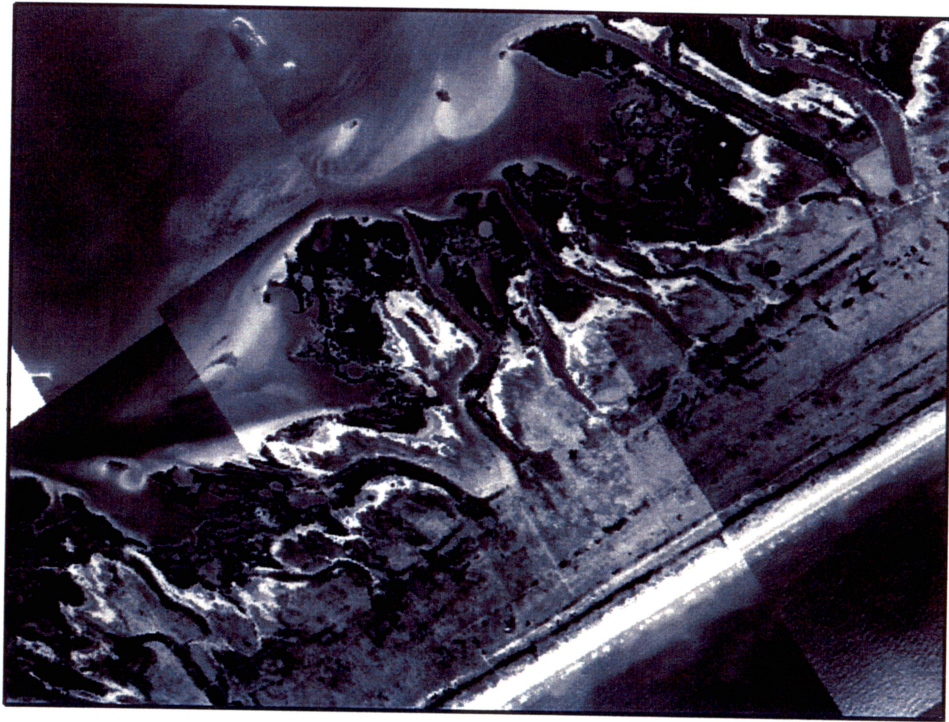


Figure 37. Marsh that existed in the 1950's, visible in top aerial photograph, has been replaced by development by 1979, as shown in bottom aerial photograph.





Figure 38. These marsh restoration projects are being used to mitigate marsh losses in the area.

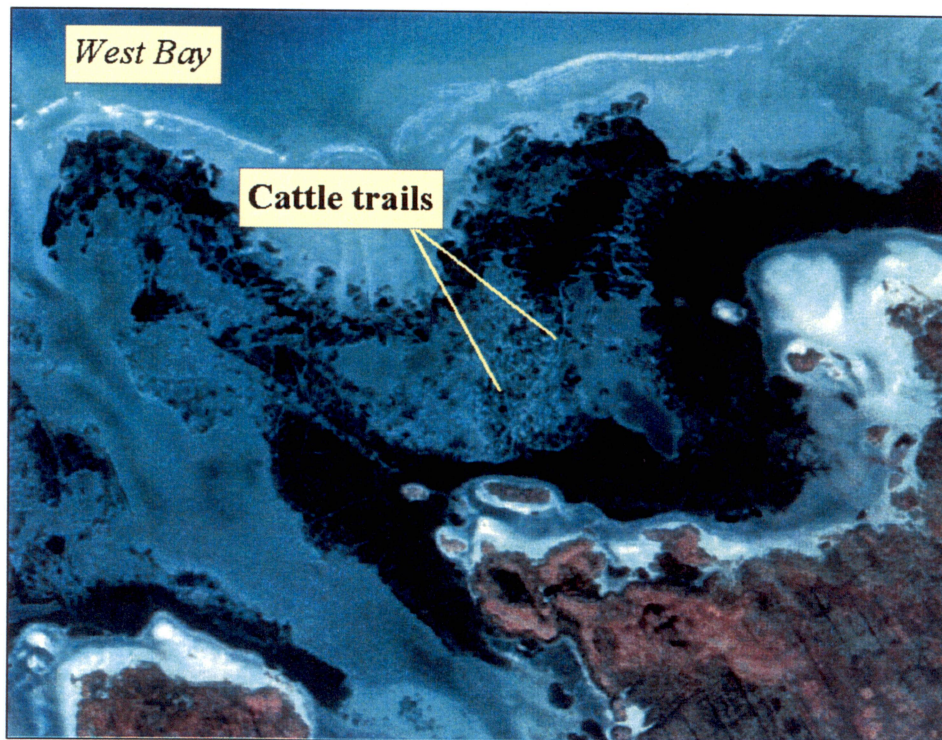


Figure 39. Cattle trails are visible in this 1995 image. The same trails are used again and again, and are made wider by flowing water.



Changes in the San Luis Pass area are dramatic. In the period between the mid-1950's and 1979, the shoreline underwent severe erosion. By 2002, the shoreline had accreted to a point close to the 1950's position, virtually resulting in a full recovery of the land area lost (Fig. 40). The dynamics in the area are caused principally by the deepwater channels within San Luis Pass that move large amounts of sediments in and out of the bay. The channels and sediments form a large flood-tidal delta in West Bay, and are constantly shifting their positions as channels fill with sediment and are abandoned while the fast-moving water creates new channels. These processes may result in rapid bank-cutting and beach erosion, or in beach accretion as sediments are deposited near shore (Fig. 41).

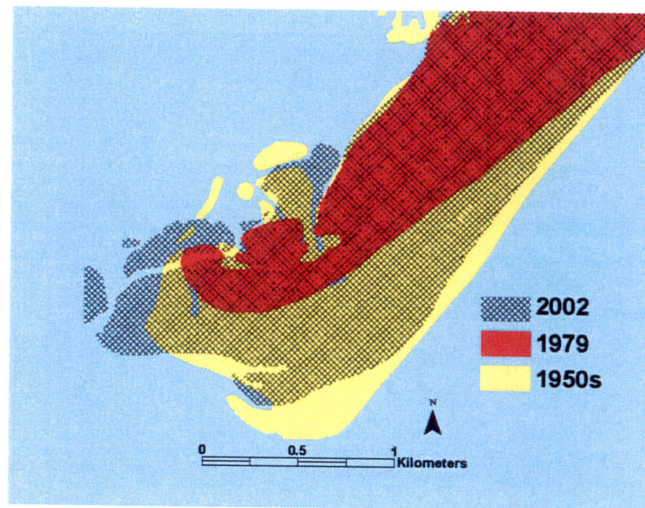


Figure 40. Changes in the San Luis Pass area over time. The southwestern tip of the island lost a considerable amount of land area, then gained most of it back by 2002.



Figure 41. San Luis Pass is characterized by shifting deep water channels and sediment. These are largely responsible for the dynamic character of the surrounding land areas.



The northeastern end of Galveston Island shows a considerable amount of estuarine marsh loss between the mid-1950's and 1979. This can be explained by the impoundment of dredged material in this area since the 1950's. The area has been cut off from tidal influence and therefore was not mapped as estuarine in 1979 (Fig. 42).

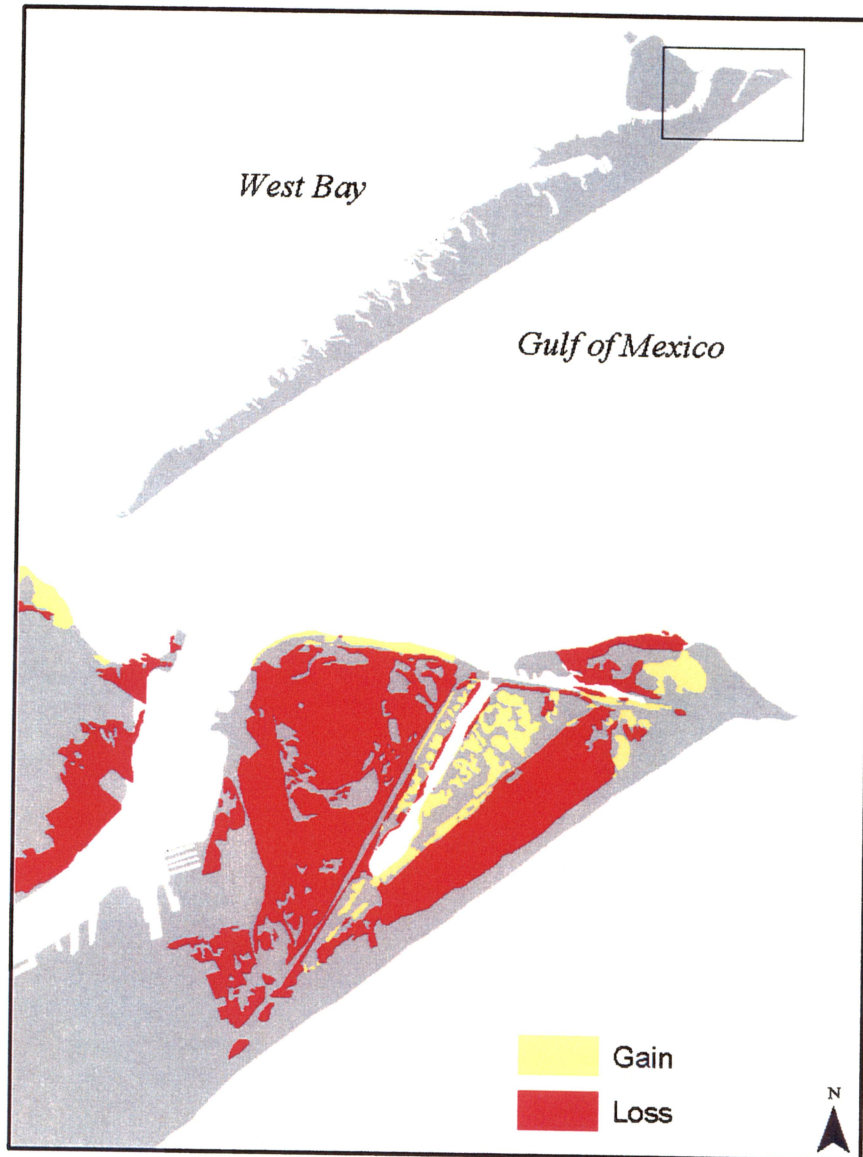


Figure 42. Marsh was lost on the northern tip of Galveston Island between the 1950's and 1979. The area became impounded and filled with dredged material.

Estuarine marshes in the interior of the island showed a gain from the mid-1950's to 1979 and a loss from 1979 to 2002 (Fig. 43). There appears to be several factors influencing this pattern. During the 1950's, drought conditions caused some marshes to shrink in size, and many were likely cut off from tidal influence. Marshes isolated from tidal influence are mapped as palustrine rather than estuarine. The 1950's map would have reflected these drier-than-normal conditions. The 1979 photos, from which the 1979 map was

interpreted, show wetter conditions, having been taken during high tides and a period in which preceding months were characterized by above normal precipitation (White et al. 1985). This would account for the considerable gains in interior marshes during the two periods, as the mapping showed abnormally dry conditions followed by wetter-than-normal conditions. The 2002 imagery showed average moisture conditions, and some marshes have again shrunk and become isolated from tidal influence. Another factor to consider in this area is interpretation error. In more complex areas only careful ground truthing can determine whether a marsh is palustrine or estuarine. Marshes may have been misidentified on one or more of the maps.

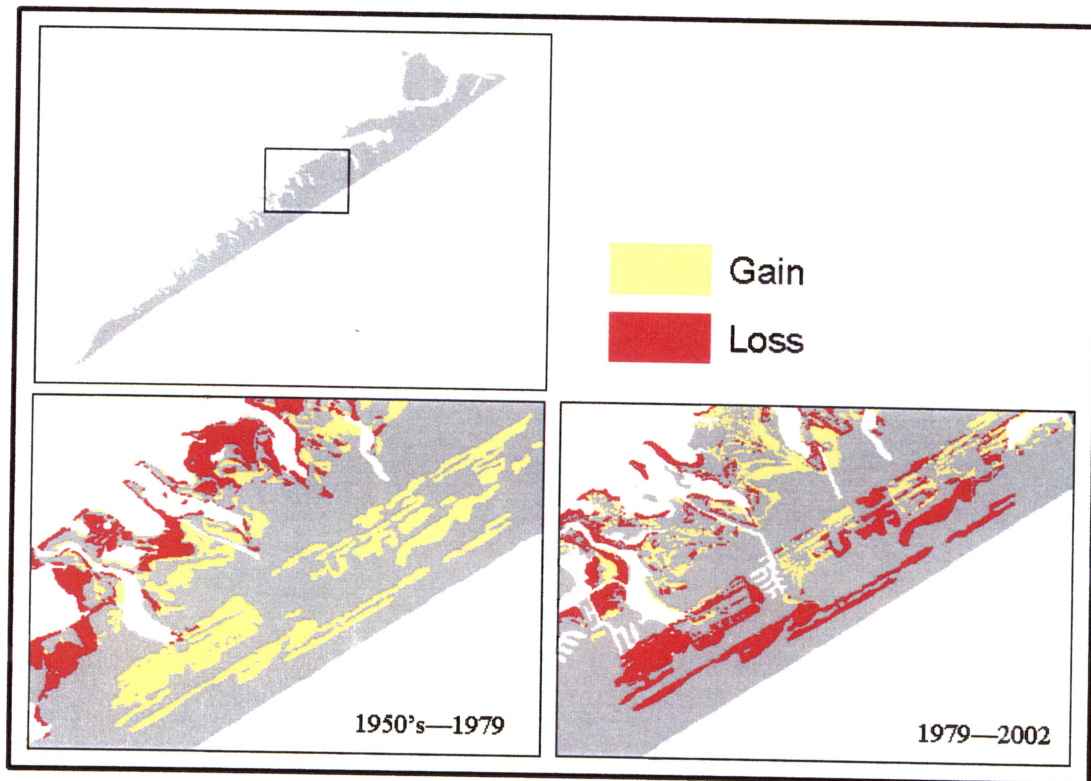


Figure 43. Marshes on the interior of Galveston Island have changed over time. From the 1950's to 1979 there was a gain in interior estuarine marsh, but from 1979 to 2002 there was a net loss.

The decline of the Gulf beach is due to erosion. Erosion rates are 2 m/yr on average on Galveston Island (see <http://www.beg.utexas.edu/coastal/intro.htm>). In some places, the 2002 beach moved inland from where it was in the mid-1950's, but it has also become narrower. Over time the vegetation line did not recede at the same rate as the shoreline eroded. In some areas the vegetation line has not moved, or it has advanced.



## Follet's Island

**General Trends.** The most significant wetland trend on Follet's Island is the systematic loss of estuarine intertidal emergent marsh (E2EM) between the mid-1950's and 2002 (Fig. 44). In the mid-1950's E2EM covered 1,771 ha, by 1979 that area had been reduced to 1,606 ha, representing an overall loss of 9 %. The area of marsh was reduced to 1,459 ha by 2002 representing a 9 % loss. Photo interpretation discrepancies lower the later loss rate to 8 % (explained below). Follet's Island has experienced a systematic loss of E2EM since the mid-1950's, but at a lower rate since 1979.

Estuarine intertidal unconsolidated shore (E2US) experienced a significant loss between the mid-1950's and 1979. In the 1950's, tidal flats occupied an area of 409 ha. That area dropped by more than half to 195 ha by 1979. Since that time, flats have gained slightly in area with a 7 % (13 ha) increase. Unlike the estuarine intertidal flats, the marine beaches (M2US) continued to decline in area throughout the study time period. Mid-1950's M2US totaled 163 ha. That number declined in 1979 to 147 ha, a loss of about 10 %. The decline in M2US area continued to 2002, when 76 ha of Gulf beach was mapped, indicating a loss of 49 % of the 1979 beach area.

Seagrasses covered an area of 127 ha in the mid-1950's but were not mapped in 1979. In 2002, estuarine subtidal aquatic beds (E1AB) totaled 70 ha. Seagrass extent is believed to have fluctuated over time but in the long term, based on aerial photos from which total distribution cannot always be determined, it appears that seagrass beds have declined in the Follet's Island barrier system.

Palustrine habitats experienced the most drastic fluctuation in area through the study period. Palustrine emergent marsh (PEM) went from an initial area of 0.6 ha to 13 ha producing a large percentage increase between the mid-1950's and 1979. Between 1979 and the 2002, about 31 % of PEM habitat was lost, resulting in area of 9 ha in 2002. A similar fluctuation in PUB occurred through time but at lower rates.

**Probable Cause of Trends.** The systematic loss of estuarine intertidal emergent marsh (E2EM) habitat in the Follet's Island barrier island system was initially due, for the most part, to human disturbance. Residential development in the communities of Surfside (Fig. 45) and San Luis Island account for a large part of the E2EM loss between 1956 and 1979. A large area of estuarine marsh on the outskirts of Surfside was converted to rangeland during this time. Disposal of dredge material along the channel connecting Cold Pass and Christmas Bay further decreased E2EM habitat. Evidence of initial E2EM loss to estuarine intertidal unconsolidated shore (E2US) is apparent during the first time period on the downthrown side of the large fault that bisects Mud Island. Mud Island, a relict flood-tidal delta/washover fan complex, is the site of most E2EM loss during the later interval of the study period. Over the duration of the study, estuarine marsh on Mud Island was converted to 32 ha of estuarine flat and 19 ha of open water (E1UB). E2EM loss resulted from inundation due to relative sea-level rise.

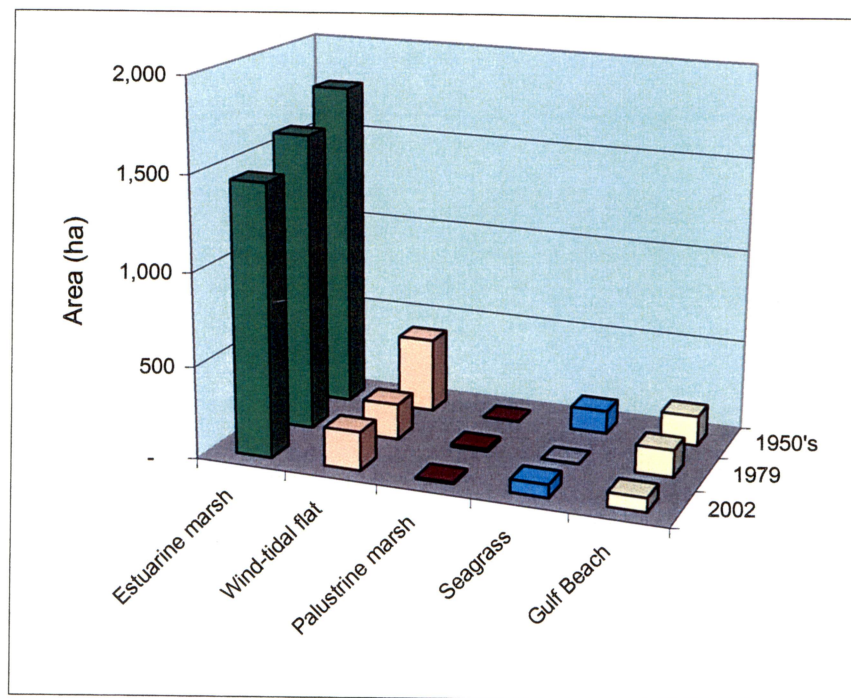


Figure 44. Areal extent of major habitats on Follet's Island in the 1950's, 1979, and 2002.

Relative sea-level rise was likely increased by subsidence along bisecting faults that traverse the island. In the later time period, a 5-hectare area of estuarine marsh was drowned on the downthrown side of the major fault. On nearby Moodys Island another estuarine flat area has formed where marsh once flourished. Mid-1950's photography reveals thick vegetation that becomes partially flooded by 1979.

Flanking Mud Island to the east is San Luis Pass. Channel migration within the pass has eroded sections of the eastern side of Mud Island and has heavily affected Bird Island and San Luis Island (Fig. 46). Most of the loss of estuarine marsh to open water (E1UB) as a result of erosion along the channel occurred between 1979 and 2002.

Much of the marsh loss to open water in the later time period is the result of more accurate mapping techniques employed for 2002 status mapping. Fragmented marsh areas were mapped continuously in the 1979 dataset. The same area mapped on 2002 photography was distinguished between open water and marsh. The earlier practice of combining marsh with open water or flats dictates that some estuarine marsh loss had occurred between 1956 and 1979 but was not documented. A significant portion of marsh loss on Follet's Island between 1979 and 2002 was due to mapping of uplands in areas previously mapped as marsh. Subtracting the marsh misclassification as upland reduces the overall loss rate from 9 % to ~8 % of the 1979 resource.

Marsh encroachment into flats accounts in large part for the large loss of flats (52 %) in the period 1950's-1979. On the northern tip of Mud Island, marsh has encroached into flats along Christmas Bay. In the mid-1950's the high-energy tidal inlet of San Luis Pass appears to be active adjacent to this end of the island. With passing time, lower energy



may have allowed marsh to become established as the active channel migrated away from the island. On Follet's Island a 10-hectare area of marsh formed in the area that once separated San Luis Island from Follet's Island proper (Fig. 46). Marsh has also migrated into previous flat areas along the southern shore of Swan Lake. This trend in Swan Lake continues through the later time period. A fan feature near Arcadia Reef in Christmas Bay experienced loss of estuarine flats to open water and migration of estuarine marsh into previous flat areas. The main channel in the fan had become well established and filled with water between the 1950's and 1979. An artificial channel parallel to the main channel was also dredged, replacing flats with open water. The pattern of estuarine flat loss to open water and encroachment of marsh continued in this area into the later time period. Between 1979 and 2002 the net amount of estuarine intertidal flat (E2US) rose slightly. Some of the net increase of estuarine flats can be attributed to more detailed mapping of complicated estuarine systems containing mixed marsh and flats. Seagrass beds (E1AB) were most extensive in the Follet's Island barrier system in the mid-1950's. Although present, water turbidity precluded mapping of seagrasses in 1979. Comparing the 1950's seagrass total of 127 ha to the 2002 total of 67 ha shows a 47 % loss of the original resource. Seagrass areas for all of Christmas Bay reported by Pulich and White (1991) also showed a decline for the years 1975 and 1987 when seagrass beds totaled 97 ha and 77 ha, respectively (Fig. 47).

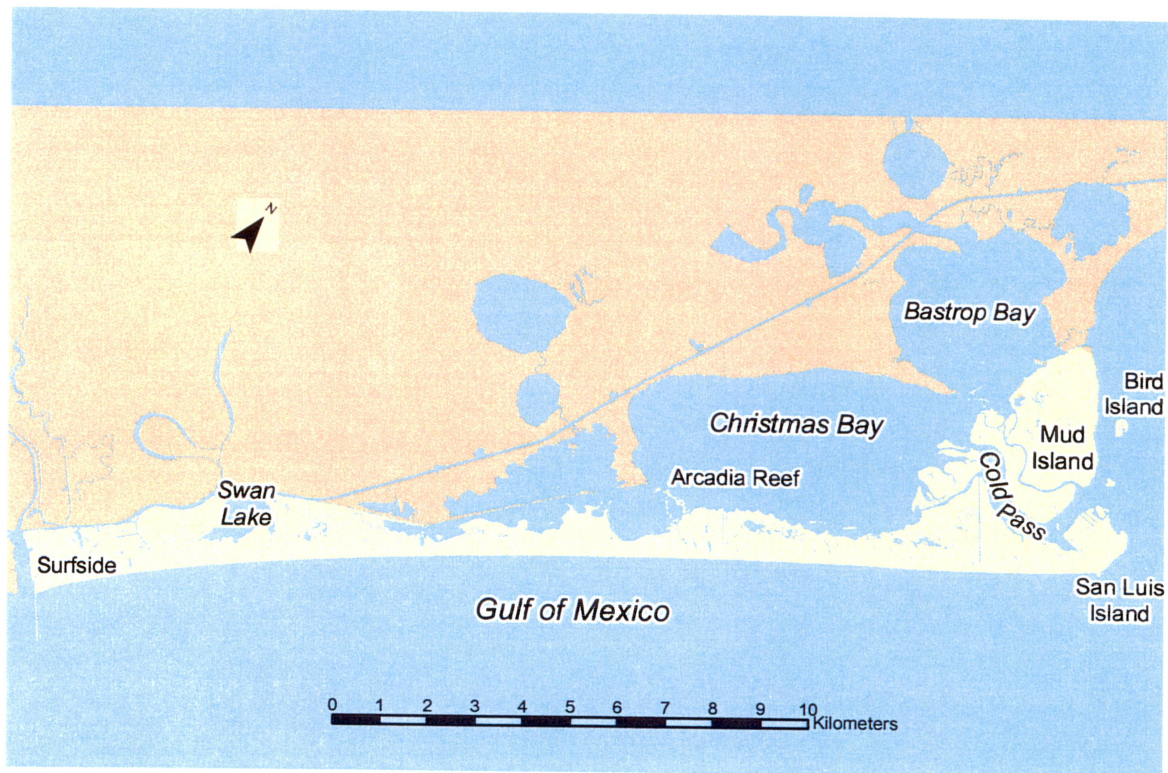


Figure 45. Index map showing features around Christmas Bay.



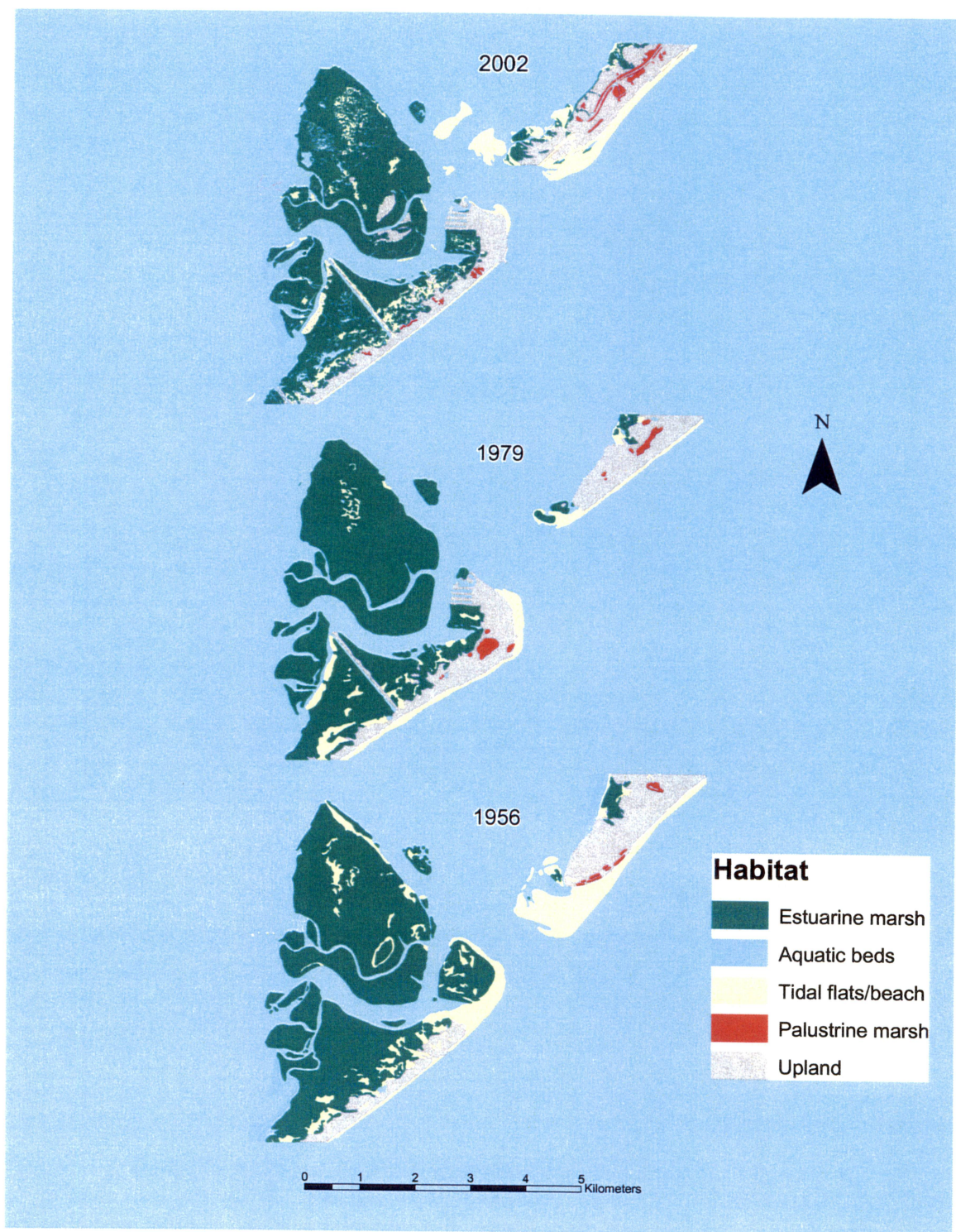


Figure 46. Map showing distribution of major wetland and aquatic habitats in 2002, 1979, and the 1950's at San Luis Pass.



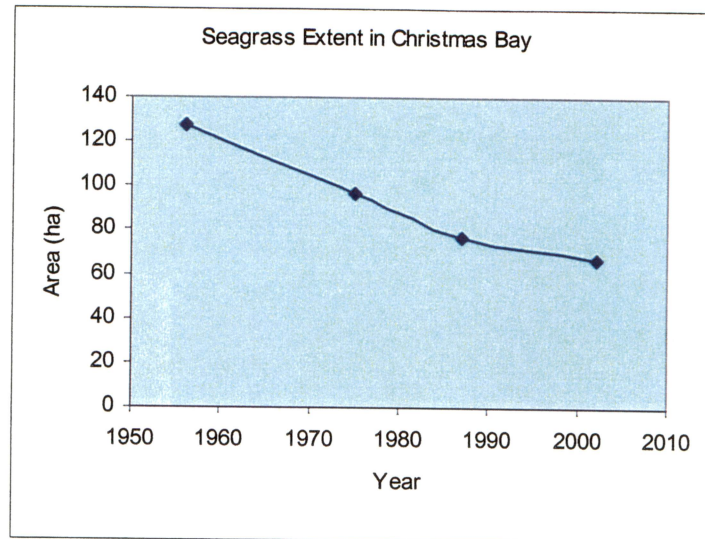


Figure 47. Total area of seagrass mapped in Christmas Bay using aerial photographs taken in 1956, 1975, 1987, and 2002. The years 1975 and 1987, from Pulich and White (1991), are for the entire bay.

Gain and subsequent loss of palustrine emergent marsh (PEM) and palustrine unconsolidated bottom (PUB) over the length of the study is due to drier conditions in 1956 and 2002 than the unusually wet 1979 period. A systematic loss of marine intertidal unconsolidated shore (M2US) is due to erosion along the dynamic tidal inlet at San Luis Pass.

## SUMMARY AND CONCLUSIONS

Wetlands and aquatic habitats on upper Texas Gulf coastal barriers are dominated by estuarine emergent wetlands (salt and brackish marshes), which in 2002 encompassed 7,715 ha and represented 92 % of the estuarine and palustrine vegetated wetland and aquatic classes (marshes, scrub/shrub, and seagrass beds). Among other mapped classes (excluding open water), wind-tidal flats are most abundant at 771 ha, followed by palustrine marshes (607 ha), the Gulf beach (556 ha), seagrass beds (116 ha), and scrub/shrub wetlands, primarily salt cedar (39 ha).

Examination of wetland distribution in the three geographic subareas (Bolivar Peninsula, Galveston Island, and Follet's Island) shows that Bolivar Peninsula, including an estuarine marsh complex at its northeast end, has by far the largest distribution of salt and brackish marshes with a total of 4,734 ha, or approximately 60 % of the estuarine marsh habitat in the study area. Estuarine marsh on Galveston Island covers 1,519 ha and on Follet's Island 1,459 ha. Tidal flats are most widely distributed on Galveston Island where there are 426 ha, or almost 55 % of this resource, followed by Follet's Island with 196 ha, and Bolivar Peninsula with 140 ha. Seagrass beds are most abundant in Christmas Bay adjacent to Follet's Island where 67 ha were mapped. In West Bay adjacent to Galveston Island, 49 ha were mapped. Palustrine marshes are most extensive on Bolivar Peninsula (322 ha), followed by Galveston Island (276 ha). Only 9 ha of palustrine marsh

habitat was mapped on Follet's Island. The area of Gulf beach habitat is largest on Galveston Island, where 278 ha occurs. Bolivar Peninsula has 202 ha of beach habitat and Follet's Island 76 ha.

Historically, losses and gains in habitats have occurred throughout the study area, but the overall trend in vegetated wetlands is one of net loss, as revealed by declines in estuarine marshes of 1,106 ha from the 1950's through 1979 and 447 ha from 1979 to 2002. The average rate of net marsh loss, however, decreased from about 48 ha/yr during the earlier period to 20 ha/yr during the later one. The total area of tidal flats decreased by 438 ha from the 1950's through 1979 and 1,162 ha from 1979 to 2002. The average rate of tidal-flat loss increased through time, from about 19 ha/yr during the earlier period to 50 ha/yr during the later period. These rates of tidal flat loss for the two periods are the inverse of the rates of estuarine marsh loss.

Of the almost 1,010 ha of seagrass beds that were mapped on the mid-1950's photos, none were mapped on the 1979 photos. There is evidence, however, that seagrasses were present in Christmas Bay in 1979 (Pulich and White, 1991), but were not mapped by NWI because of turbid conditions at the time the photos were taken. In West Bay, seagrasses apparently disappeared between the 1950's and mid-1980's (Pulich and White, 1991), indicating a loss of about 882 ha, the amount mapped on the mid-1950's aerial photos. The total area of seagrass beds mapped in the study area in 2002 was 116 ha. There has been a partial recovery in West Bay where 49 ha were mapped on the 2002 photos, primarily in the vicinity of Galveston Island State Park

Palustrine marshes with an area of about 1,045 ha in the 1950's, decreased in total area by almost 427 ha between the 1950's and 1979. A much smaller decline of 10 ha occurred between 1979 and 2002, leaving a total of 607 ha in 2002. Scrub-shrub wetlands (estuarine and palustrine), with an area of 34 ha in the 1950's, increased by about 11 ha during the first period, and declined about 5 ha during the second period. There was a decline in the area of mapped Gulf beaches during both periods, with losses of 384 ha and 74 ha for the 1950's through 1979 and 1979 to 2002 periods, respectively.

Analysis of habitat distribution by geographic subarea reveals local differences in historical trends.

On **Bolivar Peninsula**, a 10 % net decline in estuarine marsh habitat since the 1950's can be attributed primarily to active surface faults that submerged and contributed to erosion of wetlands, and secondarily to bay shoreline erosion, local development, including draining and filling of marshes, and differences in classification of marsh types. The total net loss of vegetated wetlands, over 90 % of which are estuarine marshes, was about 720 ha from the 1950's to 1979. Although there were losses and gains locally from 1979 to 2002, only 12 ha of net gain occurred during this period. The most extensive losses of marsh habitat occurred along two active surface faults that intersect marshes on a relict flood-tidal delta and washover-fan complex that extends into West Bay. On the downthrown sides of the faults, marshes were replaced by open water, indicating rates of subsidence and erosion that exceeded marsh vertical accretion. Losses in this area



occurred from the 1950's through 1979. The timing of wetland loss coincides with the period in which annual gas production peaked at the Clam Lake Oil and Gas Field in the late 1960's to early 1980's. The spatial and temporal relationships between oil and gas production, faulting, and marsh loss support Ewing's (1985) conclusion of a causal relationship between fluid production at the field and fault movement. Marsh loss in this area amounted to more than 400 ha from the 1950's to 2002.

Analysis of habitat trends on **Galveston Island** reveals a loss of wetland habitats over time. Estuarine marsh, estuarine tidal flats, and palustrine marsh have all declined in area. Seagrasses, which were absent in 1979, have made a modest comeback in 2002. The Gulf beach declined from the mid 1950's to 1979 but had recovered slightly by 2002. The declines in wetland habitat are mostly due to subsidence, but development and cattle trails have had an impact locally. In some areas, marsh restoration projects are being used in an effort to help the marshes recover. Some changes in habitat distribution are due to impoundment of marsh areas, and to differences in prior weather and ground conditions in the aerial photography used to interpret the maps. The southwestern tip of the island has experienced large changes over time due to erosion caused by shifting deep-water channels in San Luis Pass.

**Follet's Island** experienced a systematic loss of estuarine intertidal marsh (E2EM) between the mid-1950's and 2002. Approximately 9 % of the estuarine marsh was lost from the 1950's through 1979, which was slightly higher than the ~ 8 % loss (after photo interpretation adjustments) that occurred from 1979 to 2002. Relative sea-level rise, compounded by subsidence along active faults on Mud Island, is a significant cause of estuarine marsh loss. By 1979, 52 % of the mid-1950's estuarine intertidal flats (E2US) had been lost. The loss of tidal flats, primarily caused by encroachment of marsh onto the flats during the earlier period, was reversed during the later period when marshes were replaced by tidal flats. Seagrass beds (E1AB) were most extensive in the Follet's Island barrier system in the mid-1950's and were not mapped in 1979. Comparing the 1950's total (127 ha) to the area of seagrass present in 2002 (67 ha) indicates a 47 % loss of the original resource, although it is possible that much of this apparent change was a seasonal phenomenon, in which the seagrasses had died back during the winter when the 2002 aerial photographs were taken. Pulich and White (1991), however, also reported a seagrass decline in Christmas Bay, from 97 ha in 1975 to 77 ha in 1987. These data show a rate of decline from 1987 to 2002 that is much lower than during the earlier periods.

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APPENDIX. Total habitat areas for 2002, 1979, and 1950's determined from GIS datasets of the study area.

2002 Habitats	Hectares	1979 Habitats	Hectares	1956 Habitats	Hectares
E1AB1	115	E1AB6L.	4	E1AB.	1,009
E1AB3	116				
E1AB5	46	E1OW.	3	E1OW.	16,747
		E1OWL.	18,651		
E1UB	18,540	E1OWLH.	2	E2AB.	13
		E1OWLX.	298		
E2EM1N	4,189			E2BB.	76
E2EM1P	3,511	E2AB2L.	23		
E2EMNs	15			E2EM.	9,267
		E2BBP.	4	E2EMFL.	1
E2RF2M	6				
		E2EM1N.	3,650	E2FL.	2,371
E2SS	14	E2EM1P.	4,515		
		EM/OW.	428	E2RF.	1
E2USM	1,035				
E2USN	333	E2FLN.	1,334	L1OW.	22
E2USNs	7	E2FLP.	540		
E2USNx	1	E2FLPH.	59	L2OW.	127
E2USP	425				
E2USPs	6	E2SS3P.	29	M1OW.	10,740
		E2SS6C.	5		
L2UBKh	253	E2SS6P.	1	M2BB.	1,013
L2USKhs	544	L2FLCH.	15	PEM.	1,045
		L2FLYH.	369	PEMFL.	6
M1UB	11,382				
		L2OWFH.	42	PFL.	6
M2USM	4				
M2USN	167	M1OWL.	10,800	POW.	83
M2USP	385				
		M2BBP.	629	PSS.	34
PEM1A	351				
PEM1C	111	PAB4F.	1	U.	12,775
PEM1F	49				
PEMAh	52	PEM1A.	8		
PEMFh	43	PEM1C.	30		
		PEM1CD.	36		
PSS	25	PEM1F.	15		
		PEM1Y.	325		
PUB	102	PEM1YH.	158		
PUBCx	2	PEM1YH/PFL	45		
PUBHx	114				
PUBKh	37	PFLY.	4		

Total habitat areas for 2002, 1979, and 1950's determined from GIS datasets of the study area.

# APPENDIX Continued...

2002 Habitats	Hectares
PUS	6
PUSC <sub>x</sub>	93
PUSK <sub>hs</sub>	2
PUS <sub>h</sub>	26
U	13,263

1979 Habitats	Hectares
PFO6A.	4
POWF.	17
POWFH.	46
POWFHX.	3
POWFX.	9
POWG.	12
POWGH.	7
POWGHX.	1
POWGX.	4
POWH.	8
POWHH.	23
POWHHX.	1
POWHX.	9
POWX.	4
PSS1A.	1
PSS6A.	1
PSS6C.	7
PSS6Y/PEM1	1
U.	11
UA.	7,430
UBD.	9
UBS.	60
UF6.	22
UR.	57
UU.	5,482
UUO.	35