STATUS AND TRENDS OF INLAND WETLAND AND AQUATIC HABITATS, BEAUMONT-PORT ARTHUR AREA

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EXECUTIVE SUMMARY

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Introduction

Wetland and aquatic habitats are essential components of estuarine and inland systems 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 is the second in a series of wetland status-and-trend investigations of inland wetlands along the Texas Coast (Tremblay et al., 2008). This report presents results of a status-and-trend study of the upper Texas coast along the inland wetland system from the Sabine River to Anahuac National Wildlife Refuge (NWR) (Fig. I).

The Beaumont-Port Arthur area is characterized by Sabine Lake, a small bay-estuary system separated from the Gulf of Mexico by a modern strandplain-chenier system (Fisher et al., 1973). The Sabine and Neches Rivers discharge into Sabine Lake. The study area encompasses most of the mainland between the Gulf Intracoastal Waterway (GIWW) and the Texas General Land Office (GLO) Coastal Management Program (CMP) boundary, an area that is located within Orange, Jefferson, and Chambers Counties (Fig. I). Natural environments include wetlands, tidal flats, riparian woodlands, and bay shorelines. The methods and classification system used in this report follow those found in the Texas coastal barrier-island report for the Upper Coast Strandplain-Chenier System (White et al., 2007).

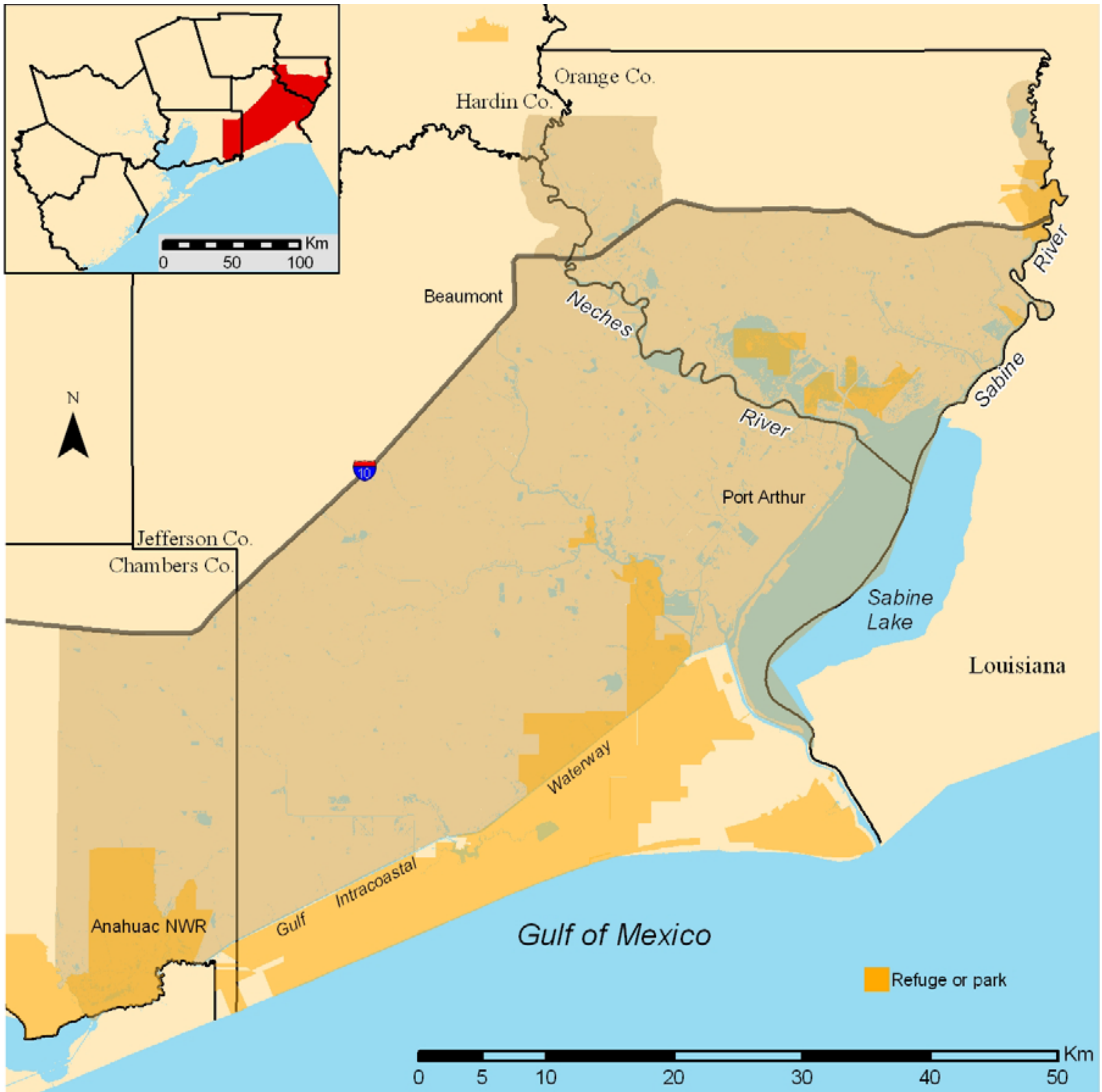

Figure I. Index map of study area.

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 2004. Historical distribution is based on 1956 black-and-white and 1979/83 CIR photographs. Mapped wetlands for each period were digitized and entered into a GIS for analysis. Historical 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 1956 and 1979/83 series USFWS maps, which are in digital format, were partly revised in this project to be more consistent with wetlands interpreted and delineated on the 2004 photographs.

Methods used to delineate 2004 habitats differed from the earlier methods. The 2004 photographs were digital images with a pixel resolution of 1 m and registered to USGS Digital Orthophoto Quadrangles (DOQ's). Wetlands and aquatic habitats were mapped through interpretation and delineation of habitats onscreen in a GIS at a scale of 1:5,000. Resulting current-status GIS maps were used to make 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 1979/83 and 2004 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.

In analyzing trends, wetland classes were emphasized over water regimes and special modifiers because habitats were mapped only down to class on 1956 photographs. We would also like to note a margin of error in 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 the direction of trends than absolute magnitudes.

Bay-Estuary System, Upper Texas Coast

The bay-estuary study area along the upper Texas coast contains the most extensive contiguous marshland along the Texas Gulf Coast. Most marshland falls within the McFaddin NWR, Anahuac NWR, and J. D. Murphree Wildlife Management Area (WMA). Extensive freshwater marshes and ponds characterize this area. Most of the freshwater marshes that are part of the McFaddin NWR occur inland of the GIWW (Dean Bossert, Refuge Manager, Personal Communication, 2006).

Current Status, 2004

Major palustrine habitats in the study area include fresh marshes and open water. Forests are next in areal distribution (Fig. II). Estuarine marshes are limited in extent. The primary habitat mapped in the fresh, open water system is the lacustrine, which consists of diked and leveed containment areas.

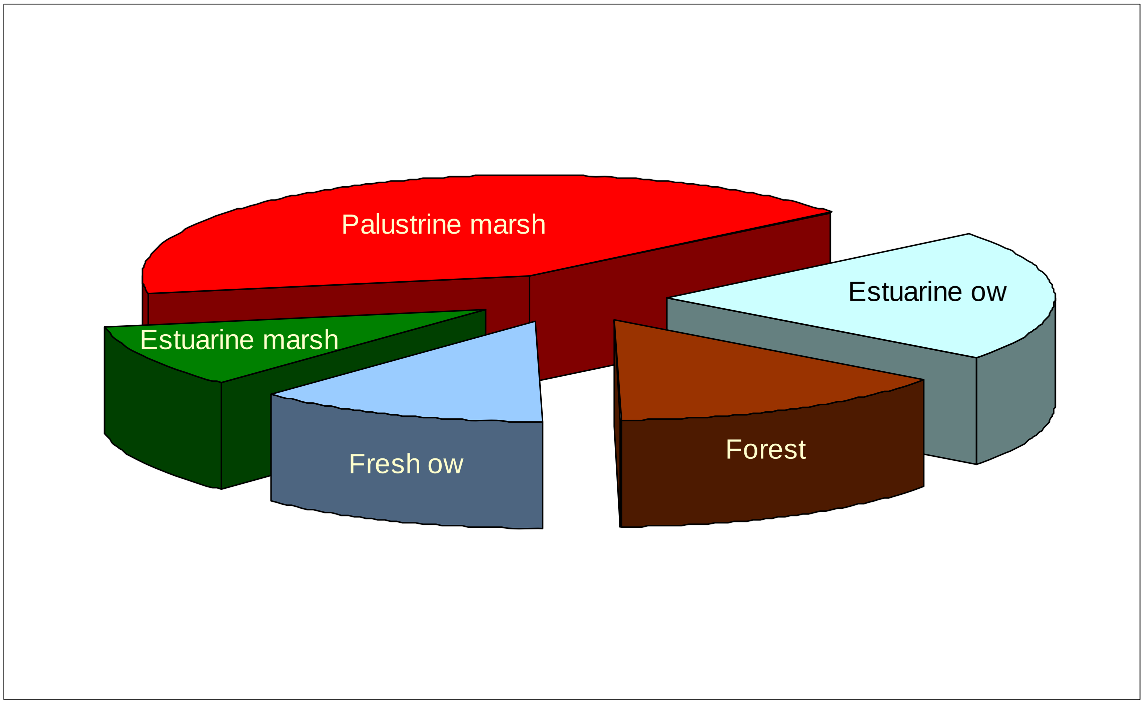

Figure II. Areal extent of selected habitats in upper coast study area in 2004. Fresh open water (ow) in this figure includes palustrine, lacustrine, and riverine waters.

In 2004, wetland and aquatic habitats were dominated by palustrine marshes, with a total area of 35,876 ha (88,654 acres), followed by estuarine open water (ow) totaling 18,043 ha (44,585 acres), and forest/scrub-shrub at 12,316 ha (30,434 acres) (Fig. III).

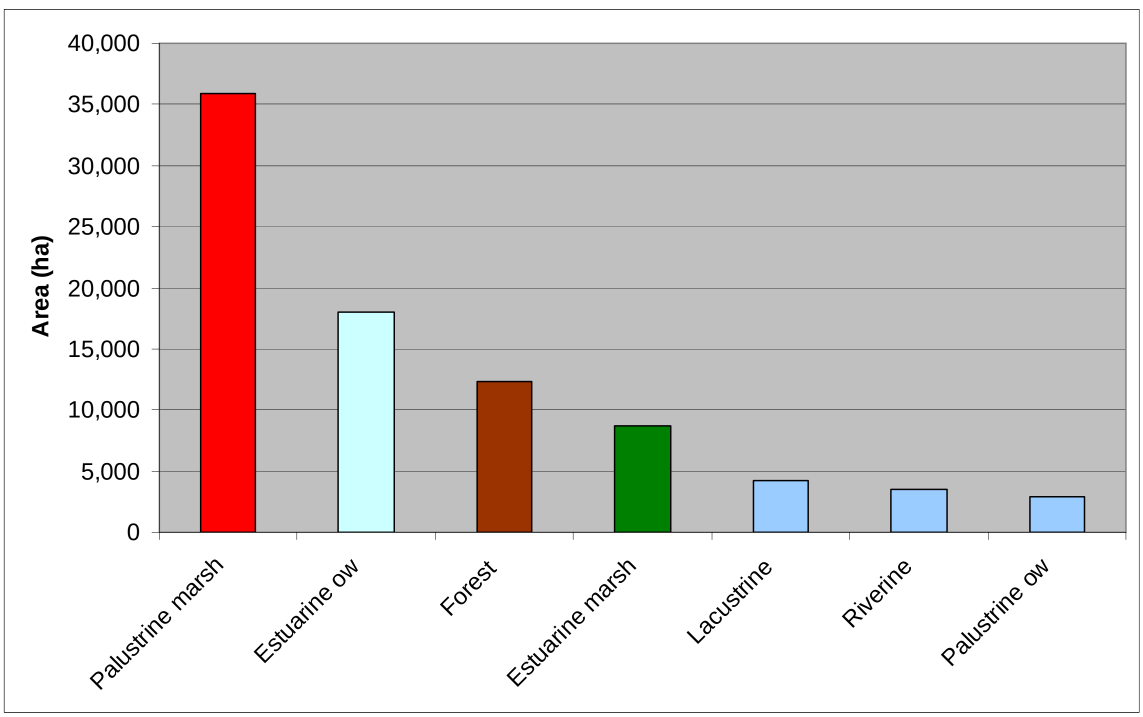

Figure III. Areal extent, in hectares, of habitats in 2004.

Estuarine marsh covered 8,759 ha (21,644 acres). Lacustrine flats and open water had a total area of 4,188 ha (10,349 acres), and rivers 3,491 ha (8,627 acres). Palustrine habitats, consisting mostly of water and some flats, had a total area of 2,900 ha (7,166 acres).

The study area, covering estuarine systems of the Sabine and Neches Rivers, Taylor Bayou, and marshes inland of the strandplain-chenier, was subdivided into geographic areas—the Sabine River, Neches River, Sabine Lake, Taylor Bayou, Spindletop Marsh, and Anahuac—to allow a more site-specific analysis of status and trends (Fig. IV).

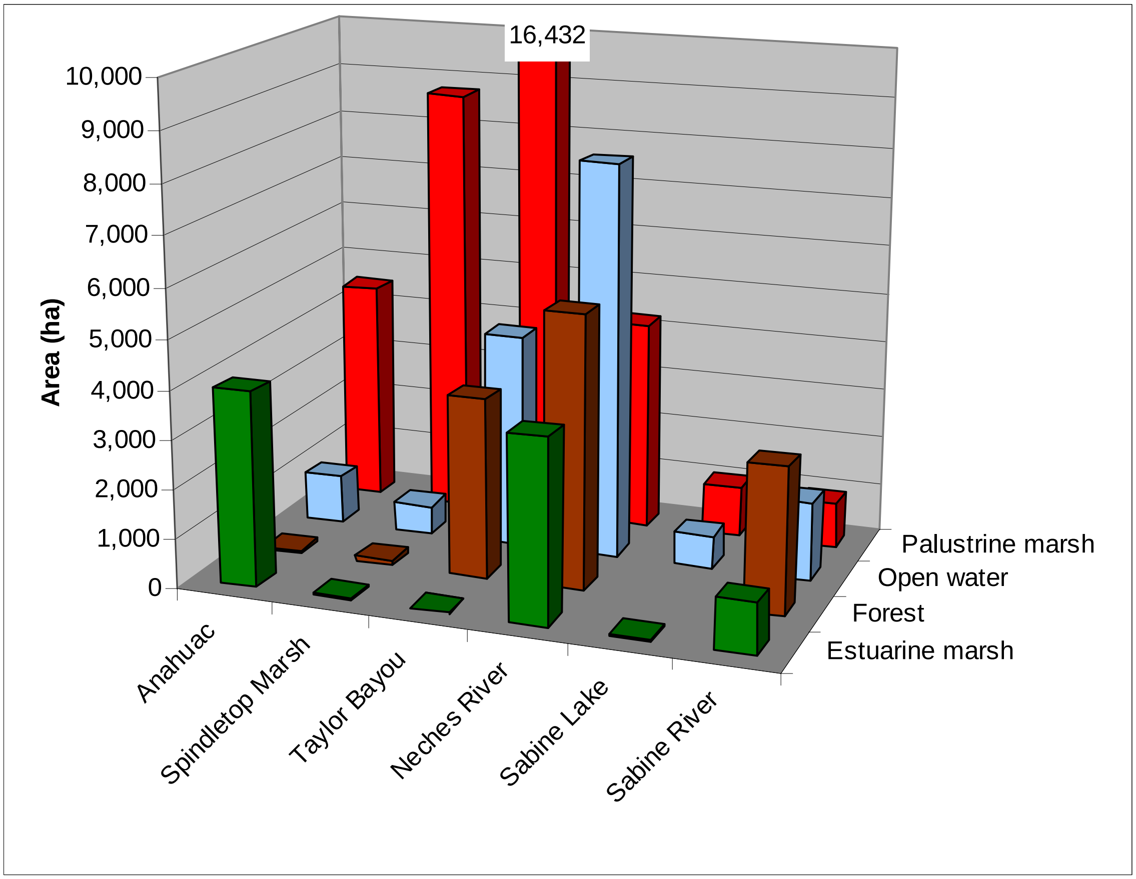

Figure IV. Distribution of selected habitats by geographic area in 2004. The most extensive distribution of palustrine marsh is in Taylor Bayou, with the highest amount of estuarine marsh in the Anahuac area. Forest is most abundant on the Neches River.

The most extensive palustrine emergent wetlands occurred in Taylor Bayou, where the total area of palustrine marshes in 2004 was 16,432 ha (40,604 acres) (Fig. IV). Spindletop Marsh was a distant second with 8,737 ha (21,590 acres). Anahuac and the Neches River had significant amounts of palustrine marsh, 4,513 ha (11,152 acres) and 4,279 ha (10,574 acres), respectively (Fig. IV). Sabine Lake contained 1,050 ha (2,595 acres) of palustrine marsh. The Neches River contains the largest amount of open water because of the large amount of estuarine water (freely connected to the Gulf). Of the 8,002 ha (19,773 acres) of water, 64% is estuarine. Taylor Bayou contains the second-highest amount of open water, with 4,344 ha (10,734 acres), but freshwater constitutes roughly 92% of the resource. Approximately 67% of the 1,603 ha (3,961 acres) of water in the Sabine River area is freshwater. Forests are abundant in the Neches River valley, where wetland trees and shrubs total 5,530 ha (13,665 acres). Taylor Bayou and the Sabine River valley also contain significant forest, 3,633 ha (8,977 acres) and 2,965 ha (7,327 acres), respectively. Anahuac, with 3,943 ha (9,743 acres), the Neches River containing 3,698 ha (9,138 acres), and the Sabine River with 1,021 ha (2,523 acres), all had significant estuarine marsh (Fig. IV).

Wetland Trends and Probable Causes, 1956–2004

In analyzing trends, broad wetland classes were emphasized over water regimes and special modifiers because habitats were mapped only down to class on 1956 photographs. In addition, interpretation of the distribution of estuarine and palustrine systems varied from year to year. Palustrine marshes are by far the dominant class of emergent wetlands in the upper-coast study area; therefore, for simplification and to reduce apparent changes due to interpretation, emergent wetland classes in the trend analysis were combined.

From 1956 through 2004, emergent wetlands (marshes) increased from about 44,104 ha (108,983 acres) to 44,635 ha (110,296 acres), a gain of approximately 531 ha (1,312 acres) (Fig. V, Table I). Marsh area fluctuated through the study time period. The rate of marsh gain from 1956 to 1979 was 56 ha/yr (138 acres/yr), and from 1979 to 2004, marsh losses were about (–)30 ha/yr (74 acres/yr). Similarly, estuarine open water and flats experienced a fluctuation in area through time. The gain in estuarine open water was approximately 2,074 ha (5,125 acres). Rates of change in estuarine open water were about (+)139 ha/yr (344 acres/yr) during the earlier period and (–)45 ha/yr (111 acres/yr) during the later period. The overall estuarine open-water trend rate (1956–2004) was a gain of 43 ha/yr (106 acres/yr). The area of forest and scrub-shrub decreased substantially through time, from 19,506 ha (48,200 acres) in 1956 to 12,316 ha (30,434 acres) in 2004. Rates of change in forest were about (–)355 ha/yr (877 acres/yr) during the earlier period and (+)39 ha/yr (96 acres/yr) during the later period. Freshwater and flats increased in area from 10,397 ha (25,691 acres) in1956 to 10,580 ha (26,144 acres) in 2004, a gain of about 183 ha (452 acres).

Analysis of habitat changes along the upper Texas coast shows a systematic increase in marshes from 1956 to 2004 (Fig. V). Complementing this trend in increasing emergent wetlands was an increase in open water, both estuarine and nonestuarine. The increase in estuarine open water since 1956 occurred partly because of drier conditions in 1956. A severe drought in Texas peaked in 1956 (Riggio et al., 1987), which apparently affected the extent of open water in the marshes on 1956 maps. These differences in wet and dry conditions during various years affected habitats, especially the extent of open water that was interpreted and mapped.

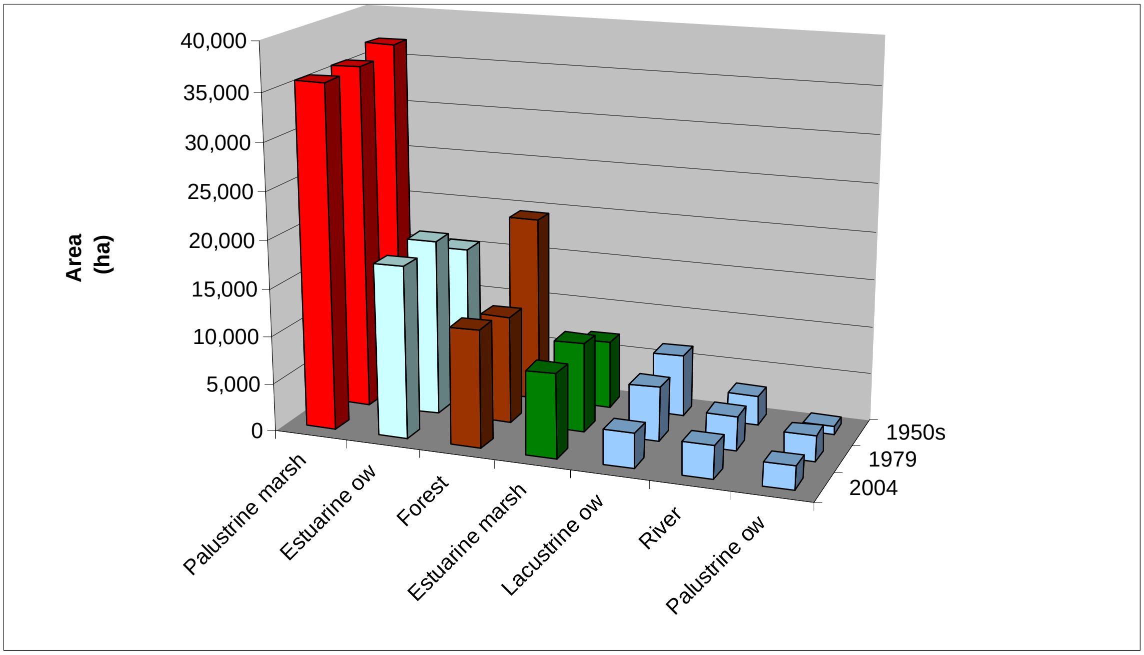

Figure V. Areal distribution of major habitats in the study area in 1956, 1979/83, and 2004.

Table I. Total area of major habitats in 1956, 1979/83, and 2004.

Habitat	*1950's*		*1979/83*		*2004*	
	ha	acres	ha	acres	ha	acres
Palustrine marsh	37,040	91,489	36,033	89,002	35,876	88,614
Estuarine ow	15,603	38,539	18,518	45,740	18,043	44,566
Forest	19,506	48,180	11,335	27,998	12,316	30,421
Estuarine marsh	7,064	17,448	9,353	23,101	8,759	21,635
Lacustrine ow	6,508	16,075	5,714	14,114	3,672	9,069
River	3,062	7,563	3,653	9,023	3,491	8,624
Palustrine ow	828	2,045	2,580	6,373	2,439	6,025

Part of the expansion of open water since 1956 was due to subsidence and relative sea-level rise. In several areas, subsidence occurred along active surface faults. For example, a major fault in the Neches River valley contributed to an increase in water on the downthrown side of the fault (Fig. VI) (White et al., 1987). Because the fault could not be seen on photographs taken in 1956, it has apparently become active more recently. Evidence shows that the fault has been activated by oil and gas production at Port Neches field (White and Tremblay, 1995; White and Morton, 1997). Multiple faults crossing marshes have been mapped along the lower Neches River valley (Fig. VII). Marsh losses have occurred on the downthrown sides of the faults, where subsidence has promoted flooding and erosion of marshes. Rate of subsidence and relative sea-level rise on the downthrown side of the faults apparently exceeded the rate of marsh vertical accretion, and the marsh was replaced primarily by open water. Relative sea-level rise also appears to have contributed to expansion of water in marsh areas where no faults are apparent.

Figure VI. Fault in Neches River valley downthrown toward the oil and gas field. Dark areas of open water increase on the downthrown side (D) of the fault relative to the upthrown side (U). This photograph was taken by the U.S. Department of Agriculture in 1966. The fault could not be seen on photographs taken in 1956. From White and Morton (1997).

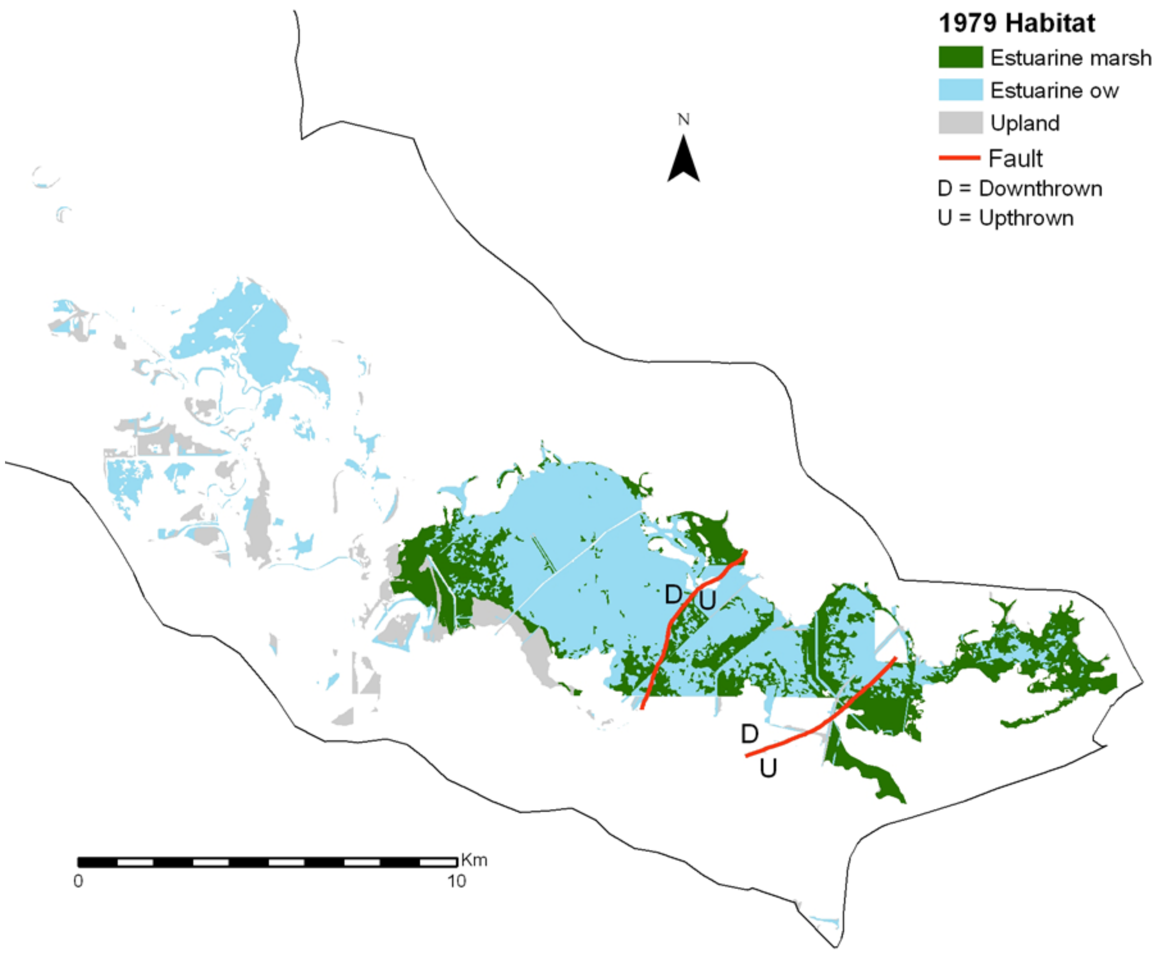

Figure VII. Faults intersecting wetlands in the lower Neches River valley. Water and low marshes increase on the downthrown (D) side of the faults relative to the upthrown side, indicating higher rates of subsidence on the downthrown side. Map shows 1979 habitat that was originally palustrine marsh in 1956.

Conversion of marsh to open water has also occurred where artificial levees, roads, and dikes have created "dams" along which water ponds and submerges marshes. Port Neches field is a good example of where roads and levees have been constructed for oil and gas field development. In summary, faults and artificial levees form topographic ridges where water is ponded and which partly account for expansion of open water into marsh areas. These factors also influence the local salinity regime. Overlay analysis of 1956 and 2004 data sets reveals that roughly 78% of the area of increase in estuarine marsh was in areas previously mapped as palustrine marsh. Over the same time period, palustrine marsh was replaced primarily by uplands and to a lesser degree by estuarine marsh. In many instances, areas mapped as palustrine marsh in 1956 had been replaced by invasive Chinese tallow (*Triadica sebifera*) by 2004. Forested wetlands suffered systematic losses throughout the study time period. Forests were harvested and cleared for agricultural and residential purposes, primarily in the upper reaches of river valleys and bayous. Nearly 71% of forest loss over the long term was due to conversion to uplands.

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INTRODUCTION

Coastal wetlands are essential natural resources that are highly productive biologically and chemically and are part of an ecosystem on 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 is the second in a series of wetland status-and-trend investigations of inland wetlands along the Texas Coast (Tremblay et al., 2008). The first series was status and trends of wetlands on the Texas Coast barrier system (White et al., 2002, 2004, 2007). Presented in this report are results of a status-and-trend study of the upper Texas coast from Anahuac NWR to Sabine Lake.

Figure 1. Hurricane-Ike-flooded pond in Anahuac National Wildlife Refuge, Chambers County.

Previous studies by the Bureau of Economic Geology (BEG) of wetland status and trends along the Texas coast, for example in the Galveston Bay system (White et al., 1993, 2004), indicate that substantial losses in wetlands have occurred owing 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 studies of 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 the Texas coast and pinpoint wetlands threatened by erosion, faulting, subsidence, and other processes. These data provide site-specific information for implementing marsh protection and restoration programs.

This study is based on wetlands interpreted and mapped using aerial photographs taken in 2004 and on historical wetlands mapped on photographs taken in 1956, 1979, and 1982. The 1956 and 1979/1983 series USFWS maps, which are in digital format, were partly revised in this project to be more consistent with wetlands interpreted and delineated on the 2004 photographs. 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 of wetlands.

Study Area

The study area, located in Chambers, Jefferson, and Orange Counties, includes the bay-estuary system (Fisher et al., 1973) along the upper coast from Anahuac NWR to Sabine Lake (Fig. 2). Geomorphic features on which various types of bay-estuary wetlands have developed are the result of numerous interacting physical processes that influence wetlands, including astronomical tides, waves, 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 to infrequently inundated environments ranging in elevation from estuarine subtidal areas to topographically higher intertidal wetlands that grade upward from the astronomical-tidal zone through the storm-tidal zone.

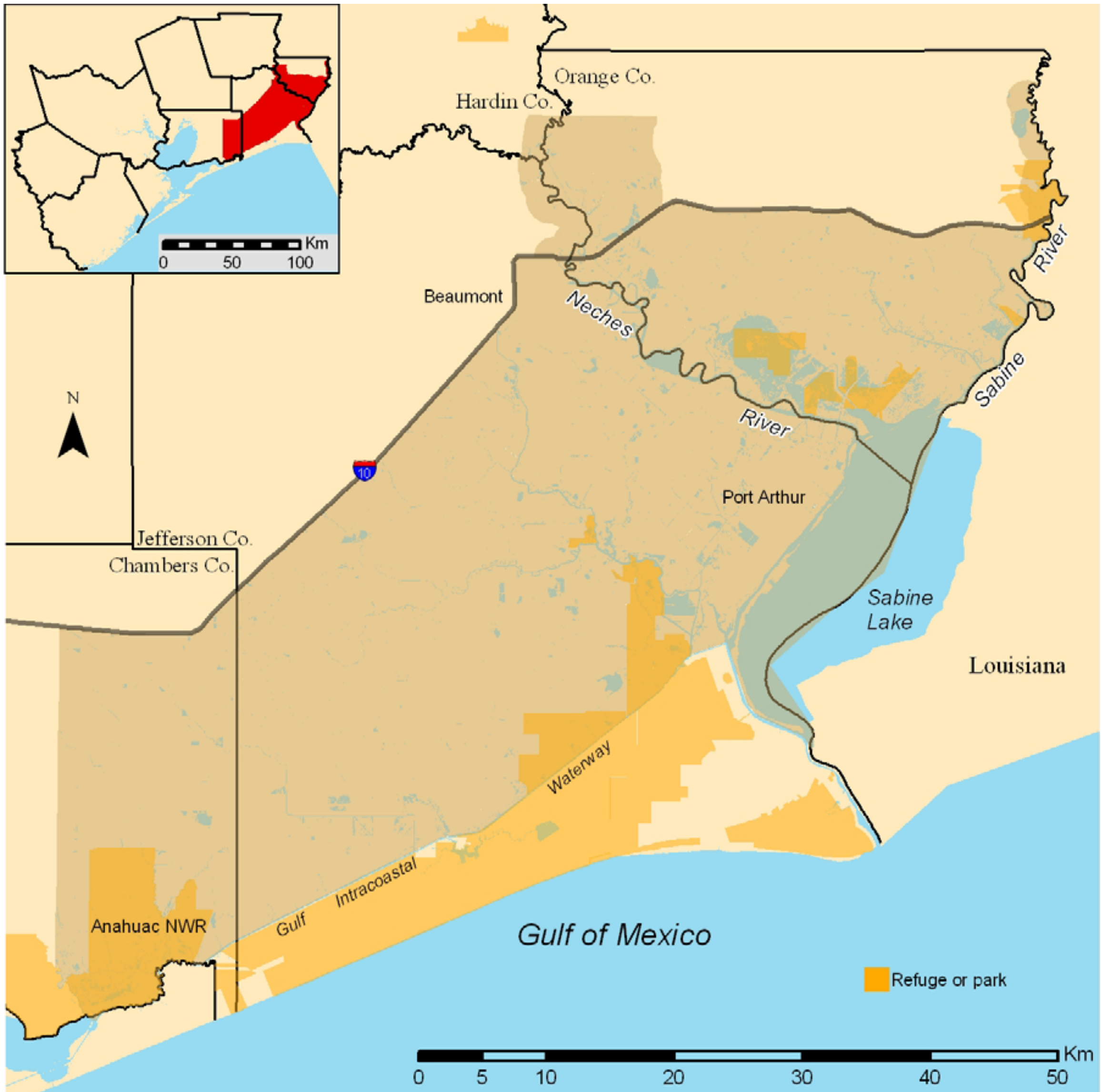

Figure 2. Index map showing study area.

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 1956, 1979, 1982, and 2004. Maps of the 1979/83 time period were prepared from a combination of sources. Final maps of the 1983 series were digitized and initially analyzed in 1983 (USFWS, 1983) under the NWI program. Some of the 1983 maps were prepared by BEG from hardcopy 1987 NWI maps. The photography date for the 1987 NWI maps was the same as that for the 1983 series (1982). In the bay-estuary system, maps for 1956 were prepared by BEG. A scanned and georeferenced unfolded hardcopy of the *Environmental Geologic Atlas of the Texas* (Fisher et al., 1973) was digitized with reference to contemporaneous Tobin black-and-white aerial photomosaics. Current USFWS NWI maps and digital data for the Texas coast were prepared using 1992 aerial photographs, and the maps were used as collateral data. Current status of wetlands in this study is based on photographs taken in 2004.

Wetland Classification and Definition

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

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

> 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[1]; (2) the substrate is predominantly undrained hydric soil[2]; 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

[1]The USFWS has prepared a list of hydrophytes and other plants occurring in wetlands of the United States.
[2]The NRCS has prepared a list of hydric soils for use in this classification system.

connected to photographs and the interpretation of wetland signatures. Wetlands were neither defined nor mapped in accordance with the USACE wetlands delineation manual for jurisdictional wetlands (USACE, 1987).

Interpretation of Wetlands

Historical Wetland Distribution

Historical distribution of wetlands is based on 1956 and 1979/83 USFWS wetland maps. The exception is on the upper coast, north of Chambers County, where 1956 USFWS maps were not available. In this area BEG mapped wetlands using an existing map and 1956 photomosaics. 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 with 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. Field-surveyed sites nevertheless represent only a small percentage of the thousands of areas (polygons) delineated. Most areas are delineated on the basis of photointerpretation alone, and misclassifications may occur. The 1956 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 CIR stereo-pair, scale 1:65,000, that were taken in November.

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 data entered into a GIS. As in the photointerpretation process, a margin of error is 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 1956 and 2004 photographs. Although 1956 photographs are black and white, they are large scale (1:24,000), which aids in the photointerpretation and delineation process. The1956 photographs may reflect the severe drought that peaked in 1956 in Texas (Riggio et al., 1987), which apparently reduced the number of open-water areas that were mapped on the upper coast. These differences in wet and dry conditions during the various years affected habitats, 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 (1956 and 1979/83) so that agreement would be closer between historical map units and current (2004) wetland map units. Revisions of USFWS data are restricted primarily to marshes, tidal flats, and areas of open water. The principal reason for the revisions was that in many areas on the historical maps, palustrine emergent wetlands (PEM) were combined with palustrine flats (PFL) or open water (POW) as a single map unit (PEM/PFL and PEM/POW). In our revisions, many of these areas were subdivided into PEM and PFL or POW where possible at the mapping scale. To accomplish revisions on USFWS maps, photographs taken in the 1950's and 1979 were scanned and georeferenced with respect to the 1950's and 1979 maps. Wetlands on the digital photos were then analyzed on the computer screen, and changes were mapped directly on the digital wetland maps. The revised data were entered into the GIS.

Current Wetland Distribution

The current distribution of wetlands is based on digital, CIR, 1-m-resolution aerial photographs taken in 2004. 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 onscreen in a GIS (ArcMap) at a scale of 1:5000. Because of the method used, current wetland maps show more detail than historical maps.

Field Investigations

Field investigations (Figs. 3, 4) were conducted to (1) characterize wetland plant communities through representative field surveys and (2) 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.

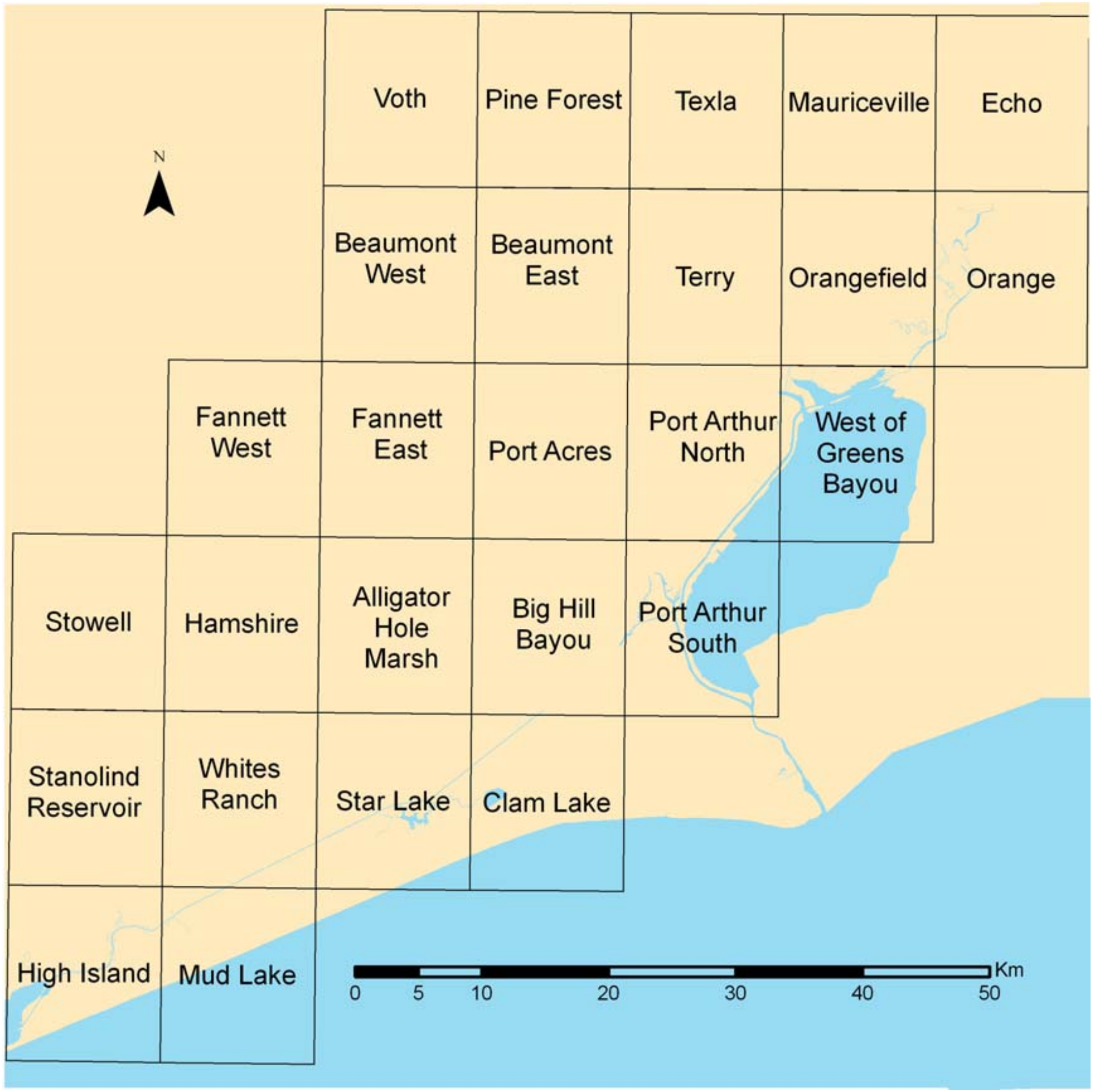

Figure 3. Index map of USGS 7.5-minute quadrangles that encompass the study area.

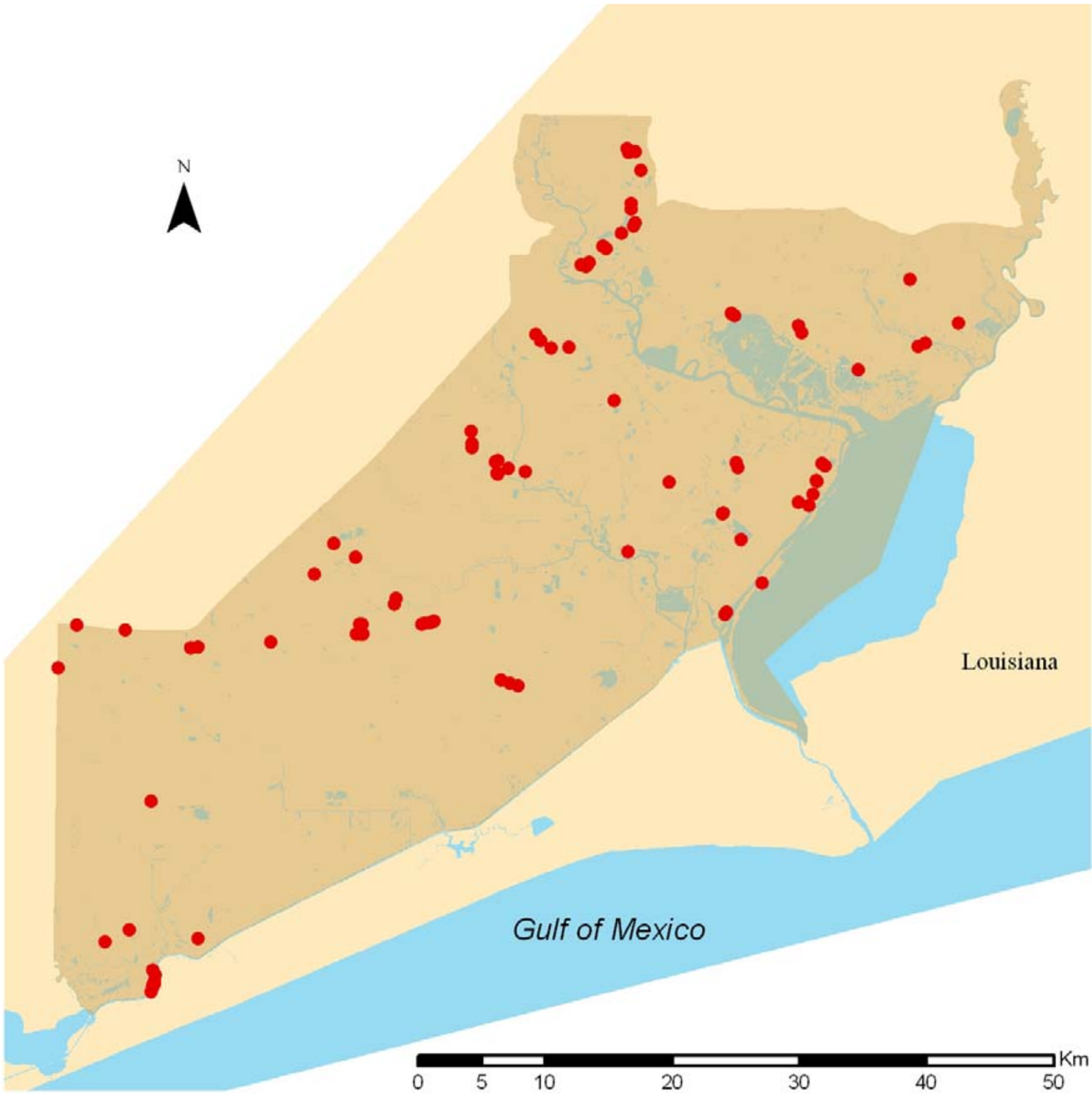

Figure 4. Index map of field-survey sites along the upper coast used for ground-truthing aerial-photo delineations and recording vegetation composition and water regimes.

Variations in Classification

Classification of wetlands varied somewhat for the different years. On 1979/83 and 2004 maps, wetlands were classified by system, subsystem, class, subclass (for vegetated classes), water regime, and special modifier, in accordance with Cowardin et al. (1979) (Fig. 5). For 1956 maps, wetlands were classified by system, subsystem, and class. On 1979/83 maps, upland areas were also mapped and classified by upland habitats using a modified Anderson et al. (1976) land-use classification system (Fig. 6). Flats and beach/bar classes designated separately on 1956 and 1979/83 maps were combined into a single class—unconsolidated shore—on 2004 maps, in accordance with updated NWI procedures, as exemplified on 1992 NWI wetland maps (Fig. 7). USFWS data for the study area were selected from 7.5-minute quadrangles (Fig. 3) from files previously digitized and maintained by the USFWS for the 1979/83 wetland maps.

Results include GIS data sets consisting of electronic-information overlays corresponding to mapped habitat features for 1956, 1979/83, and 2004. Data can be manipulated as information overlays, whereby scaling and selection features allow parts 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. Users must nonetheless be aware of potential errors—for example, from registration differences, which can arise from direct analysis of GIS overlays.

Map-Registration Differences

Map registration differences occur in the historical and recent digital data, which cause errors when data sets are overlain and analyzed in a GIS. The 2004 aerial photographs are georeferenced to USGS DOQQ's, and there is good agreement in registration with these base photographs. However, historical data sets are not as well registered, and there is an offset in wetland boundaries between historical and 2004 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. Reregistration of the USFWS digital data sets was done by georeferencing them to the USGS DOQQ's, which improved agreement of the historical maps with the 2004 maps. Still, agreement in registration is not "perfect" between the different maps, so 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 one another was done primarily to identify significant wetland changes that could be verified by analyzing and comparing aerial photographs.

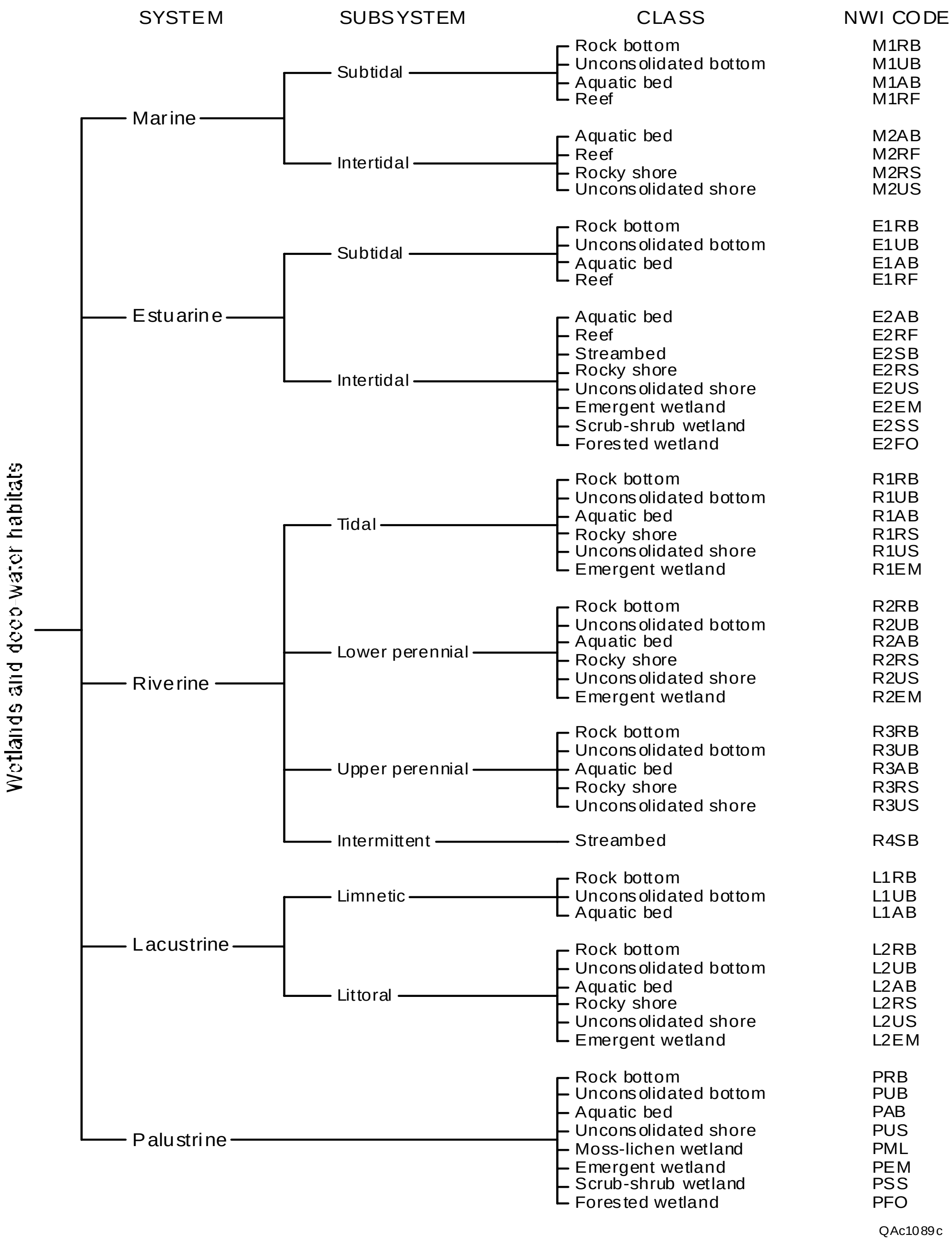

Figure 5. Classification hierarchy of wetlands and deepwater habitats showing systems, subsystems, and classes. From Cowardin et al. (1979).

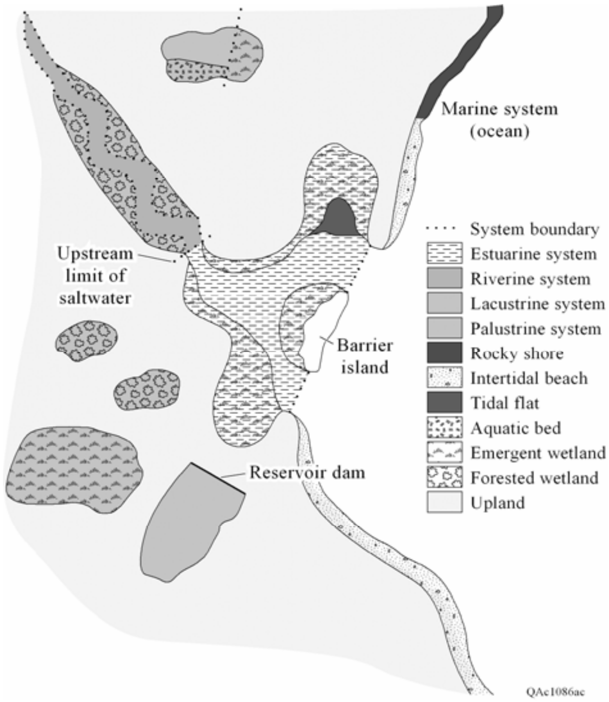

Figure 6. Schematic diagram showing major wetland and deepwater habitat systems. From Tiner (1984).

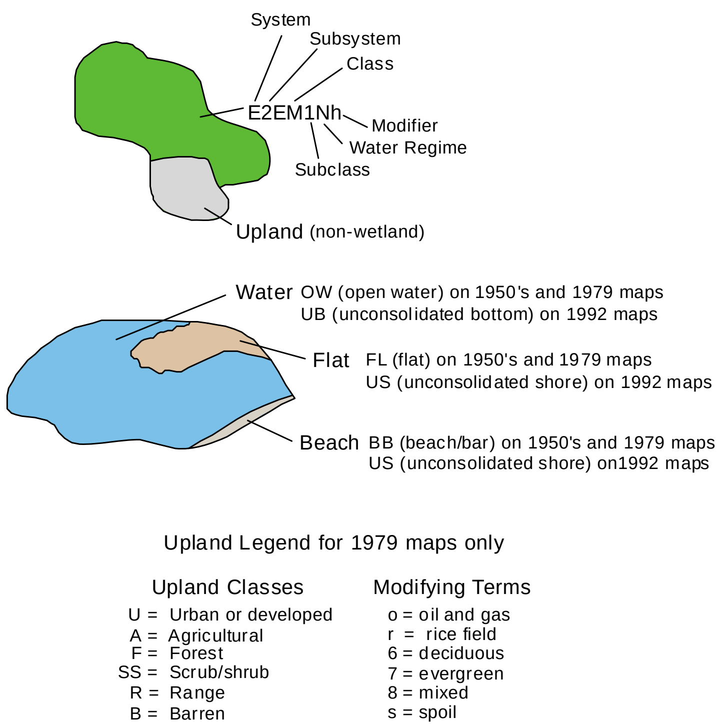

Figure 7. Example of symbology used to define wetland and upland habitats on NWI maps.

Methods Used to Analyze Historical Trends in Wetland Habitats

Trends in wetland habitats were determined by analyzing habitat distribution as mapped on 2004, 1982, 1979, and 1950's aerial photographs. In analyzing trends, wetland classes were emphasized (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.

ArcGIS was used to analyze trends, which allowed for direct comparison not only between years, but also by geographic areas. 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 ArcGIS.

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 scale larger (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. Some apparent losses in palustrine wetlands were documented in the bay-estuary system but appear to be due to drier conditions when the 2004 photographs were taken.

In the analysis of trends, wetland areas for different time periods are compared without an attempt to factor out all misinterpretations or 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. Users of the data should nevertheless keep in mind that a margin of error is inherent in photo interpretation and map preparation.

Wetland Codes

As mentioned in the introduction, some wetland codes used on 2004 maps are different from those used on the 1950's and 1979/83 maps (Fig. 7). In the following discussion of trends, E2US rather than E2FL (used on the 1950's and 1979/83 maps) is generally used to denote tidal flats, and UB (rather than OW) is used to represent open water.

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. 5). 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 1979/83 and 2004. In addition, water-regime modifiers (Table 1) and special modifiers were used for these years.

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 2, Fig. 7). Symbols for certain habitats changed after 1979; these changes are shown in Figure 7 and are noted in the section on trends in wetland and aquatic habitats.

Table 1. Water-regime descriptions defined by Cowardin et al. (1979).

Nontidal	***Water-Regime Symbols and Description***
(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
Tidal	
(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, freshwater systems.

Table 2. Wetland codes and descriptions from Cowardin et al. (1979). Codes listed below were used in mapping wetlands on the 2004 delineations, which varied in some cases from 1956 and 1979/83 maps (see Fig. 7).

NWI code (water regime)	NWI description	Common description	Characteristic vegetation
E1UBL (L)	Estuarine, subtidal unconsolidated bottom	Estuarine bays	Unconsolidated bottom
E1AB (L)	Estuarine, subtidal aquatic bed	Estuarine seagrass or algae bed	*Halodule wrightii* *Halophila engelmannii* *Ruppia maritima*
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	*Spartina alterniflora* *Spartina patens* *Distichlis spicata*
E2SS (P)	Estuarine, intertidal scrub-shrub	Estuarine shrubs	*Iva frutescens* *Baccharis halimifolia*
R1UB (V)	Riverine, tidal, unconsolidated bottom	Rivers	Unconsolidated bottom
R1AB	Riverine, tidal, aquatic bed	Rivers	Unknown submergent
R2UB (H)	Riverine, lower perennial, unconsolidated bottom	Rivers	Unconsolidated bottom
R2AB	Riverine, lower perennial, aquatic bed	Rivers	Unknown submergent
L1UB (H, V)	Lacustrine, limnetic, unconsolidated bottom	Lakes	Unconsolidated bottom
L2UB (H, V)	Lacustrine, littoral, unconsolidated bottom	Lakes	Unconsolidated bottom
L2US (K)	Lacustrine, littoral, unconsolidated shore	Lakes	Unconsolidated shore
L2AB (H, V)	Lacustrine, littoral, aquatic bed	Lake aquatic vegetation	*Nelumbo lutea* *Ruppia maritima*
PUB (F, H, K)	Palustrine, unconsolidated bottom	Pond	Unconsolidated bottom
PAB (F, H, K, T)	Palustrine, aquatic bed	Pond, aquatic beds	*Nelumbo lutea*
PEM (A, C, F, K, S, R, T, V)	Palustrine emergent	Freshwater marshes, meadows, depressions, or drainage areas	*Schoenoplectus californicus* *Typha spp.*
PSS (A, C, F, S, R)	Palustrine scrub-shrub	Willow thicket, river banks	*Salix nigra* *Parkinsonia aculeata* *Sesbania drummondii*
PFO (A, C, F, S, R, T, V)	Palustrine forested	Swamps, woodlands in floodplains depressions, meadow rims	*Salix nigra* *Fraxinus spp.* *Ulmus crassifolia* *Celtis spp.*

Examples of alphanumeric abbreviations used in the section on status of wetlands apply only to 2004 maps. Much of the following discussion of wetland systems, as defined by Cowardin et al. (1979), has been modified from White et al. (1993, 1998, 2002). Nomenclature and symbols (Appendix) in this discussion are based primarily on 1992 NWI maps.

Estuarine System

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

Emergent areas closest to estuarine waters consist of regularly flooded salt-tolerant grasses (low salt and brackish marshes) (E2EM1N). Along the upper coast, these communities are composed mainly 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 *Borrichia frutescens* (sea oxeye), *Spartina patens*, *Spartina spartinae* (gulf cordgrass), *Distichlis spicata*, *Fimbrystylis castanea* (marsh fimbry), *Aster* spp. (aster), and many others (Fig. 8).

Estuarine scrub-shrub wetlands (E2SS) are much less extensive than estuarine emergent wetlands. Representative plant species in irregularly flooded zones (E2SS1P) between emergent wetland communities and upland habitats include *Tamarix* spp. (salt cedar).

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.

Figure 8. *Spartina* spp. and *Andropogon glomeratus* (bushy bluestem) dominated high salt marsh (E2EM1P) transitional area at Anahuac NWR.

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

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 seasonally or permanently or semipermanently flooded (PUBC, PUBH, or PUBF). Tidally influenced ponds are identified as semipermanent- or permanent-tidal (PUBT and PUBV). Excavated or impounded ponds and borrow pits are labeled with their respective modifiers (PUBHx or PUBHh), and artificially flooded areas are labeled as 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. Tidally influenced emergent wetlands are identified as temporary-, seasonal-, semipermanent- , or permanent-tidal (PEMS, PEMR, PEMT, and PEMV).

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 (Fig. 9). 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. (panicgrass), *Polygonum* sp. (smartweed), and scattered *Andropogon glomeratus* (bushy bluestem), to mention a few.

Note that in many areas, field observations revealed the existence of small depressions or mounds with plant communities and moisture regimes that could not 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. Palustrine scrub-shrub wetlands that were mapped are typically temporarily flooded (PSS1A) or seasonally flooded (PSS1C) and may include *Tamarix* spp., *Baccharis* sp., and *Iva frutescens*.

Palustrine forested areas consist primarily of broad-leaved deciduous, temporarily (PFO1A), seasonally (PFO1C), and semipermanently flooded (PFO1F) forested areas and needle-leaved deciduous semipermanently flooded (PFO2F) forested areas. Forests incorporate a large mixture of tree species, including *Liquidambar styraciflua* (sweetgum), *Quercus* spp. (oak), *Salix nigra* (black willow), *Ulmus crassifolia* (cedar elm), *Fraxinus* spp. (ash), *Celtis spp*. (hackberry), and others. Swamp areas are predominately *Taxodium distichum* (bald cypress) and *Nyssa aquatica* (water tupelo) (Figs. 10–12).

Figure 9. Palustrine marsh along flooded sand quarry pits near Ross Ridge. The dominant vegetation is *Tyhpa* sp. (cattail).

Figure 10. Palustrine forest (PFO1C) on the banks of Hillebrandt Bayou. The dominant vegetation is *Taxodium distichum* (bald cypress).

Figure 11. *Taxodium distichum* (bald cypress) downstream from previous photo. Note root structures (cypress knees) at the water surface.

Figure 12. Palustrine forest (PFO1C) on North Taylor Bayou. Vegetation is dominated by *Taxodium distichum* (bald cypress) and *Sabal minor* (dwarf palmetto).

Lacustrine System

Water bodies greater than 8 ha are included in this system, with both limnetic and littoral subsystems represented. Nonvegetated water bodies are labeled limnetic or littoral unconsolidated bottom (L1UB or L2UB) (L1OW or L2OW in 1956 and 1979/83 data sets), depending on water depth. Bodies of water with vegetation are classified in the subclass of algal (L2AB1), floating (L2AB4) or unknown (L2AB5) 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 are diked or leveed and water levels are affected by water associated with pumped, disposed sediments.

Riverine System

Two riverine subsystems occur in the study area: tidal (R1) and lower perennial (R2). Major rivers/streams composing the fluvial-deltaic system are the Sabine and Neches Rivers and Taylor Bayou.

FLUVIAL-DELTAIC AND BAY-ESTUARY SYSTEMS

Study Area

The bay-estuary system along the upper Texas coast contains the most extensive contiguous marshland along the Texas Gulf Coast. Most of the marshland falls within the McFaddin NWR, Texas Point NWR, J. D. Murphree WMA, and Sea Rim State Park (Fig. 13). Extensive brackish- and salt-water marshes and ponds characterize the area gulfward of the GIWW. Most freshwater marshes in the area occur inland of the GIWW.

General Setting of Fluvial-Deltaic and Bay-Estuary Systems

Geologically the upper Texas coast is characterized by a modern bay-estuary system formed around Sabine Lake and the fluvial-deltaic systems containing the Sabine and Neches Rivers (Fig. 14) (Fisher et al., 1973). Relict Pleistocene-age river valleys that were not filled with Holocene-Modern fluvial-deltaic sediments form present-day bays and estuaries (White et al., 1987). Flood-prone areas inland from the bays are the site of salt, brackish, and freshwater wetlands. Faults have had a significant impact on wetlands in the Beaumont-Port Arthur area. The study area extends landward from the GIWW to the GLO coastal management zone boundary.

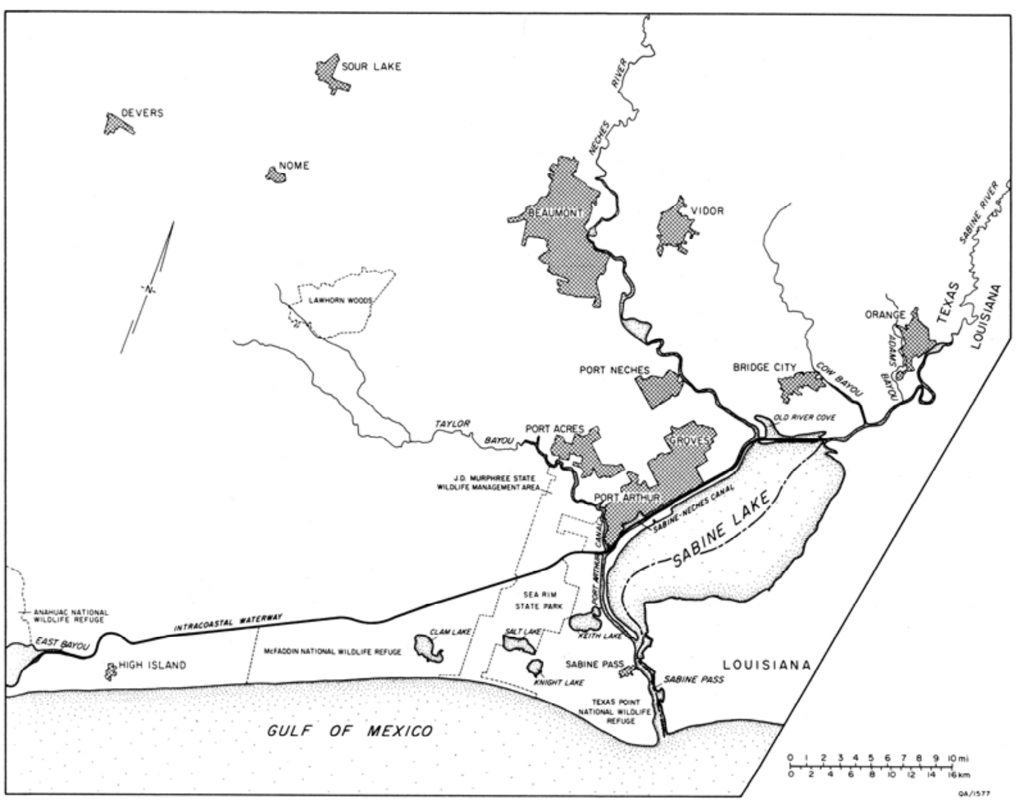

Figure 13. Location of Federal and State refuges, parks, and management areas. From White et al. (1987).

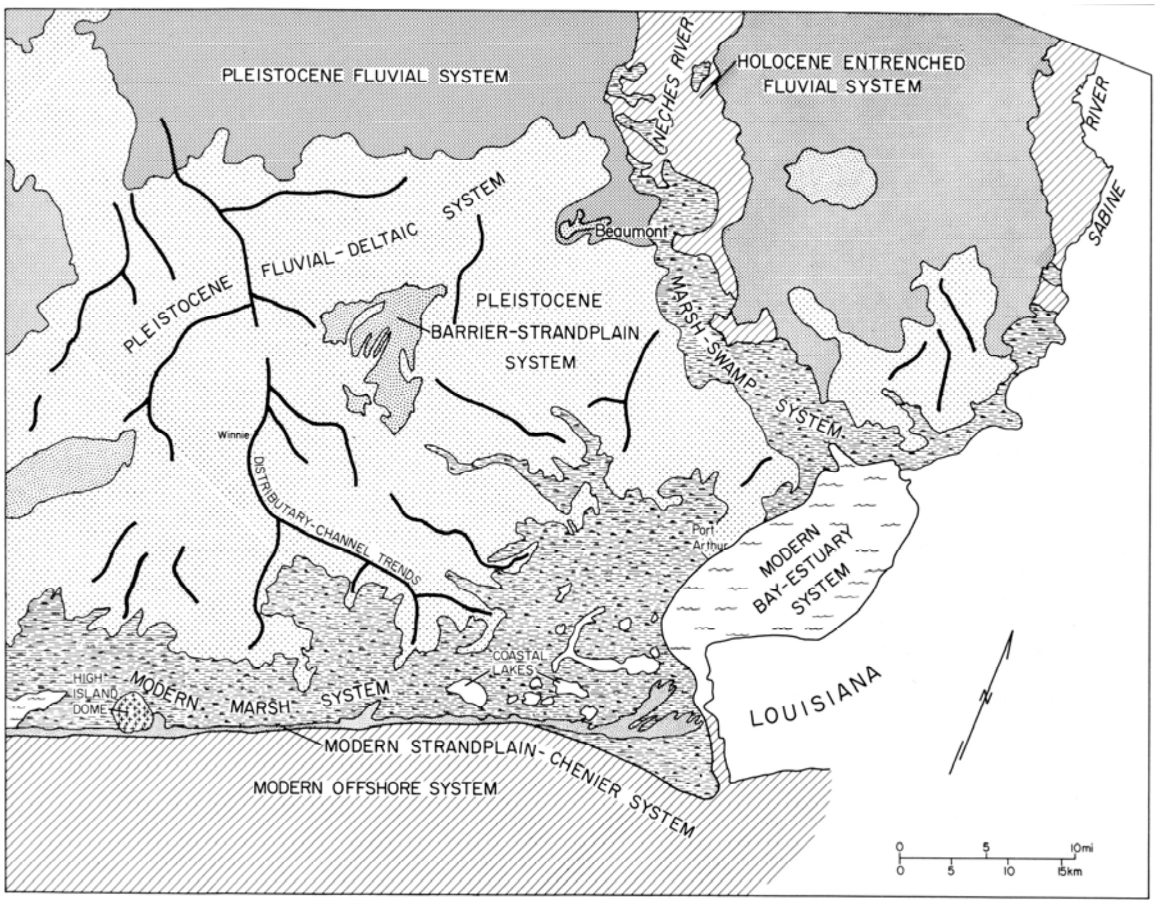

Figure 14. Modern bay-estuary and fluvial-deltaic systems along the upper Texas coast. From Fisher et al. (1973).

Relative Sea-Level Rise

An 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 groundwater 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. 15). Rates of sea-level rise recorded by the tide gauge reached a high of 1.9 cm/yr from 1963 to mid-1975. The mean sea-level trend at Sabine Pass is approximately 6.54 mm/yr (Fig. 16). 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 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).

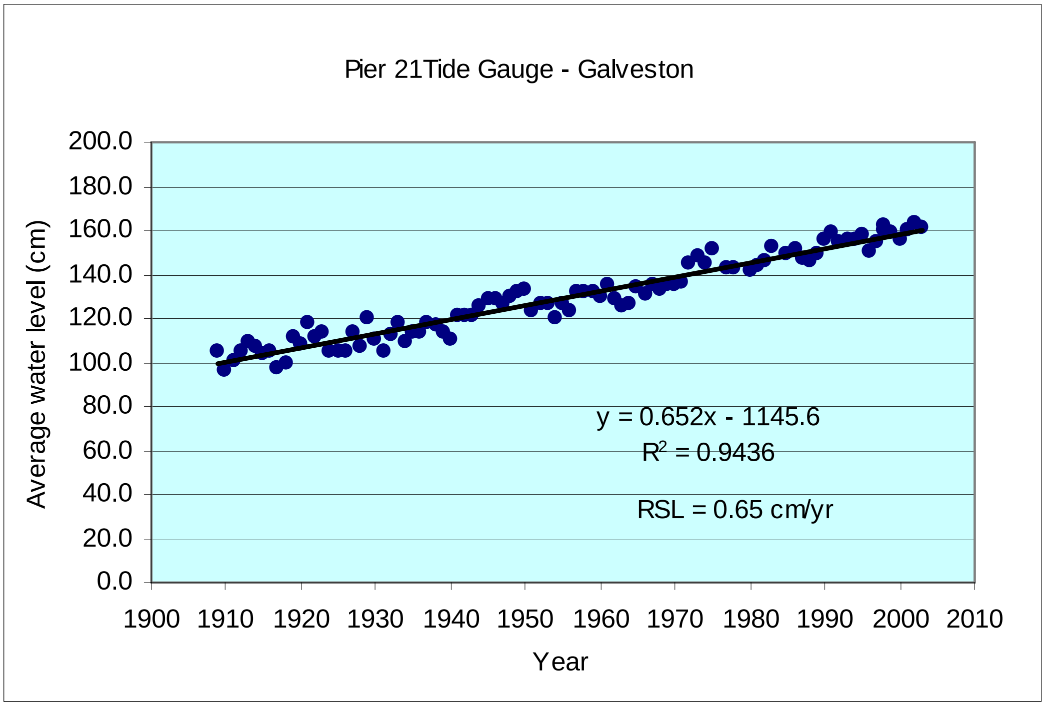

Figure 15. Tide gauge record at Pier 21, Galveston. The average rate of sea-level rise from 1909 to 2003 was 0.65 cm/yr. The highest short-term rate (1963–1975) was 1.92 cm/yr. Data from NOAA National Ocean Service.

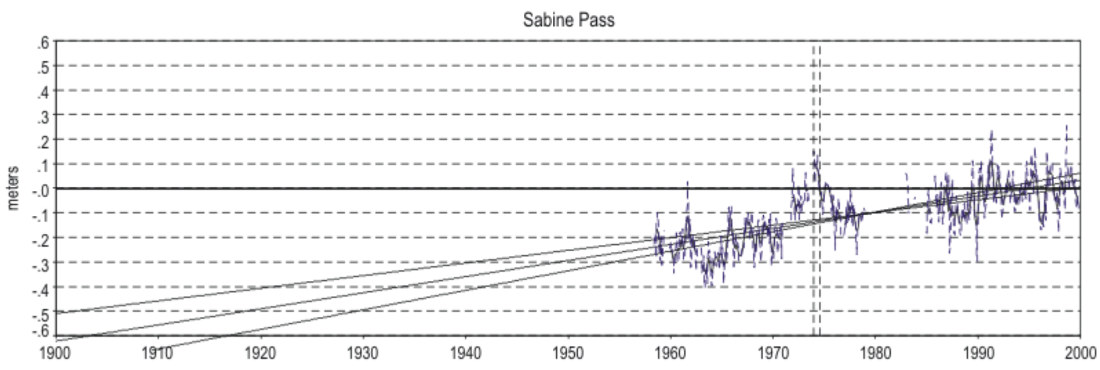

Figure 16. Mean sea-level trend at Sabine Pass. The trend is 6.54 mm/yr (2.15 ft per century), with a standard error of 0.72 mm/yr that is based on monthly mean sea-level data from 1958 to 1999. Station 8770570. Data from NOAA.

Subsidence

Subsidence of varying amounts has occurred along the entire Texas coast, including the Beaumont-Port Arthur area, where land-surface subsidence between 1918 and 1977 was generally less than 0.15 m. A subsidence "bowl" with over 4 m of subsidence near its center, has formed southeast of Beaumont (Figs. 17, 40). Localized subsidence occurred between 1925 and 1977 as a result of oil and gas, associated water, and sulfur withdrawal. The subsidence bowl centered on Spindletop Dome encompasses over 2,000 ha, where almost 40 ha of lakes, not present in 1956, had formed near the center of the bowl by 2004.

The causes of subsidence are many, including regional downwarping or tilting of the Earth's crust because of loading, which is significant over a geologic time frame along the Texas coast but not over a historic time frame (Winker, 1979). Within a historic time frame, the cause of subsidence in the Spindletop Dome area is primarily oil and gas production that began in the early part of the 20th century and secondarily to sulfur mining (Ratzlaff, 1980).

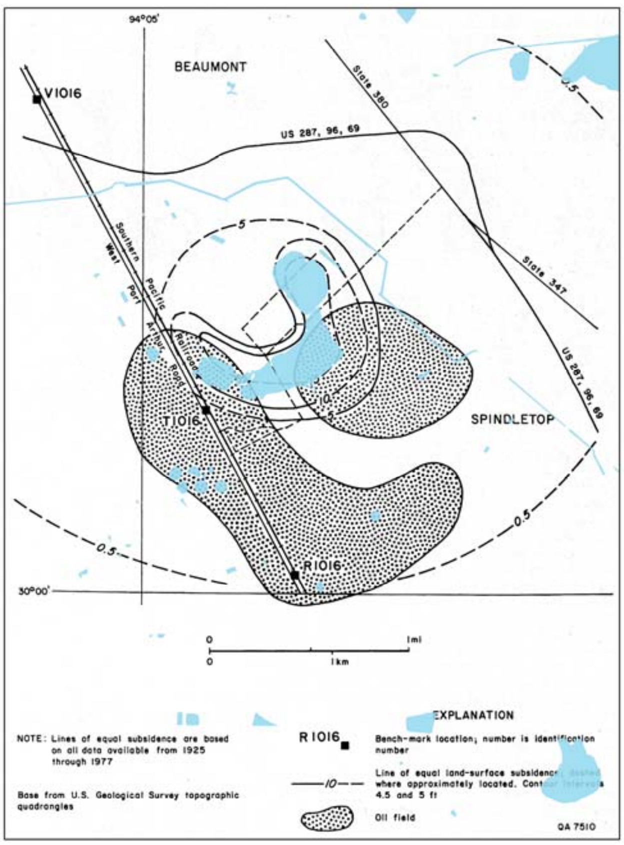

Figure 17. Spindletop Dome area subsidence from 1925 to 1977 caused primarily by groundwater and hydrocarbon withdrawal. Maximum subsidence by 1977 was near 15 ft at the center of the subsidence bowl southeast of Beaumont. Blue areas are open water mapped in 2004. After Ratzlaff (1980).

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 difference 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, airfield runways, and other features. Millions of dollars of damage is 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. 18) (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. 19) (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 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 faults in the Houston-Galveston area occur within the subsidence bowl caused by groundwater 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).

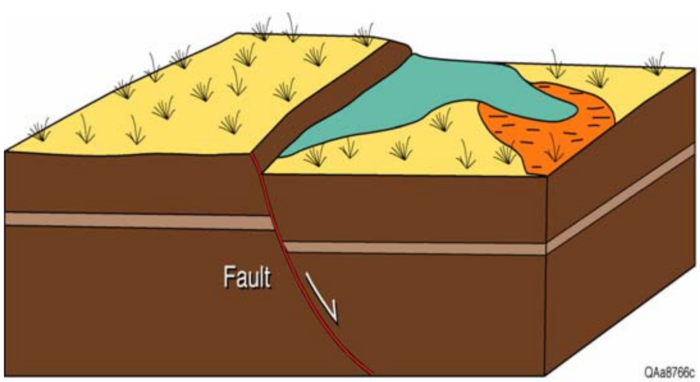

Figure 18. Diagram illustrating changes in wetlands along an active surface fault. Low marshes and ponded water generally increase on the side of the fault that is moving downward. From White and Tremblay (1995).

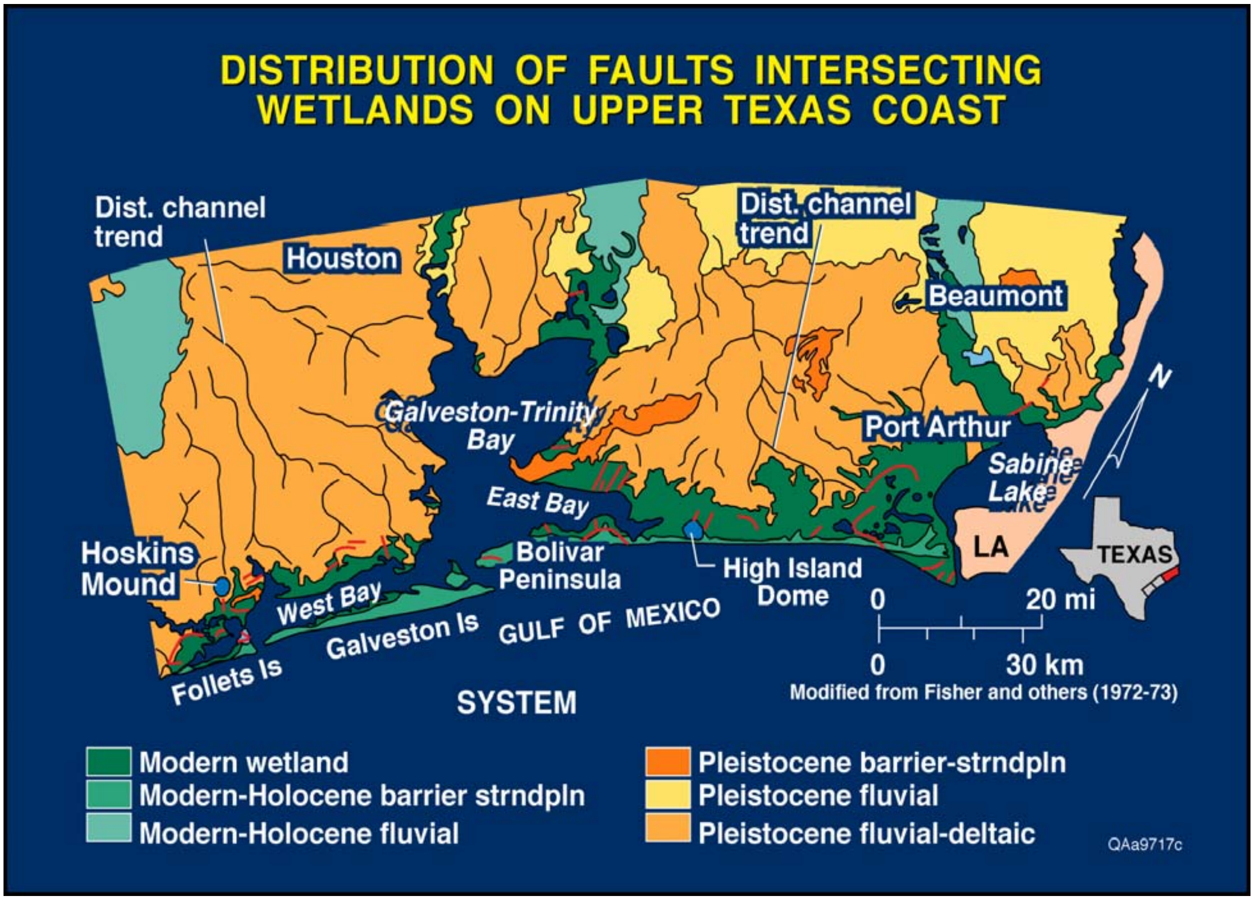

Figure 19. Surface faults, shown in red, that intersect marshes between Follet's Island and the Louisiana border. The faults were mapped from sequential aerial photographs. Only about 25% of the faults were visible on photographs taken in the 1930's, but the remaining 75% could be seen on later photographs, indicating that they have become active since the 1930's. From White and Morton (1997).

Many faults are not visible on historical photographs but are visible on more recent photographs, indicating that they have become active recently. Other lines of evidence of fault activity are (1) recurring 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 releveling profiles.

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; 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 replacement of parts 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.

Water and low marshes increase on the downthrown (D) side of the faults relative to the upthrown side (U), indicating higher rates of subsidence on the downthrown side. Relative sea-level rise on the downthrown sides is apparently exceeding rates of marsh vertical accretion.

Status of Wetlands and Aquatic Habitats, 2004

As mentioned previously, the bay-estuary system in Beaumont-Port Arthur is part of the most extensive contiguous marshland along the Texas Gulf Coast. Major palustrine habitats in the study area include freshwater marsh, forest, and open water. Estuarine marshes are more limited (Figs. 20, 21). Most freshwater marshes apparently occur inland of the GIWW (Dean Bossert, McFaddin NWR Manager, Personal Communication, 2006).

In 2004, wetland and aquatic habitats were dominated by palustrine marshes, with a total area of 35,876 ha, followed by estuarine open water and flats totaling 18,043 ha and palustrine forest and scrub-shrub at 12,316 ha (Fig. 20; Tables 3, 4). Estuarine marsh and scrub-shrub had a total area of 8,759 ha. Freshwater habitats, consisting of lacustrine, riverine, and palustrine habitats, had a total area of 10,580 ha. The study area was subdivided into geographic areas—Sabine River, Neches River, Sabine Lake, Taylor Bayou, Spindletop Marsh, and Anahuac—to provide for a more site-specific analysis of status and trends (Figs. 22, 23; Table 5).

Estuarine System

Marshes (Estuarine Intertidal Emergent Wetlands)

The estuarine intertidal emergent wetland habitat (E2EM) consists of 8,759 ha of salt and brackish marshes (Figs. 20, 21). The irregularly flooded estuarine marsh, or high marsh, is most abundant at 5,415 ha (Tables 3, 4). The regularly flooded estuarine marsh, or low marsh, covers 3,287 ha. The most extensive estuarine emergent wetlands (salt and brackish marshes) occur in the Anahuac NWR (Figs. I, 21). The estuarine intertidal marsh habitat makes up about 10% of the study area, excluding the upland map unit.

Tidal Flats (Estuarine Intertidal Unconsolidated Shores)

Estuarine intertidal unconsolidated shores (E2US) include tidal flats and algal flats. Approximately 9 ha of E2US was mapped in the study area (Table 3). Low, regularly flooded tidal flats are more prevalent than high flats. Because of the low astronomical tidal range, many flats are flooded only by wind-driven tides. These tidal habitats represent a negligible percent of the intertidal wetland system (excluding subtidal habitats and the E1 map unit). The mapped extent of the tidal flats can be affected by tidal levels at the time that aerial photographs were taken. Accordingly, absolute areal extent of flats may vary from that determined using aerial photographs.

Aquatic Beds (Estuarine Subtidal Aquatic Beds)

Estuarine subtidal aquatic beds (E1AB5) represent areas of unknown submerged vegetation. Accurate delineation of submerged vegetation on aerial photographs depends on the season in which the photographs were taken and water turbidities, which can obscure submerged vegetation areas. About 103 ha of unknown submerged vegetation was mapped in the bay-estuary system.

Open Water (Estuarine Subtidal Unconsolidated Bottom)

Estuarine subtidal unconsolidated bottom (E1UBL), or open water, includes water features across the bay-estuary system that are not completely isolated from wind tides and storm tides. Part of the GIWW and other channels and Sabine Lake waters are included. The total area of estuarine open water is 18,043 ha, which is about 21% of all mapped habitats in the study area, excluding uplands.

Table 3. Areal extent of mapped wetland and aquatic habitats, 2004.

NWI Code	National Wetlands Inventory Description	Hectares	Acres	%
E1AB4	Estuarine Subtidal Aquatic Bed, Floating Vascular	0	1	0
E1AB5	Estuarine Subtidal Aquatic Bed, Unknown Submergent	103	255	0
E1AB6	Estuarine Subtidal Aquatic Bed, Unknown Surface	2	5	0
E1UB	Estuarine Subtidal Unconsolidated Bottom	17,937	44,305	21
E2EM1N	Estuarine Intertidal Emergent Wetland, Regularly Flooded	3,287	8,119	4
E2EM1P	Estuarine Intertidal Emergent Wetland, Irregularly Flooded	5,415	13,375	6
E2SS	Estuarine Intertidal Scrub-Shrub	57	141	0
E2USM	Estuarine Intertidal Flat, Irregularly Exposed	5	12	0
E2USN	Estuarine Intertidal Flat, Regularly Flooded	1	3	0
E2USP	Estuarine Intertidal Flat, Irregularly Flooded	3	7	0
Subtotal		**26,811**	**66,223**	**31**
L1UB	Lacustrine Limnetic Unconsolidated Bottom	1,271	3,140	1
L2AB1	Lacustrine Littoral Aquatic Bed, Algal	178	440	0
L2AB4	Lacustrine Littoral Aquatic Bed, Floating Vascular	42	103	0
L2AB5	Lacustrine Littoral Aquatic Bed, Unknown Submergent	144	356	0
L2UB	Lacustrine Littoral Unconsolidated Bottom	155	384	0
L2UBF	Lacustrine Littoral Unconsol Bottom, Semipermanently Flooded	836	2,064	1
L2UBK	Lacustrine Littoral Unconsol Bottom, Artificially Flooded	1,224	3,023	1
L2USK	Lacustrine Littoral Flat, Artificially Flooded	338	835	0
Subtotal		**4,188**	**10,344**	**5**
PAB1F	Palustrine Aquatic Bed, Algal, Semipermanently Flooded	46	115	0
PAB1K	Palustrine Aquatic Bed, Algal, Artificially Flooded	319	789	0
PAB4F	Palustrine Aquatic Bed, Floating Vascular	303	748	0
PAB5	Palustrine Aquatic Bed, Unknown Submergent	163	402	0
PEM1A	Palustrine Emergent Wetland, Temporarily Flooded	4,579	11,310	5
PEM1C	Palustrine Emergent Wetland, Seasonally Flooded	21,358	52,754	25
PEM1F	Palustrine Emergent Wetland, Semipermanently Flooded	5,784	14,286	7
PEM1K	Palustrine Emergent Wetland, Artificially Flooded	2,351	5,808	3
PEM1R	Palustrine Emergent Wetland, Seasonal-Tidal	1,196	2,954	1
PEM1S	Palustrine Emergent Wetland, Temporary-Tidal	31	76	0
PEM1T	Palustrine Emergent Wetland, Semipermanent-Tidal	529	1,306	1
PEM1V	Palustrine Emergent Wetland, Permanent-Tidal	48	119	0
PFO1A	Palustrine Forested, Broad-Deciduous, Temp Flooded	5,438	13,432	6
PFO1C	Palustrine Forested, Broad-Deciduous, Seasonally Flooded	2,803	6,924	3
PFO1F	Palustrine Forested, Broad-Deciduous, Semiperm Flooded	2,085	5,150	2
PFO1R	Palustrine Forested, Broad-Deciduous, Seasonal-Tidal	79	195	0
PFO1S	Palustrine Forested, Broad-Deciduous, Temporary-Tidal	74	182	0
PFO1T	Palustrine Forested, Broad-Deciduous, Semiperm-Tidal	13	32	0
PFO1V	Palustrine Forested, Broad-Deciduous, Permanent-Tidal	1	3	0
PFO2C	Palustrine Forested, Needle-Deciduous, Seasonally Flooded	13	32	0
PFO2F	Palustrine Forested, Needle-Deciduous, Semiperm Flooded	940	2,321	1

PFO2R	Palustrine Forested, Needle-Deciduous, Seasonal-Tidal	5	13	0
PFO4A	Palustrine Forested, Needle-Evergreen, Temp Flooded	38	95	0
PSS1A	Palustrine Scrub-Shrub, Broad-Deciduous, Temp Flooded	386	953	0
PSS1C	Palustrine Scrub-Shrub, Broad-Deciduous, Season Flooded	340	840	0
PSS1F	Palustrine Scrub-Shrub, Broad-Decid, Semiperm Flooded	11	27	0
PSS1R	Palustrine Scrub-Shrub, Broad-Deciduous, Seasonal-Tidal	77	191	0
PSS1S	Palustrine Scrub-Shrub, Broad-Deciduous, Temporary-Tidal	9	23	0
PSS2C	Palustrine Scrub-Shrub, Needle-Deciduous, Season Flooded	3	6	0
PUB	Palustrine Unconsolidated Bottom	170	420	0
PUBC	Palustrine Unconsolidated Bottom, Seasonally Flooded	64	157	0
PUBF	Palustrine Unconsolidated Bottom, Semipermanently Flooded	151	372	0
PUBH	Palustrine Unconsolidated Bottom, Permanently Flooded	1,500	3,704	2
PUBK	Palustrine Unconsolidated Bottom, Artificially Flooded	61	152	0
PUBT	Palustrine Unconsolidated Bottom, Semipermanent-Tidal	4	9	0
PUBV	Palustrine Unconsolidated Bottom, Permanent-Tidal	17	41	0
PUS	Palustrine Flat	18	45	0
PUSC	Palustrine Flat, Seasonally Flooded	20	49	0
PUSK	Palustrine Flat, Artificially Flooded	58	143	0
Subtotal		**51,084**	**126,178**	**60**
R1AB5	Riverine Tidal Aquatic Bed, Unknown Submergent	2	4	0
R1UBV	Riverine Tidal Unconsolidated Bottom, Permanent-Tidal	1,272	3,141	1
R2AB5	Riverine Lower Perennial Aquatic Bed, Unknown Submergent	5	12	0
R2UBH	Riverine Lower Perennial Unconsol Bottom, Perm Flooded	2,220	5,483	3
Subtotal		**3,498**	**8,641**	**4**
Total		**85,581**	**211,386**	**100**

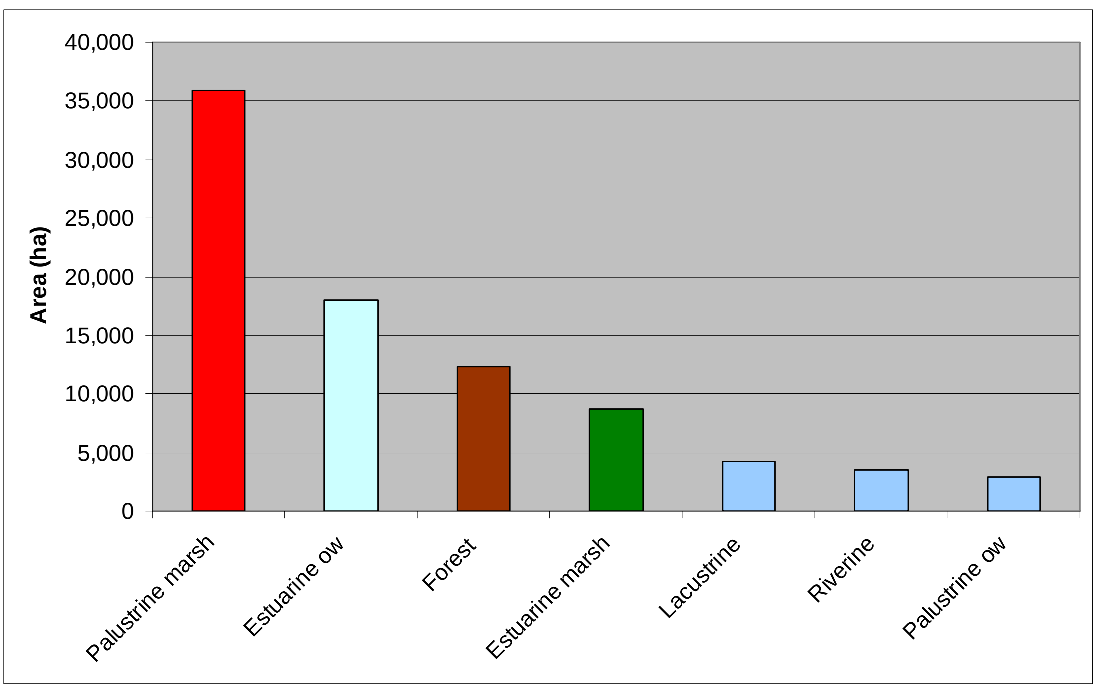

Figure 20. Areal distribution of selected habitats in the study area in 2004.

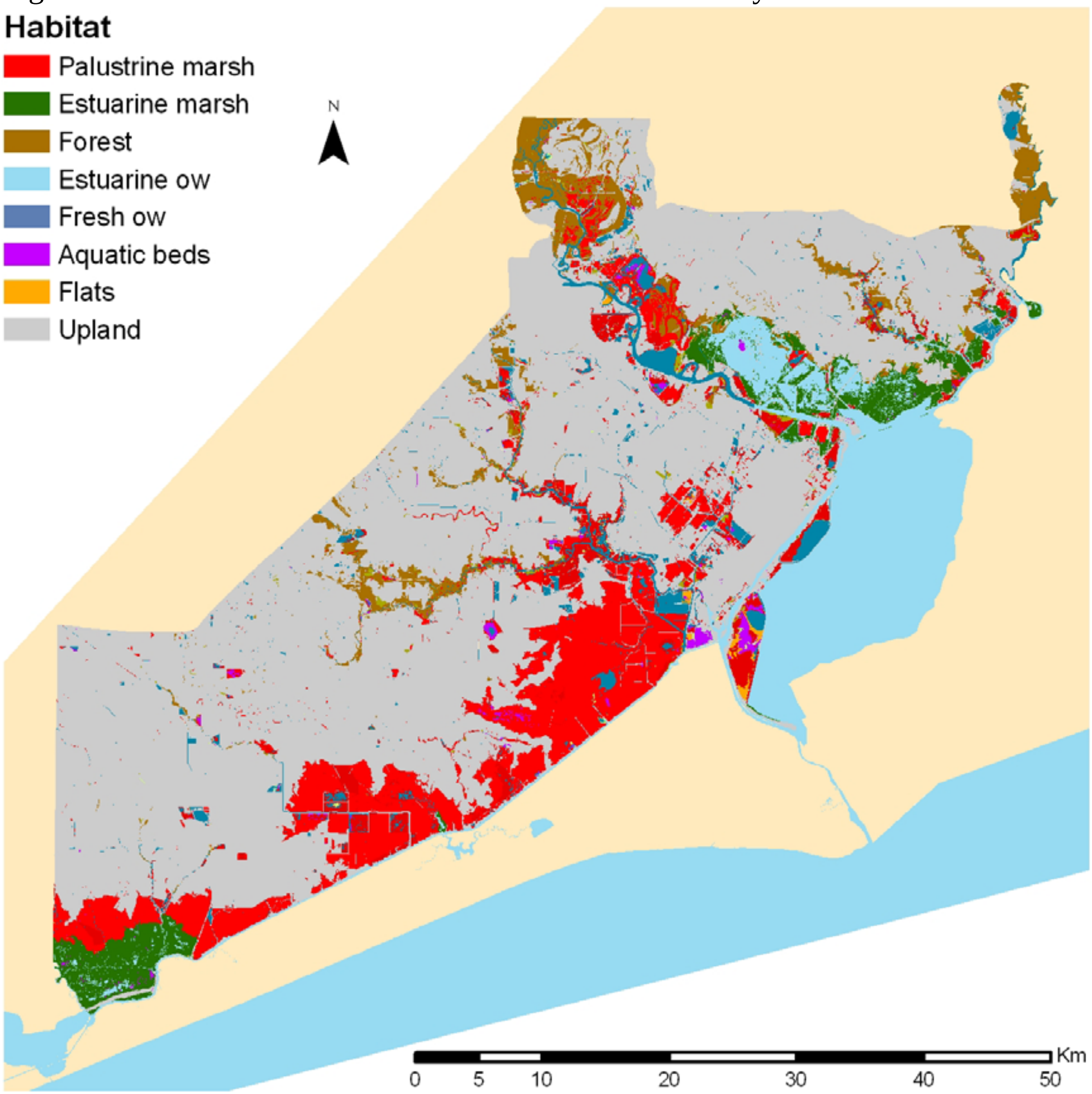

Figure 21. Distribution of major habitats in 2004.

Table 4. Areal extent (ha) of selected habitats, 2004.

Habitat	*Area (ha)*
Palustrine marsh	35,876
Estuarine open water	18,043
Forest	12,316
Estuarine marsh	8,759
Lacustrine open water/flat	4,188
River	3,491
Palustrine open water	2,900

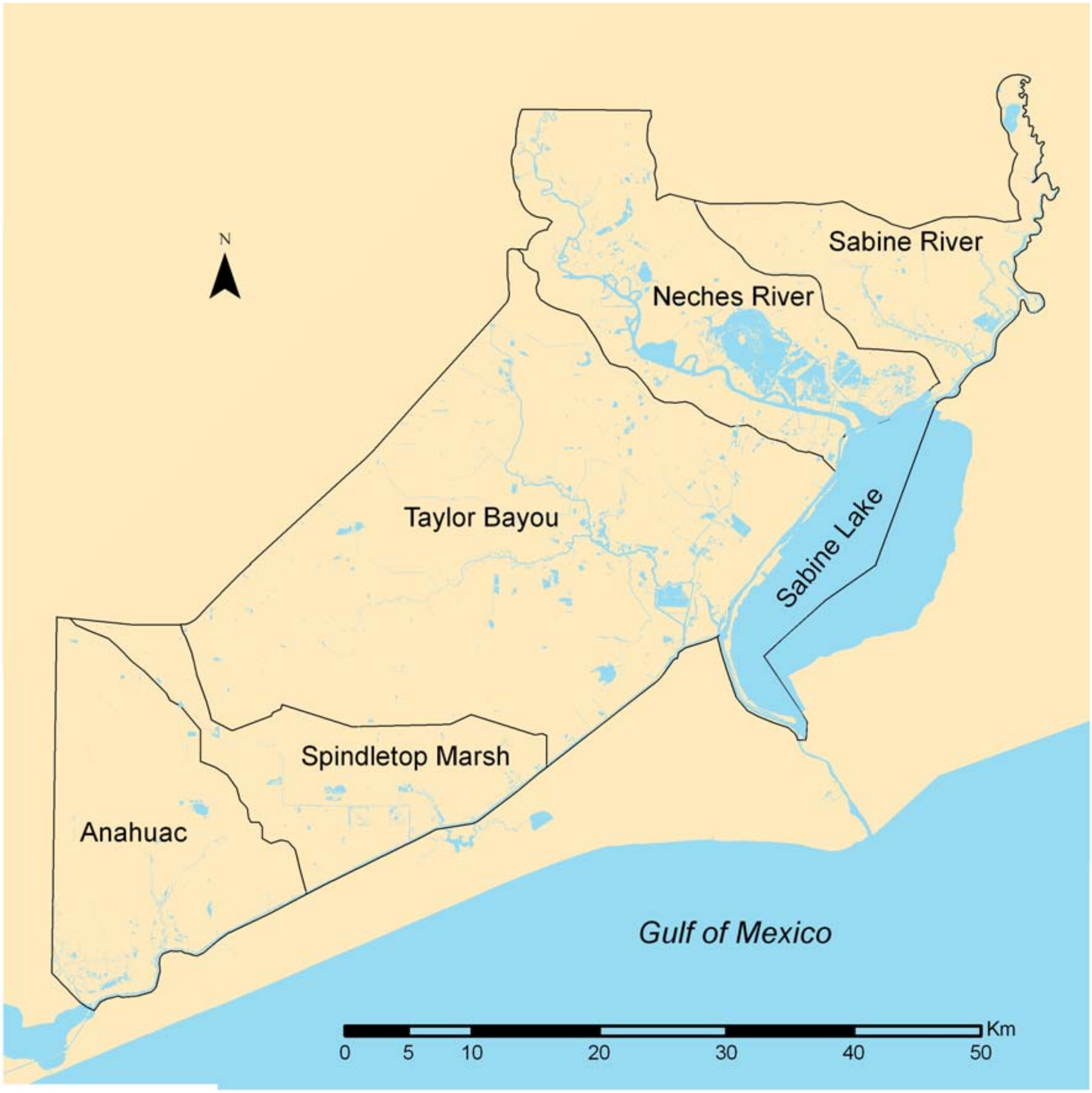

Figure 22. Map showing boundaries of different geographic areas investigated.

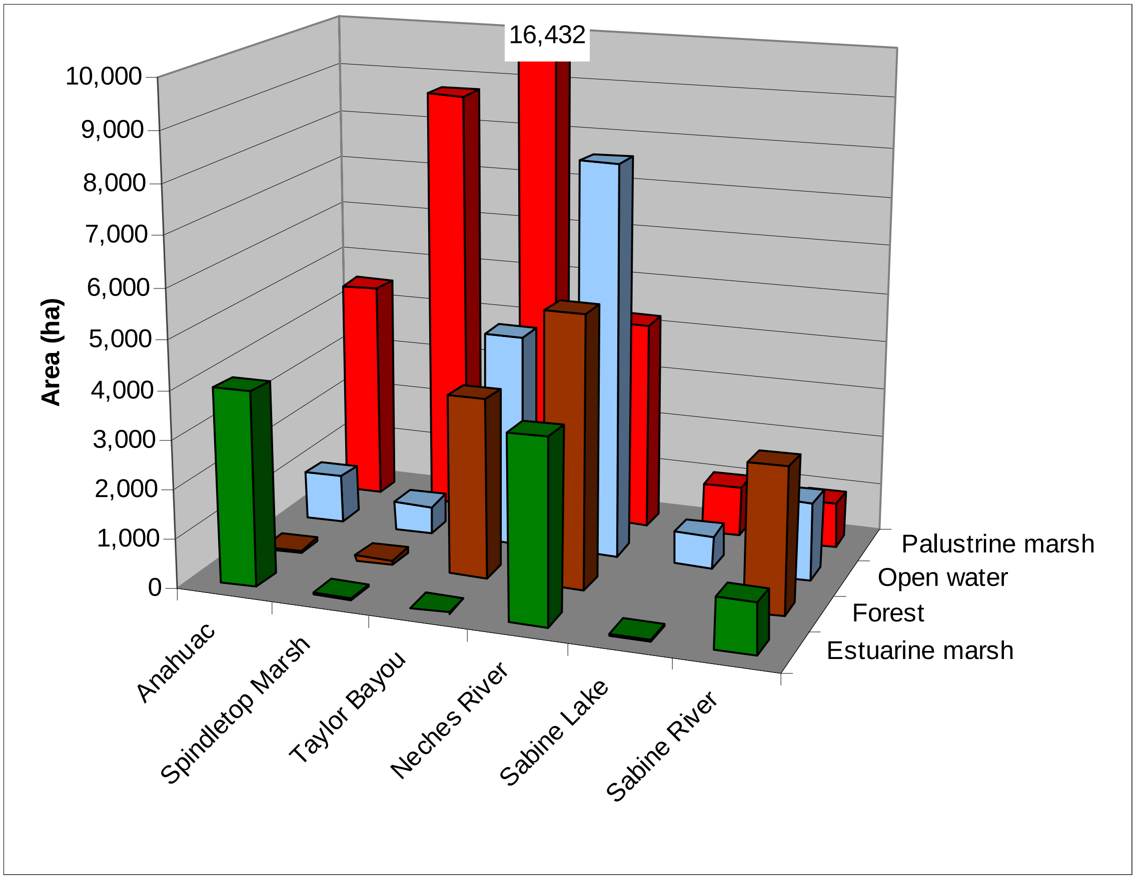

Figure 23. Areal distribution of selected habitats by geographic area in 2004. The most extensive distribution of palustrine marsh is in Taylor Bayou.

Table 5. Areal extent (in hectares) of selected habitats by geographic area, 2004.

Location	***Palustrine marsh***	***Open water***	***Forest***	***Estuarine marsh***	**Total**
Taylor Bayou	16,432	4,344	3,633	9	**24,418**
Neches River	4,279	8,002	5,530	3,698	**21,508**
Anahuac	4,513	989	56	3,943	**9,502**
Spindletop Marsh	8,737	575	113	48	**9,473**
Sabine River	923	1,603	2,965	1,021	**6,512**
Sabine Lake	1,050	665	0	41	**1,756**

Palustrine System

Marshes (Palustrine Emergent Wetlands)

Palustrine emergent wetlands (PEM), or “freshwater marshes,” cover 35,876 ha (Fig. 20; Table 4) and represent 63% of vegetated wetlands (EM + SS+FO). Typically, palustrine marshes were classified into one of four water regimes: (1) temporarily flooded, (2) seasonally flooded, (3) semipermanently flooded, and (4) artificially flooded. Tidally influenced marshes were also classified.

Forest (Palustrine Forested and Scrub-Shrub Wetlands)

Palustrine forested wetlands (PFO), comprising fluvial woodlands and swamps, cover an area of 11,490 ha (Fig. 20; Table 4). Forests were primarily classified into broad- and needle-leaved deciduous trees. Palustrine scrub-shrub (PSS) habitat covers 826 ha. Owing to difficulty in distinguishing forest regrowth from scrub-shrub, the two classes were combined for analysis.

Open Water and Flat (Palustrine Unconsolidated Bottom and Shore)

Palustrine unconsolidated bottom (PUB), or open water, including unknown and floating aquatic beds, and palustrine unconsolidated shore (PUS) or flat habitats are generally small, fresh- to brackish-water ponds and flats. The total mapped area of these habitats was 2,900 ha, almost 52% of which was water in permanently flooded channels and reservoirs (Table 3).

Lacustrine and Riverine Systems

Open Water and Flat (Lacustrine Unconsolidated Bottom and Shore)

Lacustrine unconsolidated bottom (L1UB), or lakes, and lacustrine unconsolidated shore (L2US), or flat, include lakes and inland reservoirs greater than 20 acres (8.33 ha). Lakes and flats associated with lakes cover 4,188 ha. Lakes are further classified according to depth—roughly 20% of the lacustrine habitat is reservoir of 6 ft or greater depth.

River (Riverine Tidal and Lower Perennial)

Riverine tidal unconsolidated bottom (R1UB) and lower perennial unconsolidated bottom (R2UB), or rivers, cover 3,491 ha. Lower perennial rivers compose about 64% of all rivers in the study area.

Historical Trends in Wetland and Aquatic Habitats

In analyzing trends, broad wetland classes were emphasized over water regimes and special modifiers because habitats were mapped only down to class on 1956 photographs. In addition, interpretation of the distribution of estuarine and palustrine systems varied from year to year. Palustrine marshes are by far the dominant class of emergent wetlands in the study area; thus, for simplification and to reduce apparent changes due to interpretation, we combined emergent wetland classes in the trend analysis. Also, because the areal extent of tidal flats and estuarine water varies with tidal conditions, we combined water and flats into a single unit for analysis of trends partly because flats interpreted and mapped in 1979/83 were more extensive than in 1956 and 2004. Tide levels at the time the photos were taken may have contributed to this difference in mapped tidal flats. As noted previously, a cumulative error 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 in absolute magnitudes.

General Trends

The total area of estuarine marshes increased from 7,064 ha in 1956 to 9,353 ha in 1979, then decreased to 8,759 ha in 2004 (Figs. 24, 25; Table 6). Palustrine marsh showed a systematic decline from 37,040 ha in 1956 to 36,033 ha in 1979 and 35,876 ha in 2004. Accompanying the gain of marsh was a gain in total estuarine open water. The gain in open water was approximately 2,074 ha. Rates of change in open water were about a 139 ha/yr gain during the earlier period and a (–)45 ha/yr loss during the later period. The long-term (1956–2004) rate of estuarine open-water gain is 43 ha/yr. Forest experienced a long-term decrease in area of 7,190 ha. The 1956 total of 19,506 ha was reduced to 11,335 ha in 1979/83, with a rebound by 2004 to 12,316 ha. Change rates of –355 ha/yr for the early period was followed by +39 ha/yr during the later period. The overall (1956–2004) change rate was a loss of 150 ha/yr.

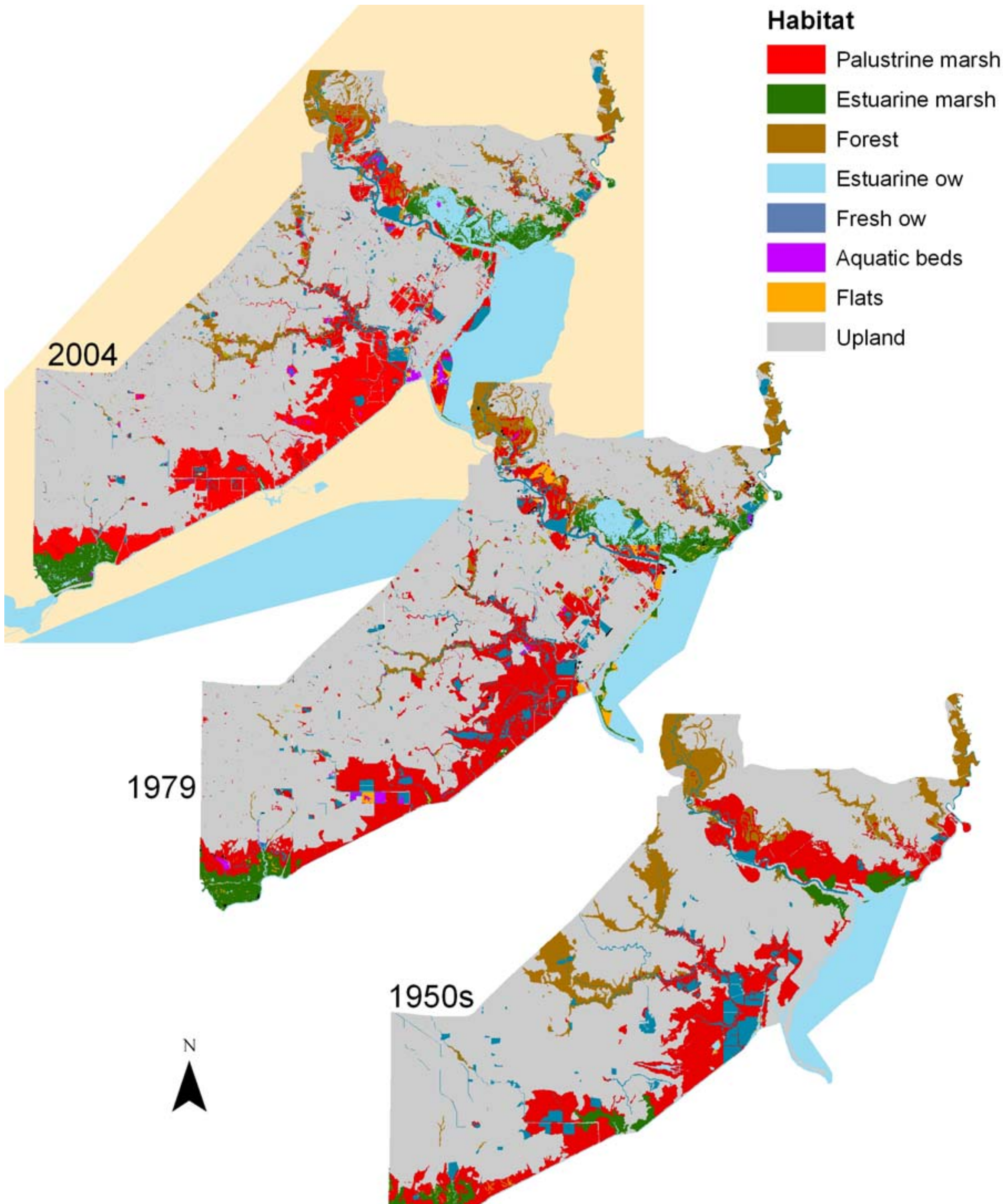

Figure 24. Map showing distribution of major wetland and aquatic habitats in 2004, 1979/83, and 1956 in the upper coast study area.

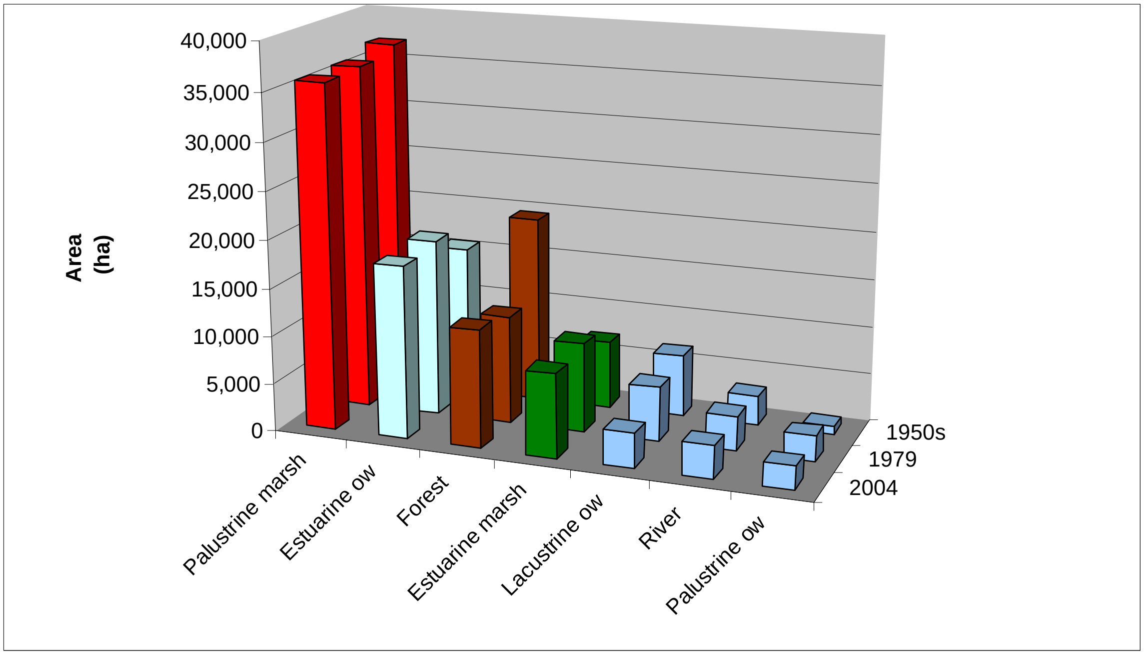

Figure 25. Areal distribution of habitats in the study area in 1956, 1979/83, and 2004.

Table 6. Total area (ha) of major habitats in 1956, 1979/83, and 2004.

Habitat	1950's		1979/83		2004	
	ha	acres	ha	acres	ha	acres
Palustrine marsh	37,040	91,489	36,033	89,002	35,876	88,614
Estuarine ow	15,603	38,539	18,518	45,740	18,043	44,566
Forest	19,506	48,180	11,335	27,998	12,316	30,421
Estuarine marsh	7,064	17,448	9,353	23,101	8,759	21,635
Lacustrine ow	6,508	16,075	5,714	14,114	3,672	9,069
River	3,062	7,563	3,653	9,023	3,491	8,624
Palustrine ow	828	2,045	2,580	6,373	2,439	6,025

Analysis of trends in wetlands and aquatic habitats in the bay-estuary system shows that there was a slight net increase (~1%) in marshes from 1956 to 2004. From 1956 through 2004, emergent wetlands (marshes) increased from about 44,104 to 44,635 ha, a gain of approximately 531 ha (Fig. 26; Table 7). Marsh area fluctuated through the study time period. The rate of marsh gain from 1956 to 1979 was 56 ha/yr (138 acres/yr), and from 1979 to 2004 marsh lost about (–)30 ha/yr (74 acres/yr). The long-term (1956–2004) change rate of marsh was a gain of 11 ha/yr.

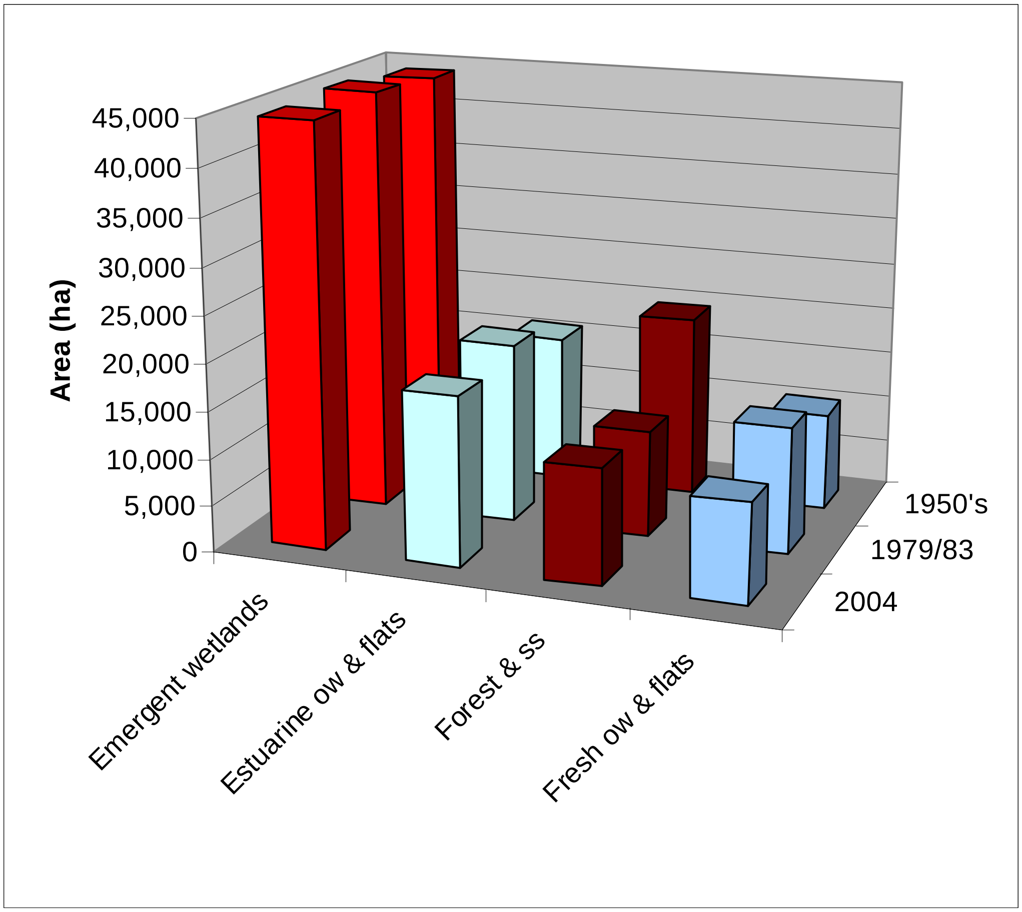

Figure 26. Areal distribution of combined major habitats in the study area in 1956, 1979/83, and 2004. Emergent wetlands include estuarine and palustrine marshes and estuarine scrub-shrub assemblages.

Table 7. Total area (ha) of combined major habitats in 1956, 1979/83, and 2004.

Habitat	*1956*	*1979/83*	*2004*
Emergent wetlands	44,104	45,386	44,635
Saltwater and flats	15,978	19,177	18,052
Forest and scrub-shrub	19,506	11,335	12,316
Freshwater and flats	10,397	13,433	10,580

Probable Causes of Trends

An analysis of habitat changes along the upper Texas coast shows an increase in marshes from 1956 to 2004 (Fig. 26). Overlay analysis of the 1956 and 2004 maps to identify the cause of the changes shows that about 78% of the increase in estuarine marsh (E2EM) was due to conversion from palustrine marsh (PEM), and a smaller amount to upland (13%). The conversion to estuarine marsh since 1956 was partly due to relative sea-level rise and canal and reservoir construction and partly to interpretational differences. Palustrine marsh was replaced primarily by uplands (37%) and estuarine marsh (24%). In many instances, areas previously mapped as palustrine marsh have been replaced by invasive Chinese tallow (*Triadica sebifera*). Disturbance caused by development has altered growing conditions, making the habitat more suitable for invasive species. Relative sea-level rise and dredging of canal systems allows more frequent inundation by saltwater, promoting the spread of salt-tolerant species. Estuarine marsh increased in the Anahuac NWR and in the Neches and Sabine River estuaries. Estuarine open water increased since 1956 partly because of drier conditions in 1956. A severe drought in Texas that peaked in 1956 (Riggio et al., 1987) apparently affected the extent of open water in the marshes on 1956 maps. Part of the expansion of open water since 1956 was due to subsidence and relative sea-level rise. In several areas, subsidence occurred along active surface faults. The faults contributed to an increase in water in the marshes on downthrown sides of the faults (Figs. 38–41). Forests experienced the most change during the early time period between 1956 and 1979/83. Nearly 71% of forest loss over the long term was due to conversion to uplands. Conversion occurred primarily in the upper reaches of river valleys and bayous. Another 16% of forest loss was to palustrine marsh.

Analysis of Wetland Trends by Geographic Area

The study area was subdivided into major natural areas and geographic components for analysis of historical trends (Fig. 27). The Beaumont-Port Arthur area is presented from northeast to southwest in the following order: (1) Sabine River, (2) Neches River, (3) Sabine Lake, (4) Taylor Bayou, (5) Spindletop Marsh, and (6) Anahuac. The subdivisions allowed a more site-specific analysis of trends and their probable causes. Palustrine marshes, forests, estuarine marshes, and open-water areas are emphasized.

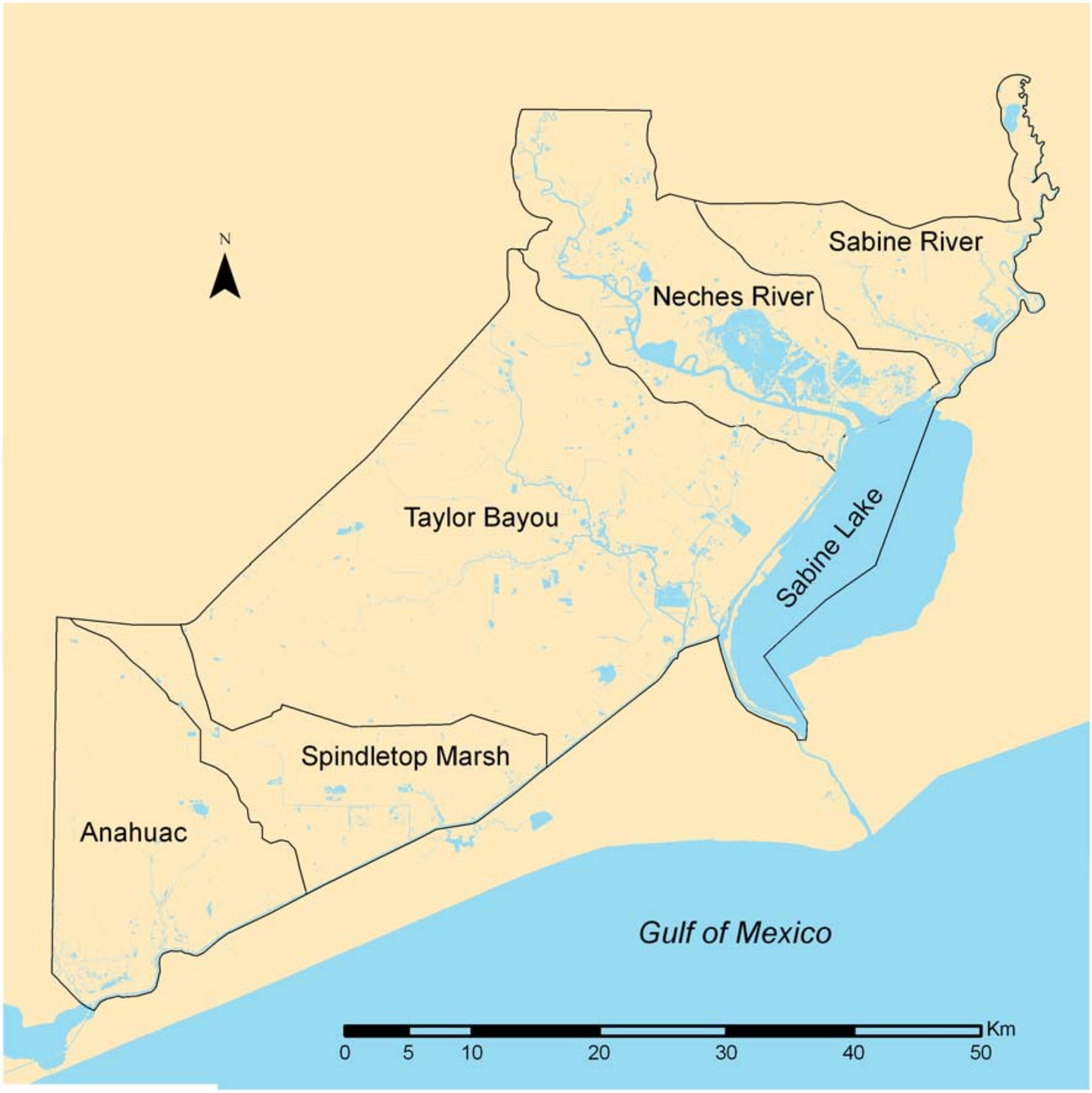

Figure 27. Map showing boundaries of different geographic areas investigated.

Sabine River

The Sabine River is the northeasternmost subarea within the study area. Major water bodies include the Sabine River and Adams and Cow Bayous (Fig. 28). Fresh and salt marshes are found along the lower reaches of the Sabine River. To the north, fluvial woodlands and swamps dominated by bald cypress (*Taxodium distichum*) occupy the entrenched river valley.

Figure 28. Locator map showing geographic features in the Sabine River study area.

The most dramatic change in the Sabine River area is the increase in estuarine marsh. Between 1956 and 2004, estuarine marsh increased 765%, from 118 to 1,021 ha (Fig. 29). Roughly 85% of the increase was from areas previously mapped as palustrine. Most of the change from palustrine to estuarine marsh had occurred by 1979. White and others (1987) mapped this area as brackish and suggested that similar areas had become more saline since dredging of the Sabine-Neches Canal system and construction of multiple reservoirs. Concurrent with the gain in estuarine marsh was the loss of palustrine marsh. A total of 2,011 ha of palustrine marsh in 1956 had been reduced by (–)54% to 923 ha in 2004. Of the total loss of palustrine marsh during this time period, 54% became estuarine marsh and another 23% was converted to uplands. When estuarine and palustrine marsh totals are combined, the long-term marsh change is a loss of (–)9%.

Freshwater, a combination of riverine, lacustrine, and palustrine habitats, gained 194% over the length of the study period. Freshwater areas increased through catchment and reservoir construction. Within the newly created freshwater areas, 76% are assigned excavated (x) or impounded (h) modifiers. About 40% of the freshwater gain was from previously forested areas, with 50% of the freshwater gain in forest from construction of a reservoir on the upper Sabine River.

Forested areas suffered the second-most-significant loss after palustrine marsh, mostly along the Sabine River and Adams and Cow Bayous. The 1956 total of 4,330 ha declined to 3,739 ha in 1979 and was further reduced to 2,965 ha in 2004. The overall loss was (–)32% of the original resource. Industrial and urban development accounted for roughly 71% of the total loss of forest. Logging has been prevalent in the area since the turn of the 20th century (Fig. 30). The above-mentioned reservoir construction displaced about 7% of the original forest total.

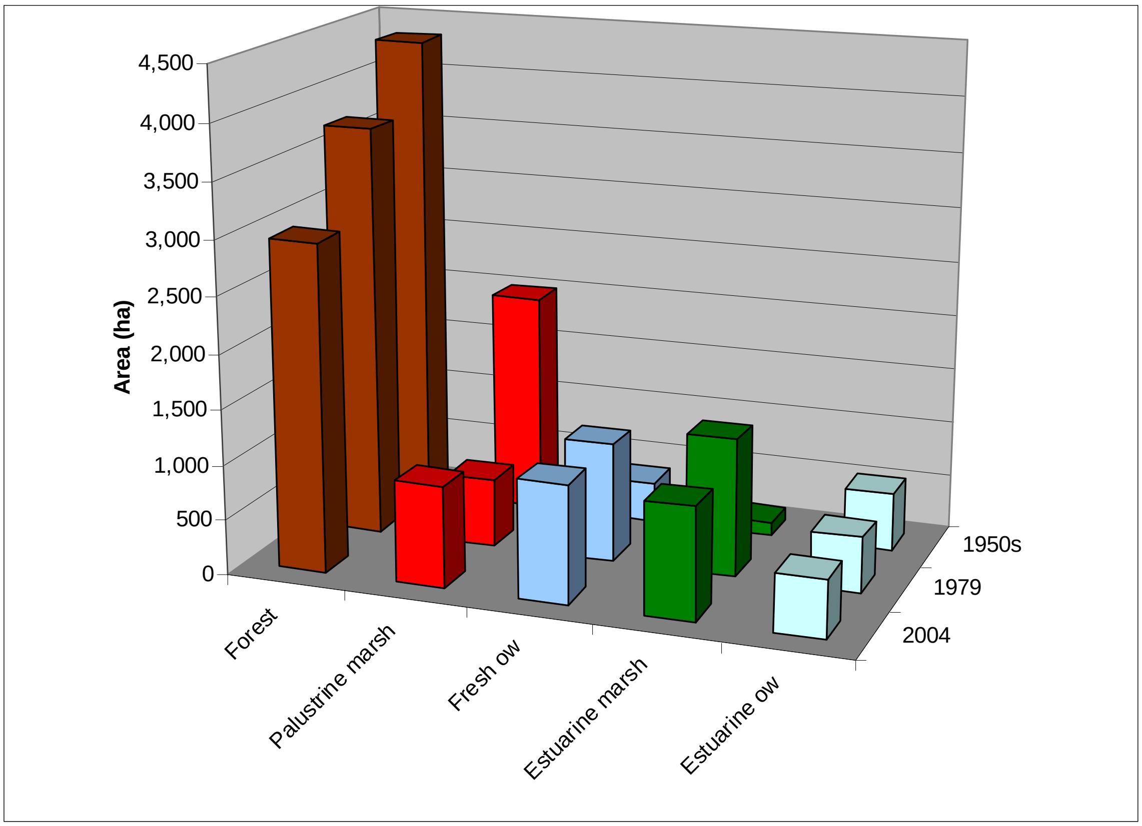

Figure 29. Areal extent of major habitats in the Sabine River area in the 1950’s, 1979/83, and 2004.

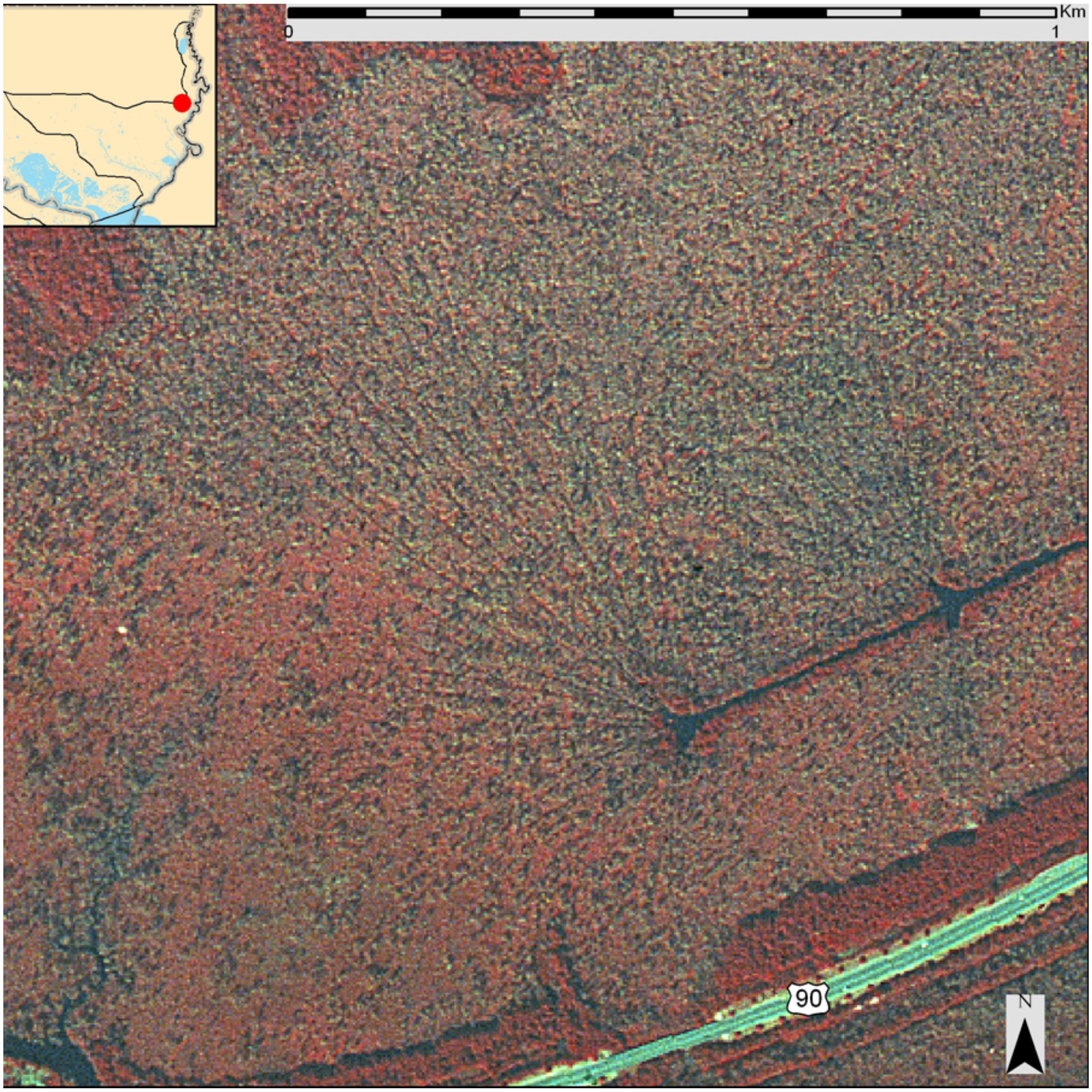

Figure 30. Logging canal and radial channels apparent in 2004 photography. Some logging canals date to the early 1900s.

Neches River

The Neches River area is characterized by the entrenched river valley starting at the marsh complex at the head of Sabine Lake, continuing up the valley to areas dominated by hardwood bottomland forests and fluvial woodlands (Fig. 31). Fresh and salt marshes and open water dominate the lower reaches of the Neches River. Faults dissect the area and affect the distribution of marsh and open water. Subaqueous flats and palustrine marsh are predominant in the midsection of the valley. To the north, fluvial woodlands and swamps dominated by bald cypress (*Taxodium distichum*) and pine occupy the entrenched river valley.

Figure 31. Locator map showing geographic features in the Neches River study area.

The most significant change in wetland habitat in the Neches River area is the increase in estuarine open water (E1UB). Between the 1950’s time period and 2004, open water increased in area from 694 to 5,080 ha (Fig. 32), representing an increase of 632%. Most of the increase (83%) came from areas previously mapped as palustrine marsh and had occurred by 1979. Fresh open water (palustrine, riverine, and lacustrine) increased from 1,793 ha in 1956 to 3,479 ha in 1979. By 2004, the amount of fresh open water had decreased to 2,922 ha. The long-term increase (1956–2004) represents a 63% gain in the resource. The increase is due partly to channelization and reservoir construction—45% of the increased open-water habitat is labeled with excavated (x) or impounded (h) modifiers. Change to fresh open water occurred largely (43%) in areas previously mapped as palustrine marsh.

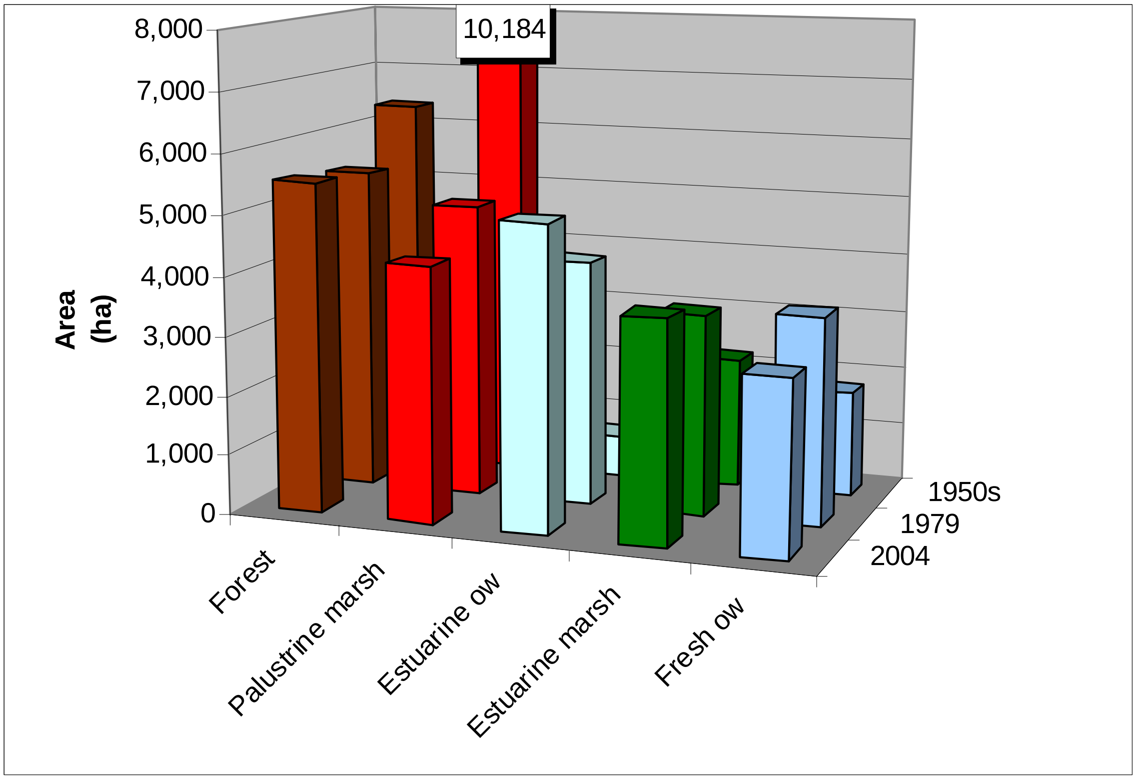

Figure 32. Areal extent of major habitats in the Neches River area in the 1950's, 1979/83, and 2004.

Associated with the gain in open water is a systematic gain in estuarine marsh. The 1956 total of 2,213 ha had increased to 3,370 ha by 1979 and further increased to 3,698 ha by 2004. The rate of estuarine marsh gain is 50 ha/yr for the early time period and 13 ha/yr for the later time period.

Palustrine marsh experienced an equally significant change through time—in this case, a systematic loss of marsh. Palustrine marsh occupied 10,184 ha in 1956, 4,952 ha in 1979, and 4,279 ha by 2004, a (–)58% loss of the resource over the study time period. A rate of –228 ha/yr in the early time period was followed by a much lower rate of –27 ha/yr in the later period. Between the 1950's and 1979/83, 40% of palustrine marsh loss was converted to estuarine open water (E1OW), and 27% loss was to estuarine marsh (E2EM). Figure 33 shows the areas where 1956 palustrine marsh was converted to estuarine marsh, open water, and other habitats by 1979. The figure also shows a pair of high-angle normal faults that are downthrown toward Port Neches field. There is evidence that the faults have been activated by oil and gas production at Port Neches field (White and Morton, 1997; Morton et al. 2001a, b) (Fig. 34). Several faults crossing marshes have been mapped along the upper coast (Fig. 35). Marsh losses have occurred on the downthrown sides of the faults where subsidence has promoted flooding and erosion of the marshes (Fig. 36). The rate of subsidence and relative sea-level rise on the downthrown side of the faults apparently has exceeded the rate of vertical accretion, and the marsh has been replaced primarily by open water. Evidence that the faults are active is illustrated in photographs, where the fault could not be seen on the photograph taken in

1956 but was easily traceable on more recent photographs (Fig. 37). Channelization and subsequent reduction in sediment supply and relative sea-level rise have also contributed to marsh loss. Canal construction prior to 1979 decreased marsh area by direct conversion to open water, erosion, and encroachment of open water (White et al., 1987). In some cases, disposal of dredge material formed a physical barrier to sediments, causing marsh aggradation rates to fall behind the rate of relative sea-level rise.

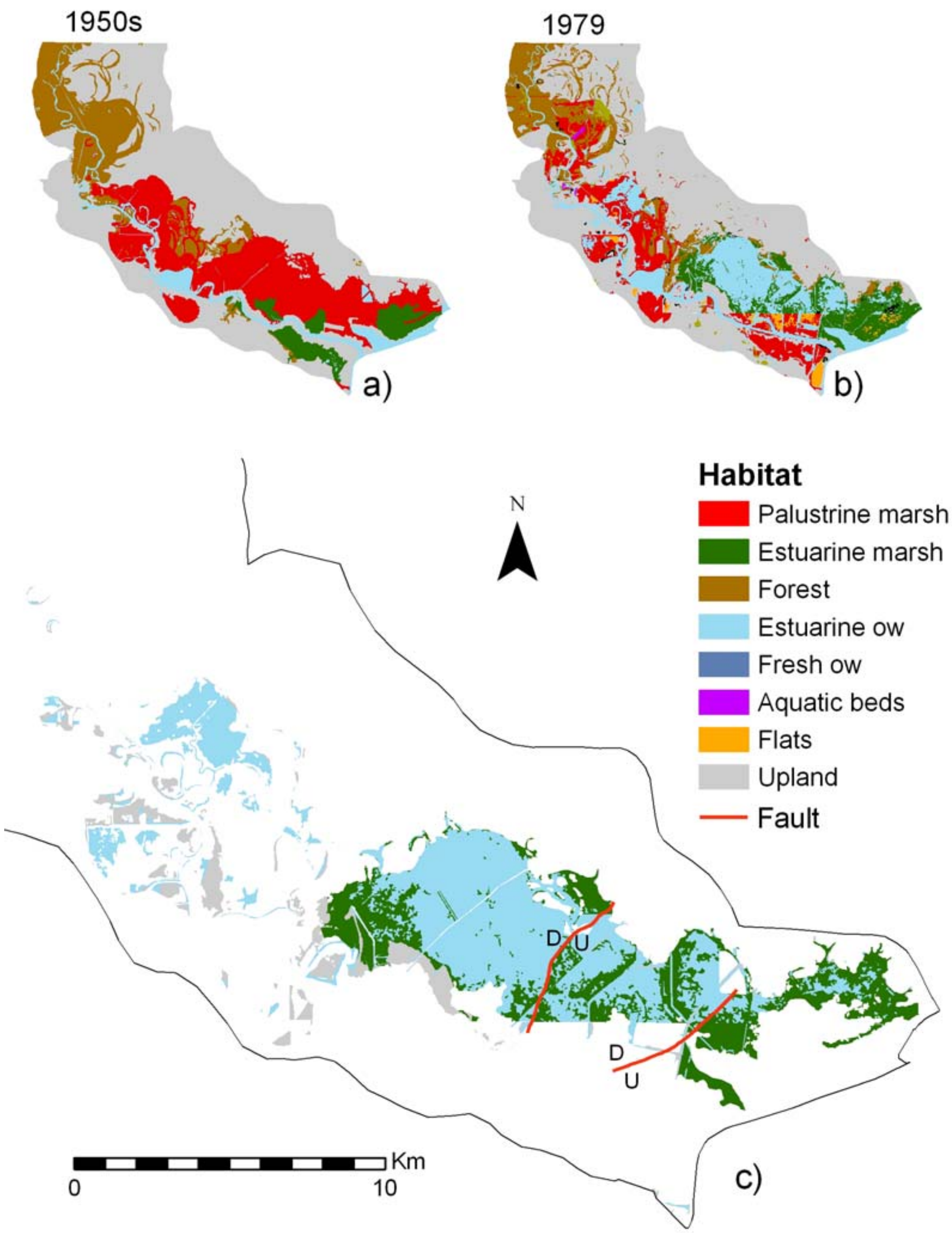

Figure 33. Map showing 1979 habitat that was originally palustrine marsh in 1956 (c). 1950’s wetlands distribution (a) and 1979/83 wetlands distribution (b). Active faults in red. Fault to northwest is discussed in Figure 37.

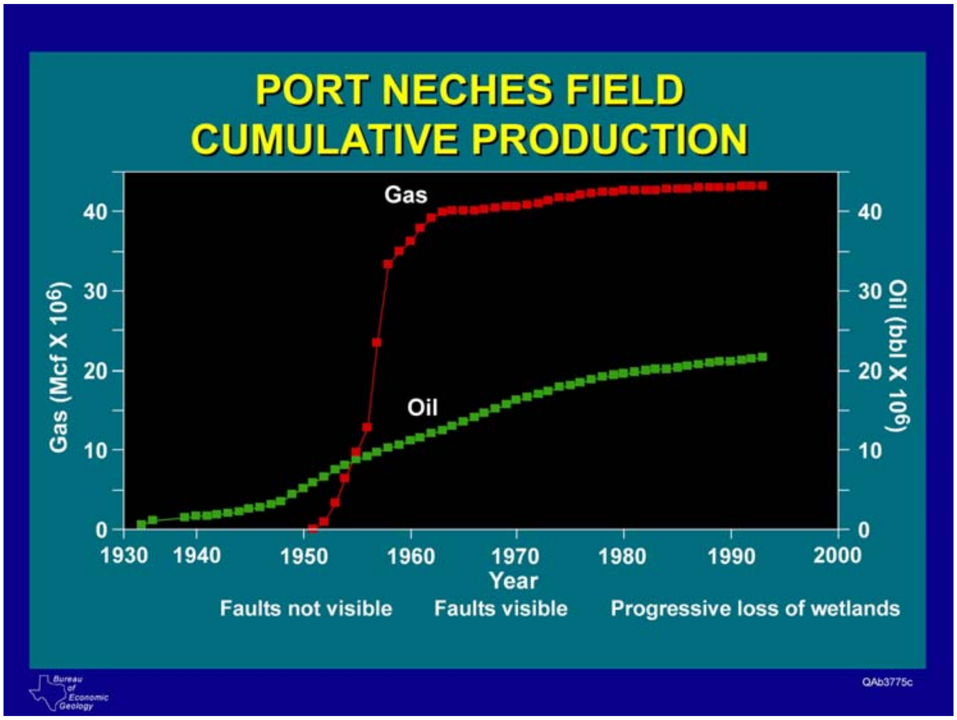

Figure 34. Hydrocarbon production at Port Neches field. Period of highest marsh loss coincides with 1950's to mid-1960's gas production peak. From White et al. (1996).

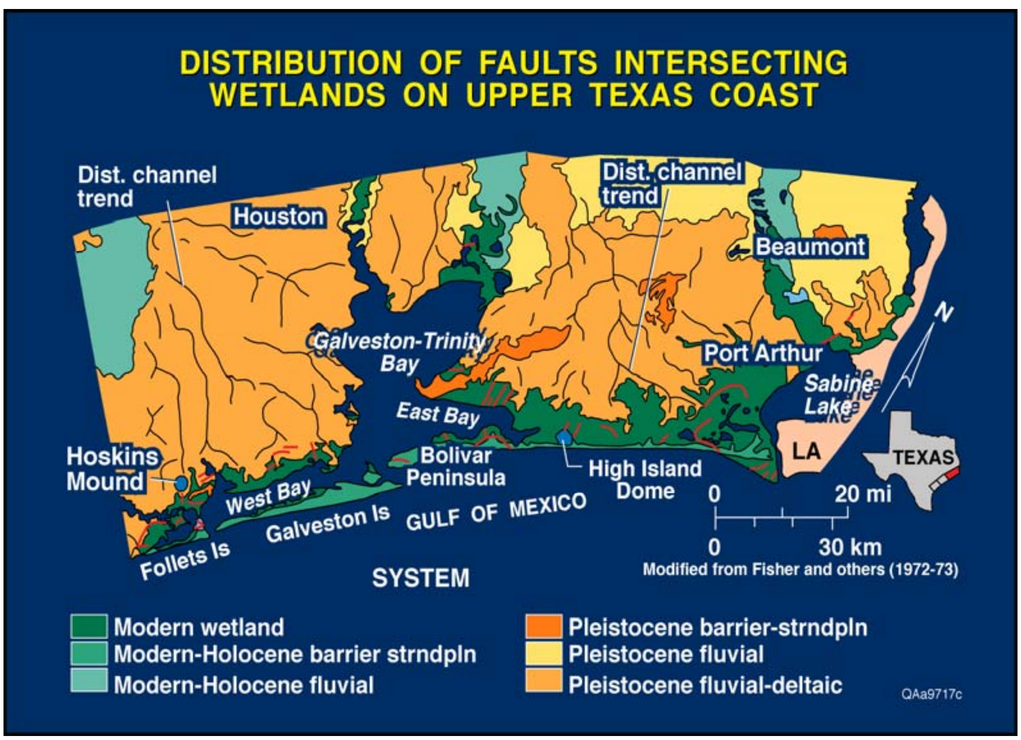

Figure 35. Surface faults, shown in red, that intersect marshes between Follet's Island and the Louisiana border. Faults were mapped from sequential aerial photographs. Only ~25% of the faults were visible on photographs taken in the 1930's, but the remaining

75% could be seen on later photographs, indicating that they have become active since the 1930's. From White and Morton (1997).

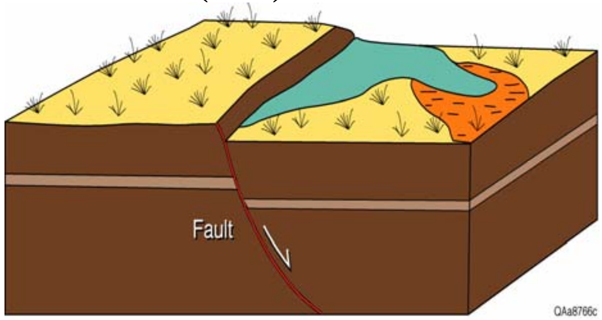

Figure 36. Diagram illustrating changes in wetlands along an active surface fault. There is generally an increase in low marshes and ponded water on the side of the fault that is moving downward. From White and Tremblay (1995).

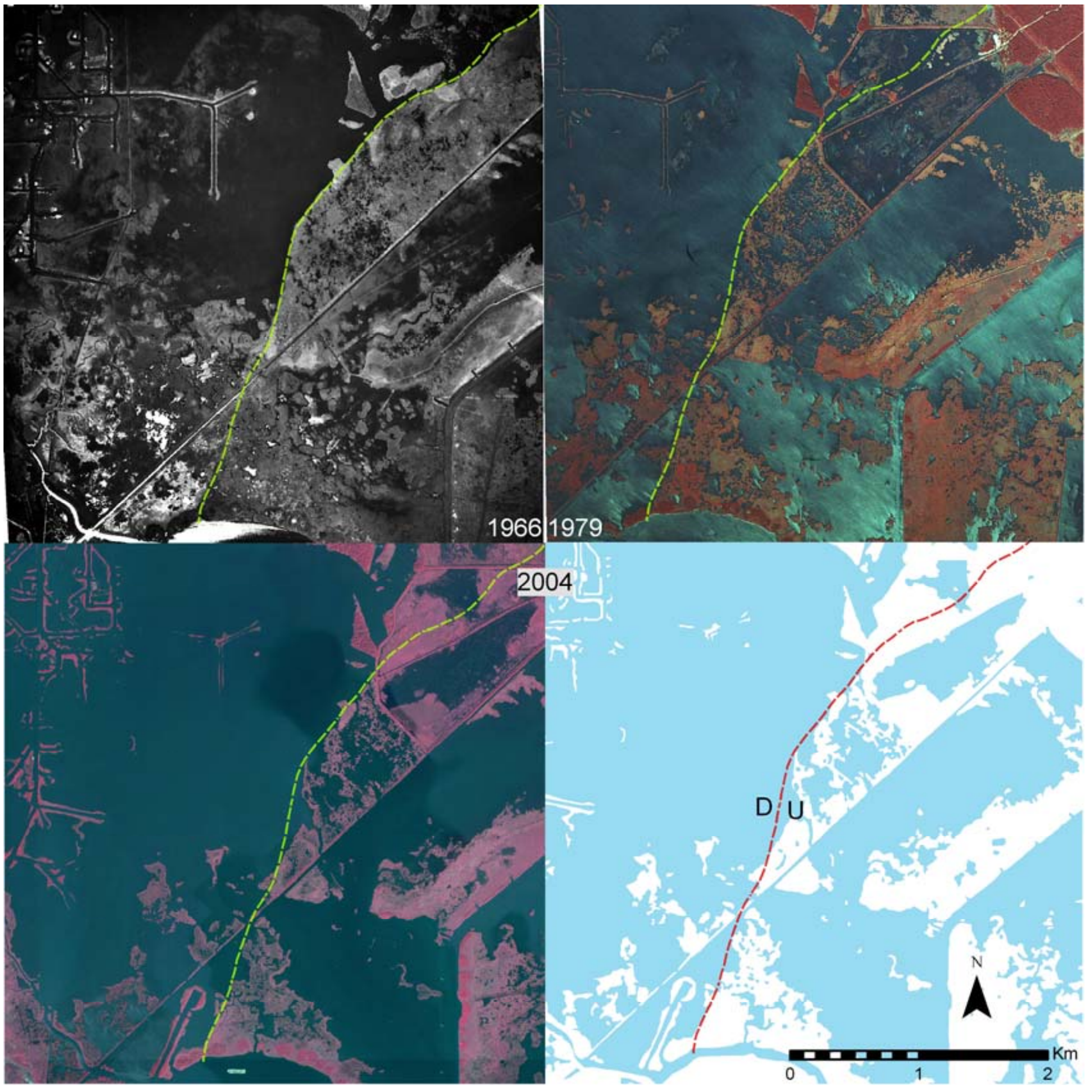

Figure 37. Fault near Port Neches field downthrown toward the oil and gas field. Dark areas of open water increase on the downthrown side (D) of the fault relative to the

upthrown side (U). The fault is not as easily identified on photographs taken in 1956. Impact of the faults on the marsh is apparent on more recent photographs.

Most forest (PFO) decline in the Neches River area occurred between 1956 and 1979/83, when 6,362 ha was reduced to 5,419 ha. A slight gain by 2004 brought the total to 5,530 ha. The overall loss of forest resource was (–)13%. Rate of change was (–)41 ha/yr for the early time period and (+)4 ha/yr for the later time period. One area of high forest loss was near Ross Ridge (Fig. 31), where the swamp was drained and mapped in later time periods as palustrine marsh. Between 1956 and 1979/83, in areas previously mapped as forest, 46% had been converted to palustrine marsh (PEM), 71% of which was mapped as semipermanently flooded (PEM1F). An additional 40% had been converted to upland. When compared with 1996 photography, 2004 photography reveals that some of the few remaining riparian forests in Port Neches had been cleared between 1996 and 2004.

Sabine Lake

Sabine Lake is a relatively small bay-estuary system bordered to the west by the Sabine-Neches Canal and to the south by the Port Arthur Canal (Fig. 38). Tidal exchange occurs through the Sabine Pass, which leads to the Gulf of Mexico. The Sabine and Neches Rivers, as well as Adams, Cow, and Taylor Bayous discharge into Sabine Lake. The lake averages 1.2 to 1.8 m (4 to 6 ft.) in depth (White et al., 1987).

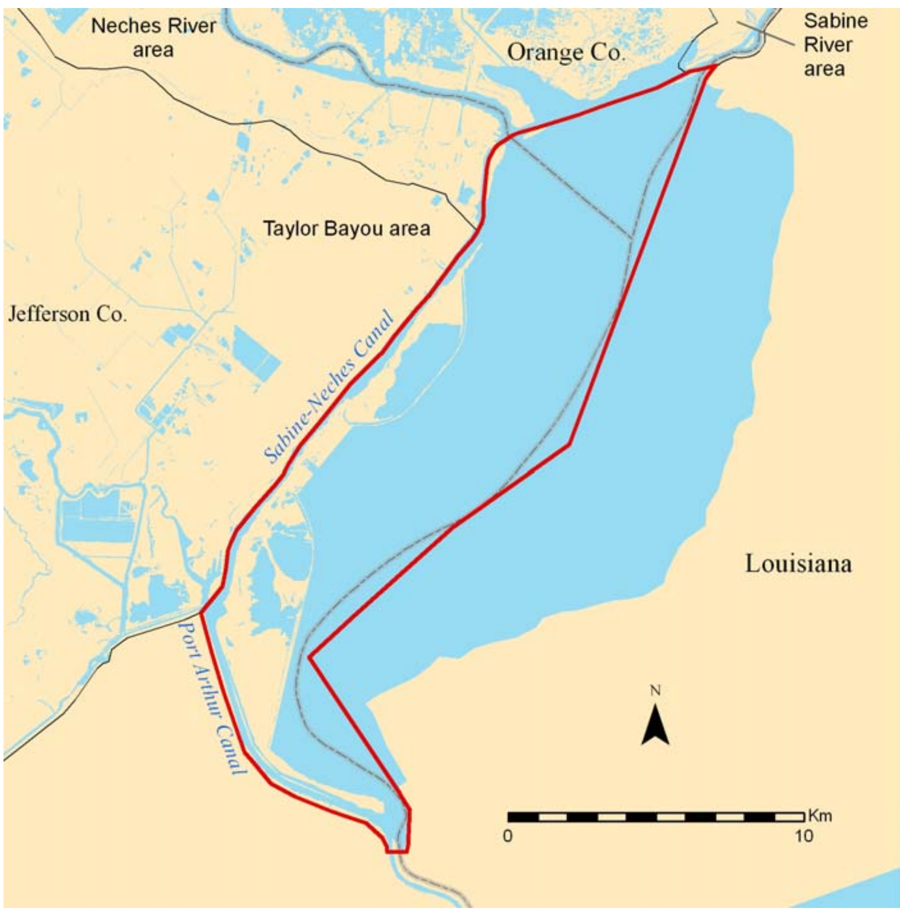

Figure 38. Locator map showing geographic features in the Sabine Lake study area.

Sabine Lake in the 1950's was mostly estuarine open water (E1OW) and upland (1,445 ha), with a small amount of estuarine marsh (15 ha) (Fig. 24). In 1956, estuarine open water occupied 13,111 ha, and in 1979/83 open water was reduced slightly to 12,836 ha. Establishment of wetland habitats on dredge material had reduced the estuarine open water area to 11,245 ha by 2004. Loss of E1OW habitat between 1956 and 2004 can be attributed to conversion to palustrine marsh (39%) and lakes (32%) with the adoption of marsh management practices (impoundments).

Dredge material, mapped as upland in the 1950's, covered 1,445 ha of the Sabine Lake area. Through time uplands were converted to wetland habitats and reduced in area to 828 ha in 1979 and 680 ha in 1956 (Fig. 39).

By 1979 estuarine marsh (556 ha), tidal flats (336 ha), and a small amount of palustrine open water (12 ha) had established in former open water and upland areas. The most significant change in wetland habitats between 1979/83 and 2004 was the establishment of palustrine marsh (PEM). In 1979 only 1 ha of PEM was mapped, but by 2004 palustrine marsh occupied 1,050 ha. Areas of PEM gained in 2004 had previously been 42% estuarine open water and 26% estuarine marsh. Of the PEM gained from estuarine marsh, 77% was from high marsh (E2EM1P). Concurrently, estuarine marsh was significantly reduced from 556 to 41 ha between 1979/83 and 2004. Areas of estuarine marsh loss were replaced by palustrine marsh (51%) and uplands (20%). Palustrine marsh that replaced estuarine marsh had formed on dredge material disposal sites and levees. Isolated from tidal influence and saltwater intrusion, estuarine marshes eventually converted to freshwater systems. Tidal flats (E2US) also lost area to palustrine marsh during the later time period, when 336 ha in 1979 was reduced to 3 ha. Roughly 62% of previously mapped tidal-flat areas had become palustrine marsh (PEM1Khs), and another 22% of tidal flats had been replaced by lacustrine flats in impoundment areas (L2USKhs).

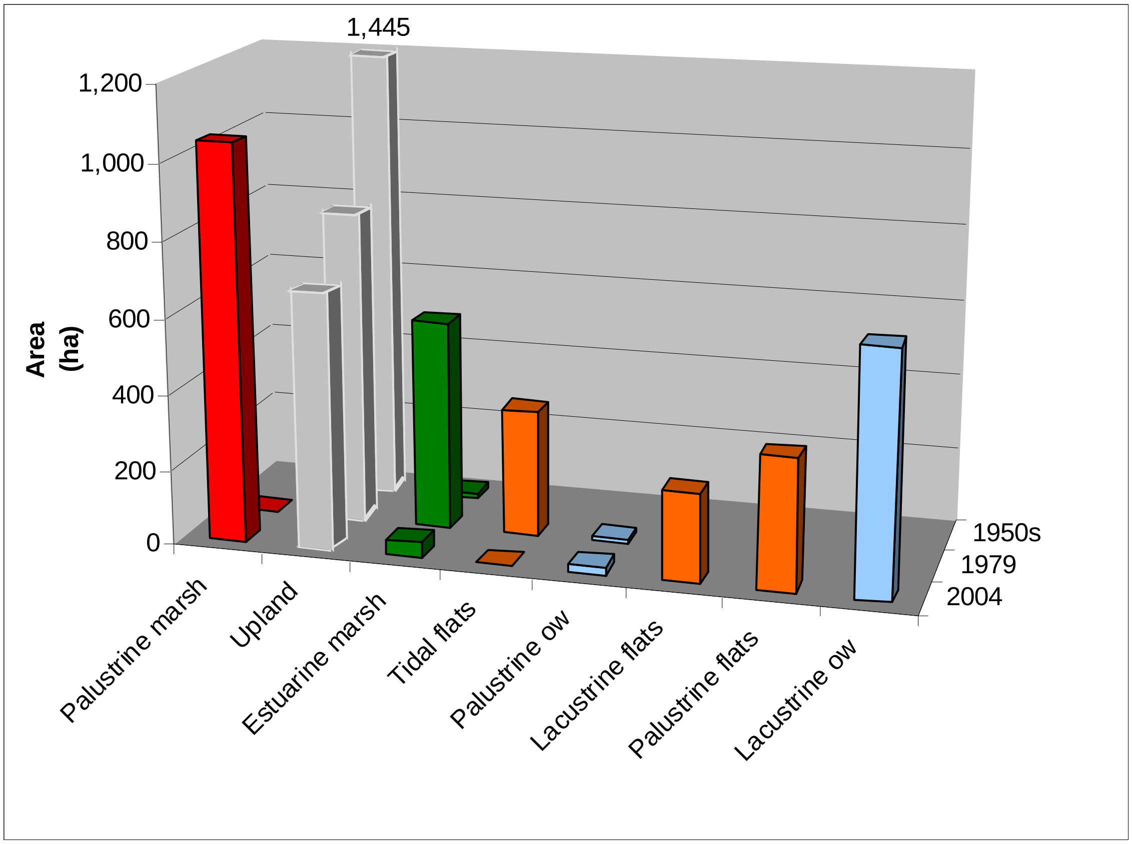

Figure 39. Areal extent of major habitats in the Sabine Lake area in the 1950's, 1979/83, and 2004.

Taylor Bayou

Taylor Bayou is a small, headward-eroding stream connected to the Port Arthur Canal near Sabine Lake (Fig. 40) (Fisher et al., 1973). Connected to the Gulf via Sabine Pass, the lower reaches of Taylor Bayou are tidally influenced, and farther upriver, salt marshes intergrade into fresh marshes. At the confluence of Taylor and Hillebrandt Bayous, broad freshwater marshes are dominant (White et al., 1987). Farther inland and at higher elevations, fluvial woodlands are common.

Figure 40. Locator map showing geographic features in the Taylor Bayou study area. Orange shaded areas are WMAs and NWRs.

The most significant change in wetland habitats in Taylor Bayou is the nearly complete loss of 11,663 ha of estuarine marsh (Fig. 41). By 1979, nearly (–)99% of the habitat was lost, 69% of the loss converted to palustrine marsh, and another 20% converted to upland. Of the loss to palustrine marsh, 95% was to seasonally (C) or semipermanently (F) flooded marsh. Estuarine marsh was also converted to settling ponds and dredge material pits. Lacustrine open-water areas account for 16% of the loss of estuarine marsh by 1979. A possible fault extending northeast from Willow Slough, curving around Blind Lake, appears to have caused the development of water features in previous marshes on the downthrown side of the fault (White et al., 1987) (Fig. 42).

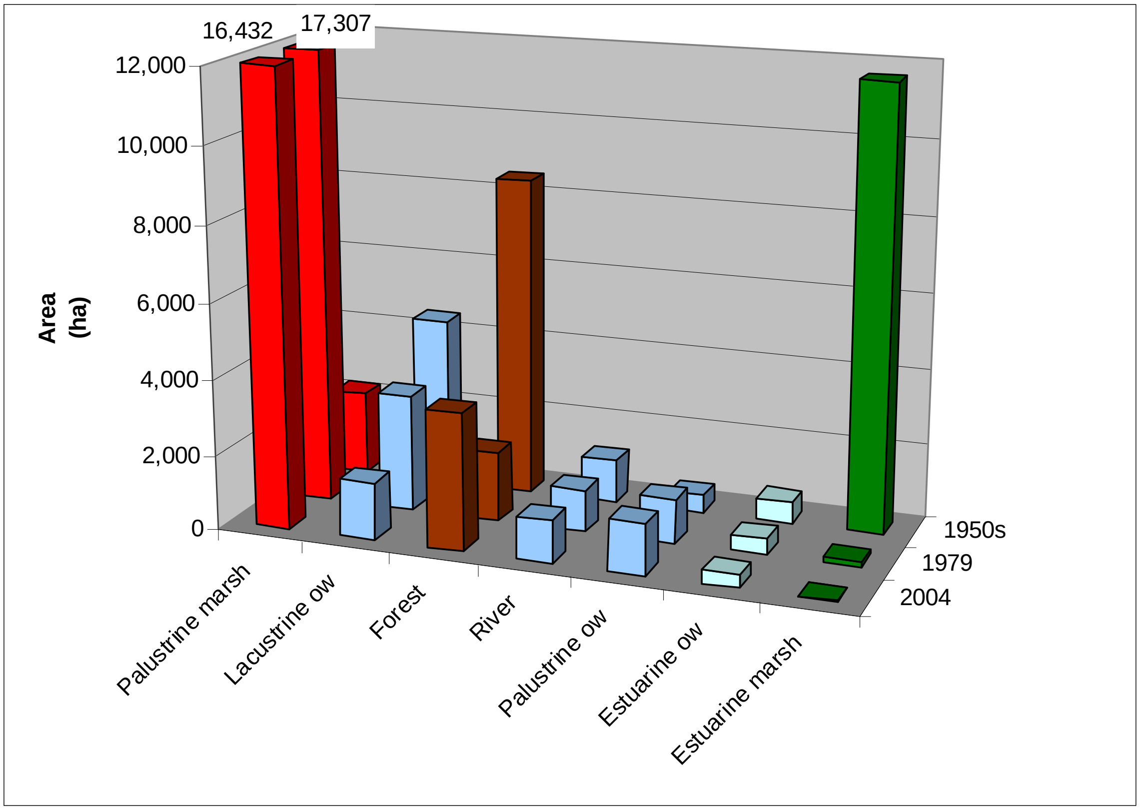

Figure 41. Areal extent of major habitats in the Taylor Bayou area in the 1950's, 1979, and 2004.

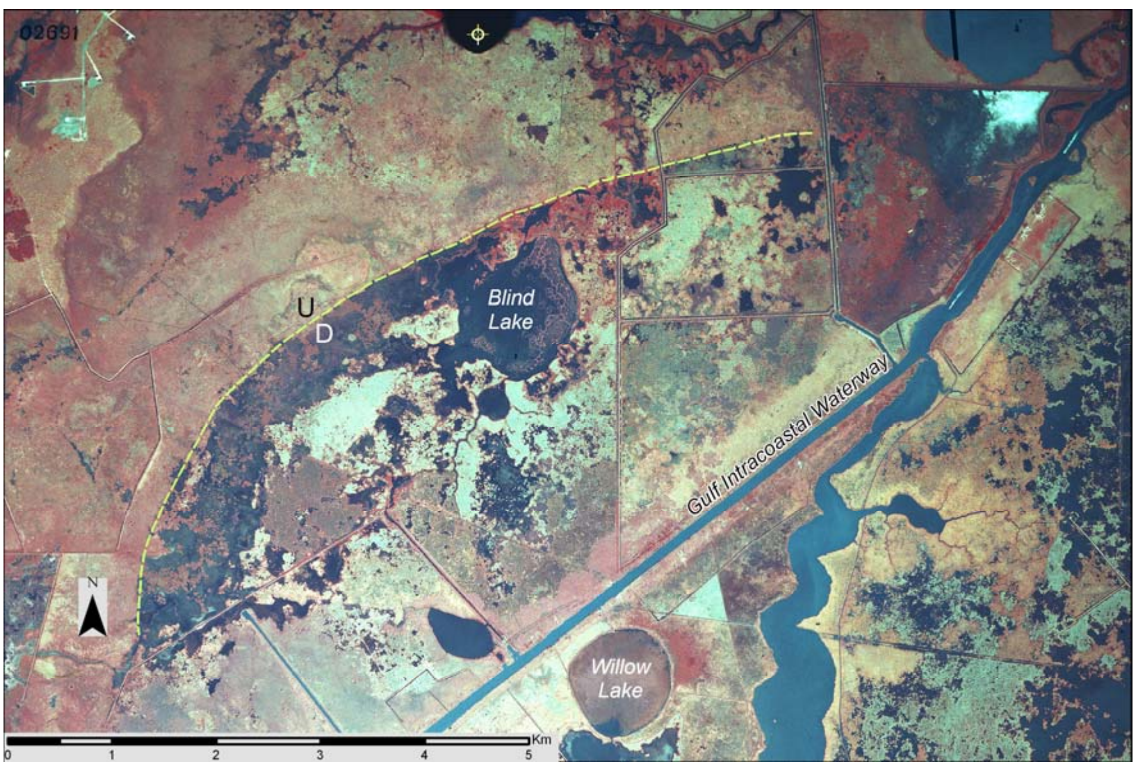

Figure 42. Curvilinear fault affecting marshes near Blind Lake. Possibly a graben related to a salt dome (Fisher et al., 1973) located to the south. 1979 NASA photo. After White et al. (1987).

Concurrently, palustrine marsh experienced a drastic increase in area between 1956 and 1979/83, when 2,219 ha increased to 17,307 ha or 656 ha/yr, representing a 680% increase from the original resource. By 2004, palustrine marsh had decreased in area to 16,432 ha or (–)35 ha/yr, a loss of (–)5%. Half of the gain in palustrine marsh, between the 1950's and 1979/83, was from marsh that was previously estuarine marsh. Palustrine marsh that formed in previously estuarine marsh is 41% impounded, so that when impoundments were constructed saltwater inflow ceased, producing an environment more suitable for vegetation adapted to freshwater conditions. Marshes inland from the GIWW and the Sabine Neches Canal were mapped as fresh to brackish water in the EGAT (Fisher et al., 1973). The difference between 1956 and 1979/83 mapping is partly interpretational but may reflect a fresher system as a result of management practices in the J. D. Murphree WMA. Palustrine marsh also moved into uplands during the early time period because 28% of the new palustrine marsh habitat was in areas previously mapped as upland. When combined, estuarine and palustrine marsh totals between 1956 and 2004 increased by 2,559 ha (+18%). The long-term marsh trend is a gain of 53 ha/yr. Palustrine marsh occurred in areas previously mapped as lacustrine open water (41%) and upland (39%), and 59% of the increase was either impounded (h) or diked (d).

Palustrine forest declined significantly during the mid-1950's to 1979 time period. The study period high of 8,495 ha in 1956 fell to 1,831 ha by 1979, a 79% loss. By 2004, forests had regained some area, with a total of 3,633 ha, a 216% increase from the 1979 total. Forests were undermapped in 1979 in the upper reaches of Hillebrandt Bayou and upstream of the confluence of North Taylor and South Taylor Bayous, where trees occupy alluvium on the Modern-Holocene fluvial system. Some of this area was being harvested at the time and experienced regrowth between 1979 and 2004. The early period trend was a loss of (–)290 ha/yr, followed by a gain of 72 ha/yr in the later time period. The long-term forest trend (1956–2004) was a loss of (–)101 ha/yr. Forest loss between the 1950's and 2004 was the result of human activity, primarily clearing of woodlands for industrial, residential, and agricultural purposes. Most forests (84%) became uplands.

Much of the lacustrine open water (L1OW) mapped in 1956 appears to be in impoundment areas. Lakes in 1956 covered 4,466 ha, fewer lakes occurred in 1979/83 with 3,115 ha, and fewer still by 2004 with 1,521 ha. Lacustrine open water decreased systematically as emergent marsh spread through impounded areas. Roughly 73% of the lacustrine open water area had become palustrine marsh by 2004. Palustrine open water gained 148% between 1956 and 1979/83, when 463 ha increased to 1,149 ha. Areas where palustrine open water appeared in 1979 had mostly been upland (41%) and estuarine marsh (28%) in 1956. Most of these open-water features were impoundments—66% of the increase in area was coded in 1979 with either impounded (h) or excavated (x) modifiers. Some of the increase by 1979 was due to wetter conditions at the time of photography, but also the higher quality of the imagery allowed more ponds to be mapped. Palustrine open water increased by 18% by 2004 to 1,359 ha.

Spindletop Marsh

Spindletop and Salt Bayou Marshes formed in a topographically low basin between Pleistocene distributary channel, levee, and crevasse-splay complexes (White et al., 1987) (Fig. 14). Forked distributary channels intersect freshwater marshes and ponded water. Large impoundments, as well as canals, dikes, and levees, dissect the marsh. Farther up Spindletop Bayou (Fig. 43), fluvial woodlands flank the river banks.

Figure 43. Locator map showing geographic features in the Spindletop Marsh study area.

The most significant change in wetland habitats in Spindletop Marsh is the nearly complete loss of 1,521 ha of estuarine marsh. By 1979, nearly (–)97% of the estuarine marsh habitat was lost, and 83% of the loss was converted to palustrine marsh and another 10% to lakes. All loss in estuarine to palustrine marsh was to seasonally (C) or semipermanently (F) flooded marsh and was located primarily in Salt Bayou Marsh and marshes north of Star Lake. Most of the 1950's estuarine marsh loss was in the form of conversion to settling ponds. Lacustrine habitat area increased slightly between the 1956 total of 1,434 ha and the 1979/83 total of 1,587 ha—an increase of 11%. However, by 2004, lakes had lost (–)674% and totaled only 205 ha. The long-term loss of lacustrine habitat was (–)600%, a long-term trend of (–)26 ha/yr. Nearly two-thirds of the lacustrine loss between the 1950's and 2004 was due to replacement by diked or excavated palustrine marsh. Another 25% of lacustrine loss over the long term was to upland.

Palustrine marsh is by far the dominant wetland habitat in the Spindletop Marsh area, comprising 76% of nonupland habitats mapped in 2004 (Fig. 44). Beginning in 1956, with a total of 6,413 ha, palustrine marsh continued to expand to 8,651 ha, a 35% increase by 1979/83. By 2004, palustrine marsh reached a high of 8,737 ha. Nearly all the marsh expansion occurred in the earlier time period, when the rate of marsh gain exceeded 97 ha/yr. Palustrine marsh over the length of the study time period (1956–2004) was characterized by spread of palustrine marsh into previous estuarine-marsh areas (38%), uplands (34%), and lacustrine habitat (27%). Many of the newly formed palustrine marshes were located in impoundments, 63% of gain in marsh was coded in 2004 with either impounded (h) or excavated (x) modifiers. Like other wetlands on the upper Texas coast, human modification has altered the nature of the marshes. Management practices, including channelization and containment, has reduced the effect of saltwater intrusion and enhanced freshwater inflow into the system, eventually increasing the relative amount of fresh to salt marsh.

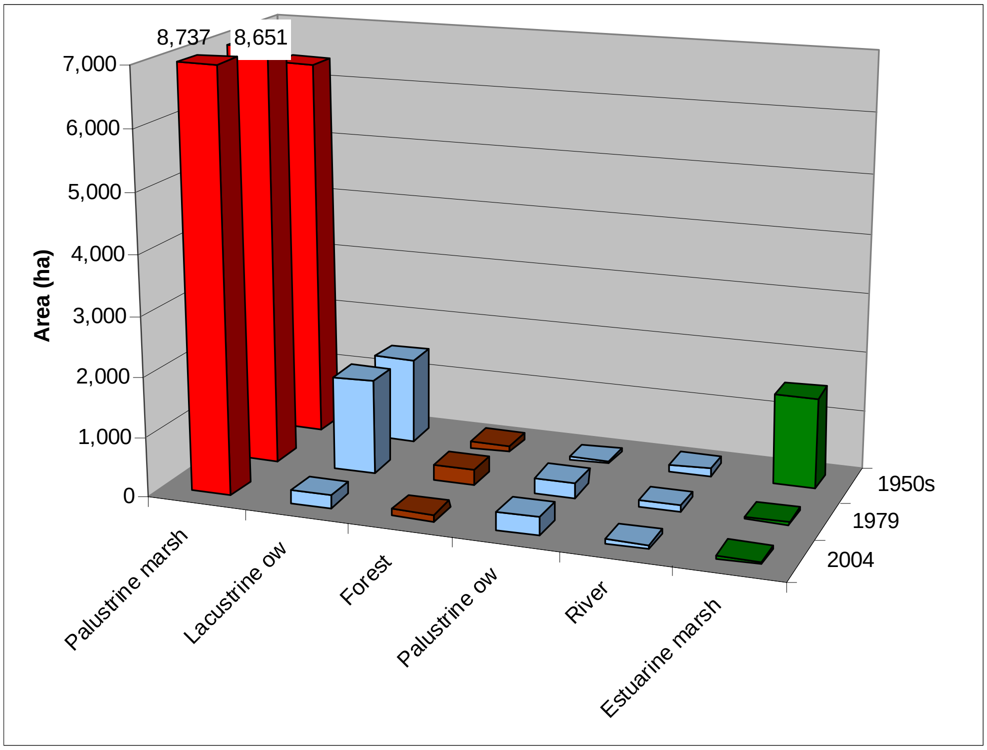

Figure 44. Areal extent of major habitats in the Spindletop Marsh area in the 1950's, 1979/83, and 2004.

Anahuac

More than half of the Anahuac NWR is located within the study area. Low saltwater marshes grading into high saltwater marshes and then into freshwater marsh characterize wetlands in the Anahuac study area. Saltwater marshes located in East Bay and Mud Bayous grade into freshwater marshes, with increasing distance from East Bay (Fig. 45).

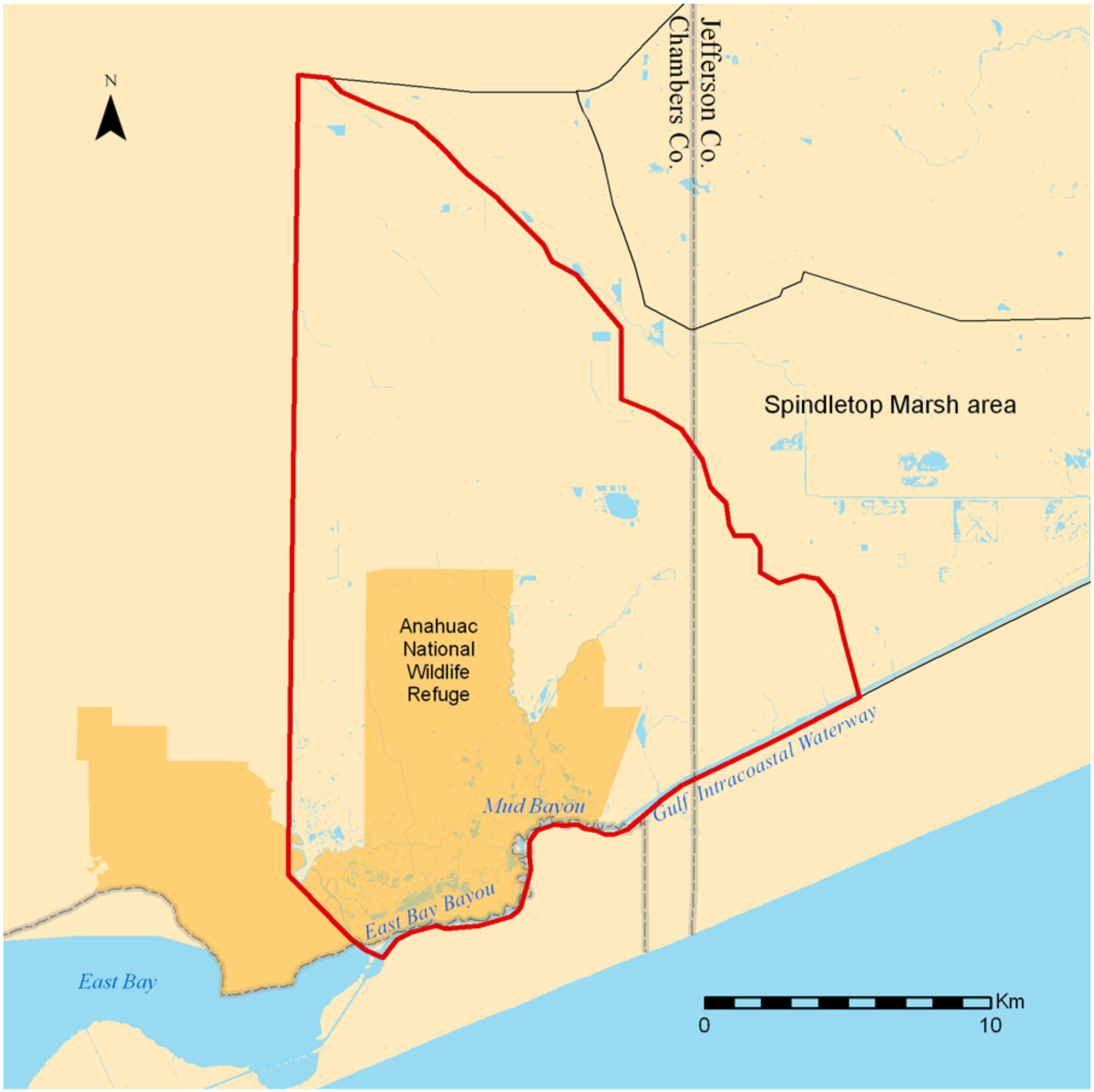

Figure 45. Locator map showing geographic features in the Anahuac study area.

The most significant wetland trend in the Anahuac area is the increase in estuarine marsh between 1956 and 1979/83. Starting with 3,197 ha in 1956, marsh area increased to 3,999 ha by 1979/83 (Fig. 46), a change that represents a 25% increase from the original amount. More than 69% of the new estuarine-marsh area was mapped as palustrine marsh in 1956. A slight 1% decrease occurred between 1979/83 and 2004.

Estuarine open water also experienced a systematic increase through time. The initial 323 ha in 1956 increased to 411 ha in 1979/83 and further increased to 625 ha by 2004. The overall increase throughout the study time period represents a 94% gain from the original resource. Half of the estuarine open-water gain between 1956 and 2004 was from areas previously mapped as estuarine marsh, and another 23% was from areas formerly occupied by palustrine marsh. Most of the open-water increase occurred on the inland flank of an upland ridge that runs parallel to East Bay Bayou. This is also the location of much of the increase in estuarine marsh mentioned earlier. The shape and location of the upland ridge suggest that it was formed through dredge material disposal from the GIWW. The ridge may have altered hydrologic conditions, creating a more salt dominated environment. Palustrine marsh experienced gains and losses in various locations throughout the study time period, resulting in minimal net change.

Fresh open water includes lacustrine, palustrine, and river habitats. Habitat area fluctuated over time, resulting in a long-term loss of 36% of the resource. A significant part of the loss was due to marsh increasing in waterfowl reservoirs on the Anahuac NWR. Of the loss of fresh open water, 66% was to upland and 34% was to palustrine marsh. Forests suffered significant systematic decline, with the most significant loss between 1956 and 1979/83. Forest area in 1956 covered 203 ha; in 1979, forest was reduced to 77 ha; and by 2004, only 56 ha remained. By 1979, 62% of the original resource was lost. The riparian forest on the west edge of the study area was replaced mostly by estuarine marsh (58%). Another 26% of forest had been replaced by uplands by 1979/83.

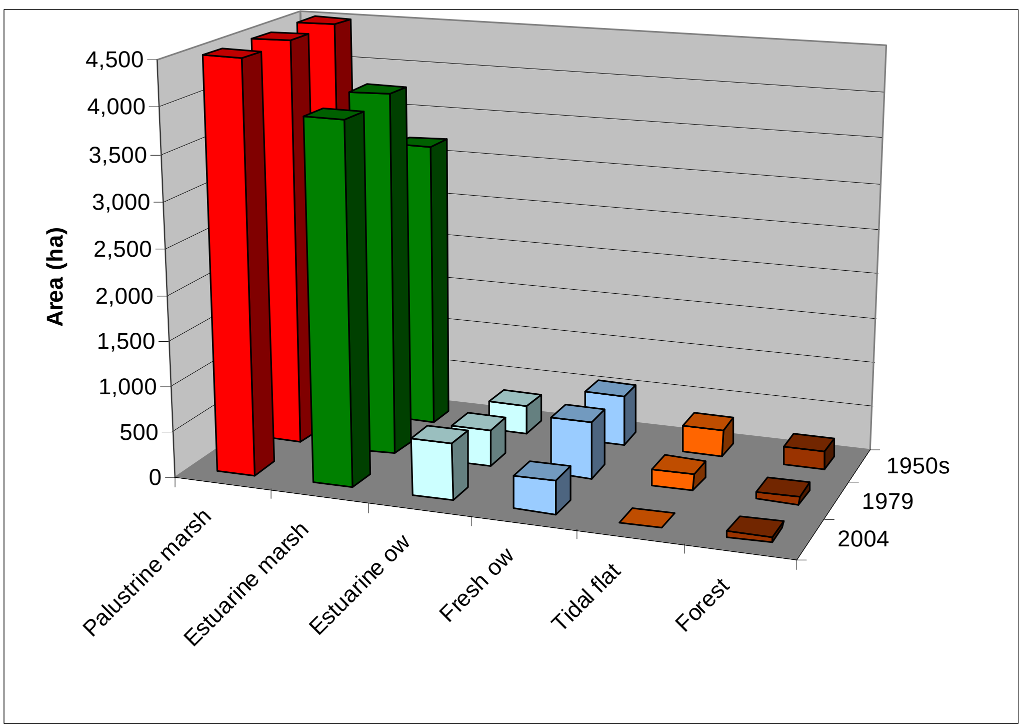

Figure 46. Areal extent of major habitats in the Anahuac area in the 1950’s, 1979/83, and 2004.

SUMMARY AND CONCLUSIONS

Wetlands and aquatic habitats in the bay-estuary system along the upper Texas Gulf Coast are dominated by palustrine marsh, which, in 2004, encompassed an area of almost 35,876 ha, accounting for about 42% of mapped wetland and aquatic habitats. The second-most-extensive habitat was estuarine open water, with an area of 18,043 ha, at about 21%. Palustrine forest covered an area of 12,316 ha, or about 14% of wetland and aquatic habitats. Among other mapped classes (excluding uplands), fresh open-water habitats are most abundant at 10,580 ha (12%) and estuarine marsh at 8,759 ha (10%).

Examination of wetland distribution in six geographic subareas within the study area (Sabine River, Neches River, Sabine Lake, Taylor Bayou, Spindletop Marsh, Anahuac) shows that Taylor Bayou has the largest distribution of palustrine marshes at 46%. The largest percent coverage of forest occurs on the Neches River at 45% of the total study area. Anahuac has the largest area of estuarine marsh (45%), and the Neches River the most open water area (50%).

From the 1950's through 2004 within the study area, some wetland classes underwent substantial net losses and gains, whereas others remained more stable. Historically losses and gains in habitats have occurred throughout the study area, but the overall trend in vegetated emergent wetlands (marshes and forests) is one of net loss, as revealed by decreases in the marsh-forest habitat of 6,659 ha from the 1950's through 2004. The average rate of marsh-forest habitat loss was about 139 ha/yr. Forests decreased in total area from 19,506 ha in 1956 to 12,316 ha in 2004, a loss of 7,190 ha. Rates of –327 ha/yr for the 1956–1979 period was followed by +43 ha/yr during the1979–2004 period. The overall (1956–2004) change rate was a loss of 150 ha/yr. Marshes gained slightly over 1% of the original 1956 area by 2004, whereas forests lost about 37% of the original resource. Forests were cleared for agriculture, industry, and urban development.

The total area of estuarine open water/flats increased by 3,199 ha from the 1950's through 1979 then decreased from 1979 through 2004 by 1,125 ha. The average rate of change in estuarine open water/flats fluctuated through time, from a gain of about 139 ha/yr during the earlier period to a loss of 45 ha/yr during the later period. The overall (1956–2004) rate was a gain of 43 ha/yr. The largest increase in estuarine open water occurred in the lower Neches River valley and was due to relative sea-level rise from oil-field development associated with hydrocarbon production at Port Neches field. Fresh open water and associated habitats (flats) increased in total area by 3,036 ha between the 1950's and 1979 but decreased by 2,853 ha between 1979/83 and 2004. The increase in open water since 1956 was partly because of drier conditions in the 1950's caused by severe drought. The drought apparently affected the extent of open water in marshes on 1956 maps. These differences in wet and dry conditions during the various time periods affected habitats, especially the extent of open water that was interpreted and mapped. Wetter ground conditions in 1979 produced more open-water areas. These areas had been converted, in many cases, to marsh or upland by 2004.

Analysis of habitat distribution by geographic subarea reveals local differences in historical trends. The most significant wetland trend on the **Sabine River** was the systematic gain of estuarine marsh. The trend is characterized primarily by expansion of estuarine marsh into palustrine marsh. Most of the change from palustrine to estuarine marsh had occurred by 1979. The area had been previously mapped as brackish, and similar areas may have become more saline since dredging of the Sabine-Neches Canal system and construction of multiple reservoirs. Concurrent with the gain in estuarine marsh was the loss of palustrine marsh. Of the total loss of palustrine marsh during this time period, most became estuarine marsh or uplands. Combined estuarine and palustrine marsh habitat decreased in area over the long term. Freshwater habitats gained area over time, increasing through catchment and reservoir construction. A significant amount of the gain in freshwater area was in areas that had previously been forested, with half of the gain from construction of a reservoir on the upper Sabine River. Forested areas suffered the second-most-significant loss after palustrine marsh, mostly within the floodplains adjacent to the Sabine River and Adams and Cow Bayous. Industrial and urban development accounted for most forest decline. Logging has been prevalent in the area since the turn of the 20th century.

Among the most significant changes in the **Neches River** study area is the increase in estuarine open water between 1956 and 2004. Most of the increase had occurred, by 1979, in areas previously mapped as palustrine marsh. The fresh open-water area fluctuated through time, increasing between 1956 and 1979 then decreasing by 2004. The long-term trend was an overall increase of fresh open water, primarily in areas previously mapped as palustrine marsh. The increase is due partly to channelization and reservoir construction. Associated with the gain in open water is a systematic gain in estuarine marsh, a rate that decreased through time. Palustrine marsh experienced an equally significant change through time—in this case, a systematic loss of marsh that consistently decreased through time. Between the 1950’s and 1979/83, most palustrine marsh loss was to estuarine open water and estuarine marsh.

Marsh losses in the Neches River area have occurred on the downthrown sides of active faults, where subsidence has promoted flooding and erosion. The rate of subsidence and relative sea-level rise on the downthrown side of the faults apparently has exceeded the rate of marsh vertical accretion, and the marsh has been replaced by open water. Channelization and subsequent reduction in sediment supply has also contributed to marsh loss. Canal construction prior to 1979 decreased marsh area by direct conversion and encroachment of open water and erosion. In some cases, disposal of dredge material formed a physical barrier to sediments, causing marsh aggradation rates to not keep pace with the rate of relative sea-level rise.

Most forest decline in the Neches River area occurred between 1956 and 1979/83. The overall loss of forest was (–)13% of the original amount. Rates of change varied through time. One area of high forest loss was near Ross Ridge, where the swamp was drained and mapped in later time periods as marsh. Areas mapped as forest in 1956 had mostly been converted to semipermanently flooded palustrine marsh and to upland. Deforestation continued between 1996 and 2004 in the City of Port Neches.

Sabine Lake in the 1950's was mostly estuarine open water and upland, with a small amount of estuarine marsh. Estuarine open-water area was reduced slightly between 1956 and 1979/83, and establishment of wetland habitats on dredge material had further reduced estuarine open-water area by 2004. Estuarine open-water habitat between 1956 and 2004 was converted to palustrine marsh and freshwater lakes. Both of the newly formed habitats occurred on impounded spoil.

Dredge material, mapped as upland in the 1950's, constituted most of the land surface in the Sabine Lake area. Through time, uplands were converted to wetland habitats and reduced in area, so that by 1979, estuarine marsh, tidal flats, and a small amount of palustrine open water had established in areas that had previously been estuarine open water and upland.

The most significant change in wetland habitats between 1979/83 and 2004 was the establishment of palustrine marsh. In 1979 only 1 ha of PEM was mapped, but by 2004, palustrine marsh occupied over 1,000 ha and occurred in areas that had previously been estuarine open water and high estuarine marsh. Palustrine marsh that replaced estuarine marsh had formed on dredge-material disposal sites. Impoundments isolated marshes from tidal influence and saltwater intrusion, eventually converting marshes to freshwater habitat. Tidal flats also lost area, mostly to palustrine marsh and impounded lacustrine flats.

The most significant change in wetland habitats in **Taylor Bayou** is the nearly complete loss of estuarine marsh. By 1979, nearly all estuarine marsh had been converted to palustrine marsh. A much smaller amount had been converted to uplands, settling ponds, and impoundments. Lacustrine open-water areas had also formed in previous estuarine marsh habitat. A possible fault extending northeast from Willow Slough, curving around Blind Lake, appears to have caused development of open water in previous marshes on the downthrown side of the fault.

Concurrently, palustrine marsh experienced a drastic increase in area between 1956 and 1979/83, with half of the gain from previous estuarine marsh. By 2004, palustrine-marsh area had decreased slightly. A high proportion of palustrine marsh that had displaced estuarine marsh was impounded. After impoundments were constructed, saltwater flow ceased, producing an environment more suitable to vegetation adapted to freshwater. Marshes inland from the GIWW and the Sabine Neches Canal had previously been mapped as fresh to brackish. The discrepancy between the 1956 and 1979/83 mapping is partly interpretational but may reflect a more freshwater system as a result of management practices. Palustrine marsh also occurred in uplands by 1979/83. When combined, estuarine and palustrine marsh increased between 1956 and 2004, with a long-term marsh trend of (+)53 ha/yr. Palustrine marsh increases, mostly impounded or diked, occurred mostly in areas previously mapped as lacustrine open water and upland. Forest declined significantly during the mid-1950's to 1979/83 time period, when forests were reduced (–)79%, but by 2004, forests had regained acreage slightly. Some forest area lost during the early time period experienced regrowth after 1979. Trends in forest area fluctuated through time but resulted in a long-term loss. Forest loss between the 1950’s and 2004 was from human activity, primarily clearing of woodlands for industrial, residential, and agricultural purposes. Most forest loss resulted in conversion to upland.

Much of the lacustrine open water (lakes) mapped in 1956 was located in impoundment areas. Lakes were most prevalent in 1956, but declined in area by 1979/83, further declining by 2004. Lacustrine open water decreased systematically as emergent palustrine marsh spread through impounded areas, so that by 2004, most lacustrine open-water area had become palustrine marsh. Palustrine open-water area increased between 1956, 1979/83, and 2004. Areas where palustrine open water occurred in 1979 had been mostly upland and estuarine marsh in 1956. Some of the gain in palustrine open water was due to increased precipitation in 1979.

By 1979, **Spindletop Marsh** had lost nearly all estuarine marsh, most becoming palustrine marsh, although a small amount had converted to lakes. Most of the loss was located in Salt Bayou Marsh and marshes north of Star Lake. Marshes that were estuarine in the 1950’s had become settling ponds by 1979.

Lacustrine habitat area increased slightly between 1956 and 1979/83; however, by 2004 most lakes had dried up. Nearly two-thirds of lacustrine loss between the 1950’s and 2004 was due to replacement by palustrine marsh, and another 25% of the change over the long term was to upland.

Palustrine marsh is by far the dominant wetland habitat in the Spindletop Marsh area. Palustrine marsh expanded throughout the study time period, with most increasing during the earlier time period of 1956–1979/83. Palustrine marsh gain over the length of the study time period (1956–2004) was characterized by spread of palustrine marsh into previous estuarine marsh, uplands, and lacustrine habitat, including impoundments. Like other wetlands on the upper Texas coast, human modification has altered the nature of the marshes. Management practices, including channelization and impoundment, have reduced the effect of saltwater intrusion and enhanced freshwater inflow into the system, eventually increasing the relative amount of fresh to salt marsh.

The most significant change in the **Anahuac** area is a 25% increase in estuarine marsh between 1956 and 1979/83, mostly in areas that had been mapped as palustrine marsh in 1956. A small decrease in estuarine marsh area occurred in the later time period between 1979/83 and 2004.

Estuarine open water also experienced a systematic increase through time, nearly doubling during the study time period. Half of the gain in estuarine open water between 1956 and 2004 was from areas previously mapped as estuarine marsh, with additional gain in areas formerly occupied by palustrine marsh. Most of the open-water increase occurred on the inland flank of an upland ridge that runs parallel to East Bay Bayou. This is also the location of much of the increase in estuarine marsh mentioned earlier. The shape of the upland ridge suggests that it was formed through dredge-material disposal from maintaining the GIWW. The ridge may have altered hydrologic conditions, creating a more salt dominated environment.

Palustrine marsh experienced gains and losses in various locations throughout the study time period, but total habitat area changed little. Fresh open water, including lacustrine, palustrine, and river habitats, fluctuated over time, but long-term change resulted in a significant loss of resource. Much of the loss occurred when two large reservoirs on the refuge became palustrine marsh. Of the loss in fresh open water, two-thirds was to upland, and the remainder was to palustrine marsh. Forests declined systematically, with the greatest loss between 1956 and 1979/83, so that by 1979, slightly more than one-third of the original resource remained. The riparian forest in the refuge on the west edge of the Anahuac study area was replaced mostly by estuarine marsh and to a lesser degree by uplands.

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APPENDIX

Total habitat areas for 2004, 1979/83, and 1950's determined from GIS data sets of the study area.

2004	
Habitats	**Hectares**
E1AB4	0.4
E1AB5	101.0
E1AB5x	2.4
E1AB6x	1.9
E1UBL	16,595.2
E1UBLs	1.9
E1UBLx	1,340.0
E2EM1N	2,220.6
E2EM1Nd	819.7
E2EM1Nh	57.5
E2EM1Ns	181.6
E2EM1Nx	7.7
E2EM1P	4,282.4
E2EM1Pd	855.9
E2EM1Ph	38.7
E2EM1Ps	238.1
E2SS	57.1
E2USM	4.8
E2USN	1.3
E2USP	2.8
L1UBH	376.9
L1UBHh	43.9
L1UBHx	850.7
L2AB1hs	178.3
L2AB4F	20.0
L2AB4Fh	21.5
L2AB5	101.1
L2AB5h	43.1
L2UB	155.4
L2UBFh	559.1
L2UBFx	276.3
L2UBKh	530.5
L2UBKhs	693.3
L2USKh	77.8
L2USKhs	255.7
L2USKx	4.5
PAB1F	24.9
PAB1Fh	21.5
PAB1Khs	319.3
PAB4F	97.8

1979/83	
Habitats	**Hectares**
E1OW.	18,518
E2EM.	9,353
E2FL.	658
L1OW.	5,714
L2FL.	469
PEM.	36,033
PFL.	1,017
PFO.	11,335
POW.	2,580
R1OW.	1,619
R1FL.	35
R2OW.	1,999
U.	155,942

1956	
Habitats	**Hectares**
E1OW.	15,603
E2EM.	7,064
E2FL.	374
L1OW.	5,651
L2OW.	857
PAB.	2
PEM.	37,040
PFO.	19,506
POW.	826
R1OW.	1,170
R2OW.	1,892
U.	155,219

PAB4Fh	69.9
PAB4Fx	135.1
PAB4Khs	6.2
PAB4T	1.9
PAB5	45.7
PAB5h	74.0
PAB5x	42.9
PEM1A	3,194.7
PEM1Ad	239.7
PEM1Ah	977.7
PEM1Ahs	115.3
PEM1Ax	51.7
PEM1C	11,453.2
PEM1Cd	546.5
PEM1Ch	8,817.2
PEM1Cx	540.8
PEM1F	3,304.7
PEM1Fh	1,824.3
PEM1Fx	655.0
PEM1Khs	2,351.3
PEM1R	1,196.0
PEM1S	30.6
PEM1T	400.8
PEM1Th	122.2
PEM1Tx	5.8
PEM1V	48.2
PFO1A	5,438.1
PFO1C	2,748.3
PFO1Cd	49.1
PFO1Ch	5.8
PFO1F	2,067.1
PFO1Fh	10.9
PFO1Fx	7.2
PFO1R	79.0
PFO1S	73.7
PFO1T	13.0
PFO1V	1.2
PFO2C	12.8
PFO2F	939.6
PFO2R	5.4
PFO4A	38.4
PSS1A	327.6
PSS1Ah	50.4
PSS1Ax	7.9
PSS1C	264.8
PSS1Cd	21.1
PSS1Ch	0.5
PSS1Chs	53.5
PSS1F	11.0
PSS1R	77.4

PSS1S	9.3
PSS2C	2.6
PUB	169.9
PUBCh	54.6
PUBCx	9.0
PUBFh	150.7
PUBHx	1,499.7
PUBKh	23.2
PUBKhs	38.3
PUBT	3.8
PUBV	12.4
PUBVx	4.3
PUS	6.4
PUSCx	19.7
PUSKhs	57.7
PUSh	11.8
R1AB5	1.6
R1UBV	964.9
R1UBVx	306.9
R2AB5	5.0
R2UBH	1,845.5
R2UBHx	367.4
U	158,819.5