STATUS AND TRENDS OF INLAND WETLAND AND AQUATIC HABITATS, MATAGORDA BAY AREA

by

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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 third in a series of wetland status-and-trend investigations of inland wetlands along the Texas Coast (Tremblay et al., 2008, 2009). This report presents results of a status-and-trend study of the central Texas Coast along the inland wetland system from San Antonio Bay to Caney Creek (Fig. I).

The study area is characterized by Matagorda Bay, a large bay-estuary system dominated by the Colorado River valley and Lavaca River fluvial-deltaic system (McGowen et al., 1976a, b). The Lavaca and Navidad Rivers discharge into Matagorda Bay, and prior to diversion in 1992, the Colorado River discharged into the Gulf of Mexico. The study area encompasses most of the mainland between Matagorda Bay and the Texas General Land Office (GLO) Coastal Management Program (CMP) boundary, an area that is located within Matagorda, Calhoun, Jackson, and Victoria 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 Matagorda Bay to San Antonio Bay (White et al., 2002).

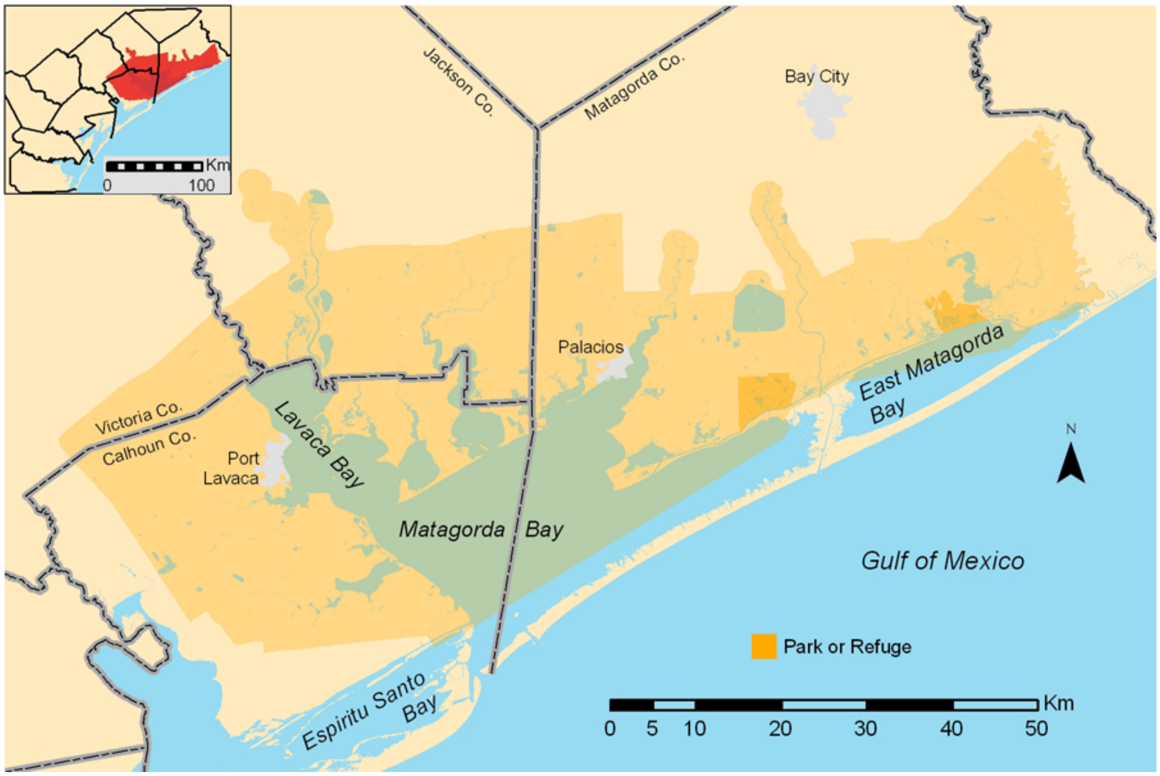

Figure I. Index map of study area.

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 2008. Historical distribution is based on 1956 black-and-white and 1979 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 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 2008 photographs.

Methods used to delineate 2008 habitats differed from earlier methods. The 2008 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 and 2008 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 trend analysis, 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, Matagorda Bay Area

The Matagorda Bay area is one of the most extensive bay-estuary systems along the central Texas Gulf Coast. Matagorda Bay is also one of the least-studied bays along the Texas Coast. Most of the marshland in the area falls within privately owned property, but large tracts of marsh are also found in Big Boggy National Wildlife Refuge (NWR), Mad Island Wildlife Management Area (WMA), and other smaller wildlife management areas (Fig. I). Extensive brackish- and salt-water marshes and ponds characterize the areas near bay margins. Most freshwater marshes occur inland of the bays.

Current Status, 2008

Major habitats in the study area include salt and fresh marshes and fresh open water. Forests are next in areal distribution (Fig. II). Tidal flats 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.

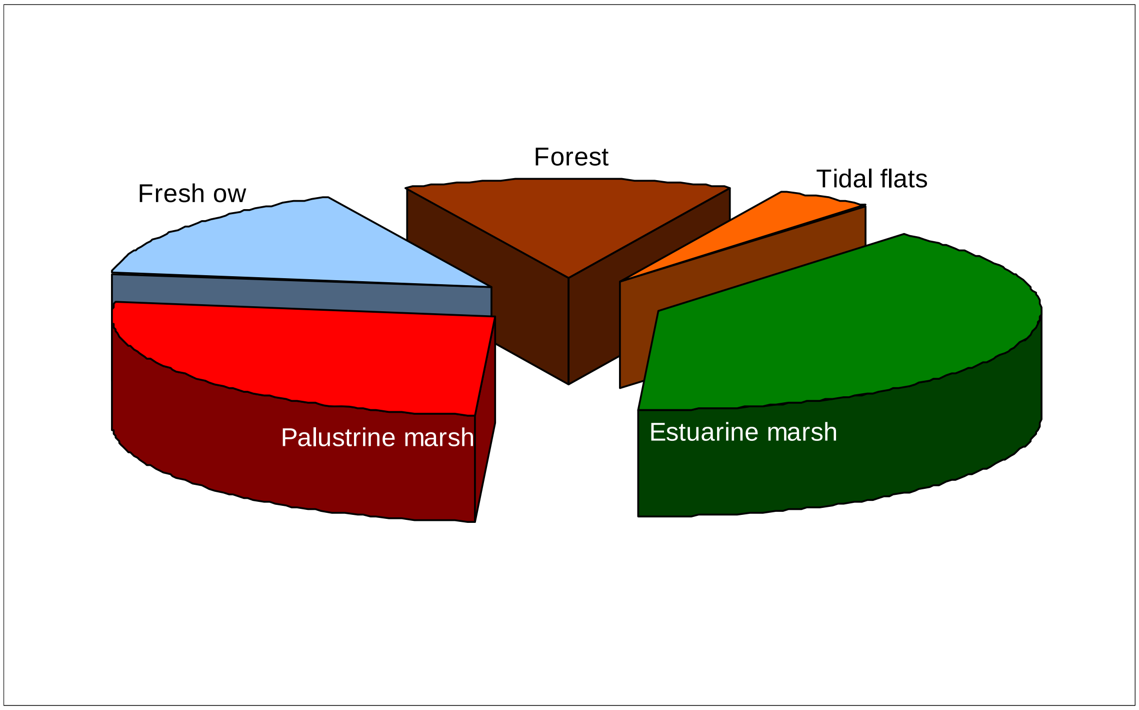

Figure II. Areal extent of selected habitats in the Matagorda Bay study area in 2008. Fresh open water (ow) in this figure includes palustrine, lacustrine, and riverine waters.

In 2008, wetland and aquatic habitats were dominated by estuarine marshes, with a total area of 17,195 ha (42,490 acres), followed by palustrine marshes totaling 11,384 ha (28,131 acres), fresh open water (ow) totaling 6,825 ha (16,865 acres), forest/scrub-shrub at 6,010 ha (14,851 acres), and tidal flats covering 1,764 ha (4,359 acres) (Fig. III).

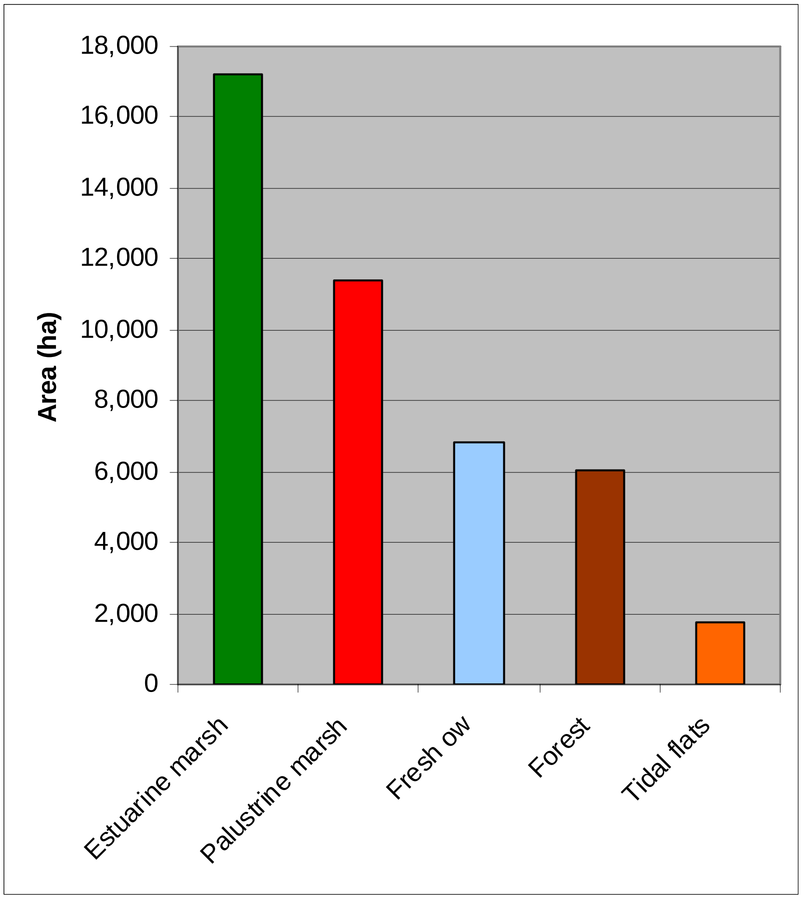

Figure III. Areal extent, in hectares, of habitats in 2008.

The most plentiful aquatic habitat was estuarine open water, covering 94,414 ha (233,302 acres). Cartographic error, at the study site scale, precluded comparisons of estuarine open-water area between study time periods. Lacustrine flats and algal beds had a total area of 545 ha (1,347 acres), and palustrine flats had a total area of 184 ha (455 acres).

The study area, covering estuarine systems of the Lavaca and Colorado Rivers, several smaller creeks, and marshes inland of the bays, was subdivided into geographic areas—Guadalupe, Lavaca, Carancahua, Tres Palacios, Colorado, and Brazos—to allow a more site-specific analysis of status and trends (Fig. IV).

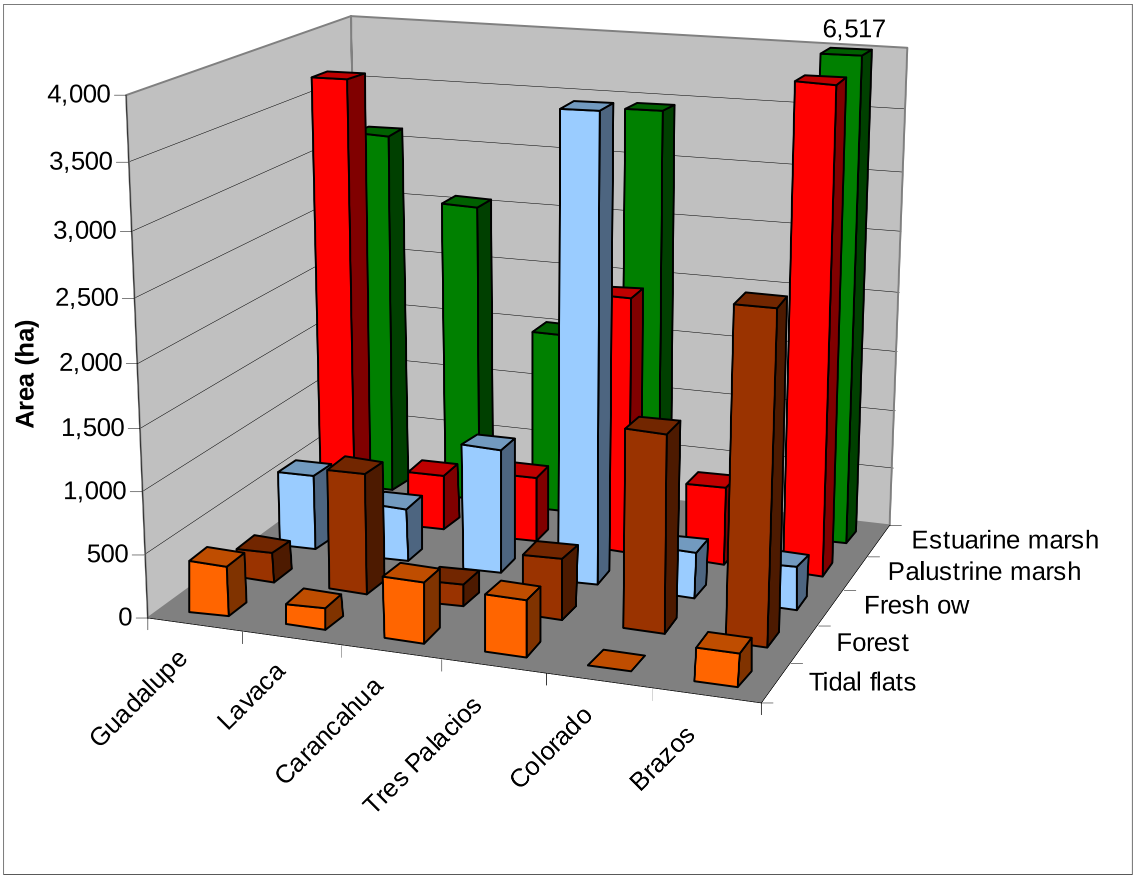

Figure IV. Distribution of selected habitats by geographic area in 2008. The most extensive distribution of estuarine and palustrine marshes and forest is in the Brazos area, with the highest amount of fresh open water in the Tres Palacios area. Tidal flats are most abundant in the Carancahua area.

The most extensive estuarine emergent wetlands occurred in the Brazos area, where the total area of estuarine marshes in 2008 was 6,517 ha (16,104 acres) (Fig. IV). Tres Palacios and Guadalupe areas contained the next-highest amounts of estuarine marsh with 3,464 ha (8,560 acres) and 3,109 ha (7,683 acres), respectively. Lavaca and Carancahua areas had significant amounts of estuarine marsh, 2,565 ha (6,338 acres) and 1,537 ha (3,798 acres), respectively (Fig. IV). Brazos and Guadalupe areas contain the largest amounts of palustrine marsh, with 3,910 ha (9,662 acres) and 3,708 ha (9,163 acres), respectively. The Tres Palacios area also contains a significant amount of palustrine marsh, with 2,115 ha (5,226 acres). The Tres Palacios area contains the largest amount of fresh open water at 3,749 ha (9,264 acres). Most of the water (2,412 ha [5,960 acres]) is contained in the cooling water reservoir for the South Texas Nuclear Generating Station (STNGS). The Carancahua area contains the second-highest amount of fresh open water, with 1,022 ha (2,525 acres). Forests are abundant in the Brazos area, where wetland trees and shrubs total 2,575 ha (6,363 acres). Colorado and Lavaca areas also contain significant forest, 1,554 ha (3,840 acres) and 980 ha (2,422 acres), respectively. Carancahua, with 481 ha (1,189 acres), Tres Palacios containing 444 ha

(1,097 acres), and Guadalupe with 404 ha (998 acres), had the largest amount of tidal flats (Fig. IV).

Wetland Trends and Probable Causes, 1956–2008

In trend analysis, 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. Estuarine marshes are by far the dominant class of emergent wetlands in the Matagorda Bay 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 2008, emergent wetlands (marshes) increased from about 27,942 ha (69,046 acres) to 28,579 ha (70,620 acres), a gain of approximately 637 ha (1,574 acres) (Fig. V, Table I). Marsh area fluctuated through the study time period. The rate of marsh gain from 1956 to 1979 was 172 ha/yr (425 acres/yr), and from 1979 to 2008, marsh losses were about (–)114 ha/yr (282 acres/yr). Fresh open water experienced a systematic increase in area through time. The gain in fresh open water was approximately 3,387 ha (8,370 acres). Rates of gain in fresh open water were about 94 ha/yr (232 acres/yr) during the earlier period and 42 ha/yr (104 acres/yr) during the later period. The overall fresh-open-water trend rate (1956–2008) was a gain of 65 ha/yr (161 acres/yr). The area of forest and scrub-shrub decreased substantially through time, from 8,734 ha (21,582 acres) in 1956 to 6,010 ha (14,851 acres) in 2008. Rates of change in forest were about (–)156 ha/yr (386 acres/yr) during the earlier period and (+)30 ha/yr (74 acres/yr) during the later period. Tidal flats decreased in area from 5,155 ha (12,738 acres) in1956 to 1,764 ha (4,358 acres) in 2008, a loss of about 3,391 ha (8,379 acres).

Analysis of habitat changes in the Matagorda Bay area shows a small increase in marshes from 1956 to 2008 (Fig. V). Complementing this trend in increasing emergent wetlands was an increase in fresh open water. The increase in fresh 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. Another significant contribution to the fresh open water area was construction of a cooling reservoir at the STNGS. Forested wetlands experienced losses over the study time period, which are mostly due to differences in mapping criteria. Mapping of palustrine forest from 1956 black-and-white photography precluded the distinction between upland forest and wetland forest. Therefore, all forest was included in the palustrine forested wetland class. Color infrared photography in 1979 and 2008 provide better distinction between upland and wetland forests. Although interpretational differences remain, palustrine forest and scrub-shrub habitat numbers are more consistent between 1979 and 2008. Roughly 90% of forest loss area between 1956 and 2008 was mapped as upland in 2008. Likewise, tidal flats suffered significant losses across the study area, as is the case along much of the Texas Coast. Of the flat loss area, roughly 70% was replaced by estuarine open water and estuarine marsh.

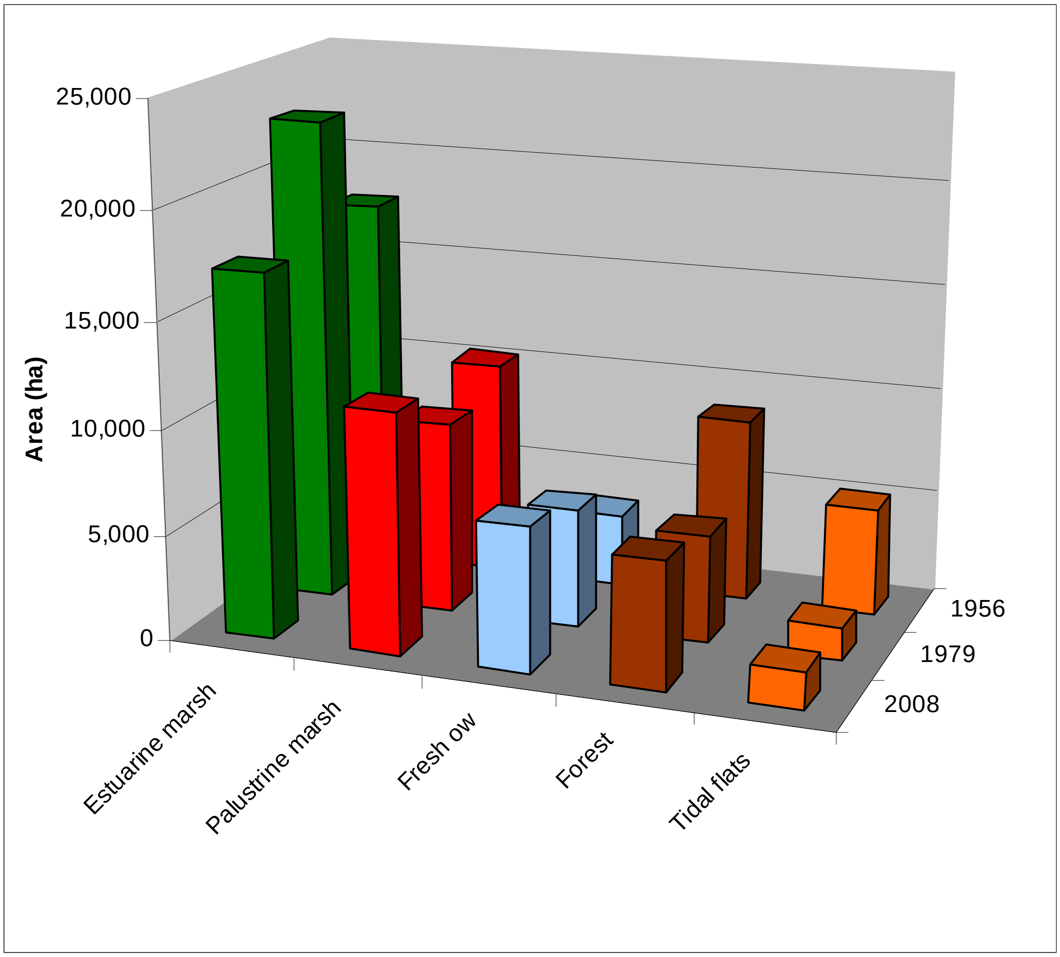

Figure V. Areal distribution of major habitats in the study area in 1956, 1979, and 2008.

Table I. Total area of major habitats in 1956, 1979, and 2008.

Habitat	*1950's*		*1979*		*2008*	
	ha	acres	ha	acres	ha	acres
Estuarine marsh	17,651	43,617	22,828	56,409	17,195	42,490
Palustrine marsh	10,291	25,430	9,065	22,400	11,384	28,131
Fresh ow	3,438	8,496	5,609	13,860	6,825	16,865
Forest	8,734	21,582	5,145	12,714	6,010	14,851
Tidal flats	5,155	12,738	1,544	3,815	1,764	4,359

On a local scale, expansion of estuarine open water since 1956 has reduced the amount of palustrine and estuarine marshland in the area around Menefee Flat (Fig. VI). Subsidence due to subsurface fluid withdrawal, combined with relative sea-level rise, increased the frequency of flooding. Rate of subsidence and relative sea-level rise apparently exceeded the rate of marsh vertical accretion, and the marsh was replaced primarily by open water.

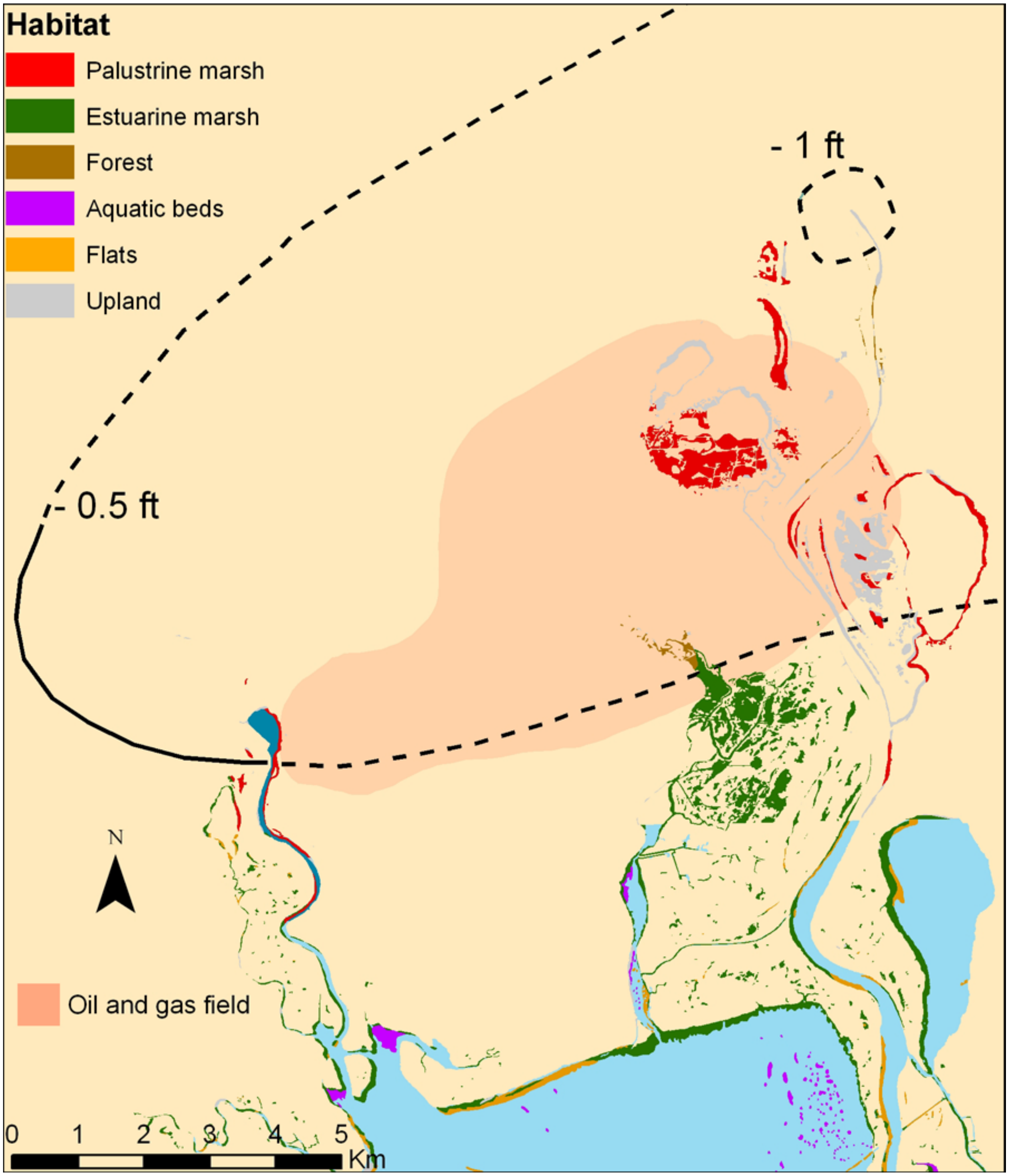

Figure VI. Movement of estuarine open water into marsh habitats near Menefee Flat. The dashed and dotted line is land-surface subsidence 1918–1973 (Ratzlaff, 1980). Map shows 1956 habitat that was replaced by estuarine open water in 2008.

Overlay analysis of 1956 and 2008 data sets in the Lavaca geographic area reveals that roughly 47% of the area of increase in estuarine open water was in areas previously mapped as estuarine marsh.

STATUS AND TRENDS OF INLAND WETLAND AND AQUATIC HABITATS, MATAGORDA BAY AREA

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, 2009). 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 Matagorda Bay area from San Antonio Bay to Caney Creek.

Figure 1. Temporary-tidal palustrine marsh (PEM1S), tributary to Carancahua Bay, Jackson 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; Tremblay et al., 2008) 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 2008 and on historical wetlands mapped on photographs taken in 1956 and 1979. The 1956 and 1979 series USFWS maps, which are in digital format, were partly revised in this project to be more consistent with wetlands interpreted and delineated on 2008 photographs. Revisions are discussed in more detail in the methods section. The USFWS National Wetlands Inventory (NWI) maps, based on 1992 photographs, were used as collateral data in the delineation of wetlands.

Study Area

The study area is characterized by Matagorda Bay, a large bay-estuary system dominated by the Colorado River valley and Lavaca River fluvial-deltaic system (McGowen et al., 1976a, b). The Lavaca and Navidad Rivers discharge into Matagorda Bay, and prior to diversion in 1992, the Colorado River discharged into the Gulf of Mexico. The study area encompasses most of the mainland between Matagorda Bay and the Texas General Land Office (GLO) Coastal Management Program (CMP) boundary, an area that is located within Matagorda, Calhoun, Jackson, and Victoria Counties (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.

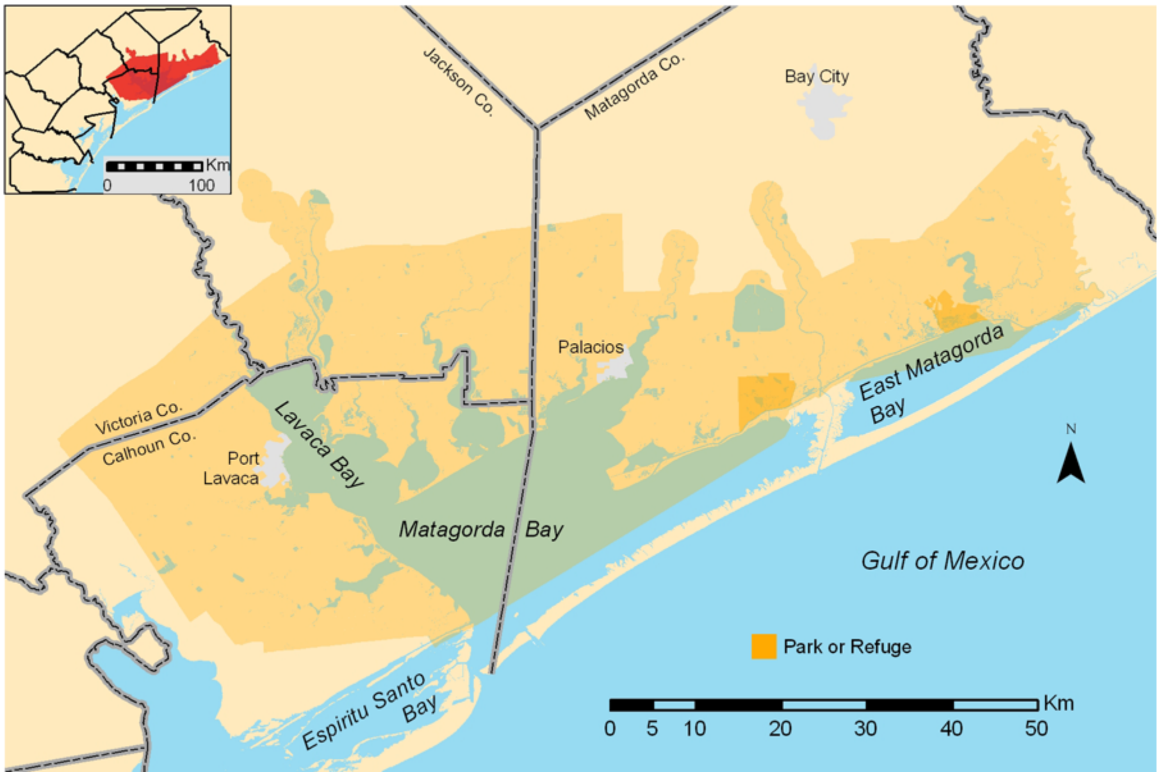

Figure 2. Index map showing study area.

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, and 2008. Maps of the 1979 time period were prepared from a combination of sources. Final maps of the 1979 series were digitized and initially analyzed in 1983 (USFWS, 1983, unpublished digital data of wetland maps) under the NWI program. Some of the 1979 maps were prepared by BEG from hardcopy 1988–1989 Submerged Lands of Texas maps (White et al. 1988, 1989), with reference to contemporaneous NASA color infrared photography. In the bay-estuary system, maps for 1956 were prepared from multiple sources. Most maps were obtained through the digitization efforts of the NWI program (USFWS, 1983, unpublished digital data of wetland maps). Where lacking, a scanned and georeferenced, unfolded hardcopy of the *Environmental Geologic Atlas of the Texas* (EGAT) (McGowen et al., 1976a, b) 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 2008.

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 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 USFWS wetland maps. Methods used by the USFWS include interpretation and delineation of wetlands and aquatic habitats on aerial photographs through stereoscopic interpretation. Field reconnaissance is an integral part of interpretation. Photographic signatures are compared 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

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

communication, 1997). The 1979 aerial photographs are NASA CIR stereo-pair images, 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 it produced more standing water than in the 1956 and 2008 photographs. Although 1956 photographs are black and white, they are large scale (1:24,000), thus aiding in the photointerpretation and delineation process. The 1956 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 down through the 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) so that agreement would be closer between historical map units and current (2008) 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. For 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. Revised data were entered into the GIS.

Current Wetland Distribution (Status)

Current distribution of wetlands is based on digital, CIR, 1-m-resolution aerial photographs taken in 2008, which 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 1:5,000. 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.

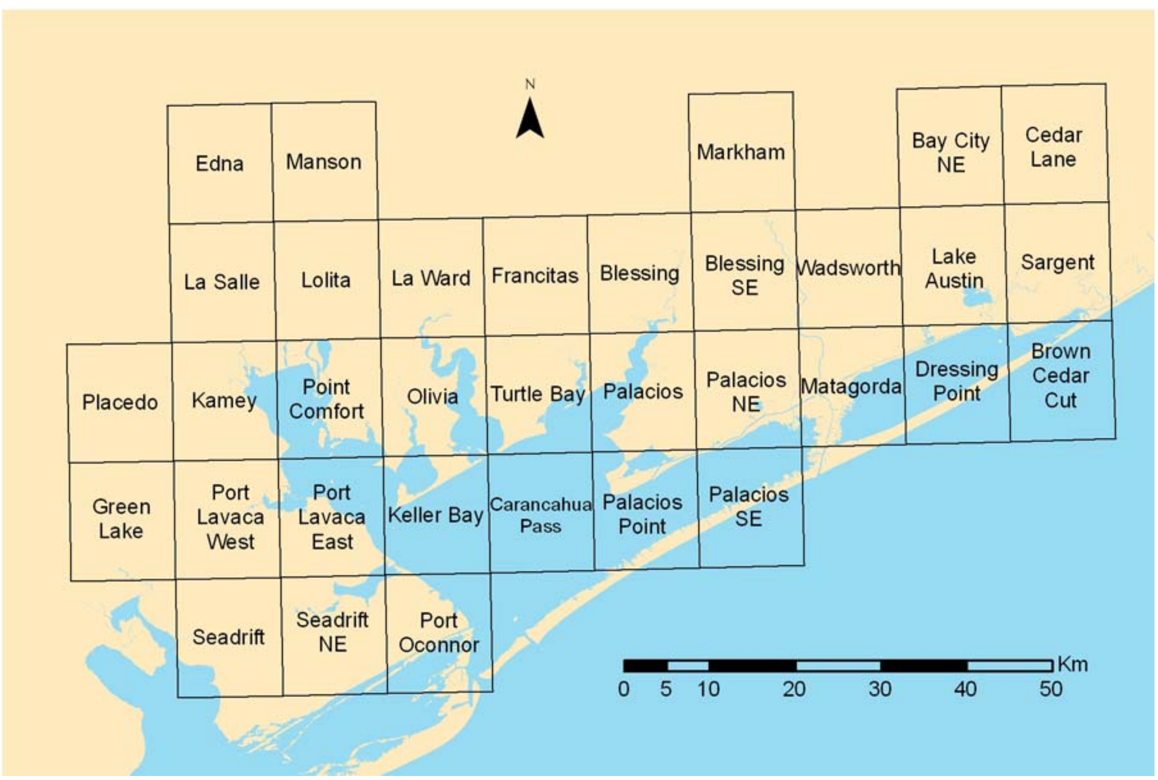

Figure 3. Index map of USGS 7.5-minute quadrangles that encompass the study area.

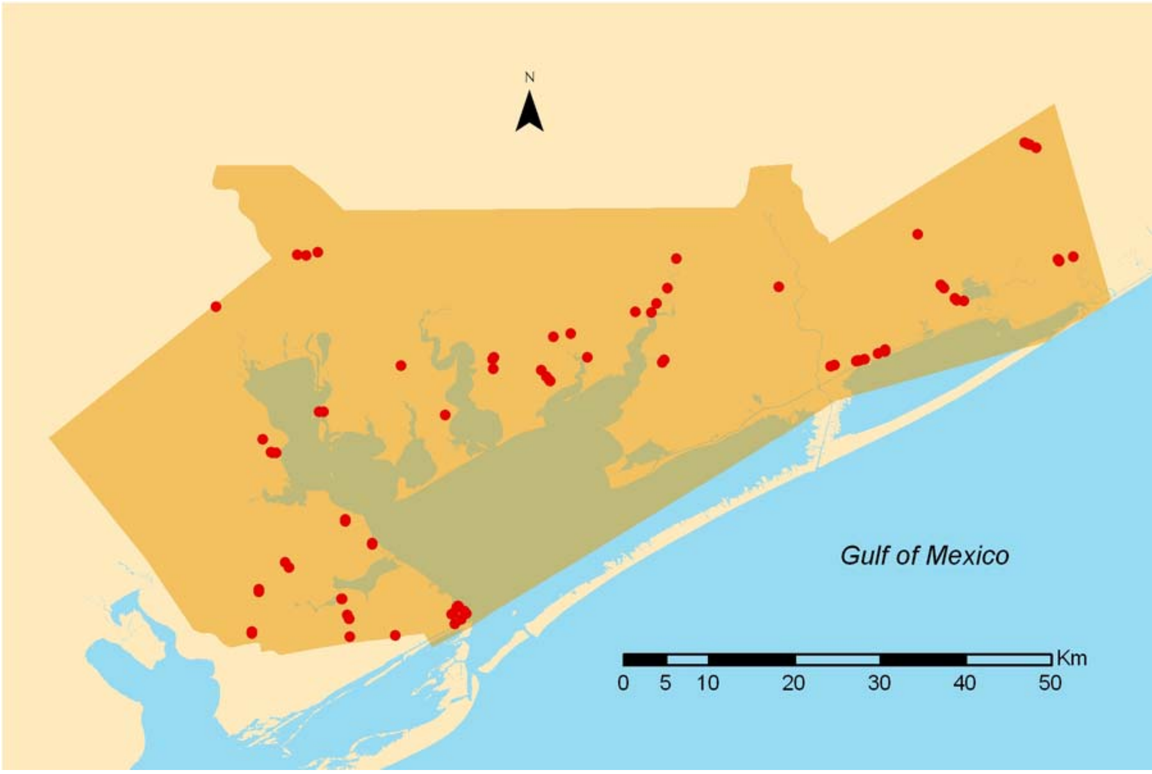

Figure 4. Index map of field-survey sites along the central coast used for ground-truthing aerial-photo delineations and recording vegetation composition and water regimes.

Variations in Classification

Classification of wetlands varied somewhat for the different years. On 1979 and 2008 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 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 maps were combined into a single class—unconsolidated shore—on 2008 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 wetland maps.

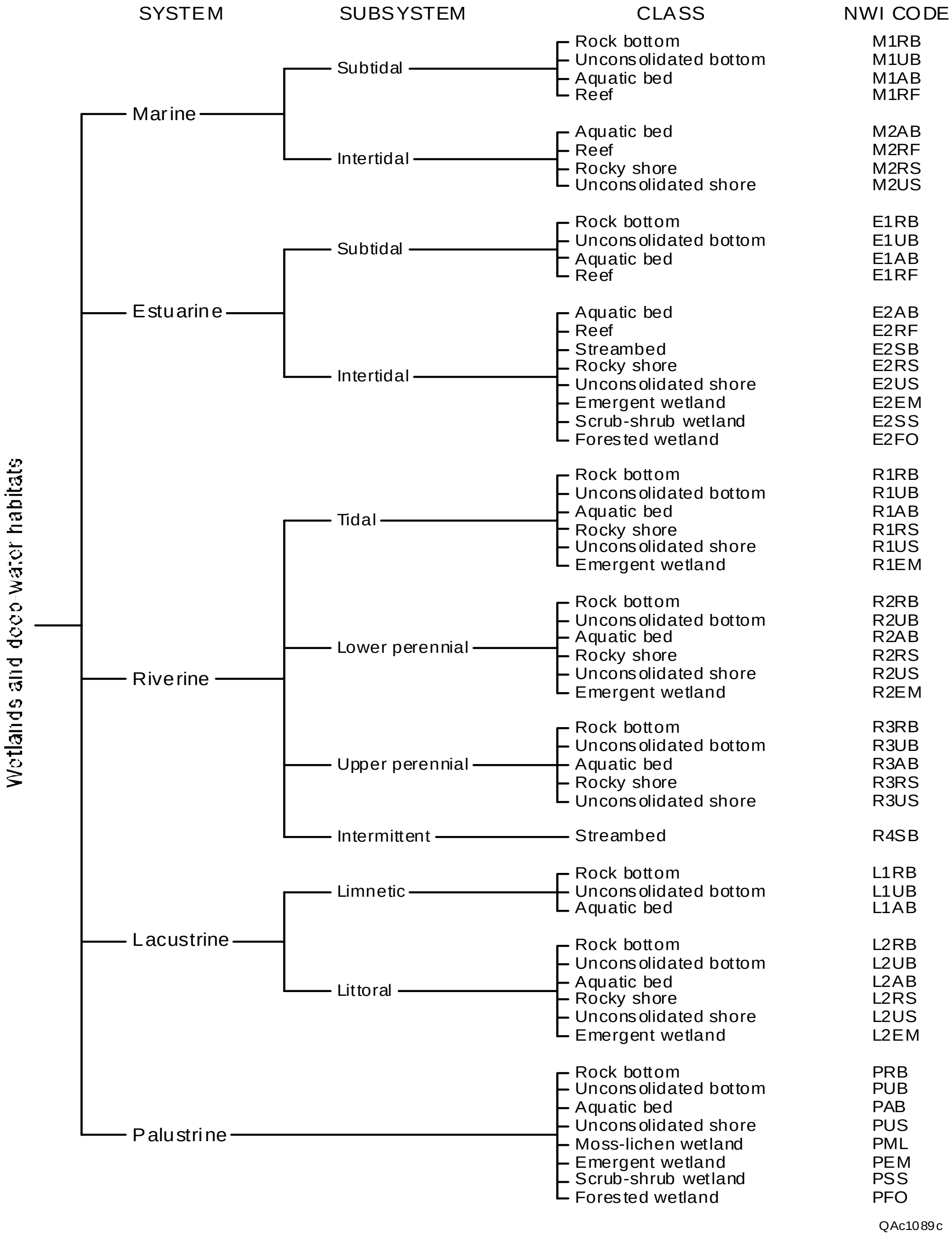

Figure 5. Classification hierarchy of wetlands and deepwater habitats showing systems, subsystems, and classes. From Cowardin et al. (1979).

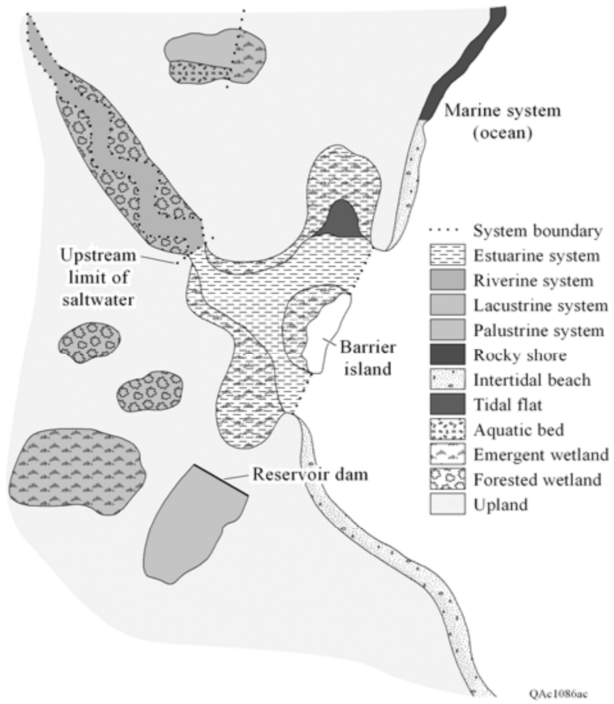

Figure 6. Schematic diagram showing major wetland and deepwater habitat systems. From Tiner (1984).

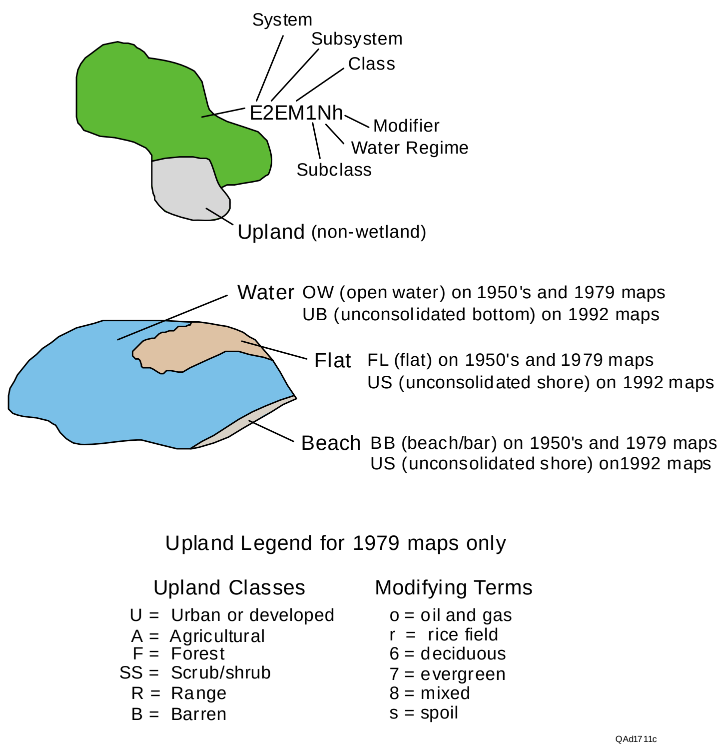

Figure 7. Example of symbology used to define wetland and upland habitats on NWI maps.

Results include GIS data sets consisting of electronic-information overlays corresponding to mapped habitat features for 1956, 1979, and 2008. 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 wary 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 historical and recent digital data, which cause errors when data sets are overlaid and analyzed in a GIS. The 2008 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 2008 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. USFWS digital data sets were reregistered by georeferencing them to the USGS DOQQ's, improving agreement of the historical maps with the 2008 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.

Methods Used to Analyze Historical Trends in Wetland Habitats

Trends in wetland habitats were determined by analyzing habitat distribution as mapped on 2008, 1979, and 1950's aerial photographs. In trend analysis, 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 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 the drier conditions when the 2008 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 photointerpretation and map preparation.

Wetland Codes

As mentioned in the introduction, some wetland codes used on 2008 maps are different from those used on the 1950’s and 1979 maps (Fig. 7). In the following discussion of trends, E2US rather than E2FL (used on the 1950’s and 1979 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 and 2008. 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 2008 delineations, which varied in some cases from 1956 and 1979 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 2008 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 central 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 (Fig. 8). 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 (Figs. 8, 9).

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 *Baccharis halimifolia* (eastern false willow), *Sesbania drummondii* (drummond's rattle-bush), and *Tamarix* spp. (salt cedar) (Fig. 10).

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. Transitional area from low salt marsh (E2EM1N) to high flat (E2USP) and high salt marsh (E2EM1P) near McNabb Lake.

Figure 9. *Spartina spartinae*-dominated transitional high salt marsh (E2EM1P) south of Lake Austin (in distance).

Figure 10. *Spartina spartinae*- and *Baccharis halimifolia*-dominated transitional area between high salt marsh (E2EM1P) and scrub-shrub (E2SS).

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). 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 (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-, or semipermanent-tidal (PEMS, PEMR, and PEMT).

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. 11). 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. 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. 12, 13).

Figure 11. Palustrine marsh along secondary bay of Turtle Bay. The dominant vegetation is *Tyhpa* sp.

Figure 12. *Salix nigra* (black willow) on Peyton Creek, source of Lake Austin, Matagorda County.

Figure 13. Palustrine forest (PFO1A) on Peyton Creek. Vegetation is dominated by *Celtis laevigata* (hackberry) 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 data sets), depending on water depth. Bodies of water with vegetation are classified in the subclass of algal (L2AB1), floating (L1AB4), or unknown (L2AB5) aquatic bed. The impounded modifier (h) is used for bodies of water impounded by levees or artificial means, and the (s) modifier is used when the impoundment contains dredge material. 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). Aquatic bed (AB) and unconsolidated bottom (UB) subclasses are present. Major rivers/streams found in the Matagorda Bay area are the Lavaca-Navidad and Colorado Rivers and Garcitas, Carancahua, Tres Palacios, and Peyton Creeks.

FLUVIAL-DELTAIC AND BAY-ESTUARY SYSTEMS

Study Area

The Matagorda Bay area is one of the most extensive bay-estuary systems along the central Texas Gulf Coast. Matagorda Bay is also one of the least-studied bays along the Texas Coast. Most of the marshland in the area falls within privately owned property, but large tracts of marsh are also found in Big Boggy NWR, Mad Island WMA, and other smaller wildlife management areas (Fig. 2). Extensive brackish- and salt-water marshes and ponds characterize the areas near bay margins. Most freshwater marshes occur inland of the bays.

General Setting of Fluvial-Deltaic and Bay-Estuary Systems

Geologically, the central Texas coast is characterized by a modern bay-estuary system formed around Matagorda Bay and the fluvial-deltaic system containing the Colorado River (Figs. 14, 15) (McGowen et al.,1976a and 1976b). Relict Pleistocene-age river valleys that were not filled with Holocene–Modern fluvial-deltaic sediments form present-day bays and estuaries (White et al., 1988). Flood-prone areas inland from the bays are the site of salt, brackish, and freshwater wetlands. The study area extends landward from the Gulf Intracoastal Water Way (GIWW) to the GLO coastal management zone boundary.

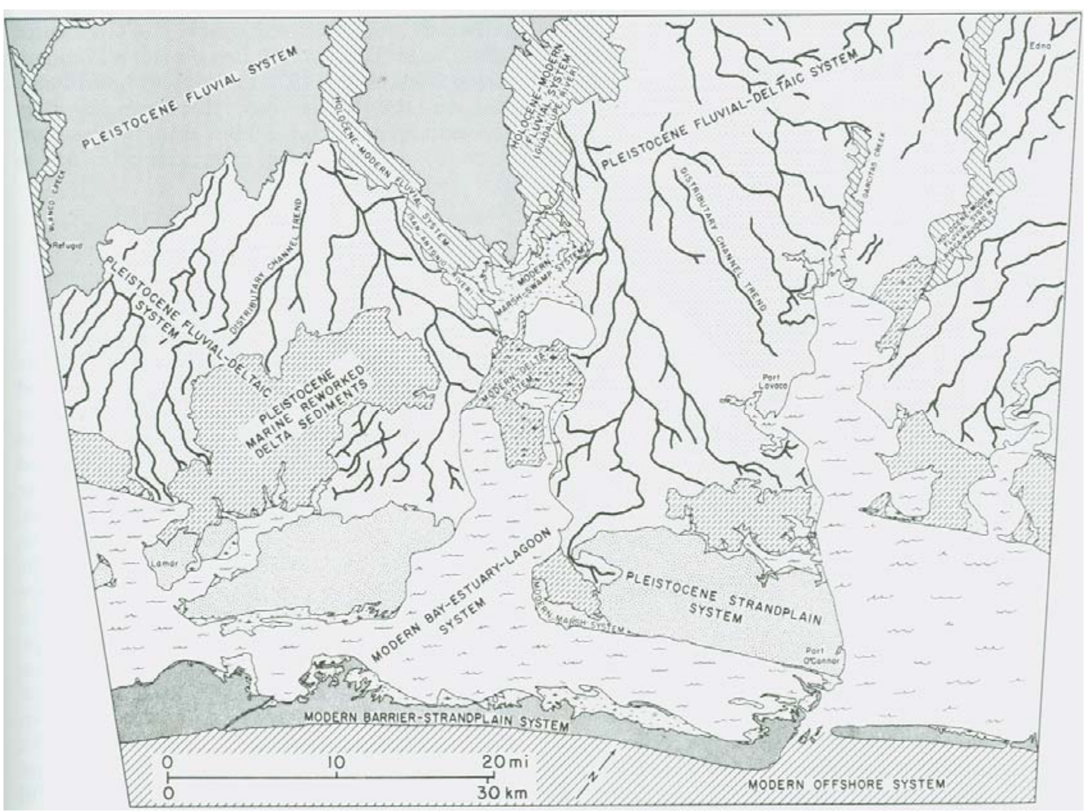

Figure 14. Natural systems in the Port Lavaca area (from McGowen et al.,1976b).

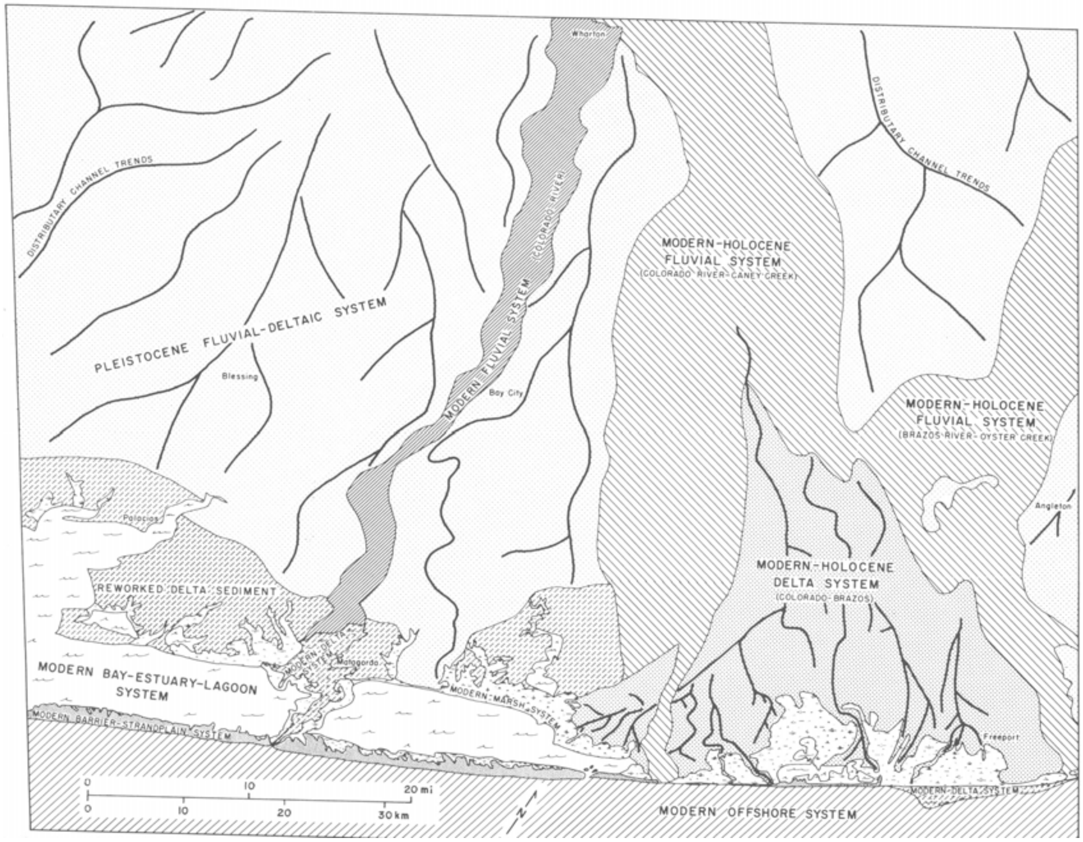

Figure 15. Natural systems in the Bay City-Freeport area (from McGowen et al.,1976a).

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 worldwide (eustatic) 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 Rockport, located along the landward shore of Aransas Bay, provides the longest continuous record of sea-level variations near the study area. The average rate of sea-level rise from the 1950's through 1993 (with data missing in the late 1950's and early 1960's) is about 0.40 cm/yr. Rates of sea-level rise recorded by the tide gauge reached a high of 1.7 cm/yr from the mid-1960's to mid-1970's (Fig. 16); this time coincides with a maximum change in some habitats, such as wind-tidal flats (White et al., 1998). The relative rise in sea level at Rockport as of 1999 averaged 4.6 mm/yr (Zervas, 2001). 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 impact that relative sea-level rise has on wetland habitats is presented in the discussion of wetland trends.

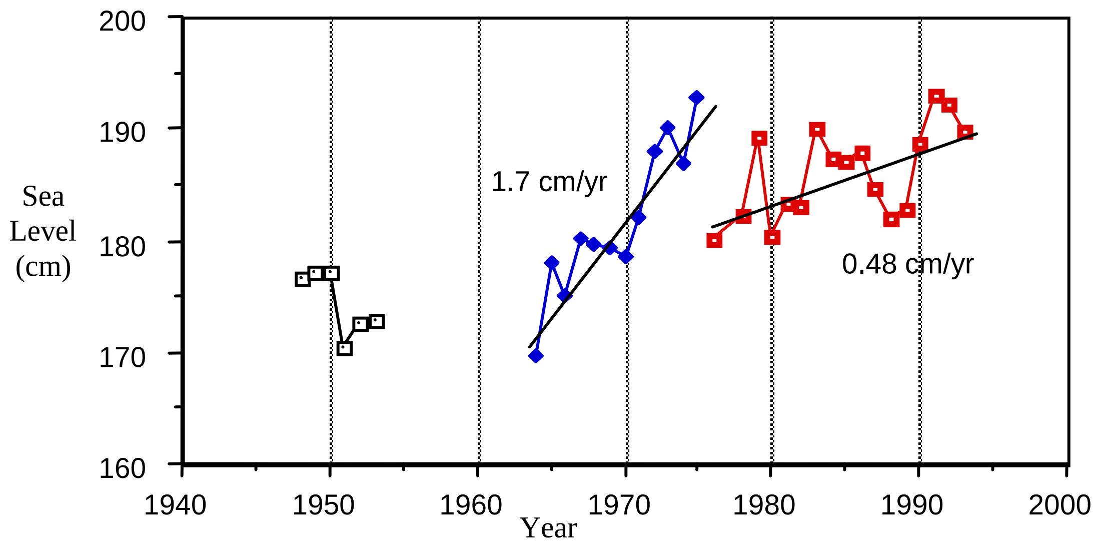

Figure 16. Sea-level rise at the Rockport tide gauge located near the landward margin of Aransas Bay. Tide data from NOAA.

Subsidence

Subsidence of varying amounts has occurred along the entire Texas Coast, including the Matagorda Bay area, where land-surface subsidence between 1918 and 1973 was generally less than 0.15 m. Localized subsidence exceeds 30 cm (1 ft). Estuarine open water inundated many other habitats between 1956 and 2008 near Menefee Flat (Fig. 17).

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 Menefee Flat area is primarily oil and gas production that began in the early part of the 20th century (Ratzlaff, 1980). Menefee Flat is discussed later in further detail.

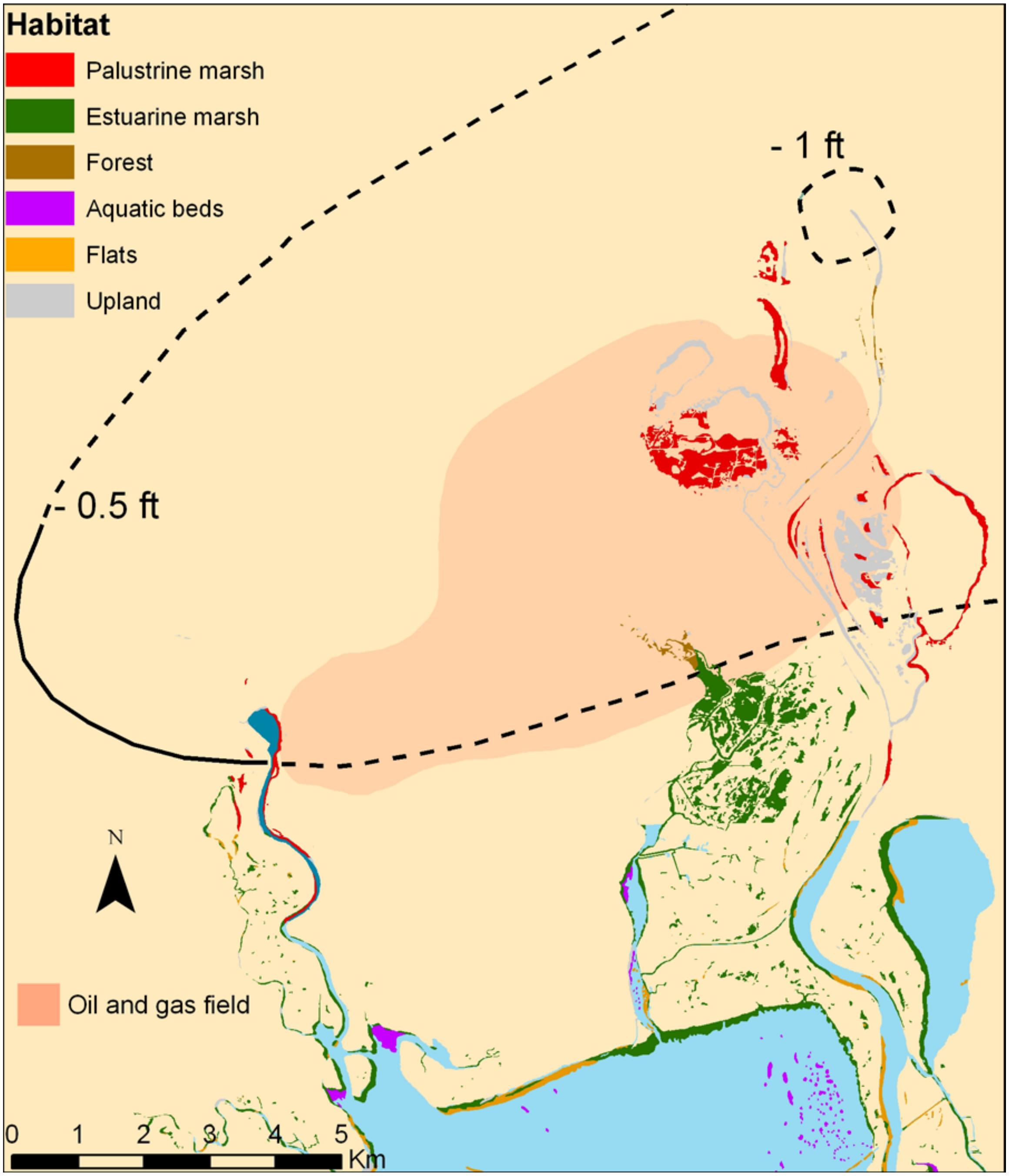

Figure 17. Movement of estuarine open water into marsh habitats near Menefee Flat. The dashed and dotted line is land-surface subsidence 1918–1973 (Ratzlaff, 1980). Map shows 1956 habitat that was replaced by estuarine open water in 2008.

Status of Wetlands and Aquatic Habitats, 2008

In 2008, wetland and aquatic habitats covered about 138,326 ha within the study area (Fig.18, Table 3). Approximately 223,753 ha within the study area was classified as uplands. Of the three wetland systems mapped, the estuarine system is the largest (Fig. 19; Table 4). Palustrine marshes and freshwater habitats are also found in significant numbers. Emergent vegetated wetlands (E2EM, PEM, PFO areas) cover about 34,589 ha, 50% of which is estuarine marsh. The extent of all mapped wetlands, deepwater habitats, and uplands for each year is presented in the appendix. The largest area of estuarine habitat by far is estuarine open water (E1UB), covering roughly 94,414 ha. Other major estuarine habitats in the study area include estuarine marsh and tidal flats (E2US) (Figs. 18, 19). Major palustrine habitats include freshwater marsh and forest/scrub shrub. Freshwater habitats, consisting of lacustrine, riverine, and palustrine habitats, had a total area of 6,825 ha. The study area was subdivided into geographic areas—Guadalupe, Lavaca, Carancahua, Tres Palacios, Colorado, and Brazos—to provide for a more site-specific analysis of status and trends (Figs. 20, 21; Table 5).

Estuarine System

Marshes (Estuarine Intertidal Emergent Wetlands)

The estuarine intertidal emergent wetland habitat (E2EM) consists of 17,195 ha of salt and brackish marshes (Figs. 18, 19). The regularly flooded estuarine marsh, or low marsh, is most abundant at 9,010 ha (Table 3). The irregularly flooded estuarine marsh, or high marsh, covers 8,185 ha. The most extensive estuarine emergent wetlands (salt and brackish marshes) occur in the Brazos area (Figs. 20, 21). The estuarine intertidal marsh habitat makes up about 12% 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 1,764 ha of E2US was mapped in the study area (Table 3). High, irregularly 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 about 9% 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 (E1AB) represent areas of 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 252 ha of seagrass (E1AB3) 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. Several bays, part of the GIWW and other channels, and Lake Austin waters are included. The total area of estuarine open water is 94,414 ha, which is about 68% of all mapped habitats in the study area, excluding uplands.

Table 3. Areal extent of mapped wetland and aquatic habitats, 2008.

NWI Code	National Wetlands Inventory Description	Hectares	Acres	%
E1AB1	Estuarine Subtidal Aquatic Bed, Algal	31	76	0
E1AB3	Estuarine Subtidal Aquatic Bed, Rooted Vascular	252	623	0
E1AB4	Estuarine Subtidal Aquatic Bed, Floating Vascular	9	22	0
E1AB5	Estuarine Subtidal Aquatic Bed, Unknown Submergent	17	42	0
E1UB	Estuarine Subtidal Unconsolidated Bottom	94,105	232,439	68
E2AB1	Estuarine Intertidal Aquatic Bed, Algal	177	437	0
E2EM1N	Estuarine Intertidal Emergent Wetland, Regularly Flooded	9,010	22,255	7
E2EM1P	Estuarine Intertidal Emergent Wetland, Irregularly Flooded	8,185	20,218	6
E2SS	Estuarine Intertidal Scrub-Shrub	5	12	0
E2USM	Estuarine Intertidal Flat, Irregularly Exposed	104	256	0
E2USN	Estuarine Intertidal Flat, Regularly Flooded	413	1,020	0
E2USP	Estuarine Intertidal Flat, Irregularly Flooded	1,044	2,579	1
Subtotal		**113,378**	**280,043**	**82**
L1AB4	Lacustrine Limnetic, Aquatic Bed, Floating Vascular	35	87	0
L1UB	Lacustrine Limnetic Unconsolidated Bottom	3,737	9,231	3
L2AB1	Lacustrine Littoral Aquatic Bed, Algal	63	155	0
L2AB5	Lacustrine Littoral Aquatic Bed, Unknown Submergent	109	270	0
L2UB	Lacustrine Littoral Unconsolidated Bottom	452	1,116	0
L2USK	Lacustrine Littoral Flat, Artificially Flooded	373	922	0
Subtotal		**4,769**	**11,780**	**3**
PAB1F	Palustrine Aquatic Bed, Algal, Semipermanently Flooded	10	25	0
PAB3H	Palustrine Aquatic Bed, Rooted Vascular	3	6	0
PAB4F	Palustrine Aquatic Bed, Floating Vascular	48	119	0
PAB5	Palustrine Aquatic Bed, Unknown Submergent	28	69	0

PEM1A	Palustrine Emergent Wetland, Temporarily Flooded	4,630	11,435	3
PEM1C	Palustrine Emergent Wetland, Seasonally Flooded	4,117	10,169	3
PEM1F	Palustrine Emergent Wetland, Semipermanently Flooded	1,574	3,888	1
PEM1K	Palustrine Emergent Wetland, Artificially Flooded	180	445	0
PEM1R	Palustrine Emergent Wetland, Seasonal-Tidal	178	439	0
PEM1S	Palustrine Emergent Wetland, Temporary-Tidal	72	178	0
PEM1T	Palustrine Emergent Wetland, Semipermanent-Tidal	633	1,564	0
PFO1A	Palustrine Forested, Broad-Deciduous, Temp Flooded	5,143	11,435	3
PFO1C	Palustrine Forested, Broad-Deciduous, Seasonally Flooded	366	905	0
PFO1F	Palustrine Forested, Broad-Deciduous, Semipermanently Flooded	5	12	0
PFO1R	Palustrine Forested, Broad-Deciduous, Seasonal-Tidal	3	7	0
PFO4A	Palustrine Forested, Needle-Evergreen, Temp Flooded	1	2	0
PSS1A	Palustrine Scrub-Shrub, Broad-Deciduous, Temp Flooded	365	902	0
PSS1C	Palustrine Scrub-Shrub, Broad-Deciduous, Season Flooded	123	303	0
PSS1F	Palustrine Scrub-Shrub, Broad-Deciduous, Semipermanently Flooded	3	7	0
PSS1R	Palustrine Scrub-Shrub, Broad-Deciduous, Seasonal-Tidal	1	2	0
PUB	Palustrine Unconsolidated Bottom	60	148	0
PUBC	Palustrine Unconsolidated Bottom, Seasonally Flooded	12	31	0
PUBF	Palustrine Unconsolidated Bottom, Semipermanently Flooded	151	374	0
PUBH	Palustrine Unconsolidated Bottom, Permanently Flooded	563	1,389	0
PUBK	Palustrine Unconsolidated Bottom, Artificially Flooded	1,011	2,496	1
PUBV	Palustrine Unconsolidated Bottom, Permanent-Tidal	13	32	0
PUS	Palustrine Flat	86	212	0
PUSC	Palustrine Flat, Seasonally Flooded	14	35	0
PUSK	Palustrine Flat, Artificially Flooded	83	206	0
Subtotal		**19,476**	**48,105**	**14**
R1AB5	Riverine Tidal Aquatic Bed, Unknown Submergent	20	48	0
R1UBV	Riverine Tidal Unconsolidated Bottom, Permanent-Tidal	280	691	0
R2AB5	Riverine Lower Perennial Aquatic Bed, Unknown Submergent	1	3	0
R2UBH	Riverine Lower Perennial Unconsolidated Bottom, Permanently Flooded	402	994	0
Subtotal		**703**	**994**	**1**
Total		**138,326**	**341,665**	**100**

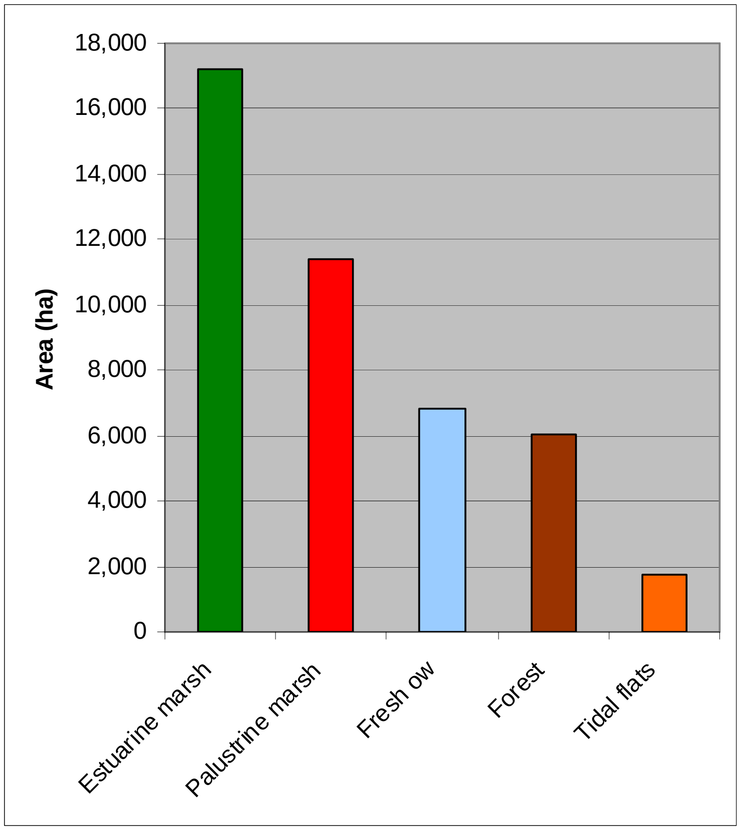

Figure 18. Areal distribution of selected habitats in the study area in 2008.

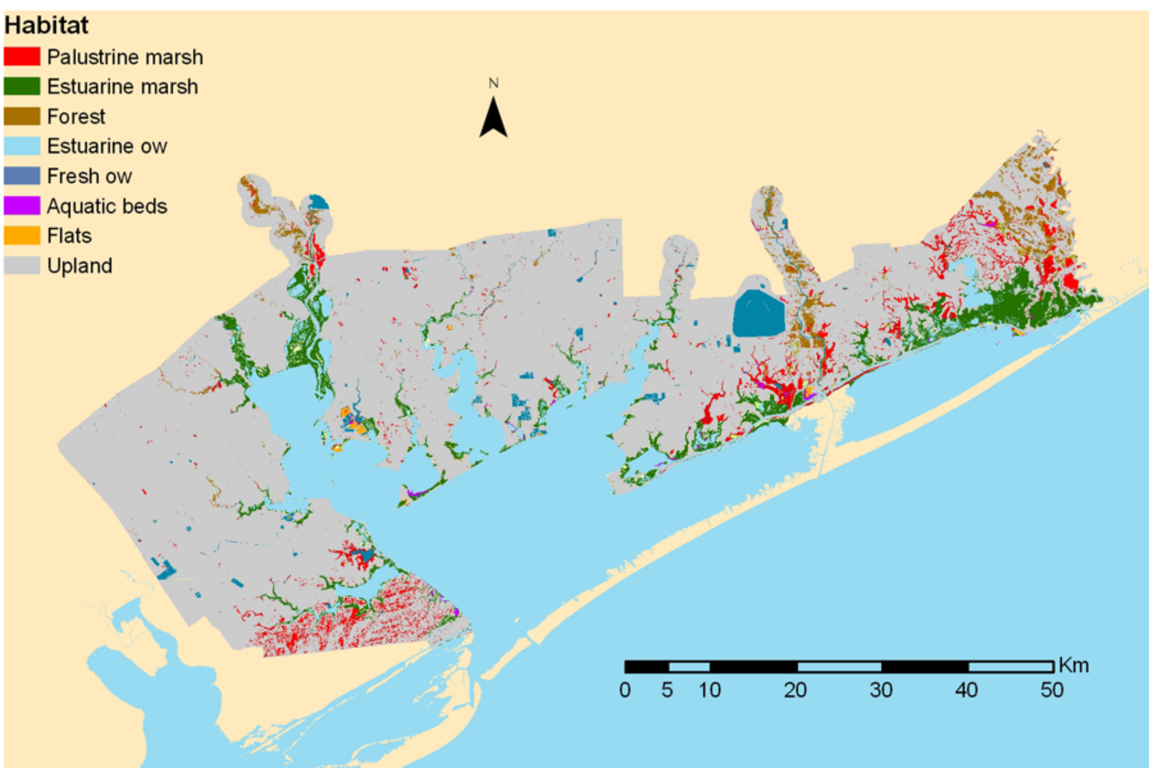

Figure 19. Distribution of major habitats in 2008.

Table 4. Areal extent (ha) of selected habitats, 2008.

Habitat	Area (ha)
Estuarine open water	94,414
Estuarine marsh	17,195
Palustrine marsh	11,384
Fresh open water	6,825
Forest	6,010
Tidal flats	1,764

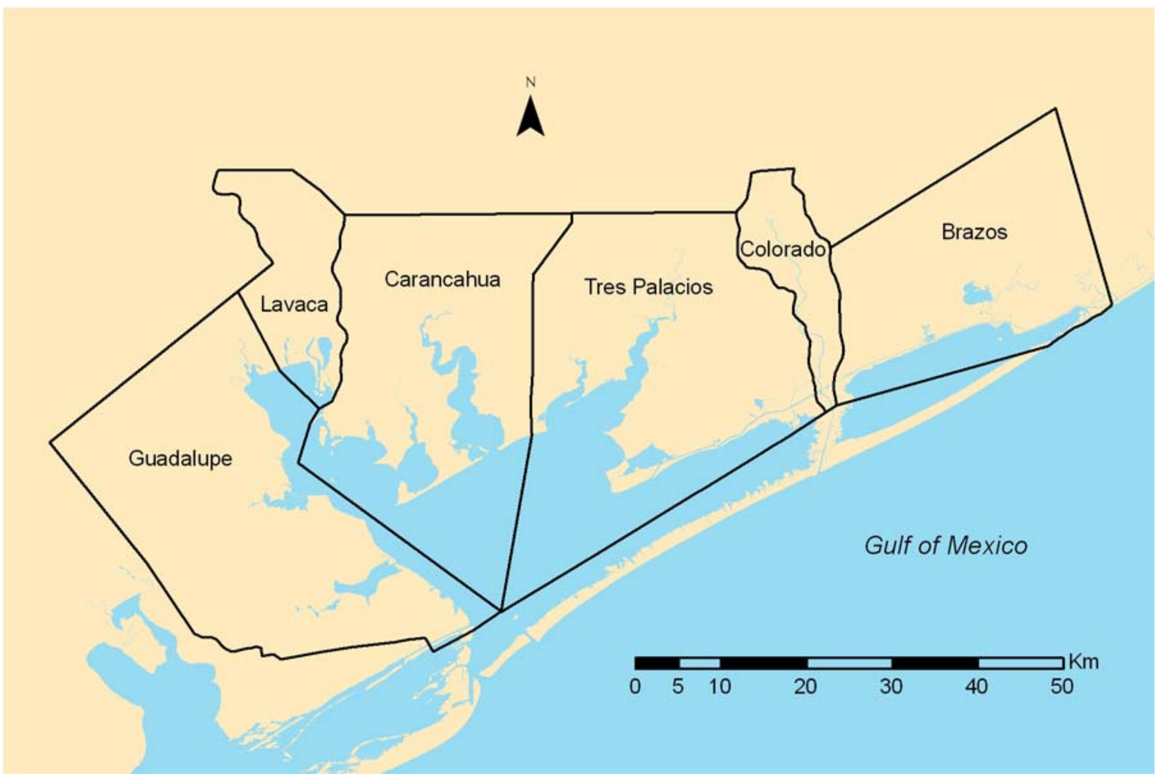

Figure 20. Map showing boundaries of different geographic areas investigated.

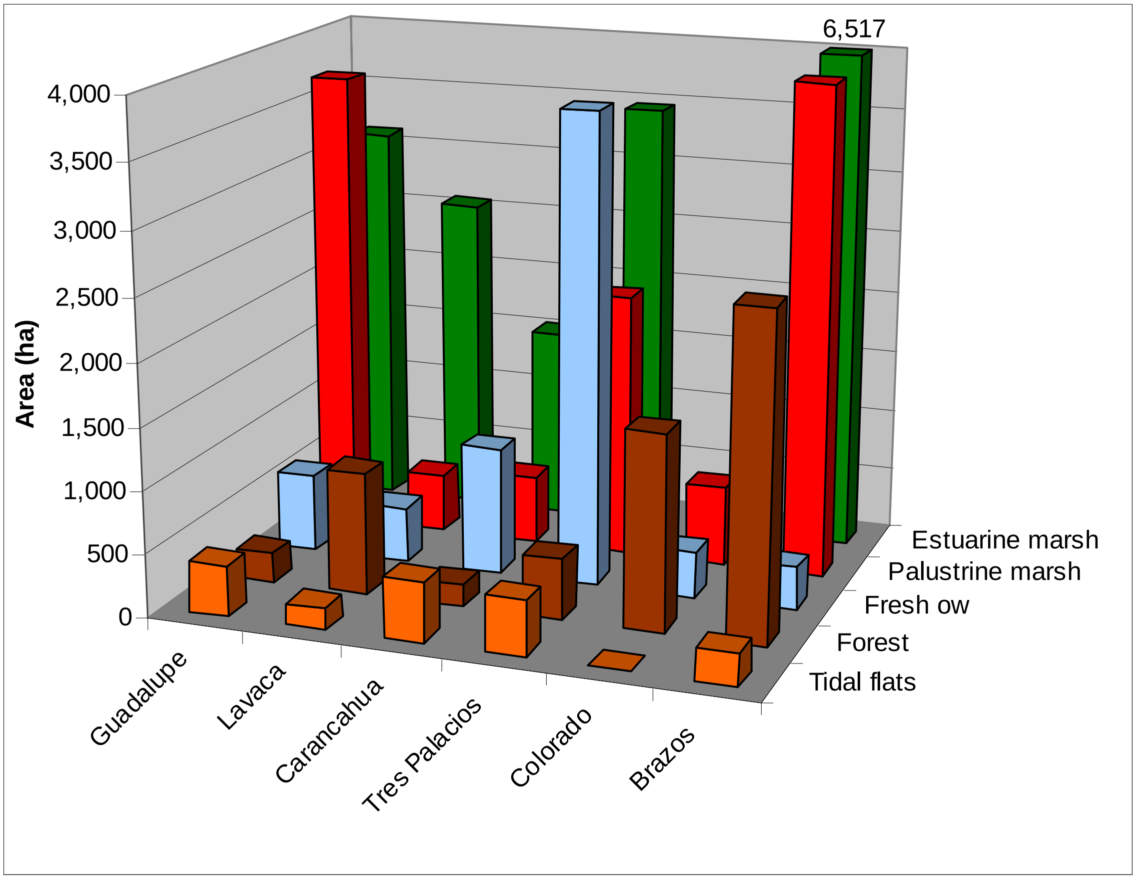

Figure 21. Areal distribution of selected habitats by geographic area in 2008. The most extensive distribution of estuarine marsh is in the Brazos area.

Table 5. Areal extent (in hectares) of selected habitats by geographic area, 2008.

Location	Estuarine marsh	Palustrine marsh	Fresh open water	Forest	Tidal flats	Total
Brazos	6,517	3,910	344	2,575	253	**7,082**
Tres Palacios	3,464	2,115	3,749	483	444	**6,791**
Guadalupe	3,109	3,708	625	236	404	**4,973**
Colorado	4	643	366	1,554	6	**2,569**
Carancahua	1,537	541	1,022	180	481	**2,224**
Lavaca	2,565	466	441	980	169	**2,056**

Palustrine System

Marshes (Palustrine Emergent Wetlands)

Palustrine emergent wetlands (PEM), or "freshwater marshes," cover 11,384 ha (Fig. 18; Table 4) and represent 33% 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 5,519 ha (Fig. 18; Table 4). Forests were primarily classified into broad-leaved deciduous and needle-leaved evergreen trees. Palustrine scrub-shrub (PSS) habitat covers 492 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 1,994 ha, almost 87% of which was water in permanently or artificially 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 flats, include lakes and inland reservoirs greater than 20 acres (8.33 ha). Lakes and flats associated with lakes cover 4,490 ha. Lakes are further classified according to depth. One cooling reservoir at the STNGS accounts for 54% of the total lacustrine open water and flat area.

River (Riverine Tidal and Lower Perennial)

Riverine tidal unconsolidated bottom (R1UB) and aquatic beds (R1AB) and lower perennial unconsolidated bottom (R2UB) and aquatic beds (R2AB), or rivers, cover 703 ha. Lower perennial rivers compose about 57% 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. Estuarine marshes are 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 (marshes) classes in the trend analysis. 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 17,651 ha in 1956 to 22,828 ha in 1979, then decreased to 17,195 ha in 2008 (Figs. 22, 23; Table 6). Palustrine marsh showed a reverse trend from estuarine marsh, with a decline from 10,291 ha in 1956 to 9,065 ha in 1979, and increased to 11,384 ha in 2008. Fresh open water (lacustrine, palustrine, and riverine) experienced a systematic gain in area through time. The gain in open water was approximately 3,387 ha, almost double the 1956 amount. Rates of change in open water were about a 94-ha/yr gain during the earlier period and 42-ha/yr gain during the later period. The long-term (1956–2008) rate of fresh open-water gain is 65 ha/yr. Forest experienced a long-term decrease in area of (–)2,724 ha. The 1956 total of 8,734 ha was reduced to 5,145 ha in 1979, with a rebound by 2008 to 6,010 ha. Change rates of (–)156 ha/yr for the early period was followed by (+)30 ha/yr during the later period. The overall (1956–2008) change rate was a loss of 52 ha/yr, or (–)31% of the original resource. Much of the change in forest habitat is due to differing mapping criteria between time periods. As is the case in many other regions of the Texas coast, tidal flats suffered severe loss of area through time. Tidal flats covered 5,155 ha in 1956, they were reduced to 1,544 ha by 1979, and they increased to 1,764 ha by 2008. The overall tidal flat resource was reduced by (–)66%. Estuarine open water experienced a systematic gain of roughly 6% through time partly because of wetter conditions since 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 at the expense of marshes since 1956 was due to subsidence and relative sea-level rise. However, the extremely large area encompassed by estuarine open water increases accumulative cartographic error. Therefore, overall change in estuarine open water is not emphasized. Trends in estuarine open water at the local scale are addressed later.

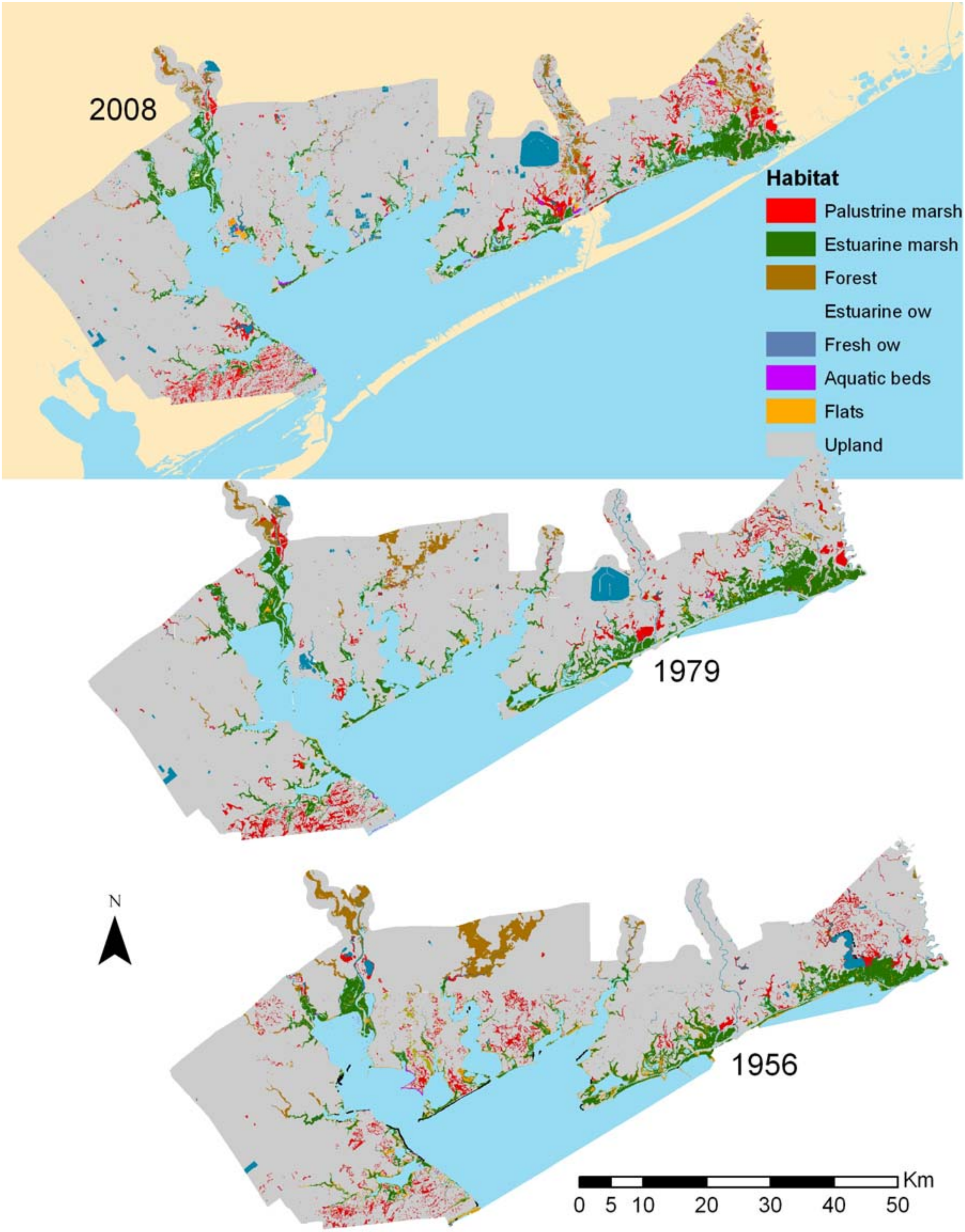

Figure 22. Maps showing distribution of major wetland and aquatic habitats in 2008, 1979, and 1956 in the Matagorda Bay area.

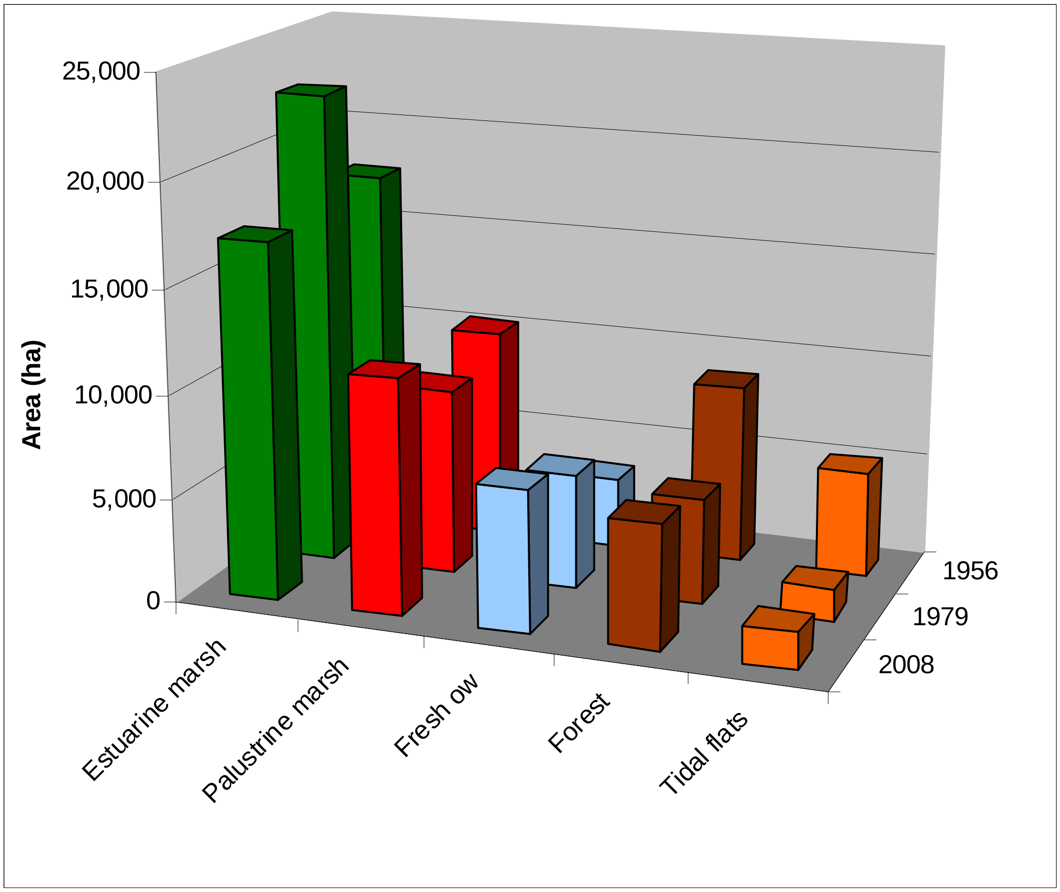

Figure 23. Areal distribution of habitats in the study area in 1956, 1979, and 2008.

Table 6. Total area (ha) of major habitats in 1956, 1979, and 2008.

Habitat	*1956*		*1979*		*2008*	
	ha	acres	ha	acres	ha	acres
Estuarine marsh	17,651	43,598	22,828	56,385	17,195	42,472
Palustrine marsh	10,291	25,419	9,065	22,391	11,384	28,118
Fresh ow	3,438	8,491	5,609	13,853	6,825	16,858
Forest	8,734	21,574	5,145	12,709	6,010	14,845
Tidal flats	5,155	12,733	1,544	3,814	1,764	4,356

Analysis of trends in wetlands and aquatic habitats in the bay-estuary system shows that there was a slight net increase (~2%) in marshes from 1956 through 2008, when emergent wetlands (marshes) increased from about 27,942 to 28,579 ha, a gain of approximately 637 ha (Fig. 24). Marsh area fluctuated through the study time period. The rate of marsh gain from 1956 to 1979 was 172 ha/yr, and from 1979 to 2008 marsh lost about (–)114 ha/yr. The long-term (1956–2008) change rate of marsh was a gain of 12 ha/yr.

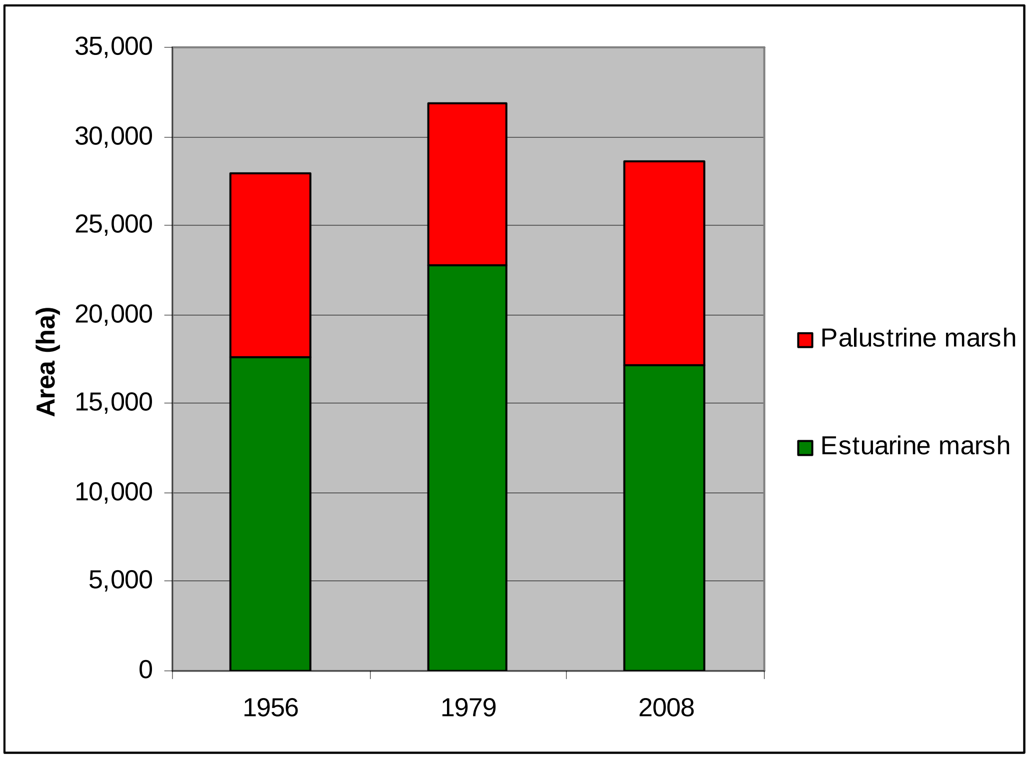

Figure 24. Areal distribution of marsh habitats in the study area in 1956, 1979, and 2008.

Probable Causes of Trends

An analysis of habitat changes along the central Texas coast shows an increase in marshes from 1956 to 2008 (Fig. 24). Overlay analysis of the 1956 and 2008 maps to identify the cause of the changes shows that about 74% of the increase in palustrine marsh (PEM) was due to conversion from uplands and a smaller amount from estuarine marsh (E2EM) (16%). Gain of palustrine marsh in uplands may be due to wetter conditions after the 1950's. Expansion of palustrine marsh into uplands may also have occurred because of Brazos River delta subsidence (Brown et al., 1974).In *Natural Hazards of the Texas Coastal Zone*, Brown et al. (1974) placed the 0.2 to 1.0 ft. maximum land subsidence contour between Lake Kilbride and Lake Austin. Palustrine marsh increased in areas of previous estuarine marsh in national and state reserve areas, such as Big Boggy National Wildlife Refuge, as a result of habitat management practices. The loss of estuarine marsh since 1956 was due partly to relative sea-level rise and partly to interpretational differences. The primary loss of estuarine marsh was conversion to upland (35%). An area near Oyster Lake was mapped in the EGAT (McGowen et al., 1976a) as areas with possibly thin marsh veneers. This change from estuarine marsh to upland is due to different mapping criteria. The area was mapped as upland in subsequent years. In other areas along the East Matagorda Bay section of the GIWW, estuarine marsh was lost to dredge material disposal. Nearly one-third of the loss of estuarine marsh was to estuarine open water, mostly along bay margins and in areas of local subsidence. The lower Lavaca River valley and the East Matagorda Bay shore are two examples. More than 19% of estuarine marsh loss resulted in the conversion to palustrine marsh, mostly in managed areas where hydrologic controls altered the salinity regime. Fresh open water increased significantly between 1956 and 1979 as a result of the construction of a cooling reservoir at the South Texas Nuclear Generating Station. Wetter surface conditions in later years and construction of additional reservoirs increased the amount of mapped open-water through time.

Forests experienced the most change (–41%) during the early time period between 1956 and 1979. In 1956 all forests, including many upland forests, were mapped as palustrine forest. This practice was continued in 1979, but not to as large an extent as in 1956. Palustrine forest mapping in 2008 was guided by 1996 photography, which more clearly displays reflectance differences between upland and wetland forests, and palustrine forest could be distinguished from upland forest. Forest loss is examined in more detail at the local scale.

Tidal flats suffered significant losses across the study area, as is the case along much of the Texas Coast. Of the flat loss area, roughly 36% was replaced by estuarine open water, and 34% was replaced by estuarine marsh. Note that because the areal extent of tidal flats varies with tidal conditions, tide levels at the time the photos were taken may have contributed to this difference in mapped tidal flats.

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. 25)—modified watershed boundaries. The county line separates Carancahua and Tres Palacios areas in what would otherwise be a single watershed. The Matagorda Bay area is presented from southwest to northeast in the following order: (1) Guadalupe, (2) Lavaca, (3) Carancahua, (4) Tres Palacios, (5) Colorado, and (6) Brazos. The subdivisions allowed a more site-specific analysis of trends and their probable causes. Estuarine and palustrine marshes, fresh-open-water, forest, and tidal-flat areas are emphasized.

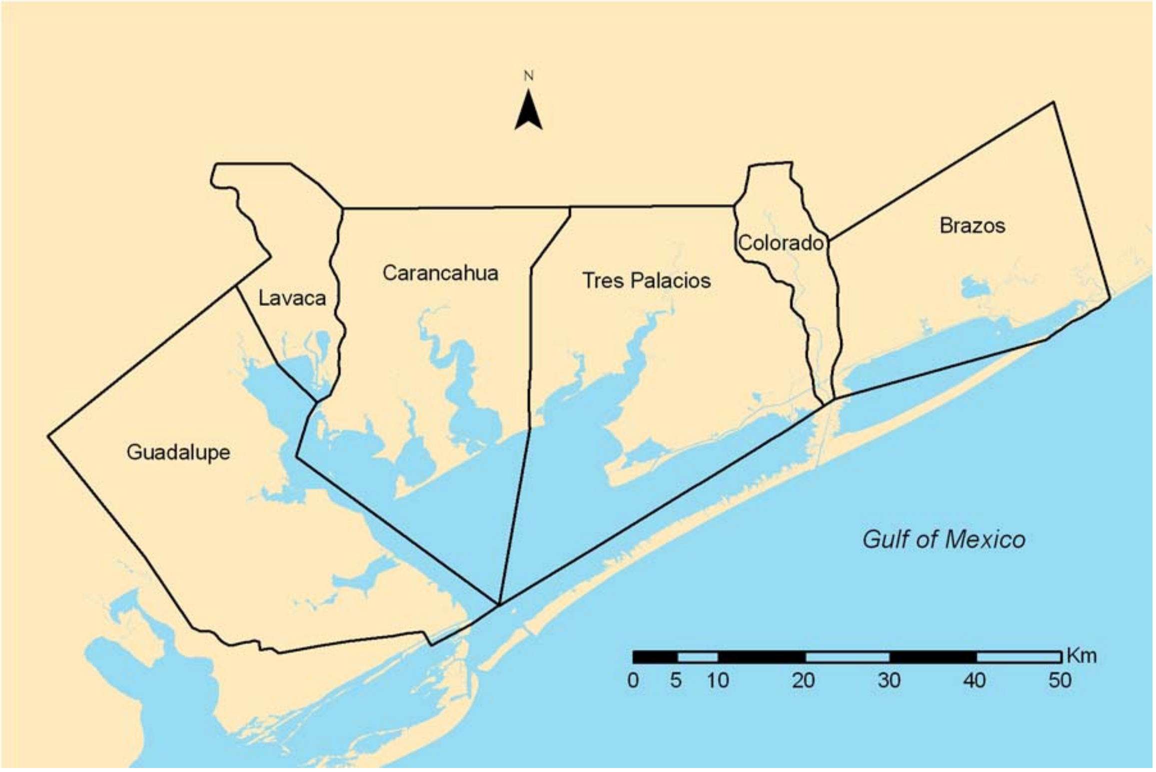

Figure 25. Map showing boundaries of different geographic areas investigated.

Guadalupe

The Guadalupe area is the westernmost subarea within the study area. Major water bodies include Lavaca Bay, Matagorda Bay, Powderhorn Lake, and Garcitas Creek (Fig. 26). Salt marshes are found along the periphery of Lavaca Bay, along secondary bays like Powderhorn Lake, and in the lower reaches of Garcitas Creek. To the south, fresh marshes occupy depressions in relict beach ridges that are characteristic of the Ingleside Barrier Strandplain (White et al., 1989). The Guadalupe area is characterized by Lavaca Bay and the Ingleside Barrier Strandplain, starting at the marsh complex at the mouth of Garcitas Creek, continuing along the western periphery of Lavaca Bay, and extending to the estuarine marshes along the margin of Powderhorn Lake (Fig. 27). Fresh marshes dominate the Ingleside Barrier Strandplain (Fig. 28).

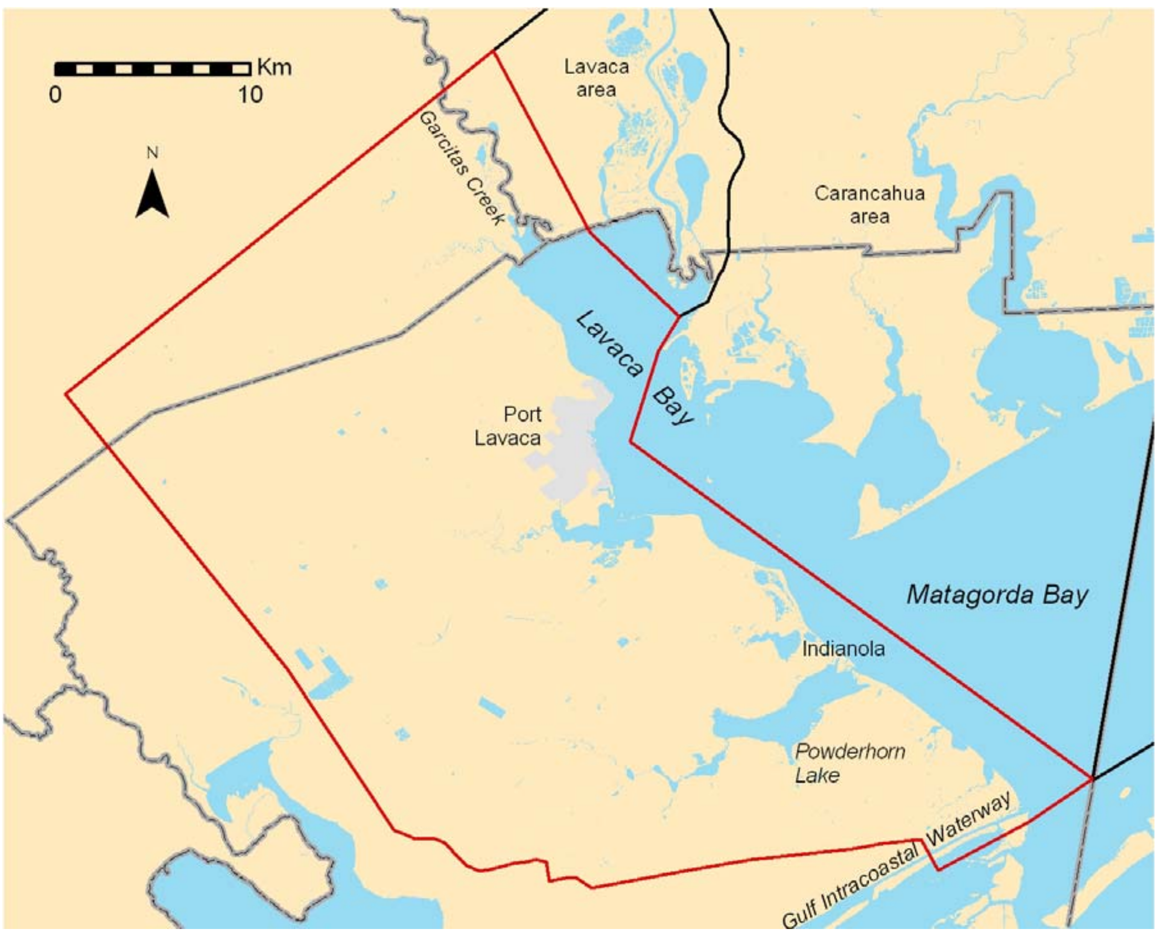

Figure 26. Locator map showing geographic features in the Guadalupe study area.

Figure 27. High salt marsh (E2EM1P) near Old Town Lake, north of Indianola.

Figure 28. Fresh marsh (PEM1A) on Ingleside Barrier Strandplain.

The most significant change in wetland habitat in the Guadalupe area is the decrease in tidal flats (E2US). Between 1956 and 2008, tidal flats decreased in area from 1,462 to 404 ha (Fig. 29), representing a decrease of (–)72%. Most of the decrease (34%) resulted in movement of estuarine marsh into flats owing to relative sea-level rise and had occurred by 1979. Conversion to uplands, through dredge-material disposal, also significantly reduced tidal-flat numbers. Fresh open water (palustrine, riverine, and lacustrine) increased from 361 ha in 1956 to 625 ha in 2008. The long-term increase (1956–2008) represents a 73% gain in the resource. The increase is due mostly to the isolation of a secondary bay north of Powderhorn Lake from Lavaca Bay. As of 1979, marshes in this isolated bay were mapped as estuarine. By 1992, the bay had become fresh and was mapped as lacustrine.

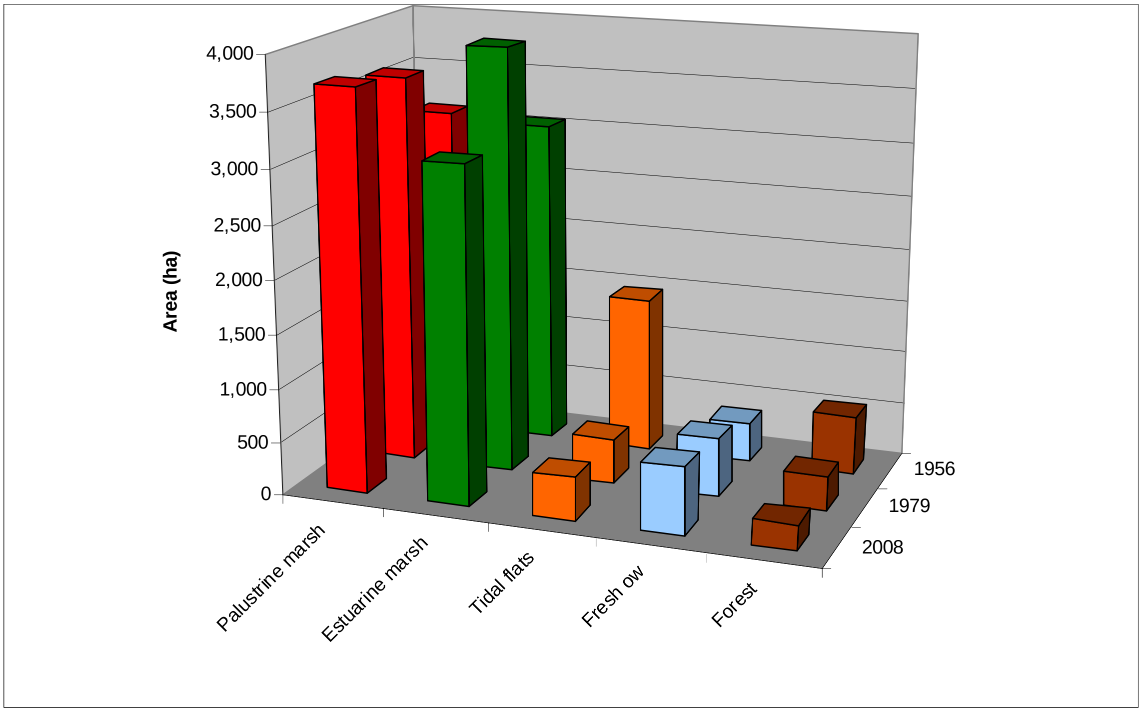

Figure 29. Areal extent of major habitats in the Guadalupe area in 1956, 1979, and 2008.

Palustrine marsh experienced a less dramatic change through time—in this case, a systematic gain of marsh. Palustrine marsh occupied 3,109 ha in 1956, 3,624 ha in 1979, and 3,708 ha by 2008, a 19% gain of the resource over the study time period. A rate of (+)22 ha/yr in the early time period was followed by a much lower rate of (+)3 ha/yr in the later period. Much of the gain in palustrine marsh was from areas that were once uplands (83%) and from estuarine marsh (10%). Most of the change from upland occurred on the barrier/strandplain. Conversion from estuarine marsh took place in the isolated bay just mentioned as the system freshened through time. Estuarine marsh retained relatively constant amounts across the study time period. The 1956 total of 3,051 ha had increased to 3,954 ha by 1979 then decreased to 3,109 ha by 2008, although the location of estuarine marsh changed through time. Estuarine marsh occurred farther up Garcitas Creek, in areas previously mapped as upland and palustrine marsh.

Movement of estuarine marsh farther upriver is likely the result of relative sea-level rise. The area, within the (–)0.5 ft subsidence contour (Riggio et al., 1987), is near West Ranch oil and gas field. Many tidal flats on the margin of Powderhorn Lake had been replaced by estuarine marsh by 2008.

Most forest (PFO) decline in the Guadalupe area occurred between 1956 and 1979, when 545 ha was reduced to 317 ha and then was further reduced to 236 ha by 2008. The overall loss of forest resource was (–)57%. Most forest change in the Guadalupe area is due to differences in mapping criteria between time periods.

Lavaca

Major water bodies in the Lavaca area include Lavaca Bay, the Lavaca River, and Swan Lake (Fig. 30). Salt marshes and tidal flats are found along the lower reaches of the Lavaca River. Farther upriver, brackish-water marshes become dominant near Menefee Flat. To the north, fluvial woodlands containing a variety of tree species occupy the entrenched Lavaca River valley.

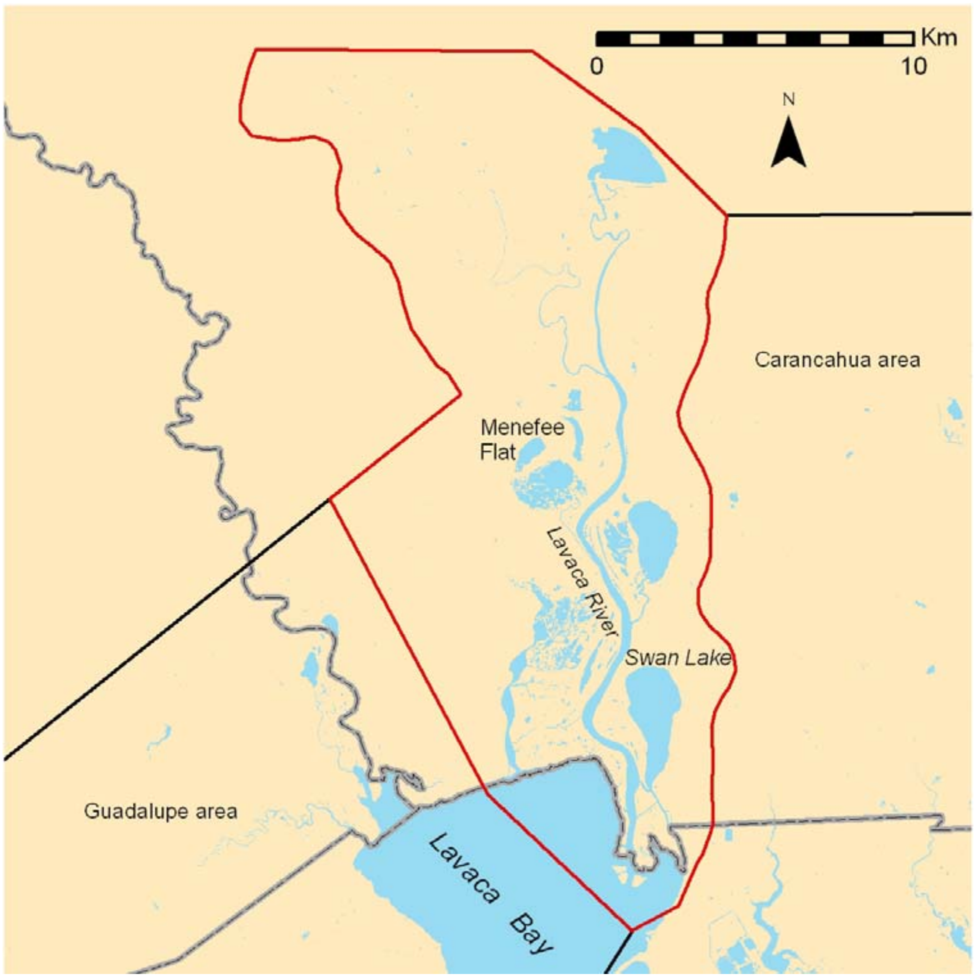

Figure 30. Locator map showing geographic features in the Lavaca study area.

The most dramatic change in the Lavaca area is the increase in estuarine open water. Between 1956 and 2008, estuarine open water increased 63%, from 2,107 to 3,426 ha (Fig. 31). Roughly 47% of the increase was from areas previously mapped as estuarine marsh. Most of the change from marsh to open water had occurred by 1979. Concurrent with the gain in estuarine open water was a gain of estuarine marsh. A total of 2,012 ha of estuarine marsh in 1956 had increased by 28% to 2,565 ha in 2008. The largest amount of estuarine marsh was mapped in 1979, with a total of 3,087 ha. Much of this marsh had been converted to open water by 2008. Of the total gain of estuarine marsh during the study time period, 66% was converted from uplands. White and others (1989) noted that some of this change is due to interpretational differences regarding species composition west of Swan Lake. Additional changes in estuarine open water and marsh is attributed to relative sea-level rise and other factors associated with subsidence from local oil-field activity (White et al., 1989). Much of the increase in open water and marsh is in close proximity to the (–)0.5-ft subsidence contour, as mapped by Riggio and others (1987). Near Menefee Flat, between 1956 and 2008 estuarine open water and estuarine marsh moved into roughly 1,437 ha of other habitats (Figs. 32–34). Between 1979 and 2008 estuarine open water area increased while estuarine marsh area decreased, possibly because of subsidence. The overall effect was a significant increase in estuarine open water and a much smaller increase in estuarine marsh.

Freshwater, a combination of riverine, lacustrine, and palustrine habitats, lost (–)37% over the length of the study period. Freshwater areas decreased systematically through time, with 698 ha mapped in 1956, 488 ha in 1979, and 441 ha in 2008. Most freshwater change had occurred by 1979 through conversion to estuarine open water. Swan and Menefee Lakes were mapped as fresh in 1956 but had become estuarine open water by 1979. The net loss of fresh open water would have been larger if not for the construction, prior to 1979, of Lake Texana on the Navidad River. The reservoir was constructed in an area previously mapped as forest.

The most dramatic loss in habitat was the loss in forests between 1956 and 1979, mostly along the entrenched valleys of the Lavaca and Navidad Rivers. However, most forest loss was interpretational (mapping criteria). The loss of (–)19%, or 225 ha, of the forest area between 1979 and 2008 provides a better approximation of the direction of resource trend. Some loss (39 ha) may be reflected in the movement of estuarine marsh up the small tributary of the Lavaca River south of Menefee Flat. The construction of Lake Texana also displaced some original forest.

Tidal flats in the Lavaca area also experienced a systematic loss through time. The original 254 ha mapped in 1956 had been reduced to 169 ha by 2008, 2 ha less than the 1979 total of 171 ha. The overall loss of resource was (–)34%. Most loss of tidal flats had occurred by 1979 and was due to replacement by estuarine marsh and estuarine open water, primarily in the bayhead delta.

Palustrine marshes experienced both gains and losses through time. The 1956 total of 405 ha increased sharply by 1979 to 721 ha, then reduced to 466 ha by 2008. Wetter conditions in 1979 may have led to a proliferation of palustrine marsh not found in other time periods. Nevertheless, palustrine marsh increased by 15% between 1956 and 2008. Around Swan Lake and Menefee Flat, palustrine marsh was replaced by estuarine marsh. Concurrently, palustrine marsh moved farther upriver into areas previously mapped as upland and, in some instances, forest. This scenario is consistent with the phenomenon observed frequently along the Texas coast, where, when able, wetland habitats move inland as a result of relative sea-level rise.

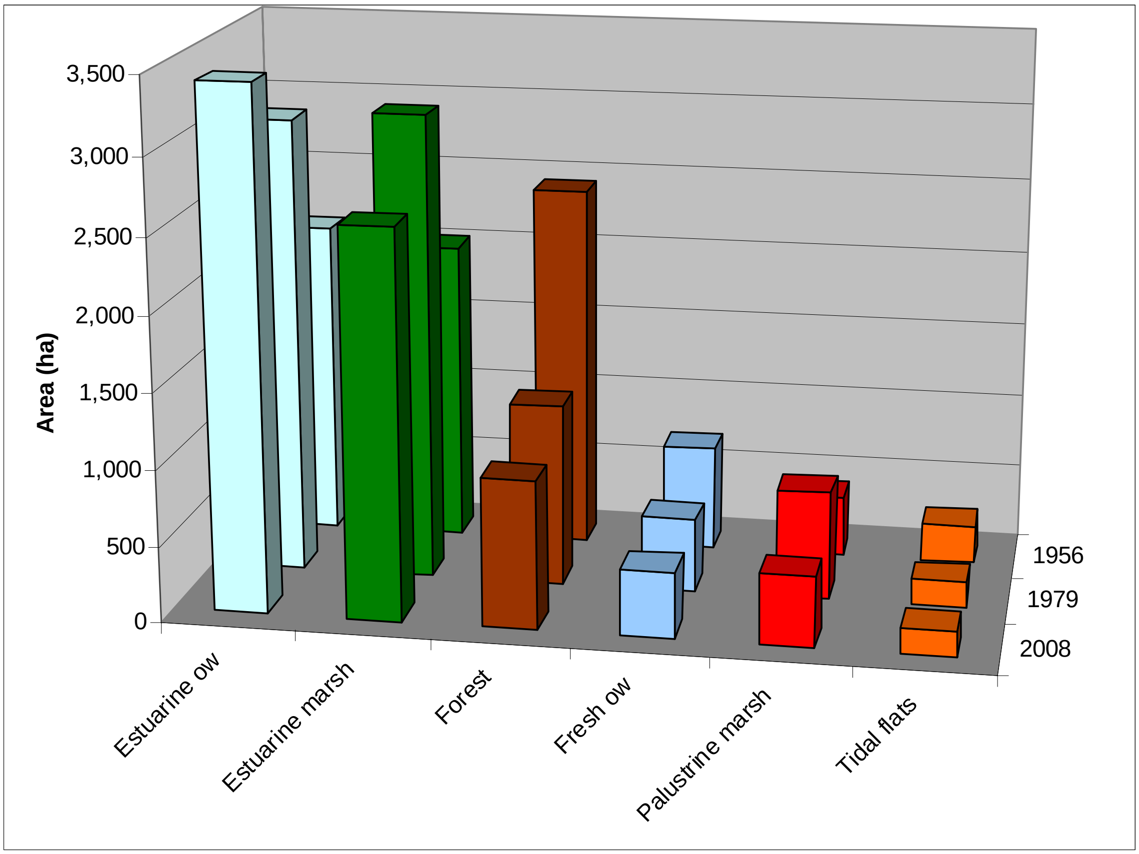

Figure 31. Areal extent of major habitats in the Lavaca area in 1956, 1979, and 2008.

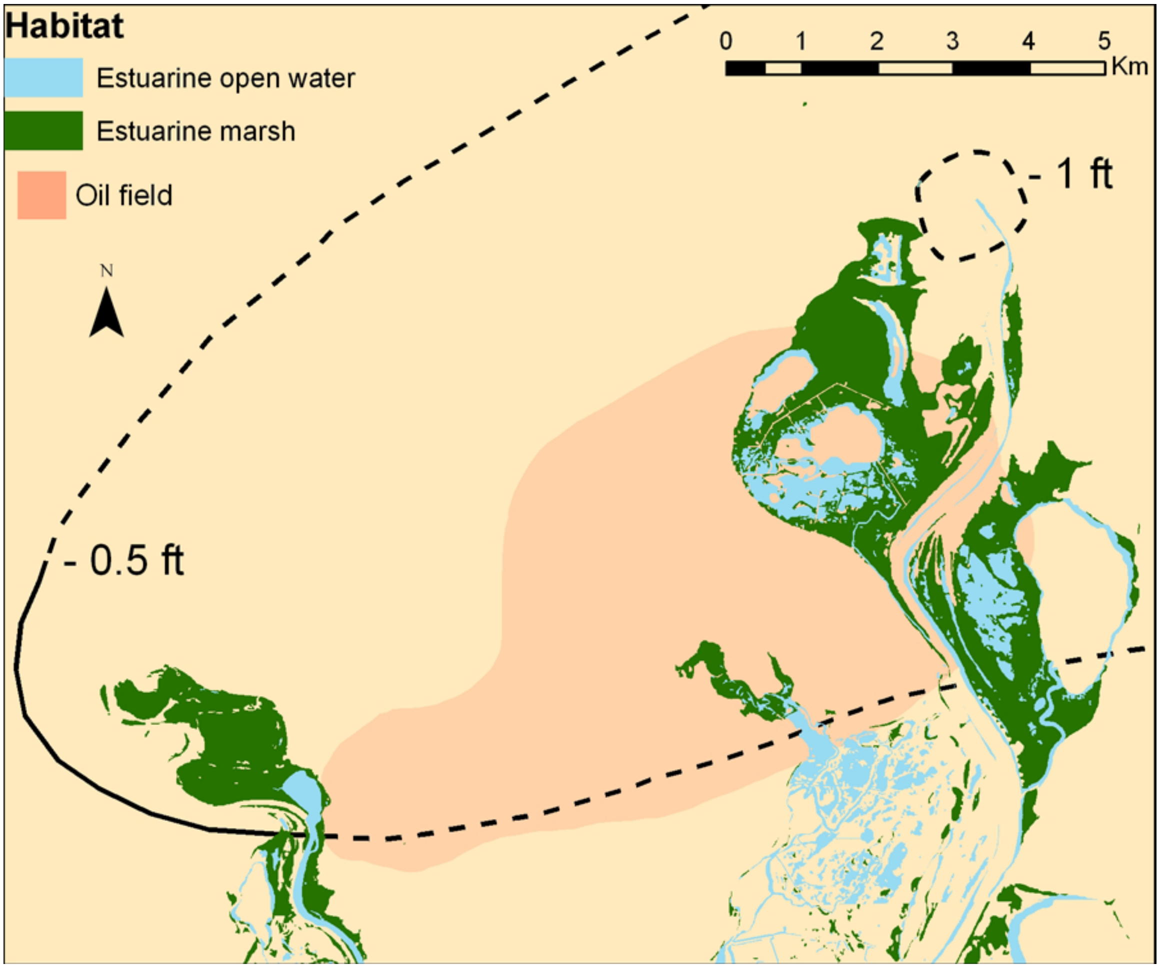

Figure 32. Estuarine open water and marsh near Menefee Flat in 2008 that replaced other 1956 habitats. Solid and dashed lines indicate equal land-surface subsidence (from Riggio et al., 1987).


Figure 33. Open water at Menefee Flat. View looking south from road (616).

Figure 34. Stressed vegetation in upper reaches of Menefee Flat. More frequent saltwater intrusion has moved estuarine marsh boundary farther inland.

Carancahua

The Carancahua area encompasses the east margin of Lavaca Bay and the north shore of Matagorda Bay and includes Carancahua Bay, Keller Bay, and Cox Bay (Fig. 35).

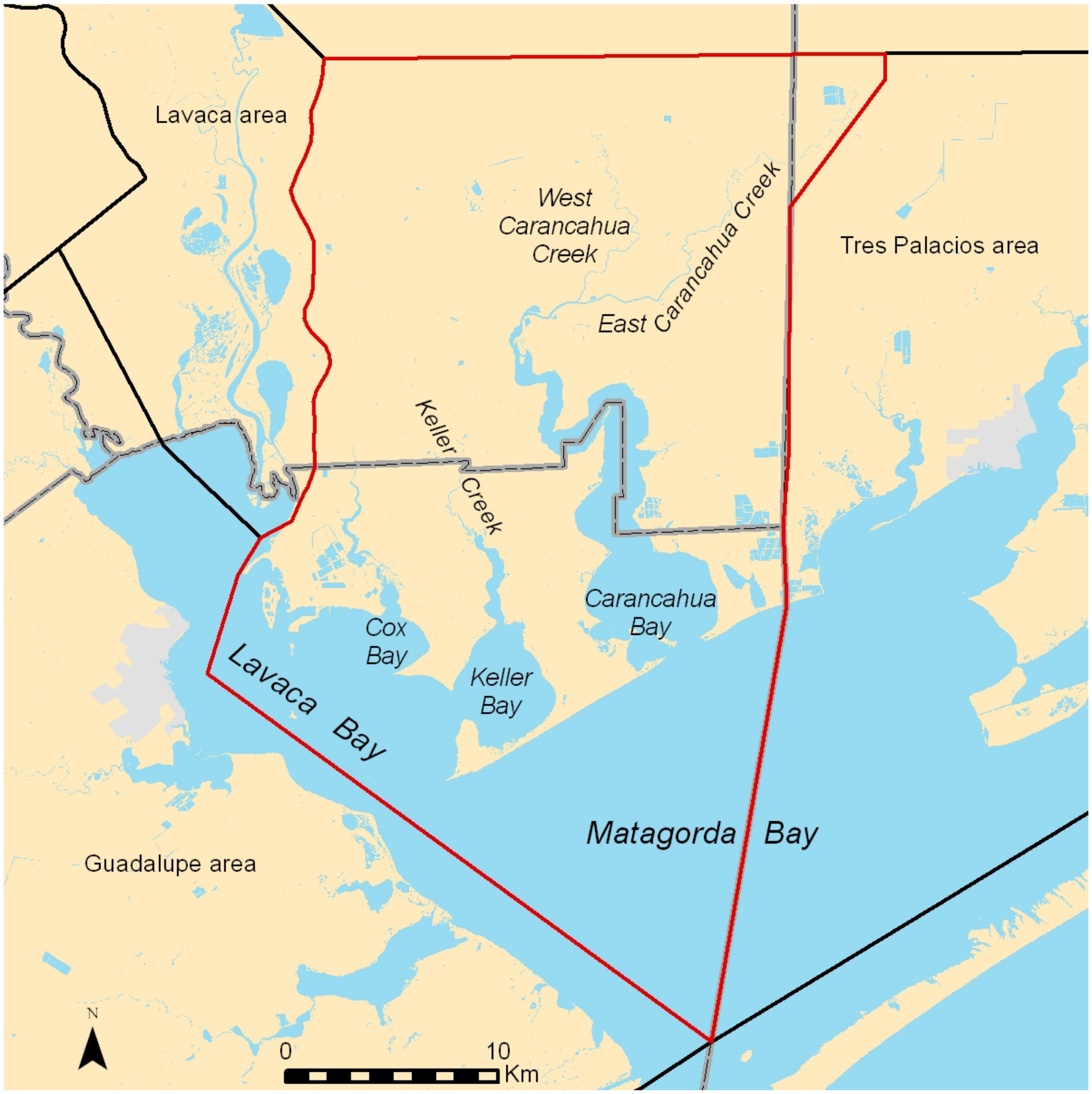

Figure 35. Locator map showing geographic features in the Carancahua study area.

The Carancahua area is predominantly estuarine open water (E1UB) and upland. In 1956, estuarine open water occupied 32,119 ha, in 1979 open water increased slightly to 32,440 ha, and it increased again to 32,738 ha by 2008. The long-term change amounts to a 2% increase over the study time period.

Initial calculations of palustrine forest (PFO) show an extreme loss (–92%) of habitat over the study time period (Fig. 36). Many forested areas along West Carancahua Creek and East Carancahua Creek were mapped as PFO in the 1950's and 1979. In the

Submerged Lands reports (White et al., 1988, 1989), forests were mapped to conform to the *Environmental Geologic Atlas of Texas* (EGAT) (McGowen et al., 1976a, b). All forest vegetation was mapped in the EGAT with no distinction made between upland and wetland forests. However, very few of these areas appear to be PFO in 1996 photography. Most forest in this area appears to be upland forest. In delineating palustrine forest for the 2008 time period, an attempt was made to map only wetland forest. Photography from 1996, in conjunction with 2008 photography, was used to more accurately depict palustrine forest along these creeks. Differing mapping criteria in forested areas is most apparent in this part of the Matagorda Bay study area, and the overall loss of palustrine forest was primarily to uplands (96%), reflecting the different mapping criteria. Some actual palustrine forest loss occurred in the later time period when forest was harvested from the upper reaches of Keller Creek.

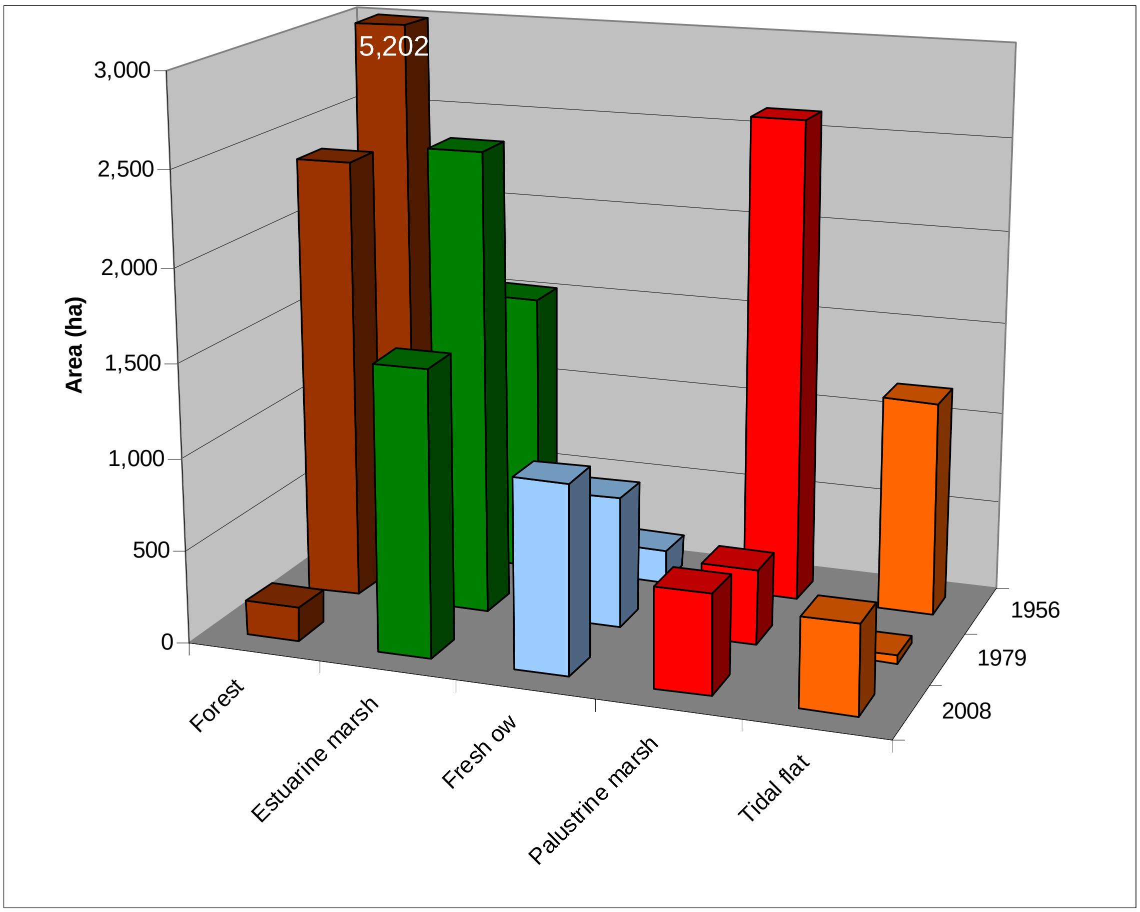

Figure 36. Areal extent of major habitats in the Carancahua area in 1956, 1979, and 2008.

Palustrine marsh (PEM) also appears to have experienced extreme loss of habitat. An initial expanse of 2,621 ha in 1956 had been drastically reduced to 408 ha by 1979, an (–)84% decrease. By 2008 the amount had rebounded to 541 ha. The 1956–2008 change amounted to a (–)79% loss of marsh habitat. Some of the loss can be attributed to draining of marshland for development, mostly between Cox and Keller Bays and between Keller and Carancahua Bays. Construction of roads effectively blocked water flow, reducing the amount of moisture available to wetlands. Many of these areas, transitional between wetland and upland, are therefore sensitive to hydrological modifications.

Despite a jump in acreage in1979, possibly due to wetter ground conditions, estuarine marsh (E2EM) numbers did not change significantly between 1956 and 2008. However, location of the salt marsh changed through time. Salt marsh was lost primarily to estuarine open water along the margins of secondary bays throughout the Carancahua area. Roughly 42% of estuarine marsh loss resulted in replacement by estuarine open water. White and others (1989) report an increase between 1956 and 1979 in tidal flats and open water west of Turtle Bay. By 2008 most estuarine marsh loss was the result of open-water inundation. Shoreline erosion at Carancahua Pass eroded estuarine marsh and joined Redfish Lake to Matagorda Bay. White and others (1989) listed the loss of estuarine marsh—a result of dam construction at Hughson Lakes (Fig. 37)—as an example of human activity that affected marsh distribution. Over the same time period, estuarine marsh increased from areas that were tidal flats in secondary bays (i.e., Salt Lake) and from uplands along bay margins. Approximately 40% of estuarine marsh gain was in areas previously mapped as tidal flat. Some estuarine marsh moved upstream into areas previously occupied by palustrine marsh at the mouth of Carancahua Creek. Changes in the location and amount of estuarine marsh in the Carancahua area are the result of a combination of factors, predominantly relative sea-level rise. Similar change scenarios are found along other parts of the Texas Gulf Coast.

Like other places in the Matagorda Bay area, tidal flats were significantly reduced in the Carancahua area. In 1956 a large area, 1,171 ha, was mapped, possibly because water levels were lower during drought conditions, with only 49 ha mapped in 1979. In 2008, 481 ha of tidal flats were mapped. Overlay analysis shows most loss of tidal flats along bay margins, where the predominant conversion of tidal flats was to estuarine open water (48%). Movement of estuarine marsh into tidal flats accounted for 30% of the loss, much of this occurring at Salt Bay, where 122 ha of tidal flat became marsh. Salt marsh was also lost at the mouth of the stream that discharges into Keller Bay. Dam construction at the Alcoa plant on the stream discharging into Cox Bay caused freshwater to replace 23 ha of tidal flat. The long-term change in tidal-flat habitat was a loss of (–)59% of the original resource. Again, most loss can be attributed to relative sea-level rise.

Only fresh open water experienced systematic gains in the Carancahua area. The 1956 total of 182 ha had grown 529% to 711 ha by 1979, mostly owing to construction of reservoirs at the Alcoa plant near Cox Bay. By 2008, the amount of fresh open water had grown to 1,022 ha, an additional 311%. By then more reservoirs had been constructed east of Carancahua Bay, possibly for agricultural purposes. The cumulative increase in freshwater is 463% of the original amount, with 72% of the gain in areas that were previously uplands.

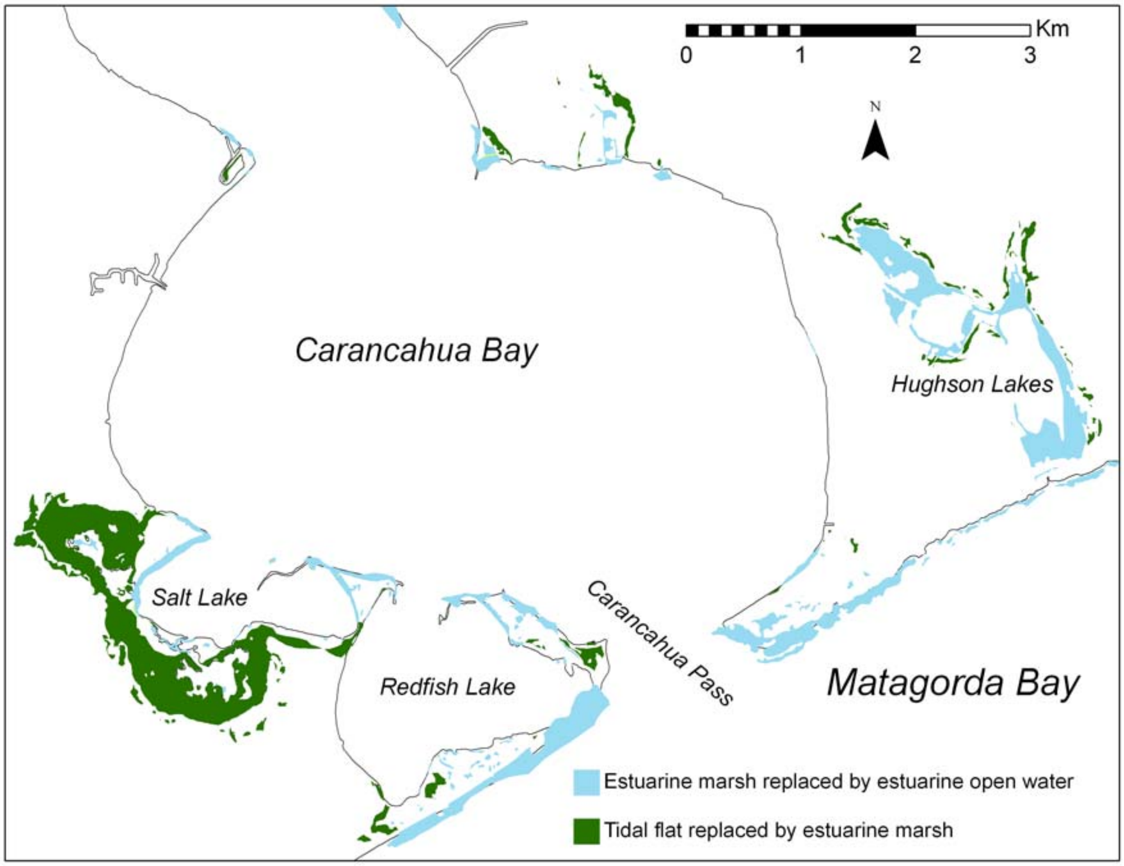

Figure 37. Estuarine marsh (E2EM) in 1956 that had become open water (E1UB) by 2008 and tidal flats (E2US) in 1956 that had become estuarine marsh by 2008. Estuarine open water drowned marshes, whereas estuarine marsh moved into previous tidal flats.

Tres Palacios

The Tres Palacios area is characterized by Matagorda Bay, Tres Palacios Bay, Turtle Bay, and Oyster Lake (Fig. 38). Salt marshes are common at bayheads, where sediment has formed narrow deltas. Farther upriver, salt marshes intergrade with fresh marshes as salinity decreases. In some places fluvial woodlands occur in inland river valleys (White et al., 1988).

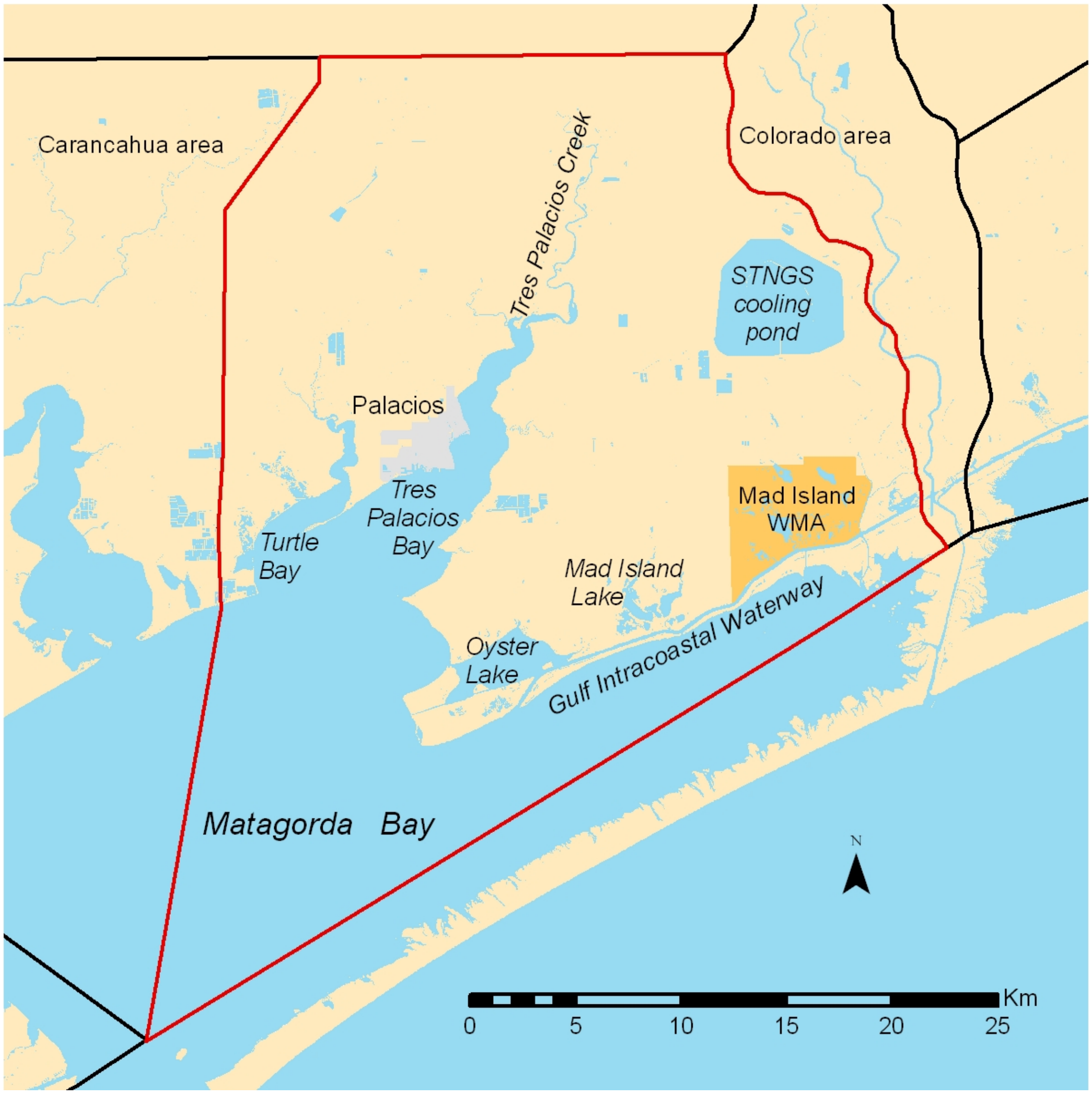

Figure 38. Locator map showing geographic features in the Tres Palacios study area.

Because the Tres Palacios area incorporates much of Matagorda Bay, it contains a large amount of estuarine open water (E1UB). Here, open water area increases systematically through time, with a 1956 total of 34,750 ha increasing to 35,897 ha by 1979, and further expanding to 36,069 ha by 2008. Most of the increase in estuarine open water had occurred by 1979. Almost half (48%) of the gain in estuarine open water was in areas previously occupied by estuarine marsh. The west side of Turtle Bay, at Buttermilk Slough and Sartwelle Lakes, was the site of much open water replacing marsh and tidal-flat habitats (Fig. 39). Another area of open-water inundation was the north margin of Matagorda Bay, opposite Matagorda Peninsula. This area appears to have been heavily eroded. Diversion of the Colorado River into this arm of the bay may have increased water flow, eroding this section of the shoreline. The long-term increase in estuarine open water in the Tres Palacios area was 4%.

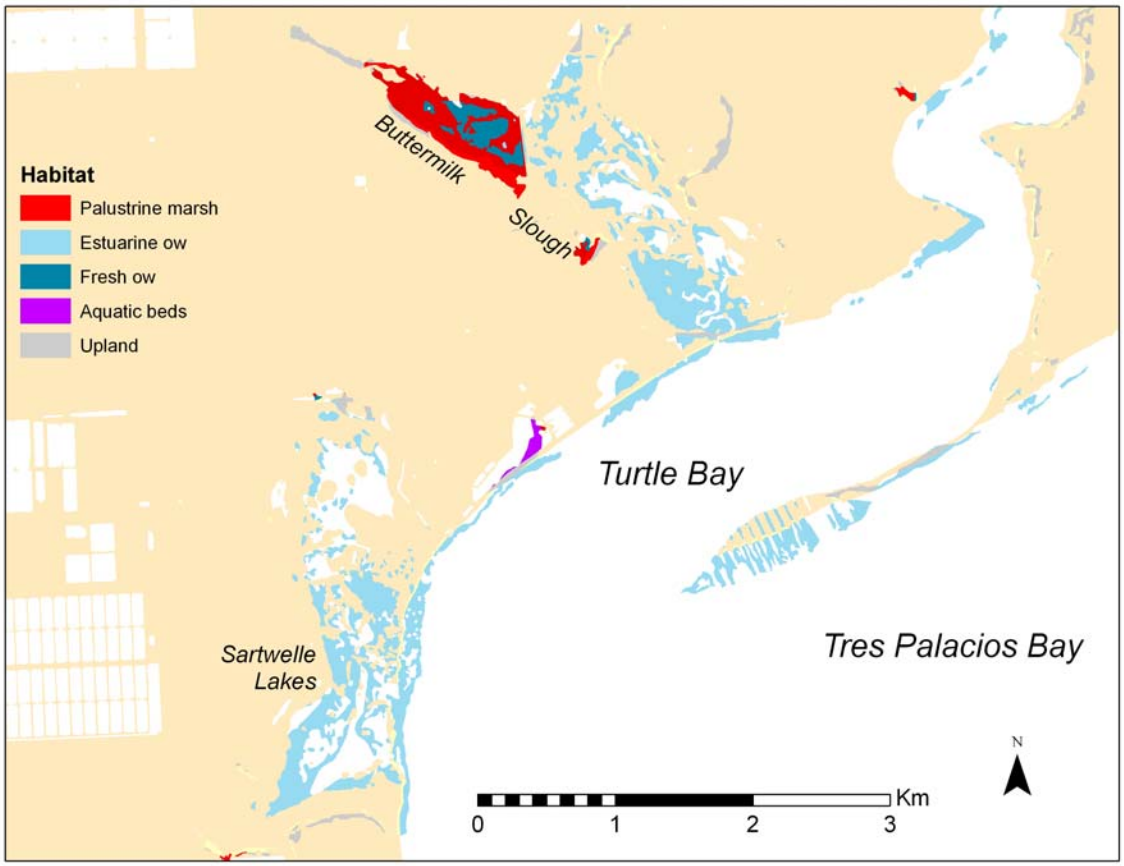

Figure 39. Replacement of estuarine marsh (E2EM) in 1956 by estuarine open water (E1UB), palustrine marsh (PEM), and other habitats in 2008.

Estuarine marsh drowned through time (Fig. 40), decreasing by more than 2,000 ha. Replacement by estuarine open water accounted for 24% of estuarine-marsh loss between 1956 and 2008. Marsh loss to open water occurred along bay margins and the GIWW, and on the delta of the West Branch of the Colorado River (Fig. 41). When Baxter Island, southwest of Matagorda, was entirely impounded, approximately 145 ha of estuarine marsh was converted to upland. Since 1979, the Tres Palacios area has experienced extensive, managed conversion of estuarine marsh to palustrine marsh in the area encompassed by Gillet Lake, Crab Lake, and the West Branch of the Colorado River. Of the estuarine-marsh-loss area, roughly 30% was to palustrine marsh, mostly in Mad Island Slough and areas inland from Robbins Lake. Mad Island Wildlife Management Area and other managed wetland areas had been diked by 1979, causing a freshening of the system. Much (41%) of the palustrine marsh that replaced estuarine marsh was mapped in 2008 as PEM1T, semipermanent-tidal, suggesting some degree of hydrologic connection with the estuarine system. A recent study conducted by PBS&J (2007) in the Matagorda Bay area between 1996 and 2002 investigated the relationship between freshwater inflow and marsh function. Modeling results showed higher productivity as a measure of marsh function during years of higher freshwater inflow. Although the marshes contained behind water-control structures were not included in the model, the effects of reduced inflow, as a result of the dams and dikes, are likely to influence marsh function in adjacent marshes. The other major (33%) loss of estuarine marsh was to upland. These areas, south and west of Oyster Lake and east of Mad Island Lake, were mapped in the EGAT (McGowen et al., 1976a) as areas with possible fringing marsh. In subsequent years, these areas were mapped as upland. Change in these areas is likely due to different mapping criteria between time periods. Some marsh was lost when wetlands were drained at the south end of Wild Cow Island. The overall change in estuarine marsh between 1956 and 2008 was a loss of (–)38% of the original resource.

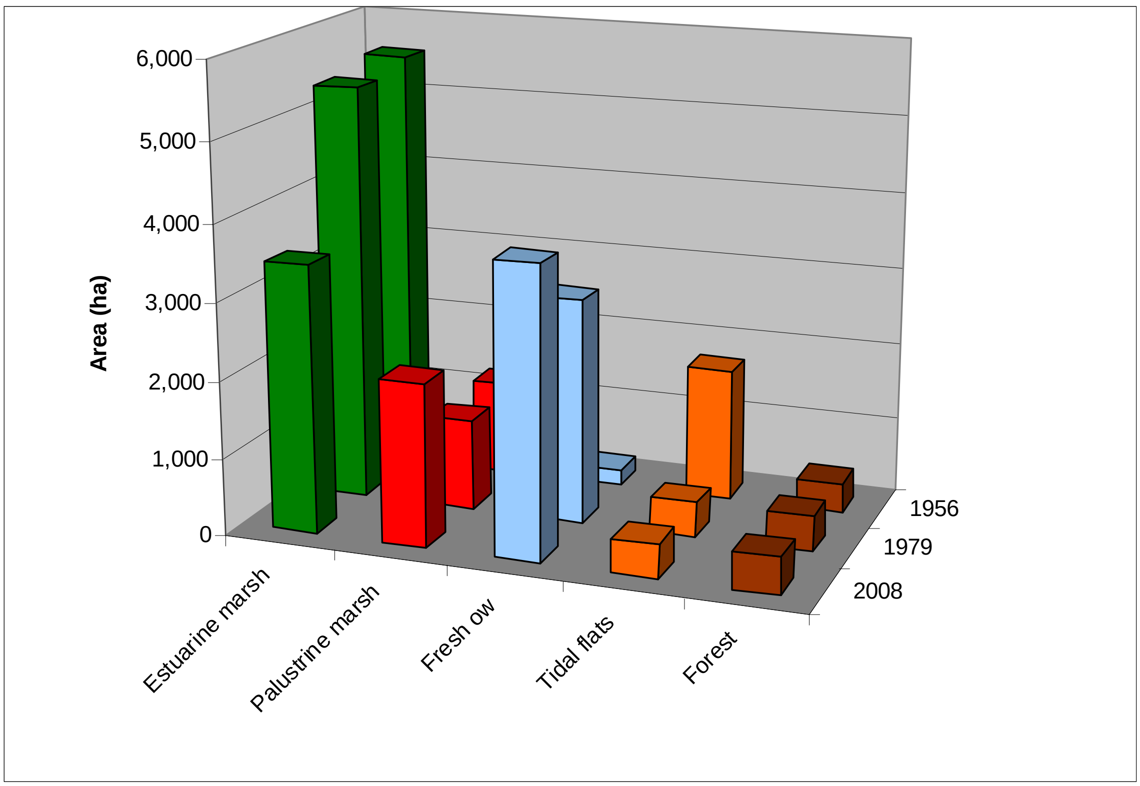

Figure 40. Areal extent of major habitats in the Tres Palacios area in 1956, 1979, and 2008.

Figure 41. Locator map showing geographic features in the east part of the Tres Palacios study area.

Concurrently, palustrine marsh increased in area through time. A slight decrease between the 1956 total of 1,227 ha and the 1979 amount was followed by a large increase to 2,115 ha by 2008. Between 1956 and 2008, palustrine marsh increased in area by 72%. Although some changes occurred in the earlier time period, wetland management promoting fresher systems was not broadly applied until after 1979. Palustrine marsh gain was primarily in areas that were once estuarine marsh (54%), mostly in the Mad Island Wildlife Management Area (WMA). To the east of the WMA, palustrine marsh occurred in previously upland areas along the West Branch of the Colorado River. Wetter conditions in later years, as compared with drought conditions in 1956, may have produced more favorable conditions for marshes to spread into transitional areas.

Palustrine forest (PFO), including palustrine scrub-shrub (PSS), is a relatively minor (483 ha) component of the wetland system in the Tres Palacios area. Most change in forest area occurred between 1956 and 1979, with a 21% increase. Whereas the total area of forest had increased only 6% by 2008, the mapped location of forest changed drastically between 1979 and 2008. Prior to 2008, a significant amount of palustrine forest was mapped along Tres Palacios Creek, whereas very little palustrine forest was mapped there in 2008. Most palustrine forest mapped in 2008 was in the Colorado River valley. Differences in mapping criteria make comparisons difficult, although during the mapping process, some forest changes were noticed. Forest clearing had occurred along the Colorado River in the Palacios NE quadrangle and along the West Branch of the Colorado River, near Wild Cow Island.

Tidal flats decreased dramatically through time in the Tres Palacios area. The largest expanse of tidal flat, 1,716 ha, was mapped in 1956. By 1979, flats had been reduced to 450 ha, with little change by 2008. Change over the length of the study time period represents a loss of 74% of the original resource. Tidal-flat loss was due primarily to estuarine marsh (37%) and estuarine open water (34%) along bay margins. Marshes moved into previous tidal-flat areas in Turtle Bay, Oyster Lake, and Mad Island Lake. Movement of marsh into tidal flats between 1956 and 2008 was from more frequent flooding in areas of relatively high rates of relative sea-level rise.

Fresh open water experienced systematic gains in the Tres Palacios area. The relatively small amount of 210 ha in 1956 increased dramatically (1,286%) to 2,917 ha in 1979 with the construction of a 2,412-ha cooling reservoir at the South Texas Nuclear Generating Station (STNGS). Construction of additional water-containment structures had added another 1,286 ha by 2008. Almost all (96%) gain in fresh open water occurred in previously upland areas.

Colorado

Wetland areas along the Colorado River are dominated by fluvial woodlands and freshwater marshes associated with abandoned river channels and other river-related depressions (White et al., 1988) (Fig. 19).

The most significant change in wetland habitats in the Colorado area was the expansion of palustrine marsh. Drought during the 1950’s may have limited the extent of marsh in that time period. However, by 1979, palustrine marsh had increased from 190 ha in 1956 to 635 ha or 445%. In 2008, the total rose slightly to 643 ha (Fig. 42). Palustrine-marsh gain was primarily (93%) in areas that were formerly uplands. Most gain was located in the abandoned river channel north of the town of Matagorda (Fig. 43).

Estuarine marsh was nearly eliminated from the Colorado area over the study time period. A 1956 total of 20 ha had increased to 51 ha by 1979, when estuarine marsh formed on dredge material along the GIWW. But by 2008, dredge material had covered marshes within the enclosed areas, and all of Baxter Island (Fig. 41) had been converted to upland through this process by 2008.

Only 12 ha of palustrine forest was mapped in 1956, possibly owing to difficulties distinguishing upland from wetland forest on black-and-white aerial photography. A similarly small amount of palustrine forest, 92 ha, was mapped in 1979. Fluvial woodlands are prevalent throughout much of the incised Colorado River valley. Variation in forest mapping criteria between study time periods prevents forest-change analysis in the Colorado area. Mapping criteria in the *Submerged Lands* volume didn't distinguish between upland and wetland forest (White et al., 1988). Apparently, the 1979 NWI took the opposite approach and mapped almost no palustrine forest. Palustrine-forest extent in 2008 is similar to that found in the *Submerged Lands* report but further refines forest habitat to distinguish between wetland and nonwetland forest. As was the case with the spread of palustrine marsh, palustrine forest in the Colorado area occurred primarily (94%) in previously upland areas. In the interpretation process it was noted that some palustrine forest and marsh had been cleared between 1979 and 1996 on Selkirk Island below Donaldson Lake.

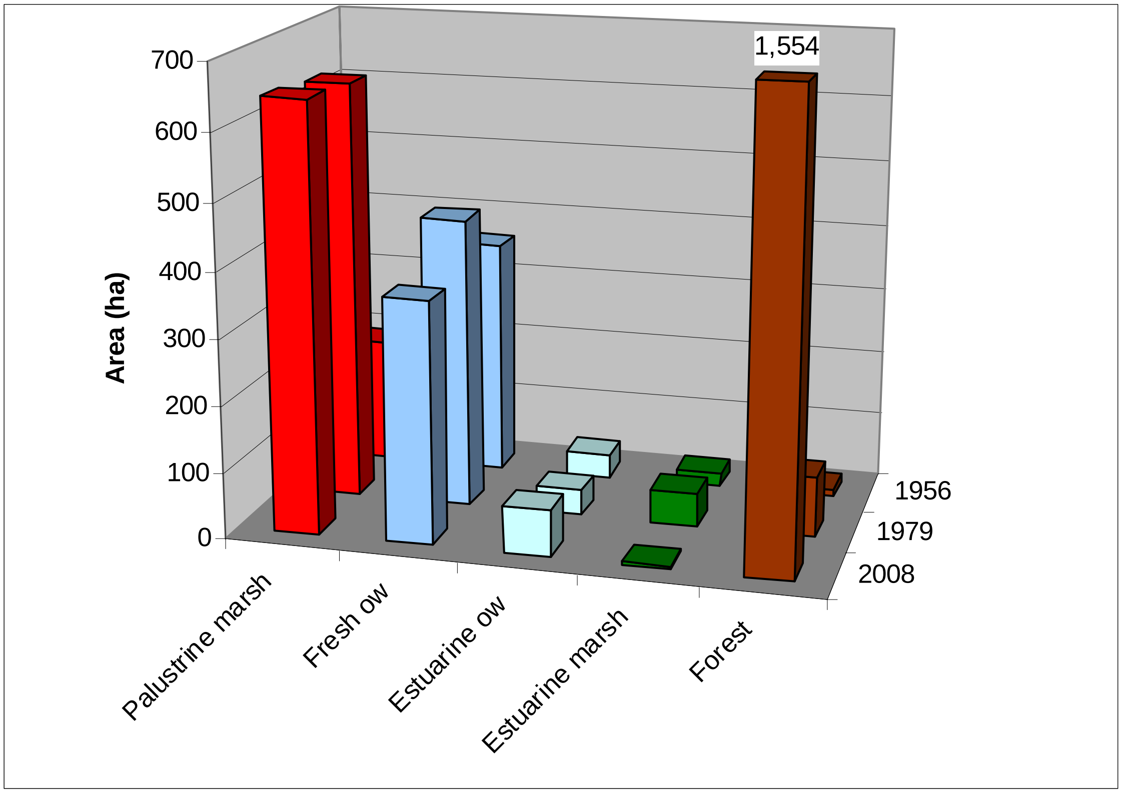

Figure 42. Areal extent of major habitats in the Colorado area in 1956, 1979, and 2008.

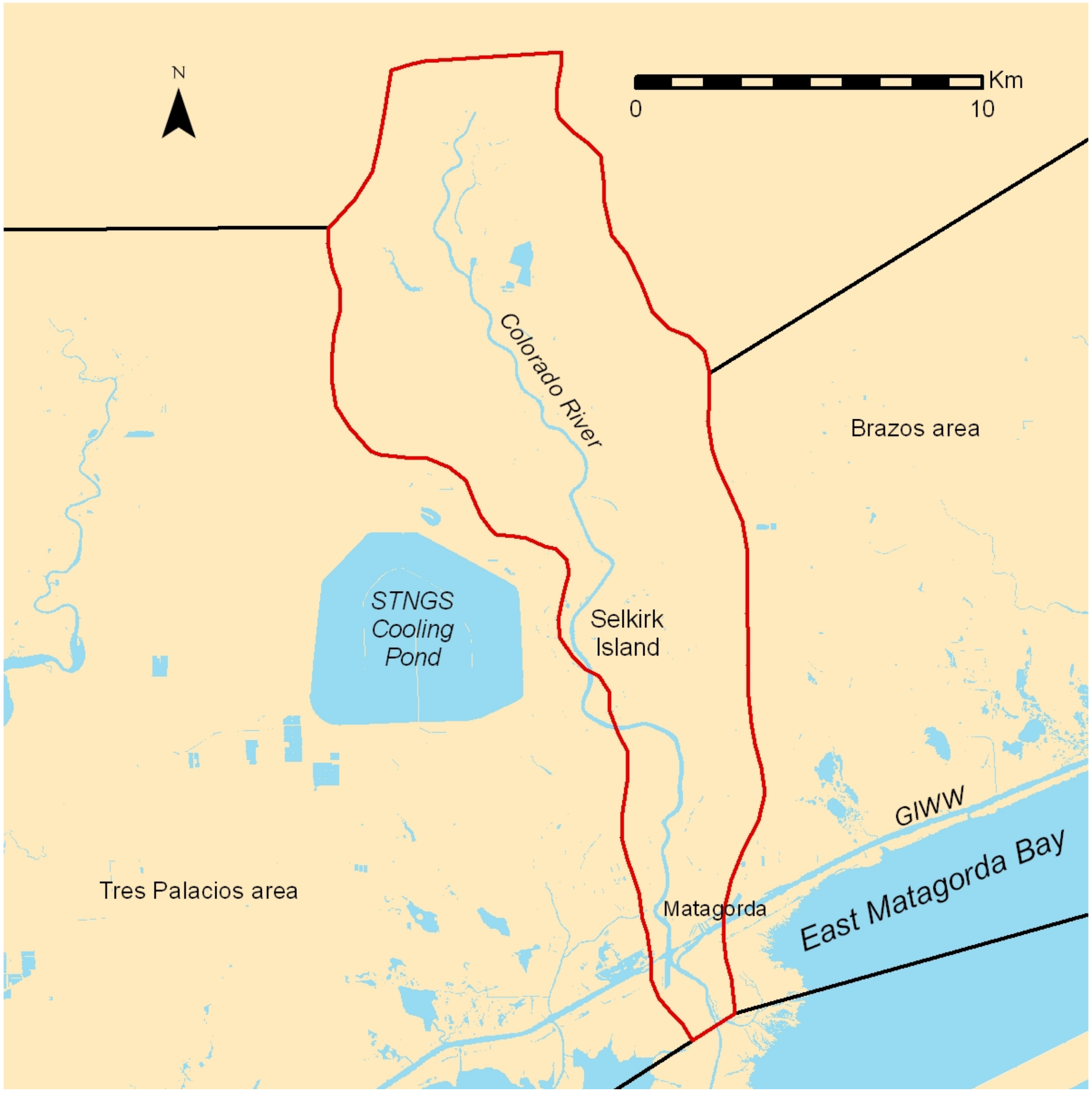

Figure 43. Locator map showing geographic features in the Colorado study area.

Fresh-open-water numbers remained relatively constant except for an additional 80 ha (22%) in 1979. The 1979 increase, resulting from reservoir construction, was reversed in 2008, when palustrine marsh occurred in Willow Lake, northeast of Selkirk Island. Estuarine-open-water area increased through time, when the boundary between fresh- and saltwater shifted farther up the Colorado River.

Brazos

Wetland character in the Brazos area is influenced by the proximity of the Brazos River delta (White et al, 1988). The system is composed of numerous small bays, lakes, and marshes, and the only national wildlife refuge (Big Boggy) in the Matagorda Bay area is located here (Fig. 44). Abundant fluvial woodlands characterize the eastern region of this area.

Figure 44. Locator map showing geographic features in the Brazos study area.

The most significant wetland trend in the Brazos area was the increase in palustrine marsh between 1956 and 2008. Starting with 2,739 ha in 1956, marsh area decreased to 2,534 ha in 1979, and had increased to 3,910 ha by 2008 (Fig. 45), or a 43% increase from the original amount. More than 85% of the new palustrine marsh area was originally mapped as upland in 1956. An 8% decrease between 1956 and 1979 occurred in areas where estuarine marsh replaced palustrine marsh. The probable cause of the significant overall increase of palustrine marsh in the Brazos area is land-surface subsidence in the Brazos River delta (Brown et al., 1974). Such subsidence extends wetter conditions farther inland, with wetlands occurring in areas previously mapped as prairie grasslands (Fig. 46). A smaller amount of palustrine marsh gain (7%) occurred from areas that had previously been estuarine marsh. Wildlife management practices, such as building of levees, in the Big Boggy National Wildlife Refuge promoted the conversion of salt- to freshwater marshes. Roughly 271 ha north of Lake Kilbride was converted from salt to fresh marsh between 1979 and 1992.

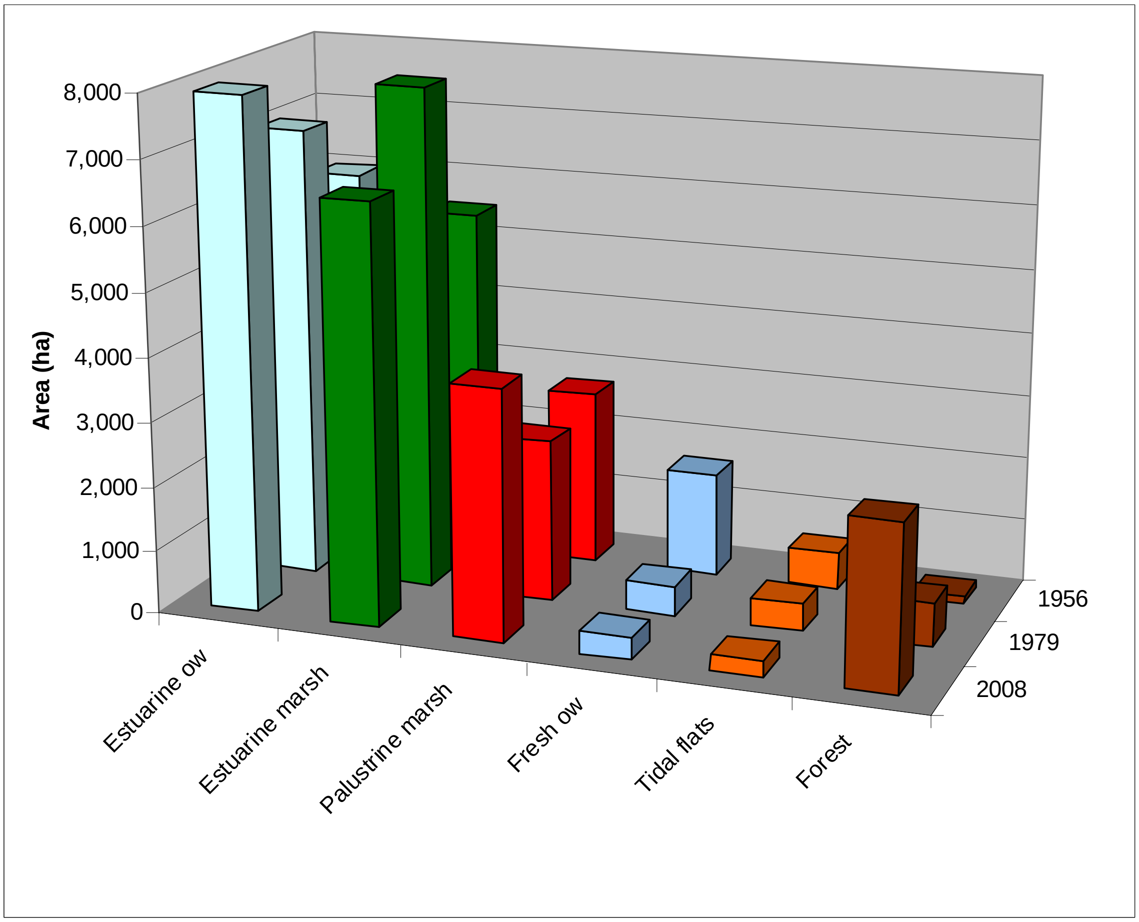

Figure 45. Areal extent of major habitats in the Brazos area in 1956, 1979, and 2008.

Estuarine marsh also experienced an increase through time. The initial 5,481 ha in 1956 increased to 7,847 ha in 1979 and had decreased to 6,517 ha by 2008. The overall increase throughout the study time period represents a 19% gain in the original resource. Much (63%) of the estuarine marsh gain between 1956 and 2008 was from areas previously mapped as upland, and another 20% was from areas formerly occupied by palustrine marsh.

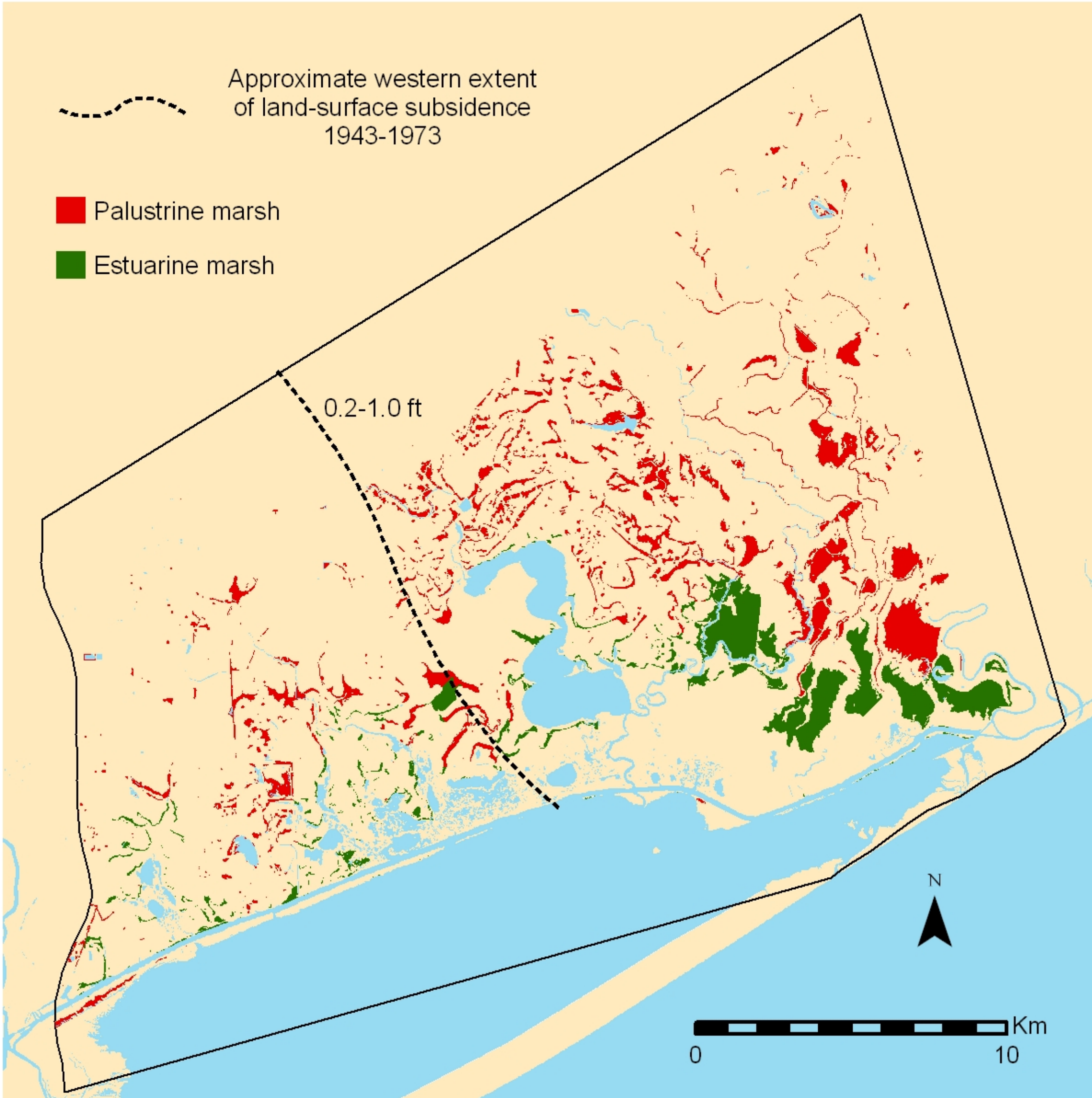

Figure 46. Marsh in 2008 replaced areas mapped as upland in 1956. Area east of dashed line had subsided up to 1 ft over a 3-decade period. Subsidence data from Brown et al. (1974).

Although tidal flats make up a relatively small part of wetland habitats in the Brazos area, they are an important component of the wetland system. Of all components in the system, tidal flats suffered the greatest loss (–56%) through time. A 1956 total of 574 ha was reduced (–24%) to 438 ha in 1979. The trend continued through 2008 with an additional loss (–42%), when flats were reduced to 253 ha. Approximately 37% of tidal-flat loss was to estuarine open water along East Matagorda Bay and segments of the GIWW. Another 30% of the loss was to estuarine marsh near East Reservoir and in East Matagorda Bay near Egret Island. An area near East Reservoir had been diked prior to 1979 and became increasingly wet. Through time, 40 ha of tidal flat was lost to palustrine marsh. Nearly 25 ha of flat converted to upland when a dredge-material pit was constructed on the landward side of the GIWW between East Reservoir and Lake

Kilbride. Some flats were converted to estuarine open water and estuarine marsh at Lake Kilbride.

Estuarine open water increased systematically in the Brazos area throughout the study time period. The 1956 total of 5,980 ha increased to 7,068 ha in 1979, an increase of 18%, and had increased another 12% to 7,945 ha by 2008. The main factor influencing the early expansion of estuarine open water was the conversion of Lake Austin from fresh- to saltwater. The increase in estuarine open water accounted for 96% (989 ha) of the expansion in the Brazos area. In the 1950's, Lake Austin was mapped as lacustrine (L1OW) and was rimmed by palustrine marshes, except for the extreme southern shore. By 1979, Lake Austin had been mapped as estuarine (E1OW), and most all bordering marshes had been mapped as estuarine marsh (E2EM). Palustrine marshes (PEM) remained along the extreme northern shore of the lake near the mouth of Peyton Creek.

The other habitat most affected by increasing estuarine open water was estuarine marsh. More than 28% of estuarine open water gain was in previous estuarine marsh. Excluding Lake Austin, the increase in estuarine open water was primarily (52%) in areas previously mapped as estuarine marsh. Marsh loss to open water occurred in Big Boggy NWR between the GIWW and Lake Kilbride. The proximity of this area to the Brazos River delta suggests that land-surface subsidence caused the drowning of vegetation as the land subsided. Accelerated rates of relative-sea-level rise also caused estuarine open water to move into estuarine marsh and tidal flats throughout the area between Big Boggy NWR and East Reservoir and around McNabb and Gottschalk Lakes.

Fresh open water, including lacustrine, palustrine, and riverine habitats, experienced a systematic decline within the Brazos area, from a high of 1,628 ha to 462 ha by 1979 (72% loss). Most of this loss was due to the conversion of Lake Austin from fresh- to saltwater.

Forest-area tabulations show a significant systematic increase, with the most significant gain between 1979 and 2008. Forest area in 1956 covered 108 ha; by 1979 forest had increased to 689 ha and to 2,575 ha in 2008. Nearly all (98%) of forest gain between 1956 and 2008 was in areas previously mapped as upland. Both the *Submerged Lands* reports (White, 1988, 1989) and the *Environmental Geologic Atlas* (McGowen 1976a, b) mapped large tracts of forest in the area around Live Oak Bayou. The NWI, in all time periods, consistently mapped few palustrine forests in this area. In the mapping process it was noted that prior to 2008 forests had been cleared for agricultural purposes northwest of Williams Lake.

SUMMARY AND CONCLUSIONS

Major habitats in the study area include salt and fresh marshes and fresh open water. Forests are next in areal distribution. Tidal flats 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. In 2008, wetland and aquatic habitats were dominated by estuarine marshes, with a total area of 17,195 ha, followed by palustrine marshes totaling 11,384 ha, fresh open water (ow) totaling 6,825 ha, forest/scrub-shrub at 6,010 ha, and tidal flats covering 1,764 ha. The most abundant aquatic habitat was estuarine open water covering 94,414 ha. Lacustrine flats and algal beds had a total area of 545 ha, and palustrine flats had 184 ha.

Analysis of habitat changes in the Matagorda Bay area shows a small increase in marshes from 1956 to 2008. Complementing this trend in increasing emergent wetlands was an increase in fresh open water. A significant contribution to the fresh-open-water area was the construction of a cooling reservoir at the South Texas Nuclear Generating Station. Forested wetlands experienced losses over the study time period, most due to differences in mapping criteria. Roughly 90% of the forest-loss area between 1956 and 2008 was mapped as upland in 2008. Likewise, tidal flats suffered significant losses across the study area, as is the case along much of the Texas Coast. Of the flat-loss area, roughly 70% was replaced by estuarine open water and estuarine marsh.

Estuarine marshes are by far the dominant class of emergent wetlands in the Matagorda Bay study area; therefore, for simplification and to reduce apparent changes due to interpretation, emergent wetland classes in the trend analysis were combined. Over the approximately 50-yr study period, from 1956 through 2008, emergent wetlands (marshes) increased from about 27,942 ha to 28,579 ha, a gain of 637 ha. The rate of marsh gain from 1956 to 1979 was 172 ha/yr, but from 1979 to 2008, marsh losses were about (–)114 ha/yr. The area of forest and scrub-shrub decreased substantially through time, from 8,734 ha in 1956 to 6,010 ha in 2008. Rates of change in forest were about (–)156 ha/yr during the earlier period and (+)30 ha/yr during the later period. Tidal flats decreased in area from 5,155 ha in1956 to 1,764 ha in 2008, a loss of about 3,391 ha.

The study area, covering estuarine systems of the Lavaca and Colorado Rivers, several smaller creeks, and marshes inland of the bays, was subdivided into geographic areas from west to east—Guadalupe, Lavaca, Carancahua, Tres Palacios, Colorado, and Brazos—to allow a more site-specific analysis of status and trends. The most extensive estuarine emergent wetlands occurred in the Brazos area, where the total area of estuarine marshes in 2008 was 6,517 ha, followed by the Tres Palacios and Guadalupe areas with 3,464 ha and 3,109 ha, respectively. The Brazos and Guadalupe areas contain the largest expanses of palustrine marsh, with 3,910 ha and 3,708 ha, respectively, followed by the Tres Palacios area, with 2,115 ha. The Tres Palacios area contains the largest amount of fresh open water at 3,749 ha. Most of the water (2,412 ha) is contained in the cooling reservoir for the South Texas Nuclear Generating Station. The Carancahua area contains the second-highest amount of fresh open water, with 1,022 ha. Forests are abundant in the Brazos area, where wetland trees and shrubs total 2,575 ha. The Colorado and Lavaca areas also contain significant forest, 1,554 ha and 980 ha, respectively. Carancahua with 481 ha, Tres Palacios containing 444 ha, and Guadalupe with 404 ha had the largest expanses of tidal flats.

Analysis of habitat distribution by geographic subarea reveals local differences in historical trends. The most significant change in wetland habitat in the **Guadalupe** area is the decrease in tidal flats (E2US). Between 1956 and 2008, tidal-flat area decreased (–)72%. Most of the decrease (34%) came from movement of estuarine marsh into flats and had occurred by 1979. Conversion to uplands, through dredge-material disposal, also significantly reduced tidal-flat numbers.

Fresh open water (palustrine, riverine, and lacustrine) increased 73% over the long term (1956–2008). The increase is due mostly to the isolation of a secondary bay north of Powderhorn Lake from Lavaca Bay. By 1992 the bay had become fresh and had been mapped as lacustrine.

Palustrine marsh experienced a less dramatic change through time—in this case, a systematic gain of marsh. Palustrine marsh increased 19% over the study time period, with a rate of 22 ha/yr in the early time period, followed by a much lower rate of 3 ha/yr in the later period. Much of the gain in palustrine marsh was from uplands (83%), although 10% of the gain was from estuarine marsh (E2EM). Most of the change from upland occurred on the barrier/strandplain. The conversion from estuarine marsh took place in the isolated bay just mentioned as the system freshened through time. As of 1979, marshes in this bay were mapped as estuarine.

Estuarine marsh retained relatively constant amounts across the study time period, although the location of estuarine marsh changed through time. Estuarine marsh occurred farther up Garcitas Creek into areas previously mapped as upland and palustrine marsh. Movement of estuarine marsh farther upriver is likely the result of relative sea-level rise. The area is within the (–)0.5-ft subsidence contour (Riggio et al., 1987) and is near West Ranch oil and gas field. Many tidal flats on the margin of Powderhorn Lake had been replaced by estuarine marsh by 2008.

Most forest (PFO) decline in the Guadalupe area occurred between 1956 and 1979. Forest area continued to decline through 2008, with an overall loss of (–)57%. Most forest change in the Guadalupe area is due to differences in mapping criteria between time periods.

The most dramatic change in the **Lavaca** area is the increase by 63% in estuarine open water between 1956 and 2008. Roughly 47% of the increase was from areas previously mapped as estuarine marsh area, most of the change occurring by 1979.

Concurrent with the gain in estuarine open water was a gain of estuarine marsh. Overall, estuarine marsh had increased by 28% by 2008; however, estuarine marsh was most extensive in 1979. Much of this marsh had been converted to open water by 2008. Of the total gain of estuarine marsh during the study time period, 66% was the result of conversion from uplands. Change in estuarine open water and marsh is attributed to relative-sea-level rise and other factors associated with local oil-field activity. Much of the increase in open water and marsh is in close proximity to the (–)0.5-ft subsidence contour, as mapped by Riggio and others (1987). Near Menefee Flat, estuarine open water and estuarine marsh moved into roughly 1,437 ha of other habitats.

Forested areas experienced the second-most-significant change after estuarine open water, mostly along entrenched valleys of the Lavaca and Navidad Rivers. However, most forest loss was interpretational (mapping criteria). The loss of (–)19% of the forest area between 1979 and 2008 provides a better approximation of the direction of the resource trend. Some loss (39 ha) may be due to movement of estuarine marsh up the small tributary of the Lavaca River south of Menefee Flat. Lake Texana construction also displaced some original forest.

Tidal flats in the Lavaca area experienced a systematic loss through time, with an overall loss of (–)34% of the original resource. Most loss of tidal flats had occurred by 1979 and was due to replacement by estuarine marsh and estuarine open water, primarily in the bayhead delta.

Palustrine marshes experienced both gains and losses, with the 1956 total increasing sharply by 1979 then decreasing by 2008. Around Swan Lake and Menefee Flat, palustrine marsh was replaced by estuarine marsh. Concurrently, palustrine marsh moved farther upriver into areas previously mapped as upland and, in some instances, forest. This scenario is consistent with the phenomenon observed frequently along the Texas Coast, where wetland habitats move inland as a result of relative-sea-level rise.

The **Carancahua** area is predominantly estuarine open water and upland. Estuarine-open-water area increased systematically throughout the study time period. The long-term change amounts to a 2% increase from the original amount.

Initial calculations of palustrine forest (PFO) show an extreme loss of habitat over the study time period. Large tracts of forest were previously mapped along West Carancahua and East Carancahua Creeks. However, very few of these areas appear to be PFO in 1996 photography and were therefore mapped as upland forest in the status (2008) map. Overall loss of palustrine forest was primarily to uplands (96%), reflecting the different mapping criteria. Some actual palustrine forest loss occurred when forest was harvested from the upper reaches of Keller Creek.

Between 1956 and 2008, palustrine marsh lost 79% of its original area. Some of the loss can be attributed to draining of marsh for development, mostly between Cox Bay and Keller Bay and between Keller Bay and Carancahua Bay. Construction of roads effectively blocked water flow, reducing the amount of moisture available to wetlands.

Many of these areas are transitional between wetland and upland and are therefore sensitive to hydrological modifications.

Despite a jump in 1979, possibly due to wetter conditions, estuarine-marsh numbers did not change significantly between 1956 and 2008. However, location of the salt marsh changed through time. Salt marsh was lost primarily to estuarine open water along the margins of secondary bays throughout the Carancahua area. Roughly 42% of estuarine-marsh-loss area was due to replacement by estuarine open water. Changes in the location and amount of estuarine marsh in the Carancahua area are the result of a combination of factors, predominantly relative sea-level rise.

As in other areas of Matagorda Bay, tidal flats were significantly reduced in the Carancahua area. In 1956 a large expanse was mapped, possibly owing to lower water levels during drought conditions. Almost no tidal flat was mapped in 1979, with some rebound by 2008. Overlay analysis shows most loss of tidal flat along bay margins, where most tidal flats became estuarine open water (48%). Movement of estuarine marsh into tidal flats accounted for 30% of the loss. Again, most loss can be attributed to relative-sea-level rise.

The **Tres Palacios** area includes much of Matagorda Bay and therefore contains a large amount of estuarine open water that increased systematically through time, most of the increase in estuarine open water having occurred by 1979. Almost half (48%) of the gain in estuarine open water occurred in areas previously occupied by estuarine marsh.

Estuarine marsh decreased through time, with the most significant decrease between 1979 and 2008. Replacement by estuarine open water accounted for 24% of estuarine-marsh loss between 1956 and 2008. Marsh loss to open water occurred along bay margins and the GIWW and on the delta of the West Branch of the Colorado River. Estuarine marsh was converted to upland when Baxter Island, southwest of Matagorda, was entirely impounded. The Tres Palacios area experienced extensive managed conversion of estuarine marsh to palustrine marsh in the area encompassed by Gillet Lake, Crab Lake, and the West Branch of the Colorado River. Of the marsh-loss area, roughly 30% was to palustrine marsh, mostly in Mad Island Slough and areas inland from Robbins Lake. Mad Island Wildlife Management Area (WMA) and other managed wetland areas had been diked by 1979, causing a freshening of the system. The other major (33%) loss of estuarine marsh was to upland. The overall change in estuarine marsh between 1956 and 2008 was a loss of (–)38% of the original resource.

Concurrently, palustrine marsh increased in area through time, increasing between 1956 and 1979 by 72%. Although some changes occurred in the earlier time period, wetland management promoting fresher systems was not broadly applied until after 1979. Palustrine marsh gain was primarily from estuarine marsh (54%), mostly in the Mad Island WMA. To the east of the WMA, palustrine marsh moved into previously upland areas along the West Branch of the Colorado River. Wetter conditions in later years, as compared with drought conditions in 1956, may have produced more favorable conditions for marshes to spread into transitional areas.

Palustrine forest (PFO), including palustrine scrub-shrub (PSS), is a relatively minor component of the wetland system in the Tres Palacios area. Most change (+21%) in forest area occurred between 1956 and 1979. Whereas the total area of forest had increased only 6% by 2008, the mapped location of forest changed drastically between 1979 and 2008. Prior to 2008, a significant amount of palustrine forest was mapped along Tres Palacios Creek. Very little palustrine forest was mapped there in 2008. Most palustrine forest mapped in 2008 was in the Colorado River valley.

Tidal flats decreased dramatically (–74%) in the Tres Palacios area. The largest expanse of tidal flat was mapped in 1956, but by 1979, flat numbers had decreased, with little change by 2008. Tidal-flat loss was primarily to estuarine marsh and estuarine open water along bay margins. Of the tidal-flat-loss area, 37% was to estuarine marsh, and 34% was to estuarine open water.

The most significant change in wetland habitats in the **Colorado** area is the large expansion (445%) of palustrine marsh between 1956 and 1979, rising only slightly in 2008. Palustrine-marsh gain was primarily (93%) from former uplands. Most gain was located in the abandoned river channel north of the town of Matagorda. Drought during the 1950's may have limited the extent of marsh in that time period.

Estuarine marsh was nearly eliminated from the Colorado area over the study time period. The 1956 total increased when, in 1979, estuarine marsh formed on dredge material along the GIWW, but by 2008, dredge material had covered marshes within the enclosed areas. All of Baxter Island had been converted to upland through this process by 2008.

Only a fraction of palustrine forest was mapped in 1956, possibly owing to difficulties distinguishing upland from wetland forest on black-and-white aerial photography. A similarly small portion of palustrine forest was mapped in 1979. Fluvial woodlands are prevalent throughout much of the incised Colorado River valley within the Colorado study area.

The most significant wetland trend in the **Brazos** area is the 43% increase in palustrine marsh between 1956 and 2008. The probable cause of the massive increase of palustrine marsh in the Brazos area is land-surface subsidence on the Brazos River delta. Such subsidence extends wetter conditions farther inland, expanding wetlands into areas previously mapped as prairie grasslands. A smaller amount of palustrine marsh gain (7%) was from previous estuarine marsh.

Estuarine marsh also experienced an increase through time, increasing by 19% between 1956 and 2008. Much (63%) of the gain was from areas previously mapped as upland, and another 20% was from areas formerly occupied by palustrine marsh.

Tidal flats make up a relatively small part of wetland habitats in the Brazos area. Of all habitats in the Brazos area, tidal flats suffered the most extreme loss through time, losing more than half (–56%) of the original resource. Approximately 37%, of tidal-flat loss was to estuarine open water along East Matagorda Bay and segments of the GIWW. Another 30% of the loss was to estuarine marsh near East Reservoir and in East Matagorda Bay near Egret Island.

Estuarine open water increased systematically throughout the study time period. The 1956 total had increased 18% by 1979, and an additional 12% by 2008. The main factor influencing the early expansion was the conversion of Lake Austin from fresh- to saltwater. In the 1950’s Lake Austin was mapped as lacustrine and rimmed by palustrine marshes, except for the extreme southern shore. By 1979, Lake Austin had been mapped as estuarine, and most all bordering marshes had been mapped as estuarine marsh. Palustrine marshes remained along the extreme northern shore of the lake near the mouth of Peyton Creek.

The other habitat most affected by increasing estuarine open water was estuarine marsh. Over 28% of the gain in estuarine open water was in areas that were previously estuarine marsh. Accelerated rates of relative-sea-level rise also caused estuarine open water to move into estuarine marsh and tidal flats throughout the area between Big Boggy NWR and East Reservoir and around McNabb and Gottschalk Lakes.

Forest area shows a significant systematic increase, with the most significant gain between 1979 and 2008. Nearly all (98%) of forest gain between 1956 and 2008 occurred in areas previously mapped as upland. Forest in this area had been mapped inconsistently in previous mapping efforts.

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REFERENCES

Anderson, J. R., Hardy, E. E., Roach, J. T., and Witmer, R. E., 1976, A land use and land cover classification system for use with remote sensor data: U.S. Geological Survey Professional Paper 964, 27 p.

Brown, L. F., Jr., Morton, R. A., McGowen, J. H., Kreitler, C. W., and Fisher, W. L., 1974, Natural hazards of the Texas Coastal Zone: The University of Texas at Austin, Bureau of Economic Geology, 13 p.

Cowardin, L. M., Carter, V., Golet, F. C., and LaRoe, E. T., 1979, Classification of wetlands and deepwater habitats of the United States: U.S. Department of Interior, Fish and Wildlife Service, Washington, D.C., USA 131 p.

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

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

McGowen, J. H., Brown, L. F., Jr., Evans, T. J., Fisher, W. L., and Groat, C. G., 1976a, Environmental geologic atlas of the Texas Coastal Zone–Bay City-Freeport area: The University of Texas at Austin, Bureau of Economic Geology, 98 p.

McGowen, J. H., Proctor, C.V., Brown, L. F., Jr., Evans, T.J., Fisher, W. L., and Groat, C. G., 1976b, Environmental geologic atlas of the Texas Coastal Zone–Port Lavaca area: The University of Texas at Austin, Bureau of Economic Geology, 107 p.

PBS&J, 2007, Matagorda Bay health evaluation: habitat assessment: final report prepared for the Lower Colorado River Authority and San Antonio Water System, 182 p.

Penland, Shea, Ramsey, K. E., McBride, R. A., Mestayer, J. T., and Westphal, K. A., 1988, Relative sea level rise and delta-plain development in the Terrebonne Parish region: Baton Rouge, Louisiana Geological Survey, Coastal Geology Technical Report No. 4, 121 p.

Ratzlaff, K. W., 1980, Land-surface subsidence in the Texas coastal region: U.S. Geological Survey Open File Report 80-969, 19 p.

Riggio, R. R., Bomar, G. W., and Larkin, T. J., 1987, Texas drought: its recent history (1931–1985): Texas Water Commission, LP 87-04, 74 p.

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

Tiner, R. W., 1984, Wetlands of the United States: current status and recent trends: U.S. Department of the Interior, U.S. Fish and Wildlife Service, 59 p.

Tremblay, T. A., and Calnan, T. R., 2009, Status and trends of inland wetland and aquatic habitats, Beaumont-Port Arthur Area: The University of Texas at Austin, Bureau of Economic Geology, final report prepared for the Texas General Land Office and National Oceanic and Atmospheric Administration, under GLO contract no. 08024, 70 p.

Tremblay, T. A., Vincent, J. S., and Calnan, T. R., 2008, Status and trends of inland wetland and aquatic habitats in the Corpus Christi Area: The University of Texas at Austin, Bureau of Economic Geology, final report prepared for the Texas General Land Office and National Oceanic and Atmospheric Administration, under CBBEP contract no. 0722, a report of the GLO Coastal Coordination Council pursuant to National Oceanic and Atmospheric Administration Award No. NA04NOS4190058, 89 p. + CD-ROM.

U.S. Army Corps of Engineers, 1987, USACE wetlands delineation manual, Environmental Laboratory, U.S. Army Corps of Engineers, Waterways Experiment Station, Vicksburg, MS, USA, Technical Report Y-87-1.

U.S. Soil Conservation Service, Soil Survey Staff, 1975, Soil taxonomy: a basic system of soil classification for making and interpreting soil surveys: U.S. Soil Conservation Service, Agricultural Handbook 436, 754 p.

White, W. A., Calnan, T. R., Morton, R. A., Kimble, R. S., Littleton, T. G., McGowen, J. H., and Nance, H. S., 1988, Submerged lands of Texas, Bay City–Freeport area: sediments, geochemistry, benthic macroinvertebrates, and associated wetlands: The University of Texas at Austin, Bureau of Economic Geology Special Publication, 130 p.

White, W. A., Calnan, T. R., Morton, R. A., Kimble, R. S., Littleton, T. G., McGowen, J. H., and Nance, H. S., 1989, Submerged lands of Texas, Port Lavaca area: sediments, geochemistry, benthic macroinvertebrates, and associated wetlands: The University of Texas at Austin, Bureau of Economic Geology Special Publication, 165 p.

White, W. A., Tremblay, T. A., Hinson, James, Moulton, D. W., Pulich, W. J., Jr., Smith, E. H., and Jenkins, K. V., 1998, Current status and historical trends of selected estuarine and coastal habitats in the Corpus Christi Bay National Estuary Program study area: Corpus Christi Bay National Estuary Program, CCBNEP-29, 161 p.

White, W. A., Tremblay, T. A., Waldinger, R. L, and Calnan, T. R., 2002, Status and trends of wetland and aquatic habitats on Texas Barrier Islands, Matagorda Bay and San Antonio Bay: The University of Texas at Austin, Bureau of Economic Geology, final report prepared for the Texas General Land Office and National Oceanic and Atmospheric Administration under GLO Contract No. 01-241-R, 66 p.

White, W. A., Tremblay, T. A., Waldinger, R. L, and Calnan, T. R., 2004, Status and trends of wetland and aquatic habitats on Texas Barrier Islands, Upper Texas Coast, Galveston and Christmas Bays: The University of Texas at Austin, Bureau of Economic Geology, final report prepared for the Texas General Land Office and National Oceanic and Atmospheric Administration under GLO Contract No. 03-057, 67 p.

White, W. A., Tremblay, T. A., Waldinger, R. L., and Calnan, T. R., 2007, Status and trends of wetland and aquatic habitats on Texas barriers, upper coast strandplain-chenier system and southern coast Padre Island National Seashore: The University of Texas at Austin, Bureau of Economic Geology, final report prepared for the Texas General Land Office and National Oceanic and Atmospheric Administration, under GLO contract no. 06-044, a report of the Coastal Coordination Council pursuant to National Oceanic and Atmospheric Administration Award No. NA05NOS4191064, 88 p. + CD-ROM.

White, W. A., Tremblay, T. A., Wermund, E. G., and Handley, L. R., 1993, Trends and status of wetland and aquatic habitats in the Galveston Bay system, Texas: Galveston Bay National Estuary Program, GBNEP-31, 225 p.

Winker, C. D., 1979, Late Pleistocene fluvial-deltaic deposition, Texas coastal plain and shelf: The University of Texas at Austin, Master's thesis, 187 p.

Zervas, C., 2001, Sea level variations of the United States 1854-1999: National Oceanic and Atmospheric Administration Technical Report NOS CO-OPS 36, 66 p.

APPENDIX

Total habitat areas for 2008, 1979, and 1956 determined from GIS data sets of the study area.

2008		1979		1956	
Habitats	Hectares	Habitats	Hectares	Habitats	Hectares
E1AB1	31	E2RF2M.	2	E1AB.	76
E1AB3	252	E1AB2L.	72	E1OW.	88,644
E1AB4	9	E1AB2LH.	3	E2AB.	190
E1AB5	16	E1OW.	47,423	E2BB.	124
E1AB5x	1	E1OWL.	44,998	E2EM.	17,646
E1UBL	92,995	E1OWLH.	3	E2FL.	4,834
E1UBLh	7	E1OWLX.	47	E2RF.	6
E1UBLs	2	E1OWX.	7	E2SS.	5
E1UBLx	1,102	E2AB2L.	27	L1OW.	1,691
E2AB1M	2	E2AB2M.	40	L2FL.	21
E2AB1N	78	E2BB2N.	7	L2OW.	180
E2AB1Ns	12	E2BB2P.	4	PAB.	3
E2AB1P	83	E2BBP.	6	PEM.	10,291
E2AB1Ps	3	E2EM.	8,746	PFL.	136
E2EM1N	8,851	E2EM1N.	5,788	PFO.	7,948
E2EM1Nd	77	E2EM1P.	7,995	POW.	410
E2EM1Nh	4	E2EM1PH.	25	PSS.	786
E2EM1Ns	51	E2FL.	633	R1OW.	906
E2EM1Nx	27	E2FL.	5	R2OW.	247
E2EM1P	7,378	E2FLM.	273	R4SB.	1
E2EM1Pd	678	E2FLN.	236	U.	227,753
E2EM1Ph	57	E2FLP.	242		
E2EM1Ps	73	E2RF2M.	68		
E2RF2M	26	E2SS.	3		
E2SS	5	L1OW.	3,429		
E2USM	104	L1OWH.	62		
E2USN	395	L1OWHX.	47		
E2USNs	18	L1OWV.	25		
E2USNx	0	L2AB2H.	13		
E2USP	982	L2AB2HH.	17		
E2USPs	62	PAB5F.	3		
L1AB4F	35	PAB6F.	15		
L1UBH	350	PABGF.	14		
L1UBHh	425	PEM.	3,437		
L1UBHx	63	PEM1A.	1,193		
L1UBKh	2,899	PEM1AH.	16		
L2AB1hs	63	PEM1C.	3,905		
L2AB5	16	PEM1CH.	6		
L2AB5Khs	11	PEM1F.	252		
L2AB5V	24	PEM1FH.	3		

L2AB5h	59
L2UB	5
L2UBFh	137
L2UBFx	15
L2UBKh	295
L2USKh	269
L2USKhs	104
PAB1F	7
PAB1Fh	3
PAB3Hx	3
PAB4F	26
PAB4Fh	5
PAB4Fx	5
PAB4Khs	12
PAB5	3
PAB5V	3
PAB5h	17
PAB5x	5
PEM1A	3,565
PEM1Ad	797
PEM1Ah	187
PEM1Ahs	40
PEM1Ax	40
PEM1C	2,766
PEM1Cd	427
PEM1Ch	713
PEM1Cx	212
PEM1F	442
PEM1Fd	82
PEM1Fh	949
PEM1Fx	101
PEM1Khs	180
PEM1R	178
PEM1S	72
PEM1T	607
PEM1Th	27
PFO1A	5,131
PFO1Ad	7
PFO1Ah	5
PFO1C	360
PFO1Cd	6
PFO1F	3
PFO1Fx	2
PFO1R	3
PFO4A	1
PSS1A	364
PSS1Ah	1
PSS1C	120
PSS1Ch	1
PSS1Chs	1
PEM1FX.	1
PEM1H.	4
PEM1R.	143
PEM1S.	15
PEM1T.	20
PEM1Y.	342
PFL.	12
PFO.	4,577
PFO1F.	10
PFO6A.	181
PFO6C.	67
PFO6F.	18
PFO6S.	41
POW	1
POW.	851
POWF.	33
POWFH.	9
POWFHX.	13
POWFX.	2
POWG.	3
POWGH.	3
POWGX.	2
POWH.	61
POWHH.	27
POWHX.	3
POWT.	1
POWVX.	6
PSS.	10
PSS6A.	182
PSS6B.	3
PSS6C.	36
PSS6F.	1
PSS6R.	12
PSS6S.	7
R1AB6V.	9
R1FLR.	4
R1OW.	285
R1OWV.	276
R2OW.	365
R2OWH.	58
U.	158,546
UA.	38,231
UAR.	12,215
UB.	27
UBS.	130
UF6.	4,184
UR.	11,234
UU.	640
UUO.	15

PSS1F	3
PSS1R	1
PUB	60
PUBCh	12
PUBFh	151
PUBHx	563
PUBKh	950
PUBKhs	61
PUBV	13
PUS	24
PUSCx	14
PUSKhs	83
PUSh	62
R1AB5	20
R1UBV	280
R2AB5	1
R2UBH	386
R2UBHx	17
U	223,753