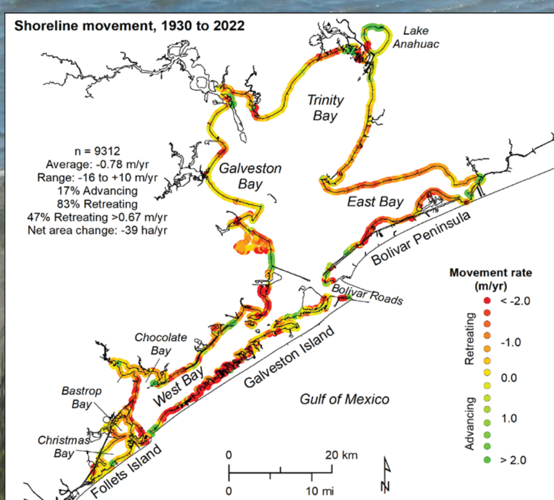
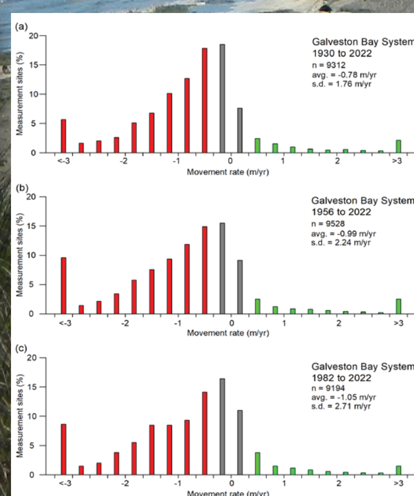
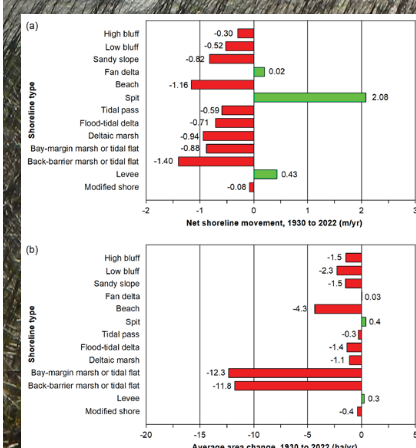
Final Report

HISTORICAL SHORELINE MOVEMENT IN GALVESTON, TRINITY, EAST AND WEST BAYS ON THE UPPER TEXAS GULF COAST

Tiffany L. Caudle and Jeffrey G. Paine







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by

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ABSTRACT

This report updates rates of shoreline movement from multiple time periods, characterizes shoreline types, and assesses vulnerability to sea-level change along bay shorelines within the Galveston Bay system (Galveston, Trinity, East, and West Bays). A current shoreline position for the Galveston Bay system was extracted from a combination of airborne lidar surveys from 2017 and 2018 and aerial photography from 2020 and 2022. This recent shoreline position was compared with previous shoreline positions determined from aerial photographs from 1930, 1956, and 1982 to determine shoreline-movement and land-loss rates for two longer-term time frames (1930 to 2022 and 1956 to 2022) and a more recent period (1982 to 2022). The lidar data and photography were also used to classify approximately 500 km of bay shoreline into 11 shoreline types. From higher to lower elevation adjacent to the shoreline, the common shoreline types are high and low Pleistocene clayey sand and sandy clay bluffs, Pleistocene sandy slopes, fan deltas, sandy and shelly beaches and spits, tidal passes, flood-tidal delta marshes and tidal flats, deltaic marshes, and back-barrier and bay-margin marshes and tidal flats. The lower-elevation shoreline types (back-barrier and bay-margin marsh and tidal flats) are the most common shoreline types in the bay system, together constituting 47 percent of the total shoreline length.

Shoreline movement was dominantly erosional over the three time periods. During the longest time period, 1930 to 2022, 83 percent of the measurement sites retreated at an average rate of 0.78 m/yr. Between 1956 and 2022, 82 percent of sites retreated at an average rate of 0.99 m/yr. During the more recent period (1982 to 2022), net shoreline retreat averaged -1.05 m/yr for the Galveston Bay system, translating to an average

land-loss rate of 52.40 ha/yr. Average shoreline retreat rates were highest in East Bay at -1.44 m/yr, followed by West Bay retreat rates at -1.39 m/yr, Galveston Bay at -0.55 m/yr, and Trinity Bay at -0.45 m/yr. The shoreline type experiencing the highest rates of retreat between all three time periods was the back-barrier marsh and tidal flat: -1.39 m/yr between 1930 and 2022, -2.02 between 1956 and 2022, and -2.17 m/yr between 1982 and 2022. The only shoreline types to experience advancement during all three periods were spits and tidal passes.

INTRODUCTION

Texas coastal shorelines include bay, lagoon, and Gulf of Mexico frontage along geomorphic features such as unconsolidated sandy barrier islands and peninsulas, semiconsolidated muddy marshes and tidal flats, consolidated clayey and sandy bluffs, and sandy and shelly beaches and spits. Common coastal processes that include wind-driven waves, storm surge and storm waves, and relative sea-level rise contribute to the dynamic nature of these coastal boundaries, leading to shoreline retreat or advance through removal or addition of sediment, or by submergence and emergence. Because the Texas coastal zone is home to millions of people in urban and rural settings, significant industrial infrastructure, an economically important coastal fishery, and critical habitat for numerous endangered and other critical species, it is important to monitor the movement of these coastal boundaries, determine coastal land loss and gain, and characterize shoreline movement and its potential impact on the varied activities, uses, and functions of coastal land, vegetation, and habitat.

Researchers at the Bureau of Economic Geology (Bureau) updated rates of shoreline movement, characterized shoreline types, and assessed vulnerability to sea-level change along bay shorelines within the Galveston Bay system including Galveston, Trinity, East, and West Bays (Figs. 1 and 2). This environmentally sensitive area is being considered for a major federal engineering project intended to protect infrastructure around Galveston Bay from inundation during future storms. It is important to have a comprehensive, current understanding of historical shoreline change trends to establish pre-project status. The purpose of this study was to examine detailed bay-margin morphology, identify shoreline types, and determine shoreline position by extracting a common elevation contour that would serve as a shoreline proxy from digital elevation models (DEMs) produced from lidar point-cloud data. We then compared past shoreline positions previously mapped by the Bureau on historical aerial photographs with the shoreline position extracted from the DEMs constructed from the 2017 and 2018 airborne lidar survey data and 2022 aerial photography. We determined longer-term net movement rates by comparing shoreline positions from 1930 and 1956 with those from 2022, and a more recent net shoreline movement rate by comparing shoreline positions from 1982 to those from the 2022 data.

The Bureau has conducted several previous studies of historical shoreline movement in Texas bays and the Gulf of Mexico shoreline. These studies have been published in a series of Bureau reports and other articles that include the bay shorelines of the Galveston Bay system (Paine and Morton, 1986, 1991), West Bay (Gibeaut and others, 2003) the Copano, San Antonio, and Matagorda Bay systems (Paine and others, 2016), and the most recent Gulf shoreline update (Paine and others, 2021). These publications focus on historical shoreline movement determined from mid- to late-1800s topographic charts produced by the U.S. Coast Survey and shoreline positions mapped on 1:24,000-scale aerial photographs taken in the 1930s, 1950s, and 1982, and in the case of the Gulf shoreline update shoreline movement was determined utilizing lidar data from 2000, 2012, and 2019. In addition to the data on historical shoreline movement, each of the previous publications contains detailed discussions of the geologic character of the bay systems and the coastal processes that influence shoreline movement, including sediment supply, wave action, tropical cyclones, and relative sea-level. Additionally, shoreline types for the upper Texas

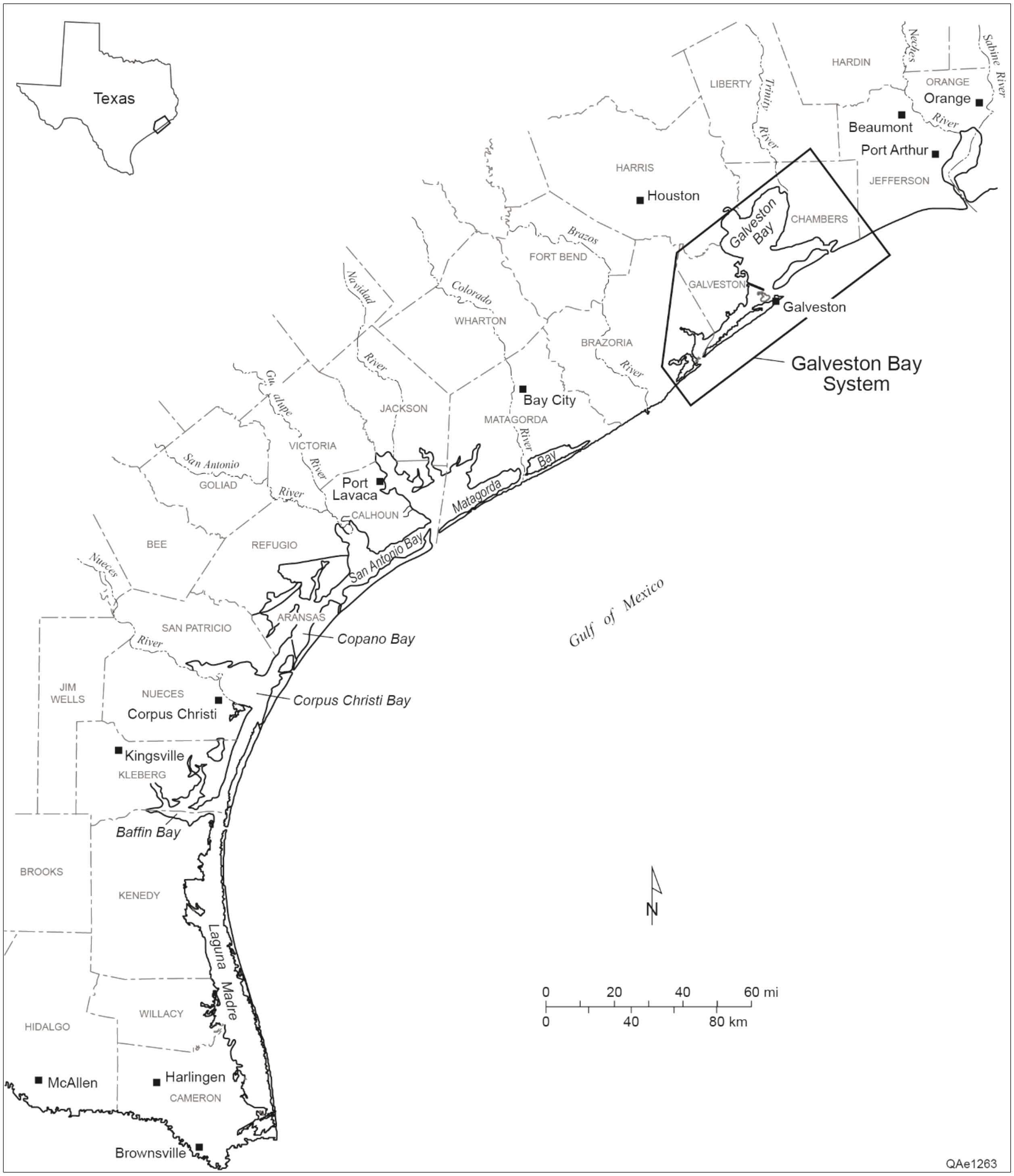

Figure 1. Map of the Texas Coastal Zone. Outlined area highlights the Galveston Bay system including Galveston, Trinity, East, and West Bays.

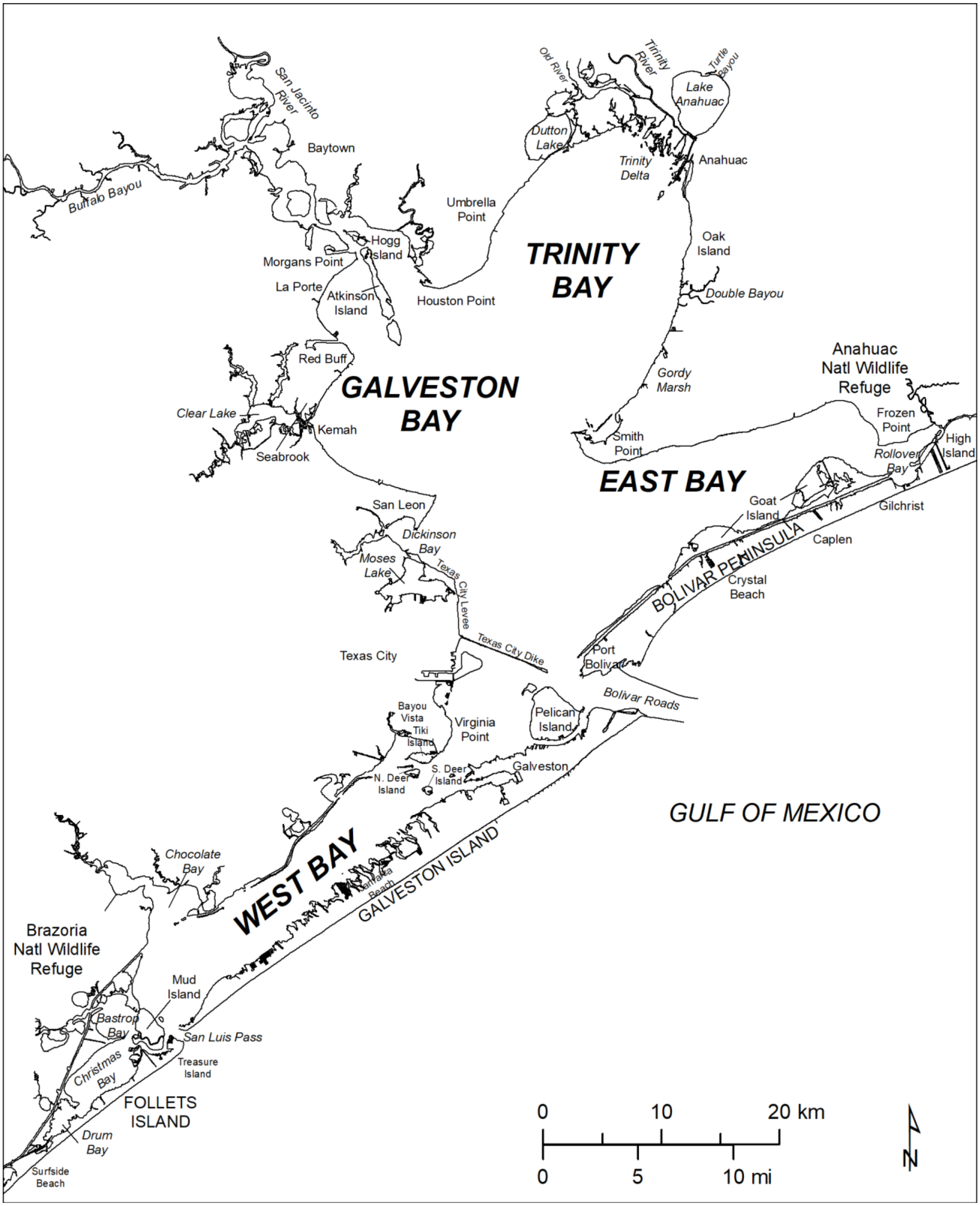

Figure 2. Geographic locations within the Galveston Bay system.

coastal zone were previously mapped by Morton and White (1995) for the purpose of oil spill response and contingency planning.

The shoreline positions determined in the previous Galveston Bay system study were digitized and georeferenced in this study for use in determining long-term and more recent shoreline movement between the 1930s and the recent airborne lidar surveys and aerial photography.

METHODS

We used previously determined shoreline positions from Bureau studies of historical shoreline change in the Galveston Bay system that were based on aerial photographic interpretation, and compared those positions with recent shoreline position extracted from 2017 and 2018 airborne lidar surveys which were edited based upon 2022 aerial photography. These shorelines were used to determine shoreline change rates for multiple time periods for the Galveston Bay system on the upper Texas coast.

Historical Shoreline Mapping

Topographic surveys, aerial photographs, and photomosaics were used to determine shoreline position and changes prior to the advent of airborne lidar. Accurate topographic charts dating from the 1850s were produced by the U.S. Coast Survey (now National Ocean Service). Aerial photographs supplemented, and in the early 1930s replaced, regional topographic surveys. Aerial photographs show shoreline position—the position of the land-water interface—when the photographs were taken.

One key to measuring shoreline movement accurately is agreement of scale and projection between the original data and the selected base map. Historical shoreline positions used in older Bureau shoreline change studies were mapped directly on aerial photomosaics (quadrangle) then optically transferred to 1:24,000 scale, 7.5-minute USGS topographic base maps. Bureau shoreline studies in the 1970s until the early 1990s (i.e., Paine and Morton, 1986) calculated shoreline change rates directly from the USGS topographic maps. For this study, Bureau researchers scanned the original paper maps from historical shoreline mapping of Galveston Bay (Paine and Morton, 1986). The maps were brought into ArcGIS and georeferenced in the NAD27 datum (datum of the USGS topographic maps) then transformed to the NAD83 datum. The historical shoreline positions recorded on the base maps were then digitized in ArcGIS. Shorelines were recorded from the 1850s topographic charts and aerial photography from 1930 and 1982.

During the course of this study, we discovered that the 1956 shoreline position was not shown on all the paper maps. For those areas, we scanned the original 1956 Edgar Tobin Aerial Survey photomosaics at 600 dpi to create a digital image, then directly georeferenced them in ArcGIS using newer imagery in the NAD83 coordinate system. We also acquired U. S. Department of Agriculture aerial images photographed in 1956 to fill gap in our Tobin collection around Morgan Point and La Porte (10 inch by 10 inch photos from USDA and photomosaics from Historical Aerials). The photography used to georeference the 1956 images was 60-cm resolution, natural color, National Agricultural Inventory Program (NAIP) digital imagery photographed in 2022. At least 8 control points were used to georeference each of the 1956 photomosaic quadrangles to the newer imagery matching objects that were visible in both images such as land features, roads, or buildings. Directly georeferencing the imagery scans eliminates errors that can be introduced through the transfer to paper maps, georeferencing in the older NAD27 coordinate system, and transformation to the newer NAD83 coordinate system. The shoreline position mapped on the 1956 photomosaics was then digitized in ArcGIS.

A general statement on the accuracy of the historical shoreline positions is that accuracy improves with advances in technology. There is some inherent uncertainty as to the precision of the data in the original topographic charts that were prepared by the U.S. Coast Survey. For aerial photography, optical resolution, the quality of photographic negatives, and mosaic compilation techniques all improved over time between the earliest photographs in 1930 and the most recent photographs (2022) used in this study. Another potential source of error is using the land-water interface on aerial photographs because the boundary normally will fall somewhere between high and low tide. This displacement depends on the tidal cycle, slope of the shore, and wind direction when the photo was taken. For this study, the 1850s shorelines were not used in the calculation of shoreline movement but they are included in the accompanying GIS dataset

Current Shoreline Extraction

The current shoreline position around the Galveston Bay system was mapped by a combination of extracting an elevation contour from lidar DEMs that represents an approximation of mean higher high-water level, and manually digitizing the water/land boundary from the aerial photography. Topographic data used for this study include a

34-cm cell size digital elevation model (DEM) constructed from topographic data acquired during an airborne lidar survey flown by Sanborn Mapping Company in 2017, and a 50-cm cell size DEM constructed from topographic data acquired by Fugro USA Land, Inc. in 2018. Both lidar surveys were conducted for the Texas Natural Resources Information System's (TNRIS) Texas Strategic Mapping (StratMap) program. Photography used in the study was 60-cm resolution, natural color, National Agricultural Inventory Program digital imagery photographed in 2022. All datasets were downloaded through the Texas Geographic Information Office (TxGIO, formerly TNRIS) DataHub (https://data.geographic.texas.gov/).

A lidar derived shoreline position was extracted from digital elevation models to represent the bay shoreline position in the Galveston Bay systems. Water level data from tides gauges located around Galveston Bay (Freeport Harbor, Galveston Bay Entrance, Galveston Railroad Bridge, Morgans Point, Pier 21, Rollover Pass, and San Luis Pass) were analyzed to select elevation contours that approximated water levels at the time of the lidar surveys (2017-2018). We compared average water levels from only the dates of the lidar survey in 2017 (February 22, 2017 through March, 23, 2017), only the dates of the lidar survey in 2018 (January 13, 2018 thru March 22, 2018), combining the dates of the 2017 and 2018 lidar surveys, and from all of 2017 and 2018.

The elevation contours were extracted from the DEMs using the "Raster Calculator", "Reclassify", and "Raster Domain" functions in ArcGIS. "Raster Calculator" is used to convert the DEM into a raster with all values above the designated elevation contour as a value of 1 and values below the designated contour as 0. "Reclassify" creates a new raster that reclassifies all "0" values to "null". The "Raster Domain" function creates a polyline footprint of the raster which corresponds to the bay shoreline contour elevation. The extracted files are then smoothed in ArcMap using the “Smooth Line” function (PAEK algorithm with a 2-meter smoothing tolerance). The number of vertices in the polyline is reduced by using ET GeoWizards “Generalize Polyline” command with a 0.25 m tolerance. This process retains the shape of the smoothed polyline while reducing the number of vertices. Topology errors, including dangles, self-overlapping lines, and self-intersecting lines, were removed. Adjacent line segments were aggregated using ArcGIS’s “Unsplit Line” function.

Extracted contour elevations were overlain on NAIP aerial photography from 2022. The elevations were examined to determine which most accurately corresponded with the land and water boundary on the photography. The elevation contour of 0.284 meters above NAVD88 (average water level from the seven tide gauges from 2017 and 2018) was determined to be the most consistent with historical bay shoreline mapping practices and the land and water boundary on the DEMs. The elevation contour was then overlain on the more recent NAIP imagery. Hand editing and manual digitization occurred in areas where the shoreline had moved landward between the dates of the lidar surveys and the dates of the aerial photography.

Determining Rates of Shoreline Movement

Rates of shoreline movement were calculated after including the 2022 lidar- and imagery-derived shoreline position into the ArcGIS database containing the historical shoreline positions for the Galveston Bay system. Shoreline movement was quantified following these steps:

(1) creating shore-parallel baselines from which shore-perpendicular transects were cast at 50-m intervals (Fig. 3) along the shoreline using the GIS-based extension software Digital Shoreline Analysis System version 5.0 (DSAS; Himmelstoss and others, 2021);

(2) calculating net (average) rates of change and associated statistics for long-term (1930 to 2022 and 1956 to 2022) and most recent (1982 to 2022) periods using the transect locations and the selected shorelines within DSAS;

(3) calculating both net (average) rates and linear-regression rates for all shorelines combined; and

(4) determining the intersection of the transect lines with the 2022 shoreline and creating GIS shape files containing (a) the rates and statistics of shoreline change measurements and (b) the measurement transects bounded by the most landward and seaward historical shoreline position for each measurement site (the shoreline change envelope).

Rates of shoreline movement were calculated for all shorelines along Galveston, Trinity, East, and West Bays with a few exceptions. Along Bolivar Peninsula, change rates were calculated following the 1850s and 1930 shoreline shape. Rates of change were not calculated along the dredged portions of the Gulf Intracoastal Waterway (GIWW) that cut through the large remnant flood-tidal delta/washover features on the bay side of the Peninsula. Shoreline segments around marsh restoration projects on the bayside of Galveston Island were removed from the 2022 shoreline file that was used to calculate movement rates (Fig. 3). Though further inland, we used the continuous shoreline position along the island for the calculations as we interpreted that position to represent the natural shoreline position in those areas.

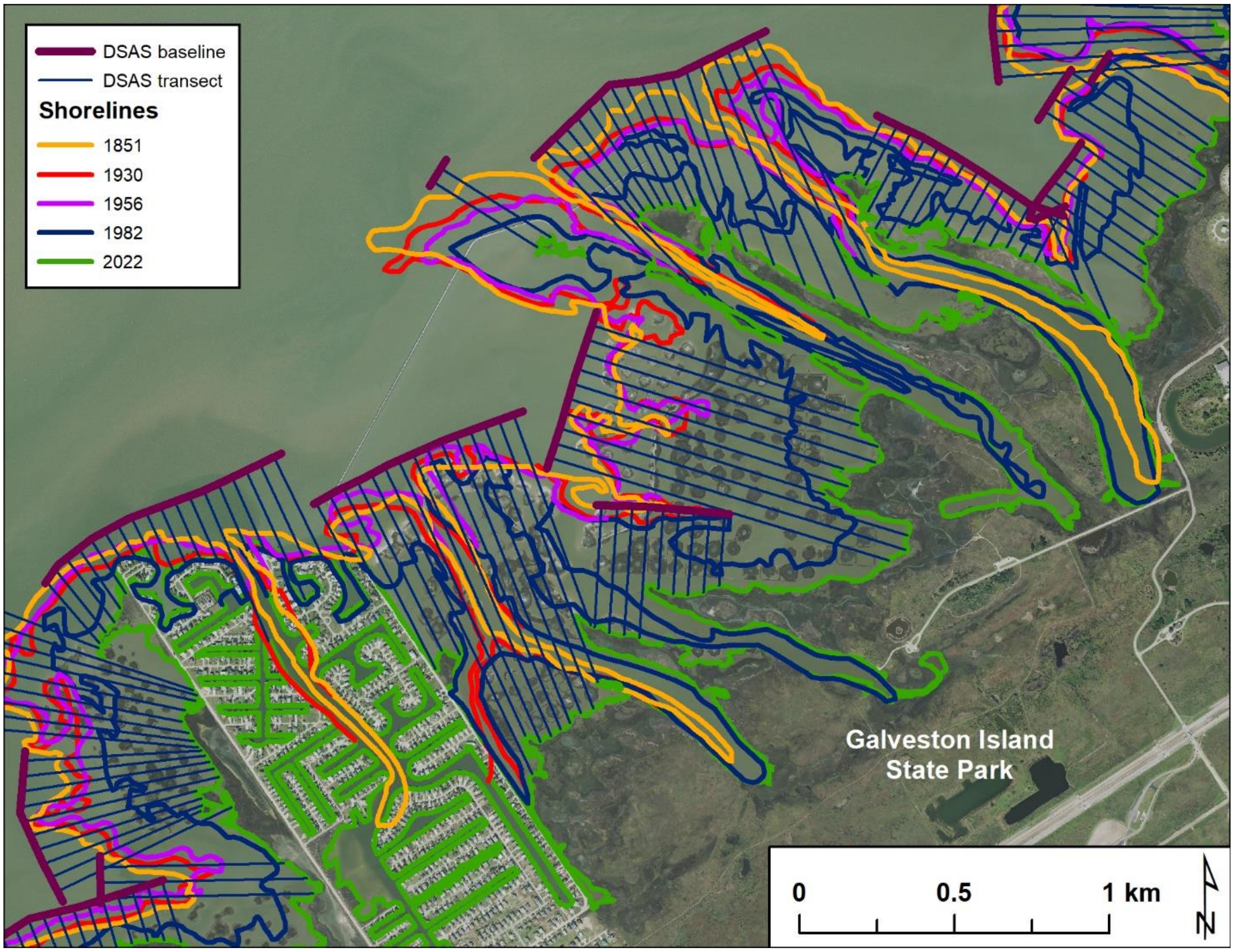

Figure 3. Example of shoreline positions and DSAS baselines and transects in West Bay near Galveston Island State Park. Shoreline positions around wetland restoration mounds were removed from the 2022 shoreline file for the DSAS shoreline movement calculation.

The point file that was created during change rate calculations was used as the base to create shapefiles with a shoreline-type and shoreline-modification classification designations. Shoreline types found along the Galveston Bay system include high bluff, low bluff, sandy slopes, fan delta (marsh and woody), deltaic marsh, beach, spit, bay-margin marsh, back-barrier marsh, flood-tidal delta, and tidal pass. Some shorelines have undergone significant modification through dredging, dredge spoil disposal, filling for land development, and emplacement of erosion control structures. The classification of levee or modified shore were used in those areas where the land had been altered to an extent that the original shoreline type could no longer be determined, such as along the Texas City Levee, Tiki Island, and the Galveston Harbor. Many shoreline segments of the Galveston Bay system have some sort of reinforcement or armoring. A shoreline-modification field was created to identify segments with rip-rap, breakwaters, bulkheads, marsh restoration projects, etc. Shoreline-types and modifications were determined through a combination of aerial photography, lidar DEMs, and ground investigations.

SHORELINE TYPES

We have classified the shorelines that serve as the boundaries of the water bodies within the Galveston Bay system into 11 types that can be distinguished by a combination of elevation, slope, depositional environment (Fig. 4), material and degree of consolidation, and vegetation or habitat (Fig. 5; Table 1). From highest to lowest elevation, these types are: high and low bluff, sandy slope, fan delta, beach, spit, tidal pass, flood-tidal delta marsh or tidal flat, deltaic marsh, back-barrier marsh or tidal flat, and bay-margin marsh or tidal flat. In areas where the land has been altered to an extent that the original shoreline type could no longer be determined, the shoreline was given the designation levee or modified shore. Together, these shoreline types extend for about 500 km throughout the Galveston Bay system (Fig. 6).

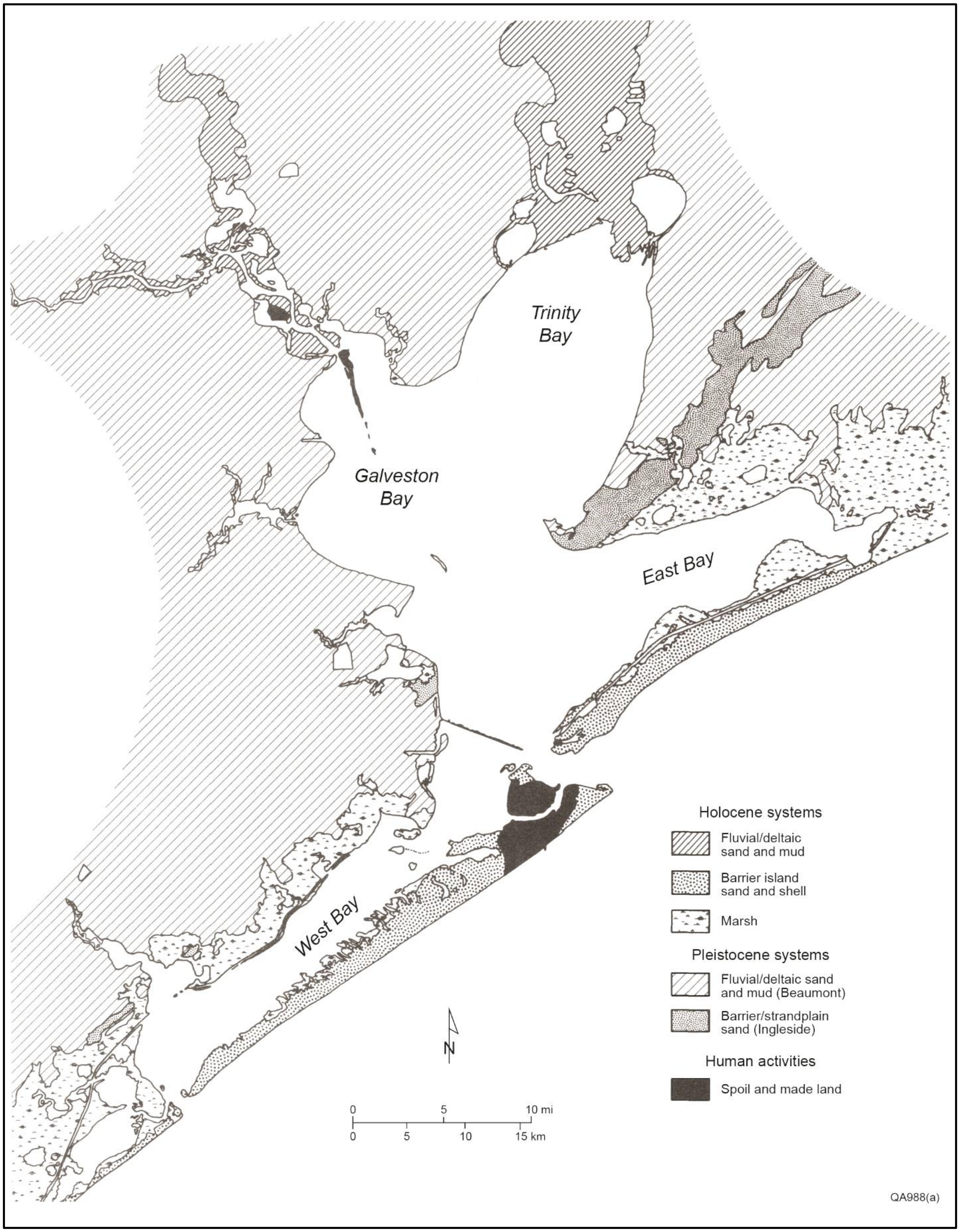

Figure 4. Generalized geologic map of the Galveston Bay system. From Paine and Morton (1986) and modified from Fisher and others (1972).

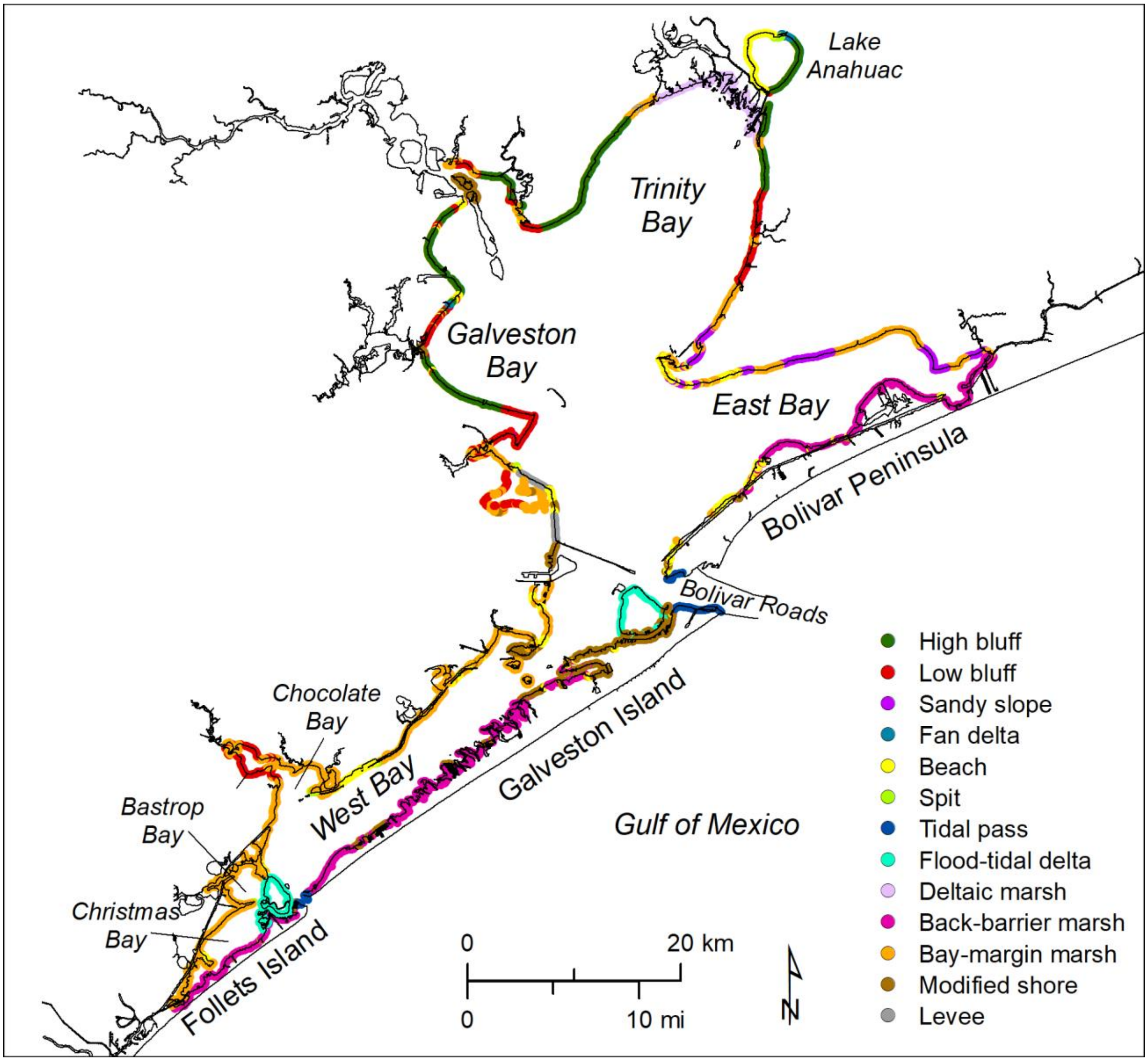

Figure 5. Distribution of principal shoreline types (Table 1) in the Galveston Bay system.

Table 1. Common bay shoreline types and their environmental, elevation, slope, and material characteristics.

Type	Environment	Elevation	Slope	Material
High bluff	Bare or vegetated slope; common slope failure	> 3 m	Steep with minimal fronting beach or marsh	Consolidated silty to sandy clay
Low bluff	Bare or vegetated slope; common slope failure	< 3 m	Steep with minimal fronting beach or marsh	Consolidated silty to sandy clay
Sandy slope	Vegetated; moderate slope failure	< 3 m	Moderate with minimal fronting beach or marsh	Fine sand to clayey sand; semiconsolidated
Fan delta	Vegetated: wetland vegetation common near shoreline	< 1 m	Minimal	Muddy sand; semiconsolidated
Beach	No or minimal vegetation	< 1 m	Moderate	Sand and shell; unconsolidated
Spit	No or minimal vegetation	< 1 m	Moderate	Sand and shell; unconsolidated
Tidal pass	Wetland vegetation	< 1 m	Minimal	Muddy sand to sandy mud; unconsolidated
Flood-tidal delta	Wetland vegetation to barren tidal flats	< 0.5 m	Negligible	Muddy sand to sandy mud; unconsolidated
Deltaic marsh	Wetland vegetation	< 0.5 m	Negligible	Mud to sandy mud; semiconsolidated
Bay-margin marsh or tidal flat	Wetland vegetation to barren tidal flats	< 0.5 m	Negligible	Sandy mud to muddy sand; semiconsolidated
Back-barrier marsh or tidal flat	Wetland vegetation to barren tidal flats	< 0.5 m	Negligible	Sandy mud to muddy sand; semiconsolidated

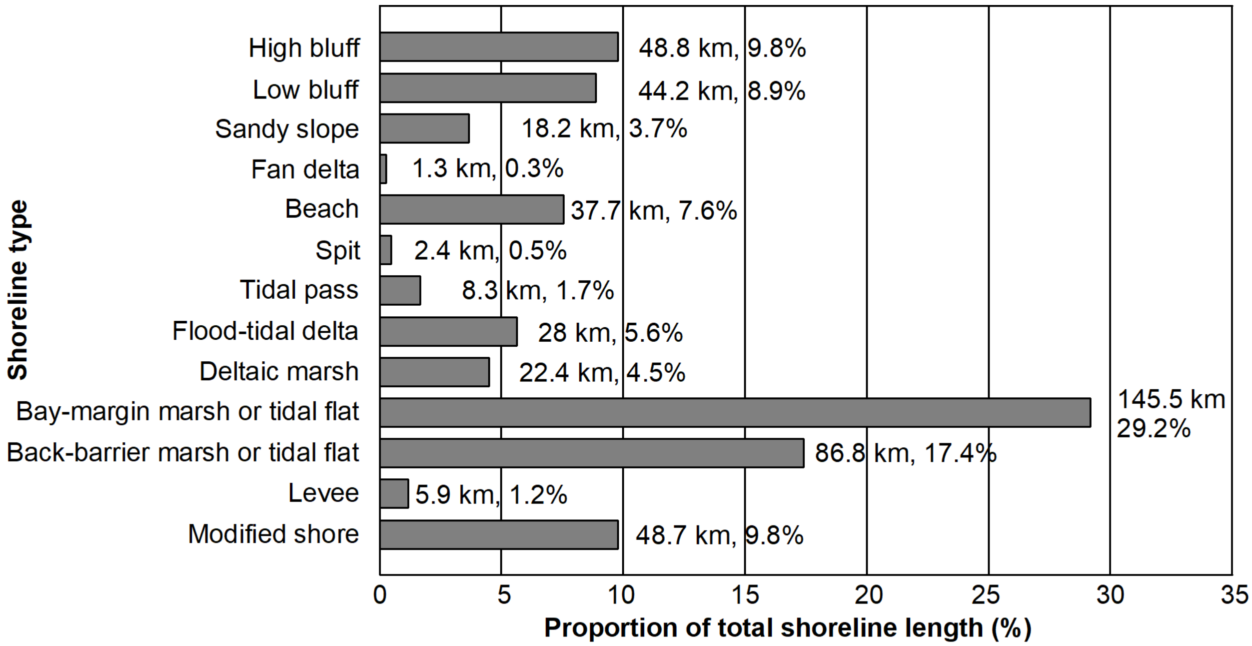

Figure 6. Total length and proportion of common shoreline types (table 3) at 9,528 sites in the Galveston Bay system (including Galveston, East, West, and Trinity Bays). Total Shoreline length is approximately 500 kilometers.

High and Low Bluffs

High (more than about 3 m) and low (less than 3 m) erosional bluffs are formed on Pleistocene Beaumont Formation strata (Fig. 4) and are a common shoreline type along the more elevated, inland parts of the bays, constituting almost 19 percent of the total bay shoreline length in the bay system (Fig. 6). These consolidated sandy clay or clayey sand strata typically form steep bluffs (Fig. 7; Table 1) that are prone to slope failure. Bluff heights increase landward, following the gentle inland topographic rise characteristic of the Texas coastal plain. Bluffs are common along the shores of Galveston Bay (Fig. 8) and the eastern shore of Trinity Bay including the eastern shoreline of Lake Anahuac (Fig. 9). High and low bluffs are highly susceptible to retreat caused by storm surge and storm waves during tropical cyclone passage and are moderately susceptible to retreat caused by non-storm wave action, but are relatively unaffected by relative sea-level rise over the historical record (Table 2).

(a)

(b)

Figure 7. Photographs of (a) high Pleistocene sandy clay bluff in McCollum Park in Beach City, Texas on the shore of upper Trinity Bay and (b) low Pleistocene sandy clay bluff near Morgan Point on the northern shore of Galveston Bay.

Sandy Slopes

Fine sand or clayey sand slopes occur along about 18 km or 4 percent of the shorelines in the Galveston Bay system (Figs. 5 and 6). This shore type slopes gradually bayward from elevations of as much as a few meters and may have a low erosional scarp at the shoreline.

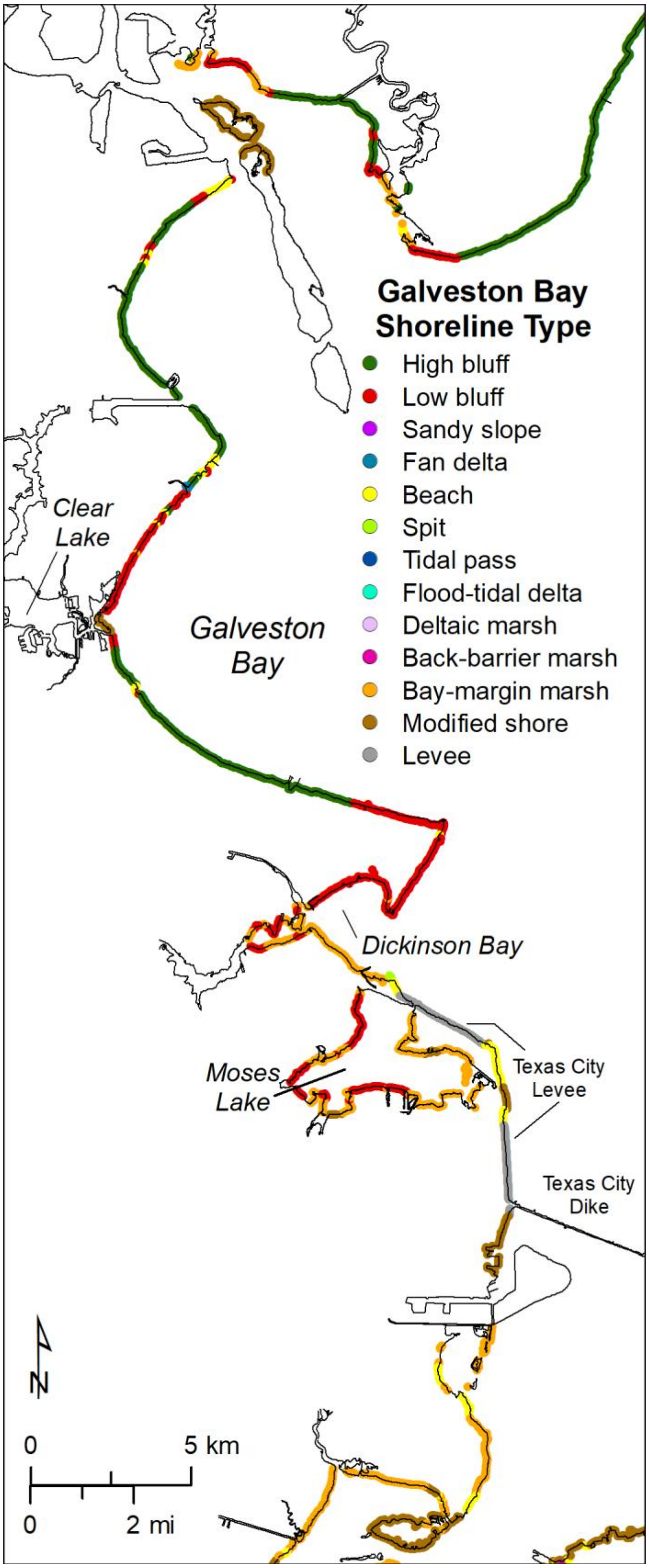

Figure 8. Distribution of principal shoreline types (Table 1) along the western shoreline of Galveston Bay.

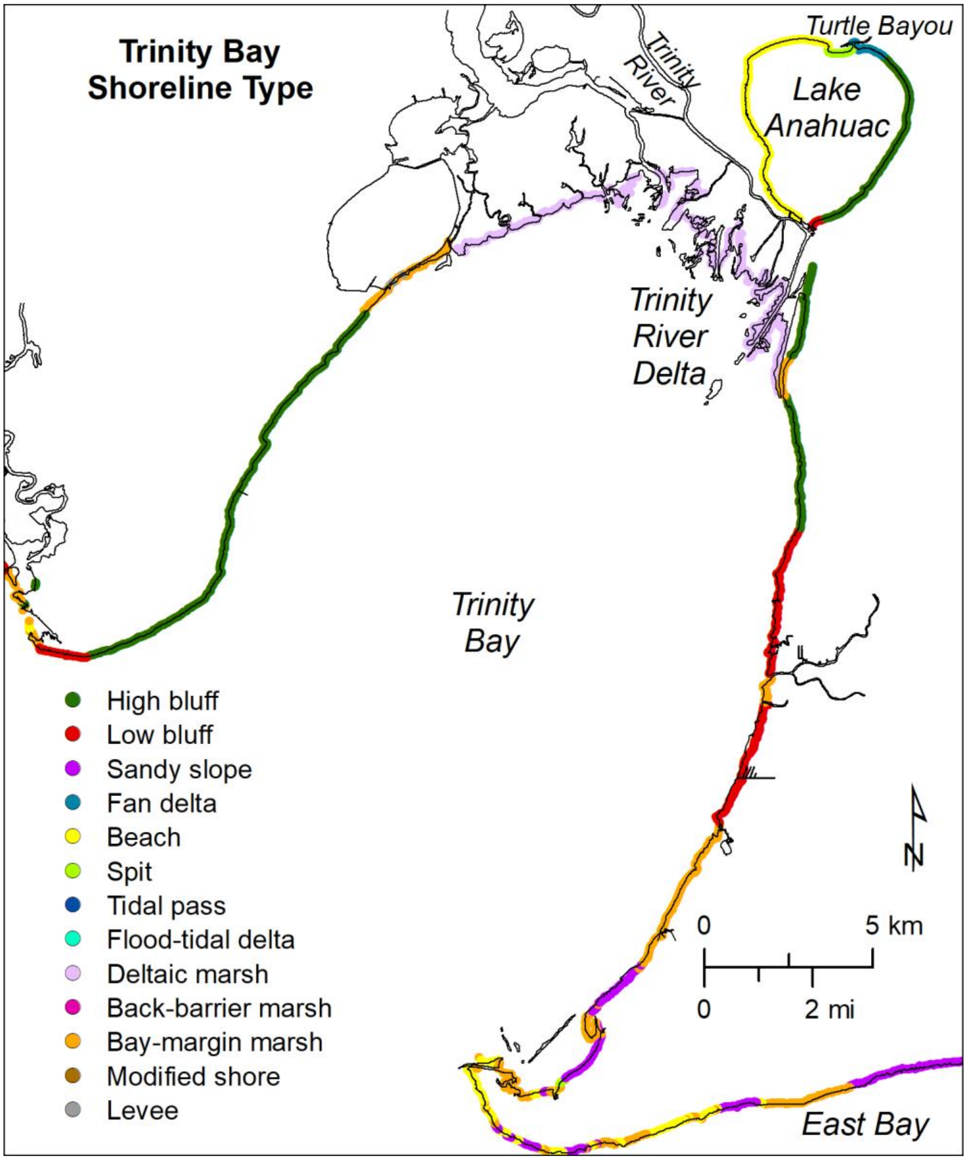

Figure 9. Distribution of principal shoreline types (Table 1) in Trinity Bay including Lake Anahuac and the Trinity River Delta.

Unconsolidated sand and clayey sand slopes are found where the Pleistocene Ingleside barrier island or strandplain coincides with the modern shoreline and are commonly stabilized by upland grasses and shrubs (Fig. 4). In the Galveston Bay system, sandy slopes occur near Smith Point along the southeastern shore of Trinity Bay (Fig. 9) and the mainland shore of East Bay (Fig. 10). Sandy slopes are highly susceptible to

Table 2. Common bay shoreline types (Table 1) and their relative susceptibility to relative sea-level rise, storm surge and waves, and non-storm wave action.

Type	Relative sea-level rise	Storm surge and waves	Non-storm wave action
High bluff	Low	High	Moderate
Low bluff	Low	High	Moderate
Sandy slope	Low	High	Moderate
Fan delta	Moderate	Moderate	High
Beach	Moderate	Moderate	High
Spit	Moderate	Moderate	High
Tidal pass	High	High	High
Flood-tidal delta	High	High	High
Deltaic marsh	High	Low	High
Bay-margin marsh or tidal flat	High	Low	High
Back-barrier marsh or tidal flat	High	Low	High

shoreline retreat caused by storm surge and storm waves and moderately susceptible to erosion from normal wave activity, but are relatively insensitive to short-term relative sea-level rise given their typical elevation (Table 2).

Fan Deltas

Fan deltas are small geomorphic features formed where local drainages discharge into major or minor bays. They form fan-shaped protrusions into the bays that may be as much as a few hundred meters across and slope gradually to the shoreline. They compose a small percentage (less than one percent; Fig. 6) of the total shoreline frontage in the Galveston Bay system. Fan deltas are composed of semiconsolidated muddy sand or sandy mud and are mostly stabilized by grasses and shrubs at higher elevations and can have wetland vegetation or woody areas that occasionally flood where elevations are low along the shoreline (Fig. 11, Table 1). Fan deltas are highly susceptible to retreat caused by non-storm wave activity and are moderately susceptible to retreat caused by relative sea-level rise and storm-related surge and waves (Table 2). An example can be found where Turtle Bayou flows into Lake Anahuac in upper reaches of Trinity Bay (Fig. 9).

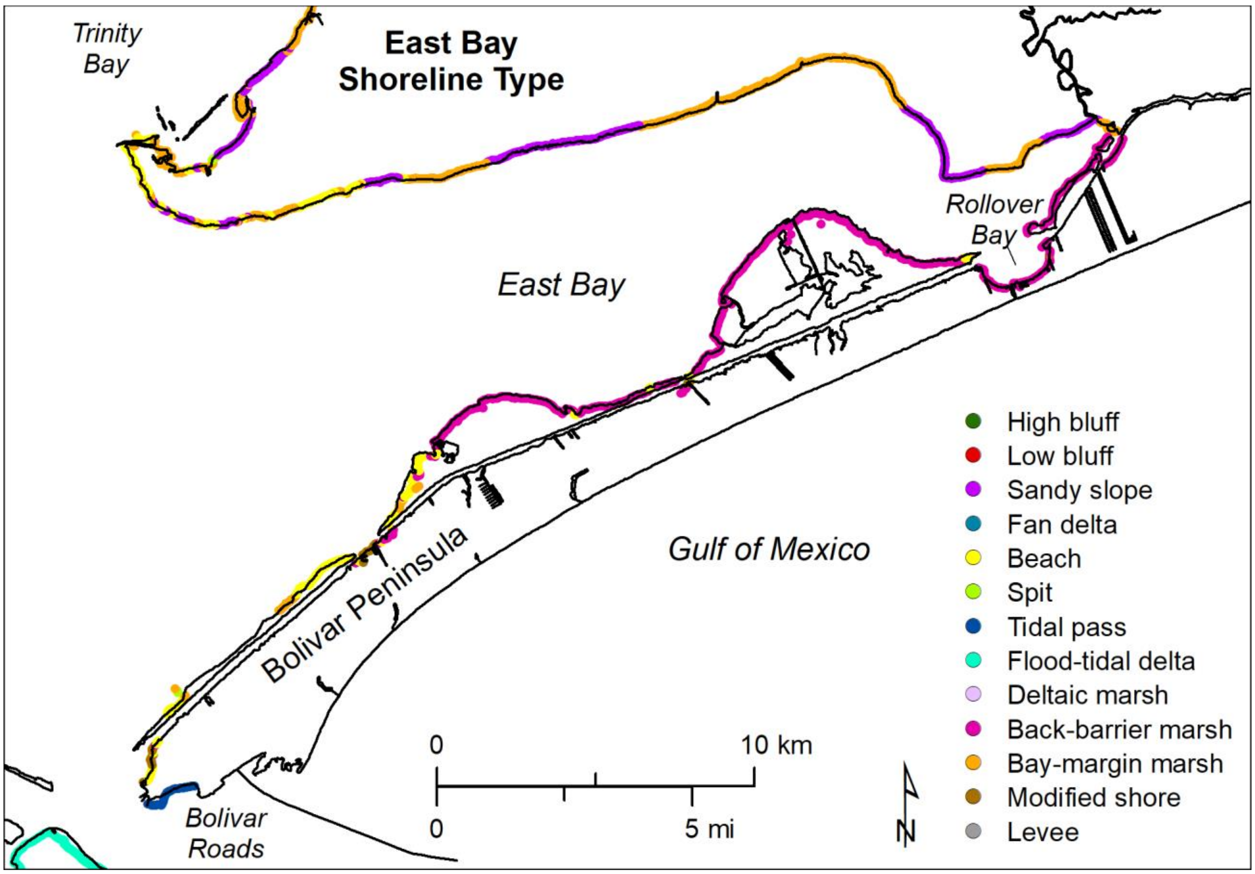

Figure 10. Distribution of principal shoreline types (Table 1) in East Bay.

Figure 11. Photograph of the flooded woody fan delta at the Anahuac National Wildlife Refuge Headquarters on Lake Anahuac.

Spits and Beaches

Small spits and beaches make up nine percent (40 km) of total bay shoreline in the Galveston Bay system (Fig. 6). Spits are low, elongate, and unconsolidated sandy and shelly beaches forming along eroding bay shorelines by longshore drift and lateral migration (Table 1). They are very limited in extent, about 2 km, and found near Moses Lake (Galveston Bay shoreline, Fig. 8); Smith Point in Trinity Bay and Lake Anahuac (Fig. 9); the western end of Bolivar Peninsula (Fig. 10); and in West Bay at the mouth of Chocolate Bay, between Bastrop Bay and Christmas Bay, and along the bay shoreline of Follets Island (Fig. 12). Beaches are more extensive, forming 7.5 percent (38 km) of the total bay shoreline length. These typically narrow and low beaches are composed of unconsolidated fine sand with some shell (Fig. 13a) and commonly occur bayward of sandy slopes or bluffs where sufficient sand has been eroded or retained to form a beach. They can also be small shelly berms that were deposited by storms (Fig. 13b). Prominent beaches are found in small pockets along the western shore of Galveston Bay and in front of the Texas City Levee (Fig. 8); along the western shore of Lake Anahuac (Fig. 9); along the mainland shore of East Bay near Smith Point and on the southwestern end of Bolivar Peninsula (Fig. 10); and along the GIWW in West Bay mainland and spoil island shorelines in West Bay; and the southwestern shoreline of Christmas Bay (Fig. 12). Similar to fan deltas, low-elevation spits and beaches are highly susceptible to erosion from non-storm wave action and are moderately susceptible to retreat caused by relative sea-level rise and storm-related surge and waves (Table 2).

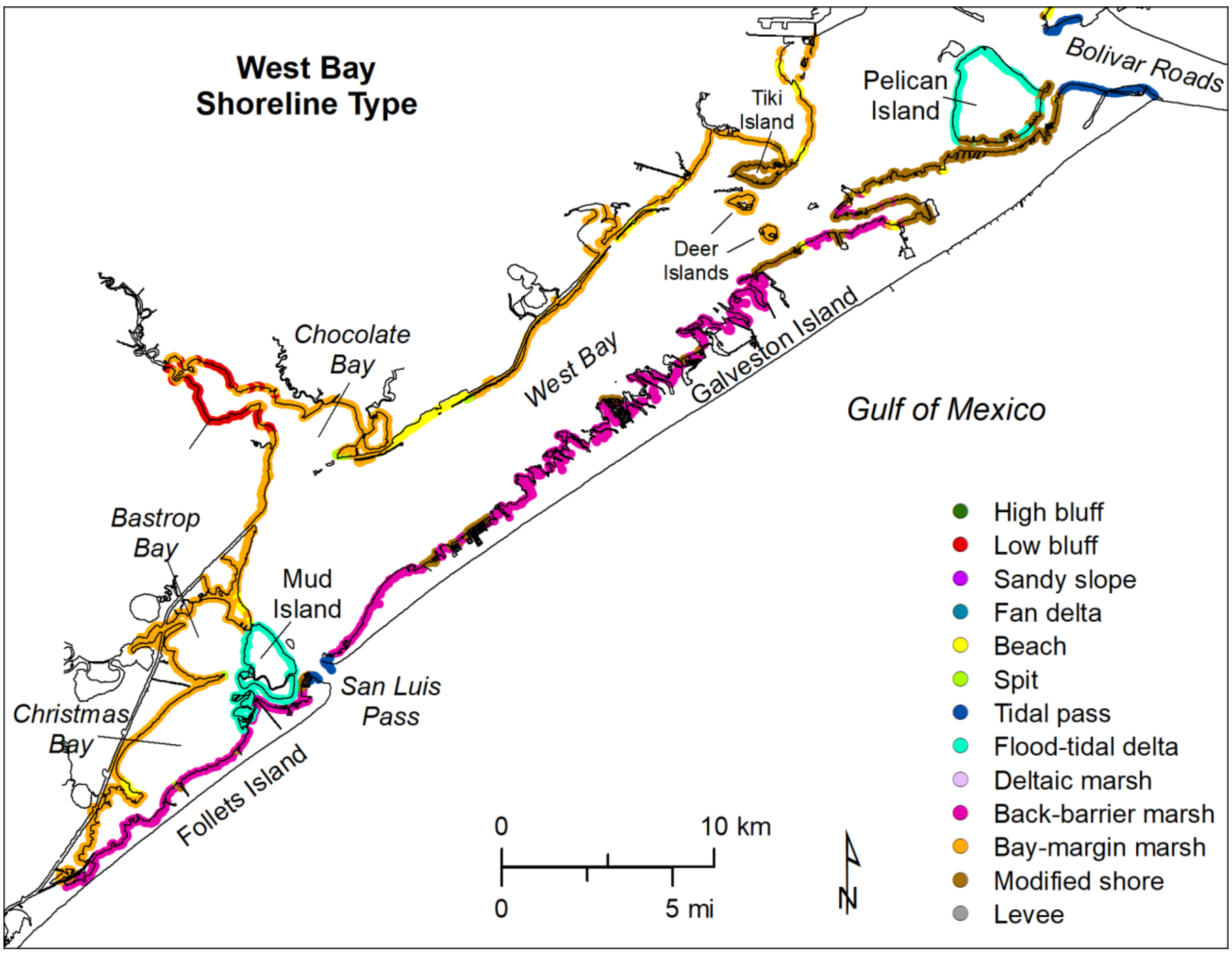

Figure 12. Distribution of principal shoreline types (Table 1) in West Bay, including Bastrop Bay, Christmas Bay, and Chocolate Bay.

(a)

(b)

Figure 13. Photographs of (a) fine sandy beach in El Jardin Beach park near Seabrook and (b) a shelly storm berm beach on the mainland shore of East Bay.

Tidal Passes

Shorelines along tidal passes represent almost two percent of the shoreline in the Galveston Bay system (Fig. 6). These shores have generally low elevations, minimal slopes, and are composed of unconsolidated muddy sand to sandy mud (Table 1). Tidal pass shorelines can have wetland vegetation, beaches, or spits. Because of their low elevation and generally long wave fetch, shores along tidal passes are highly susceptible to erosion from non-storm wave action, tidal currents, and relative sea-level rise (Table 2). They are also highly susceptible to shoreline movement caused by flood and ebb surge currents during tropical cyclone passage.

Two major tidal passes allow exchange of bay and Gulf of Mexico water within the Galveston Bay system. Tidal-pass shorelines are associated with San Luis Pass between Follets Island and Galveston Island (Figs. 2 and 12) and with Bolivar Roads, the major shipping channel for the ports within Galveston Bay, between Galveston Island and Bolivar Peninsula (Figs. 2, 10, and 12).

Flood-tidal Deltas

Closely associated with tidal passes are flood-tidal deltas, which are submerged shoals, emergent landforms, and associated wetlands located on the bayward side of current and former tidal passes. Major flood-tidal deltas are located bayward from San Luis Pass (Fig. 12) and Bolivar Roads (Fig. 12). Shorelines bounding these features represent about 6 percent of the total shoreline in the Galveston Bay system (fig. 10). Flood-tidal deltas have surface elevations below 0.5 m and are composed of unconsolidated muddy sand to sandy mud that may host wetland vegetation or tidal-flat environments. Because of their low elevation and proximity to tidal passes, they can be highly susceptible to erosion from non-storm wave activity and the effects of relative sea-level rise. Storm waves generated by tropical cyclones generally have little impact on flood-tidal deltas because they flood early during storm passage, but are highly susceptible to movement and reconfiguration caused by storm-generated flood and ebb currents.

Deltaic Marshes

The Trinity River and several other smaller steam channels associated with the river flow into Trinity Bay. The river carries sand, silt, and clay to the bay, where those sediments are deposited in low-elevation deltaic environments at the head and margins of the Trinity Bay. A large delta has formed separating Lake Anahuac from Trinity Bay (Fig. 9). Shoreline along the delta makes up about 4 percent of the total Galveston Bay system shoreline (Fig. 6).

Marshes and tidal flats commonly occupy low-relief, semiconsolidated, muddy sand and sandy mud substrates (Fig. 14), which are highly susceptible to erosion caused by non-storm wave activity, and to land loss related to relative sea-level rise (Table 2). Storm surge and storm waves have little impact on deltaic marshes located far from the open Gulf at the head of bays, but heavy rainfall and stream flooding that commonly occurs during tropical cyclone passage can contribute to significant instantaneous advance of the deltas into the bays.

Back-barrier Marshes or Tidal Flats

Marshes and tidal flats are the most common shoreline type on the bay shore of Bolivar Peninsula on East Bay (Fig. 10), Follets Island on Christmas Bay, and Galveston Island on West Bay (Fig. 12). This shoreline type is the second-most extensive in the three bays, accounting for more than 17 percent or 87 km of the total shoreline (Fig. 6). Semiconsolidated sandy mud to muddy sand substrates support dominant marsh and tidal-flat environments (Fig.15a) that, like other low-elevation types, are highly susceptible to retreat from non-storm waves and land loss from inundation caused by relative sea-level rise (Table 2). Susceptibility to retreat from tropical cyclone surge and waves is low except near tidal passes and washover channels where surge-related flood and ebb currents are concentrated.

Figure 14. Photograph of marsh vegetation and tidal channels in the Trinity River Delta near Anahuac.

Bay-margin Marshes or Tidal Flats

The most extensive shoreline type in the study area is bay-margin marsh or tidal flat, which constitutes 30 percent of all bay shoreline types by length (Fig. 6). This type shares many characteristics with the back-barrier marsh or tidal flat type, including low elevation, minimal slope, muddy sand or sandy mud substrate, and dominant marsh vegetation with interspersed tidal flats (Fig. 15b; Table 1). It also shares erosion-susceptibility characteristics with the back-barrier type: high susceptibility to erosion by non-storm waves and to land loss related to relative sea level rise, and low susceptibility to erosion related to storm surge and waves (Table 2). Because they are not located on barrier islands, bay-margin marshes or tidal flats are not as susceptible to sediment redistribution from flood and ebb currents generated during tropical cyclone passage. Bay-margin marshes or tidal flats are along the shoreline of Moses Lake (Fig. 8); adjacent to the Trinity River Delta (Fig. 9); and the mainland shorelines of East Bay (Fig. 10), West Bay, Chocolate Bay, Bastrop Bay and Christmas Bay (Fig. 12).

(a)

(b)

Figure 15. Photographs of (a) back-barrier marsh on Bolivar Peninsula near Rollover Pass and (b) bay-margin marsh in the Anahuac National Wildlife Refuge.

Modified and Protected Shorelines

Eleven percent of the 500 km of bay shoreline in the Galveston Bay system has been designated as levee or modified shore. This classification was used when the shoreline had been modified to the extent that characteristics of the original shoreline environment are no longer recognizable. These shorelines can be found along the Texas City Levee (Fig. 8), the dredged canals and bulkheads of the Tiki Island coastal community, and the wharves and bulkheads of the Port of Galveston on Pelican Island and Galveston Island (Fig. 12). Twenty-three percent of the shorelines in the study area have been armored with shore protection features such as breakwaters, seawalls (Fig. 7a), riprap (Figs. 7b and 16a), bulkheads (Fig. 16b), dredged material, and in some cases, combinations of material (Fig 7a). These modifications have been employed on all of the natural shoreline types, excluding the Trinity River Delta, in an attempt to stabilize the shoreline position and protect bayfront property, but are easily overtopped and are prone to damage or failure during storms, can reduce or eliminate the function of the natural habitat, and can increase erosion rates on adjacent unprotected property.

SHORELINE CLASSIFICATION BY EROSION SUSCEPTIBILITY

As discussed in the previous section, the physical and environmental characteristics of the shorelines can be used to classify them by type (Table 1) and to assess the relative susceptibility of the shoreline types to common causes of shoreline retreat in Texas bays, including relative sea-level rise, storm surge and storm waves, and non-storm wave activity Table 2).

(a)

(b)

Figure 16. Photographs of (a) riprap protecting bay-margin marsh in Anahuac National Wildlife Refuge on East Bay and (b) a bulkhead along a sandy slope shoreline in Oak Island on Trinity Bay.

Relative sea-level rise, which combines sea-level rise caused by ocean-water volume increases as well as land-surface subsidence, is in the range of a few millimeters per year. Shoreline types along low-elevation coastal lands, including along tidal passes, flood-tidal deltas, deltaic marshes, and back-barrier and bay-margin marsh and tidal flats, are most susceptible to retreat caused by relative sea-level rise (Table 2, Fig. 17). Shoreline types with slightly higher elevations landward of the shoreline (fan deltas, beaches, and spits) are moderately susceptible to potential retreat associated with relative sea-level rise. Shoreline types with relatively high elevations adjacent to the shoreline (high and low Pleistocene bluffs and sandy slopes) are relatively insensitive to short-term relative sea-level rise.

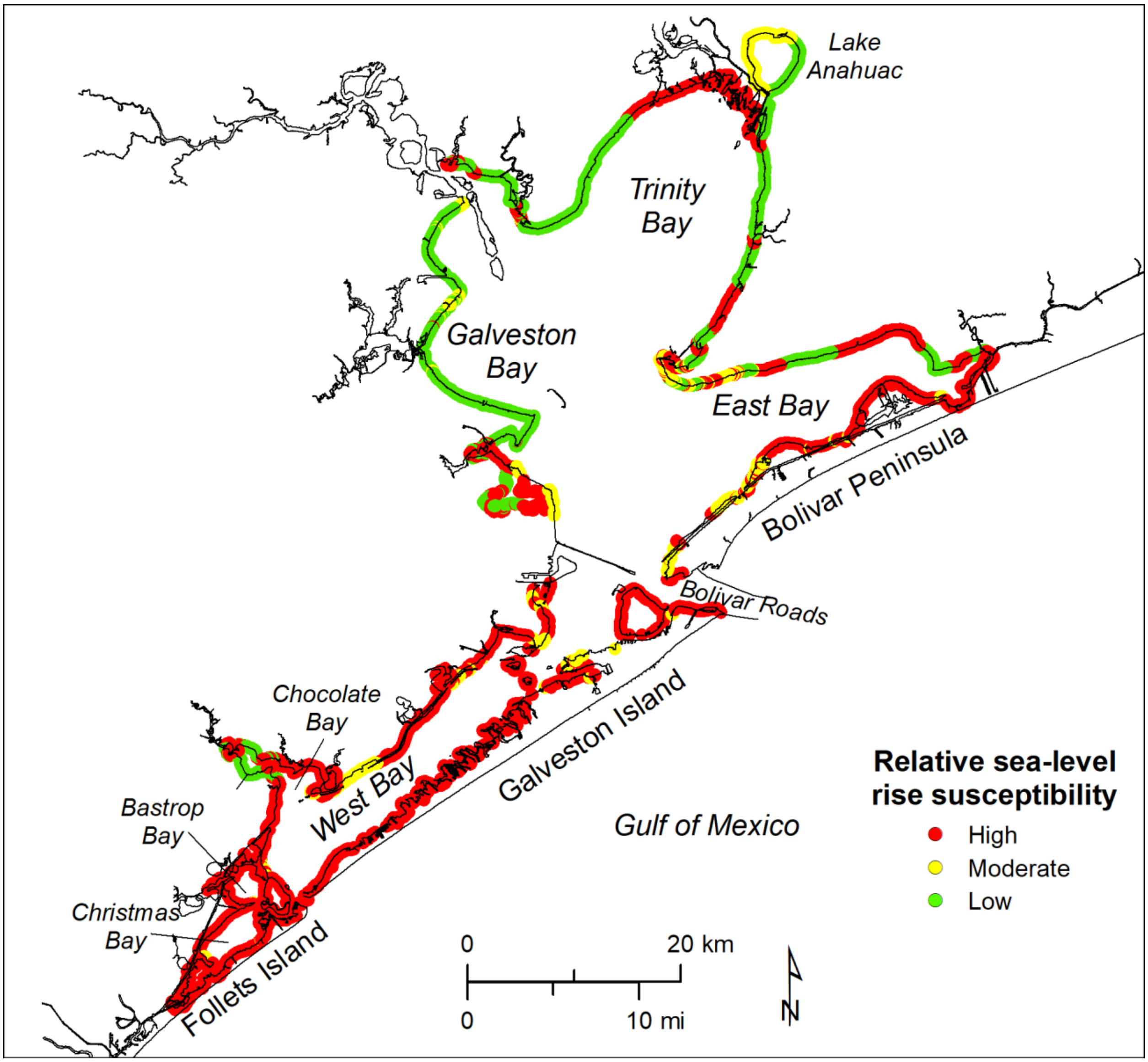

Figure 17. Shoreline type classified by susceptibility to retreat associated with relative sea-level rise.

Elevated water levels and strong, storm-driven waves accompany the passage of tropical cyclones. Rising water levels tend to flood low-elevation shoreline types before the storm makes landfall, which can reduce the impact of storm-driven waves on those bay shoreline types. Shorelines along deltaic marshes and back-barrier and bay-margin marshes and tidal flats have lower susceptibility to storm-related erosion than do shorelines along types with higher near-shoreline elevations. Shorelines along fan deltas, beaches, and spits are classified as moderately susceptible to storm surge and storm-driven waves. Shorelines with higher elevations along the shoreline, including low and high bluffs and sandy slopes, are highly susceptible to erosion during tropical cyclone passage because storm-driven waves can directly attack the higher- elevation bluffs and slopes and increase the likelihood of erosion and slope failure (Table 2; Fig. 18). Tidal passes and flood-tidal deltas are highly susceptible to reshaping during flood and ebb currents associated with storm passage.

Normal wave activity is probably the most significant agent of erosion along bay shorelines. All shoreline types are susceptible to wave action, but the higher-elevation shoreline types (high and low bluffs and sandy slopes) may be only moderately and indirectly susceptible to normal waves because the toe of the bluffs and slopes may be protected by narrow beaches, marshes, or tidal flats that absorb direct wave action. In the case of Galveston Bay and Trinity Bay, these shorelines are commonly armored with seawalls, bulkheads, or rip rap which protects the toe of the bluff or slope from normal wave activity. All shoreline types with lower elevations (fan delta, beach, spit, tidal pass, flood-tidal delta, deltaic marsh, and back-barrier and bay-margin marsh and tidal flats) are highly susceptible to erosion from wave action (Table 2; Fig. 19).

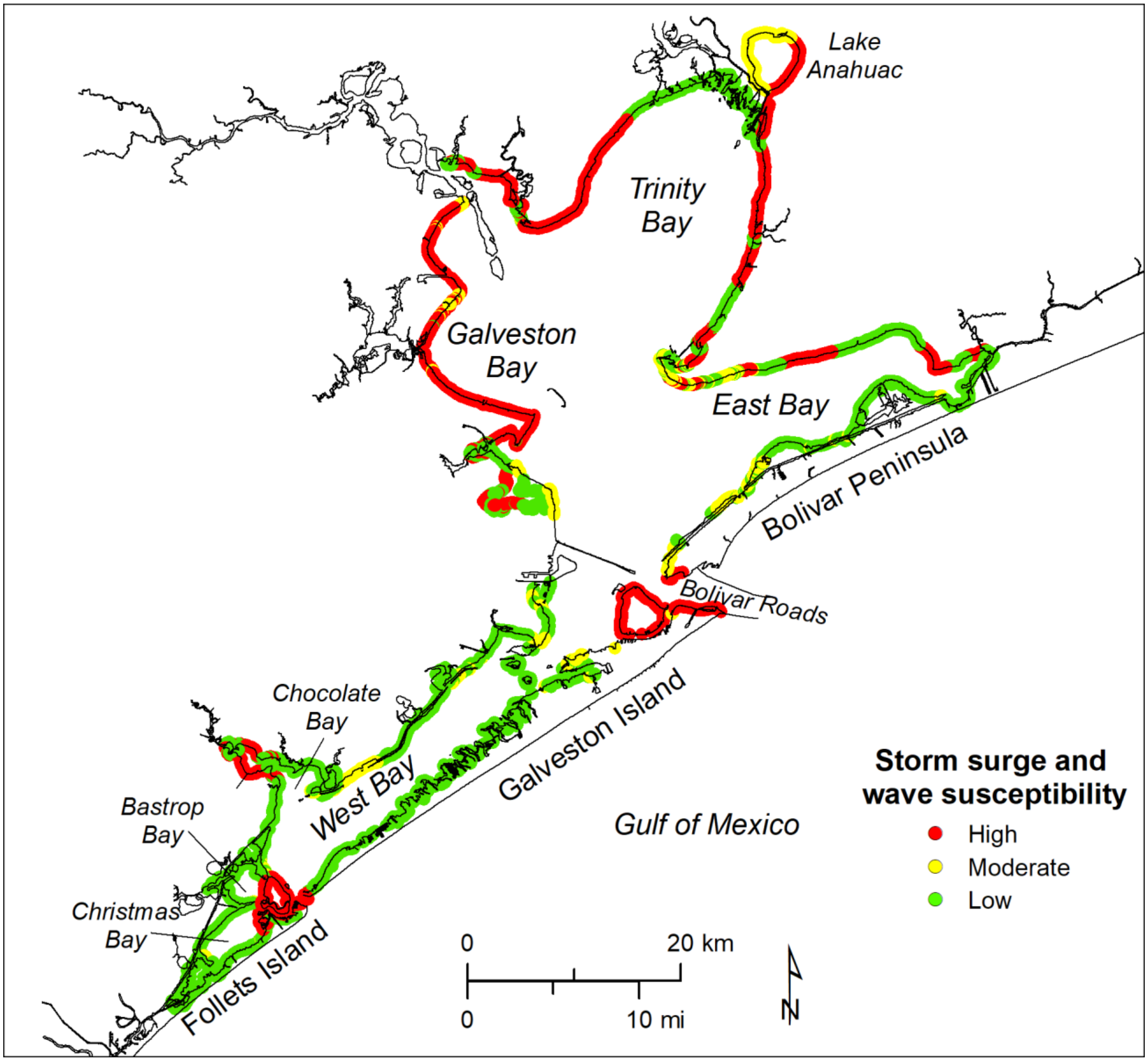

Figure 18. Shoreline types classified by susceptibility to erosion associated with storm surge and storm wave action.

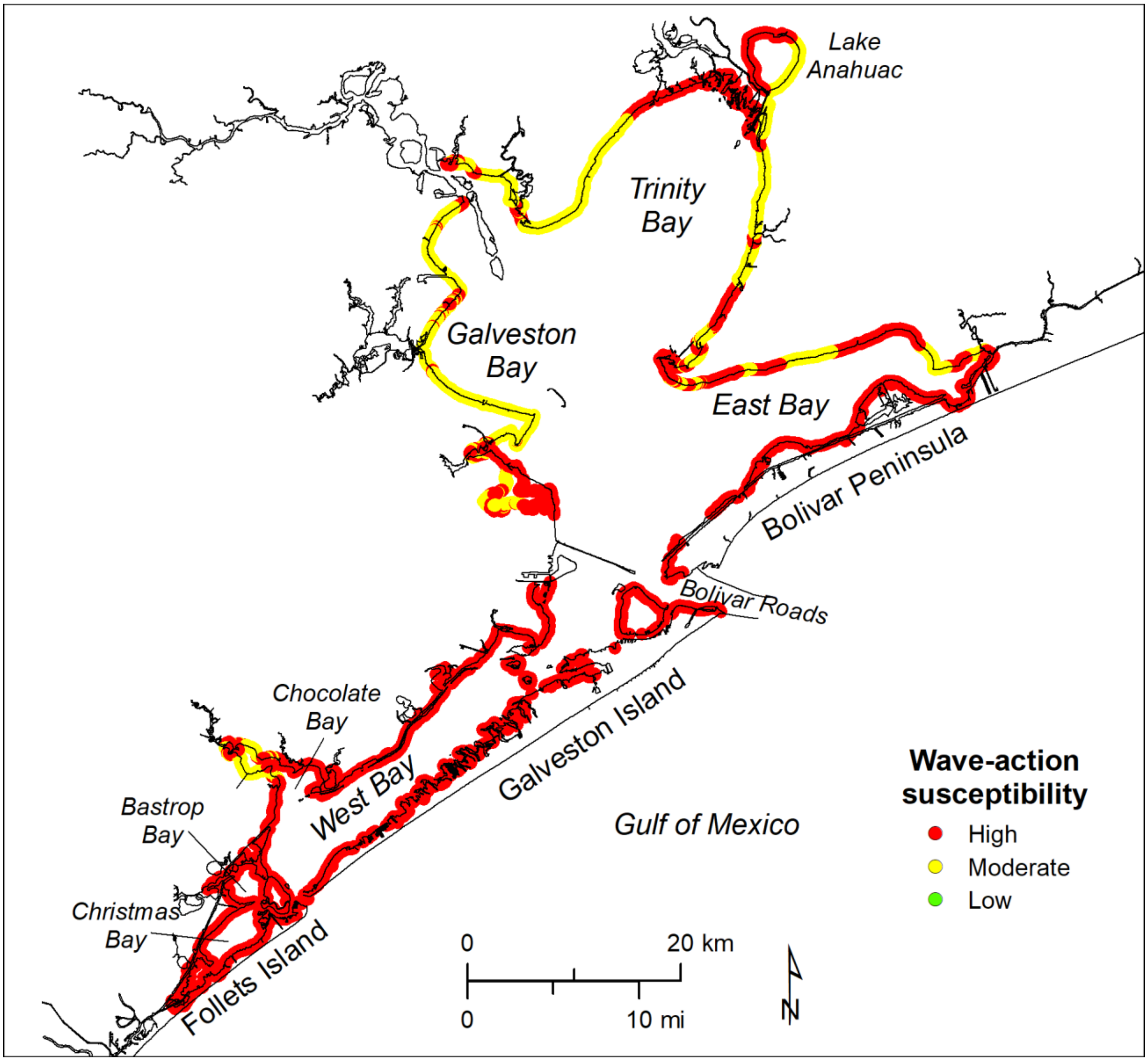

Figure 19. Shoreline types classified by susceptibility to retreat associated with wave action.

BAY SHORELINE MOVEMENT IN THE GALVESTON BAY SYSTEM

Net shoreline movement was determined at nearly 10,000 measurement sites in the Galveston Bay system. These sites are spaced at 50 m along the bay shorelines and include sites along all major shoreline types (Fig. 5). Three periods were examined: a long-term period, which begins with shoreline position determined from 1930 aerial photographs and ends with the shoreline extracted from DEMs produced from airborne lidar surveys in 2017 and 2018 and edited to match aerial photography from 2022; a long-term period comparing shoreline positions from1956 and 2022; and a more recent period, which begins with shoreline position determined from 1982 aerial photographs and ends with the 2022 shoreline.

Long-term Shoreline Movement, 1930 to 2022

Net shoreline movement in all bays between 1930 and 2022, measured at 9,312 sites, was -0.78 (Fig. 20 and Table 3). Shoreline retreat was observed at 83 percent of the sites. The distribution of long-term shoreline movement rates is weighted toward retreat (Fig. 21a and 22a), with the most common range being retreat at 0 to -0.33 m/yr (almost 20 percent of all sites). A map depicting rates of net long-term movement (Fig. 20) shows many areas throughout the bays that retreated, but relatively few isolated areas where the shoreline advanced. Net shoreline movement averaged retreat across all of the individual bay systems with the highest rate of shoreline retreat found in East Bay (-0.94 m/yr), with over twenty percent of sites eroding in a range of -1 to -1.33 m/yr (Fig. 22e). West Bay shorelines retreated at -0.86 m/yr (Fig. 22d) and Galveston Bay shoreline movement rate averaged -0.77 m/yr (Fig. 22b). The lowest retreat rates were calculated in Trinity Bay (-0.38 m/yr, Fig. 22c). The trend in distribution of shoreline movement rates was similar across Galveston, Trinity and West Bays with the largest percentage of sites measuring between 0 and -0.33 m/yr.

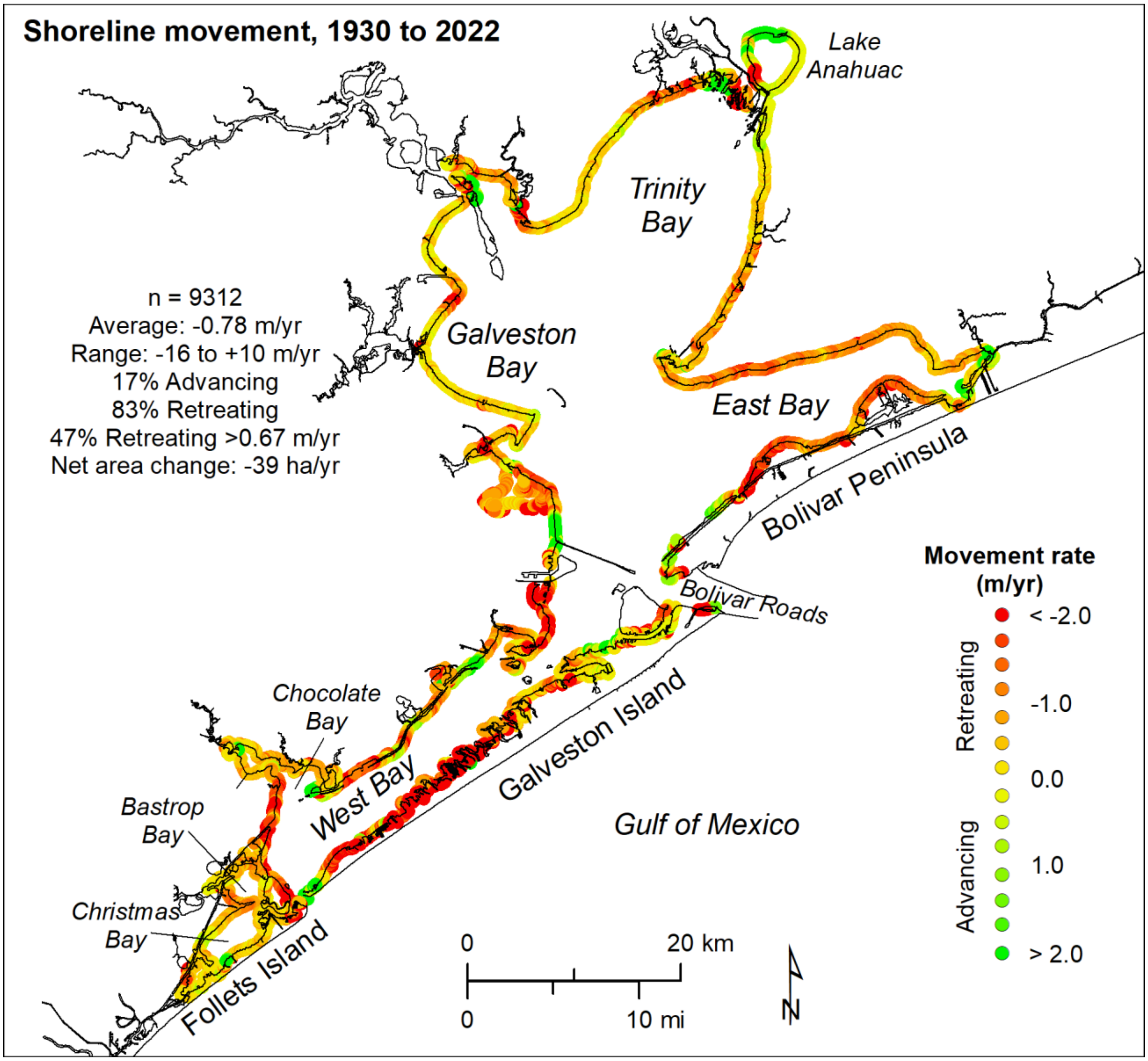

Figure 20. Net rates of long-term shoreline movement for the Galveston Bay system calculated from shoreline positions from 1930 to 2022.

Table 3. Long-term (1930 to 2022) shoreline movement statistics in the Galveston Bay system, upper Texas coast.

	Length (km)	Rate (m/yr)	Area (ha/yr)	Range (m/yr)	Advancing sites (%)	Retreating sites (%)
Whole Bay System	**499.1**	**-0.78**	**-38.83**	**-16.29 to 10.16**	**16.8%**	**83.2%**
Galveston Bay	**105.9**	**-0.77**	**-8.15**	**-16.29 to 9.02**	**17.6%**	**82.4%**
Trinity Bay	**88.8**	**-0.38**	**-3.37**	**-10.58 to 10.04**	**27.1%**	**72.9%**
Main Bay	56.9	-0.47	-2.67	-6.07 to 2.69	14.6%	85.4%
Trinity River Delta	16.3	-0.94	-1.53	-10.58 to 10.04	16.7%	83.3%
Lake Anahuac	15.6	0.30	0.47	8.12 to 5.19	75.6%	24.4%
East Bay	**78.7**	**-0.95**	**-7.48**	**-7.02 to 9.34**	**8.6%**	**91.4%**
Bolivar Peninsula	41.9	-0.94	-3.94	-7.02 to 9.34	15.5%	84.5%
Mainland	36.8	-0.96	-3.53	-2.51 to 3.12	1.6%	98.4%
West Bay	**222.6**	**-0.86**	**-19.14**	**-12.17 to 10.16**	**15.4%**	**84.6%**
Tiki Island	6.0	-0.65	-0.39	-2.82 to 0.15	11.3%	88.7%
Mainland	45.9	-0.95	-4.36	-5.16 to 6.70	18.9%	81.1%
Chocolate Bay	24.8	-0.48	-1.19	-2.49 to 7.19	11.7%	88.3%
Bastrop Bay	16.2	-0.58	-0.94	-3.05 to 0.89	13.1%	86.9%
Christmas Bay	44.4	-0.40	-1.78	-5.56 to 2.18	11.1%	88.9%
Mud Island	3.7	-2.29	-0.85	-5.10 to -0.65	0.0%	100.0%
Galveston Island	68.0	-1.27	-8.64	-12.17 to 10.16	18.8%	81.2%
Pelican Island	9.7	-0.89	-0.86	-3.41 to 1.60	7.0%	93.0%
North Deer Island	3.6	-0.40	-0.14	-2.28 to 1.11	27.4%	72.6%

Average rates of net shoreline movement for the longest observation period were erosional for all shoreline types except fan deltas and spits (Fig. 23a). Spits advanced at relatively high rates, 2.08 m/yr, between 1930 and 2022. Retreat rates were highest for shorelines along back-barrier marsh or tidal flats (-1.40 m/yr), sandy beaches (-1.16 m/yr), and deltaic marshes (-0.94 m/yr). Lowest rates of net retreat were measured along the high and low bluffs (-0.30 and -0.52 m/yr respectively) and tidal passes (-1.59 m/yr).

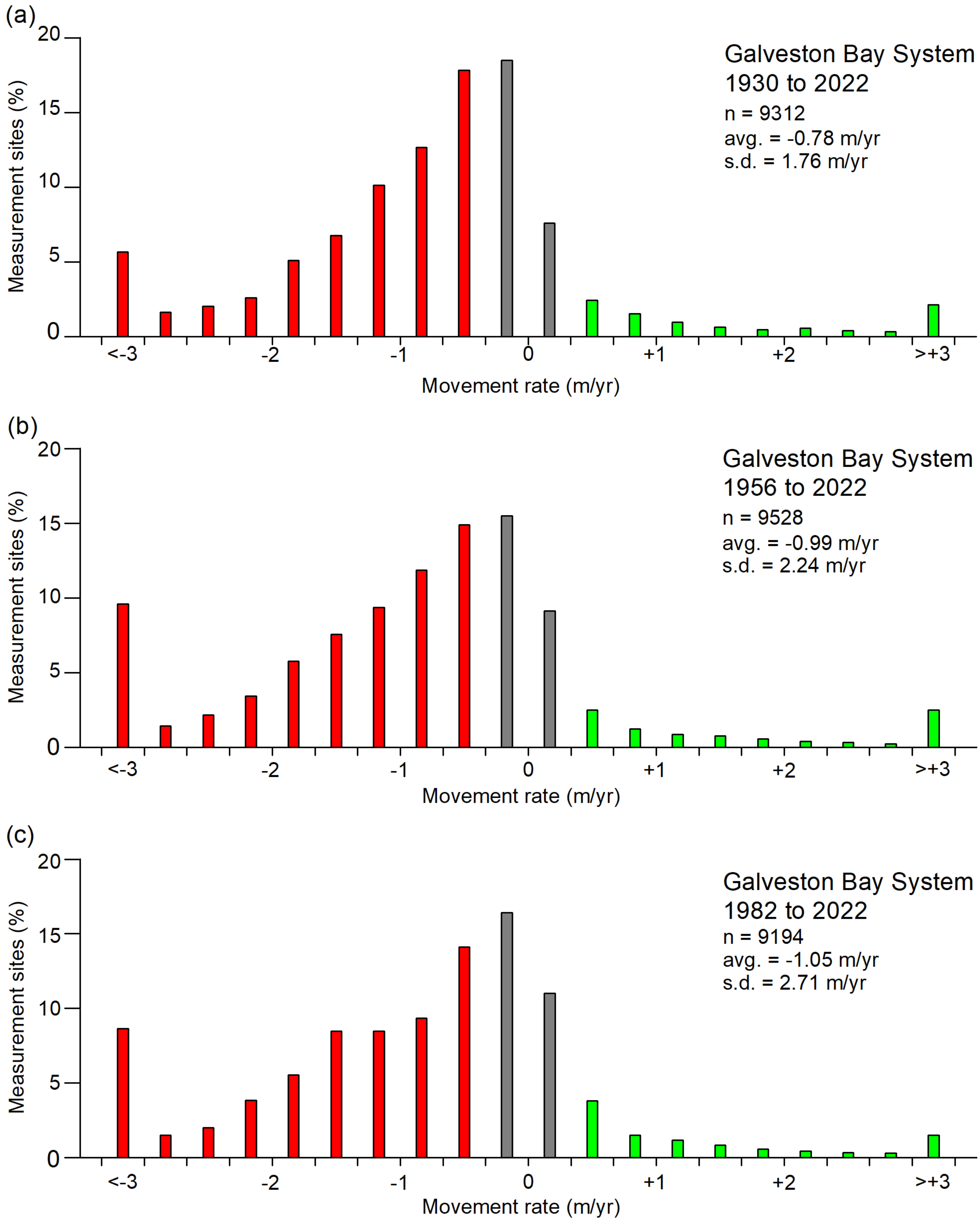

Figure 21. Distribution of (a) longer-term (1930 to 2022), (b) 1956 to 2022, and (c) more recent (1982 to 2022) shoreline movement rates in the Galveston Bay system on the upper Texas coast.

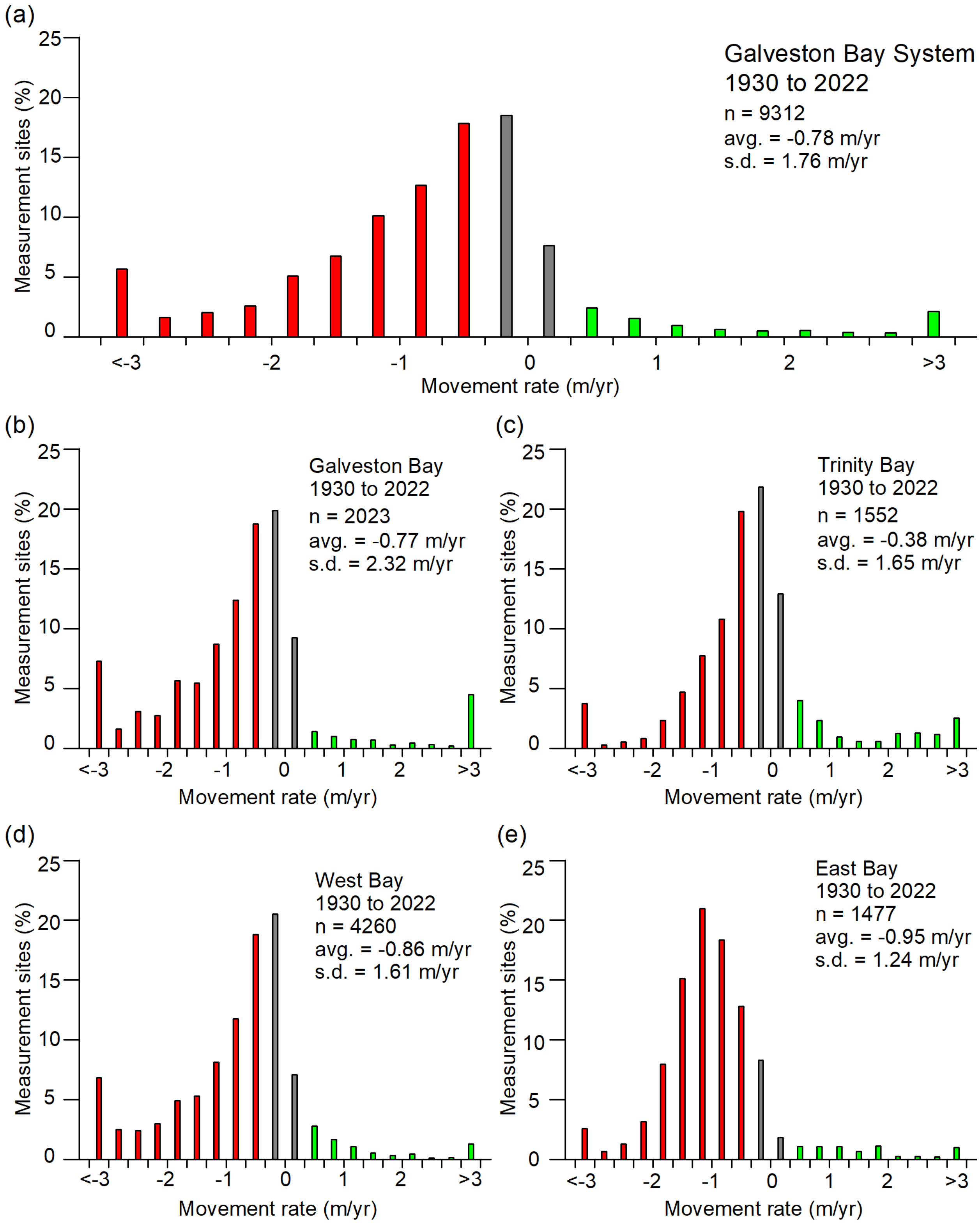

Figure 22. Distribution of longer-term (1930 to 2022) shoreline movement rates in (a) the entire Galveston Bay system, (b) Galveston Bay, (c) Trinity Bay, (d) West Bay, and (e) East Bay.

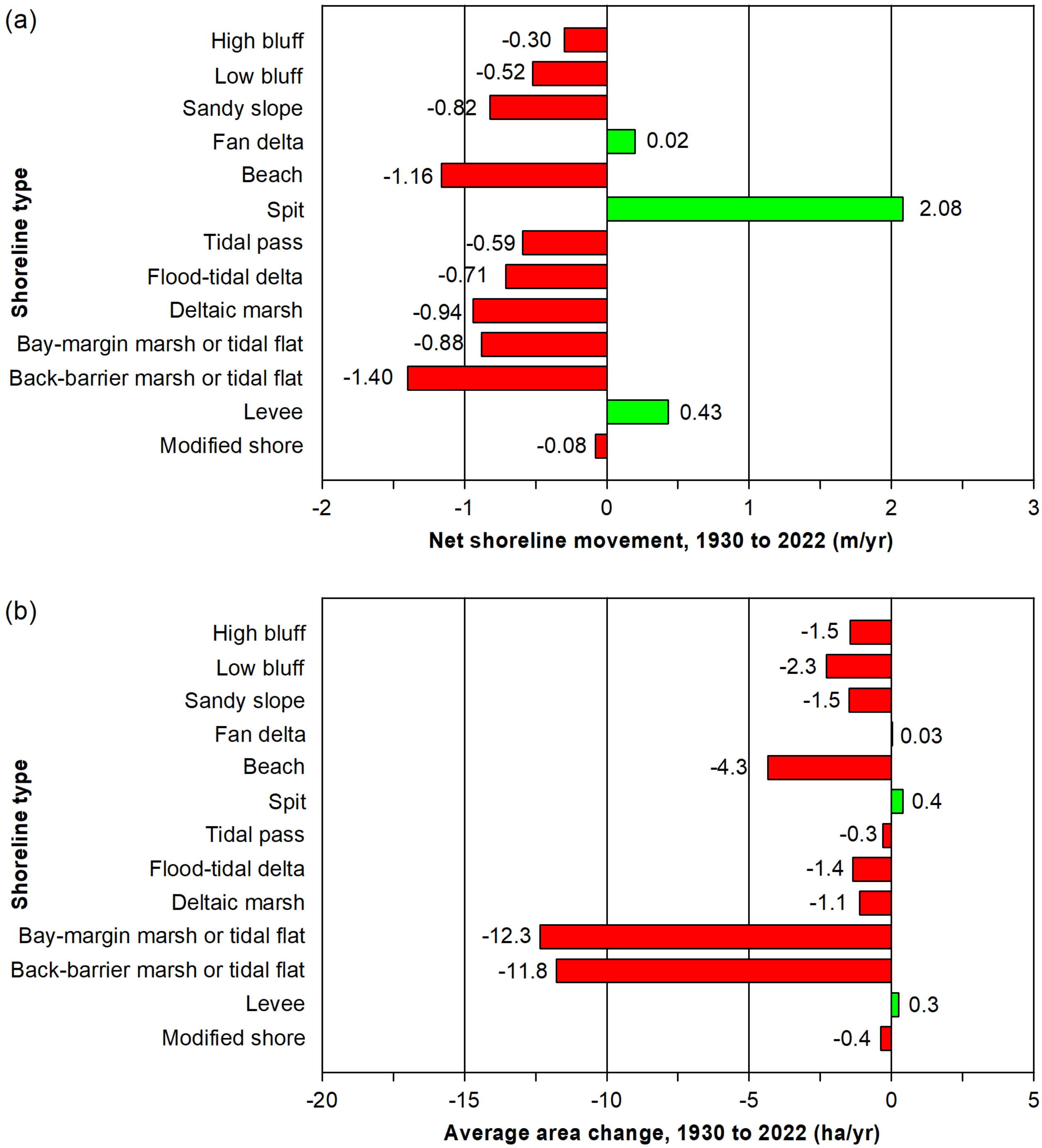

Figure 23. Average long-term, 1930 to 2022, (a) net shoreline movement rates and (b) area change rates for common bay shoreline types (table 3) in the Galveston Bay system.

Combining the net shoreline movement rates with the total shoreline length classified as a particular type yields an estimate of land loss or gain for that shoreline type (Fig. 23b). High rates of land loss occurred along the bay-margin and back-barrier marshes and tidal flats (24 ha/yr combined), and sandy beaches (4.3 ha/yr). Slight land gains were made to spits and fan deltas (0.5 ha/yr) but these shoreline types comprise the smallest shoreline types throughout the Galveston Bay system (less than one percent).

Long-term Shoreline Movement, 1956 to 2022

Net shoreline movement rates between 1956 and 2022, measured at 9,528 sites, was more erosional averaging -0.99 m/yr of retreat (Fig. 24, Table 4). The shoreline retreated at 82 percent of the sites, with sixteen percent falling within the most common range of 0 and -0.33 m/yr (Fig.21b). Shorelines in West Bay (the largest of the four bay systems) retreated at the highest rates during this time period (-1.23 m/yr, Fig. 25d) with almost 15 percent of sites eroding at a rate of more than 3 m/yr of retreat. The net rate of shoreline movement within the other three bay systems was also higher than the longer time period: East Bay at -1.16 m/yr (Fig. 25e), Galveston Bay at -0.76 m/yr (Fig. 25b), and Trinity Bay at -0.57 m/yr (Fig. 25c).

Average rates of net shoreline movement for the 1956 to 2022 observation period were erosional for all shoreline types except spits and flood-tidal deltas (Fig. 41a). Retreat rates were higher among all of the shoreline types for shorelines with the highest rates along back-barrier marsh or tidal flats (-2.02 m/yr), sandy beaches (-1.73 m/yr), and deltaic marshes and bay-margin marsh or tidal flats (both at -1.15 m/yr). Lowest rates of

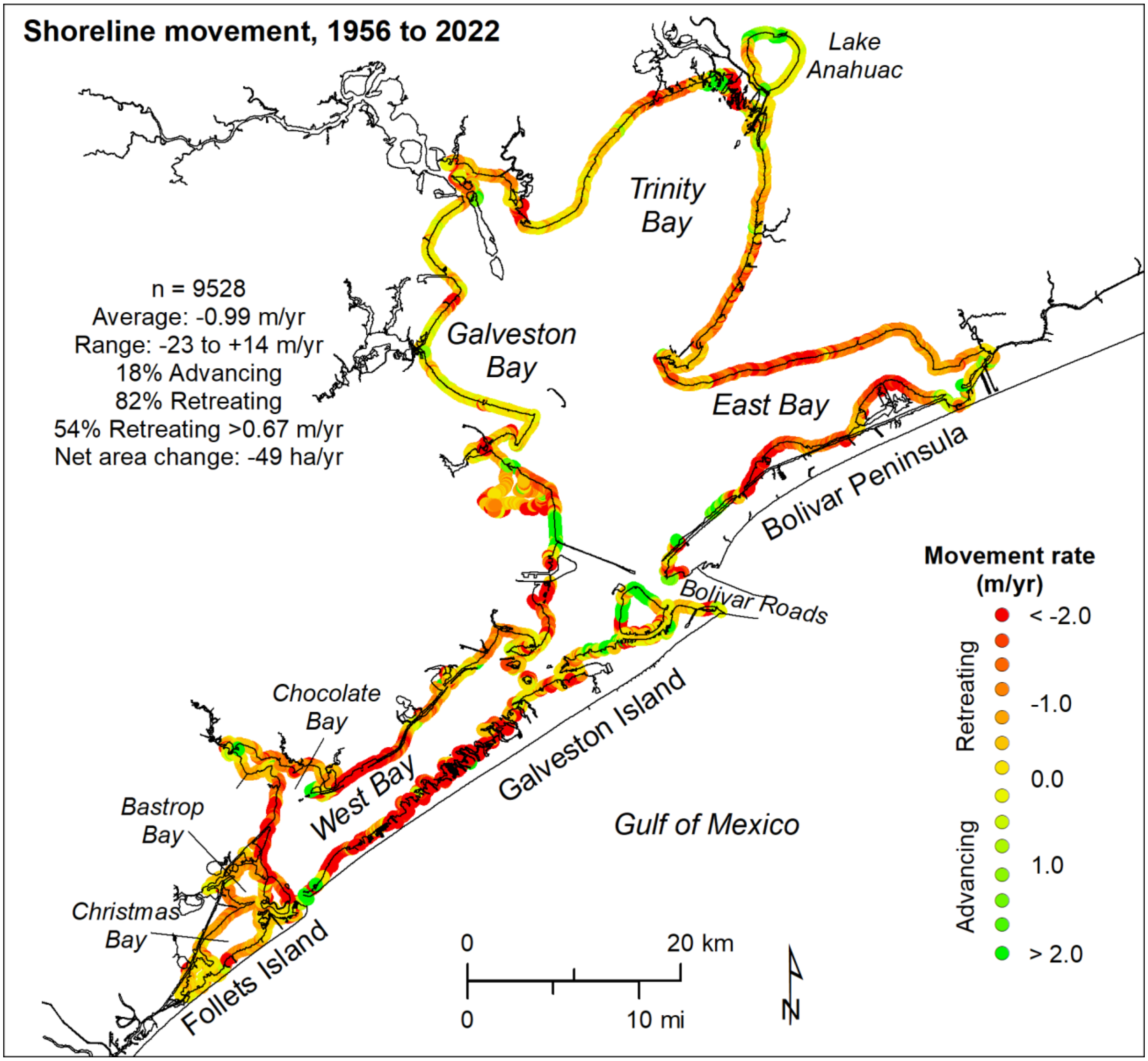

Figure 24. Net rates of long-term shoreline movement for the Galveston Bay system calculated from shoreline positions from 1956 to 2022.

net retreat were measured along fan deltas (-0.11 m/yr). Retreat rates along the high and low bluffs were similar to the longer observation period (-0.31 and -0.53 m/yr respectively).

The increases in movement rates in the 1956 to 2022 observation period changed the total land-loss contributions across most of the shoreline types (Fig. 26b), with the exception of the high and low bluffs which remained the same. Highest rates of land loss were again measured at shorelines along the back-barrier and bay-margin marsh or tidal flats (32 ha/yr combined) and sandy and shelly beaches (6.4 ha/yr). Small gains were measured at flood-tidal deltas and spits (0.4 and 0.2 ha/yr respectively).

Table 4. Long-term (1956 to 2022) shoreline movement statistics in the Galveston Bay system, upper Texas coast.

	Length (km)	Rate (m/yr)	Area (ha/yr)	Range (m/yr)	Advancing sites (%)	Retreating sites (%)
Whole Bay System	**499.1**	**-0.99**	**-49.41**	**-22.85 to 14.09**	**18.2%**	**81.8%**
Galveston Bay	**105.9**	**-0.76**	**-8.05**	**-22.85 to 8.24**	**24.9%**	**75.1%**
Trinity Bay	**88.8**	**-0.57**	**-5.06**	**-16.47 to 12.70**	**21.7%**	**78.3%**
Main Bay	56.9	-0.65	-3.70	-7.87 to 2.67	10.9%	89.1%
Trinity River Delta	16.3	-1.15	-1.87	-16.47 to 12.70	18.4%	81.6%
Lake Anahuac	15.6	0.41	0.64	-1.72 to 5.11	60.9%	39.1%
East Bay	**78.7**	**-1.16**	**-9.13**	**-9.76 to 14.09**	**10.2%**	**89.8%**
Bolivar Peninsula	41.9	-1.12	-4.69	-9.76 to 14.09	17.8%	82.2%
Mainland	36.8	-1.21	-4.45	-3.31 to 4.18	2.4%	97.6%
West Bay	**225.6**	**-1.23**	**-27.74**	**-17.01 to 11.64**	**16.2%**	**83.8%**
Tiki Island	6.0	-0.53	-0.32	-4.20 to 1.69	33.3%	66.7%
Mainland	45.9	-1.66	-7.62	-6.85 to 9.64	11.5%	88.5%
Chocolate Bay	24.8	-0.63	-1.56	-3.24 to 5.43	13.8%	86.2%
Bastrop Bay	16.2	-0.72	-1.16	-4.63 to 1.51	19.2%	80.8%
Christmas Bay	44.4	-0.58	-2.58	-4.60 to1.05	14.3%	85.7%
Mud Island	3.7	-2.00	-0.74	-5.30 to -0.68	0.0%	100.0%
Galveston Island	68.0	-2.07	-14.08	17.01 to 11.64	19.3%	80.7%
Pelican Island	9.7	0.31	0.30	-5.09 to 9.75	28.4%	71.6%
North Deer Island	3.6	-0.65	-0.23	-1.74 to 0.58	9.3%	90.7%
South Deer Island	3.0	-1.11	-0.33	-3.31 to 0.44	11.7%	88.3%

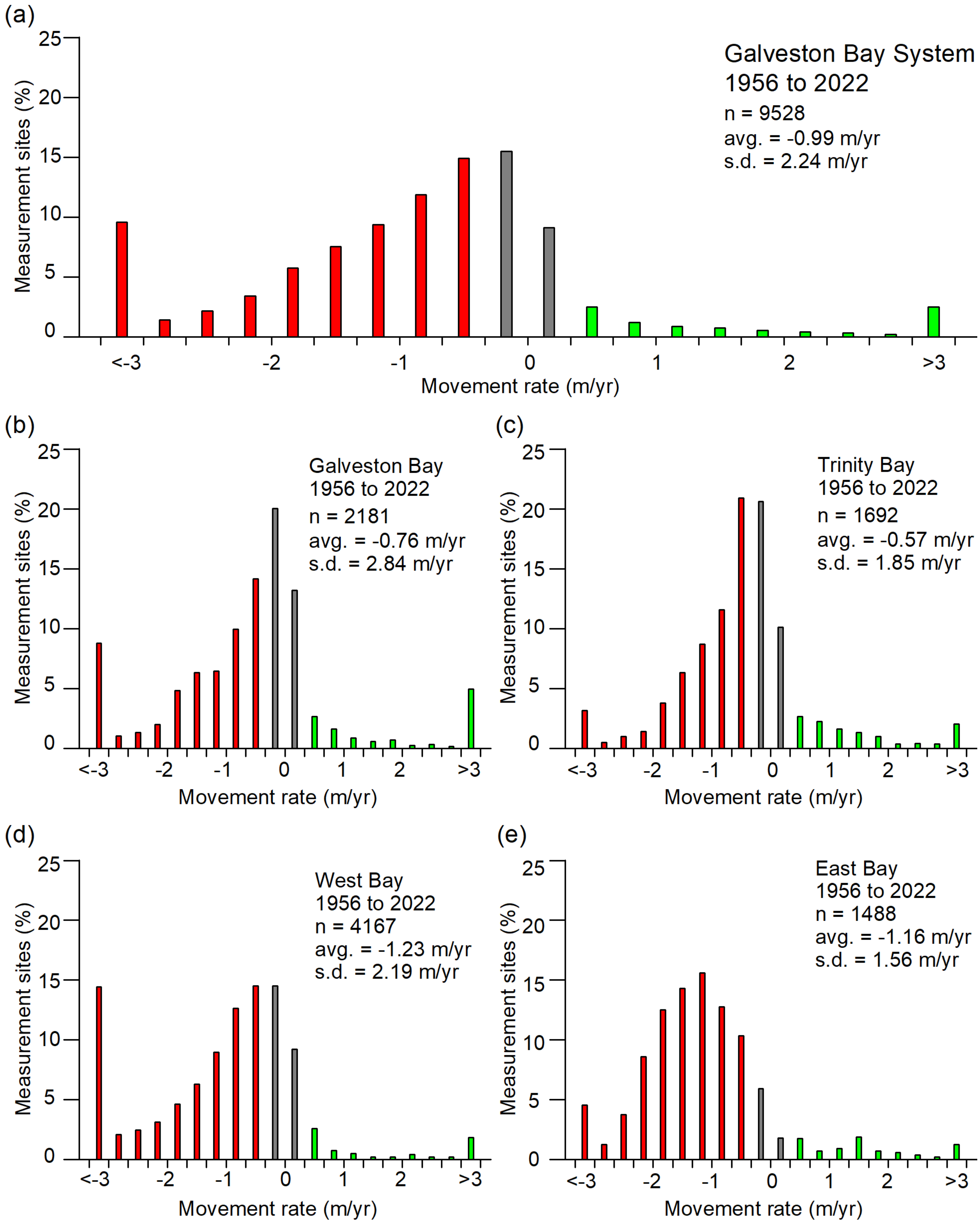

Figure 25. Distribution of long-term (1956 to 2022) shoreline movement rates in (a) the entire Galveston Bay system, (b) Galveston Bay, (c) Trinity Bay, (d) West Bay, and (e) East Bay.

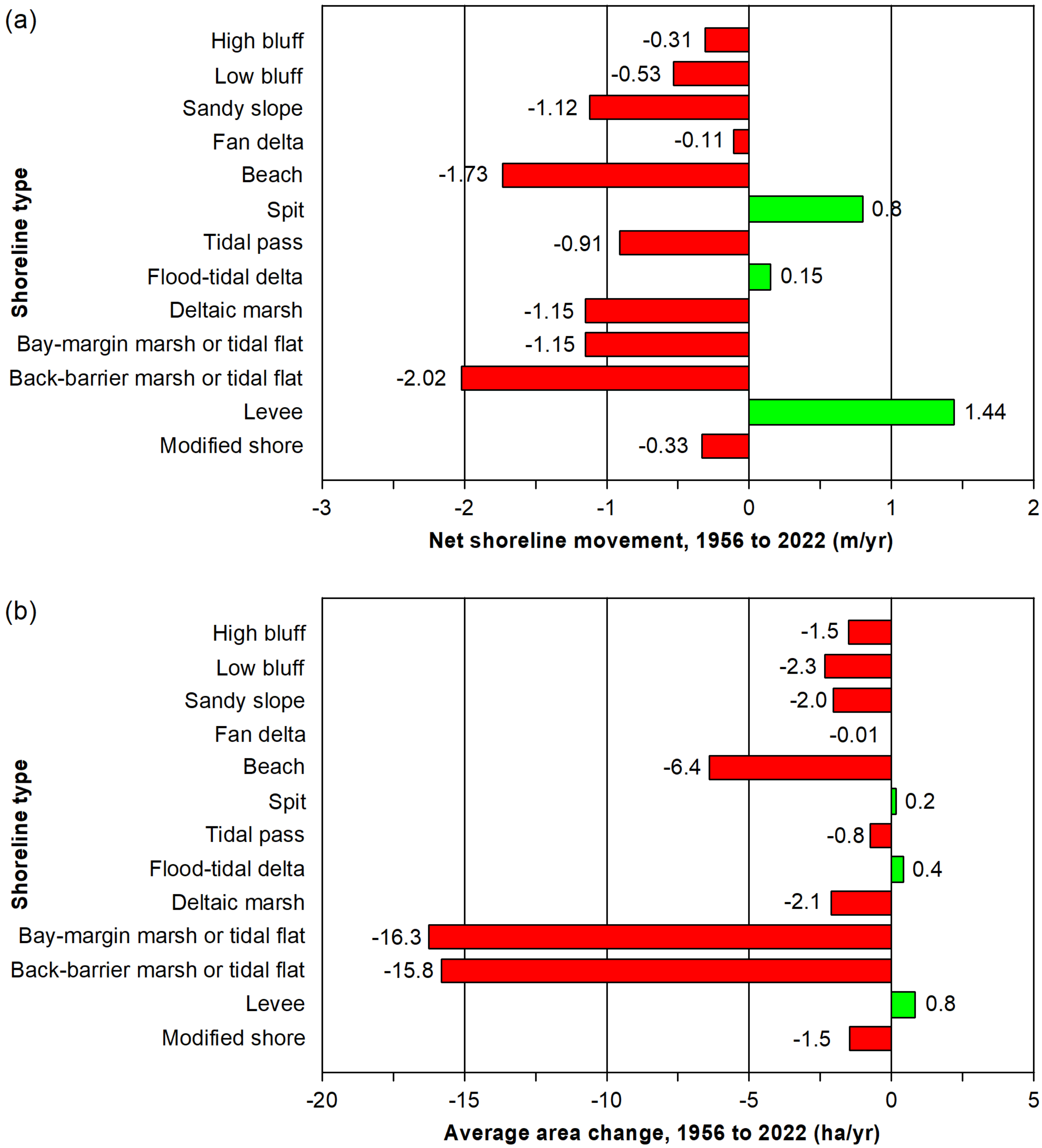

Figure 26. Average long-term, 1956 to 2022, (a) net shoreline movement rates and (b) area change rates for common bay shoreline types (table 3) in the Galveston Bay system.

Recent Shoreline Movement, 1982 to 2022

More recent net shoreline movement, measured at 9,194 sites around the Galveston Bay system, was more dominantly erosional than it was during the longer-term periods, averaging -1.05 m/yr of retreat (Fig. 27; Table 5). Despite the average retreat rate being more erosional, the shoreline retreated at fewer sites (79 percent). More than 15 percent of the sites fell within the most common range of retreat between 0 and -0.33 m/yr (Fig. 21c). Eleven percent of sites advanced at a range of 0 and 0.33 m/yr, the third most common range. Combining the average movement rate with the total shoreline length yields an average annual land-loss rate of 52 ha/yr (Table 5). East Bay and West Bay shorelines retreated at their highest rates (-1.44 and -1.39 m/yr, respectively) during the shortest time period of comparison (Fig. 28d,e). While still erosional, shoreline movement rates steadily decreased in Galveston Bay over time, to -0.55 m/yr between 1982 and 2022 with over 25 percent of sites retreating at rates between 0 and -0.33 m/yr, the most common range (Fig. 28b).

Similar relative movement and area change trends are seen in the comparison of the shortest observation period (1982 and 2022 shoreline positions, Fig. 29) and the longest observation period (1930 and 2022 shoreline position, Fig. 23). Highest rates of net retreat were measured for shorelines along back-barrier marsh and tidal flats (-2.17 m/yr), deltaic marshes (-1.63 m/yr), and bay-margin marsh and tidal flats (-1.17 m/yr). These three, low-lying, shoreline types are among least modified shorelines. The high and low Pleistocene bluffs retreated at rates lower than during the longer observation periods. Net rates of shoreline advancement were measured at spits (1.6 m/yr) and fan deltas (1.07 m/yr).

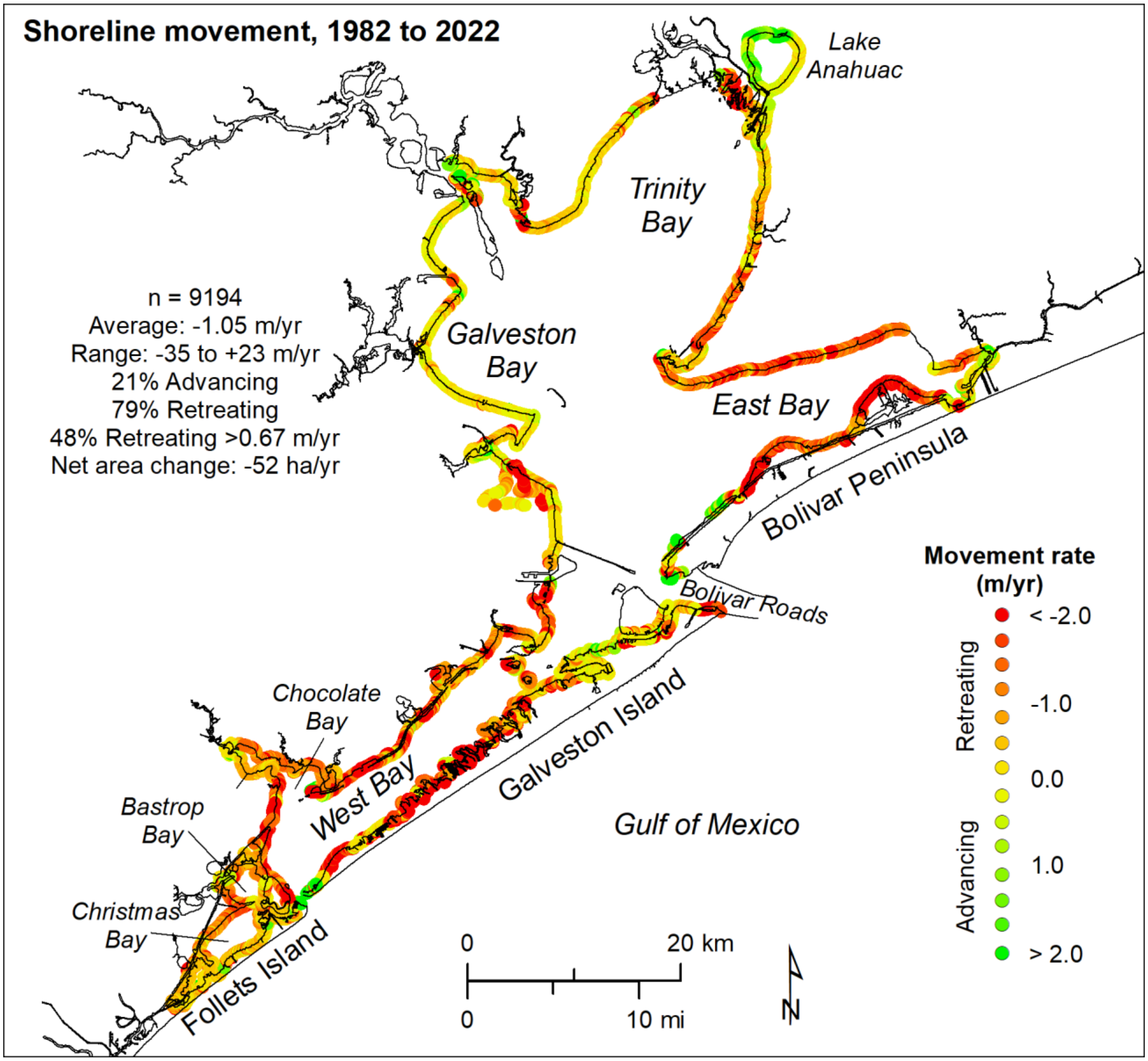

Figure 27. Net rates of recent shoreline movement for the Galveston Bay system calculated from shoreline positions from 1982 to 2022.

The increases in movement rates in the more recent period, along with relative changes in average rates among shoreline types, changed the total land-loss contributions among the types (Fig. 29b). Highest rates of land loss were measured at shorelines along back-barrier marsh or tidal flats (18.7 ha/yr), bay-margin marsh or tidal flats (15.8

ha/yr), beaches (4 ha/yr), and deltaic marshes (2.6 ha/yr). Land gains to spits and fan deltas again measured 0.5 ha/yr.

Table 5. Recent (1982 to 2022) shoreline movement statistics in the Galveston Bay system, upper Texas coast.

	Length (km)	Rate (m/yr)	Area (ha/yr)	Range (m/yr)	Advancing sites (%)	Retreating sites (%)
Whole Bay System	**499.1**	**-1.05**	**-52.40**	**-35.17 to 23.28**	**21.3%**	**78.7%**
Galveston Bay	**105.9**	**-0.55**	**-5.82**	**-35.17 to 23.28**	**34.3%**	**65.7%**
Trinity Bay	**88.8**	**-0.45**	**-3.99**	**-19.44 to 8.60**	**30.7%**	**69.3%**
Main Bay	56.9	-0.60	-3.41	-5.66 to 3.97	17.9%	82.1%
Trinity River Delta	16.3	-1.63	-2.65	-19.44 to 5.56	21.8%	78.2%
Lake Anahuac	15.6	1.25	1.94	-0.51 to 8.60	81.0%	19.0%
East Bay	**78.7**	**-1.44**	**-11.33**	**-15.07 to 15.89**	**10.4%**	**89.6%**
Bolivar Peninsula	41.9	-1.53	-6.41	-15.07 to 6.93	16.3%	83.7%
Mainland	36.8	-1.33	-4.89	-3.52 to 15.89	3.2%	96.8%
West Bay	**225.6**	**-1.39**	**-31.35**	**-29.52 to 15.00**	**15.1%**	**84.9%**
Tiki Island	6.0	-0.31	-0.18	-5.10 to 0.52	52.9%	47.1%
Mainland	45.9	-1.81	-8.31	-9.92 to 15.00	7.6%	92.4%
Chocolate Bay	24.8	-0.81	-2.01	-4.78 to 3.67	15.0%	85.0%
Bastrop Bay	16.2	-0.88	-1.42	-6.53 to 1.93	15.5%	84.5%
Christmas Bay	44.4	-0.69	-3.06	-6.90 to 3.25	7.0%	93.0%
Mud Island	3.7	-2.46	-0.91	-5.81 to -0.40	0.0%	100.0%
Galveston Island	68.0	-1.99	-13.53	-29.52 to 13.58	25.8%	74.2%
Pelican Island	9.7	-0.45	-0.43	6.05 to 2.29	13.6%	86.4%
North Deer Island	3.6	-0.44	-0.16	-2.10 to 0.93	35.6%	64.4%
South Deer Island	3.0	-1.15	-0.34	-4.99 to 0.17	3.3%	96.7%

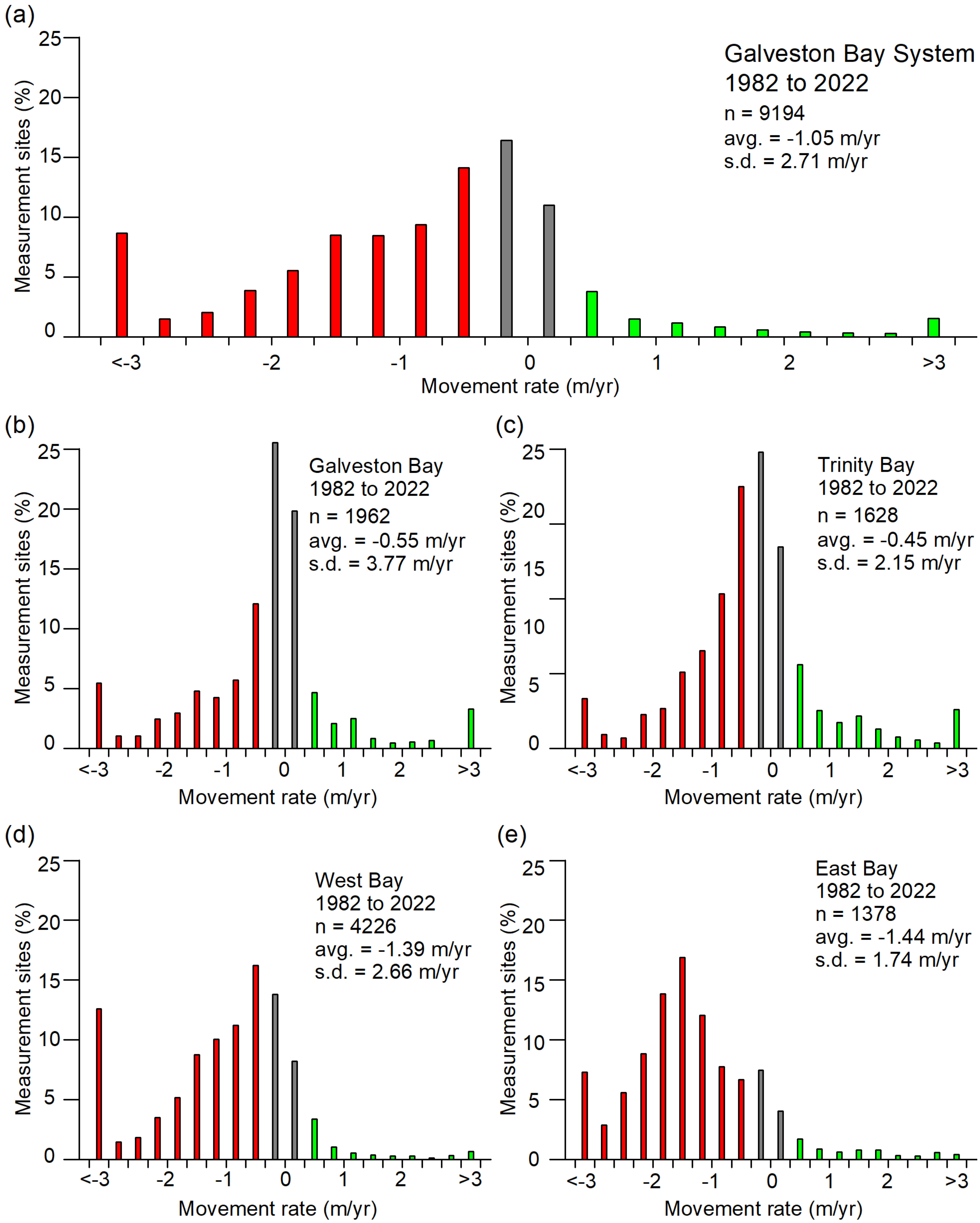

Figure 28. Distribution of more recent (1982 to 2022) shoreline movement rates in (a) the entire Galveston Bay system, (b) Galveston Bay, (c) Trinity Bay, (d) West Bay, and (e) East Bay.

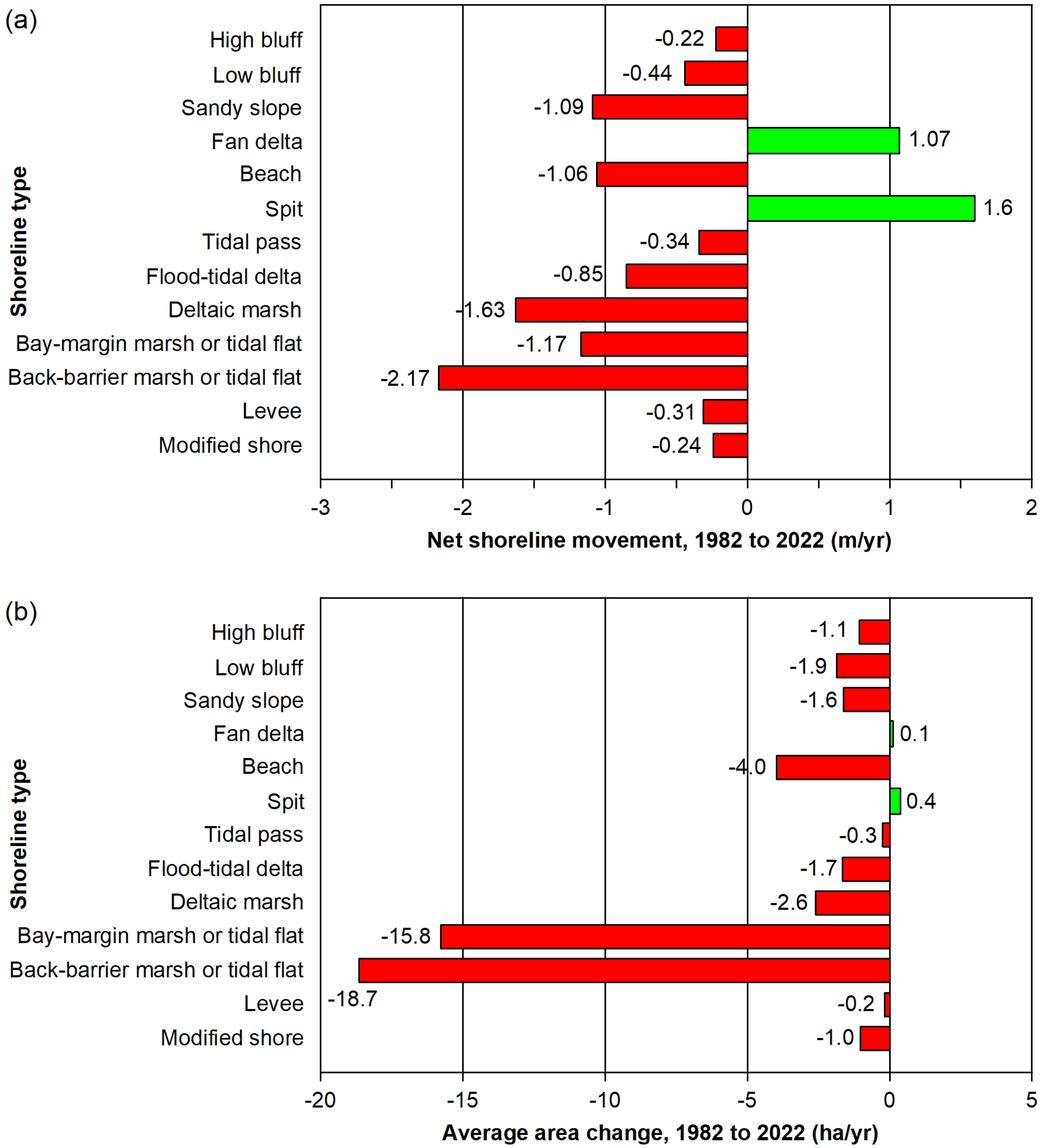

Figure 29. Average more recent, 1982 to 2022, (a) net shoreline movement rates and (b) area change rates for common bay shoreline types (table 3) in the Galveston Bay system.

Shoreline Movement in Galveston Bay

Galveston Bay refers to the western shoreline of Galveston Bay proper between Umbrella Point and Virginia Point (Galveston Causeway). It also includes the shorelines along the Bolivar Roads tidal pass on Galveston Island and Bolivar Peninsula and the north eastern side of Pelican Island.

Galveston Bay has approximately 105 km of bay shoreline that includes mostly high and low bluff and bay-margin marsh or tidal flats. Other shoreline types found in Galveston Bay include beaches, a flood-tidal delta (Pelican Island), and tidal pass shores along Bolivar Roads. Fan deltas and spits are found along less than one percent of the shorelines. The Galveston Bay shoreline is heavily modified with over 70 percent of the shoreline having some type of armoring. This includes the Texas City Levee and infrastructure around the Texas City petrochemical complex in the southern portion of the bay, and the made-land spoil islands Hogg Island and Atkinson Island near the mouth of the San Jacinto River which are designated as levee or modified shore. The bay shoreline also includes numerous protection devices such as bulkheads and rip-rap along the Pleistocene bluffs. Communities bordering Galveston Bay include Morgans Point, La Porte, Red Bluff, Seabrook, Kemah, San Leon, and Texas City. Moses Lake and Dickinson Bay shorelines were included in the shoreline change analysis.

Galveston Bay 1930 to 2022

Comparison of Galveston Bay system shoreline positions in 1930 with those extracted from the combination of lidar surveys and current photography reveals that the shoreline retreated at 82 percent of the 2,023 measurement sites (Fig. 30; Table 3). The average rate of long-term shoreline movement was retreat at -0.77 m/yr. That average movement rate translates to an average annual land loss of 8 ha/yr in Galveston Bay. An examination of the distribution of shoreline movement rates shows an almost equal number of sites falling within the two lowest retreat-rate categories (0 to -0.33 and -0.33 to -0.67 m/yr), which accounts for almost 40 percent of the total sites (Fig. 31a).

All shoreline types represented in Galveston Bay experienced retreat with the exception of 200 m of sandy or shell spits which advanced at a rate of 0.59 m/yr between 1930 and today. Highest rates of shoreline retreat occurred along the Bolivar Roads tidal pass shoreline (-1.98 m/yr), the small fan delta at Pine Gully Park (-2.73 m/yr), and beaches scattered throughout Galveston Bay (-2.13 m/yr). Both high and low bluffs retreated at rates near -0.5 m/yr. Bay margin marsh and tidal flats, which comprise almost 24 percent of all the shoreline in Galveston Bay, are found along the shores of Dickinson Bay, Moses Lake, and near the mouth of the San Jacinto River. These marsh shorelines retreated at -1.73 m/yr and account for half the land loss in Galveston Bay during this observation period.

Extensive areas of net retreat include the marsh and low bluffs in Moses Lake; the marsh and beach shorelines south of Texas City and near Umbrella Point; the bluffs, beach, and fan delta shores near Pine Gully and El Jardin Beach parks, and a segment of shoreline bayward of the northwestern arm of the Texas City Levee (Fig. 30). Areas of shoreline advancement include segments on either side of the Texas City Dike bayward of the Levee, at the mouth of Moses Lake, and the eastern side of the spoil islands in the upper most reaches of Galveston Bay (Fig. 30).

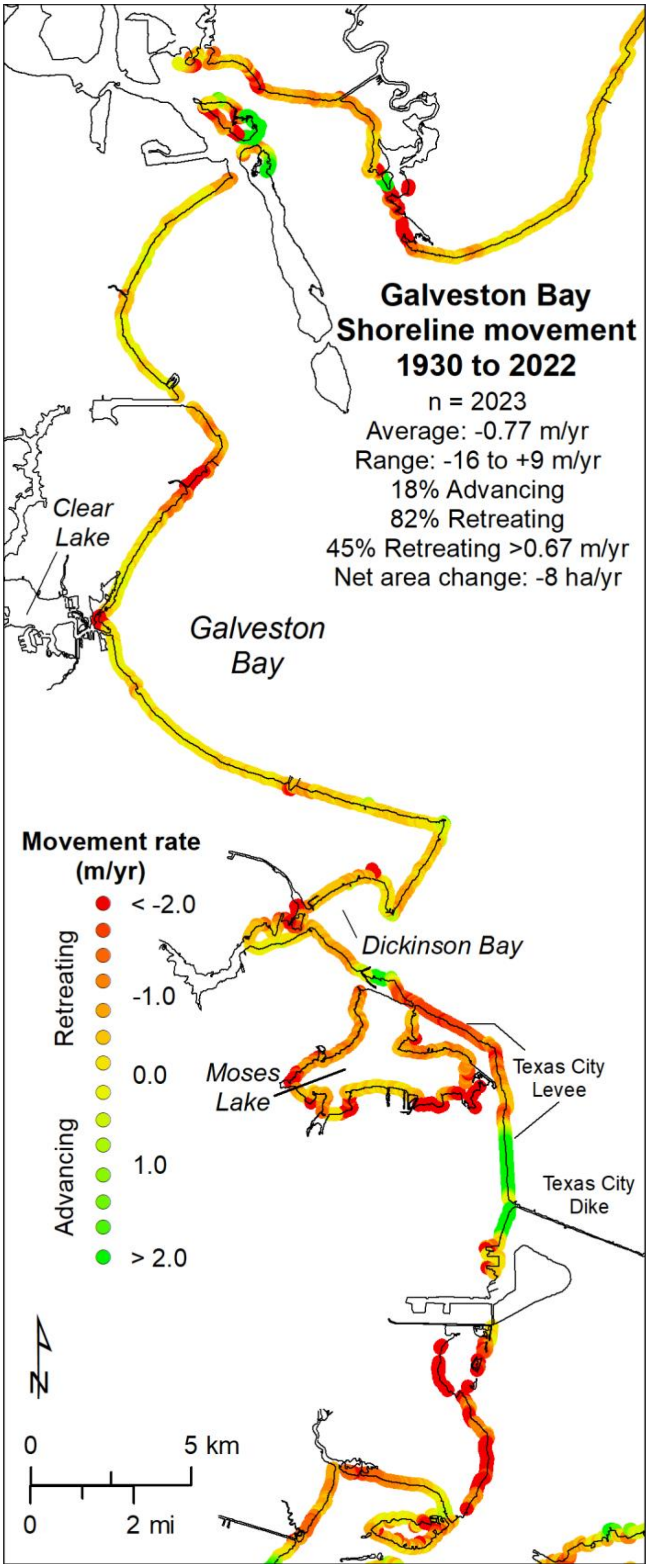

Figure 30. Net longer-term shoreline movement rates for the western shoreline of Galveston Bay calculated from positions from 1930 to 2022.

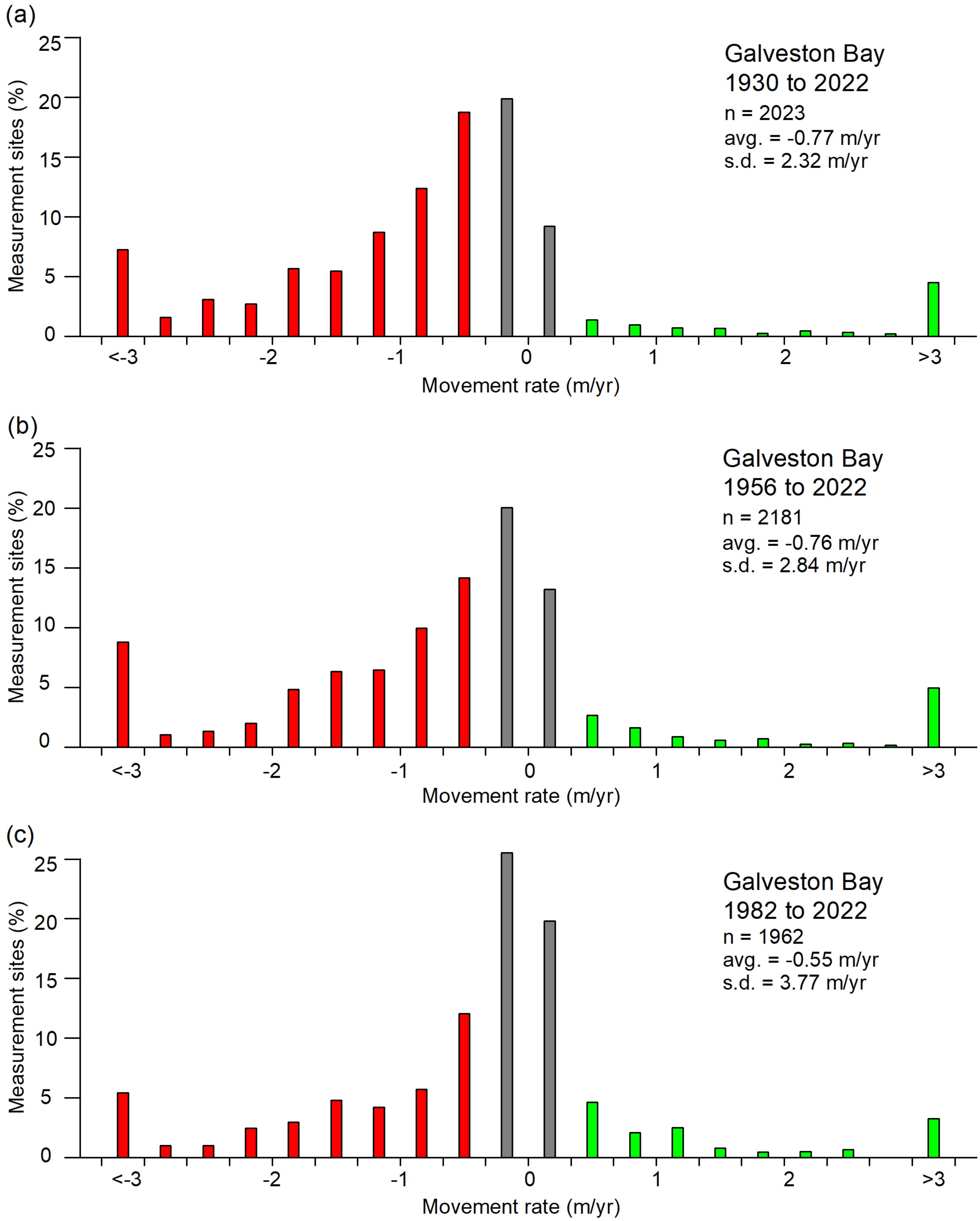

Figure 31. Distribution of (a) longer-term (1930 to 2022), (b) 1956 to 2022, and (c) more recent (1982 to 2022) shoreline movement rates along the western shoreline of Galveston Bay on the upper Texas coast.

Galveston Bay 1956 to 2022

Shoreline movement and average land-loss between 1956 and 2022 in Galveston Bay is similar to the longer time period (Fig. 31b, 32; Table 4) but retreat occurred at fewer sites. Shorelines in Galveston Bay retreated at 75 percent of the 2,181 measurement sites at an average rate of -0.76 m/yr, for an average land-loss rate of 8.2 ha/yr since 1956. Total land loss along the Galveston Bay shoreline between 1956 and 2022 is about 540 ha. The trend in distribution of shoreline movement rates between the two longer-term observation periods is also similar with the exception of almost equal number of sites falling within the -0.33 to -0.67 m/yr retreat category and 0 to 0.33 m/yr advancement category between 1956 and 2022 (Fig. 31b).

All shoreline types in Galveston Bay experienced retreat with the exception of spits (1.02 m/yr) and the flood-tidal delta shoreline on Pelican Island (2.25 m/yr). Additional measurement sites for this time period are from observations on Pelican Island (for West Bay in later section as well). The highest retreat rates were measured at the Pine Gully Park fan delta (-3.01 m/yr), bay beaches (-2.72 m/yr), and the Bolivar Roads tidal pass (-1.38 m/yr). Retreat rates at bay-margin marshes were higher than the longer period at -1.89 m/yr and accounted for over half of the land-loss in Galveston Bay at 4.4 ha/yr.

The areas displaying extensive retreat are similar to the longer time period: the marsh and beach shorelines south of Texas City and near Umbrella Point; the marsh and low bluffs in Moses Lake; the bluffs, beach, and fan delta shores near Pine Gully and El Jardin Beach parks, and along the northernmost section of the Texas City Levee (Fig.

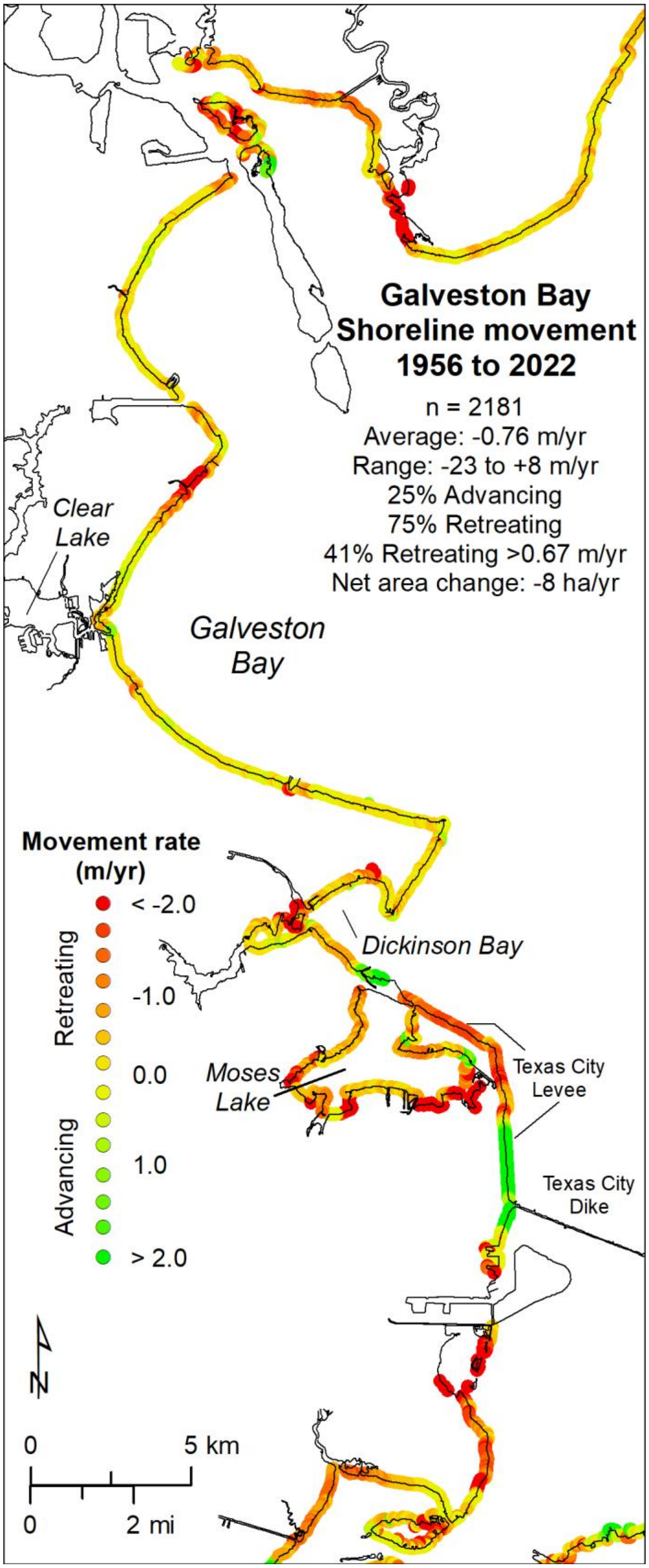

Figure 32. Net longer-term shoreline movement rates for the western shoreline of Galveston Bay calculated from positions from 1956 to 2022.

32). Areas of shoreline advancement include Pelican Island, segments on either side of the Texas City Dike bayward of the Levee and at the mouth of Moses Lake (Fig. 32).

Galveston Bay 1982 to 2022

Recent shoreline movement (1982 to 2022) in Galveston Bay is less erosional than during the longer periods of observation (Fig. 31c, 33; Table 5). Shorelines in Galveston Bay retreated at 66 percent of the 1,962 measurement sites at an average rate of -0.55 m/yr. Average land loss rate for the bay since 1982 is 5.4 ha/yr or about 216 ha of loss total. The distribution of shoreline movement rates illustrates the dominance of fairly stable shorelines in the 1982 to 2022 observation period (Fig. 31c). Over a quarter of sites fall within the lowest retreat-rate category (0 to -0.33 m/yr) and an additional 20 percent of sites fall within the 0.33 to 0 m/yr advancement category.

Despite less sites experiencing retreat in the shortest observation period, all shoreline types recorded average rates as retreating. Highest rates of shoreline retreat were measured along beaches (-1.42 m/yr), bay-margin marshes and the fan delta (both -1.03 m/yr), and the tidal pass (-0.91 m/yr). Lowest rates of shoreline retreat were recorded at the high and low bluffs (-0.24 and -0.2 m/yr respectively) and at spits. (-0.34 m/yr). The decreasing rate of shoreline retreat at the bluffs during the shorter time period could be a result of increased armoring (bulkheads, rip-rap, etc.) along these shorelines. Of the 47 km of Galveston Bay shoreline classified as either high or low bluff, 81 percent of those shores have been modified with a shore protection structure.

Extensive areas of net retreat include the mouth of Moses Lake, the eastern marsh shoreline of Moses Lake, and the marsh and beach shorelines near Umbrella Point and

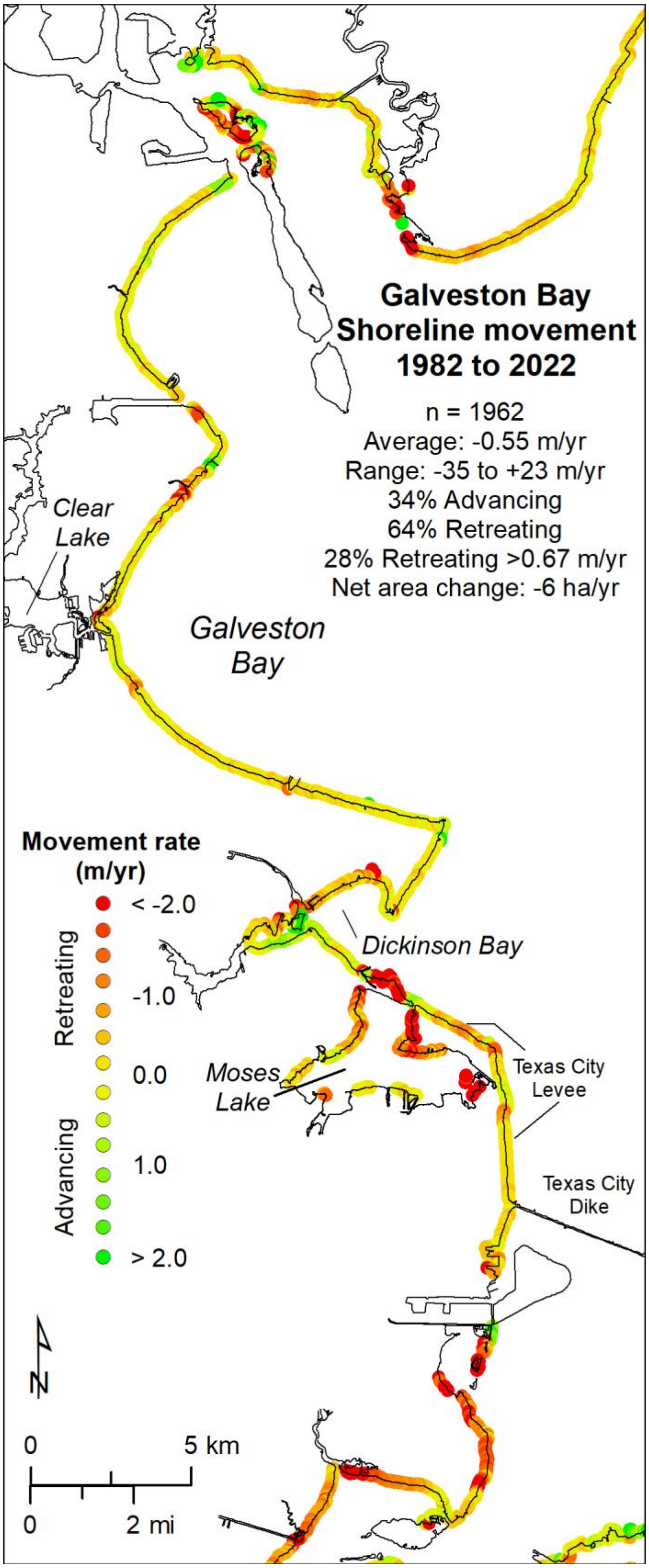

Figure 33. Net rates of recent movement for the western shoreline of Galveston Bay calculated from shoreline positions from 1982 to 2022.

south of Texas City (Fig. 33). Areas of shoreline advancement occurred along the southwestern shore of Dickinson Bay, the eastern shores of the spoil islands, at El Jardin Beach, and in limited areas along the mainland shoreline near the mouth of the San Jacinto River and Morgans Point (Fig. 33).

Shoreline Movement in Trinity Bay

The Trinity Bay study area includes Trinity Bay proper as well as Lake Anahuac and the Trinity River Delta (Fig. 2). Bay and delta shorelines studied in this report have a total length of 84 km between Umbrella Point and Smith Point. Lake Anahuac, previously called Turtle Bay, receives freshwater from a diversion channel from the Trinity River (Big Hog Bayou) and the Turtle Bayou watershed. The main channel of the Trinity River has formed the modern delta between Lake Anahuac and Trinity Bay. More than twenty percent of the shorelines in this subsystem are deltaic marshes. Other shoreline types in Trinity Bay include high and low bluffs (31 and 12 percent of shorelines, respectively), bay margin marsh (17 percent), beaches (10 percent), and sandy slopes (5 percent). A fan delta and spit created by Turtle Bayou and sandy spits at Smith Point combined comprise 2.5 percent of the shorelines in the Trinity Bay. Shoreline modifications were mapped at approximately 33 percent of sites. Communities bordering Trinity Bay include Anahuac, Beach City, Oak Island, and Smith Point.

Trinity Bay 1930 to 2022

Comparisons of shoreline positions in 1930 with those from 2022 at 1,552 sites distributed around Trinity Bay and Lake Anahuac (Fig. 34, Table 3) reveal that the shoreline has retreated at 73 percent of the sites at an average rate of -0.38 m/yr. This rate is the lowest of the four bays that comprise the Galveston Bay system (Fig. 22c). The most common rate of change in Trinity Bay (22 percent of sites) is the lowest retreat-rate category, 0 to -0.33 m/yr, followed by -0.33 to -0.67 m/yr with an additional 20 percent of the measurement sites (Fig. 35a).

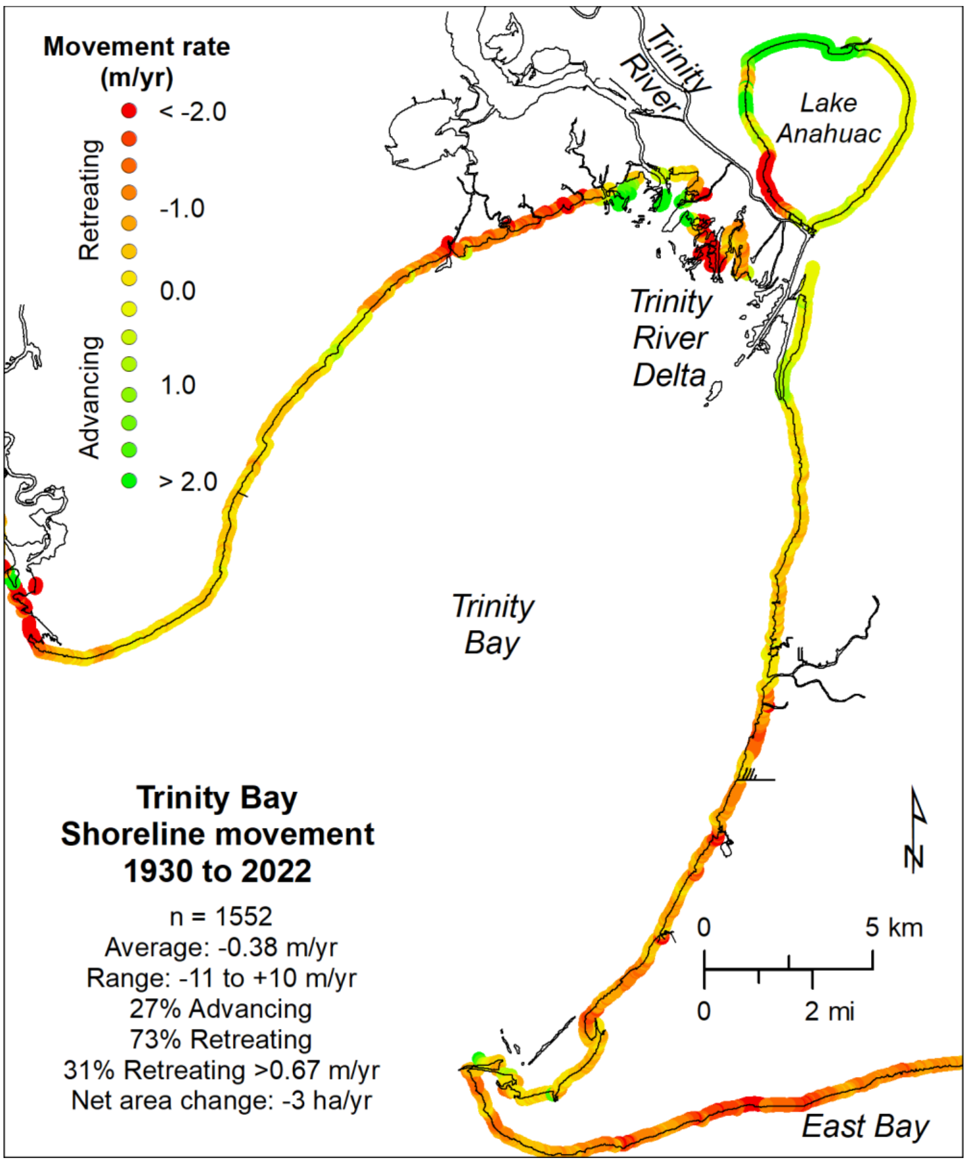

Figure 34. Net longer-term shoreline movement rates for Trinity Bay including Lake Anahuac and the Trinity River Delta calculated from shoreline positions from 1930 to 2022.

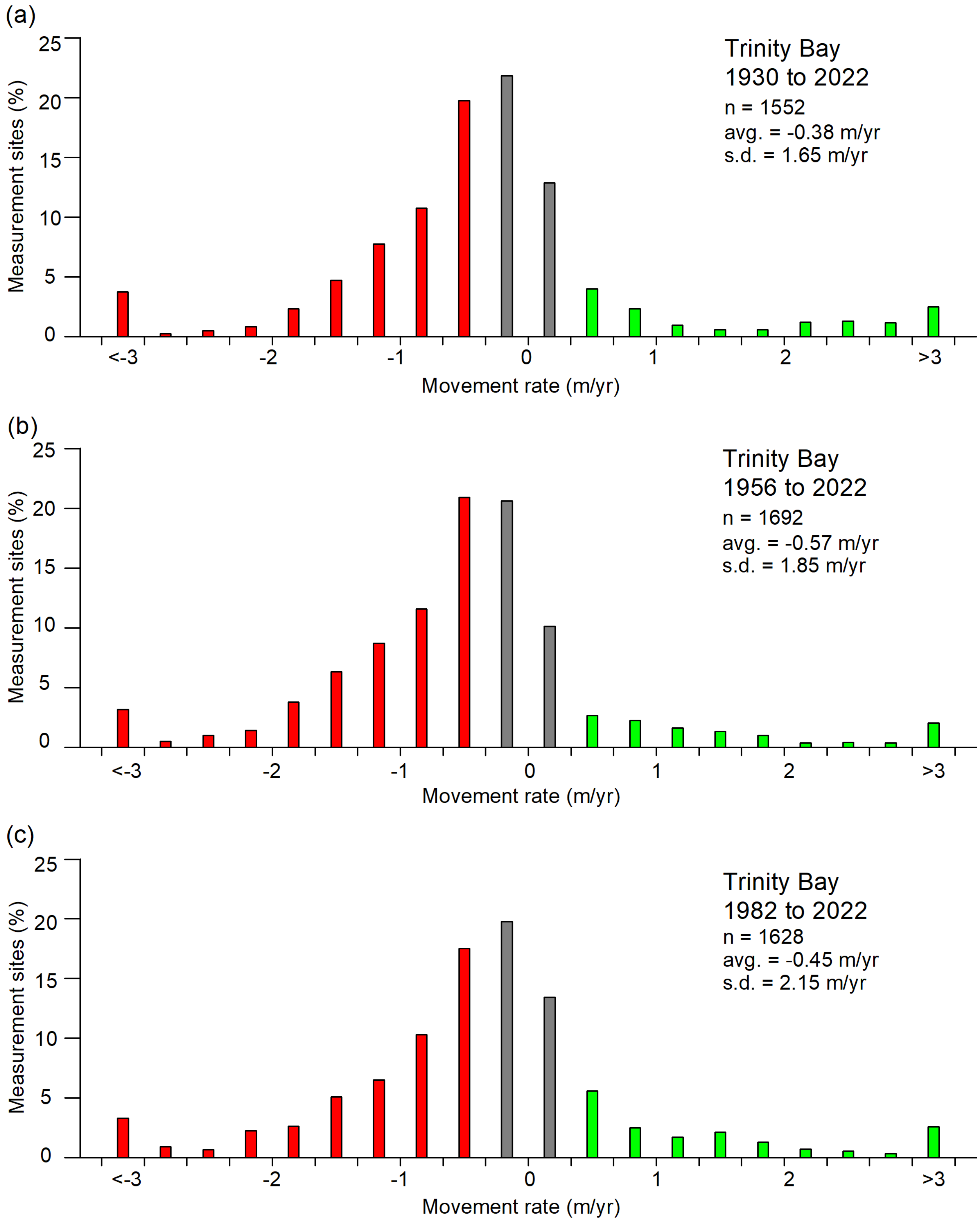

Figure 35. Distribution of (a) longer-term (1930 to 2022), (b) 1956 to 2022, and (c) more recent (1982 to 2022) shoreline movement rates in Trinity Bay, including Lake Anahuac and the Trinity River Delta.

The deltaic marshes of the Trinity River Delta experienced the highest rate of shoreline retreat of all the shoreline types with an average rate of -0.94 m/yr. This equates to a little over 1 ha/yr of land loss in Trinity Bay. Shoreline retreat occurred at rates greater than 0.5 m/yr along sandy slopes (-0.74 m/yr), bay-margin marshes (-0.67 m/yr), and low bluffs (-0.58 m/yr). Retreat occurred at minimal rates along high bluffs (-0.12 m/yr) and beaches (-0.11 m/yr). The smallest shoreline features in the Trinity Bay system were the two that experienced shoreline advancement. The sandy spits at Smith Point advanced at an average rate of 3.4 m/yr and the Turtle Bayou fan delta averaged 0.73 m/yr.

Areas experiencing higher net retreat include the deltaic marshes west of Old River channel and the central part of the delta (between the main Trinity River and Old River channels), bay-margin marshes fronting Dutton Lake (west of the delta), and beaches on the southwestern shoreline of Lake Anahuac (Fig. 34). Areas of shoreline advancement include beaches along the north and northwestern shores of Lake Anahuac, the Turtle Bayou fan delta, around the mouth of the Old River channel, and the sandy spits at Smith Point and Turtle Bayou (Fig. 34).

Trinity Bay 1956 to 2022

For the period between 1956 and 2022, Trinity Bay shorelines retreated at an average rate of -0.57 m/yr (Fig. 36, Table 4). The analysis observed 1,692 sites of which 78 percent of the sites reported retreat. Examining the distribution of shoreline movement rates for Trinity Bay shows an equal number of sites falling into the lowest retreat rate categories, 0 to -0.33 m/yr and -0.33 to -0.67 m/yr (Fig. 35b).

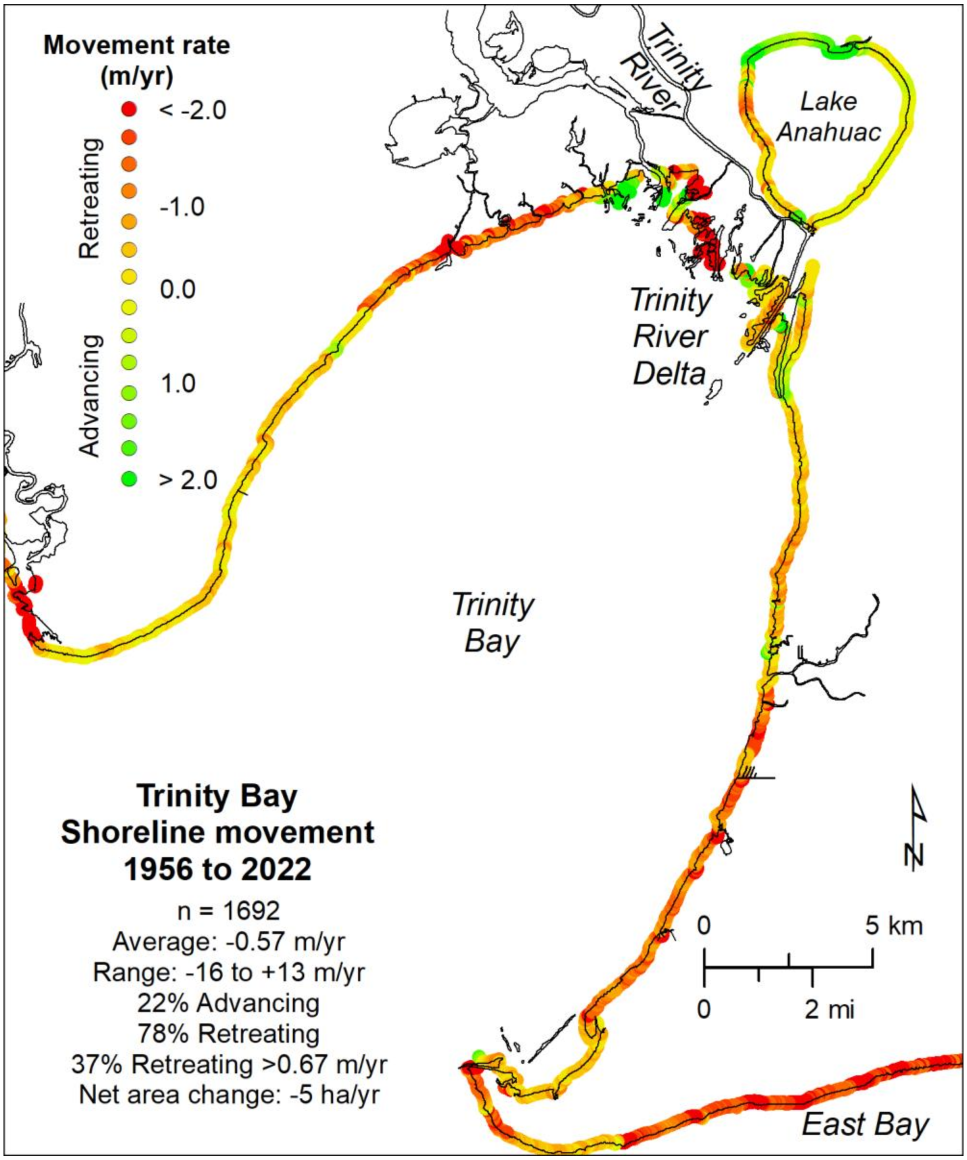

Figure 36. Net longer-term shoreline movement rates for Trinity Bay including Lake Anahuac and the Trinity River Delta calculated from shoreline positions from 1956 to 2022.

Similar to the longer-term observation period, highest rates of shoreline retreat were recorded at deltaic marshes (-1.15 m/yr). This change rate equates to almost 140 ha of land loss in the delta over 66 years. Shoreline retreat rates were also higher over this time period at bay-margin marshes (-1 m/yr), sandy slopes (-0.82 m/yr), low bluffs (-0.67 m/yr), and high bluffs (-0.2 m/yr). In addition to shoreline advancement recorded at the

Smith Point and Turtle Bayou sandy spits (3.06 m/yr) and the Turtle Bayou fan delta (0.41 m/yr), the beach shorelines found in Lake Anahuac averaged advancement of 0.11m/yr.

Retreating shoreline segments were located at the deltaic marshes west of Old River channel and the central part of the delta (between the main Trinity River and Old River channels); bay-margin marshes fronting Dutton Lake; the low bluffs, Gordy Marsh bay-margin marshes, and sandy slopes on the southeastern shoreline (Fig. 36). Areas of shoreline advancement include beaches along the northern shoreline of Lake Anahuac, the Turtle Bayou fan delta, around the mouth of the Old River channel, the deltaic marshes of the Trinity River distributary channels, and the sandy spits at Smith Point and Turtle Bayou (Fig. 36).

Trinity Bay 1982 to 2022

During the more recent period between 1982 and 2022, the proportion of measurement sites where the shoreline retreated decreased to 69 percent, although the average rate of retreat increased slightly from the longest-term monitoring period to -0.45 m/yr (Fig. 37, Table 5). Average land-loss rate for Trinity Bay since 1982 is 3.7 ha/yr. Assessing the distribution of shoreline movement categories reveals that a slightly higher percentage of the sites were advancing (Fig. 35c), although the trends are similar to the longest-term observation period.

1982 shorelines for the delta west of the Old River channel were not recorded on the original paper maps that were scanned for this project; therefore, there is a small gap in calculated shoreline movement rates. The marshes of the Trinity River Delta reported

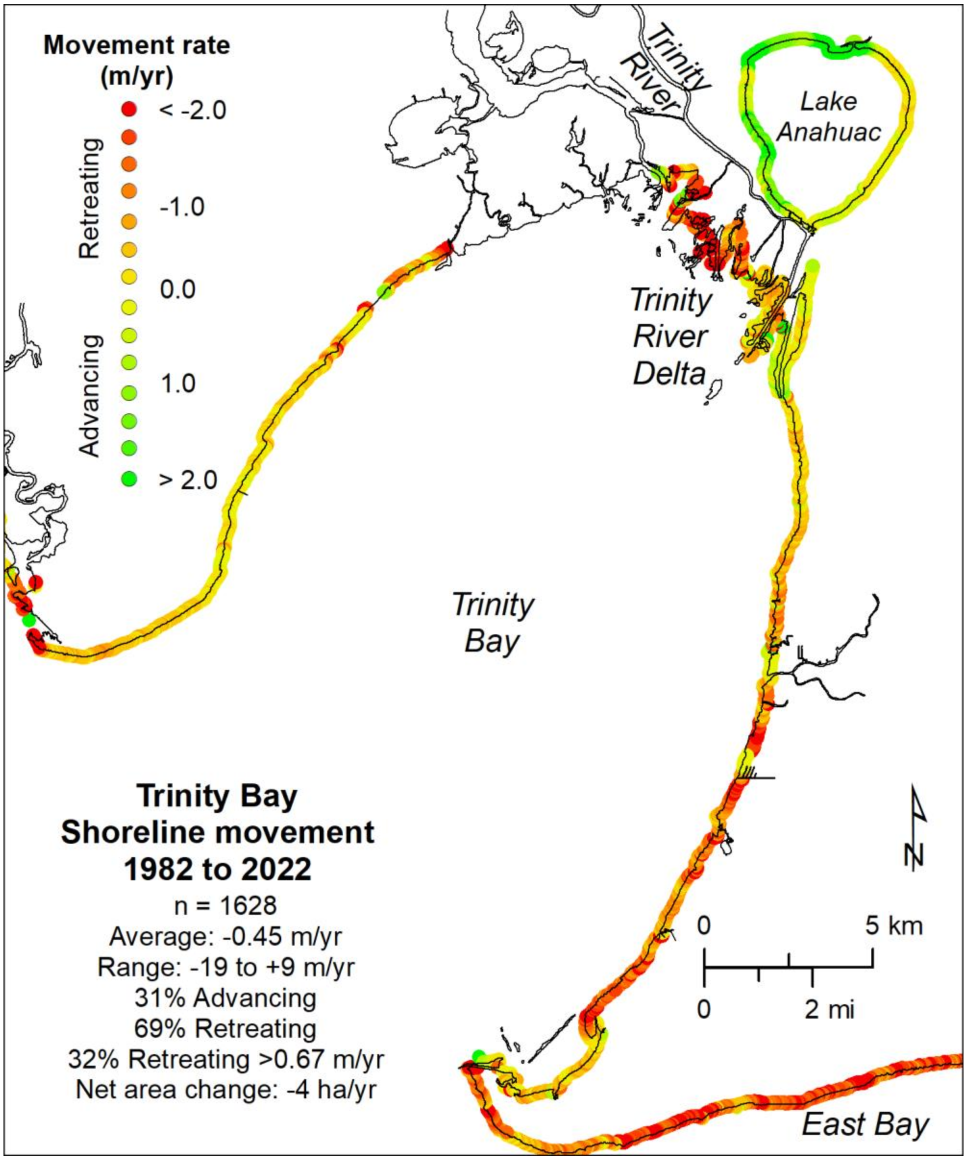

Figure 37. Net rates of more recent shoreline movement for Trinity Bay including Lake Anahuac and the Trinity River Delta calculated from shoreline positions from 1982 to 2022.

the highest average rates of shoreline retreat of the three observation periods at -1.63 m/yr. Net average rates of shoreline retreat were also recorded at bay-margin marsh and tidal flats (-0.85 m/yr) and the low and high bluffs (-0.76 and -0.2 m/yr, respectively). The highest rates of average net shoreline advancement were measured during this time period at the Turtle Bayou and Smith Point spits (5.6 m/yr), the fan delta (1.48 m/yr), Lake Anahuac beaches (1.28 m/yr), and at sandy slopes (0.41 m/yr).

Significant retreating shoreline segments were located at the deltaic marshes between the main Trinity River and Old River channels and the low bluffs and the Gordy Marsh bay-margin marshes on the southeastern shoreline of Trinity Bay (Fig. 37). Areas of shoreline advancement include beaches along the northern and western shoreline of Lake Anahuac, the Turtle Bayou fan delta, around the mouth of the main Trinity River channel (easternmost portion of delta), and the sandy spits at Smith Point (Fig. 37).

Shoreline Movement in East Bay

East Bay has approximately 75 km of shoreline that includes back barrier marsh or tidal flat, bay-margin marsh or tidal flat, beaches, and sandy slopes. Notable are extensive back-barrier marshes and tidal flats along the Bolivar Peninsula shoreline and bay-margin marsh and tidal flat and sandy slopes adjacent to the Pleistocene barrier island deposits along the mainland shore. Change rates were calculated following the 1930 shoreline shape along the large remnant flood-tidal delta/washover features on the bayside of Bolivar Peninsula. Rates of change were not calculated along the dredged portions of the GIWW that cut through these features. The Bolivar Peninsula communities of Crystal Beach, Caplen, and Gilchrist and the community of Smith Point border East Bay. The Anahuac National Wildlife Refuge is on both the mainland and Bolivar Peninsula East Bay shorelines.

East Bay 1930 to 2022

Of the 1,477 measurement sites around East Bay, 91 percent retreated between 1930 and 2022 (Fig. 38, Table 3), the most of the four bay subsystems. The average shoreline retreat was -0.95 m/yr, the highest retreat rate of the four bays. The average land-loss rate in East Bay was 7 ha/yr. The rate histogram for East Bay shows that over 20 percent of the measurement sites fell within the -1 to -1.33 m/yr category (Fig. 39a).

All shoreline types in East Bay experienced high average rates of retreat between the measurement dates. In order from highest rates of retreat to lowest were bay beaches at -1.08 m/yr, back-barrier marshes and tidal flats at -0.96 m/yr, bay-margin marshes and tidal flats at -0.94 m/yr, and sandy slopes at -0.84 m/yr. Notable shoreline retreat occurred along the back-barrier marshes and tidal flats and beaches of Goat Island, the remnant flood-tidal delta/washover feature on the bayside of Bolivar Peninsula, and the sandy slopes on the western end of mainland shore. Shorelines having net long-term advance include the eastern-most shorelines where Oyster Bayou and East Bay Bayou flow into East Bay and the back-barrier marsh and tidal flat on the spoil islands by Rollover Bay and near the western end of Bolivar Peninsula.

East Bay 1956 to 2022

There was net shoreline retreat at 90 percent of the 1,488 measurement sites around East Bay between 1956 and 2022 (Fig. 40, Table 4). Net rates of change during this time period ranged from retreat at -9.8 m/yr to advance at 14 m/yr with an average net shoreline movement rate of retreat at -1.16 m/yr. The histogram showing distribution of shoreline movement rates displays a more even allocation of measurement sites among the retreat rates between -0.3 m/yr to -2.33 m/yr, with the highest percentage of sites retreating at rates between -1 to -1.33 m/yr (Fig. 39b).

Average net rates of shoreline movement were more erosional for all shoreline types represented in East Bay during this observation period. Shorelines retreated -1.26 m/yr at bay beaches, -1.2 m/yr at sandy slope shorelines, and -1.15 and -1.12 m/yr at bay-margin and back-barrier marshes and tidal flats respectively. Similar to the longer-term

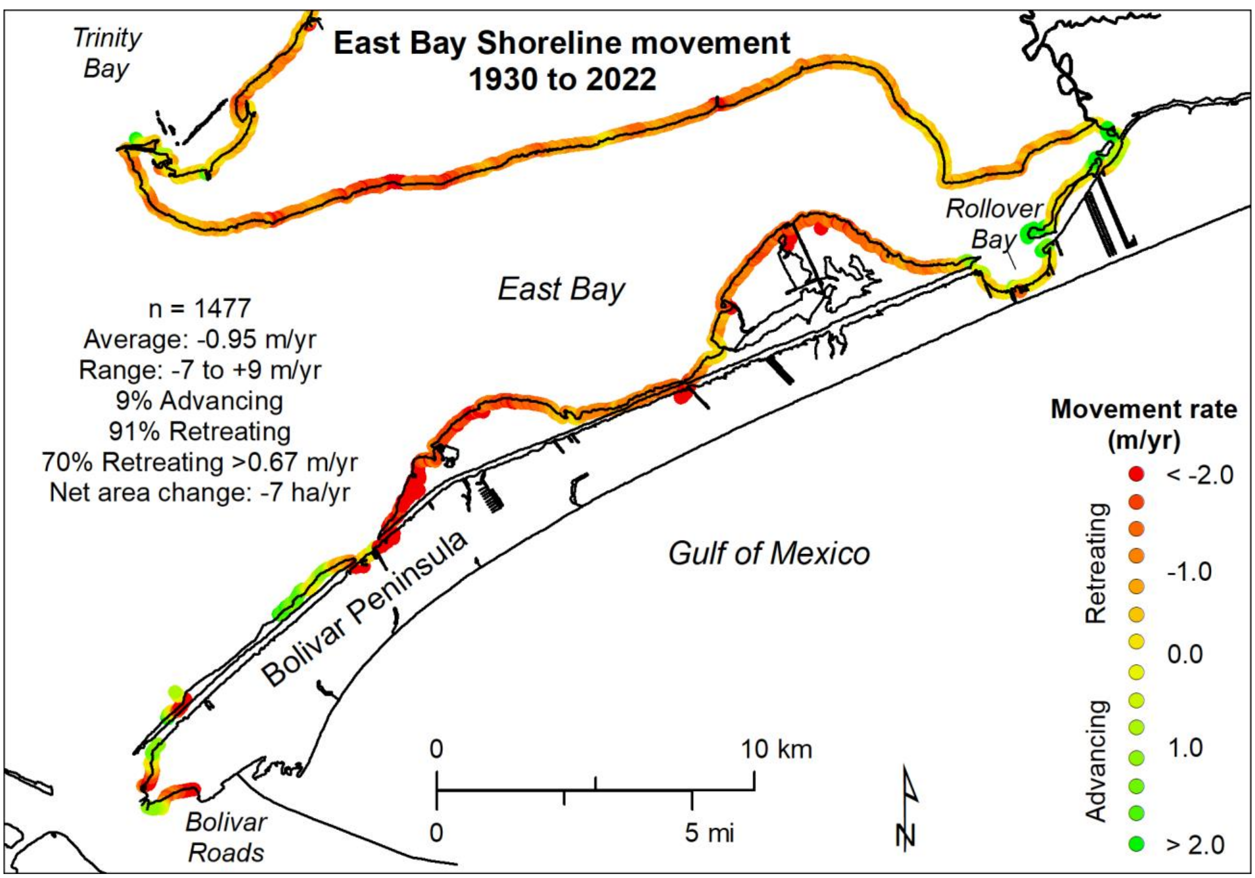

Figure 38. Net longer-term shoreline movement rates for Galveston East Bay calculated from shoreline positions from 1930 to 2022.

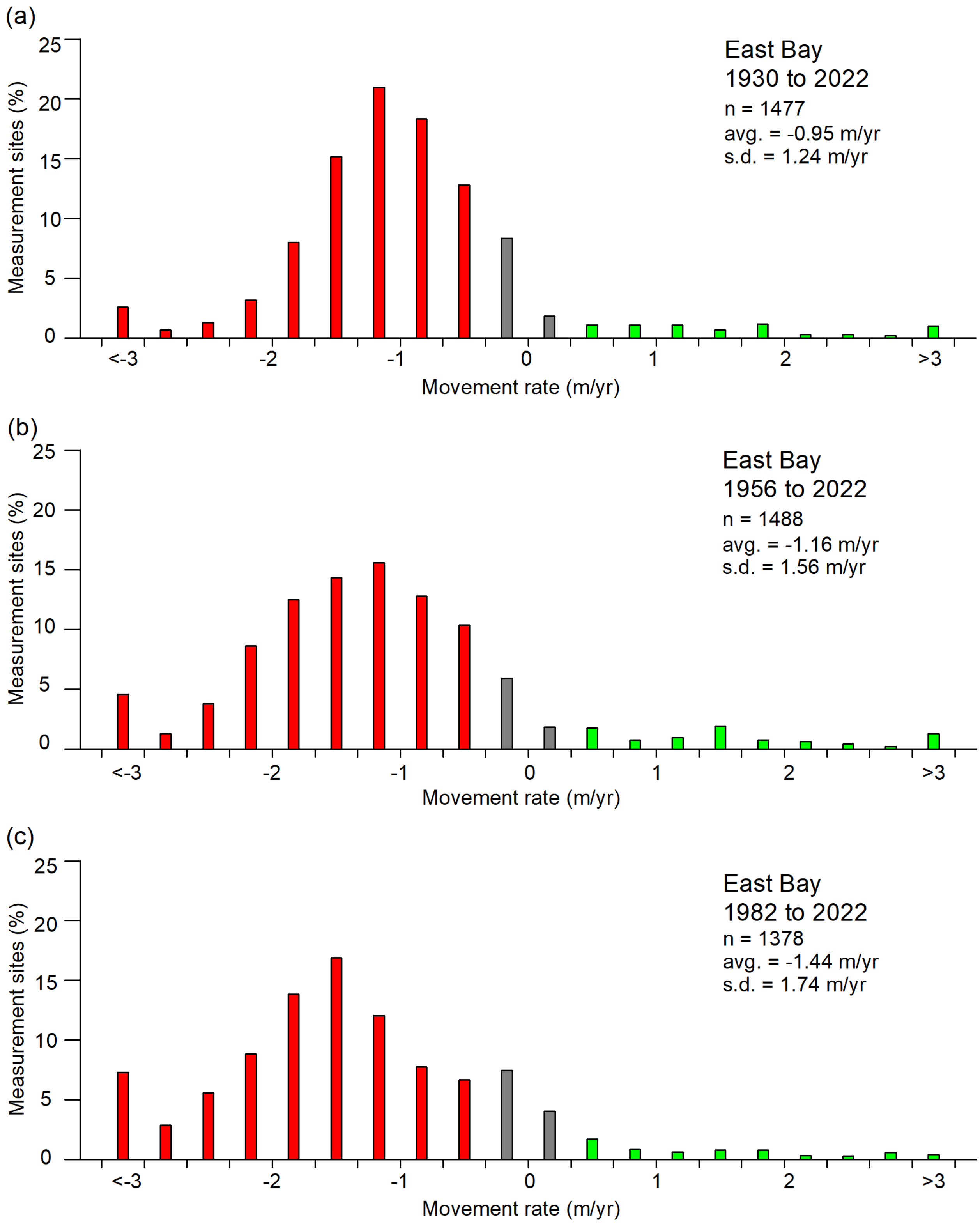

Figure 39. Distribution of (a) longer-term (1930 to 2022), (b) 1956 to 2022, and (c) more recent (1982 to 2022) shoreline movement rates in East Bay system on the upper Texas coast.

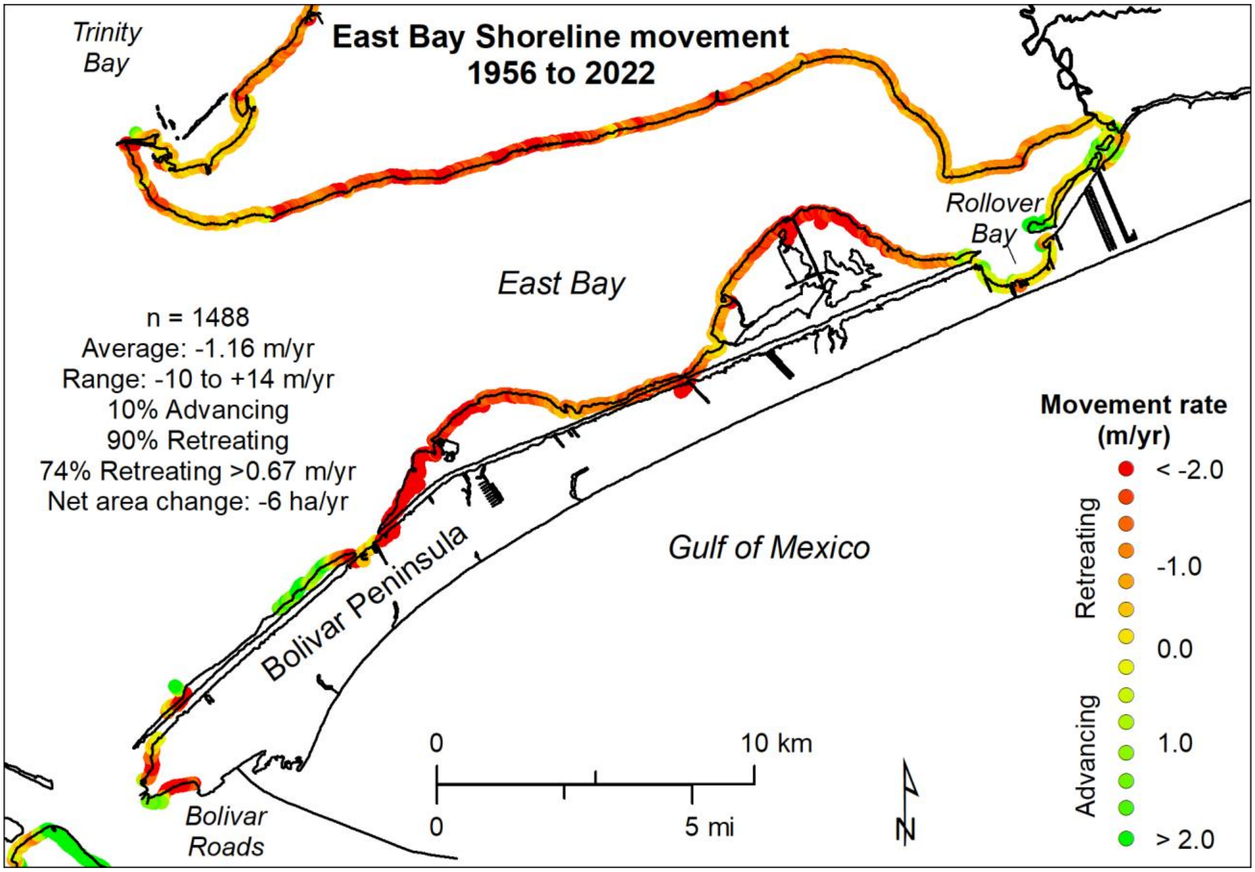

Figure 40. Net long-term shoreline movement rates for Galveston East Bay calculated from shoreline positions from 1956 to 2022.

period, highest rates of net retreat were measured along the back-barrier marshes on Goat Island, the sandy slope shoreline near the western end of the mainland, the beaches along Smith Point, and bay-margin shorelines along the mainland (Fig. 40). Small pockets of advancement were found along the back-barrier marsh or tidal flat shorelines of Rollover Bay, near the mouth of East Bay Bayou, and the western end of Bolivar Peninsula (Fig. 40).

East Bay 1982 to 2022

Ninety percent of the 1,378 measurement sites in East Bay underwent net shoreline retreat from 1982 to 2022 (Fig. 41, Table 5). Net rates at individual sites ranged from retreat at -15 m/yr to advance at 15.9 m/yr. Net shoreline movement averaged retreat of -1.44 m/yr, the highest retreat rate measured in any of the individual bay systems. The most common rates of shoreline movement were 17 percent of sites between -1.33 and -1.67 m/yr and 14 percent falling between -1.68 and -2 m/yr (Fig. 38c).

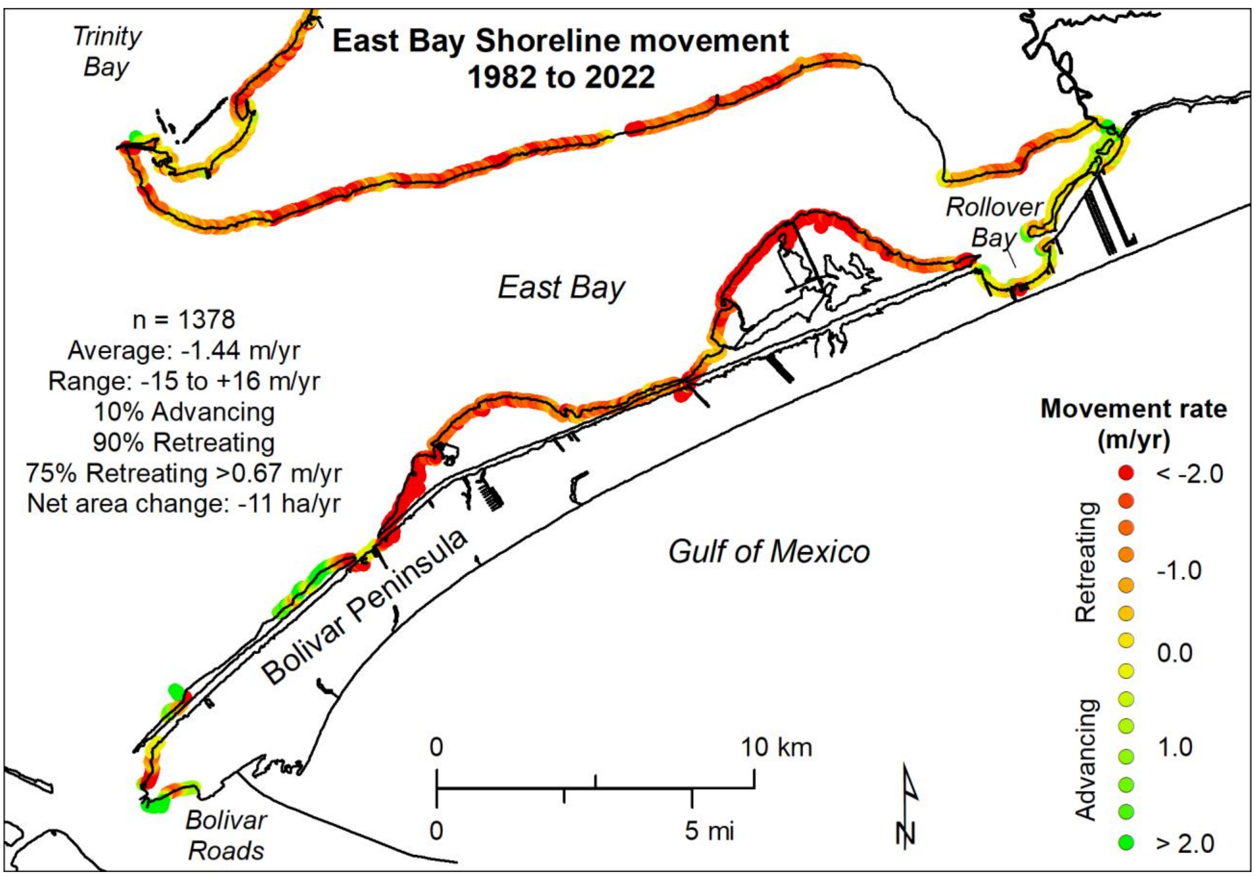

Figure 41. Net rates of recent shoreline movement for Galveston East Bay calculated from shoreline positions from 1982 to 2022.

This high rate of retreat for East Bay corresponds with an increase in average shoreline retreat at back-barrier marshes and tidal flats of -1.58 m/yr, bay beaches of -1.48 m/yr, and bay-margin marshes and tidal flats of -1.38. Notable shoreline retreat occurred along the back-barrier marshes and beaches on the shores of Bolivar Peninsula, the bay-margin marshes in Anahuac National Wildlife Refuge, and beaches along the western and southern shores of Smith Point (Fig. 41). Once more, small segments of shoreline advancement were measured at the back-barrier marsh or tidal flat shorelines of Rollover Bay, near the mouth of East Bay Bayou, and the western end of Bolivar Peninsula (Fig. 41).

Shoreline Movement in West Bay

The Galveston West Bay system includes West Bay proper as well as the smaller bays of Christmas Bays, Bastrop Bay, and Chocolate Bay. This is the largest of the four bay subsystems with over 220 km of shoreline. Almost 40 percent of all the shorelines in the West Bay system are bay-margin marshes and tidal flats. The other shoreline types in decreasing order include back-barrier marshes or tidal flats on Galveston Island and Follets Island, the Pelican Island and Mud Island flood-tidal deltas, beaches, low bluffs along the shores of Chocolate Bay, tidal pass shorelines bordering San Luis Pass, and a few spits. Sixteen percent of the West Bay shoreline is designated as modified shore. This includes the shorelines bordering Galveston Channel between Galveston Island and Pelican Island that have been heavily modified to accommodate port activities. The shorelines of Tiki Island have been broadly altered by dredging and bulkheads. An additional 10 percent of shorelines have smaller protection devices in place such as low bulkheads or rip-rap. Other modifications include marsh restoration projects and breakwaters like in Galveston Island State Park. Communities bordering West Bay include Bayou Vista and Tiki Island on the mainland shore, the city of Galveston and Jamaica Beach on Galveston Island, and Treasure Island and Surfside Beach on Follets Island.

West Bay 1930 to 2022

Of the 4,260 measurement sites around the West Bay system, 85 percent retreated between 1930 and 2022 (Fig. 42, Table 3). The average shoreline retreat was -0.86 m/yr and an average land-loss rate of 19 ha/yr. The rate histogram for West Bay illustrates that retreating sites predominate with the most common rates for this time period falling in the 0 to -0.33 (21 percent of sites) and -0.34 to -0.67 (19 percent of sites, Fig. 43a) range. The protected minor bays had shoreline retreat rates that were less than the bay system average: Christmas Bay (-0.40 m/yr), Chocolate Bay (-0.48 m/yr), and Bastrop Bay (-0.58 m/yr). The shorelines along West Bay proper include Galveston Island retreating at -1.27 m/yr and the mainland at -0.95 m/yr, both above the bay system average.

All shoreline types in the West Bay system experienced retreat with the exception of tidal pass shores along San Luis Pass (2.81 m/yr) and spits which advanced at 0.52 m/yr. The highest retreat rates were measured at Galveston Island back-barrier marshes and tidal flats (-1.64 m/yr), bay beaches (-1.33 m/yr), and Pelican Island (Bolivar Roads) and Mud Island (San Luis Pass) flood-tidal delta shorelines (-0.71 m/yr). Average retreat rates were also high at bay-margin marshes and the low bluffs of Chocolate Bay (-0.6 and -1.57 m/yr, respectively).

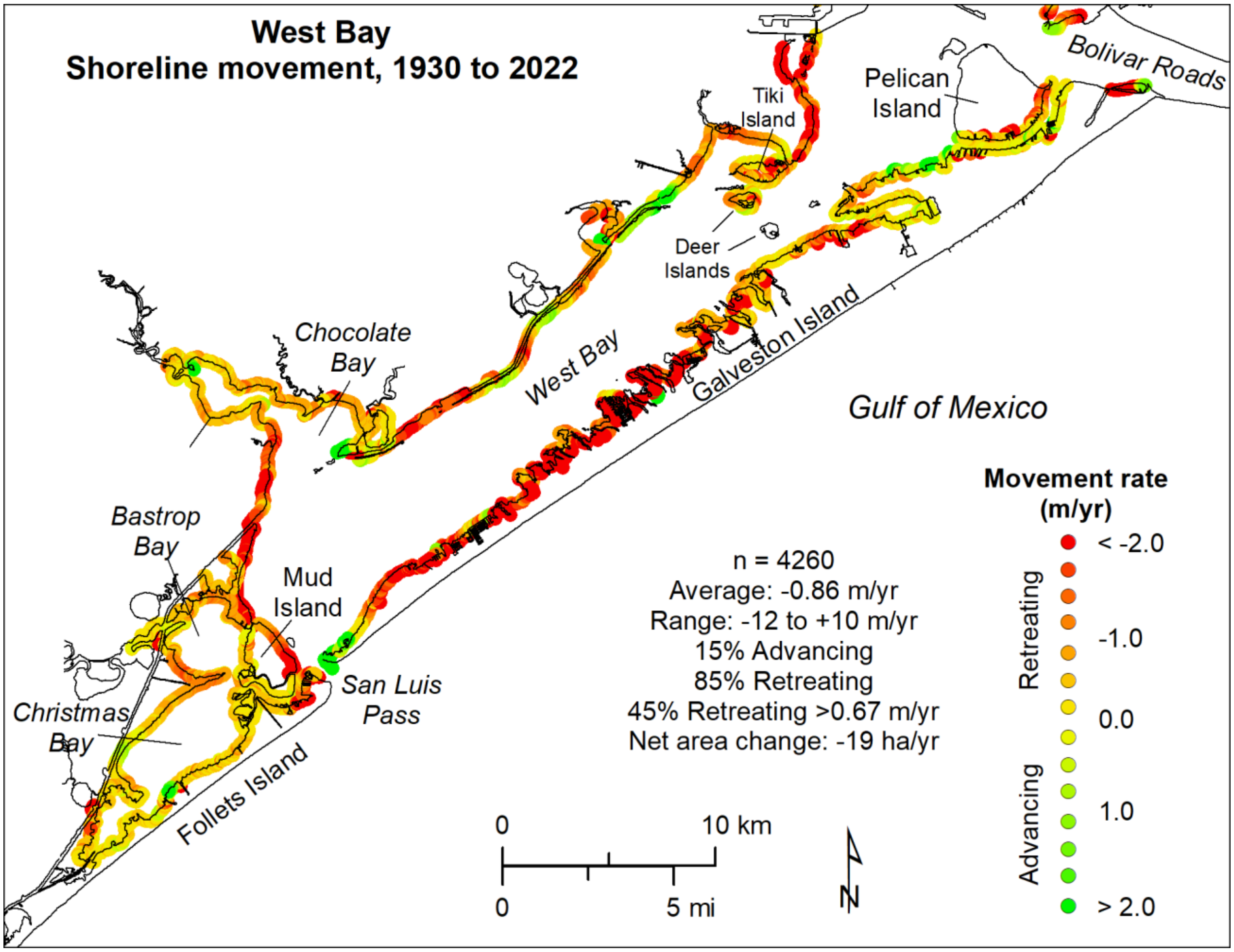

Figure 42. Net longer-term shoreline movement rates for Galveston West Bay including Christmas Bay, Bastrop Bay and Chocolate Bay calculated from shoreline positions from 1930 to 2022.

Highest rates of net shoreline retreat were measured along a 20 km-long segment of back-barrier marsh or tidal flat on Galveston Island, the northeastern shoreline of the Mud Island flood-tidal delta (facing San Luis Pass), and a 6 km-long segment of shoreline stretching south from Chocolate Bay toward Bastrop Bay (Fig. 42). Sites along the Galveston Island shore of San Luis Pass, the southeastern corner of Chocolate Bay, short segments along the West Bay mainland shore, and the Follets Island and mainland of southwestern Christmas Bay recorded net shoreline advancement (Fig. 42).

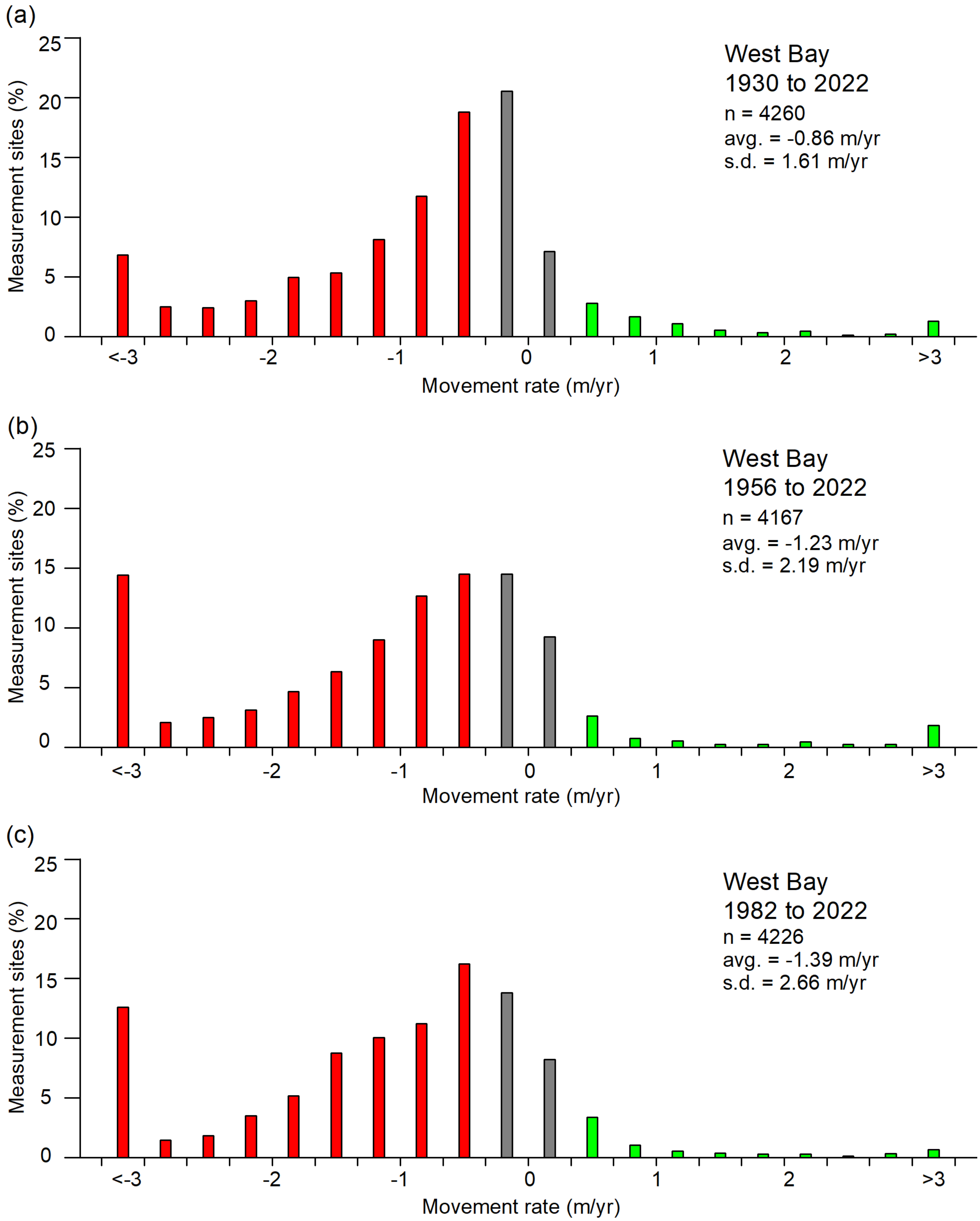

Figure 43. Distribution of (a) longer-term (1930 to 2022), (b) 1956 to 2022, and (c) more recent (1982 to 2022) shoreline movement rates in Galveston West Bay.

West Bay 1956 to 2022

The West Bay system shoreline retreated at 84 percent of the 4,167 measurement sites between 1956 and 2022 (Fig. 44, Table 4). Net change rates ranged from retreat at -17 m/yr to advance at 12 m/yr. The overall average shoreline movement rate for this system was retreat at -1.23 m/yr. Average net shoreline movement rates for components of the West Bay system were retreat at -2.07 m/yr on Galveston Island, -1.66 m/yr on the West Bay mainland shoreline, -0.72 m/yr in Bastrop Bay, -0.63 m/yr in Chocolate Bay, and -0.58 in Christmas Bay. Three shoreline movement categories contained an equal number of measurement sites on the histogram plot for the 1956 to 2022 time period. Fifteen percent of all measurement sites recorded rates greater than 3 m/yr of retreat (Fig. 43b) which is the same as the 0 to -0.33 m/yr and -0.34 to -0.67 m/yr categories.

The San Luis Pass tidal pass shoreline was the only shoreline type to experience net advancement during this time period (1.1 m/yr) although at a lower rate from the longer-term observation period. The rate of retreat at flood-tidal deltas was less during this period (-0.29 m/yr,). All other shoreline types retreated at higher rates: beaches (-3.02 m/yr), back-barrier marshes and tidal flats (-2.58 m/yr), spits (-1.59 m/yr), bay-margin marshes and tidal flats (-0.98 m/yr), and low bluffs (-0.64 m/yr).

Notable areas of shoreline retreat occurred along 25 km of Galveston Island back-barrier marsh or tidal flat, the mainland shoreline between Chocolate Bay and Mud Island, the southeastern shoreline of the Mud Island flood-tidal delta, and an 8 km-long segment of mainland shoreline along the GIWW (Fig. 44). Advancing shorelines are found along a 1.5 km segment on Pelican Island, at San Luis Pass, short segments at the head and mouth of Chocolate Bay, and short segments along the mainland of West Bay (Fig. 44).

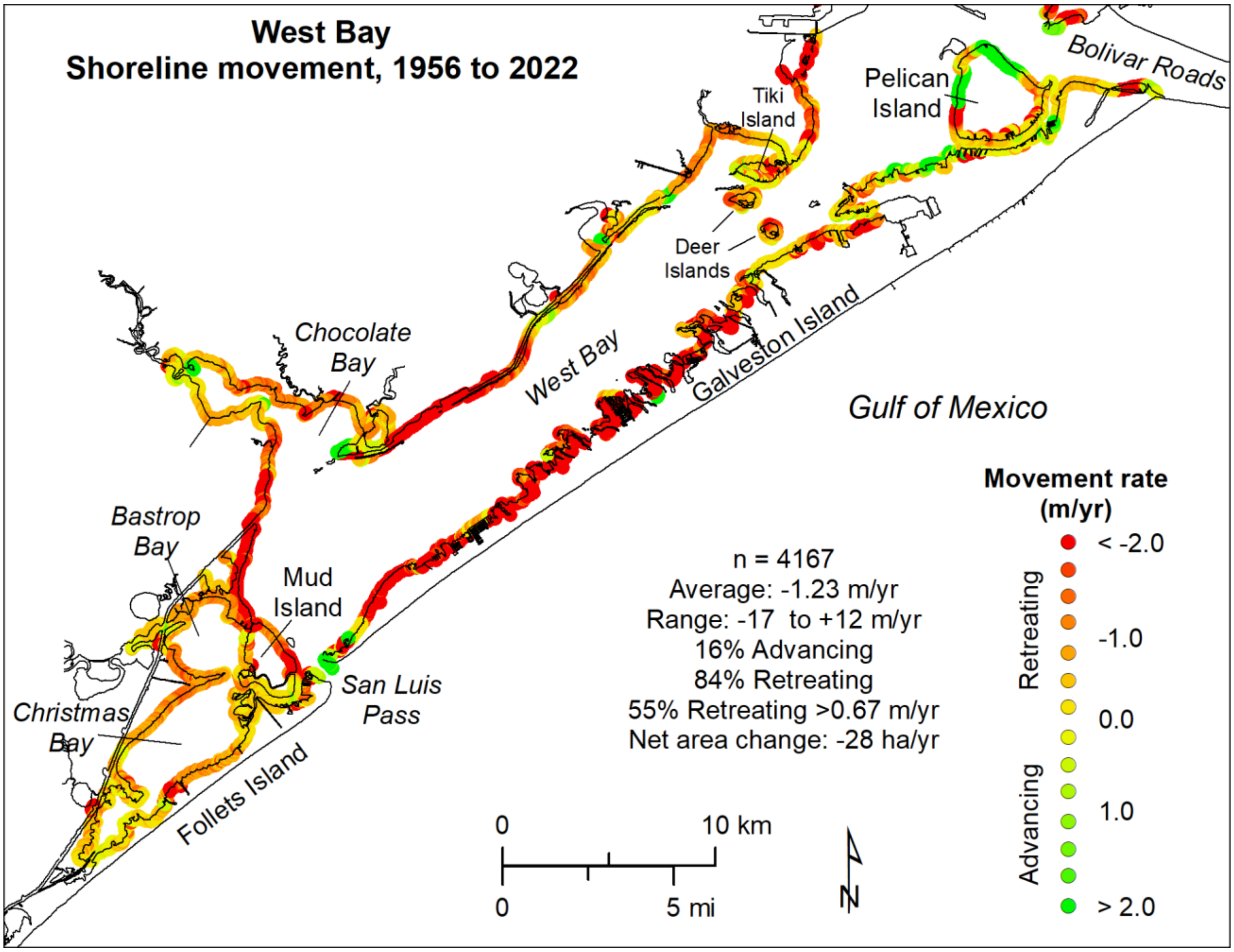

Figure 44. Net long-term shoreline movement rates for Galveston West Bay including Christmas Bay, Bastrop Bay and Chocolate Bay calculated from shoreline positions from 1956 to 2022.

West Bay 1982 to 2022

During the more recent comparison period (1982 to 2022), the proportion of measurement sites where the shoreline retreated increased to 85 percent of the 4,226 sites and the average rate of retreat in West Bay also increased to -1.39 m/yr (Fig. 45, Table 5). The resulting land-loss rate for the system was 29 ha/yr. The component bays and shorelines also saw increased retreat rates between 1982 and 2022. Galveston Island shorelines retreated at -1.99 m/yr, West Bay mainland shores at -1.81 m/yr, Bastrop Bay at -0.88 m/yr, Chocolate Bay at -0.81 m/yr, and Christmas Bay at -0.69 m/yr. The shoreline movement category with the largest percentage of measurement sites (16 percent) was -0.33 to -0.67 m/yr, followed by 0 to -0.33 m/yr with 14 percent, and the highest retreat rate category with 13 percent of sites (Fig. 43c). Net change rates ranged from retreat at -29 m/yr to advance at 15 m/yr.

All shoreline types in the West Bay system experienced retreat with the exception of the tidal pass shoreline at San Luis Pass advancing at 3.55 m/yr. This is the highest average rate of advance along this shoreline type among the three monitoring periods. Back-barrier marshes and tidal flats on Galveston and Follets Islands retreated at an average rate of -2.49 m/yr, beaches at -2.32 m/yr, spits at -1.95, mainland bay-margin marshes and tidal flats at -1.21 m/yr, the flood-tidal deltas and Mud Island and Pelican Island at -0.85 m/yr, and the low bluff shorelines of Chocolate Bay at -0.74 m/yr.

Areas reporting extreme shoreline retreat rates include the southwestern shore of Bastrop Bay, the northern shoreline of Christmas Bay, the mainland shoreline between Chocolate Bay and Mud Island, the eastern Mud Island flood-tidal delta shoreline, a 12 km-long segment of back-barrier marsh in the central part of Galveston Island and another 3.5 km-long segment near the southwestern end of the island, the shoreline near Bayou Vista on the mainland, and segments 7 km, 1.4 km and 1.2 km-long along the GIWW (Fig. 45). Advancing shorelines were recorded at the head of Chocolate Bay and the tidal pass shorelines of San Luis Pass (Fig. 45).

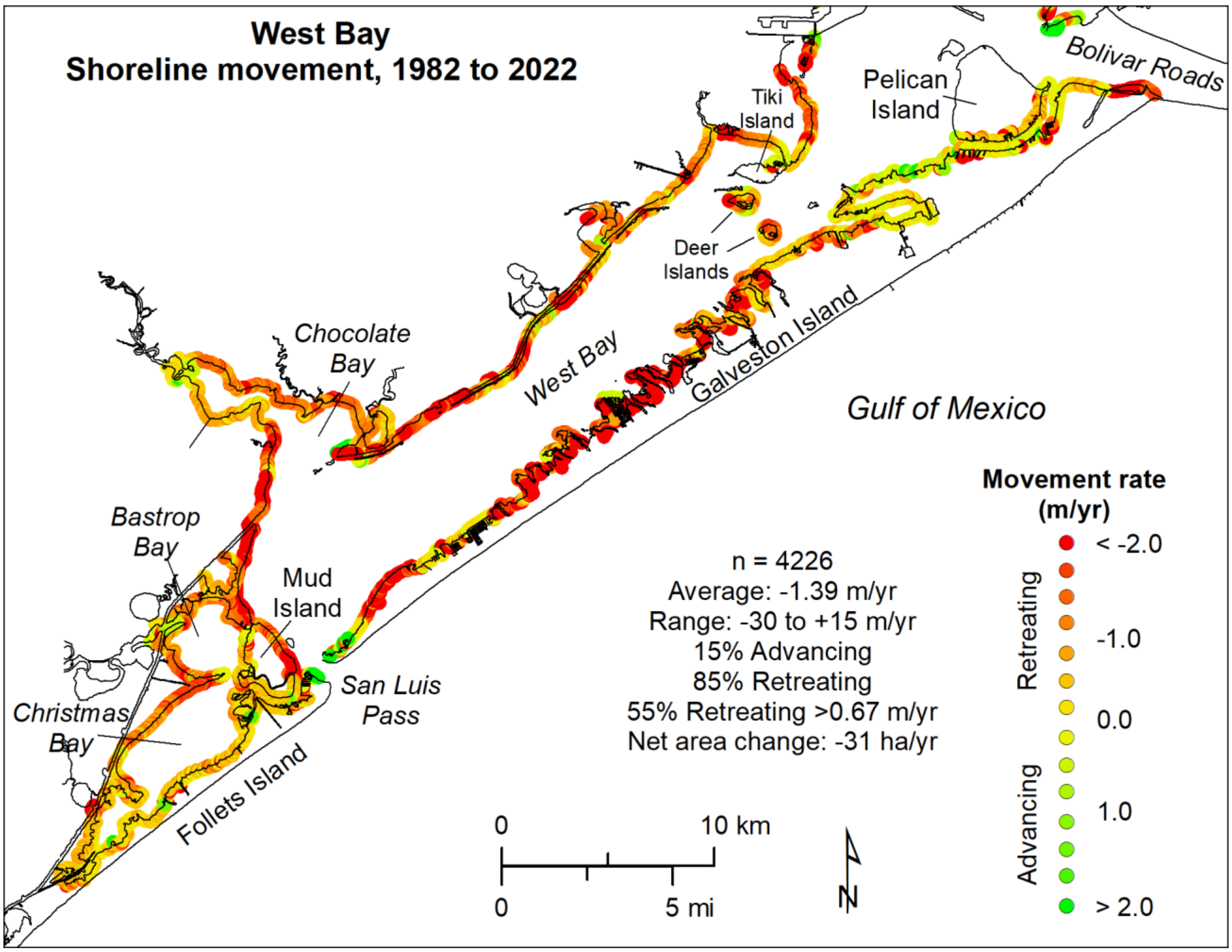

Figure 45. Net rates of recent shoreline movement for Galveston West Bay including Christmas Bay, Bastrop Bay and Chocolate Bay calculated from shoreline positions from 1982 to 2022.

CONCLUSIONS

A combination of airborne lidar data from 2017 and 2018 and aerial photography from 2022 was used to characterize bay shoreline morphology and determine bay shoreline movement rates in the Galveston Bay system on the upper Texas coast. The current shoreline proxy extracted from lidar DEMs and photography was compared to past shoreline positions mapped on aerial photographs taken in 1930, 1956, and 1982. These comparisons indicate that long-term bay shoreline movement is dominantly erosional; 83 percent of 9,312 measurement sites recorded shoreline retreat between 1930 and 2022. Shorelines in the Galveston Bay system retreated at 82 percent of 9,528 measurement sites at an overall average rate of -0.99 m/yr between 1956 and 2022. This rate yields a land-loss rate averaging 49 ha/yr. During the more recent comparison period (1982 to 2022), 79 percent of the 9,194 measurement sites recorded an increased average rate of retreat of -1.05 m/yr.

Eleven common shoreline types were identified in the Galveston Bay system and examined for their relative susceptibility to shoreline retreat related to relative sea-level rise, storm surge and storm waves, and wave action. The shoreline types with higher elevations such as high bluffs, low bluffs, and sandy slopes have low susceptibility to retreat related to short-term relative sea-level rise, moderate susceptibility to non-storm wave action, and high susceptibility to storm surge and waves. Fan deltas, beaches, and spits have high susceptibility to retreat by non-storm wave action and moderate susceptibility to storm surge and waves and relative sea-level rise. Shorelines along low-lying tidal passes, flood-tidal deltas, and back-barrier and bay-margin marshes and tidal flats are highly susceptible to retreat associated with relative sea-level rise and non-storm wave action. Susceptibility to retreat associated with storm waves is generally low for these types, with the exception of tidal-pass and flood-tidal delta shorelines which are highly susceptible to movement caused by flood and ebb currents through tidal channels associated with storm passage. Highest average rates of shoreline retreat were found along back-barrier and bay margin marsh and tidal flats, beaches, and deltaic marshes. Shoreline advancement was recorded along spits and fan delta shorelines.

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REFERENCES

Fisher, W.L., McGowen, J.H., Brown, L.F., Jr., and Groat, C.G., 1972, Environmental geologic atlas of the Texas Coastal Zone—Galveston-Houston Area: The University of Texas at Austin, Bureau of Economic Geology, Environmental Geologic Atlas, EA0005, scales 1:250,000 and 1:125,000, 91 p.

Gibeaut, J.C., Waldinger, R., Hepner, T., Tremblay, T.A., White, W.A., 2003, Changes in Bay Shoreline Position, West Bay System, Texas: The University of Texas at Austin, Bureau of Economic Geology, Report prepared for General Land Office under contract no. 02-225R, 27 p.

Himmelstoss, E.A., Henderson, R.E., Kratzmann, M.G., and Farris, A.S., 2021, Digital Shoreline Analysis System (DSAS) version 5.1 user guide: U.S. Geological Survey Open-File Report 2021-1091, 104 p., https://doi.org/10.3133/ofr20211091.

Morton, R.A. and White, W.A., 1995, Shoreline Types of the Upper Texas Coast: Sabine-Galveston-Freeport-Sargent Areas: The University of Texas at Austin, Bureau of Economic Geology, Final Report prepared for the Texas Natural Resources Inventory Program, TGLO, TNRCC, TPWD, and MMS, 42 p.

Paine, J.G., Caudle, T., and Andrews J., 2016, Shoreline Movement in the Copano, San Antonio, and Matagorda Bay Systems, Central Texas Coast, 1930s to 2010s: The University of Texas at Austin, Bureau of Economic Geology, Final Report prepared for General Land Office under contract no. 13-258-000-7485, 72 p.

Paine, J.G., Caudle, T., and Andrews J., 2021, Shoreline Movement and Beach and Dune Volumetrics along the Texas Gulf Coast, 1930s to 2019: The University of Texas at Austin, Bureau of Economic Geology, Final Report prepared for General Land Office under contract no. 16-201-000, 101 p.

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

Paine, J.G., and Morton, R.A., 1991, Historical Shoreline Changes in the Galveston Bay system, in Shipley, F.S., and Kiesling, R.W., eds., Proceedings: Galveston Bay Characterization Workshop: The Galveston Bay National Estuary Program, Publication GCNEP-s, P. 165-167.