Shoreline Types of the South Texas Coast: Laguna Madre and Baffin Bay Areas

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CONTENTS

FIGURES

Tables

EXECUTIVE SUMMARY

The following report describes how the Bureau of Economic Geology (BEG) classified and mapped the shores of the south Texas coast, provides definitions of each shoreline type, and presents examples that illustrate how physical attributes of the shoreline habitats control the impact of spilled oil. This information is an integral part of the Environmental Sensitivity Index (ESI) maps used for oil-spill response and contingency planning. Shorelines were classified according to an ESI scheme established by Research Planning, Inc. (RPI) and the BEG. The ESI rankings (1–10) are described, examples of each type are illustrated, and the common occurrences of multiple adjacent shoreline types are given.

Shoreline types were mapped at a scale of 1:24,000 based on U.S.G.S. topographic quadrangles using recent low-altitude color video surveys taken in 1999, oblique color slides taken in 1999, digital orthophoto quadrangles derived mostly from 1995 aerial photographs, and previous field experience. The maps were spot field checked during winter and spring of 2000. The Corpus Christi to Brownsville region was selected for the final phase of ESI mapping in Texas. Shore types there are diverse; extant wetlands and tidal flats are environmentally sensitive; and significant volumes of oil are produced and transported through shipping channels and the Intracoastal Waterway of the region.

ESI rankings characterize the sensitivity of the shore and associated biota to oil impacts and the relative difficulty of cleanup activities. Low numbers indicate low sensitivity to environmental damage, whereas high numbers indicate priority areas that should be protected from damage. The ESI rankings for Texas are as follows: **1** Exposed walls and other structures made of concrete, wood, or metal; **2A** Scarps and steep slopes in clay; **2B** Wave-cut clay platform; **3A** Fine-grained sand beaches; **3B** Scarps and steep slopes in sand; **4** Coarse-grained sand beaches; **5** Mixed sand and gravel (shell) beaches; **6A** Gravel (shell) beaches; **6B** Exposed riprap structures; **7** Exposed tidal flats; **8A** Sheltered solid man-made structures, such as bulkheads and docks; **8B** Sheltered riprap structures; **8C** Sheltered scarps; **8D** Sheltered rocky/karst shores; **9** Sheltered tidal flats; **10A** Salt- and brackish-water marshes; **10B** Fresh-water marshes (herbaceous vegetation); **10C** Fresh-water swamps (woody vegetation); and **10D** Mangroves and other estuarine scrub-shrub wetlands.

All of these shoreline types are present along the south Texas coast, except for coarse-grained sand beaches. Beaches consist primarily of fine-grained sand, mixtures of sand and gravel (shell), or gravel (primarily shell).

INTRODUCTION

Shores are dynamic elements of the Texas coast that constantly change position because of local erosion and deposition. In some places these processes along with human activities cause changes in other physical attributes such as sediment composition, sediment textures, and nearshore slopes. The lengths and types of shores also determine their economic and recreational value, their ability to support certain plant and animal communities, and their value as productive nesting and nursery grounds for certain threatened and endangered species. Knowing shoreline characteristics also provides a fundamental basis for oil-spill response and contingency planning and for post-spill damage assessments.

The purpose of this coastal mapping project was to produce a set of large-scale, high-quality maps of shoreline characteristics of the south Texas coast that were suitable for digitization and incorporation into a geographic information system (GIS). The shoreline maps and digital databases represent a significant component of Environmental Sensitivity Index (ESI) maps used for oil-spill response and contingency planning by the State trustee agencies.

Inventories of shoreline types and updated ESI maps are needed for the entire Texas coast. The upper and central Texas coast have been previously mapped (Morton and White, 1995; 1998). This report of the South Texas coast, Corpus Christi to Brownsville region (Figure 1), completes the coastal series. The region contains highly diverse shoreline types that undergo closely spaced changes because the regional geology and shoreline orientations are diverse and human modifications of the shore are extensive and highly varied. The large lagoon and estuaries, barrier islands, navigation channels, and spoil islands of the region create more than 1,900 km of shoreline that are represented on 38 topographic quadrangle maps (Figure 2). A list of the quadrangle maps used as base maps is given in Table 1.

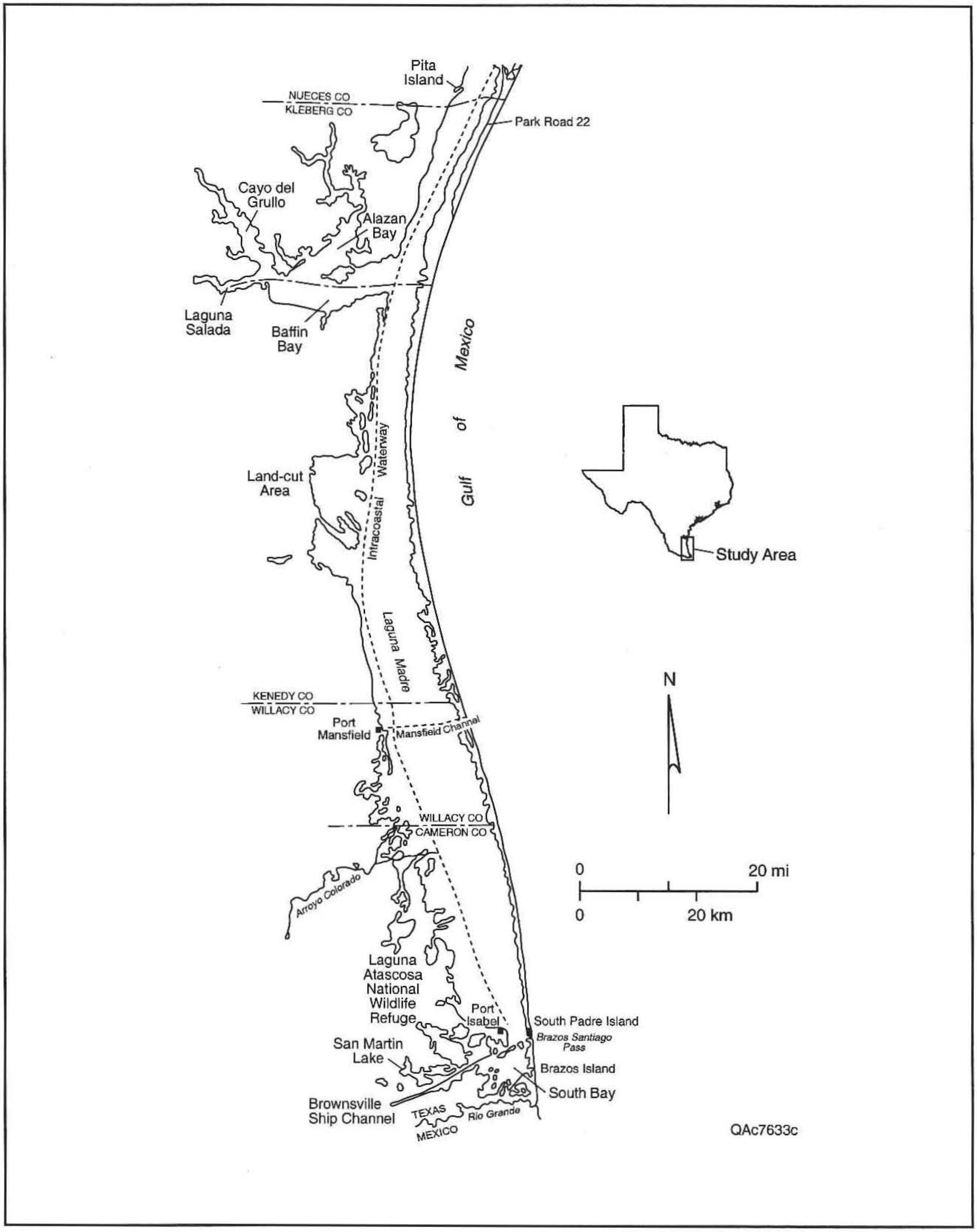


Figure 1. Index map of study area.

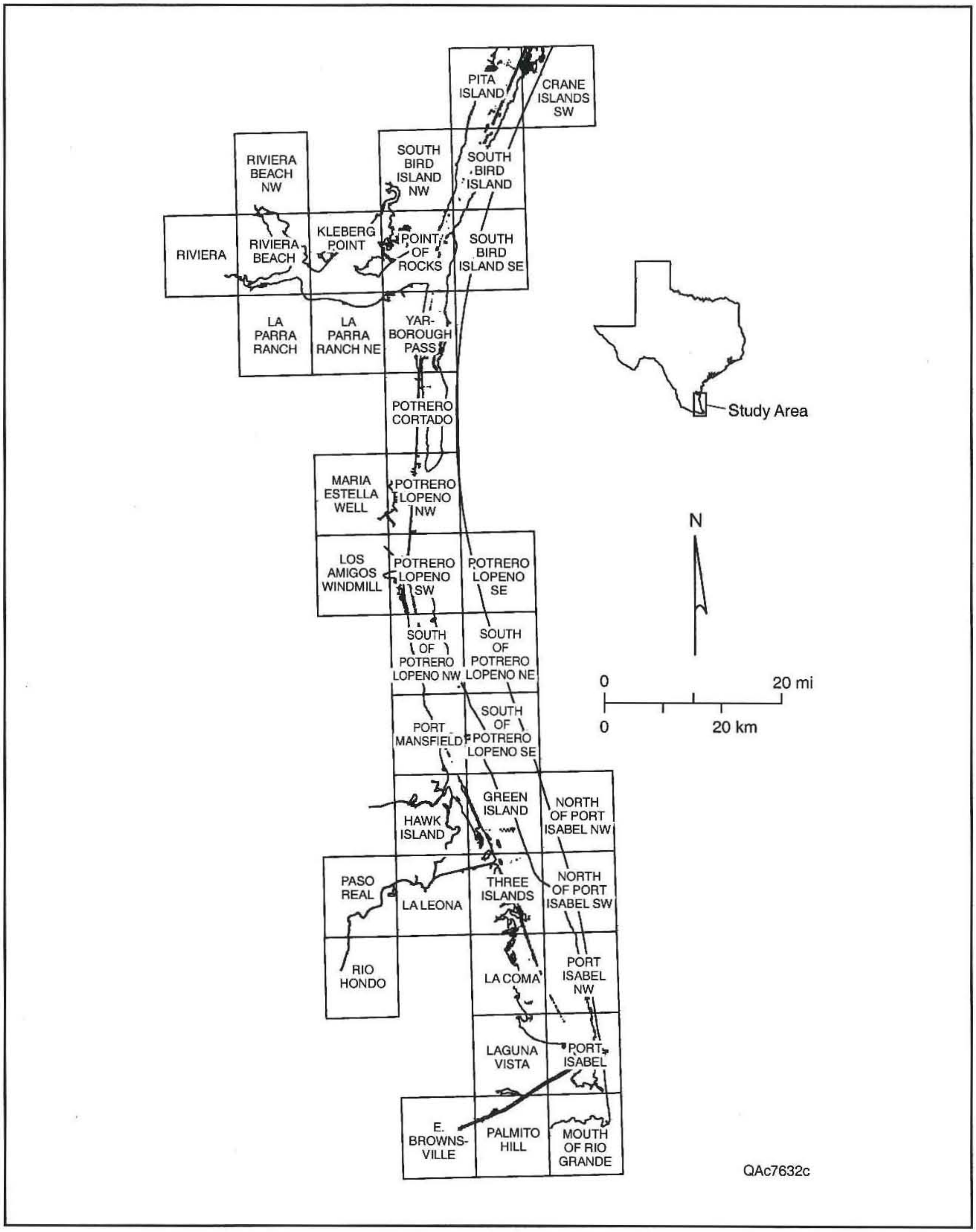


Figure 2. Index map of the study area showing the locations of 7.5-minute USGS topographic maps.

Table 1. List of 7.5-minute topographic quadrangles used for the south Texas coast.

Crane Island SW	North of Port Isabel NW	Rio Hondo
East Brownsville	North of Port Isabel SW	Riviera
Green Island	Palmito Hill	Riviera Beach
Hawk Island	Paso Real	Riviera Beach NW
Kleberg Point	Pita Island	South Bird Island
La Coma	Point of Rocks	South Bird Island NW
La Leona	Port Isabel	South Bird Island SE
La Parra Ranch	Port Isabel NW	South of Potrero Lopeno SE
La Parra Ranch NE	Port Mansfield	South of Potrero Lopeno NW
Laguna Vista	Potrero Cortado	South Potrero Lopeno NE
Los Amigos Windmill	Potrero Lopeno NW	Three Islands
Maria Estella Well	Potrero Lopeno SE	Yarborough Pass
Mouth of Rio Grande	Potrero Lopeno SW	

RATIONALE FOR UPDATING SHORELINE INVENTORIES AND ESI MAPS

Environmental Sensitivity Index (ESI) mapping represents a conceptual advancement that recognizes different susceptibilities to environmental damage depending on shoreline characteristics. First developed for the shores of lower Cook Inlet in Alaska (Hayes et al., 1976; Michel et al., 1978), this method of classifying shoreline features has gained wide acceptance and is now a standard resource management tool used to develop contingency plans in the event of an oil spill or to minimize environmental damage during a spill.

ESI mapping employs a qualitative ranking system that characterizes the sensitivity of the shore and associated biota to oiling and cleanup activities. The ESI rankings typically range from 1 to 10, with low numbers indicating short persistence of stranded oil and minor susceptibility to environmental degradation, and high numbers indicating long-term oil persistence, difficulty of oil cleanup, and a high sensitivity to damage. Standard ESI map units and symbols have been established by the National Oceanic and Atmospheric Administration (NOAA) in conjunction with Research Planning, Inc. (RPI) to facilitate the use of ESI maps nationwide by all potential users, including State and Federal officials, industry representatives, and oil-spill cleanup contractors (Michel and Dahlin, 1993).

ESI maps previously prepared for Texas (Gundlach et al., 1981; Texas Water Commission, 1989) do not conform to the current NOAA standards, and the classifications on the Texas maps are not the same as those generally presented on most ESI maps. Also, the older ESI maps for Texas do not show other information that is pertinent to natural resource inventories and oil-spill contingency planning and response efforts. The first ESI maps for Texas (Gundlach et al., 1981) encompassed only the lower coast south of Corpus Christi. They were prepared in 1979 at a scale of 1:24,000 to 1:40,000 (Michel and Dahlin, 1993). Subsequent ESI maps covering the entire coast were published at scales ranging from 1:32,000 to 1:125,000 (Texas Water Commission, 1989). These scales are convenient for viewing and handling, but they are too small for onsite use. A scale of 1:24,000 is rapidly becoming the standard scale for mapping and digitization of ESI maps in the United States (Michel and Dahlin, 1993).

ESI maps for Texas are being updated because most of the developed shores have changed dramatically and more shores have been developed since the first ESI maps were prepared. Current systematic mapping for the entire coast is needed that employs a standard classification scheme, large-scale format, and established digital cartographic techniques.

PREVIOUS RELATED WORK

Numerous coastal studies previously conducted over the past 25 years by the Bureau of Economic Geology (BEG) served as a foundation for the ESI rankings and mapping of shoreline types. Physical attributes of natural and artificial shores of the Texas coast had been mapped by the BEG, but none of the prior mapping projects inventoried the physical attributes of the shores or presented the data in a form suitable for oil-spill response, contingency planning, or damage assessment.

Modern systematic geologic mapping of the Texas coast began in the late 1960s when the Environmental Geologic Atlas Series was conceived and implemented (Fisher et al., 1972, 1973). This multiyear Bureau-initiated program set the standard for comprehensive synthesis of physical, chemical, and biological data that were specifically designed to address the need for baseline inventories suitable for environmental investigations. The Environmental Geologic Atlas Series organized diverse types of information and presented it in tables, charts, and multicolor maps that were intended for use by planners and regulators as well as by scientists and engineers. The principal mapping techniques that supported this work involved interpretation of aerial photographs, extensive field investigations, and aerial overflights. To make the maps even more useful, other related data also were compiled such as ecological surveys, climatological and oceanographic records, engineering properties, locations of energy and mineral resources, and locations of transmission routes. The Environmental Geologic Atlas Series includes maps of (1) topography and bathymetry, (2) current land use, (3) man-made features and water systems, (4) environments and biological assemblages, (5) physical properties, (6) active processes, (7) rainfall, discharge, and surface salinity, and (8) mineral and energy resources. The maps are accompanied by an interpretive text and user's guide that explain the interrelationships among geological processes, physical substrates, and biological assemblages.

In the early 1970s, the BEG initiated a study of beach changes along the Texas Gulf shoreline including the lower coast between North Padre Island and the Rio Grande (Morton and Pieper, 1975; 1977a; 1977b). This study was updated (Paine and Morton, 1989) to provide more recent information on shoreline movement. Results of these and similar studies for the bay shores (Morton and Paine, 1984) provide a basis for classifying shore stability in any of the bays and estuaries or the Gulf shore of the south Texas coast. In the mid 1970s, the BEG also initiated another atlas series that focused on the subtidal region of the Texas coast (White et al., 1983; 1986, 1989). The submerged lands were inventoried, and significant physical, chemical, and biological properties were identified and measured. The resulting quantitative maps and reports, known as the Submerged Lands of Texas Atlases, cover the wetlands, bays, estuaries, lagoons, and inner continental shelf environments where navigation projects, industrial site development, and mineral resource extraction activities are being conducted or are planned for the future.

In 1997, the Bureau conducted a study of wetland and aquatic habitats in the Corpus Christi Bay system in support of the Corpus Christi Bay National Estuary Program (White et al., 1998). The work involved field descriptions and interpretations of the wetland habitats, mapping of wetlands on aerial photographs, digitizing the maps, processing the data in ARC/INFO, and illustrating the trends of gain and loss in wetland habitat. A final phase of the project involved assessing the probable causes of wetland trends including relative sea-level rise and human activities.

In 2000, the BEG through funding by the GLO, began a series of studies to update shoreline changes (Jim Gibeaut, Principal Investigator). Among the remote sensing techniques being used to map shoreline position and monitor change are Light Detection and Ranging (LIDAR) terrain mapping.

METHODS OF MAPPING AND APPLYING ESI RANKINGS

Mapping Procedures

Shorelines were mapped and classified using numeric or alphanumeric codes that define the ESI rankings and shoreline types (Tables 2 and 3; Figures 3-19). The mapping procedure consisted of identifying shoreline boundaries, marking the boundaries on base maps, and labeling each shoreline segment with the appropriate ESI code. Shorelines were delineated by USGS topographic map areas (scale 1:24,000) (Table 1) using shoreline positions updated by the Texas General Land Office from U.S. Fish and Wildlife Service National Wetlands Inventory (NWI) maps. Areas that had been modified since NWI mapping were updated where necessary using 1995 digital orthophoto quadrangles (DOQ's).

Shoreline types were mapped by BEG research staff primarily using low-altitude aerial videotape surveys of coastal Texas produced by the Center for Coastal, Energy, and Environmental Resources

(CCEER) (Westphal et al., 1999) and recorded during a cooperative helicopter flight in July 1999 by staff of the CCEER and BEG. Videotapes were high quality and were accompanied by Global Positioning System (GPS) locations and audio commentaries of shoreline types made by experienced coastal scientists. Shoreline types were classified and mapped by scientists viewing the videotapes on a 27-inch high-resolution color monitor and using a videocassette recorder with slow and fast advance and reverse features. Available color slides were used to provide additional fine detail on shoreline types in complex areas. In areas not covered by videography, shorelines were mapped using U.S. Geological Survey color-infrared DOQ's taken in 1995.

Application of ESI Rankings to Complex Shorelines

Along many segments of the Texas coast, several shoreline types occur in proximity to each other going from the water inland. Several ESI rankings are assigned to a shoreline segment where multiple shoreline types are subject to oiling. The ESI rankings are given in the order in which they occur going from the most landward to the most seaward position. For example, many shorelines have been armored by both riprap and bulkheads to prevent or to minimize shoreline erosion. Commonly, a vertical metal or wooden bulkhead will be protected along its seaward side by riprap (Figure 3a). Such a configuration would be designated on maps as 1/6B in a high-energy or exposed setting and as 8A/8B in a protected or sheltered setting (Tables 2 and 3). The first alphanumeric code, 1 and 8A in the above cases, refers to the landwardmost feature, or bulkhead, and the succeeding codes refer to the seawardmost feature, or in the above cases, riprap (6B and 8B) (Figure 3). Along some shores, riprap may be placed landward of partially failed vertical bulkheads. These areas are designated as 6B/1 or, in sheltered areas 8B/8A, to designate the seaward progression from riprap to bulkheads (Table 3).

Locally, as many as three shoreline types may be recognized in an alphanumeric sequence, such as 8C/10A/3A, which details a shoreline that progresses from a sheltered scarp to a fringing salt/ brackish marsh bordered by a sand beach.

Table 2. Standardized ESI rankings for Texas.

ESI no.	Shoreline type
1	Exposed walls and other structures made of concrete, wood, or metal
2A	Scarps and steep slopes in clay
2B	Wave-cut clay platform
3A	Fine-grained sand beaches
3B	Scarps and steep slopes in sand
4	Coarse-grained sand beaches
5	Mixed sand and gravel (shell) beaches
6A	Gravel (shell) beaches
6B	Exposed riprap structures
7	Exposed tidal flats
8A	Sheltered solid man-made structures, such as bulkheads and docks
8B	Sheltered riprap structures
8C	Sheltered scarps
8D	Sheltered rocky/karst shores
9	Sheltered tidal flats
10A	Salt- and brackish-water marshes
10B	Fresh-water marshes (herbaceous vegetation)
10C	Fresh-water swamps (woody vegetation)
10D	Mangroves

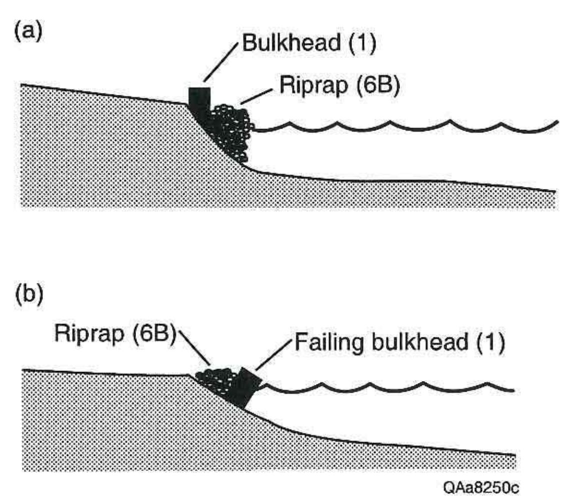


Figure 3. Multiple shoreline types consisting of exposed bulkheads and riprap. The shorelines are classified as 1/6B or 6B/1, depending on whether the bulkhead is (a) landward or (b) seaward of the riprap.

Table 3. Annotated and combined ESI rankings for Texas.

ESI no.	Shoreline type
Shorelines generally exposed to high physical energy	
1	Exposed walls and other solid structures made of concrete, wood, or metal
2A	Scarps and steep slopes in clay
2B	Wave-cut clay platform
3A*	Fine-grained sand beaches
3B	Scarps and steep slopes in sand
4*	Coarse-grained sand beaches
5*	Mixed sand and gravel (shell) beaches
6A*	Gravel (shell) beaches
6B	Exposed riprap structures
7	Exposed tidal flats

* These types may be mapped (rarely) in sheltered areas

Shorelines generally exposed to low physical energy	
8A	Sheltered solid man-made structures, such as bulkheads and docks
8B	Sheltered riprap structures
8C	Sheltered scarps and steep slopes
8D	Sheltered rocky/karst shores
9	Sheltered tidal flats
Wetlands	
10A	Salt- and brackish-water marshes
10B	Fresh-water marshes (herbaceous vegetation)
10C	Fresh-water swamps (woody vegetation)
10D	Mangroves and other estuarine scrub-shrub wetlands

Examples of ESI Combinations

1/6B or 8A/8B	Bulkhead shoreward of riprap
6B/1 or 8B/8A	Riprap shoreward of bulkhead
2A/10A or 8C/10A	Relatively narrow fringing marsh seaward of scarp
10A/2A or 10A/8C	Typically high marsh shoreward of low scarp
2A/1	Several possibilities: Failed bulkhead or breakwater seaward of scarp Short piers or boat docks seaward of scarp

Examples of Energy Levels

High-Energy Environments (Exposed)	Low-Energy Environments (Sheltered)
Gulf	Branch channels off of main ship channels and rivers
Bays	Bayous and creeks
Ship channels	Marinas and boat basins
Intracoastal Waterway	Narrow bays with limited fetch
Major rivers	

Table 4. General relationship between NWI wetland classes and ESI wetland types.

ESI ranking	NWI classification	NWI map symbol
10A Salt- and brackish-water marshes	Estuarine intertidal emergent wetland (persistent and nonpersistent)	E2EM
10B Fresh-water marshes	Palustrine Emergent Wetland (persistent)	PEM
10C Fresh-water swamps	Palustrine Forested Wetland and Scrub/Shrub Wetland (all subclasses	PFO and PSS
	Estuarine Intertidal Scrub/Shrub Wetland (Broad-leaved deciduous) (Needle-leaved deciduous) (Needle-leaved evergreen)	E2SS 1, 2, & 4
10D Mangroves	Estuarine Intertidal Scrub/Shrub Wetland (Broad-leaved evergreen)	E2SS3

U.S. Fish and Wildlife Service National Wetlands Inventory (NWI) digital data were used as collateral information and to provide a more complete spatial view of wetland distribution and the possible extent of wetland impact should the shoreline be subjected to an oil spill. The NWI data that was most useful included those polygons classified on NWI maps as emergent, scrub/shrub, and mangrove wetlands (Table 4).

Field Verification and Modifications

The ESI rankings and boundaries of selected shoreline units mapped by the BEG were checked on the ground at selected sites to verify anomalous shoreline conditions or to observe the arrangement of multiple shoreline types in densely developed areas. Examples of ground checks and verification involved examining armored shorelines such as along the landward margin of Laguna Madre near Pita Island, at Port Mansfield, Port Isabel, Brownsville Ship Channel, and the lagoonward side of South Padre Island.

Quality Control

Researchers at the BEG were responsible primarily for mapping shorelines using procedures detailed in the methods section of this report. Research staff from BEG were responsible for field checking and completing original work maps during postmapping surveys. Maps were field checked to ensure completeness and accuracy of shoreline designations. Completed and field-checked maps were digitized and entered into a geographic information system (GIS). The BEG staff was responsible for converting digital or hard copy data or information into a GIS product and for maintaining and filing GIS records.

Digitized shorelines were superimposed on digital orthophoto quadrangles to spot check for accuracy and completeness. BEG reviewers were responsible for determining if the GIS map adequately portrayed the original base maps provided by GLO and if the GIS presentation had introduced any inaccuracies not present on the original maps. Orthophoto quadrangles were useful in making this determination. Areas needing correction were marked on the GIS map.

SHORELINE TYPES OF THE SOUTH TEXAS COAST

ESI rankings and classification of shoreline types represent an integration of several physical and biological attributes. These attributes refer to the materials that make up the shore, the dynamic processes acting on the shore, the locations along the shore where water is exchanged, susceptibility of biological community to oil-spill impacts, and water depths (bathymetry) near the shore, among others. From these attributes and additional information, other qualitative shoreline characteristics can be derived such as oil retention and trafficability.

Eighteen shoreline types ranked on a scale of 1 to 10 were identified for the South Texas coast from field surveys, aerial videotape surveys, and coastal change analyses. The shoreline classification for Texas (Table 2) is similar to those used for the other coastal states, which have been standardized by NOAA/RPI (Michel and Hayes, 1992). The current ESI classification is modified from the classifications proposed for Texas by Gundlach et al. (1981) and Michel and Dahlin (1993). The physical and biological characteristics of each shoreline type as well as the general sensitivity, oil behavior, and cleanup concerns for the shoreline types are presented in the following sections. More detailed explanations of the environmental conditions and sensitivity rankings are presented by Gundlach and Hayes (1978), Hayes et al. (1980), and Michel and Hayes (1992).

The environmental parameters and physical settings characteristic of the South Texas coast were used to classify the shoreline types. Exposure to or protection from wave energy was a major criterion used to determine the ESI ranking because wave energy also influences the natural ability of the environment to remove and disperse oil. Wind direction and fetch and shore morphology were guides to the energy exposure of a particular shoreline segment, but those parameters were not always indicative of the local conditions. For example, where it is landlocked, the Gulf Intracoastal Waterway has essentially no fetch. Nevertheless, frequent barge traffic generates waves that erode banks and construct sand beaches. Additional examples of sheltered and exposed shorelines are given in Table 3. Note that the wetland classifications do not contain specific taxonomic connotations.

All of the shoreline types are subject to modification by human activities, which is the primary reason why ESI maps need to be updated periodically. Most of the natural shoreline types are unaffected by temporal variability in nearshore processes, but a few can change rapidly, especially after high-energy events that produce strong waves and currents. For example, shell concentrations on Gulf beaches depend on short-term beach cycles that can either concentrate or dilute the amount of shell present on the beach surface. These general conditions apply to the erosional beaches of the Gulf shoreline, and they should be recognized and incorporated into the oil-spill contingency planning process.

Coastal Structures

The coastal structures category (Figure 4) includes ESI Rankings 1 (exposed seawalls), 6B (exposed riprap), 8A (sheltered seawalls), and 8B (sheltered riprap). Coastal structures are the various man-made hard structures that typically are used to protect the shore from waves and currents such as seawalls, jetties, breakwaters, groins, revetments, piers, and port facilities; they also include

(a)

(b)

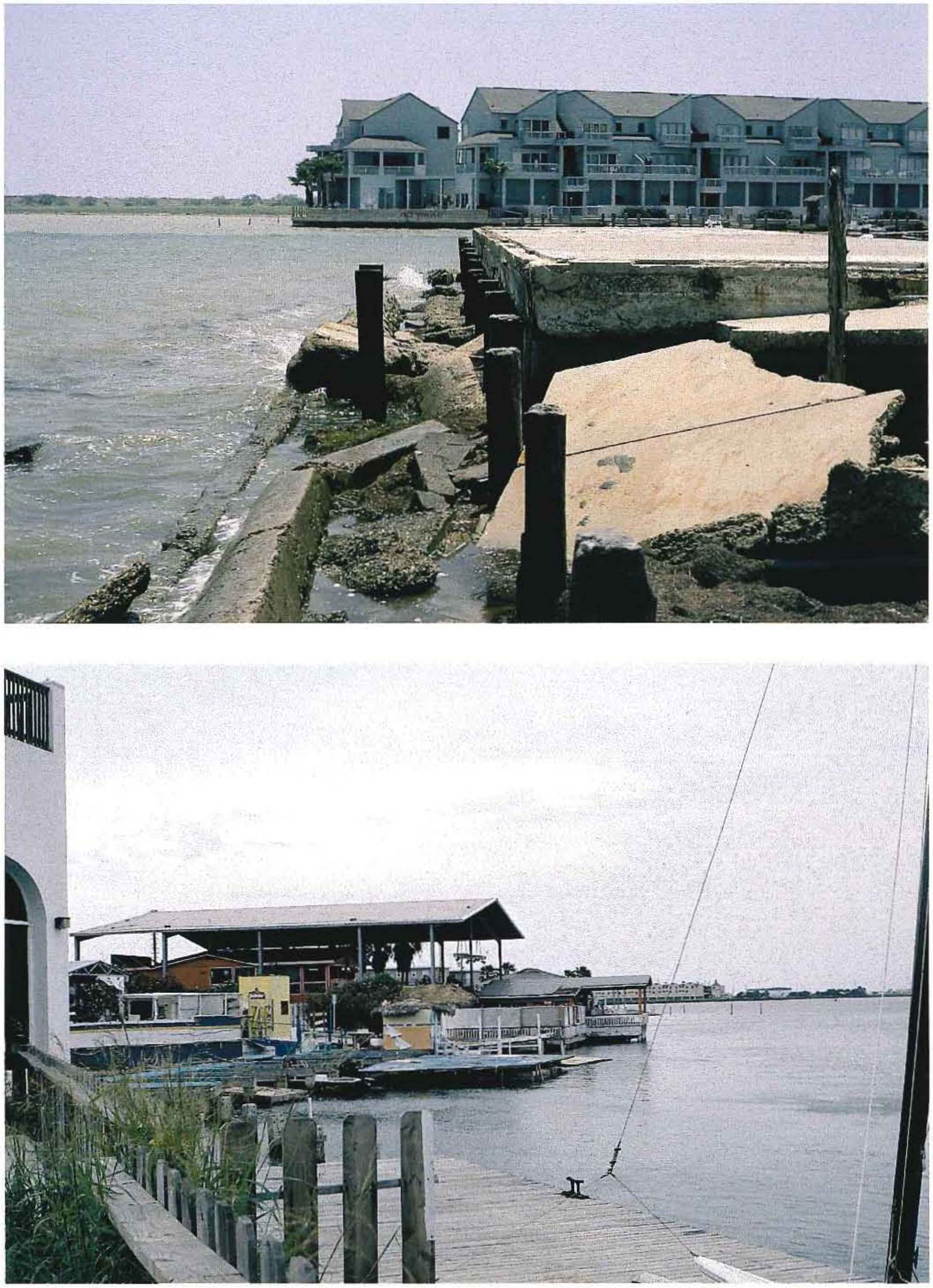


Figure 4. Examples of coastal structures (a) exposed riprap and seawall at the mouth of Port Mansfield and (b) typical structures along the lagoon shore of South Padre Island.

miscellaneous structures such as roads and bridges that cross open water. Jetties are constructed perpendicular to the shore and are used to protect navigation channels. In Texas, they are constructed mostly of blocks of granite or limestone. Seawalls and revetments are coastal protection structures built parallel to shore (Figure 4) and constructed of rock, concrete, riprap, or junk such as old appliances and broken concrete. Breakwaters are built parallel to the shore but are detached from the shore so they block waves from reaching the coast. They are usually built of concrete, riprap, or wood. Groins are short, shore-normal structures that are designed to trap sediment and slow erosion. They also are constructed of granite, riprap, or wood. Piers are shore-normal structures on pilings built of concrete or wood. They are typically used for recreation such as fishing. Port facilities describe the major developed waterfronts that include wharves, piers, seawalls, and other structures made of steel, rock, wood, and concrete (Figure 4b). Most of the miscellaneous other structures found in Texas, such as bridges, are constructed of concrete.

Coastal structures along the Gulf shoreline of the South Texas coast include two sets of paired jetties. Long jetties constructed of large granite blocks are located at each of the major ship channels: Brownsville Ship Channel, which crosses between South Padre Island and Brazos Island and coincides with Brazos-Santiago Pass, and Port Mansfield channel, which crosses Padre Island east of Port Mansfield. Most of the coastal structures within north Laguna Madre are along Encinal Peninsula on the western shore of Laguna Madre, and across the lagoon in a housing and channel development on North Padre Island. Major coastal structures in southern Laguna Madre are along the lagoonward shore of South Padre Island and on the mainland shore in the communities of Port Isabel, Laguna Vista, and Laguna Heights. Structures include seawalls, riprap, groins, piers, and other features that would be impacted by an oil spill. Port Mansfield is lined with various types of structures, including riprap and concrete bulkheads. In the Baffin Bay system, coastal structures are principally along shores at the communities of Riviera Beach and Loyola Beach. Other examples where coastal structures are common are along the Arroyo Colorado at Arroyo City, at Port of Harlingen, and at the Brownsville Ship Harbor. The cumulative length of shorelines with structures, excluding piers, is more than 145 km (Table 5).

Oil typically coats the coastal structures and the sparse plant and animal life associated with them. Vertical wall structures (seawalls, bulkheads) exposed to open ocean waves have the lowest ESI ranking because they are either self-cleaning or they typically can handle the use of intrusive

Table 5. Cumulative length of various shorelines in the study area. Lengths based on totals of each type where it is in the seawardmost position.

ESI no.	Shoreline type	Length (km)
1	Exposed walls and other structures made of concrete, wood, or metal	36
2A	Scarps and steep slopes in clay	68
2B	Wave-cut clay platform	1
3A	Fine-grained sand beaches	343
3B	Scarps and steep slopes in sand	120
4	Coarse-grained sand beaches	0
5	Mixed sand and gravel (shell) beaches	97
6A	Gravel (shell) beaches	8
6B	Exposed riprap structures	15
7	Exposed tidal flats	328
8A	Sheltered solid man-made structures, such as bulkheads and docks	86
8B	Sheltered riprap structures	9
8C	Sheltered scarps	259
8D	Sheltered rocky/karst shores	8
9	Sheltered tidal flats	233
10A	Salt- and brackish-water marshes	218
10B	Fresh-water marshes (herbaceous vegetation)	1
10C	Fresh-water swamps (woody vegetation)	0
10D	Mangroves	71
	Total	1,901

cleanup techniques such as low- and high-pressure washing and sandblasting. Oil penetration on vertical walls is limited to surface roughness features and cracks. The reason riprap revetments have a moderately high ESI ranking is the increased surface area and large voids that trap oil between the blocks. Some of the major cleanup concerns regarding coastal structures are logistics and the recovery of treated oil.

Clay and Sand Scarps and Steep Slopes

The scarp classification (Figure 5) includes ESI rankings 2A (clay scarps), 3B (sand scarps), and 8C (sheltered scarps). Scarps and steep slopes commonly are created by eroding bluffs that slump and are undercut by waves. They may represent natural shoreline features, or they may form along mounds and embankments of dredged material. Scarps and steep slopes normally occur downwind of the prevailing winds where fetch across the bay and wave energy are greatest. Scarps

(a)

(b)

Figure 5. Examples of scarps composed of (a) clay near Riviera Beach in Laguna Salada and (b) clay along the Brownsville Ship Channel.

and steep slopes may be a couple of meters or more high in some areas. In other areas they are relatively low features but offer some protection to landward environments from oil spills. Some scarps are fronted by narrow beaches, and others are not. Whether a narrow beach forms depends

Figure 6. Example of scarp sheltered by vegetation along the Arroyo Colorado.

on the activity of the bluff. Rapidly eroding bluffs have no beach, whereas those where a major slump occurs may temporarily form a beach reworked from the slump material.

High to moderately high clay bluffs in the South Texas bay and lagoon system are found along the shores of Laguna Salada, Cayo del Grullo, and Alazan Bay, and along the Arroyo Colorado and Brownsville Ship Channel (Figure 5b). Low scarps are found along much of the mainland shores of Laguna Madre except in areas where an erosional shoreline intersects a clay dune. In these areas high scarps are present.

Some shorelines, such as along the Arroyo Colorado, are characterized by relatively steep slopes composed of either clay or sand that are covered with vegetation (Figure 6). The steep topographic gradient in such areas is manifested by relatively high nearshore elevations, which support upland to transitional vegetation rather than emergent marsh vegetation. Although there may be some fringing marsh along the water's edge, it is considered too narrow and not important enough to delineate on the maps. These shorelines were classified as either sheltered scarps (8C), clay scarps and steep slopes (2A), or sand scarps and steep slopes (3B). Along many shores there is a mixture of sand, silt, and clay. The most abundant textural component was difficult to determine without site-specific field examination. These scarps and steep slopes were typically coded 3B.

Sheltered scarps are a major shoreline type in the South Texas area. Much of the eastern shoreline of Laguna Madre along north Padre Island was mapped as a sheltered low scarp (8C) because the prevailing winds are southeasterly and these westerly facing shores are protected by Padre Island (Figure 7). This shoreline, however, is not sheltered during northers, and offshore sand bars are evidence of wave action during those events. The western shoreline of northern Laguna Madre is characterized in many areas by sand and clay scarps fronted by a narrow intertidal clay flat that shelters the landward low scarps and steep slopes.

The shores along small embayments between Alazan Bay and Baffin Bay were coded as sheltered because of adjacent seaward-exposed tidal flats, resulting in a combination code of 8C/7. Some shores along northern Baffin Bay were classified as sheltered because of offshore serpulid worm reefs that offer protection from waves.

The environmental sensitivity of exposed bluffs and steep slopes is low because of limited plant and animal colonization, and exposure to waves that provide some measure of natural cleanup. Oiling is limited to the lowest elevations because of the steep slopes. Oil typically stains the sediments and the nearshore debris that accumulates at the toe of the slope. The sediment penetration potential is low because of the steep slopes and clay substrates, but penetration potential increases slightly where substrates are composed of sand. Bluffs and steep slopes may be difficult to clean because of poor access and poor trafficability. Sheltered scarps and slopes have a higher environmental sensitivity because they are less often exposed to waves and currents and thus retain oil for a longer period.

Wave-Cut Clay Platforms

The wave-cut clay platform classification (ESI Ranking 2B) describes a shoreline type that forms as a result of exposure to erosive waves generated naturally by wind or artificially by boats. Erosion of muddy substrates along navigation channels, the Gulf shoreline, or bay shores may produce a narrow shelf or platform bordering the water that is sometimes flooded and sometimes exposed, depending on water level. There are no wave-cut platforms on the Gulf shore in the South Texas coastal map area; however, a clay platform is located on the mainland shore of north Laguna Madre just north of Baffin Bay. In some areas along the mainland shore of Laguna Madre north of Baffin Bay, narrow clay substrates along erosional shores were mapped as tidal flats because of their intertidal nature, but these areas possibly could be interpreted as wave-cut clay platforms. These shores are protected from large erosional waves, however, by shallow nearshore seagrass beds. Wave-cut clay platforms generally have a low sensitivity to oil-spill impacts and cleanup methods. Oil typically covers the platform near the high-water line, but penetration is low because muds have low permeability. However, burrows formed by fiddler crabs in the muddy sediments allow deep oil penetration that is difficult to remove.

Fine-Grained Sand Beaches

The fine-grained sand beaches classification (ESI Ranking 3A) describes beaches that have low slopes and an average grain size of 0.0625 to 0.25 mm (Figure 8). Generally these beaches also contain a small percentage of shell or shell hash. In Texas, the fine-grained sand beaches of the Gulf shore are 50 to 100 m wide, whereas in the bays, fine sand beaches are about 15 m wide.

Examples of fine-grained sand beaches occur along most of the Gulf shoreline of the South Texas coast. This shoreline type makes up most of the Gulf beaches on north and south Padre Island and Brazos Island.

Fine-grained sand beaches within the Laguna Madre and Baffin Bay system are located along the southern shore of Baffin Bay and locally in Alazan Bay and Cayo del Grullo. They occur along the Land-Cut Area, on the mainland shore of Laguna Madre south of the Land-Cut Area, and on the shores of spoil islands. In the Baffin Bay system, sandy beaches in many areas include oolitic sand. These sand-sized carbonate grains are precipitated and deposited in high-energy intertidal zones (Alaniz and Goodwin, 1974).

Fine-grained sand beaches generally have a low sensitivity to oil-spill impacts and cleanup methods. Oil typically stains and covers the beach near the high-water line, but penetration is low

Figure 7. Example of low sand scarp on the lagoonward shore of North Padre Island.

Figure 8. Example of a fine-grained sand beach, South Padre Island.

to moderate, depending on the water table and the position of oil on the shoreline. A major environmental concern during beach cleanup is the protection of the dune habitat from the cleanup operations and the removal of sand from eroding beaches. Large volumes of stained sand and debris can be generated by cleanup of fine sand beaches. Most of the fine-grained sand beaches of the Gulf shore are accessible and can support heavy equipment. In the bays they are generally inaccessible, and trafficability is limited.

Coarse-Grained Sand Beaches

The coarse-grained sand beaches classification (ESI Ranking 4) describes beaches that have moderate to steep slopes and an average grain size of 0.5 to 2.00 mm. Generally coarse-grained beaches are composed mostly of small shells or broken shells that form a shell hash. In Texas, coarse-grained sand beaches are located mostly in the bays, and their distribution is limited. They commonly occur around mounds of dredged material that are reworked by waves. Coarse-grained sand beaches were not identified separately on the shoreline type maps because they almost always occur in conjunction with mixed sand and gravel (shell) beaches, and all of the shell-rich beaches were mapped as either ESI 5 or 6A.

Coarse-grained sand beaches generally have a moderate sensitivity to oil-spill impacts and cleanup methods. Oil typically stains and covers the beach near the high-water line, and penetration is moderate, depending on the water table and the position of oil on the shoreline. A major environmental concern during beach cleanup is the potential for deep penetration and possible burial of oil, making cleanup difficult. Large volumes of stained sand and debris can be generated by cleanup of coarse-grained sand beaches. Most of the coarse-grained sand beaches of the Gulf shore are accessible, but they are soft and cannot support heavy equipment. In the bays they are generally inaccessible, and trafficability is limited.

Mixed Sand and Gravel (Shell) Beaches

The mixed sand and gravel (shell) beach classification (ESI Ranking 5) includes those beaches composed mostly of fine-grained sand that also contain a moderately high percentage of shell (Figure 9). These beaches occur along a stretch of central Padre Island where shells have been concentrated along the Gulf shoreline. In the Laguna Madre and Baffin Bay system, this shoreline type occurs locally in Cayo del Grullo and on beaches on the margin of spoil islands in Laguna Madre.

In Texas, the environmental sensitivity of mixed sand and shell beaches is moderate because of the presence of relatively coarse material. Oil typically coats and covers the sediment, and penetration potential is moderate because of the abundant shell. This shoreline type is characterized by poor trafficability. Mixed sand and gravel (shell) beaches are accessible where they occur along the Gulf shore, but they generally are only accessible by boat in the bays.

Gravel (Shell) Beaches

The gravel (shell) beach classification (ESI Ranking 6A) is used to describe shores that are composed almost entirely of shell (Figure 10). The shell material may be in the form of shell hash or whole shells. The sources for the shells include the nearshore zone or the bays. Shell beaches form steep beach faces because of the coarse shell fragments and whole shells making up the shore.

Beaches of the Gulf shore containing high concentrations of gravel (shell) are located along Central Padre Island (Figure 9) and are mapped as ESI Ranking 5 because they are composed of mixed sand and gravel (shell). In the bays, gravel (shell) beaches are common along spoil islands where waves and currents rework spoil material and concentrate shells in steep berms and beaches.

The environmental sensitivity of gravel (shell) beaches is moderate because of the use of this shore type by estuarine organisms and extensive washover terrace development. Oil typically stains and coats the shell hash and whole shells composing the beach. Oil penetration is high because of the porous beach character created by the shell material. This beach type quickly turns into an asphalt pavement under heavy oiling conditions. Shell beaches have poor trafficability owing to the low bearing strength and steep beach face. Accessibility to shell beaches in Texas is variable, depending on location. On the Gulf shore they are easily accessible, but shell beaches in the bays are generally inaccessible except by boat.

Figure 9. Example of a mixed sand and gravel (shell) beach, central Padre Island.

Figure 10. Example of gravel (shell) beach on a spoil island along the Intracoastal Waterway south of Baffin Bay.

Exposed Tidal Flats

The exposed tidal-flat classification (ESI Ranking 7) is used to describe broad intertidal areas normally consisting of fine sand and minor amounts of shell but also, locally, composed of mud, particularly along the mainland shore. Exposed tidal flats are typically found in association with barrier islands (Figure 11) and tidal-inlet systems. In Texas, tidal flats can be either submerged or exposed, depending on water level, wind strength, and wind direction. Because of the low flat gradient, slight changes in water levels can produce significant changes in position where the water meets the shore. Salt marsh vegetation often develops along the upper intertidal areas of the exposed flats.

Tidal flats within the Laguna Madre system are located along Padre Island and the Land-Cut Area. In some areas, such as near the mouth of the Arroyo Colorado and on the margins of South Bay at the southern tip of Laguna Madre, the flats are also intermixed with salt marshes, and the unit was locally included with marshes because of the higher environmental sensitivity of marshes relative to flats. On the lagoonward side of Padre Island, frequently flooded (exposed) flats intergrade with higher, less frequently flooded sheltered tidal flats. Along the mainland shore of Laguna Madre north of Baffin Bay, narrow exposed intertidal flats border the shoreline. Other examples of exposed tidal flats are at the heads of Alazan Bay, Cayo del Grullo, and Laguna Salada. The environmental sensitivity of sandy tidal flats is moderate because of the presence of abundant infauna. Oil tends to be transported across the flat and accumulate at the high-tide line. The oil penetration potential is low to moderate, depending on the water level and location of the oil deposits. The trafficability is highly variable, depending on substrate character. In Texas, many of the sandy tidal flats associated with backbarrier environments have poor trafficability and will not support heavy equipment. Access to exposed tidal flats in Texas is generally poor except by boat.

Sheltered Tidal Flats

The sheltered tidal-flat classification (ESI Ranking 9) is used to describe broad intertidal areas (Figure 12) normally consisting of mud, sandy mud, muddy sand, and minor amounts of shell hash. The flats are sandier on the bayward side of Padre Island compared with those on the mainland, where abundant mud produces mud flats (Fisk, 1959). The grain size of theses shores typically is less than 0.0625 mm. Sheltered tidal flats are broadly distributed in the study area. Recently deposited muddy tidal flats are soft and dynamic shores rich in newly developed habitat. Older muddy flats

Figure 11. Example of an exposed tidal flat. The exposed flat intergrades with a sheltered wind tidal flat.

Figure 12. Example of a sheltered tidal flat.

are firm and exhibit a stable marsh vegetation. The amount of exposed mud flat may decrease as the density of marsh vegetation increases until eventually little exposed mud flat remains. In some areas, ESI 9 was used to denote sand flats (common on barrier islands) that are sheltered from wave energy by their slightly higher elevations. These flats are not affected by the daily tidal cycle but are subject to inundation by wind-generated tides. Along the barrier island lagoonward shore, sheltered flats are typically bordered by a narrow belt of more frequently flooded exposed tidal flats. Because of the infrequent inundation of the sheltered flats, oil that covers sediment and vegetation remains on the surface and is not removed by tidal action.

Sheltered tidal flats are common along the bay shore of Padre and Brazos Islands and along the Intracoastal Waterway in the Land-Cut Area. They are also extensive to the south along the mainland shore of Laguna Madre near the mouth of the Arroyo Colorado and southward to the Laguna Atascosa National Wildlife Refuge. At the south end of Laguna Madre they border South Bay. Locally, sheltered flats have developed on the margins of spoil islands.

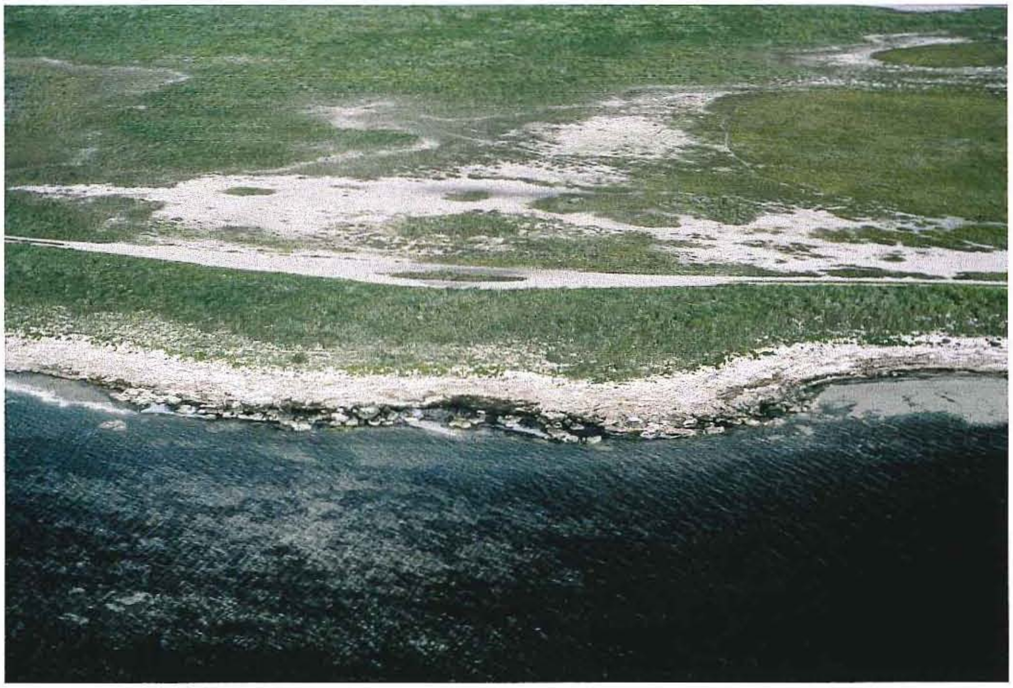
The environmental sensitivity of muddy tidal flats is high owing to their high utilization by infauna and difficulty of cleanup. Oil does not adhere to the wet muddy substrates but can penetrate into burrows. A major environmental concern associated with muddy tidal flats is the damage done by cleanup operations. Both access and trafficability of muddy tidal flats are poor.

Sheltered Rocky/Karst Shores

The sheltered rocky/karst shores classification (ESI Ranking 8D) has not been used elsewhere along the Texas coast. Its use in the South Texas area is to describe a unique rocky shore consisting of a Pleistocene coquina that is riddled with karst features characterized by solution pipes and caliche crusts (Prouty, 1996) (Figure 13). This shoreline type extends southward from the mouth of Baffin Bay along the mainland shore of Laguna Madre for a distance of almost 8 km.

According to Jennifer Prouty (personal communication, 2000) outcrops of coquina are as much as 1 to 1.5 m above mean high tide but extend into subtidal waters where karst features are visible. Outcrop permeability is variable, ranging from low to high. Local areas of caliche crust on the outcrop surfaces are essentially impermeable to fluids, whereas the underlying coquina itself appears moderately permeable. The solution pipes are local conduits for rapid downward fluid flow, and water drains quickly through them.

(a)



(b)

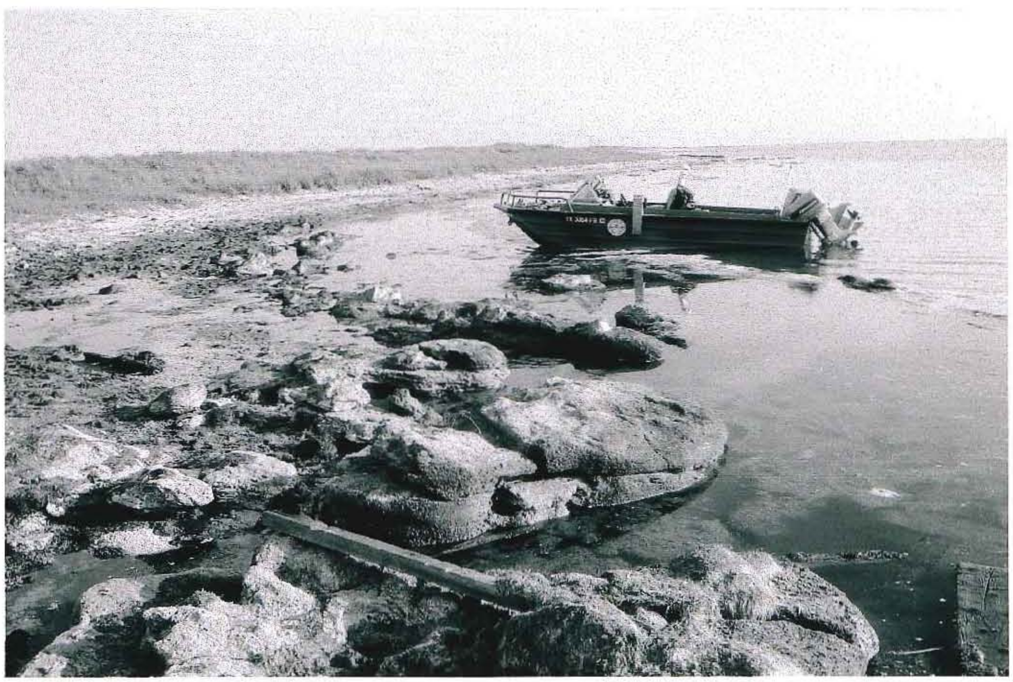


Figure 13. Examples of sheltered rocky/karst shores along the mainland shore of Laguna Madre south of the mouth of Baffin Bay as seen from (a) aerial view and (b) ground shot.

Nearshore areas along this shore are characterized by shallow seagrass beds, which diminish the effect of waves. Still it is a windward shore facing prevailing southeasterlies and is constantly impacted by small onshore waves. Characterizing this shoreline as sheltered is based more on the occurrence of large rocks in shallow waters that partially shelter the shore (Figure 13). The rocky nature of the shore is similar to riprap in that it has an increased surface area and large voids that could trap oil. Oil washed into solution pipes would be difficult to remove and might saturate considerable volumes of underlying coquina.

Salt- and Brackish-Water Marsh

The salt- and brackish-water marsh classification (ESI Ranking 10A) describes wetlands vegetated by plant species that tolerate salt and brackish water (Figure 14). The sediments of salt- and brackish-water marshes commonly are highly organic and muddy except on the margins of barrier islands where sand is abundant. Salt- and brackish-water marshes are most extensive along the mainland margins of Laguna Madre near the mouth of the Arroyo Colorado and southward along Laguna Atascosa National Wildlife Refuge. Other notable occurrences are along the mainland shore of northern Laguna Madre west of Pita Island, near the southern end of Laguna Madre on the margins of South Bay and fringing San Martin Lake, and at the heads of Alazan Bay and Cayo del Grullo. Fringing marshes characterize mainland and small island shorelines in central Laguna Madre near the south end of the Land-Cut Area. Salt marshes are intermixed locally with tidal flats and black mangroves. The total length of salt- and brackish-water marsh shorelines mapped alone and in combination with other shoreline types is approximately 340 km.

The environmental sensitivity of salt- and brackish-water marshes is high because of the presence of wetland habitat. Oil typically stains and covers both sediment and vegetation. The oil penetration is low because of the high water table and the muddy composition of the sediments. A major environmental concern about salt- and brackish-water marsh is that the cleanup may be more damaging than the oil itself. In Texas, the access and trafficability of salt- and brackish-water marshes are generally poor owing to the muddy sediment.

(a)

(b)

Figure 14. Example of a salt- and brackish-water marsh (a) on the bayward side of South Padre Island and (b) along the mainland shore of Laguna Madre north of the mouth of the Arroyo Colorado.

Fresh-Water Marsh

The fresh-water marsh classification (ESI Ranking 10B) is used to describe emergent wetlands that are not inundated by salt water. The sediments typically are highly organic and muddy. Fresh-water marshes are characterized by high biodiversity and rich wetland habitat. This shoreline type is rare in this area of low rainfall and was mapped only inland along the Arroyo Colorado (Figure 15). Fresh-water marshes occur predominantly upstream of the brackish-water marshes along inland stretches of streams receiving fresh-water inflows. Except in one abandoned channel along the Arroyo Colorado, the mapped fresh-water marshes could probably have been mapped as brackish because of tidal influence along much of the Arroyo. The environmental sensitivity of fresh-water marsh is also high for the same basic reasons as those given for salt- and brackish-water marshes. Oil tends to coat the above-ground vegetation. The oil penetration is low because of the high water table and the muddy composition of the sediments, except in burrows. A major environmental concern about fresh-water marsh is that the cleanup may be more damaging than the oil itself. In Texas, the access and trafficability of fresh-water marshes are generally poor owing to the muddy sediment.

Fresh-Water Swamps

The fresh-water swamp classification (ESI Ranking 10C) describes shores that consist of shrubs and hardwood forested wetlands (Figure 16). This shoreline type, which is essentially a flooded forest, is not common but does occur locally in abandoned channels on the south Texas coast. The sediments within the interior swamps tend to be silty clay and contain a large amount of organic debris. Mapped forested swamps within the study area are very restricted and located upstream along the Arroyo Colorado valley, typically at the mouths of small tributary drainages. In some areas on the Arroyo Colorado, trees and shrubs that occur along the scarps of the entrenched channel down to the water's edge were not classified as swamps, but because the trees shelter the shoreline these areas were mapped as sheltered scarps.

Figure 15. Example of a fresh-water marsh inland along the Arroyo Colorado.

Figure 16. Example of a fresh-water swamp inland along the Arroyo Colorado.

The environmental sensitivity is high for swamps because of the ecological value of the swamps, presence of oil-sensitive organisms, and difficulty of cleanup. Oil usually coats vegetation and can heavily contaminate accumulated debris. The sediment penetration is low because of the high water

Figure 17. Example of black mangroves on the margin of San Martin Lake.

table and the muddy composition of the sediments. A major environmental concern is that the cleanup may be more damaging than the oil itself. The access and trafficability of swamps are poor because of the soft sediment and the dense tree growth.

Mangroves

The mangrove classification (ESI ranking 10D) primarily describes the presence of black mangroves (*Avicennia germinans*), which are locally abundant as shrubs along the south Texas coast (Figure 17). Because they are commonly shrubs, they are often considered as part of the marsh system. Among the tallest mangroves on the Texas coast are those in a small stand along a canal that connects to the Rio Grande near its mouth. Mangroves in this area are as tall as 3.5 m (Robert Lonard and Frank Judd, personal communication, 2000).

In the study area, mangroves are most abundant south of the Arroyo Colorado, where they occur along the mainland shore, on the margins of spoil islands, on the bay shore of south Padre

Island, and on the margins of South Bay and San Martin Lake (Figure 17). More than 77 linear kilometers of this type shoreline (Table 5) was mapped either as a single shoreline type or in combination with other shorelines. The most extensive shoreline type that includes mangroves is 9/10D (sheltered tidal flat fringed by mangrove), which accounted for a total length of about 25 km.

The environmental sensitivity of mangroves is high because of the ecological value of mangroves, associated flora and fauna, and the difficulty of cleanup. Oil typically coats both sediment and vegetation. The oil penetration is low because of the high water table and muddy composition of the sediments, although more permeable sandy substrates characterize some mangrove areas. Mangroves typically occur in association with salt-water marshes. As in the salt and brackish marshes and swamps, a major environmental concern is that the cleanup may be more damaging than the oil itself. Accessibility is poor because of soft, saturated sediments and the presence of dense mangrove shrubs.

EXAMPLES OF MULTIPLE SHORELINE TYPES AND THEIR ESI RANKINGS

Many of the bay-lagoon shore segments exhibit several different types of shorelines that are juxtaposed. Because the adjacent shoreline types are vulnerable to spilled oil, they are mapped as combined shoreline types with an emphasis on the shoreline type closest to the water. The following sections briefly describe some of the most common multiple shoreline types found in the South Texas region.

Mangrove- and Marsh-Lined Tidal Flats (9/10A/10D)

On some estuarine islands mixtures of salt marshes and black mangrove shrubs are common. Where salt marsh vegetation is lined with mangroves, the classification is 10A/10D, and where marshes are seaward of the mangroves, this order is reversed. These classifications are common along spoil islands south of the Arroyo Colorado, and on the margins of South Bay and San Martin Lake.

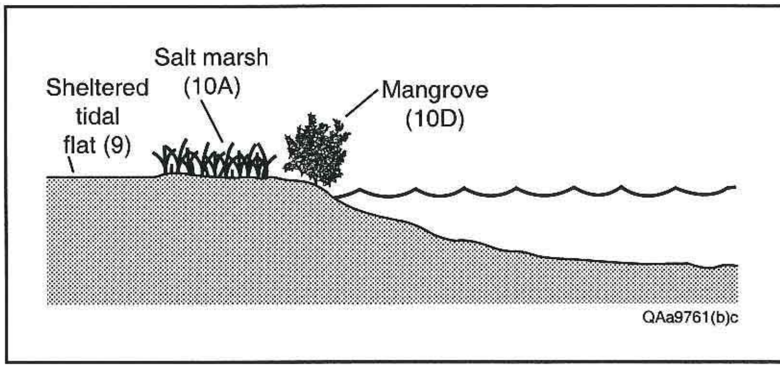


Figure 18. Multiple shoreline types consisting of fresh-water marsh and mangroves lining a sheltered tidal flat. These shorelines are classified as 9/10A/10D.

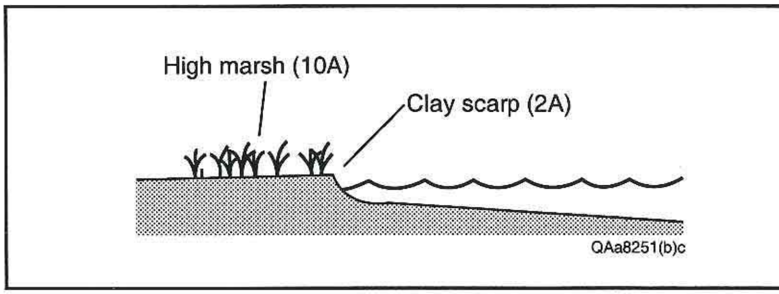


Figure 19. Multiple shoreline types consisting of marshes and a clay scarp. These shorelines are classified as 10A/2A.

Along some stretches of the mainland shore of Laguna Madre and along spoil islands near the Arroyo Colorado and southward, wind-tidal flats are bordered by marshes and mangroves. Because the tidal flats are protected or sheltered by this emergent vegetation, they are classified as sheltered. This type of shoreline is designated as 9/10A/10D, indicating a sequence progressing in a seaward direction from sheltered tidal flat, to salt marsh, to mangrove (Figure 18).

Marshes Bordered by Low Wave-Cut Clay Scarps (10A/2A)

In some areas, shorelines are undergoing erosion and are characterized by a high marsh, along the seaward margin of which is a low clay scarp. If the clay scarp is considered significant and could provide the marsh some protection, both the scarp and the marsh are mapped. A classification of 10A/2A in such cases indicates that the clay scarp is seaward of the marsh (Figure 19). In some sheltered areas, shorelines are locally characterized by marshes fringing sheltered scarps and are designated as 8C/10A.

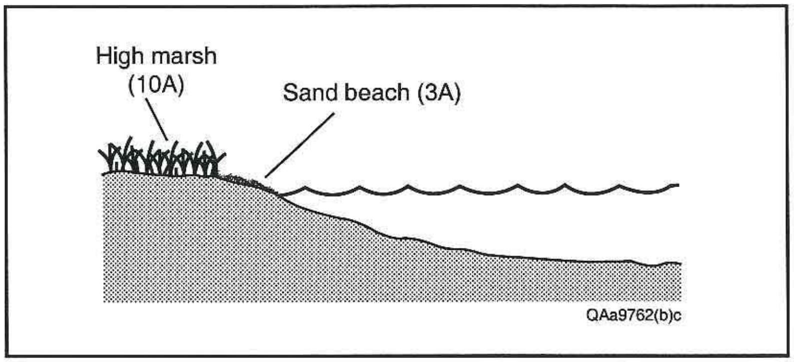


Figure 20. Multiple shoreline types consisting of a marsh and sand beach. These shorelines are classified as 10A/3A.

Sheltered/Exposed Tidal Flats (9/7)

One of the most common shoreline designations occurs along the lagoonward shore of Padre Island south of Baffin Bay. This area is characterized by broad, sandy wind-tidal flats that are fringed by a narrow, more frequently flooded exposed tidal flat. These areas are designated as 9/7, indicating a bayward progression of tidal flat from sheltered to exposed (Figure 11). In a few places the sequence is reversed (7/9) with a narrow topographically higher flat positioned bayward of a topographically lower, frequently flooded flat. Typically, the exposed tidal flat intergrades landward with another higher sheltered flat.

Salt-Water Marshes Lined by Sand Beaches (10A/3A)

Along some shores, salt-water marsh habitat is bordered on the seaward side by narrow sand beaches. These areas are mapped as 10A/3A (Figure 20) to reflect both the marsh and the sandy beach.

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REFERENCES

Alaniz, R. T., and Goodwin, R. H., 1974, Recent sediments of a hypersaline estuarine bay: Gulf Coast Association of Geological Societies Transactions, v. 24, p. 308–313.

Fisher, W. L., Brown, L. F., Jr., McGowen, J. H., and Groat, C. G. 1973, Environmental geologic atlas of the Texas coastal zone, Beaumont–Port Arthur area: The University of Texas at Austin, Bureau of Economic Geology, 93 p.

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, 91 p.

Fisk, H. N., 1959, Padre Island and the Laguna Madre flats, coastal south Texas: Louisiana State University, Proceedings of the Second Coastal Geography Conference, p. 103–151.

Gundlach, E. R., Finklestein , K. J., and Sadd, J. L., 1981, Impact and persistence of *Ixtoc I* oil on the south Texas coast: Proceedings of the 1981 Oil Spill Conference, American Petroleum Institute, Washington, D.C., p. 477–485.

Gundlach, E. R., and Hayes, M. O., 1978, Vulnerability of coastal environments to oil spill impacts: Marine Technology Society Journal, v. 12, p. 18–27.

Hayes, M. O., Gundlach, E. R., and Getter, C. D., 1980, Sensitivity ranking of energy port shorelines, *in* Proceedings, Specialty Conference: American Society of Civil Engineers, New York, N.Y., p. 697–709.

Hayes, M. O., Michel, J., and Brown, P. J., 1976, Coastal geomorphology and sedimentation, Lower Cook Inlet, Alaska: University of South Carolina, Columbia, Department of Geology, Technical Report No. 12-CRD, 107 p.

Michel, J., and Dahlin, D., 1993, Guidelines for developing digital environmental sensitivity index atlases and databases: Research Planning, Inc., report prepared for the National Oceanic and Atmospheric Administration, Hazardous Materials Response and Assessment Division, 43 p.

Michel, J., and Hayes, M. O., 1992, An introduction to coastal habitats and biological resources for oil spill response: National Oceanic and Atmospheric Administration, Hazardous Materials Response and Assessment Division, Report No. HMRAD 92-4, 83 p.

Michel, J., Hayes, M. O., and Brown, P. J., 1978, Application of an oil spill sensitivity index to the shoreline of lower Cook Inlet Alaska: Environmental Geology, v. 2, p. 107–117.

Morton, R. A., and Paine, J. G., 1984, Historical shoreline changes in Corpus Christi, Oso, and Nueces Bays, Texas Gulf coast: The University of Texas at Austin, Bureau of Economic Geology Geological Circular 84-6, 66 p.

Morton, R. A., and Pieper, M. J., 1975, Shoreline changes on Brazos Island and South Padre Island (Mansfield Channel to Mouth of Rio Grande), an analysis of historical changes of the Texas Gulf shoreline: The University of Texas at Austin, Bureau of Economic Geology Geological Circular 75-2, 39 p.

Morton, R. A., and Pieper, M. J., 1977a, Shoreline changes on Mustang Island and North Padre Island (Aransas Pass to Yarborough Pass), an analysis of historical changes of the Texas

Gulf shoreline: The University of Texas at Austin, Bureau of Economic Geology Geological Circular 77-1, 45 p.

Morton, R. A., and Pieper, M. J., 1977b, Shoreline changes on central Padre Island (Yarborough Pass to Mansfield Channel), an analysis of historical changes of the Texas Gulf shoreline: The University of Texas at Austin, Bureau of Economic Geology, Geologic Circular 77-2, 35 p.

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, contract report prepared for the Texas Natural Resources Inventory Program, Interagency Contract IAC 94-0198, 40 p.

Morton, R. A., and White, W. A., 1998, Shoreline types of the central Texas coast: Matagorda to Corpus Christi areas: The University of Texas at Austin, Bureau of Economic Geology, contract report prepared for the Texas General Land Office and Minerals Management Service under contracts IAC 97-081R and CMI-30660-19901, 36 p.

Paine, J. G., and Morton, R. A., 1989, Shoreline and vegetation-line movement, Texas Gulf Coast, 1974 to 1982: The University of Texas at Austin, Bureau of Economic Geology, Geological Circular 89-1, 50 p.

Prouty, J. S., 1996, Late Pleistocene–early Holocene karst features, Laguna Madre, South Texas: a record of climate change: Gulf Coast Association of Geological Societies Transactions, v. 46, p. 345–351.

Texas Water Commission, 1989, Spill Response Map Series Coastal Region: Austin, Texas.

Westphal, K. A., Zganjar, C., and White, W. A., 1999, Aerial videotape survey of the Laguna Madre and Baffin Bay, Texas: Center for Coastal, Energy, and Environmental Resources, Louisiana State University, Coastal Geology Map Series No. 23.

White, W. A., Calnan, T. R., Morton, R. A., Kimble, R. S., Littleton, T. G., McGowen, J. H., Nance, H. S., 1989, Submerged lands of Texas, Kingsville area: sediments, geochemistry, benthic macroinvertebrates, and associated wetlands: The University of Texas at Austin, Bureau of Economic Geology, 137 p.

White, W. A., Calnan, T. R., Morton, R. A., Kimble, R. S., Littleton, T. G., McGowen, J. H., Nance, H. S., and Schmedes, K. E., 1983, Submerged lands of Texas, Corpus Christi area: sediments, geochemistry, benthic macroinvertebrates, and associated wetlands: The University of Texas at Austin, Bureau of Economic Geology, 154 p.

White, W. A., Calnan, T. R., Morton, R. A., Kimble, R. S., Littleton, T. G., McGowen, J. H., Nance, H. S., and Schmedes, K. E., 1986, Submerged lands of Texas, Brownsville–Harlingen area: sediments, geochemistry, benthic macroinvertebrates, and associated wetlands: The University of Texas at Austin, Bureau of Economic Geology, 138 p.

White, W. A., Tremblay, T. A., Hinson, J., and Moulton, D. W., Smith, E. H., and Jenkins, K., 1998, Current status and historical trends of selected estuarine and coastal habitats in the Corpus Christi Bay National Estuary Program study area: Report prepared for the Corpus Christi Bay National Estuary Program, 120 p.