SEDIMENT BUDGET ANALYSIS FOR LAGUNA MADRE, TEXAS:
AN EXAMINATION OF SEDIMENT CHARACTERISTICS,
HISTORY, AND RECENT TRANSPORT

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SUMMARY

This study was designed to improve the understanding of sediment fluxes in Laguna Madre and the principal processes responsible for introduction and redistribution of sediments within and around the lagoon. Other tasks included quantifying the long-term average annual sediment budget of the lagoon, and comparing the natural fluxes of sediment from eolian transport, storm washover, upland runoff, tidal exchange, shore erosion, and authigenic (formed in place) mineral production with fluxes related to dredging and disposal of material removed from the Gulf Intracoastal Waterway (GIWW) for maintenance of the navigation channel. Long-term analysis of sediment transport mechanisms and associated sediment flux provides a basis for evaluating the potential influence of reworked dredged material on the distribution of seagrasses in the lagoon. Considering long-term annual averages, the total volume of new sediment introduced into Laguna Madre is substantially less than the volume dredged from the GIWW. Furthermore, the average sedimentation rate in Laguna Madre is less than the rate of relative sea-level rise. This condition coupled with erosion of the western shore indicates that the lagoon is slowly migrating westward rather than filling up as some have suggested.

Comparison of cumulative volumes of sediment dredged from representative segments of the GIWW in both northern and southern Laguna Madre with volumes of sediment remaining in the placement areas demonstrates that shoaling of the GIWW is primarily caused by reworking of dredged material, which is controlled by water depth and location with respect to the predominant wind-driven currents. Reworking is minimized where dredged material is placed on flats that are either flooded infrequently or where the water is extremely shallow. In contrast, nearly all of the dredged material in relatively deep-water placement areas is reworked and either transported back into the GIWW or dispersed into surrounding areas of the lagoon.

Evaluation of several experimental designs in the high maintenance placement areas (PA 233-234) of southern Laguna Madre suggest that none of the designs (shallow subaqueous mound, submerged levee, emergent levee) was successful in retaining large volumes of dredged material at those sites because cross currents cause extensive sediment reworking. Of the three experimental methods tested, the emergent levee design provided the greatest retention potential approximately two years after construction.

Inclusion of in situ sediment densities, water contents, and void ratios in the volumetric calculations improved the accuracy of the quantitative evaluation and provided unequivocal evidence that the observed volumetric losses from the placement areas are primarily the result of sediment erosion and not post-emplacement sediment compaction. Comparison of sediment

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textures in the placement areas with those of natural sediments of the surrounding lagoon floor indicate that much of the dredged material remaining in the placement areas is a residual of initial channel construction.

INTRODUCTION

Laguna Madre (fig. 1) is a long, shallow marine lagoon that originated during the most recent eustatic rise in sea level that inundated the coastal plain bordering the Gulf of Mexico. This vast water body flooded several geological provinces including a former barrier island system (Ingleside), an eolian plain, and abandoned portions of the Rio Grande delta (Lohse, 1958; Rusnak, 1960a; Morton and McGowen, 1980; Morton and Price, 1987; Morton, 1993). The channel of the Gulf Intracoastal Waterway (fig. 1), which was dredged through Laguna Madre from the fall of 1946 to the summer of 1948 (Lockwood, Andrews, and Newnam, 1959), intercepts these diverse geological provinces, consequently the sediments underlying Laguna Madre primarily control the compositions of islands and shoals formed by open-water placement of the original dredged material.

It is well established that construction of the Texas portion of the Gulf Intracoastal Waterway (GIWW) in the late 1940s and Mansfield Channel in the early 1960s altered bathymetry and hydrodynamic conditions in Laguna Madre (Hansen, 1960). An ecological benefit of these projects is increased water circulation within the lagoon and reduced salinities (Simmons, 1957; Breuer, 1962; Quamann and Onuf, 1993), even during low rainfall periods that previously resulted in hypersalinities. Deposition of dredged material taken from the GIWW during the past 50 years has eliminated seagrass habitat in some areas of the lagoon and created new habitat in others. However, it is still uncertain if reworking of the dredged material is a significant factor in the reported losses in seagrass from southern Laguna Madre, or if other factors are responsible or at least contribute to the losses.

Unconfined open-water placement of dredged material can have both direct and indirect adverse impacts on marine grasses in Laguna Madre. Direct impacts of placement in shallow water involve burying the grass beds and decreasing water depths to the extent that the grasses never recover. These impacts are readily documented by mapping the location of placement sites relative to existing grass beds. Less certain is the relationship between reworked dredged material and the vitality of nearby grass beds. This uncertainty arises from the fact that few studies have monitored the resuspension and redistribution of dredged material long after a dredging cycle. Most studies examine the short-term physical processes that entrain and transport sediment (Hellier and Kornicker, 1962; Bassi and Basco, 1974) without looking at the large-scale patterns of sediment redistribution. Onuf (1994) measured photosynthetically active

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radiation (PAR) before and after dredging in southern Laguna Madre to evaluate if light attenuation persisted long after termination of the dredging disposal. Using a multivariate statistical analysis, Onuf (1994) found that increased light attenuation was detectable at one location 15 months after dredging as a result of resuspension and dispersion of the dredged material. The concentrations of suspended sediments and distances sediments are transported from a placement site are poorly understood. Also unknown are residence periods of the reworked deposits, and the importance of size sorting that occurs during reworking of dredged material.

Except for a few geological studies conducted in the late 1950s (Lohse, 1958; Fisk, 1959; Rusnak, 1960a) and the mid 1970s (White et al., 1983; 1986; 1989), most of the scientific research in Laguna Madre has tended to focus on biological issues and the important relationships among water quality (salinity, brown tide, turbidity), highly-productive marine grasses, and economically vital marine fisheries. Several recent studies have examined the physical impacts of channelization (GIWW) and causeway construction (JFK Causeway at Corpus Christi) on flow patterns in the lagoon (Duke, 1990; Solis and Matsumoto, 1991; Brown and Kraus, 1996; Militello et al., 1996). Despite all the prior work in South Texas lagoons and estuaries, no study has attempted to determine the regional sediment budget of Laguna Madre. Also lacking is a comprehensive study specifically addressing the issue of reworked dredged material and its contribution to turbidity in the lagoon as compared to turbidity before the GIWW was constructed.

A primary objective of this study was to assess the importance of reworked dredged material on suspended sediment in Laguna Madre compared to natural sediment influx and resuspension. Of particular concern are the marine grasses and their ability to tolerate long-term exposure to repeated resuspension of sediments in concentrations sufficient to eventually alter bottom sediment textures and water depths. Other objectives involved answering questions regarding sediment transport by wind, washover, and waves and currents generated within Laguna Madre and the effects of changing climate on these processes.

To accomplish these objectives, it was necessary to conduct a large-scale temporal and spatial analysis of sediment budget to establish the primary sources and sinks of sediment in Laguna Madre. Within the context of regional sediment budget, the issue of reworked dredged material was examined, the sources of mud were determined, and the historical changes in sediment textures and water depths were evaluated. This comprehensive sediment analysis provides a basis for assessing the potential impact of reworking of dredged material on the marine grasses in Laguna Madre.
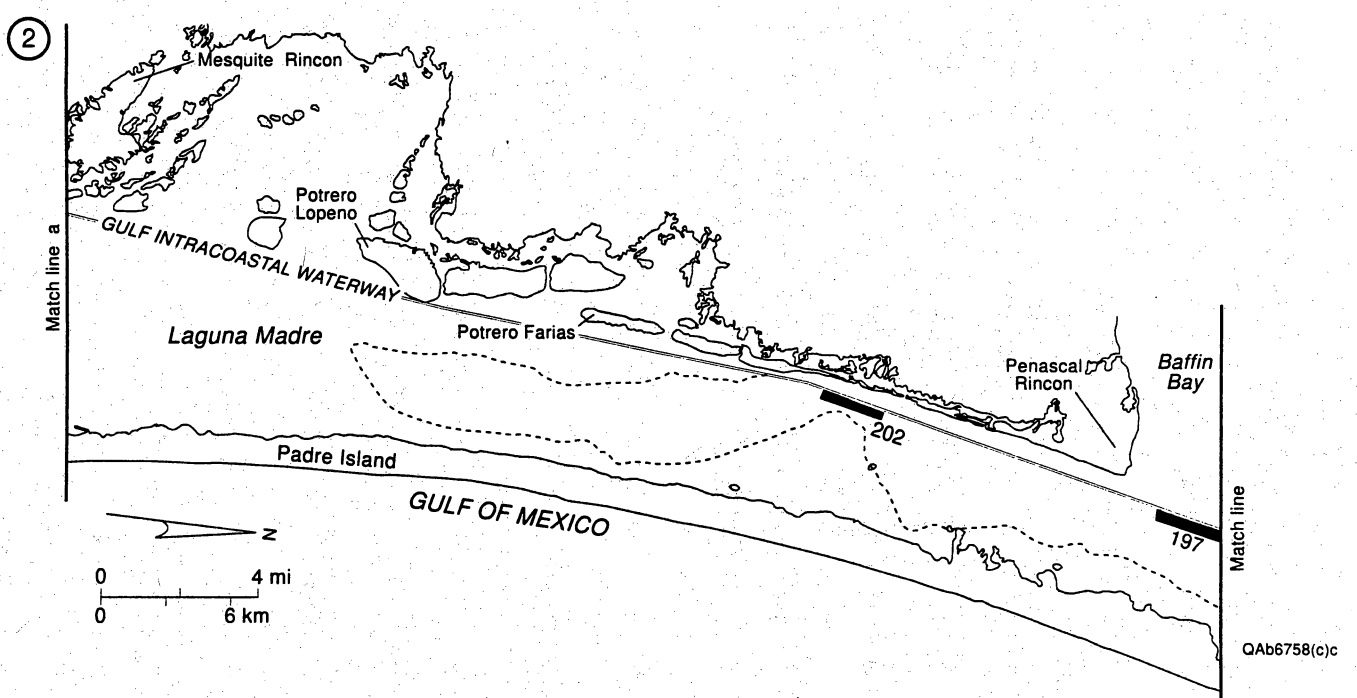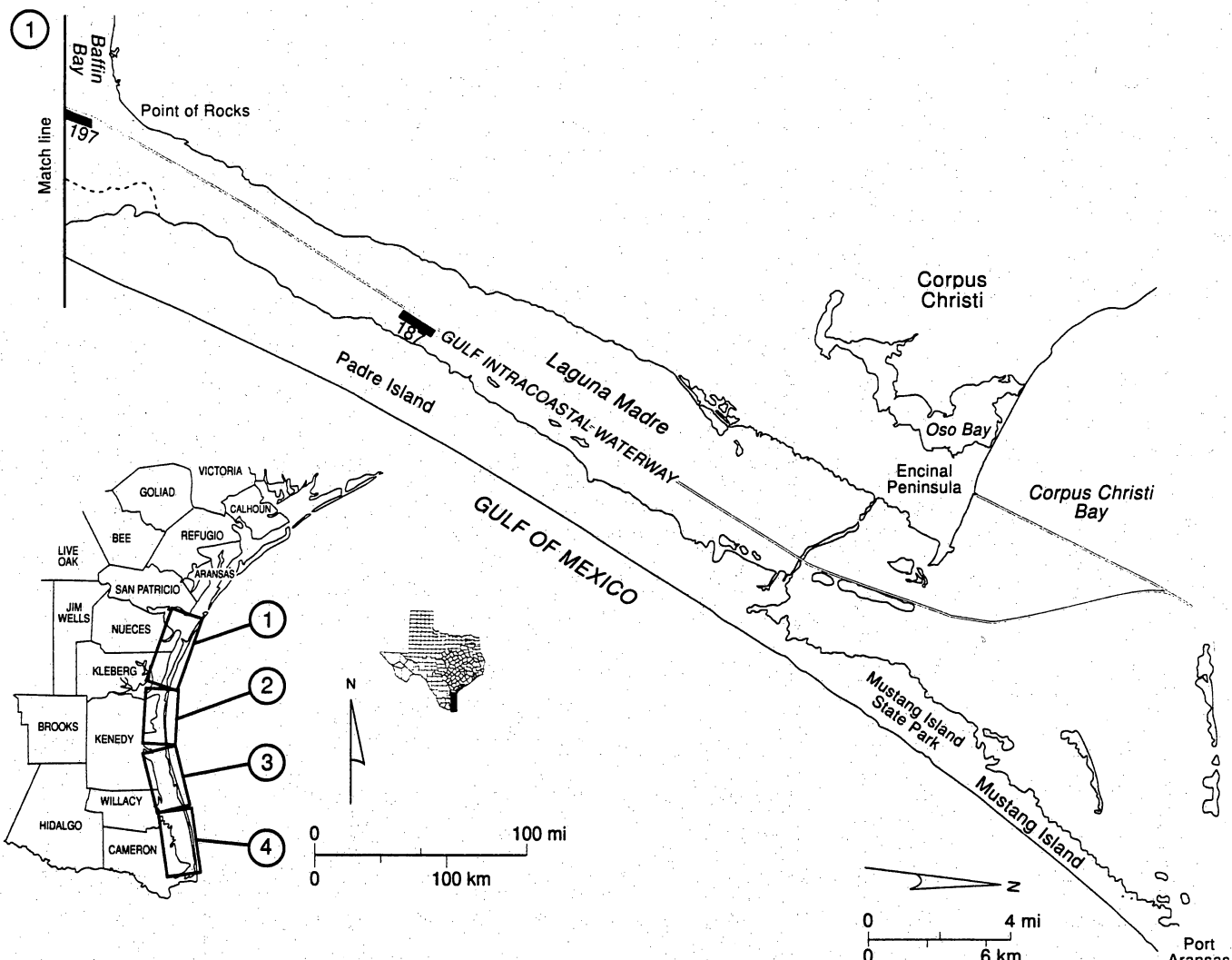
Figure 1. Index map showing locations of geographic features, the Gulf Intracoastal Waterway, and placement areas of dredged material investigated in Laguna Madre.

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221

GULF INTRACOASTAL WATERWAY

211

Match line b

Match line a

Laguna Madre

Padre Island National Seashore

GULF OF MEXICO

N

0   4 mi

0   6 km

④

Laguna Atascosa National
Wildlife Refuge

Laguna
Larga

Arroyo
Colorado

Horse
Island

233   GULF INTRACOASTAL WATERWAY

Port
Isabel

Match line b

Laguna Madre

GULF OF MEXICO

Padre Island

N

0   4 mi

0   6 km

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Figure 1. (cont.)

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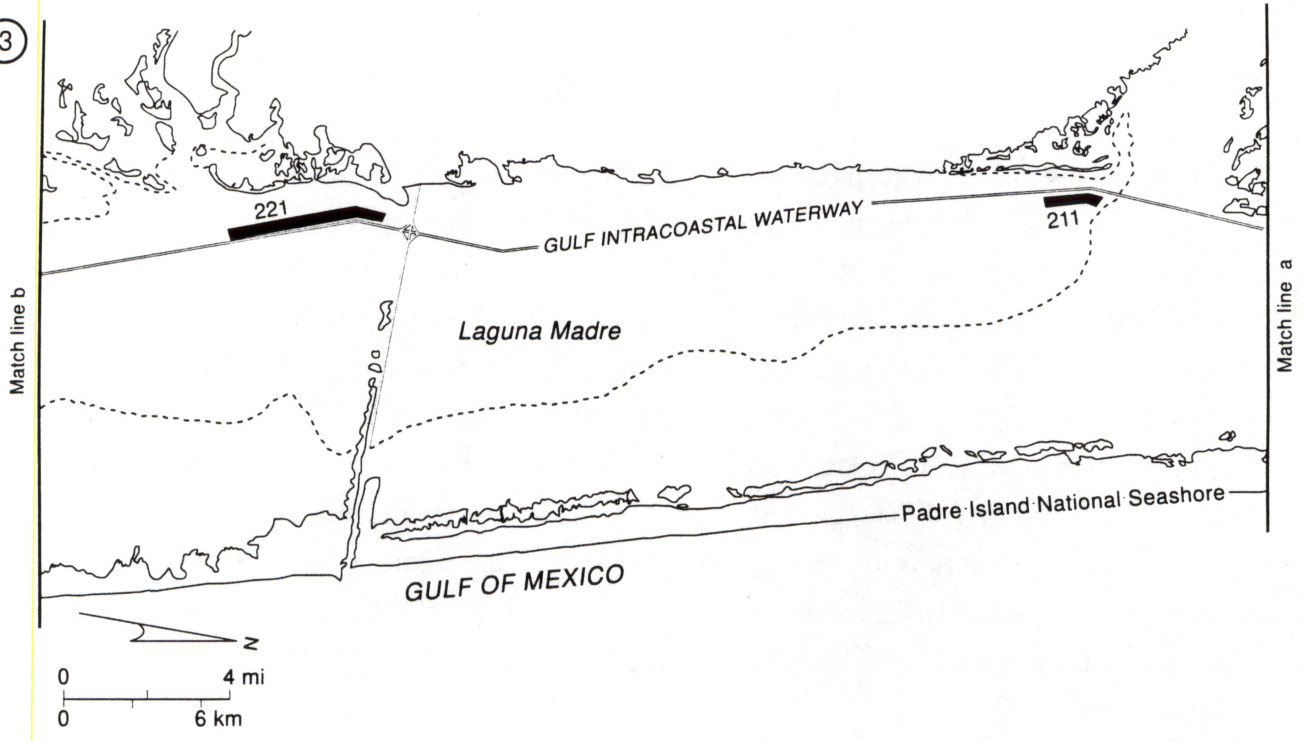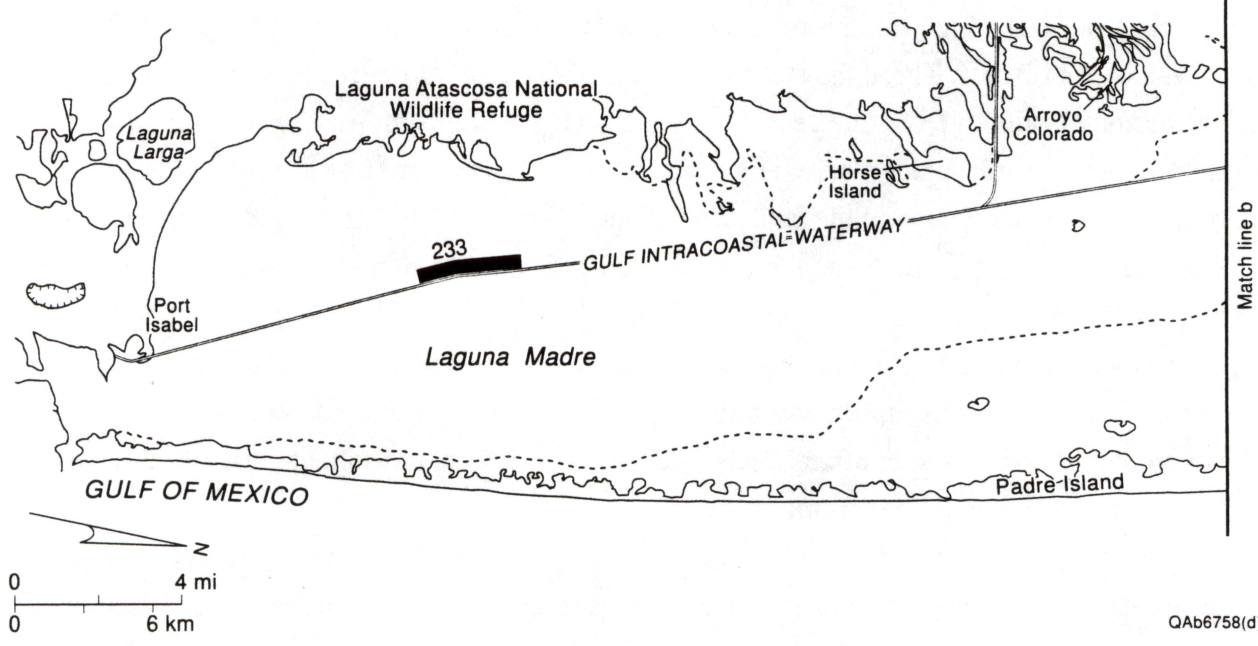
SOUTH TEXAS CLIMATE

There is a distinct climatic gradient from east to west along the Texas coast that reflects the temperatures and rainfall within each region. In general there is a surplus of rainfall in the humid eastern part of the state, whereas the southwestern part is semi-arid, and rainfall is less than the amount of moisture lost to the atmosphere by evaporation and transpiration by plants. The long-term average balance between rainfall and evapotranspiration occurs near Corpus Christi. South of Corpus Christi the potential for evaporation exceeds the annual rainfall (Shepard et al., 1960).

The dry climate of south Texas has a profound influence on the plant assemblages, physical processes, and landforms of the region. Because average annual temperatures are high, evaporation is high, rainfall is low, and freshwater inflow to the lagoon is low, coastal waters commonly have abnormally high salinities (hypersaline) and salt marshes are only minor environments that rim the lagoon margin. Also large dune fields and wind-tidal flats dominate the landscape (fig. 2).

Precipitation and Evapotranspiration

Average annual rainfall in counties bordering Laguna Madre is about 66 cm (Brown et al., 1977) and the rainfall is seasonally distributed. Periods of greatest rainfall occur in the late summer and early fall and are associated with the passage of tropical storms and hurricanes. A secondary period of high rainfall occurs in the winter and spring and is associated with the passage of cold fronts. Throughout the remainder of the year, rainfall is generally low. The distribution of rainfall from one year to the next is also nonuniform leading to wet periods (high rainfall) as well as droughts (extremely low rainfall). According to Lowry (1959), severe droughts dramatically altered the landscape of south Texas in 1937-1939, 1950-1952, and 1954-1956. During droughts, the water table is lowered and surface sediments are easily eroded by the wind.

Evapotranspiration is the total amount of moisture released to the atmosphere by evaporation and by transpiration through the leaves of plants. In south Texas, the evapotranspiration potential often exceeds the annual precipitation so that normally there is a deficiency in the amount of soil moisture.

The deficit in rainfall relative to the amount of moisture returned to the atmosphere along the southern part of the Texas coast is magnified during prolonged droughts. Periodically these droughts accelerate onshore wind transport of sand by lowering the water table, reducing the
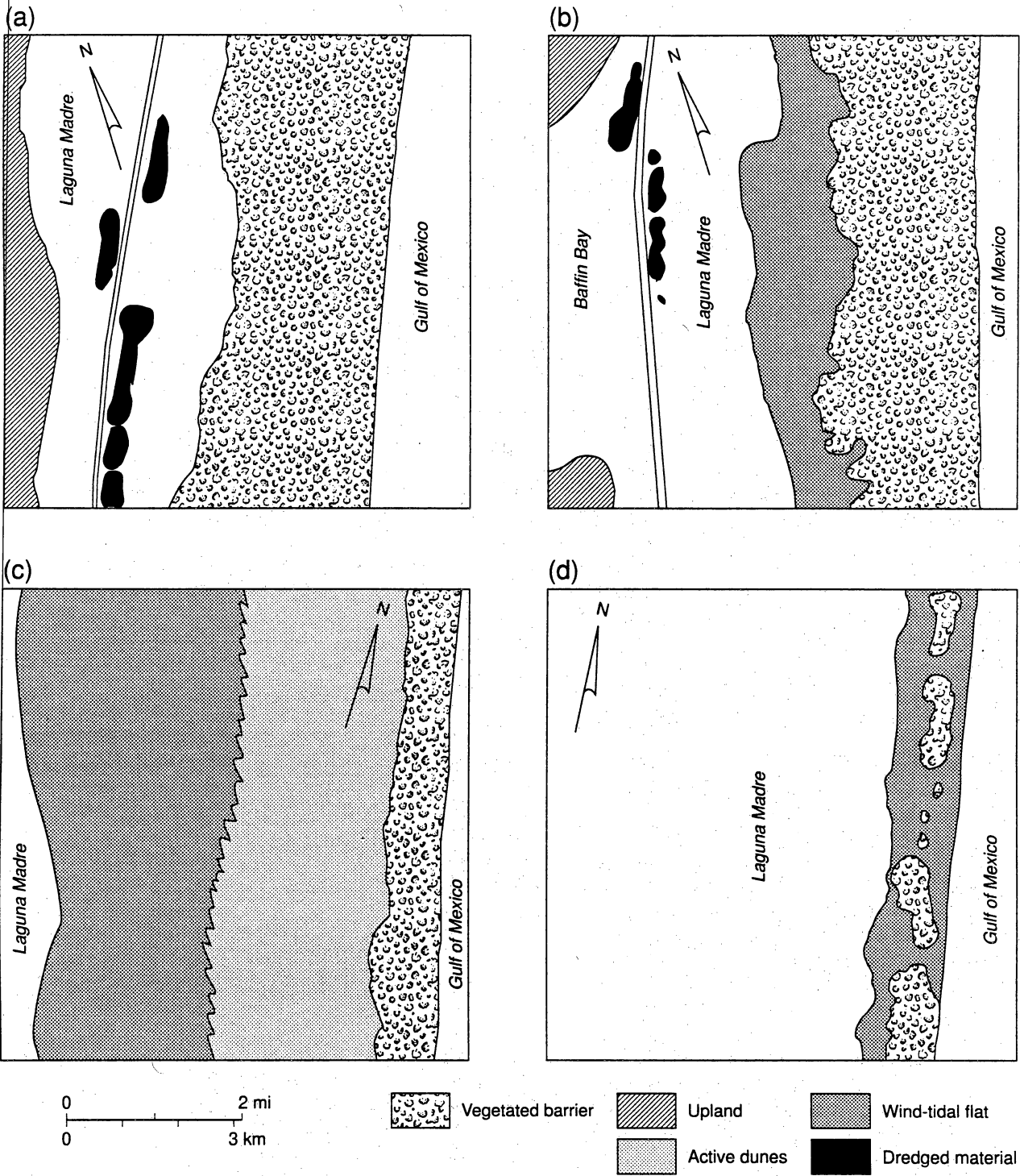
Figure 2. Variations in backisland morphologies along Laguna Madre within different geographic regions. The vegetated barrier unit also includes formerly active dunes that are now stable. The wind-tidal flat unit on South Padre Island also includes washover channels and fans.

internal moisture of the sediments, and weakening or killing the vegetation that stabilizes the sediments.

PHYSICAL PROCESSES

Wind Characteristics

Wind is the most important physical agent affecting the south Texas coast. When coupled with the semi-arid climate, wind is responsible for shaping the coastal plain and directly or indirectly controlling the erosion and deposition on the wind-tidal flats and in the other coastal environments. The surface wind patterns crossing Laguna Madre are determined by the seasons. Southeast winds prevail from March through November while northerly winds prevail from December through February (Brown et al., 1977).

The prevailing winds are determined by their direction and duration. An even more important concept is wind predominance, or the ability of wind to do geological work (Price, 1933). Wind predominance, which combines both duration and speed of the wind, measures the potential effectiveness of the wind to transport sediment and to generate waves and currents in coastal waters. The southeasterly onshore winds generally do not reach high velocities, but they persist from the spring through the fall. Therefore they are the predominant winds in south Texas. In contrast, northerly winds associated with the passage of cold fronts in the winter and with tropical cyclones in the summer are strong but brief, and their total energy dissipated at the coast is less than that of the predominant southeasterly winds (Brown et al., 1977). However, the high-velocity northerly winds, whether generated by cold fronts or counterclockwise circulation associated with tropical cyclones, have the capability of doing more sedimentological work by transferring their high energy to the water in Laguna Madre and creating relatively high waves and strong currents.

Water Level Fluctuations

The western Gulf of Mexico is a microtidal region where the astronomical tides are diurnal (once every 24 hours) or mixed. The astronomical tides in Laguna Madre are extremely small, and water level fluctuations depend more on the meteorological conditions (wind speed and direction, barometric pressure) than the astronomical forcing in much of the lagoon (Fisk, 1959; Hansen, 1960; Rusnak, 1960a; Zetler, 1980; Gill et al., 1995). The low tide range is attributed to the small number of tidal inlets into Laguna Madre, the large area of the lagoon, and the long

distances from the inlets to the center of the lagoon. All of these factors tend to reduce the impact that oceanic tides have on adjacent water bodies.

Water level fluctuations in extreme northern and southern Laguna Madre at the Packery Channel and Port Isabel gauges have discernible astronomical tidal signals, but tide gauges in central Laguna Madre (Yarborough Pass, El Toro, Rincon de San Jose, and Port Mansfield) show that water level fluctuations are largely controlled by meteorological forces and the astronomical tide explains only a few percent of the variability (Fisk, 1949; Rusnak, 1960a; Copeland et al., 1968; Gill et al., 1995). Smith (1978) estimated that only about 5% of the water level variation in northern Laguna Madre was caused by tidal constituents. The predominance of wind tides over astronomical tides is the reason that the flats forming the margin of Laguna Madre were named wind-tidal flats by W. A. Price and Fisk (1959). The surface of the area is so flat that the wind is capable of pushing the water out of the lagoon basins and up onto the flats. Both southeasterly and northerly wind regimes can flood the flats. Flooding under the influence of northerly winds is typically faster but of shorter duration than flooding by southeasterly winds (Fisk, 1959).

Field observations and daily monitoring in 1948 by Fisk (1949) clearly show that the flats are inundated by non-channelized sheet flow. As the wind-driven water encroaches onto the flats, it is diverted by the highest topographic features, but the flow does not conform to the topography of the flats. Instead, the detailed maps presented by Fisk (1949) show that the wind blows the water "uphill" and across the flats and some higher areas are flooded while lower areas are dry.

The Gulf Intracoastal Waterway (GIWW) was dredged through the wind-tidal flats of Kenedy County in 1948 with two dredges working simultaneously from opposite ends of the flats. As the dredges approached one another, a strong southeast wind transported water onto the south side of the flats and blew water away from the north side, creating a difference in water levels of about 1.5 m (Fisk, 1949). Immediately after the GIWW was dredged through the flats, water ponded on the flats cascaded into the Waterway because the water level was higher on the flats than in the Waterway. Physical evidence for the rapid draining of water off the flats and into the Waterway is provided by the closely spaced channels with headwardly eroding dendritic patterns that lined the Waterway on the west side (Fisk, 1949).

Coastal Storms

Northers and tropical cyclones are two types of storms that periodically affect Laguna Madre. Tropical cyclones are summer storms that include both tropical storms and hurricanes. Winter storms, or northers, derive their energy from the atmosphere, whereas the ocean is the

principal energy source for tropical cyclones. Winter storms and tropical cyclones form around centers of low barometric pressure and their winds circulate counterclockwise around the storm center. Although the two types of storm systems are quite different, their influence on coastal water bodies and nearshore environments is similar. Both can rapidly change water levels and generate waves and currents that are capable of eroding and transporting large volumes of sediment.

Cold fronts with associated north winds cross the Texas coast about every ten days throughout the winter. As a result of this frontal activity, several strong winter storms occur each year. Before the front passes the coast, strong winds blow onshore from the southeast in response to the low pressure system that is farther inland. In Laguna Madre, the strong onshore wind drives water onto the southern part of the flats in central Laguna Madre (fig. 2) and off the northern part of the flats (Fisk, 1949). After the frontal boundary passes the coast and moves off to the east, the wind rapidly changes direction and blows from the north, driving water onto the northern part of the flats and off the southern part of the flats.

Tropical storms and hurricanes enter or form in the Gulf of Mexico between June and October, but the most intense tropical cyclones typically occur in August or September. Hurricanes strike the Texas coast about twice every three years (Hayes, 1967), but the probability of a major hurricane striking at any particular site is much lower and on the order of once every ten to twelve years (Simpson and Lawrence, 1971). The climate and geographic setting of Laguna Madre ensures that it has been influenced by several hundred hurricanes ever since it was formed. Attempts to explain recent changes in the distribution of seagrasses in Laguna Madre in terms of recent hurricanes should consider that these storms and their attendant rainfall and currents have been operating in Laguna Madre throughout its long history. Thus they probably are not the primary cause of change unless the adverse stresses imposed by the storms are coupled with prior conditions that weakened or otherwise exceeded threshold values of some factor (water quality, water depth) that controls the vitality of the seagrasses.

Relative Sea Level Changes

Changes in the land-sea relationship at the coast can be caused by movement of the water level with respect to the land, movement of the land surface with respect to the water level, or both. At present, the best scientific evidence indicates that both processes are acting together to produce a relative rise in sea level along the Texas coast (Swanson and Thurlow, 1973; Lyles et al., 1988). Historical records at Texas tide gauges since the turn of the century all show the same general variations in sea level that coincide with droughts and periods of abnormally high rainfall (fig. 3). The tide gauge records also show a relative rise in sea level that currently averages from

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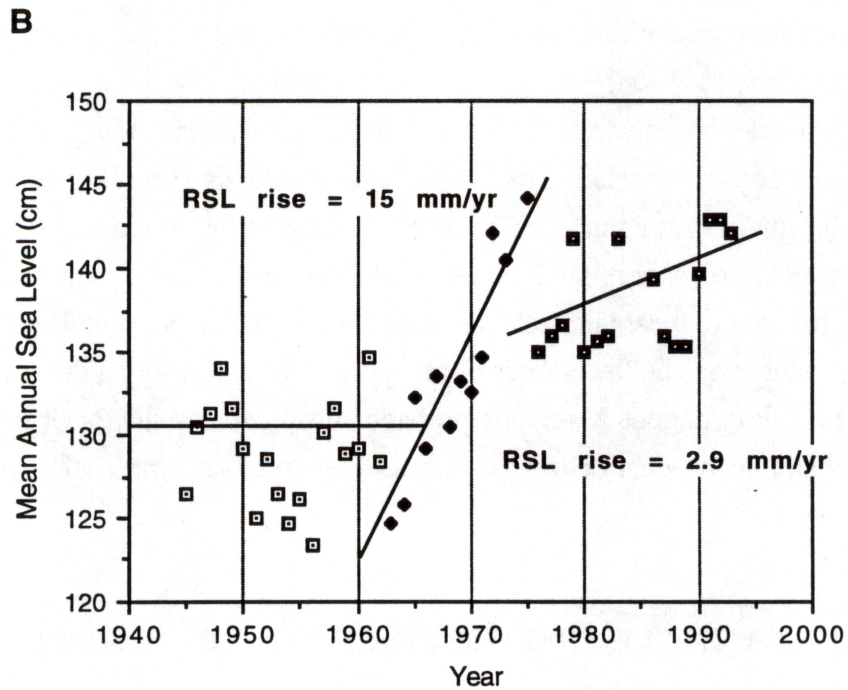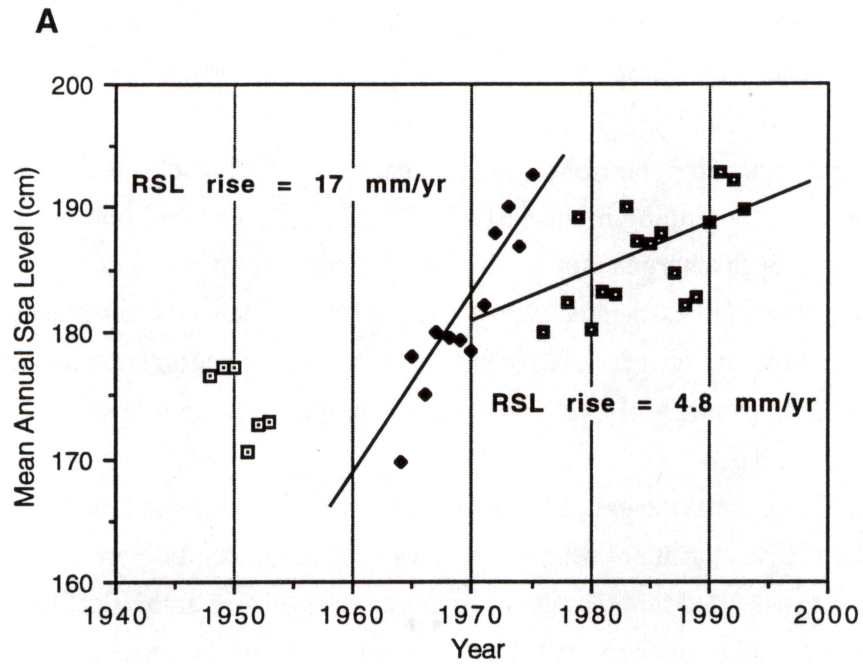
Figure 3. Temporal variations in annual average sea-level at A. Rockport and B. Port Isabel for selected decadal periods. Data from the National Oceanic and Atmospheric Administration National Ocean Service.

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3.7 mm/yr at Port Isabel to 4.3 mm/yr at Rockport (Gill et al., 1995). The rate of relative sea level rise in Laguna Madre is about three times as fast as the worldwide eustatic rise in sea level, which averages about 1.2 mm/yr (Gornitz and Lebedeff, 1987).

When examined for temporal trends, the tide gauge at Port Isabel reveals significant increases in water level beginning in the early 1960s (fig. 3). This trend may be partly related to increased surface water discharge associated with irrigation return flows in the lower Rio Grande valley and to greater rainfall associated with a minor climate change (Quammen and Onuf, 1993). But not all of the increase in relative sea level is a local phenomenon as demonstrated by the high correlation of secular sea level variations observed at all the tide gauges along the Texas coast (Lyles et al., 1988).

There are no long-term tide gauge records between Port Isabel and Rockport that can be used to determine the recent rate of relative sea level rise in the central part of Laguna Madre. For this study it was assumed that the rate of relative sea level rise at the Port Isabel gauge (3.7 mm/yr or about 0.37 m per century) is a reasonable estimate for other parts of Laguna Madre because the Port Isabel and Rockport gauges both show the same secular variations and long-term, statistically valid trends of relative sea level rise. The rate of relative sea level rise in Laguna Madre is probably no less than the rate at Port Isabel because the tide gauge at Port Isabel records the lowest rate of relative sea level rise for the entire Texas coast (Swanson and Thurlow, 1973; Lyles et al., 1988).

The different rates of relative sea level rise at different locations along the Texas coast are poorly understood. Most of the relative rise in sea level is actually subsidence of the land surface (Swanson and Thurlow, 1973; Paine, 1993) caused by compaction of sediments within the Gulf Coast Basin. The higher rates of relative sea-level rise measured, for example at the Galveston tide gauge, are attributed to local land-surface subsidence induced by ground-water withdrawal and oil and gas production. The lower rates of relative sea-level rise along the southern part of the Texas coast including Laguna Madre are probably attributable to the lower rates of ground-water withdrawal and the production of gas instead of oil and formation water from the deeper subsurface.

SEMIQUANTITATIVE ANALYSIS OF REGIONAL SEDIMENT BUDGET

Morphological Setting

Laguna Madre generally has an asymmetrical cross section that is characterized by broad smooth flats on the east side that gradually slope toward the lagoon center, and moderately steep and irregular slopes along the west side. This asymmetry is predominantly the result of

deposition of sediments from the Gulf of Mexico on the east side and erosion of preexisting sediments on the west side. The lagoon is an efficient sediment trap that receives externally derived sediment primarily from onshore eolian transport, storm washover, flood tidal currents, and fluvial (upland) runoff. Sediments generated entirely within the lagoon are products of chemical and biochemical processes. These authigenic sediments include shell detritus and evaporite deposits, primarily gypsum and some carbonates. Also important in the regional sediment budget is the redistribution of sediment within the lagoon. The internal transfers are related to lagoon margin erosion and resuspension of lagoon floor sediments by waves and strong currents.

The morphologies of Padre Island and the adjacent lagoon reflect the predominant surficial processes and the interaction among wind, waves, and currents. Topographic maps and aerial photographs show essentially four different backbarrier-lagoon morphologies that are related to the width of the wind-tidal flats. From Packery Channel to Baffin Bay, the wind-tidal flats are either very narrow or absent, and the lagoon limit of the backisland dune fields and the high water feature are essentially the same (fig. 2a). From Baffin Bay to the Hole, the backbarrier dune complex is relatively stable, the wind-tidal flats are moderately wide, and the high-water features coincide with the lagoon edge of the vegetated dunes (fig. 2b).

The backbarrier morphology from the Hole to the Arroyo Colorado is significantly different because the dune fields are presently active and the wind-tidal flats are extremely wide (fig. 2c). The backbarrier to lagoon transition includes three zones that are products of the dominant surficial processes and the duration of inundation by marine waters. The first zone encompasses the active dunes with high angle oblique orientations to the Gulf shoreline. These dunes are rarely inundated by marine water although they commonly pond fresh water and the ground water level is raised after heavy rainfall. The lagoonward limit of the active dunes is irregular and the dune complex passes in transition into a broad zone of wind-tidal flat that either has no distinct bedforms or low-relief interference patterns that represent the reworking of remnant eolian bedforms by unidirectional currents under high water conditions in the lagoon. The interference patterns observed on aerial photographs indicate that sediments reworked by the currents in the wind-tidal flat transition zone are transported to the north. The wind-tidal flat transition zone, which is the second of the three zones, is inundated by marine water more frequently and for longer periods than the complex of active dunes, but less frequently and for less time than the third zone, which is a continuation of the wind-tidal flats. The most lagoonward portion of the flats are at a slightly lower elevation than the transition zone, and it is covered by bands of lagoon parallel features either without any discernible bedforms or with bedforms showing interference patterns. The bands of lagoon parallel features, including dense

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algal mats, represent frequent flooding at different water levels by marine water from the open lagoon.

On South Padre Island from the Arroyo Colorado to Brazos Santiago Pass, the wind-tidal flats merge with washover fans (fig. 2d) and the entire barrier island becomes much narrower to the south. The elevation gradient is relatively steep on South Padre, consequently the transition from active dunes to the wind-tidal flats is better defined than to the north. Also the wind-tidal flat zone of lagoon-parallel features including dense algal mats is narrow. Subaqueous reworking of sand along the lagoon margin of the wind-tidal flats is also apparent in the vicinity of the Town of South Padre Island (Morton, 1978; 1979).

Sediment Sources and Sinks

This phase of the investigation (1) examined the primary sources of sediments delivered to Laguna Madre on geological and historical time scales, (2) delineated the geographic zones where certain physical processes and sediment types predominate (fig. 4), and (3) developed a quantitative ranking of the primary sediment sources (Table 1). Potential sources of sediment were evaluated from available data on upland erosion, sediment yield, and freshwater inflow (Greiner, 1982; International Boundary Water Commission; Texas Department of Water Resources, 1983). Also we evaluated data pertaining to changes in land use (Texas Water Development Board, 1991), changes in upland runoff (land clearing, artificial drainage networks), droughts (dune migration), and hurricanes (washover) that could influence the volume and rate of sediment transported into Laguna Madre.

Results of other field studies indicate that sediment influx by eolian and washover processes is highly variable in time and space. Major hurricanes crossing shallow water can deposit and redistribute large volumes of sediment in a few hours (Morton, 1978; 1979). Active dunes migrating across Padre Island can also supply large volumes of sediment to the lagoon in several years (Hunter et al., 1972; White et al., 1978; Morton and McGowen, 1980; Kocurek et al., 1992). However, much of the time these processes are either inactive or operate at much lower rates.

Eolian Sediment Supply

The wind is a highly efficient sorter and transporter of sediment and it has been responsible for supplying large volumes of sediment to Laguna Madre on both geological and historical time scales. As a general rule, wind selectively transports grains of sand-size material by saltation

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Table 1. Estimated average annual sediment volumes delivered to Laguna Madre by primary physical and biochemical processes and comparison of calculated sedimentation rate with rate of relative sea level rise at Rockport and Port Isabel.

Source	Est. Volume m^3/yr	Est. Vol. in GIWW m^3/yr
Upland Runoff		
Northern Laguna Madre	24,200	2,400
Southern Laguna Madre	30,000	4,200
Eolian Transport		
North Padre Dune Field	254,200	6,600
South Padre Dune Field	175,000	2,150
Tidal Currents		
Yarborough Pass	0	0
Mansfield Channel	168,000	3,100
Brazos Santiago Pass	215,000	25,800
Boca Chica Pass	0	0
Storm Washover		
North Padre Island	1,200	insignificant
South Padre Island	78,600	insignificant
Shore Erosion	23,400	insignificant
Subtotal	969,600	44,320
Authigenic Sediments*	38,800	0
Ave. Annual Sediment Supply	1,008,400	44,320
Ave. Annual Dredging	Not Applicable	1,659,429

* Authigenic sediments were estimated as 4% of the subtotal

Attribute/Process	Northern Laguna	Southern Laguna
Area	310 km^2	700 km^2
Sediment Budget	291,300 m^3/yr	295,300 m^3/yr
Relative Sea Level Rise	3.68 mm/yr	3.03 mm/yr
Sedimentation Rate	0.94 mm/yr	0.42 mm/yr
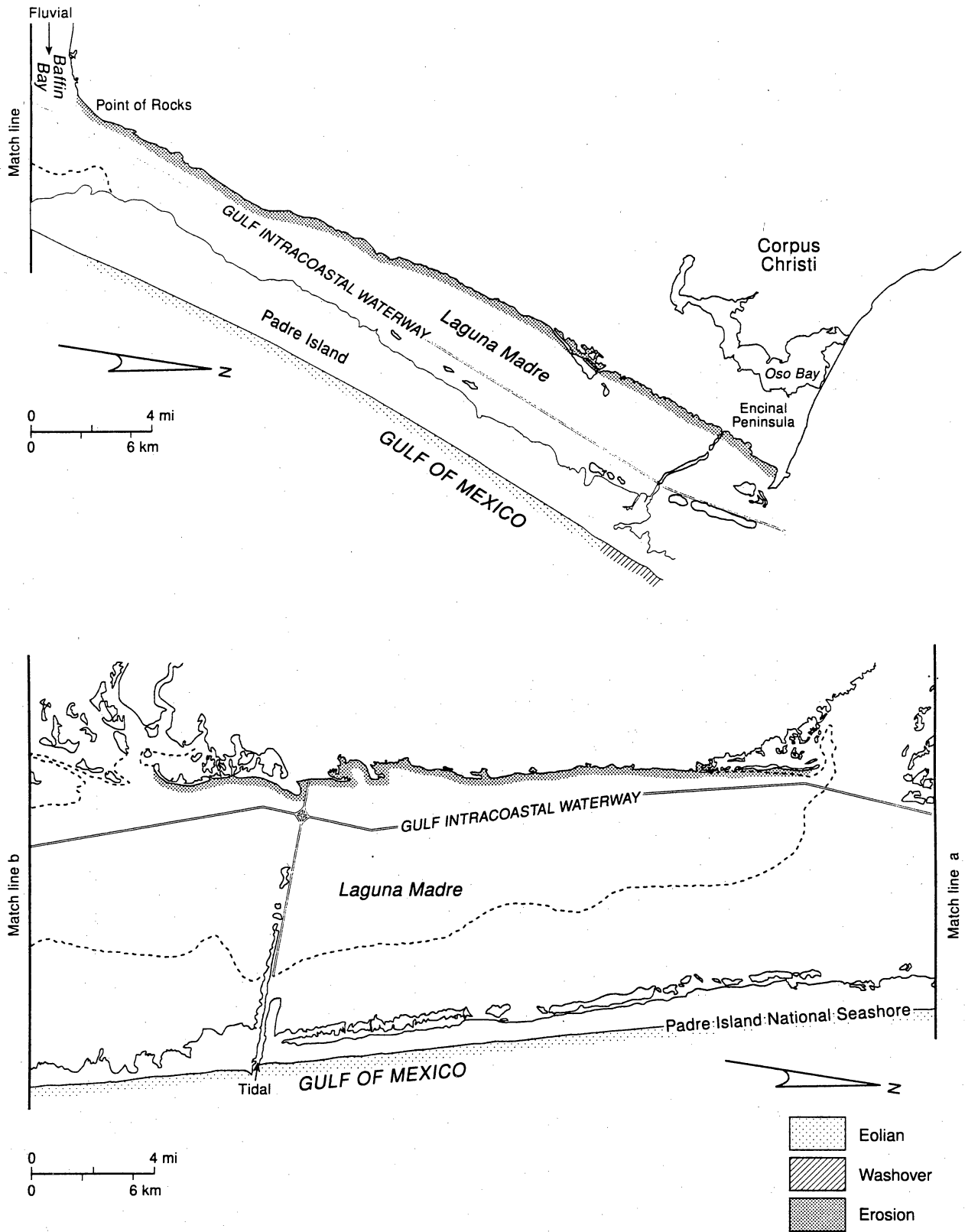
Figure 4. Primary sources of sediment delivered to Laguna Madre and the regions where sediment transport by a particular process is most active.

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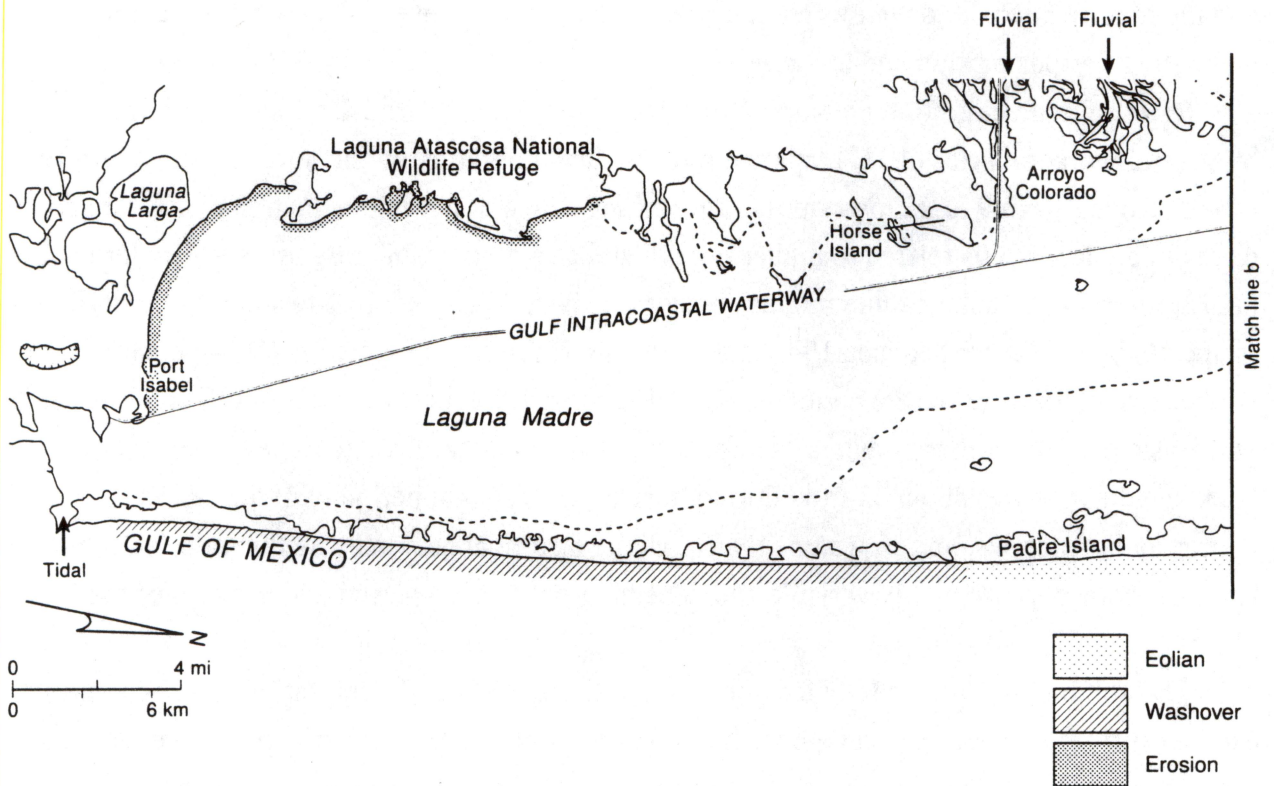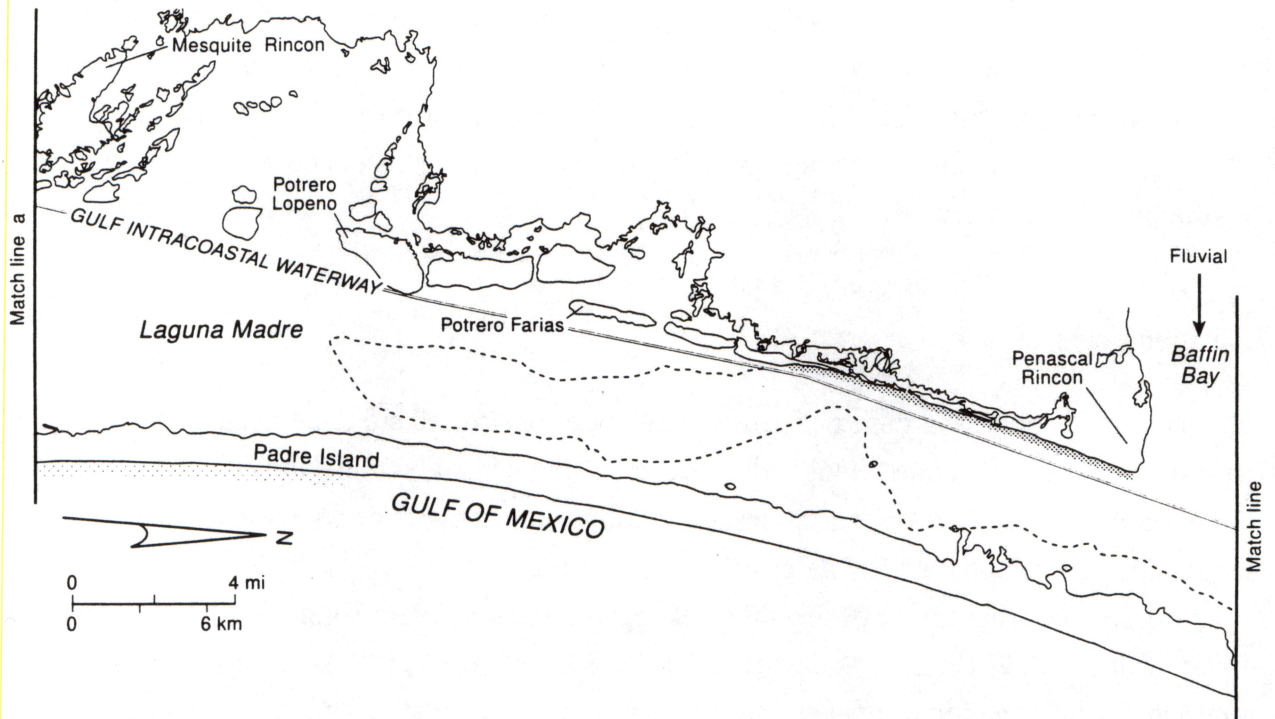
Figure 4. (cont.)

along the ground and silt and clay-size material by suspension within the air column. These two different processes were used to subdivide the eolian transport, which is the largest component of the sediment budget estimate (Table 1). These same processes also were used by Ward (Appendix C) to estimate the average annual volume of sand and dust deposited in Laguna Madre by eolian activity.

Saltation Transport

Dunes - Simple sand dune patterns generally are constructed either perpendicular (transverse dunes) or parallel (longitudinal dunes) to the wind direction. However, most of the dunes on Padre Island are oblique dunes that exhibit characteristics of both transverse and longitudinal morphologies. The fields of migrating oblique dunes on North and South Padre Islands have been the subject of several investigations (Boker, 1956; Hunter et al., 1972; Price, 1971; Weiner, 1982; Hummel and Kocurek, 1984; Kocurek et al., 1992). The grain sizes reported for dune sand indicate that transport is primarily by saltation and not by suspension. Most of these studies focused on the various types of internal stratification observed in the dunes, and the modifications to dune morphology caused by seasonal reversals in wind direction and alternating periods of high and low rainfall.

Rates of dune migration on North Padre Island near South Bird Island have been measured by several workers. Price (1971) reported rates of dune migration on the northern end of Padre Island ranging from 9 to 25 m/yr during dry periods with a noticeable reduction in area of active dunes in the late 1960s related to higher rainfall and growth of stabilizing grasses. Hunter et al. (1972) mapped backisland dune migration near the shore of Laguna Madre south of South Bird Island at about 11 m/yr between 1948 and 1968, and Hummel and Kocurek (1984) documented a similar rate of 15 m/yr for the period between 1950 and 1980. Farther to the south in the Green Hill Basin area of northern Laguna Madre, Lohse estimated that the rate of advancement of backisland dunes was about 43 m/yr during the extreme drought period of 1952-1959 (Lockwood, Andrews, and Newnam, 1959). All the historical data indicate that rates of eolian sediment transport are highly variable and depend largely on the period and location of the observations.

The volume of sand recently transported into Laguna Madre by migration of large dunes can be estimated by comparing lagoon shoreline positions mapped on aerial photographs. This time series analysis also reveals that the rate of eolian sediment supply is not constant. For example, sequential shoreline positions from 1948 to 1974 show progressive advancement into Laguna Madre near PA 187, but aerial photographs in 1985 and 1992 show subsequent reworking of the lagoon margin sand and retreat of the shore. From 1948 to 1974, the lagoon

shore advanced an average distance of 367 m and then retreated an average of 50 m between 1974 and 1992. Dune migration in the same area in recent years has been negligible because backbarrier dune fields are covered with dense vegetation. The entire 50 year period (1948-1998) was used to calculate the rate of deposition to avoid biasing the estimate with high rates from drought-dominated periods and overestimating the traction contribution. Assuming that the time-averaged supply of sand was uniform along the 30 km of shore and that the average depth of fill was 0.5 m, then the average rate of eolian sediment supplied by traction in northern Laguna Madre is about 110,000 m^3/yr. This is about half of the total volume of eolian sediment estimated by Ward (Appendix C) to be deposited in northern Laguna Madre (Table 1).

During periods of dune advancement, sand migrated over and buried seagrasses along the lagoon margin but did not reach placement area 187 or the GIWW because the westward transport stops once the sand reaches the open water of Laguna Madre. Field observations and aerial photographs indicate that eolian sand deposition by dune migration and reworking is restricted to a zone about 150 m wide near the low-water shore of the lagoon.

Wind-tidal flats - Where they are present, the wind-tidal flats of Padre Island play an important role in the storage and transfer of sand from the dunes to the lagoon. When the flats are dry, the wind entrains grains of sand, shell, and small particles of mud that are about the size of sand grains. The eroded sediments are transported westward by the predominant southeasterly wind and are either relocated on the flats or transferred into the lagoon depending on the speed and duration of the wind. Wind erosion typically lowers the land surface until the moisture of the sediments prevents further erosion. Thus the elevation of the flats is controlled by the height of the water table. It is through this deflation process that the broad almost featureless flat surfaces are maintained even as additional sediments are added to the flats.

The width of the wind-tidal flats along the western margin of Padre Island and their relationship to the open waters of Laguna Madre are closely related to the stability of the island and sediment supply over geological time. The flats are widest where the island has been relatively stable for several thousand years and where there is an abundant onshore transport of sand (Fisk, 1959). However, flats are narrow along South Padre Island, where the barrier is migrating landward and the sediment supply from the Gulf of Mexico is relatively low. Most of the eolian transported sand is consumed in construction of a washover/wind-tidal flat complex, which forms a platform and serves as a base for eolian transport. The platform elevations are slightly above the long-term average water level in Laguna Madre and the sand in the flats remains saturated or damp much of the time. The flats aggrade vertically at times of higher water level and deflate to lower elevations at times when water levels are lower and the flat surfaces are dry.

How long the dune fields on Padre Island have been active is uncertain, but it is clear that the dune fields along the lagoon margin north of Baffin Bay are a relatively recent addition to the coastal landscape. As illustrated by Hunter et al. (1972), the 1880s topographic maps prepared by the U.S. Coast Survey show that the backisland areas were vegetated and low-lying with distinct small-scale topography including narrow beaches and irregular embayments. Today those same backbarrier areas exhibit a hummocky topography characterized by formerly active dunes that buried the small beaches and embayments.

It is difficult to assess the traction load eolian contribution in central and southern Laguna Madre because the backbarrier geomorphology is different from that in northern Laguna Madre. In central Laguna Madre the wind-tidal flats are broad and the transition from wind-tidal flat to open lagoon is gradational because the gradient of the surface is extremely low (fig. 2c). There is ample evidence that the eolian contribution at present is low. For example, there are no active dunes near the open-water lagoon, the shore parallel bands of algal mats are persistent, there is a pronounced increase in mud toward the open water lagoon, and there is no subaqueous evidence of reworked dune sand along the low-water shore like there is in northern Laguna Madre. Furthermore, comparison of positions of the low-water shoreline in the vicinity of Los Bancos de en Medio suggests that between 1960 and 1975, the low-water shore retreated (McGowen et al., 1977) rather than advanced, as would be expected if eolian supply to the lagoon was significant. In southern Laguna Madre, the dominant processes supplying sediment to the wind-tidal flats are storm washover and wind. Because it is difficult to assign accurate volumes to each of these processes, the sediment budget analysis will assume that the washover process is predominant (Table 1), even though a substantial portion of the washover sand is reworked dune sediments.

Suspension Transport

Unlike migrating sand dunes, which can be mapped and quantified, large volumes of silt and clay can be transported by wind without any readily identifiable morphological features. In order to evaluate this contribution to the sediment budget Ward (Appendix C): (1) analyzed the climatology of wind velocity and wind stress, based on National Weather Service first-order data stations, and short- period records from anemometers on Padre Island (Hsu, 1973), and (2) evaluated transport competency of the wind stress, based on studies of mobilization of particles as a function of applied stress, grain-size distribution, and turbulent structure of the atmospheric boundary layer. Results of this effort provide insight into the winnowing of finer particles from the nearshore and dune fields, long-term variation and seasonality of wind climatology, and probable inland distances of fine-grain sediment transport.

The eolian contribution by aerosols can be indirectly evaluated by examining the silt/clay content in the lagoon sediments. Where dunes historically have been active along northern Laguna Madre near South Bird Island, textural analyses (White et al., 1983) show that most lagoonal sediments consist of sand and only a few samples contain more than 15% of the finer fractions. This low percent of silt and clay coupled with the recent history of dune migration suggests that air borne particulates are not inordinately large contributors to the sediment budget of northern Laguna Madre.

Tidal Inlets

Recent History of Tidally Influenced Channels

The oldest reliable maps and geological analyses of Laguna Madre indicate that only two "permanent" tidal inlets were active after Padre Island became a continuous barrier island several thousand years ago. A narrow and relatively unstable inlet in the Corpus Christi Pass-Newport Pass-Packery Channel area of northern Laguna Madre served as the principal inlet/drain system for Nueces and Corpus Christi Bays. Brazos Santiago Pass apparently has been a stable inlet connecting southern Laguna Madre with the Gulf of Mexico as South Padre Island has migrated landward. Both of these inlets were in extreme northern and southern locations relative to Laguna Madre and the Kenedy County wind-tidal flats that separated the two water bodies. As South Padre Island migrated landward and the delta plain of the Rio Grande subsided, a minor shallow inlet formed at Boca Chica that occupied a former mouth of the Rio Grande. This ephemeral inlet, which allowed water exchange between the Gulf and South Bay, was last open in about 1910 and has not played an important role in the recent sediment budget of southern Laguna Madre or the Gulf Intracoastal Waterway.

Corpus Christi Pass-Newport Pass-Packery Channel

The natural tidal inlet located at the juncture between Corpus Christi Bay and northern Laguna Madre (fig. 1) historically has occupied several positions, and therefore has had several different names including Corpus Christi Pass, Newport Pass, and Packery Channel. These three identifiable inlet locations are within a 6.4 km segment of barrier separating Mustang and north Padre Islands. The inlet was long, narrow, and relatively shallow (less than 3.5 m), and it migrated to the southwest under the influence of net littoral drift (Morton and McGowen, 1980).

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Packery Channel, the last active tidal channel in the area, closed in 1929 as a result of the engineering modifications at Aransas Pass (Collier and Hedgpeth, 1950; Price, 1952) that diverted the flow into the Ship Channel and out the jetties at Port Aransas. Several attempts to reopen Corpus Christi Pass beginning in 1939 were unsuccessful because shoaling of the channel was rapid (Lockwood and Carothers, 1967). The three former passes remain as low, unvegetated areas that are active washovers during major storms. The washover channels are reactivated for brief periods following intense hurricanes such as Beulah and Allen, but they close at their Gulf entrances in a short period.

Brazos Santiago Pass

Brazos Santiago Pass is a natural inlet located at the southern extremity of South Padre Island (fig. 5) that allows tidal exchange between the Gulf of Mexico and Laguna Madre. It is a flood-dominated inlet because freshwater inflow into the lagoon is negligible, evaporation exceeds precipitation, and wind-blown currents commonly flow northward, away from the inlet. Peak tidal currents in the inlet of 140 cm/s were recorded by the Texas Water Development Board (Ruben Solis, personal communication, 1998).

Before it was enlarged and jettied for a deep-draft navigation channel, Brazos Santiago Pass displayed a morphology and dimensions typical of a microtidal inlet. Bars of the ebb delta formed a moderately large shoal with northward asymmetry that extended approximately 1 km into the Gulf and to water depths of about 8 m (fig. 5). The inlet throat was about 10 m deep and incised about 4.5 m into the underlying Holocene Rio Grande delta. According to historical records, the inlet was relatively stable and probably did not migrate as a result of stiff muddy substrates. Both ebb and flood deltas were composed of well-sorted sand containing some shell.

The narrow channel forming the inlet throat bifurcated and became indistinct near the crest of the ebb delta. Multiple tidal channels of the flood delta, which were oriented at high angles to the inlet throat, served both as drains for ebb tides and conveyances for flood tides. Bases and sides of these secondary channels were contained entirely within the unconsolidated sand deposits of the flood delta (fig. 5). South of the inlet the flood tidal delta was entirely submerged and poorly developed partly because the tidal prism of South Bay was small, but more importantly because rapid transgression of the barrier prevented formation of subaerial flats.

Before the Gulf Intracoastal Waterway and Mansfield Channel were constructed, currents in Laguna Madre flowed northward in the summer as a result of high evaporation rates (Breuer, 1962). The high evaporation rates and lack of substantial freshwater inflow to southern Laguna Madre indicates that Brazos Santiago Pass was flood dominated much of the year when winds
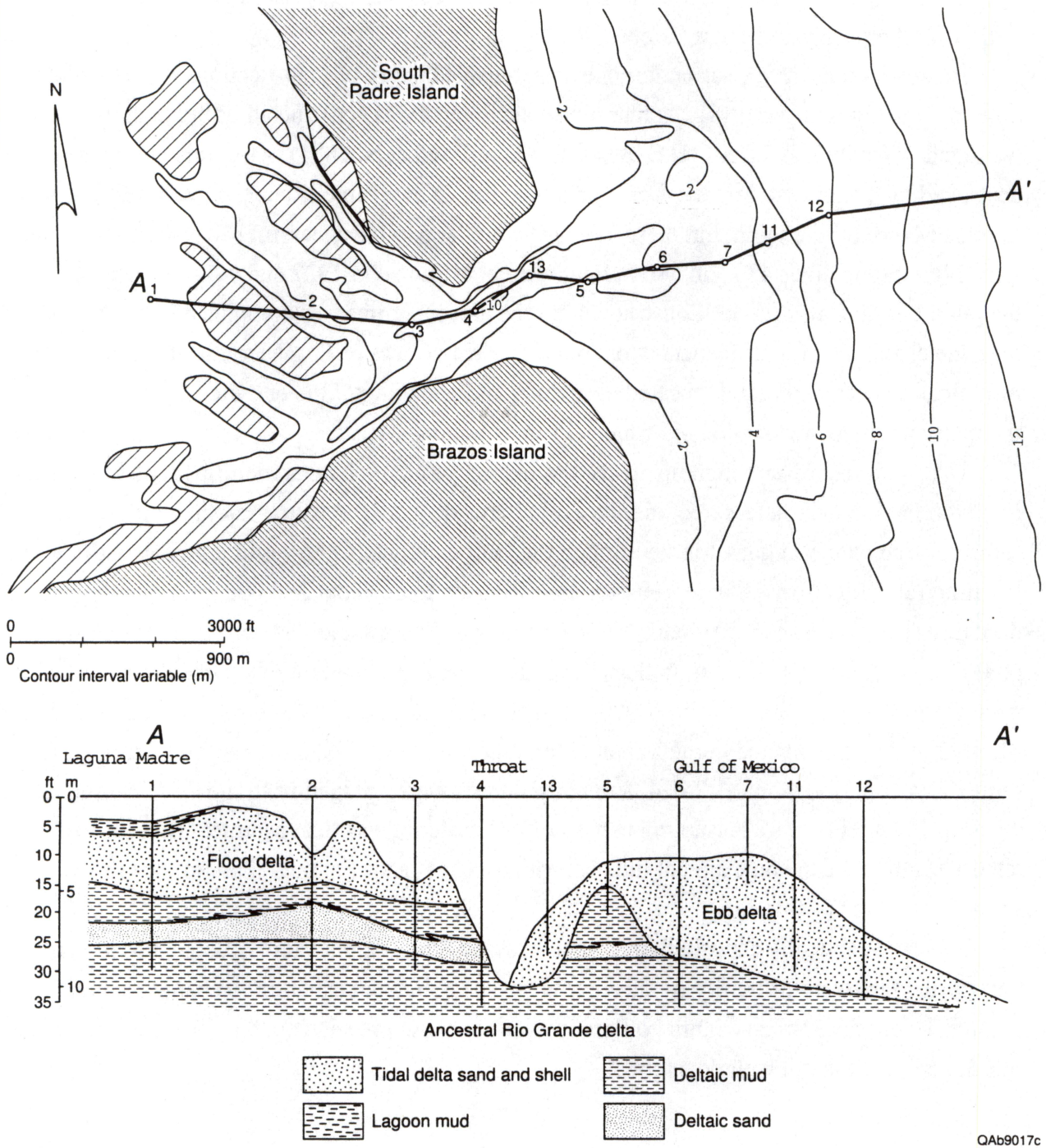
Figure 5. Channels and shoals associated with ebb and flood tidal deltas at Brazos Santiago Pass before inlet modifications. Interpreted from data of the U.S. Army Corps of Engineers, 1919.

were from the southeast and temperatures were high. After the Gulf Intracoastal Waterway and Mansfield Channel were constructed, large-scale circulation patterns developed between northern and southern Laguna Madre and between Brazos Santiago Pass and Mansfield Channel within southern Laguna Madre (Breuer, 1962).

Brazos Santiago Pass has undergone an extensive history of modifications by the Federal government beginning in 1881. At that time a south jetty was constructed of brush mattresses weighted down by clay bricks (U.S. Army Corps of Engineers, 1881). After this work was destroyed by a storm, attempts were made to maintain a navigable channel across the bar and Laguna Madre by dredging, but these attempts were largely unsuccessful because shoaling rates were high. Stone dikes 430 and 580 m long were constructed in 1927 and 1928 on each side of the inlet, but they also failed. Construction on the present jetties was completed in 1935 at which time the channel was also deepened to 7 m (U.S. Army Corps of Engineers, 1936). Subsequent modifications have included repeated deepening and widening of the entrance channel through the inlet and the Brownsville Ship Channel across Laguna Madre.

Dredging records are incomplete for the first 65 years of channel modifications at Brazos Santiago Pass. Nevertheless, records since 1947 are adequate for estimating the volume of sediment that enters Laguna Madre through the Gulf entrance (fig. 6). Initial post-construction shoaling rates for Brazos Santiago Pass were estimated to be about 270,000 m^3/yr on the basis of dredging records between 1936 and 1957 (Lockwood, Andrews, and Newnam, 1959). A longer record of dredging (1947-1996) indicates that the average annual rate of sediment deposition from the jetties to Long Island (299,000 m^3/yr) has remained about the same. Of this total, about 215,000 m^3/yr is deposited in the Laguna Madre portion of the channel (Table 1). During this same 49-year period, about 1,261,425 m^3 of sediment were dredged from the GIWW segment of the Ship Channel (fig. 6). Assuming that all of that material was tidal sediment (not locally reworked) then the average annual tidal contribution at Brazos Santiago Pass to the GIWW is about 25, 800 m^3 (Table 1).

The sands and silts deposited in the Brownsville Ship Channel across Laguna Madre are transported landward primarily by tidal currents. The eolian contribution to channel shoaling in Laguna Madre near Brazos Santiago Pass is minor because the adjacent barrier island is narrow and dune fields are not well developed.

Mansfield Ship Channel

Mansfield Channel is an artificial navigation channel that was dredged to encourage economic development and marine transportation at Port Mansfield. The channel was originally dredged through Padre Island in 1957 by the Willacy County Navigation District (Hansen,
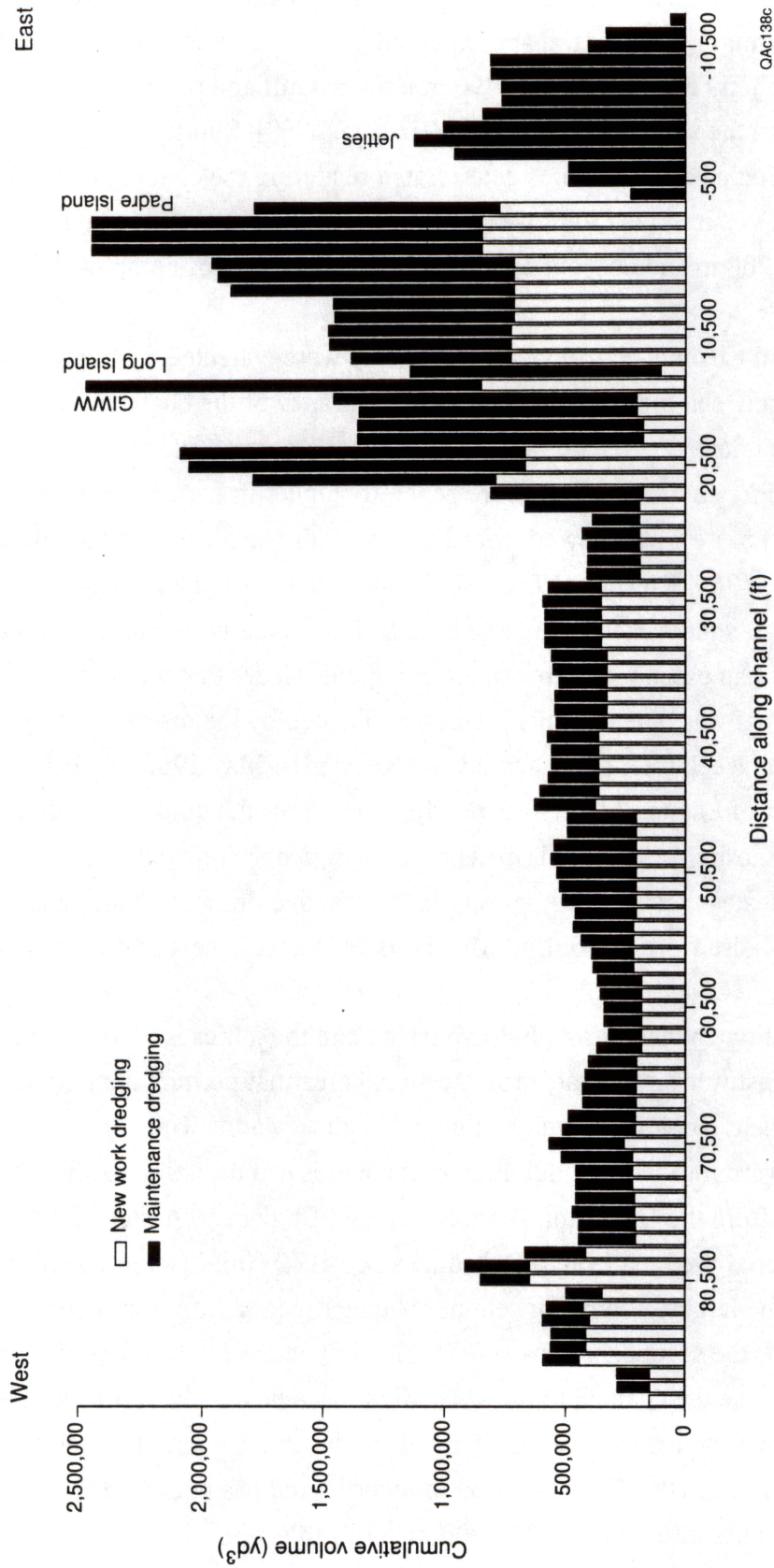
Figure 6. Cumulative volume of material dredged between 1947 and 1996 from the entrance and Laguna Madre segments of the Brazos Island Harbor and Brownsville Ship Channel. Spatial allocations of dredged material are based on records provided by the Galveston District, U.S. Army Corps of Engineers.

1960). The original channel was 30 m wide and 3 m deep across Laguna Madre increasing to 75 m wide and 5 m deep through Padre Island and into the Gulf. Experimental tetrapod jetties were constructed, the north jetty extending about 490 m into the Gulf and the south jetty extending about 270 m from the shoreline at that time (Hansen, 1960). Shortly after its initial construction the channel shoaled and the jetties deteriorated rendering the channel unfit for navigation. In 1959 Congress authorized improvement of Mansfield Channel as a Federal project that extended the jetties to 700 m and deepened the channel. This work was completed in 1962 (Hansen, 1960).

Shortly after Mansfield Channel was reopened, tidal data were collected for approximately two years at six locations between the GIWW and the Gulf entrance of the channel (Hansen, 1960; Kieslich, 1977). The tide gauge records showed that (1) the normal tide range in Laguna Madre is very low (3 to 9 cm), (2) water levels were generally higher in Laguna Madre than in the Gulf of Mexico, and (3) more water flowed from Laguna Madre into the Gulf than in the opposite direction (Hansen, 1960; Kieslich, 1977). The predominance of ebb flow out of Laguna Madre under the influence of southeasterly winds (Kieslich, 1977) clearly demonstrates that Mansfield Channel provides an escape route for water in Laguna Madre that would have flowed northward before the Channel was opened. This is clearly indicated by the discrepancy between ebb flow and flood flow one week after the channel was reopened in May 1962. At that time the volume of water ebbing out of Laguna Madre was nearly seven times the volume flooding in from the Gulf of Mexico (Kieslich, 1977). This exceptionally high ebb flow immediately after reopening the Channel indicates that the Channel acts as an effective drain and that transport of sediment far into Laguna Madre from the Gulf of Mexico is not likely except under unusual conditions.

At present, the navigation channel through Padre Island and the jetties is 75 m wide and 5 m deep. These dimensions constitute a moderate cross-sectional area that permits the flow of moderate volumes of sediment laden water into and out of Laguna Madre. The volume of sediment transported landward into the channel through the jetties can be estimated from the dredging records available from the Galveston District Corps of Engineers. A plot of the cumulative volume of material dredged from the channel since 1962 (fig. 7) shows a strongly bimodal distribution with the largest volume of sediment being dredged from the segment that coincides with Padre Island; the secondary peak reflects shoaling at the intersection of the ship channel with the GIWW. Since the channel to Port Mansfield became a Federal project, maintenance dredging has removed about 5,200,000 m^3 from the channel entrance between stations 0+000 and 8+000. During the 31-year period of record, sand has been transported into the channel at an average annual rate of about 168,000 m^3/yr (Table 1).
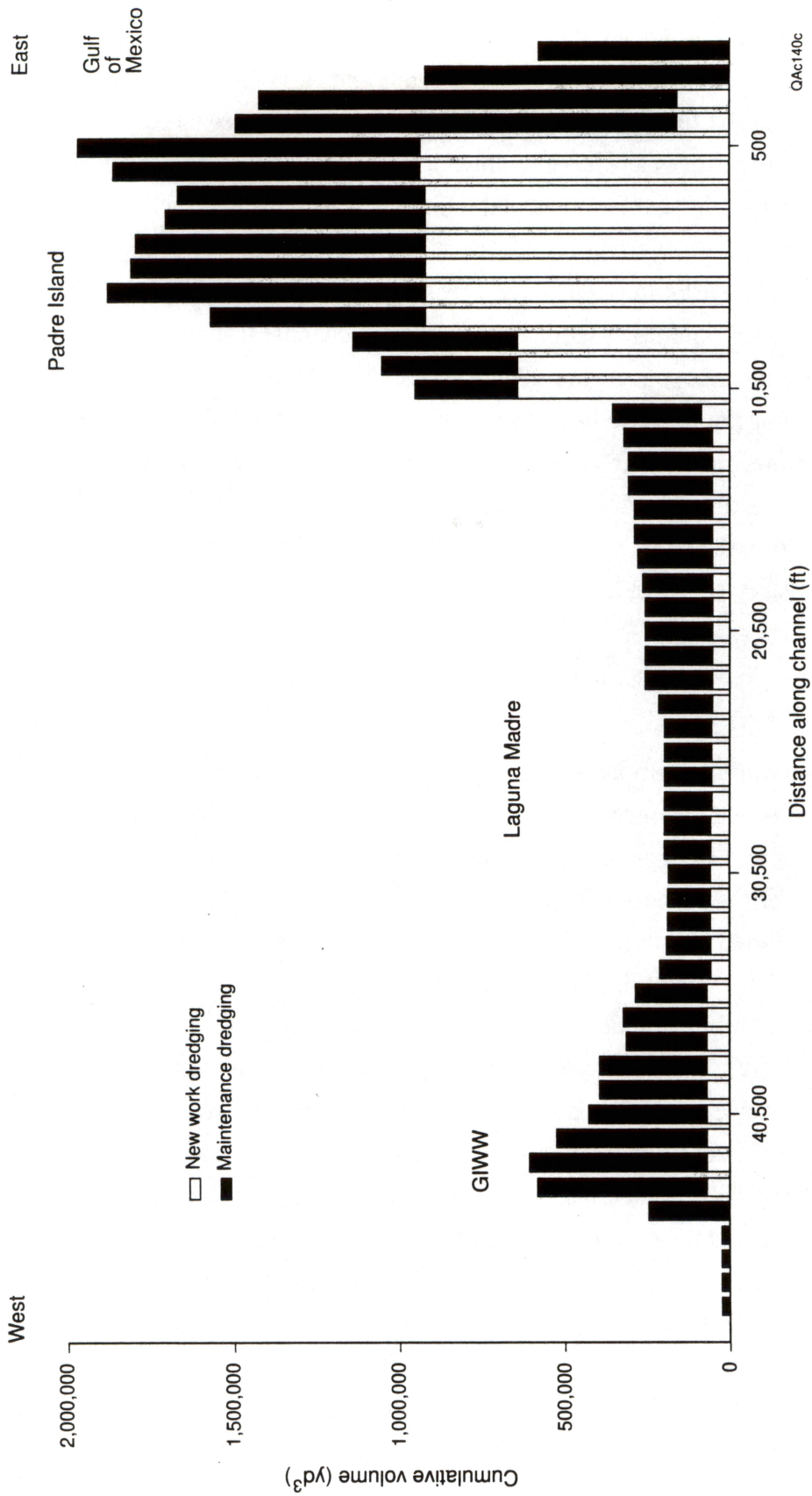
Figure 7. Cumulative volume of material dredged between 1948 and 1994 from the entrance and Laguna Madre segments of the Port Mansfield Ship Channel. Spatial allocations of dredged material are based on records provided by the Galveston District, U.S. Army Corps of Engineers.

Most of the sediment dredged from the channel to Port Mansfield, which is primarily beach quality sand, has been transported and deposited by tidal currents. Some of the sand and silt may have been delivered by wind, especially during the 1960s and early 1970s when the dunes and mounds of dredged material lining the southern side of the channel were largely unvegetated. However in more recent years as a result of abundant rainfall, the dunes and dredged material are densely vegetated and the only bare sand available for easy transport into the channel is on the beach at the south jetty.

The along-channel distribution of material dredged from Mansfield Channel (fig. 6) suggests that only a minor volume of sediment entering the channel from the Gulf is transported farther landward than the lagoon margin of Padre Island. The channel segment between Padre Island and the GIWW is not likely to be a bypass zone for suspended sediments transported by tidal currents. Therefore, shoaling at the intersection of the ship channel and the GIWW is probably from the deposition of sediment derived from within the lagoon and not sediments directly transported from the Gulf. The maximum direct deposition of 95,500 m^3 in the GIWW during the 31 year history (fig. 7) averages about 3,100 m^3/yr (Table 1).

Yarborough Pass

There were at least five attempts by the Texas Fish and Game Commission to dredge a channel across Padre Island at a location known as Yarborough Pass or Murdoch's Landing Pass (Gunter, 1945; Collier and Hedgpeth, 1950). The Texas Legislature authorized the project about 1931 (Bailey, 1933) for the purpose of improving water circulation in Laguna Madre. The inlet and channel were designed to intersect Laguna Madre north of Middle Ground shoal where the barrier island and adjacent wind-tidal flats are relatively narrow and slightly deeper water of the lagoon is closest to the Gulf of Mexico.

Initial dredging of Yarborough Pass began in December 1940 and was completed in April 1941, but the Gulf entrance remained open only for 5 months before it was closed by littoral processes (Breuer, 1957). Additional attempts were made to open the pass in November 1942, May 1944, November 1944, and February 1952. After the last attempt to establish tidal exchange between Laguna Madre and the Gulf of Mexico, the channel entrance shoaled in about three weeks (Breuer, 1957). Eventually the foreisland dunes were reestablished naturally in the vicinity of the abandoned pass and now the beach-dune zone is essentially the same as conditions that existed prior to dredging.

Although no sediment budget data were collected during the brief period that Yarborough Pass was open, it is apparent that no significant volumes of sediment were transported far into Laguna Madre through the channel. Channel shoaling was always at the beach entrance, which

closed rapidly, preventing lagoonward transport by tidal currents. Large migrating eolian dunes eventually closed most of the channel where it crossed Padre Island, and a short segment of the channel at the lagoon shore has been kept open by dredging to support oil field activities on the barrier island.

Storm Washover

Sediments transported into Laguna Madre by barrier washover during storms are spatially restricted to the lagoon margins of Padre Island and those segments of the barrier that are narrow and where washover channels breach the dune ridge. Sediment washover into Laguna Madre (fig. 4) is concentrated along South Padre Island between La Punta Larga and Brazos Santiago Pass, where the barrier island is migrating landward (Brown et al., 1974; Morton, 1978). Therefore the most significant contribution of washover to the sediment budget during recent storms, such as Hurricanes Beulah (1967), Anita (1977), Allen (1980), and Gilbert (1988), is in southern Laguna Madre. Washover channels that breach the dunes are also present along central Padre Island extending from just south of The Hole (northern Laguna Madre) and Big Shell Beach to south of Mansfield Channel in the vicinity of La Punta Larga. However, post-storm photographs clearly show that along this barrier segment washover sediments are deposited as fans in interdune storm runways (Hayes, 1967) or on the broad wind-tidal flats that form the eastern margin of the lagoon. These washover fans do not extend entirely across the island to the open waters of the lagoon as they do farther to the south.

The semiarid climate as well as rapid migration and frequent inundation of South Padre Island prevent a vegetated barrier flat from forming. Hence, the predominant morphological characteristic is the alternation of dune clusters and washover channels in a shore-parallel direction. At least 60 washover channels were opened during back-to-back hurricanes in 1933 and an equal number were reported following Hurricanes Beulah and Allen (U.S. Army Corps of Engineers, 1981). The closely spaced washover channels are frequently occupied by high-velocity currents flowing across the island. Large storm channels scour deep axial troughs midway between the Gulf and Laguna Madre as a result of phase differences in storm surge and flow constriction between clusters of dunes.

Large sand waves oriented perpendicular to the barrier trend form the outer fringes of washover fans where they terminate in Laguna Madre (Morton, 1979). The transverse bedforms have wavelengths from 50 to 85 m and amplitudes less than 0.5 m. Their down-current asymmetry and convex curvature indicate preferential development and slightly higher rates of downcurrent migration at intermediate water depths. These sand waves represent redistribution of distal washover fans by northward flowing wind-driven currents. Conditions are optimum for

their formation just after hurricane landfall when winds change direction and the flats are still flooded. Apparently their development is limited to broad, barren sand flats on the barrier platform where shallow water depths and high wind stress promote sediment transport parallel to the barrier axis (Morton, 1979).

An approximate volume of sand transported into Laguna Madre by storm washover can be calculated by examining the rates of backbarrier progradation on North Padre Island in the vicinity of Packery Channel and on South Padre Island north of the developed area.

North Padre Island

Since the closing of Packery Channel in 1929, the low, barren sand flats of the Corpus Christi Pass-Newport Pass-Packery Channel area have functioned as a zone of washover between the Gulf and extreme northern Laguna Madre. Sequential shoreline positions of Laguna Madre mapped from aerial photographs in 1967 and 1982 show general migration of the shore as a result of washover associated with Hurricane Allen in 1980. The zone of backbarrier migration ranged in width from 30 to 300 m, and averaged 145 m wide along the 400 m of shore that fronts the washover area (fig. 4). Assuming that the average thickness of the deposit, which is equal to the depth of shoaling, is about 0.3 m across the zone of washover, the total volume of sand deposited along the backbarrier margin of North Padre Island is about 17,520 m^3. This works out to be an average rate of about 1,200 m^3/yr (Table 1) for the 15 year period. The GIWW is within 2 km of the zone of washover deposition but the high mounds of dredged material between the washover and GIWW effectively block any direct transport into the navigation channel. Therefore the minor average annual volume of washover sand transported into Laguna Madre is not a significant contributor to shoaling in the GIWW.

South Padre Island

Backbarrier shoreline positions of South Padre Island mapped on aerial photographs span the 14 year period from 1955 to 1969, which includes a major washover and depositional event associated with Hurricane Beulah in 1967. The zone of backbarrier migration ranged in width from 60 to 480 m, and averaged 247 m along the 14.6 km length of shore that is significantly influenced by storm washover (fig. 4). Dunes are also active along this same segment of beach, so a minor amount of the backbarrier migration may be attributed to eolian deposition, but post-Beulah aerial photographs indicate that any eolian contribution is minor compared to the washover event. Assuming that the average thickness of the deposit, which is equal to the depth

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of shoaling, is about 0.3 m across the zone of washover, the total volume of sand deposited along the backbarrier margin of South Padre Island is about 1,100,800 m³. This works out to be an average rate of about 78,600 m³/yr (Table 1) for the 14 year period.

This volume is a reasonable number for a major hurricane of historical record, but it may overestimate long-term average annual rates of sediment transported into Laguna Madre by washover processes. Along the Gulf shore of South Padre Island where washover channels are predominant, long-term average annual retreat rates are about 3 to 4 m/yr (Morton and Pieper, 1975), which is substantially less than the average backbarrier migration rate of 17 m/yr. South Padre Island is a migrating, or transgressive barrier island, and it is not likely that it is growing wider as a result of washover. Therefore the long-term average volume of sand delivered to Laguna Madre by washover is probably less than the value derived from the shoreline changes between 1955 and 1969. Even though the volume of sand entering Laguna Madre as a result of washover is measurable, the volume of externally derived sediment deposited in the GIWW by washover is probably negligible (Table 1) because the zone of greatest deposition is more than 4.5 km seaward of the GIWW.

Upland Runoff

During and after heavy rains in south Texas, water drains into Laguna Madre from higher elevations transporting some sediment, mainly in suspension, that was eroded from upland areas. The lack of a well integrated network of streams on the upland surface between Corpus Christi Bay and the Rio Grande demonstrates that upland runoff is significant only in two areas; the Baffin Bay drainage of northern Laguna Madre and the Arroyo Colorado and North Floodway drainage of southern Laguna Madre. Between Baffin Bay and the Arroyo Colorado, the coastal plain is covered by a thick sand sheet that has been molded by eolian processes. This sand sheet has internal drainage and no surface expression of an organized drainage system. Furthermore, the predominant sediment transport directions are landward and away from Laguna Madre not toward it (dune migration is onshore), so the Kenedy Ranch is not a source area of significant sediment delivery to Laguna Madre.

Greiner (1982) used the universal soil loss equation (USLE) to estimate gross erosion and average annual sediment yields at various points within drainage basins along the Texas coast including those bordering Laguna Madre. Greiner (1982) divided the upland area between Corpus Christi Bay and the Rio Grande into five subbasins and calculated the average annual erosion caused by particle detachment and overland flow at a point for each subbasin. This value was then applied to the area within the subbasin to estimate the average annual sediment delivered to Laguna Madre (Table 2).

Table 2. Estimated average annual sediment volume delivered to Baffin Bay, the Arroyo Colorado, and the margins of Laguna Madre by surface runoff. Sediment yield data and drainage areas from Greiner (1982).

Subbasin Code	Area acres	Sediment Yield tons/ac	Sediment Rate tons/yr	Sediment* Rate m³/yr	Geographic Region
258	74,573	0.10	7,457	4,218	Pita Island to Baffin Bay
259	850,387	0.15	127,558	72,163	Northern Baffin Bay
260	1,289,178	0.18	232,052	131,278	Southern Baffin Bay
262	1,989,706	0.07	139,279	78,794	Baffin Bay to Pt. Mansfield
263	1,576,057	0.38	598,902	338,816	Pt. Mansfield to Rio Grande
Total			1,105,248	625,270	

* Converted using 0.566 m^3/ton

Baffin Bay Drainage System

Baffin Bay is the head of a former minor incised valley that was excavated during the falling phases and lowstands in sea level associated with Wisconsin glaciation; the valley was later partly filled during the rising phase (Holocene transgression) and highstand in sea level (Behrens, 1963; Brown et al., 1977). The primary tributaries to Baffin Bay (Olmos Creek, Tunas Creek, San Fernando Creek) are headwardly eroding streams that drain the surrounding upland, which is composed of Pleistocene muds and sands that were deposited by deltas and rivers during a pre-Wisconsin highstand in sea level. The creeks that empty into Baffin Bay are ephemeral, and their combined discharges are the least of any bay along the Texas coast (Texas Department of Water Resources, 1983). Normally they are dry or have minor flows after rain, but they delivered more than 123,300,000 m^3 of water as a result of the flooding associated with Hurricane Beulah in 1967 (Grozier et al., 1968).

The ephemeral streams transport minor volumes of sediment into Baffin Bay. However, the lack of well developed marshes or historical progradation of the mud and sand flats near the mouths of the streams is clear physical evidence that sediment transport is insignificant (Texas Department of Water Resources, 1983). Sediment deposited in Baffin Bay is composed of more than 90% silt and clay (White et al., 1989). These fine-grained muddy sediments decrease in grain size toward the bay center, where water depths are greater than 2 m. Most of the sediment load that is delivered to Baffin Bay by the creeks or is eroded by waves from the surrounding bluffs and other shores is deposited in the deeper central part of the bay. Water depths in Baffin Bay are deepest in the center and shoal at its mouth where it joins Laguna Madre. This barred basin morphology makes it an efficient sediment trap. Only minor volumes of sediment are either flushed through the system by exceptionally high discharge or escape as suspended sediment reworked from the bay floors. Therefore little sediment delivered to Baffin Bay is available for redistribution into Laguna Madre, including shoaling of the GIWW.

The volume of sediment delivered each year to Baffin Bay by the surrounding creeks can be estimated using the sediment yield values reported by Greiner (1982). Approximately 203,441 m^3/yr is available for transport from the two subbasins into the upper reaches of Baffin Bay (Table 2), but it is estimated that only about 10% (20,000 m^3/yr) leaves the system and enters Laguna Madre. The estimated volume of sediment delivered each year to northern Laguna Madre consists of the upland runoff from the mainland between Pita Island and Baffin Bay (4,200 m^3/yr) and the volume that leaves Baffin Bay (20,000 m^3/yr, Table 1). Of the 24,000 m^3/yr entering northern Laguna Madre, it is estimated that less than 10% (2,400 m/yr) is deposited directly in the GIWW (Table 1).

Arroyo Colorado and North Floodway

The Arroyo Colorado is a headwardly eroding coastal plain stream that occupies the
northeastern side of the Holocene Rio Grande delta system. Radiocarbon dates reported by
Fulton (1975), McGowen et al. (1977), and Herber (1981) indicate that the Resaca de los Cuates
distributary system of the Rio Grande delta was active between 5,000 and 2,700 years ago.
Deltaic deposits of the Arroyo Colorado cut across and onlap the Resaca de los Cuates, therefore
the Arroyo Colorado system is younger than the Rio Grande delta lobe that was abandoned when
the locus of deltaic deposition shifted to the south near the mouth of the modern river (Lohse,
1958). During its most active period of headward erosion and progradation, the Arroyo Colorado
transported enough sediment to the margin of Laguna Madre to build a small delta with levees
along the channel margins (Brown et al., 1980) and a shallow prodelta platform across Laguna
Madre. A flood relief and navigation channel was dredged connecting the Arroyo Colorado to
Laguna Madre just south of the delta of the Arroyo Colorado.

At present, the Arroyo Colorado cutoff channel and North Floodway comprise a major
network designed to divert excessive discharge from the Rio Grande to Laguna Madre. In
addition to storm runoff, the Arroyo Colorado carries moderate loads of sewage and industrial
waste that are discharged from Harlingen and other communities along the channel (Galtsoff,
1954; Greiner, 1982; Davis, 1983, 1985, and Davis et al., 1995). Also, more than 1,600 linear km
of drainage ditches and irrigation canals constitute an artificial drainage system for return flows
that is interconnected with the Arroyo Colorado and North Floodway (Brown et al., 1980).

The floodway was completed in 1926 and was used 9 times before the record flooding in
September and October 1967 associated with exceptionally high rainfall of Hurricane Beulah
(Grozier et al., 1968). With Beulah, about 710 million m^3 of water were discharged into Laguna
Madre through the Arroyo Colorado channel and about 974 million m^3 through the North
Floodway (Grozier et al., 1968). This is the gauged flow and does not take into consideration the
unchannelized overland flow and minor drainages into Laguna Madre.

Surveys conducted by the International Boundary and Water Commission and Davis et al.
(1995) show that concentrations of suspended sediments in the Arroyo Colorado and North
Floodway are proportional to discharge (fig. 8) and flow velocities. Unfortunately, very few
sediment samples have been collected from any of the drainage systems during the high
discharge events that are responsible for delivering the largest volume of sediment to Laguna
Madre. Textural analyses of both bottom and suspended sediments from the Arroyo Colorado
between Harlingen and Laguna Madre show that the load is composed of more than 90% silt and

A

B
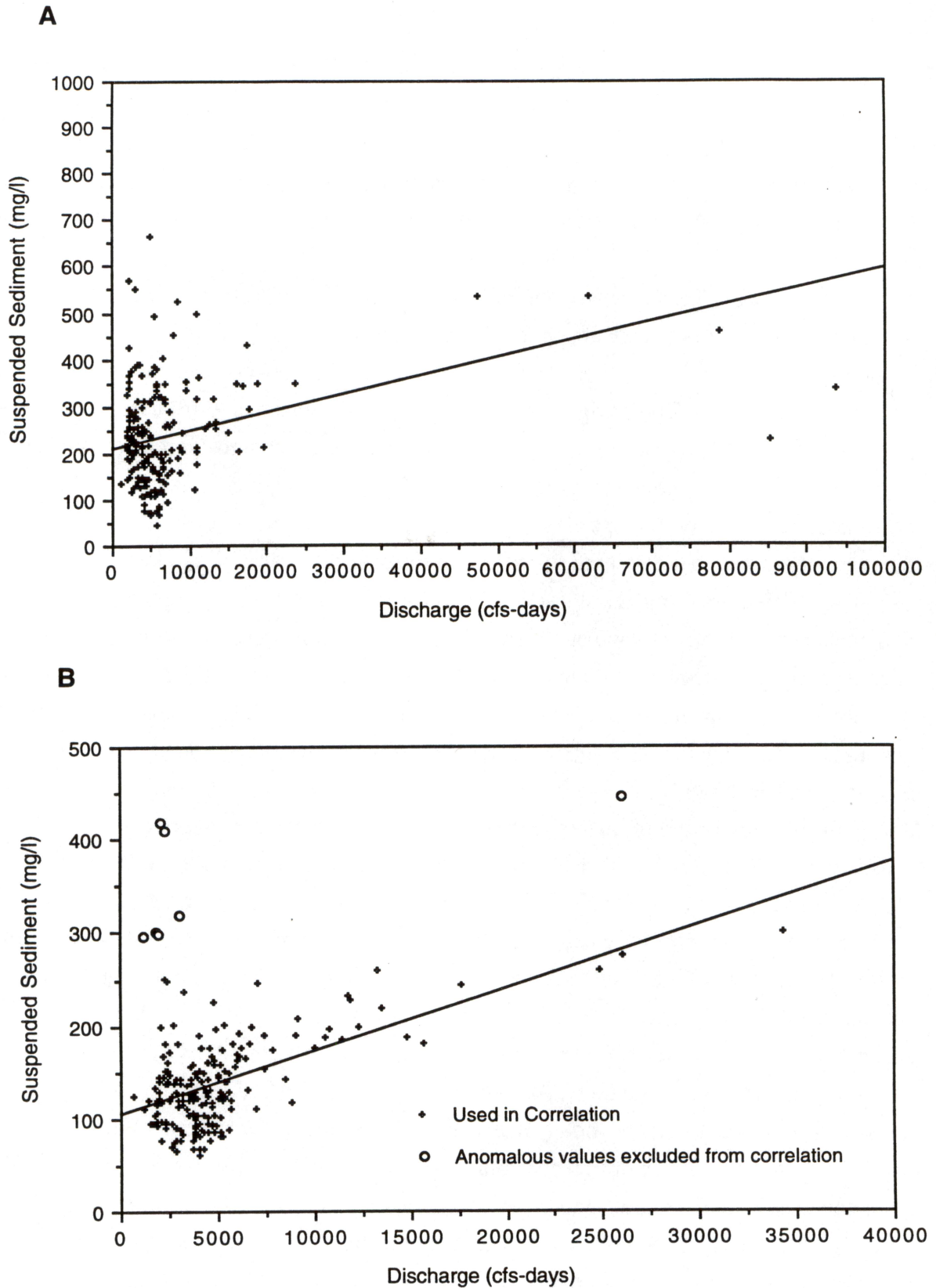
Figure 8. Relationships of suspended sediment and stream discharge at the A. North Floodway near Sebastian and B. Arroyo Colorado El Fustes gauging stations, 1966-1982. Data are from the International Boundary and Water Commission.

clay (U. S. Geological Survey, 1988-91; Davis et al., 1995). Concentrations of suspended sediments decrease downstream (fig. 9) because flow velocities decrease substantially where the dredged channel is influenced by water levels in Laguna Madre (Davis, 1983 and 1985). Sediments transported by the North Floodway are also mostly composed of silt and clay (66%, Davis et al., 1995) but near the termination of the channel they contain more sand than does the Arroyo Colorado.

A report by the Texas Department of Water Resources (1983) concluded that relatively small amounts of sediment are deposited in Laguna Madre from the Arroyo Colorado or North Floodway due to their low channel gradient and the fact that they carry mainly storm runoff and irrigation return flows. The dredged depth of the navigation channel (5 m) has greatly reduced the gradient of the Arroyo Colorado, which has caused the channel to aggrade or deposit its load in the reach where the gradient was artificially changed by dredging, which is at Harlingen. Some sediment, mostly in suspension, is flushed through the system, but that volume appears to be minor compared to the volume stored within the channel as a result of altered gradient.

The efficient trapping and storage of sediment in the lower reaches of the Arroyo Colorado is independently verified by the cumulative volume of sediment dredged from the navigation channel between Harlingen and the GIWW (fig. 10), which shows that much of the sediment transported by floodwaters and upland runoff is deposited in the upstream reaches of the Arroyo Colorado and does not reach Laguna Madre. According to records provided by the Galveston District Corps of Engineers, slightly more than 14.5 million m^3 of sediment have been removed during the 47 year period of maintenance dredging, at an average annual rate of 309,053 m^3/yr. This value of 309,053 m^3/yr also agrees well with the average annual sediment delivery (Table 2) for the Arroyo Colorado drainage (338,816 m^3/yr) calculated from the data reported by Greiner (1982). The difference between the two values (approximately 30,000 m^3/yr or 10%) is a reasonable estimate of the volume of sediment that actually is flushed through the channel and deposited either on the margins of Laguna Madre or within the GIWW (Table 1). Ten percent is also a gross estimate of the sediment delivered to coastal areas compared to sediment yield within drainage basins in the U.S. (Osterkamp and Toy, 1997). Sediment storage, for example on hill slopes, in floodplains, and along channel margins, accounts for the other 90%.

The spatial deposition of upland supplied sediment is also confirmed by dredging volumes along the GIWW at the entrance to the Arroyo Colorado cutoff channel. Although the frequency of dredging at the entrance (PA 226) has been moderately high (14 times since 1952), the volumes of sediment removed are low, averaging only about 4,200 m^3/yr (Table 1).
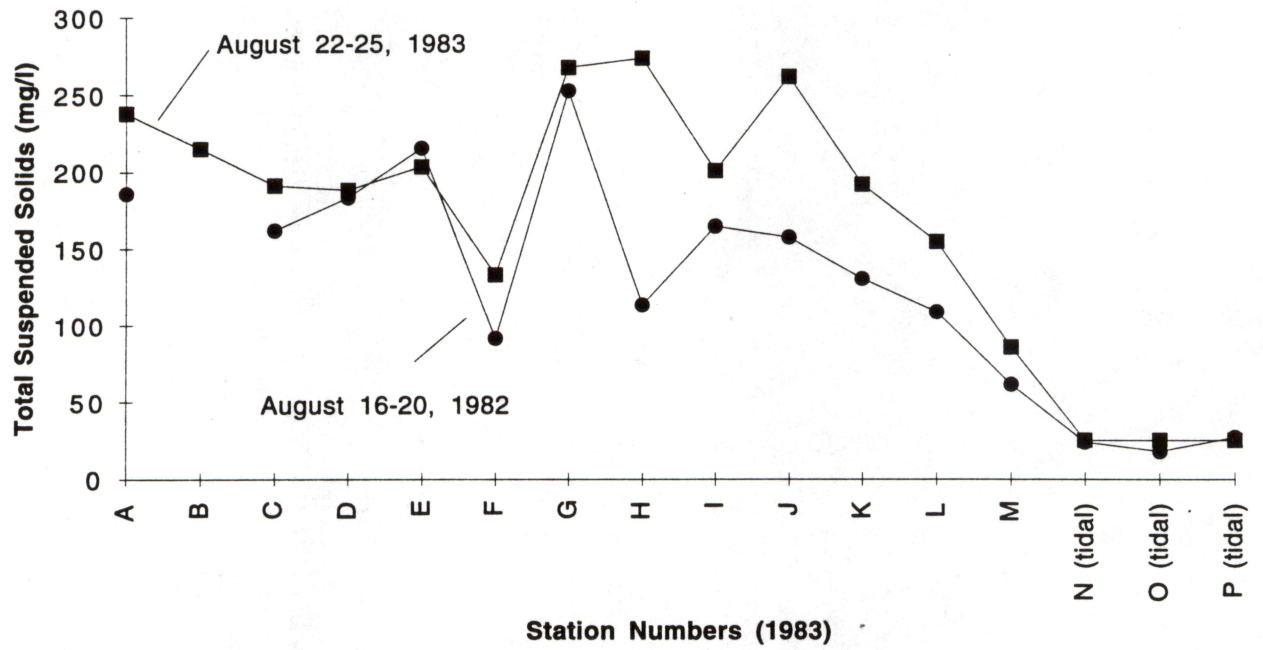
Figure 9. Downstream changes in concentration of total suspended solids in the Arroyo Colorado from Harlingen to Laguna Madre. Data are from Davis (1983 and 1985).
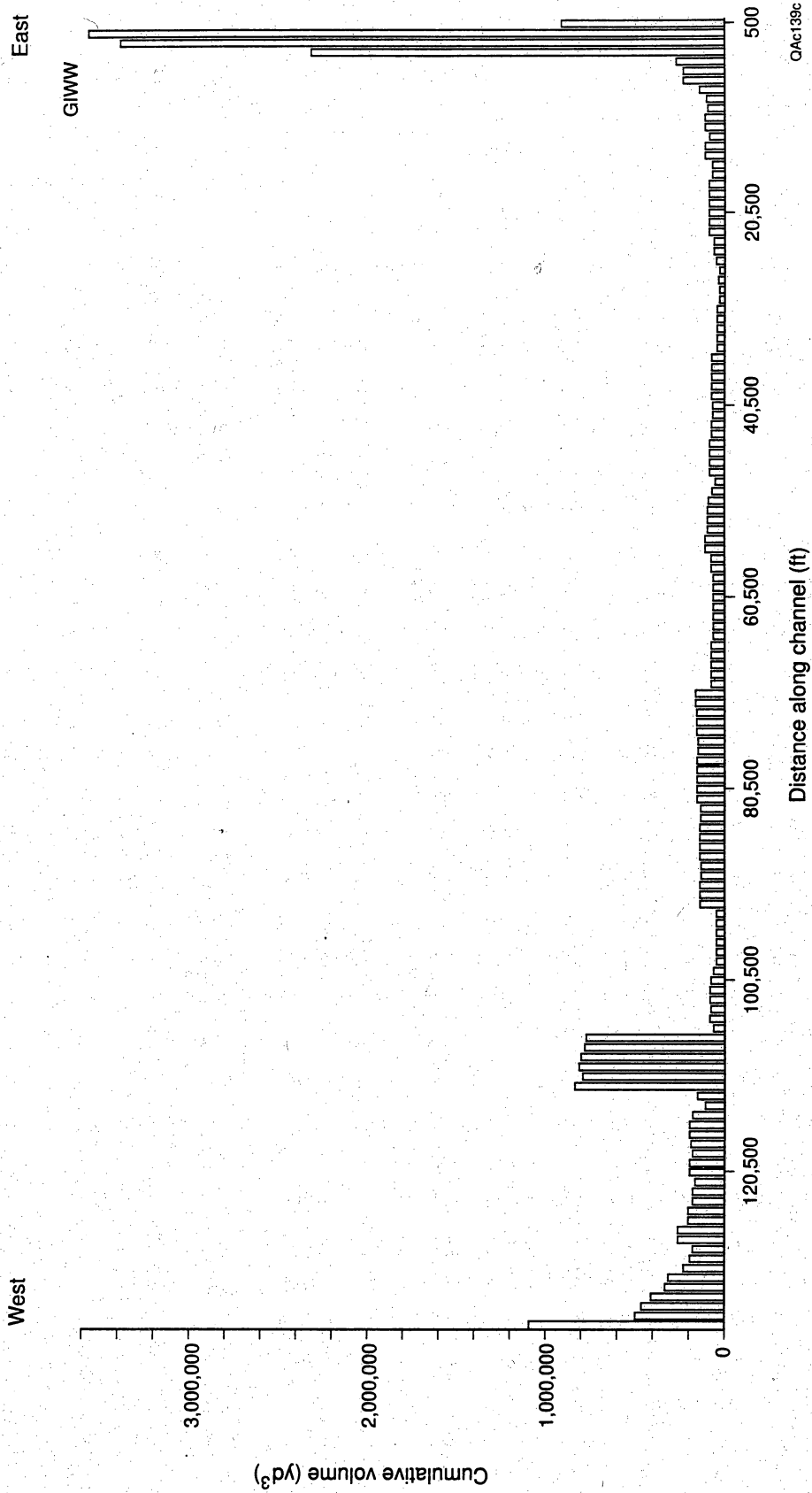
Figure 10. Cumulative volume of material dredged between 1948 and 1995 from the Harlingen Ship Channel (Arroyo Colorado). Spatial allocations of dredged material are based on records provided by the Galveston District, U.S. Army Corps of Engineers.

Other Local Discharges

Slope wash from the western margin of Laguna Madre adds only a very minor amount of sediment to the wind-tidal flats, and deposition of the slope wash material is areally restricted to a narrow zone where the uplands merge with the flats. Therefore slopewash is not an important source of sediment for Laguna Madre or the GIWW.

Minor volumes of water and sediment are discharged locally into southern Laguna Madre in association with shrimp farms (Buzan, 1996) and other mariculture activities located near the shores. Although no quantitative data are available to calculate the average annual sediment influx into Laguna Madre from these sources, the volume has increased in the past two decades as the number and size of the operations has increased.

Land Use - Lower Rio Grande Valley

Land use in the Lower Rio Grande valley was examined to determine if significant historical changes have occurred that might have influenced upland sediment yield and sediment deposition in Laguna Madre. Since the early 1900s, 95% of the Tamaulipan native brushland has been cleared for agricultural, urban, and recreational development (Jahrsdoerfer and Leslie, 1988). The predominant current land use in the Lower Rio Grande Valley is agriculture. In the Cameron, Hidalgo, Willacy County area, land used as cropland and related agriculture makes up between 54 and 62% of the area, and rangeland about 30 to 35% of the area (Tables 3 and 4). These proportions have remained relatively stable for at least the past two decades.

The predominant land use in the Valley also can be inferred from water allocations. The Rio Grande provides more than 97% of the water used in the Valley and irrigation comprises about 85% of the total water use (McCoy, 1990). The area of land under irrigation in Cameron, Willacy, Hidalgo, and Starr counties remained relatively constant from 1958 to 1989 (fig. 11) because of the adjudicated water rights to the use of Rio Grande waters (TWDB, 1991). Water use was greatest in 1980, and projections based on consumption in 1980 and 1985 suggest that water use through the year 2010 will not exceed that used in 1980 (McCoy, 1990). Although municipal water use is projected to slowly increase, the additional demands will likely be fulfilled by reduced irrigation.

There has been a steady growth in population in the Lower Rio Grande Valley since the 1900s. The estimated population in 1995 of the four county area (Cameron, Hidalgo, Starr, and Willacy) was 858,515, an average increase by county of almost 20 percent over the 1990 population (Dallas Morning News, 1997). The general trend in land use appears to be one of

Table 3. Land use in the Lower Rio Grande Valley in the mid-1970s. Includes Cameron, Hidalgo, and Willacy Counties. From Kier and Fruh (no date).

Land Use	Area (acres)	Percent
Cropland	1,286,060	54
Range-Pasture Land	678,650	29
Natural and Man-Made Water Features		8
Barren Sand and Muddy Sand		5
Urban and Industrial Land	73,349	3
Subaerial Spoil and Made Land		0.4
Marshes		

Table 4. Land use in the Lower Rio Grande Valley including Cameron, Hidalgo, and Willacy Counties. From Texas Water Commission Report WLE 90-04 (1990).

Land Use	Percent
Agricultural use	62.4
Rangeland	34.7
Residential	1.8
Industrial	0.8
Commercial	0.4

Combined population of 510,545 in 1980

Other land use identified but not quantified included open space, mixed urban, forest land, water, wetlands, barren land and institutional.
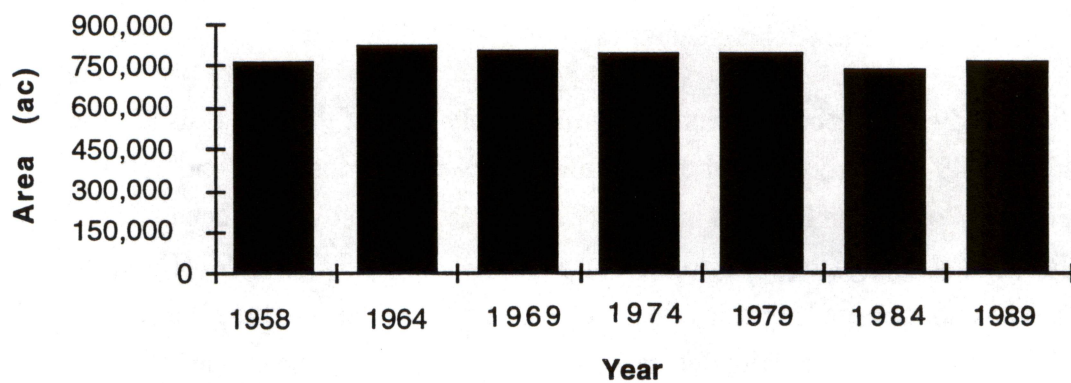
Figure 11. Irrigated acreage in the Lower Rio Grande Valley from 1958 to 1989. Includes Cameron, Hidalgo, Starr, and Willacy Counties. From Texas Water Development Board (1991).

urban development at the expense of agricultural land, but urbanization has also contributed to clearing of native brush, for example associated with housing subdivisions on many resacas (Jahrsdoerfer and Leslie, 1988). The recent urbanization of agricultural land has not been so extensive that the areal proportions have changed (see Tables 3 and 4).

Based on general trends since the 1950s and the fact that most of the land had been cleared by then, it is doubtful that land use changes have contributed to significant changes in sediment delivery and deposition in Lower Laguna Madre. This conclusion is also supported by sediment load measurements and geomorphic observations along the Arroyo Colorado in particular where it intersects with Laguna Madre.

Land Use - Kenedy and Kleberg Counties

In Kenedy and Kleberg Counties, approximately 64% of the land is used for agriculture, of which about 4% is cultivated and the remaining 96% is used for range and pasture land (Brown et al., 1977). Population changes in these two counties generally have been minor. Although the population in Kleberg County increased by about 4% from 1990 to 1995 (Dallas Morning News, 1997), it has not changed significantly since the 1960s (Dallas Morning News, 1971). In Kenedy County, the population actually decreased from 884 in 1960 to an estimated 330 in 1995. Based on aerial photographs taken in the 1950s-60s and in 1979, there is little evidence of land use changes in these counties at a scale that would have significantly increased sediment transport into Baffin Bay and Laguna Madre during this period. Supporting this conclusion is the observation that seagrass beds have become established in the Baffin Bay system since the 1950s (Martin, 1979).

Erosion of Lagoon Margin

A minor volume of lagoon sediment is supplied by erosion of the uplands and wetlands bordering Laguna Madre. Although rates of erosion around the margin of Laguna Madre have not been systematically quantified, most of the western shore from North Bird Island to Rocky Slough (northern lagoon) and from Rincon de San Jose to Port Mansfield and Stover Cove to Port Isabel (southern lagoon) exhibit morphological evidence of long-term erosion (fig. 4). Low wave-cut scarps, shore parallel zones without vegetation, dislocated blocks of cemented beach rock, and irregular or serrated shoreline shapes observed along the western shore are all reliable field indicators of erosion by lagoonal waves and currents even though the lagoon is relatively calm much of the time.

The component of the sediment budget that is attributable to erosion of the lagoon shores can be calculated by making reasonable estimates of the average rate of retreat and depth of scour. If the 130 km western lagoon shore is eroding at an average annual rate of 0.3 m/yr and the average depth of erosion is 0.6 m, then the volume of sediment liberated for redistribution would be 23, 400 m^3/yr (Table 1). The composition of the eroded sediments controls the degree of subsequent reworking and potential for transport either into the GIWW or to other parts of the lagoon. The western shore of northern Laguna Madre is composed primarily of sand or indurated sand and coquina (beach rock). Once eroded, these sediments are probably deposited near the erosion site and cover the floor of the adjacent lagoon. In contrast, some segments of the western shore and floor of southern Laguna Madre are composed of sand and shell whereas others are composed of mud. Erosion of the muddy segments releases fine-grained suspended sediment that increases turbidities and can be transported long distances from the erosion site before it is deposited.

Chemical and Biochemical Sediments

The preceding discussion of sediment budget focuses on the clastic (broken) material derived from the land that is transported into Laguna Madre from external sources. However, there are autochthonous sources of sediment within the lagoon, such as chemical precipitates and the biogenic detritus that is generated through the birth, life, and death cycle of marine organisms. On the basis of sediment composition determined for many samples from Laguna Madre (White et al., 1983; 1986; 1989), the contribution of biochemical components to the sediment budget is estimated to be approximately 4% of the total volume of clastic sediments (Table 1). There is no evidence that authigenic sediments are forming directly in the GIWW and the muddy channel bottom is not preferred habitat for mollusks. Therefore direct deposition of precipitates in the GIWW is negligible (Table 1).

Carbonates and Evaporites

The highest concentrations of chemical precipitates are associated with the brines that make up the shallow ground water beneath the wind-tidal flats. The origin and movement of these waters have been studied by Fisk (1959), Amdurer (1978), Gudramovics (1981), and Long and Gudramovics (1983). All of these studies show that the highly saline water beneath the flats has

a marine origin. Sea water periodically floods the flats resulting in a layer of water that ranges in thickness from a thin film to more than a meter. Some of the saline water drains off the flats, some infiltrates the sediments of the flats, and some of the water evaporates from the surface. It is the evaporation of the surface water and shallow ground water that produces the carbonate and evaporite minerals; additional contributions come from the microbial processes associated with the algal mats (Masson, 1955; Fisk, 1959).

The wind-tidal flat deposits contain crystals and thin layers of aragonite, calcite, dolomite, gypsum, and halite. Aragonite, calcite, and dolomite are referred to as carbonate minerals because they are composed of calcium carbonate. Gypsum is composed of calcium sulfate and halite is composed of sodium chloride, which is the same as common table salt. Gypsum and halite are known as evaporite minerals because they commonly form as precipitates from evaporating sea water.

The gypsum in the wind-tidal flat sediments occurs in three forms: (1) layers or lenses of granular gypsum, (2) single bladed crystals or small interlocking crystalline aggregates (gypsum rose), and (3) discrete nodules without any crystalline shape. The continuous thin beds and lenses of gypsum were deposited at or near the surface by evaporating sea water (Fisk, 1959; Masson, 1955; McBride et al, 1992). In contrast, the discrete nodules, crystalline aggregates, and single bladed crystals were precipitated in the porous sand by highly saline ground water that is periodically recharged by marine water flooding the flats (Fisk, 1949; Amdurer, 1978; Gudramovics, 1981; Long and Gudramovics, 1983).

Oolites are also nonskeletal chemical precipitates, but they form at the surface in warm, shallow, agitated hypersaline water that is saturated with respect to calcium carbonate. Oolites are concentrated in shoals and bars near the shore; in Laguna Madre their abundance decreases rapidly away from the shore in slightly deeper water (Rusnak, 1960a). Oolites and coated grains grow by nucleation around some preexisting grain such as a shell fragment or clastic mineral. Several workers (Rusnak, 1960a; 1960b; Freeman, 1962; Behrens, 1964) have reported oolites in the sand fraction in sediments bordering the western margin of northern Laguna Madre near the mouth of Baffin Bay. Oolites are areally limited in their distribution and their concentrations are less than 10%, so they constitute only a very small percentage of the total authigenic sediments in Laguna Madre.

Shells, Tests, and Reefs

Whole shells and shell fragments of marine mollusks are common constituents in all of the cores and most of the sediment samples from Laguna Madre. The primary contributors to this class of sediments are the mollusks, including both pelecypods (clams) and gastropods (snails).

The shells occur either as individual pieces or as concentrated deposits mixed with the other sediments. The most abundant mollusk species in the sediments of Laguna Madre are *Anomalocardia auberiana* and *Mulinia lateralis* (Fisk, 1959; Rusnak, 1960a; White et al., 1983; 1986; 1989).

The volume of shell material at a given location is a function of two variables, rates of shell production and rates of clastic sediment deposition that dilutes the shell concentration. Highest concentrations of whole shells and shell fragments are found where biological productivity is high or where the shells have been winnowed from the sediments and physically concentrated by waves and currents. Because shell is the primary constituent of the gravel fraction in these sediments, grain size analyses of 286 sediment samples from Laguna Madre are a reasonable proxy to estimate shell concentrations, (White et al., 1983; 1986; 1989). Examination of those data show that there is a significant difference in shell abundance across the region. Average concentrations of gravel size material is 4.3% in northern Laguna Madre (105 samples), 2.8% in southern Laguna Madre (157 samples), and less than 1% in the GIWW (24 samples).

Foraminiferal tests are also carbonate skeletal remains that contribute to the volume of sediments generated within Laguna Madre. However, the amount of sediment that they provide is insignificant relative to the other constituents. According to thin section counts of samples from Laguna Madre, foraminifers constitute less than one percent of the total sediment volume (Rusnak, 1960a).

Reefs of calcareous worm tubes occur along the western margin of Laguna Madre near Point of Rocks, south of Penascal Rincon, and across the mouth of Baffin Bay (Rusnak, 1960a). Andrews (1964) reported that these serpulid reefs, which occur as individual patch reefs and in clusters, are dead remnants of a vibrant ecological community that apparently thrived at a time when waters in Baffin Bay and Laguna Madre were not hypersaline, but were closer to normal sea water. On the basis of oyster shells attached to the reefs, Andrews (1964) concluded that the reef growth occurred prior to the hypersaline conditions that characterized the most recent salinity regime near Baffin Bay. Breuer (1957) described the lower salinity hydrographic implications of oyster shells deposited in Indian middens lining the low bluffs surrounding Baffin Bay. Judging from the heights of the serpulid reefs, which are essentially at sea level, and the ages of oyster-shell middens in the Corpus Christi area (Ricklis, 1993), the serpulid reefs are probably more than 1,000 years old, but less than 4,000 years old. Regardless of their age, they do not contribute to the modern sediment budget of Laguna Madre. Rock debris eroded from the reefs by strong currents forms an apron that is incorporated into the sediments surrounding the reefs, but there is no net change in sediment volume.

Organic Matter

Chemical analyses show that organic matter is normally a minor component of the lagoon sediments (White et al., 1983; 1986; 1989); however, organic matter can be concentrated in algal mats that form continuous laminations on the wind-tidal flats. The algal mats form in place at the surface of the flats and grow when the flats are flooded, but they become desiccated and may be destroyed when the flats are dry. Where the flats are flooded frequently, the algal mats form layers of organic matter that is leathery and resists erosion. Repeated growth of thin but dense algal mats at the same location eventually leads to a recognizable organic deposit that is preserved in the sedimentary record.

The total organic carbon (TOC) content of sediments is a good measure of the nonskeletal sediment component generated internally by marine organisms. In Laguna Madre sediments, TOC averages about 0.75% (White et al., 1983; 1986; 1989). This value would also include aragonite precipitated in the open waters of Laguna Madre as carbonate mud by chemical or biochemical reactions. The abundance of TOC reflects the organic productivity of the lagoon, especially by the marine grasses. There is a strong inverse correlation between TOC and sediment textures with the highest concentrations of TOC corresponding to the finest grained sediments (muds). The deeper parts of the lagoon are sinks for the mud and the organic detritus generated in the lagoon. Consequently the highest concentrations of TOC in sediments are found in the GIWW (White et al., 1989).

CHARACTERISTICS OF LAGOON SEDIMENTS

Composition and Textures

General Distribution

The oldest regional record of shallow subsurface sediments in Laguna Madre is provided by the engineering plans prepared in 1931-32 by the Galveston District Corps of Engineers before construction of the GIWW. These plans use symbols to represent the general sediment types that were identified in borings collected along the centerlines of both the proposed bay and alternate inland routes. The sediment types illustrated on the plans (soft clay, medium clay, loose sand, tight packed sand, shell, caliche) lack detail, and sections of strata 2 to 3 m thick appear to be generalized, probably on the basis of visual field descriptions. Even in their generalized form, the boring descriptions demonstrate that nearsurface sediments in northern Laguna Madre are sandy

and contain abundant shell, whereas the sediments of southern Laguna Madre are muddy and contain very little shell. The same stratigraphic sections, which were interpreted by Rusnak (1960a), show lagoonal sediments in southern Laguna Madre are less than one meter thick. Sediment samples collected by McGowen et al. (1977) and by Herber (1981) confirm that a thin veneer of lagoonal sediments overlies Rio Grande deltaic deposits in southern Laguna Madre between Port Isabel and the Arroyo Colorado.

Comparison of Sediment Maps

Shepard and Rusnak (1957) and Rusnak (1960a) presented the results of textural analyses of about 180 surface sediment samples collected from transects across both northern and southern Laguna Madre. Each sample was classified according to what is now a widely used ternary diagram depicting end members and mixtures of sand, silt, and clay. Their maps show that the surface sediments in northern Laguna Madre are composed primarily of sand except for some clayey sand that occupies the deeper areas east of Laguna Larga and in The Hole. A tongue of silty sand and clayey sand also extends southward from the mouth of Baffin Bay. In southern Laguna Madre, sand predominates from the wind-tidal flats of Kenedy County to Port Mansfield except for some clayey sand and silty clay that occupies the deeper areas south of Rincon de San Jose. From Port Mansfield to Brazos Santiago Pass, there is a distinct textural gradient across the lagoon with sediments becoming finer grained toward the western shore. In this sub-region, bands of sand, silty sand, and mixtures of sand, silt, and clay are juxtaposed in northwest southeast trending bands. These bands of finer textures reflect the influence of suspended sediments transported by the Arroyo Colorado and the connection of Laguna Madre with the Gulf of Mexico through the tidal inlet at Brazos Santiago. Both maps presented by Shepard and Rusnak (1957) and Rusnak (1960a) show the same general textures, but there are slightly different patterns in the details of the maps that appear to be related to differences in interpretations of the data.

White et al. (1983, 1986, 1989) reported textural analyses of about 90 surface sediment samples collected along transects from northern Laguna Madre and about 200 samples from southern Laguna Madre. On the basis of the grain size distribution of each sample, they prepared maps of percent sand, mean grain size, gravel-sand-mud, and sand-silt-clay. The sand-silt-clay classification used by White et al. (1983, 1986, 1989) is similar to the classification used by Shepard and Rusnak (1957) and Rusnak (1960a) except for minor differences in the percents used as limits for the mixtures of the three primary components. The class limits used by White et al. (1983, 1986, 1989) minimize the two component mixtures and emphasize the three component mixtures, which occupies a large field in the center of the ternary diagram.

The maps of White et al. (1983, 1986, 1989) show patterns of sediment distribution similar to those presented by Shepard and Rusnak (1957) and Rusnak (1960a). The floor of northern Laguna Madre between Corpus Christi Bay and Baffin Bay is covered with sand except for an area of silty sand near the JFK Causeway. Silty sand, clayey sand, and mixtures of all three components form tongues where water depths increase across the mouth of Baffin Bay and to the south toward the Middle Ground shoal. The same three classes of finer-grained sediments also cover the northern part of The Hole. Only a few samples in each of these trends of finer-grained sediments contains less than 50% sand. The eastern half of southern Laguna Madre is covered by sand from the Hook to the Three Island area. The western half of the lagoon in this same region and the entire lagoon from Three Islands south to Port Isabel are dominated by silty sand with patches of all three components occupying areas near the mouth of the Arroyo Colorado, Stover Cove, and Laguna Vista Cove. A narrow fringe of clayey sand and sand-silt-clay borders the western margin of South Padre Island.

Geological Interpretation of Sediment Patterns

The distribution of surface sediments can be used to identify the primary sources of sediment in Laguna Madre and to interpret the long-term, time-averaged geological processes. For example, the predominance of sand and shelly sand in northern Laguna Madre primarily is the result of the lagoon originating over the sandy sediments of the Pleistocene Ingleside beach deposits or eolian sand sheet that form the upland from Corpus Christi Bay to the wind-tidal flats of Kenedy County (Brown et al., 1977). Once the lagoon formed, sediments delivered into this segment of the lagoon have been mostly sand transported by eolian and washover processes. The tongues of mud extending across the mouth of Baffin Bay and extending to the south reflect the suspended sediment introduced from upland runoff transported by streams draining into the bay or from erosion of the mud bluffs surrounding Baffin Bay. Most of the fine-grained sediments are trapped in the deepest part of Baffin Bay. Consequently, the direct influence of fluvial sediment supply in northern Laguna Madre is minor and the fine-grained sediments are either concentrated in the deeper parts of the northern lagoon (the deep area north of Middle Ground shoal and The Hole) or are diluted by advection and are distributed throughout the lagoonal sediments.

In southern Laguna Madre, the band of lagoonal sand that parallels Padre Island from Rincon de San Jose to Three Islands is a product of the long-term westward transport of barrier island sand by eolian and washover processes. Furthermore, the abrupt decrease in the width of this band south of Three Islands is conditioned by the rapid landward migration of South Padre Island and the substantial reduction in area of barrier island sand available for transport into the

lagoon. The greater abundance of mud (silt and clay) in the remaining areas of southern Laguna Madre is related to the underlying strata and the Holocene geologic history of the region. Surficial fluvial-deltaic deposits of the Pleistocene Beaumont Formation and the Holocene Rio Grande system are composed primarily of mud (Fulton, 1975; Brown et al., 1977). These muddy sediments formed the lagoon floor when the coastal plain was inundated in this region. Reworking of the in-place mud as well as introduction of additional fine-grained sediments during flooding of the Rio Grande supplied the mud that is incorporated into the modern lagoon sediments. Until frequent flooding on the Rio Grande was eliminated by human intervention, suspended fluvial sediments could be deposited directly into southern Laguna Madre during deltaic sedimentation several thousand years ago when the Resaca de los Cuates distributary system was active (Fulton, 1975; McGowen et al., 1977) or more recently by overflow into these same courses and the Arroyo Colorado after the primary distributary had shifted to the south near its present position. Suspended sediments of fluvial origin also have entered southern Laguna Madre through Brazos Santiago Pass. The zone of turbid, relatively fresh water discharged by the Rio Grande flows to the north and hugs the coast. Before the jetties at Brazos Santiago Pass were constructed, some of this water would flow into Laguna Madre during the flooding phase of the tidal cycle and under the influence of southeast wind. This is probably not a significant source of fine-grained sediment at present because sediment and water discharges of the Rio Grande have been drastically reduced and the jetties at Brazos Santiago Pass deflect the alongshore flow of suspended sediment seaward, away from the inlet.

Throughout the Laguna Madre-Baffin Bay system, the bathymetric lows are traps for the finest sediment textures, and in Laguna Madre the greatest water depths are associated with the GIWW. Sediment samples collected from the Intracoastal Waterway in southern Laguna Madre are composed mostly of mud (silt and clay). An exception to these general conditions is Mansfield Channel where the infilling sediments are composed mostly of sand. Sediments filling the Intracoastal Waterway typically contain less than 15% sand even where the surrounding surface sediments are composed predominantly of sand (White et al., 1986). Some of the mud filling the channel may be derived from erosion of the channel perimeter, which is composed mostly of mud. Erosive forces in the channel include wind-driven currents and highly turbulent prop wash generated by tug boats and other boats.

Estimated Rates of Lagoon Sedimentation

Accurate estimates of the long-term average rates of sedimentation in the sub-environments of Laguna Madre help constrain the estimates of the regional sediment budget because the

overall average rate of sedimentation in the lagoon should equal the contribution of individual components identified in the sediment budget analysis.

Dating Techniques

The sediment budget analysis clearly demonstrates that the rates of sedimentation are not uniform throughout Laguna Madre. The difficulty is trying to establish a scientifically valid method for determining reasonably accurate sedimentation rates. The accounts of surficial changes in and around Laguna Madre related to droughts, hurricanes, or ranching practices given by Price and Gunter (1943) are based on interviews with long-time residents and individuals familiar with South Texas and Padre Island. The reliability of these anecdotal accounts is uncertain and they do not provide a basis for quantifying sedimentation rates in Laguna Madre. For example, the observed burial of cattle in Laguna Madre following the 1919 hurricane (Price and Gunter, 1943) was more likely caused by liquefaction of the existing sand rather than by deposition of sand washed over Padre Island during the storm. Furthermore, Middle Ground shoal and the wind-tidal flats of the Land Cut have been attributed respectively to large volume depositional events associated with migrating dunes in 1916 (Zupan, 1971) and the hurricane of 1919 (Price and Gunter, 1943; Fisk, 1949). And yet there is no scientific basis to support recent historical construction of these features, and they could be the South Texas equivalents of large depositional fans on other barrier islands of the southeastern and central Texas coast.

Perhaps the most reliable method of documenting long-term average sedimentation rates is through the use of isotopic dating. Radiocarbon dates indicate that the compound washover fans/flood-tidal deltas of San Jose Island were initially deposited about 1700 yrs before present during the progradational phase of barrier construction (Andrews, 1970). This is the same date that Zupan (1971) reported for open lagoon sediments in northern Laguna Madre, which means that the change in depositional environment from open lagoon to wind-tidal flat probably occurred shortly after that time.

Apparently misinterpretation of the 1881 topographic maps and anecdotal accounts of the 1919 hurricane led some authors to incorrectly conclude that portions of Laguna Madre had filled recently. A map published by Burr (1930) purported to show a rapid accumulation of sediment near the mouth of Baffin Bay. Subsequent workers have perpetuated the erroneous information by citing the map by Burr as evidence for historical shoaling in Laguna Madre (Price and Gunter 1943; Gunter, 1945; Hedgpeth, 1947; and Simmons, 1957) or by making invalid assumptions about the timing of depositional events (Price, 1958; Fisk, 1959). Inspection of the oldest reliable maps of the region surveyed by the U.S. Coast Survey in 1881 clearly shows the same shoal in essentially the same position and shape as illustrated by Burr (1930). In fact,

comparison of the late 1800s topographic maps (Topographic sheets 1627, 1678, and 1679) and recent aerial photographs shows remarkably little geomorphic change except for the man-made alterations such as the GIWW, well-access channels, and associated islands of dredged material (Morton and Garner, 1993).

Wind-Tidal Flats

Fisk (1959), Miller (1975), Watson (1989), and Morton and Garner (1993) collected cores and obtained radiocarbon dates for organic material from beneath the wind-tidal flats of Kenedy County west of the Gulf Intracoastal Waterway. They reported long-term average sedimentation rates that ranged from 0.6 to 1.2 mm/yr. The vertical distribution of data in cores taken by Miller (1975) and Morton and Garner (1993) also revealed a time-dependent decrease in sedimentation rates with average rates for deposition of near surface sediments during the past few hundred years being about 0.06 mm/yr, or about one tenth the rate of sediment accumulation documented for the past few thousand years.

One study has yielded radiocarbon dates for organic material beneath the flats of southern Laguna Madre. McGowen et al. (1977) reported a date of 2540 ± 200 yr BP for marine shells from a former grassflat environment at a depth of about 1.5 m below the flats near La Punta Larga on South Padre Island. The long-term average sedimentation rate for the sample is about 0.6 mm/yr.

Although abundant data are available for calculating sedimentation rates on the wind-tidal flats, they probably are not representative of sedimentation rates in the open water areas of the lagoon for the following reasons. The elevations of the wind-tidal flats are controlled by ground water levels in the sediments beneath the flats. When the water table is relatively high, sand transported onto the flats is stored on the flats, but when the water level is low and the surface is dry, deflation by wind removes the upper layers of sediment and lowers the surface to a depth where the moisture in the sediments prevents further erosion. The slow rate of relative sea-level rise will limit the accumulation of sediment on the flats considering that some sediment is regularly removed during dry periods.

Open Lagoon

Rusnak (1960a) used three different methods to estimate sedimentation rates in the central portion of Laguna Madre away from the shoals and other topographic anomalies. The first method involved comparison of bathymetric maps from southern Laguna Madre that were

surveyed in 1887 and 1954. That comparison indicated shoaling of about 152 mm in 67 years, which gives an average sedimentation rate near the tidal inlet of about 2.3 mm/yr. The second method of estimating sedimentation rate was based on a radiocarbon date of 3910 yr BP for material at a depth of about 4 m in a core from northern Laguna Madre near the JFK Causeway. This depth/age relationship gives an average sedimentation rate of about 1.0 mm/yr. The third, and least reliable method, took the average thickness of Holocene sediments in Laguna Madre and assumed an age of 5,000 years for initial deposition of lagoonal sediments. This method yielded long-term average sedimentation rates of 1.2 mm/yr and 0.3 mm/yr for northern and southern Laguna Madre respectively. On the basis of all three of these estimates, Rusnak (1960a) concluded that the best approximation of long-term average sedimentation rate in Laguna Madre was about 1.2 mm/yr.

The calculated rates of sedimentation in Laguna Madre are substantially lower than those of other large coastal water bodies in Texas, including Corpus Christi Bay, the deepest bay of the Texas coast. Shepard (1953) compared bathymetric charts for the major Texas bays and calculated average sedimentation rates between the mid to late 1800s and 1935 that range from 3.8 mm/yr to 9.1 mm/yr, depending on the local rates of subsidence. The relatively high rates of sedimentation in the other bays are attributed primarily to the deposition of fluvial sediments supplied by rivers draining directly into the bays (Shepard, 1953).

Lockwood, Andrews, and Newnam (1959) used historical bathymetric changes in Baffin Bay to estimate shoaling rates of 0.4 m in 70 yrs, or about 4.2 mm/yr. They also calculated estimates of upland runoff near Baffin Bay on the basis of annual precipitation records and, using a Soils Conservation Service estimate of sediment yield, they determined that sedimentation rates in the deeper parts of Baffin Bay should also be about 3 to 5 mm/yr.

Sediment Budget Limitations and Verification

The long-term average annual volume of new sediment delivered to Laguna Madre from the surrounding principal sources is estimated to be about 969,600 m^3 (Table 1). This sediment volume is substantially less than the average annual volume of sediment dredged from the GIWW in Laguna Madre, which for the past 45 years has averaged 1,659,429 m^3/yr (Table 1). Even more important for this comparison is the fact that very little of the new sediment introduced into Laguna Madre is deposited directly into the GIWW. For example, most of the eolian dune, storm washover, and tidal inlet sediments are composed of sand that is deposited on the eastern margin of the lagoon and not in the GIWW. The large difference between the volume of new sediment deposited directly in the GIWW and the volume removed by maintenance

dredging indicates that the primary source of mud filling the GIWW is from local reworking of dredged material or subregional redistribution of lagoonal sediments.

The estimated average volume of sediment delivered to Laguna Madre annually (Table 1) can be tested within an order of magnitude by establishing the area of the lagoon and multiplying that value by the estimated long-term average annual sedimentation rate. This calculation has a potentially high error associated with it because depositional events within the lagoon are episodic and both the temporal and spatial variability of sedimentation rates are high. Nevertheless, a first approximation of the total sediment budget can be obtained using this simple method.

The surface areas of open-water in northern and southern Laguna Madre have been reported by various authors (Rusnak, 1960a; Breuer, 1962; Brown et al, 1976, 1977, and 1980). Because the reported values are within 15% of each other, the surface area of water in Laguna Madre originally given by Rusnak (1010 km^2) is used with his reported long-term average sedimentation rate (1.2 mm/yr) to calculate a long-term average annual total sediment budget of 1,212,612 m^3/yr. This value is about 20 % larger than the value derived by summing the individual contributions estimated for each of the identified components (Table 1).

Geological Significance of Sediment Budget Analysis

Lagoons are products of coastal plain flooding by a relative rise in sea level, such as the condition that is observed today at many coastal regions (Gornitz and Lebedeff, 1987). Despite this recent coastal inundation, there is a common misconception that lagoons are destined to be filled by sediments and to eventually lose their capacity for primary production (Barnes, 1980; Britton and Morton, 1989). Although no coastal depositional environment, including lagoons, retains its characteristics forever, their histories are controlled by the interaction of sediment supply and sea-level fluctuations. The perception that extant lagoons, including Laguna Madre, are filling is perhaps based on the observation that much of the East Coast of the US is characterized by sandy barrier islands adjacent to broad salt marshes that are thought to be former lagoons.

The long-term balance between sedimentation and sea level changes and its impact on the future state of Laguna Madre can be tested with the available data (Table 1). For these calculations the estimated volume of sediment entering at Mansfield Channel and Brazos Santiago Pass were not included in the sediment budget because they are deposited in the deep part of the channels well below the lagoon floor and do not contribute significantly to the aggradation. The relative rise in sea level as recorded at the tide gauges at Rockport and Port Isabel is about 3 mm/yr, whereas the rate of aggradation calculated from the sediment budget is

about 0.9 mm/yr for northern Laguna Madre and about 0.4 mm/yr for southern Laguna Madre. Considering these values it is apparent that the rate of relative sea-level rise is 4 to 7 times faster than the rate of sediment aggradation (Table 1). This means that Laguna Madre is not filling, as some have predicted, but is slowly being submerged. Furthermore, southern Laguna Madre is migrating westward as the upland (western) margin erodes and the eastern side adjacent to South Padre Island advances as a result of storm overwash.

SEDIMENT REWORKING BY WAVES AND CURRENTS

Repeated dredging of the GIWW and shoaling of channels dredged for petroleum exploitation are clear indicators of frequent and rapid sediment transfers within Laguna Madre. The volume of sediment suspended in the water of Laguna Madre depends on wave energy, composition of bottom sediments, and specific gravity of aquatic vegetation (Breuer, 1962). Highest turbidity occurs in the deepest parts of the lagoon where waves are highest, the lagoon floor is composed of mud, and seagrasses are absent. Conversely, turbidity is minimal where the water is shallow, seagrasses are dense, and the floor is composed of sand. In general, conditions for low turbidity are optimum in northern Laguna Madre between Corpus Christi Bay and Baffin Bay. Conditions in southern Laguna Madre near the GIWW between Port Mansfield and Port Isabel favor high turbidity. Turbidity tends to increase toward the west because waves generated by southeast winds are larger, substrates tend to be muddier, and water depths are greater than those along the lagoon margin of Padre Island.

Shideler (1984) measured hydrographic and suspended sediment parameters in Corpus Christi and Nueces Bays during different seasons and under different wind conditions. The results of his two-year study show that the concentrations of suspended sediment in the water column are a short-term response to wind conditions as demonstrated by the correlation of suspended sediment with the cumulative wind effects within a 30 hr period before the measurements. The suspended sediment is composed mostly of inorganic material that is poorly sorted and textures that are in the clay to fine silt range except in the winter when high energy is capable of entraining and transporting some very fine sand (Militello et al., 1996).

The most recent intense hurricanes that caused significant changes in water levels in Laguna Madre were Hurricanes Carla (1961), Beulah (1967), and Allen (1980). The physical characteristics and extent of damage caused by these storms was reported by the U.S. Army Corps of Engineers (1962, 1968, 1981).

Hurricane Carla made landfall near Port Lavaca, Texas, therefore Laguna Madre was far from the storm center, and the strongest winds between Corpus Christi and Brownsville were directed offshore (U.S. Army Corps of Engineers, 1962). The resulting wind stress caused below

normal water levels in northern Laguna Madre for several days. Water levels were higher than normal only in extreme southern Laguna Madre where Brazos Santiago Pass allowed the open-coast storm surge to propagate into the lagoon. The Gulf shoreline along Padre Island retreated during Carla (U.S. Army Corps of Engineers, 1962; Hayes, 1967), but there is no evidence that the hurricane caused abnormal shoaling in Mansfield Channel because the channel had closed naturally before the storm. Shoaling of the GIWW in Laguna Madre related to Carla was primarily adjacent to the shallow flats between Corpus Christi Bay and North Bird Island and from Baffin Bay through the shallow flats of Kenedy County (U.S. Army Corps of Engineers, 1962).

Hurricane Beulah had a profound effect on Laguna Madre because it crossed the coast near the Rio Grande, which placed the lagoon in the right front quadrant where wind velocities and storm surges are highest. The 1.5-1.8 m increase in water levels throughout Laguna Madre during Beulah (U.S. Army Corps of Engineers, 1968) inundated the wind-tidal flats and caused wave erosion along the western lagoon margins. Herbich (1975) estimated that about 15 million m^3 of sediment were deposited in the GIWW by Hurricane Beulah, but the method used to make this estimate is not given.

Hurricane Allen was a large storm that weakened as it approached and crossed the Texas coast north of the Town of South Padre Island. Allen increased water levels in southern Laguna Madre as much as 2.2 to 2.8 m, whereas water levels were slightly lower in the northern lagoon (U.S. Army Corps of Engineers, 1981). Waves superimposed on the storm surge eroded the western shores of Laguna Madre, in particular those segments between Port Mansfield and Port Isabel. Abnormally high water in the Gulf of Mexico during Allen opened 68 washover channels across South Padre Island (U.S. Army Corps of Engineers, 1981) that transported sand into Laguna Madre. An 8 km segment of the GIWW in Laguna Madre shoaled to about 1 m as a result of Allen (U.S. Army Corps of Engineers, 1981). Post-Allen dredging of the GIWW was scattered between the shallow flats of Kenedy County and Port Isabel, but the largest volume of sediment was removed from the channel at PAs 233 and 234.

Examination of the dredging records for Laguna Madre since the GIWW was constructed indicates that increased channel shoaling lasts several years after a major hurricane affects the area. The frequent dredging of the GIWW in the 1960s and early 1970s reflects this relationship.

Documented Effects of Storms on Seagrasses

Little is known about how the sediments and seagrasses of Laguna Madre have been affected by hurricanes of historical record, such as the major storms of 1880 (Brownsville) and 1919 (Sarita), or prior hurricanes that have been common since the lagoon formed several

thousand years ago. Therefore it is difficult to evaluate the effects of more recent hurricanes, especially those that have made landfall since the GIWW was opened. Some sedimentological and hydrodynamic inferences can be made on the basis of storm characteristics and post-storm observations in shallow lagoons located in other temperate regions.

Aerial photographs show that after the eye of a hurricane crosses the coast, high velocity wind-driven currents flow northward, parallel to the lagoon. These strong currents erode sand from the wind-tidal flats and locally scour troughs between islands of dredged material. The currents, which have velocities estimated to be from 2 to 3 m/s (Morton, 1979), can affect large areas but cause only minor changes in elevation by redistributing some of the near-surface sediments. The northward flow obliterates any evidence of sediment reworking by southward flowing currents prior to storm landfall that would be predicted on the basis of atmospheric circulation patterns and wind directions. After Beulah, transverse sand bars connected with the washover fans (wind-tidal flats) clearly showed that substantial sediment reworking had occurred along the western margin of South Padre Island. What remains uncertain is the extent of sediment reworking in deeper parts of the lagoon, and the effect on sediment entrainment of decreased shear velocities at the lagoon floor caused by dense meadows of seagrass.

Effects of Waves and Currents on Lagoonal Sediments and Seagrasses in Other Regions

Dense meadows of seagrasses are efficient traps of fine-grained sediment and their root systems are effective binders that prevent erosion by currents associated with the normal tidal cycle (Scoffin, 1970; Burrell and Schubel, 1977; Ward et al, 1984). Scoffin (1970) measured sediment entrainment by unidirectional currents under low-wave energy, non-storm conditions. His field experiments with an underwater flume in a sand-rich lagoon showed current velocities of 50, 100, and 150 cm/s, as measured at the tops of the leaves, were necessary to remove sediments at the sediment-water interface and erode the roots in sparse, medium, and dense stands of *Thalassia* respectively. Under most current conditions, the long, wide blades of *Thalassia* are capable of reducing bottom velocities to zero at the lagoon floor. The reduction in flow velocity near the tops of the leaves prevents sediment reworking and transport, and promotes deposition of sediments falling out of suspension. These same principles also apply to other grass species, such as *Halodule* and *Ruppia*, but because of their leaf size and morphology, they are slightly less effective in reducing current velocities compared to *Thalassia*. As a result of these conditions, grassbeds typically have higher sedimentation rates than nearby barren areas of the lagoon (Scoffin, 1970; Ward et al, 1984).

The results of a field study by Ward et al. (1984) indicate that wave-orbital velocities are more important than unidirectional currents in resuspending lagoonal sediments. They examined

resuspension of shallow-bottom sediments in barren and grass-covered margins of Chesapeake Bay under a range of current and wave conditions, and they observed that in water depths of less than 2 m, sediments were resuspended when wind velocities with the greatest fetch exceeded 25 km/hr. They also observed that concentrations of suspended sediment in the grass beds increased when bay water levels were increased by spring tides or storm surges.

In 1969, Hurricane Camille dramatically altered the Gulf Coast landscape near Biloxi, Mississippi. With peak wind velocities of 94 m/s and a storm surge of 8 m, Camille is still the most intense storm of historical record in the Gulf Coast region. Eleuterius and Miller (1976) used aerial photographs and prestorm surveys to estimate that about 58% of the total area of aquatic vegetation in Mississippi Sound was destroyed by Camille. Most of the lost submerged vegetation (41%) was seaweed (algae) whereas the remaining lost vegetation (17%) was marine grasses. The vegetation losses related directly to the storm were attributed to erosion of the shallow seafloor around the barrier islands and burial of grass beds beneath sand washed over the barrier islands by storm waves.

The effects of hurricanes on the distribution and productivity of grass beds in South Florida have been the focus of several studies. Thomas et al. (1960) measured the large amount of grass blades that were deposited along the shores of Biscayne Bay after Hurricane Donna. Peak wind gusts of about 40 m/s and water levels about 1 m above normal were reported for the study site by the Weather Bureau. On the basis of prior work and post-storm observations, including the general absence of plant rhizomes in the organic debris, Thomas et al. (1960) concluded that the storm caused no severe damage to the grass beds.

Storm Effects on Seagrasses in South Texas

In September 1933, a major storm crossed Laguna Madre north of Brownsville that contributed sediment to the lagoon and probably caused some changes in sediment distribution. Bailey (1933) reported that the storm opened at least 20 washover channels between the Gulf and Laguna Madre along South Padre Island. Little else has been written about the storm and possible impacts on Laguna Madre despite adequate access to the area and ample opportunity for documentation.

After Hurricane Carla, Oppenheimer (1963) examined the seagrass beds in Redfish Bay, which is not too far from northern Laguna Madre. Despite noticeable erosion of mounds of dredged material along the Ship Channel, the adjacent algal flats and grassflats did not experience any detectable damage. Dead grass was exported from the grassflats, but there was no evidence of bottom erosion and excavation of seagrasses by storm driven-currents (Oppenheimer, 1963).

Hurricane Beulah is perhaps best known for its extremely high rainfall that ranged from 35 to 60 cm in the lower Rio Grande valley. The heavy prolonged rainfall that lasted for nearly a week, caused extensive surface flooding of the land bordering Laguna Madre and overloaded the few organized streams and canals that drain the upland area (U.S. Army Corps of Engineers, 1968). Runoff of sediment-laden fresh water from the uplands also continued for an extended period following the storm. No references have been found that adequately describe the status of seagrasses in south Texas immediately following the storm. Brown and Kraus (1996) suggested that Hurricane Beulah was responsible for the observed losses in seagrasses in southern Laguna Madre. However, the evidence from Texas and other temperate coastal areas strongly indicates that hurricanes by themselves are probably not the primary reason that seagrass beds would be permanently destroyed. A hurricane might serve as a catalyst that triggers a decline in seagrass density but unless long-term average sediment or water quality are degraded, the documented effects of hurricanes on seagrasses are either negligible or short lived. The large number of hurricanes that would have drastically lowered salinities and increased turbidities for prolonged periods in southern Laguna Madre before construction of the GIWW indicates that factors other than Beulah probably caused the loss of seagrasses.

Morgan and Kitting (1984) measured above ground biomass in two sheltered seagrass meadows near Port Aransas before and after Hurricane Allen. They reported that storm currents removed dead leaves from the sites, but the living biomass and primary productivity of the seagrasses were not adversely affected by the storm. However, nearby open-water grass beds exposed to the storm waves were buried by sand. No details were given about the location of the disturbed seagrass beds or the area lost by burial so the extent of permanent change in seagrass distribution caused by the storm can not be evaluated by more recent mapping.

REWORKING OF DREDGED MATERIAL

Prior Studies in Texas

Several investigators have compiled dredging records of the Corps of Engineers to determine the volume and frequency of dredging for particular reaches of the GIWW including those in Laguna Madre (Herbich, 1975; Atturio et al., 1976; Espey Huston and Associates, 1976; Brown and Kraus, 1996; Militello et al., 1996; and Martin Arhelger, personal communication, 1996). All of these studies identified variable shoaling rates along the waterway. Field surveys in Texas lagoons and laboratory experiments confirm that dredged material placed in open water can be rapidly reworked and redistributed. These prior studies, which employed different

monitoring methods, also show that the erosion rates of dredged material are time dependent, and the erosion rates follow an exponential decay function that begins at the time of disposal.

Bassi and Basco (1974) used graduated stakes to survey a disposal site in Galveston Bay immediately before and after maintenance dredging of the GIWW. They documented that 47% of the original volume of dredged material was dispersed within one week and 63% was removed within 5 months of the disposal event. A combined air photo and field survey of dredged material in upper Laguna Madre by Stinson (1977) showed that the island was reduced 73% within 7 years of its deposition. Vyas (1977) used the data of Stinson (1977) to validate a movable bed model that predicted that most of the losses observed by Stinson occurred within the first year after deposition of the dredged material.

Militello et al. (1996) and Brown and Kraus (1996) used echosounder surveys to monitor dredged material at numerous placement areas along the GIWW in northern and southern Laguna Madre during the 1994-1995 dredging cycle. They reported rapid reworking of the dredged material and concomitant shoaling of the GIWW. As much as 70% of the dredged material was reworked and consolidated within 8 months of the dredging activity (Brown and Kraus, 1996).

Analytical Procedures

Sediments dredged from the GIWW and transferred to open-water placement sites are partly reworked by wind-driven waves and currents. To evaluate the magnitude of sediment reworking, several tasks were conducted that address the morphology of the placement areas, and the volume of material still at those sites compared to the total volume of material dredged from the adjacent reach of the GIWW. Many of the techniques used to assess the reworking of dredged material in Laguna Madre were described by Dortch (1990).

Using the field sampling sites of other investigators (EHA, NMFS, CBI/MSI) as a guide, a site sampling plan was prepared for geological field work and historical analysis of changes at six field sites (placement areas 187, 197, 202, 211, 221, 233). Another reason for selecting these placement areas is that all of them, except 221, have been monitored by some type of instrumented platform operated by the Conrad Blucher Institute, Texas A&M-Corpus Christi.

The analysis of changes in dredged material in Laguna Madre must recognize different practices and policies that determine the disposal site. Prior to 1975, dredged material was placed more than 360 m from the GIWW, whereas after 1975 dredged material was placed no more than 360 m from the waterway (Neil McClellan, personal communication, 1997). This change in policy means that post-1975 placement is closer to the channel and possibly below the berm crest

created by the pre-1975 placement. Furthermore, the post-1975 material is more likely to be reworked back into the channel than the older material.

Topography and Bathymetry

The subaerial and subaqueous morphologies and sizes of the placement areas were recorded in the field using two different types of topographic surveys. Axial and transverse profiles of large islands within placement areas were surveyed using an electronic total station and rod with reflecting prism. Short linear surveys of small islands surrounded by water were conducted rapidly using the Emery (1961) method that employs graduated rods connected by a chain of fixed length. Water depths were recorded at most stations along the profiles and also at each of the coring sites (Tables 5 and 6). High waves prevented accurate measurement of water depths at the PA 233 CBIE and CBIW sites, therefore the average water depth reported by Brown and Kraus (1996) was used in the computations of Table 5.

1996 topographic elevations for each profile were estimated using the water level observed at the time of the survey as an approximate datum of zero elevation. This appears to be a reasonable assumption considering the close agreement between elevations derived from this method and the elevations above low water reported for five NOAA bench marks along transect 202T1, that are correlated to the nearby Yarborough tide gauge. The close agreement between observed water levels and the low water datum is not surprising considering that water level fluctuations in Laguna Madre are minor under normal meteorological conditions.

Topographic surveys in Laguna Madre of segments of placement areas 187, 197, 202, 211, 221, and 233 were conducted on September 18-26, 1996. These limited field surveys supplemented the more extensive topographic and hydrographic surveys conducted by the Brownsville area office of the Corps of Engineers in preparation for the 1994-95 maintenance dredging operations (Terry Roberts, personal communication, 1997).

Pre-dredging water depths at the placement areas of intensive investigation were estimated using soundings shown on bathymetric maps surveyed in 1931-32 by the Galveston District Corps of Engineers, Corps of Engineers dredging plans, U.S. Geological Survey topographic maps, and NOAA navigation charts. In order to identify large-scale changes in water depths associated with dredging the GIWW, pre-dredging (1931-32) water depths at placement areas 197, 202, 211, and 221 were digitized and compared to extant water depths surveyed in the same areas by John Chance and Associates in 1995. The John Chance surveys were conducted from an air boat with GPS horizontal positions and sounding rod water depths corrected to mean lower low water tidal datum using the network of tide gauges in Laguna Madre operated by the Conrad Blucher Institute. The Brownsville office of the Corps of Engineers conducted detailed surveys

Table 5. Comparison of core depths, water depths, and thickness of dredged material (DM) in cores from Laguna Madre. Units of measurement are meters. First three numbers of the core designation indicate the Placement Area.

Core	1996 WD	1931 WD	31WD-96WD	Core Length	DM Thickness	Lagoon Depth
187PC1	0.66	1.42	0.76	1.03	1.03	1.69
187PC2	1.32	1.42	0.10	0.69	0.39	1.71
187PC3	0.76*	1.42	0.66	0.98	0.62	1.38
187PC4	1.22	1.42	0.20	0.58	0.21	1.43
187PC5	1.22	1.42	0.20	0.65	0.18	1.40
187VC1	0.66*	1.42	0.76	1.37	0.69	1.35
187VC2	0.46	1.42	0.96	1.26	0.92	1.38
187VC3	0.38	1.42	1.04	1.62	1.04	1.42
187VC4	1.45	1.75	0.30	1.25	0.50	1.95
197PC1	0.28	1.00	0.72	1.10	0.73	1.01
197PC2	0.38	1.00	0.62	1.03	0.66	1.04
197PC3	0.46	1.00	0.54	1.16	0.55	1.01
197PC4	0.99	1.89	0.90	1.09	0.86	1.85
197PC5	0.76	1.30	0.54	0.69	0.56	1.32
197PC6	0.38	1.30	0.92	1.15	1.00	1.38
197VC1	0.36	1.00	0.64	1.12	0.66	1.02
197VC2	0.97	1.00	0.03	1.45	0.23	1.20
197VC3	1.22	1.89	0.67	1.52	0.72	1.94
197VC4	1.00*	1.89	0.89	1.28	0.62	1.62
197VC5	1.22	1.30	0.08	1.40	0.12	1.34
202PC1	0.69	1.20	0.51	1.21	0.99	1.68
202PC2	0.23	2.15	1.92	0.59	0.60	NR
202VC1	0.38	1.20	0.82	1.44	0.76	1.14
202VC2	0.38*	1.30	0.92	1.47	0.91	1.29
202VC3	1.30*	1.80	0.50	1.77	0.79	2.09
202VC4	1.37	2.15	0.78	1.82	0.81	2.18
211PC1	0.38	0.67	0.29	1.16	0.50	0.88
211PC2	0.38	0.91	0.53	1.22	0.80	1.18
211PC3	0.38	0.38	0.00	1.22	0.00	0.38
211PC4	0.38	0.38	0.00	1.15	0.00	0.38
211VC1	0.38	0.67	0.29	1.66	0.59	0.97
211VC2	0.38	0.85	0.47	1.48	0.39	0.77
211VC3	0.43	1.00	0.57	1.63	0.57	1.00
211VC4	0.43	1.00	0.57	1.28	0.71	1.14
211VC5	1.30*	1.00	-0.30	1.59	0.00	1.30
221PC1	0.91	1.30	0.39	1.14	0.37	1.28
221VC1	0.38	1.30	0.92	1.39	0.72	1.10
221VC2	1.00*	1.30	0.30	1.20	0.30	1.30
221VC3	1.22	1.50	0.28	1.19	0.42	1.64
221VC4	1.14	1.50	0.36	1.68	0.31	1.45
221VC5	0.97	1.50	0.53	1.49	0.47	1.44
233PC1	0.36	1.20	0.84	1.28	0.86	1.22
233PC2	0.84	1.20	0.36	1.24	0.35	1.19
233PC3	0.66	1.30	0.64	1.25	0.63	1.29
233VC1	0.99	1.30	0.31	1.50	1.11	2.10
233VC2	1.32	1.30	-0.02	1.74	0.10	1.42
233CBIE	1.50*	1.70	0.20	0.79	0.27	1.77
233CBIW	1.50*	1.70	0.20	0.64	0.00	1.50
R233CBIW	1.50*	1.70	0.20	0.76	0.20	1.70

*Estimated water depth
NR - Not reached

Table 6. Relationship of seagrasses and dredged material in six placement areas. A=absent, B=buried, D=dead, L=living, P=present.

Placement Area Core Number	Bottom Sediment	Water Depth (meters)	Seagrass Status	Dredged Material
187PC1	organic muddy sand	0.66	L	P
187PC2	organic shelly sand	1.32	D	A
187PC3	organic shelly sand	0.76*	L	P
187PC4	organic sand	1.22	A	P
187PC5	organic muddy sand	1.22	L	P
187VC1	soft mud	0.66*	A	P
187VC2	organic muddy sand	0.46	L	P
187VC3	organic sandy mud	0.38	L	P
187VC4	organic sandy mud	1.45	L	P
197PC1	organic shelly sand	0.28	L	P
197PC2	organic shelly sand	0.38	L	P
197PC3	organic mud	0.46	L	P
197PC4	shelly sand	0.99	A	P
197PC5	organic shelly sand	0.76	L	P
197PC6	soft organic mud	0.38	L	P
197VC1	organic muddy sand	0.36	L	P
197VC2	slightly sandy mud	0.97	A	P
197VC3	sandy mud	1.22	A	P
197VC4	very soft mud	1.00*	D	P
197VC5	sandy mud	1.22	A	P
202PC1	very soft mud	0.69	A	P
202PC2	organic shelly sand	0.23	L	P
202VC1	sandy shelly mud	0.38	L	P
202VC2	mud and sandy mud	0.38*	L	P
202VC3	sandy mud	1.30*	A	P
202VC4	slightly shelly sand	1.37	L	P
211PC1	sand	0.38	B	P
211PC2	shelly sand	0.38	L	P
211PC3	organic shelly sand	0.38	L	A
211PC4	organic shelly sand	0.38	L	A
211VC1	organic muddy sand	0.38	L	P
211VC2	slightly sandy mud	0.38	B	P
211VC3	sandy mud	0.43	B	P
211VC4	mud and muddy sand	0.43	B	P
211VC5	organic sandy mud	1.30*	L	
221PC1	sand and shelly sand	0.91	A	P
221VC1	organic muddy sand	0.38	L	P
221VC2	sandy shelly mud	1.00*	A	P
221VC3	shelly sand	1.22	A	A
221VC4	sandy mud	1.14	A	P
221VC5	organic sand	0.97	L	P
233PC1	organic shelly sand	0.36	L	P
233PC2	shelly sand	0.84	A	P
233PC3	organic muddy sand	0.66	L	P
233VC1	muddy shelly sand	0.99	B	P
233VC2	organic shelly mud	1.32	L	P
233CBIE	mud	1.50*	A	P
233CBIW	shelly muddy sand	1.50*	A	P
R233CBIW	mud	1.50*	A	P

* Estimated water depth

in October and November 1994 of topography and bathymetry around selected placement areas in Laguna Madre including those investigated in this study. The 1994 surveys provide elevations for the placement areas and more control (data points) for the water surrounding the mounds, whereas the 1995 surveys provide more control for the water depths away from the disposal areas. Because each data set has advantages not provided by the other, both were combined into a composite data set that was used to quantify the changes in bathymetry associated with dredging the GIWW and the remaining volumes of dredged material in the placement areas.

The 1930s bathymetry did not adequately cover placement areas 187 and 233, so estimates of large-scale bathymetric changes and residual volumes of dredged material at these sites are based on the pre-dredging lagoon depth derived from the sediment cores. Also bathymetric profiles taken from the 1995 John Chance surveys were used to evaluate bathymetric changes in placement areas 187 and 233 that are related to construction and maintenance of the GIWW.

Apparently none of the three independent bathymetric surveys in Laguna Madre have the same horizontal and vertical control. The 1930s data appear to be NAD 27, mean sea level, latitude and longitude; the 1994 data are in NAD 27, mean low water, state plane feet; and the 1995 data are NAD 83, mean lower low water, state plane feet.

Errors in the original data and in the electronic manipulation of the data can degrade the accuracy of the bathymetric comparison; therefore, it is critical to identify and quantify as many sources of error as possible. No documentation of accuracy is available for any of the three bathymetric surveys. Primary sources of bathymetry error would be positioning inaccuracies, errors in measuring water depths, and errors in datum adjustments. Because of technological advances in surveying and tide gauge equipment during the past 65 years, the 1994 and 1995 surveys should be the most accurate and the 1930s data should be the least accurate.

Land-based surveying instruments were probably used to locate the positions of soundings during the 1930's surveys as indicated by the uniform spacing of transects across the lagoon, uniform spacing of observations along each transect, and the direct correlation of the transects with onshore control points. GPS positions were used to locate the soundings during the 1994 and 1995 surveys. The combined internal error for the 1930s data caused by differences in geographic positioning and measurement inaccuracies can be evaluated by examining the discrepancies where survey lines cross one another. On the 1930s maps there are numerous misties where transects oriented perpendicular to the shore cross transects oriented parallel to the lagoon and proposed route of the GIWW. Discrepancies in reported water depths at these intersections range from 0.06 to 0.15 m.

Another possible source of error would be a change in the sea level or tidal datum used as a reference for reporting water depths. This error should appear as a systematic difference in water depths in those areas where the bathymetry is least likely to change and where the orientation of

the contours have remained unchanged. At all four placement areas with 1930s bathymetry, the 1995 water depths are about 0.3 m deeper than those surveyed in the early 1930s. Consequently an adjustment of 0.3 m was made so that the data sets would show better overall agreement. The cumulative residual error value was estimated by examining the random (patchy) differences that cover broad shallow areas far from the dredging and disposal activities. An error bar of ± 0.24 m was used to emphasize changes in bathymetry that exceed 0.24 m.

Apparently the channelized turbulent flow of suspended sediments along the GIWW has constructed low submerged levees that along some reaches are colonized by seagrasses. Cross channel transects of the 1995 bathymetry illustrate the levees that appear as topographic rises adjacent to the Waterway even on the side away from the placement area.

Detailed topographic and bathymetric surveys of Laguna Madre have been conducted in 1966, 1986, and 1993-94 between the GIWW and the depositional sites of dredged material. Visual comparisons of the sequential bathymetric surveys at most of the placement areas investigated show systematic shoaling as additional dredged material has been deposited with each maintenance dredging cycle.

Distribution of Dredged Material

The thickness, composition, and lateral extent of the dredged material were documented at selected placement areas using both fixed-piston cores and vibracores. Fixed-piston cores (Appendix A) allow rapid collection of data in the field for reconnaissance purposes. The core barrel is a 7.6 cm diameter aluminum tube containing a piston with O-rings that creates suction and helps hold the core in the barrel when it is withdrawn from the sediment. The core barrel, which is 1.5 m long, is pushed into the sediment, then withdrawn, and the sediment core is extruded on site by pushing against the piston, which drives the core out of the barrel into a half-tube receptacle. The fixed-piston core is split with a thin wire, described, and photographed in the field. This on-site operation provides immediate results regarding the characteristics of dredged material and natural lagoonal sediments supporting seagrasses and establishes a framework for selecting the vibracore sites. Vibracores are also collected in 7.6 cm diameter aluminum tubes, but they range in length from 1.5 to 3 m, depending on water depth at the placement area and the desired depth of sediment penetration. The vibracore barrels also have core catchers to keep the cored sediment in place. As their name implies, the vibracores are vibrated down using a modified concrete mixer that is powered by a gasoline engine. The vibracore is winched out of the sediment, excess barrel length is trimmed with a pipe cutter, both ends are capped and sealed with duct tape, the barrel is oriented and marked, and the entire sealed barrel is transported to the BEG core repository in Austin for processing.

Thicknesses of dredged material at each placement area also can be independently estimated by subtracting the 1995 water depths from the 1931 water depths (Tdm=WD1931-WD1995). Positive numbers indicate shoaling that is likely associated with deposition of dredged material, whereas negative numbers indicate either erosion or a problem with one or both of the bathymetric measurements.

Eolian Reworking of Dredged Material

There are both physical and demographic explanations for the blowing dust periodically reported in central and southern Laguna Madre. Complaints of blowing dust correlate temporally with droughts and periods of low rainfall, whereas they correlate spatially with population centers bordering southern Laguna Madre such as Port Isabel and Port Mansfield. Most of the blowing dust within and immediately adjacent to Laguna Madre is derived from the broad flats and deflation depressions that are common surficial features in the region (Price, 1958, 1963, 1968; Brownsville Navigation District, 1983); however, some of the blowing dust is directly related to eolian reworking of dredged material (Price, 1968; U.S. Army Corps of Engineers, 1971).

The south Texas climate is semi-arid, and evapotranspiration commonly exceeds precipitation (Brown et al., 1980). This deficit in rainfall causes increased salinities in shallow water bodies that can result in hypersaline conditions. During prolonged severe droughts, these water bodies evaporate and the associated mud flats are exposed to the prevailing south and southeast winds. The wind erodes (deflates) the mud flats and transports the eroded sediment inland as dust. These eolian processes have slightly increased the depths of the depressions down to the water table, which is lowered by the drought conditions. Some of the dust is deposited in ridges that rim the downwind edges of the depressions forming clay dunes (lomas) that attain heights of as much as 9 m. Price (1958, 1963) explained how repeated flooding of the muddy flats and depressions in south Texas by salt water and subsequent drying releases clay aggregates from the surface. The sand-size pellet-shaped particles of clay are then removed by the wind and transported inland to form either dust or nonmigratory clay dunes. The large number and sizes of the clay dunes indicate that eolian processes and wind-blown dust have been common for centuries.

Subaerial mounds of dredged material deposited above storm surge elevations in Laguna Madre have been subjected to some reworking by eolian processes (fig. 12). The probability of eolian reworking is increased when the deposits are greater than 1 m above sea level because the water table is well below the surface of the sediments. The problem of eolian reworking of dredged material is most severe either immediately after deposition and before colonization by
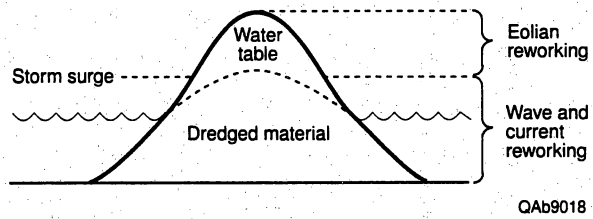
Figure 12. Principal physical processes in Laguna Madre responsible for reworking dredged material and the general vertical limit of their influence.

plants, or during periods of unusually low rainfall. All of these conditions coexisted during the 1950s shortly after the GIWW was constructed and south Texas was experiencing a severe drought.

Surficial lags of coarse sediment (shells, rock fragments) on mounds of dredged material in northern Laguna Madre are clear evidence that eolian reworking was active before the mounds were stabilized with vegetation. The mounds of dredged material in southern Laguna Madre are even more susceptible to deflation because they are largely composed of dense clayey sediments that have low permeabilities. These fine-grained sediments are not easily leached by rainwater and they retain high concentrations of salt, which inhibit the colonization and growth of vegetation. Furthermore, they are composed mostly of expandable clays that have high-shrink-swell properties. Repeated expansion and contraction of the clays when they are wetted and dried causes them to disaggregate and to form small particles capable of being transported by the wind. Several attempts to mitigate the dust blowing from a disposal site on Long Island near Port Isabel were unsuccessful despite repeated plowing and contouring of the surface, flooding of the placement area by pumps, constructing brush barriers, erecting sand fences, constructing containment levees, and planting 50 species of trees, shrubs, and grasses (U.S. Army Corps of Engineers, 1971).

The volume of sediment removed from deposits of dredged material by wind is extremely difficult to quantify because no field measurements have been made at any time including the most severe conditions when transport rates are highest. Although blowing dust from exposed mounds of dredged material may be a nuisance, it does not represent large volumes of sediment loss nor is it primarily responsible for shoaling of the GIWW.

Recognition of Lagoon Sediments and Dredged Material

Natural lagoon sediments and dredged material were differentiated on the basis of physical properties observed in the piston cores and vibracores (Appendix A). Sediment textures and shapes, sediment colors, sediment composition, presence or absence of stratification, stratigraphic contacts, and vertical successions were the sedimentological characteristics used to interpret the origins of the sediments (Table 7). The contacts between dredged material and lagoon sediments are distinct and easily identified in some cores, whereas they are less obvious in others. In general, contrasts between the two classes of sediment are greater in the southern lagoon than in the northern lagoon where sand and shelly sand are the dominant sediment types of both dredged material and natural lagoon deposits.

The primary criteria for recognizing natural lagoonal sediments is the preservation of sedimentary structures and stratigraphic contacts that are products of physical or chemical

Table 7. Criteria used to differentiate between lagoonal sediments and dredged material.

Diagnostic Characteristics of Lagoon and Wind-Tidal Flat Sediments

- Horizontal laminations of algal mats or amorphous (chalky) carbonate minerals
- Horizontal alternating laminations and thin interbeds of homogeneous sand and mud; without shells or burrows in central Laguna Madre
- Horizontal alternating light and dark color-laminated beds of mud
- Horizontal thin, in-situ carbonate-cemented crusts
- Relatively thick intervals of shelly sand with disseminated carbonaceous material

Diagnostic Characteristics of Dredged Material

- Rounded clasts of mud, rock fragments, caliche, or cemented sediments
- Distinct differences in sediment color, such as reddish brown, brown, and white juxaposed with gray or tan sediments that are typical colors of lagoon sediments
- Chaotic or contorted sand and mud intervals without bedding
- Thick intervals of homogeneous sediments without bedding
- Chemically reduced sediments (gray) overlying oxidized sediments (tan)
- Finer textures than lagoonal sediments, especially in northern Laguna Madre
- General absence of shells or bioturbation in northern Laguna Madre*
- Deepest sediments penetrated are repeated as disturbed intervals in upper part of core (observations limited to PA 221)

* except for homogeneous sand of eolian origin near Padre Island

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processes that would be difficult or impossible to mimic with typical hydraulic emplacement of dredged material. Algal laminations, carbonate laminations, and continuous carbonate-cemented crusts are examples of diagnostic sedimentological features that could not be preserved if the material had been dredged and pumped through a pipe. In contrast, dredged material is characterized by anomalous sedimentological characteristics that are never or not normally associated with lagoonal deposits. These characteristics include large matrix supported clasts of lithified or cohesive sediments and other sedimentological features that are typical of specific gravity flows such as contorted bedding.

Although most of the sedimentological criteria for lagoonal sediments (Table 7) are unequivocally diagnostic, there is no single criteria for dredged material that is unequivocal and all of them can be produced by other physical processes. For example, rounded clasts of extraneous sediments can be produced by storms as rip-up clasts, and contorted bedding can be produced by sediment liquefaction as a result of the vibracoring operation if the original cohesiveness of the sediments was destroyed by hydraulic emplacement. Also formerly reduced sediments can become oxidized when suspended and redeposited near the sediment-water interface. Therefore simultaneous confirmation of several criteria may be necessary to correctly identify dredged material.

Prolonged colonization of dredged material by seagrasses also can obscure its recognition. This is because bioturbation by roots and burrowing organisms plus the addition of shells generated in situ transform the upper 2 to 10 cm of dredged material and give it the appearance of normal lagoonal deposits.

Placement Area 187

Placement area 187 (figs. 1 and 13) is located approximately 2.5 km southwest of the Bird Island Basin channel and about 360 m southeast of the GIWW. It is the second mostly subaqueous placement area south of the broad shoal that forms the floor of Laguna Madre between South Bird Island and Corpus Christi Bay. PA 187 is 0.8 km west of the lagoon shore of Padre Island and Laguna Madre is about 4 km wide at the site. Because of its location within the lagoon, greatest fetch is from the northeast, north and northwest, and least from the southeast, which is the direction of predominant winds. Preferential reworking of the north and west sides of the islands is indicated by the location of storm berms and overwash deposits (figs. 14-15). However, the principal geomorphic indicators of reworking suggest that sediment was initially eroded from the southern margins of the islands and transported to the north during the 1950s, which was a non-hurricane period.
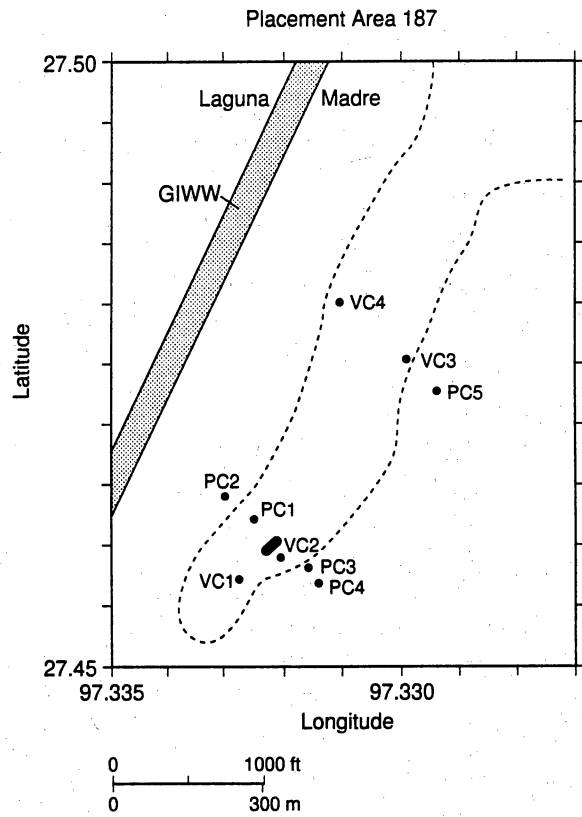
Figure 13. Locations of the GIWW and sediment cores in placement area 187.
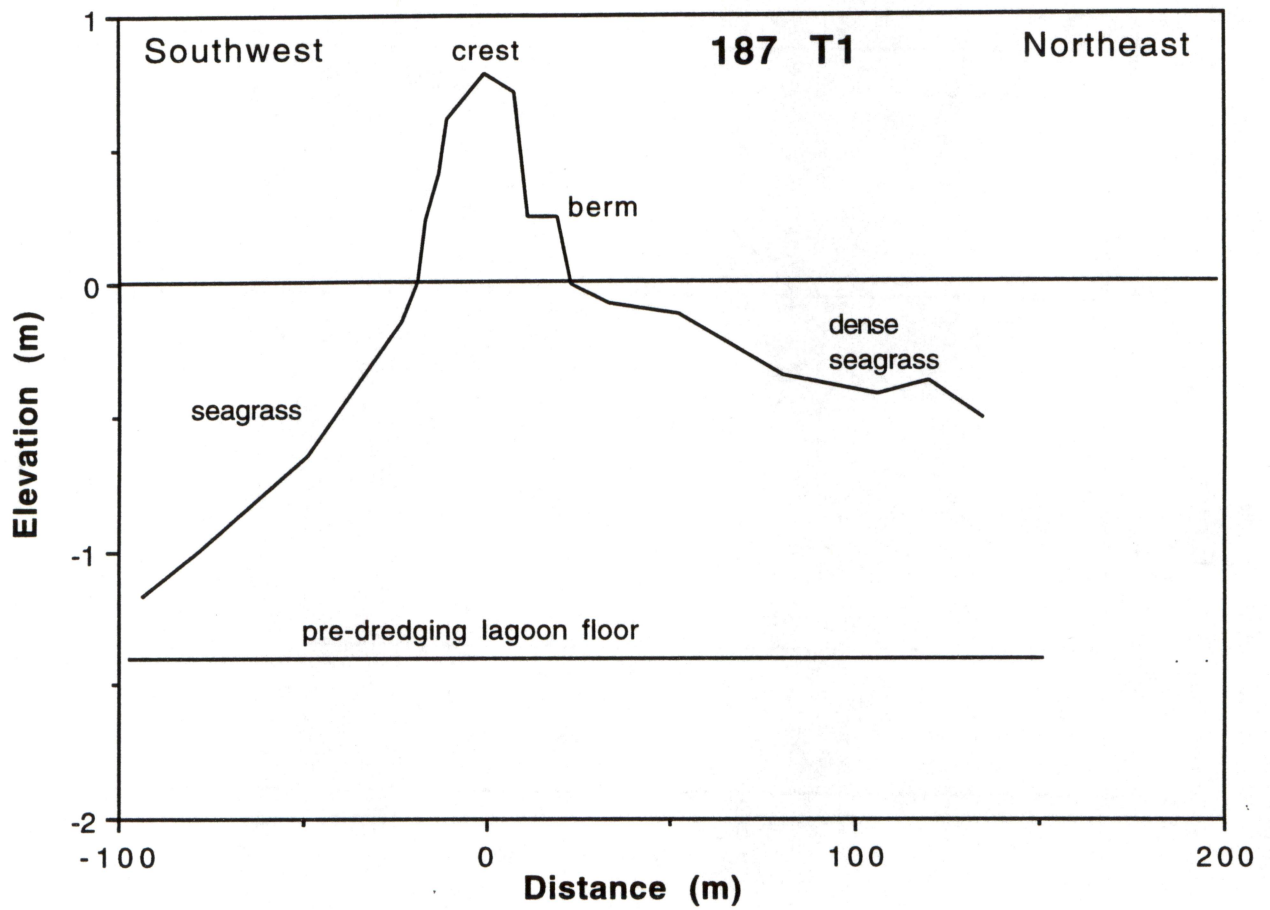
Figure 14. Axial topographic profile of placement area 187 surveyed in 1996. Profile is located on island and shoal between cores PC 1 and VC 2. Core locations shown in fig. 13.
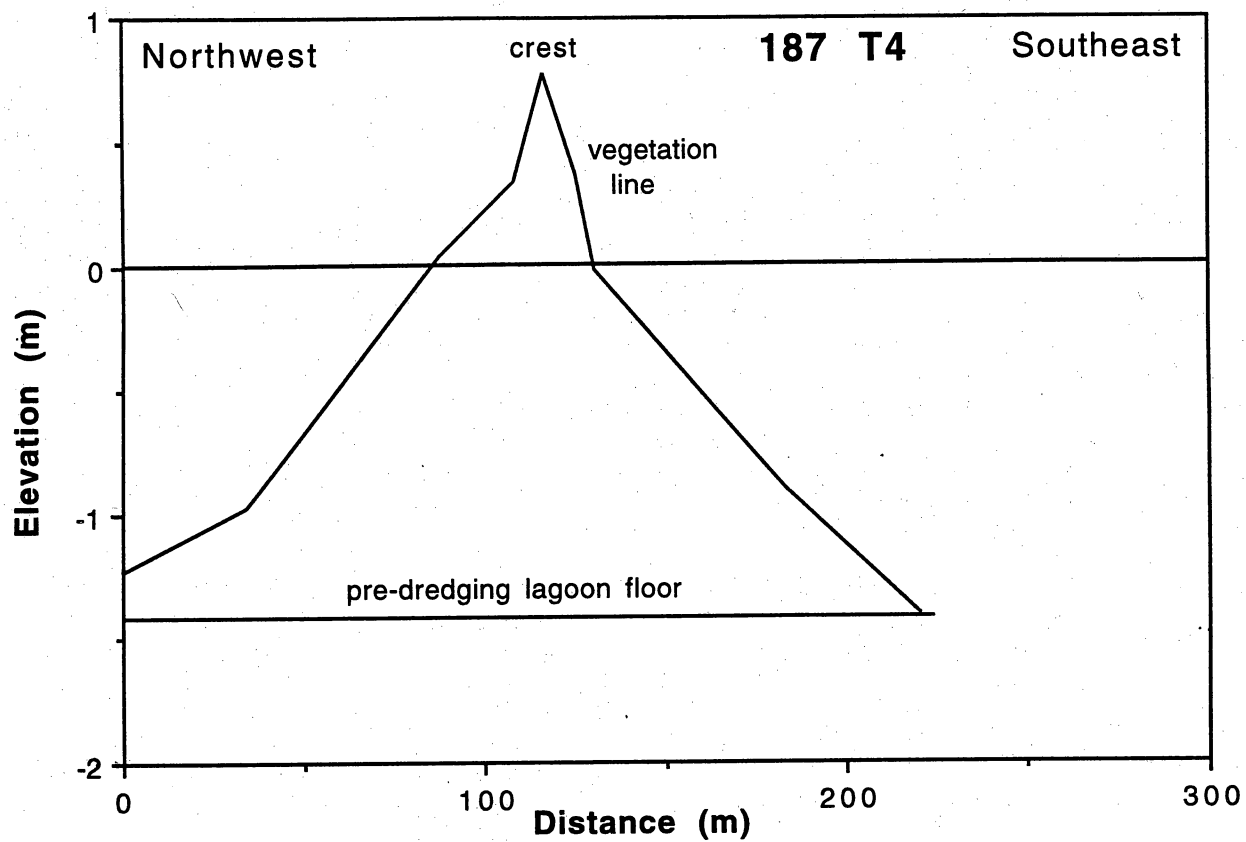
Figure 15. Transverse topographic profile of placement area 187 surveyed in 1996. Profile is located on island and shoal at VC 3. Core location shown in fig. 13.

At PA 187, the subaqueous expression of the dredged material covers an area about 1500 m long and about 180 to 300 m wide. There were no seagrasses present at the site before construction of the GIWW, but now dense to sparse stands of seagrass cover the shoals created by the dredged material. Very narrow linear islands with irregular eroded edges have historically occupied the axes of the shoals. Average water depth around the placement area is about 1.4 m, and water depths gradually decrease eastward from the lagoon center toward the placement area and the margin of Padre Island. Pre-dredging water depths reconstructed for placement area 187 show that the axis of the islands is parallel to the bathymetric contours. The axis of the islands also coincides with a change in gradient where water depths over the backbarrier platform increased toward the center of the lagoon. A 1995 bathymetric profile illustrates the large vertical changes in water depth associated with dredging the GIWW (fig. 16). On the northwest side of the GIWW across from PA 187 is a low ridge on the edge of and parallel to the channel. The ridge, which is covered with seagrass, is similar to a natural levee of a river channel.

In 1996, placement area 187 was characterized by two low islands connected by shallow submerged shoals that are covered by dense stands of seagrass. The islands and grass covered shoals are all composed of dredged material. The shoals and terminal islands form an arc that curves to the northwest. A transverse profile of the subaerial island at channel marker 131 shows that it is asymmetrical (fig. 15), being flatter on the northwest side and slightly steeper on the southeast side. The western beach exhibits a low-water berm and a slightly higher storm berm that also coincides with the vegetation line. Both berm crests are composed of sandy shell and shelly sand, and they are covered by mats of dead seagrass that are typically found along bay/lagoon margins as a result of seasonal die back of aquatic vegetation. Separating the two berms is a sandy ramp covered with shells that form a surficial lag deposit. The shells are common marine species such as *Aequipecten*, *Busycon*, and *Polinices*.

The dredged material at PA 187 is composed primarily of sand and shelly sand. Muddy sediments are generally absent but when present are restricted to thin layers near the contact between dredged material and the lagoon floor (Appendix A). Gravel and cobble-size clasts on the beach and in the nearshore water are cemented rock fragments that have been winnowed from the original dredged material and concentrated in patches, such as on the eastern side of the island. A barren subaqueous zone about 4 to 6 m wide separates the beach from the submerged marine grasses. The barren zone outlines an area where shoaling waves mobilize the sediments and prevent colonization and stabilization by plant rhiozomes.

At PA 187, surfaces of the emergent islands are covered by moderately dense terrestrial vegetation and shell or rock fragments depending on the elevation above water level. The highest elevations are less than 1 m and the typical vegetation is *Iva frutescens* with the succulent *Sesuvium* rimming the upper (storm) berm crest. The surface lag of shell indicates selective
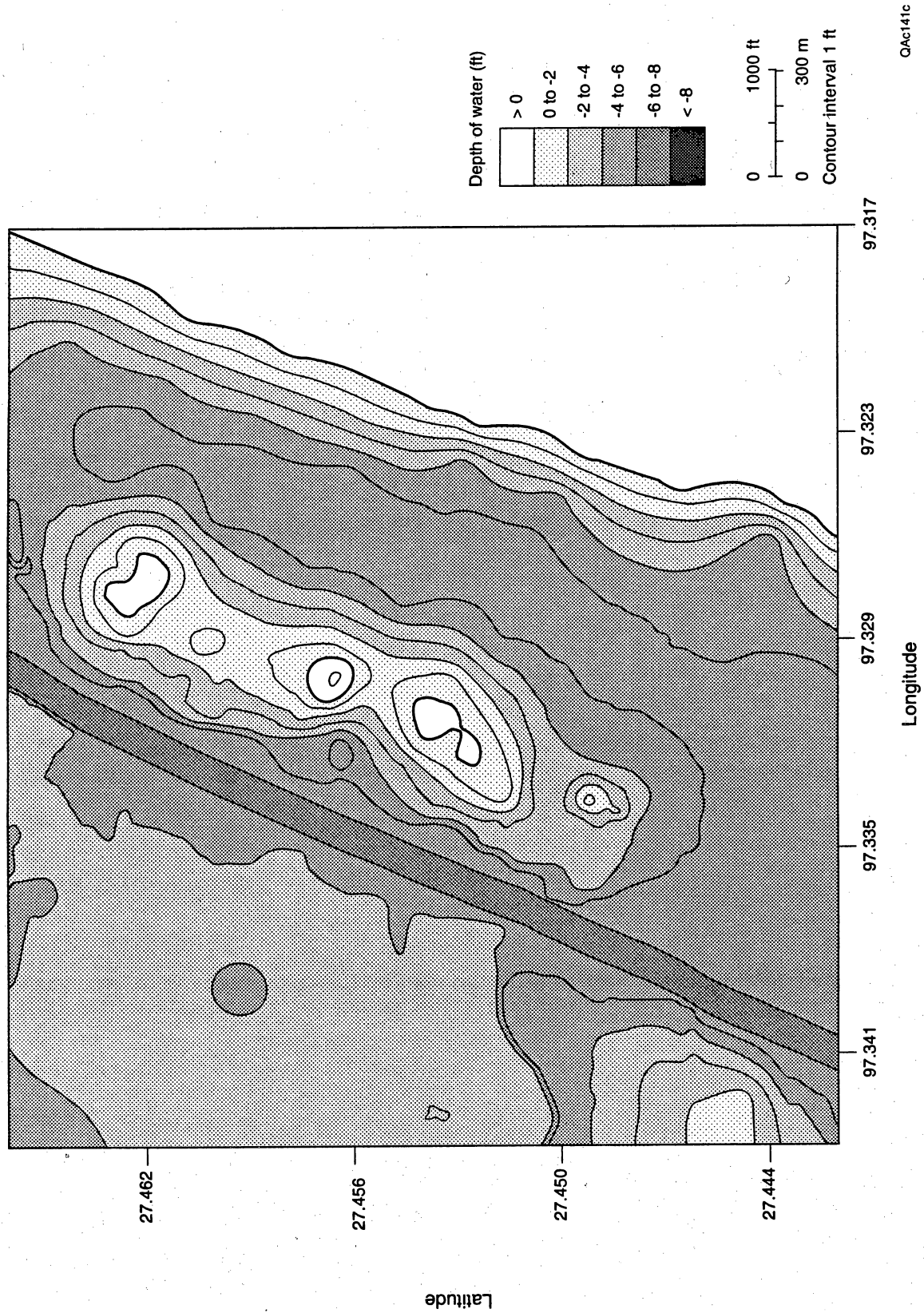
Figure 16. Bathymetric map of placement area 187 based on integration of 1994 and 1995 data.

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sorting of sediments either by wind or water that leaves a layer of the coarsest material after the finer sediments have been removed.

Prior to disposal of dredged material, lagoon sediments around PA 187 were composed of mottled sandy shell and shelly sand. At present, the lagoon floor on the southeast side of PA 187 is firm and composed of organic-rich shelly sand and muddy sand. In contrast, bottom sediments are composed of as much as 0.3 m of soft mud on the west and northeastern and northwestern sides of the placement site extending to channel marker 129, where dredged material had been recently deposited. The initial deposition of dredged material consisted of a thin layer of mud overlain by sand without any shell. This material probably represents the pre-lagoon (Pleistocene Ingleside) deposits that form the floor and deeper walls of the dredged channel.

Maximum thickness of dredged material is 2.2 m beneath the crest of the island at channel marker 131. Elsewhere, the thickness of dredged material is less than 1.0 m (fig. 17). The thickness of dredged material decreases a short distance southeast of the islands, but at least 0.4 m of dredged material covers the former lagoon floor toward the GIWW in water depths of 1.5 m (fig. 17). Some of the unexpectedly thick dredged material toward the GIWW was probably deposited by turbidity flows during initial dredging. However, considering the 13 dredging events at PA 187 and compositional variability of the post-construction dredged material (Appendix A), it appears that most of the thickness is attributable to either direct deposition during subsequent dredging operations or reworking and redistribution. There does not appear to be significant transport and deposition of reworked dredged material southeast of the island and shoals (fig. 17).

The contact between dredged material and lagoon sediments at the PC-1 coring site is below the general surface trend. This condition suggests vertical scour of about 0.2 m around the discharge pipe during initial implacement of dredged material. Scour and infilling locally increases the thickness of dredged material but does not significantly alter the average thickness at the disposal site.

In 1950, after construction of the GIWW but before maintenance dredging, PA 187 consisted of a narrow elongate chain of islands that were irregular in shape and about 1.3 km long. Small points on the west side of the PA were formed by bi-directional currents that reworked the sandy sediments and transported them to the north. Reworking was concentrated mainly on the western side of the island chain. At that time the islands were mostly barren and there was no evidence of seagrasses on the shoals of dredged material surrounding the islands. By 1956, additional dredged material was added to the islands and there still was no evidence of seagrasses, but the greatest change was erosional transformation of the island chain to shoals and two small remnant islands in the extreme northern and southern parts of the PA. During the 20 yr period between 1956 and 1974 there were 6 disposal events that added dredged material
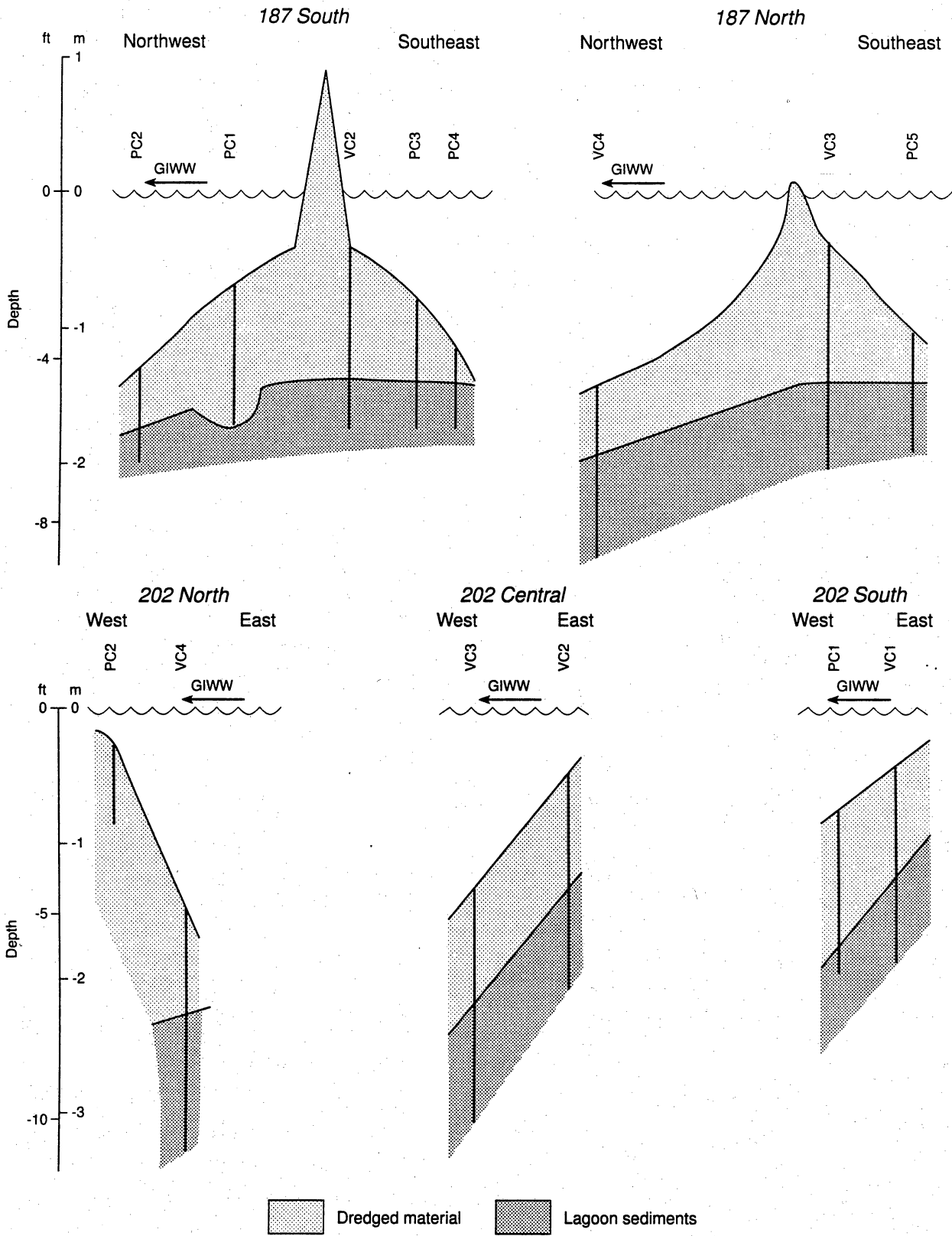
Figure 17. Cross sections illustrating the thickness and lateral extent of dredged material within placement areas 187 and 202. Core locations shown in figs. 13 and 26. Horizontal scale is variable.

primarily to the northern island. The shallow shoals also expanded and seagrasses were established at this time. In 1982 the narrow configuration of remnant islands persisted as seagrasses expanded and reworked sediments were transported to the north. In 1992, the combined length of the remnant islands was about 150 m, or about 10% of the original length of the island chain. In the past few years there has been continued reworking of added dredged material and continued conversion of the remnant subaerial islands to shallow subaqueous shoals.

Placement Area 197

Placement area 197, which is at the mouth of Baffin Bay (figs. 1 and 18), is approximately 3.6 km long. It is located about 240 m east of the GIWW and is situated between twin shoals that protrude from the west side of Padre Island. The large rounded mounds of dredged material that form the northern segment of the placement area originally were discrete separate islands but they have coalesced as a result of repeated deposition that eventually constructed subaerial flats between the islands. A narrow levee-like ridge has formed on the edge of the GIWW on the west side of the channel on the side opposite PA 197.

The natural shoals of Laguna Madre are covered with moderately dense to sparse seagrass, whereas there is substantially less seagrass in deeper areas adjacent to the shoals of dredged material. In general, seagrasses are more extensive to the south. The seagrasses on the dredged material became well colonized by 1974. The barren zone immediately adjacent to the islands of dredged material ranges in width from 6 to 80 m depending on bottom sediment composition and time since the last disposal event.

Fetch at PA 197 is greatest to the west and southwest along the axis of Baffin Bay and to the south and southeast along the axis of Laguna Madre. Fetch is limited to the east by Padre Island and to the north by the narrows and shoals between Padre Island and the mainland at Point of Rocks as well as the large islands of dredged material at PA 196. Despite limited fetch to the north, erosion of dredged material is concentrated on the northern side of the islands (figs. 19-20) and reworked sediments are generally transported to the south. An exception to this statement is northerly transport of reworked material eroded from the southernmost isolated island. At present, water depths on the western side of the island near the GIWW at the northern end of the placement area are very shallow, about 0.3 m. Natural water depths in the surrounding area are 0.6 m or less and increase to about 1.5 m at the southern end.

The two large merged islands of dredged material on the northern end of the placement area and the two isolated islands on the southern end were the sites of detailed topographic surveys and coring activities (fig. 18). Longitudinal and transverse topographic profiles were surveyed
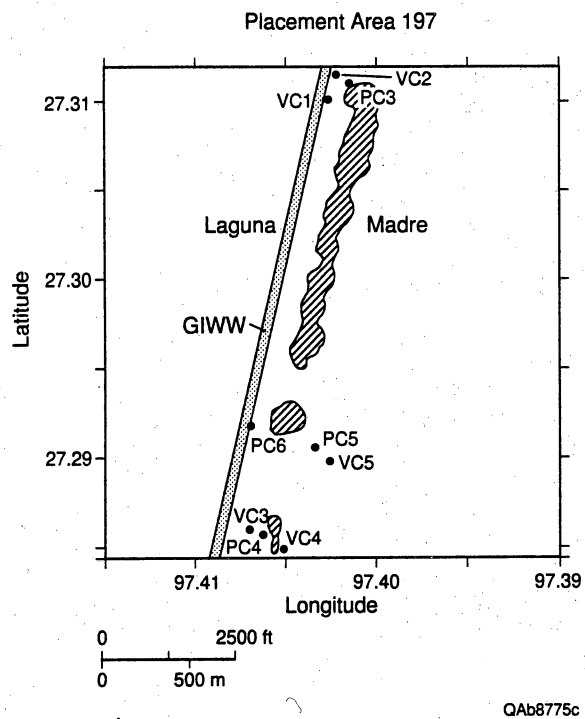
Figure 18. Locations of the GIWW and sediment cores in placement area 197.
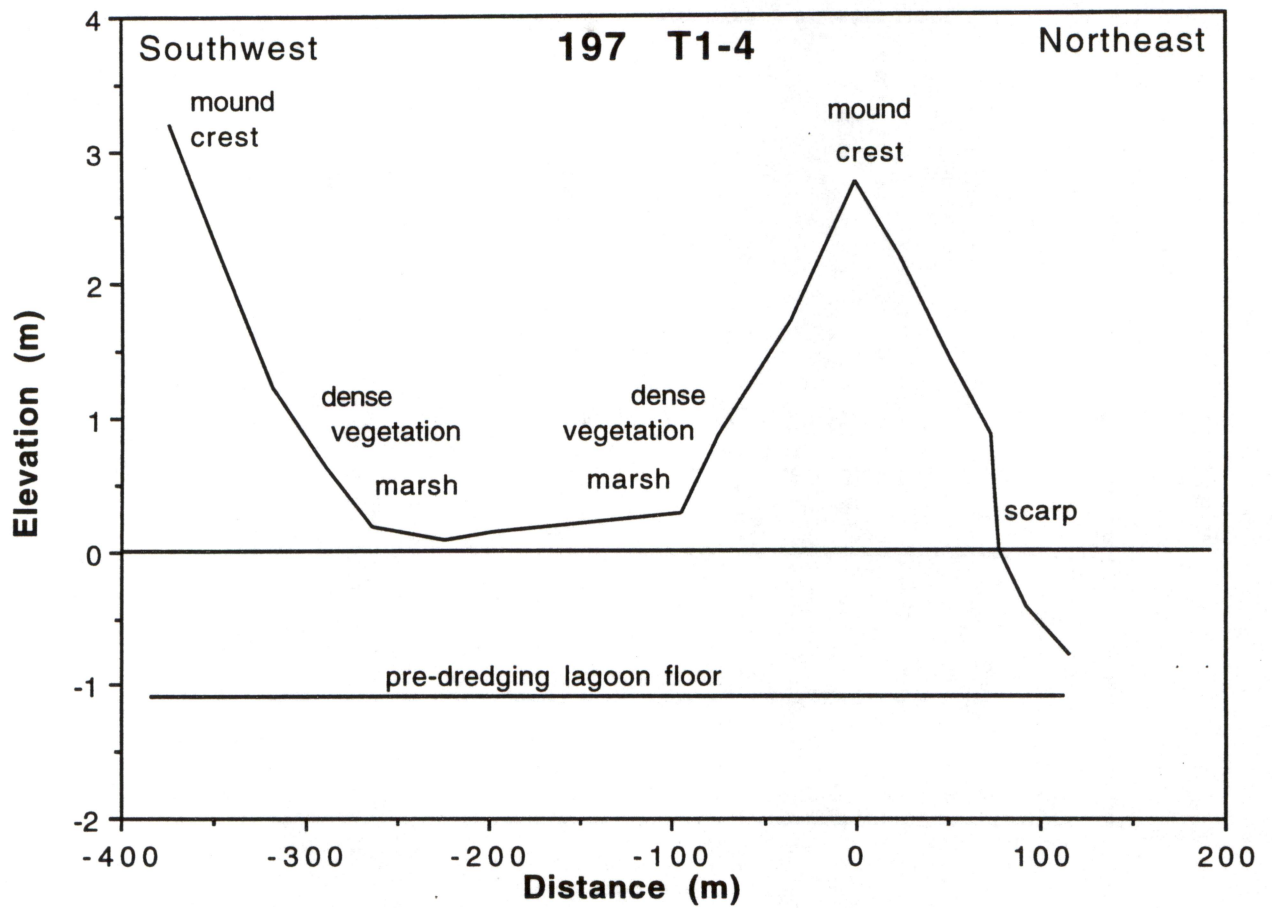
Figure 19. Axial topographic profile of placement area 197 surveyed in 1996. Profile extends along two large islands at the north end of the placement area shown in fig. 18.
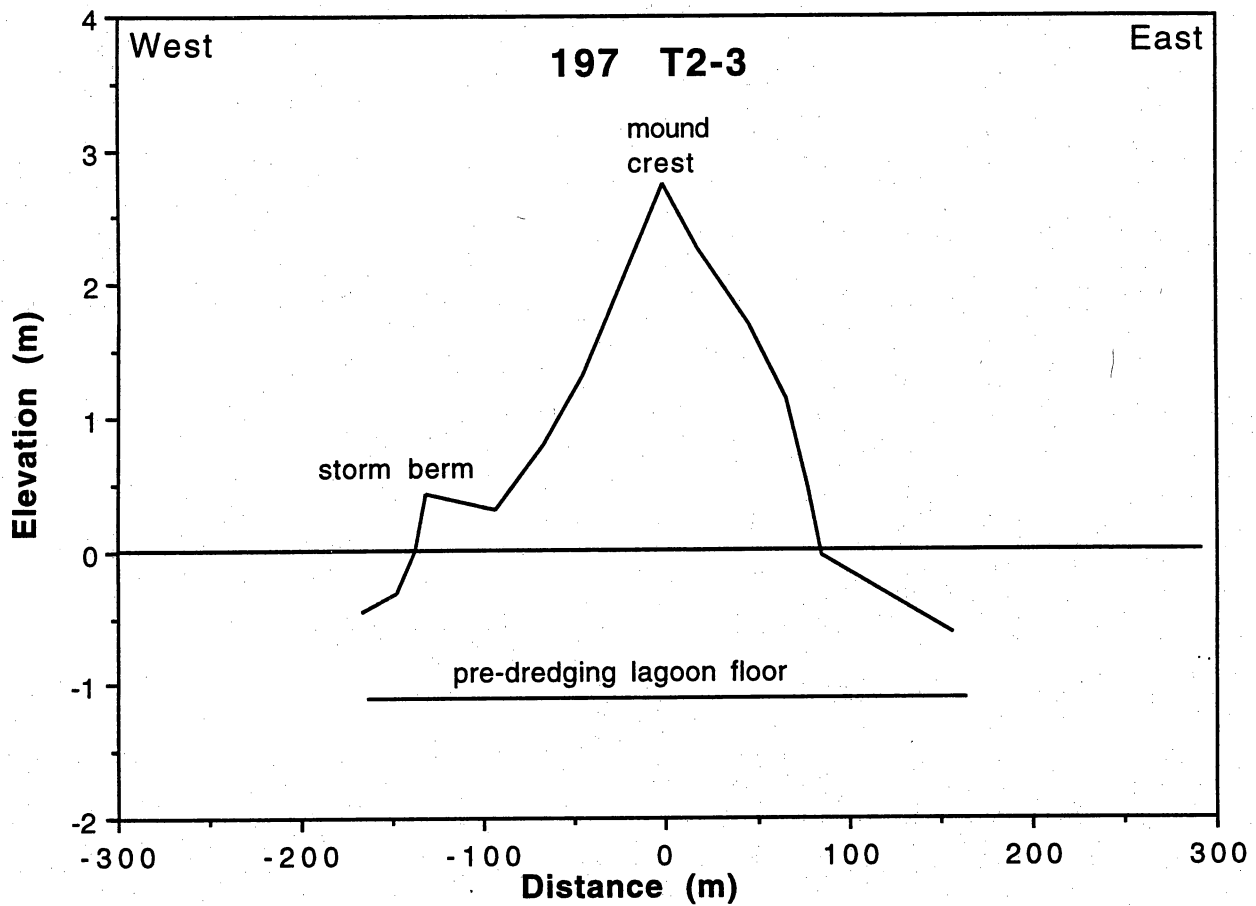
Figure 20. Transverse topographic profile of placement area 197 surveyed in 1996. Profile crosses northernmost island in placement area and ties with profile T 1-4 at the crest of the mound.

across the two large islands located at the northern end of PA 197 between channel markers 207 and 209. The western shore of the islands are characterized by a narrow, barren beach that is covered with shell fragments and patches of cobble size rock fragments. The beach consists of a low-water mat of dead seagrass and a storm berm that coincides with the vegetation line. The flanks of the islands are densely vegetated and plant assemblages are zoned with respect to elevation above average water level. The western and southern margins form an apron that rises in elevation toward the island crest. Dense stands of marsh plants such as *Salicornia, Borrichia, Monanthachloe*, and *Batis* cover the low gradient apron. Prickly pear cactus, grasses, and low shrubs cover the higher elevations. The crests of the mounds are less densely vegetated than the flanks owing to the surficial abundance of coarse rock fragments (coquina) and marine shells such as *Mulinea, Anadara, Oliva, Busycon, Dinocardium*, and *Crassostrea*. The northern margin of the island is a narrow, steep shore with a low wave-cut scarp (fig. 19). The top of the scarp and adjacent surface are covered with a narrow (2 m) band of dense *Disticlis*. The eastern shore of the island is extremely narrow and the water, mat of dead seagrass, vegetation line, and low scarp essentially coincide.

Bottom sediments on the eastern and northern sides of the northern placement area are composed of soft mud that increases in thickness from 0.3 m to as much as 0.6 m away from the shore. In contrast, bottom sediments on the western side are composed of organic-rich shelly and muddy sand that is covered by a dense stand of seagrasses. A bare zone about 10 m wide separates the seagrasses from the western shore of the island.

The two northern islands are connected by a low, sand flat that is covered with dead seagrass and is sparsely vegetated with *Salicornia*. A shallow channel between the islands allows water exchange across the flats during periods of high water. Scour pools preserved on the surface of the flats are evidence of excavation by strong currents during storms.

The small isolated island at the southern end of the placement area near channel marker 221 is low, and although elevations are generally less than 1 m, the island is densely vegetated. The island is surrounded by a narrow sand beach covered with shell fragments and dead seagrass. The slightly higher storm berm, which is composed mostly of shell fragments, also coincides with the vegetation line. On the east side of the island, a low erosional scarp delineates the crenulated shore. Bottom sediments on the west side of the island are dark gray shelly sand, whereas on the east side of the island they are composed of as much as 0.5 m of gray mud with a high water content. Thickness of the surficial mud increases away from the island where water depths increase.

Pre-dredging water depths near PA 197 increase to the south (fig. 21), which is also the present direction of lagoon deepening (fig. 22). This comparison also shows that the axis of the placement area is oriented perpendicular to the contour gradient of the natural lagoon floor
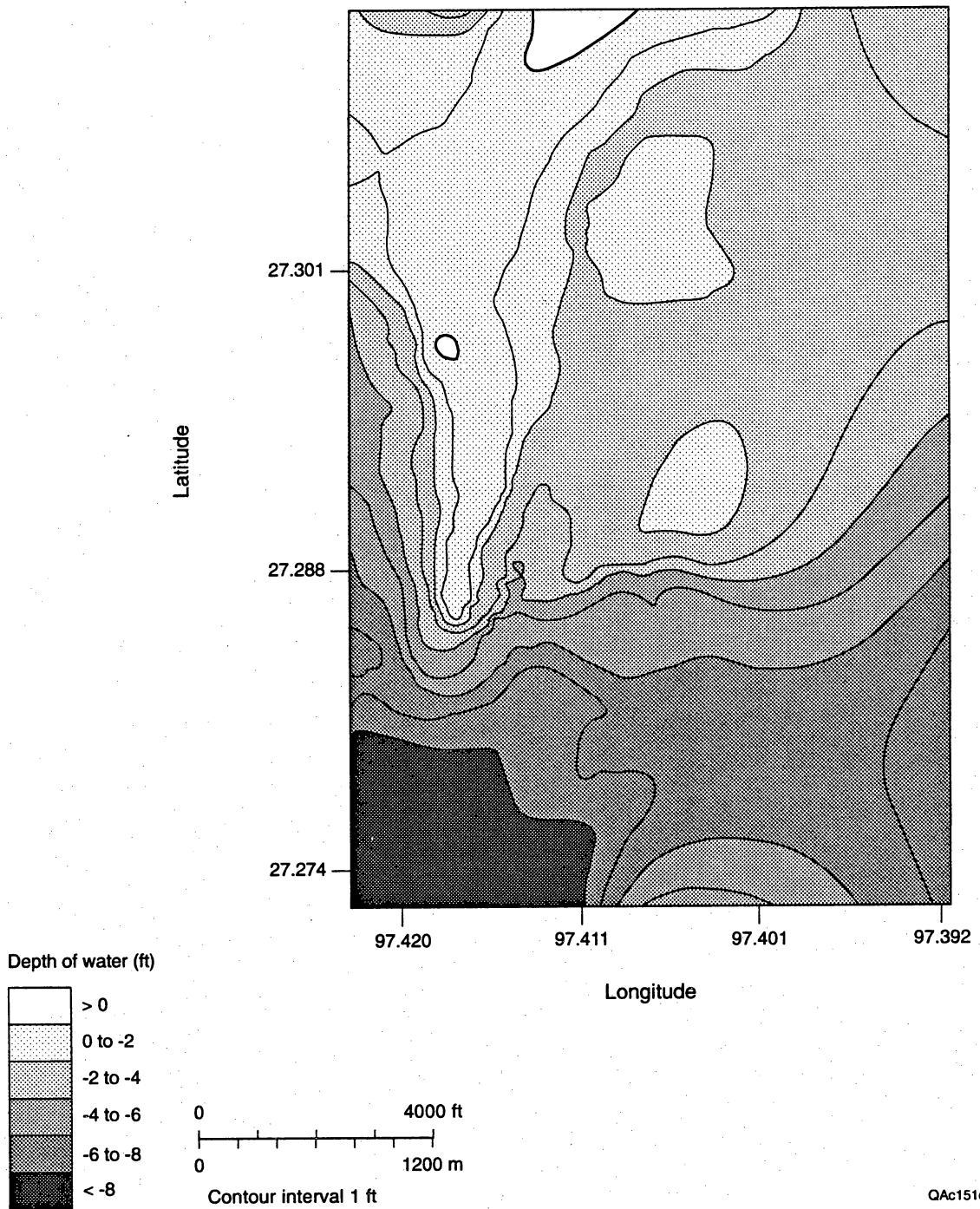
Figure 21. 1931-32 bathymetric map of placement area 197. Digitized from maps of the Galveston District, U.S. Army Corps of Engineers.
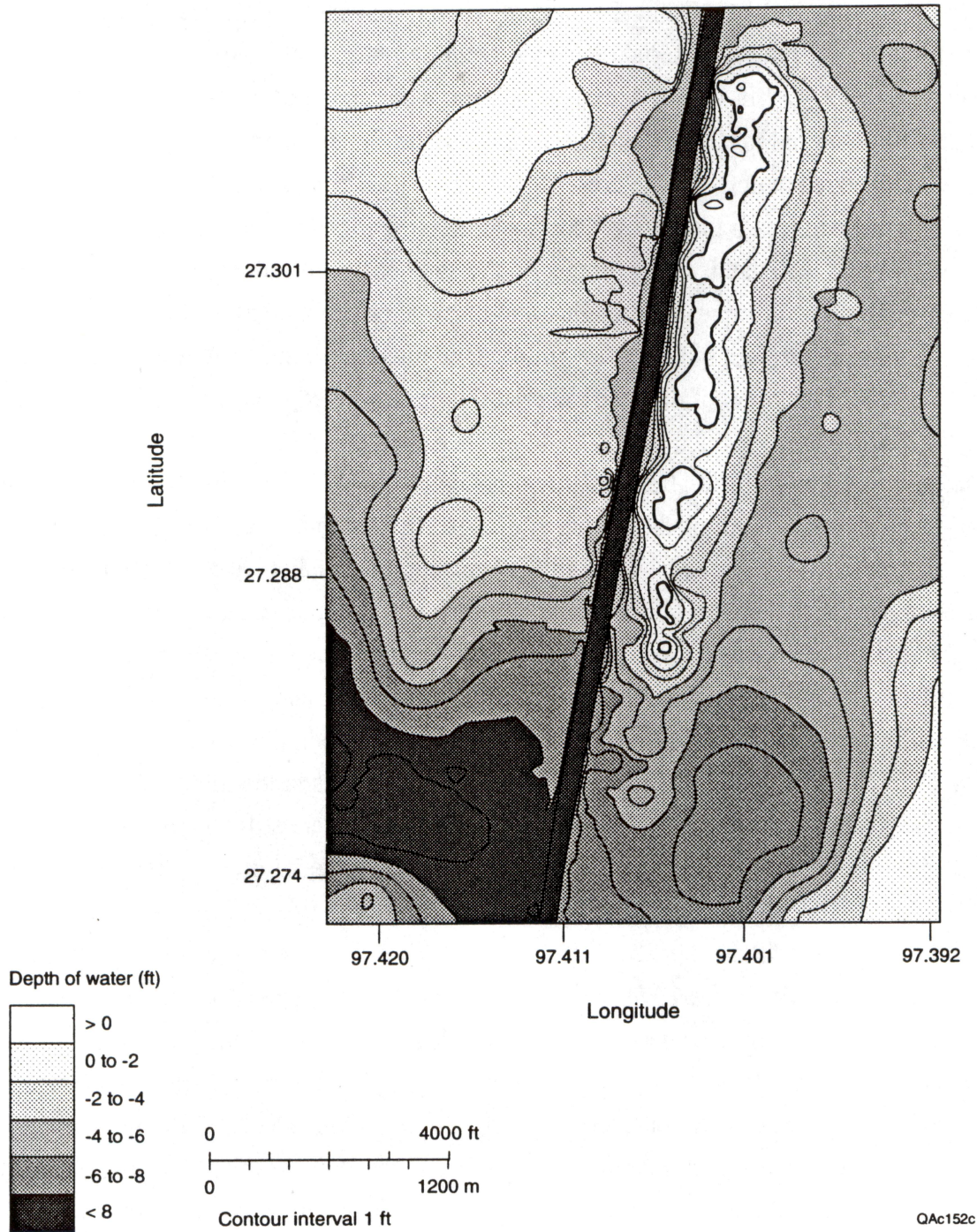
Figure 22. Bathymetric map of placement area 197 based on integration of 1994 and 1995 data.

(figs. 23 and 24). On the northwest side of the GIWW, opposite PA 197, is a low depositional ridge parallel to the dredged channel that is similar to a levee (fig. 23).

Composition of dredged material at PA 197 is highly variable and includes sand, shelly sand, muddy sand, sandy mud, and shelly-sandy mud (Appendix A). On a volumetric basis there is more mud in the dredged material deposited at the southern limit of the placement area near channel marker 221. Also, muddy sediments are more common at PA 197 than at PA 187. Most of the dredged material is retained on the large islands in the northern segment. Maximum thickness of dredged material at the crest of the islands is 3.75 m along the northern transect and 2.2 m along the southern transect (fig. 25). Subaqueous dredged material is asymmetrically distributed around the islands being thinner on the southeast side and thicker on the northwest side toward the GIWW. Repeated dredging and disposal (17 events) at the northern end of the placement area has resulted in direct flow of dredged material to the west, toward and into the GIWW (fig. 25). Thickness of dredged material on the eastern edge of the GIWW in the southern part of the PA is 0.7 m.

Air photos taken in 1950 after construction of the GIWW, but before any maintenance dredging, show isolated individual islands of dredged material that were similar in size except the southernmost island, which was and still is considerably smaller. At that time the islands were barren and there were no seagrasses on the shoals of dredged material. By 1956 the dredged material had been reworked considerably, and sand was deposited in spits indicating sediment transport from north to south with an easterly component at the ends of the spits and northerly transport at the southernmost islands but still with an easterly component at the ends of the spits. Also by 1956 additional dredged material had joined the islands in the middle of the PA and some sparse vegetation was established. By 1961 the islands were still mostly barren; however, some seagrasses were established on the shoals of dredged material on the west side of the islands. Additional dredged material in the northern part of the PA created flats that joined the islands and buried the former spits while in the southern part of the PA the dredged material continued to be reworked. The 1974 photos show expansion of vegetation on the islands, reworking of the connecting flats causing lowered elevations, and establishment of seagrasses on the shoals on the east side of the PA. The flats were again the site of deposition of dredged material in 1981 and reworking of the island margins continued. The 1983 dredging cycle involved a large volume of sediment that was placed on the flats creating an island chain from the former isolated islands. This shallow subaerial and subaqueous disposal event caused extensive spreading of dredged material back to the edge of the GIWW (fig. 25). In 1985 there were prominent scarps on the northeastern and northwestern sides of the islands, the upland vegetation was dense, and the area of dense seagrasses had expanded. Since then, additional dredged material has been added, and there has been a decrease in the extent of seagrasses in the
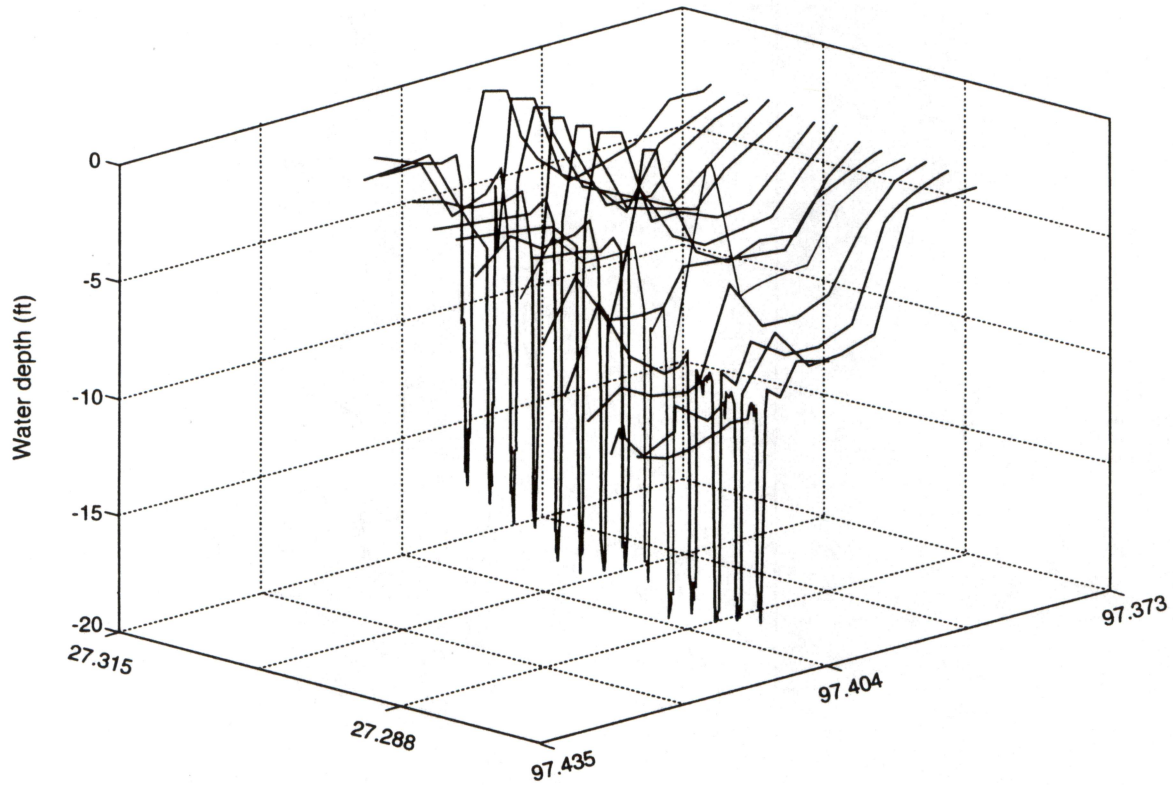
Figure 23. Bathymetric transects in placement area 197 surveyed in 1995. This northeast view shows the mounds of dredged material, the dredged channel and the low levee feature that runs parallel to the GIWW on the west side of the channel.
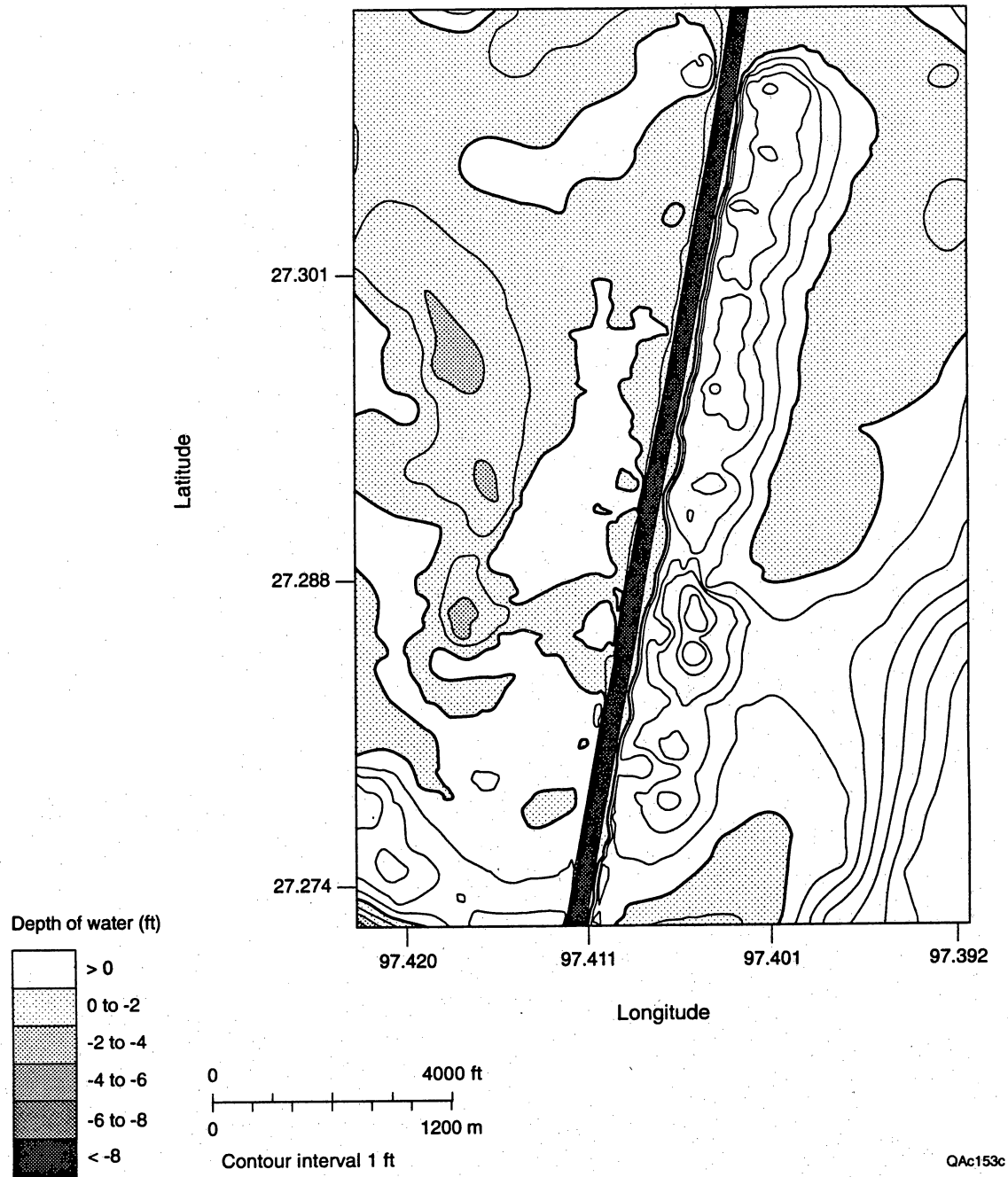
Figure 24. Adjusted difference between 1930s and 1995 bathymetry of placement area 197.
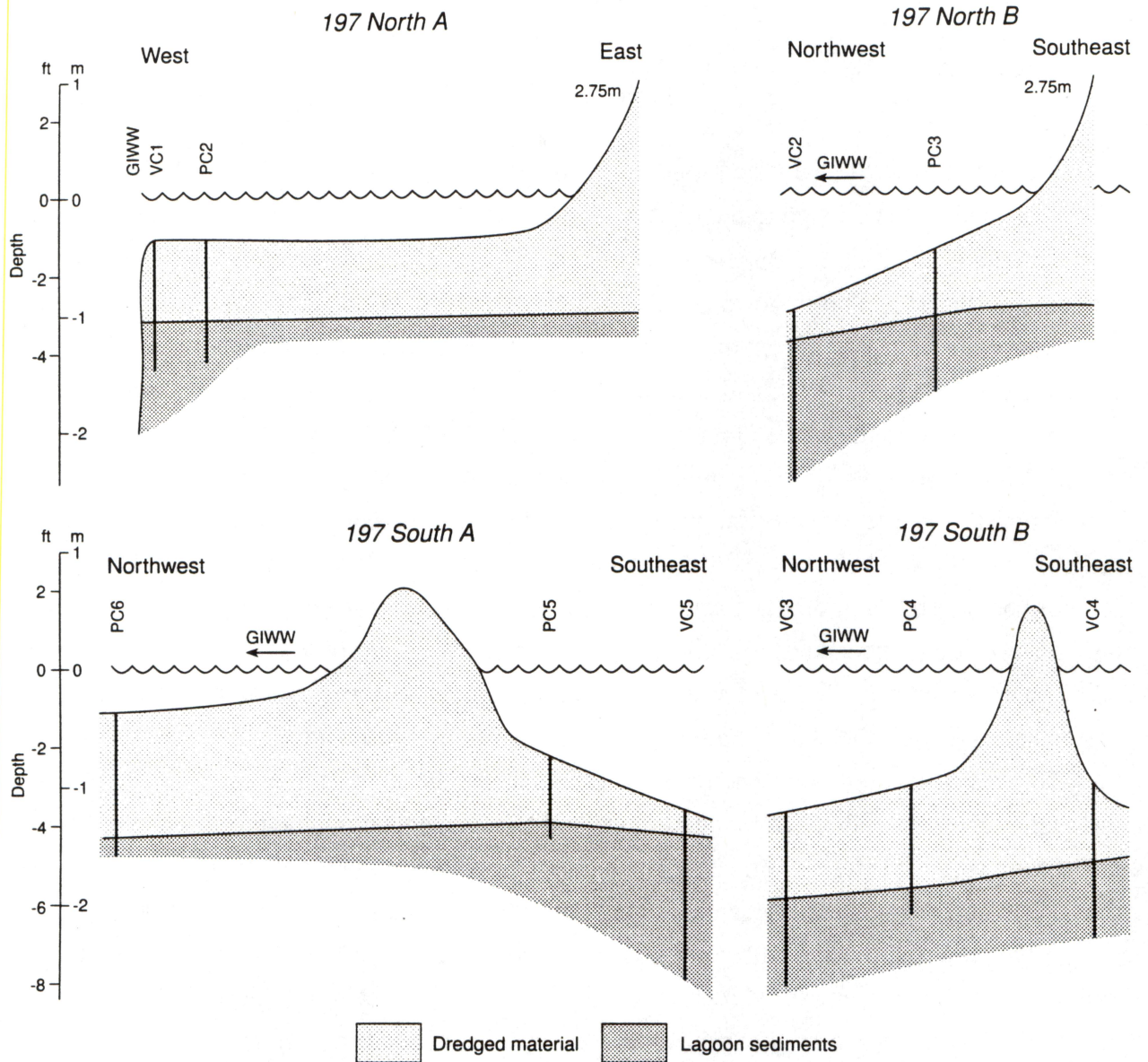
Figure 25. Cross sections illustrating the thickness and lateral extent of dredged material within placement area 197. Core locations shown in fig. 18. Horizontal scale is variable.

southern part of the PA, while the upland vegetation has expanded. Overall, there has been an expansion of the island chain from about 1.5 km in 1956 to about 2.0 km in 1992.

Placement Area 202

Placement area 202 is located south of Baffin Bay (fig. 1) between the Middle Ground shoal to the east and Rocky Slough to the west. Shoals and emergent flats of dredged material at the northern end of PA 202 (fig. 26) are about 250 m east of the GIWW. Fetch at the site is greatest from the northeast and north down the axis of Laguna Madre. Winds that are from the south can also drive water northward from the Hole along the eastern margin of the island chain. Fetch is limited to the northwest, west, and southwest by close proximity of the mainland shore and to the east by Middle Ground shoal and Padre Island. Predominant drift directions of reworked dredged material appear to be to the north and to the west into the GIWW.

Judging from the oldest aerial photographs of the area, there were no meadows of dense seagrasses at the site before placement of the dredged material. However by 1974, seagrasses growing on the shoals of dredged material were concentrated in narrow bands 10 to 15 m wide on the west side of the islands near the GIWW in the southern part of the placement area. To the north, there are narrow fringes of seagrasses on both the east and west sides of the islands. The barren zone between the islands and seagrasses is about 8 to 12 m wide.

The site of detailed investigation at PA 202 includes the low island chain between GIWW channel markers 51 and 55. Both longitudinal and transverse topographic profiles of the island chain were surveyed (figs. 27 and 28). The highest elevations along the islands are generally less than 1.2 m and they generally decrease to the north. Beaches surrounding the islands are generally composed of sand with some cover of shell. Near the storm berm, the beaches are composed of barnacle-encrusted rock fragments. The island surfaces at higher elevations are covered with grasses and prickly pear cactus and by a lag of shells and granule to cobble size clasts of beach rock and some gypsum. The low flats connecting the islands are composed of sand, and they are only about 0.3 m above the average level of the lagoon. The sand flats and low fringes of the islands are colonized by marsh plants including *Batis*, *Salicornia*, and *Borricia*.

Even before confining levees were constructed at the southern end of PA 202, there was a marked difference in the size and morphology of adjacent islands near channel marker 55. Large circular symmetrical mounds of dredged material were constructed to the south on the preexisting flats, whereas narrow shoals capped by linear, irregular ridges with crenulated erosional shores were formed to the north. This abrupt change in island characteristics near Rocky Slough coincides with the bathymetric transition zone located between the Middle Ground shoal and segments of Laguna Madre to the north that are deeper than 1.5 m (fig. 29).

Figure 26. Locations of the GIWW and sediment cores in placement area 202.
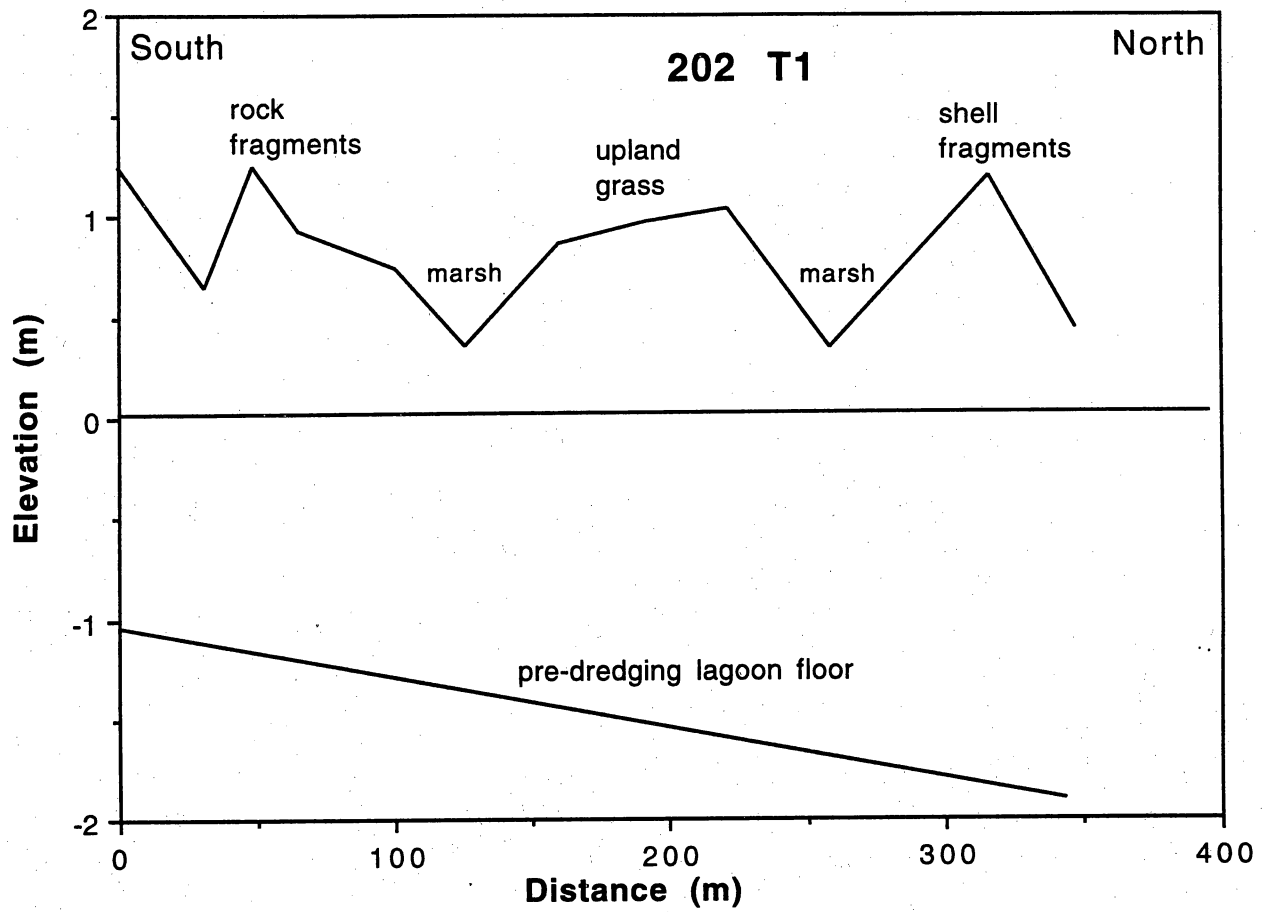
Figure 27. Axial topographic profile of placement area 202 surveyed in 1996. Profile extends along the low island south of VC 2. Core location shown in fig. 26.
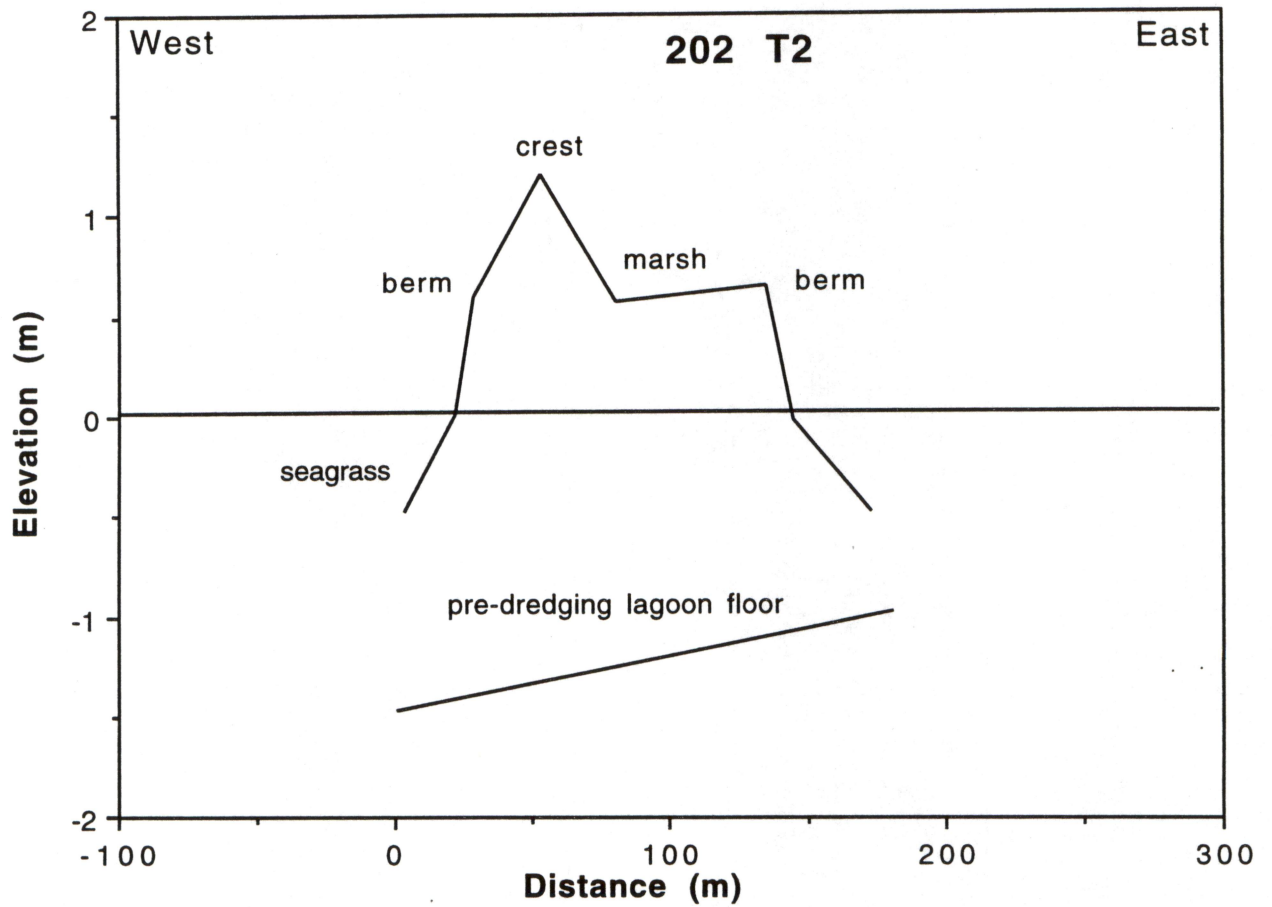
Figure 28. Transverse topographic profile of placement area 202 surveyed in 1996. Profile extends across the low island at VC 2 and ties with T 1 at the crest of the island. Core location shown in fig. 26.

Depth of water (ft)

	>0
	0 to -2
	-2 to -4
	-4 to -6
	<-6

0   4000 ft

0   1200 m

Contour interval 1 ft

QAc148c
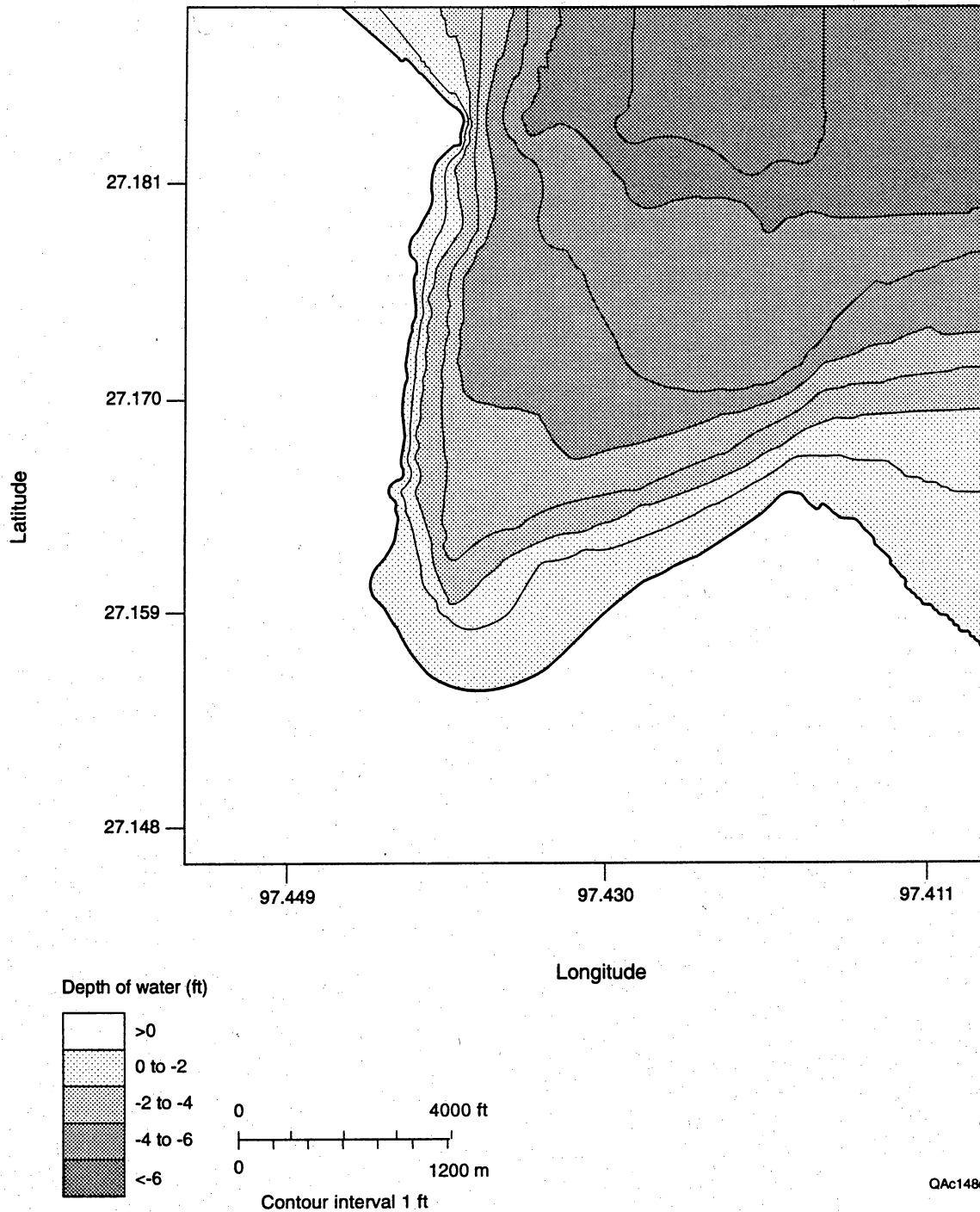
Figure 29. 1931-32 bathymetric map of placement area 202. Digitized from maps of the Galveston District, U.S. Army Corps of Engineers.

The GIWW crosses the pre-dredging bathymetric contours at a high angle, which explains the abrupt change in island morphology (compare figs. 29 and 30).

Present-day lagoon floor gradients are slightly steeper on the west side than on the east side where a narrow platform has been constructed from the dredged material (figs. 30 and 31). There is also a narrow levee-like ridge on the west side of the GIWW parallel to the channel (fig. 31). Bottom sediments on the west side of the island chain consist of very soft organic-rich dark gray mud as much as 0.5 m thick. The subaqueous dredged material east of the small island at channel marker 51 consists of highly mobile sand covered by sparse seagrass and small bedforms such as oscillation ripples.

Dredged material consists of sand, slightly muddy shelly sand, interbedded shelly sand and sandy shell, and organic-rich mud with a high water content. Muddy dredged material is common at the central and southern coring sites, whereas sand and shelly sand predominate at the northern site. Muddy sediments in the dredged material are derived from the underlying lagoonal sediments, which are composed of interbedded mud and sand layers near the flats of Kenedy County. The sand and shelly sand near channel marker 51 (PC-2 and VC-4) appear to be material dredged from the lagoon farther to the north and hydraulically emplaced during the initial construction of the GIWW. Maximum thicknesses of dredged material along the island crests are 2.5 to 3.0 m (fig. 17), whereas thicknesses of subaqueous dredged material range from 0.75 to 1.0 m and are relatively uniform or increase to the west toward the GIWW.

The oldest air photos available for analysis of changes in PA 202 were taken in 1960 (Appendix B) after three maintenance dredging events. By then the large mounds were partially vegetated around their lower elevations but the narrow chain of low islands was still barren. Also there had been substantial reworking of the dredged material and the coarser sediments were deposited as spits attached to the chain of narrow islands. The predominant sediment transport direction was to the north, but some reworked sediment was transported to the south. Reworking of dredged material was concentrated on the west side of the low irregular islands, and erosional scarps are steeper on the west side of the islands, which is toward the GIWW. Photographs taken in 1974 and 1975 show breaching of the island chain that had been formed previously by spit accretion. Seagrasses were established as narrow fringes on shoals of the dredged material. Fragmentation of the island chain continued in the northern part of the placement area while more dredged material was added to the flats surrounding the large mounds in the southern part of the PA. By 1985 all the islands were densely vegetated and high containment levees had been constructed around the large mounds. Dredged material had been placed between the large mounds and the narrow island near channel marker 55. The 1992 photos showed additional
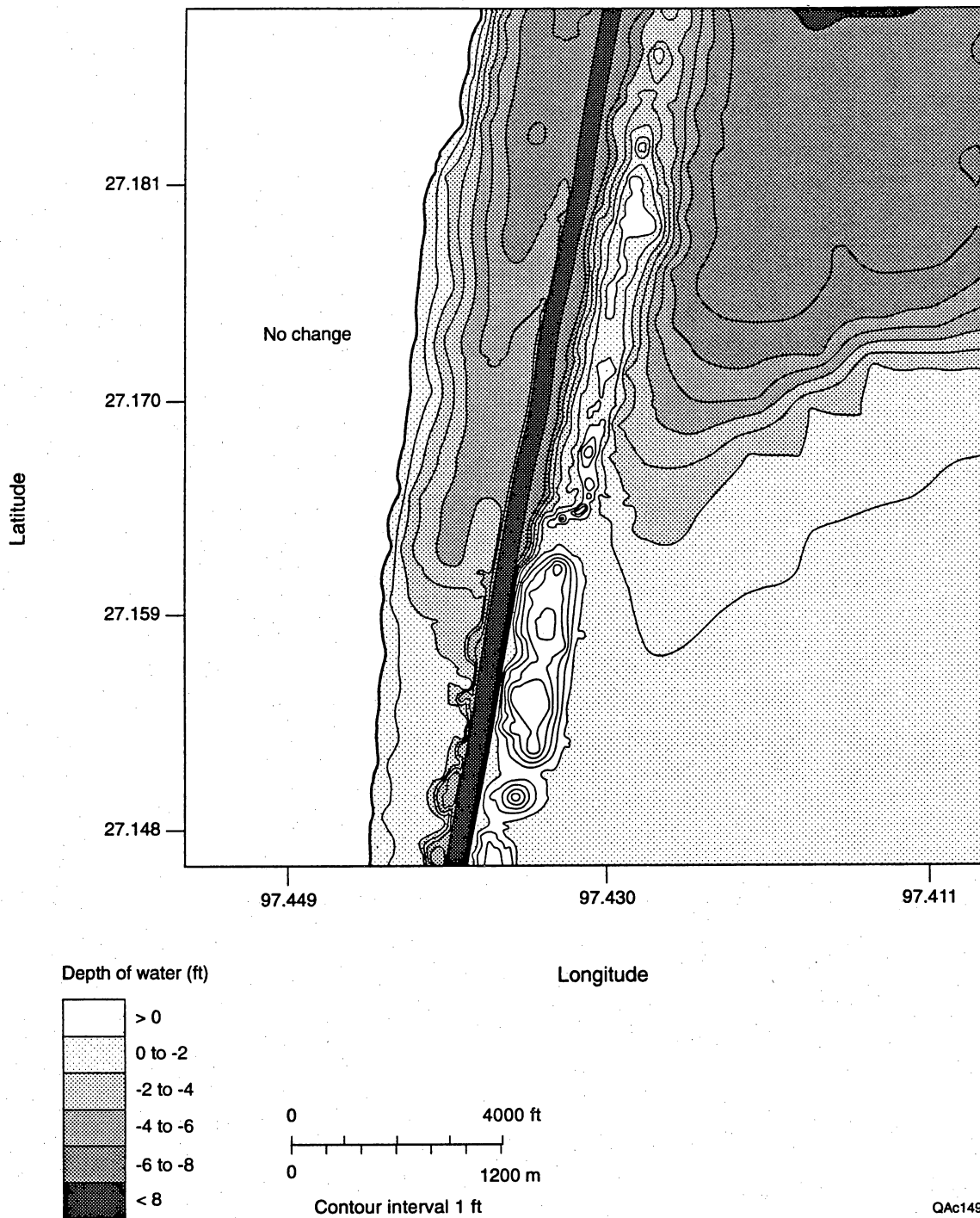
Figure 30. Bathymetric map of placement area 202 based on integration of 1994 and 1995 data.
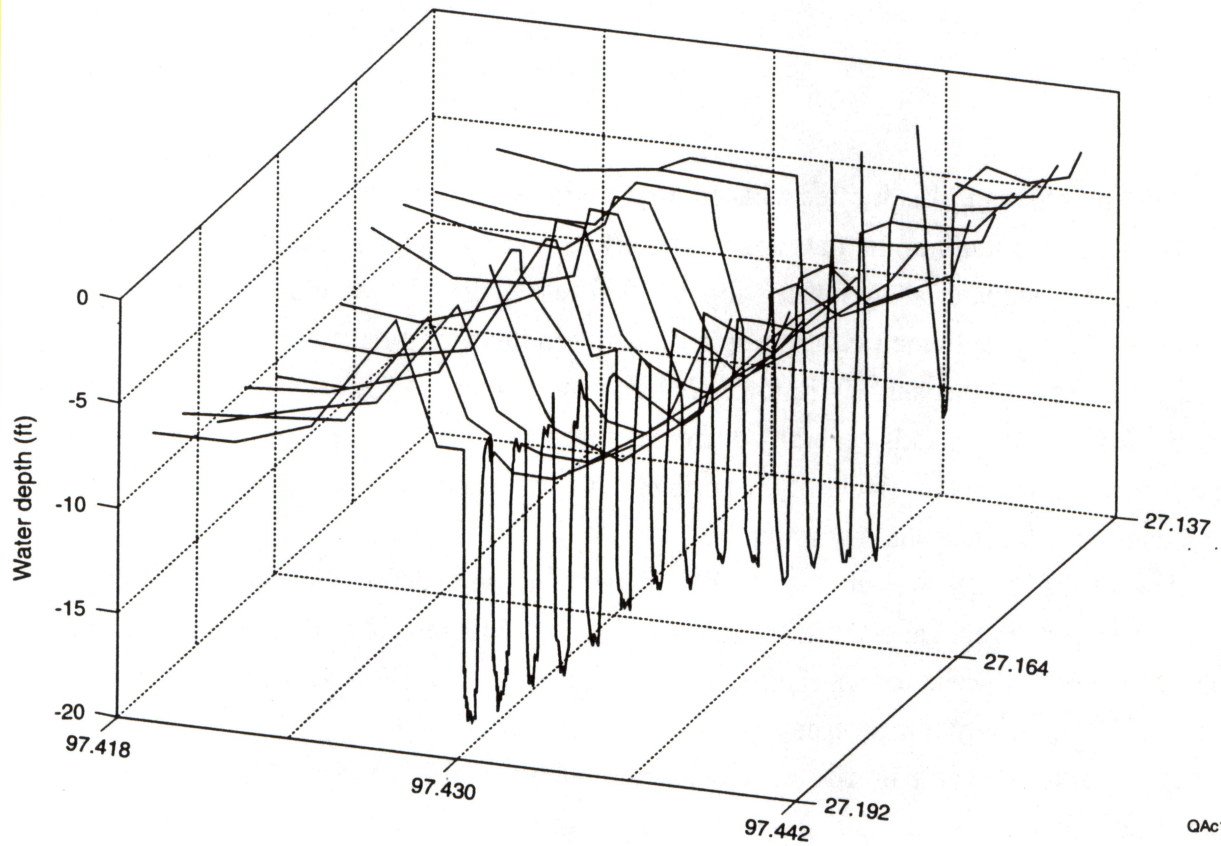
Figure 31. Bathymetric transects in placement area 202 surveyed in 1995. This southwest view shows the mounds of dredged material, the dredged channel and the low levee feature that runs parallel to the GIWW on the west side of the channel.

dredged material within the containment levees but no significant changes in the shapes or positions of the narrow islands.

The area of inferred shoaling that projects northeast of the GIWW at PA 202 (fig. 32) is actually related to deposition of sediments repeatedly dredged from a network of oilfield channels constructed across the Middle Ground shoal. Aerial photographs of the region show extensive reworking of the dredged material and transport to the north and northwest toward the GIWW.

Placement Area 211

Placement area 211 is located adjacent to the wind-tidal flats of Kenedy County (figs. 1 and 33) and it extends south of the flats approximately 2.75 km. Emergent islands and intervening shoals of dredged material are located about 250 m east of the GIWW. Placement area 211 coincides with the bathymetric transition zone between the wind-tidal flats and deeper segments of Laguna Madre to the south. Within PA 211 and contiguous PA 212, size of the rounded nearly symmetrical circular islands generally decreases to the south. The largest volume of dredged material is retained in the islands at the north end of the placement area where disposal was on the flats or in extremely shallow water.

The site of PA 211 was covered with moderately dense to dense seagrasses before the GIWW was constructed and seagrasses continue to grow on both sides of the dredged material. The barren zone adjacent to the islands, which ranges from 15 to 30 m wide, is typically wider on the west side where it is protected by waves from the southeast.

An axial topographic profile surveyed across the two small islands and intervening flats near channel marker 33 (fig. 34) shows that the surface elevations are less than 1.5 m above the average water level in the lagoon. A surficial lag of caliche nodules and shell fragments as well as dense stands of grasses and a few shrubs cover the higher elevations. The lower fringes of the emergent islands are covered with marsh plants including *Borrichia* and *Salicornia*, whereas the low flats connecting the islands are covered with dead seagrass, algal mats, or sparse *Salicornia*. The islands are rimmed by narrow sand beaches and adjacent slightly elevated storm berms covered with dead seagrasses. Average water depth in Laguna Madre surrounding the placement area ranges from 0.4 m at the northern end (channel marker 23) to 0.75 m at the southern end (channel marker 33). Comparison of pre-dredging and post-construction water depths at placement area 211 (figs. 35-37) show that the axes of the islands are at a high angle to the trend of lagoonal bathymetric contours. The water depths derived from the cores (Table 5) agree well with the 1930s bathymetry for the northern end of southern Laguna Madre.

Depth of water (ft)

	> 0
	0 to -2
	-2 to -4
	-4 to -6
	-6 to -8
	< -8

0   4000 ft

0   1200 m

Contour interval 1 ft

QAc150c
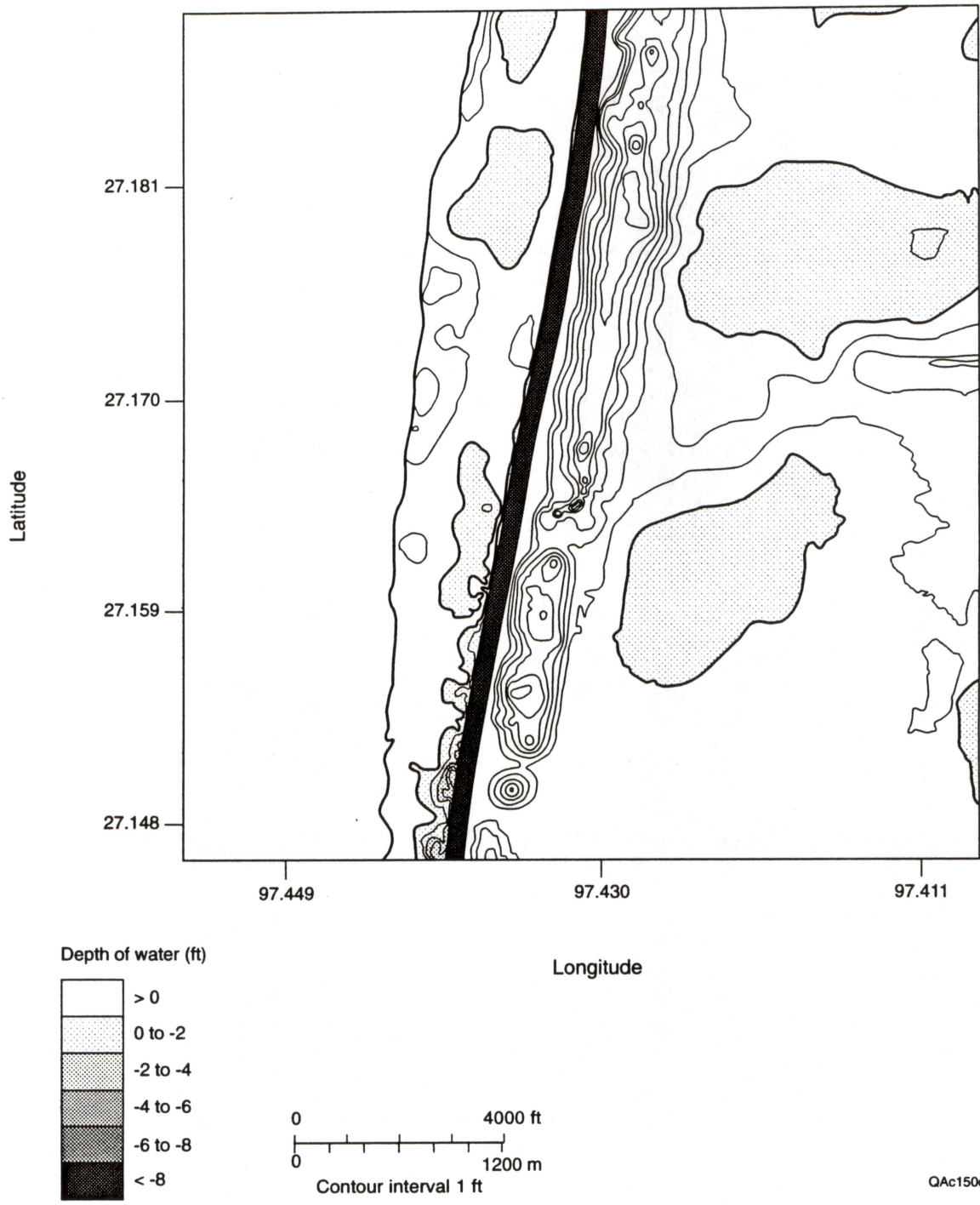
Figure 32. Adjusted difference between 1930s and 1995 bathymetry of placement area 202.
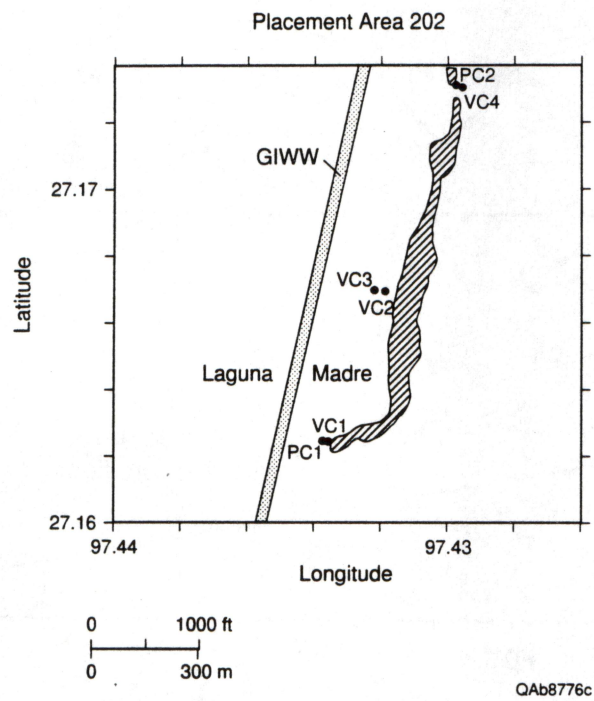
Figure 33. Locations of the GIWW and sediment cores in placement area 211.

98
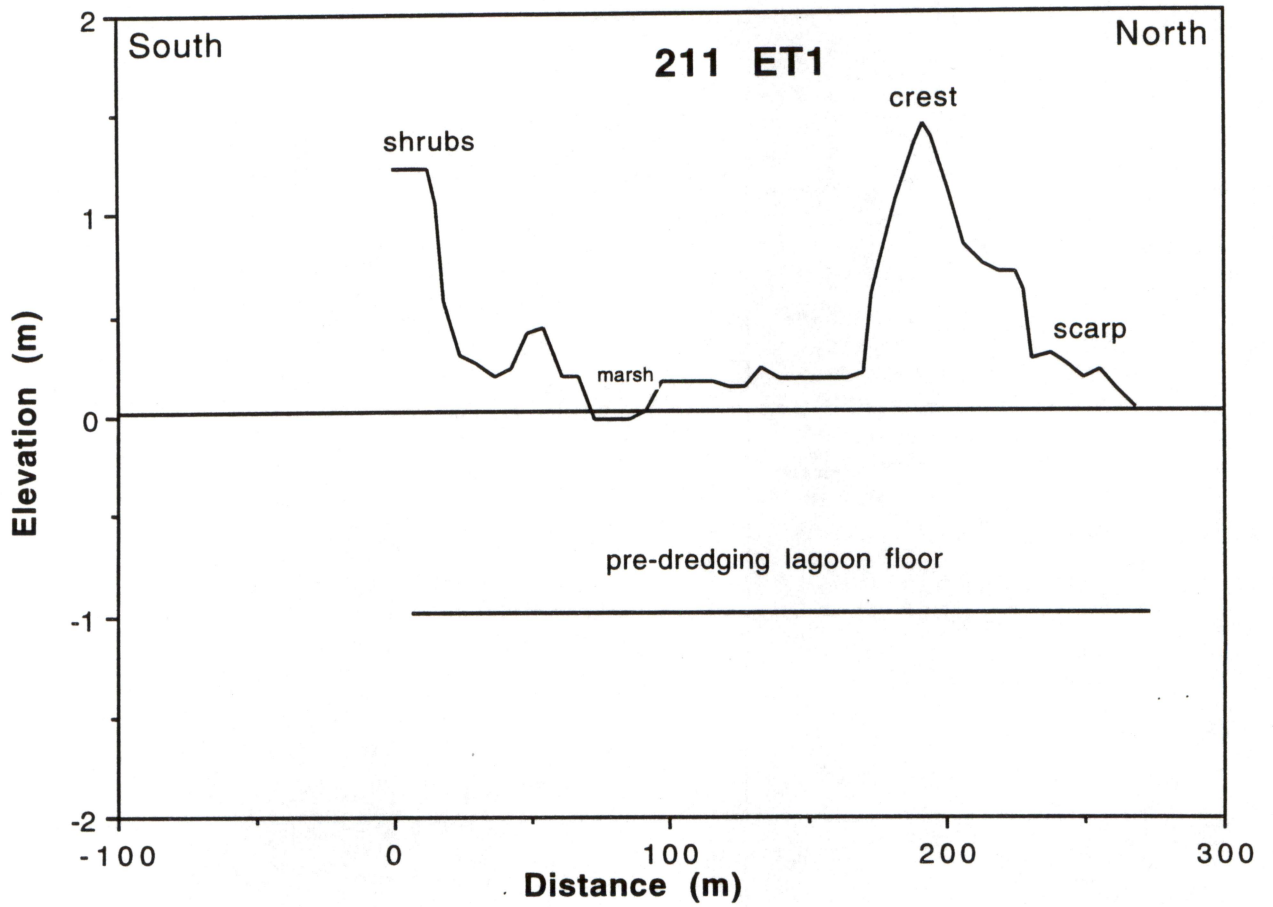
Figure 34. Axial topographic profile of placement area 211 surveyed in 1996. Profile extends along the two low islands east of PC 2. Core location shown in fig. 33.

Depth of water (ft)

- > 0
- 0 to -2
- -2 to -4
- -4 to -6
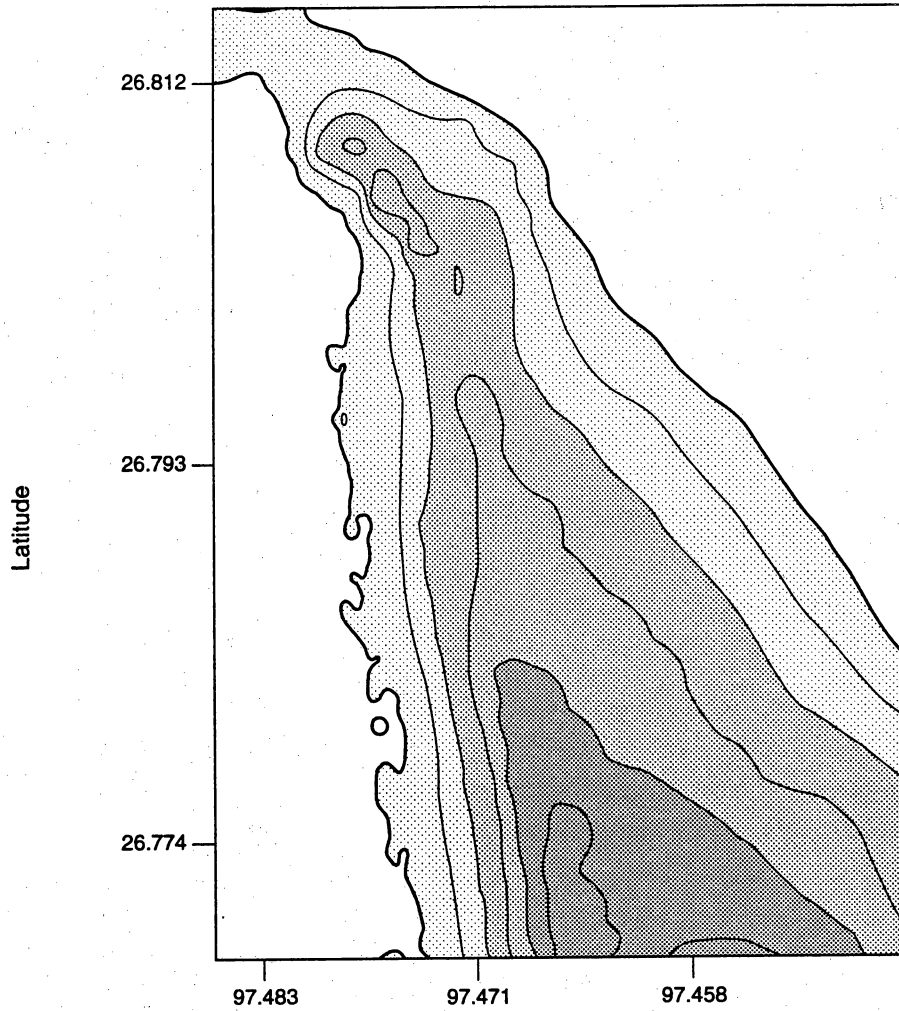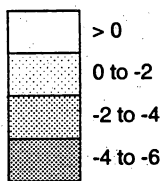
0   4000 ft

0   1200 m

Contour interval 1 ft

QAc154c

Figure 35. 1931-32 bathymetric map of placement area 211. Digitized from maps of the Galveston District, U.S. Army Corps of Engineers.
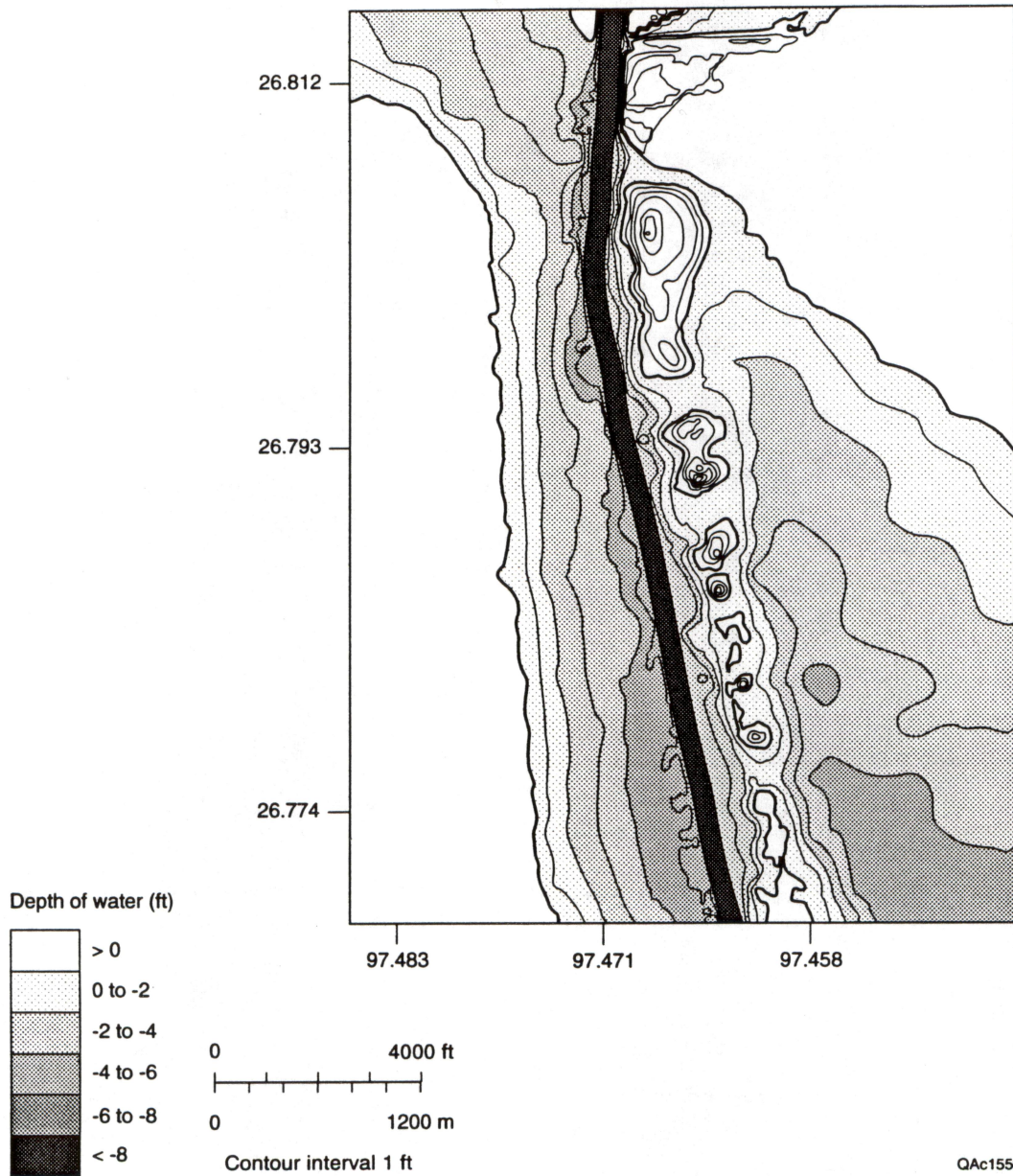
Figure 36. Bathymetric map of placement area 211 based on 1995 data. 1994 surveys were not available for this placement area.

101
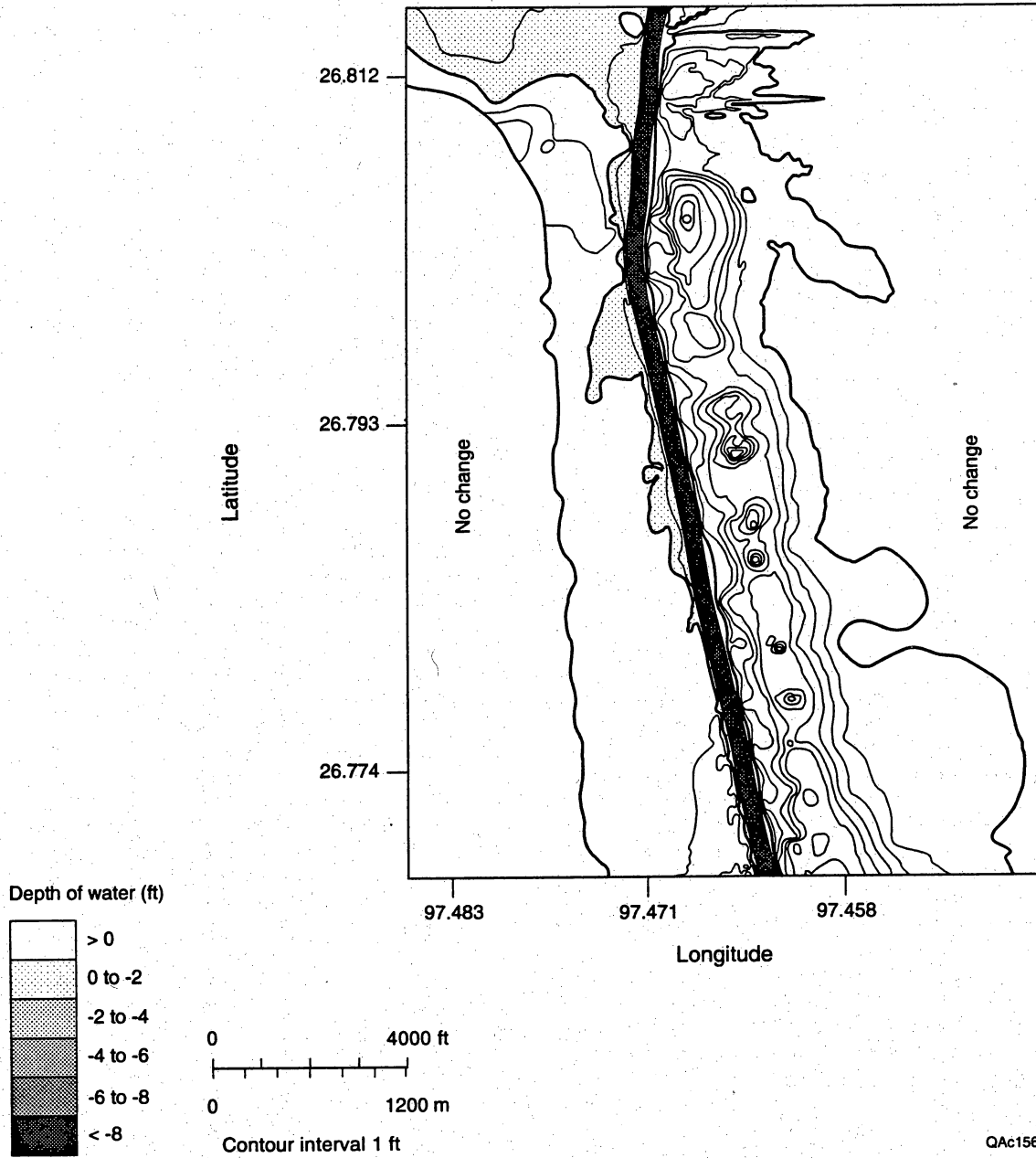
Figure 37. Adjusted difference between 1930s and 1995 bathymetry of placement area 211.

Depth of water (ft)

- \> 0
- 0 to -2
- -2 to -4
- -4 to -6
- -6 to -8
- < -8

Contour interval 1 ft

QAc156c

Greatest fetch for wave and current reworking of the dredged material at PA 211 is along the axis of Laguna Madre from the southeast and south, which are the directions of prevailing winds. Fetch is limited to the north and east by the vast wind-tidal flats, and to the west by the mainland shore of Rincon de San Jose. The bathymetry and island orientations cause sediment reworking and transport to the northwest toward and across the GIWW, which probably contributes to the levee-like ridge that has formed at the edge of the GIWW on the opposite side of PA 211.

Two piston cores were collected near PA 211 to characterize natural Laguna Madre sediments far from and near the GIWW. Piston core 211 PC3 (Appendix A) was taken on the west shore of Laguna Madre about 50 m from shore and 2.4 km west of the GIWW. This location was selected to represent a marine grassflat where wave reworking of adjacent upland deposits is a significant process. Piston core 211 PC4 was taken on the western edge of the GIWW at channel marker 23 where the water is only 0.38 m deep. This shallow water site represents natural grassflat conditions near the placement area, but where placement of dredged material is on the opposite side of the channel.

Bottom sediments around the emergent islands are composed of organic-rich sand and shelly sand. In September, 1996, bare or sparsely vegetated fine sand representing recently deposited dredged material covered the lagoon floor on the east side of the GIWW near channel marker 27. The sparse aquatic vegetation is the marine algae *Acetabularia crenulata*. In core 211 PC1, the surficial sand is about 14 cm thick (Appendix A), and it overlies a layer of brown gray sand containing roots and shells. The latter sediments represent the lagoon floor grassflat before the most recent deposition of dredged material.

Dredged material at PA 211 is composed typically of a mixture of muddy sand and sandy mud. Shells and shell fragments are absent or only rarely present in the sediments. The dredged material commonly contains caliche nodules or pebble-size fragments of cemented sand and shell. These anomalous sediments probably are derived from the soil profile at the Pleistocene-Holocene unconformity. Maximum thickness of dredged material of the low islands is about 2.5 m (fig. 38) and the thickness of subaqueous dredged material surrounding the islands ranges from 0.4 to 0.8 m (Table 5). Subaqueous dredged material generally is thin (< 0.4 m) on the eastern side of the placement area and thickens toward the GIWW.

No aerial photographs are available for the immediate post-construction distribution of dredged material in PA 211, and four maintenance dredging cycles were completed before the 1960 photographs were taken (Appendix B). By that time the mostly barren isolated subaerial mounds were separated by frequently submerged flats. Water surrounding the islands promoted substantial reworking and the reworked material was transported to the northwest along the waterway. The coarsest material (sand and shell) was deposited as spits attached to the islands
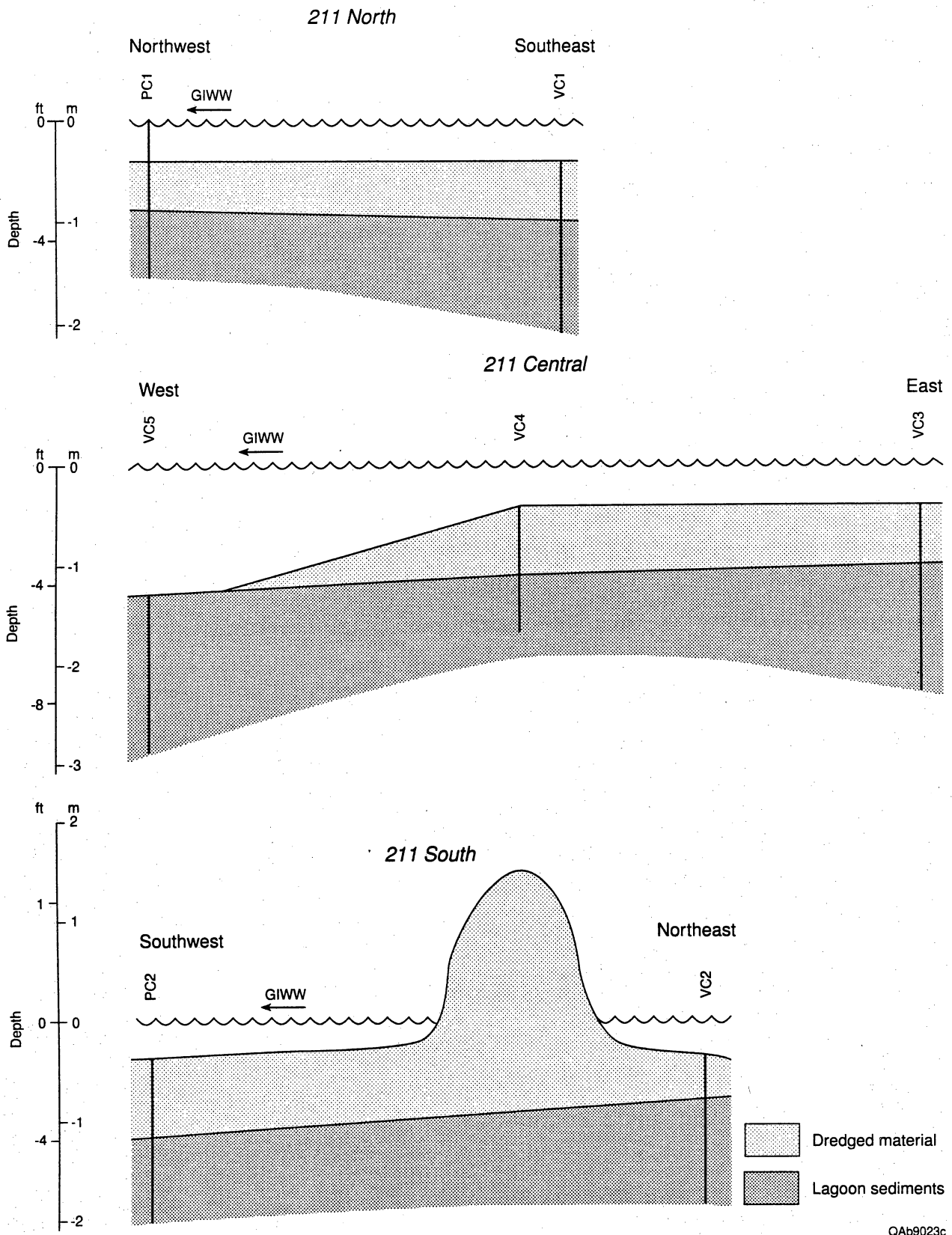
Figure 38. Cross sections illustrating the thickness and lateral extent of dredged material within placement area 211. Core locations shown in fig. 33. Horizontal scale is variable.

that point in the direction of transport. The 1960 dredging cycle constructed an additional mound in the northern end of the PA between existing mounds. By 1974 the spits had been eliminated by erosion and prominent scarps had formed around the islands, but the islands remained stationary as more dredged material was added and the upland vegetation expanded. By 1982 additional dredged material was placed on several of the islands but most of it was deposited on the cluster of islands that form the northern part of the placement area. Between 1982 and 1992, only minor reworking occurred and no new dredged material was added. When the maintenance strategy shifted to disposal on the high islands in the northern end of the PA the frequency of dredging was reduced dramatically, even though the deposited material was placed closer to the waterway. The high elevations at the northern end of the PA protect most of the dredged material from reworking by the predominant north flowing currents.

Placement Area 221

Placement area 221 (figs. 1 and 39) includes about 5.5 km of the GIWW extending from just south of the channel to Port Mansfield to channel marker 167. The remaining dredged material forms elongate subaqueous shoals about 100 to 240 m wide that are capped with narrow irregular islands down their axes.

Because of the orientation of Laguna Madre, PA 221 is exposed to all the predominant winds emanating from the northwest, north, east, and southeast. Fetch is limited from the southwest and west by the mainland shore. Long-term geomorphic indicators of sediment reworking suggest that sediment transport is primarily to the west although some southerly transport is also indicated locally. Water transporting high concentrations of suspended sediment is driven westward by southeast wind and then diverted to the north by the western shore of the lagoon. Natural water depths in Laguna Madre around PA 221 increase to the north from about 0.6 m near channel marker 167 to about 1.8 m near channel marker 149.

When the GIWW was excavated, dredged material was placed on dense to moderately dense meadows of seagrasses with density of seagrasses decreasing to the north in deeper water. There was a general loss of seagrasses by 1974. Today natural seagrass meadows persist east of the placement area and sparse patchy seagrasses grow on the crests of the shoals of dredged material. The barren zones adjacent to the islands of dredged material range in width from 8 to 30 m. As at the other placement sites, there is a minor levee-effect along the GIWW on the side opposite the placement area. Examination of 1974 and 1986 aerial photographs shows numerous barren swaths in the seagrasses that form arcs and zig-zag patterns. The barren zones appear to be enlarged scars created by dragging nets or churning boat props. By 1993, the seagrasses expanded covering many of the former scars.
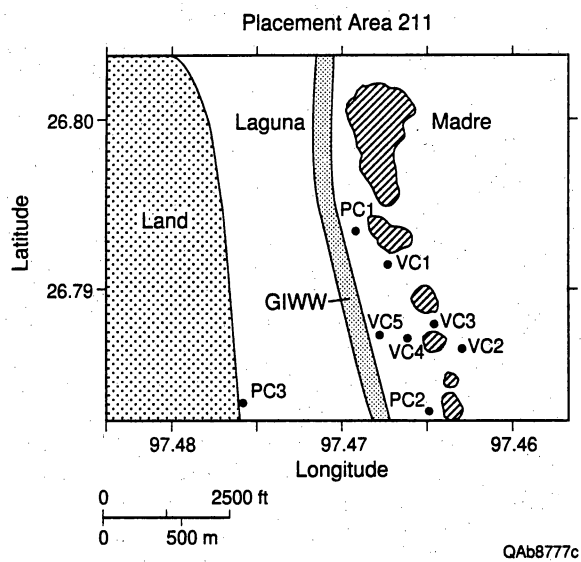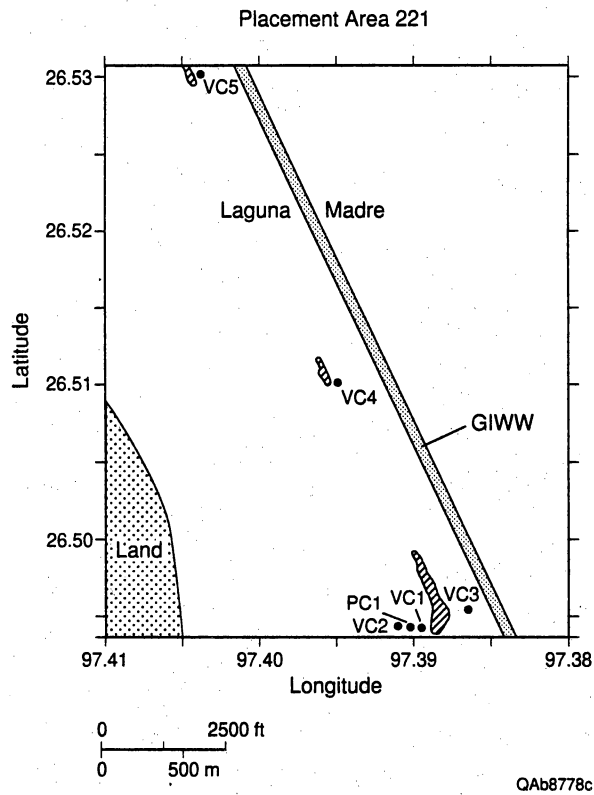
Figure 39. Locations of the GIWW and sediment cores in placement area 221.

On the southernmost island in the PA near channel marker 167, recently deposited dredged material is composed of large mud balls of pebble and cobble size in a matrix of mud that together form a conglomerate. The crest and upper flanks of the island are bare and subjected to slope wash and incision by narrow gullies. In contrast, the lower flanks are stable and vegetated with prickly pear, grasses, and other types of vegetation. The red, tan, and brown cohesive mud is virgin material and not sediments that were deposited in the GIWW since it was dredged. The colors and consistency of the dredged material are similar to the oxidized Pleistocene delta plain deposits of the coastal plain that are exposed along the lagoon margin about 1.6 km to the west. The topographic profile of this island is highly asymmetrical. A steep, wave-cut bluff about 1.5 m high forms the west side, whereas the east side has a moderate slope with a low (0.5 m) scarp that coincides with the vegetation line (fig. 40). The high mound merges to the north with a narrow strip of land that is less than 1 m above the lagoon water. The narrow neck of land is composed of sand and shell and is covered by dense marsh plants, predominantly *Borrichia*.

The shoal and low mound between channel markers 159 and 161 is cored by mud but surrounded by reworked sand, shell and dead seagrass that form a low berm and sand flat on the west side. The east side is characterized by a low erosional scarp. The subaerial part of the island is mostly barren and only sparsely vegetated with *Sesuvium* on the highest elevations, which are less than 0.6 m above the water level.

The lagoon floor around PA 221 is firm and composed of sand and shelly sand. Between channel marker 159 and 161, in about 1.1 m of water, the sandy lagoon floor also is covered by abundant dead but articulated *Mercenaria campechiensis*. West of the GIWW at channel marker 153 in about 1 m of water, the lagoon floor is composed of rippled sand with seagrass and a few *Mercenaria* shells.

The islands of dredged material, which are located about 300 m west and southwest of the GIWW, are oriented nearly parallel to the bathymetric contours of the pre-dredging lagoon floor that slopes to the east (compare figs. 41 and 42). Water depths derived from the sediment cores agree well with the 1930s bathymetry (Table 5). The placement area coincides with the bathymetric transition zone between shallow water near the mouth of the Arroyo Colorado and deeper water to the north in Laguna Madre. In general, islands of dredged material decrease in length but increase in height to the north in response to the greater water depths (fig. 43).

Most of the cores contain no more than three units of dredged material, which seems unusually low compared to the total number of dredging events (8). Maximum thickness of dredged material at PA 221 is 4.8 m beneath the crest of the high island at channel marker 167 (fig. 44). Elsewhere thicknesses of submerged dredged material surrounding the islands is 0.3 to 0.7 m (Table 5) and dredged material is at least 0.3 m thick toward the GIWW (fig. 44).

Figure 40. Transverse topographic profile of placement area 221 surveyed in 1996. Profile extends across the high island east of VC 1. Core location shown in fig. 40.

Figure 41. 1931-32 bathymetric map of placement area 221. Digitized from maps of the Galveston District, U.S. Army Corps of Engineers.

Depth of water (ft)

	>0
	0 to -2
	-2 to -4
	-4 to -6
	<-6

0   4000 ft

0   1200 m

Contour interval 1 ft

QAc146c
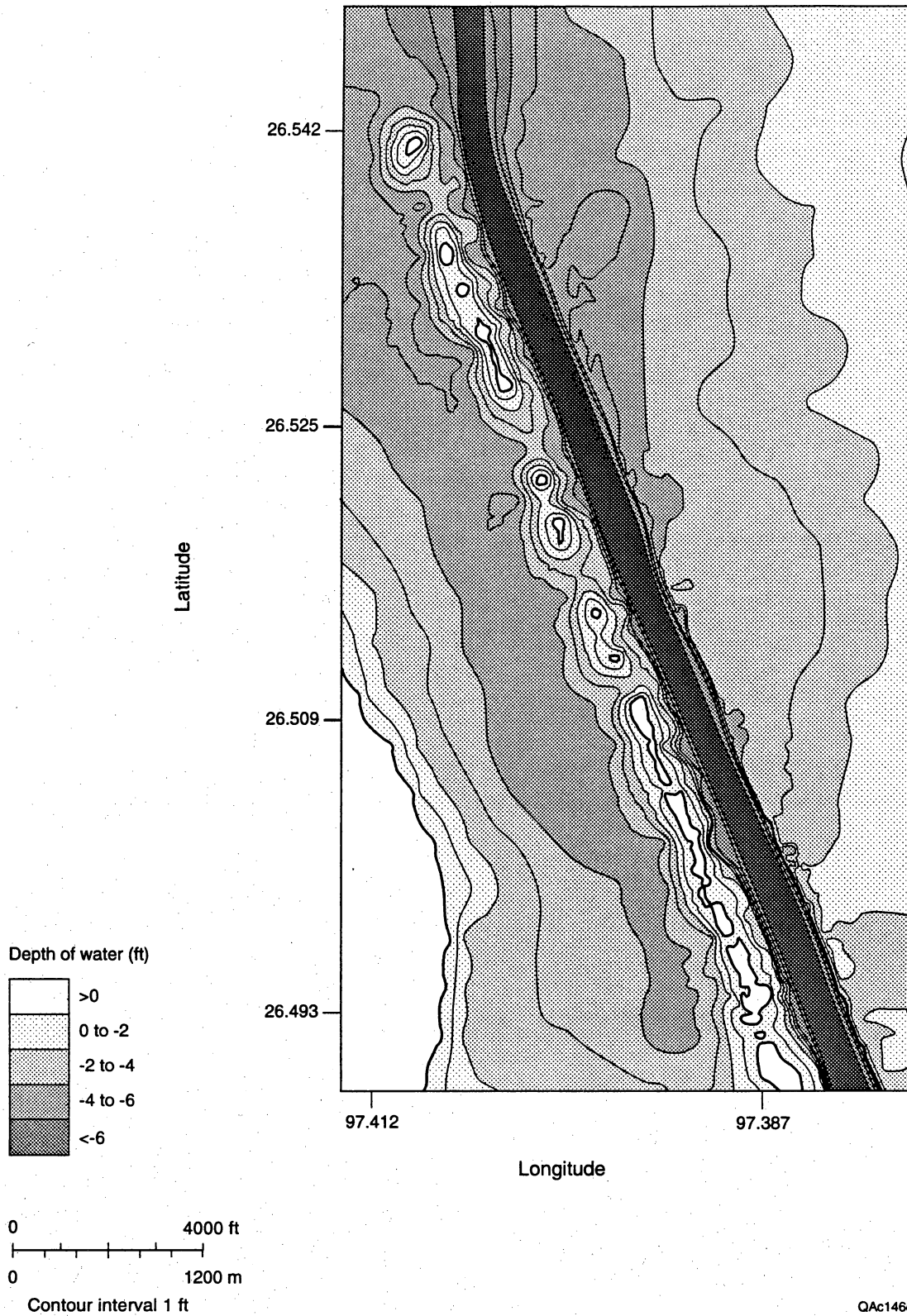
Figure 42. Bathymetric map of placement area 221 based on integration of 1994 and 1995 data.

110
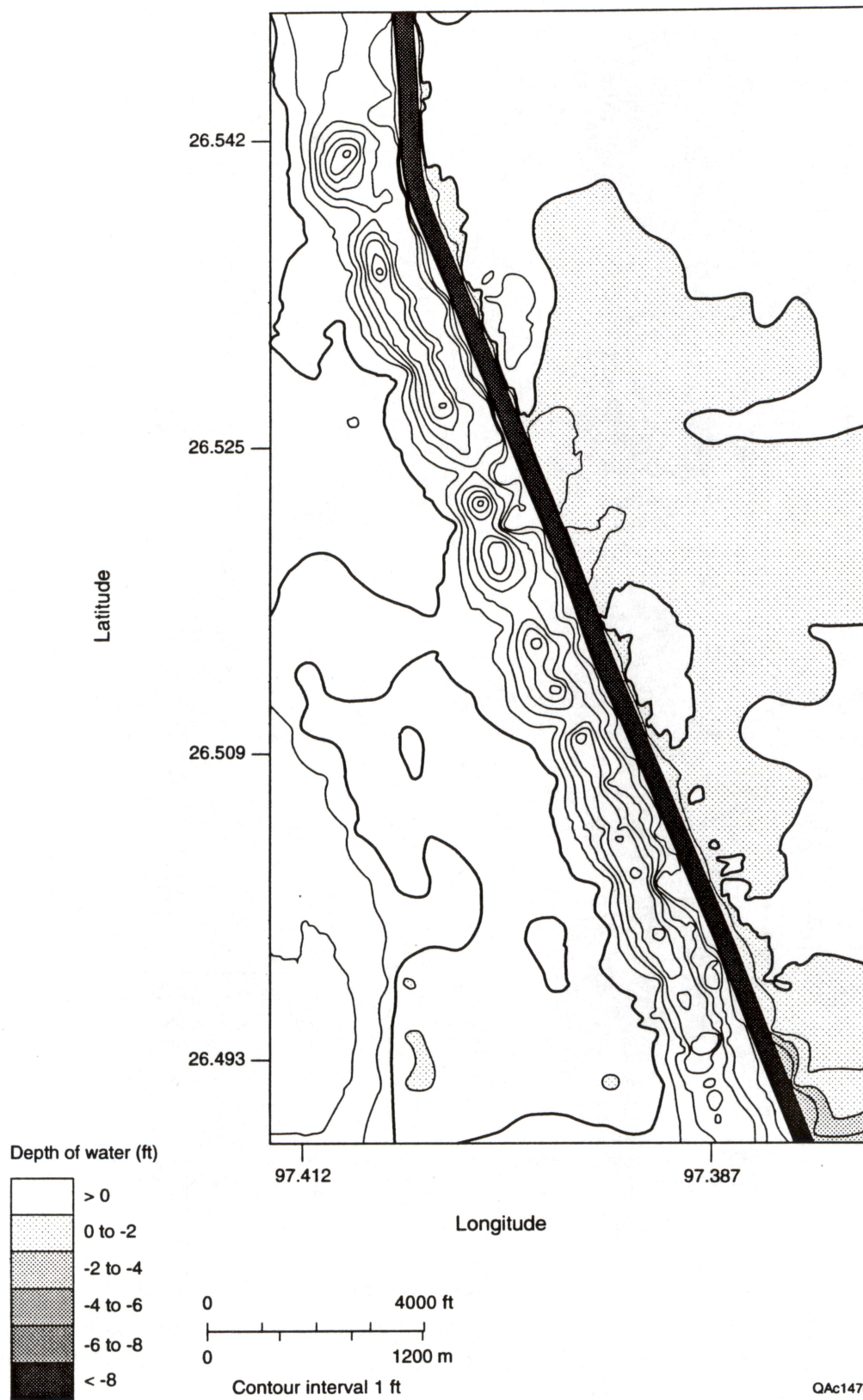
Figure 43. Adjusted difference between 1930s and 1995 bathymetry of placement area 221.

111
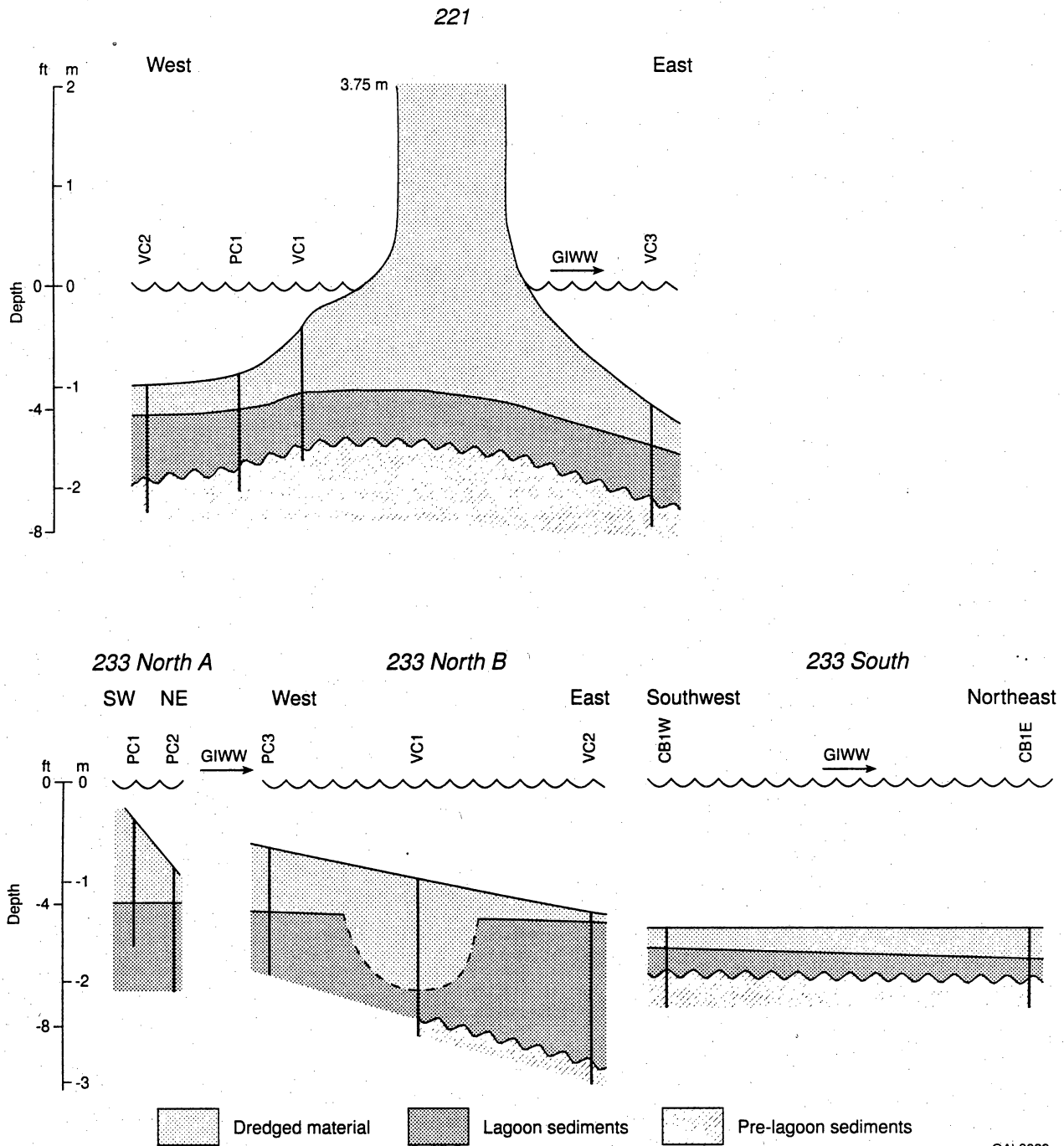
Figure 44. Cross sections illustrating the thickness and lateral extent of dredged material within placement area 221 and 233. Pre-lagoon sediments are the Pleistocene Beaumont Formation in placement area 221 and Holocene Rio Grande delta deposits in placement area 233. Core locations shown in fig. 39 and 45. Horizontal scale is variable.

Cores at PA 221 encountered stiff brown mud and sandy mud at depths of 1.6 to 2.1 m below sea level. Cores collected before dredging the Port Mansfield Channel also encountered stiff brown mud at about the same depth (U.S. Army Corps of Engineers, 1958). The stiff muds represent the Pleistocene Beaumont Formation (fig. 44), which consists of fluvial-deltaic deposits (Brown et al., 1977). Holocene sediments overlying the Beaumont deposits are only about 0.5 m thick, indicating low natural rates of lagoonal sedimentation.

Aerial photographs taken between 1950 and 1993 (Appendix B) show the progressive reworking and systematic loss of dredged material from placement area 221. Initially the deposits of dredged material were constructed of closely-spaced steep-sided conical mounds of mud that formed a chain of islands. Shortly after their construction the islands began eroding on the southeast side. In 1954, the islands were barren except for subaerial vegetation at lower elevations surrounding the mounds (probably marshes), and seagrasses were abundant away from the dredged material. The addition of dredged material during the 1961 dredging cycle did not increase the island areas. By 1962, there had been a substantial loss of elevation and conversion of the islands into shallow shoals. This period marked the breakup of the island chain into shorter island segments by breaching and washout through topographic lows. By 1974 deposition of dredged material had reestablished connections between a few breached segments, but in general, most islands continued to diminish in area and height. After 1974 the remaining islands continued to be reworked and transformed into shoals that were colonized by seagrasses, and by 1993 only three small subaerial mounds and one island remained (near channel marker 167). Between 1954 and 1992, the combined lengths of the islands decreased from 4.5 km to 0.6 km and the number of emergent areas decreased from 20 to 4.

Dominant currents in Laguna Madre transport reworked sediments primarily to the west and southwest away from the GIWW. Extensive meadows of seagrass to the east of the GIWW also minimize the volume of reworked lagoonal sediment that is transported into the GIWW by westerly flowing currents. Because the dredged material is composed mostly of clay, the reworked sediments are transported in suspension, dispersed over a wide area, and probably are deposited in the lagoon between the waterway and the mainland shore. Transportation in suspension also explains why spits are not formed at PA 221 like those constructed around reworked islands in northern Laguna Madre where the dredged material is mainly sand.

Placement Area 233

Placement area 233 (figs. 1 and 45) is located in southern Laguna Madre east of Stover Point and the Laguna Atascosa National Wildlife Refuge. It coincides with the bathymetric transition zone between shallow water and subaerial flats near the mouth of the Arroyo Colorado
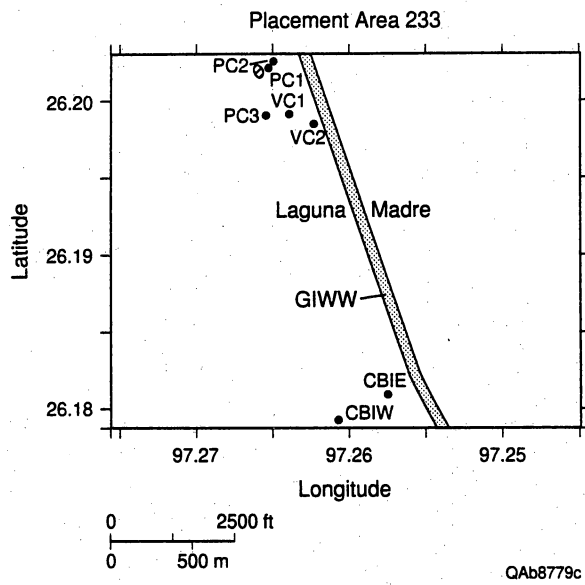
Figure 45. Locations of the GIWW and sediment cores in placement area 233.

and deeper water to the south in Laguna Madre. PA 233 is about 4 km in length, and extends from GIWW channel marker 81 to 91. Ample open water surrounds the placement site, and it can be effected by wind-driven currents from any direction although greatest fetch is from the northeast and southeast. The closest mainland shore is about 3 km to the west. The dredged material forms mounds and adjacent shoals with irregular shapes that change into narrow linear islands coinciding with the axis of the shoals. Only sparse stands of seagrass occupy the shoals of dredged material. The barren zone between the islands and seagrasses ranges in width from 15 to 75 m.

PA 233 is mostly submerged and in 1996 the subaerial expression of dredged material was limited to a narrow, low island located near channel marker 81 (figs. 46 and 47). The island has a shape and composition similar to the small island in PA 221 between channel marker 159 and 161. It is composed of a core of stiff mud surrounded by a fringe of sand and shell representing reworked dredged material and lagoon deposits. A depositional storm berm forms the western shore of the island, whereas the eastern shore is marked by a low, wave-cut scarp (fig. 47). A low ridge along the eastern margin of the island forms the highest elevations (< 0.6 m) that are covered by dense marsh vegetation including *Borrichia*, *Salicornia*, and *Batis*. Bottom sediments forming the fringe around the island are firm, composed of shelly sand, and covered with sparse seagrasses.

Water depths in Laguna Madre near PA 233 increase to the south (fig. 48) from about 0.6 m near channel marker 81 to about 1.5 m near channel marker 91 and the instrumented platform operated by the Conrad Blucher Institute. The axis of the placement area is nearly perpendicular to the pre-dredging bathymetric contours, which can be reconstructed from the sediment cores (Table 5).

Dredged material at placement area 233 is composed mostly of mud and sandy mud with some minor amounts of shell and shell fragments. The coarser sediments consisting of sand and shell are more common in the northern end of the placement area where they were derived from the pre-dredging shoals. Elsewhere, the predominance of mud in the dredged material is consistent with the composition of the pre-dredging lagoonal sediments and ancestral Rio Grande delta deposits that underlie Laguna Madre and form the walls and bottom of the dredged channel. Several of the vibracores encountered stiff red-brown mud at depths of 2 to 3 m below sea level that represent formerly subaerially exposed (oxidized) delta plain deposits of the Rio Grande (fig. 44).

Most of the cores at PA 233 penetrated less than 1 m of dredged material and thickness of dredged material decreases to the south (fig. 44). Dredged material is anomalously thick in core VC 1 because it encountered a trough scoured during the initial deposition of dredged material. PA 233 is the second most frequently dredged segment of the GIWW in Laguna Madre and it
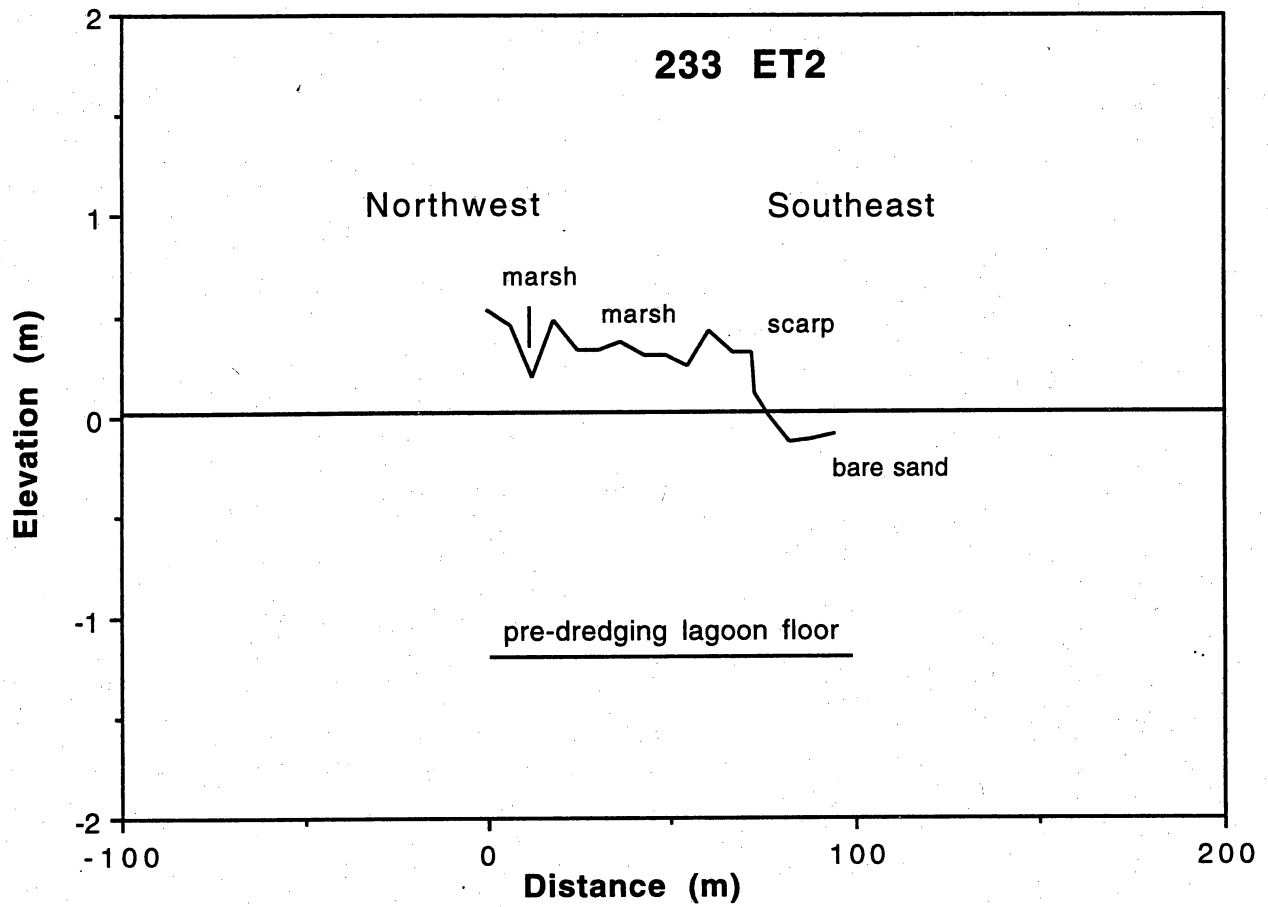
Figure 46. Axial topographic profile of placement area 233 surveyed in 1996. Profile extends along the low island west of PC 1. Core location shown in fig. 45.
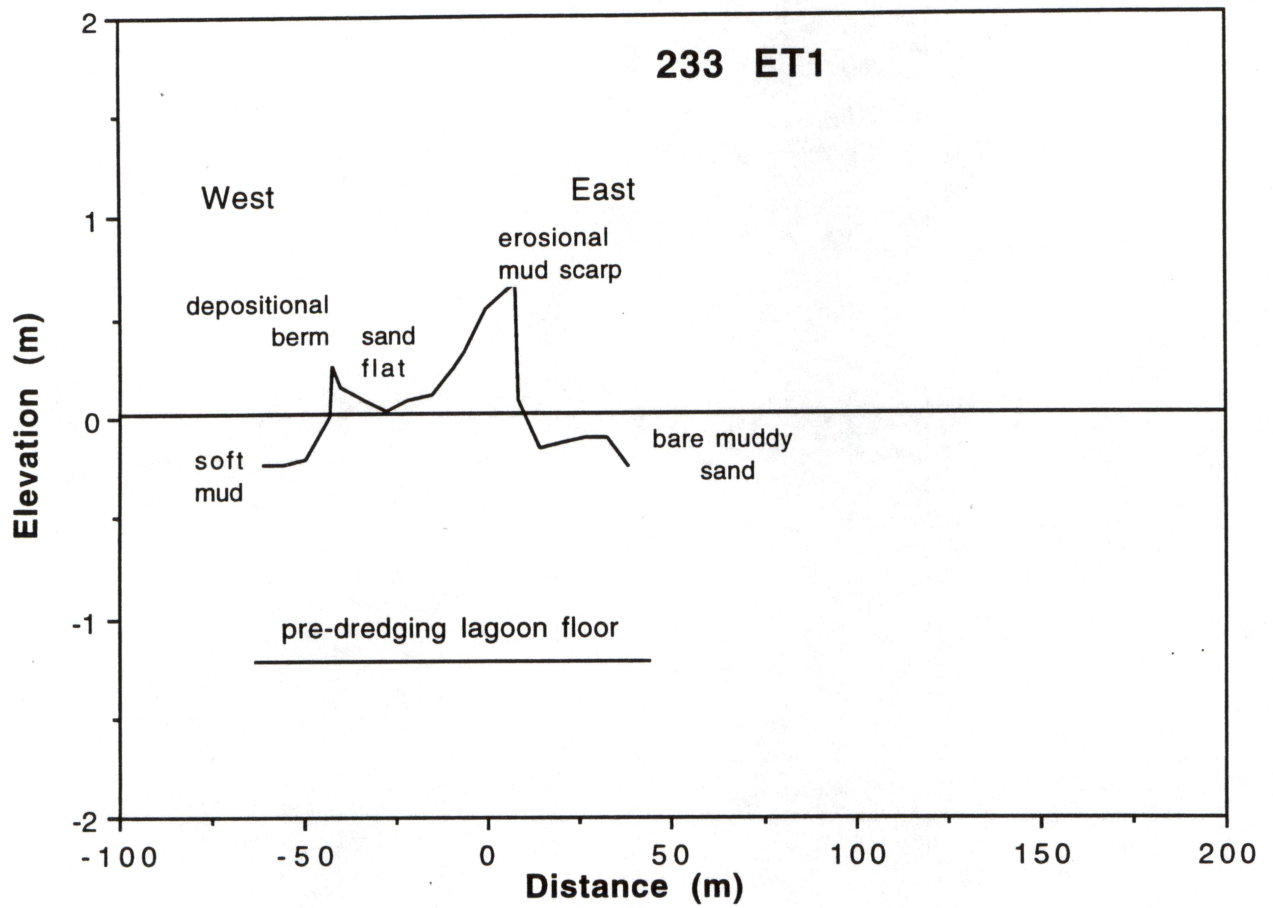
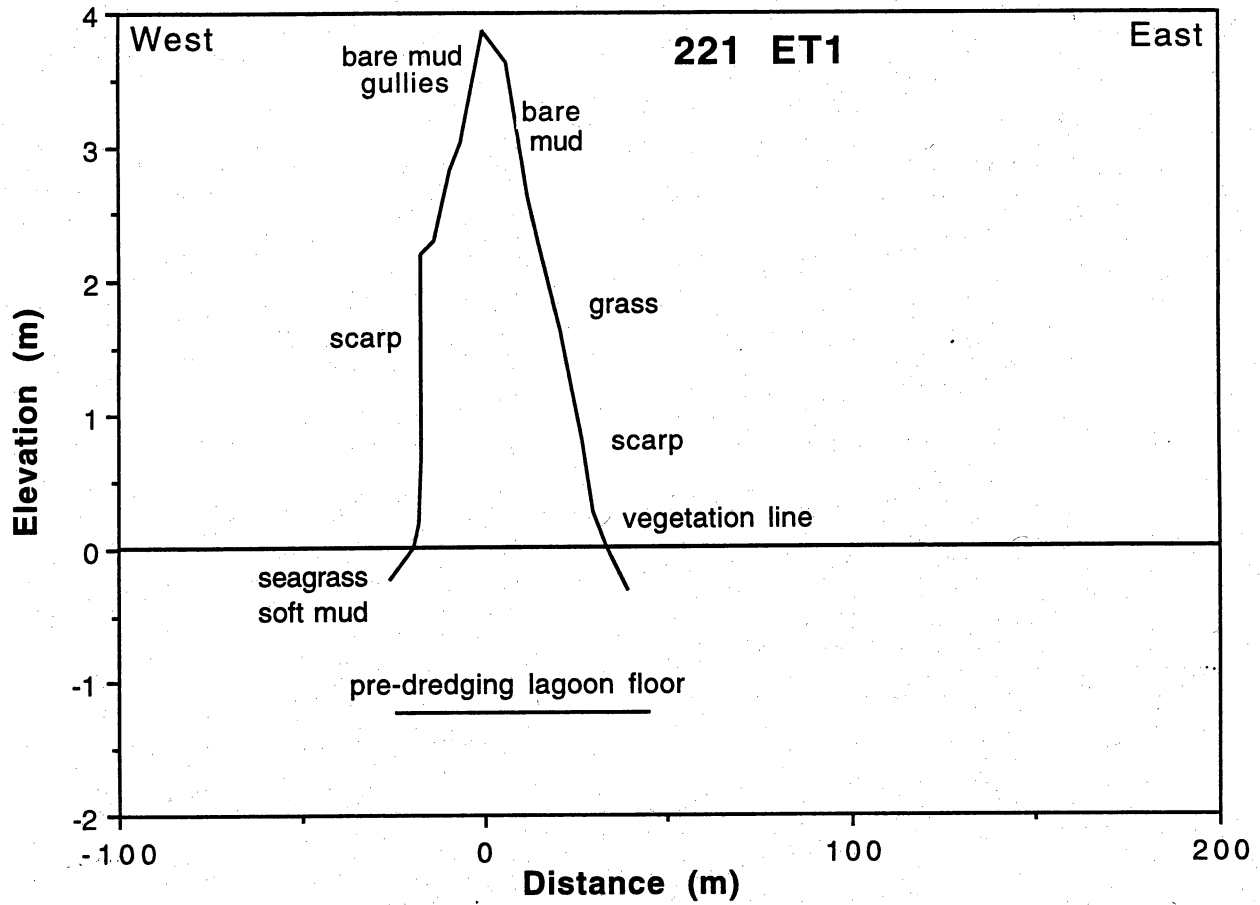Figure 47. Transverse topographic profile of placement area 233 surveyed in 1996. Profile extends across the low island west of PC 1. Core location shown in fig. 45.
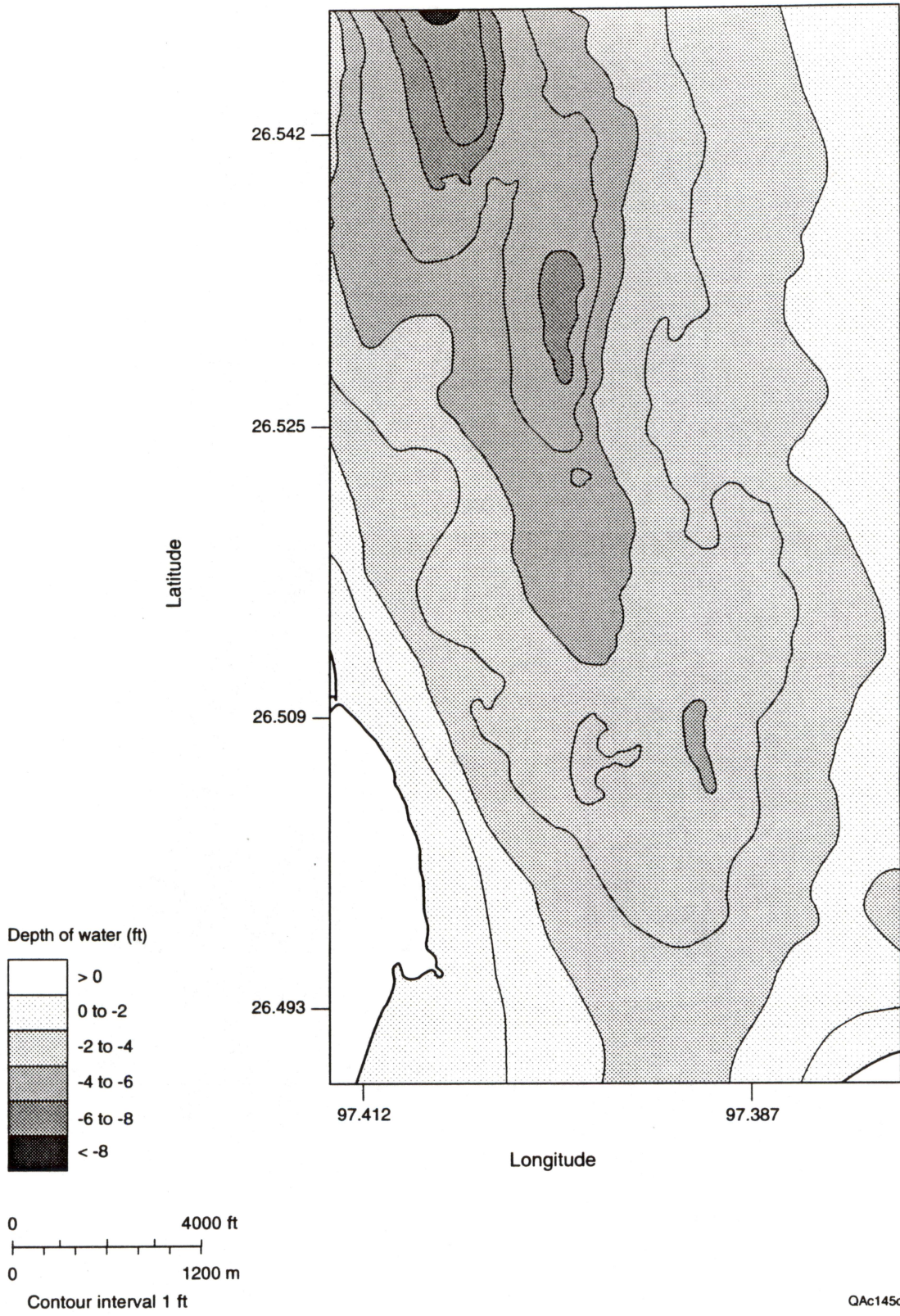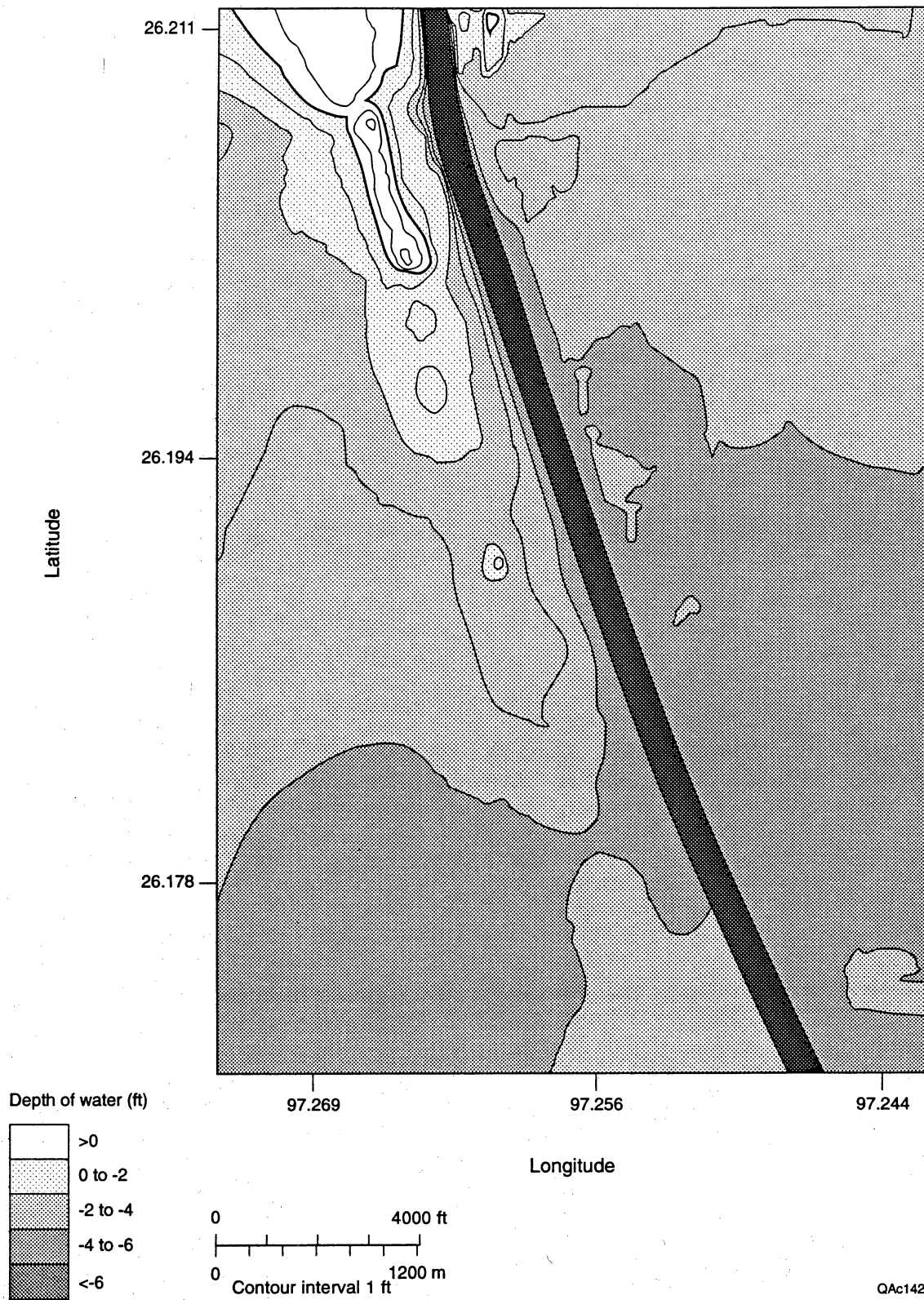
Figure 48. Bathymetric map of placement area 233 based on integration of 1994 and 1995 data.

accounts for the largest cumulative volume of dredged material since construction of the waterway (> 6 million m^3). Despite the large number of disposal events (23), only a few events are preserved in the cored sediments (Appendix A). The lack of preservation of disposal events and generally thin accumulation of dredged material (fig. 44) demonstrates that the dredged material is rapidly reworked and dispersed to other parts of the lagoon including the GIWW.

Inspection of air photos (Appendix B) spanning a 53 year period allows reconstruction of the history of deposition and reworking of dredged material at PA 233. Because most of the disposal site is subaqueous, the following analysis is based on changes of the short island chain and shoals in the northern part of PA 233. In the late 1930s, before the GIWW was constructed, a navigation channel was dredged connecting the deeper parts of southern Laguna Madre with the Arroyo Colorado. The original new works reported for the GIWW in PA 233 (Table 8) may be low because of prior dredging of this navigation channel. The dredged material was placed in areas of moderately dense to dense seagrass that coincide with the northern part of PA 233 and the density of seagrasses decreased to the south in deeper water. Pre-dredging grass conditions in the southern part of PA 233 are uncertain because water turbidities are high on all available photographs. However, the low light conditions and relatively deep water suggest that seagrasses would have been sparse if they existed at all. Post-dredging photographs show that seagrasses were reestablished on and around dredged material at PA 233 by 1954. The seagrasses progressively diminished in density between 1954 and 1974 and by 1986 they were absent. Some narrow fringes and patches of seagrasses were reestablished by 1992.

The volume of dredged material deposited at PA 233 increased substantially in the late 1940s when the GIWW was constructed. The emergent islands were asymmetrical with steep erosional scarps on the southeast side and depositional berms on the west side, and this morphology has persisted as shown on all the stereo-pair photographs. With each subsequent addition of dredged material, the emergent islands have expanded and then have been reworked. Most of the photographs were taken in the winter so instantaneous flow is to the south but net flow of reworked dredged material is also to the south and west. The January 1962 photographs also show several side channels dredged to the west from the GIWW for well locations in the Holley Beach gas field and narrow linear surficial features that are most likely the effects of seismic surveys.

James et al. (1977) used six satellite images to characterize the influences of tidal stage and wind direction on suspended sediment transport patterns in southern Laguna Madre. All of the images show sediment-laden currents crossing the GIWW near PAs 233 and 234 with flow of a gyre directed to the southwest by north winds and to the west and northeast by the predominant southeast winds. This large-scale gyre is formed by deflected currents that match the general shape and upland boundary conditions imposed by the embayment between Three Islands and

Table 8. Estimated reworking of dredged material at six placement areas along the Gulf Intracoastal Waterway. The original dredging value also includes any sediment eroded around the channel perimeter. Volumetric units, which are m^3, have not been adjusted for density differences between higher density original sediments and lower density sediments dredged for channel maintenance.

Placement Area	Original Dredging (O)	Maintenance Dredging (M)	Remaining Material (R)	Loss (O+M-R)	Percent Loss	Proportional Shoaling (m^3/m)
187	501,497	1,269,938	918,558	852,8777	48.1	534
197	1,013,268	3,955,859	1,465,410	3,503,717	70.5	920
202	1,507,652	2,722,628	1,918,708	2,311,572	54.6	790
211	647,225	1,560,665	1,446,720	761,170	34.5	616
221	1,129,778	678,065	1,781,137	26,706	1.5	108
233	899,837	6,779,826	414,613	7,265,050	94.6	1482

Port Isabel. Preliminary results of a two-dimensional hydrodynamic model of southern Laguna Madre confirmed that prevailing southeast winds generate cross currents that flow to the northeast and transfer sediment from the placement area into the GIWW at PA 233 (Militello and Kraus, 1994).

ESTIMATED VOLUMES OF REWORKED DREDGED MATERIAL

Procedures and Assumptions

To evaluate the magnitude of reworking of dredged material along a particular reach of the GIWW it is necessary to determine the volumes of (1) sediment originally removed from the waterway during its construction and subsequent enlargement, (2) cumulative volume of maintenance dredging, and (3) volume of dredged material remaining in the placement area. The relationships of these volumes are illustrated in fig. 49 and can be represented by the following equation:

$$L = O + M - R \text{ (equation 1)}$$

where L is the estimate of sediment loss

O is the original dredged volume

M is the cumulative volume of maintenance dredging

and R is the residual volume of dredged material in the PA

If L=0 then all the dredged material is contained in the placement area and there has been no significant sediment reworking or compaction, if L<0 then additional material has been deposited in the placement area from sources other than dredging of the adjacent reach, and if L>0 then the dredged material has been eroded and/or compacted, and L estimates the volume of sediment either transported back into the GIWW or redistributed elsewhere in Laguna Madre.

The cumulative volume of sediment removed from the GIWW as maintenance dredging (M) has been summarized and apportioned to specific placement areas by Espey Huston (Martin Arhelger, personal communication 1997). The cumulative maintenance dredging values reported for the placement areas were used to quantify M in equation 1. Values for R were obtained by comparing the combined 1994-1995 bathymetry with the 1930's bathymetry and limiting the volumetric calculation to the disposal side of the waterway. If some dredged material bypassed the GIWW and was deposited on the opposites side, that volume is considered to be reworked and is not included in the residual volume estimate.

The original volume of sediment dredged from the GIWW (O) can be estimated using at least three different techniques and each technique places individual limitations on accuracy of the results. One estimate of original channel volume can be obtained by digital comparison of the
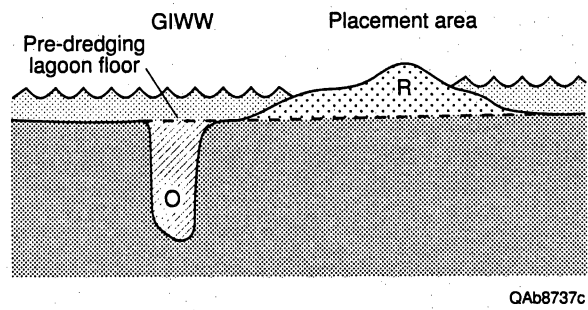
Figure 49. Illustration of sediment volumes quantified to evaluate reworking at placement areas. O=original dredged material, R=dredged material remaining at site. R=O+M-E where M=cumulative maintenance dredging and E=volume removed by erosion.

integrated 1994-95 bathymetry and the 1930's bathymetry. The GIWW is a relatively straight channel of uniform width and depth, whereas the dredged material deposited in the placement areas forms rounded mounds that are alternately high and low. These morphological differences between the channel and placement areas create complications with the contouring software, which attempts to smooth the contours between adjacent control points. The rounded shapes of the mounds introduce a shape factor that results in unrealistic "shoals" between the bathymetric survey lines that are an artifact of the contouring routine. The unsupervised program consistently calculates "original volumes" that are substantially less than volumes obtained by any other method and therefore they are considered to be unreliable because of the error introduced by the computer program. A second estimate of channel volume can be made by calculating volumes interpolated between adjacent cross sectional areas determined from the 1995 survey profiles (for example figs. 23 and 31). Accuracy of the integrated cross section technique is limited because (1) not all of the 1995 survey profiles are perpendicular to the channel, thus the volume calculated from the cross sectional area may be an overestimate and (2) even if the cross sections were perpendicular to the axis of the waterway, the volume of sediment assigned to original dredging would also include unintentional enlargement of the channel that might also have been reported as maintenance dredging. To avoid the potential double counting of channel enlargement, a minimum value for the original volume of sediment removed at each placement area was obtained from the aggregated 1945-1949 new-works dredging records obtained from the Galveston District Corps of Engineers. These original dredging values (Table 8) underestimate the actual volumes of sediment removed from the GIWW by the amount of unintentional channel enlargement during subsequent maintenance dredging that fell outside the approved template and was not acknowledged and therefore not reported. The volumetric difference between the original new-works dredging of the GIWW and the present channel dimensions was estimated by comparing the results of techniques 2 and 3. The results of this comparison show that the original (1945-49) volumes reported for channel excavation are within ±17% of the volumes determined from actual channel dimensions.

Results of Evaluation

The estimated magnitude of reworking for each of the six placement areas is summarized in Table 8. The volume of dredged material removed from a placement area by reworking can be expressed either in absolute amounts or as a percent of the total volume of dredged material deposited at the site since construction of the waterway. This normalized value of sediment loss provides a way of comparing sediment reworking in other placement areas of different sizes and characteristics. The total volume of sediment removed from each placement area as a result of

reworking by waves and currents (Table 8) ranges from 26,706 m^3 to 7,265,050 m^3 that represent respectively 1.5% to 95% of the total volume of sediment deposited either by original channel construction or subsequent maintenance dredging.

The cumulative volume of sediment dredged from the waterway for maintenance adjacent to a particular placement area can also be normalized on the basis of the length of channel dredged. This parameter, which is referred to as proportional shoaling, ranges from 108 m^3/m to 1482 m^3/m (Table 8). Both the absolute values and normalized values in Table 8 indicate that for the placement areas investigated, the greatest reworking occurs in PA 233 and the least reworking occurs in PA 221.

A comparison of proportional shoaling and sediment loss for each placement area (fig. 50) provides a quantitative basis for evaluating the contribution of channel shoaling attributable to sediment reworking in the placement area or elsewhere in the lagoon. If the GIWW shoaling rate is high but the percent loss from the placement area is low, then sediment is being imported into the channel from some other area. In contrast, if the loss of dredged material from the placement area is high but the proportional shoaling rate in the GIWW is low, then the reworked sediments are being exported from the placement area to parts of the lagoon other than the adjacent channel.

SEDIMENT DENSITY - THE PROBLEM OF BULKING AND DEWATERING

Direct comparison of hydraulically dredged and deposited sediment volumes are inherently inaccurate because physical properties of the sediments that influence volume, such as water content and void ratios, are altered by dredging, channel shoaling, and sediment compaction. Hydraulic dredging introduces large volumes of water into the sediments, which tend to increase water contents and void ratios; however, time-dependent processes in the placement area, including sediment compaction, dewatering, and desiccation, tend to decrease volume by decreasing water content and void ratio. The balance among these processes at a particular placement area generally is unknown and it is difficult to know if the sediment volume in the placement area eventually returns to its original in situ volume, settles or dries to a volume less than the original in situ volume, or never dewaters completely and remains greater than the original in situ volume. Consequently it is uncertain exactly how to adjust the pre-dredging and post-dredging volumes obtained from field measurements so that the removed and remaining volumes are comparable. The important variables to consider are composition of the original sediments, composition of the material encountered by maintenance dredging, the volume of
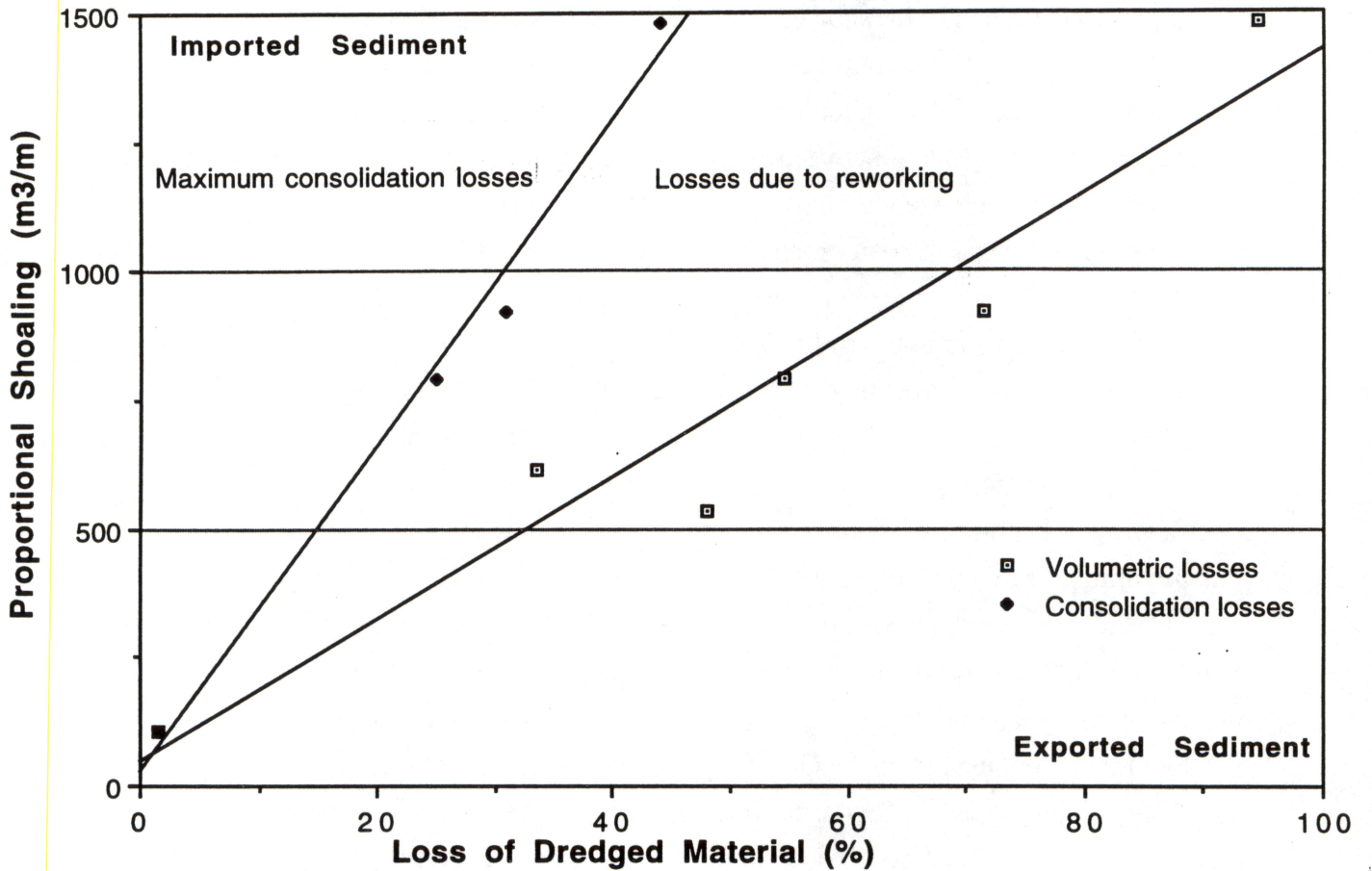
Figure 50. Comparison of proportional shoaling rate in the GIWW with cumulative percent loss of dredged material from the six placement areas. The linear relationship is an expression of the degree of sediment reworking and the potential for increased turbidity in surrounding waters of Laguna Madre as a result of sediment resuspension.

water introduced either by hydraulic dredging or natural reworking, the time elapsed since dredging, and whether the post-dredging emplacement was subaerial or subaqueous.

The increase in volume of sediment as a result of the hydraulic dredging process is known as bulking (Herbich, 1992). Laboratory tests conducted on native sediments from Texas bays by DiGeorge and Herbich (1978) showed that bulking factors estimated for new work dredging of clay and sandy clay typically range from 2.2 to 3.5. These values derived from laboratory measurements are generally higher than values obtained by field measurements. There is a moderate positive correlation between percent mud and bulking factors such that sediments composed of silt and clay tend to have higher bulking factors (increase in volume) than sandy sediments, and coarser sediments such as sand and gravel have bulking factors near 1 because there is little change in volume between the dredging site and containment area.

Native sediments in northern Laguna Madre are composed predominantly of sand and shell whereas clay and silt are the predominant sediment types in southern Laguna Madre (White et al., 1983; 1986; 1989). The high permeabilities of granular, non-cohesive sand-rich sediments promote rapid dewatering even of subaqueous deposits and a return to pre-dredging in situ specific gravity conditions. Therefore adjustments in the dredged and deposited volumes are probably minor in northern Laguna Madre. Where the stiff, cohesive native muds of southern Laguna Madre were emplaced subaerially, there has been sufficient time for them to dry to specific gravities that approach pre-dredging conditions; however, high water saturations may be retained by the low-permeability muds that were emplaced subaqueously.

Sediments removed from the GIWW during maintenance dredging present the greatest uncertainty, in particular the low-specific gravity (high water saturation) muds that constitute much of the channel shoal material in southern Laguna Madre (Aturrio et al., 1976, Table 9). The water saturations of these sediments typically decrease as they compact even under subaqueous conditions. Consequently, the reported volume of material dredged from the GIWW will be greater than the compacted volume in the placement area.

In Situ Physical Properties

Testing

Discussions with personnel at the Waterways Experiment Station, Galveston District Corps of Engineers, and Center for Dredging Studies at Texas A&M University indicated that no prior data were available for in situ specific gravities, water contents, and void ratios of sediments from the GIWW or the placement areas in Laguna Madre. To overcome this deficiency, a total of 77 samples (30 in the GIWW, 43 in placement areas, and 4 of the natural lagoon) were collected

Table 9. Samples collected for in situ specific gravities, water contents, and void ratios in Laguna Madre. Sample sites included the dredged channel (GIWW), placement areas of dredged material (dm), and the natural lagoon. Samples were collected on October 28-30, 1997. Water depth is in meters; specific gravity, water content, and void ratio are dimensionless numbers.

Sample	Water Depth	Purpose	Lat.	Long.	Sediment Type	In Situ Sp Gr	Water Contents	Void Ratios
197-S1	0.15	subaerial dm (west side)	27.310	-97.402	shelly sandy mud	1.493	66	1.97
197-S2	0.15	subaerial dm (east side)	est.	est.	shelly sandy mud	1.915	29	0.82
197-S3	0.46	subaqueous dm (east side)	est.	est.	gray sandy mud	1.449	63	2.02
197-S4	1.13	subaqueous dm (west side)	27.310	-97.403	shelly sandy mud	1.284	156	4.35
197-S5	4.73	GIWW bottom upper	27.310	-97.403	black watery mud	1.226	233	6.29
197-S6	4.73	GIWW bottom lower	27.310	-97.403	black watery mud	1.228	224	6.06
197-S7	0.85	subaqueous dm	27.304	-97.404	clean sandy shell	1.973	27	0.73
197-S8	4.18	GIWW bottom upper	27.303	-97.405	black watery mud	1.188	264	7.21
197-S9	4.18	GIWW bottom lower	27.303	-97.405	black watery mud	1.213	224	6.16
197-S10	0.90	subaqueous dm	27.290	-97.403	shelly muddy sand/Halodule	1.876	31	0.87
197-S11	4.12	GIWW bottom 0-.3	27.293	-97.407	black watery mud	1.175	272	7.48
197-S12	4.12	GIWW bottom .3-3.0'	27.293	-97.407	black watery mud	1.256	276	7.02
197-S13	0.30	subaerial dm (west side)	est.	est.	shelly sand	1.830	30	0.91
197-S14	0.30	subaerial dm (east side)	27.285	-97.405	gray shelly mud	1.332	131	3.65
197-S15	1.00	subaqueous dm upper	27.286	-97.405	watery shelly sand	1.711	39	1.18
197-S16	1.00	subaqueous dm lower	27.286	-97.405	shelly sand	1.977	25	0.70
197-S17	3.3	GIWW bottom upper	27.285	-97.410	black watery mud	1.172	299	8.11
197-S18	3.3	GIWW bottom lower	27.285	-97.410	dark gray muddy sand	1.586	54	1.61
197-S19	2.10	natural lagoon	est.	est.	muddy shelly sand	1.831	33	0.94
202-S1	exposed	subaerial dm	27.174	-97.429	rocks, sand and shell	1.902	25	0.77
202-S2	1.37	subaqueous dm upper	27.174	-97.429	organic shelly sand	1.879	26	0.80
202-S3	1.37	subaqueous dm lower	27.174	-97.429	gray mud	1.353	124	3.44
202-S4	4.48	GIWW bottom upper	27.174	-97.433	gray watery mud	1.205	235	6.45
202-S5	4.48	GIWW bottom lower	27.174	-97.433	gray mud/shelly sand @ btm	1.251	136	4.05

Table 9 (cont.)

202-S6	exposed	subaerial dm	27.166	-97.432	rock, shell and mud	36	1.11
202-S7	1.07	subaqueous dm upper	27.165	-97.435	gray shelly mud	41	1.34
202-S8	1.07	subaqueous dm lower	27.165	-97.435	gray mud	42	1.65
202-S9	1.59	natural lagoon	27.166	-97.436	gray shelly sandy mud	37	1.10
202-S10	4.54	GIWW bottom	27.166	-97.435	gray watery mud	196	5.22
202-S11	exposed	subaerial dm	27.163	-97.433	brown sandy shelly mud	35	1.16
202-S12	0.49	subaqueous dm upper	27.164	-97.434	gray shelly sand/Halodule	37	0.86
202-S13	0.49	subaqueous dm lower	27.164	-97.434	gray shelly sand/Halodule	22	0.64
202-S14	4.45	GIWW bottom upper	27.164	-97.435	black watery mud	232	6.44
202-S15	4.45	GIWW bottom lower	27.164	-97.435	black slighty firm mud	171	4.73
202-S16	exposed	confined subaerial dm	27.162	-97.435	black firm mud	108	2.77
202-S17	exposed	confined subaerial dm	27.162	-97.435	black firm mud	136	3.83
202-S18	4.91	GIWW bottom 0-.3'	27.162	-97.436	black watery mud	246	6.75
202-S19	4.91	GIWW bottom .3-1'	27.162	-97.436	black mud	161	4.45
221-S1	4.18	GIWW bottom upper	26.540	-97.406	black mud	152	4.15
221-S2	4.18	GIWW bottom lower	26.540	-97.406	gray mud	102	2.81
221-S3		subaerial dm (east side)	no	sample	site submerged		
221-S4	0.40	subaqueous dm (east side)	26.530	-97.404	firm shelly sand/Halodule	19	0.32
221-S5	0.90	subaqueous dm from 1.5'	26.530	-97.403	sandy shelly mud	32	0.83
221-S6	4.18	GIWW bottom upper	26.531	-97.401	black mud	147	3.98
221-S7	4.18	GIWW bottom lower	26.531	-97.401	gray mud	101	2.74
221-S8	exposed	subaerial dm	26.510	-97.395	clean sandy shell	21	0.58
221-S9	1.13	subaqueous dm upper	26.510	-97.395	shelly sand/Halodule	22	0.61
221-S10	1.13	subaqueous dm lower	26.510	-97.395	firm shelly mud	33	0.89
221-S11	4.57	GIWW bottom 0-.3'	26.511	-97.392	black watery mud	171	4.56
221-S12	4.57	GIWW bottom .3-2'	26.511	-97.392	gray firm mud	123	3.37
221-S13	exposed	subaerial dm (west side)	26.494	-97.390	brown stiff mud	11	0.26
221-S14	1.10	subaqueous dm 0-.3	26.494	-97.390	muddy shelly sand/Halodule	40	1.11

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Table 9 (cont.)

ID								
221-S15	1.10	26.494	-97.390	subaqueous dm .3-1'	shelly muddy sand/Halodule	1.656	33	1.16
221-S16		no	sample	subaqueous Pleistocene	too deep			
221-S17	4.36	26.496	-97.386	GIWW bottom 0-.3	black watery mud	1.312	154	4.2
221-S18	4.36	26.496	-97.386	GIWW bottom .3-3'	gray firm mud	1.487	80	2.24
221-S19	1.13	26.496	-97.385	natural lagoon	sandy shelly mud/Halodule	1.825	35	0.98
233-S1	0.09	est.	est.	subaerial dm (west side)	silty muddy sand	1.864	33	0.92
233-S2	exposed	est.	est.	subaerial dm (east side)	silty muddy sand	1.879	29	0.84
233-S3	1.10	26.201	-97.262	submerged dm upper	shelly sand	1.983	23	0.66
233-S4	1.10	26.201	-97.262	submerged dm lower	gray mud	1.550	78	2.07
233-S5	4.12	26.201	-97.261	GIWW bottom	watery mud	1.280	164	3.16
233-S6	0.98	26.198	-97.262	submerged dm upper	sandy mud	1.624	50	1.48
233-S7	0.98	26.198	-97.262	submerged dm lower	mud	1.624	64	1.70
233-S8	4.12	26.198	-97.260	GIWW bottom	watery mud	1.410	114	3.07
233-S9	1.16	26.190	-97.260	submerged dm in levee	sandy mud	1.446	85	2.43
233-S10	1.06	26.190	-97.259	constructed levee	brown firm mud	1.980	30	0.77
233-S11	3.42	26.190	-97.257	GIWW bottom	gray firm mud	1.489	93	2.46
233-S12	1.68	26.180	-97.256	submerged dm	gray sandy mud	1.729	43	1.21
233		no	sample	Rio Grande delta	too deep			
233-S13	3.42	26.182	-97.254	GIWW bottom	gray mud	1.406	92	2.65
233-S14	1.74	26.183	-97.251	natural lagoon	gray firm shelly sandy mud	1.874	36	0.95
234-S1	1.71	26.168	-97.247	submerged dm	shelly sand	1.907	26	0.77
234-S2	3.11	26.168	-97.246	GIWW bottom	gray watery mud	1.398	118	3.18
234-S3	1.31	26.163	-97.247	submerged dm upper	sandy shelly mud	2.017	25	0.67
234-S4	1.31	26.163	-97.247	submerged dm lower	firm sandy shelly mud	1.849	33	0.93
234-S5	3.72	26.165	-97.244	GIWW bottom	gray watery mud	1.385	110	3.06
234-S6	1.71	26.160	-97.243	within submerged levee	gray shelly sandy mud	1.925	31	0.82
234-S7	1.49	26.159	-97.243	submerged dm	gray sandy mud	1.520	76	2.11
234-S8	3.78	26.160	-97.241	GIWW bottom	gray watery mud	1.353	135	3.63

jointly by the Bureau of Economic Geology and Espey Huston and Associates in October, 1997 from PAs 197, 202, 221, 233, and 234 (figs. 51-54 and Table 9). Samples were obtained with a 1 m plastic core tube to compare the differences in physical properties among (1) sediments in the GIWW (channel bottom) before dredging, (2) sediments in the placement area after dredging, (3) nearby natural lagoonal sediments, and (4) changes in sediment within the first meter below the lagoon floor.

Technicians in the Espey Huston laboratory used pycnometers to determine in situ specific gravities of Laguna Madre sediments following techniques provided by the Corps of Engineers Waterways Experiment Station. In situ specific gravities include the associated water and therefore the measured values (Table 9) are substantially lower than typical dry sediment specific gravities, which range from to 2.5 (montmorillonite clay) to 2.95 (aragonite shells).

Using conventional engineering geotechnical terminology, water contents of sediments are expressed as the ratio of the weight of water in the sample to the weight of solids in the sample; therefore the water content can be greater than 100% (U.S. Army Corps of Engineers, 1987). Water contents of samples collected in Laguna Madre (Table 9) were determined by the Espey Huston laboratory by weighing the sample before and after drying. They range from 11 to 298%, but most are less than 100% (Table 9). Sediments with high water contents (> 100%) are from the GIWW or from the confined disposal site at PA 202, whereas sediments with low water contents are coarse in grain size, such as shelly sand and sandy shell, or subaerially exposed deposits that have dried (221-S13). At the time of sampling, the range of water contents and the average water content within a given placement area was greatest in PA 197 (Table 10). The water content ranges and averages decreased in a southerly manner in PA 202, PA 211, and PA 233. The water content range and average water content in PA 234 was similar to that in PA 233 (Table 10).

The void ratio compares the volume of voids to the volume of solids in a sample. At 100% saturation, the void space in a sample is completely filled with water. The void ratio of the samples was calculated using the specific gravity of water, the measured water content, and the specific gravity of solids. No assumptions as to the degree of saturation were made in the current void ratio calculation. Because the composition of the sediments in Laguna Madre are well known, an average dry sediment specific gravity of 2.68 was used to calculate the void ratios (Table 9). The void ratio ranges and averages for the respective placement area followed the same pattern as the water contents (Table 10).

There are high correlations among in situ specific gravities, void ratios, and water contents. There is a positive linear relationship between void ratio and water content, whereas the relationships between in situ specific gravity and both water content and void ratio are expressed as negative exponential functions, which result in high values of water content and void ratio as
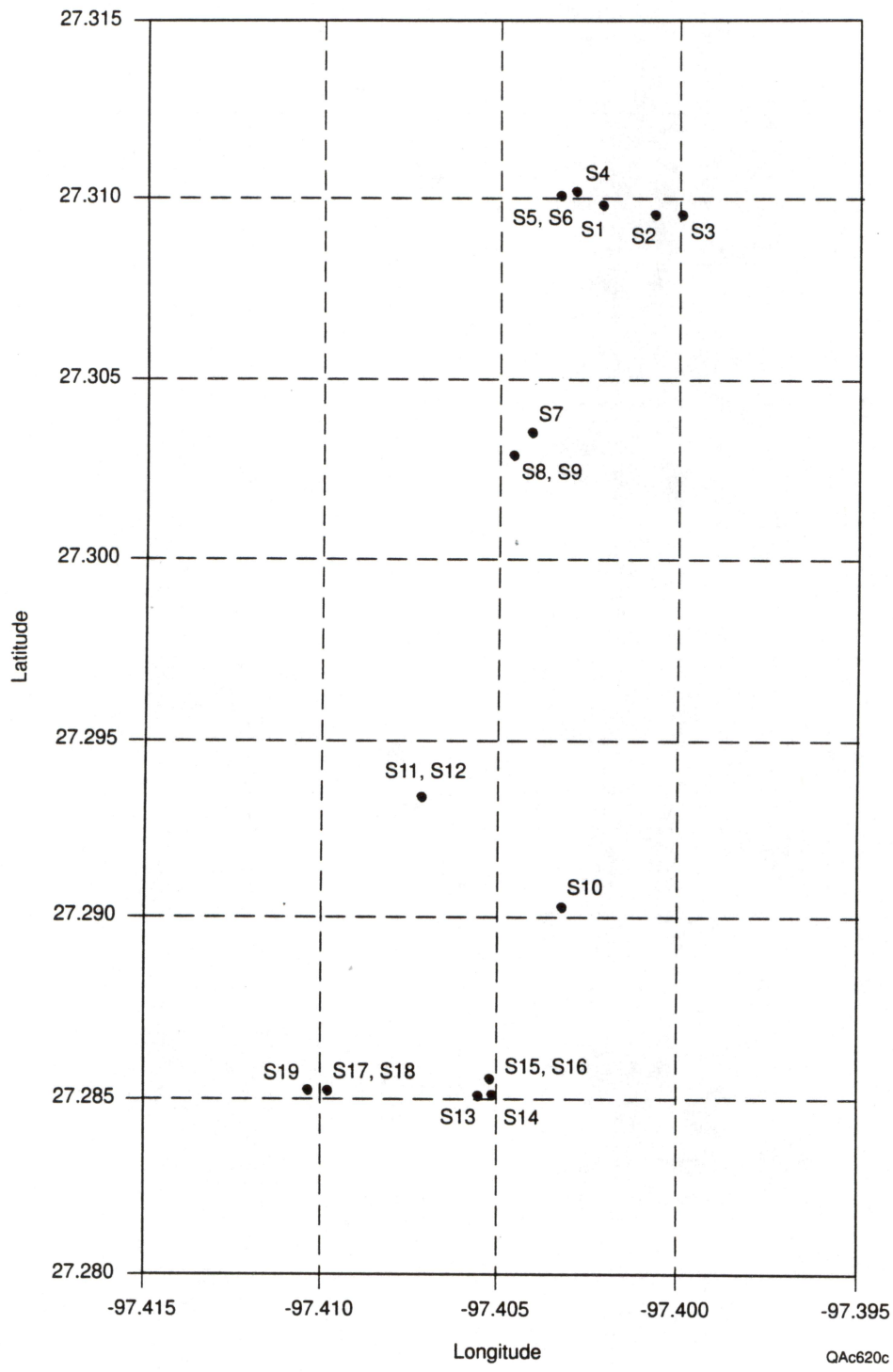
Figure 51. Locations of sediment samples in placement area 197 collected for analysis of physical properties. Brief sample descriptions and geotechnical data are presented in Table 10.

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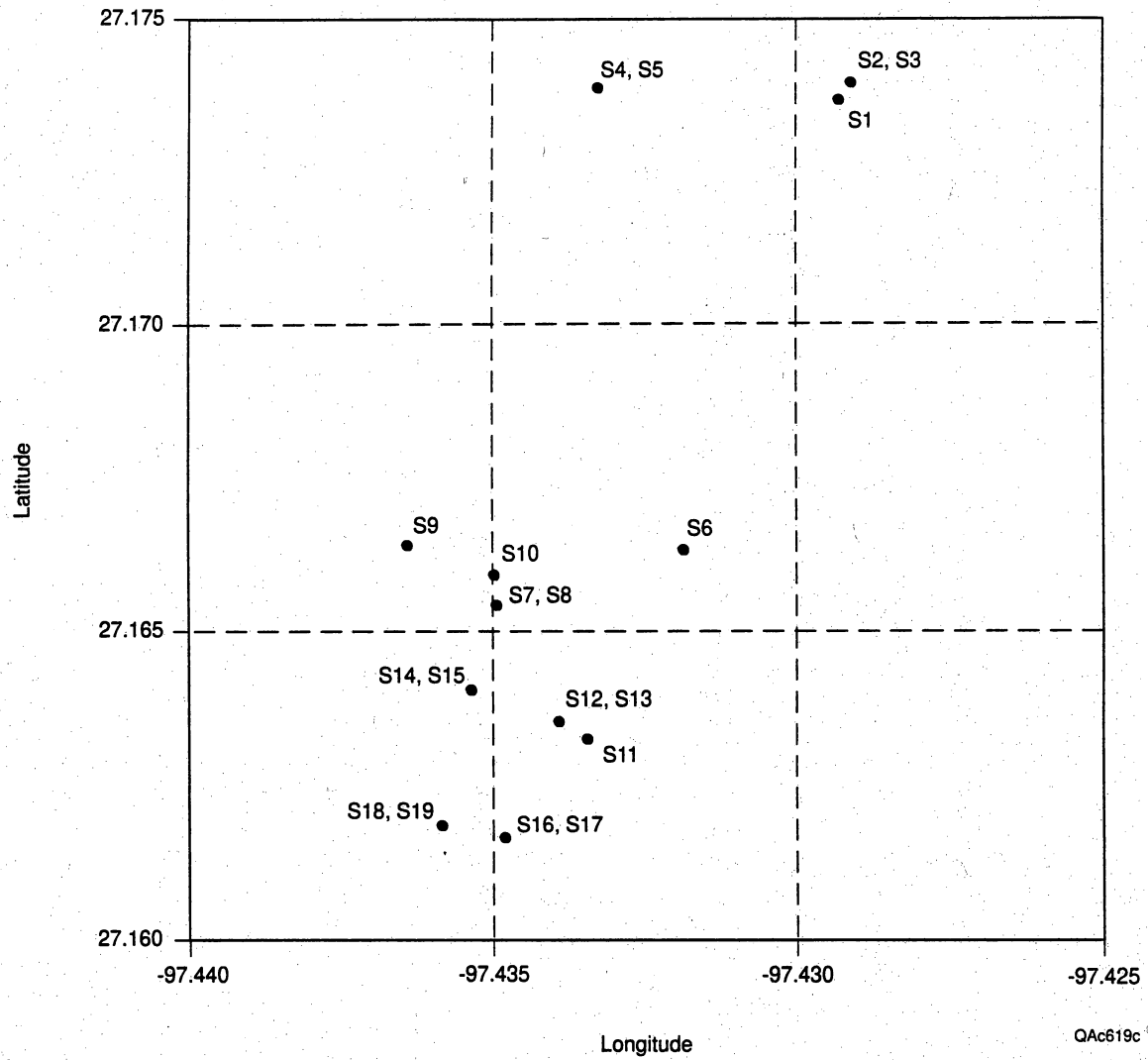
Figure 52. Locations of sediment samples in placement area 202 collected for analysis of physical properties. Brief sample descriptions and geotechnical data are presented in Table 10.
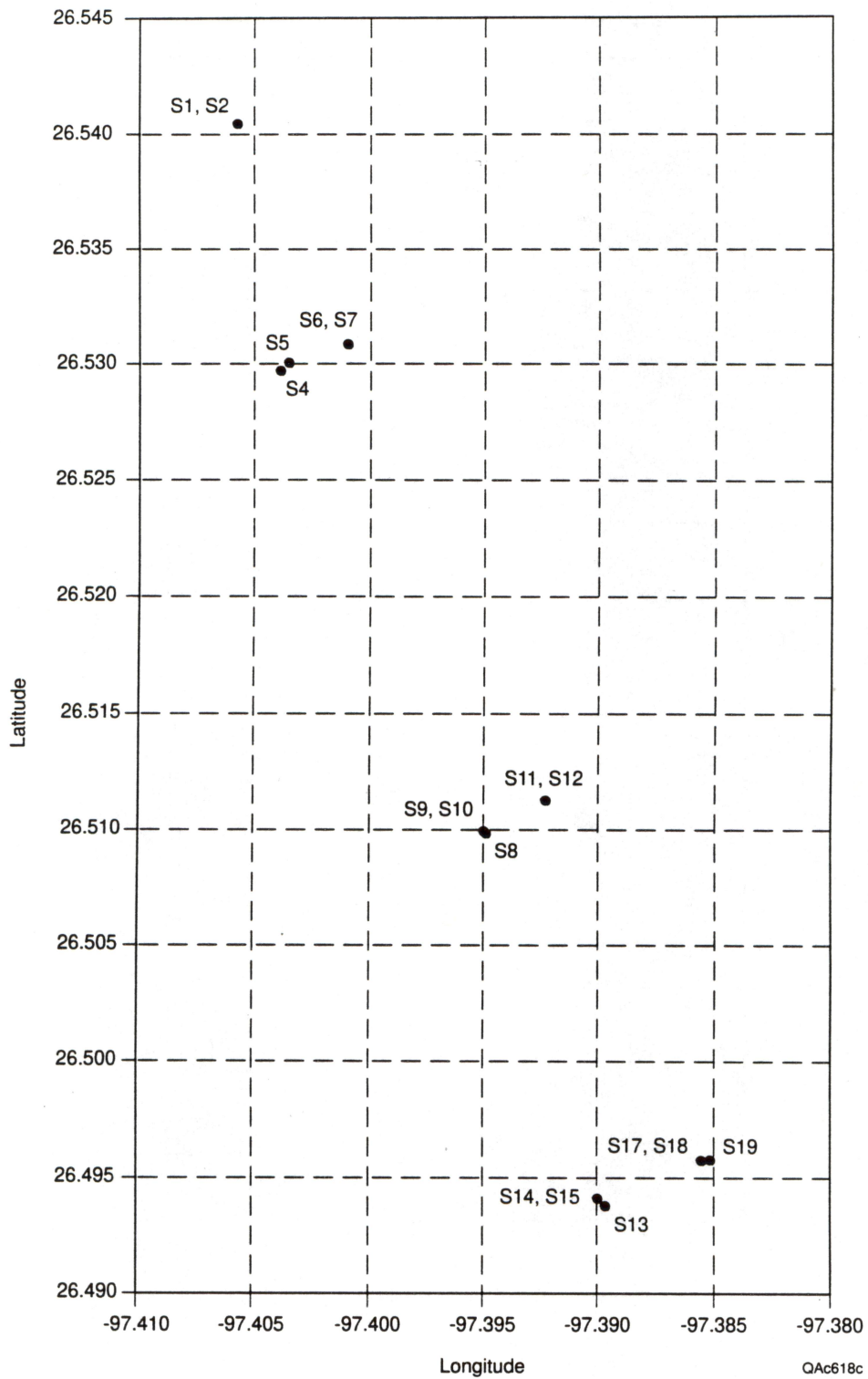
Figure 53. Locations of sediment samples in placement area 221 collected for analysis of physical properties. Brief sample descriptions and geotechnical data are presented in Table 10.

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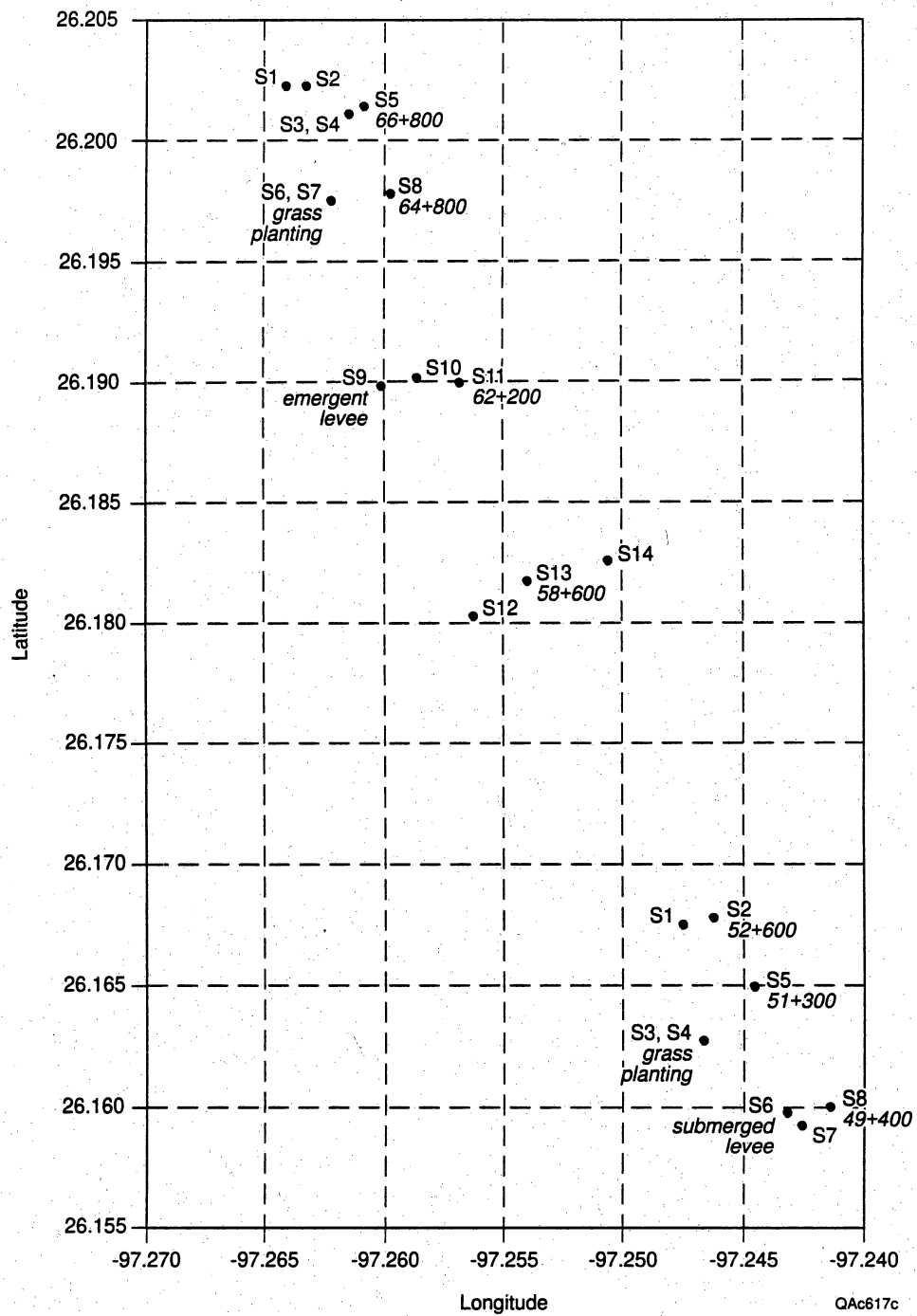
Figure 54. Locations of sediment samples in placement areas 233-234 collected for analysis of physical properties. Brief sample descriptions and geotechnical data are presented in Table 10.

Table 10. Ranges and averages of in situ specific gravities, water contents, and void ratios sorted by geographic location of sediment samples collected in Laguna Madre from dredged material (dm) in selected placement areas and the GIWW (ch). Specific gravity, water contents, and void ratios are dimensionless numbers.

Location	Specific Gravities			Water Contents			Void Ratios		
	Min.	Max.	Ave.	Min.	Max.	Ave.	Min.	Max.	Ave.
197 dm	1.28	1.98	1.68	25	156	60	0.70	4.35	1.72
197 ch	1.17	1.59	1.26	54	299	231	1.61	8.11	6.24
202 dm	1.35	2.01	1.73	22	136	43	0.64	3.83	1.31
202 ch	1.20	1.28	1.24	136	246	197	4.05	6.75	5.44
221 dm	1.66	2.42	1.97	19	40	29	0.32	1.16	0.79
221 ch	1.30	1.49	1.37	80	171	129	2.24	4.56	3.51
233 dm	1.45	1.98	1.71	23	85	52	0.66	2.43	1.44
233 ch	1.28	1.49	1.40	92	164	116	2.46	3.16	2.84
234 dm	1.85	2.02	1.84	25	76	38	0.67	2.11	1.06
234 ch	1.35	1.40	1.38	110	135	121	3.06	3.63	3.29

the specific gravity approaches unity, the value for water. Consequently a wide range of in situ specific gravities are associated with a small range in water content (25-50%) and a small range in void ratios (0.5-1.0). Calculated void ratios of samples collected in Laguna Madre (Table 9) range from 0.26 to 7.48. Sediments with high void ratios (> 3) are from the GIWW or from the confined disposal site at PA 202, whereas sediments with low void ratios (<1) are clean shelly sand and sandy shell without any mud or subaerially exposed deposits that have dried (221-S13).

Test Results

Of the nineteen samples taken from PA 197 (fig. 51), one sample was natural lagoon sediment and ten samples were taken from the dredged material. The dredged material consisted of a mixture of sand, shell, and mud with water contents ranging from 25% to 156% and void ratios ranging from 0.70 to 4.35 (Table 10). Eight samples were taken from four sample locations in the GIWW. The water content of seven GIWW samples ranged from 224 to 299% and the void ratio for these samples ranged from 6.16 to 8.11. One anomalous GIWW sample was dark gray muddy sand having a water content of 54% and a void ratio of 1.61.

Nineteen samples were taken from PA 202 (fig. 52). One sample was natural lagoon sediment, eleven samples were dredged material, and seven samples were taken from the GIWW. The dredged material contained sandy shell and shelly sand with intermixed mud. Water contents of the dredged materials ranged from 22% to 136% and void ratios ranged from 0.64 to 3.83. With respect to the seven GIWW samples, upper and lower samples were taken from cores in three locations and a single sample taken in a fourth location. The water content of these GIWW samples ranged from 136 to 246% and void ratios ranged from 4.05 to 6.75. The sediment descriptions indicate less mud in the dredged materials for PA 202 than for PA 197.

Eighteen samples were taken from PA 221 (fig. 53); however, no sample was acquired at the 221-S16 location. One sample was taken from natural lagoon sediment, seven samples were taken from dredged material and eight samples were taken from the GIWW. The dredged material consisted primarily of sandy shell and shelly sand with some intermixed sand, shell, and mud. Water contents of the dredged materials ranged from 19 to 40% and void ratios ranged from 0.32 to 1.16. The eight GIWW samples were upper and lower samples taken from four core locations. The water content of these GIWW samples ranged from 80 to 171% and void ratios ranged from 2.24 to 4.56. The water contents and void ratios were distinctly lower in both the dredged materials and the GIWW samples at PA 221 as compared to PA 197 or PA 202 (Table 10).

Fourteen samples were taken from PA 233 (fig. 54), which included one sample of natural lagoon sediment, eight samples of dredged material, and four samples from the GIWW. One

sample was taken from the constructed levee surrounding PA 233. The dredged material consisted of a mixture of sand, shell, and mud with water contents ranging from 23 to 85% and void ratios ranging from 0.66 to 2.43. Four samples were taken from four different locations in the GIWW near PA 233. The water content of these GIWW samples ranged from 92 to 164% and void ratios ranged from 2.46 to 3.16 (Table 10). The water contents and void ratios of the dredged material at PA 233 were notably lower than in the dredged materials at PA 221. No such distinction existed between the GIWW samples taken near PA 233 as compared to PA 221.

Eight samples were taken from PA 234 (fig. 54), including four samples of dredged material, three samples from the GIWW, and one sample was taken from the submerged levee surrounding PA 234. The dredged material consisted of a mixture of sand, shell and mud with water contents ranging from 25 to 76% and void ratios ranging from 0.67 to 2.11 (Table 10). The three GIWW samples were taken from different locations in the GIWW. The water content of these GIWW samples ranged from 110 to 135% and void ratios ranged from 3.06 to 3.63. The range of water contents and void ratios of both the dredged material and the GIWW sediments at PA 233 and PA 234 are essentially equivalent. This observation is consistent with the sediment descriptions for PA 233 and PA 234, which are similar.

Sediment composition, sample depth, and time since deposition are all factors that influence sediment in situ specific gravity, water contents, and void ratios. As expected, sediment in situ specific gravities consistently increase with depth and water contents and void ratios decrease with depth if there is no change in composition that has a greater effect on the measured parameters (Table 9). This is shown by comparing the 20 pairs of samples taken at different depths from the same cores. For example, the in situ specific gravities of all samples collected within the GIWW increase with depth and the magnitude of the increase is about 0.1 in the upper 10 cm. Sediment specific gravity also increases with depositional age, and water contents and void ratios decrease with depositional age even though most of the material is very young compared to geological time scales. The recently deposited sediments in the GIWW have the lowest specific gravities, highest water contents, and highest void ratios. Sediments recently deposited in the disposal areas have higher specific gravities, lower water contents, and lower void ratios, and the geologically oldest sediments have some of the highest in situ specific gravities, lowest water contents, and lowest void ratios (Table 9).

Six groups of sediments are recognized on the basis of their composition and depositional setting (Table 11). Sediments with the lowest in situ specific gravities, highest water contents, and highest void ratios are homogeneous watery muds that are very recent (post-dredging) deposits accumulating at the bottom of the GIWW. Dominantly muddy sediments with mixtures of shell and sand have slightly lower average in situ specific gravities (higher water contents and higher void ratios) than dominantly sandy sediments with mixtures of shell and mud

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Table 11. Ranges and averages of in situ specific gravities, water contents, and void ratios sorted by sediment types of representative sediment samples collected in Laguna Madre from dredged material (dm) in selected placement areas, the GIWW, and the natural lagoon. Specific gravity, water contents, and void ratios are dimensionless numbers.

Composition	Sample Type	In situ Sp. Gravities			Water Contents			Void Ratios		
		Min.	Max.	Ave.	Min.	Max.	Ave.	Min.	Max.	Ave.
Homogeneous watery mud and mud	GIWW	1.17	1.41	1.26	110	299	208	3.06	7.48	5.55
Homogeneous mud	Subaqueous dm	1.25	1.62	1.39	64	171	116	1.65	4.73	3.21
Shelly sandy mud, shelly mud, sandy mud	Subaqueous dm	1.44	2.02	1.69	25	85	52	0.67	3.65	1.50
Shelly sand, sandy shell, muddy sand	Subaqueous dm	1.59	2.42	1.92	19	40	30	0.32	1.18	0.82
Homogeneous firm mud	Delta plain dm	1.98	2.25	2.12	11	30	20	0.26	0.77	0.51
Shelly sandy mud, muddy shelly sand	Natural lagoon	1.75	1.87	1.82	33	37	35	0.94	1.10	0.99

(Tables 9 and 11). These sediments with intermediate in situ specific gravities, water contents, and void ratios are subaqueous dredged material that have been in the placement areas long enough (several years to decades) that they have dewatered as much as possible given their composition and saturated (subtidal) setting. Sediments with the highest average in situ specific gravities, lowest water contents, and lowest void ratios are several thousand years old and they represent material dredged from deltaic deposits of the Beaumont Formation (subaerial dredged material in PA 221) or the Rio Grande delta (constructed levees in PA 233 and 234). These sediments are overcompacted because they were subaerially exposed for long periods after they were originally deposited. Natural lagoonal sediments are mixtures of shell, mud, and sand and they have a low range of in situ specific gravities, water contents, and void ratios that fall within the range of dredged material (Table 11).

Geotechnical Evaluation of Volume Losses

The purpose of settlement calculations for the Laguna Madre disposal areas is to determine the potential contribution of self-weight consolidation of recently deposited dredged material to the estimated volume losses (Table 8). These unconfined placement areas have been used for decades and are subjected to natural physical processes in addition to sediment consolidation. The goal of the exercise is not to determine the precise amount of settlement that has occurred at a given time but rather to quantify the volume reduction that could be attributable to settlement in the context of the overall volume loss of a particular placement area.

Model Settlement Calculations

The Corps of Engineers has developed procedures for predicting consolidation in soft fine-grained dredged material (Cargill, 1983). This model was further refined to estimate settlement as a function of time for self-weight consolidation, crust formation due to desiccation, and additional surcharge consolidation due to crust formation for dredged material in a confined disposal area (Cargill, 1985). The comprehensive model uses consolidation and permeability test results, site specific loading histories and water balances, and the known boundary conditions of a confined disposal area to determine the settlement potential for the dredged material.

Geotechnical analyses use both time-dependent and load-dependent consolidation relationships to determine settlement. Unfortunately, only limited information is available for the time and magnitude of loading at the placement areas in the Laguna Madre. Espey Huston compiled maintenance dredging records indicating year and quantity for each maintenance

dredging event. These records indicate that dredging occurred at irregular intervals over more than 45 years. No information is available regarding the thickness or sediment characteristics of the load at the time of placement. Furthermore, the configuration and boundary conditions at the placement areas differ from those used in the COE model in that the disposal areas are not confined, the dredged materials may have been alternately subaqueous or subaerial, and the placement areas are affected by physical processes other than consolidation. Information as to loading events, depth of sediment, variation in sediment type, sediment characteristics, and geotechnical characteristics such as coefficient of consolidation is lacking with respect to the Laguna Madre placement areas. Because there are significant information gaps, the use of the COE's computer program would misrepresent the level of analysis that can be performed with respect to settlement of dredged material in the Laguna Madre disposal areas. Instead, ultimate settlement calculations were used to determine the maximum settlement that may occur given the known volumes and sediment characteristics.

Ultimate Settlement Calculations

Ultimate settlement occurs when excess pore pressure has dissipated. This is a time-dependent process that is controlled by sediment loading and permeability. By calculating ultimate settlement, the time factor is removed from the analysis, eliminating the need for permeability, rate of consolidation, and pore pressure to calculate degree of consolidation. It is reasonable to assume that ultimate settlement has occurred for most of the dredged materials because they have been placed over decades of time and loading of the sediments beyond self-weight considerations has not occurred. With respect to the more recently placed dredged material, ultimate settlement provides a conservative estimate of the potential volume reduction.

A simplified model was developed to determine a reasonable maximum settlement for the Laguna Madre disposal areas. It was assumed that all original and maintenance dredging volume remained in the disposal area and that each volume of dredged fill was evenly distributed over the disposal area. It was also assumed that the surface area of each disposal area is constant and that consolidation was the only process that was contributing to volume loss within the disposal area. Using this model, the maximum volume reduction attributable to consolidation may be calculated and compared to the volume loss determined from the bathymetry data (Table 8).

General settlement calculations are based on the following equation (Das, 1990):

$$S = [CcH/(1+e_0)]* \log [(p_0 + p)/p_0] \text{ (equation 2)}$$

where: S is the ultimate settlement

Cc is the compression index

H is the layer thickness

e_0 is the initial void ratio

p_0 is the initial pressure

p is the increase in pressure

This general settlement equation is used for single layer models where p_0 is the average pressure at the midpoint of the layer and p is the surcharge added to the layer. The Laguna Madre placement areas better correspond to a multiple layer model because the material was placed episodically with each maintenance dredging event. Settlement calculations in multiple layer models are similar to those in a single layer model except the settlement for each layer is calculated from the overburden pressure and surcharge on that layer and then the total settlement is calculated as the sum of the settlements for the individual layers.

The average layer thickness (H) was determined for each maintenance dredging event in a particular disposal area. The volumes of maintenance dredging compiled by Espey Huston and the approximate size of the disposal area determined from bathymetry were used to calculate the layer thickness. An assumption was made that the layer was uniformly thick across the disposal area. Using the layer thickness (H), the initial pressure (p_0) for each layer was calculated at the midpoint of that layer. The increase in pressure (p) was calculated as the overburden pressure from subsequent layers of fill.

As a conservative measure, the in situ specific gravity of the natural lagoon sediment sample taken nearest a disposal area was used in the overburden pressure calculation. The average void ratio in the upper GIWW samples near each disposal area was input into the settlement calculations as the initial void ratio. This was also conservative in that the GIWW sediments have the greatest void ratio and largest settlement potential of the material types encountered in the investigation.

Typically the compression index is calculated directly from laboratory consolidation tests using a graph of void ratio versus logarithm of pressure. The compression index is calculated as the change in void ratio divided by the difference in the logarithms of pressure [$Cc = (e_1 - e_2)/(\log p_1 - \log p_2)$] (Das, 1990). Consolidation test data were not available for these disposal areas so the compression index was estimated using test results of the upper and lower samples from the GIWW. Unless sample descriptions indicated otherwise, it was assumed that lithologically the sediments in the upper and lower samples were the same. Any difference in void ratio and in situ specific gravity was considered a function of sediment consolidation. The

void ratio of the upper sample was used as e_1 and the void ratio of the lower sample was used as e_2. The upper samples were taken from 0- 0.1 m in the core and the lower samples were taken from 0.1-1.0 m in the core. The midpoint pressures in these zones were considered the overburden pressures that corresponded to the upper and lower void ratios.

Upper and lower samples from the same core location were available for PA 197, 202, and 221. No upper and lower samples were available for PA 233. For PA 197, the compression index input into the settlement calculations (0.53) was the average index for samples 197-S5 and S6, 197-S8 and S9, and 197-S11 and S12. For PA 202, the compression index (2.14) was the average index for samples 202-S4 and S5, 202-S14 and S15, and 202-S18 and S19. For PA 221, the compression index (1.28) was the average index for samples 221-S1 and S2, 221-S6 and S7, 221-S11 and S12, and 221-S17 and S18. Due to the similarities between PA 221 and 233 with respect to test results and sediment descriptions, the compression index calculated for PA 221 was also used in calculating the settlement for PA 233.

Volume Loss Estimates Using Placement Area Compression Indices

In PA 197, the maximum settlement calculated was 0.256 m uniformly distributed over the disposal area, yielding a potential volume reduction due to settlement of 525,177 m^3. The total volume of original and maintenance dredging placed in PA 197 was 4,969,487 m^3. Therefore, potential settlement may account for approximately 11% loss of the overall material volume placed in PA 197. Based on bathymetry, the volume loss was determined to be 1,465,410 m^3. Of the volume loss determined by bathymetry, 36% of that loss may be attributable to sediment consolidation and the remaining 64% loss would be attributable to other processes.

In PA 202, the maximum settlement calculated was 0.558 m uniformly distributed over the disposal area, yielding a potential volume reduction due to settlement of 1,708,661 m^3. The total volume of original and maintenance dredging placed in PA 202 was 4,230,280 m^3. Therefore, potential settlement may account for approximately 40% loss of the overall material volume placed in PA 202. Based on bathymetry, the volume loss was determined to be 2,311,572 m^3. Of the volume loss determined by bathymetry, 74% of that loss may be attributable to sediment consolidation and the remaining 26% loss would be attributable to other processes.

In PA 221, the maximum settlement calculated was 0.082 m uniformly distributed over the disposal area, yielding a potential volume reduction due to settlement of 343,180 m^3. The total volume of original and maintenance dredging placed in PA 221 was 1,807,843 m^3. Therefore, potential settlement may account for approximately 19% loss of the overall material volume placed in PA 221. Based on bathymetry, the volume loss was determined to be 26,706 m^3. Potential settlement at PA 221 exceeds the volume loss determined from bathymetry; however,

the bathymetry data are considered to be a more reliable indicator of actual change rather than an estimate of potential change.

In PA 233, the maximum settlement calculated was 1.786 m uniformly distributed over the disposal area, yielding a potential volume reduction due to settlement of 3,306,173 m^3. The total volume of original and maintenance dredging placed in PA 233 was 7,679,663 m^3. Therefore, potential settlement may account for approximately 43% loss of the overall material volume placed in PA 233. Based on bathymetry, the volume loss was determined to be 7,265,050 m^3 (Table 8). Of the volume loss determined by bathymetry, 45% of that loss may be attributable to sediment consolidation and the remaining 55% loss would be attributable to other processes.

Volume Loss Estimates Using Average Compression Index

The previous calculations were based on the assumption that the placement area sediments settled in a manner similar to the GIWW sediments. A risk with this assumption is that the compression index for a particular placement area, calculated from a few void ratios and overburden pressures, would skew the settlement results for that placement area. To address this risk, the average compression index for the ten sets of upper and lower GIWW samples taken near the three placement areas was calculated. This average compression index (1.319) was then used to calculate the settlement at each of the placement areas.

Using the average compression index, the maximum settlement calculated for PA 197 was 0.756 m uniformly distributed over the disposal area, yielding a potential volume reduction due to settlement of 1,551,646 m^3. The total volume of original and maintenance dredging placed in PA 197 was 4,969,487 m^3. Therefore, potential settlement may account for approximately 31% loss of the overall material volume placed in PA 197. Based on bathymetry, the volume loss was determined to be 3,503,717 m^3. Of the volume loss determined by bathymetry, 44% of that loss may be attributable to sediment consolidation and the remaining 56% loss would be attributable to other processes (fig. 50).

In PA 202, the maximum settlement calculated was 0.344 m uniformly distributed over the disposal area, yielding a potential volume reduction due to settlement of 1,052,660 m^3. The total volume of original and maintenance dredging placed in PA 202 was 4,230,280 m^3. Therefore, potential settlement may account for approximately 25% loss of the overall material volume placed in PA 202. Based on bathymetry, the volume loss was determined to be 2,311,572 m^3. Of the volume loss determined by bathymetry, 45% of that loss may be attributable to sediment consolidation and the remaining 55% loss would be attributable to other processes (fig. 50).

In PA 221, the maximum settlement calculated was 0.098 m uniformly distributed over the disposal area, yielding a potential volume reduction due to settlement of 401,109 m^3. The total

volume of original and maintenance dredging placed in PA 221 was 1,807,843 m^3. Therefore, potential settlement may account for approximately 22% loss of the overall material volume placed in PA 202. Based on bathymetry, the volume loss was determined to be 26,706 m^3. More volume loss may be attributed to settlement at PA 221 than the volume loss that was determined from bathymetry.

In PA 233, the maximum settlement calculated was 1.809 m uniformly distributed over the disposal area, yielding a potential volume reduction due to settlement of 3,350,608 m^3. The total volume of original and maintenance dredging placed in PA 233 was 7,679,663 m^3. Therefore, potential settlement may account for approximately 44% loss of the overall material volume placed in PA 233. Based on bathymetry, the volume loss was determined to be 7,265,050 m^3. Of the volume loss determined by bathymetry, 46% of that loss may be attributable to sediment consolidation and the remaining 54% loss would be attributable to other processes.

Additional Observations

The fact that most subaqueous sediments in the placement areas have in situ specific gravities, water contents, and void ratios similar to natural lagoonal sediments suggests that the dredged material has dewatered from the bulking processes associated with dredging and there are only minor physical differences between the state of the sediments before and approximately 2 yr after dredging. However, the vast difference between the composition of shoal material in the channel (homogeneous low-density mud) and sediments in the placement area and natural lagoon (mixtures of sand, shell, and mud) strongly indicate that the deposits remaining in the placement areas are residuals primarily from original works dredging and not subsequent maintenance dredging. There is no adequate physical or biogenic process that would rapidly convert large volumes of watery homogeneous mud of the channel into shelly sandy mud or shelly muddy sand of the placement area. Even introduction of coarse biogenic detritus (shell) by extensive burrowing would require time periods that are much greater than those between dredging cycles. This interpretation is also confirmed by the ubiquitous presence of rock fragments, mud balls, old shells, or other remnants of original sediments on many of the islands of dredged material.

Regional differences in sedimentation are recognized when parameter ranges and means are calculated on the basis of depositional setting (Table 11). This spatial analysis shows that sediment properties exhibit patterns both within placement areas and between placement areas. Within placement areas sediment specific gravities are consistently lower and water contents and void ratios are consistently higher in channel sediments than in dredged material. Furthermore,

specific gravities are lower and water contents and void ratios are higher for subaqueous dredged material than for subaerial dredged material at the same or nearby sites (Table 9).

In situ specific gravities increase slightly, whereas water contents and associated void ratios decrease significantly to the south in channel sediments of the GIWW (Table 11). Comparing northern and southern Laguna Madre, there are no differences in geotechnical properties of the natural lagoonal sediments, and dredged material

Implications of Island Morphology

Shapes of dredged material deposits were examined (1) subregionally between placement areas and (2) locally around islands within placement areas to evaluate the significance of post-depositional reworking. Island morphologies within the placement areas and between the placement areas change systematically throughout Laguna Madre because they are controlled primarily by changes in water depths and long-term time-averaged depositional and erosional processes. End members in the linear spectrum of island morphologies are large, nearly circular, mostly subaerial mounds deposited on flats, and absence of surficial expression of dredged material deposited in water usually greater than 1.5 m. These end members are the basis for the three patterns of morphological change observed within the placement areas: (1) progressive changes in mound morphology, (2) transition from mound to ridge, and (3) narrow ridges (fig. 55). The same three morphological patterns recognized within placement areas are also repeated at much larger scales between placement areas. Most of the changes in island morphologies are gradual whereas some are abrupt. The most abrupt changes occur within PA 202.

The shapes and sizes of mounds of dredged material change progressively along many segments of the GIWW in Laguna Madre. Large, moderately high, nearly circular mounds typically become lower, narrower, and more irregular in shape (fig. 55a) where water depths increase and where the orientation of the placement area is perpendicular to the gradient of the natural (pre-dredging) lagoon floor. These changes in mound patterns and sizes are found within PA 186, 197, and 235, and between PA 211/212. Another common pattern observed in island morphology is the transition from nearly circular mounds to low, narrow, irregular ridges (fig. 55b). This transitional morphology is found where the lagoon floor changes from a broad platform of uniform depth into adjacent deeper water such as between PA 185/186, 195/196, 201/202, 221/ 222, and within PA 233. Another persistent pattern in island morphology consists of low, narrow irregular ridges (fig. 55c) constructed in water depths greater than 1.2 m. The narrow ridges also coincide with placement areas that are oriented parallel to the gradient of the natural (pre-dredging) lagoon floor. In northern Laguna Madre this pattern in island morphology

PLAN VIEW

Island patterns	Placement area

a) Progressive changes in mounds

197, 211

b) Mound to ridge transition

202, 233

c) Narrow ridges

187, 221

TRANSVERSE CROSS SECTION

d) Decreased thickness   **e)** Uniform thickness

187 North	187 South	197 North A	197 South A
197 North B	197 South B	202 Central	202 South
202 North	221	211 North	211 Central
233 North A	233 North B	211 South	233 South

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Figure 55. Typical morphologies of islands of dredged material formed by placement in open water of Laguna Madre. In plan view the patterns are A. Progressive change in mound shape and size, B. Transition from mound to ridge, and C. Crenulated irregular ridges. In cross section view the patterns are D. Decreased thickness away from the axis, and E. Uniform thickness relative to water depth.

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extends from PA 187 to 195 and PA 198 to 202. The ridges of dredged material have highly irregular outlines as a result of wave reworking and the islands are commonly ephemeral features that are destroyed by erosion because their flanks are less than 0.5 m above water levels and they are frequently inundated by storm waves.

When viewed in transverse cross sections, the deposits of dredged material exhibit two different styles of deposition depending on the slope of the lagoon floor. Where the pre-dredging lagoon floor is relatively flat, the thickness of dredged material systematically decreases away from the axis of the placement area (fig. 55d). The cross-sectional shape is rarely symmetrical and most of the placement areas have greater thicknesses of dredged material on the side nearest the GIWW. The second depositional pattern recognized is a uniform thickness of dredged material relative to the change in water depth (fig. 55e). For these conditions, the pre-dredging slope of the lagoon floor controls the thickness of dredged material away from the axis of the placement area.

AREAS OF MINIMUM DREDGING

Segments of the GIWW in Laguna Madre were identified that either have not needed maintenance dredging or the frequency and volume of maintenance dredging are unusually low. The physical characteristics of these sites were also examined to compare with characteristics of the six sites where maintenance dredging is frequent and involves removal of large volumes of sediment.

The segment of the waterway in northern Laguna Madre between placement areas 173 and 178 fits the definition of low maintenance as do segments between placement areas 224-225 and 230-231 in southern Laguna Madre. PAs 173-178 have been dredged only twice or not at all and the total volume of maintenance dredging at each PA has been less than 150,000 m^3 since the GIWW was originally constructed. The PAs are located at the northern end of the lagoon on broad flats and the dredged material is placed near Padre Island, which essentially eliminates reworking by wind-generated waves and currents from the southeast. Furthermore, constriction of Laguna Madre created by the fill of the Kennedy Causeway at its intersection with Corpus Christi Bay forces large volumes of water through the dredged channel. Strong velocities generated by these conditions keep the channel flushed of sediments, which are then deposited where the flow expands (larger cross-sectional area) and velocities are reduced, such as north and south of this reach. PA 224 and 225 are located at the mouth of the Arroyo Colorado and north of the artificial cutoff channel. The disposal sites are on subaerial flats and they are protected from reworking on the west side by uplands. PA 230 and 231 are located on subaerial

flats south of the Arroyo Colorado cutoff channel and they also are protected from reworking on the west side by uplands.

Characteristics common to each of the low maintenance sites are: (1) the dredged material is sheltered by uplands and exposure to waves and currents is limited to only one side of the placement area, (2) reworking is also limited because dredged material is deposited on broad flats that are either subaerial much of the time or inundated by less than 0.3 m of water, (3) each site is located along a straight segment of the waterway without a bend, (4) the sites are within a confined portion of the waterway that constricts flow and tends to accelerate velocities thus minimizing deposition and promoting transportation.

EXPERIMENTAL CONTAINMENT DESIGNS IN PLACEMENT AREAS 233 AND 234

During the 1994 maintenance dredging cycle in southern Laguna Madre, several different techniques of open-water placement of dredged material were used in PA 233 and 234 including an emergent confining levee, a submerged confining levee, and shallow unconfined mounds. Apparently there has been no systematic monitoring of the different disposal sites and subsequent analysis of the behavior of the dredged material that considers how the different placement techniques responded to physical processes in the lagoon.

The concept of bulking not only applies to material hydraulically dredged from the GIWW but also to sediments extracted to construct levees in PA 233 and 234. Consequently, the volume of sediment mined from below the lagoon floor should be less than the volume of material in the levees because pore space was added to the sediments in the levees. However the topographic profiles show that the levees actually account for substantially less volume of material than that removed by dragline (figs. 56-57).

Sequential Topographic Surveys

Bathymetric surveys at some of the experimental sites were conducted by the Conrad Blucher Institute immediately, 8 months and 13 months after dredging (Brown and Kraus, 1996). Surveys at transects in the unconfined open bay disposal area showed rapid loss or compaction of dredged material from the placement area and concomitant shoaling of the GIWW (Brown and Kraus, 1996). Surveys at transects in the emergent levee segment of PA 233 showed little change in volume of dredged material in the placement area and systematic deepening of the GIWW after dredging. Surveys at transects in the northern segment of PA 233 where shallow
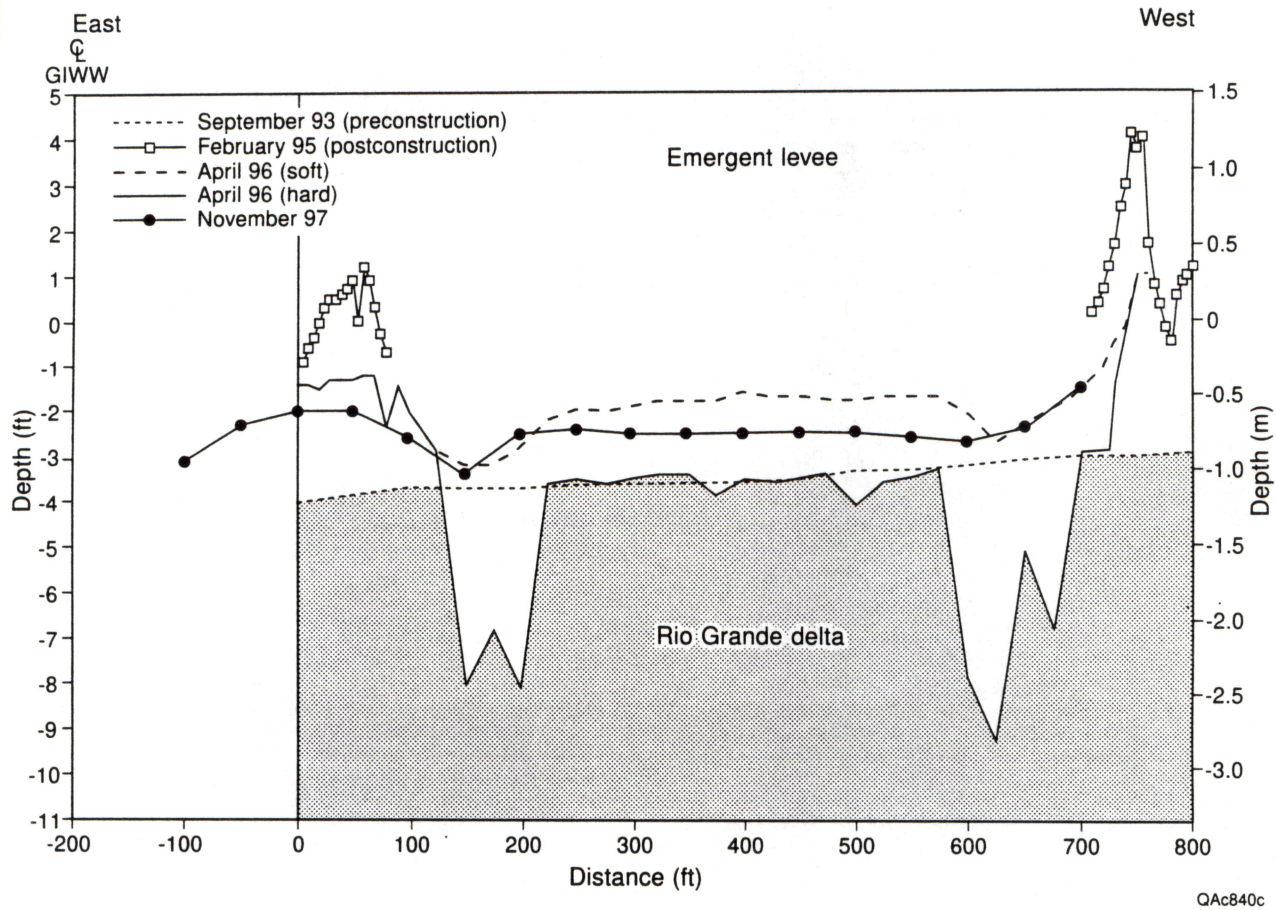
Figure 56. Topographic profiles of experimental emergent levee at station in PA 233.
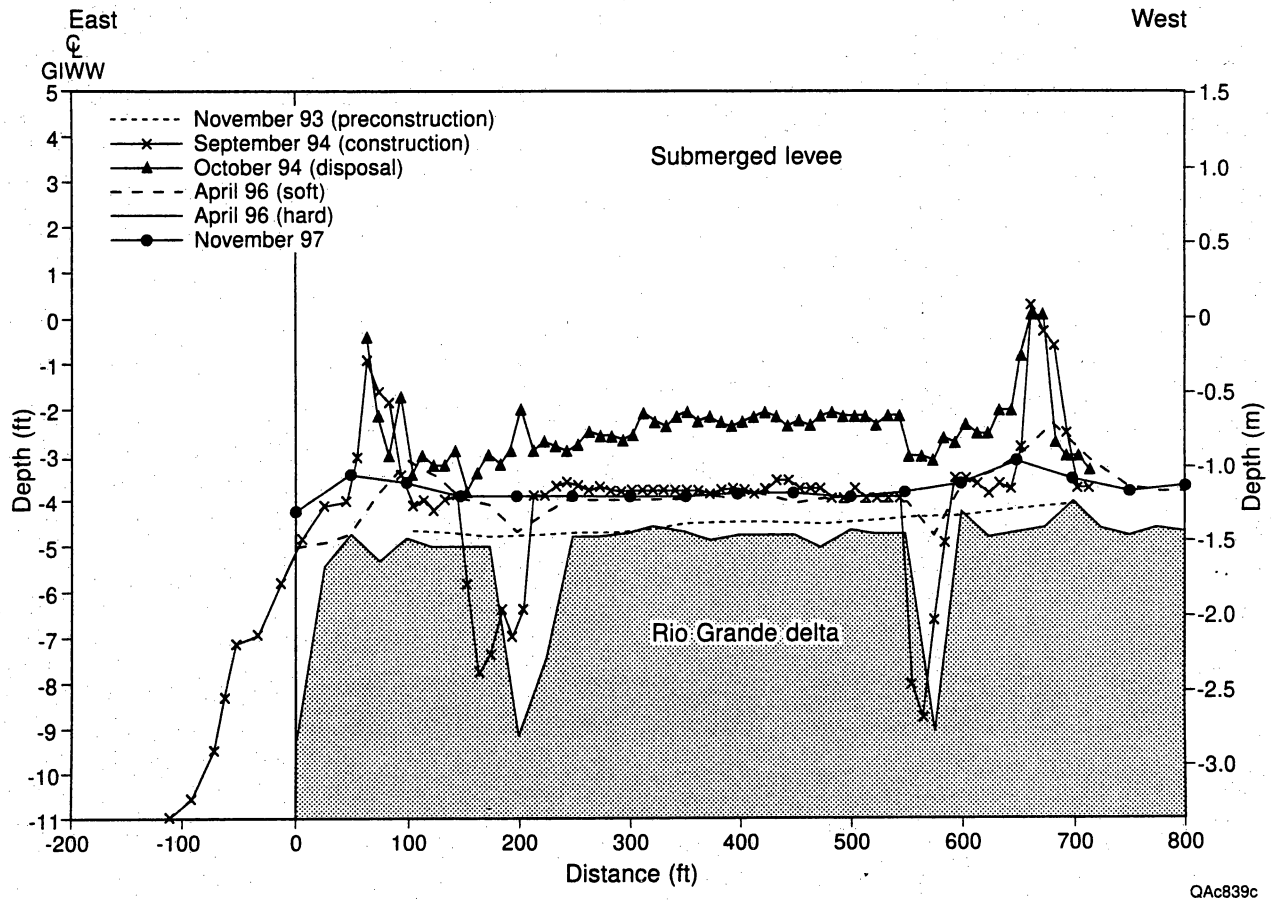
Figure 57. Topographic profiles of experimental submerged levee at station in PA 234.

mounds were formed also showed systematic deepening of the GIWW after dredging and only minor changes in the volume of sediment in the placement area (Brown and Kraus, 1996).

Brown and Kraus (1996) recognized that the systematic deepening of the GIWW, which was recorded at 6 of the 9 transects included in their report, could have been caused by scour from strong currents flowing along the waterway. Nevertheless, they favored an explanation that involved a false bottom return to the echo sounder caused by a layer of high-density sediment 1.5 to 2 m thick observed during the immediate post-dredging survey. However, a false bottom return would not explain the systematic deepening observed 8 and 13 months after dredging. The immediate post-dredging bathymetric surveys in PA 233 were done in November, 1994 and the 8 months post-dredging surveys were done in June, 1995 so the observed changes in channel depth could have been the result of scour by currents driven by strong north winds during the preceding winter and spring months. Shoaling in the GIWW adjacent to the southern part of the placement area during the same period would also be consistent with southerly sediment transport and deposition.

The Brownsville office of the Corps of Engineers also conducted pre- and post-dredging surveys of some experimental disposal sites in Placement Areas 233 and 234. The boat-based surveys involved establishing horizontal positions with a GPS receiver and reading average water depth on a rod that was then corrected with a nearby tide gauge reading to obtain the water depth to the soft sediment surface with respect to the COE low-water datum (Isidro Garcia, personal communication, 1998). Only the April 1996 surveys attempted to differentiate between the soft upper surface and a deeper firm surface (figs. 56-58). Comparisons of the sequential surveys show general trends that can be used to interpret changes in the emergent levee, submerged levee, and shallow subaqueous mound sites. Obvious discrepancies in the repeated surveys are attributed to the boat-based surveying techniques that preclude precise reoccupation of the same stations from one survey to the next.

Emergent Levees

Of the three experimental designs, the emergent levees were constructed in the shallowest water not far from the southern extent of subaerial remnants (islands) of dredged material. In Placement Area 233 between stations 61+ 000 and 63+ 000, trenches were excavated 1.2 to 1.5 m below the lagoon floor on the east and west sides of the elongate disposal site to construct emergent levees. The levees, which were constructed in September 1994, were 1.5 to 2.0 m above the lagoon floor and had elevations 0.6 to 1.5 m above the low-water datum (fig. 56). Immediate post-construction levee heights were typically greater on the west side of the confinement structure than on the east side. Construction material for the levees was stiff mud of
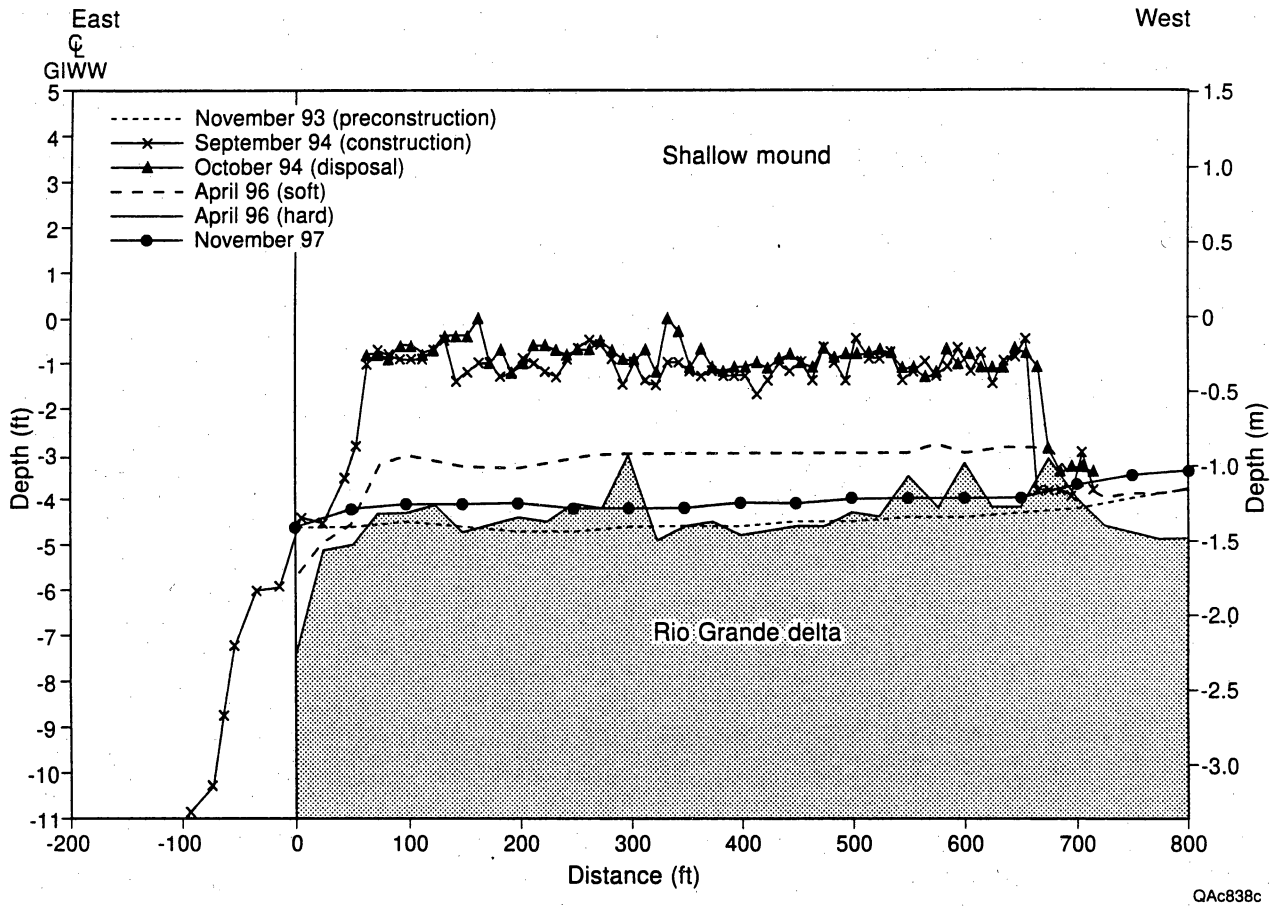
Figure 58. Topographic profiles of experimental shallow mound at station in PA 234.

the Holocene Rio Grande delta plain. Comparison of post-construction topographic surveys show that outside slopes of the levees are convex upward on the east side and concave upward on the west side. Furthermore, the volumes of sediment in the levees are nearly the same or less than the volume excavated from the trenches, whereas they should be much greater than the volume extracted because of voids introduced during construction. Although the levee volumes may be slightly underestimated because the February 1995 surveys did not reach closure (surface of the lagoon floor), the differences in volumes suggest immediate reworking and dispersion of some of the excavated sediment.

There are no post-disposal topographic surveys that show the surface between the levees, so the analysis of elevation changes is restricted to the levees. Post-construction topographic surveys (fig. 56) show that the levees were still in place approximately five months after construction (February 1995), but after 19 months (April 1996), their elevations had been reduced as much as 1.5 m. There is relatively close agreement between the November 1993 pre-construction bathymetry and the April 1996 hard surface showing the lagoon bottom before the levees were constructed. The 19-month post-construction profiles indicate that the entire levee system on the east side of the placement area and the levee on the southwestern side were below the low-water datum. Only the portion of the levee on the northwestern side remained slightly above the low-water datum and it was below water much of the time and no longer functioning as an emergent levee. From April 1996 to November 1997, 38 months after levee construction, there was additional loss of about 0.3 m of surface elevation on the levees and the dredged material, and both of the levee remnants retained some low relief above the surrounding dredged material (fig. 56).

In the April 1996 (soft) profiles, sags in the sediment surface over the excavation trenches suggest possible minor compaction of dredged material. Although some compaction may have contributed to the lowered levee elevations, most of the lowering probably was caused by erosion for the following reasons. First the levees were constructed of sediments compacted over periods of geological time, not of dredged material that was emplaced hydraulically. This levee material, consisting of firm brown mud, had an in situ specific gravity of 1.98, water content of 30% and void ratio of 0.77 (Table 9). There was significantly less water in the levee material than in the disposed sediment dredged from the channel. The disposed sediment had water contents up to 93%. The February 1995 surveys were conducted at least four months after levee construction, which is ample time for rapid subaerial dewatering of the levees. In addition, the preferential preservation of some levee height above the low-water datum on the northwestern side would be consistent with sheltering from erosion by waves originating from the southeast.

Loss of maximum levee height is observed for the eastern levee both between February 1995 and April 1996 and between April 1996 and November 1997. From February 1995 and

April 1996 the maximum levee thickness decreased approximately 0.85 m. This loss was a 53% reduction in maximum levee thickness from 1.6 m in February 1995 to 0.75 m in April 1996. During this 19-month period, it is likely that some volume reduction was due to compaction of void spaces within the levees as a result of construction as opposed to reductions in the void ratios due to consolidation within the sediment structure. It is likely that the compaction of the construction void spaces was complete by April 1996. An additional 0.2 m decrease in levee thickness occurred between April 1996 and November 1997, resulting in a 27% thickness reduction since April 1996 and a 66% reduction of levee thickness since February 1995.

The submerged dredged material has similar characteristics to the recent shoal material in the GIWW. The dredged material, sampled in November 1997, has an in situ specific gravity of 1.45, water content of 85% and a void ratio of 2.43. In comparison, the shoal material in the GIWW has an in situ specific gravity of 1.49, water content of 93% and a void ratio of 2.46 (Table 9). These results indicate that some of the GIWW material placed within the emergent levee has been retained and has not undergone significant consolidation. Normally, sediment consolidation is expected within dredged material and results in a decrease in water content and void ratio and an increase in specific gravity. Based on the absence of these indicators and the volume loss of dredged materials determined from the site surveys, it is apparent that other processes are reworking the dredged materials within the emergent levees and that a net volume loss is occurring.

In April 1996, approximately 0.6 m of dredged material was retained between the levees (fig. 56). The maximum height of this dredged material was approximately 0.1 m below the eastern levee height. In November 1997, approximately 0.3 to 0.5 m of these soft sediments remained between the lowered levees. Again, the maximum height of the remaining dredged material was approximately 0.1 m below the reduced height of the eastern levee. Based on the similarity of the material properties, this reduction in sediment thickness of 17 to 50% is not attributable to sediment consolidation. Therefore, non-consolidation processes caused 17 to 50% loss of dredged material within the emergent levees (fig. 56).

A comparison of the April 1996 and the November 1997 surveys further indicates that processes other than consolidation are affecting the dredged sediments. In April 1996, distinct swales in the top of the dredged sediment were noted near the internal base of slope of both the eastern and western levees. These swales were directly above the trenches excavated for the levee material. These locations have the greatest thickness of dredged material, assuming that these excavations were filled as the dredged material was placed between the levees. The amount of settlement due to consolidation should increase with the greater sediment thickness. The November 1997 survey however indicates a relatively uniform sediment surface over the western

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trench. At the eastern trench, the swale remains with approximately the same depth as shown in the April 1996 survey (fig. 56).

Submerged Levees

The submerged levees constructed in September 1994 in PA 234 between stations 49+ 200 and 49+ 800 experienced the same general history as the emergent levees of PA 233. The submerged levees were formed from Rio Grande deltaic sediments excavated about 1.2 to 1.5 m below the lagoon floor and they attained an equal height above the lagoon floor (fig. 57). This height placed them at or just below the low-water datum. Comparison of post-construction topographic surveys show that the volumes of sediment in the levees are nearly the same or less than the volume excavated from the trenches, whereas they should be much greater than the volume extracted because of voids introduced during construction. The differences in extracted and constructed volumes suggest immediate reworking and dispersion of some of the excavated sediment. The submerged levee has an in situ specific gravity of 1.92, water content of 31% and void ratio of 0.82. The material properties of the submerged levees are essentially identical to those of the emergent levees.

The October 1994 surveys show that dredged material deposited between the levees increased elevations 0.3 to 0.6 m, the levee crests did not change elevation one month after construction, and the excavation trenches were not completely filled (fig. 57). There is relatively close agreement between the November 1993 pre-construction bathymetry and the April 1996 hard surface showing the lagoon bottom before the levees were constructed. The April 1996 surveys, approximately 18 months after dredging, also show that the levees were lowered 0.6 to 0.9 m, but they retained their general shape and relief above the adjacent dredged material. The soft dredged material between the levees was reduced uniformly in height even over the excavation trenches and the surface elevation of dredged material between the trenches returned to its immediate post-construction position. The 18-month post-dredging surveys indicate an overall reduction in sediment volume of about 71%. By November 1997, approximately 38 months after construction, there was additional minor loss of elevation on the levees of 0.1 to 0.2 m, but the dredged material between the levees remained unchanged.

At the submerged levee site, the dredged sediments and the shoal sediments in the GIWW have different properties. A sample of the dredged material has an in situ specific gravity of 1.52, a water content of 76%, and a void ratio of 2.11. In comparison, the GIWW sample has an in situ specific gravity of 1.35, a water content of 135%, and a void ratio of 3.63 (Table 9). This comparison of material properties indicates that some consolidation of the dredged material has occurred since it was placed within the submerged levees, assuming material properties similar

to the GIWW material at the time of placement. Only 40 to 45% of the volume reduction in dredged materials noted between the post-dredging surveys may be attributed to consolidation of the sediments. The remaining 31 to 36% of volume reduction is attributable to other processes acting upon the dredged sediments. Some erosion and transport of dredged material to the west beyond the containment levee is suggested by the sequential surveys.

This conclusion is confirmed by comparing the November 1997 and the preconstruction surveys. In the November 1997 survey, there is no indication where the levee material excavation trenches underlie the dredged materials. Because the thickness of dredged material is greatest in these areas, the settlement potential due to consolidation is also greatest in these areas. If consolidation was the only process affecting the sediments and causing the volume reduction, the November 1997 survey would have shown increased settlement in these areas. Rather, the survey indicates a relatively uniform sediment surface between the reduced levees, indicating the dominance of other processes.

Shallow Unconfined Mounds

Another experimental design for the containment of dredged material involved the construction in PA 234 of shallow submerged mounds without any confining levees (fig. 58). Pre- and post-construction surveys of two submerged mound sites are available for stations 49+ 000 and 50+ 000 (fig. 54). Comparing pre-construction and immediate post-construction surveys show that in September 1994, the crest of the mound was at or 0.3 m below the low-water datum, and surveys one month after construction indicate essentially no change in the height of the mound crest. However, the 19 month post-construction surveys record a lowering of the surface by 0.6 to 1.2 m (fig. 58) and a 55% volume reduction in the subaqueous mound. After 19 months only about 0.3 to 0.6 m of soft dredged material remained in the placement area. In these April 1996 surveys, both the surface of the soft dredged material and the interface between the soft dredged material and underlying hard material were noted. There is relatively close agreement between the November 1993 pre-construction bathymetry showing the lagoon bottom before the mound was constructed and the April 1996 hard surface survey. Total volumetric reduction of the submerged mound was 87% after 38 months.

Sediment properties in the shallow unconfined mound were distinctly different than sediment properties in the GIWW. Three samples of the mound material were taken and the material was shelly to firm sandy shelly mud. The shallow mound material had in situ specific gravities of 1.85 to 2.02 with a mean of 1.93, water contents of 25 to 33% with a mean of 28%, and void ratios of 0.67 to 0.93 with a mean of 0.79. These material properties are notably similar to the properties of the Rio Grande delta material used in both the emergent and submergent

levees. Two samples taken from the GIWW near PA 234 had material properties similar to other GIWW samples. In situ specific gravities were 1.38 and 1.40, water contents were 110 and 118% and void ratios were 3.06 and 3.18 for the two samples (Table 9).

The clear distinction between properties of the remaining shallow mound material and the properties of the GIWW sediments indicates that little or no GIWW dredged material remains in the shallow mound. The material remaining in the shallow mound is approximately 0.1 m thick based on a comparison of the preconstruction survey to the November 1997 survey and the remaining material possesses the material properties of the Rio Grande delta sediment. It is possible that the surveys indicating a 0.1 m remaining thickness are limited by the method of data collection and the samples were taken from underlying in situ Rio Grande delta sediment.

Little or no volume reduction in the shallow mound may be attributed to sediment consolidation as it appears from both the surveys and material testing that little or no dredged material remains in the shallow mound area to be consolidated. The Rio Grande delta sediment in the shallow mound area is not expected to consolidate without loading. Therefore the volume reduction in the shallow mound is attributable to other processes including sediment erosion.

Seagrass Planting Areas

Two shallow mounds also were constructed in PAs 233 and 234 to test the feasibility of establishing seagrass habitats that would also possibly stabilize the sediment surface and reduce shoaling in the GIWW. The northern grass planting site is near CM 83 ($\approx 64+800$) and the southern site is near CM 101 ($\approx 51+300$). Field verification in October, 1997 of the transplanting sites was made by locating the four white PVC pipes that mark the corners of the plots. Seagrass transplanting was conducted in June and again in September of 1995 (Dunton and Kaldy, 1997), approximately 8 months and one year after disposal of the dredged material.

Surficial sediments in the northern grass planting area are composed of sandy mud and mud with specific gravities of 1.62 (Table 9), whereas those in the southern planting area are composed of sandy shelly mud with specific gravities of 1.85 and 2.02. The presence of shell debris and higher specific gravities of sediments in the southern planting site suggest nearly complete dispersion of the low-density (1.38 or less) GIWW dredged material, which is more than 90% mud (White et al., 1986). This interpretation is also supported by the systematic coarsening of sediment textures from November 1995 to November 1996, and an increase in water depth at the grass planting sites of about 0.3 m as a result of sediment erosion (Dunton and Kaldy, 1997).

Results of Analysis

Although physical monitoring of the sites did not extend longer than a normal dredging cycle, some conclusions regarding the long-term retention of dredged material by techniques other than unconfined open water disposal can be made. On the basis of the profiles presented by Brown and Kraus (1996) and the Brownsville office of the Corps of Engineers, it appears that open water disposal is the most susceptible to reworking and dispersion of dredged material. The shallow mound was not effective in retaining soft sediment within the placement area and they are subject to extensive reworking similar to submerged unconfined disposal. According to field observations (Dunton and Kaldy, 1997; Charles Belaire, personal communication, 1997; Peter Sheridan, personal communication, 1997), seagrasses planted in PAs 233 and 234 on shallow submerged mounds did not survive because the surface of dredged material was lowered considerably. The geotechnical data indicate that loss of surface elevation was probably caused by erosion. This conclusion is also supported by the grain size data of Dunton and Kaldy (1997) which shows a substantial increase in the coarse fraction of sediments (sand and shell) in November, 1995, 1996, and 1997 samples taken 1, 2, and 3 years after the disposal event. Size fractionation and associated coarsening of sediments results from removal of fine grained sediments (silt and clay) by currents. This progressive systematic coarsening would not result from dewatering because sediment textures would remain constant and only water content would be reduced if dewatering was the primary mechanism causing loss of surface elevation. Reworking is greatest in the shallow water toward the northern end of PA 233. The most effective technique for holding dredged material was the emergent levee, which retained some of the soft sediment that is most easily resuspended and transported into the channel. The submerged levee technique was considerably less effective in retaining the sediments than the emergent levee; however, the emergent levee also required excavation of more material than the submerged levee.

BRINE DISCHARGE, DREDGED MATERIAL, AND SEAGRASSES

Surface Discharge of Brine

The locations and drilling dates for oil and gas wells in Laguna Madre were investigated because drill cuttings and brine have been discharged into the water, and channels have been dredged to provide access to drilling sites. Twenty-four oil and gas fields in Laguna Madre and adjacent shores were located on maps and Railroad Commission records were used to determine

field discovery dates. Maps of well locations and electric logs in BEG files also were examined to determine drilling dates of individual wells.

Impacts from drilling and disposing of drill cuttings in seagrasses apparently have not been investigated. However, if studies of drilling effects on benthic fauna are any indication, physiological impacts on seagrasses should be localized. Depending on total drilling depth, each well would generate approximately 390 to 735 m^3 of drill cuttings (Minerals Management Service, 1989). Studies show that the cuttings form a low mound beneath the discharge point. Plants and animals that are nonmotile are smothered, but observations in offshore areas indicate that the mounds are recolonized and eventually become indistinguishable from the surrounding bottom (Zingula, 1975, as cited in Minerals Management Service, 1989). Where there are changes in the benthic fauna, it is due to physical changes in the substrate rather than toxic effects (Menzie, 1983, as cited in Minerals Management Service, 1989). A biological resources subgroup at a Mobile Bay Area Drilling Fluids Transport Workshop concluded that toxicity from drilling fluids resulting primarily from diesel oil does not seem to be a problem at distances greater than 200-500 m from the discharge point, and certainly not at distances greater than 1,000 m (Minerals Management Service, 1989). These data suggest that changes in seagrass beds caused by disposal of drill cuttings and drilling fluids in the marine environment would be localized and of short duration.

Oil field brine, or produced formation water, is a common byproduct of oil and gas production. Normally the produced water is separated from the hydrocarbons and reinjected into subsurface formations or it can be released into tidal waters as permitted discharges, which are regulated by the Texas Railroad Commission (1997). Railroad Commission records dating back to the early 1970s report that 27 discharge sites were initially permitted in the Laguna Madre-Baffin Bay area between December 1968 and November 1991 (Taylor, 1997). Most of the records are incomplete because the earliest permits did not require the reporting of water volumes discharged. Surface disposal sites are being phased out as a result of new EPA regulations, and by August, 1997, only two discharge sites remained in Laguna Madre (Taylor, 1997).

The effects of brine discharge on Texas coastal sediment and water quality, benthic macroinvertebrate populations, and marshes have been investigated by several researchers (see summary by Harper, 1986). Studies of the impacts to seagrass, however, apparently have not been conducted; consequently the following discussion focuses primarily on studies of estuarine fauna and emergent vegetation, with possible implications for seagrasses.

Brine composition depends on the formation from which it is produced, but it is significantly different from surface waters including the high salinity water of Baffin Bay and Laguna Madre. In addition to high levels of dissolved solids, brine commonly contains

hydrocarbons from petroleum residues, trace metal concentrations higher than surface water, and ionic ratios that are different from estuarine waters. These constituents can be toxic to flora and fauna and interfere with organism metabolism (Shipley, 1991).

The most important factor controlling the degree of contamination and biological impact is the degree of mixing in the receiving water (Harper, 1986; Roach et al., 1993). Generally, mixing is more complete in the open Gulf or bays where currents and water depths are greater, whereas mixing is less complete in protected, intermittent streams and shallow water bodies. Where the degree of mixing is low, concentrations of harmful constituents are more likely to be retained in the water and sediments and to produce an adverse impact on the flora and fauna. Biological impacts are most severe near the discharge sites and decrease with distance from the site. In a study of discharge into Tabbs Bay, which is north of Galveston Bay, Roach et al. (1993) reported that benthic and macroinvertebrate communities were significantly impacted at distances of 80 m offshore and 140 m alongshore from a discharge point at the shoreline. The estimated area of impact was between 1.3 and 5.3 acres, which is similar to the areas impacted at discharge sites in other parts of the Galveston Bay system reported by Armstrong et al. (1979) and Mackin (1971).

The water associated with seagrass beds offers some protection as an agent of mixing and dispersion of the discharged water. Because volumes of discharge in the Laguna Madre-Baffin Bay system have a large range (from <1 to >5,000 bbl/day) and have not been consistently reported, it is difficult to estimate their potential impacts. If it is assumed that seagrass beds in Laguna Madre could be adversely affected by brine disposal over an area of two to five acres per discharge site (based on studies of impacts to benthic fauna), the nine sites where discharges have exceeded 100 bbl/day could have a cumulative affect over an area of between 18 and 45 acres. This estimate may be high, however, because seagrass beds would probably be effected only at sites very near the discharge where hydrocarbons, total dissolved solids, and other contaminants are concentrated. Given the location of discharge sites and quantities of brine discharged, it seems unlikely that brine discharges are responsible for the loss of large areas of seagrass beds reported in Laguna Madre.

Dredged Material

Mackin (1961) described the relationship of turbidity and water depth during open water disposal operations in a shallow Louisiana bay. Turbidities were high during initial placement and prior to emergence of the dredged material above water level but after the deposit became

subaerial, turbidities were greatly reduced in water surrounding the placement area. Other studies have also shown that turbidities associated with dredging rapidly return to ambient conditions shortly after disposal operations cease. Windom (1975) describes some of the geochemical aspects of dredging such as the sequestering of heavy metals and later release to the estuarine environment.

After conducting an ecological survey of southern Laguna Madre shortly after initial dredging of the GIWW, Breuer (1962) reported that *Ruppia* preferentially colonized the marginal shoals surrounding natural islands and the islands of dredged material. He also reported that *Halodule* and *Ruppia* increased in areal extent and density between 1955 and 1961 in the vicinity of Mansfield Channel. Hunter and Hill (1973) recognized that some islands of dredged material are systematically colonized for long periods by seagrasses in lagoonal areas that otherwise would be barren. They mapped the floor of northern Laguna Madre near South Bird Island from placement area 184 to 191, and reported that the islands of dredged material, including high-use areas such as 187, were vegetated by *Halodule, Halophila,* and *Ruppia*. Merkord (1978) also reported that in relatively deep, unvegetated areas of the lagoon, seagrasses were growing on islands of dredged material that had shoaled the water depths to less than one meter. These seagrasses did not exist before deposition of the dredged material because the lagoon waters at the site were too deep to allow sufficient light penetration. Circe (1980) described the physical and biological zonations of seagrasses around disposal sites and how original seagrasses in deeper parts of northern Laguna Madre colonized adjacent mounds of dredged material.

Natural low gradients of the lagoon floor and associated water depths control the dense, moderately dense, and sparse zones of aquatic vegetation. Changes from one density to another or to the barren lagoon floor are gradual and there are no sharp boundaries separating the different conditions. Concentric patterns formed by seagrasses around the shoals and abrupt changes from dense grass to barren sediment reflect multiple disposal events.

CONCLUSIONS CONCERNING LAGUNA MADRE

Considering long-term annual average rates of sediment flux in Laguna Madre, the total volume of new sediment introduced by eolian, fluvial, tidal, and washover processes is substantially less than the volume dredged from the GIWW (Table 1). This means that the primary source of shoal material in the GIWW is internal reworking within the lagoon. Furthermore, the average sedimentation rate in Laguna Madre is less than the rate of relative sea-level rise. This condition coupled with erosion of the western shore indicates that the lagoon is slowly migrating westward rather than filling up as some have suggested.

Comparison of cumulative volumes of sediment dredged from representative segments of the GIWW in both northern and southern Laguna Madre with volumes of sediment remaining in the placement areas demonstrates that reworking of dredged material is controlled by water depth and location with respect to the predominant wind-driven currents. Reworking is minimized where dredged material is placed on flats that are either flooded infrequently or where the water is extremely shallow. In contrast, nearly all of the dredged material in relatively deep-water placement areas is reworked and either transported back into the GIWW or dispersed into surrounding areas of the lagoon. Our inclusion of in situ sediment densities, water contents, and void ratios in the volumetric calculations improved the accuracy of the quantitative evaluation and provided unequivocal evidence that the observed volumetric losses in the placement areas are primarily the result of sediment erosion and not post-emplacement sediment compaction. Comparison of sediment textures in the placement areas with those of natural sediments of the surrounding lagoon floor indicate that much of the dredged material remaining in the placement areas is a residual of initial channel construction.

In Laguna Madre, the greatest reworking of dredged material occurs where the GIWW crosses transition zones between the shallowest and deepest portions of the lagoon. The degree of reworking is directly related to water depth and to the surface area of dredged material exposed to waves and currents. On the flats of Kenedy County and across the broad shoals of Laguna Madre, reworking of dredged material is minimal, but reworking increases as water depth and the surface area increase. In northern Laguna Madre, reworking of dredged material is greatest in the transition zones south of South Bird Island (PA 186-195) and north of the Middle Ground shoal to Baffin Bay (PA 198-202). In southern Laguna Madre, there are three transition zones where reworking is significant: (1) immediately south of the Kenedy County flats near Rincon de San Jose (PA 211-213), (2) north of the Arroyo Colorado shoal area and south of Port Mansfield (PA 221), and (3) south of the Arroyo Colorado shoal area in the vicinity of Port Isabel (PA 233-236). Changes in size and morphology of the placement sites is abrupt between placement areas 170-171, 185-186, 201-202 and 221-22, whereas changes in physical characteristics are more gradual between placement areas 210-211, and south of the Arroyo Colorado channel (PA 233).

The volume of material dredged when the waterway was originally constructed decreased where water depth in the Laguna increased. Most of the sediments that were dredged from the channel in deeper parts of the lagoon formed a subaqueous platform and only a minor volume formed the subaerial islands. The relatively large volume of submerged dredged material in deeper water is continuously exposed to waves and currents that tend to resuspend and transport sediment, whereas subaerial deposits on the flats and across the shoals are less frequently inundated and subjected to reworking by water.

Reworking and redistribution of dredged material is greatest on the GIWW side of the placement areas as a result of water masses moving in Laguna Madre parallel to the GIWW that are coupled with more focused flow in the channel. All placement areas with high shoaling rates also contain or are near a bend in the GIWW and within a zone of flow expansion. The lack of well developed spits on the islands of dredged material, except those ephemeral features formed after initial channel construction, indicate that reworking is primarily by resuspension and the resuspended sediments are transported away from the islands. Seagrasses stabilize the lagoon floor reducing the local generation of suspended sediments, but sediments are still reworked from the margins of the islands where seagrasses are not present. Sedimentation rates generally are higher in seagrass beds because they extract suspended sediments from adjacent barren areas and retain biogenic detritus produced within grass beds.

When the islands of dredged material were first constructed, the wind was responsible for the greatest reworking of large subaerial deposits. This eolian reworking was important for a few years after initial emplacement because the sediments were exposed and dry during the drought of the early and mid 1950s. Eventually the winnowing action formed a lag of coarse sediments (rock fragments and shell) and vegetation became established, both of these conditions essentially terminated significant eolian reworking of the dredged material.

There is no compelling evidence that regional decreases in seagrass distribution in southern Laguna Madre were related to discharge of drilling fluids or produced formation water associated with petroleum exploration and production. Less certain is the change in land-use practices for the agricultural and industrial development bordering Laguna Madre. Although there has not been a significant change in the volume of sediment entering the lagoon from upland areas, this study did not address the potential changes in water and sediment quality related to runoff and effluent discharge.

Evaluation of several experimental designs in the high maintenance placement areas (PA 233-234) of southern Laguna Madre suggest that none of the designs (shallow subaqueous mound, submerged levee, emergent levee) was successful in retaining large volumes of dredged material. Of the three experimental methods tested, the emergent levee design provided the greatest retention potential approximately two years after construction. Attempts to construct seagrass beds using dredged material were unsuccessful in PA 233 and 234 primarily because the muddy substrates are unstable and turbidities are high. Conditions are more favorable for successful construction of seagrass beds in northern Laguna Madre and the northern part of southern Laguna Madre where substrates are sandy, turbidities are relatively low, and fringes of dredged material islands naturally have been colonized by seagrasses.

REFERENCES

Amdurer, M., 1978, Geochemistry, hydrology, and mineralogy of the Laguna Madre Flats, South Texas: MS thesis, University of Texas at Austin, 172 p.

Andrews, P. B., 1964, Serpulid reefs, Baffin Bay, southeast Texas *in* Depositional environments, south-central Texas coast: Gulf Coast Association of Geological Societies, field trip guidebook, p. 101–120.

Andrews, P. B., 1970, Facies and genesis of a hurricane washover for St. Joseph Island, Central Texas Coast: The University of Texas at Austin, Bureau of Economic Geology Report of Investigations 67, 147 p.

Armstrong, H. W., Fucik, K, Anderson, J. W., and Neff, J. M., 1979, Effects of oilfield brine effluent on sediments and benthic organisms in Trinity Bay, Texas: Marine Environmental Research, v. 2, p. 55–69.

Atturio, J. M., Basco, D. R., and James, W. P., 1976, Shoaling characteristics of the Gulf Intracoastal Waterway in Texas: Texas A&M University Sea Grant, TAMU-SG-76-207, 93 p.

Bailey, T. W., 1933, Padre Island: Texas Highway Department Rept. Sept. 11, 1933, Corpus Christi District Office.

Barnes, 1980, Coastal lagoons - the natural history of a neglected habitat: Cambridge University Press, Cambridge, 106 p.

Bassi, D. E., and Basco, D. R., 1974, Field study of an unconfined spoil disposal area of the Gulf Intracoastal Waterway in Galveston Bay, Texas: Texas A&M University, TAMU-SG-74-208, 74 p.

Behrens, E. W., 1963, Buried Pleistocene river valleys in Aransas and Baffin Bays, Texas: University of Texas, Publications of the Institute of Marine Science, v. 9, p. 70–18.

Behrens, E. W., 1964, Oolite formation in Baffin Bay and Laguna Madre, Texas, *in* Depositional environments, south-central Texas coast: Gulf Coast Association of Geological Societies, field trip guidebook, p. 82–100.

Boker, T. A., 1956, Sand dunes on northern Padre Island, Texas: MS thesis, University of Kansas, 100 p.

Breuer, J. P., 1957, An ecological survey of Baffin and Alazan Bays, Texas: The University of Texas at Austin, Publication of the Marine Science Institute, v. 4, p. 134–155.

Breuer, J. P., 1962, An ecological survey of the lower Laguna Madre of Texas, 1953-1959: The University of Texas at Austin, Publication of the Marine Science Institute, v. 8, p. 153–183.

Britton, J. C., and Morton, B., 1989, Shore ecology of the Gulf of Mexico: University of Texas Press, Austin, 287 p.

Brown, C. A., and Kraus, N. C., 1996, Environmental monitoring of dredging and processes in lower Laguna Madre, Texas: Conrad Blucher Institute for Surveying and Science, Texas A&M Corpus Christi, Report prepared for the Galveston District Corps of Engineers, 109 p.

Brown, L. F. Jr, Morton, R. A., McGowen, J. H., Kreitler, C. W., and Fisher, W. L., 1974, Natural hazards of the Texas coastal zone: The University of Texas at Austin, Bureau of Economic Geology, 20 p.

Brown, L. F. Jr, Brewton, J. L., McGowen, J. H., Evans, T. J., Fisher, W. L., and Groat, C. G., 1976, Environmental geologic atlas of the Texas coastal zone - Corpus Christi area: The University of Texas at Austin, Bureau of Economic Geology, 140 p.

Brown, L. F. Jr, McGowen, J. H., Evans, T, J., Groat, C. G., Fisher, W. L., 1977, Environmental geologic atlas of the Texas coastal zone - Kingsville area: The University of Texas at Austin, Bureau of Economic Geology, 140 p.

Brown, L. F., Jr., Brewton, J. L., Evans, T. J., McGowen, J. H., White, W. A., Groat, C. G., and Fisher, W. L., 1980, Environmental geologic atlas of the Texas coastal zone - Brownsville-Harlingen area: The University of Texas at Austin, Bureau of Economic Geology, 140 p.

Brownsville Navigation District, 1983, Dust control and development of recreational areas, San Martin and Bahia Grande areas, lower part of Cameron County, Texas: Report prepared for National Oceanic and Atmospheric Administration, Grant Nos. 81-AA-D-CZ029P and CZ-81M295010, alpha-numeric pagination.

Burr, J. G., 1930, Sail down the laguna: Texas Game Fish and Oyster Commission Yearbook, conservation of Wildlife 1929-1930, Austin, Tx, p. 54–58.

Burrell, D. C., and Schubel, J. R., 1977, Seagrass ecosystem oceanography, *in* C. P. McRoy and C. Helfferich, eds., Seagrass Ecosystems, A Scientific Perspective: Dekker, New York, p. 195–232.

Buzan, D., 1996, Report on a case of sedimentation in the lower Laguna Madre: Texas Parks and Wildlife Department, Austin Tx., 10 p.

Cargill, K. W., 1983, Procedures for prediction of consolidation in soft fine-grained dredged material: U.S. Army Corps of Engineers, Waterways Experiment Station, Technical Report D-83-1, 96 p.

Cargill, K. W., 1985, Mathematical model of the consolidation/desiccation processes in dredged material: U.S. Army Corps of Engineers, Waterways Experiment Station, Technical Report D-85-4, 68 p.

Circe, R. C., 1980, A seasonal study of seagrass colonization at a dredged material disposal site in upper Laguna Madre, Texas: MS thesis, Corpus Christi State University, 62 p.

Collier, A., and Hegpeth, J. W., 1950, An introduction to the hydrography of tidal waters of Texas: The University of Texas at Austin, Publication of the Marine Science Institute, v. 1, p. 125–194.

Copeland, B. J., Thompson, J. H., and Ogletree, W. B., 1968, Effects of wind on water levels in the Texas Laguna Madre: Texas Journal of Science, v. XX, p. 196–199.

Dallas Morning News, 1971, Texas Almanac, 1972-1973, A. H. Belo Corporation, 704 p.

Dallas Morning News, 1997, Texas Almanac, 1998-1999, The Dallas Morning News, Inc., Dallas, Texas, 672 p.

Das, B. M., 1990, Principles of geotechnical engineering: PWS-KENT Publishing, Boston, 665 p.

Davis, J. R., 1983, Intensive survey of the Arroyo Colorado segment 2201: Texas Department of Water Resources, IS-49, 43 p.

Davis, J. R., 1985, Intensive survey of the Arroyo Colorado segment 2201: Texas Department of Water Resources, IS-69, 41 p.

Davis, J. R., Kleinsasser, L. J., and Cantu, R., 1995, Toxic contaminants survey of the lower Rio Grande, lower Arroyo Colorado, and associated coastal waters: Texas Natural Resource Conservation Commission, Report AS-69, 127 p.

DiGeorge, F. P., and Herbich, J. B., 1978, Laboratory determination of bulking factors for Texas coastal fine-grained materials: Texas A&M University Center for Dredging Studies, Report 218, 94 p.

Dortch, M. S., ed., 1990, Methods of determining the long-term fate of dredged material for aquatic disposal sites: U.S. Army Engineers Waterways Experiment Station, Technical Report D-90-1, 157 p.

Duke, J. H., 1990, Upper Laguna Madre modeling study in the vicinity of the John F. Kennedy Causeway, Corpus Christi, Texas: contract report prepared for the Texas General Land Office, 67 p.

Dunton, K. H., and Kaldy, J. E., 1997, Factors controlling the success of seagrass revegetation in the lower Laguna Madre, Texas: University of Texas at Austin, Marine Science Institute contract report prepared for the U.S. Environmental Protection Agency, Gulf of Mexico Program, 70 p.

Eleuterius, L. N., and Miller, G. J., 1976, Observations of seagrasses and seaweeds in Mississippi Sound since Hurricane Camille: Journal of Mississippi Academy of Science, v. 21, p. 58–63.

Emery, K. O., 1961, A simple method of measuring beach profiles: Limnology and Oceanography, v. 6, p. 90–93.

Espey, Huston & Associates, Inc., 1976, A study of the placement of materials dredged from Texas ports and waterways: Report prepared for the Texas General Land Office, v. 1, variously paginated.

Fisk, H. N., 1949, Geological investigation of the Laguna Madre flats: Humble Oil and Refining Company, Houston, Texas, 152 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.

Freeman, T., 1962, Quiet water oolites from Laguna Madre, Texas: Journal of Sedimentary Petrology, v. 32, p. 475–483.

Fulton, K. J., 1975, Subsurface stratigraphy, depositional environments, and aspects of reservoir continuity - Rio Grande delta, Texas: Ph.D. dissertation, University of Cincinnati, 314 p.

Galtsoff, P. S., 1954, Gulf of Mexico, its origin, waters, and marine life: U.S. Fish and Wildlife Fishery Bulletin 89, p. 604.

Gill, S. K., Hubbard, J. R., and Dingle, G., 1995, Tidal characteristics and datums of Laguna Madre, Texas: National Oceanic and Atmospheric Administration Technical Memorandum NOS OES 008, 57 p.

Gornitz, V., and Lebedeff, S., 1987, Global sea-level changes during the past century in Nummedal, D., Pilkey, O. H. Jr., Howard, J. D., eds, Sea-level fluctuation and coastal evolution: Society of Economic Paleontologists and Mineralogists Special Publication 34, p. 3–16.

Greiner, J. H., 1982, Erosion and sedimentation by water in Texas average annual rates estimated in 1979: Texas Department of Water Resources, Rept. 268, 145 p.

Grozier, R. U., Hahl, D. C., Hulme, A. R., and Schroeder, E. E., 1968, Floods from Hurricane Beulah in south Texas and northeastern Mexico, Sept.-Oct. 1967: Texas Water Development Board Report 83, 195 p.

Gudramovics, R., 1981, A geochemical and hydrological investigation of a modern coastal marine sabkha: MS thesis, Michigan State University, 107 p.

Gunter, G., 1945, Some characteristics of ocean waters and Laguna Madre: Texas Game and Fish, v. 3, p. 19–22.

Hansen, E. A., 1960, Studies of a channel through Padre Island, Texas: American Society of Civil Engineers, Journal of Waterways and Harbors Div., v. 86, p. 63–82.

Harper, D. E., Jr., 1986, A review and synthesis of unpublished and obscure published literature concerning produced water fate and effects: Report prepared for the Offshore Operators Committee, 135 p.

Hayes, M. O., 1967, Hurricanes as geological agents: case studies of Hurricanes Carla, 1961, and Cindy, 1963: The University of Texas at Austin, Bureau of Economic Geology, Report of Investigations 61, 54 p.

Hedgpeth, J. W., 1947, The Laguna Madre of Texas: Proceedings of 12th North American Wildlife Conference, p. 364–380.

Hellier, T. R., and Kornicker, L. S., 1962, Sedimentation from a hydraulic dredge in a bay: University of Texas at Austin, Publ. of Institute of Marine Science, v. 8, p. 212–215.

Herber, J. P., 1981, Sediments under Laguna Madre, Cameron County, Texas: MS thesis, University of Texas at Austin, 664 p.

Herbich, J. B., 1975, Engineering aspects of operation and maintenance of the Gulf Intracoastal Waterway in Texas: Texas A&M University TAMU-SG-15-202, p. 55–129.

Herbich, J. B., 1992, Handbook of dredging engineering: New York, McGraw Hill.

Hummel, G., and Kocurek, G., 1984, Interdune areas of the back-island dune field, North Padre Island, Texas: Sedimentary Geology, v. 39, p. 1–26.

Hunter, R. E., Watson, R. L., Hill, G. W., and Dickinson, K. A., 1972, Modern depositional environments and processes, northern and central Padre Island, Texas: Padre Island National Seashore Field Guide, Gulf Coast Association of Geological Societies, p. 1–27.

Hunter, R. E., and Hill, G. W., 1973, Bottom features and sediments of part of northern Laguna Madre, Texas: U.S. Geological Survey map, 1:24,000, open file report.

Hsu, S. A., 1973, Computing eolian sand transport from shear velocity measurements: Journal of Geology, v. 81, p. 739–743.

International Boundary and Water Commission, Water Bulletins.

Jahrsdoerfer, S. E., and Leslie, D. M., Jr., 1988, Tamaulipan brushland of the Lower Rio Grande Valley of South Texas: description, human impacts, and management options: U.S. Fish and Wildlife Service, Biological Report 88 (36), 63 p.

James, W. P., Giesler, G., DeOtte, R. and Masamichi, I., 1977, Environmental considerations relating to operation and maintenance of the Texas Gulf Intracoastal Waterway: Texas A&M University, TAMU-SG-78-204, 227 p.

Kier, R. S. and Fruh, E. Gus, no date, Methodology to evaluate alternative management policies: application in the Texas Coastal Zone, Transferability of the Methodology to the Lower Rio Grande Valley, Final Report for Research Applied to National Needs Program, National Science Foundation, Grant No. AEN74-13590-A01, and Office of the Governor of Texas, Interagency Agreement IAA: The University of Texas at Austin, Center for Research in Water Resources, variable pagination.

Kieslich, J. M., 1977, A case history of Port Mansfield, Texas: Coastal Engineering Research Center, General Investigation of Tidal Inlets Rept. 12, 66 p.

Kocurek, G., Townsley, M., Yeh, E., Havholm, K., and Sweet, M. L., 1992, Dune and dune-field development on Padre Island, Texas, with implication for interdune deposition and water-table controlled accumulation: Journal of Sedimentary Petrology, v. 62, p. 622–635.

Lockwood, Andrews & Newnam, 1959, Development report on fish passes and water interchange for the Upper Laguna Madre and Corpus Christi Bay, Coastal Texas: Report to the Texas Game and Fish Commission, 86 p.

Lockwood, M. G., and Carothers, H. P., 1967, Preservation of estuaries by tidal inlets: Am. Soc. Civil Engineers, Journal of Waterways and Harbors Division, WW4, p. 133–152.

Lohse, E, A., 1958, Mouth of Rio Grande and Buena Vista mudflat, in Sedimentology of South Texas: Corpus Christi Geological Society Annual Field Trip, p. 55–60.

Long, D. T., and Gudramovics, R., 1983, Major-element geochemistry of brine from the wind-tidal flat area, Laguna Madre, Texas: Journal of Sedimentary Petrology, v. 53, p. 797–810.

Lowry, R. L., Jr., 1959, A study of droughts in Texas: Texas Board of Water Engineers Bulletin 5914, 76 p.

Lyles, S. D., Hickman, L. E. Jr., and Debaugh H. A. Jr., 1988, Sea level variations for the United States, 1855-1986: U.S. Department of Commerce, NOAA-NOS, Rockville, Md, 182 p.

Mackin, J. G., 1961, Canal dredging and silting in Louisiana bays: The University of Texas at Austin Publication of the Institute of Marine Science, v. 7, p. 262–314.

Mackin, J. G., 1971, A study of the effect of oil field brine effluents on biotic communities in Texas estuaries: Texas A&M Research Foundation Project 735, Final report to Humble Oil & Refining Company, Amoco Production Company, and Texaco, Inc., 73 p.

Martin, J. H., 1979, A study of the feeding habits of the black drum in Alazan Bay and the Laguna Salada, Texas: Texas A&I University, Master's thesis, 104 p.

Masson, P. H., 1955, An occurrence of gypsum in southwest Texas: Journal of Sedimentary Petrology, v. 25, p. 72–77.

McBride, E. F., Honda, H., Abdel-Wahab, A. A., Dworkin, S., and McGilvery, T. A., 1992, Fabric and origin of gypsum sand crystals, Laguna Madre, Texas: Gulf Coast Association of Geological Societies Transactions, v. 42, p. 543–552.

McCoy, T. W., 1990, Evaluation of ground-water resources in the Lower Rio Grande Valley, Texas: Texas Water Development Board Report 316, 48 p.

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McGowen, J. H., et al., 1977, History and processes involved in development of South Padre Island, Laguna Madre and Los Bancos de en Medio: The University of Texas at Austin, Bureau of Economic Geology Report prepared for the Texas General Land Office IAC (76-77) 1244, 142 p.

Menzie, C. A., 1983, Diminishment of recruitment: a hypothesis concerning impacts on benthic communities: Marine Pollution Bulletin.

Merkord, G. W., 1978, The distribution and abundance of seagrasses in Laguna Madre of Texas: Texas A & I University Masters Thesis, 56 p.

Militello, A., and Kraus, N. C., 1994, Reconnaissance investigation of the current and sediment movement in the lower Laguna Madre between Port Isabel and Port Mansfield, Texas: Texas A&M University-Corpus Christi, Conrad Blucher Institute for Surveying and Science Report 94-04, 33 p.

Militello, A., Kraus, N. C., and Kite, R. D., 1996, Environmental monitoring of dredging and processes in upper Laguna Madre, Texas: Conrad Blucher Institute for Surveying and Science, Texas A&M Corpus Christi, Report prepared for the Galveston District Corps of Engineers, 110 p.

Miller, J. A., 1975, Facies characteristics of Laguna Madre wind-tidal flats *in* Ginsburg, R. N., ed., Tidal deposits: Springer-Verlag, New York, p. 67–73.

Minerals Management Service, 1989, Gulf of Mexico Sales 123 and 125: Central and Western Planning Areas, Draft Environmental Impact Statement: U.S. Department of the Interior, Gulf of Mexico OCS Region., variable pagination.

Morgan, M. D., and Kitting, C. L., 1984, Productivity and utilization of the seagrass *Halodule wrightii* and its attached epiphytes: Limnology and Oceanography, v. 29, p. 1066–1076.

Morton, R. A., 1978, Large-scale rhomboid bed forms and sedimentary structures associated with hurricane washover: Sedimentology, v. 25, p. 183–204.

Morton, R. A., 1979, Subaerial storm deposits formed on barrier flats by wind-driven currents: Sedimentary Geology, v. 24, p. 105–122.

Morton, R. A., 1993, Texas Barriers, *in* Davis, R. A., ed., Geology of Holocene Barrier Islands: Springer-Verlag, Berlin, p. 75–114.

Morton, R. A., and Garner, L. E., 1993, Geological investigation of the wind-tidal flat area, Kenedy County, Texas: The University of Texas at Austin, Bureau of Economic Geology Report prepared for the Texas Office of the Attorney General IAC (92-93)2170, 99 p.

Morton, R. A., and McGowen, J. H., 1980, Modern depositional environments of the Texas Coast: The University of Texas at Austin, Bureau of Economic Geology, Guidebook 20, 167 p.

Morton, R. A., and Price, W. A., 1987, Late Quaternary sea-level fluctuations and sedimentary phases of the Texas coastal plain and shelf, *in* Nummedal D., Pilkey O. H. Jr., Howard J. D. (eds) Sea-level fluctuations and coastal evolution: Soc. Econ. Paleontol. and Mineral. Spec. Publ. 34, p. 181–198.

Morton, R. A., and Pieper, M. J., 1975, Shoreline changes on Brazos Island and South Padre Island: The University of Texas at Austin, Bureau of Economic Geology, Geol. Circ. 75-2, 39 p.

Oppenheimer, C. H., 1963, Effects of Hurricane Carla on the ecology of Redfish Bay, Texas: Bulletin of Marine Science of the Gulf and Caribbean, v. 13, p. 59–92.

Onuf, C. P., 1994, Seagrasses, dredging and light in Laguna Madre, Texas, U.S.A.: Estuarine, Coastal and Shelf Science, v. 39, p. 75–91.

Osterkamp, W. R., and Toy, T. J., 1997, Geomorphic considerations for erosion prediction: Environmental Geology, v. 29, p. 152–157.

Paine, J. G., 1993, Subsidence of the Texas coast: inferences from historical and late Pleistocene sea levels: Tectonophysics, p. 445–458.

Price, W. A., 1933, Role of diastrophism in topography of Corpus Christi area, south Texas: Bulletin American Association of Petroleum Geologists, v. 17, p. 907–962.

Price, W. A., 1952, Reduction of maintenance by proper orientation of ship channels through tidal inlets: Proceedings 2nd Coastal Engineering Conference, p. 243–255.

Price, W. A., 1958, Sedimentology and Quaternary geomorphology of South Texas: Transactions Gulf Coast Association of Geological Societies, v. 8, p. 41–75.

Price, W. A., 1963, Physiochemical and environmental factors in clay dune genesis: Journal of Sedimentary Petrology, v. 33, p. 766–778.

Price, W. A., 1971, Environmental impact of Padre Isles development: Shore and Beach, v. 39, p. 4–10.

Price, W. A., and Gunter, G., 1943, Certain recent geological and biological changes in South Texas, with consideration of probable causes: Texas Academy of Science, v. 26, p. 138–156.

Price, W. A., 1968, Abatement of blowing salt conditions inland from Laguna Madre, Texas: Report prepared for the Coastal Bend Regional Planning Commission, Corpus Christi, Texas, unpaginated.

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Quammen, M. L., and Onuf, C. P., 1993, Laguna Madre - seagrass changes continue decades after salinity reduction: Estuaries, v. 16, p. 302–310.

Railroad Commission of Texas, 1997, Statewide rules for oil, gas and geothermal operations: Oil and Gas Division, 392 p.

Ricklis, R. A., 1993, A model of Holocene environmental and human adaptive change on the central Texas coast: Coastal Archaeological Studies Inc., 122 p.

Roach, R. W., Carr, R. S., Howard, C. L., and Cain, B. W., 1993, An assessment of produced water impacts in the Galveston Bay System, Draft Report: U. S. Fish and Wildlife Service, 51 p.

Rusnak, G. A., 1960a, Sediments of Laguna Madre, in: Shepard F. P., Phleger, F. B., and van Andel, T. J., eds., Recent sediments, Northwest Gulf of Mexico: American Association of Petroleum Geologists, Tulsa, Okla., p. 153–196.

Rusnak, G. A., 1960b, Some observations of recent oolites: Journal of Sedimentary Petrology, v. 30, p. 471–480.

Scoffin, T. P., 1970, The trapping and binding of subtidal carbonate vegetation in Bimini Lagoon, Bahamas: Journal of Sedimentary Petrology, v. 40, p. 249–273.

Shepard, F. P., 1953, Sedimentation rates in Texas estuaries and lagoons: American Association of Petroleum Geologists, v. 37, p. 119–134.

Shepard F. P., Phleger, F. B., and van Andel, T. J., 1960, Recent sediments, Northwest Gulf of Mexico: American Association of Petroleum Geologists, Tulsa, Oklahoma.

Shepard, F. P., and Rusnak, G. A., 1957, Texas bay sediments - Laguna Madre: Publication of the Institute of Marine Science, v. 4, p. 5–13.

Shideler, G. L., 1984, Suspended sediment responses in a wind-dominated estuary of the Texas Gulf coast: Journal of Sedimentary Petrology, v. 54, p. 731–745.

Shipley, R. S., 1991, Oil field-produced brines in a coastal stream: water quality and fish community recovery following long term impacts: The Texas Journal of Science, v. 43, p. 51–64.

Simmons, E. G., 1957, An ecological survey of the upper Laguna Madre of Texas: The University of Texas at Austin, Publication of the Marine Science Institute, v. 4, p. 156–200.

Simpson, R. H., and Lawrence, M. B., 1971, Atlantic hurricane frequencies along the U.S. coastline: National Oceanic and Atmospheric Administration, NOAA Technical Memorandum NWS SR-581, 15 p.

Smith, N. P., 1978, Intracoastal tides of upper Laguna Madre, Texas: Texas Journal of Science, v. 30, p. 85–95.

Solis, R., and Matsumoto, J., 1991, Simulation analysis of changes in flow exchange in the upper Laguna Madre with removal of portions of the John F. Kennedy Causeway: Texas Water Development Board, contract report prepared for the Texas General Land Office, unpaginated.

Stinson, J. E., 1977, Engineering criteria for dredged material disposal in upper Laguna Madre: MS thesis, Texas A&M University, 92 p.

Swanson, R. L., and Thurlow, C. L., 1973, Recent subsidence rates along the Texas and Louisiana coasts as determined from tide measurements: Journal of Geophysical Research, v. 78, p. 2665–2671.

Taylor, Windle, 1997, Letter and table listing permits, dates and volumes of produced water discharges into the Laguna Madre/Baffin Bay systems: Railroad Commission of Texas, Oil and Gas Division, September 18, 1997, to Bill White, Bureau of Economic Geology.

Texas Department of Water Resources, 1983, Laguna Madre estuary: A study of the influence of freshwater inflows: LP-182, 286 p.

Texas Water Commission, 1990, Waste load evaluation for the Arroyo Colorado in the Nueces-Rio Grande Coastal Basin, Segments 2201 and 2202 - Arroyo Colorado tidal and above tidal, Report WLE 90-04, 163 p.

Texas Water Development Board, 1991, Surveys of Irrigation in Texas—1958, 1964, 1969, 1974, 1979, 1984, and 1989: Texas Water Development Board Report 329, 124 p.

Thomas, L. P., Moore, D. R. and Work, R. C., 1960, Effects of Hurricane Donna on the turtle grass beds of Biscayne Bay, Florida: Bulletin of Marine Science of the Gulf and Caribbean, v. 10, p. 191–197.

U.S. Army Corps of Engineers, 1881, Annual report of Chief of Engineers, Improvement of Rivers and Harbors: House Executive Document 1, 46th Congress, 3rd Session, pt. 1, p. 176; pt. 2, p. 1272.

U.S. Army Corps of Engineers, 1919, Brazos Island, Texas: House Document 1710, 65th Congress, 3rd Session, 30 p.

U.S. Army Corps of Engineers, 1936, Annual report of Chief of Engineers, Improvement of Rivers and Harbors: p. 783–785.

U.S. Army Corps of Engineers, 1958, Review of reports on Gulf Intracoastal Waterway, tributary channel to Port Mansfield: Galveston District, 59 p.

U.S. Army Corps of Engineers, 1962, Report on Hurricane Carla, 9-12 September 1961: Galveston District Corps of Engineers, 29 p.

U.S. Army Corps of Engineers, 1968, Report on Hurricane Beulah, 8-21 September 1967. Galveston District Corps of Engineers, 26 p.

U.S. Army Corps of Engineers, 1971, Report on Long Island, Port Isabel, Texas - Dust control study: Galveston District Corps of Engineers, 25 p.

U.S. Army Corps of Engineers, 1981, Report on Hurricane Allen, 3-10 August 1980: Galveston District Corps of Engineers, 62 p.

U.S. Army Corps of Engineers, 1987, Confined disposal of dredged material: U.S. Army Engineers Waterways Experiment Station Engineer Manual EM 1110-2-5027.

U.S. Geological Survey, 1988-1991, Water Resources Data for Texas: Water Resources Division, Austin, Tx.

Vyas, Y. K., 1977, Erosion of dredged material islands due to waves and currents: Ph.D. dissertation, Texas A&M University, 202 p.

Wang, P., Kraus, N., and Heilman, D., 1996, Wind-blown sand transport at Packery Channel: Conrad Blucher Institute, Texas A&M University-Corpus Christi, progress report to Naismith Engineering, 19 p.

Ward, L. G., Kemp, W. M., and Boynton, W. R., 1984, The influence of waves and seagrass communities on suspended particulates in an estuarine embayment: Marine Geology, v. 59, p. 85–103.

Watson, R. L., 1989, Sedimentation rates Kenedy Ranch supratidal flats: Report prepared for the Kenedy Memorial Foundation, 20 p.

Weiner, S. P., 1982, Deposition and stratification of oblique dunes, South Padre Island: Transactions Gulf Coast Association of Geological Societies, v. 32, p. 521–525.

White, W. A., Morton, R. A., Kerr, R. S., Kuenzi, W. D., and Brogden, W. B., 1978, Land and water resources, historical changes, and dune criticality: Mustang and North Padre Islands, Texas: The University of Texas at Austin, Bureau of Economic Geology, Report of Investigations 92, 46 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, 145 p.

White, W. A., Calnan, T. R., Morton, R. A., Kimble, R. S., and Littleton, T. G., 1989, State 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.

Windom, H. L., 1975, Water-quality aspects of dredging and dredge-spoil disposal in estuarine environments, in Cronin, L. E., ed., Estuarine Research Vol. II, Geology and Engineering, Academic Press, New York, p. 559–571.

Zetler, B. D., 1980, Tides at Port Mansfield, Laguna Madre, Texas: Marine Geodesy, v. 4, p. 237–247.

Zingula, R. P., 1975, Effects of drilling operations on the marine environment, In Conference proceedings: environmental aspects of chemical use in well-drilling operations (May 1975, Houston, TX): Washington, DC, U. S. Environmental Protection Agency, Office of Toxic Substances.

Zupan, A-J. W., 1971, Surficial sediments and sedimentary structures: Middle Ground, Padre Island Texas: Texas A&M University, Department of Oceanography, Report 71-12-T, 71 p.

APPENDIX A

Piston Core Descriptions

| NUMBER: | 187 PC-1 | Core Type | Piston |
| LOCATION: | Northern Laguna Madre | WaterDepth | 0.66 |

Depth (cm)	Description
0-3	dark, slightly muddy sand, marine grass and roots
3-26	dark muddy sand
26-40	shelly sand, light tan, upward fining
40-50	dark, muddy sand
50-60	shelly sand
60-100	light gray/tan sand
100-103	light gray mud

| NUMBER: | 187 PC-2 | Core Type | Piston |
| LOCATION: | Northern Laguna Madre | WaterDepth | 1.32 m |

Depth (cm)	Description
0-5	dead grass roots; dark, shelly, organic, rich sand
5-11	mottled slightly shelly sand
11-15	mixed dark mud and shelly sand
15-24	shell broken and whole
24-31	sandy shell, light gray
31-39	gray, sandy mud
39-46	gray, sandy shell
46-54	gray, slightly shelly sand
54-69	gray, sandy shell

| NUMBER: | 187 PC-3 | Core Type | Piston |
| LOCATION: | Northern Laguna Madre | WaterDepth | 0.76 m |

Depth (cm)	Description
0-5	dense roots; dark, organic, rich, shelly sand
5-12	dark gray, shelly sand
12-17	shelly sand, light
17-19	shell fragments
19-22	shelly sand, light tan
22-27	shelly sand (more shell)
27-46	shelly sand
46-61	sand (little shell)
61-62	mud
62-98	sand and shell

NUMBER:	187 PC-4	Core Type	Piston
LOCATION:	Northern Laguna Madre	WaterDepth	1.22 m

Depth (cm)	Description
0-2	dark sand
2-18	dark gray sand, few shell fragments
18-21	gray, muddy, shelly sand
21-58	sandy shell and shelly sand

NUMBER:	187 PC-5	Core Type	Piston
LOCATION:	Northern Laguna Madre	WaterDepth	1.22 m

Depth (cm)	Description
0-2	grass and roots; dark sand and muddy sand
2-9	gray sand
9-18	gray mud
18-32	gray, shelly sand
32-38	gray sand, some shell
38-65	shell and sandy shell

NUMBER:	197 PC-1	Core Type	Piston
LOCATION:	Northern Laguna Madre	WaterDepth	0.28 m

Depth (cm)	Description
0-4	roots of grass
4-14	sandy shell
14-45	dark gray mud, burrowed with shell-filled burrows
45-59	sandy shell
59-66	dark gray mud
66-73	dark gray shelly mud
73-99	sandy shell
99-110	tan sand, some shell

NUMBER:	197 PC-2	Core Type	Piston
LOCATION:	Northern Laguna Madre	WaterDepth	0.38 m

Depth (cm)	Description
0-10	dark, organic, rich, shelly, muddy sand with some grass roots
10-20	dark gray mud with sand-filled burrows
20-32	dark gray, muddy, shelly sand
32-46	light gray, sandy shell
46-49	dark gray mud
49-58	sandy shell
58-66	dark gray mud
66-103	tan sandy shell

NUMBER:	197 PC-3	Core Type	Piston
LOCATION:	Northern Laguna Madre	WaterDepth	0.46 m

Depth (cm)	Description
0-6	dark gray mud/few shells, dense grass roots, minor burrows
6-20	gray sand
20-30	gray, shelly sand
30-37	gray sand
37-47	gray, slightly shelly sand
47-55	gray sand
55-116	tan, sandy shell

NUMBER:	197 PC-4	Core Type	Piston
LOCATION:	Northern Laguna Madre	WaterDepth	0.99 m

Depth (cm)	Description
0-3	dark gray, shelly sand
3-6	dark gray, sandy mud
6-9	dark gray, shelly mud
9-38	alternating laminations, sand and shelly sand
38-70	tan shelly sand
70-80	tan sand
80-86	gray mud
86-109	shelly sand

NUMBER: 197 PC-5   **Core Type** __Piston__

LOCATION: Northern Laguna Madre   **WaterDepth** 0.76 m

Depth (cm)	Description
0-4	brown shelly sand with dense roots and seagrass
3-7	dark gray muddy sand
7-20	shelly sand
20-32	alternating gray and tan sand
32-54	tan, slightly shelly sand
54-56	gray mud
56-69	tan shelly sand

NUMBER: 197 PC-6   **Core Type** __Piston__

LOCATION: Northern Laguna Madre   **WaterDepth** 0.38 m

Depth (cm)	Description
0-3	dark gray/brown muddy sand with dense roots of seagrass
3-11	gray slightly muddy sand
11-19	alternating laminations of tan sand and gray mud
19-26	shelly, sandy mud
26-28	shell
28-41	mottled tan and gray, shelly sand
41-47	sandy mud/ shell-filled burrows
47-50	tan shelly sand
50-54	gray mud
54-60	gray shelly sand
60-86	tan shelly sand
86-96	gray sand
96-100	light gray sand
100-115	burrowed, shelly sand

NUMBER: 202 PC-1   **Core Type** __Piston__

LOCATION: Northern Laguna Madre   **WaterDepth** 0.69 m

Depth (cm)	Description
0-48	soupy, organic rich, dark gray mud over sand in core
48-99	tan/gray sand
99-113	alternating thin sand and mud laminations
113-121	tan sand

NUMBER: 202 PC-2   **Core Type** _Piston_

LOCATION: Northern Laguna Madre   **WaterDepth** _0.23 m_

Depth (cm)	Description
0-15	gray, slightly muddy, shelly sand with roots
15-24	gray shelly sand
24-29	shells and rock fragments
29-37	gray sand
37-43	sandy shell
43-59	upward fining from sandy shell to shelly sand

NUMBER: 211 PC-1   **Core Type** _Piston_

LOCATION: Southern Laguna Madre   **WaterDepth** _0.38 m_

Depth (cm)	Description
0-14	gray sand (dredged material)
14-20	brown/gray sand with roots and few Mulinia shells
20-29	gray muddy sand
29-43	gray sand, mud-filled burrows
43-50	gray mud with few sand-filled burrows
50-56	tan sand
56-60	gray, slightly muddy sand
60-63	gray mud
63-66	tan mud
66-70	tan sand
70-103	gray mud/ few sand-filled burrows
103-116	alternating sand, mud, evaporite laminations

NUMBER: 211 PC-2   **Core Type** _Piston_

LOCATION: Southern Laguna Madre   **WaterDepth** _0.38 m_

Depth (cm)	Description
0-3	gray/brown sand with some shell and grass roots
3-7	gray/brown muddy sand (burrowed)
7-53	mixed green, gray, and brown sand and mud with caliche nodules
53-55	tan sand
55-65	dark gray mud with burrows
65-79	light gray mud with burrows
79-82	muddy sand, gray
82-86	dark gray mud
86-94	shelly sand
94-100	brown, gray mud
100-105	shelly sand
105-108	alternating mud and sand laminations
108-122	sand and shelly sand

NUMBER: 211 PC-4   **Core Type** Piston

LOCATION: Southern Laguna Madre   **WaterDepth** 0.38 m

Depth (cm)	Description
0-6	brown/gray, slightly shelly sand with roots and grass at top
6-37	brown/gray sand and shelly sand, shell increasess upward, burrowed
37-38	brown/gray mud
38-41	brown/gray sand
41-44	gray mud
44-47	alternating laminations of sand and mud
47-54	gray sand
54-61	gray mud, large sand-filled burrow
61-62	shelly sand
62-73	gray mud with sand laminations, burrowed
73-80	gray mud, burrowed
80-93	gray and brown sand with mud wedge (rip-up clasts)
93-93.5	light gray mud with carbonate
93.5-96	tan sand
96-96.5	gray mud
96.5-99	sand
99-102	gray mud with thin sand laminations
102-105	gray mud with thin sand laminations
105-108.5	gray mud with thin sand laminations
108.5-115	gray mud with thin sand laminations (sand left in red cap)

NUMBER: 221 PC-1   **Core Type** Piston

LOCATION: Southern Laguna Madre   **WaterDepth** 0.91 m

Depth (cm)	Description
0-12	sand and shelly sand upward fining
12-34	brown mud
34-37	gray mud
37-55	gray shelly sand
55-72	sand with mud laminations, gray
72-93	mud with sand and shell laminations
93-114	dark brown, red, and gray mud and mud clasts

NUMBER:	233 PC-1	Core Type	Piston
LOCATION:	Southern Laguna Madre	WaterDepth	0.36 m

Depth (cm)	Description
0-3	dark shelly, slightly muddy sand with dense roots, seagrass at top
3-16	upward fining sand and shelly sand
16-71	red, tan, and gray mottled clay, burrowed (dredged material)
71-86	gray mud
86-98	upward coarsening muddy sand and shelly sand
98-104	upward fining muddy, shelly sand and muddy sand
104-110	alternating sand and mud laminations
110-116	laminating mud, burrowed (sand-filled)
116-120	gray sand/ shell
120-128	burrowed mud/ with white laminations

NUMBER:	233 PC-2	Core Type	Piston
LOCATION:	Southern Laguna Madre	WaterDepth	0.84 m

Depth (cm)	Description
0-3	shelly sand, dark organic
3-27	gray, alternating sand and shelly sand
27-28	gray mud
28-35	upward fining shelly sand and muddy sand
35-45	gray muddy, shelly sand, burrowed with grass roots
45-58	alternating laminations, dark and light gray mud with sand, shell-filled burrow
58-90	alternating laminations of thick mud and thin sand, no shell
90-97	upward coarsening mud to sandy mud
97-119	muddy, shelly sand
119-122	gray mud
122-124	shelly, muddy sand

NUMBER:	233 PC-3	Core Type	Piston
LOCATION:	Southern Laguna Madre	WaterDepth	0.66 m

Depth (cm)	Description
0-3	dark, organic,slightly muddy sand, few shells
3-15	upward fining shelly, muddy sand
15-28	gray mud with sand-filled burrows
28-32	gray sand
32-50	gray sandy mud
50-56	alternating sand and mud laminations
56-58	gray mud
58-62	shell
62-63	gray mud
63-69	organic, rich shelly sand/ roots
69-74	shelly sand
74-85	laminations, alternating dark and light gray mud
85-87	shelly sand
87-107	gray laminations, mud
107-110	shelly sand
110-113	mottled mud, light and dark
113-125	muddy sand and sandy mud laminations

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NUMBER:	South Bird Island #1	Core Type	Piston
LOCATION:	Northern Laguna Madre	WaterDepth	

Depth (cm)	Description
0-63.5	light brown to medium gray, very well sorted, very fine sand; homogeneous; 1% shell fragments; wind-blown sand down to 63.5 and lagoonal sediments below
63.5-68.58	light-to-medium gray, muddy, shelly, fine sand; plant debris layer @ 64.77 cm looks like Halodule, homogeneous
68.58-85.09	light gray sandy shell; sand fine, well sorted; shell is fragmented; plant debris layer @ 71.12 cm, Halodule roots and leaves throughout
85.09-92.71	light gray to medium gray, slightly muddy, shelly, fine sand; homogeneous, with Halodule leaves and roots throughout
92.71-97.79	medium gray, massive mud; 1% plant debris; irregular contact with 2.54 cm relief

NUMBER:	South Bird Island #2	Core Type	Piston
LOCATION:	Northern Laguna Madre	WaterDepth	

Depth (cm)	Description
0-7.62	light gray, homogeneous, shelly, fine sand; Halodule roots and leaves abundant on upper surface
7.62-12.70	light-medium gray, slightly muddy and sandy shell; fine sand to granule-size fragments; roots and leaves of Halodule thoughout
12.70-33.02	light-medium gray, muddy, shelly, fine sand; mottled due to burrowing; has Halodule roots and leaves
33.02-35.56	light-medium gray, thin mud zone at top and bottom; irregular basal unit with 2.54 cm relief; shelly, muddy, homogeneous, fine sand between Halodule roots and leaves
35.56-43.18	light gray, 3.81 cm slightly shelly, fine sand; lower grades from sandy shell to shelly fine sand; mostly shell fragments from fine sand to granules
43.18-43.82	medium gray mud drape; Halodule roots and leaves
43.82-50.8	light gray, slightly shelly, fine sand; faintly paralleled laminations; no roots or leaves
50.8-51.44	medium gray, sandy; shell fragments; fine sand to granules
51.44-58.42	medium gray, fine sand; homogeneous/trace Halodule roots and leaves

NUMBER:	South Bird Island #3	Core Type	Piston
LOCATION:	Northern Laguna Madre	WaterDepth	

Depth (cm)	Description
0-45.72	slightly muddy, sandy shell fragments of sand granules; abundant Halodule roots and leaves (0-20.32 cm), 10.16-20.32 mud increases @ 29.21 cm; bed of sand, fragments of coarse shell may be coated grains down to 43.18 cm
43.18-45.72	shelly fine sand; homogeneous
45.72-48.26	sandy shell, fragments of sand-granules; 15% plant debris; homogeneous
48.26-54.61	medium gray, shelly, fine sand; Halodule roots and leaves
54.61-55.25	medium gray, sandy mud with Halodule roots and leaves
55.25-59.69	medium to light gray fine to coarse sand; coarse sand is shell; well-rounded, faint, parallel laminations; lower 1.27 cm contains 5% plant debris
59.69-71.12	light gray, sandy and shelly, fine sand, @ 61 cm zone of sandy shell, 66 cm sandy shell < 0.6 cm thick and faint parallel bed

NUMBER:	South Bird Island #4	Core Type	Piston
LOCATION:	Northern Laguna Madre	WaterDepth	

Depth (cm)	Description
0-6.35	brown-gray, massive shelly, fine sand; Halodule roots and plant debris
6.35-24.13	mottled burrow; light-medium gray, sandy shell fragments and sand granules, mixed with shelly, sandy mud mixed by burrowing
24.13-40.64	light gray, shell, fine sand; slightly muddy in upper 5.08 cm; shell fragments; fine sand granules
40.64-54.61	light gray, sandy shell fragments; fine sand granules; plant debris 5% in upper 5.08 cm/ lower 2.54 cm; Halodule roots and leaves
54.61-66.04	medium gray, shelly, muddy, fine sand; 1.27 cm shell zone @ 60 cm; 25% plant debris with uniform distribution
66.04-78.74	light-medium gray, shelly, fine sand; shell fragments; fine sand granules; 5% plant debris; contact gradational with underlying
78.74-88.90	medium gray, slightly shelly, fine sand; homogeneous; trace plant debris

NUMBER:	South Bird Island #5	Core Type	Piston
LOCATION:	Northern Laguna Madre	WaterDepth	

Depth (cm)	Description
0-8.89	brown-light gray, mottled, medium-gray, muddy shell; fine sand; shell fragments; plant roots 6.35 cm-8.89 cm Halodule
8.89-20.32	brown, light gray, shelly, fine sand; homogeneous; 5% plant in upper 12.7 cm
20.32-24.13	light gray sand, fine, slightly shelly/mud diaper 0.32-0.42 cm occur at bottom and top; inclined bed, rippled surface
24.13-30.48	light gray, slightly shelly, fine sand; coarse size fragments; mud clasts, dark gray, 0.64 cm
30.48-36.83	alternating medium gray mud and light gray sand; inclined beds; mud @ top 0.64 cm thick; 0.64 cm mud at bottom over rippled surface
36.83-45.72	light gray, slightly shelly, fine sand/ faint, inclined laminations
45.72-60.96	mud drape .64 cm, medium gray, graded from fine bottom, coarse sandy shell at top; granular mud clasts, medium gray-light green, medium gray-light brown @ bottom in horizontal zones
60.96-71.12	graded shelly, fine sand at base; sandy shell at top; fragments; 68.58 cm mud drape, medium gray
71.12-80.01	slightly shelly, fine sand with slightly muddy lamination at 74.93 cm, 0.64 cm thick
80.01-82.55	shelly, fine sand; shell fragments; fine sand granules
82.55-86.36	light gray, slightly shelly, fine sand; homogeneous
86.36-97.79	mud clast gravel; granules pebble-sized; angular to well-rounded, slightly shelly, fine sand in interstices

Number:	1A2	Core Type	Push
Location:	Wind tidal flat, Kenedy Co., Texas	Elevation	0.52 m

Depth (cm)	Description
0-2.5	mud with algal mat.
2.5-3.5	sand.
3.5-5	sandy mud.
5-5.8	sand.
5.8-8.3	sandy mud with interbedded sand.
8.3-12.8	muddy sand*.
12.8-14.4	laminated sand and mud; thin discontinuous evaporite laminae at 13.6; evaporite laminations at 13.9-14.
14.4-28.5	interbedded sand and mud; erosional surface on sand at 21.2.
28.5-31.5	sand with organic matter (root zone) from 28.5 to 30; contains discontinuous mud laminations; gypsum crystals at 31.
31.5-47.5	muddy sand*; evaporite mottles at 35-39 and 40.5-46; gypsum crystals at 41-43.5; shell at 47.
47.5-84	muddy sand with organic (root) mottles*; shell material at 49.8 and 51.5; evaporite mottles 48-56; evaporite zone 82.5-82.7; slightly laminated 82-84.
84-86.5	laminated sandy mud with interbedded sand; contains root mottles, shells, and organic laminations.
86.5-106	sand with laminated mud interbeds 87-88, 92.8-96,103-104, 104.5-106; evaporite mottles in sand 90-92.8; shell material at 95.5-104.
106-108.5	sand and shell and shell fragments; discontinuous laminated clay.
108.5-114	slightly laminated sand with shell and evaporite*, and discontinuous clay laminations.
114-124.5	laminated clay with interbedded sand; 114-119 very thin sand and organic material laminations; shell at 114.7-115.1.
124.5-126	sand, with shell layer at base.

APPENDIX B

List of Aerial Photographs Used

PA	Date	Type	Source
187	03/27/50	9 × 9 B&W	U.S. Department of Agriculture
187	02/04/56	15 × 15 B&W	U.S. Department of Agriculture
187	06/17/74	9 × 9 B&W	Texas Department of Transportation
187	06/75	B&W mosaic	Tobin Aerial Surveys
187	07/09/82	9 × 9 CIR	Texas General Land Office
187	12/07/85	9 × 9 CIR	Corps of Engineers
187	12/11/92	9 × 9 B&W	Texas Department of Transportation
197	03/27/50	9 × 9 B&W	U.S. Department of Agriculture
197	02/04/56	15 × 15 B&W	U.S. Department of Agriculture
197	06/17/74	9 × 9 B&W	Texas Department of Transportation
197	06/75	B&W mosaic	Tobin Aerial Surveys
197	07/09/82	9 × 9 CIR	Texas General Land Office
197	12/07/85	9 × 9 CIR	Corps of Engineers
197	04/22/92	9 × 9 Color	Williams-Stackhouse Inc.
197	12/11/92	9 × 9 B&W	Texas Department of Transportation
202	04/60	B&W mosaic	Tobin Aerial Surveys
202	02/25/61	9 × 9 B&W	U.S. Department of Agriculture
202	06/17/74	9 × 9 B&W	Texas Department of Transportation
202	06/75	B&W mosaic	Tobin Aerial Surveys
202	07/09/82	9 × 9 CIR	Texas General Land Office
202	12/07/85	9 × 9 CIR	Corps of Engineers
202	04/22/92	9 × 9 Color	Williams-Stackhouse Inc.
202	12/11/92	9 × 9 B&W	Texas Department of Transportation
211	04/60	B&W mosaic	Tobin Aerial Surveys
211	02/25/61	9 × 9 B&W	U.S. Department of Agriculture
211	08/23/74	9 × 9 B&W	Texas Department of Transportation
211	06/75	B&W mosaic	Tobin Aerial Surveys
211	07/09/82	9 × 9 CIR	Texas General Land Office
211	01/13/86	9 × 9 CIR	Corps of Engineers
211	04/22/92	9 × 9 Color	Williams-Stackhouse Inc.
211	12/11/92	9 × 9 B&W	Texas Department of Transportation
221	01/09/50	9 × 9 B&W	U.S. Department of Agriculture
221	11/01/50	9 × 9 B&W	U.S. Department of Agriculture
221	11/20/54	15 × 15 B&W	U.S. Department of Agriculture
221	04/60	B&W mosaic	Tobin Aerial Surveys
221	02/12/62	9 × 9 B&W	U.S. Department of Agriculture
221	08/23/74	9 × 9 B&W	Texas Department of Transportation
221	06/75	B&W mosaic	Tobin Aerial Surveys
221	07/09/82	9 × 9 CIR	Texas General Land Office
221	01/13/86	9 × 9 CIR	Corps of Engineers
221	12/11/92	9 × 9 B&W	Texas Department of Transportation
221	09/28/93	9 × 9 B&W	Texas Department of Transportation
233	12/10/39	index B&W	U.S. Department of Agriculture
233	11/25/50	9 × 9 B&W	U.S. Department of Agriculture
233	12/06/54	15 × 15 B&W	U.S. Department of Agriculture
233	01/60	B&W mosaic	Tobin Aerial Surveys
233	01/29/62	9 × 9 B&W	U.S. Department of Agriculture
233	08/23/74	9 × 9 B&W	Texas Department of Transportation
233	07/09/82	9 × 9 CIR	Texas General Land Office
233	01/13/86	9 × 9 CIR	Corps of Engineers
233	12/11/92	9 × 9 B&W	Texas Department of Transportation
233	03/08/93	9 × 9 B&W	Texas Department of Transportation

APPENDIX C

ANALYSIS AND MODELING OF
AEOLIAN SEDIMENT TRANSPORT
INTO THE LAGUNA MADRE

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Submitted to:

Bureau of Economic Geology
University of Texas at Austin

Robert Morton, Principal Investigator

10 June 1998

SUMMARY AND CONCLUSIONS

This project undertook the direct calculation of sediment loading to the Laguna Madre by wind-blown sediments from Padre Island. The approach was to formulate a mathematical model of sediment mobilization and transport by wind based on the present state of the theory of aeolian transport, and to apply this model with wind data from the barrier island environment of South Texas. The wind climatology of the study area was addressed and the predominant meteorological regimes establishing this climatology were reviewed. The project therefore entailed both data analysis and theoretical modeling; neither of these proved straightforward.

Two primary sources of wind data exist for South Texas: the long-term data logs of National Weather Service and military airport stations, available on the Airways data file of NCDC, and the more recent network of telemetering anemometer stations operated by the Texas Coastal Ocean Observation Network of CBI at Texas A&M University–Corpus Christi. The former are located inland from the coast and therefore are not reflective of the barrier island environment. The latter are distributed along the beachfront and back bays of the coast, but the records are spotty and there are a few data quality problems. Multivariate regression was applied to establish relations between these sets of data to allow synthesis of a long period of record for both the Upper and Lower Laguna Madre barrier island. Still there were major problems in transferring the inland data to the coast, especially in the Lower Laguna Madre, due to lengthy gaps in the data record. The synthetic records so constructed vary in their quality and reliability.

Generally, the region is dominated by onshore flow from the Gulf of Mexico, from the southeasterly quadrant, i.e., winds ranging from south to east, which maintains warm, moist, convectively unstable marine air over the South Texas area. This prevailing onshore flow is interrupted by synoptic disturbances in the westerlies, especially in winter, whose effect on the wind is to turn its direction to the north, from which quadrant the wind will be sustained as long as the midlatitude system is controlling, and to replace the marine air with drier continental air. The resulting climate of the area vacillates between temperate-midlatitudinal in winter and tropical in summer, according to whether it is dominated by either the continental airmasses brought to the area by midlatitude disturbances in the westerlies or by the warm, humid Gulf of Mexico airmass associated with the easterly trades.

Superposed on this synoptic-scale flow pattern is the daily seabreeze cycle, driven by the diurnal variation in density of the lower atmosphere resulting from the surface temperature differential of land and water. The seabreeze component of the wind turns clockwise ("veers") with a periodicity of 24 hours, and is best developed under quiescent conditions with large land-

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sea temperature differentials. Superposed on the onshore prevailing flow, it leads to a maximum in onshore component in late afternoon and a minimum in early morning.

The stress of the wind exerted on the barrier island surface mobilizes particles which are then transported with the wind by a combination of quasi-suspension in the airflow and near-inelastic collisions upon the surface, the latter dislodging additional particles in a cascade that markedly increases the rate of particle mobilization. Quantification of the operative processes involves combining planetary boundary layer dynamics (especially the constant stress layer, the lowermost 100 m or so of the atmosphere), particle aerodynamics, and physical observations into separate equations for saltation, applicable to sand-size particles, and suspension, applicable to dust (silts and clays). Equations for these transports were extracted from the literature and combined into a computational model for transport from a barrier island to a bay in the lee of the island. Inputs to these equations are wind speed and physical properties of the atmosphere and surface, including sediment properties.

The raw wind velocity includes random fluctuations due to gustiness, storms, and frontal passages, as well as diurnal variation due to the seabreeze. From the standpoint of determining long-term climatological sediment loading, much of this variability is irrelevant and obscures the more meaningful day-to-day variation as controlled by regional meteorology. Therefore, the wind velocity was pre-processed, to average out this hour-to-hour variation, before being input to the model by being subjected to a sliding 24-hr vector mean. The computer display EXHIBIT shows the time variation of wind at several key anemometer stations, as a vector display of the sliding mean and an instantaneous residual. The climatological analysis period was selected to be 1981-1997. For sediment transport calculations over this period, the hourly (averaged) wind data were subsampled at noon to create an input file of daily wind, from which daily sediment loads were computed. The daily loads so computed were then subjected to various statistical summary to characterize the long-term features of aeolian sediment loading to the bay.

The basic results of this study are summarized in Tables 13 and 14, displaying the average aeolian sediment loads to the Laguna Madre. Loads are reported in mean daily sediment volume transfer rates per unit length of barrier island (m^3/km/d). This can be converted to an approximate equivalent depth of sediment per unit time by dividing by the width of the lagoon (10 km). Several conclusions emerge from an examination of these results and the model runs that generated them:

(1)   The aeolian loads to both the Upper and Lower Laguna is substantial, about 82,000 and 25,000 m^3/km annually (equivalent volume of sediment in water), resulting in an equivalent annual rate of depth accumulation of 0.82 and 0.25 cm, respectively.

(2)   The unit sediment load to the Upper Laguna is about three times that of the Lower Laguna. This is due primarily to the more favorable orientation of the barrier island for the Upper Laguna, which is both wider (by a factor of 3) and is oriented more normal to the onshore windflow.

(3)   The sediment load to the Laguna is dominated by saltation of fine sands. The contribution of dust loading to the total sediment load is less than 1%.

(4)   The average annual cycle of loading is maximum in the late spring, as shown in Fig. 10 and minimum in winter. This is governed by the strength of the onshore flow, especially the larger speeds (since sediment transport responds nonlinearly to wind speed). The spring maximum is evidently due to the enhanced southerly winds in advance of spring frontal systems in combination with the seasonal strengthening of the onshore prevailing southeasterlies.
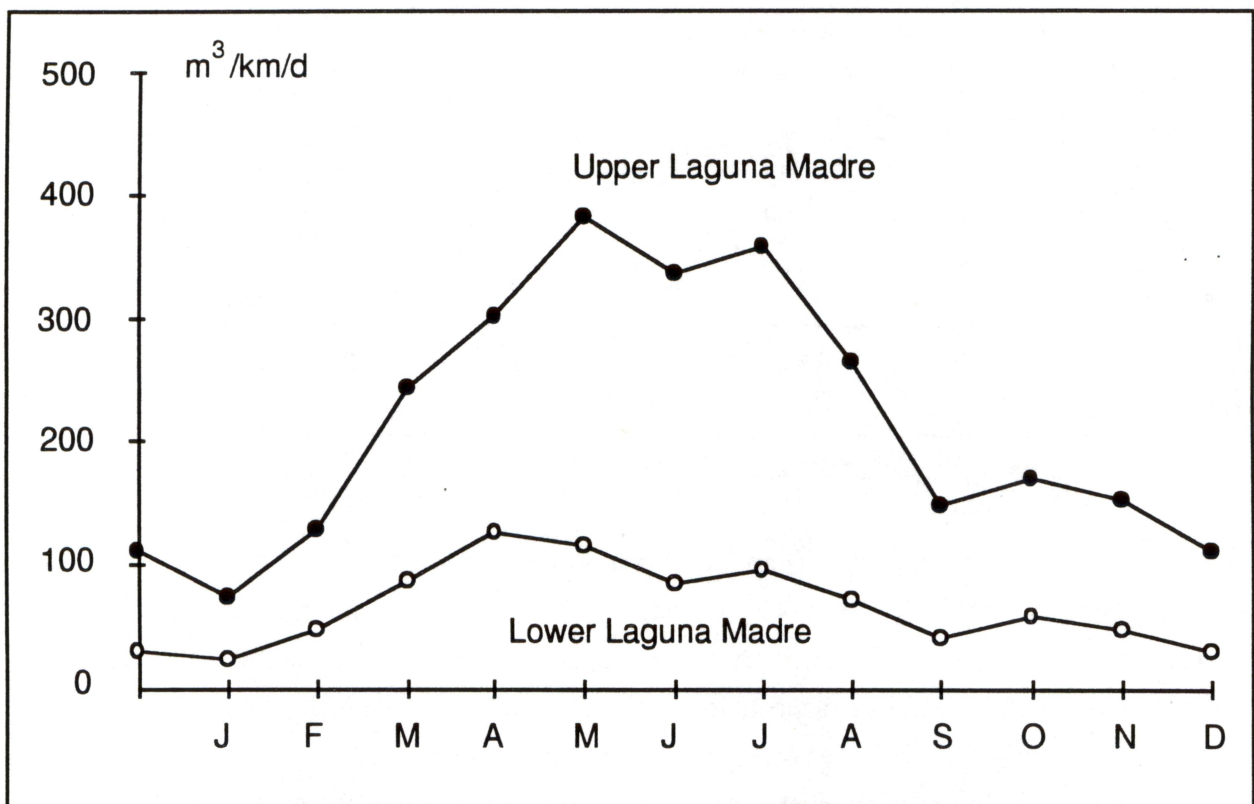

Figure 10 - Average annual variation of monthly-mean sediment loads

(5) On a year-to-year basis, there is little indication of a trend in sediment load over the 17-year period of the present analysis, as indicated in Fig. 11. The hint of an increasing trend in the Upper Laguna is primarily due to the position of the two outlying points of 1981 and 1996 in the time record. We accord no significance to this trend: the linear least-squares trend line explains less than 10% of the variance in the data.
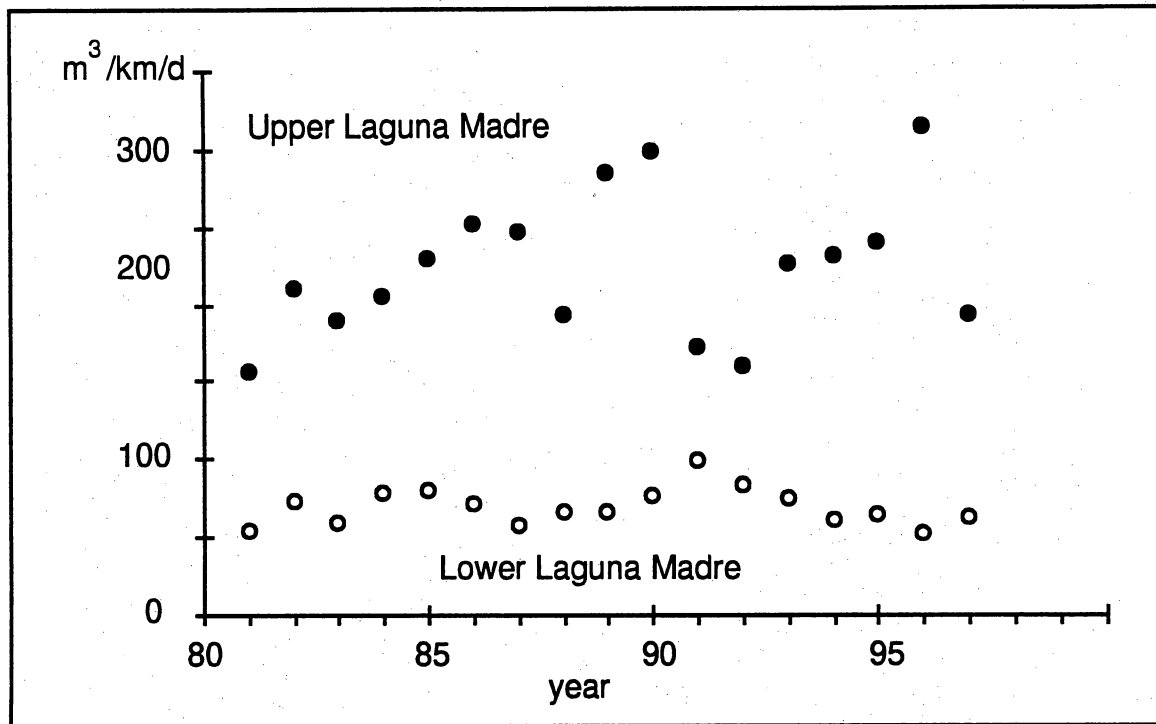
Figure 11 - Average annual-mean sediment loads for 1981-97 period

The model formulation and its application to Laguna Madre adopt a rather coarse-grained approach to the problem. While this is consistent with the limitations of the data and the objectives of closing a sediment budget of the Laguna on the largest scale, it is appropriate to note limitations of the analysis, aspects in which the model could be refined with additional work, and significant deficiencies for its application to the study area.

From the standpoint of the planetary boundary layer, the use of the neutral profile with a fixed roughness ignores effects of the dune field on wind and the substantial alterations in the wind field as it passes over the barrier island. Considering that dunes (ranging up to perhaps 10 m) are at least an order-of-magnitude smaller than the depth of the constant stress layer, this treatment should be adequate for determining bulk transports, which should be viewed as integrated over hundreds of meters in the horizontal and tens of meters in the vertical. This treatment is not, however, sufficiently detailed to resolve sorting of sand on the faces of dunes,

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destabilization of crests, or blow-outs. The greatest deficiency of the treatment of the planetary boundary layer is not, however, the model formulation but, rather, the record of wind data available by which to drive the model. More detailed evaluation of the TCOON wind data already archived should be carried out to improve the quality of the data record, by better-formulated screening algorithms, re-calibration of data sets, and detection and elimination of anomalous records. This effort was beyond the scope of the present study, but would greatly improve the confidence in the model application. Also, in the next couple of years, the TCOON data collection program will log additional data on the barrier island wind field that, together with data from the Airways stations, should greatly improve the applicability of sediment transport model to the Laguna Madre.

Both the saltation equations for sand and the suspension equations for dust involve empirical parameters that have been quantified in regions different from the South Texas coast. Generally, we regard the sand saltation model as the more secure of the two. The modelling of dust transport in suspension suffers from a paucity of good, solid field data, especially from arid, unvegetated regions. The extremely small values of dust loading to the Laguna computed here are somewhat lower than expected, but that expectation was not founded on any firm data.

In this context, the unpublished sediment transport study of CBI (Wang et al., 1996) should be mentioned, as it would appear to offer some direct measurements of transport with which the present work could be compared. In the CBI project, its staff installed a profile array of anemometers and a sand trap in the vicinity of Packery Channel and Newport Channel, apparently on the beach (though this is not entirely clear from the report). They measured transports averaging 438 m^3/km/d, ranging 82 - 850 m^3/km/d, in 23 measurements during the period April - May 1996. In comparison, the model computations of monthly mean transport for April and May 1996 in this study (see Table C-1 in the appendices) average 570 m^3/km/d.

At first blush, this would appear to validate the model results of this project. However, we regard this as a fluke. First, the CBI results are not strictly comparable to monthly mean data, since their 23 measurements all took place under windy conditions during daylight hours, while the model computations include calms and low-wind periods. Second, and much more importantly, the CBI field measurements are fundamentally flawed. The sand traps employed were 1.5 × 2.0 m trays of depth 20 cm. The horizontal dimensions of the trap were not large enough to intercept all of the saltating particles. Moreover, the trap was too shallow to prevent re-mobilization by wind gusts and loss of some of the sediment intercepted. At best, the trap data significantly underestimate the total transport. Indeed, when the aeolian transport model is operated with values of wind measured at 1 m by CBI, the predicted sand transport is about 4 times that inferred from the trap accumulations.

The aspect of the sand/dust transport model most needing research attention is mobilization from the surface. No account is made in the present theory of the distribution of particle sizes in the surface sediments or of the effects of water. The transport equations employ an average grain size, and there is no source sediment differentiation in estimating the empirical coefficients that enter these equations. Moreover, the assumption is made that the surface flux does not alter the sediments in the source, so processes of winnowing and armoring cannot be represented. Almost all of the data from which these relations were determined, both field and laboratory measurements, represent desiccated surfaces. The presence of moisture would increase the threshold of mobilization and reduce the flux into the lower atmosphere. Because such effects are not accounted for in the present model, the resulting transport rates probably overestimate those under conditions of a wetted surface or high humidity.

In the application to the Laguna Madre, a constant barrier island/bay geometry is assumed for the Upper and Lower systems. In principle, it would be possible to depict the variation in island and bay width, as well as island orientation, along the length of the Laguna. This resolution in detail would be meaningless, however. First, we have no solid information on the variation of wind field along the barrier island. Second, once the sediment enters the water it is moved laterally by circulations within the bay, so the differences in loading rates along the barrier island are smeared by the mixing processes within the water. Some regional differentiation could be probably be made if better information on the distribution of the wind field were to become available.

The influence of average sediment load on Laguna sediment accumulation must be interpreted cautiously. This is especially true of the equivalent depth accumulation rates given as the final entries in Tables 13 and 14. The aeolian sediment load will not enter the bay waters uniformly, but will accumulate preferentially in the back bay areas in the lee of the barrier island, and only gradually migrate into the remainder of the bay due to reworking by waves and currents. In the case of the Upper Laguna some, perhaps most, of the aeolian load will be trapped on the mud flats. Under seasonal high water, these sediments can be carried by currents from the flats into the adjacent Laguna waters. Under seasonal low water, especially during drought conditions in which the mud flats become desiccated, these sediments can be remobilized by wind. During the summer low-water stand, we can expect this wind transport to carry the sediments predominantly from the flats into the lagoon waters. During the winter low-water stand, the effect of northerly winds behind frontal passages will be to return some of the sediment back to the barrier island. Therefore, the monthly and annual sand transports of Tables 13, probably overestimate somewhat the actual total aeolian load to the Upper Laguna, since this additional interaction with the mud flats is not considered.

Table 13

Aeolian sediment load into Upper Laguna Madre
computed daily based on 24-hr noon-centered vector-mean wind
Summary statistics for period of record: 810101-971231

(a) Monthly mean load (m^3/km/d) of total (sand+dust) sediment

Month	sediment load	Month	sediment load
1	74	7	360
2	130	8	265
3	245	9	148
4	303	10	170
5	383	11	152
6	339	12	111

(b) Annual-mean total sediment load (m^3/km/d)

Year	sediment load	Year	sediment load
81	157	90	300
82	211	91	172
83	189	92	161
84	205	93	226
85	229	94	231
86	252	95	240
87	247	96	314
88	193	97	194
89	285		

Period-of-record mean sediment load =	223.9	m^3/km/d
Equivalent annual sediment load =	81710	m^3/km
Equivalent annual depth increment =	0.82	cm

Table 14

Aeolian sediment load into Lower Laguna Madre
computed daily based on 24-hr noon-centered vector-mean wind
Summary statistics for period of record: 810101-971231

(a) Monthly mean load ($m^3/km/d$) of total (sand+dust) sediment

Month	sediment load	Month	sediment load
1	23	7	96
2	48	8	72
3	87	9	42
4	126	10	59
5	117	11	49
6	85	12	30

(b) Annual-mean total sediment load ($m^3/km/d$)

Year	sediment load	Year	sediment load
81	53.6	90	76.5
82	73.7	91	98.8
83	60.0	92	83.0
84	78.0	93	74.4
85	80.5	94	61.7
86	71.4	95	65.0
87	57.1	96	53.1
88	66.4	97	62.6
89	67.2		

Period-of-record mean sediment load =	69.59	$m^3/km/d$
Equivalent annual sediment load =	25399	m^3/km
Equivalent annual depth increment =	0.25	cm