HISTORICAL MONITORING OF SHORELINE CHANGES IN CORPUS CHRISTI, NUECES, AND OSO BAYS

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Prepared for the
Texas Energy and Natural Resources Advisory Council
Division of Natural Resources
Under Contract No. IAC(82-83)-1342

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January 1983

TABLE OF CONTENTS

ABSTRACT 1

INTRODUCTION. 2

General Statement on Shoreline Changes 2

Related Studies 3

METHODS AND PROCEDURES 3

Sources of Data 4

Procedure. 4

Factors Affecting Accuracy of Data 5

Original Data. 5

Topographic Surveys. 5

Aerial Photographs 5

Interpretation of Photographs 6

Cartographic Procedure. 6

Topographic Charts 6

Aerial Photographs 7

Measurements and Calculated Rates 7

Justification of Method and Limitations 8

Sources and Nature of Supplemental Information 8

ORIGIN OF TEXAS BAYS 9

Late Pleistocene Sea-Level Highstand 9

Late Pleistocene Sea-Level Lowstand 12

Holocene Sea-Level Rise and Highstand 12

Sea-Level Changes 12

Sedimentation 14

TYPES OF SHORELINES 16
Unstabilized Shorelines 16
Clay Bluffs 16
Sandy Slopes 19
Marshes 19
Sand and Shell Beaches 19
Made Land 23
Stabilized Shorelines 23
Bulkheads and Seawalls 25
Riprap. 29
Beach Nourishment 31
FACTORS AFFECTING SHORELINE MOVEMENT 35
Climate 35
Sea-Level Position 37
Compactional Subsidence 37
Secular Variations 38
Sediment Supply 38
Sources 39
Sinks 42
Storm Frequency and Intensity 42
Human Activities 44
HISTORICAL CHANGES 46
Northern Corpus Christi Bay 48
1867 to 1930 50
1930 to 1982 50
1867 to 1982 53

Southern Corpus Christi Bay 53
Late 1800's to Early 1930's 53
Early 1930's to 1982 55
Late 1800's to 1982 56
Eastern Corpus Christi Bay 57
1867 to 1937 57
1937 to 1982 58
1867 to 1982 58
Oso Bay 59
1881-82 to 1934 59
1934 to 1982 60
1881-82 to 1982 61
Nueces Bay 61
Late 1800's to 1930 61
1930 to 1982 62
Late 1800's to 1982 63
CONCLUSIONS 63
ACKNOWLEDGMENTS 64
REFERENCES 65
APPENDIX A: Summary of Historical Changes 74
APPENDIX B: Tropical Cyclones Affecting the Texas Coast 80
APPENDIX C: Materials and Sources 81

Figures

1. Sea-level changes associated with expansion and contraction of continental glaciers 10
2. Generalized geologic map of the Corpus Christi area 11

3. Contour map of the late Pleistocene erosional surface beneath Corpus Christi Bay . . 13

4. Geographic locations and types of shorelines forming the margins of Corpus Christi, Nueces, and Oso Bays 15

5. High, nearly vertical clay bluffs of southern Corpus Christi Bay 17

6. Sandy slopes of eastern Oso Bay 20

7. Broad salt-water marshes of the Nueces delta, upper Nueces Bay 21

8. Low and narrow sand and shell beaches of Indian Point 22

9. Broad, low-lying flats composed of dredged material (mostly sand), southern Nueces Bay 24

10. Low concrete bulkheads backed by consolidated riprap and graded fill at Cole Park, southern Corpus Christi Bay 26

11. Storm-surge hydrographs for Hurricanes Carla, Beulah, Celia, and Allen recorded at Corpus Christi 27

12. Concrete riprap used as shoreline protection near Ward Island, southern Corpus Christi Bay 30

13. North Beach in 1974 before beach nourishment 32

14. North Beach in 1982 after beach nourishment 33

15. Profile of North Beach measured in 1978 and 1982 34

16. Interaction of factors affecting land losses 36

17. Total suspended sediment and discharge of the Nueces River at the Three Rivers Station (1928-1971) 41

18. Oyster-shell production in Nueces Bay from 1965 to 1974 45

19. Location of measuring points (stations) in Corpus Christi, Nueces, and Oso Bays . . 47

20. Distribution of accreting (A), stable (S), and eroding (E) linear shoreline segments for early (late 1800's to 1930's), late (1930's to 1982), and cumulative (late 1800's to 1982) periods 49

21. Net rates of change in shoreline position between the late 1800's and the 1930's . . 51

22. Net rates of change in shoreline position between the 1930's and 1982 52

23. Net rates of change in shoreline position between the late 1800's and 1982 54

Table

1. Maximum hurricane surge heights recorded near Corpus Christi Bay 1919 to 1982 . . 28

ABSTRACT

Changes in the position and stability of shorelines in Corpus Christi, Nueces, and Oso Bays since the late 1800's were documented using historical monitoring techniques. This is accomplished by comparing shorelines from topographic charts (dated 1867 to 1882) and aerial photographs (taken in 1930 to 1937 and 1982), measuring the magnitude (distance) of shoreline movement at specific sites, and calculating the rates of change for particular time periods (late 1800's to 1930's, 1930's to 1982, and late 1800's to 1982). Geological interpretations of the maps and photographs are used in conjunction with meteorological data and historical records to explain the important trends revealed in the tabulated shoreline data.

Unprotected sediments forming the margins of Corpus Christi, Nueces, and Oso Bays are subjected to natural processes and modified by human activities that together cause shoreline movement. These unstabilized shorelines include high clay bluffs, moderate slopes composed mainly of sand, salt-water marshes, sand and shell beaches, and newly formed areas filled by dredged material. Composition of the shoreline material and orientation of the shoreline with respect to prevailing wind directions and wave fetch largely determine the response and consequent movement of the shoreline. In some areas property owners have attempted to stabilize the shoreline and prevent further movement by building seawalls and bulkheads and using riprap to dissipate wave energy.

Factors contributing to shoreline changes include (1) regional and worldwide climate, (2) local changes in relative sea-level position, (3) local alterations in sediment supply, (4) storm frequency and intensity, and (5) human activities. Historical data compiled for these various factors indicate that warming temperatures, rising sea level, decreasing sediment supply, recurring severe storms, and ongoing human activities all favor continued erosion of exposed shorelines.

INTRODUCTION

Texas bays are fronted by both stable and unstable shorelines that together stretch for more than 3,300 mi. Field observations and regional mapping suggest that many of the shorelines are unstable and are retreating landward at rates ranging from a few feet to a few tens of feet per year. In some bays, biologically productive wetlands and other areas of State-owned natural resources are diminishing in size. The cumulative land areas removed through erosion at any time or over several decades are substantial and translate directly to significant economic losses. Furthermore, legal questions regarding ownership of property may arise because of shoreline movement, and public and private investments may be jeopardized and real property damaged or destroyed as shoreline positions change. Taken together, the individual and corporate losses are of sufficient magnitude to warrant investigation of shoreline movement.

Bay shoreline changes are attributable to both natural causes and human activities. Regardless of the cause, vast areas of land are being lost in some places and gained in others; accurate estimates of land losses and gains or their equivalent economic value are unavailable because bay shoreline changes have not been systematically investigated. The purpose of this study is (1) to quantify the significant shoreline changes that occurred near Corpus Christi during the past century, (2) to describe the physical processes that cause shoreline movement, and (3) to discuss the anticipated future changes on the basis of long-term historical records and present-day coastal conditions.

General Statement on Shoreline Changes

Shorelines are in a state of erosion, accretion, or are stabilized either naturally or artificially. Erosion produces a net loss in land, accretion produces a net gain in land, and equilibrium conditions produce no net change. Shorelines move in response to a hierarchy of natural cyclic phenomena including (from lower order to higher order) tides, storms, sediment supply, and relative sea-level changes. Time periods for these cycles range from daily to several thousand years. Most shoreline segments undergo both erosion and accretion for lower order events, no matter what their long-term trends may be. Furthermore, long-term trends can be unidirectional or cyclic; that is, shorelines may persistently either accrete or erode, or they may undergo periods of both erosion and accretion.

Related Studies

In 1971, the Bureau of Economic Geology initiated a program on historical monitoring of the Texas coast to identify and determine the long-term magnitude and rates of shoreline changes. The usefulness of historical monitoring is based on the location and quantification of past changes in shoreline position and the prediction of future changes.

Qualitative descriptions of shoreline stability for Corpus Christi, Nueces, and Oso Bays were presented on regional maps of a Texas Coastal Zone atlas (Brown and others, 1976) and an atlas of natural hazards of the Texas Coastal Zone (Brown and others, 1974); however, the bay shoreline along Mustang Island (White and others, 1978) is the only segment of Corpus Christi Bay that has previously been studied using historical monitoring techniques. Because the shoreline conditions published in the present report are updated and quantitative, they supersede the conditions presented in the previous publications.

METHODS AND PROCEDURES

Historical shoreline monitoring is the documentation of direction and magnitude of shoreline changes through specific time periods using accurate vintage charts, maps, and aerial photographs.

Sources of Data

Basic materials used to determine changes in shoreline position are individual near-vertical aerial photographs, photographic mosaics, and topographic charts (Appendix C). Accurate topographic charts dating from 1867, available through the U.S. Department of Commerce, National Oceanic and Atmospheric Administration (NOAA), were mapped by the U.S. Coast Survey using plane table procedures. Reproductions of originals are used to establish shoreline position (mean high water) before the early 1930's. Aerial photographs supplemented and later replaced regional topographic surveys in the early 1930's; therefore, subsequent shoreline positions are mapped on individual stereographic photographs and aerial photographic mosaics taken between 1930 and 1982. These photographs show shoreline position based on the sediment-water interface at the time the photographs were taken.

Procedure

The key to detecting shoreline movement is agreement of scale and projection between the original data and the selected map base; U.S. Geological Survey 7.5-minute quadrangle topographic maps (1:24,000, or 1 inch = 2,000 ft) are used for this purpose. Topographic charts and aerial photographs are either enlarged or reduced to the precise scale of the topographic maps. Shorelines shown on topographic charts and sediment-water interface mapped directly on sequential aerial photographs are transferred, mechanically with a reducing pantograph or optically with a Saltzman projector, from the topographic charts and aerial photographs onto the common base map. Lines transferred to the base map allow direct comparison and quantification of changes in shoreline position with time.

Factors Affecting Accuracy of Data

Original Data

Topographic surveys

Some inherent error probably exists in the original topographic maps prepared by the U.S. Coast Survey (now called National Ocean Survey). Shalowitz (1964) described the possible sources of error and the degree of accuracy of these maps. In general, the accuracy of a particular survey is related to its date; recent surveys are more accurate than older surveys. Error can also be introduced by physical changes in material on which the original data appear. However, chart distortions caused by reproduction and changes in atmospheric conditions are usually minor and can be corrected by cartographic techniques.

Aerial photographs

Use of aerial photographs of various scales introduces differences in resolution with concomitant differences in mapping precision. The sediment-water interface can be mapped with greater precision on larger scale photographs, whereas the same boundary can be delineated with less precision on smaller scale photographs. Fortunately, photographs with a scale equal to or larger than the topographic base map were available for this study.

Optical aberration causes the margins of photographs to be slightly distorted. To avoid this distortion only the central portion of the photographs was used for mapping purposes, and distances between fixed points within the center of the photograph were adjusted to the 7.5-minute topographic base.

Meteorological conditions before and during photography also affect the accuracy of documented shoreline changes. For example, deviations from normal astronomical tides caused by barometric pressure, wind velocity and direction, and attendant wave activity may introduce anomalies in shoreline positions. Most photographic missions, however, are flown during calm weather, thus minimizing the effects of abnormal meterological conditions.

Interpretation of Photographs

On a few photographs, both the beach and wave zone are bright white (albedo effect) and cannot be precisely differentiated; the shoreline is projected through these areas, and therefore, some error may have been introduced. In general, these difficulties were resolved through an understanding of coastal processes and a thorough knowledge of factors that may affect the appearance of shorelines on photographs.

Use of the mean high-water line on topographic charts and the sediment-water interface on aerial photographs to define the same boundary is inconsistent because the sediment-water interface normally falls somewhere between high and low tide. Horizontal displacement of the shoreline mapped using the sediment-water interface is almost always seaward of the mean high-water line. This displacement is dependent on the tidal cycle, slope of the beach, and wind direction when the photograph was taken. The low tide range (0.5 ft) and the narrow beach width along most of the Texas bay shorelines substantially reduces the potential difference between mean high water and the sediment-water interface.

The advantage of consecutive mapping of sediment-water interface is the internal consistency from one shoreline type to another, but a definite disadvantage is the underestimated bluff retreat in areas where a rapidly receding cliff is separated from the sediment-water interface by a horizontal distance of several hundred feet.

Cartographic Procedure

Topographic charts

The topographic charts include a one-minute grid, along with permanent geographic features, that can assist in transfering the shoreline from chart to base map. Where distortions in the material are present, routine adjustments were made across the map with the aid of the one-minute latitude and longitude cells.

Aerial photographs

Accuracy of aerial photograph mosaics is similar to topographic charts in that quality is related to vintage; more recent mosaics are more accurate. Photograph negative quality, optical resolution, and techniques of compiling controlled mosaics have improved with time; thus fewer adjustments are necessary when working with newer photographs.

Cartographic procedures may introduce minor errors associated with the transfer of shoreline position from aerial photographs and topographic charts to the base map. Cartographic procedures do not increase the accuracy of mapping; however, they tend to correct the photogrammetric errors inherent in the original materials, such as distortions and optical aberrations.

Measurements and Calculated Rates

Actual measurements of linear distances on maps can be made to 100th of an inch, which corresponds to 20 ft on maps with a scale of 1 inch = 2,000 ft (1:24,000). This is more precise than the significance of the data warrants. However, problems do arise when rates of change are calculated because: (1) time intervals between photographic coverage are not equal; (2) erosion or accretion is assumed constant over the entire time period; and (3) different rates can be obtained at any given point using various combinations of lines.

Perhaps the two most important assumptions made regarding rates of shoreline change are that (1) calculated rates of change are constant over a particular time period and (2) the direction or trend of shoreline change is also invariant over the same time period. If one or both of these assumptions are invalid, then the calculated rates tend to underestimate the actual rates of change.

The problems listed above are interrelated, and solutions require the averaging of rates of change for discrete time intervals. Tables, numerical ranges, and graphic displays can be used to illustrate shoreline changes, but the calculated rates should be used with caution and in context for several reasons. First, periods between mapped shoreline positions commonly were not equal. This may have introduced some sampling bias because of the inability to determine the optimum time interval: an interval that would include those periods when the true changes in shoreline position not only followed the same trend but also when shoreline changes happened at similar rates.

Secondly, the sampling technique commonly fails to show precisely when the reversals in trend occurred. If the trend remains unchanged, then it is still possible to detect variability in the rates of change (acceleration and deceleration), but when the trend reverses between two sequential periods, then the mid-date or date common to both periods is assumed to be the time of trend reversal.

Justification of Method and Limitations

As shown by the preceding discussion, the methods used in long-term historical monitoring may be slightly imprecise, hence trends and rates of shoreline changes determined from these techniques have limitations. Rates of change are to some degree subordinate in accuracy to trends or direction of change; however, there is no doubt about the significance of the trends of shoreline change documented over more than 100 yr.

Limitations of the method require that emphasis be placed first on trend of shoreline changes; rates of change are secondary. Although rates of change from map measurements can be precisely calculated well beyond the limits of accuracy of the procedure, they are most important as indicators or as relative values; that is, do the data indicate that changes are occurring at a few feet per year or at significantly higher rates?

Sources and Nature of Supplemental Information

Sources of aerial photographs, topographic charts, and topographic base maps used for this report are identified in Appendix C. Additional information was derived from miscellaneous reports published by the U.S. Army Corps of Engineers and on-the-ground measurements and observations, including beach profiles, prepared as a part of this investigation.

ORIGIN OF TEXAS BAYS

Texas bays owe their origin principally to the large-scale sea-level fluctuations (on the order of a few hundred feet) that occurred during the Quaternary Period in conjunction with repeated advance and retreat of great continental ice sheets (fig. 1). As the ice sheets grew, large volumes of water were stored as ice, causing a fall in sea level. Subsequent melting of the ice sheets released large volumes of water and caused the sea level to rise.

The Quaternary Period, which has been divided into the Pleistocene and Holocene Epochs, began 2 to 3 million yr ago with the onset of a major continental glaciation (sea-level fall). The Pleistocene lasted from the beginning of the Quaternary to approximately 18,000 yr ago and was characterized by several major glacial advances and retreats. The Holocene, spanning from the end of the Pleistocene to the present, is defined as the time since the peak of the last major glaciation. The Holocene has therefore been a time of sea-level rise. The term "Modern" is commonly used to refer to the last 5,000 yr, when the Holocene sea-level rise slowed considerably.

Late Pleistocene Sea-Level Highstand

Pleistocene fluvial and deltaic sediments cover much of the western part of the Corpus Christi area (fig. 2). These sediments were deposited in both marine and nonmarine environments (Brown and others, 1976), indicating sea level was near its present-day level at some time during the Pleistocene. There were at least three Pleistocene sea-level highstands related to major interglacial stages, and Wilkinson and others (1975) consider these Coastal Plain deposits to be contemporaneous with the last Pleistocene highstand, the Sangamon interglacial stage. If this correlation is correct, then these units were deposited approximately 150,000 to 200,000 yr before present.

The Pleistocene fluvial and deltaic deposits form the bluffs common in Corpus Christi, Nueces, and Oso Bays. These deposits are found at elevations greater than 10 to 15 ft above

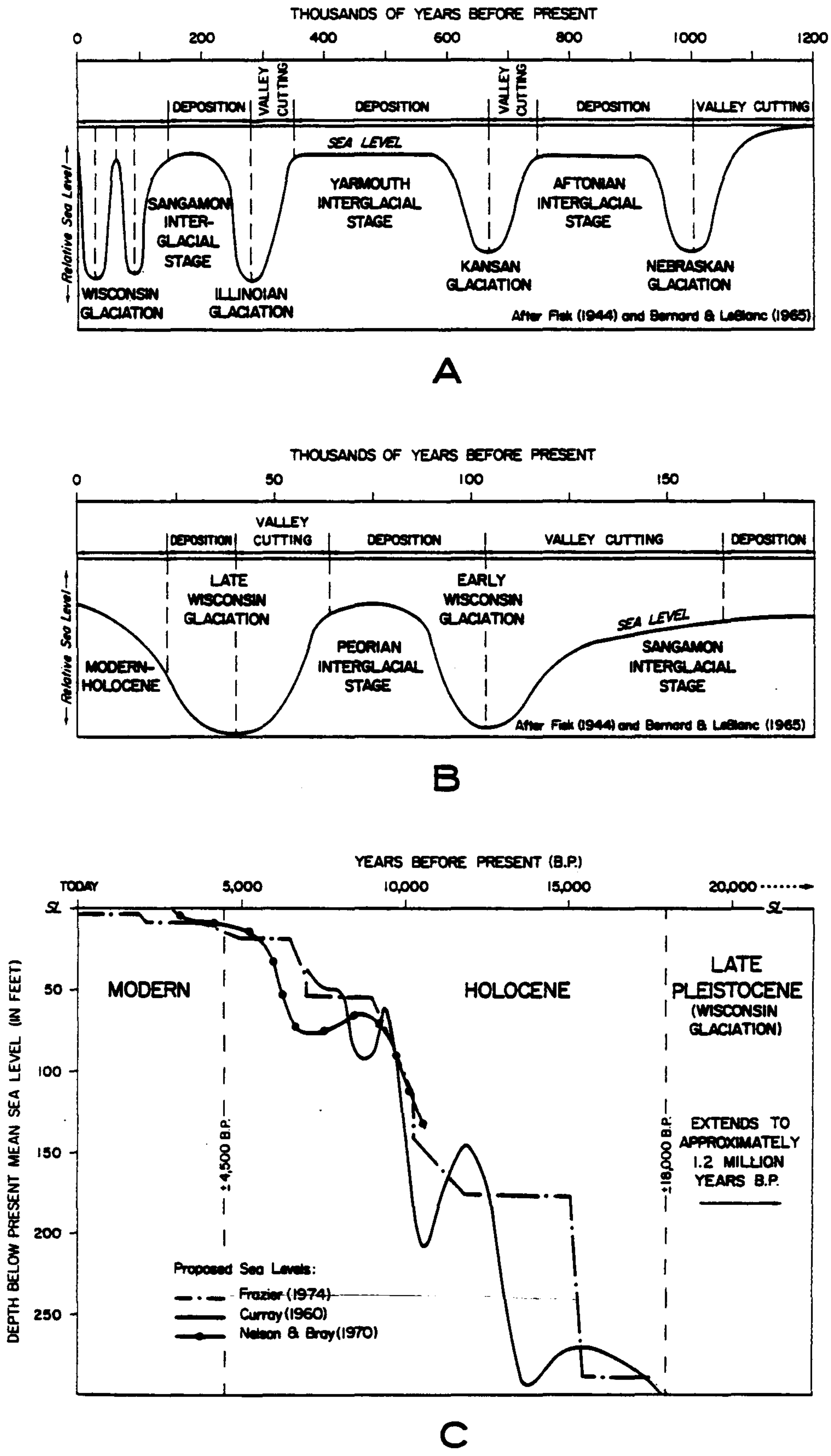

Figure 1. Sea-level changes associated with expansion and contraction of continental glaciers. (A) Generalized Pleistocene sea-level variations and attendant erosional and depositional episodes. (B) Generalized sea-level changes during Wisconsin glacial and interglacial stages. (C) Interpreted sea-level changes during the last 20,000 yr. From Brown and others (1976).

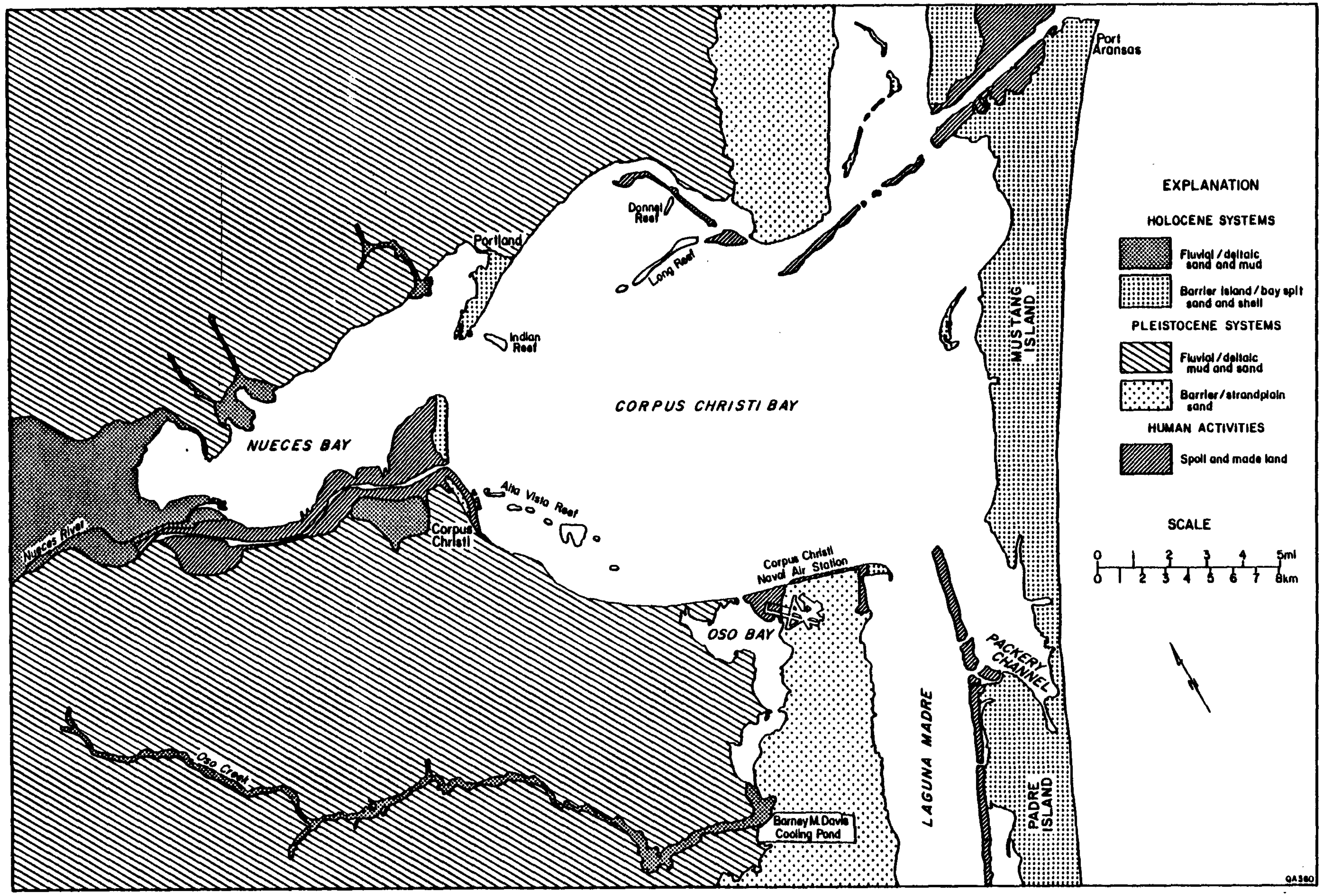

Figure 2. Generalized geologic map of the Corpus Christi area, modified from Brown and others (1976).

present sea level, and are predominantly composed of interdistributary mud with lesser amounts of distributary and fluvial sand and silt (Brown and others, 1976).

Late Pleistocene Sea-Level Lowstand

Another laterally extensive Pleistocene unit is the Ingleside barrier/strandplain system (fig. 2), composed almost entirely of sand. This unit has been interpreted as a barrier island/lagoon system (Price, 1958) and as a strandplain system with no continuous lagoon landward of the major sand body (Wilkinson and others, 1975).

After deposition of the Ingleside sand, sea level fell at the onset of the last major Pleistocene glaciation (late Wisconsin). Estimates of the magnitude of sea-level fall cluster near 400 ft below present sea level (LeBlanc and Hodgson, 1959; Curray, 1960; Frazier, 1974). This sea level fall caused the downcutting and entrenchment of rivers and streams in response to a lowered base level. Wright (1980) used cores and seismic reflection profiles to show that valleys of the ancestral Nueces River and tributaries were incised about 125 ft below present sea level (fig. 3).

Holocene Sea-Level Rise and Highstand

Sea-Level Changes

The last major glaciation began to wane about 18,000 yr ago, causing sea level to rise. The rise occurred at an average rate of about 2 to 3 ft per century, though it is clear that the rate was neither constant nor was sea level always rising (fig. 1). In fact, the Holocene sea-level rise was probably punctuated by several minor stillstands and reverses (Frazier, 1974; Wright, 1980).

About 5,000 yr ago, the rate of sea-level rise decreased (fig. 1). Estimates of rates of rise during the last 3,000 yr range from 1 to 5 inches per century (Flint, 1971); higher rates of change can be justified if fragmentary evidence for reversals in the global sea-level trend for this period is accepted (Froomer, 1980; DePratter and Howard, 1981).

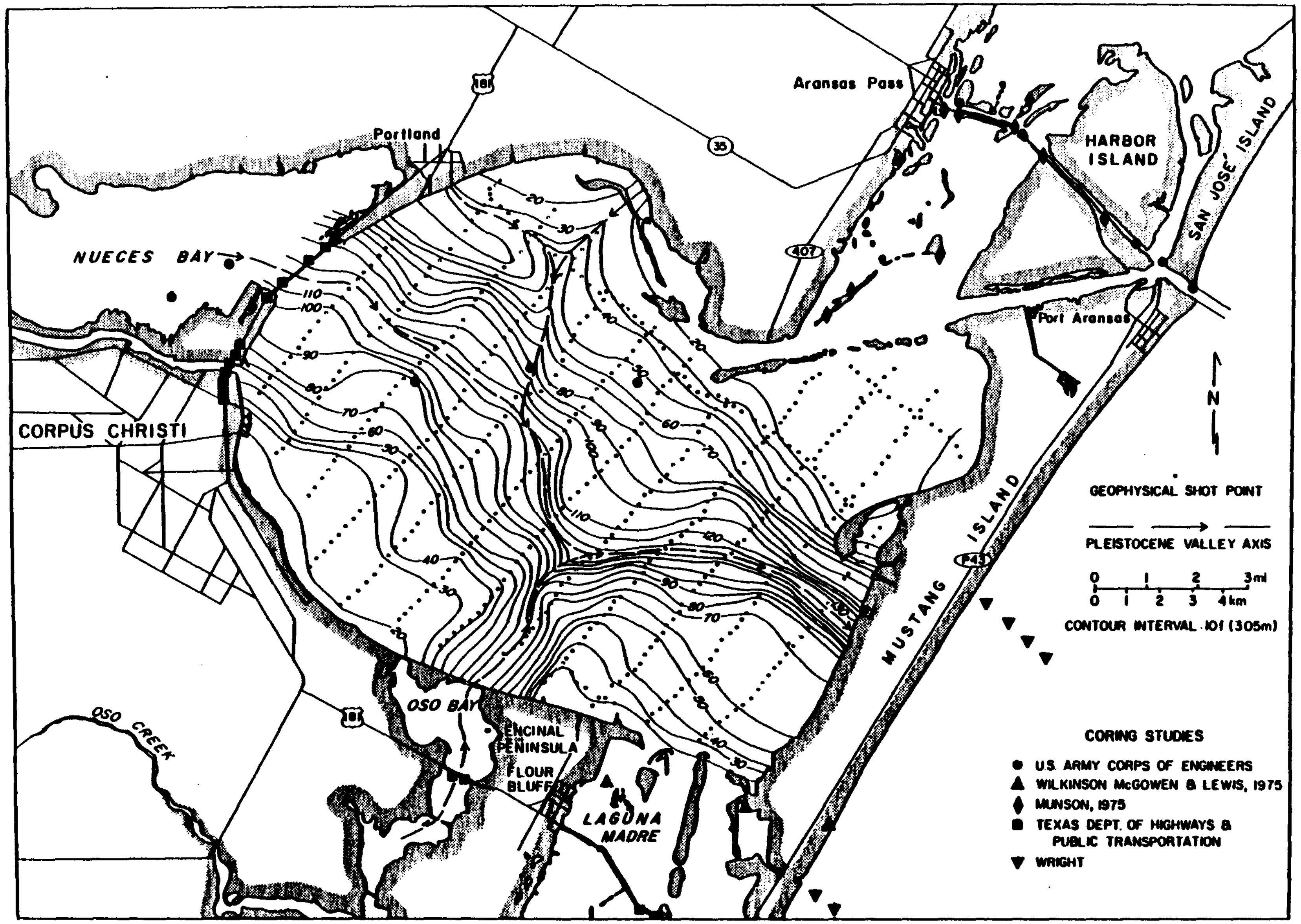

Figure 3. Contour map of the late Pleistocene erosional surface beneath Corpus Christi Bay. From Wright (1980).

Sedimentation

During the Holocene sea-level rise, deposition of fluvial, deltaic, estuarine, and marine sediments partly filled the stream valleys incised during the late Pleistocene sea-level lowstand (Brown and others, 1976; Wright, 1980). The rate of sedimentation was less than the rate of sea-level rise; thus the transgressive sequence preserved in the valley fill records the increasing marine influence during the early Holocene. Wright (1980) used the Holocene sea-level curves and the depth of Pleistocene valleys to estimate that marine waters entered the area of present-day Corpus Christi Bay 9,000 to 11,000 yr ago. As marine waters encroached into the valleys, waves broadened the newly formed estuaries by eroding valley walls.

By 4,500 yr ago, sea level was probably within 15 ft of its present-day level. Filling of the estuaries by erosion of valley walls, deltaic deposition, influx of Gulf sediments through tidal inlets, and reef growth continued as the rate of sea-level rise diminished (Brown and others, 1976). About 3,000 to 2,500 yr ago, the nuclei for north Padre, Mustang, and San Jose Islands had formed with material derived from the erosion of deltaic headlands. Longshore transport and spit accretion caused the barrier-island nuclei to grow and coalesce, resulting in the restriction and minor lateral migration of tidal inlets (Brown and others, 1976). Open-marine conditions in present-day northern Laguna Madre, Corpus Christi Bay, and Redfish and Aransas Bays were lost as the barrier island continued to accrete and tidal inlets closed. In addition, slow sea-level rise allowed the progradation of bayhead deltas such as the Nueces delta (fig. 2); this process has continued to the present in some areas (McGowen and Brewton, 1975).

Prevailing southeasterly winds (fig. 4) have produced net longshore sediment transport in a counter-clockwise sense in northern Corpus Christi Bay and a clockwise sense in southern Corpus Christi Bay. The result has been the formation of Rincon Peninsula and Indian Point Peninsula during the late Holocene, primarily by spit accretion (fig. 2; fig. 4 for location). Shamrock Island is another late Holocene spit deposit formed by southwesterly directed currents that were predominant when a tidal outlet was open in the southeastern part of Corpus Christi Bay.

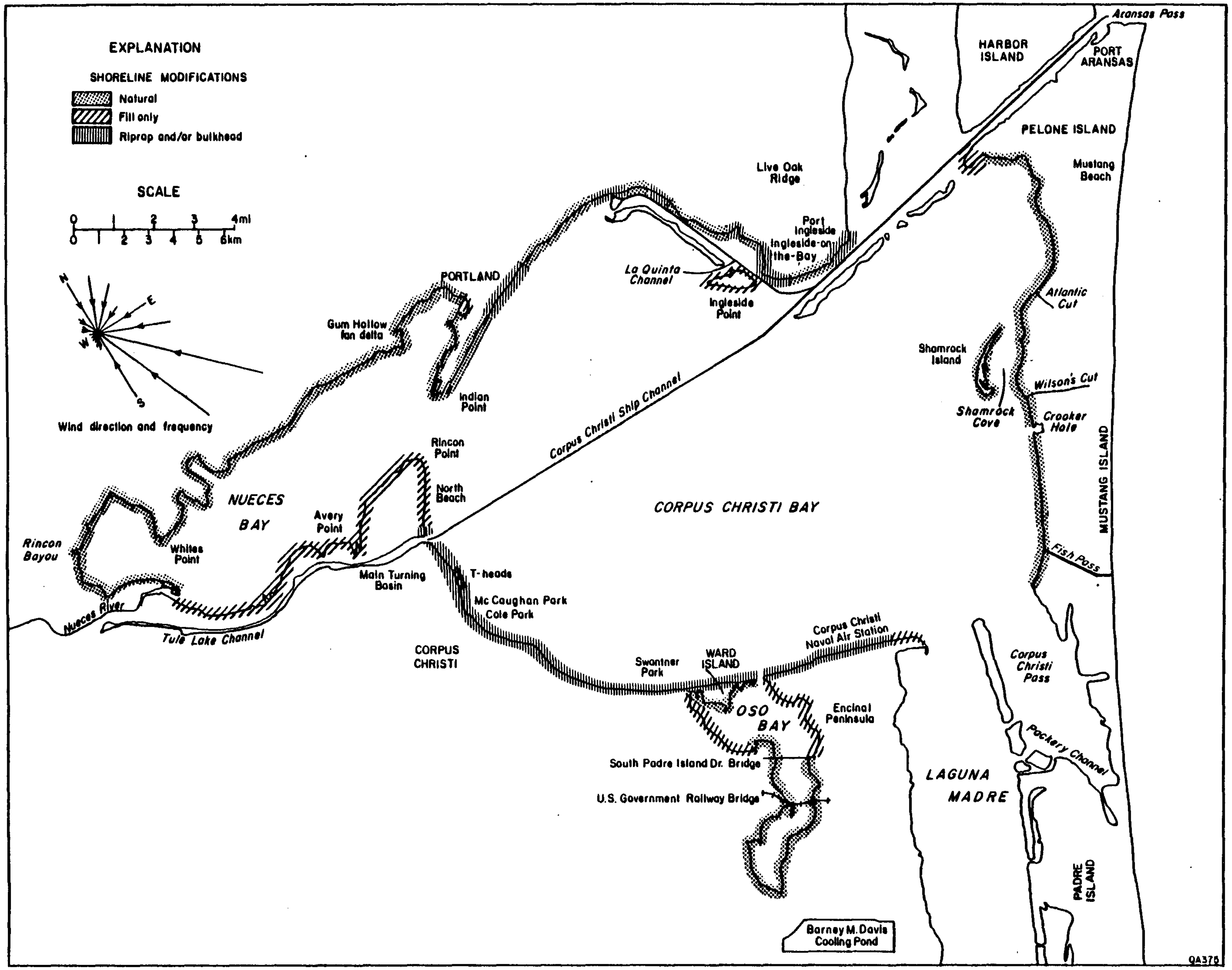

Figure 4. Geographic locations and types of shorelines forming the margins of Corpus Christi, Nueces, and Oso Bays. Wind vectors from Corpus Christi Naval Air Station (1951-1960), as shown by Brown and others (1976).

TYPES OF SHORELINES

Clay bluffs, sandy slopes, marshes, and sand and shell beaches compose the four main types of natural shorelines found around Corpus Christi Bay; shorelines that have been altered and are not in their natural state include these same shoreline types as well as structurally stabilized shores. Before human alterations, shoreline morphology and composition were chiefly controlled by the regional geology (fig. 2) and local coastal processes. High clay bluffs of Pleistocene mud and sand formed the northern and southern boundaries of Nueces Bay and Corpus Christi Bay and the western margin of Oso Bay (figs. 2 and 4). These bays were separated by baymouth spits (North Beach, Indian Point, Ward Island) composed of sand and shell. Marshes of the Modern Nueces delta formed the headward margin of Nueces Bay. The bay margin of Mustang Island consisted of sand and shell beaches, and the short bay segments near Port Ingleside and the Corpus Christi Naval Air Station most likely were constructed of sand derived from the adjoining Pleistocene barrier-strandplain sand. Sandy slopes along eastern Oso Bay were also associated with the Pleistocene Ingleside sand (fig. 2).

Unstabilized Shorelines

For the purpose of this report, all shorelines currently composed of unconsolidated sediments and subjected to erosion by the bay waves and nearshore currents are considered unstabilized. Both natural shorelines and unprotected landfills are included in this category.

Clay Bluffs

Steep bluffs composed of interbedded mud and sand (fig. 5) characterize much of the shoreline along northern Nueces and Corpus Christi Bays, western Oso Bay, and short stretches of southern Corpus Christi Bay. Bluffs exhibit the greatest disequilibrium with extant coastal processes, and therefore are the most vulnerable to wave attack and undercutting; they are also the most resistant to wave erosion. Elevations of bluffs vary from a few feet to more than

Figure 5. High, nearly vertical clay bluffs of southern Corpus Christi Bay. Photograph by L. Wenger.

50 ft and generally decrease eastward because of the gentle ($\approx$5 ft/mi) gulfward slope of the Coastal Plain surface. Bluff steepness and corresponding beach width are partly dependent on sediment composition (sand percent), but bluff orientation with respect to predominant wind directions, deep-water fetch across the bay, and presence or absence of intervening land features primarily caused bluff morphology. North-, south-, or southeast-facing clay bluffs that are exposed to long wave fetches have steep slopes, whereas sandy bluffs that face other directions or receive protection from promontories have lower slopes.

Both topographic elevation and wave characteristics make bluff shape along northern Nueces and Corpus Christi Bays more complex than along southern Corpus Christi or western Oso Bays. Large, unimpeded hurricane waves raised to unusually high elevations by storm surge erode the upper levels of the high bluffs and form wave-cut slopes and terraces. Sediment eroded from the bluffs is transported bayward and deposited as broad beaches and bay-margin shoals. These deposits are subsequently reworked by the smaller waves of less intense storms and by the waves generated by the prevailing daily winds.

Apparently, bluff orientation with respect to wind direction (fig. 4) accounts for the different widths that exist between beaches and erosional escarpments. Wide intervening slopes are found along northern Corpus Christi Bay where weak, low-amplitude waves generated by persistent southeasterly winds cannot remove the planar wave-cut surface and adjacent beach. In contrast, narrow beaches formed along southern Corpus Christi Bay because northerly winter waves of moderate size erode the beach and adjoining bay shoals. Elsewhere, the zone of barren or grass-covered sediment at the base of the erosional escarpment is locally controlled by deposition at the mouths of steep-walled, headwardly eroding gullies that transect the tall bluffs. The recently formed Gum Hollow fan delta (McGowen, 1971) is a large example of such a deposit; laterally extensive but narrower berms have also formed in Nueces Bay by coalescing small fans at the bases of numerous gullies and rills scoured into the bluff faces.

Sandy Slopes

Grass- and shrub-covered slopes composed of fine sand and clayey sand commonly grade bayward into sand beaches or merge with barren and marsh-covered sand flats; therefore they are the least distinctive of the principal shoreline types. Prominent sandy slopes are not widespread and occupy only the eastern perimeter of Oso Bay (fig. 6), where they coincide with the landward limit of the Pleistocene Ingleside sand (fig. 2). The slopes are hummocky, have moderate surficial gradients, and are up to 15 ft high.

Marshes

Bay shorelines partly stabilized by marsh vegetation (fig. 7) are most abundant in Nueces Bay. There the marsh vegetation grows in wave-shadow zones behind spits, in shallow embayments, or in other protected areas of low wave energy.

Before massive shell dredging during the latter half of this century, water depths were a few feet in the center of Nueces Bay and a few inches in the upper reaches near the Nueces River. The extremely shallow depths (1) prevented formation of large erosive waves and (2) promoted extensive growth of marshes fed by the river-borne nutrients and the mixing of fresh water and seawater.

Salt-water marshes grow not only on muddy substrates of the Nueces delta but also on sandy flats throughout Nueces, Corpus Christi, and Oso Bays. A particularly robust stand of marsh in northern Oso Bay is supplied by effluent discharge from the nearby sewage treatment plant.

Sand and Shell Beaches

Shorelines composed of sand with varying amounts of shell are generally restricted to Corpus Christi Bay. They are located along Indian Point (fig. 8) and the bayside of Mustang Island, and formerly along North Beach. The beach along Shamrock Island contains the highest concentrations of shell debris, a mixed assemblage of mollusk species that live in the bay and

Figure 6. Sandy slopes of eastern Oso Bay.

Figure 7. Broad salt-water marshes (Spartina alterniflora) of the Nueces delta, upper Nueces Bay. Photograph by W. A. White.

Figure 8. Low and narrow sand and shell beaches of Indian Point.

open Gulf. These low-lying (less than 5 ft) shoreline features are commonly backed by salt-water marsh or salt-tolerant grasses that occupy slightly elevated areas and provide some sediment stability.

Perhaps as recently as 100 yr ago many of these sand and shell beaches were at least stable, if not actively accreting. The ridge-and-swale topography associated with some of these bay-margin features marks the positions of older beaches and berms. Some of these former shoreline deposits are now eroding because recent changes in the bay system have altered sediment supply and current patterns.

Made Land

Vast areas of newly created land lie next to the major deep-draft channels in Corpus Christi and southern Nueces Bays (figs. 2 and 9). Initial excavation, subsequent deepening, and maintenance dredging of the channels supplied the sand and mud that were hydraulically emplaced to form the fill. Broad, low-lying sand flats and higher spoil mounds formed by dredged material are located along the south side of Nueces Bay (Tule Lake Channel and turning basin), near Ingleside (LaQuinta Channel), and near Port Aransas (Corpus Christi Ship Channel).

Smaller land areas created by activities other than spoil disposal include (1) several sand flats in southern Oso Bay near the Barney Davis cooling pond, (2) the Naval Air Station runway extension in northeastern Oso Bay, and (3) the Corpus Christi waterfront district near Shoreline Boulevard. The latter two areas have been structurally stabilized and, therefore, are also included in the following discussion.

Stabilized Shorelines

Coastal lands are subject to a variety of geological processes (collectively known as coastal processes), and thus these lands are among the most dynamic on earth. Fluctuations in the relative importance of the many agents active along a coastline occur on virtually any time scale, be it daily, seasonally, annually, or otherwise. Because shoreline positions are mainly

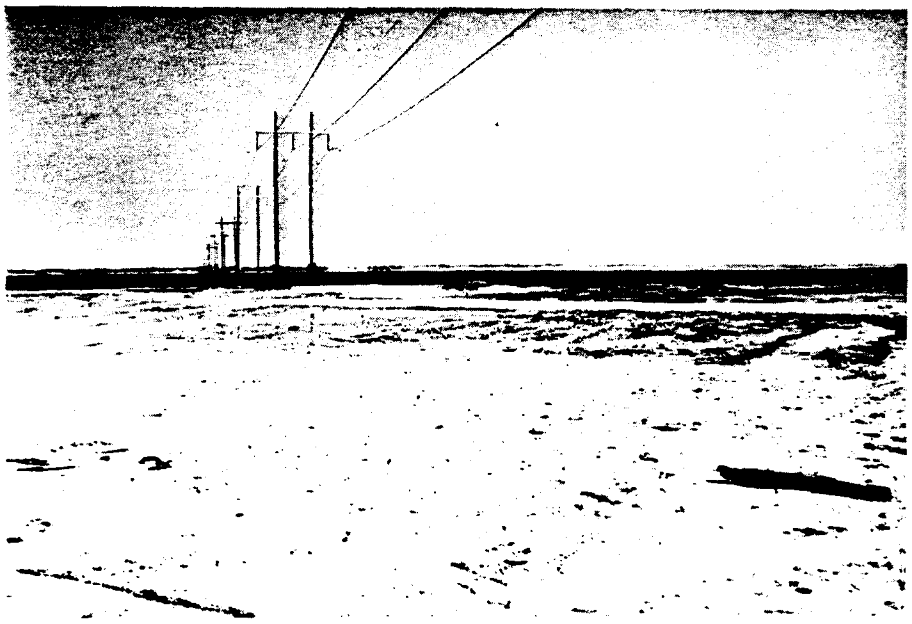

Figure 9. Broad, low-lying flats composed of dredged material (mostly sand), southern Nueces Bay.

determined by coastal processes, the ability of coastal agents to change in relative importance through time causes shoreline positions also to change through time. Owners of bayfront property have employed several methods to stabilize transient shorelines; the methods used in the Corpus Christi area include constructing bulkheads and seawalls, placing rubble (riprap) along the shoreline, and nourishing recreational beaches.

Bulkheads and Seawalls

The primary purpose of bulkheads and seawalls is the prevention of shoreline retreat by the reflection of wave energy that would otherwise impinge upon coastal lands. This is accomplished by the construction of vertical or near-vertical walls parallel to the shoreline (fig. 10). Reinforced concrete is the most common construction material; however, examples of wooden and metal bulkheads also exist. Seawalls are generally higher and more laterally extensive than bulkheads and are designed to reflect wave energy up and away from protected material.

Bulkheads and seawalls stop shoreline retreat during the life of the structure. However, wave reflection and water turbulence at the seaward toe of a bulkhead can cause erosion in this area, increasing the likelihood of bulkhead failure. A second disadvantage to the use of bulkheads in shoreline erosion control is the concentration of wave energy at the ends of a bulkhead. This causes rapid shoreline retreat if adjacent waterfront property is unprotected. Because many bulkheads in the Corpus Christi vicinity are built on a lot-by-lot basis, increased erosion of adjacent property is a common problem. A third disadvantage involves tropical cyclones, an infrequent but important agent in shoreline retreat. Along with high winds and heavy rain, these storms are accompanied by large local sea-level increases (storm surge). Though each storm varies, bay levels of nearly 10 ft above mean sea level (MSL) have been reached for short periods of time (see table 1 and fig. 11). During periods of intense wave action and elevated sea level, most bulkheads are overtopped and are thus more prone to failure.

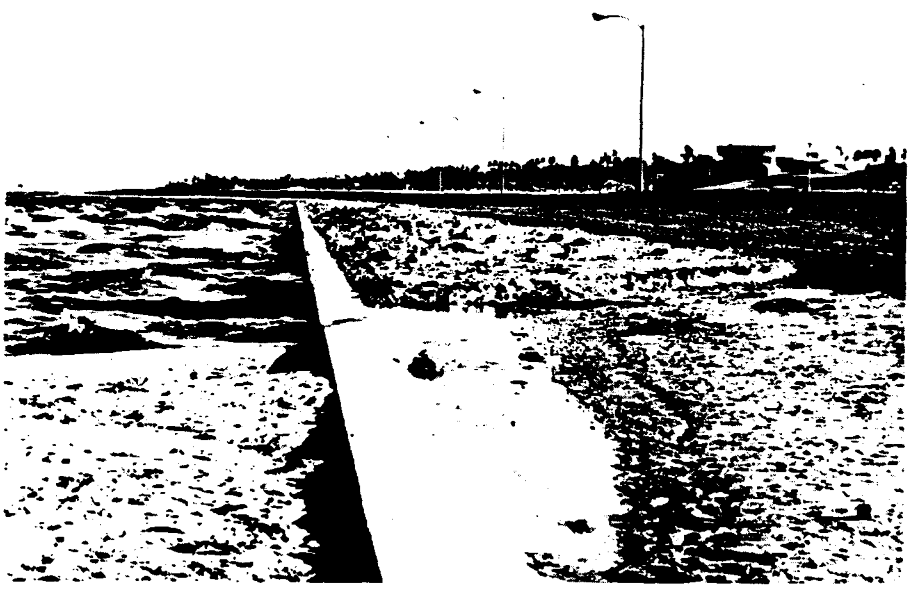

Figure 10. Low concrete bulkheads backed by consolidated riprap and graded fill at Cole Park, southern Corpus Christi Bay.

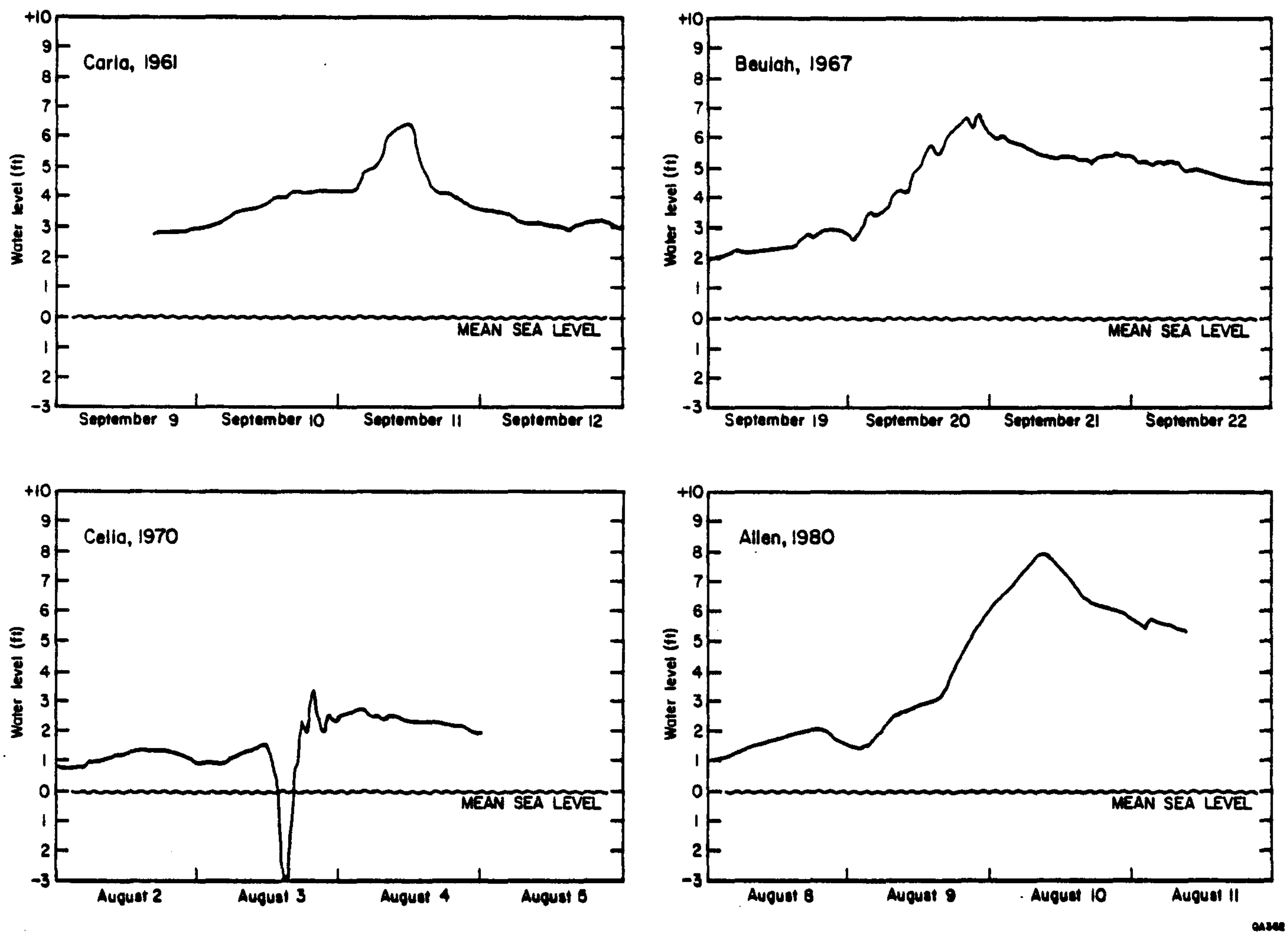

Figure 11. Storm-surge hydrographs for Hurricanes Carla, Beulah, Celia, and Allen recorded at Corpus Christi. Data from U.S. Army Corps of Engineers (1962, 1968, 1972, 1981).

Table 1. Maximum hurricane surge heights recorded near Corpus Christi Bay 1919 to 1982.

Date	Surge Height (ft)	Location	Reference
1916	5.9	Corpus Christi	Sugg and others, 1971
1919	11.1	Port Aransas	Sugg and others, 1971
	16.0	Corpus Christi	Sugg and others, 1971
1933 (July)	5.0	Port Aransas	Price, 1956
1933 (August)	4.5	Port Aransas	Bailey, 1933
1933 (September)	8.0	Corpus Christi	Sugg and others, 1971
1945	4.0	Port Aransas	Sumner, 1946
	4.5	Corpus Christi	Sumner, 1946
1961	9.3	Port Aransas	U.S. Army Corps of Engineers, 1962
(Carla)	6.5	Corpus Christi	U.S. Army Corps of Engineers, 1962
1967	8.0	Port Aransas	U.S. Army Corps of Engineers, 1968
(Beulah)	7.3	Corpus Christi	U.S. Army Corps of Engineers, 1968
1970	9.2	Port Aransas	U.S. Army Corps of Engineers, 1971
(Celia)	4.9	Corpus Christi	U.S. Army Corps of Engineers, 1971
1971	3.1	Port Aransas	U.S. Army Corps of Engineers, 1972
(Fern)	3.0	Corpus Christi	U.S. Army Corps of Engineers, 1972
1980	8.9	Port Aransas	U.S. Army Corps of Engineers, 1981
(Allen)	9.4	Corpus Christi	U.S. Army Corps of Engineers, 1981

The most intense shoreline stabilization efforts are concentrated on the southern and western shores of Corpus Christi Bay, from the North Beach - Rincon Point area eastward to the Corpus Christi Naval Air Station (fig. 4). These efforts include, but are not restricted to, the placement of seawalls and bulkheads. Seawalls, attaining heights of 10 or more feet above mean sea level, protect the northern end of Corpus Christi Naval Air Station and downtown Corpus Christi. Bulkheads extending only a few feet above sea level are more common between the seawalls. Wall heights and construction materials vary greatly from site to site; however, city-owned parks have bulkheads that are consistent for hundreds of feet in form and composition.

Bulkheads rather than true seawalls are found at various points around Nueces Bay, Corpus Christi Bay, and Oso Bay. These bulkheads are usually also less than 5 ft above sea level and are localized. Bulkheads are common on both the Corpus Christi Bay and Nueces Bay sides of Portland, near Ingleside-on-the-Bay on the northeastern shore of Corpus Christi Bay, and surrounding residential, commercial, and oil field developments on the bay shore of Mustang Island.

Riprap

Another common technique used to prevent shoreline retreat is the placement of coarse rubble (riprap) along a shoreline in the zone of wave attack. The random orientation of blocks causes a scattering of incident wave energy, reducing the effectiveness of wave attack. Diverse materials, including large rocks, blocks of aggregate, pavement, and rubber tires, have been used as riprap in the Corpus Christi Bay system (fig. 12). Because these materials are generally readily available and no construction is required, placement of riprap is one of the least expensive methods of shoreline protection.

In addition to serving as a single inexpensive method of erosion control, riprap is commonly used in conjunction with other erosion control structures. Bulkheads, for example, are vulnerable to both undermining caused by a concentration of wave energy at their base and

Figure 12. Concrete riprap used as shoreline protection near Ward Island, southern Corpus Christi Bay.

overtopping during storms. Riprap has been used in some areas both in front of and behind bulkheads to increase the effective life of the structures.

The placement of riprap is less complex than the construction of bulkheads. Thus, riprap is likely to be found in a wider variety of settings around the bays, notably where shoreline control is desired but bulkheads are impractical or economically unfeasible. In southern Corpus Christi Bay, riprap is used on a lot-by-lot basis either by itself or as protection for bulkheads. Most bulkheads in city parks are fronted and backed by riprap of some type. Though riprap is most common along the southern shores of Corpus Christi Bay, it is locally found throughout the bay system. Other notable concentrations are near Portland and Ingleside-on-the-Bay, along the bay shore of Mustang Island, and at scattered localities in Nueces Bay.

Beach Nourishment

Bulkheads, seawalls, and riprap attempt to stop shoreline movement by decreasing the amount of wave energy reaching shoreline sediments. Beach nourishment projects differ in that they attempt to maintain shoreline position by the addition of material to the littoral system and require continual replenishment as the nourished beaches are eroded by natural processes.

A major beach nourishment project was completed by the U.S. Army Corps of Engineers in 1978 for North Beach (figs. 13 and 14). This area was selected for nourishment because it has experienced consistent erosion in historical time, even though Rincon Peninsula is an accretionary feature when viewed in a geological context. The reclamation and nourishment of North Beach was accomplished by the importation of coarse sand from the Nueces River, which covered fill material dredged from Corpus Christi Bay (U.S. Army Corps of Engineers, 1974). Material was added to approximately 7,000 ft of shoreline; the restored beach width along this length was 300 to 400 ft (fig. 15). It is estimated that 125,000 cubic yards of cover material will be necessary every 5 yr to maintain the beach at its current size (U.S. Army Corps of Engineers, 1974).

Figure 13. North Beach in 1974 before beach nourishment.

Figure 14. North Beach in 1982 after beach nourishment. Same location as figure 13 but taken from an angle farther out on the beach.

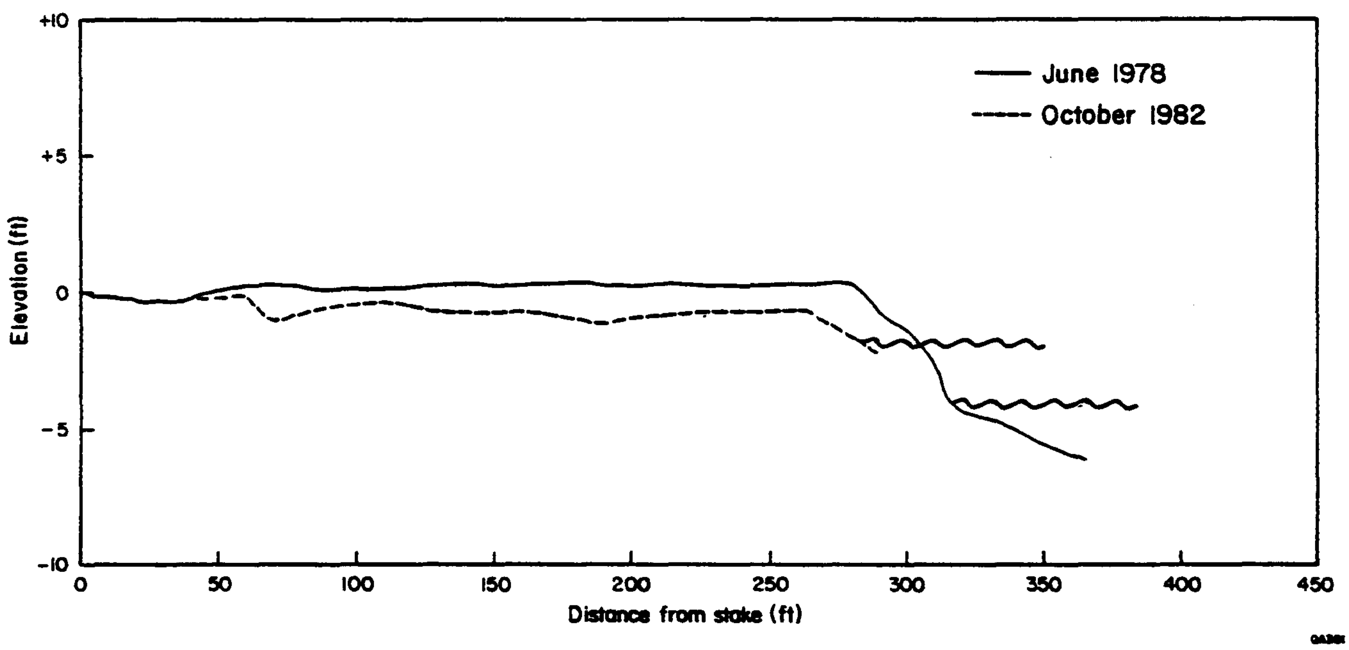

Figure 15. Profile of North Beach measured in 1978 and 1982 at same location as figure 14.

Beach nourishment on a smaller scale has been undertaken at McCaughan Park in Corpus Christi, just south of the seawall. Approximately one-third of a mile of beach has been nourished to a width of 70 to 100 ft.

FACTORS AFFECTING SHORELINE MOVEMENT

It is impossible to isolate and quantify the individual factors that cause shoreline changes (fig. 16). Despite the difficulties, evaluation of the various factors and their interactions is necessary to understand past shoreline changes and to anticipate future changes.

Climate

Global changes in climate since the last glacial stage have indirectly affected positions of bay shorelines. In general, temperature was lower (Flint, 1971) and precipitation was greater (Schumm, 1965) at the end of the Pleistocene than at present; the warmer and drier conditions that now prevail indicate that vegetal cover, runoff, and sediment yield have diminished during the past few thousand years.

According to Dury (1965), many rivers transported 5 to 10 times more water during the early Holocene than today. This is confirmed by the geologic map of Brown and others (1976), which shows that the ancestral Nueces River was larger and capable of transporting greater volumes of sediment. This decrease in river size, in turn, affected sediment budget primarily by reducing the volume of sediment supplied to the Nueces delta and Nueces Bay. The discharge of Oso Creek was probably not appreciably affected by climatic changes because of its limited size and drainage area.

The effects of drought on shoreline changes are also minor and indirect. They cause a slight but perceptible lowering of sea level that may give rise to apparent, rather than actual, accretion. This ephemeral influence is eliminated when normal water levels return after the drought. Real accretion that is attributable to droughts occurs only locally where active sand

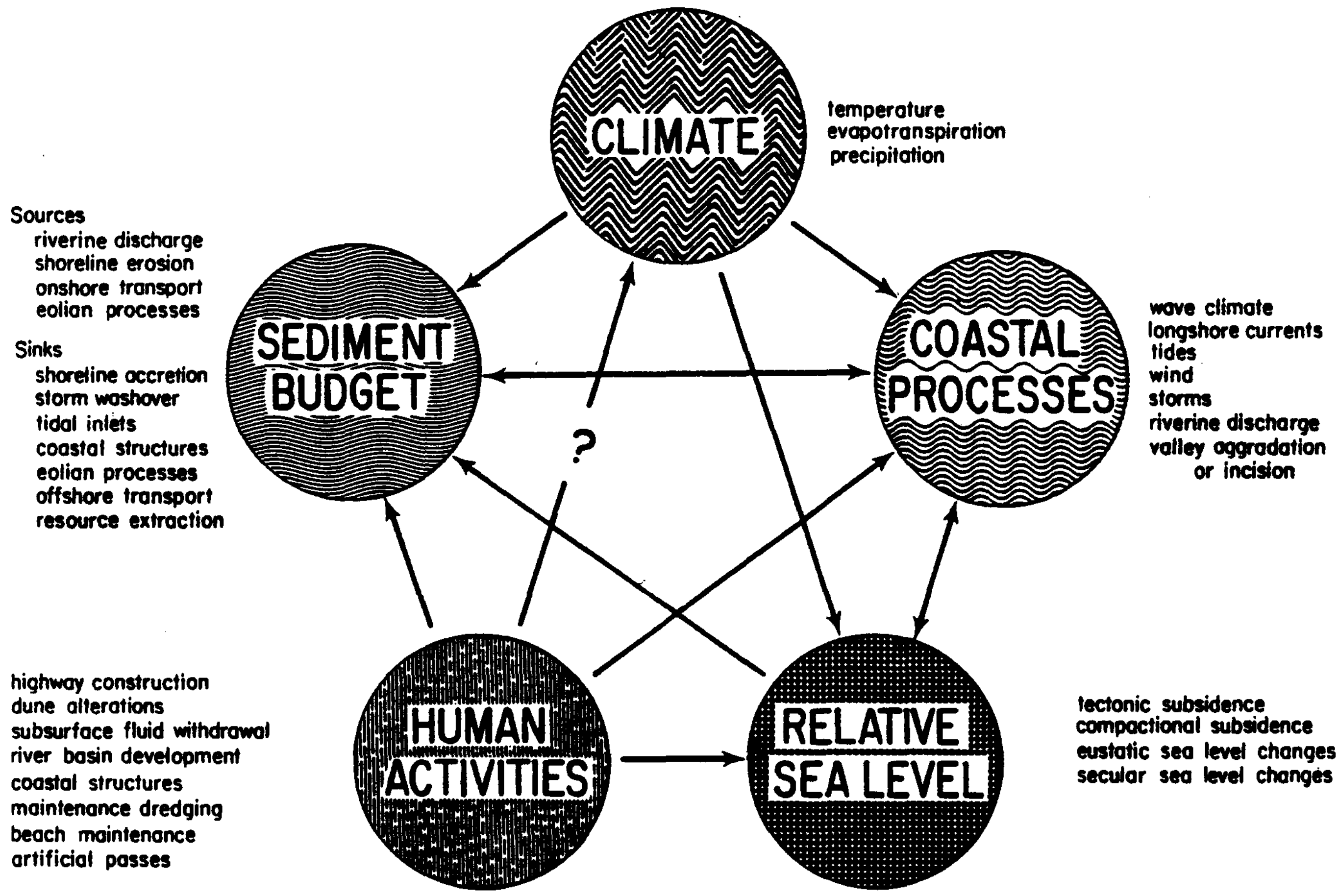

Figure 16. Interaction of factors affecting land losses. Arrows point towards the dependent variables: The number of arrows originating from or terminating at a particular factor indicates the relative degree of independence or interaction. For example, human activities are independent of the other factors, but they affect sediment budget, coastal processes, relative sea-level conditions, and perhaps, climate. From Morton (1977).

dunes migrate across the backbarrier flats and advance the bay shoreline toward the mainland. Overall climate is the least important factor when considering long-term historical shoreline changes.

Sea-Level Position

The single factor receiving the most attention in recent years is relative sea-level changes (Hicks, 1978) resulting from natural movement of the Earth's crust (Holdahl and Morrison, 1974), human-induced subsidence (Gabrysch, 1969), as well as climatic changes (Etkins and Epstein, 1982). At least four factors govern land-sea relationships at the shoreline (fig. 16), but only two are significant enough to influence shoreline changes along the Texas coast. Tectonic subsidence is imperceptible on a historical time scale; eustatic (worldwide) sea-level rise, although documented (Lisitzin, 1974), is probably a minor factor and of less magnitude than compactional subsidence or local secular sea-level variations.

Compactional Subsidence

Relative sea-level changes have been determined during the past few decades by monitoring mean sea level and establishing trends based on long-term tide gauge measurements (Gutenberg, 1941; Marmer, 1951; Hicks, 1972). Because this method cannot differentiate sea-level rise from land-surface subsidence, Swanson and Thurlow (1973) used statistical techniques to adjust tidal data for the glacial-eustatic component and concluded that the slight rise in sea level recorded along most of the Texas coast is due to compactional subsidence.

A minor vertical rise in sea level caused by compactional subsidence (or any other factor) theoretically can result in considerable landward movement of the shoreline if slopes are sufficiently low (Bruun, 1962). However, both the natural beach slopes and the tide gauge measurements at Port Aransas (Swanson and Thurlow, 1973) indicate that compactional subsidence in the Corpus Christi area is minor if significant at all.

Natural compaction of the thick sedimentary section that underlies the Coastal Plain and continental shelf can be augmented and actually surpassed by compaction associated with hydrocarbon production (Pratt and Johnson, 1926) and ground-water withdrawal (Gabrysch, 1969). Land-surface subsidence appears to be minor in the Corpus Christi area and is primarily centered near Clarkwood and southern Nueces Bay (Brown and others, 1974; Ratzlaff, 1980). However, continued withdrawal and concomitant dewatering of shales and decline in pore pressures could eventually cause significant decreases in surface elevation and lead to future land losses, especially where volumetrically large production occurs at or near the shoreline.

Secular Variations

Secular sea-level variations, or time-dependent oscillations (Hicks and Crosby, 1975), may also contribute to short-term (years) shoreline changes. For example, anomalous shoreline accretion along parts of the central coast during the mid-1950's was probably related to slightly lower sea-level conditions (Morton and Pieper, 1977). This trend is well illustrated by many tide gauge records around the United States (Swanson and Thurlow, 1973; Hicks and Crosby, 1975), including the Galveston and Port Isabel gauges. Most of the State was affected by drought from 1950 to 1956; the most severe drought, between 1954 and 1956 (Lowry, 1959), was manifested by reduced riverine discharge and excessive evaporation. These conditions would cause apparent shoreline accretion by lowering the water level. Similarly, the recent rise in sea level (Hicks and Crosby, 1975) may be partly responsible for increased and nearly coastwide shoreline erosion elsewhere.

Sediment Supply

The balance between sediment supply and forces produced by nearshore waves and currents determines shoreline stability. Shorelines accrete when sediment supply exceeds nearshore energy, whereas they erode when sediment supply is deficient. Sediment sources and sinks (fig. 16) and coastal processes can be drastically altered by human activities, but none of these factors change appreciably under natural conditions and over periods of several hundred years.

Sources

The primary processes and associated sources of bay shoreline sediments in relative order of decreasing importance are (1) redistribution of existing sediments, (2) introduction of terrigenous sediments, (3) deposition of washover fans and flood-tidal deltas, and (4) migration of active backbarrier dunes.

The continuous reworking of bay margins by waves and nearshore currents causes both major and minor shifts in sediment distribution. Minor shifts are largely imperceptible and occur as beach material moves a short distance offshore during periods when waves are slightly higher than normal and returns to the beach during quiescent periods. In contrast, major shifts in sediment account for the most noticeable long-lasting changes that result in net losses along some shoreline segments. During intense storms, bay shorelines erode and coarse-grained material is transported away from the site (downdrift) by longshore currents, while the fine-grained material is suspended, transported away from the site, and usually deposited in a slack-water or low-energy environment.

The undercutting and scouring action of waves is particularly devastating to clay bluffs because the predominantly fine-grained sediment is permanently removed from the shore. The sand transported alongshore feeds nearby beaches and bay-margin shoals, but the volume of sand added at the expense of bluff retreat is only significant on time scales of hundreds or thousands of years. For example, the original sand deposits on North Beach and Indian Point were supplied partly by updrift clay-bluff erosion along southern and northern Corpus Christi Bay. Because of shoreline alterations in adjacent areas (mainly channel and bulkhead construction) that eliminated the sand supply, these formerly accreting beaches are now eroding.

The only significant source of new fluvial sediment is the Nueces River that delivers terrigenous clastics primarily to Nueces Bay and deposits them near the river mouth. Influx of fluvial sand and mud was undoubtedly more important several hundred years ago than it is today, but natural decreases in precipitation, runoff, and sediment yield, as well as historical reductions in discharge and sediment transport (fig. 17) have essentially nullified the sediment contribution from the Nueces River. The diminished discharge and sediment load of the river reflect river-basin development (flood control, surface storage, irrigation) and the sediment impounded in reservoirs associated with these upstream projects.

Both the volume of sediment delivered to bay shores by storm washover and tidal currents and the areas influenced by those processes are minor. A major washover area on Mustang Island (Corpus Christi Pass, Newport Pass, and Packery Channel) comprises what was previously a natural tidal inlet - tidal delta complex that has been modified by storm washover since the inlet closed. The inlet shoaled and became inactive after the Corpus Christi Ship Channel was opened (Price, 1952). Storm waves periodically inundate the washover areas and deposit tongues of sand that project into Corpus Christi Bay and cause perturbations in the shoreline. However, these features are localized, and little sediment is added to the littoral drift system.

The baymouth bar across Oso Bay is another washover area that was frequently flooded until the highway was elevated and riprap was placed along the shore. Now the areas adjacent to Ward Island receive minor quantities of sand when bay levels and storm waves overtop the road.

Dune migration is a locally minor source of sediment for the bay shore of Mustang Island. The sand supply is also ephemeral and occurs less frequently than does overwash. During severe droughts, dune fields north of Corpus Christi Pass become active and migrate across the barrier. The sand transported by eolian processes enters the bay where it nourishes nearby beaches; unfortunately the positive effect on the bay shoreline is short lived and the recurrence interval of this sand nourishment is both infrequent and unpredictable.

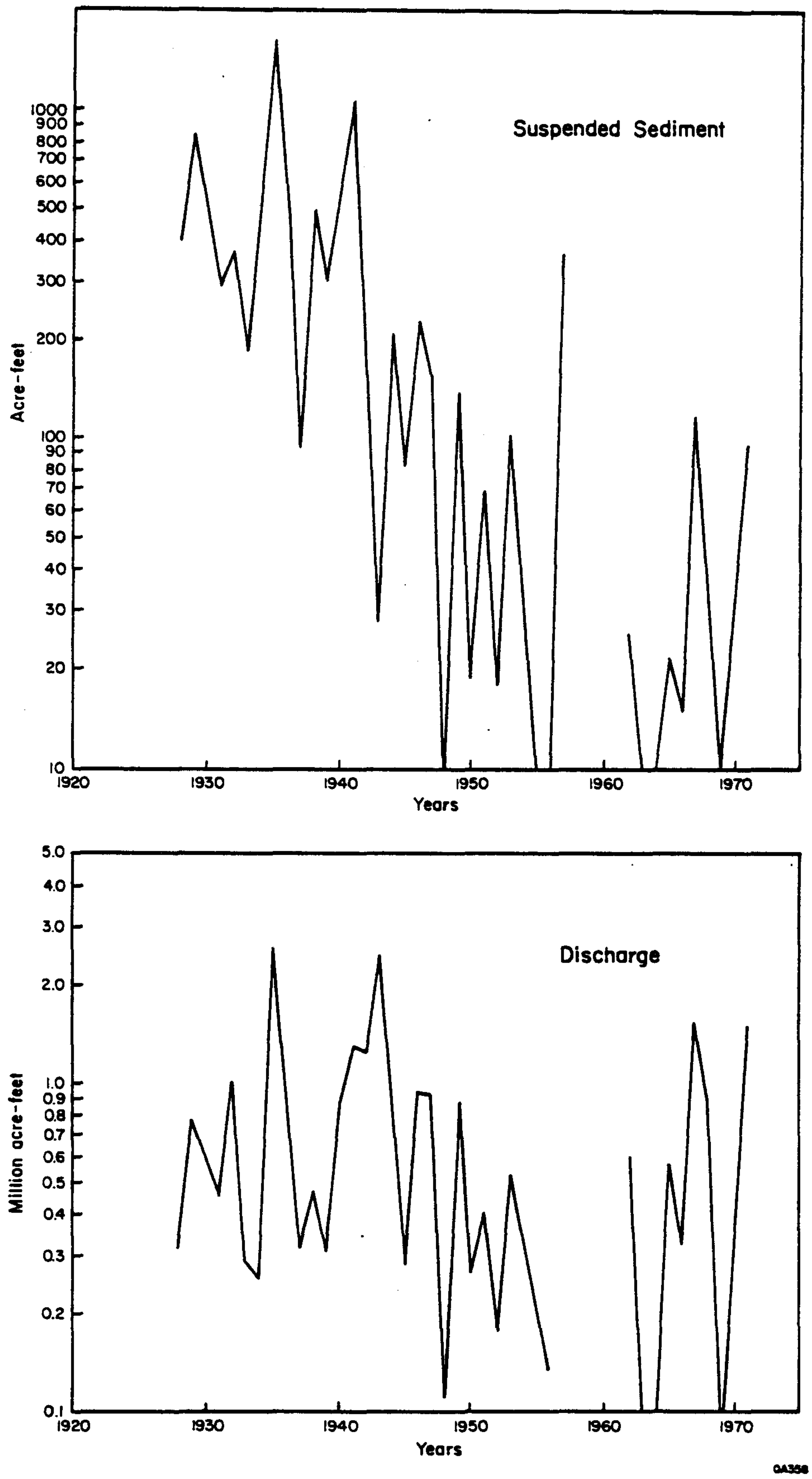

Figure 17. Total suspended sediment and discharge of the Nueces River at the Three Rivers Station (1928-1971). Data from the Texas Board of Water Engineers (1961); Texas Water Commission (1964); Texas Water Development Board (1967a, 1970, 1974).

Sinks

Processes and associated sinks that tend to permanently remove sediment from the nearshore bay system include (1) deposition in the deep bay centers, (2) deposition in artificial and natural channels, (3) containment by coastal structures, and (4) dredging and mining of bay sediment.

Shepard and Moore (1960) reported that Corpus Christi Bay shoaled an average of slightly more than 1 ft between 1868 and 1934. These bay-margin and bay-center deposits are mostly composed of fine silt and mud (White and others, in press) that settle from suspension and some sand and shell debris that are transported by storms into deeper water where they are incorporated into the muddy sediments by burrowing organisms. Sediments that fill both natural and artificial channels can also be fine grained, but usually they contain some sand and gravel-size shell concentrated near the channel base by strong currents. If the fine fraction has been winnowed from the coarse sediments, then the channel fill may be composed mostly of sand with a few mud drapes.

The cumulative losses of coarse material (sand and shell) to deeper water below wave base and away from the shore has a negative effect on sediment budget and leads to a deficit in sand supplied to the shoreline. Emplacement of coastal structures and removal of sediment from the bay system by humans also cause deficits in sediment supply.

Storm Frequency and Intensity

Storms are brief, yet they release enormous amounts of energy. They also cause rapid shoreline retreat that commonly results in net losses of land.

The frequency of tropical cyclones is dependent, in part, on cyclic fluctuations in atmospheric temperature; hurricane frequency supposedly increases during warm cycles (Dunn and Miller, 1964), but the historical data indicate little variation in frequency. According to summaries based on records of the U.S. Weather Bureau (Appendix B), 67 tropical cyclones have either struck or affected the Texas coast during this century (1900-1982). The average of 0.8 storms per yr obtained from these data is similar to the 0.67 per yr average reported by Hayes (1967). Simpson and Lawrence (1971) used comparable historical data to calculate the probability of storms striking 50-mi segments of the Texas coast. Their data indicate that each year the Corpus Christi - Mustang Island area has a 13-percent probability of experiencing a tropical storm, a 7-percent probability of experiencing a hurricane, and a 4-percent probability of experiencing a catastrophic hurricane.

During storms, high windspeeds and low barometric pressures raise bay levels to extraordinary heights (fig. 11) that may last for several hours or several days. The surge heights and consequently the damage to the beach that occurs during these peak periods depends on such factors as direction of storm approach, configuration of the shoreline, shape and slope of the bay bottom, maximum wind velocities, forward speed of the storm, distance from the eye of the storm, stage of astronomical tide, lowest atmospheric pressure, and duration of the storm.

Surge heights in Corpus Christi Bay have equaled or exceeded 4 ft at least 10 times during the past 66 yr (table 1). Waves superimposed on these water levels overtop beaches, berms, and marshes and dissipate their energy by internal friction (breaking waves), drag (over vegetation or mobile sediment), or they run up against higher elevations such as dunes and bluffs. Under these extreme conditions, the bay shores are completely out of equilibrium with the scouring forces. To achieve equilibrium between landforms and physical forces, sediment is eroded and transfered from high-energy to low-energy areas. Where surge heights exceed land elevations (marshes, sand and shell beaches), the dominant transport direction is onshore. Where surge heights are below the land crest (clay bluffs, sandy slopes), the eroded sediment is carried offshore. The sediment transported away from the bay shores by storms accounts for most of the net losses in land area.

Human Activities

Roughly half of the shores of Corpus Christi, Nueces, and Oso Bays have been altered by coastal projects (fig. 4). These projects are clearly responsible for the shoreline changes of greatest magnitude, but it is uncertain whether these activities also augment changes coastwide, throughout the entire bay system, or just in adjacent shoreline sectors. Moreover, the components of shoreline changes induced by local, regional, and global influences are difficult to quantify because human activities promote imbalances in sediment budget, coastal processes, and relative sea-level conditions (fig. 16). For example, construction of dams and navigation channels, erection of seawalls, bulkheads, and groins, and excavation of sediment all tend to reduce the volume and size of sediment available to the bay shores. Building impermeable structures and mining sediment have immediate, site-specific impacts as well as long-term effects, whereas many years may pass before the effects of other activities such as subsurface fluid withdrawal, flood control, and sediment impoundment are detected.

Dredging ship channels to Corpus Christi and Ingleside and building bulkheads along the southern shore of Corpus Christi Bay began during the early twentieth century and are continuing today. These and other projects alter natural processes, such as wave refraction and current circulation, and their effects on shoreline changes are debatable. It is well known, however, that impermeable structures and deep-draft channels interrupt littoral drift, and sediment impoundment occurs at the expense of beaches downdrift of the structures.

The tremendous volume of sediment that has been and continues to be removed from the bay is indicated by incomplete data for two independent activities, exploitation of bay sediments as an economic resource and maintenance dredging of shipping routes. Records of the Texas Parks and Wildlife Department show that for the first activity, over 2.5 million cubic yards of shell material were mined from Nueces Bay between 1969 and 1974 (fig. 18).

These high rates of shell production could not be sustained for more than two decades, given the limited bay area and mining depths. Nevertheless, the cumulative volume of sediment

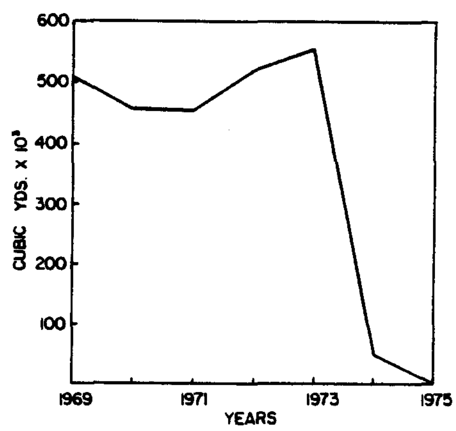

Figure 18. Oyster-shell production in Nueces Bay from 1965 to 1974. Illustration from Kier and White (1978); data from the Texas Parks and Wildlife Department (1969 through 1975).

removed was substantial enough to increase water depths by several feet. Maintenance dredging of navigation channels also accounts for removing several hundred thousand cubic yards of sediment annually. For example, dredging requirements for the Gulf Intracoastal Waterway between Corpus Christi and Baffin Bay average about 200,000 cubic yards per year (U.S. Army Corps of Engineers, 1975). The deeper and longer network of ship channels that cross Corpus Christi Bay has even greater maintenance dredging requirements. For example, the La Quinta and Corpus Christi Ship Channels each have average shoaling rates of 500,000 cubic yards annually (U.S. Army Corps of Engineers, 1975). Both shell production and maintenance dredging contribute to shoreline erosion by increasing wave energy, changing wave refraction patterns, and decreasing sediment supply.

Predicting future human impact on the bay shoreline is even more difficult than documenting human influence on historical shoreline changes. For example, some scientists have speculated that the release of carbon dioxide and fluorocarbons into the atmosphere from burning fossil fuels and using canned aerosols will cause a greenhouse effect that, in turn, will cause warming of average temperatures, melting of polar ice caps, and raising of sea level (Emery, 1980; Etkins and Epstein, 1982). Although some meteorological data have been used as evidence to support such a theory, the conclusions are unsubstantiated and other scientists have used different arguments to suggest that reductions in solar radiation by particulate matter in the atmosphere would cause a cooling effect (Lamb, 1970), consequently expanding continental ice sheets with attendant lowering of sea level. Regardless of the future consequences, both theories suggest that human activities may eventually alter weather patterns and possibly sea-level position.

HISTORICAL CHANGES

The Corpus Christi Bay system has been divided into five continuous segments (fig. 19), composed of northern Corpus Christi Bay (Port Ingleside to Indian Point), southern Corpus

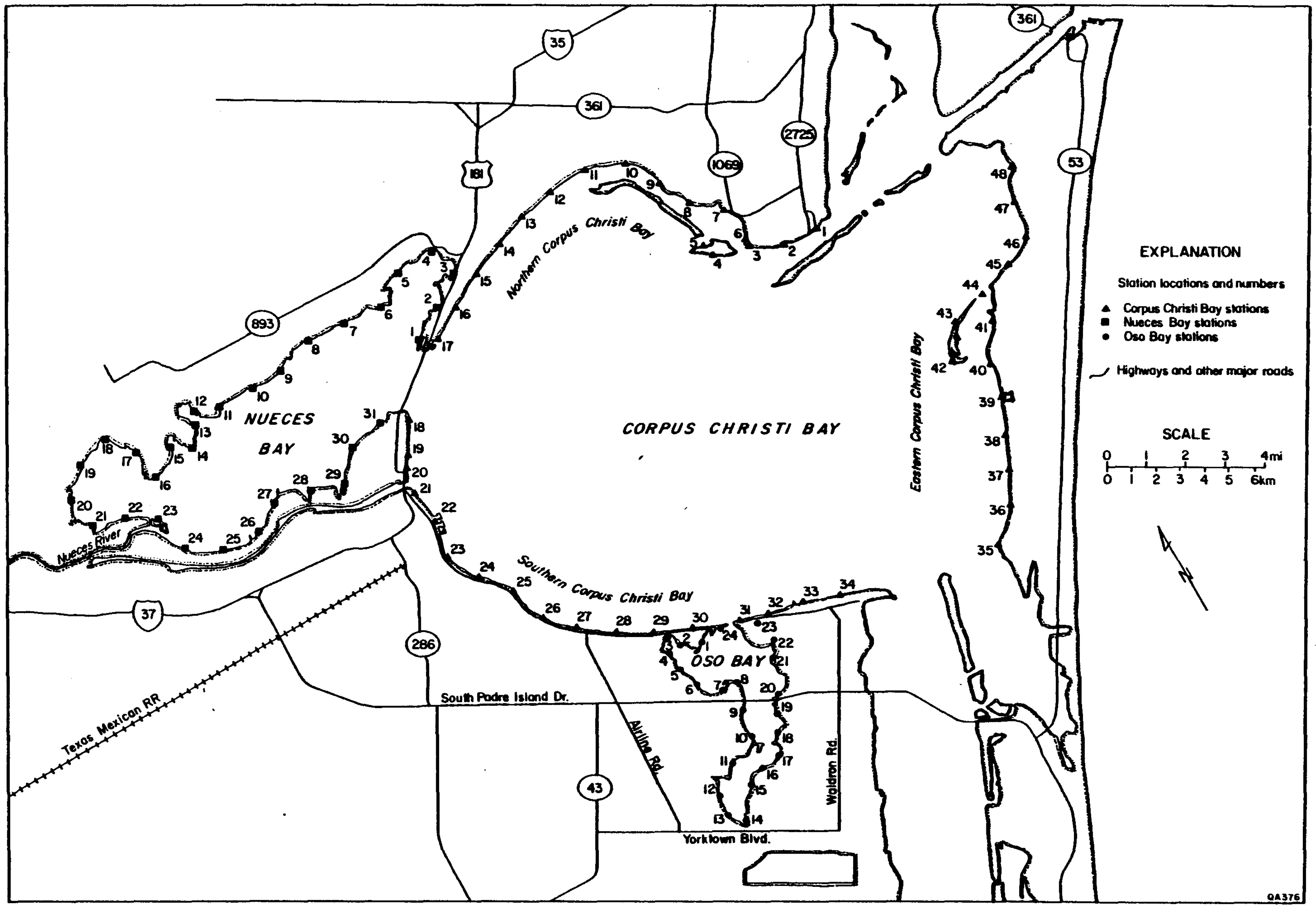

Figure 19. Location of measuring points (stations) in Corpus Christi, Nueces, and Oso Bays.

Christi Bay (Rincon Point to Encinal Peninsula), eastern Corpus Christi Bay (Mustang Island), Oso Bay, and Nueces Bay. Shoreline positions mapped for three time periods (late 1800's, 1930's, and 1982) indicated whether lengths of shoreline have moved bayward, landward, or remained stationary between these periods; the positions have also been used to calculate amounts and net rates of shoreline advance or retreat. Aerial photography between the 1930's and 1982 was used to determine more precisely the date of specific shoreline changes.

Two methods were used to quantify shoreline changes. First, a shoreline segment for a particular period (for example, northern Corpus Christi Bay from 1867 to 1930) was divided into lengths of shoreline that moved bayward (accreted), landward (eroded), or showed no net movement (stable). Each length was added to others of its type to account for the total length of accreting, eroding, and stable shoreline (fig. 20). Second, measuring points (stations) were distributed throughout the bay system (fig. 19), and amounts and rates of shoreline change were measured at these stations. Station spacing was approximately 5,000 ft in Corpus Christi and Nueces Bays. Spacing was irregular in Oso Bay, averaging 3,500 ft. Rates of shoreline change are presented graphically in figures 21 through 23 and in tables in Appendix A.

To place these measurements in proper context, it should be emphasized that Corpus Christi Bay owes its present shape predominantly to wave erosion during the Holocene sea-level rise and highstand. This erosion has transformed the area from an angular incised river valley (fig. 3) to a nearly circular bay in approximately 10,000 yr, implying an average long-term erosion rate of about 3 ft per yr.

Northern Corpus Christi Bay

The northern shoreline of Corpus Christi Bay extends from Port Ingleside to Indian Point and includes Corpus Christi Bay stations 1 through 17 (fig. 19). Historical shoreline changes were determined from 1867 topographic maps and from 1930 and 1982 aerial photographs.

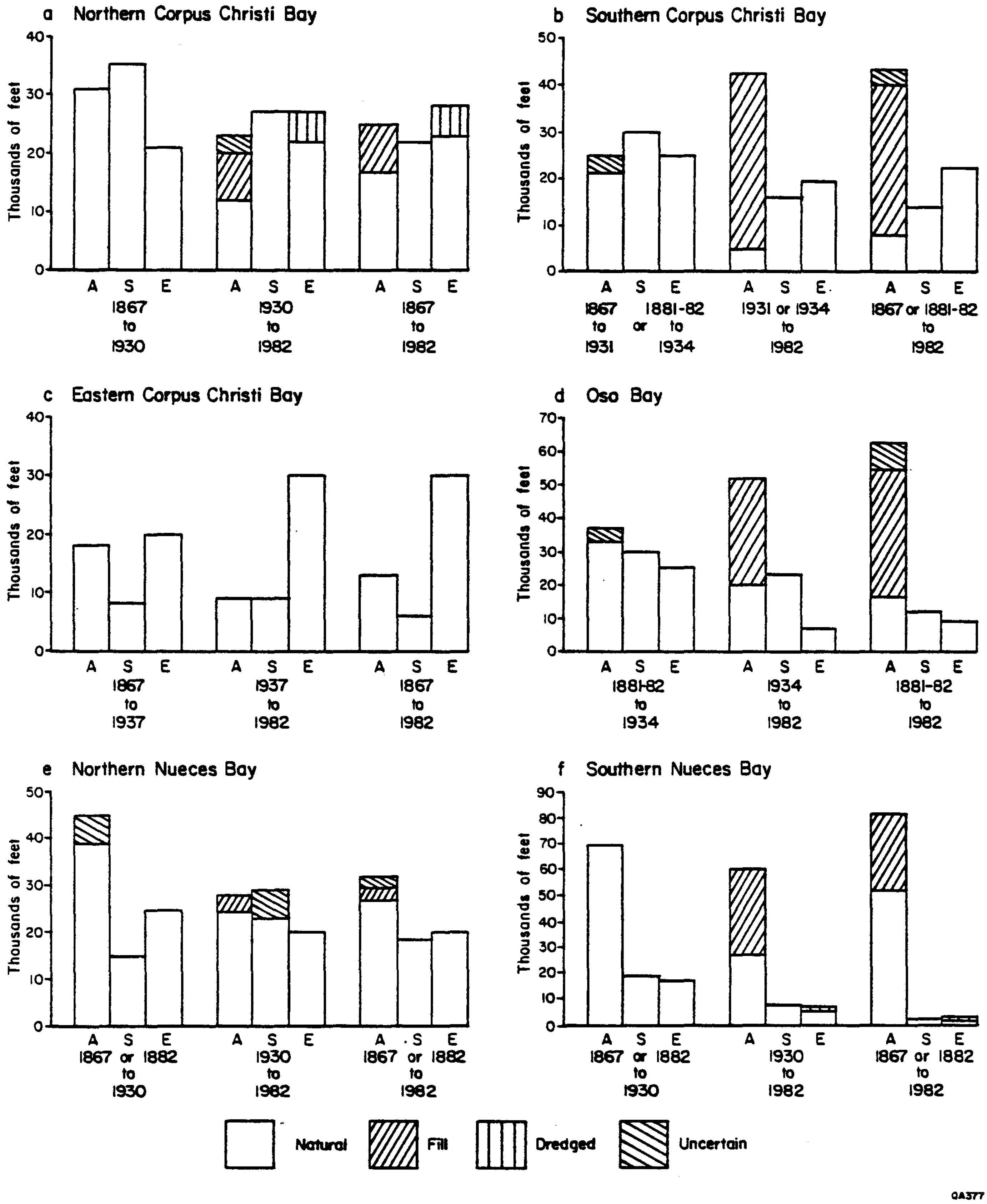

Figure 20. Distribution of accreting (A), stable (S), and eroding (E) linear shoreline segments for early (late 1800's to 1930's), late (1930's to 1982), and cumulative (late 1800's to 1982) periods.

1867 to 1930

Only one major human modification (dredging of the Corpus Christi Ship Channel) had begun by 1930, indicating that most shoreline changes for the area and period were due to natural processes. The 1930 shoreline was generally bayward of its position in 1867; nearly 35 percent of the 1930 shoreline experienced net accretion, whereas 24 percent had net erosion when compared with its 1867 position (fig. 20a). The remainder of the shoreline showed no measurable net accretion or erosion during this period.

The amount of shoreline advance or retreat along northern Corpus Christi Bay during this period was generally small; net rates of change were less than 2 ft per yr for all but two measuring stations (fig. 21a). The largest amount of shoreline retreat (about 240 ft) was measured at station 1 near Port Ingleside. This station is located about 1,000 ft west of a small channel cut into Ingleside sand made before 1930 for the establishment of a dock at Port Ingleside. The largest amount of accretion (about 150 ft) occurred at station 5 on Ingleside Point, a spit building westward from Live Oak Ridge. Ingleside Point has since been separated from Live Oak Ridge by the dredging of La Quinta Channel.

Near Portland, no net change was recorded at stations 13 and 14, indicating a stable shoreline for this period. Station 15 showed a net shoreline retreat of less than 1 ft per yr, whereas stations 16 and 17 on Indian Point Peninsula recorded small amounts of net accretion.

1930 to 1982

During this period, 36 percent of the northern Corpus Christi Bay shoreline experienced measurable net erosion, a significant increase from the 1867 to 1930 period (fig. 20a). In addition, spoil and made land accounted for almost half of the net accreting shoreline in the 1930 to 1982 period.

The magnitude of shoreline advance or retreat was generally less than 2 ft per yr (fig. 22a); rates higher than this were found at stations 4, 5, and 10 and were commonly due to single large events rather than to continuing processes. Net accretion on Ingleside Point of

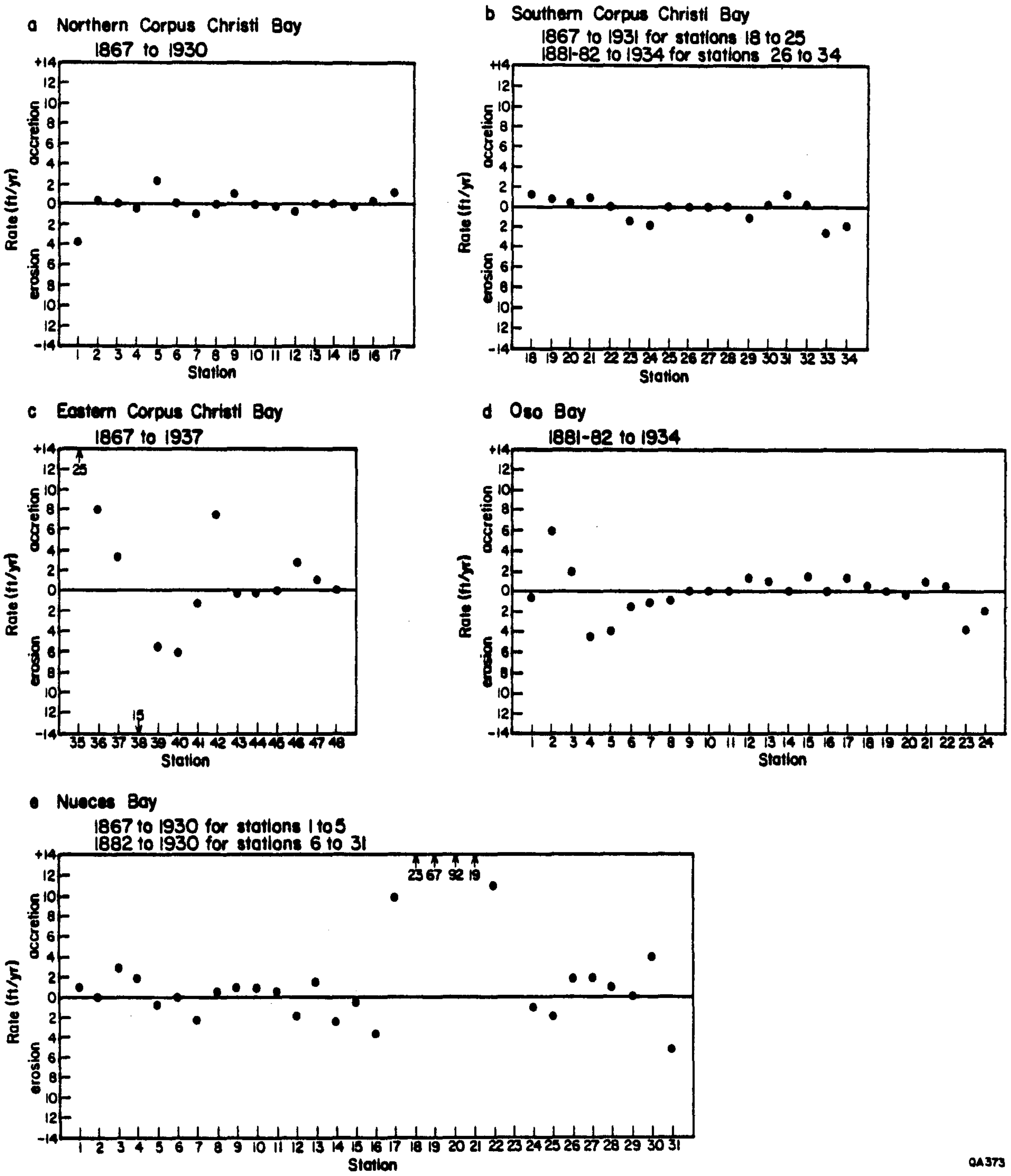

Figure 21. Net rates of change in shoreline position between the late 1800's and the 1930's. Rates higher than 14 ft/yr denoted by arrows and labelled by rate.

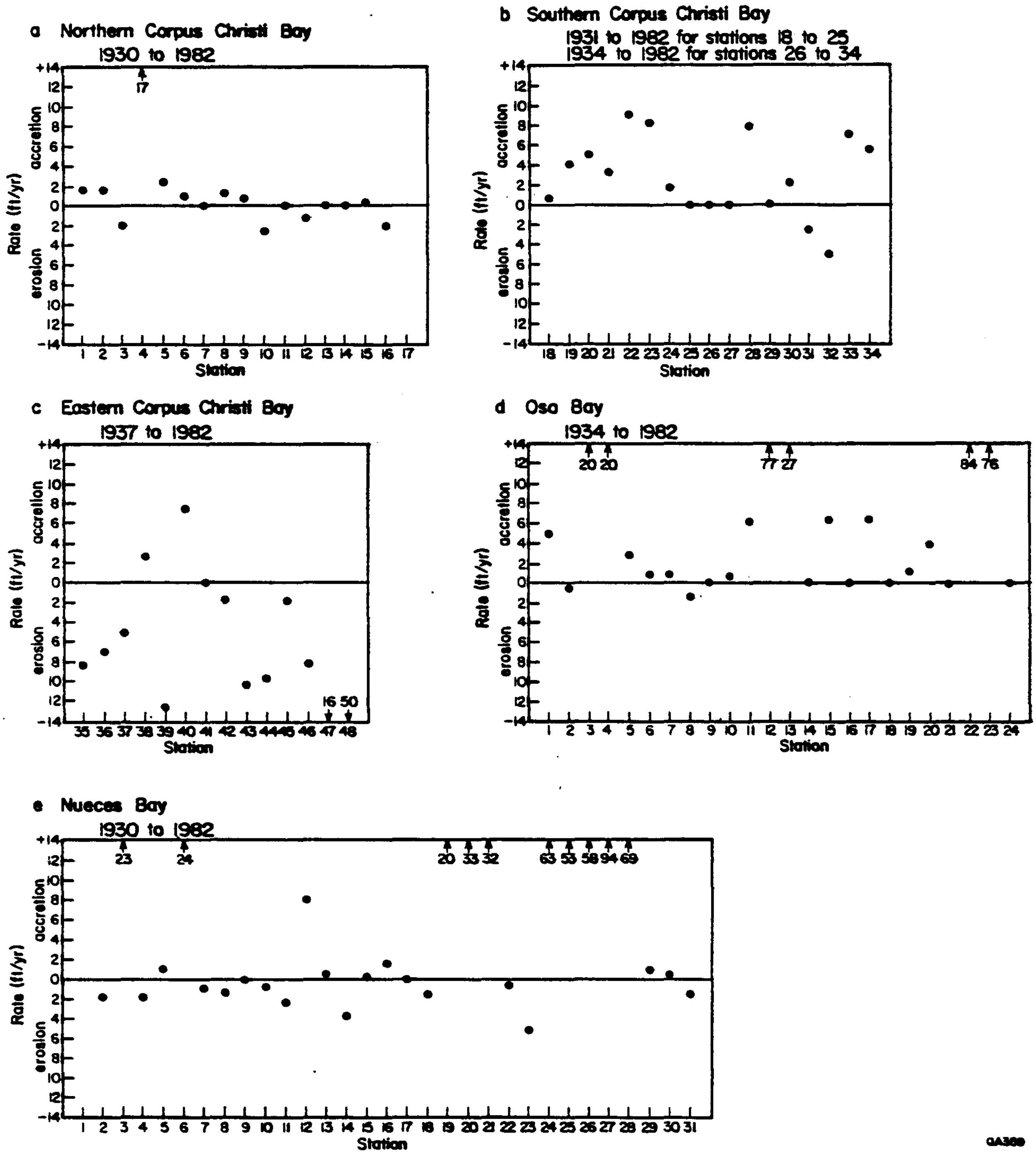

Figure 22. Net rates of change in shoreline position between the 1930's and 1982. Rates higher than 14 ft/yr denoted by arrows and labelled by rate.

878 ft at station 4 and 146 ft at station 5 was due to disposal of dredge material, probably from La Quinta Channel. Net erosion of 108 ft at station 3 was related to the dredging of La Quinta Channel before 1956, whereas net erosion of 144 ft at station 10 was not clearly related to any single event.

Net rates of shoreline change for the Portland area were near zero for this period as well. Station 16 on Indian Point Peninsula had net erosion of 112 ft, in contrast to net accretion for the period 1867 to 1930.

1867 to 1982

Cumulative results over the 115-yr period were similar to those of the constituent periods. Nearly 40 percent of the 1982 northern Corpus Christi Bay shoreline occupied a position landward of that in 1867 (fig. 20a), whereas 33 percent of the shoreline held a position seaward of its position in 1867. A third of the accreting shoreline consisted of spoil or made land.

At all but two stations, net rates of shoreline change were below 2 ft per yr (fig. 23a). Stations 4 and 5 on Ingleside Point experienced net accretion of 840 and 292 ft respectively, caused at least in part by disposal of dredge material. Station 4 showed net erosion before dredge disposal, whereas station 5 exhibited net accretion before disposal. Zero net change was observed at Portland area stations 13, 14, and 15. Station 16 on Indian Point Peninsula, showing net accretion for the period 1867 to 1930, had net erosion in the 1930 to 1982 period of sufficient magnitude to give it net erosion for 1867 to 1982 of 88 ft.

Southern Corpus Christi Bay

Late 1800's to Early 1930's

The earliest time period was unequal for different segments of southern Corpus Christi Bay. At stations 18 to 25 (fig. 19), it lasted from 1867 to 1931, whereas at stations 26 through 34, it lasted from 1881-82 to 1934. This was because early topographic charts and 1930's aerial

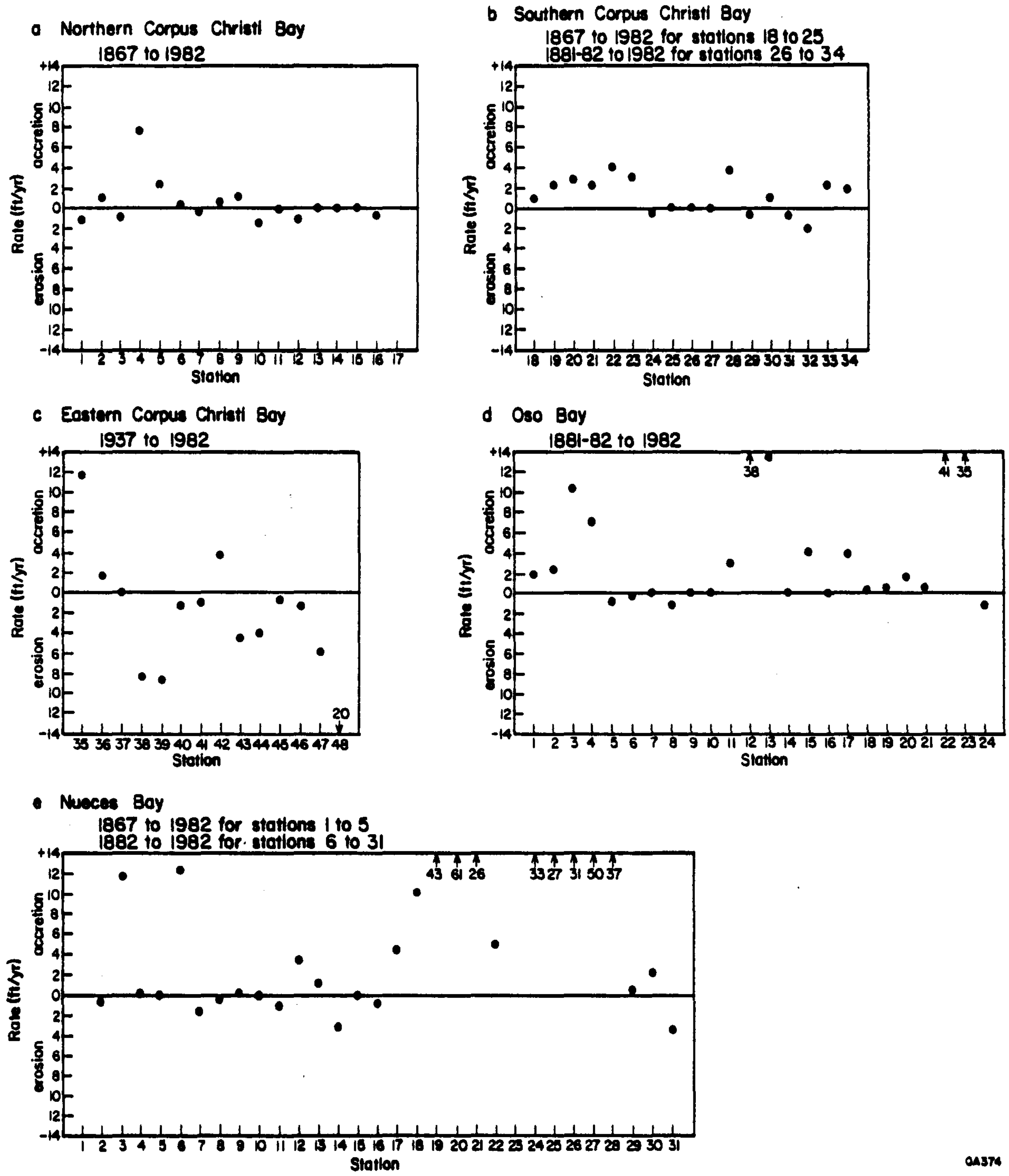

Figure 23. Net rates of change in shoreline position between the late 1800's and 1982. Rates higher than 14 ft/yr denoted by arrows and labelled by rate.

photography were not completed for the entire bay at the same time. This inequality does not appreciably affect the results and interpretations, if rates of change rather than amounts are used for comparison among stations.

Between 1867 and 1931, Corpus Christi grew from a small community of less than 20 blocks near the present-day sea wall to a city many times that size. By 1931, agricultural development behind the Pleistocene bluffs stretched from present-day Cole Park eastward to Oso Bay, and a major engineering project (dredging of the Corpus Christi Turning Basin) had breached Rincon Peninsula. In addition, a breakwater protecting the downtown area had been constructed by this time.

Over 30 percent of the southern shore of Corpus Christi Bay was measurably landward of its 1800's position in the early 1930's (fig. 20b). Net rates of shoreline change were generally less than 2 ft per yr (fig. 21b). Four of the seven stations experiencing net accretion were located in the western half of southern Corpus Christi Bay, whereas three of the five stations recording net erosion were in the eastern half of this segment. Stations 18 through 21 occur in a zone of longshore accumulation from prevailing southeasterly winds (fig. 4); all showed net accretion for the period. Values for these stations ranged up to 1.5 ft per yr. Among the highest rates of change were those at stations 33 and 34 on Encinal Peninsula. Net erosion rates of 2.4 and 1.7 ft per yr, respectively, were observed at these stations.

Early 1930's to 1982

Human modifications have been concentrated along the southern shores of Corpus Christi Bay since the 1930's. By 1938, the Corpus Christi Ship Channel had been extended from the Corpus Christi Turning Basin to Avery Point Turning Basin. By 1956, Tule Lake Channel had been cut inland, the downtown area was extended bayward with fill material, the Corpus Christi seawall was in place, the T-heads had been constructed, and the Corpus Christi Naval Air Station occupied the northern end of Encinal Peninsula. The North Beach nourishment project was completed in 1978 (figs. 13, 14, and 15), and by 1982 most of the shoreline between Rincon

Point and Encinal Peninsula had been stabilized with the emplacement of riprap, bulkheads, and seawalls (fig. 4).

Most of the southern Corpus Christi Bay shoreline (54 percent) exhibited a 1982 shoreline position bayward of that in the early 1930's (fig. 20b). Made land accounted for almost 90 percent of this total. Twenty-five percent of the southern Corpus Christi Bay shoreline occupied a position landward of that in the early 1930's.

Only two stations experienced net erosion during this period (fig. 22b), and both were located on the small spit west of Encinal Peninsula. Several stations had net accretion rates of 1 ft per yr or less and were located approximately midway between Encinal Peninsula and Rincon Peninsula. Net accretion at North Beach stations 18, 19, and 20 was due to beach nourishment (figs. 13 and 14); profiles completed at station 20 after the restoration indicate that the beach is currently eroding (fig. 15). Net accretion of 460 and 412 ft at stations 22 and 23 is caused by landfill behind the Corpus Christi seawall; landfill at Swantner Park accounts for 376 ft of net accretion at station 28. Landfill associated with the construction of Corpus Christi Naval Air Station moved the shoreline bayward about 300 ft near stations 33 and 34.

Late 1800's to 1982

Approximately 28 percent of the southern Corpus Christi Bay shoreline occupied a position in 1982 landward of that in the late 1800's, whereas over 50 percent of the shoreline exhibited net accretion over the same period (fig. 20b). However, over 80 percent of the accreting shoreline had been subject to landfill, and another 8 percent occurred in an area of uncertain 1800's shoreline location. It is certain that the amount of shoreline experiencing net erosion would increase dramatically were these two factors not operating.

Four stations (24, 29, 31, and 32) had net erosion rates for this period; net rates for these stations ranged from less than 1 ft to about 2 ft per yr (fig. 23b). Stations 25 through 27 experienced no measurable change; 10 stations had net accretion rates of a least 1 ft per yr, in general caused by discrete events such as landfilling. Exceptional amounts of accretion were recorded at stations 22, 23, and 28. All are sites of extensive filling at the Corpus Christi seawall, Cole Park, and Swanter Park, respectively.

Eastern Corpus Christi Bay

Shorelines mapped along the bay margin of Mustang Island from 1867 topographic charts and aerial photography from 1937 and 1982 were used to determine shoreline changes for eastern Corpus Christi Bay during these periods (fig. 19, stations 35 to 48). Additional information on historical monitoring in the north Padre and Mustang Island area is contained in White and others (1978).

1867 to 1937

Before 1937, the only major human modifications in the Mustang Island vicinity were dredging and jetty construction at Aransas Pass, beginning in the late 1800's (summarized in Morton and Pieper, 1977), and dredging of the Corpus Christi Ship Channel across Harbor Island. These projects had direct effects on Mustang Island as a whole, but there was no addition or removal of material by fill or dredging on the bay shoreline of Mustang Island between stations 35 and 48.

About 46 percent of the Mustang Island bay shoreline experienced net erosion (fig. 20c), more than any other shoreline segment in the bay system during the same period. Only 18 percent of the shoreline showed no net movement during the period. Natural net rates of change were generally higher on the Mustang Island shoreline than for other bay shoreline segments (fig. 21c). Stations 35 through 37 accreted at net rates of 3 to 25 ft per yr, possibly related to shoaling in Corpus Christi Pass, which was open in 1881-82. Farther north, stations 38 through 41 experienced net erosion at rates of 1 to 15 ft per yr. The southwestern tip of Shamrock Island experienced net accretion of approximately 7 ft per yr at station 42. No change to slight net erosion was observed at stations 43 to 45. Stations 46 through 48 are located in areas of extremely low slope (grass flats) where slight changes in water level produce large lateral displacement of the shoreline.

1937 to 1982

Numerous human and natural changes occurred in this period which have direct and indirect effects on bay shoreline position. Natural changes include the extensive vegetation of dunes and barrier flats on southern Mustang Island (White and others, 1978). This spread of vegetation was well underway by 1956, reducing dune migration and sediment supply at the bay shoreline. Human modifications completed by 1956 were the dredging of Wilson's Cut, Croaker Hole, Atlantic Cut across Shamrock Island, and several canals in Shamrock Cove. Hurricane Celia breached Shamrock Island in 1970, canal dredging across Pelone Island and at Mustang Beach was complete by 1970, and the Corpus Christi Water Exchange Pass (fish pass) was completed in 1972.

In 1982, nearly 62 percent of the shoreline between stations 35 and 48 occupied a position landward of that in 1937 (fig. 20c). This value was almost twice as high as the part of shoreline experiencing net erosion for any other Corpus Christi Bay system segment during the same period. Only two stations (38 and 40) experienced net accretion (fig. 22c). Stations 35 through 37 had net accretion for the period 1867 to 1937, but these stations registered net erosion rates of 5 to 8 ft per yr for 1937 to 1982. Erosion at stations 36 and 37 was probably due to tidal currents near the fish pass. Assuming all erosion at these stations took place since completion of the pass in 1974, rates of erosion since 1974 average 30 to 40 ft per yr. Large net erosion at station 39 occurred during a single event, the dredging of Croaker Hole. Shamrock Island stations 42 through 45 had net erosion rates of 2 to 10 ft per yr. Stations 47 and 48 showed large net rates of erosion, an effect of submergence rather than lateral erosion.

1867 to 1982

In 1982, about 61 percent of the shoreline was located landward of its position in 1867, making eastern Corpus Christi Bay an area of widespread shoreline retreat (fig. 20c). In addition, the magnitude of change in shoreline position from natural processes is consistently larger than in other parts of the bay system (fig. 23c).

For the 115-yr period, stations 35, 36, and 42 experienced net accretion despite net erosion in the period 1937 to 1982. Ten stations recorded net erosion. Extreme net rate of erosion at station 48 was due to submergence rather than erosion. Net rates of erosion at stations 43 and 44 on Shamrock Island increased from less than 1 ft per yr for 1867 to 1937 to about 10 ft per yr for 1937 to 1982, resulting in net erosion rates for 1867 to 1982 of about 4 ft per yr.

Oso Bay

Many promontories and embayments characterize the shoreline of Oso Bay, making the regular placement of measuring stations impractical. Instead of systematic and unbiased station placement, station locations were selected to provide an even distribution of stations in various bay environments. The total length of Oso Bay shoreline is approximately 85,000 ft; the 24 stations selected (fig. 19) give an average station spacing of about 3,500 ft. Amounts of shoreline change for Oso Bay were determined from 1881-82 topographic charts and aerial photography from 1934 and 1982.

1881-82 to 1934

Before 1934, only scattered human modifications had affected Oso Bay. These included road construction connecting Corpus Christi and Encinal Peninsula across the mouth of Oso Bay, bridge construction across the upper reaches of the bay, and a small water impoundment near western Oso Bay.

Percentages of stable, accreting, and eroding shoreline were approximately equal for this early period (fig. 20d). With a few exceptions, rates of net accretion and erosion were 2 ft per yr or less (fig. 21d). Rates of net accretion higher than 2 ft per yr occurred at station 2 on Ward Island. Net erosion greater than 2 ft per yr occurred at stations 4 and 5 in western Oso Bay and at stations 23 and 24, located in an active washover area.

1934 to 1982

Numerous human modifications, both major and minor, have changed the position of the Oso Bay shoreline since 1934. Although there were no major changes in the area between 1934 and 1938, by 1958 the runway at Corpus Christi Naval Air Station had been extended into Oso Bay, the South Padre Island Drive bridge and the government railroad bridge had been built across the bay, sewage disposal had begun in western Oso Bay, and filling associated with oilfield activities had begun. Between 1971 and 1974, excavation of the Barney M. Davis cooling pond and subsequent discharge into Oso Bay produced approximately 0.6 mi^2 (370 acres) of subaerial and subaqueous sediment at the southern end of Oso Bay. By 1982, some of this material had been transported northward by natural processes and partly filled embayments south of the government railroad bridge.

For this period, 64 percent of the 1982 bay shoreline was bayward of its position in 1934 (fig. 20d). If accretion from fill and new sediment from human modifications is subtracted, then only about 25 percent of the bay shoreline showed net accretion. The amount of shoreline experiencing net erosion decreased to less than 10 percent.

Net rates of shoreline change calculated for this period showed larger fluctuations in magnitude than for the 1881-82 to 1934 period (fig. 22d). Exceptionally high rates of net accretion occurred at stations 3, 4, 12, 13, 22, and 23. Station 4 is the site of marsh growth associated with sewage disposal, stations 12 and 13 are located near the area of Davis cooling pond discharge, and stations 22 and 23 occur on landfill sites for the Corpus Christi Naval Air Station. Large net accretion rates of nearly 6 ft per yr occurred at stations 11, 15, and 17; these stations are located in former embayments now being filled by the natural transport of sediment deposited at the head of Oso Bay. Most of the new sediment in the southern portion of Oso Bay is probably related to the excavation of the cooling pond and subsequent water discharge. Two stations recorded net erosion for the period of less than 2 ft per yr; these stations were located on promontories within the bay.

1881-82 to 1982

Changes in shoreline position over this 100-yr period generally reflect changes that have occurred since 1934. There was more accreting shoreline over the 100-yr period than in the period 1934 to 1982 (fig. 20d), indicating that fill and new sediment occupied areas that were previously stable or eroding. Only about 10 percent of the bay shoreline occupied a position in 1982 landward of its position in 1881-82, a value significantly less than that for the 1881-82 to 1934 period. The magnitudes of net rates of change were generally smaller for the 100-yr period than for 1934 to 1982 (compare figs. 22d and 23d), indicating that most of the significant shoreline changes took place during the period 1934 to 1982. In addition, only one station recording erosion in the period 1881-82 to 1934 also recorded erosion in the period 1934 to 1982. Five stations had net erosion for the 100-yr period; rates were 1 ft per yr or less.

Nueces Bay

The earliest shoreline position for Nueces Bay was determined from an 1867 topographic chart that covered the eastern part of Nueces Bay near Portland (fig. 19, stations 1 to 5). The early shoreline position for the remainder of the bay was taken from an 1882 topographic chart. Later shoreline positions were mapped from 1930 and 1982 aerial photography.

Late 1800's to 1930

Changes in shoreline position were predominantly caused by natural processes, though by 1930 dredging of the Corpus Christi Turning Basin resulted in spoil disposal into Nueces Bay along Rincon Peninsula. From the late 1800's to 1930, Portland had grown from a single house to a small community; by 1930 roads had been established north and south of the bay, and agricultural development had spread over the Pleistocene fluvial/deltaic deposits.

Over 50 percent of the 1930 Nueces Bay shoreline held a position seaward of its position in 1867 and 1882 (figs. 20e and 20f). Laterally extensive accretion occurred as a result of marsh progradation in the Rincon Bayou - Whites Point vicinity, near the mouth of the Nueces

River. Net rates of shoreline change for the bay as a whole were generally 2 ft per yr or less, with some exceptions (fig. 21e). High net rates of accretion were reported in the area of active marsh progradation (stations 17 through 22). Rates of accretion for these stations ranged from 10 to 90 ft per yr. The highest net rate of erosion (5 ft per yr) occurred at Rincon Point (station 31).

1930 to 1982

After 1930, human modifications joined natural processes as an important factor in the position of the Nueces Bay shoreline. Between 1930 and 1938, spoil from the dredging of Avery Point Turning Basin was deposited along the southern shore of Nueces Bay. Spoil from the dredging of the Tule Lake Channel had been placed along the southern shore of the bay by 1958; spoil and reworked spoil stretched from the mouth of Nueces Bay to Rincon Peninsula at this time. Extensive oil field development, including the creation of islands and peninsulas to support oil field equipment, had begun near Whites Point. In addition, the construction of a major highway across Rincon Peninsula and Indian Point Peninsula required the placement of fill material in the Portland area. Gum Hollow fan delta prograded into Nueces Bay during the flooding associated with Hurricane Beulah in 1967. By 1971, spoil associated with the dredging of the Tule Lake Channel to its present extent had been placed near the mouth of the Nueces River.

In areas of comparatively small human modification, such as northern Nueces Bay, the lengths of accreting, eroding, and stable shoreline were approximately equal (fig. 20e). However, the 1982 shoreline in southern Nueces Bay predominantly occupied a position bayward of its position in 1930 (fig. 20f). Approximately half of the shoreline accretion in southern Nueces Bay was a result of spoil disposal; marsh growth in western Nueces Bay was the other significant contributor.

Net rates of shoreline change in Nueces Bay were generally less than 2 ft per yr for both accreting and eroding shorelines (fig. 22e). Six stations experienced net erosion in northeastern

Nueces Bay, including two in the Portland vicinity. Only three stations experienced net accretion in northeastern Nueces Bay; high net rates of accretion at stations 3 and 6 are due to landfilling and the rapid progradation of the Gum Hollow fan delta, respectively. Stations 19 through 21 showed net rates of accretion of 20 to 30 ft per yr related to marsh growth in western Nueces Bay. Net erosion was recorded along the northern flanks of subaerial Nueces River deltaic deposits. High rates of net accretion were found at stations 24 through 28, primarily caused by spoil disposal.

Late 1800's to 1982

For northern Nueces Bay, about 45 percent of the 1982 shoreline held a position bayward of its late 1800's position (fig. 20e). In contrast, 93 percent of the shoreline in southern Nueces Bay occupied a position in 1982 bayward of its position in 1882 (fig. 20f). The disparity is caused by rapid marsh progradation and spoil disposal in southern Nueces Bay.

Net rates of accretion and erosion for most bay environments were less than 2 ft per yr (fig. 23e). More stations record net erosion than net accretion in northeastern Nueces Bay, where no widespread marsh growth or landfill has occurred. Extremely high net rates of accretion were recorded in western Nueces Bay during marsh progradation; aerial photography flown in 1959, 1971, and 1974 have shown that marsh progradation stopped between 1930 and 1959. High net rates of accretion caused by spoil disposal were found at several stations in southern Nueces Bay.

CONCLUSIONS

Except for major shoreline advances associated with spoil disposal and minor accretion adjacent to coastal structures, human activities in and near Corpus Christi Bay tend to contribute to shoreline erosion. The widespread alteration of shorelines coupled with decreased and disrupted sediment supply, minor relative sea-level rise, and frequent intense storms is essentially insurmountable. Furthermore, there is no evidence that suggests a long-term reversal in any trend of the major causal factors that promote shoreline erosion. In fact, some studies such as Gornitz and others (1982) have demonstrated that worldwide magnitudes and rates of shoreline recession will increase if sea-level rise maintains or exceeds a pace comparable to that of the past few decades. Considering the cumulative and additive effects of the principal forces, it appears that most unprotected shorelines in Corpus Christi Bay will continue to retreat landward in response to natural erosional conditions that were mainly established before the 1800's, have continued since then, and are likely to persist into the foreseeable future.

ACKNOWLEDGMENTS

Funding for this study was provided by the Texas Energy and Natural Resources Advisory Council (TENRAC) under Contract No. IAC(82-83)-1342. We appreciate the assistance of Jack Bowen and Johnna Nichols of the Texas General Land Office in providing the 1982 aerial photography under a separate TENRAC contract and other photography under an interagency contract with the Bureau of Economic Geology.

Cartographic work was performed by Richard L. Dillon and Dan F. Scranton. The manuscript was typed by Dorothy Johnson and Jana McFarland, under the direction of Lucille C. Harrell. Drafting of text figures was by Richard Platt and photographs were prepared by James A. Morgan.

REFERENCES

Bailey, T. W., 1933, Padre Island: Texas Highway Department Report, September 11, 1933, available through Corpus Christi District Office.

Bernard, H. A., and LeBlanc, R. J., 1965, Resume of the Quaternary geology of the northwestern Gulf of Mexico province, in Wright, H. E., Jr., and Frey, D. G., eds., The Quaternary of the United States: Princeton, N.J., Princeton University Press, p. 137-185.

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, 123 p.

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

Bruun, P., 1962, Sea-level rise as a cause of shore erosion: American Society of Civil Engineers Proceedings, Journal Waterways and Harbors Division, WW1, v. 88, p. 117-130.

Cry, G. W., 1965, Tropical cyclones of the north Atlantic Ocean: U.S. Weather Bureau Technical Paper 55, 148 p.

Curray, J. R., 1960, Sediments and history of Holocene transgression, continental shelf, northwest Gulf of Mexico, in Shepard, F. P., Phleger, F. B., and van Andel, T. H., eds., Recent sediments, northwest Gulf of Mexico: Tulsa, American Association of Petroleum Geologists, p. 221-266.

DePratter, C. B., and Howard, J. D., 1981, Evidence for a sea level lowstand between 4,500 and 2,400 years B.P. on the southeast coast of the United States: Journal of Sedimentary Petrology, v. 51, p. 1287-1295.

Dunn, G. E., and Miller, B. I., 1964, Atlantic hurricanes: Baton Rouge, Louisiana State University Press, 377 p.

Dury, G. H., 1965, Theoretical implications of underfit streams: U.S. Geological Survey Professional Paper 452-C, 43 p.

Emery, K. O., 1980, Relative sea levels from tide-gauge records: Proceedings, National Academy of Science, v. 77, p. 6968-6972.

Etkins, R., and Epstein, E. S., 1982, The rise of global mean sea level as an indication of climate change: Science, v. 215, p. 287-289.

Fisk, H. N., 1944, Geological investigation of the alluvial valley of the lower Mississippi River: Vicksburg, Mississippi River Commission, 78 p.

Flint, R. F., 1971, Glacial and Quaternary geology: New York, John Wiley and Sons, 892 p.

Frazier, D. E., 1974, Depositional-episodes: their relationship to the Quaternary stratigraphic framework in the northwestern portion of the Gulf basin: The University of Texas at Austin, Bureau of Economic Geology Geological Circular 74-1, 28 p.

Froomer, N. L., 1980, Sea level changes in the Chesapeake Bay during historic times: Marine Geology, v. 36, p. 289-305.

Gabrysch, R. K., 1969, Land-surface subsidence in the Houston-Galveston region, Texas: United Nations Educational, Scientific and Cultural Organization (UNESCO), Studies and Reports in Hydrology, Land Subsidence Symposium, v. 1, p. 43-54.

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

Gutenberg, B., 1941, Changes in sea level, postglacial uplift, and mobility of the earth's interior: Geological Society of America Bulletin, v. 52, p. 721-772.

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 No. 61, 54 p.

Hicks, S. D., 1972, On the classification and trends of long period sea level series: Shore and Beach, v. 40, p. 20-23.

———— 1978, An average geopotential sea level series for the United States: Journal of Geophysical Research, v. 83, p. 1377-1379.

Hicks, S. D., and Crosby, J. E., 1975, An average, long period, sea-level series for the United States: National Oceanic and Atmospheric Administration Technical Memoir NOS 15, 6 p.

Holdahl, S. R., and Morrison, N. L., 1974, Regional investigations of vertical crustal movements in the U.S., using precise relevelings and mareograph data: Tectonophysics, v. 23, p. 373-390.

Kier, R. S., and White, W. A., 1978, Land and water resources of the Corpus Christi area, Texas: The University of Texas at Austin, Bureau of Economic Geology Report of Investigations No. 95, 22 p.

Lamb, H. H., 1970, Volcanic dust in the atmosphere: Philosophical Transactions of the Royal Society London, Series A, v. 255, p. 425-533.

LeBlanc, R. J., and Hodgson, W. D., 1959, Origin and development of the Texas shoreline: Gulf Coast Association of Geological Societies Transactions, v. 9, p. 197-220.

Lisitzin, E., 1974, Sea level changes: Elsevier, Amsterdam, Oceanography Series, v. 8, 286 p.

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

Marmer, H. A., 1951, Changes in sea level determined from tide observations: Proceedings, Second Conference on Coastal Engineering, p. 62-67.

McGowen, J. H., 1971, Gum Hollow fan delta, Nueces Bay, Texas: The University of Texas at Austin, Bureau of Economic Geology Report of Investigations No. 69, 91 p.

McGowen, J. H., and Brewton, J. L., 1975, Historical changes and related coastal processes, Gulf and mainland shorelines, Matagorda Bay area, Texas: The University of Texas at Austin, Bureau of Economic Geology, 72 p.

McGowen, J. H., Groat, C. G., Brown, L. F., Jr., Fisher, W. L., and Scott, A. J., 1970, Effects of Hurricane Celia--a focus on environmental geologic problems of the Texas Coastal Zone: The University of Texas at Austin, Bureau of Economic Geology Geological Circular 70-3, 35 p.

Morton, R. A., 1977, Historical shoreline changes and their causes, Texas Gulf Coast: Gulf Coast Association of Geological Societies Transactions, v. 27, p. 352-364.

Morton, R. A., and Pieper, M. J., 1977, Shoreline changes on Mustang Island and north Padre Island (Aransas Pass to Yarborough Pass): The University of Texas at Austin, Bureau of Economic Geology Geological Circular 77-1, 45 p.

Nelson, H. F., and Bray, E. E., 1970, Stratigraphy and history of the Holocene sediments in the Sabine-High Island area, Gulf of Mexico, in Morgan, J. P., and Shaver, R. H., eds., Deltaic sedimentation, modern and ancient: Society of Economic Paleontologists and Mineralogists Special Publication 15, p. 48-77.

Pratt, W. E., and Johnson, D. W., 1926, Local subsidence of the Goose Creek oil field: Journal of Geology, v. 34, p. 577-590.

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

———— 1956, Hurricanes affecting the coast of Texas from Galveston to the Rio Grande: U.S. Department of the Army, Corps of Engineers, Beach Erosion Board Technical Memorandum No. 78, 17 p.

———— 1958, Sedimentology and Quaternary geomorphology of South Texas: Gulf Coast Association of Geological Societies Transactions, v. 8, p. 41-75.

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

Schumm, S. A., 1965, Quaternary paleohydrology, in Wright, H. E., Jr., and Frey, D. G., eds., The Quaternary of the United States: Princeton, New Jersey, Princeton University Press, p. 783-794.

Shalowitz, A. L., 1964, Shore and sea boundaries: U.S. Department of Commerce Publication 10-1, v. 2, 749 p.

Shepard, F. P., and Moore, D. G., 1960, Bays of central Texas coast, in Shepard, F. P., Phleger, F. B., and van Andel, T. H., eds., Recent sediments, northwest Gulf of Mexico: Tulsa, American Association of Petroleum Geologists, p. 117-152.

Simpson, R. H., and Lawrence, M. B., 1971, Atlantic hurricane frequencies along the U.S. coastline: National Oceanic and Atmospheric Administration Technical Memorandum NWS SR-58, 14 p.

Sugg, A. L., Pardue, L. G., and Carrodus, R. L., 1971, Memorable hurricanes of the United States since 1873: National Oceanic and Atmospheric Administration Technical Memorandum NWS SR-56, April, 52 p.

Sumner, H. C., 1946, North Atlantic hurricanes and tropical disturbances of 1945: Monthly Weather Review, v. 74, p. 1-6.

Swanson, R. L., and Thurlow, C. I., 1973, Recent subsidence rates along the Texas and Louisiana coasts as determined from tide measurements: Journal of Geophysical Research, v. 78, no. 15, p. 2665-2671.

Tannehill, I. R., 1956, Hurricanes, their nature and history: Princeton, New Jersey, Princeton University Press, 308 p.

Texas Board of Water Engineers, 1961, Silt load of Texas streams, a compilation report, June 1889-September 1959: Texas Board of Water Engineers Bulletin 6108, p. 221-228.

Texas Parks and Wildlife Department, 1969 through 1975, Shell dredger's reports.

Texas Water Commission, 1964, Suspended-sediment load of Texas streams, a compilation report, October 1959-September 1961: Texas Water Commission Bulletin 6410, 49 p.

Texas Water Development Board, 1967a, Suspended-sediment load of Texas streams, a compilation report, October 1961-September 1963: Texas Water Development Board Report 45, p. 26.

———— 1967b, Dams and reservoirs in Texas, historical and descriptive information, December 31, 1966: Texas Water Development Board Report 48, 257 p.

———— 1970, Suspended-sediment load of Texas streams, a compilation report, October 1963-September 1965: Texas Water Development Board Report 106, p. 26.

———— 1974, Suspended-sediment load of Texas streams, a compilation report, October 1965-September 1971: Texas Water Development Board Report 184, p. 76-78.

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

———— 1968, Report on Hurricane Beulah, 8-21 September 1967: Galveston District Corps of Engineers, 26 p.

———— 1971, Report on Hurricane Celia, 30 July - 5 August 1970: Galveston District Corps of Engineers, 13 p.

———— 1972, Report on Hurricane Fern, 7-13 September 1971: Galveston District Corps of Engineers, 11 p.

———— 1974, Corpus Christi Beach, Texas environmental statement: Galveston District Corps of Engineers, 38 p.

———— 1975, Final environmental statement, maintenance dredging, Corpus Christi Ship Channel, Texas: Galveston District Corps of Engineers, 83 p.

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

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

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 No. 92, 46 p.

Wilkinson, B. H., McGowen, J. H., and Lewis, C. R., 1975, Ingleside strandplain sand of central Texas coast: American Association of Petroleum Geologists Bulletin, v. 59, p. 347-352.

Wright, S. S., 1980, Seismic stratigraphy and depositional history of Holocene sediments on the central Texas Gulf Coast: Master's thesis, The University of Texas at Austin, 123 p.

APPENDIX A

Summary of historical shoreline changes in Corpus Christi, Nueces, and Oso Bays.

Corpus Christi Bay

Station	Dates	Distance (ft)	Rate (ft/yr)	Dates	Distance (ft)	Rate (ft/yr)	Dates	Distance (ft)	Rate (ft/yr)
1	1867 to 1930	-244	-3.9	1930 to 1982	+98	+1.9	1867 to 1982	-146	-1.3
2	"	+28	+0.4	"	+96	+1.8	"	+124	+1.1
3	"	0	0	"	-108	-2.1	"	-108	-0.9
4	"	-38	-0.6	"	+878	+16.9	"	+840	+7.3
5	"	+146	+2.3	"	+146	+2.8	"	+292	+2.5
6	"	0	0	"	+46	+0.9	"	+46	+0.4
7	"	-52	-0.8	"	0	0	"	-52	-0.5
8	"	0	0	"	+78	+1.5	"	+78	+0.7
9	"	+68	+1.1	"	+44	+0.8	"	+112	+1.0
10	"	0	0	"	-144	-2.8	"	-144	-1.3
11	"	-22	-0.3	"	0	0	"	-22	-0.2
12	"	-38	-0.6	"	-64	-1.2	"	-102	-0.9
13	"	0	0	"	0	0	"	0	0
14	"	0	0	"	0	0	"	0	0
15	"	-24	-0.4	"	+24	+0.5	"	0	0
16	"	+24	+0.4	"	-112	-2.2	"	-88	-0.8
17	"	+82	+1.3	"	--	--	"	--	--

Corpus Christi Bay (cont.)

Station	Dates	Distance (ft)	Rate (ft/yr)	Dates	Distance (ft)	Rate (ft/yr)	Dates	Distance (ft)	Rate (ft/yr)
18	1867 to 1931	+90	+1.4	1931 to 1982	+40	+0.8	1867 to 1982	+130	+1.1
19	"	+54	+0.8	"	+216	+4.2	"	+270	+2.3
20	"	+38	+0.6	"	+262	+5.1	"	+300	+2.6
21	"	+78	+1.2	"	+180	+3.5	"	+258	+2.2
22	"	0	0	"	+460	+9.0	"	+460	+4.0
23	"	-80	-1.3	"	+412	+8.1	"	+332	+2.9
24	"	-122	-1.9	"	+84	+1.7	"	-38	-0.3
25	"	0	0	"	0	0	"	0	0
26	1881-82 to 1934	0	0	1934 to 1982	0	0	1881-82 to 1982	0	0
27	"	0	0	"	0	0	"	0	0
28	"	0	0	"	+376	+7.8	"	+376	+3.8
29	"	-52	-1.0	"	0	0	"	-52	-0.5
30	"	+20	+0.4	"	+96	+2.0	"	+116	+1.2
31	"	+74	+1.4	"	-134	-2.8	"	-60	-0.6
32	"	+20	+0.4	"	-238	-5.0	"	-218	-2.2
33	"	-124	-2.4	"	+334	+7.0	"	+210	+2.1
34	"	-88	-1.7	"	+274	+5.7	"	+186	+1.9
35	1867 to 1937	+1750	+25.0	1937 to 1982	-376	-8.4	1867 to 1982	+1374	+11.9

Corpus Christi Bay (cont.)

Station	Dates	Distance (ft)	Rate (ft/yr)	Dates	Distance (ft)	Rate (ft/yr)	Dates	Distance (ft)	Rate (ft/yr)
36	"	+554	+7.9	"	-326	-7.2	"	+228	+2.0
37	"	+225	+3.2	"	-225	-5.0	"	0	0
38	"	-1048	-15.0	"	+108	+2.4	"	-940	-8.2
39	"	-388	-5.5	"	-572	-12.7	"	-960	-8.3
40	"	-425	-6.1	"	+342	+7.6	"	-83	-1.1
41	"	-96	-1.4	"	0	0	"	-96	-0.8
42	"	+516	+7.4	"	-76	-1.7	"	+440	+3.8
43	"	-24	-0.3	"	-468	-10.4	"	-492	-4.3
44	"	-32	-0.5	"	-438	-9.7	"	-470	-4.1
45	"	0	0	"	-88	-2.0	"	-88	-0.8
46	"	+198	+2.8	"	-364	-8.1	"	-166	-1.4
47	"	+60	+0.9	"	-720	-16.0	"	-660	-5.7
48	"	0	0	"	-2246	-50.0	"	-2246	-19.5

Oso Bay

Station	Dates	Distance (ft)	Rate (ft/yr)	Dates	Distance (ft)	Rate (ft/yr)	Dates	Distance (ft)	Rate (ft/yr)
1	1881-82 to 1934	-40	-0.8	1934 to 1982	+242	+5.0	1881-82 to 1982	+202	+2.0
2	"	+308	+5.9	"	-36	-0.8	"	+272	+2.7
3	"	+98	+1.9	"	+954	+19.9	"	+1052	+10.5
4	"	-232	-4.5	"	+932	+19.4	"	+700	+7.0

Oso Bay (cont.)

Station	Dates	Distance (ft)	Rate (ft/yr)	Dates	Distance (ft)	Rate (ft/yr)	Dates	Distance (ft)	Rate (ft/yr)
5	"	-214	-4.1	"	+144	+3.0	"	-70	-0.7
6	"	-72	-1.4	"	+42	+0.9	"	-30	-0.3
7	"	-60	-1.2	"	+42	+0.9	"	-18	-0.2
8	"	-46	-0.9	"	-56	-1.2	"	-102	-1.0
9	"	0	0	"	0	0	"	0	0
10	"	0	0	"	+22	+0.5	"	+22	+0.2
11	"	0	0	"	+292	+6.1	"	+292	+2.9
12	"	+74	+1.4	"	+3690	+76.9	"	+3764	+37.6
13	"	+64	+1.2	"	+1288	+26.8	"	+1352	+13.5
14	"	0	0	"	0	0	"	0	0
15	"	+90	+1.7	"	+326	+6.8	"	+416	+4.2
16	"	0	0	"	0	0	"	0	0
17	"	+78	+1.5	"	+328	+6.8	"	+406	+4.1
18	"	+36	+0.7	"	0	0	"	+36	+0.4
19	"	0	0	"	+50	+1.0	"	+50	+0.5
20	"	-16	-0.3	"	+180	+3.8	"	+164	+1.6
21	"	+54	+1.0	"	0	0	"	+54	+0.5
22	"	+32	+0.6	"	+4046	+84.3	"	+4078	+40.8
23	"	-194	-3.7	"	+3668	+76.4	"	+3474	+34.7
24	"	-108	-2.1	"	0	0	"	-108	-1.1

Nueces Bay

Station	Dates	Distance (ft)	Rate (ft/yr)	Dates	Distance (ft)	Rate (ft/yr)	Dates	Distance (ft)	Rate (ft/yr)
1	1867 to 1930	+64	+1.0	1930 to 1982	--	--	1867 to 1982	--	--
2	"	0	0	"	-88	-1.7	"	-88	-0.8
3	"	+172	+2.7	"	+1194	+23.0	"	+1366	+11.9
4	"	+124	+2.0	"	-94	-1.8	"	+30	+0.3
5	"	-54	-0.9	"	+54	+1.0	"	0	0
6	1882 to 1930	0	0	"	+1254	+24.1	1882 to 1982	+1254	+12.5
7	"	-104	-2.2	"	-36	-0.7	"	-140	-1.4
8	"	+30	+0.6	"	-62	-1.2	"	-32	-0.3
9	"	+52	+1.1	"	0	0	"	+52	+0.5
10	"	+44	+0.9	"	-44	-0.8	"	0	0
11	"	+28	+0.6	"	-108	-2.1	"	-80	-0.8
12	"	-80	-1.7	"	+434	+8.3	"	+354	+3.5
13	"	+74	+1.5	"	+34	+0.6	"	+108	+1.1
14	"	-108	-2.3	"	-190	-3.7	"	-298	-3.0
15	"	-20	-0.4	"	+20	+0.4	"	0	0
16	"	-164	-3.4	"	+84	+1.6	"	-80	-0.8
17	"	+466	+9.7	"	0	0	"	+466	+4.7
18	"	+1096	+22.8	"	-68	-1.3	"	+1028	+10.3

Nueces Bay (cont.)

Station	Dates	Distance (ft)	Rate (ft/yr)	Dates	Distance (ft)	Rate (ft/yr)	Dates	Distance (ft)	Rate (ft/yr)
19	"	+3210	+66.9	"	+1064	+20.5	"	+4274	+42.7
20	"	+4406	+91.8	"	+1690	+32.5	"	+6096	+61.0
21	"	+908	+18.9	"	+1668	+32.1	"	+2576	+25.8
22	"	+532	+11.1	"	-26	-0.5	"	+506	+5.1
23	"	--	--	"	-242	-4.7	"	--	--
24	"	-42	-0.9	"	+3294	+63.3	"	+3252	+32.5
25	"	-78	-1.6	"	+2748	+52.8	"	+2670	+26.7
26	"	+102	+2.1	"	+3012	+57.9	"	+3114	+31.1
27	"	+108	+2.3	"	+4864	+93.5	"	+4972	+49.7
28	"	+58	+1.2	"	+3600	+69.2	"	+3658	+36.6
29	"	0	0	"	+50	+1.0	"	+50	+0.5
30	"	+200	+4.2	"	+26	+0.5	"	+226	+2.3
31	"	-248	-5.2	"	-74	-1.4	"	-322	-3.2

APPENDIX B

Tropical cyclones affecting the Texas coast 1854-1982
(compiled from Tannehill, 1956; Dunn and Miller, 1964; Cry, 1965).

Intensity Classification from Dunn and Miller

	Maximum Winds	Minimum Central Pressures
Minor:	Less than 74	Above 29.40 inches
Minimal:	74 to 100	29.03 to 29.40 inches
Major:	101 to 135	28.01 to 29.00 inches
Extreme:	136 and higher	28.00 inches or less

Year	Area	Intensity	Year	Area	Intensity	Year	Area	Intensity
1854	Galveston southward	major	1902	Corpus Christi	minimal	1942	Upper coast	minimal
1857	Port Isabel	?	1908	Brownsville	?	1942	Matagorda Bay	major
1866	Galveston	minimal	1909	Lower coast	minor	1943	Galveston	minimal
1867	Galveston southward	major	1909	Velasco	major	1943	Upper coast	minor
1868	Corpus Christi	minimal	1909	Lower coast	minimal	1945	Central Padre Island	minor
1871	Galveston	minor	1910	Lower coast	minor	1945	Middle coast	extreme
1871	Galveston	minimal	1910	Lower coast	minimal	1946	Port Arthur	minor
1872	Port Isabel	minimal	1912	Lower coast	minimal	1947	Lower coast	minor
1874	Indianola	minimal	1913	Lower coast	minor	1947	Galveston	minimal
1874	Lower coast	minor	1915	Upper coast	extreme	1949	Freeport	major
1875	Indianola	extreme	1916	Lower coast	extreme	1954	South of Brownsville	minor
1876	Padre Island	?	1918	Sabine Pass	minimal	1955	Corpus Christi	minimal
1877	Entire coast	minimal	1919	Corpus Christi	extreme	1957	Beaumont	minor
1879	Upper coast	minor	1921	Entire coast	minimal	1957	Sabine Pass	minimal
1880	Lower coast	major	1921	Lower coast	minor	1958	Extreme southern coast	minimal
1880	Sargent	?	1922	South Padre Island	minor	1958	Corpus Christi	minimal
1880	Brownsville	major	1925	Lower coast	minor	1959	Galveston	minimal
1881	Lower coast	minimal	1929	Port O'Connor	minimal	1960	South Padre Island	minor
1885	Entire coast	minimal	1931	Lower coast	minor	1961	Palacios	extreme
1886	Upper coast	minor	1932	Freeport	major	1963	High Island	minimal
1886	Entire coast	extreme	1933	Lower coast	minor	1964	Sargent	minor
1886	Lower coast	minimal	1933	Matagorda Bay	minor	1967	Mouth Rio Grande	major
1886	Upper coast	minimal	1933	Brownsville	major	1968	Aransas Pass	minor
1887	Brownsville	minimal	1933	Brownsville	minimal	1970	Corpus Christi	major
1888	Upper coast	minimal	1934	Rockport	minimal	1970	High Island	minor
1888	Upper coast	minor	1934	Entire coast	minor	1971	Aransas Pass	minimal
1891	Entire coast	minimal	1936	Port Aransas	minimal	1973	High Island	minor
1895	Lower coast	minor	1936	Lower coast	minor	1978	Padre Island	minor
1895	Lower coast	minor	1938	Upper coast	minor	1979	Central coast	minor
1897	Upper coast	minimal	1940	Upper coast	minimal	1980	South Padre Island	major
1898	Upper coast	minor	1940	Upper coast	minor	1980	Galveston Island	minor
1900	Upper coast	extreme	1941	Matagorda	minimal	1982	Upper coast	minor
1901	Upper coast	minor	1941	Upper coast	minimal			

APPENDIX C

Materials and Sources

Topographic maps used in the determination of shoreline position.

Date	Name	Source
1867	#1043, Corpus Christi Bay, Texas	National Oceanic and Atmospheric Administration (NOAA)
1867	#1044, Corpus Christi Bay, Texas	NOAA
1882	#1513, Nueces Bay, Texas	NOAA
1881-82	#1626, Shores of Laguna Madre, Texas	NOAA

Aerial photographs used in the determination of shoreline position. Asterisk indicates photography on which measurements were based.

Date	Name	Source
February 1930 to April 1937	* Black-and-white mosaics, 1:24,000	Tobin Research, Inc.
November 1938	Black-and-white mosaics, 1:31,680	U.S. Dept. of Agriculture
January and February 1940	Black-and-white mosaics, 1:63,360	U.S. Dept. of Agriculture
January 1956	Black-and-white mosaics, 1:20,000	U.S. Dept. of Agriculture
December 1958 and January and February 1959	Black-and-white mosaics, 1:24,000	Tobin Research, Inc.
October 1971	Black-and-white mosaics, 1:48,000	Tobin Research, Inc.
June 1974	Black-and-white 1:24,000	General Land Office of Texas
June and July 1982	* False-color infrared, 1:24,000	General Land Office of Texas

The U.S. Geological Survey 7.5-minute quadrangle maps used in the construction of base maps.

Annaville, Texas
Aransas Pass, Texas
Corpus Christi, Texas
Crane Islands, Texas
Gregory, Texas
Odem, Texas
Oso Creek NE, Texas
Port Aransas, Texas
Port Ingleside, Texas
Portland, Texas
Taft, Texas