GEOLOGICAL CIRCULAR 77-1

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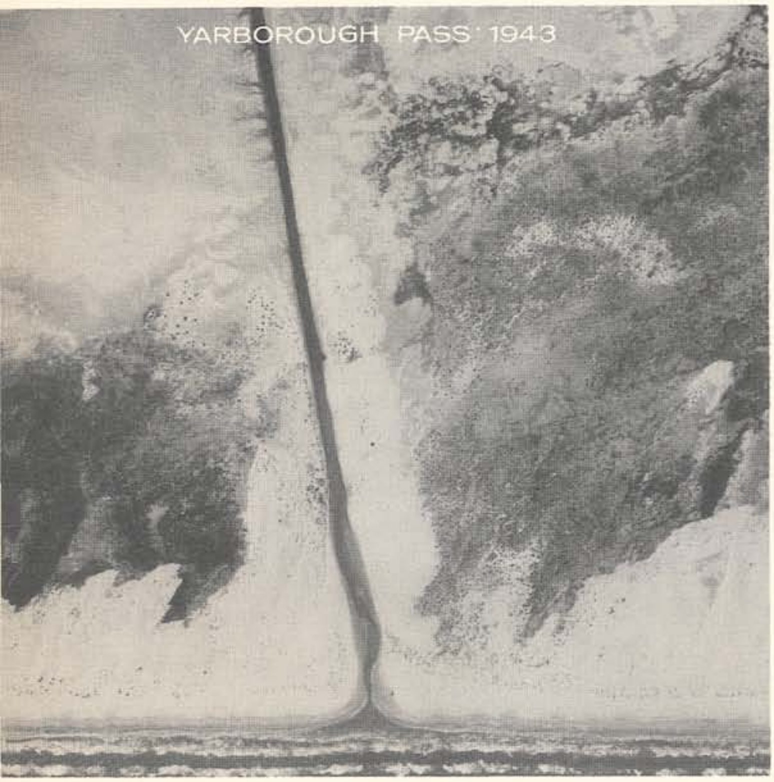
AN ANALYSIS OF HISTORICAL CHANGES OF THE TEXAS GULF SHORELINE

BY ROBERT A. MORTON
AND MARY J. PIEPER



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AN ANALYSIS OF HISTORICAL CHANGES OF THE TEXAS GULF SHORELINE

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Robert A. Morton and Mary J. Pieper

ABSTRACT

Historical monitoring along Mustang and north Padre Islands records the nature and magnitude of changes in position of the shoreline and vegetation line and provides insight into the factors affecting those changes.

Documentation of changes is accomplished by the compilation of shoreline and vegetation line position from topographic maps, aerial photographs, and coastal charts of various vintages. Comparison of shoreline position based on topographic charts (dated 1860-82) and aerial photographs (taken in 1937, 1956-60, 1969-70, and 1974-75) indicates short-term changes of accretion and erosion along the Gulf shoreline between Aransas Pass and Yarborough Pass. *Erosion* produces a net loss in land, whereas *accretion* produces a net gain in land. Comparison of the vegetation line based on the aforementioned aerial photographs indicates short-term cycles of retreat related to storms (primarily hurricanes) and recovery during intervening years of low storm incidence.

Long-term trend or direction of shoreline changes averaged over the 115-year time period of this study indicates that Mustang Island has experienced net erosion with two exceptions. Net accretion adjacent to Aransas Pass, which decreased from 1,600 feet near the south jetty to 350 feet about 2 miles south of the pass, was caused principally by inlet migration and concomitant outbuilding of the north end of the island prior to jetty construction in 1889. Net accretion also occurred about 1.5 miles north of the Nueces/Kleberg county line attendant with the infilling of Packery Channel. The remainder of Mustang Island recorded net erosion ranging from 75 to 350 feet and averaging 225 feet. Net rates of change, however, were low along Mustang Island except where net accretion ranged from approximately 3 feet per year to 14 feet per year. Net erosion on the island ranged from less than 1 foot per year to 3.8 feet per year and averaged 2.0 feet per year.

Net changes on north Padre Island were predominantly accretionary; however, net erosion was recorded from Packery Channel southward for a distance of about 7 miles. Minimum net erosion was 50 feet, whereas maximum net erosion was 500 feet, and average net erosion was 220 feet. The shoreline from 6.5 to 9 miles north of the Kleberg/Kenedy county line experienced only minor net changes of 25 feet or less. The remaining shoreline of north Padre Island experienced net accretion ranging from less than 10 feet to 275 feet; net accretion, which increased southward along the island, averaged 140 feet. Net rates of change were also low along north Padre Island. Net erosion ranged from less than 1 foot to 5.4 feet per year and averaged 2.0 feet per year. Similarly, net accretion varied from less than 1 foot to 3.0 feet and averaged 1.5 feet per year.

Because of limitations imposed by the technique used, rates of change are subordinate to trends or direction of change. Furthermore, values determined for long-term net changes should be used in context. The values for rates of net change are adequate for describing long-term trends; however, rates of short-term changes may be of greater magnitude than rates of long-term changes, particularly in areas where both accretion and erosion have occurred.

Major and minor factors affecting shoreline changes include: (1) climate, (2) storm frequency and intensity, (3) local and eustatic sea-level conditions, (4) sediment budget, and (5) human activities. The major factors affecting shoreline changes along the Texas Coast, including Mustang and north Padre Islands, are relative sea-level conditions, compactional subsidence, and changes in sediment supply. Changes in position of the vegetation line are primarily related to storms.

Studies indicate that changes in shoreline and vegetation line on Mustang and north Padre Islands

are largely the result of natural processes, perhaps expedited by man's activities. A basic comprehension of these physical processes and their effects is requisite to avoid or minimize physical and economic losses associated with development and use of the coast.

INTRODUCTION

The Texas Coastal Zone is experiencing geological, hydrological, biological, and land use changes as a result of natural processes and man's activities. What was once a relatively undeveloped expanse of beach along deltaic headlands, peninsulas, and barrier islands is presently undergoing considerable development. Competition for space exists among such activities as recreation, construction and occupation of seasonal and permanent residential housing, industrial and commercial development, and mineral and resource production.

Studies indicate that shoreline and vegetation line changes on Mustang and north Padre Islands and along other segments of the Texas Gulf Coast are largely the result of natural processes. A basic comprehension of these physical processes and their effects is requisite to avoid or minimize physical and economic losses associated with development and use of the coast.

The usefulness of historical monitoring is based on the documentation of past changes in position of shoreline and vegetation line and the prediction of future changes. Reliable prediction of future changes can only be made from determination of long-term historical trends. Topographic maps dating from 1860 provide a necessary extension to the time base, an advantage not available through the use of aerial photographs which were not generally available before 1930.

Purpose and Scope

In 1971, the Bureau of Economic Geology initiated a program in historical monitoring for the purpose of determining quantitative long-term shoreline changes. The recent acceleration in Gulf-front development provides additional incentive for adequate evaluation of shoreline characteristics and the documentation of where change is occurring by erosion and by accretion, or where the shoreline is stable or in equilibrium.

The first effort in this program was an investigation of Matagorda Peninsula and the adjacent Matagorda Bay area, a cooperative study by the Bureau of Economic Geology and the Texas General Land Office. In this study, basic techniques of historical monitoring were developed; results of the Matagorda Bay project were published by McGowen and Brewton (1975).

In 1973, the Texas Legislature appropriated funds for the Bureau of Economic Geology to conduct historical monitoring of the entire 367 miles of Texas Gulf shoreline during the 1973-1975 biennium. Work versions of base maps (scale 1:24,000) for this project are on open file at the Bureau of Economic Geology. Results of the project are being published in a series of reports; each report describes shoreline changes for a particular segment of the Texas Gulf Coast. This report covering the Gulf shoreline from Aransas Pass to Yarborough Pass (fig. 1) is the seventh in that series.

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. Shoreline changes are the response of the beach 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 beach 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, shoreline changes may persist in one direction, either accretion or erosion, or the shoreline may undergo periods of both erosion and accretion. Thus, the tidal plane boundary defined by the intersection of beach and mean high water is not in a fixed position (Johnson, 1971). Shoreline erosion assumes importance along the Texas Coast because of active loss of land, as well as the potential damage or destruction of piers, dwellings, highways, and other structures.

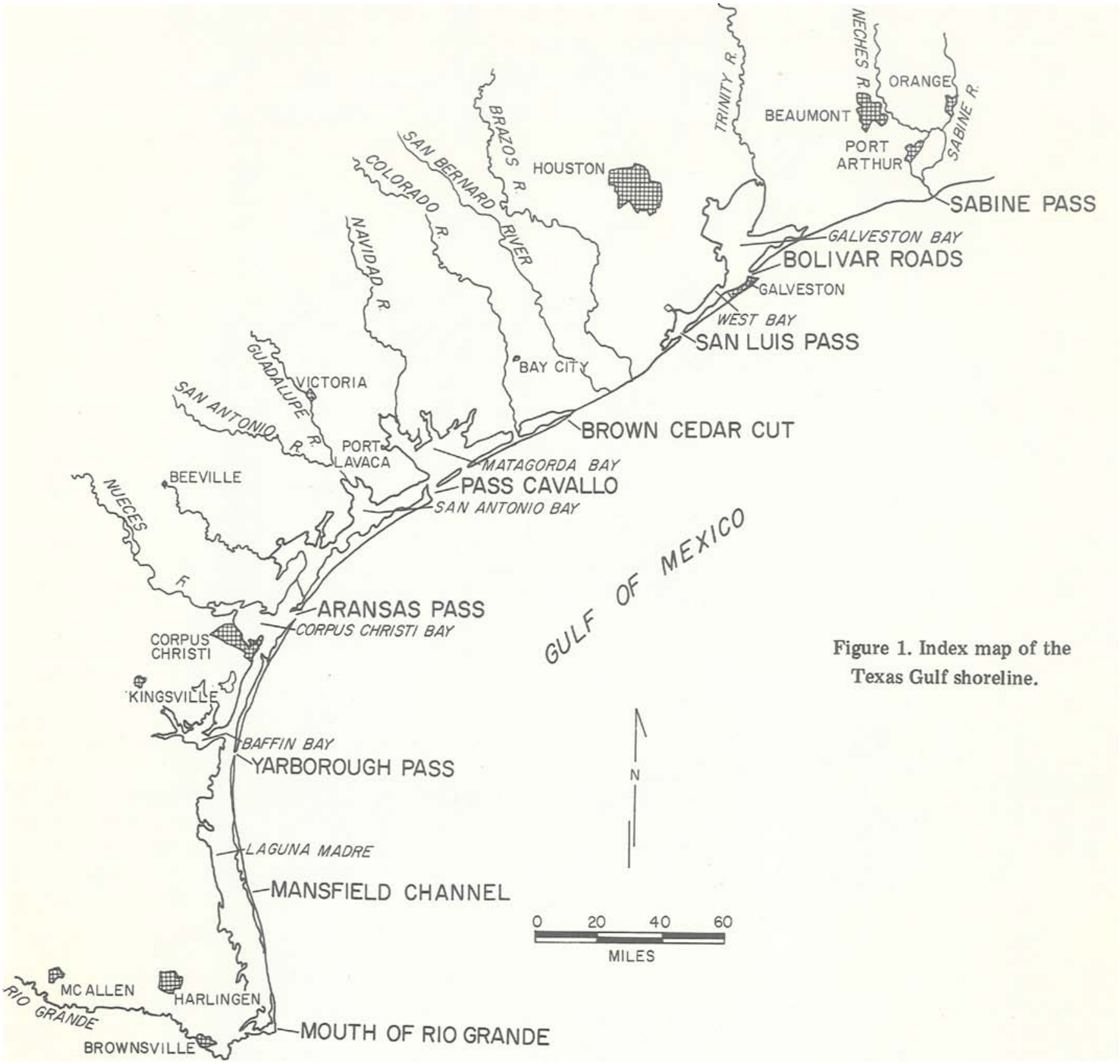

Figure 1. Index map of the Texas Gulf shoreline.

Acknowledgments

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Cooperation of personnel with the U. S. Army Corps of Engineers, Galveston District aided in the acquisition of materials and information. The Texas General Land Office and Texas Highway Department provided access to some of the aerial photographs. Meteorological data were provided by the National Climatic Center and the National Hurricane Center.

HISTORICAL SHORELINE MONITORING

GENERAL METHODS AND PROCEDURES USED BY THE BUREAU OF ECONOMIC GEOLOGY

Definition

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

Sources of Data

Basic data used to determine changes in shoreline position are near-vertical aerial photographs and mosaics and topographic charts. Accurate topographic charts dating from 1850, available through the 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) prior to the early 1930's. Aerial photography 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 representing a diversity of scales and vintages. These photographs show shoreline position based on the sediment-water interface at the time the photographs were taken.

Procedure

The key to comparison of various data needed to monitor shoreline variations is agreement in scale and adjustment of the data to the projection of the selected map base; U. S. Geological Survey 7.5-minute quadrangle topographic maps (1:24,000 or 1 inch = 2,000 feet) 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 from the topographic charts and aerial photographs onto the common base map mechanically with a reducing pantograph or optically with a Saltzman projector. Lines transferred to the common base map are compared directly and measurements are made to quantify any changes in position with time.

Factors Affecting Accuracy of Data

Documentation of long-term changes from available records, referred to in this report as *historical monitoring*, involves repetitive sequential mapping of shoreline position using coastal charts (topographic surveys) and aerial photographs. This is in contrast to short-term monitoring which employs beach profile measurements and/or the mapping of shoreline position on recent aerial photographs only. There are advantages and disadvantages inherent in both techniques.

Long-term historical monitoring reveals trends which provide the basis for projection of future changes, but the incorporation of coastal charts dating from the 1850's introduces some uncertainty as to the precision of the data. In contrast, short-term monitoring can be extremely precise. However, the inability to recognize and differentiate long-term trends from short-term changes is a decided disadvantage. Short-term monitoring also requires a network of stationary, permanent markers which are periodically reoccupied because they serve as a common point from which future beach profiles are made. Such a network of permanent markers and measurements has not been established along the Texas Coast and even if a network were established, it would take considerable time (20 to 30 years) before sufficient data were available for determination of long-term trends.

Because the purpose of shoreline monitoring is to document past changes in shoreline position and to provide basis for the projection of future changes, the method of long-term historical monitoring is preferred.

Original Data

Topographic surveys.—Some inherent error probably exists in the original topographic surveys conducted by the U. S. Coast Survey [U. S. Coast and Geodetic Survey, now called National Ocean Survey]. Shalowitz (1964, p. 81) states "... the degree of accuracy of the early surveys depends on many factors, among which are the purpose of the survey, the scale and date of the survey, the standards for survey work then in use, the relative importance of the area surveyed, and the ability and care which the individual surveyor brought to his task." Although it is neither possible nor practical to comment on all of these factors, much less attempt to quantify the error they represent, 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. Distortions, such as scale changes from expansion and contraction of the base material, caused by reproduction and changes in atmospheric conditions, can be corrected by cartographic techniques. Location of mean high water is also subject to error. Shalowitz (1964, p. 175) states "... location of the high-water line on the early surveys is within a maximum error of 10 meters and may possibly be much more accurate than this."

Aerial photographs.—Error introduced by use of aerial photographs is related to variation in scale and resolution, and to optical aberrations.

Use of aerial photographs of various scales introduces variations in resolution with concomitant variations 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. Stated another way, the line delineating the sediment-water interface represents less horizontal distance on larger scale photographs than a line of equal width delineating the same boundary on smaller scale photographs. Aerial photographs of a scale less than that of the topographic base map used for compilation create an added problem of imprecision because the mapped line increases in width when a photograph is enlarged optically to match the scale of the base map. In contrast, the mapped line decreases in width when a photograph is reduced optically to match the scale of the base map. Furthermore, shorelines mechanically adjusted by pantograph methods to match the scale of the base map do not change in width. Fortunately, photographs with a scale equal to or larger than the topographic map base can generally be utilized.

Optical aberration causes the margins of photographs to be somewhat distorted and shorelines mapped on photographic margins may be a source of error in determining shoreline position. However, only the central portion of the photographs are used for mapping purposes, and distances between fixed points are adjusted to the 7.5-minute topographic base.

Meteorological conditions prior to and at the time of photography also have a bearing on the accuracy of the documented shoreline changes. For example, deviations from normal astronomical tides caused by barometric pressure, wind velocity and direction, and attendant wave activity may introduce errors, the significance of which depends on the magnitude of the measured change. Most photographic flights are executed during calm weather conditions, thus eliminating most of the effect of abnormal meteorological conditions.

Interpretation of Photographs

Another factor that may contribute to error in determining rates of shoreline change is the ability of the scientist to interpret correctly what he sees on the photographs. The most qualified aerial photograph mappers are those who have made the most observations on the ground. Some older aerial photographs may be of poor quality, especially along the shorelines. On a few photographs, both the beach and swash zone are bright white (albedo effect) and cannot be precisely differentiated; the shoreline is projected through these areas, and therefore, some error may be introduced. In general, these difficulties are resolved through an understanding of coastal processes and a thorough knowledge of factors that may affect the appearance of shorelines on photographs.

Use of mean high-water line on topographic charts and the sediment-water interface on aerial photographs to define the same boundary is inconsistent because normally the sediment-water interface 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 tide cycle, slope of the beach, and wind direction when the photograph was taken. The combination of factors on the Gulf shoreline which yield the greatest horizontal displacement of the sediment-water interface from mean high water are low tide conditions, low beach profile, and strong northerly winds. Field measurements indicate that along the

Texas Gulf Coast, maximum horizontal displacement of a photographed shoreline from mean high-water level is approximately 125 feet under these same conditions. Because the displacement of the photographed shoreline is almost always seaward of mean high water, shoreline changes determined from comparison of mean high-water line and sediment-water interface will slightly *underestimate rates of erosion* or slightly overestimate rates of accretion.

Cartographic Procedure

Topographic charts.—The topographic charts are replete with a 1-minute-interval grid; transfer of the shoreline position from topographic charts to the base map is accomplished by construction of a 1-minute-interval grid on the 7.5-minute topographic base map and projection of the chart onto the base map. Routine adjustments are made across the map with the aid of the 1-minute-interval latitude and longitude cells. This is necessary because: (1) chart scale is larger than base map scale; (2) distortions (expansion and contraction) in the medium (paper or cloth) of the original survey and reproduced chart, previously discussed, require adjustment; and (3) paucity of culture along the shore provides limited horizontal control.

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, more adjustments are necessary when working with older 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 one-hundredth of an inch which corresponds to 20 feet on maps with a scale of 1 inch = 2,000 feet (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) multiple rates ($\frac{n^2-n}{2}$, where n represents the number of mapped shorelines) can be obtained at any given point using various combinations of lines.

The beach area is dynamic and changes of varying magnitude occur continuously. Each photograph represents a sample in the continuum of shoreline changes and it follows that measurements of shoreline changes taken over short time intervals would more closely approximate the continuum of changes because the procedure would approach continuous monitoring. Thus, the problems listed above are interrelated, and solutions require the averaging of rates of change for discrete intervals. Numerical ranges and graphic displays are used to present the calculated rates of shoreline change.

Where possible, dates when individual photographs actually were taken are used to determine the time interval needed to calculate rates, rather than the general date printed on the mosaic. Particular attention is also paid to the month, as well as year of photography; this eliminates an apparent age difference of one year between photographs taken in December and January of the following year.

Justification of Method and Limitations

The methods used in long-term historical monitoring carry a degree of imprecision, and 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 years. An important factor in evaluating shoreline changes is the total length of time represented by observational data. Observations over a short period of time may produce erroneous conclusions about the long-term change in coastal morphology. For example, it is well established that landward retreat of the shoreline during a storm is accompanied by sediment removal; the sediment is eroded, transported, and temporarily stored offshore. Shortly after storm passage, the normal beach processes again become operative and some of the sediment is returned to the beach. If the shoreline is monitored during this recovery period, data would indicate beach accretion; however, if the beach does not accrete to its prestorm position, then net effect of the storm is beach erosion. Therefore, long-term trends are superior to short-term observations. Establishment of long-term trends based on changes in shoreline position necessitates the use of older and less precise topographic surveys. The applicability of topographic surveys for these purposes is discussed by Shalowitz (1964, p. 79) who stated:

> "There is probably little doubt but that the earliest records of changes in our coastline that are on a large enough scale and in sufficient detail to justify their use for quantitative study are those made by the Coast Survey. These surveys were executed by competent and careful engineers and were practically all based on a geodetic network which minimized the possibility of large errors being introduced. They therefore represent the best evidence available of the condition of our coastline a hundred or more years ago, and the courts have repeatedly recognized their competency in this respect . . . ."

Because of the importance of documenting changes over a long time interval, topographic charts and aerial photographs have been used to study beach erosion in other areas. For example, Morgan and Larimore (1957), Harris and Jones (1964), El-Ashry and Wanless (1968), Bryant and McCann (1973), and Stapor (1973) have successfully used techniques similar to those employed herein. Previous articles describing determinations of beach changes from aerial photographs were reviewed by Stafford (1971) and Stafford and others (1973).

Simply stated, the method of using topographic charts and aerial photographs, though not absolutely precise, represents the best method available for investigating long-term trends in shoreline changes.

Limitations of the method require that emphasis be placed first on *trend* of shoreline changes with rates of change being secondary. Although rates of change from map measurements can be calculated to a precision well beyond the limits of accuracy of the procedure, they are most important as *relative* values; that is, do the data indicate that erosion is occurring at a few feet per year or at significantly higher rates. Because sequential shoreline positions are seldom exactly parallel, in some instances it is best to provide a range of values such as 10 to 15 feet per year. As long as users realize and understand the limitations of the method of historical monitoring, results of sequential shoreline mapping are significant and useful in coastal zone planning and development.

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. Laws relating to the improvement of rivers and harbors are synthesized in House Documents 379 and 182 (U. S. Army Corps of Engineers, 1940, 1968c).

Relative wave intensity, estimated from photographs, and the general appearance of the beach dictate whether or not tide and weather bureau records should be checked for abnormal conditions at the time of photography. Most flights are executed during calm weather conditions, thus eliminating most of this effect. On the other hand, large-scale changes are recorded immediately after the passage of a tropical storm or hurricane. For this reason, photography dates have been compared with weather bureau records to determine the nature and extent of tropical cyclones prior to the overflight. If recent storm effects were obvious on the photographs, an attempt was made to relate those effects to a particular event.

Considerable data were compiled from weather bureau records and the U. S. Department of Commerce (1930-1974) for many of the dates of aerial photography. These data, which include wind velocity and direction and times of predicted tidal stage, were used to estimate qualitatively the effect of meteorological conditions on position of the sediment-water interface (fig. 2).

Monitoring of Vegetation Line

Changes in position of the vegetation line are determined from aerial photographs in the same manner as changes in shoreline position with the exception that the line of continuous vegetation is mapped rather than the sediment-water interface.

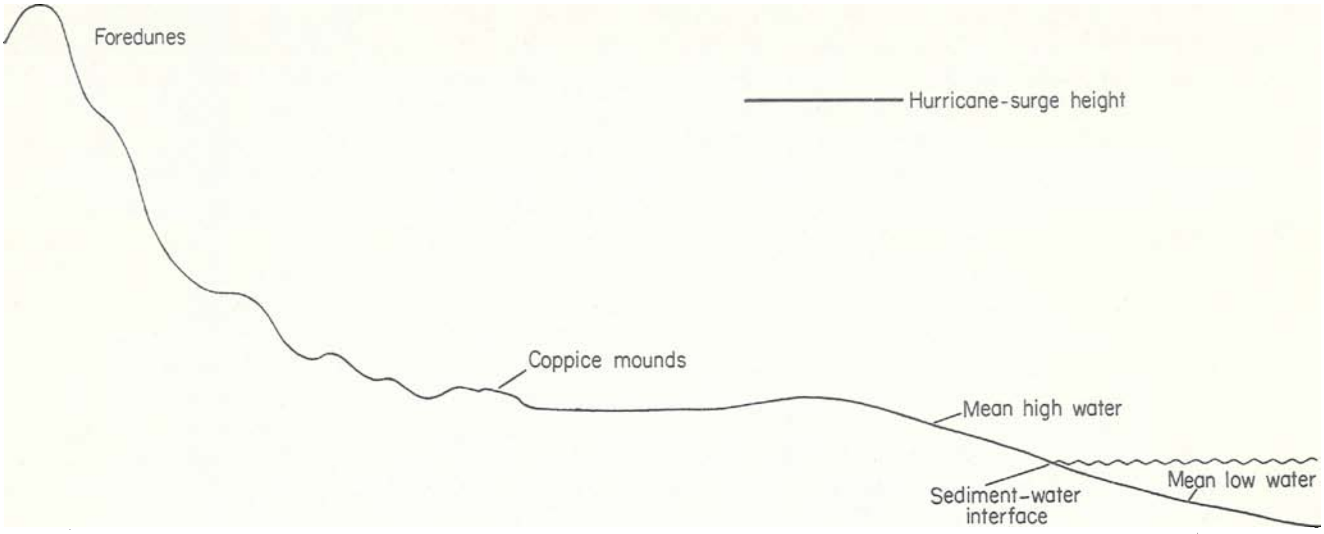

Figure 2. Generalized diagram of beach profile.

Problems associated with interpretation of vegetation line on aerial photographs are similar to those encountered with shoreline interpretation because they involve scale and resolution of photography as well as coastal processes. In places, the vegetation "line" is actually a zone or transition, the precise position of which is subject to interpretation; in other places the boundary is sharp and distinct, requiring little interpretation. The problems of mapping vegetation line are not just restricted to a geographic area but also involve changes with time. Observations indicate that the vegetation line along a particular section of beach may be indistinct for a given date, but subsequent photography may show a well-defined boundary for the same area, or vice versa. In general, these difficulties are resolved through an understanding of coastal processes and a thorough knowledge of factors that affect appearance of the vegetation line on photographs. For example, the vegetation line tends to be ill defined following storms because sand may be deposited over the vegetation or the vegetation may be completely removed by wave action. The problem of photographic scale and optical resolution in determination of the position of the vegetation line is opposite that associated with determination of the shoreline. Mapping the vegetation line is more difficult on larger scale photographs than on smaller scale photographs, particularly in areas where the vegetation line is indistinct, because larger scale photographs provide greater resolution and much more detail. Fortunately, vegetation line is not affected by processes such as tide cycle at the time the photographs were taken.

PREVIOUS WORK

Originating in the middle 1800's and continuing to the present, numerous studies of Aransas Pass have been conducted by the U. S. Army Corps of Engineers. Earlier studies monitored inlet migration, changes in channel width, changes in depth of water within the channel and over the channel-mouth bars, and shoreline changes on northern Mustang Island attendant with jetty construction. Furthermore, beach profiles surveyed by the U. S. Army Corps of Engineers (1968-1974) document short-term Gulf shoreline changes adjacent to Aransas Pass.

In 1933, the Texas Highway Department made a field reconnaissance to evaluate the feasibility of constructing a highway on Padre Island. Bailey (1933) described foredune damage and the location of washover channels on north Padre Island caused by three hurricanes (June, August, and September 1933) that made landfall while that study was in progress.

A regional inventory of Texas shores was conducted by the U. S. Army Corps of Engineers (1971b); however, between Aransas Pass and

Yarborough Pass no areas of critical or non-critical erosion were identified.

Hunter and others (1972) compared 1860-1882 topographic surveys with more recent maps and aerial photographs and concluded that no consistently measurable shoreline changes were evident on north and central Padre Island. It was their opinion that relatively stable conditions extended to about the southern limit of Big Shell Beach or approximately 30 miles north of Mansfield Channel.

In a recent study, Seelig and Sorensen (1973) presented tabular data documenting mean low-water shoreline changes along the Texas Coast; values calculated for the rates of shoreline change along Mustang and north Padre Islands were included in their report. Their technique involved the use of only two dates (early and recent); the change at any point was averaged over the time period between the two dates. Cycles of accretion and erosion were not recognized and few intermediate values were reported; thus, in certain instances, the data are misleading because of technique. Furthermore, data retrieval is difficult because points are identified by the Texas coordinate system. Rates of erosion in the area of interest determined by Seelig and Sorensen (1973, p. 14-15) range from 0 to -36 feet per year with most values falling between -1 and -2 feet per year. Three isolated points of accretion on north Padre Island ranged from 1 to 4 feet per year.

Behrens and Watson (1974) studied changes in and around the Corpus Christi Water Exchange Pass on Mustang Island during its first year of operation. Seasonal and short-term net changes in the shoreline included accretion adjacent to both north and south jetties; however, farther south the beach experienced net erosion.

Changes in the Gulf shoreline have also been mapped by the Bureau of Economic Geology as part of the Environmental Geologic Atlas of the Texas Coastal Zone. The active processes maps of that publication series delineate four shoreline states: (1) erosional, (2) depositional, (3) equilibrium, and (4) artificially stabilized. Although the Gulf shoreline conditions presented in the Coastal Atlas and in the publications of the historical monitoring project are in general agreement, there are certain areas where the acquisition of more recent data indicates conditions that are different from those presented in the Coastal Atlas. The shoreline conditions published in the present report are both current and quantitative rather than qualitative; therefore where there is disagreement, the conditions published herein supersede the conditions presented on the active processes maps of the Coastal Atlas.

PRESENT BEACH CHARACTERISTICS

Texture and Composition

Beach and dune sediment on Mustang and north Padre Islands have been the subject of numerous investigations (Bullard, 1942; Shepard and Moore, 1955, 1956; Beal and Shepard, 1956; Curray, 1956; Mason, 1957; McKee, 1957; Bradley, 1957; Mason and Folk, 1958; Rogers and Strong, 1959; Hsu, 1960; Shepard, 1960a; Shepard and Young, 1961; McBride and Hayes, 1962; Hayes, 1965; Milling and Behrens, 1966; Garner, 1967; Andrews and van der Lingen, 1969; Dickinson and Hunter, 1970; Watson, 1971; Hunter and others, 1972; Moiola and Spencer, 1973; Foley, 1974). The beach between Aransas Pass and Yarborough Pass comprises well-sorted, fine to very fine sand composed primarily of quartz, some feldspar, and heavy minerals (Bullard, 1942; Shepard and Moore, 1955; Mason and Folk, 1958). Black opaques, hornblende, leucoxene, tourmaline, and zircon are the most common heavy minerals with minor amounts of epidote, garnet, rutile, and staurolite (Bullard, 1942; Shepard and Moore, 1955).

Padre Island can be divided into a southern sedimentologic province, characterized by basaltic hornblende and pyroxene from the Rio Grande, and a northern sedimentologic province, characterized by more durable heavy minerals typical of rivers to the north (Bullard, 1942; Shepard and Moore, 1955). The two sedimentologic provinces are separated by a transition zone of approximately 10 miles (Hayes, 1965) located along central Padre Island. North Padre Island falls predominantly within the northern province with only the southernmost 8 miles located in the transition zone (Hunter and others, 1972). Shell on north Padre Island is restricted primarily to *Donax* sp. Say. It varies from less than 1 percent to nearly 50 percent of the sediment content. The 50-percent shell content is found on Little Shell Beach which falls within the northernmost limits of the transition zone (Watson, 1971).

Accumulations of tar ranging from less than 1 inch to several feet in diameter are frequently found on segments of the coast that are not periodically cleaned. The Writers' Roundtable (1950) referred to "great amounts of asphalt on the beach" of Padre Island. Geyer and Sweet (1973) concluded that the tar occurs naturally from offshore seeps.

Beach Profiles

The Gulf shoreline of Mustang and north Padre Islands is characterized by a broad (approximately 200 to 300 feet wide), gently sloping (between 1°30′ and 3°) forebeach. The backbeach is generally horizontal, but along some segments the backbeach slopes slightly toward the dunes. Daily changes in beach appearance reflect changing conditions such as wind direction and velocity, wave height, tidal stage, and the like. Accordingly, beach profiles are subject to change depending on beach and surf conditions that existed when measurements were recorded. In general, the most seaward extent of a beach profile is subjected to the greatest changes because in this area breakpoint bars are created, destroyed, and driven ashore. Under natural conditions, the landward portion of a beach profile is affected only by spring and storm tides of more intense events such as tropical cyclones. With increased use of the beach, however, minor alterations in beach profiles occasionally may be attributed to vehicular traffic and beach maintenance such as raking and scraping.

Beach profiles presented in figure 3 were constructed using the method described by Emery (1961). The profiles, considered typical of certain segments of Mustang and north Padre Islands, represent beach conditions on June 17 and 18, 1975. Beach profiles in the vicinity of Aransas Pass and south of Yarborough Pass have also been surveyed by the Galveston District, U. S. Army Corps of Engineers (1968-1974). Comparison of beach profiles and beach scour patterns on Galveston Island by Herbich (1970) suggests that beach condition (breaker bar spacing and size) may be similar over a relatively long period of time except during and immediately following storm conditions. Therefore, unless beach profiles are referenced to a permanent, stationary control point on the ground, comparison of profiles at different times may be very similar, but the absolute position of the beach can be quite different. Thus, a beach profile may appear similar (except after storms) for a long period of time, but the entire profile may shift seaward (accretion) or landward (erosion) during the same period.

Except in previously active hurricane washovers, abandoned tidal inlets, and active blowout areas, extant dunes on Mustang Island and north Padre Island are relatively continuous and well vegetated. Individual dunes attain heights up to 50 feet on north Padre Island; however, dune heights of 20 to 25 feet are more common. On Mustang Island, dune heights average from 15 to 20 feet.

Because foredunes are the last natural defense against wave attack, experiments on dune growth were conducted by the Corps of Engineers in the washover areas of Packery Channel, Newport Pass, and Corpus Christi Pass (Gage, 1970). These experiments utilized junk car bodies and wood picket (snow) fences to trap sand and initiate dune formation. Results of the experiments were encouraging with regard to establishment of low (generally less than 5 feet) dunes in less than 2 years. However, the project dunes were destroyed by Hurricane Beulah in 1967, emphasizing the inadequacy of low unstabilized dunes as protection against hurricane surge and wave attack.

Additional experiments concerned primarily with dune development using fences and grass plantings on north Padre Island were conducted by the Gulf Universities Research Consortium in cooperation with the Corps of Engineers (Otteni and others, 1972; Dahl and others, 1974).

Beach profile is controlled primarily by wave action. Other factors determining beach characteristics are type and amount of beach sediment available and the geomorphology of the adjacent land (Wiegel, 1964). In general, beach slope is inversely related to grain size of beach material (Bascom, 1951). Thus, beaches composed of fine sand are generally flat. Beach width along the Texas Coast is primarily dependent on quantity of sand available. Beaches undergoing erosion due to a deficit in sediment supply are narrower than beaches where there is an adequate supply or

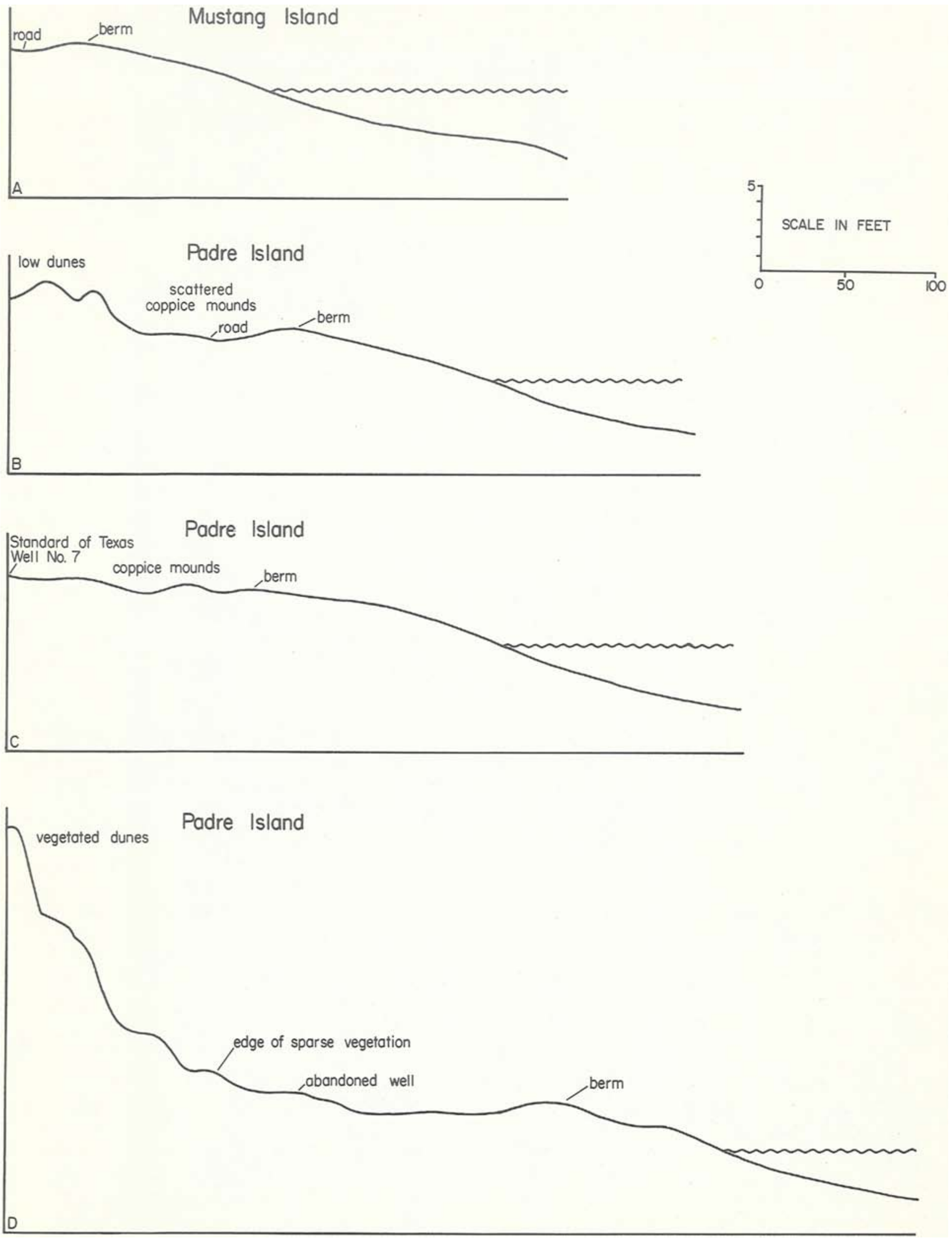

Figure 3. Beach profiles, Aransas Pass to Yarborough Pass, recorded June 17-18, 1975. Locations plotted on figure 6.

surplus of beach sand. For example, the beach on south Padre Island is not as wide as the beach on central Padre Island where there is a greater supply of sand.

HUMAN ALTERATIONS OF NATURAL CONDITIONS

Aransas Pass

Aransas Pass was extremely unstable during the middle to late 1800's. Relocation of the channel axis, changes in channel depth of several feet, and shifting of the inlet-mouth bars accompanied southerly migration of the inlet. Frequent changes caused navigation problems for trade vessels traveling over the outer bars and through the inlet. Not only were the changes frequent but they occurred rapidly as well. It was reported that during one week in 1853, the channel migrated from the north to the south breakers. The new channel provided 9 feet of clearance but the old channel shoaled to 4 feet (U. S. Army Corps of Engineers, 1853). Between 1851 and 1890, depths over the inlet-mouth bars varied from 7 to 10.5 feet (U. S. Army Corps of Engineers, 1890).

Erosion of the north end of Mustang Island and deposition on the south end of San Jose Island progressed at a rate of 260 feet per year (U. S. Army Corps of Engineers, 1900). Because of the importance of Aransas Pass as a route for commercial vessels and because of the continuous changes in channel position and depth, numerous efforts were made by governmental and private interests to stabilize the channel and maintain navigable depths.

The first attempt at improvement was made in 1868 when a 600-foot dike of brush- and stone-filled cribs was constructed on the southern end of San Jose Island to close a swash channel (U. S. Army Corps of Engineers, 1871). This dike was destroyed by storms within 3 years.

Recommendations following a survey of the pass in 1871 included construction of groins and a revetment on the northern extremity of Mustang Island and a jetty extending into the Gulf from the northeast side of the island (U. S. Army Corps of Engineers, 1871). Between 1871 and 1879, the channel depth remained about 7 feet, which prevented the entrance of deeper draft vessels; therefore, trade in the area was severely curtailed. A report based on an 1879 survey (U. S. Army Corps of Engineers, 1879) reiterated the recommendations of 1871 and also proposed construction of a jetty from San Jose Island parallel to the proposed jetty on Mustang Island. The erection of a dam across Corpus Christi Pass had also been proposed since the pass had decreased in size during the previous 30 years (U. S. Army Corps of Engineers, 1880). In May 1880, the work was begun but in August a storm removed most of the improvement.

By 1882, six groins extending from an 870-foot breakwater (fig. 4) along the channel face of Mustang Island, a revetment along the same area, and a 450-foot groin from Harbor Island into Lydia Ann Channel had been built, and construction was proceeding on the south (or Government) jetty. When work was suspended in 1885, the jetty was 5,500 feet long; 1,500 feet of this was shore work. During June 1885, the depth of the channel increased to 11 feet and the rate of southward migration was reduced (U. S. Army Corps of Engineers, 1886). However, the jetty was damaged by a hurricane in September 1885, and the channel shoaled.

A survey made in 1888 revealed that the jetty had subsided an average of 6.2 feet in the 3 years following its construction; more than 1,750 feet of the total length was submerged. During the same time, the channel shoaled to 8.5 feet (U. S. Army Corps of Engineers, 1888). The breakwater and sand fences on Mustang Island had been destroyed, and the groins had settled 9 to 38 feet into the sand. The revetment along the channel face had reduced erosion of Mustang Island to 70 feet per year even though it had been undermined and isolated from the shoreline which had eroded 100 to 200 feet to the south.

During 1888 and 1889, the revetment was lengthened to 2,725 feet and strengthened by an 18-inch-thick wall of riprap from the bottom of the channel to the high-water line. These additions succeeded in stabilizing the northern tip of Mustang Island (U. S. Army Corps of Engineers, 1900). On March 22, 1890, the Aransas Pass Harbor Company was incorporated as a result of the limited annual appropriations and because

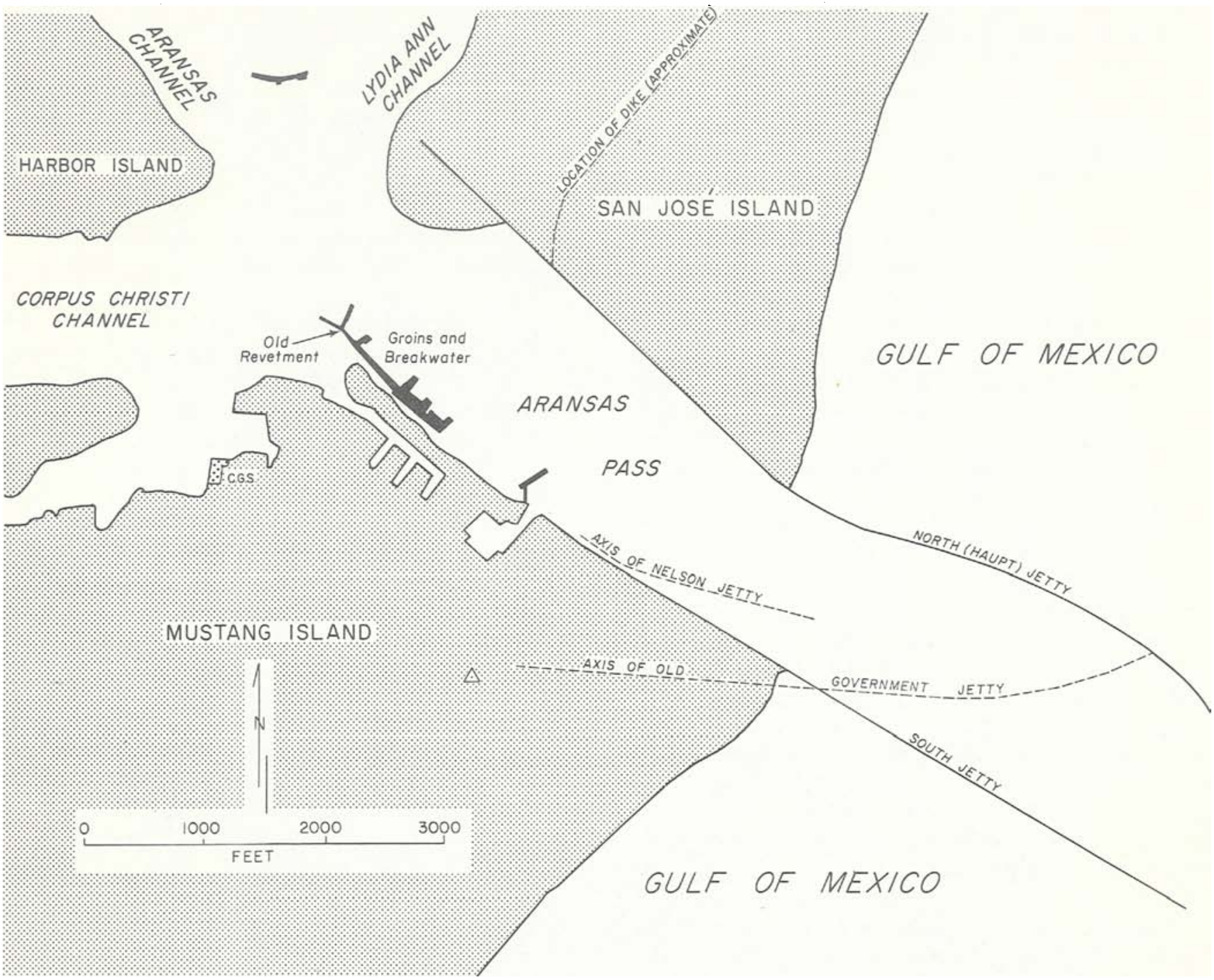

Figure 4. Location of significant coastal structures and alterations of Aransas Pass and adjacent areas.

people believed that proposed improvements for Galveston Harbor would receive any forthcoming large appropriations. In exchange for certain rights and privileges granted by Congress, the company was to provide a deep-water channel (20 feet) through Aransas Pass by 1899 (U. S. Army Corps of Engineers, 1897-1898). In 1892, the south (or Nelson) jetty was constructed 1,800 feet along the southern edge of Aransas Pass. The north (or Haupt) jetty was constructed between August 1895 and September 1896. This jetty extended 5,750 feet shoreward from the 15-foot contour line to a point 1,500 feet offshore from San Jose Island. Only 1,250 feet of the jetty was completed breakwater with the remainder being either core with partial capping or just core (U. S. Army Corps of Engineers, 1897-1898).

The old Government jetty which crossed the channel at an angle of 45 degrees and obstructed further operations was partially removed by dynamite in 1897. The explosion scattered rocks over a considerable area of the channel (Welker, 1899). Examination revealed that the Nelson jetty had been extensively damaged and partially removed by storms and teredos. The north jetty, which had not been completed, also suffered storm damage.

The responsibility of the north jetty was transferred to the Federal Government in 1899 after the Aransas Pass Harbor Company was unable to obtain a 20-foot channel required by contract. Although erosion of the north end of Mustang Island had been eliminated, accretion of San Jose

Island continued and the pass narrowed by 300 feet between 1899 and 1900. In turn, flow velocities increased as revealed by the landward and seaward 650-foot shift of both the inner and outer 18-foot contours (U. S. Army Corps of Engineers, 1900).

By 1900, the outer 1,200 feet of the jetty had settled or had been washed away, and the inner portion, though stable, had been breached in several places (U. S. Army Corps of Engineers, 1900). In addition, a second channel, 600 feet wide and 6 feet deep, had broken through the shoal between San Jose Island and the landward end of the north jetty (U. S. Army Corps of Engineers, 1913). During 1902, a mound of riprap was emplaced to connect the jetty with San Jose Island; gaps in the north jetty were also repaired (U. S. Army Corps of Engineers, 1902).

In 1902, the narrow and sinuous channel through Aransas Pass was navigable only by boats with less than 10 feet of draft. Construction continued slowly on the north jetty, and it was completed, as originally planned, in June 1906 (U. S. Army Corps of Engineers, 1905, 1910). One year later the channel was navigable by boats drawing only 8 feet of water, and it was apparent that the north jetty alone was ineffective in maintaining a deep channel.

Construction of a south jetty, extending from the tip of Mustang Island roughly parallel to the north jetty, had been proposed since 1887. Owing to rapid channel deterioration, work on this jetty was begun in March 1908. The channel deepened and widened starting at the inner end and progressing outward as the south jetty was extended. By 1909, a navigable channel 12 feet deep extended across the outer bar (U. S. Army Corps of Engineers, 1910).

The partially completed south jetty was slightly damaged by the August 1909 hurricane and attendant high tides that inundated the ends of Mustang and San Jose Islands. As construction continued, the south jetty was extended from 4,000 feet in 1910 to 6,400 feet in 1913, and with additional dredging, the channel was deepened to 20 feet (U. S. Army Corps of Engineers, 1913). By 1916, the 7,385-foot south jetty was completed (U. S. Army Corps of Engineers, 1917) and the channel was 22.5 feet deep (U. S. Army Corps of Engineers, 1916).

Extreme hurricanes in 1916 and 1919 caused extensive damage along the central Texas Coast. The 1919 storm caused the channel to shoal from 21 to 14.5 feet, and by June 1920, the channel was still only 17 feet deep; during the next year it was redredged to 24.5 feet (U. S. Army Corps of Engineers, 1920). Another hurricane in June 1921 caused shoaling of Aransas Pass to 22.5 feet (U. S. Army Corps of Engineers, 1921).

Four spurs projecting at right angles from the north jetty into Aransas Pass were constructed in 1922 in order to straighten the channel and move it southward away from the jetty (U. S. Army Corps of Engineers, 1922). This improvement was relatively successful, but the channel maintained its depth of 22.5 feet for several years (U. S. Army Corps of Engineers, 1924).

By 1932, the channel between the jetties had been dredged to 30.7 feet (U. S. Army Corps of Engineers, 1932). Both north and south jetties were repaired in 1936 (U. S. Army Corps of Engineers, 1936) possibly as a result of the 1934 hurricane. In 1937, the channel was deepened to 34.5 feet between the jetties and 35 feet over the outer bar (U. S. Army Corps of Engineers, 1937). In 1947, these areas were again deepened to 33 feet and 39 feet, respectively (U. S. Army Corps of Engineers, 1947-1948), and in 1958, the channel was 38 feet deep between the jetties and 39 feet over the bar (U. S. Army Corps of Engineers, 1958).

Hurricane Carla (1961) caused extensive damage to the jetties but the damage was later repaired (U. S. Army Corps of Engineers, 1962b). The channel was also redredged to 39 feet (U. S. Army Corps of Engineers, 1962c). Hurricane Beulah caused only minor damage but restoration of the channel to its project depth required dredging of over 605,000 cubic yards of sediment (U. S. Army Corps of Engineers, 1968b).

A 1968 act provided for a deepening of the channel to 45 feet between the jetties and 47 feet over the outer bar. These depths were attained as reported in 1972 (U. S. Army Corps of Engineers, 1972a).

Corpus Christi Water Exchange Pass

Intermittent opening and closing of Packery Channel, Newport Pass, and Corpus Christi Pass gave impetus to construction of a jettied channel across Mustang Island connecting Corpus Christi Bay with the open Gulf. The fish or water exchange pass was completed August 1972. Detailed changes of shoreline position and bathymetry in and around the pass during its first year of operation were studied by Behrens and Watson (1974); analyses of tidal hydraulics and inlet stability in the first 6 months were also conducted by Defehr and Sorensen (1973). Maximum discharge recorded at the fish pass was about 4,000 cubic feet per second. Maximum tidal current velocities averaged about 3 feet per second; however, most measured flow velocities were less than 2 feet per second (Behrens and Watson, 1974).

Corpus Christi Pass, Newport Pass, Packery Channel

Three passes located within a 4-mile segment of southern Mustang Island have functioned intermittently as natural tidal inlets (fig. 6). Documentation through the literature of their migration and periods of closure is difficult because Corpus Christi Pass, identified on the U. S. Coast Survey topographic chart (1881-1882), was later referred to as Packery Channel. The northernmost and middle passes are now Corpus Christi Pass and Newport Pass, respectively. Beginning in 1939, attempts were made to reopen Corpus Christi Pass; however, the project was soon abandoned because of rapid siltation and closure (Lockwood and Carothers, 1967). The inability of these inlets to maintain tidal exchange for extended periods may be due to the deepening of Aransas Pass (Collier and Hedgpeth, 1950; Price, 1952). The three passes are reopened periodically by hurricanes but close within a relatively short period of time.

Yarborough Pass

Initial dredging of Yarborough Pass, also referred to as Murdoch's Landing Pass in the literature (Gunter, 1945; Writers' Roundtable, 1950; Collier and Hedgpeth, 1950), was authorized by the Texas Legislature around 1931 (Bailey, 1933) for the purpose of improving water circulation in the Laguna Madre. Dredging commenced December 5, 1940, and was completed in April 1941, but the pass remained open only for 5 months before it was closed by littoral processes (Breuer, 1957). Additional attempts were made to open the pass in November 1942, May 1944, November 1944, and February 1952 (Breuer, 1957); however, all attempts were unsuccessful and the pass has remained closed. Dunes established naturally in the vicinity of the abandoned pass are vegetated and the fore-island area appears to be approaching conditions that existed prior to dredging.

CHANGES IN SHORELINE POSITION

Late Quaternary Time

Significant changes in sea level have occurred along the central Texas Coast during the past 10,000 years (Shepard, 1956, 1960b). Ridge and swale topography from abandoned beach ridges, visible on aerial photographs along the northern part of Mustang Island, attests to the fact that accretion was predominant after sea level reached its stillstand position about 3,000 years before present (fig. 5). Ridge and swale topography on southern Mustang Island and north Padre Island has not been preserved because of inlet migration and eolian processes resulting from a semiarid climate. Radiocarbon methods (Shepard, 1956, 1960b) provide dates for the interpretation of sea-level positions along the central Texas Coast prior to stillstand.

Barrier island development was initiated about 6,500 years ago (Shepard, 1956, 1960b). Vertical accretion of the barrier islands attendant with sea-level rise was augmented by eolian processes. Lateral accretion accompanied landward transport of sediment from the inner shelf as well as transport of shell and sediment from the bottom of Corpus Christi Bay and Laguna Madre. Progradation of Mustang Island and Padre Island, respectively, into Corpus Christi Bay and Laguna Madre was associated with hurricane washover and eolian processes.

During the past several hundred years, conditions that promoted seaward accretion have been altered both naturally and more recently to some extent by man. Consequently, sediment supply to the Texas Coast has diminished and erosion is prevalent. The effects of these changes, as well as the factors related to the changes, are discussed in following sections.

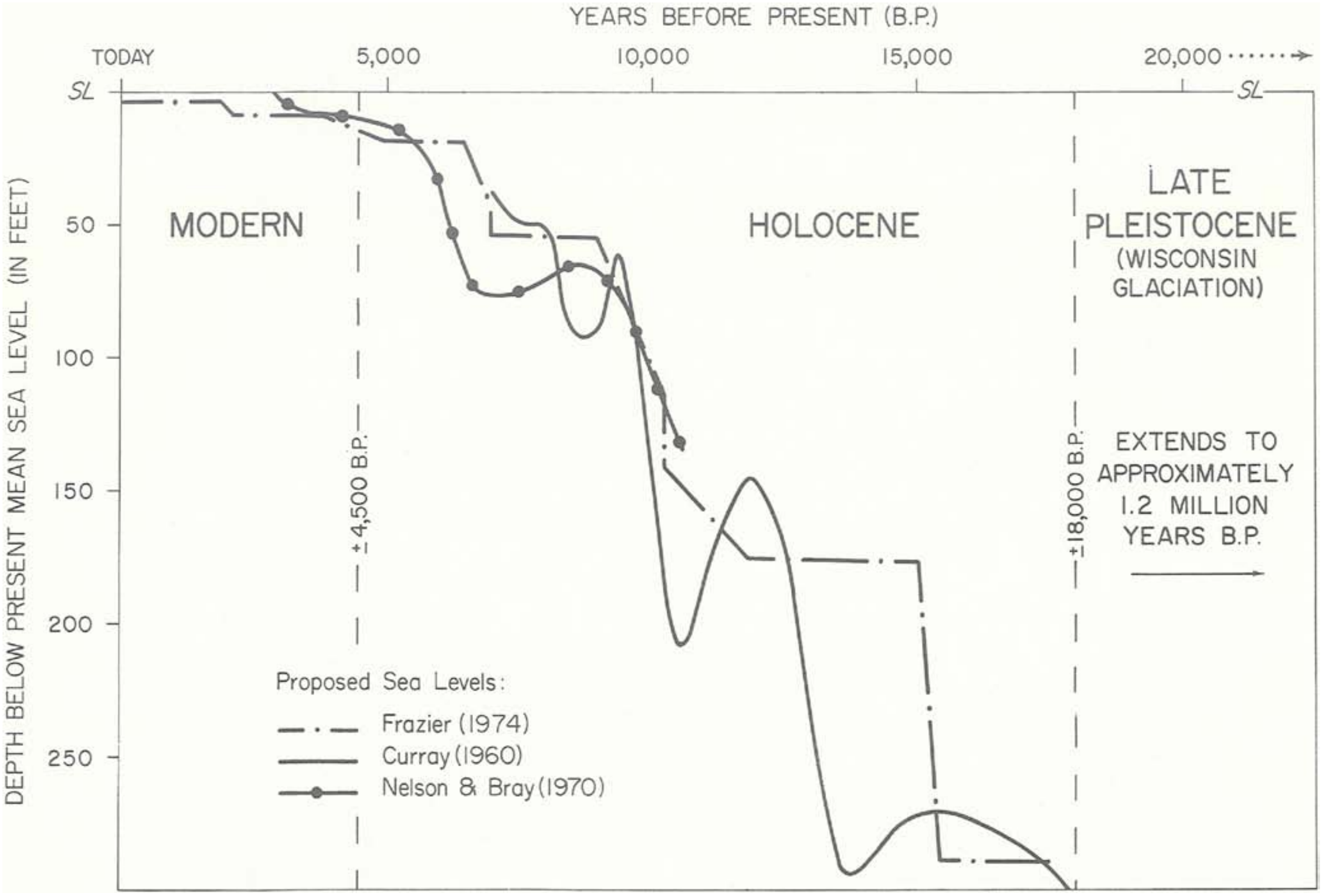

Figure 5. Proposed sea-level changes during the last 20,000 years; sketch defines use of Modern and Holocene. After Fisher and others (1973).

Historic Time

Shoreline changes and tabulated rates of change between 1860-82 and 1974-75, at 51 arbitrary points spaced 5,000 feet apart along the map of Mustang and north Padre Islands (fig. 6), are presented in appendix A. Excluding points in proximity to passes, Mustang Island has experienced three periods of erosion (1860-82 to 1937, 1956-60 to 1969-70, and 1969-70 to 1974-75) and one period dominated by accretion (1937 to 1956-60). In contrast, north Padre Island has undergone two periods dominated by accretion (1882 to 1937 and 1956-60 to 1969), one period of erosion (1969 to 1974-75), and one period of both erosion and accretion (1937 to 1956-60).

The following classification of rates of change is introduced for the convenience of describing changes that fall within a particular range:

Rate (ft/yr)	Designation
0-5	minor
5-15	moderate
15-25	major
>25	extreme

1860-82 to 1937.—Of the 51 points monitored for this time interval, 28 experienced accretion and 23 recorded erosion (appendix A). The greatest accretion occurred on Mustang Island attendant with migration of Aransas Pass and concomitant outbuilding of the north end of the island. Accretion also occurred in the same area after construction of the south jetty (table 1). Maximum accretion was 1,650 feet (point 1) and minimum accretion was 75 feet (point 4). During this same period, however, the shoreline of Mustang Island was dominated by erosion. Between points 5 and 27, erosion ranged from 25 to 450 feet and averaged about 120 feet. From

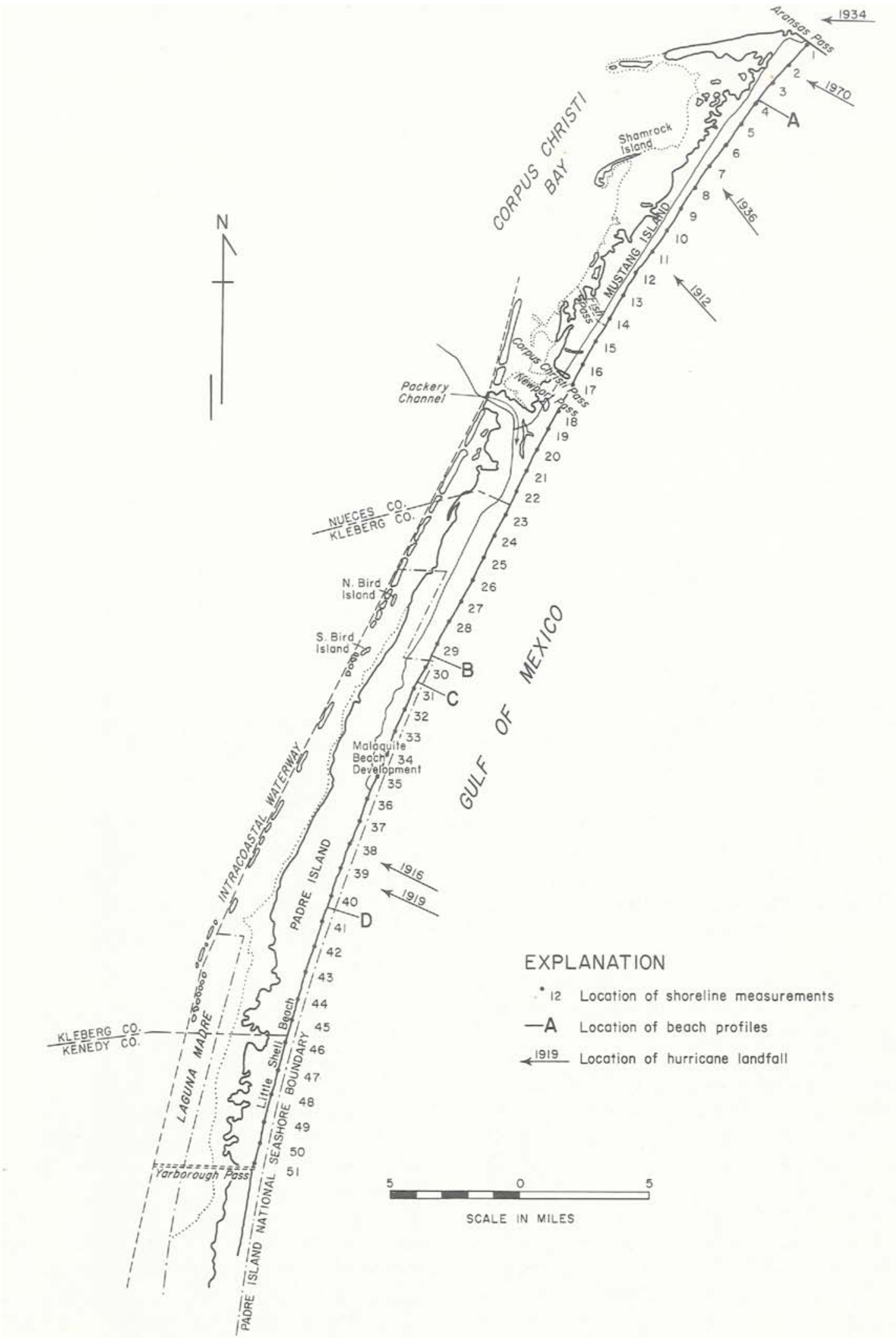

Figure 6. Location map of points of measurement and beach profiles, Aransas Pass to Yarborough Pass.

Table 1. Short-term shoreline changes between 1860-66 and 1937 near Aransas Pass.

Point	Time	Dist. ft	Rate ft per yr	Time	Dist. ft	Rate ft per yr	Time	Dist. ft	Rate ft per yr
1	1860-66-1899	+1150	+31.9	1899-1923	+775	+32.3	1923-1937	-275	-19.6
2	1867-1899	+ 375	+11.7		+600	+25.0		+ 50	+ 3.6
3		- 75	- 2.3		+550	+22.9		+ 25	+ 1.8
4				1867-1923	+175	+ 3.1		-100	- 7.1
5					- 25	-<1.0		- 50	- 3.6
6					-200	- 3.5		+150	+10.7
7					-350	- 6.25		+250	+17.9
8					-450	- 8.0		+325	+23.2

point 27 to Yarborough Pass, however, the shoreline accreted between 25 and 250 feet. With the exception of minor erosion at point 37, accretion averaged about 140 feet.

Anomalous accretion at point 21 (550 feet) was associated with the closing of Packery Channel and establishment of a continuous shoreline in that area. Therefore, the quantitative data should not be construed as an accretion seaward of the general trend of the shoreline. Similarly, moderate erosion recorded at point 22 reflects realignment of the shoreline by elimination of the downdrift offset that existed when Packery Channel was permanently open and functioned as a tidal inlet.

Between 1860 and 1937, the central Texas Coast was affected by numerous hurricanes (appendix B) which either made landfall in the area or were of sufficient size to cause high tides and wind damage in the area even though they made landfall elsewhere. Surge heights of 11.1 and 5.0 feet, respectively, were recorded during the 1919 and 1933 hurricanes (table 2). Bailey (1933) described damage resulting from three storms that made landfall on Padre Island in July, August, and September 1933 and documented 60 feet of foredune erosion at the Nueces/Kleberg county line during the July and August storms. Because field measurements were not possible after the severe September storm, Bailey made an aerial surveillance of damage to the island and reported that major damage was south of Murdoch's Landing (Yarborough Pass), whereas vegetated dunes on north Padre Island sustained only moderate damage (Bailey, 1933).

1937 to 1956-60.—Shoreline changes on Mustang Island were dominated by accretion between 1937 and 1956-60, but changes on Padre Island were variable. Of the 51 points monitored, 24 experienced accretion, 22 underwent erosion, and 5 recorded no change.

On Mustang Island, points 1 through 8 generally experienced both minor accretion and erosion. Average accretion for this segment was 75 feet while average erosion was 25 feet. From point 9 to point 22, accretion ranged from a minimum of 25 feet to a maximum of 175 feet and averaged approximately 110 feet. The shoreline was relatively stable at points 20 and 21 where no change was recorded.

Shoreline changes between points 23 and 39 were dominated by erosion. Minimum erosion of less than 10 feet occurred at points 27 and 36 and maximum erosion of 275 feet was recorded at point 30; average erosion for this shoreline segment was approximately 115 feet. Minor accretion of 50 feet was recorded at points 26 and 37.

From point 40 to Yarborough Pass, the shoreline was predominantly stable or accretionary. The shoreline remained relatively unchanged at points 40 and 41, while minimum

Table 2. Maximum hurricane surge height recorded along the central Texas Coast, 1916-1975.

Date	Surge Height (feet)	Location	Reference
1916	9.2	central Padre Island	Cry, 1965
1919	11.1	Port Aransas	Sugg and others, 1971
1921	7.1	Pass Cavallo	Cry, 1965
1933 (July)	5.0	Port Aransas	Price, 1956
1933 (Aug.)	4.5	Port Aransas	Bailey, 1933
1933 (Sept.)	8.0	Corpus Christi	Sugg and others, 1971
1934	10.2	Rockport	U. S. Army Corps of Engineers, 1953
1941	11.0	Matagorda	Sugg and others, 1971
1942	13.8	Port O'Connor	Sugg and others, 1971
1945	4.0	Port Aransas	Sumner, 1946
1949	8.0	Matagorda	Sugg and others, 1971
1961 (Carla)	9.3	Port Aransas	U. S. Army Corps of Engineers, 1962a
1967 (Beulah)	8.0	Port Aransas	U. S. Army Corps of Engineers, 1968a
1970 (Celia)	9.2	Port Aransas	U. S. Army Corps of Engineers, 1971c
1971 (Fern)	3.1	Port Aransas	U. S. Army Corps of Engineers, 1972b

accretion of less than 10 feet occurred at point 42. Maximum accretion of 200 feet occurred at points 50 to 51 and point 45 recorded no change. Average accretion for this segment was approximately 110 feet. Aerial photographs covering the 1956-60 time period (appendix C) were not available for points 46 and 47; however, coverage was continuous from points 48 through 51. Supplementary 1943 aerial photographs used in the compilation of shoreline changes at points 46 and 47 (appendix C) also included points 48 through 51 (table 3). It is of interest to note that between 1937 and 1943, the shoreline from points 46 to 51 eroded from a minimum of 100 feet at points 49 through 51 to a maximum of 225 feet at point 47, whereas shoreline changes for points 48 through 51 based on the 1937 to 1960 time interval were accretionary. The short-term erosion between 1937 and 1943 may have been attributed to a major hurricane which crossed Matagorda Bay in August 1942. Surge data were not available for north Padre Island; however, Price (1956) noted that Corpus Christi Pass was reopened during that storm. Storm frequency did not diminish during this time period even though storm intensity was minor in the study area. Most of the tropical cyclones affected either the upper or lower coast and not the central coast. Except for the 1945 hurricane, those few storms that impacted Mustang and north Padre Islands caused only minor damage.

Shoreline accretion on Mustang Island between 1937 and 1958 was not restricted to the Gulf shoreline but occurred on the bay shoreline also. Some bay shoreline accretion can be attributed to placement of spoil, but spoil does not account for all the accretion or for its widespread and relatively consistent nature. There are several possible explanations for a period of general accretion, including changes in sediment supply

Table 3. Short-term shoreline changes between 1937 and 1960 near Yarborough Pass.

Point	Time	Dist. ft	Rate ft per yr	Time	Dist. ft	Rate ft per yr
48	1937-1943	-200	-33.3	1943-1960	+300	+17.1
49		-125	-20.8		+275	+15.7
50		-100	-16.7		+300	+17.1
51		-100	-16.7		+300	+17.1

and changes in relative sea-level conditions. An influx of additional sediment from a nearby source such as a river could cause accretion. In the Mustang Island area, however, no new sediment sources are apparent; in fact, recent increases in erosion on Mustang and San Jose Island suggest that the amount of sand available is actually decreasing. It is also unlikely that any new influx of sediment could affect such widely spaced areas in such a similar manner.

Another explanation for the anomalous accretion would be unusual meteorological conditions. For example, strong southeast winds could blow water away from the bay shoreline and produce apparent accretion. However, this would not account for accretion on both the Gulf and bay shorelines. Perhaps the most likely explanation is that the apparent accretion during the middle fifties was, in part, due to a regional lowering of sea level. Relative sea-level curves for Galveston, Freeport, and Port Isabel (Swanson and Thurlow, 1973), as well as an average sea-level curve for the United States (Hicks and Crosby, 1975), all show a minor lowering of sea level in the mid-1950's. Therefore, sea-level lowering is postulated as a mechanism to partially account for the accretionary trend.

Most of the State was affected by drought conditions between 1950 and 1956; the most severe drought occurred between 1954 and 1956 (Lowry, 1959). This extended drought period was manifested by reduced riverine discharge into the bays and by excessive evaporation in the coastal areas. The net effect of these conditions would be a general lowering of water level.

This lowering is clearly demonstrated by the 1956 aerial photographs; however, it is uncertain what effect the drought had on sea level in 1958 and 1960.

1956-60 to 1969-70.—Between 1956-60 and 1969-70, shoreline changes along Mustang Island were predominantly erosional, but changes along north Padre Island were dominated by accretion. Of the 51 points monitored, 22 points experienced erosion, 22 recorded accretion, and 7 recorded no change.

Sixteen of the 22 points that recorded erosion were on Mustang Island between points 1 and 19. Maximum erosion of 175 feet was reported at points 3 and 4, minimum erosion of less than 10 feet was reported at point 11, and average erosion for this segment was approximately 75 feet. Exceptions to this erosional trend were minor accretion of less than 10 feet at point 14 and relative shoreline stability at points 13 and 16.

A transition zone of relative shoreline stability between points 20 and 26 separated shoreline segments dominated by erosion and accretion. All points along that segment recorded no change except for minor accretion and erosion at points 23 and 25, respectively. The shoreline from point 27 through point 47 experienced substantial accretion ranging from 50 feet at points 37 and 43 to 325 feet at point 47; average accretion was 150 feet. Minor erosion of 25 feet was recorded at point 29. The remaining portion of Padre Island (points 48 through 51) experienced erosion ranging from 75 feet at point 49 to 150 feet at points 50 and 51.

Two major hurricanes affected this segment of the coast between 1956-60 and 1969-70; Hurricane Carla (1961) made landfall near Pass Cavallo, and Hurricane Beulah (1967) crossed the coast just south of Brownsville. Post-Carla aerial photographs from Aransas Pass to point 6 indicate that erosion was greatest adjacent to the south jetty. South of the jetty, discontinuous foredunes were eroded approximately 50 feet; however, in areas of a well-developed foredune ridge, little damage was incurred. Based on field observations on Mustang Island, McBride and Hayes (1962) documented that a belt of low foredunes 60 to 150 feet wide was removed by Carla. Wave-cut cliffs up to 10 feet high were observed by Hayes (1967) who reported foredune erosion of 150 to 300 feet on Mustang Island.

Aerial photographs taken shortly after Beulah (appendix C) from Packery Channel to Yarborough Pass show that greatest erosion along this segment occurred in the vicinity of Packery Channel which was reopened by storm surge. By October 1969, however, the channel had narrowed from approximately 600 feet to 150 feet. In general, storm damage was restricted to areas which lacked a well-developed foredune ridge.

1969-70 to 1974-75.—During this period, shoreline retreat was predominant on Mustang and north Padre Islands as erosion was recorded at 49 of the 51 points monitored. The only exceptions were minor accretion (25 feet) at point 3 and relative stability recorded at point 48.

Erosion on Mustang Island (points 1 through 21) ranged from 50 feet at point 2 to 225 feet at points 13 and 14; average erosion was 140 feet. On north Padre Island (points 22 through 51), minimum erosion of 25 feet was recorded at points 46, 47, 50, and 51, whereas maximum erosion of 200 feet occurred at point 41; average erosion was about 100 feet.

Apparently, magnitudes and rates of erosion between 1969-70 and 1974-75 are exaggerated because of tidal differences during respective times of photography. Low tide conditions during the 1969-70 overflight and high tide conditions during the 1974-75 overflight tend to reduce estimated amounts and rates of erosion between 1956-60 and 1969-70 and to increase estimated amounts and rates of erosion between 1969-70 and 1974-75. To compensate for the tidal differences, shoreline changes were averaged for the entire period 1956-60 to 1974-75. These data indicate that the most recent trend is erosion but at reduced rates. Between 1956-60 and 1974-75, shoreline erosion ranged from 25 to 275 feet and averaged 150 feet or 9.6 feet per year. A notable exception was the segment between points 30 and 39 where the shoreline either was relatively stable or accreted between 25 and 100 feet.

Hurricanes Celia (1970) and Fern (1971) affected this segment of the shoreline between 1970 and 1975. Celia, an intense storm of relatively small size, is noted for damage associated with extremely high winds. Although storm surge of 9.2 feet was recorded at Port Aransas (table 2), McGowen and others (1970) reported that no foredune erosion was observed on Mustang Island after Celia. Hurricane Fern was a relatively small, low-intensity storm that produced open-coast surge of less than 4 feet at Port Aransas (U. S. Army Corps of Engineers, 1972b). Following Fern, Davis (1972) observed that storm damage was restricted to the beach.

Net Historic Changes (1860-82 to 1974-75)

Calculations from previously determined changes provide information on the net effect of shoreline retreat and advance along Mustang and north Padre Islands (appendix A and figure 7). Using the earliest shoreline as a base line, the comparison is equal to the difference between the earliest and latest shorelines.

Net changes along Mustang Island have been predominantly erosional. Net erosion ranged from 75 to 350 feet and averaged 225 feet. Net accretion between points 1 and 3 was the result of inlet migration and outbuilding of the north end of the island prior to jetty construction in 1889. The shoreline continued to accrete shortly after construction of the jetties, but subsequent changes along this segment were predominantly erosional. At point 21, short-term accretion attendant with the infilling of Packery Channel between 1882 and 1937 influenced the overall net change.

Net erosion along north Padre Island decreased southward from 500 feet at point 22 to 50 feet at point 30; average net erosion for this segment was 220 feet.

Net accretion was recorded from point 31 to Yarborough Pass except at point 37, which recorded no net change, and points 38 and 39, where minor net erosion (25 feet) occurred. Maximum net accretion for this segment was 275 feet and minimum net accretion was less than 10 feet; average net accretion was 140 feet. Since 1960, however, the shoreline between points 40 and 51 has been erosional.

Rates of change were also calculated for net change between 1860-82 and 1974-75; the results

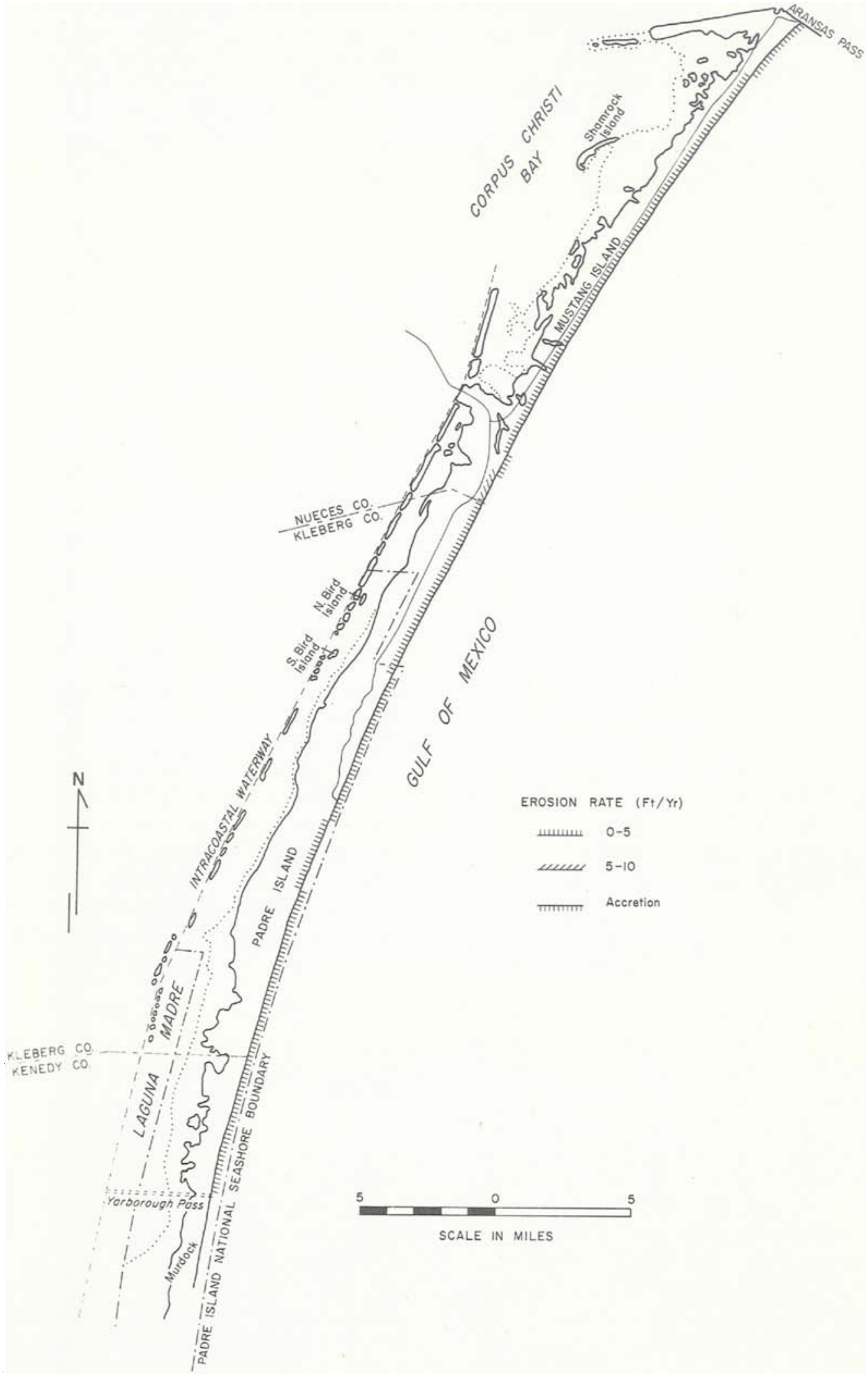

Figure 7. Net shoreline changes between Aransas Pass and Yarborough Pass based on the time period from 1862-82 to 1974-75.

are included in appendix A. These figures estimate long-term net effect, but the values should be used in context. The values for rates of net change are adequate for describing long-term trends; however, rates of short-term changes may be of greater magnitude than rates of long-term changes, particularly in areas where both accretion and erosion have occurred.

In general, net rates of change were low for Mustang Island with the exception of points 1 through 3 where net accretion ranged from 3.3 to 14.4 feet per year. Net erosion ranged from less than 1 foot per year to 3.8 feet per year and averaged 2.0 feet per year. Erosional rates on north Padre Island varied from less than 1 foot to 5.4 feet per year. Net erosion along this segment also averaged 2.0 feet per year. Accretionary rates were also low, ranging from less than 1 foot to 3.0 feet per year; average rates of net accretion were 1.5 feet per year. For the time period of this study, the shoreline of Mustang and north Padre Islands has been relatively stable, especially between points 29 and 42. The most recent data, however, indicate that much of the shoreline is experiencing short-term erosion.

CHANGES IN POSITION OF VEGETATION LINE

Changes in the vegetation line (appendix A) are considered independently from shoreline changes because, in many instances, the nature of change and rate of shoreline and vegetation line recovery are quite dissimilar. Thus, the shoreline and vegetation line should not be viewed as a couplet with fixed horizontal distance; this is illustrated in figure 8. Although response of the shoreline and vegetation line to long-term changes is similar, a certain amount of independence is exhibited by the vegetation line because it reacts to a different set of processes than does the shoreline. Furthermore, documentation of changes in vegetation line for this particular study draws on considerably more data (appendix C) than does documentation of shoreline changes.

Accurate information on position of vegetation line is available neither for the middle 1800's nor for the early 1900's. Therefore, accounts of changes in vegetation line are restricted to the time period covered by aerial photographs (1937 to 1974-75).

1937 to 1956-60.—Major advances in the vegetation line along Mustang and north Padre Islands between 1937 and 1956-60 were associated with recovery from the 1933 and 1934 storms as well as with shoreline accretion. Perhaps drought conditions from 1937 to 1939 contributed to slow initial recovery following the storms. During this period, only two points (13 and 24) experienced retreat of the vegetation line; both points were located in areas of localized blowouts. Data were not available for points 15, 18, 19, 41, and 51 which were void of vegetation. The greatest advances were located either in areas of pass migration (point 20) or revegetated blowouts (points 1, 12, and 43 through 50).

Advancement of the vegetation line on Mustang Island varied from 125 to 2,250 feet; advances averaged 670 feet. Similarly, advances of the vegetation line on north Padre Island ranged from 250 to 2,650 feet and averaged 845 feet. The low incidence of storms after 1949 (table 2) was largely responsible for the recovery of vegetation by 1956-60.

1956-60 to 1969-70.—Vegetation line changes between 1956-60 and 1969-70 were dominated by retreat with only 8 of the 51 points recording advances. On Mustang Island, vegetation line retreat from point 1 through point 10 ranged from 25 to 225 feet and averaged about 100 feet. The remaining portion of Mustang Island (points 11 through 21) experienced both advance and retreat of the vegetation line. Points 15, 18, and 20 recorded retreat ranging from 125 to 300 feet, while points 11, 14, 17, and 21 recorded advancement varying from 50 to 475 feet; points 12, 13, and 16 recorded no change.

Vegetation line changes on north Padre Island between points 22 and 29 were also intermixed, with points 23 and 25 recording retreat, points 24 and 27 recording advancement, and point 28 recording no change. Data were not available for points 22, 26, and 29 which were located in active blowout areas. The vegetation line retreated from point 30 to point 50 with the exception of points 46 and 47 where minor advances occurred. Retreat ranged from 25 to 1,675 feet. Point 50 recorded no change and 51 was located in a blowout area. Average retreat on north Padre Island was 360 feet.

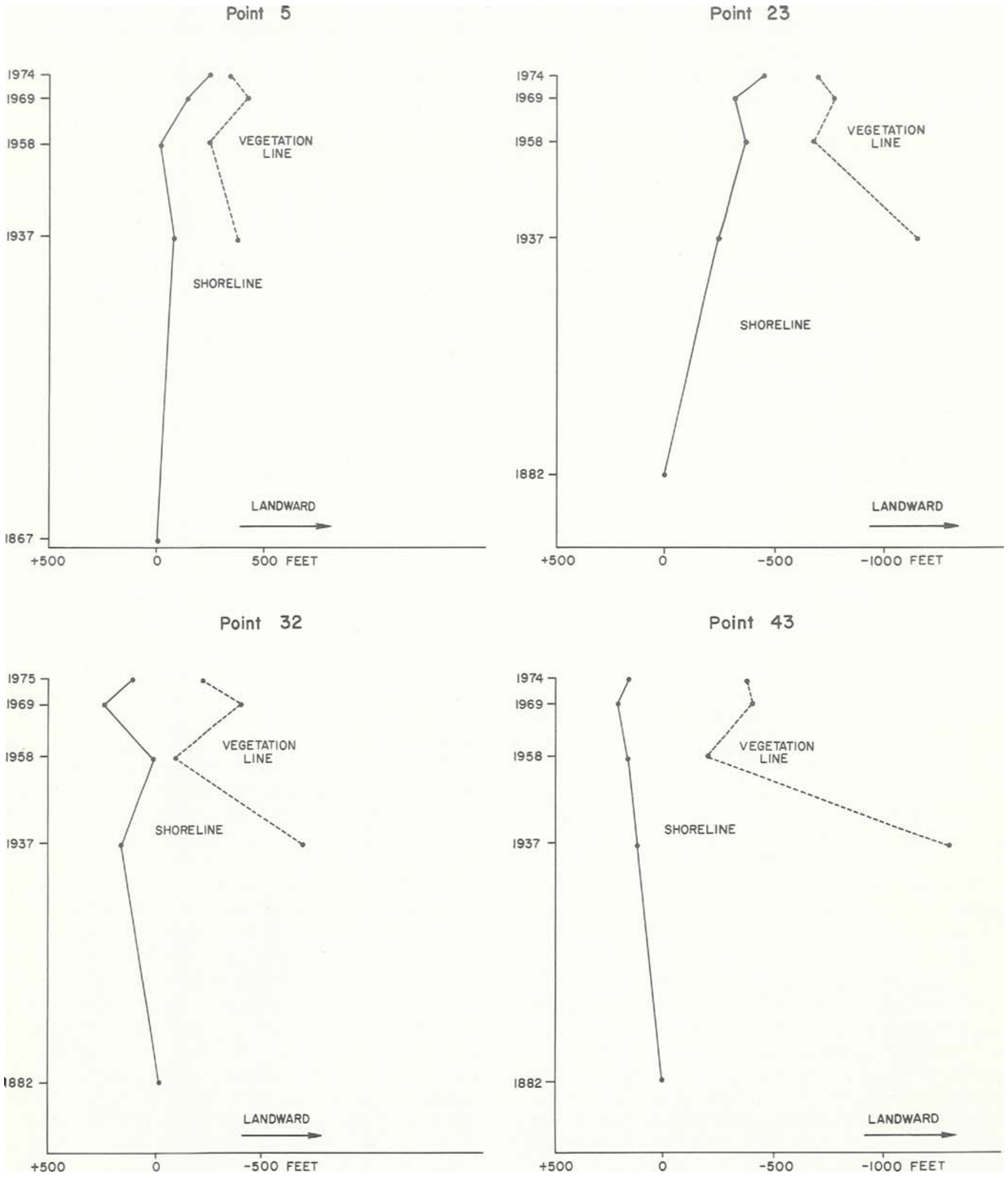

Figure 8. Relative changes in position of shoreline and vegetation line at selected locations, Aransas Pass to Yarborough Pass.

Retreat of the vegetation line between 1956-60 and 1969-70 can be attributed largely to Hurricanes Carla (1961) and Beulah (1967). Aerial photographs taken shortly after Carla (1961, appendix C) show that the entire frontal margin of low dune vegetation retreated up to 200 feet between Aransas Pass and point 4. South of point 4 through point 6, the continuous dune ridge retreated from 50 to 100 feet; greater retreat was associated with localized dune blowouts.

Hurricane Beulah made landfall between Brownsville and the mouth of the Rio Grande before turning northward parallel to the coast. Post-Beulah photographs show considerable damage to the vegetation on north Padre Island especially in areas where the dune ridge was not continuous. Only a few measurements were made because of the lack of control points; however, those few points indicated that the low dunes and associated vegetation line retreated approximately 100 feet between Malaquite Beach and Yarborough Pass.

1969-70 to 1974-75.—In general, this time interval was dominated by advancement of the vegetation line with local areas of retreat. Of the 51 points monitored, 28 recorded advancement, 13 recorded retreat, and 6 experienced no change. Four points (19, 22, 26, and 29) were located in active blowout areas which were void of vegetation.

Vegetation on Mustang Island advanced between points 1 and 7 with the exception of point 6 where retreat of 100 feet occurred in association with a small blowout. Recovery ranged from less than 10 feet to 150 feet and advancement averaged 70 feet. South of point 8 through point 12, the vegetation line retreated from a minimum of 75 feet to a maximum of 100 feet. Advancement of the vegetation line was also dominant from point 14 through point 21 with the exception of point 17, where retreat of 100 feet occurred, and point 15, where no change was recorded. Recovery ranged from 50 feet to 400 feet and averaged 160 feet. The vegetation line advanced on north Padre Island with few exceptions. Minor retreat of 25 to 50 feet was reported at points 25, 30, 35, and 45. In addition, substantial retreat ranging from 150 to 525 feet was recorded from points 39 through 41 in association with active blowouts. Other than points 31, 34, and 37, which recorded no change, the remaining points recorded advancement that ranged from less than 10 feet to 200 feet and averaged 75 feet.

Celia (1970) and Fern (1971) were the only two storms to affect this segment of the coast between 1969-70 and 1974-75. In both cases, damage to vegetation was minimal and the general recovery can be attributed to a lack of storm damage. The 1969-70 and 1974 photographs of Mustang Island reveal that a row of low, sparsely vegetated dunes had formed gulfward of the continuous vegetation line by 1974. This suggests a period of dune stability and potential for future advancement; however, the volume of sand (dunes) accumulated along snow fences in the backbeach area greatly exceeded dune growth observed where snow fences were not utilized. Low, sparsely vegetated dunes also formed along the backbeach of Padre Island National Seashore where beach use has been restricted to non-vehicular traffic since 1968.

Net changes in vegetation line were calculated as they were for shoreline changes. However, it should be emphasized that shifts in vegetation line are related primarily to storms, and the time period over which observations were made was not of sufficient length to establish long-term trends. Nonetheless, the general trend of change in vegetation line has been net advancement (fig. 8) because of the changes that occurred between 1937 and 1956-60. The 1956-60 vegetation line occupied the most seaward position at the greatest number of points monitored. With the exception of point 13, the vegetation line on Mustang Island experienced net advancement that ranged from 25 to 2,300 feet. Greatest advancement occurred in revegetated washover and blowout areas. Average net recovery in areas unaffected by such drastic changes was 255 feet. Net changes were not available for points 15, 18, and 19 as these points were located either in active washovers or blowouts in 1937.

Net recovery was recorded on north Padre except at five points. Minor net retreat of 75 feet occurred at point 29 which is situated in a localized blowout. Net retreat was also recorded between points 39 and 42, an active blowout area since 1956. Greatest net recovery occurred between points 43 and 51 where advancement of the vegetation line ranged from 325 to 2,675 feet and averaged 1,480 feet. Average net recovery for the remainder of north Padre Island (points 22 through 38) was 430 feet.

In general, the long-term change in position of the vegetation line is similar to that of the shoreline. However, short-term changes in position of the vegetation line reflect climatic conditions and take place independent of shoreline changes. This is demonstrated in figure 8 which illustrates that the horizontal separation between shoreline and vegetation line displays short-term variations.

FACTORS AFFECTING SHORELINE AND VEGETATION LINE CHANGES

Geologic processes and, more specifically, coastal processes are complex dynamic components of large-scale systems. Coastal processes are dependent on the intricate interaction of a large number of variables such as wind velocity, rainfall, storm frequency and intensity, tidal range and characteristics, littoral currents, and the like. Therefore, it is difficult, if not impossible, to isolate and quantify all the specific factors causing shoreline changes. Changes in vegetation line are more easily understood. However, in order to evaluate the various factors and their interrelationship, it is necessary to discuss not only major factors but also minor factors. The basis for future prediction comes from this evaluation.

Climate

Climatic changes during the 18,000 years since the Pleistocene have been documented by various methods. In general, temperature was lower (Flint, 1957) and precipitation was greater (Schumm, 1965) at the end of the Pleistocene than at the present; the warmer and drier conditions, which now prevail, control other factors such as vegetal cover, runoff, sediment concentration, and sediment yield. Schumm (1965) stated that "... an increase in temperature and a decrease in precipitation will cause a decrease in annual runoff and an increase in the sediment concentration. Sediment yield can either increase or decrease depending on the temperature and precipitation before the change."

Changes in stream and bay conditions, as well as migration of certain plant and animal species in South Texas since the late 1800's, were attributed to a combination of overgrazing and more arid climatic conditions (Price and Gunter, 1943). A more complete discussion of the general warming trend is presented in Dunn and Miller (1964). Manley (1955) reported that postglacial air temperature has increased 13°F in the Gulf region. Furthermore, Dury (1965) estimated that many rivers carried between 5 and 10 times greater discharge than present-day rivers. His remarks included reference to the Brazos and Mission Rivers of Texas. Observations based on geologic maps prepared by the Bureau of Economic Geology (Fisher and others, 1972) confirm that many rivers along the Texas Coastal Plain were larger and probably transported greater volumes of sediment during the early Holocene. This, in turn, affected sediment budget by supplying additional sediment to the littoral drift system. Droughts are a potential though indirect factor related to minor shoreline changes via their adverse effect on vegetation. Because dunes and beach sand are stabilized by vegetation, sparse vegetation resulting from droughts offers less resistance to wave attack. Severe droughts have occurred periodically in Texas; the chronological order of severe droughts affecting Mustang and north Padre Islands is as follows: 1891-1893, 1896-1899, 1901, 1916-1918, 1937-1939, 1950-1952, 1954-1956 (Lowry, 1959).

Unfortunately, past changes in the position of vegetation line resulting from storms and droughts generally cannot be independently distinguished by sequential aerial photography. By monitoring hurricanes and droughts in relation to time of available photography, however, one can correlate the short-term effects of these factors, providing the time lapse between photos is not too great.

Storm Frequency and Intensity

The frequency of tropical cyclones is dependent on cyclic fluctuations in temperature; increased frequency of hurricanes occurs during warm cycles (Dunn and Miller, 1964). Because of their high frequency of occurrence and associated devastating forces and catastrophic nature, tropical cyclones have received considerable attention in recent years. Accurate records of hurricanes affecting the Texas Gulf Coast are incomplete prior to 1887, when official data collection was initiated simultaneously with the establishment of the Corpus Christi weather station (Carr, 1967).

According to summaries based on records of the U. S. Weather Bureau (Price, 1956; Tannehill, 1956; Dunn and Miller, 1964; Cry, 1965), some 62 tropical cyclones have either struck or affected the Texas Coast during this century (1900-1973). The average of 0.8-hurricane per year obtained from these data is similar to the 0.67 per year average reported by Hayes (1967) who concluded that most of the Texas coastline experienced the passage of at least one hurricane eye during this century. He further concluded that every point on the Texas Coast was greatly affected by approximately half of the storms classified as hurricanes.

Simpson and Lawrence (1971) conducted a study of the probability of storms striking 50-mile segments of the Texas Coast during any given year. The 50-mile segment of the coast, which includes Mustang and north Padre Islands, has a 12-percent probability of experiencing a tropical storm, a 7-percent probability of experiencing a hurricane, and a 5-percent probability of experiencing a great hurricane.

Comparisons of the different types of some of the more recent hurricanes are available; the effects of Hurricanes Carla (1961) and Cindy (1963) on South Texas beaches were compared by Hayes (1967). Hurricanes Carla, Beulah (1967), and Celia (1970) were compared by McGowen and others (1970); individual studies of Hurricanes Carla, Beulah, Celia, and Fern were conducted by the U. S. Army Corps of Engineers (1962a, 1968a, 1971c, 1972b).

Destructive forces and storm damage.—Carla, one of the most violent storms on record, crossed the Texas Coast at Pass Cavallo and inundated approximately 88 percent of Mustang Island with a recorded surge of 9.3 feet above mean sea level (U. S. Army Corps of Engineers, 1962a). Flooding on north Padre Island was less extreme because of distance from storm landfall and protection provided by a well-developed dune ridge. Storm surge associated with Hurricane Beulah also caused major flooding of low-lying areas along the central Texas Coast. High-water elevations in the study area ranged from 8.0 to 9.4 feet (U. S. Army Corps of Engineers, 1968a). Approximately 80 percent of Mustang Island was flooded (Morton and Amdurer, 1974). Major hurricanes also affected the area of study in 1887, 1916, 1919, 1933, and 1945 (table 2).

High velocity winds with attendant waves and currents of destructive force scour and transport large quantities of sand during hurricane approach and landfall. The amount of damage suffered by the beach and adjoining areas depends on a number of factors including angle of storm approach, configuration of the shoreline, shape and slope of Gulf bottom, wind velocity, forward speed of the storm, distance from the eye, stage of astronomical tide, decrease in atmospheric pressure, and longevity of the storm. Hayes (1967) reported erosion of 60 to 150 feet along the fore-island dunes on Padre Island after the passage of Hurricane Carla. Most tropical cyclones have potential for causing some damage, but as suggested by McGowen and others (1970), certain types of hurricanes exhibit high wind velocities, others have high storm surge, and still others are noted for their intense rainfall and aftermath flooding.

Hurricane surge is the most destructive element on the Texas Coast (Bodine, 1969). This is particularly true for low-lying areas that lack continuous foredunes that can dissipate most of the energy transmitted by wave attack. Because of the role hurricane surge plays in flooding and destruction, the frequency of occurrence of high surge on the open coast has been estimated by Bodine (1969). Included in his report are calculations for Mustang Island, which suggest that surge height of 10 feet can be expected approximately 2 times every 100 years. Maximum hurricane surge predicted was 12.5 feet. These estimates were based on the most complete records of hurricane surge elevations available for the Texas Coast. Surge for specific storms was compiled by Harris (1963). Wilson (1957) estimated deep-water hurricane wave height of between 30 and 40 feet once every 50 years for the Brownsville area. Maximum deep-water hurricane wave height predicted for the same location was 45 feet with a recurrence frequency of once every 100 years. Consequently, dissipated energy from breaking storm waves can be tremendous under certain conditions.

Changes in beach profile during and after storms.—Beach profiles adjust themselves to changing conditions in an attempt to maintain a profile of equilibrium; they experience their greatest short-term changes during and after storms. Storm surge and wave action commonly plane off preexisting topographic features and produce a featureless, uniformly seaward-sloping beach. Eroded dunes and washover fans are common products of the surge. The sand removed by erosion is (1) transported and stored temporarily in an offshore bar, (2) transported in the direction of littoral currents, and/or (3) washed across the barrier island through hurricane channels. Sediment transported offshore and stored in the nearshore zone is eventually returned to the beach by bar migration under the influence of normal wave action. The processes involved in beach recovery are discussed by Hayes (1967) and McGowen and others (1970).

Foredunes are the last line of defense against wave attack, and thus, afford considerable protection against hurricane surge and washover. Dunes also serve as a reserve of sediment from which the beach can recover after a storm. Sand removed from the dunes and beach, transported offshore and returned to the beach as previously described, provides the material from which coppice mounds and eventually the foredunes rebuild. Thus, dune removal eliminates sediment reserve, as well as the natural defense mechanism established for beach protection.

Whether or not the beach returns to its prestorm position depends primarily on the amount of sand available. The beach readjusts to normal prestorm conditions much more rapidly than does the vegetation line. Generally speaking, the sequence of events is as follows: (1) return of sand to beach and profile adjustment (accretion); (2) development of low sand mounds (coppice mounds) seaward of the foredunes or vegetation line; (3) merging of coppice mounds with foredunes; and (4) migration of vegetation line to prestorm position. The first step is initiated within days after passage of the storm and adjustment is usually attained within several weeks or a few months. The remaining steps require months or possibly years and, in some instances, complete recovery is never attained. This sequence is idealized for obviously if there is a post-storm net deficit of sand, the beach will not recover to its prestorm position; the same holds true for the vegetation line. Occasionally the vegetation line will recover completely, whereas the shoreline will not; these conditions essentially result in reduction in beach width.

Apparently three basic types of shift in vegetation line are related to storms, and consequently, the speed and degree of recovery is dependent on the type of damage incurred. The first and simplest change is attributed to deposition of sand and ultimate burial of the vegetation. Although this causes an apparent landward shift in the vegetation line, recovery is quick (usually within a year) as the vegetation grows through the sand and is reestablished.

The second type of change is characterized by stripping and complete removal of the vegetation by erosion. This produces the featureless beach previously described; oftentimes the wave-cut cliffs and eroded dunes mark the seaward extent of the vegetation line. Considerable time is required for the vegetation line to recover because of the slow processes involved and the removal of any nucleus around which stabilization and development of dunes can occur.

Selective and incomplete removal of vegetation gives rise to the third type of change. Frequently, long, discontinuous, linear dune ridges survive wave attack but are isolated from the post-storm vegetation line by bare sand. Recovery under these circumstances is complicated and also of long duration. The preserved dune ridge does provide a nucleus for dune development; at times, the bare sand is revegetated and the vegetation line is returned to its prestorm position. This type of erosion was not observed on Mustang and north Padre Islands; however, it has been documented on other segments of the Texas Coast.

Local and Eustatic Sea-Level Conditions

Two factors of major importance relevant to land-sea relationships along Mustang and north Padre Islands are (1) sea-level changes, and (2) compactional subsidence. Shepard (1960b) discussed Holocene rise in sea level along the Texas Coast based on C^{14} data. Relative sea-level changes during historical time are deduced by monitoring mean sea level as determined from tide observations and developing trends based on long-term measurements (Gutenberg, 1933, 1941; Marmer, 1949, 1951, 1954; Hicks and Shofnos, 1965; Hicks, 1968, 1972). However, this method does not distinguish between sea-level rise and land-surface subsidence. More realistically, differentiation of these processes or understanding their individual contributions, if both are operative, is an academic question; the problem is just as real no matter what the cause. A minor vertical rise in sea level relative to adjacent land in low-lying coastal areas causes a considerable horizontal displacement of the shoreline in a landward direction (Bruun, 1962). Unfortunately, the tide records at Port Aransas are not of sufficient duration so that a definitive statement can be made about relative sea-level changes.

Shepard and Moore (1960) speculated that coastwise subsidence was probably an ongoing process augmented by sediment compaction. More recent data tend to support the idea of land subsidence along the Texas Coast (Swanson and Thurlow, 1973).

Through geologic time, the central Texas Coast, in a regional sense, has been situated over a more stable and positive tectonic element, the San Marcos arch, than the adjacent areas that occupy the Rio Grande embayment to the south and the East Texas embayment to the northeast. Furthermore, stream gradients for the Guadalupe and Nueces Rivers suggest that uplift has been greater in areas updip of the hingeline over the San Marcos arch than in adjacent areas.

Because Swanson and Thurlow were interested in the subsidence component reflected in tide level variations, their data were intentionally adjusted so that the contribution from sea-level rise would be eliminated from their analysis. Nevertheless, tidal data gathered from numerous coastal areas indicate that sea level continues to rise at the rate of approximately 1 foot per century.

In the overall analysis, it would appear that the balance between factors of tectonic stability and sea-level rise would favor continued sea-level rise relative to the land surface.

Sediment Budget

Sediment budget refers to the amount of sediment in the coastal system and the balance among quantity of material introduced, temporarily stored, or removed from the system. Because beaches are nourished and maintained by sand-sized sediment, the following discussion is limited to natural sources of sand for Mustang and north Padre Islands.

Johnson (1959) discussed the major sources of sand supply and causes for sand loss along coasts. His list, modified for specific conditions along the Texas Coast, includes two sources of sand: major streams and onshore movement of shelf sand by wave action. Sand losses are attributed to (1) transportation offshore into deep water, (2) accretion against natural littoral barriers and man-made structures, (3) excavation of sand for construction purposes, and (4) eolian processes.

The sources of sediment and processes referred to by Johnson have direct application to the area of interest. Sources of sand responsible for the incipient stages of development and growth of Mustang and north Padre Islands probably include sand derived from shelf sediment, the Colorado and Brazos Rivers, and perhaps some sand derived from updrift shoreline erosion. Van Andel and Poole (1960) and Shepard (1960a) suggested that sediments of the Texas Coast are largely of local origin. Shelf sand derived from the previously deposited sediment was apparently reworked and transported shoreward by wave action during the Holocene sea-level rise (fig. 5). McGowen and others (1972) also concluded that the primary source of sediment for Modern sand-rich barrier islands such as Mustang and north Padre Islands was local Pleistocene and early Holocene sources on the inner shelf, based on the spatial relationship of the different age deposits.

Sediment supplied by major streams is transported alongshore by littoral currents. It is generally recognized that the combination of basin configuration and shoreline orientation plus predominant wind direction produce southwesterly littoral drift along the upper and central Texas Coast, whereas littoral drift is northerly along the lower coast (Lohse, 1955). Apparently, the zone of convergence is located near 27°N latitude, but seasonal conditions can cause the convergence to shift up the coast toward north Padre Island (Curray, 1960). Although the direction of littoral drift at any given time is dependent primarily on wind direction, the net direction of drift along the central Texas Coast is southwesterly. This is documented historically by the migration of Aransas Pass and inlets in the Corpus Christi Pass/Packery Channel area. Remote sensing techniques have also been used to document the characteristics and southwestward direction of suspended-sediment transport (Berryhill, 1969; Hunter, 1973).

Because of the seasonal reversals in direction of littoral transport associated with changing wind direction (Blankenship, 1953; Kimsey and Temple, 1962, 1963; Watson and Behrens, 1970; Hunter and others, 1974; Hill and others, 1975), net littoral drift along the central Texas Coast is only about 10 to 20 percent of the gross littoral drift (Carothers and Innis, 1962; Behrens and Watson, 1974). Gross littoral drift in the vicinity of Corpus Christi fish pass from July 1972 to June 1973, computed by Behrens and Watson (1974), was about 1 million cubic yards (Behrens and Watson, 1974); net littoral drift (southward) was from 39,250 to 85,200 cubic yards. A sediment bypass system utilizing the outer bar was not established until the pass was dredged open. Prior to its opening, the jetties entrapped 1 million cubic yards of sediment. Net loss downdrift from the pass exceeded 120,000 cubic yards.

Carothers and Innis (1962) estimated that southward drift of 30,000 cubic yards of sediment occurred in the vicinity of Mustang and north Padre Islands, whereas a net annual volume of 146,000 cubic yards was transported northward at Yarborough Pass.

The highest dunes and most extensive dune fields along the Texas Coast occur south of Yarborough Pass; however, eolian transport is an important factor in the distribution of sand on north Padre Island. Active blowouts and migrating dune fields (Blankenship, 1953; Boker, 1956; Hunter and Dickinson, 1970; Price, 1971) indicate that a substantial volume of sand supplied to beaches by longshore currents is removed from the littoral drift system by eolian processes.

Sand losses listed by Johnson (1959) do not include sediment removed by deposition from tidal deltas and hurricane washovers; these are two important factors on the Texas Coast (fig. 9). During storms, sand may be moved offshore in deeper water or into lagoons through washover channels. Sand removed by man-made structures and for construction purposes is discussed in the following section on human activities.

Human Activities

Shoreline changes induced by man are difficult to quantify because human activities promote alterations and imbalances in sediment budget. For example, construction of dams, erection of seawalls, groins, and jetties, and removal of sediment for building purposes all contribute to changes in quantity and type of beach material delivered to the Texas Coast. Even such minor activities as vehicular traffic and beach scraping can contribute to the overall changes, although they are in no way controlling factors. Erection of impermeable structures and removal of sediment have an immediate, as well as a long-term effect, whereas a lag of several to many years may be required to evaluate fully the effect of other changes such as river control and dam construction.

Construction of the jetties at Aransas Pass was initiated in 1880 and completed in 1916; the Corpus Christi Water Exchange Pass was completed in 1972. Aransas Pass has been dredged periodically to maintain and deepen the channel. Projects such as these serve to alter natural processes such as inlet siltation, beach erosion, and hurricane surge. Their effects on shoreline changes are subject to debate, but it is an elementary fact that impermeable structures interrupt littoral drift and impoundment of sand occurs at the expense of the beach downdrift of the structure. Therefore, it appears reasonable to expect that any sand trapped west of the south jetty is compensated for by removal of sand downdrift, thus increasing local erosion problems.

EVALUATION OF FACTORS

Shore erosion is not only a problem along United States coasts (El-Ashry, 1971) but also a problem worldwide. Even though some local conditions may aggravate the situation, major factors affecting shoreline changes are eustatic conditions (compactional subsidence on the Texas Coast) and a deficit in sediment supply. The deficit in sand supply is related to climatic changes, human activities, and the exhaustion of the shelf supply through superjacent deposition of finer material over the shelf sand at a depth below wave scour.

Tropical cyclones are significant geologic agents and during these events, fine sand, which characterizes most of the Texas beaches, is easily set into motion. Silvester (1959) suggested that swell is a more important agent than storm waves in areas where longshore drift is interrupted and sand is not replenished offshore. For the purposes of this discussion, the individual effects of storms and swell is a moot question. Suffice it to say that water in motion is the primary agent delivering

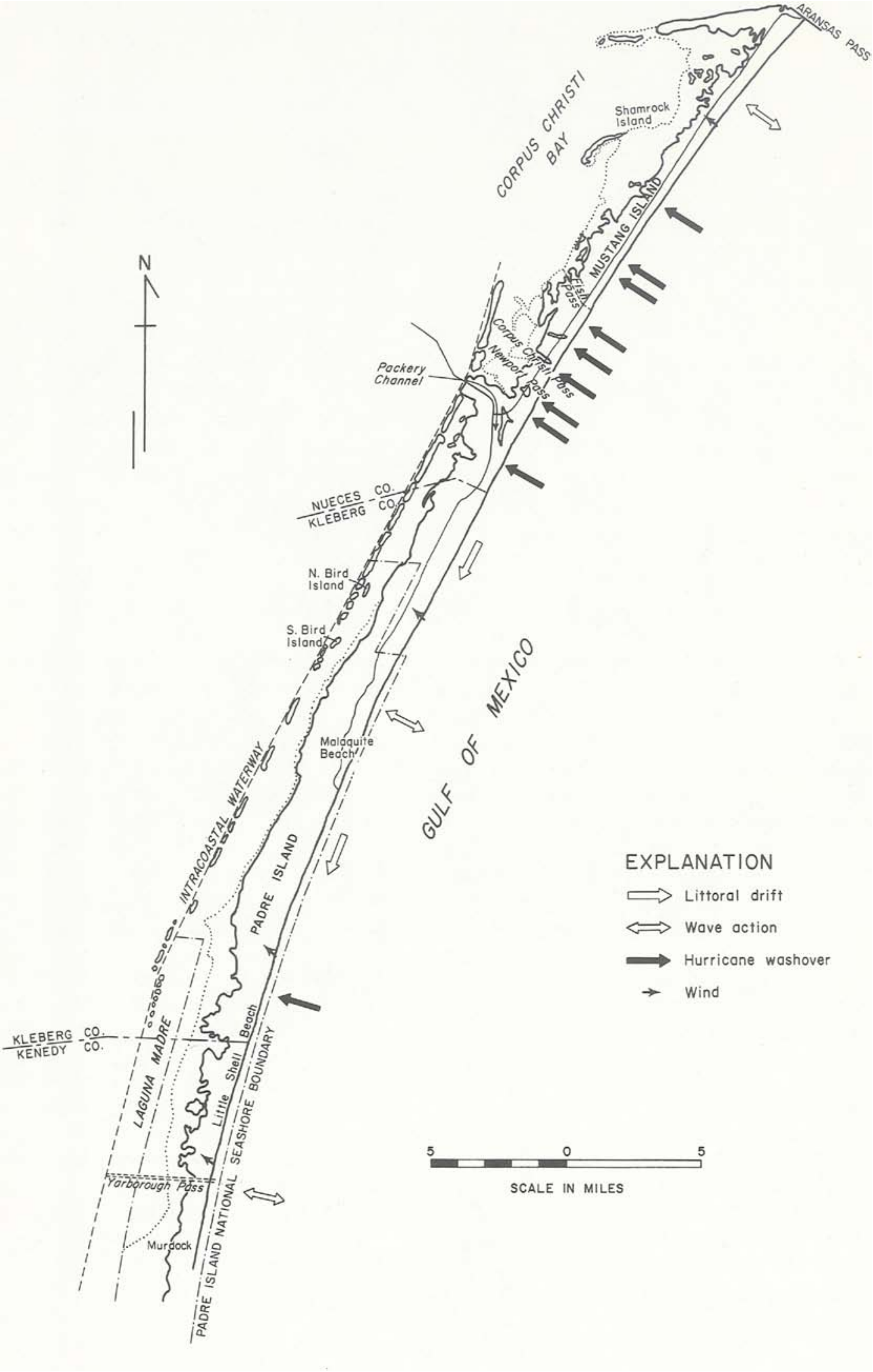

Figure 9. Generalized diagram of sediment transport directions between Aransas Pass and Yarborough Pass.

sand to or removing sand from the beach and offshore area. There is little doubt, however, that storms are the primary factor related to changes in vegetation line.

PREDICTIONS OF FUTURE CHANGES

The prediction of future shoreline changes on Mustang and north Padre Islands is more speculative than along most other segments of the Texas Coast because short-term trends have varied considerably. Based on information from this study, it appears reasonable to assume that long-term net changes of the future will occur at relatively low rates. A critical factor which has not been evaluated fully is sediment budget, especially the balance between sand supplied to north Padre Island by updrift erosion and sand removed by eolian processes. Until sources and sinks of sand along the Texas Coast are known, prediction of future shoreline changes in the zone of convergence is uncertain.

The logical conclusion drawn from factual information, however, is that the position of shoreline and vegetation line on Mustang Island and north Padre Island will retreat landward as part of a long-term erosional trend. The combined influence of interrupted and decreased sediment supply, relative sea-level rise, and tropical cyclones is insurmountable except in very local areas such as river mouths. There is no evidence that suggests a long-term reversal in any trends of the major causal factors. Weather modification research includes seeding of hurricanes (Braham and Neil, 1958; Simpson and others, 1963), but human control of intense storms is still in incipient stages of development. Furthermore, elimination of tropical storms entirely could cause a significant decrease in rainfall for the southeastern United States (Simpson, 1966).

Sand stored in the barrier islands should tend to minimize erosion and keep rates relatively low. Foundation borings and jet-down samples indicate that sand thickness beneath the barrier islands increases southward from Aransas Pass. Sand thickness on Mustang Island is generally from 33 to 38 feet but is greater than 45 feet near Aransas Pass. Wilkinson and others (1975) encountered approximately 45 to 50 feet of sand under southern Mustang Island (in the vicinity of Packery Channel), and Dickinson and others (1972) reported 60 feet of sand from borings on north Padre Island (in the vicinity of point 32). Although total sand thickness is important in terms of barrier island stability, it should be noted that the sand sequence probably represents two distinctly different stratigraphic units based on their origin and age. For example, Wilkinson and others (1975) concluded that the lower 22 feet of sand under southern Mustang Island was deposited as a strandplain during a Pleistocene interglacial. In contrast, the overlying sand was interpreted as Holocene barrier island deposits.

The shoreline could be stabilized at enormous expense by a solid structure such as a seawall; however, any beach seaward of the structure would eventually be removed unless maintained artificially by sand nourishment (a costly and sometimes ineffective practice). The U. S. Army Corps of Engineers (1971a, p. 33) stated that "While seawalls may protect the upland, they do not hold or protect the beach which is the greatest asset of shorefront property." Moreover, construction of a single structure can trigger a chain reaction that requires additional structures and maintenance (Inman and Brush, 1973).

Maintenance of some beaches along the Outer Banks of North Carolina has been the responsibility of the National Park Service (Dolan and others, 1973). Recently the decision was made to cease maintenance because of mounting costs and the futility of the task (New York Times, 1973).

It seems evident that eventually nature will have its way. This should be given utmost consideration when development plans are formulated. While beach-front property may demand the highest prices, it may also carry with it the greatest risks.

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Appendix A

+ accretion
- erosion

Shoreline Changes

beach segment Aransas Pass-Yarborough Pass

Point	Time	Dist. ft	Rate ft per yr	Time	Dist. ft	Rate ft per yr	Time	Dist. ft	Rate ft per yr	Time	Dist. ft	Rate ft per yr	Net Time	Net Dist.	Net Rate
1	1860-66 1937	+1650	+22.3	1937 1958	+ 50	+ 2.3	1958 1970	- 25	- 2.2	1970 1974	- 75	-18.7	1860-66 1974	+1600	+14.4
2	1867 1937	+1025	+14.6	"	- 25	- 1.2	"	-125	-10.9	"	- 50	-12.5	1867 1974	+ 825	+ 7.7
3	"	+ 500	+ 7.1	"	-< 10	-< 1.0	"	-175	-15.2	"	+ 25	+ 6.2	"	+ 350	+ 3.3
4	"	+ 75	+ 1.1	"	+125	+ 5.8	"	-175	-15.2	"	-100	-25.0	"	- 75	-< 1.0
5	"	- 75	- 1.1	"	+ 50	+ 2.3	1958 1969	-125	-11.4	1969 1974	-100	-22.2	"	- 250	- 2.3
6	"	- 50	-< 1.0	"	- 25	- 1.2	"	-125	-11.4	"	- 75	-16.7	"	- 275	- 2.6
7	"	- 100	- 1.4	"	- 50	- 2.3	"	- 50	- 4.5	"	-100	-22.2	"	- 300	- 2.8
8	"	- 125	- 1.8	"	- 25	- 1.2	"	- 75	- 6.8	"	-125	-27.8	"	- 350	- 3.3
9	"	- 175	- 2.5	"	+150	+ 7.0	"	-100	- 9.1	"	-125	-27.8	"	- 250	- 2.3
10	"	- 225	- 3.2	"	+175	+ 8.1	"	- 25	- 2.3	"	-200	-44.4	"	- 275	- 2.6
11	"	- 200	- 2.9	"	+ 75	+ 3.5	"	-< 10	-< 1.0	"	-200	-44.4	"	- 325	- 3.0
12	"	- 125	- 1.8	"	+100	+ 4.6	"	- 25	- 2.3	"	-200	-44.4	"	- 250	- 2.3
13	"	- 100	- 1.4	"	+100	+ 4.6	"	0	0	"	-225	-50.0	"	- 225	- 2.1
14	"	- 75	- 1.1	"	+100	+ 4.6	"	+< 10	+< 1.0	"	-225	-50.0	"	- 200	- 1.9
15	"	- 50	-< 1.0	"	+175	+ 8.1	"	- 50	- 4.5	"	-150	-33.3	"	- 75	-< 1.0
16	1862 1937	- 100	- 1.3	"	+150	+ 7.0	"	0	0	"	-150	-33.3	1862 1974	- 100	-< 1.0
17	"	- 100	- 1.3	"	+150	+ 7.0	"	- 50	- 4.5	"	-125	-27.8	"	- 125	- 1.1
18	1882 1937	- 125	- 2.3	"	+ 50	+ 2.3	"	- 75	- 6.8	"	-200	-44.4	1882 1974	- 350	- 3.8
19	"	- 100	- 1.8	"	+ 75	+ 3.5	"	- 50	- 4.5	"	-200	-44.4	"	- 275	- 3.0
20	"	- 25	-< 1.0	1937 1959	0	0	1959 1969	0	0	"	-100	-22.2	"	- 125	- 1.4

+ accretion
- erosion

Shoreline Changes

beach segment Aransas Pass-Yarborough Pass

Point	Time	Dist. ft	Rate ft per yr	Time	Dist. ft	Rate ft per yr	Time	Dist. ft	Rate ft per yr	Time	Dist. ft	Rate ft per yr	Net Time	Net Dist.	Net Rate
21	1882 1937	+ 550	+10.0	1937 1959	0	0	1959 1969	0	0	1969 1974	-125	-27.8	1882 1974	+ 425	+ 4.6
22	"	- 450	- 8.2	"	+ 25	+ 1.1	"	0	0	"	- 75	-16.7	"	- 500	- 5.4
23	"	- 250	- 4.5	"	-125	- 5.7	"	+ 50	+ 4.8	"	-125	-27.8	"	- 450	- 4.9
24	"	- 125	- 2.3	"	-125	- 5.7	"	0	0	"	-100	-22.2	"	- 350	- 3.8
25	"	- 25	-< 1.0	"	- 25	- 1.1	"	- 25	- 2.4	"	-175	-38.9	"	- 250	- 2.3
26	"	- 25	-< 1.0	"	+ 50	+ 2.3	"	0	0	"	-150	-33.3	"	- 125	- 1.4
27	"	- 25	-< 1.0	"	-< 10	-< 1.0	"	+ 75	+ 7.1	1969 1975	-150	-27.3	1882 1975	- 100	- 1.1
28	"	+ 50	+< 1.0	"	-100	- 4.5	"	+100	+ 9.5	"	-150	-27.3	"	- 100	- 1.1
29	"	+ 100	+ 1.8	1937 1956	- 50	- 2.6	1956 1969	- 25	- 1.8	"	-100	-18.2	"	- 75	-< 1.0
30	"	+ 125	+ 2.3	"	-275	-14.5	"	+200	+14.8	"	-100	-18.2	"	- 50	-< 1.0
31	"	+ 150	+ 2.7	"	-225	-11.8	"	+225	+16.7	"	-125	-22.7	"	+ 25	+< 1.0
32	"	+ 175	+ 3.2	"	-150	- 7.9	"	+225	+16.7	"	-125	-22.7	"	+ 125	+ 1.3
33	"	+ 250	+ 4.5	"	-175	- 9.2	"	+225	+16.7	"	-175	-31.8	"	+ 125	+ 1.3
34	"	+ 250	+ 4.5	"	-150	- 7.9	"	+250	+18.5	"	-175	-31.8	"	+ 175	+ 1.9
35	"	+ 100	+ 1.8	"	-100	- 5.3	"	+175	+13.0	"	-100	-18.2	"	+ 75	+< 1.0
36	"	+ 75	+ 1.4	"	-< 10	-< 1.0	"	+100	+ 7.4	"	-125	-22.7	"	+ 50	+< 1.0
37	"	- 50	-< 1.0	"	+ 50	+ 2.6	"	+ 50	+ 3.7	"	- 50	- 9.1	"	0	0
38	"	+ 100	+ 1.8	"	-125	- 6.6	"	+ 75	+ 5.6	"	- 75	-13.6	"	- 25	-< 1.0
39	"	+ 50	+< 1.0	"	-100	- 5.3	"	+125	+ 9.3	"	-100	-18.2	"	- 25	-< 1.0
40	"	+ 75	+ 1.4	"	0	0	"	+100	+ 7.4	"	-150	-27.3	"	+ 25	+< 1.0

+ accretion
- erosion

Shoreline Changes

beach segment Aransas Pass-Yarborough Pass

Point	Time	Dist. ft	Rate ft per yr	Time	Dist. ft	Rate ft per yr	Time	Dist. ft	Rate ft per yr	Time	Dist. ft	Rate ft per yr	Net Time	Net Dist.	Net Rate
41	1882 1937	+ 125	+ 2.3	1937 1956	0	0	1956 1969	+125	+ 9.3	1969 1975	-200	-36.4	1882 1975	+ 50	+< 1.0
42	"	+ 25	+< 1.0	"	+< 10	+< 1.0	"	+100	+ 7.4	"	-125	-22.7	"	+< 10	+< 1.0
43	"	+ 125	+ 2.3	"	+ 50	+ 2.6	"	+ 50	+ 3.7	"	- 50	- 9.1	"	+ 175	+ 1.9
44	"	+ 150	+ 2.7	"	+ 50	+ 2.6	"	+ 75	+ 5.6	"	-100	-18.2	"	+ 175	+ 1.9
45	"	+ 150	+ 2.7	"	0	0	"	+175	+13.0	"	- 50	- 9.1	"	+ 275	+ 3.0
46	"	+ 125	+ 2.3	1937 1943	-150	-25.0	1943 1969	+225	+ 8.5	"	- 25	- 4.5	"	+ 175	+ 1.9
47	"	+ 200	+ 3.6	"	-225	-37.5	"	+325	+12.3	"	- 25	- 4.5	"	+ 275	+ 3.0
48	"	+ 250	+ 4.5	1937 1960	+100	+ 4.3	1960 1969	-100	-25.0	"	0	0	"	+ 250	+ 2.7
49	"	+ 150	+ 2.7	"	+150	+ 6.5	"	- 75	- 7.9	"	- 50	- 9.1	"	+ 175	+ 1.9
50	"	+ 150	+ 2.7	"	+200	+ 8.7	"	-150	-15.8	"	- 25	- 4.5	"	+ 175	+ 1.9
51	"	+ 200	+ 3.6	"	+200	+ 8.7	"	-150	-15.8	"	- 25	- 4.5	"	+ 225	+ 2.4

\+ accretion
\- erosion

Vegetation Line Changes

beach segment Aransas Pass-Yarborough Pass

Point	Time	Dist. ft	Rate ft per yr	Time	Dist. ft	Rate ft per yr	Time	Dist. ft	Rate ft per yr	Time	Dist. ft	Rate ft per yr	Net Time	Net Dist.	Net Rate
1				1937 1938	+2250	+104.6	1958 1970	- 25	- 2.2	1970 1974	+ 75	+ 18.7	1937 1974	+2300	+62.2
2				"	+ 550	+ 25.6	"	- 100	- 8.7	"	+ 25	+ 6.2	"	+ 475	+12.8
3				"	+ 375	+ 17.4	"	- 150	- 13.0	"	+150	+ 37.5	"	+ 375	+10.1
4				"	+ 250	+ 11.6	"	- 75	- 6.5	"	+< 10	+< 1.0	"	+ 175	+ 4.7
5				"	+ 125	+ 5.8	"	- 175	- 15.2	"	+ 75	+ 18.7	"	+ 25	+< 1.0
6				"	+ 300	+ 13.9	1958 1969	- 125	- 11.4	1969 1974	-100	- 22.2	"	+ 75	+ 2.0
7				"	+ 475	+ 22.1	"	- 225	- 20.4	"	+100	+ 22.2	"	+ 350	+ 9.5
8				"	+ 325	+ 15.1	"	- 50	- 4.5	"	0	0	"	+ 275	+ 7.4
9				"	+ 375	+ 17.4	"	- 75	- 6.8	"	-100	- 22.2	"	+ 200	+ 5.4
10				"	+ 150	+ 7.0	"	- 25	- 2.3	"	- 75	- 16.7	"	+ 50	+ 1.3
11				"	+ 225	+ 10.5	"	+ 50	+ 4.5	"	-100	- 22.2	"	+ 175	+ 4.7
12				"	+1600	+ 74.4	"	0	0	"	-100	- 22.2	"	+1500	+40.5
13				"	- 175	- 8.1	"	0	0	"	0	0	"	- 175	- 4.7
14				"	+ 175	+ 8.1	"	+ 475	+ 43.2	"	+< 10	+< 1.0	"	+ 650	+17.6
15				"	washover		"	- 150	- 13.6	"	0	0			
16				"	+ 800	+ 37.2	"	0	0	"	+400	+ 88.9	"	+1200	+34.3
17				"	+ 850	+ 39.5	"	+ 200	+ 18.2	"	-100	- 22.2	"	+ 950	+25.7
18				"	washover		"	- 125	- 11.4	"	+ 50	+ 11.1			
19				"	Packery Channel										
20				1937 1959	+2200	+100.0	1959 1969	- 300	- 28.6	"	+ 75	+ 16.7	"	+1975	+53.4

+ accretion
- erosion

Vegetation Line Changes

beach segment Aransas Pass-Yarborough Pass

Point	Time	Dist. ft	Rate ft per yr	Time	Dist. ft	Rate ft per yr	Time	Dist. ft	Rate ft per yr	Time	Dist. ft	Rate ft per yr	Net Time	Net Dist.	Net Rate
21				1937 1959	+ 375	+ 17.0	1959 1969	+ 325	+ 30.9	1969 1974	+125	+ 27.8	1937 1974	+ 825	+22.3
22				"	+ 250	+ 11.4	"	park construction					"	+ 650	+17.6
23				"	+ 475	+ 21.6	"	- 100	- 9.5	"	+ 75	+ 16.7	"	+ 450	+12.2
24				"	-1550	- 70.4	"	+1525	+145.2	"	+100	+ 22.2	"	+ 75	+ 2.0
25				"	+ 300	+ 13.6	"	- 50	- 4.8	"	- 50	- 11.1	"	+ 200	+ 5.4
26				"	+ 350	+ 15.9	"	blowout					"	+ 350	+ 9.4
27				"	+ 375	+ 17.0	"	+ 100	+ 9.5	1969 1975	+ 25	+ 5.6	1937 1975	+ 500	+13.2
28				"	+ 375	+ 17.0	"	0	0	"	+ 75	+ 16.7	"	+ 450	+11.8
29				1937 1956	+ 475	+ 25.0	1956 1969	blowout							
30				"	+ 525	+ 27.6	"	- 50	- 3.7	"	- 25	- 5.6	"	+ 450	+11.8
31				"	+ 725	+ 38.2	"	- 75	- 5.6	"	0	0	"	+ 650	+17.1
32				"	+ 600	+ 31.6	"	- 325	- 24.1	"	+200	+ 44.4	"	+ 475	+12.5
33				"	+ 600	+ 31.6	"	- 150	- 11.1	"	+ 25	+ 5.6	"	+ 475	+12.5
34				"	+ 450	+ 23.7	"	- 125	- 9.3	"	0	0	"	+ 325	+ 8.5
35				"	+ 650	+ 34.2	"	- 125	- 9.3	"	- 50	- 11.1	"	+ 475	+12.5
36				"	+ 450	+ 23.7	"	- 250	- 18.5	"	+ 25	+ 5.6	"	+ 225	+ 5.9
37				"	+ 925	+ 48.7	"	- 300	- 22.2	"	0	0	"	+ 625	+16.4
38				"	+ 775	+ 40.8	"	- 325	- 24.1	"	+ 75	+ 16.7	"	+ 525	+13.8
39				"	+ 525	+ 27.6	"	- 400	- 29.6	"	-525	-116.7	"	- 400	-10.5
40				"	+ 875	+ 46.0	"	-1200	- 88.9	"	-150	- 33.3	"	- 475	-12.5

+ accretion
- erosion

Vegetation Line Changes

beach segment Aransas Pass-Yarborough Pass

Point	Time	Dist. ft	Rate ft per yr	Time	Dist. ft	Rate ft per yr	Time	Dist. ft	Rate ft per yr	Time	Dist. ft	Rate ft per yr	Net Time	Net Dist.	Net Rate
41				1937 1956	blowout		1956 1969	- 700	- 51.8	1969 1975	-300	- 54.5	1937 1975		
42				"	+ 650	+ 34.2	"	-1675	-124.1	"	+175	+ 31.8	"	- 850	-22.4
43				"	+1100	+ 57.9	"	- 200	- 14.8	"	+ 25	+ 4.5	"	+ 925	+24.3
44				"	+2000	+105.3	"	- 300	- 22.2	"	+100	+ 18.2	"	+1800	+47.4
45				"	+1550	+ 81.6	"	- 150	- 11.1	"	- 25	- 4.5	"	+1375	+36.2
46				"	+2275	+119.7	"	+ 50	+ 3.7	"	+ 50	+ 9.1	"	+2375	+62.5
47				1937 1943	+ 250	+ 13.2	"	+ 25	+ 1.8	"	+ 50	+ 9.1	"	+ 325	+ 8.5
48				1937 1960	+1500	+ 65.2	1960 1969	- 25	- 2.6	"	+ 25	+ 4.5	"	+1500	+39.5
49				"	+1150	+ 50.0	"	- 150	- 15.8	"	+100	+ 18.2	"	+1100	+28.9
50				"	+2650	+203.8	"	0	0	"	+ 25	+ 4.5	"	+2675	+70.4
51				"	blowout					"	+125	+ 22.7			

APPENDIX B

Tropical Cyclones Affecting the Texas Coast 1854-1973

(compiled from Tannehill, 1956; Dunn and Miller, 1964; and Cry, 1965).

Intensity Classification from Dunn and Miller

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

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

APPENDIX C

List of Materials and Sources

List of aerial photographs used in determination of changes in vegetation line and shoreline. * Indicates that vegetation line and/or shoreline was used in map preparation.

Date		Source of Photographs
Apr. 1937	*	Tobin Research Inc.
Feb. 1943	*	U. S. Dept. Agriculture
Feb., Mar. 1956	*	U. S. Dept. Agriculture
Dec. 1958	*	Tobin Research Inc.
Jan. 1959	*	Tobin Research Inc.
Apr. 1960	*	Tobin Research Inc.
Sept. 1961		U. S. Army Corps Engineers
Sept. 1961		Natl. Oceanic and Atmospheric Adm.
June 1967		U. S. Army Corps Engineers
Nov. 1967		International Boundary Comm.
Oct. 1969	*	Natl. Oceanic and Atmospheric Adm.
Aug. 1970	*	Natl. Oceanic and Atmospheric Adm.
June 1974	*	Texas General Land Office
May, June 1975		Texas General Land Office
July 1975	*	Texas General Land Office

List of Maps Used in Determination of Shoreline Changes

Date	Description	Source of Maps
1860-1866	topographic map 823	Natl. Oceanic and Atmospheric Adm.
1867	topographic map 1044	Natl. Oceanic and Atmospheric Adm.
1881	topographic map 1679	Natl. Oceanic and Atmospheric Adm.
1881-1882	topographic map 1626	Natl. Oceanic and Atmospheric Adm.
1881-1882	topographic map 1628	Natl. Oceanic and Atmospheric Adm.
1881	topographic map 1627	Natl. Oceanic and Atmospheric Adm.
Feb. 1899	topographic map 2354	Natl. Oceanic and Atmospheric Adm.
1923	topographic map— 15-minute quadrangle	U. S. Geological Survey

List of 7.5-minute quadrangle topographic maps used in construction of base map. Source of these maps is the U. S. Geological Survey.

Port Aransas, Texas
Crane Islands NW, Texas
Crane Islands SW, Texas
Pita Island, Texas
South Bird Island, Texas
South Bird Island SE, Texas
Yarborough Pass, Texas