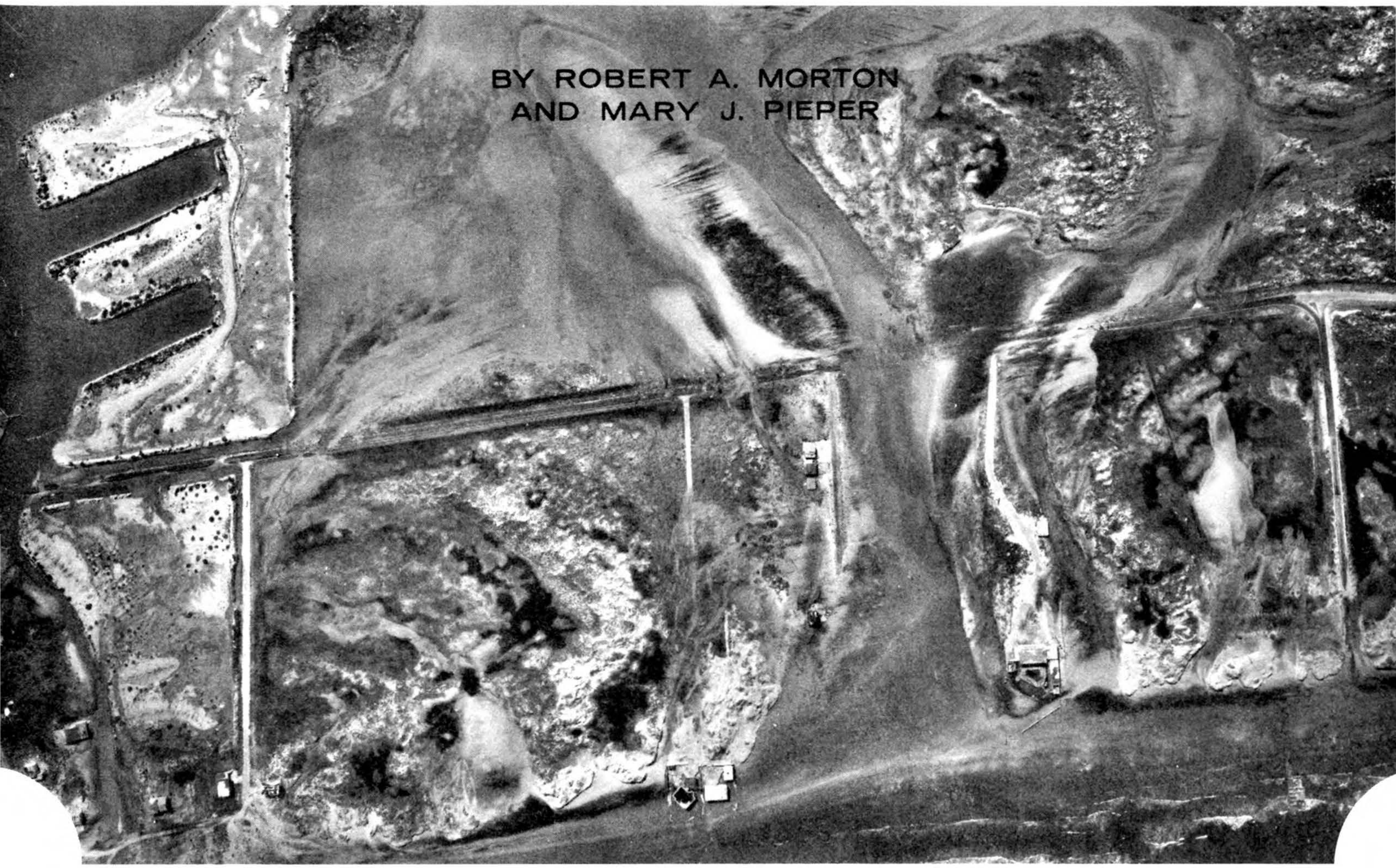
GC
75-2

GEOLOGICAL CIRCULAR **75-2**

SHORELINE CHANGES ON BRAZOS ISLAND AND SOUTH PADRE ISLAND (MANSFIELD CHANNEL TO MOUTH OF THE RIO GRANDE)

AN ANALYSIS OF HISTORICAL CHANGES OF THE TEXAS GULF SHORELINE

BY ROBERT A. MORTON
AND MARY J. PIEPER



BUREAU OF ECONOMIC GEOLOGY
THE UNIVERSITY OF TEXAS AT AUSTIN
AUSTIN, TEXAS 78712
W. L. FISHER, DIRECTOR
1975

QAe4338

GEOLOGICAL CIRCULAR 75-2

Shoreline Changes on Brazos Island and South Padre Island (Mansfield Channel to Mouth of the Rio Grande)

An Analysis of Historical Changes Of The Texas Gulf Shoreline

BY ROBERT A. MORTON
AND MARY J. PIEPER

BUREAU OF ECONOMIC GEOLOGY
THE UNIVERSITY OF TEXAS AT AUSTIN
AUSTIN, TEXAS 78712
W. L. FISHER, DIRECTOR

1975

CONTENTS

LIST OF ILLUSTRATIONS

SHORELINE CHANGES ON BRAZOS ISLAND AND SOUTH PADRE ISLAND (MANSFIELD CHANNEL TO MOUTH OF THE RIO GRANDE)

AN ANALYSIS OF HISTORICAL CHANGES OF THE TEXAS GULF SHORELINE

by Robert A. Morton and Mary J. Pieper

ABSTRACT

Historical monitoring along Brazos and south 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 1854, 1867, 1879-1880, 1917, 1934) and aerial photographs (taken in 1937, 1960, 1970, 1974) indicates short-term changes of accretion and erosion along the beach between the mouth of the Rio Grande and Mansfield Channel. *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 erosion 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 120-year time period of this study indicates net erosion for south Padre Island; maximum net erosion for this segment was 1,400 feet or approximately 13.1 feet per year. Minimum net erosion, in proximity to the north jetty at Brazos Santiago Pass, was 75 feet or less than 1 foot per year. The shoreline at the southern tip of south Padre Island has undergone accretion since construction of the jetties in 1935.

The long-term shoreline trend of Brazos Island has been one of accretion; however, this is attributed to moderate and extreme accretion between 1854 and 1937. After this period, shoreline changes were short-term erosional and accretionary cycles.

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 Brazos and south Padre Islands, are relative sea-level rise, compactional subsidence, and a deficit 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 Brazos and south Padre Islands are largely the result of natural processes, perhaps expedited by man's activities. The apparent effect of Falcon Dam upon the discharge of water and suspended sediment of the Rio Grande is marked, and the entrapment of sediment by the south jetties at Brazos Santiago Pass and Mansfield Channel is obvious. Structures that retard or eliminate sediment transport add to the sediment deficit already present in the littoral drift system. 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 Brazos and south 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 1854 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 are now nearing publication (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. Results of the project will be published ultimately in the form of maps summarizing the changes in shoreline position. Work versions of base maps will be on open file at the Bureau of Economic Geology until final publication. In advance of the final report and maps, a series of preliminary interim reports will be published. This report covering Brazos Island and south Padre Island from Mansfield Channel to the mouth of the Rio Grande (fig. 1) is the second in that series.

General Statement on Shoreline Changes

Shorelines are in a state of erosion or 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.

Acknowledgments

Assistance in preparation of this report was provided by M. Amdurer. Drafting was under the supervision of J. W. Macon. Cartographic work was performed by D. F. Scranton. Critical review was provided by W. L. Fisher and L. F. Brown, Jr.

The report was typed by Elizabeth T. Moore and edited by Kelley Kennedy. Composing was under the direction of Fannie M. Sellingsloh.

Cooperation of personnel with the U. S. Army Corps of Engineers, Galveston District; Texas Highway Department; and General Land Office aided in the acquisition of materials and information. Meteorological data was supplied by the National Climatic Center and the National Hurricane Center. Detailed information concerning changes in position of the mouth of the Rio Grande was provided by B. L. Everitt, International Boundary and Water Commission.

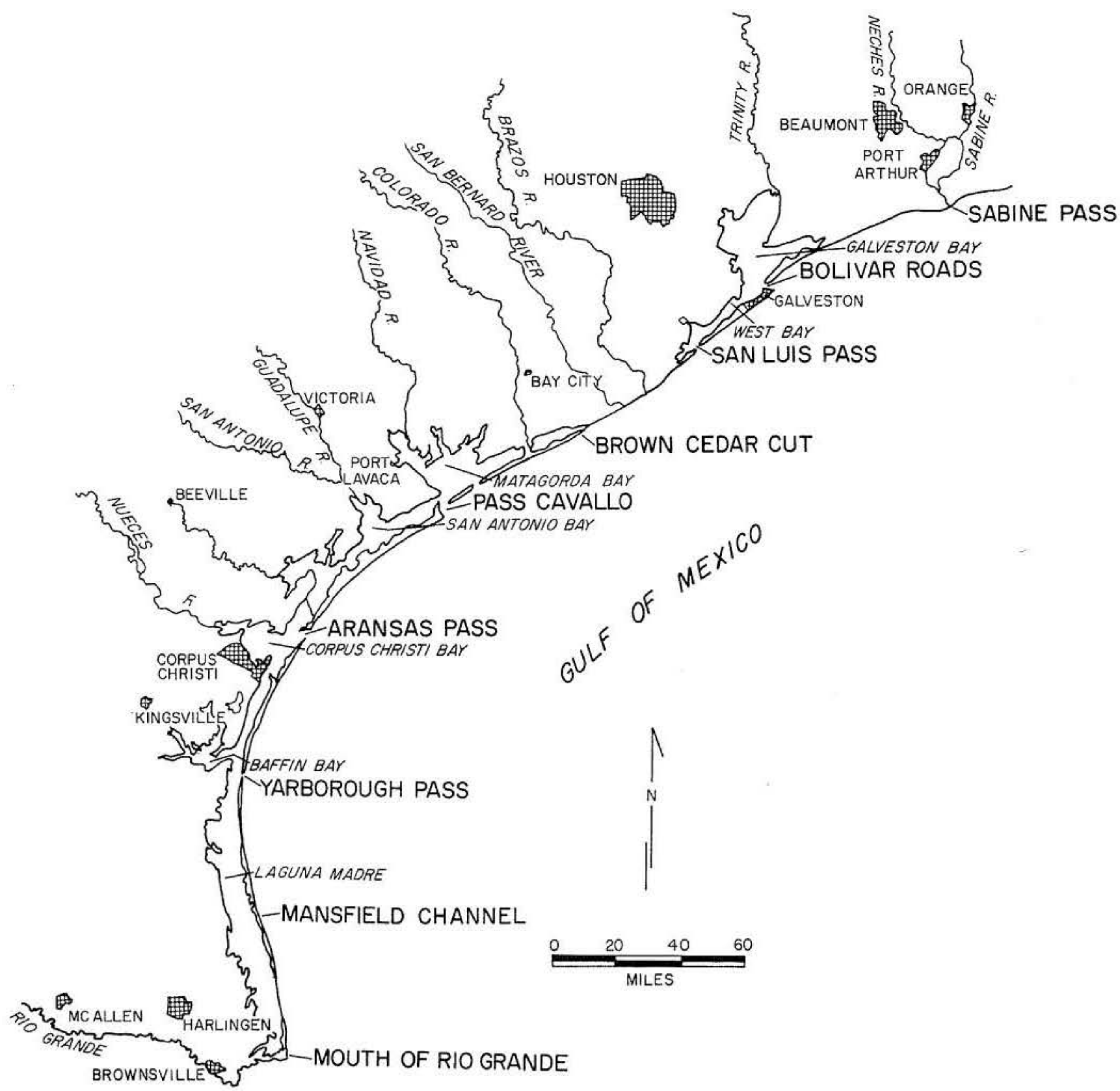


Figure 1. Index map of the Texas Gulf shoreline.

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 was 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 Engineers, 1940, 1968a).

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).

Northward from station 13 (fig. 3), ground control is lacking; therefore, transfer of data to the base map is entirely dependent on the location of the stable dunes and the shape of the back-island area. As a result, the degree of accuracy declines slightly and the chance for error may increase in some areas.

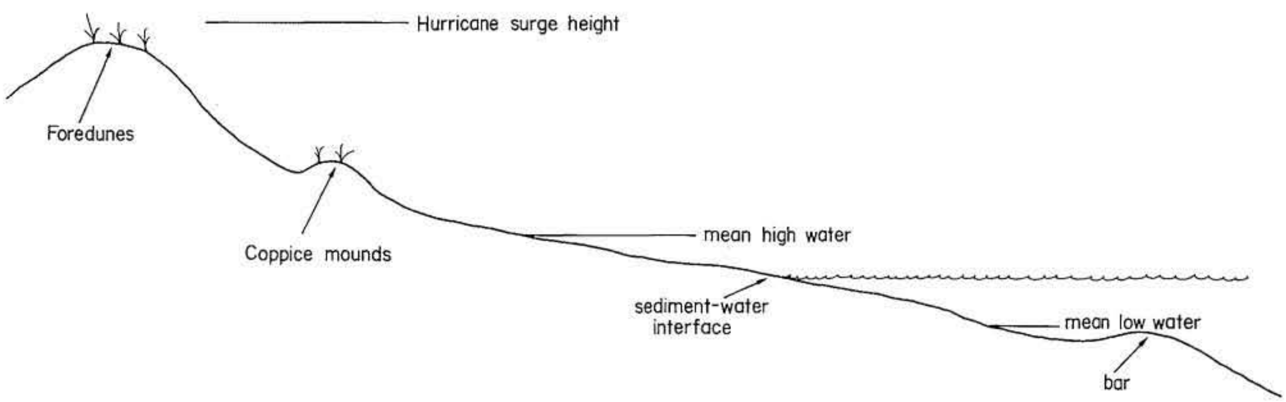


Figure 2. Generalized diagram of beach profile.

Monitoring of Vegetation Line

Changes in position of the vegetation line (fig. 4) 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. 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 (see page 5). 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 photography was taken.

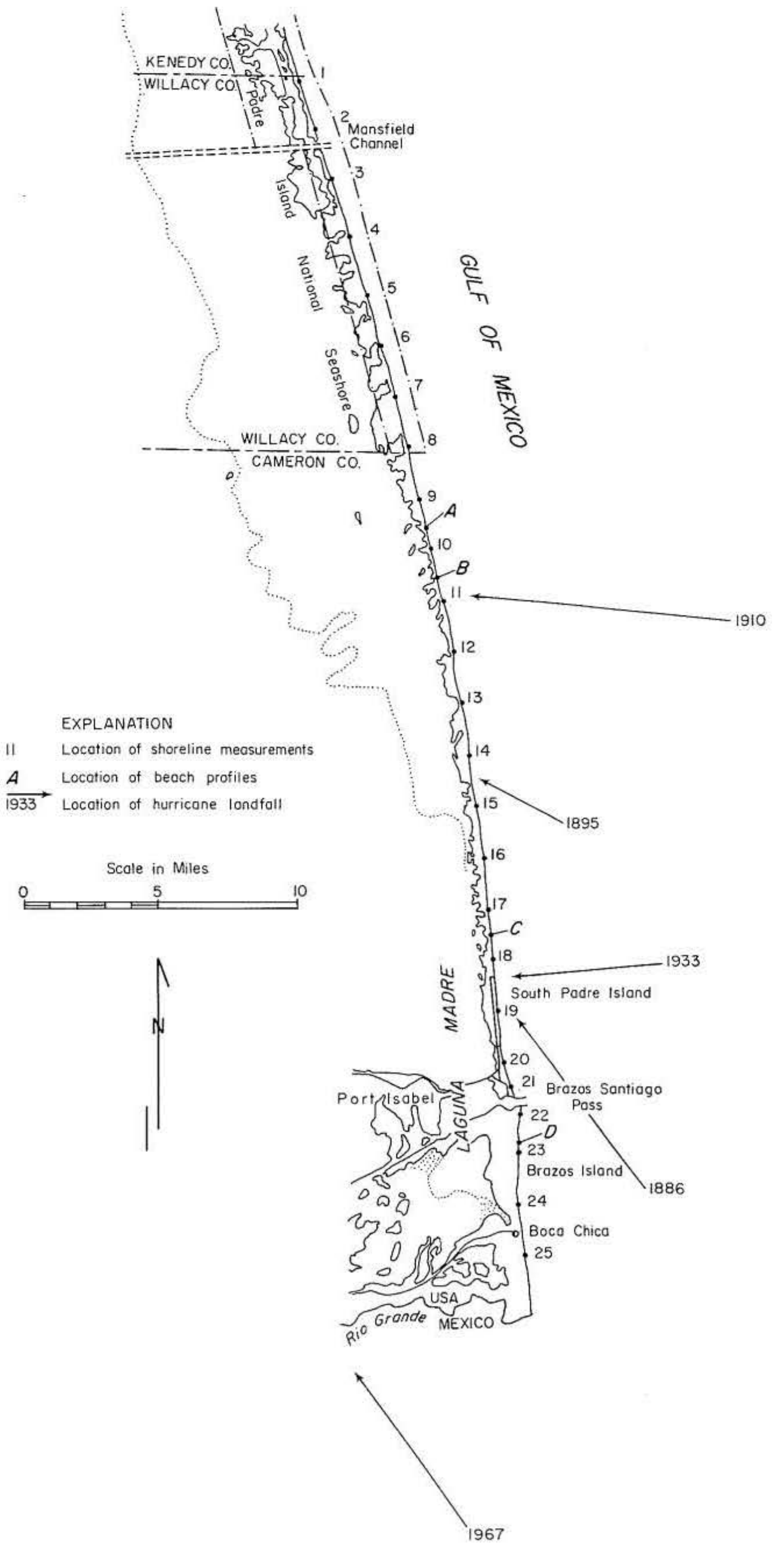


Figure 3. Generalized diagram showing location of shoreline measurements, beach profiles, and hurricane landfall.

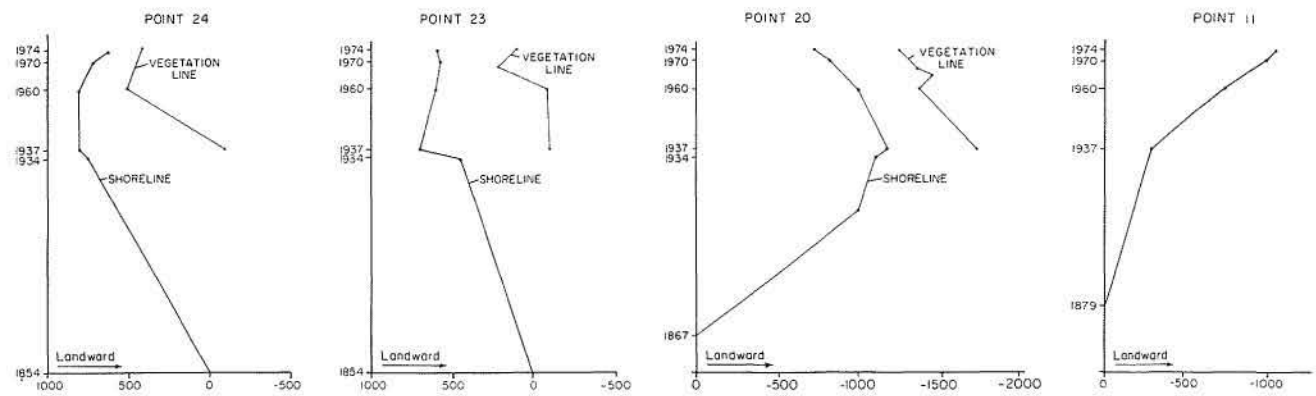


Figure 4. Relative changes in position of shoreline and vegetation line at selected locations, Brazos Island and south Padre Island.

PREVIOUS WORK

Brazos Santiago Pass has been the subject of numerous studies by the U. S. Army Corps of Engineers, originating as early as 1850 and continuing to the present. The early studies monitored changes in width of the natural channel, as well as depth of water within the channel and Laguna Madre. As a result of these studies, jetty construction was proposed as the only means of maintaining a navigable channel. Emory (1857), in an early survey for the Boundary Commission, also commented on the channels and bars of Brazos Santiago Pass and the Rio Grande.

Erosional and accretionary shoreline changes resulting from construction of the jetties at Mansfield Channel were discussed by Hansen (1960) and the U. S. Army Corps of Engineers (1958b). Beach profiles surveyed by the U. S. Army Corps of Engineers (1968-1972) document short-term shoreline changes in proximity to the Mansfield Channel jetties, Brazos Santiago jetties, and the Cameron-Willacy county line.

A regional inventory of Texas shores was conducted by the U. S. Army Corps of Engineers (1971c). No quantitative data were given; however, the study delineated areas of critical and noncritical erosion along the Texas Coast. On the southern end of south Padre Island, a 7.5-mile segment of shoreline one mile north of Brazos Santiago Pass was divided into one area of critical erosion bracketed by two smaller areas of noncritical erosion.

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 Brazos Island and south Padre Island 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 accretion ranging from 2 to 8 feet per year are given for Brazos Island with erosion of 5 and 18 feet per year in the vicinity of the mouth of the Rio Grande. Rates of erosion determined by Seelig and Sorensen (1973, p. 13) for south Padre Island range from 0 to 15 feet per year.

PRESENT BEACH CHARACTERISTICS

Texture and Composition

The beaches of Brazos Island and south Padre Island are comprised of fine sand (Lohse, 1952; Hayes, 1965; Garner, 1967) which is well sorted and contains abundant volcanic rock fragments, volcanic quartz, and sanadine. These sediments were derived presumably from the volcanic areas of West Texas and Mexico and transported by the Rio Grande (Bullard, 1942; Hayes, 1964). The presence of volcanic material gives the sand a reddish color in contrast to the grayish color typical of sand transported by other Texas rivers. Heavy mineral analysis indicates a suite of minerals distinctive to the Rio Grande source composed of 60 percent basaltic hornblende and pyroxene, 10 percent green hornblende, and 30 percent of the more durable minerals including zircon, garnet, staurolite, tourmaline, and rutile (Bullard, 1942).

Beach Profiles

Brazos and south Padre Islands are characterized by a diversity of beach conditions (fig. 5) owing to the intermittent vegetated dunes and washover areas. In general, the beaches are narrow (about 150 feet wide) and steep in areas of vegetated dunes. Beach width increases (200 to 350 feet) and slope decreases in washover areas. Extant dunes are generally 15 feet in height and discontinuous because they are breached by numerous active storm channels. 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 5 were constructed using the method described by Emery (1961). The profiles, considered typical of certain segments of Brazos and south Padre Islands, represent beach conditions on August 21, 1974. High tide mark was identified by sand wetness and position of debris line. Beach profiles in the vicinity of Mansfield Channel, Brazos Santiago Pass, and just north of the Cameron-Willacy county line have also been surveyed by the Galveston District, U. S. Army Corps of Engineers (1968-1972). Comparison of beach profiles and beach scour patterns by Herbich (1970) suggests that beach conditions (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.

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

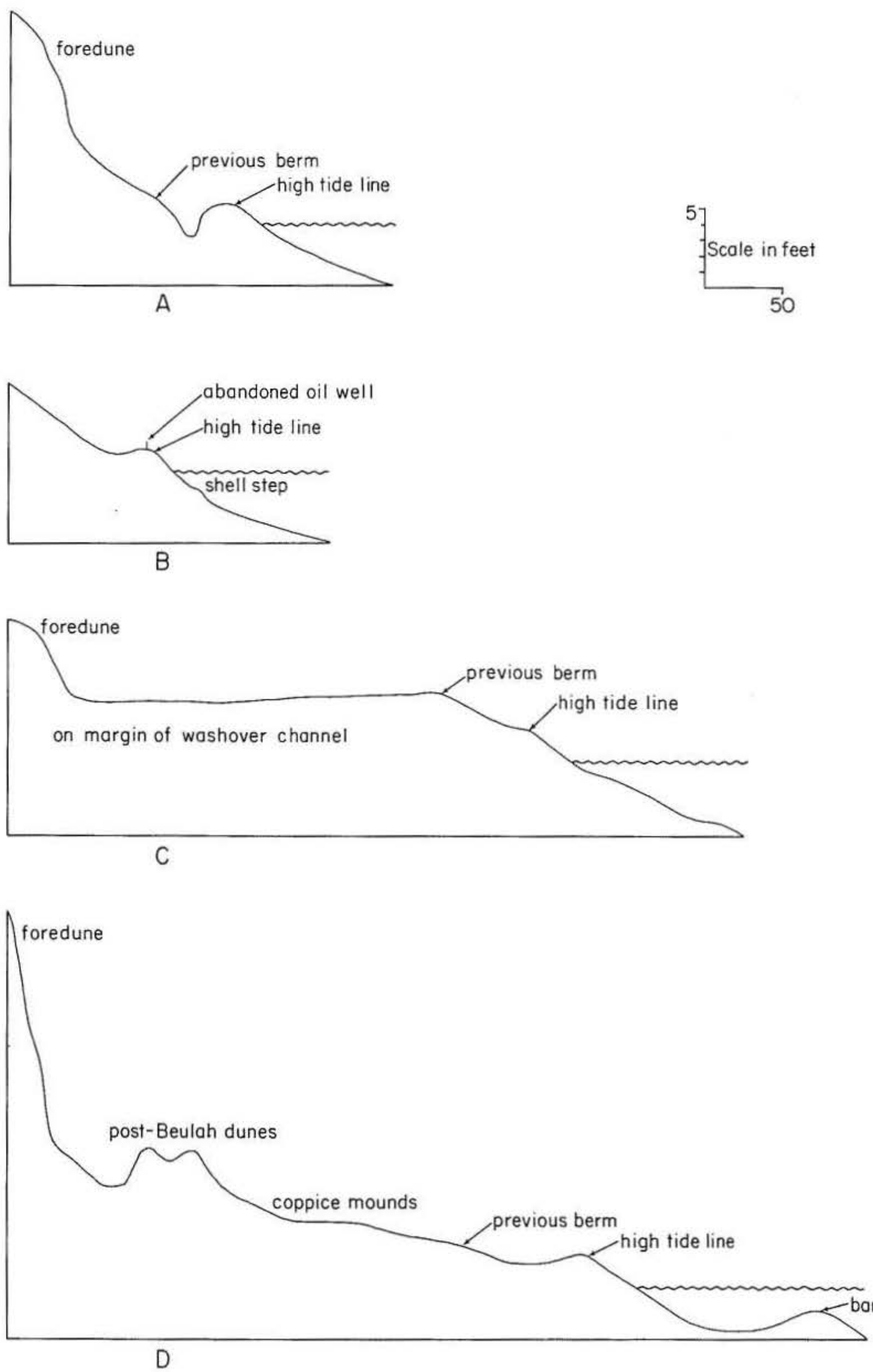


Figure 5. Beach profiles, Brazos Island and south Padre Island, recorded August 21 and 22, 1974. Locations plotted on figure 3.

HUMAN ALTERATION OF NATURAL CONDITIONS

Brazos Santiago Pass

Historically, Brazos Santiago Pass has been more important than other areas along south Padre and Brazos Islands because it serves as a natural pass from the Gulf to Laguna Madre and the mainland of the lower Texas Coast.

Prior to jetty construction, channel depth at Brazos Santiago Pass varied from 6.5 to 11 feet (U. S. Army Corps Engineers, 1963), and channel position shifted continually. The width of the pass also varied from 700 to 1,700 feet between 1882 and 1910 (U. S. Army Corps Engineers, 1913).

The first federal improvement was initiated in 1878 with the removal of a wreck from the channel. In 1881, the River and Harbor Act authorized construction of a south jetty consisting of brush mattresses weighted down by clay bricks (U. S. Army Corps Engineers, 1881). Work on the jetty was suspended in 1884; the remaining jetty was destroyed by a major storm in 1887, which crossed the coast in Mexico (U. S. Army Corps Engineers, 1888, 1895).

Between 1887 and 1927, all jetty work was abandoned and an attempt was made to maintain the channel across the bar and within the Laguna Madre at a desirable depth by dredging (U. S. Army Corps Engineers, 1900, 1905, 1913, 1914, 1916, 1919, 1928). This operation was largely unsuccessful because shoaling was rapid.

During 1927 and 1928, work commenced on two stone dikes extending 1,400 feet from Brazos Island and 1,899 feet from Padre Island (U. S. Army Corps Engineers, 1928). The dikes, constructed mainly as a protective device for the dredging barge, were ineffective in maintaining natural depth of the channel, and they deteriorated rapidly after construction.

The River and Harbor Act of 1930 authorized the construction of the present-day jetties. Not until the present jetties were completed in February 1935, was any success achieved in maintaining a dependable navigation channel. The jetties are 1,200 feet apart; length of the north jetty is 5,370 feet, whereas the south jetty is 5,092 feet long (U. S. Army Corps Engineers, 1963). In 1935, small rock groins were constructed to prevent bank erosion and protect the inner end of the jetties.

Upon completion of the project, the channel from the Gulf had been dredged to 23 feet (U. S. Army Corps Engineers, 1936). Channel dimensions were increased by dredging in 1939 and by 1940 the channel from the Gulf through Brazos Santiago Pass was 32 feet deep (U. S. Army Corps Engineers, 1939, 1940b). Channel dredging continued until the channel through the pass was 35 feet deep (U. S. Army Corps Engineers, 1941). At the same time the channel to Brownsville as well as the turning basins were deepened and widened.

No further improvements were reported during the 1940's, but in 1950 new plans for improvement called for a channel 38 feet deep and 300 feet wide from the Gulf through Brazos Santiago Pass; the proposed depth in all other channels and basins was 36 feet (U. S. Army Corps Engineers, 1950). Project maintenance and dredging continued until completion in 1960 (U. S. Army Corps Engineers, 1960). Major rehabilitation of the north and south jetties in 1966 and maintenance dredging have been the only activities reported for this project since a stone embankment was constructed in 1961 on Padre Island between the north jetty and the remains of the 1935 rock groin (U. S. Army Corps Engineers, 1963). A 1,000-foot extension of the north jetty authorized by the River and Harbor Act of 1960 had not been finished by 1972 (U. S. Army Corps Engineers, 1961, 1965, and 1972).

Mansfield Channel

Southern Padre Island is traversed by one artificial pass, Mansfield Channel, located approximately 38 miles north of Brazos Santiago Pass. The channel, 10 feet deep and 100 feet wide, was dredged through Padre Island by the Willacy County Navigation District in 1957. After the channel was dredged, two jetties were constructed of concrete tetrapods. The north jetty extended 1,600 feet into the Gulf, and the south jetty extended 900 feet (Hansen, 1960). Subsequent to completion, extensive deterioration of both jetties occurred because of subsidence and erosion at the shore ends. With the effectiveness of both jetties destroyed, shoaling at the mouth of the channel occurred by 1958 making the channel useless for navigation (Hansen, 1960). Hansen also reported that the shoreline north of the channel entrance had undergone extensive erosional and accretionary cycles since completion of the channel and jetties.

In September 1959, Congress authorized improvement of Mansfield Channel as a Federal project. The project included dredging of the channel and construction of a north jetty and a south jetty extending 2,300 feet and 2,270 feet, respectively. Work under contract for construction of rubble stone jetties was completed May 8, 1962 (U. S. Army Corps Engineers, 1962a).

CHANGES IN SHORELINE POSITION

Late Quaternary Time

Significant changes along the south Texas Coast during the past few thousand years have resulted from sea-level fluctuations (fig. 6) as well as from fluvial-deltaic and marine processes. Lohse (1958) discussed the Recent history of the Rio Grande delta and concluded that the distributary system during Early Recent time transported sufficient material to allow progradation of the

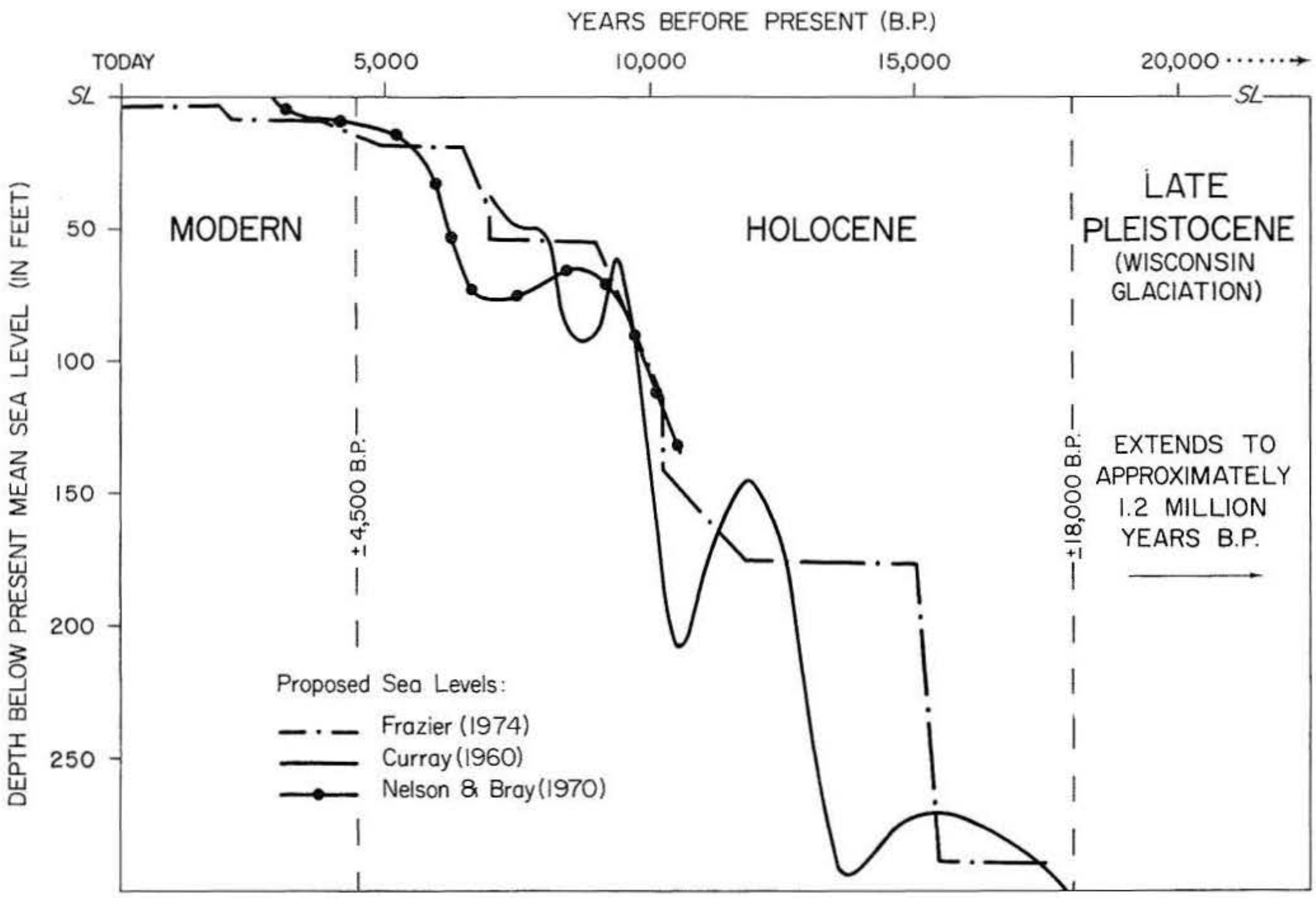


Figure 6. Proposed sea-level changes during the last 20,000 years; sketch defines use of Modern and Holocene used in text. From Fisher and others (1973).

shoreline seaward of its present position. This is substantiated by outcrops of mud and poorly consolidated sandstone in the swash zone of south Padre Island. Lateral shifting of sites of active deltation, subsidence, and transgression of abandoned subdeltas have been subsequently responsible for the present configuration of the coastline.

During the past few 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 common.

Historic Time

Shoreline changes and tabulated rates of change between 1854 and 1974 at 25 arbitrary points spaced 10,000 feet apart along the map of Brazos Island and south Padre Island (fig. 3) are presented in appendix A. Excluding points in proximity to passes and the Rio Grande, Brazos Island has experienced one early period of accretion (1854-1937) and more recently a trend dominated by erosion (1937-1974). In contrast, south Padre Island has undergone varying rates of erosion since 1854 with the exception of stations 20 and 21, which have been either in equilibrium or in accretion since construction of the Brazos Santiago jetties in 1935.

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

Brazos Santiago Pass

Prior to jetty construction, Brazos Island and south Padre Island experienced two periods of accretion (1854-1867 and 1917-1934) and one period of erosion (1867-1917) in the vicinity of Brazos Santiago Pass (table 1). Since completion of the jetties, the shoreline has accreted 1,050 feet or 29 feet per year at the north jetty on south Padre Island, the greatest rate being between 1937 and 1955. On Brazos Island, in proximity to the south jetty, the shoreline has accreted 1,700 feet or 47 feet per year. The greatest period of accretion was between 1934 and 1937. Supplementary shorelines mapped on aerial photographs taken in 1955 and 1968 confirm the accretionary trend established by comparison of the 1938, 1960, and 1970 shorelines. The shoreline has continued to accrete near the north jetty (point 21) as indicated by the 1974 photographs.

Table 1. Short-term shoreline changes between 1854 and 1937 near Brazos Santiago Pass.

Time	Point 20		Point 21		Point 22	
	Dist ft	Rate ft/yr	Dist ft	Rate ft/yr	Dist ft	Rate ft/yr
1854-1867			+450	+34.6	+675	+51.9
1867-1917	-1000	-20.0	-1200	-24.0	-525	-10.5
1917-1934	-125	-7.4	+150	+8.8	+325	+19.1
1934-1937	-75	-25.0	-75	-25.0	+50	+16.7

Until 1955, the accretionary rate adjacent to the south jetty was extreme (1934-1937) to major (1937-1955). Accretion slowed to 15 feet per year between 1955 and 1960; total accretion between 1937 and 1960 was 300 feet. Since 1960, the shoreline has accreted slightly.

Mouth of the Rio Grande

Perhaps the most dramatic shoreline changes have taken place on Brazos Island in the vicinity of the Rio Grande. Repeated changes in the position of the mouth of the river have directly affected the shoreline along this segment of the coast (fig. 7).

In 1854, the mouth of the river was located in approximately the same position as today (1975). Between 1854 and 1937, the mouth migrated to a point approximately 4,000 feet north of the 1854 location. Northward migration continued between 1937 and 1958; in 1958, the mouth reached its most northern position since 1854 (B. L. Everitt, personal communication, 1974). Between 1958 and 1960, the mouth migrated approximately 1,000 feet to the south. During high water produced by Hurricane *Carla* (1961), the river cut a new course, shifting the position of the mouth approximately 4,000 feet to the south, not far from its 1897 position (B. L. Everitt, personal communication, 1974). Beginning in 1962, the mouth again started a slow migration to the north. During Hurricane *Beulah* (1967), the river changed

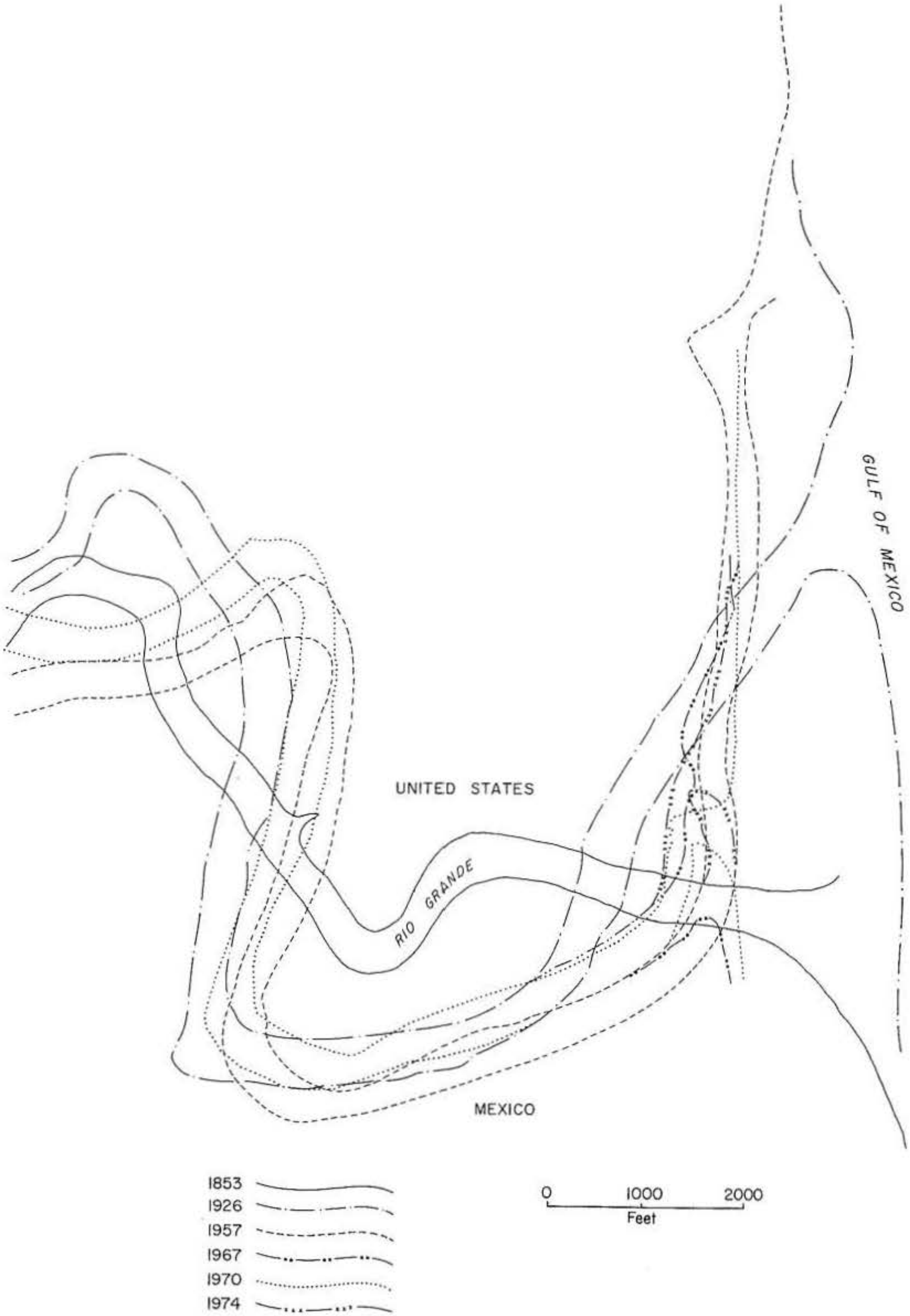


Figure 7. Changes in location of mouth of Rio Grande, 1853-1974. Data from International Boundary and Water Commission (1853-1967), National Oceanic and Atmospheric Administration (1970), and Texas Highway Department (1974). *See* appendix C.

its course resulting in a shift of the mouth again to the south. The mouth of the river is currently located approximately 750 feet north of the 1967 location.

Brazos Island

The shoreline on Brazos Island has experienced both accretion and erosion. The shoreline accreted between 1854 and 1937; after 1937, the shoreline was characterized by a combination of erosional and accretionary cycles at the individual stations.

1854-1937.—During this time interval, all stations on Brazos Island experienced accretion. Accretion ranged from 525 feet at point 22 to 1,425 feet at the mouth of the Rio Grande.

This time period is broken into four shorter increments (1854-1867, 1867-1917, 1917-1934, and 1934-1937); however, measurements are not available for all stations (table 1). These shorter increments are also dominated by accretion. The greatest accretion (675 feet at point 22) occurred between 1854 and 1867; however, between 1867 and 1917, erosion of 525 feet occurred at station 22.

The 1937 photomosaics illustrate the foredune erosion, which took place during the 1933 hurricane. Unfortunately, shoreline erosion related to the storm cannot be determined, but storm channels that breached the foredune remnants were still present in 1937. Boca Chica Pass was opened by the storm surge but was again closed in 1937.

1937-1960.—During this time interval, station 22 experienced accretion (300 feet), station 24 was in equilibrium, and stations 23 and 25 experienced erosion. Shoreline erosion of 400 feet at station 25 can be explained in part by the northern migration of the mouth of the Rio Grande (fig. 7) and reorientation of a prominent bulge in the shoreline just north of the earlier position of the river mouth. Beginning with this time interval, there was a marked change in the previous accretionary trend of Brazos Island. Probably this change, in part, reflects the construction of Falcon Dam, which was completed in 1953 resulting in a sharp decline in volume of water and sediment carried downstream from the structure by the Rio Grande (figs. 8 and 9).

1960-1970.—Station 22, near the south jetty at Brazos Santiago Pass, experienced moderate accretion (75 feet) between 1960 and 1970. The shoreline at station 23 remained relatively unchanged, whereas the two southernmost stations (24 and 25) experienced erosion of 75 and 375 feet, respectively. The erosion may be attributed in part to a shift in the river course to a position approximately 5,000 feet south of the 1960 location. Also, straightening of the shoreline may have been a factor.

1970-1974.—Measurements for this time period are available only at stations 23 through 25. The shoreline between the south jetty and station 22 is not covered by the 1974 photography.

Between 1970 and 1974, the shoreline at station 23 accreted 25 feet, while the stations at the southern end of Brazos Island (24 and 25) experienced erosion of 100 and 125 feet, respectively.

South Padre Island

The shoreline of south Padre Island has been retreating at least since the late 1800's. The barrier island is traversed by numerous washover channels (fig. 10), which are opened periodically by storm surges. Generally, washover channels heal quickly after a storm by normal littoral processes. The filled channels characteristically exhibit planar surfaces that are void of large dunes and lower than adjacent areas.

1867-1880 to 1937.—The earliest shoreline position on south Padre Island is based on a composite of U. S. Coast and Geodetic Survey charts dated 1867, 1879, and 1880. This early composite shoreline was compared to the 1937 shoreline position mapped on aerial photomosaics. Two intermediate maps are also available for comparison in the vicinity of Brazos Santiago Pass: a 1917 U. S. Coast and Geodetic Survey chart and a 1934 U. S. Geological Survey 15-minute topographic quadrangle.

Between 1867-1880 and 1937, all 21 stations on south Padre Island experienced erosion. Four stations experienced major rates of erosion (15 to 25 feet per year), 11 stations recorded rates between 5 and 15 feet per year, and 6 stations recorded minor erosion (0 to 5 feet per year).

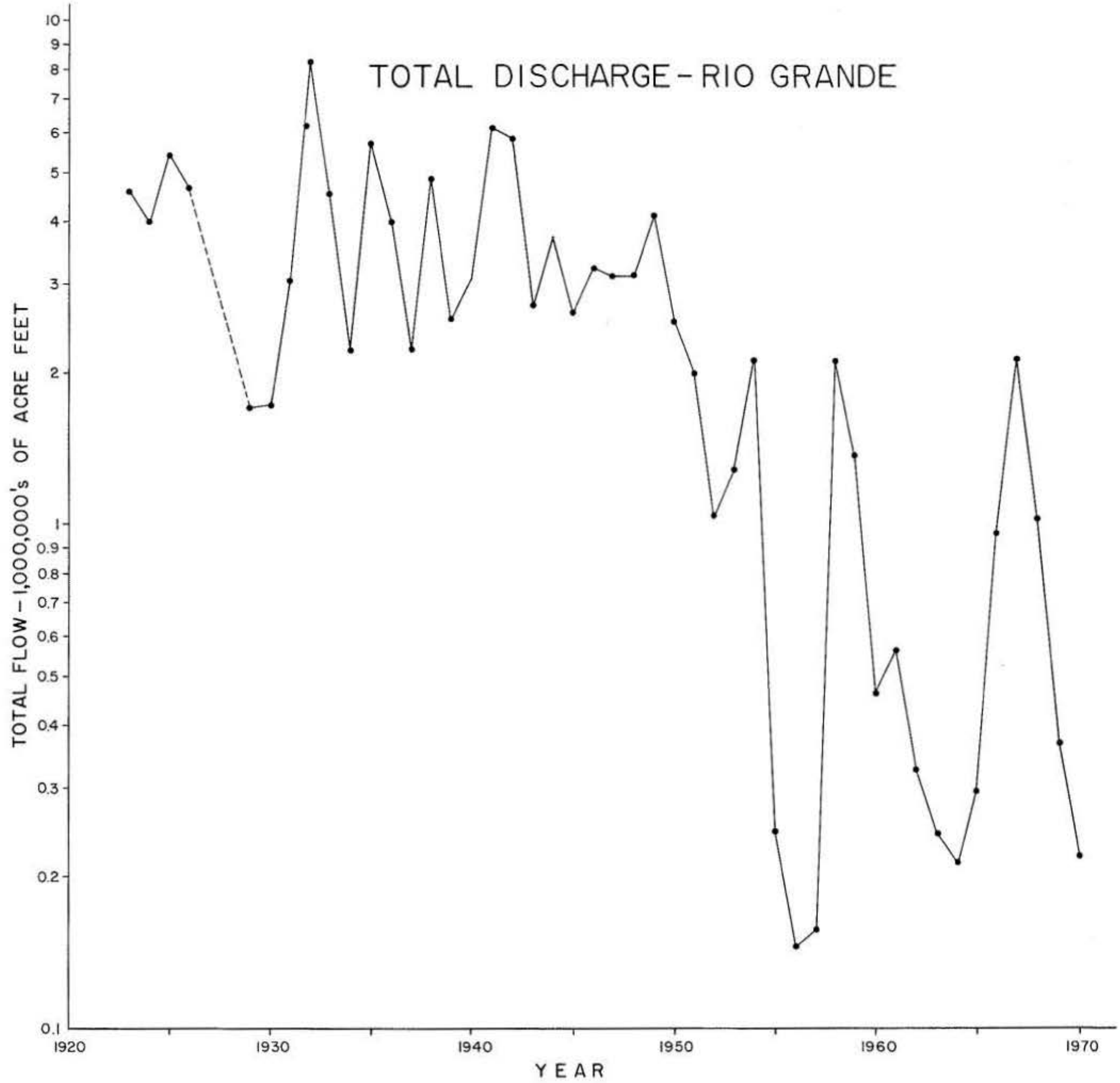


Figure 8. Total discharge of Rio Grande recorded at Roma Station (1923-1954) and San Benito Station (1955-1965). Data from Texas Board of Water Engineers (1961 and 1970), U. S. Geological Survey (1927, 1928, 1929, 1930, 1932a, 1932b), and International Boundary and Water Commission (1931-1944, 1945-1946, 1952-1970).

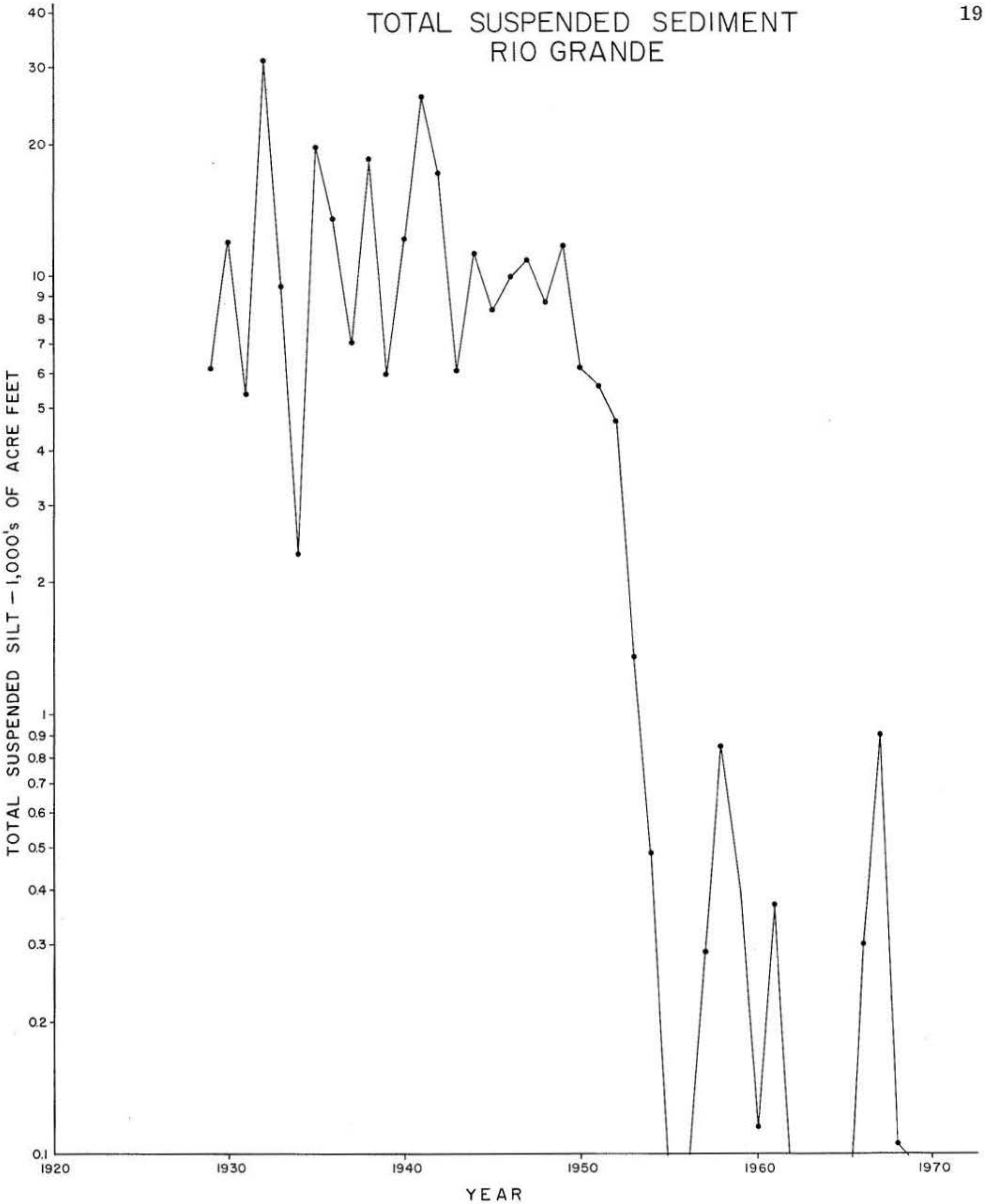


Figure 9. Total suspended sediment of Rio Grande recorded at Roma Station (1929-1954). Data from Texas Board of Water Engineers (1961), U. S. Geological Survey (1927, 1928, 1929, 1930, 1932a, 1932b), and International Boundary and Water Commission (1931-1944, 1945-1946, 1952-1970).

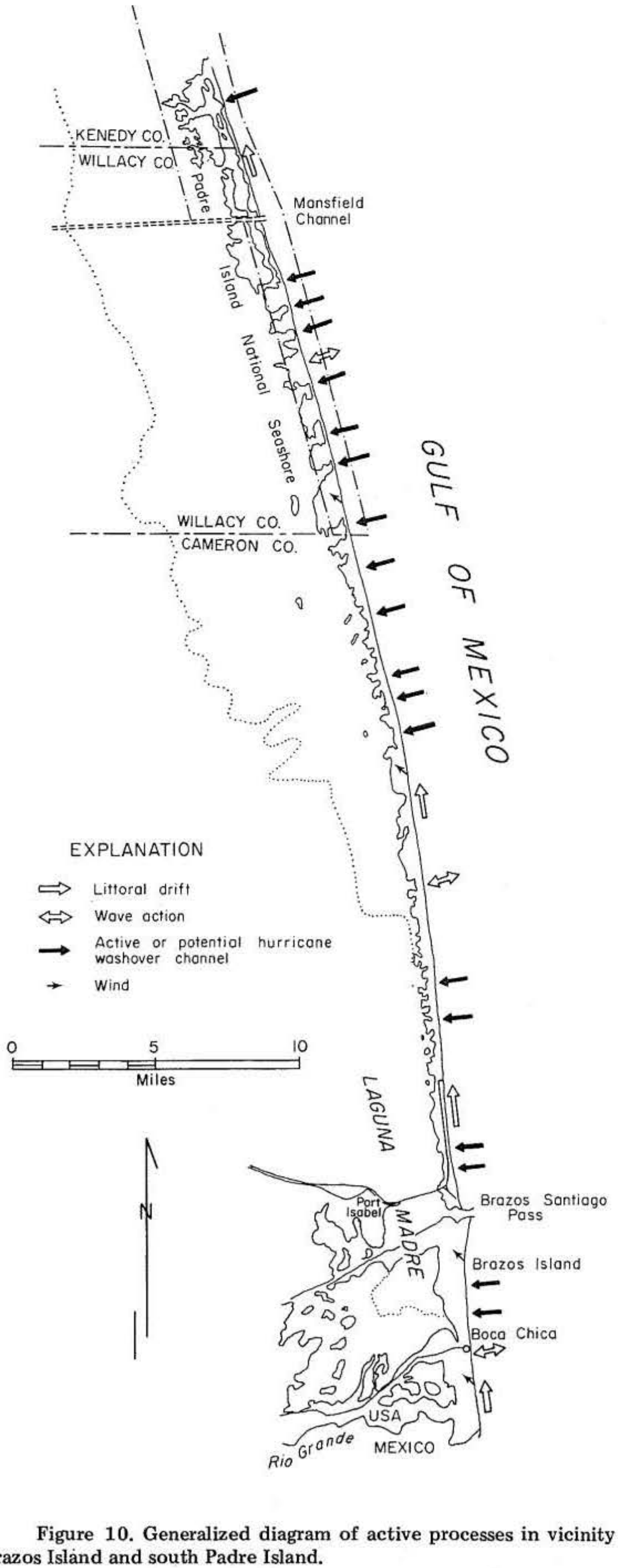


Figure 10. Generalized diagram of active processes in vicinity of Brazos Island and south Padre Island.

Greatest shoreline erosion, recorded at points 17 to 21, ranged from 900 to 1,250 feet. Erosion for the remaining beach segment ranged from 25 to 675 feet and averaged 375 feet. A total of 14 tropical cyclones, 6 of which were major hurricanes, affected the lower part of the coast during this period. Apparently the 1933 storm caused more damage to the island than any of the other storms between 1867 and 1937. During the 1933 hurricane, a 12- to 15-foot storm surge was recorded at Brownsville (Sugg and others, 1971). Price (1956a) reported that as a result of the storm, 40 channels were opened and nearly all of the dunes were eroded from the southern part of Padre Island; however, no quantitative data on shoreline erosion are available. The extreme effects of the storm are exhibited on the 1937 photomosaics. The area recovered slowly because a drought following the storm retarded growth of vegetation, thus slowing down the process of dune stabilization.

1937 to 1960.—Between 1937 and 1960, erosion continued along most of south Padre Island, the exception being between stations 20 and 21 where the shoreline was directly affected by the north jetty at Brazos Santiago Pass. These two stations experienced accretion of 200 and 550 feet, respectively. The shoreline accreted 50 feet at point 13 and remained unchanged at point 14. Erosion at the remaining 17 points ranged from 25 to 450 feet; average erosion was 230 feet. Areas of most rapid shoreline erosion included stations 8 to 12 and stations 1 to 4.

No major hurricanes made landfall in the area during this period; however, the area may have been affected four times (July 1945, August 1947, June 1954, June 1958) by 4- to 5-foot surges associated with hurricanes crossing the coast to the north or south of the area.

1960 to 1969-1970.—Shoreline erosion on south Padre Island continued between 1960 and 1970. One station (14) recorded erosion of 325 feet, and five points recorded erosion between 150 and 225 feet. Shoreline erosion along the remaining segments was between 25 and 150 feet except at point 7 which remained unchanged. Again, points 20 and 21 at the southernmost part of the island near the north jetty showed accretionary values. Measurements are not available north of point 7 because lack of ground control made it impossible to transfer the 1970 shoreline to the base map within the limits of error established for this study. During this 10-year period, the area was affected by two major hurricanes (Carla, 1961, and Beulah, 1967). Although Celia, in 1970, was an extreme storm, its radius of damage was relatively small and did not extend to south Padre Island.

Storm surge from Carla, ranging from 4.4 feet at Port Isabel to 5.5 feet on south Padre Island (U. S. Army Corps Engineers, 1962b), increased in height northward along the Texas Coast. Carla surge opened Mansfield Channel and 40 storm channels on Padre Island (Hayes, 1967). Erosional effects, however, were restricted mainly to the area north of Mansfield Channel. A series of beach profiles in proximity to Mansfield Channel taken by the U. S. Army Corps of Engineers after Carla indicate shoreline erosion ranging from 60 ft to 160 ft (U. S. Army Corps Engineers, 1962b).

Beulah (1967) crossed the Texas Coast just east of Brownsville. Maximum storm tides of 12 feet (measured high water mark at Port Isabel) and 18 feet (estimated at latitude 26° 4′ N.) were reported by Sugg and Pelissier (1968). Twenty-seven storm washover channels varying in width from several hundred feet to approximately 5,000 feet breached the island between Andy Bowie County Park and Mansfield Channel (observations made from 1967 Texas Highway Department low-altitude aerial photos). Immediately south of Andy Bowie County Park, the highway (Park Road 100) was breached in several places; however, the washovers did not cut through the island. South of this area, no washover channels are evident; erosion was restricted to the immediate beach and foredune area.

Comparison of June 1967 aerial photographs (U. S. Army Corps Engineers) with September 1967 aerial photographs (Texas Highway Department) reveals dune erosion of 50 to 350 feet that resulted in wave-cut faces on the seaward margins of the foredunes. Areas of greatest dune erosion occurred along lateral margins of active washover channels opened by the storm surge.

1969-1970 to 1974.—The dominant erosional trend on south Padre Island continued between 1970 and 1974. As before, points 20 and 21, near the north jetty, experienced accretion while the rest of south Padre Island experienced erosion at highly variable rates; most of the island experienced moderate erosion, however, the shoreline at points 9, 17, and 19 remained relatively unchanged. Erosion at the other points ranged from 25 to 150 feet and averaged about 70 feet.

Shoreline changes north of the Cameron-Willacy county line were not determined because of the inability to transfer shoreline data to the base map with the desired degree of accuracy. The lack of ground control along this portion of the island in conjunction with migrating dunes makes exact cartographic adjustment nearly impossible. Consequently, quantitative figures are not available, but generalized observations suggest that the erosional trends typical of the shoreline from points 8 to 19 continue northward between points 1 and 7.

The shoreline adjacent to the south jetty at Mansfield Channel accreted 150 feet between 1967 and 1974 or at a rate of 21.4 feet per year. This accretion was predictable because the jetty entraps sediment transported northward by the prevailing longshore current. The shoreline adjacent to the north jetty, where longshore sediment supply was deficient, eroded 100 feet or at a rate of 14.3 feet per year.

No tropical storms crossed this segment of the coast between 1970-1974. The erosional effects of Beulah are still visible; however, coppice mounds are again beginning to encroach upon the storm channels.

Shoreline changes documented by historical monitoring techniques, such as repetitive sequential mapping using aerial photographs, have been confirmed by field measurements. For example, in 1956 the Gilbert Kerlin #1 well (Cameron County) was drilled by Magnolia Petroleum Company about 5 miles south of the Cameron-Willacy county line. The well location plat, on file at the Texas Railroad Commission, shows that the well was drilled 330 feet landward from the mean tide line; the mean tide line is presently near the abandoned well. Beach erosion at point 11 of 300 feet between 1960 and 1974 is in close agreement with the measurement obtained from the survey records of the oil well.

Net Historic Change (1854-1974)

Net shoreline change (fig. 11) was calculated using the 1854 shoreline between points 21 and 25, the 1867 shoreline from points 16 to 20, and the 1879-80 shoreline from points 1 to 15 as a baseline; net shoreline change is equal to the difference between this baseline and the 1974 shoreline (appendix A).

The shoreline along Brazos Island has undergone net accretion since 1854; however, this trend is influenced predominantly by the moderate to extreme accretion which occurred between 1854 and 1937. With the exception of point 22, where accretion has continued due to entrapment of sediment by the south jetty, the accretionary trend reversed after 1937, and Brazos Island entered a trend dominated by erosion at rates varying from 10 feet to 37.5 feet per year. Extreme erosion is restricted to south Brazos Island (point 25), which is greatly influenced by the location of the mouth of the Rio Grande (fig. 7).

South Padre Island has experienced a history of erosion with the exception of the extreme southern tip of the island, which has undergone accretion since construction of the jetties in 1935. At many points, rates of erosion increased between 1960 and 1969 with parts of the island experiencing extreme erosion. Comparison of net changes on south Padre Island is difficult because of the composite nature of the late 1800's shoreline and the lack of 1970 and 1974 data on shoreline positions between points 1 and 7. Nevertheless, the trend is clearly established because erosion prevailed at all points removed from the direct influence of the north jetty at Brazos Santiago Pass. The most complete record for these points (8 through 20) indicates net erosion ranging from 725 to 1,400 feet and averaging about 990 feet. Overall net erosion was moderate, ranging from 8 to 13 feet per year.

These data indicate long-term net change, but the values should be used with caution because of their misleading implications. 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. Furthermore, if for any reason the equilibrium between sediment supply and littoral processes is upset, then even long-term trends of the past may not reflect long-term trends of the future.

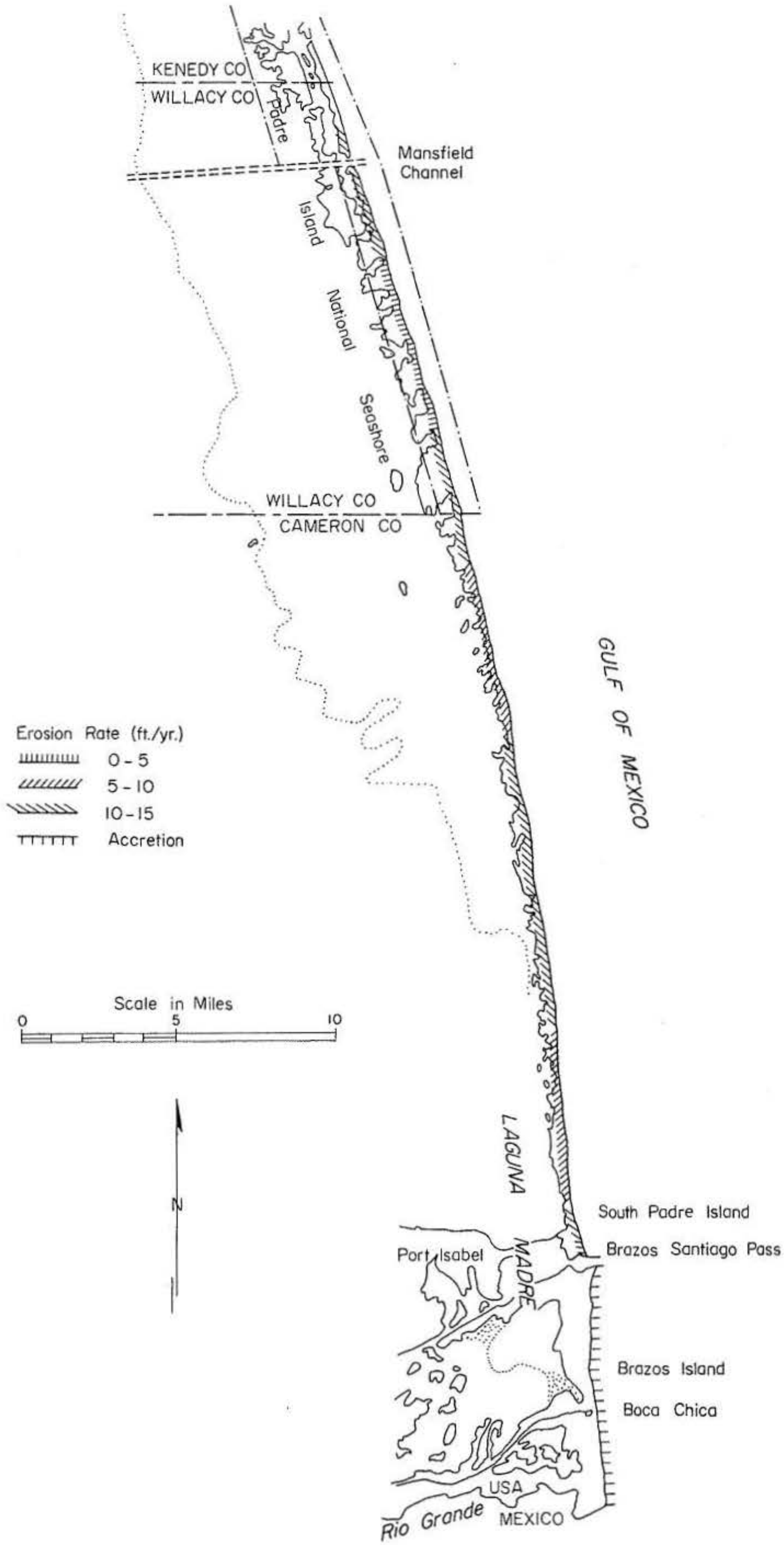


Figure 11. Net shoreline changes along Brazos Island and south Padre Island, based on variable time periods from 1854-1880 to 1974. Maximum extent of time on which these changes are based is 120 years; minimum extent is 94 years.

CHANGES IN POSITION OF VEGETATION LINE

The first descriptive survey of Padre Island was recorded in 1828 by Domingo Fuente (Meixner, 1948), who described the area of south Padre Island between Brazos Santiago Pass to just north of the present Cameron-Willacy county line as salty bays and dunes with very little pasture land except in the vicinity of the county line. North of this line, the density of vegetation increased. He noted the presence of small fresh-water lakes, willows, small oaks, and abundant grass on north Padre Island.

Apparently vegetation was more prolific from the early 1900's to about 1930. Pat Dunn, a cattle rancher, reported continuous pasture land on Padre Island extending 110 miles long and 2½ to 4 miles wide (Meixner, 1948). As many as 1,600 head of cattle were on the island at one time; however, Dunn reported that after the 1933 storm it would not have been possible to support 25 head of cattle on the southernmost 40 miles of Padre Island (Meixner, 1948). The effect of extensive grazing on the island's vegetation is only speculative; however, it must be considered as a factor in the general decline in abundance of vegetation (U. S. Dept. Interior, National Park Service, 1959).

Price (1956a) reported that prior to 1933 there was a relatively continuous line of vegetated foredunes (15 to 25 feet high) on the island broken by irregularly spaced storm channels. The grass cover was destroyed and much of south Padre Island was reduced to relatively smooth sand plains at or below beach-ridge levels by the 13-foot surge which accompanied the 1933 storm. By 1946, the vegetation had begun to recover (Price, 1956a); progress was slow because droughts occurred in the area from 1933 to 1934 and from 1937 to 1939. Droughts also affected the area in 1950-52 and 1954-56. The drought of 1954-56 was one of the most severe experienced by the State (Lowry, 1959). During these droughts, the active dune fields were greatly expanded.

The effects of local droughts upon vegetation in this semiarid region are further exemplified by low-altitude aerial photographs taken in 1955 during the extended drought of the 1950's. No major storms made landfall in this area in the late 1940's and 1950's, thus the paucity of vegetation is related to drought conditions.

A general rather than quantitative description of changes in position of the vegetation line on Brazos Island and south Padre Island is necessary because, in most instances, with the exception of a portion of south Padre Island between the north jetty and Park Highway 100, the vegetation line is characteristically discontinuous and confined to areas of stabilized dunes.

1937.—The effects of the September 1933 hurricane on vegetation of south Padre Island and Brazos Island were still visible on the 1937 photomosaics. The eroded dunes were separated by broad, smooth, washover channels; only isolated remnants of vegetated foredunes remained. Except for the remnants, the southern half of Padre Island was virtually denuded of vegetation.

Vegetation on Brazos Island was also restricted to erosional remnants of the foredunes and scattered coppice mounds seaward of the foredune remnants.

1955.—Despite the effects of extended droughts (1937-39, 1950-52, 1954-56), the line of vegetation on Brazos and south Padre Islands advanced gulfward between 1937 and 1955. Aerial photographs taken in 1955 show the effects of drought on density and condition of the vegetation. During the drought, considerable unstabilized sand was permitted to migrate due not only to the sparse vegetation but also to the poor condition of the vegetation. Major revegetation prior to the 1954-1956 drought occurred on foredune remnants; minor revegetation occurred in washover areas which had been partially filled by coppice mounds. Sparsely vegetated coppice mounds seaward of the foredunes were also abundant in 1955.

1937-1960.—The vegetation line recovered considerably in the 23 years between 1937 and 1960. Two major factors affecting this recovery were the low frequency of major storms striking the southern part of the Texas Coast during this period and the cessation of the 1954-56 drought. An increase in density was the most significant change in vegetation between 1955 and 1960 which can be attributed to increased rainfall. Because of the lack of geographic control points on the 1937 mosaics, it is difficult to make detailed measurements comparing the 1937 and 1960 vegetation line.

The vegetation on Brazos Island accreted both seaward and parallel to the shoreline by 1960. Revegetation along the lateral margins of washover channels occurred where dunes with sparse vegetation partially infilled the washover channels; a decrease in channel width of about 1,000 feet occurred in the areas immediately north of points 24 and 25. In addition, coppice mounds developed across the washover channels and gulfward of the continuous segments of vegetation.

A rather continuous vegetation line was present on south Padre Island from point 21 to near point 20. Vegetation obscured two of the three washover channels present along this segment of the beach in 1937. One of the channels, present east of Park Road 100, had decreased in width by about 200 feet.

From point 20 to point 14, the vegetation in 1960 was confined to areas of stabilized dunes which were cut by washover channels. These areas of stabilized dunes were more extensive than in 1937. Coppice mounds with sparse vegetation were numerous within the washover channels and in front of the stabilized foredunes.

In 1960, the vegetation north of point 14 was sparse and the area was dominated by actively migrating dune fields. An exception to this occurred one mile on either side of point 9 where vegetation was nearly continuous. This same area was barren in 1937 except for a few small erosional remnants.

1960-1970.—The difference between net changes and short-term changes is illustrated by comparison of the position of vegetation lines from 1960 to 1970. Air photos taken in June 1967 and September 1967 (appendix C) show the direct effect of Hurricane Beulah; however, the erosional effects of Beulah are overshadowed by the accretionary trend documented for the entire 1960-to-1970 time period.

Between 1960 and 1970, two major hurricanes affected the southern part of the Texas Coast: Carla (1961) and Beulah (1967). Erosional effects of Carla were restricted to active storm channels on south Padre and Brazos Islands; apparently the destructive effect of Carla on vegetated areas was only minor.

Erosion of the dunes and vegetation line is obvious on the post-Beulah photographs (September 25, 1967); however, erosion and denudation of the vegetation from Beulah (fig. 4) was not as severe as it was in 1933. Unfortunately, the September 25, 1967 photographs do not include Brazos Island. On south Padre Island, the vegetation line experienced the same amount of erosion as the foredunes because vegetation was restricted to the stabilized foredune areas. Erosion of the foredunes varied from 50 to 350 feet; the most extensive dune erosion occurred along lateral margins of the washover channels. Between points 8-17 and 20-21, a vegetated zone up to 200 feet wide, which was buried by washover sand in 1967, had recovered by 1970, and coppice mounds with sparse vegetation had begun to form in front of the foredunes and within the lateral margins of the storm channels.

Although Celia (1970) was an intense storm, it was small in size and maximum effects were restricted to the vicinity of Corpus Christi. The 1970 photographs were taken immediately after Celia, and no erosional effects are visible on south Padre Island or Brazos Island.

The vegetation line on Brazos Island experienced net accretion between 1960 and 1970, except within an area immediately north of the Rio Grande where the vegetation line receded 500 feet. In 1961, however, as a result of flooding associated with Carla, the Rio Grande changed course by avulsion to a position about 4,500 feet south of its location in 1960.

The vegetation line along a segment one mile on either side of station 23 was more continuous by 1970. Irregularities in the 1960 vegetation line were nearly eliminated by accretion up to 200 feet. Two isolated vegetated areas located approximately 2,000 feet south of Brazos Santiago Pass accreted from 200 to 700 feet. In addition, numerous coppice mounds developed between these vegetated areas and the south jetty.

In 1970, the vegetation line from point 21 to point 20 was continuous. Although the vegetation line was approximately in the same position as in 1960, the vegetation was extended parallel to the shoreline to cover three washover channels that were present in 1960.

A segment of the vegetation line extending 5,400 feet south from station 19 accreted from 100 to 350 feet between 1960 and 1970. South

Padre Island was nearly barren of vegetation in 1960; perhaps the devegetation was associated with predevelopment road construction. The same area was covered by vegetation in 1970.

For an area extending approximately 4,000 feet north of station 19, the vegetation line accreted from 0 to 200 feet seaward of the 1960 vegetation line. In addition, a storm channel located approximately 3,000 feet north of station 19 was covered by vegetation in 1970.

North from station 18, the continuous vegetation line ended, and vegetation was restricted to areas of stable dunes. The dunes were cut by numerous washover channels. Coppice mounds were present seaward of the foredune areas but not within the channels. The shape and position of the stabilized dunes changed little in the ten-year span between 1960 and 1970.

1970-1974.—During this period, the vegetation on Brazos and south Padre Islands continued to recover and advance. The area of greatest accretion on Brazos Island was located just north of the Rio Grande. Storm channels were still present in 1974; however, between 1970 and 1974, sparsely vegetated coppice mounds migrated into the channels. Vegetation existing on stabilized dunes accreted 50 to 100 feet coincident with development of a line of post-Beulah dunes seaward of the earlier foredunes (fig. 5).

On south Padre Island, the vegetation accreted 50 to 150 feet in areas of stabilized dunes. Coppice mounds also formed seaward of the foredunes, but not to the extent that they did on Brazos Island. Most of the coppice mound development was parallel to the beach and along the lateral margins of storm channels.

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 Brazos and south Padre Islands is as follows: 1891-1893, 1896-1899, 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, 1956a; 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 south Padre and Brazos Islands, has a 9-percent probability of experiencing a tropical storm, an 8-percent probability of experiencing a hurricane, and a 2-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 (1962b, 1968b, 1971a, 1972).

Destructive forces and storm damage.—The most intense storms on record to strike the south Padre area were the storm of 1933 and Beulah; both storms were accompanied by surges in excess of 12 feet (Price, 1956a; Sugg and Pelissier, 1968). Although both storms caused extensive erosion of foredunes and vegetation on Brazos Island and south Padre Island, descriptions by Price (1956a) indicate that more extensive erosion took place during the 1933 storm. This can probably be attributed to the angle and approach to the coast when the hurricanes made landfall. The 1933 storm moved from the east approaching nearly normal to the shoreline, whereas Beulah moved in from the southeast striking the coast obliquely; thus, the movement of the water during Beulah was nearly parallel to the coast. Fresh-water flooding also occurred as the result of heavy rains associated with Beulah. Amounts varying from 10 to 20 inches were recorded in South Texas.

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 south Padre Island because of low elevations and lack of 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 Port Isabel which suggest that surge height of 8 feet can be expected approximately four times every 100 years. Maximum hurricane surge predicted was 12 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 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 either (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. An example of this can be seen by comparison of aerial photographs taken in June 1967, September 1967, 1968, 1969, 1970, and 1974. The September 1967 photographs depict post-storm conditions following Hurricane Beulah.

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. This process is well illustrated by comparison of June 1967, September 1967, 1968, 1969, 1970, and 1974 photographs between points 40 and 42 and 30 and 32.

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 Brazos and south 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 Brazos and south 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).

Swanson and Thurlow (1973) attributed the relative rise in sea level at Port Isabel to compactional subsidence (fig. 12). Their conclusion was based on tide records between 1948 and 1971. Interpreted rates of sea-level rise depend a great deal on the specific time interval studied; thus, short-term records can be used to demonstrate most any trends. On the other hand, long-term records provide a better indication of the overall trend and are useful for future prediction. Rates of relative sea-level rise determined by previous workers range from 0.013 to 0.020 feet per year or 1.3 to 2.0 feet per century. It is readily apparent that rises in sea level of this order of magnitude may cause substantial changes in shoreline position.

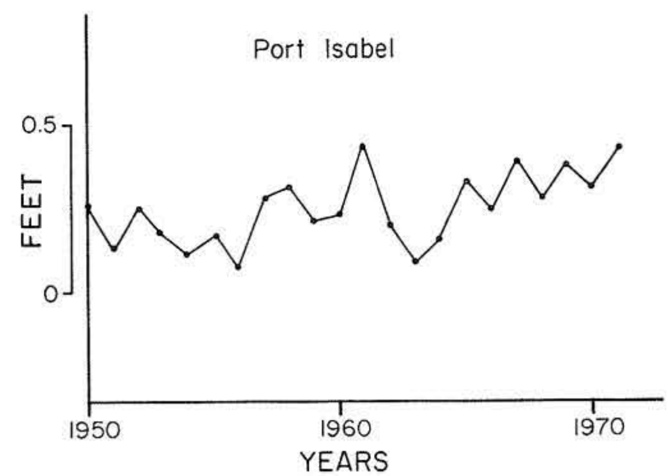


Figure 12. Relative sea-level changes based on tide gage measurements for Port Isabel, Texas. Data from Swanson and Thurlow (1973).

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-size sediment, the following discussion is limited to natural sources of sand for Brazos and south 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 Brazos and south Padre Islands probably include both sand derived from shelf sediment and the Rio Grande. 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. 6). The shelf off Brazos and south Padre Islands is underlain by fluvial-deltaic and interdeltaic sediments comprised predominantly of mud with some interbedded sand. Therefore, reworked shelf sediments in this area provided only minor amounts of sand for beach maintenance.

Sediment supplied by major streams is transported alongshore by littoral currents. Because of the orientation of the southern part of the Texas Coast, the prevailing south-southwest and east winds promote northward-flowing longshore currents (fig. 10). The Rio Grande is the only major river in an updrift direction from Brazos and south Padre Islands that supplies sediment directly into the littoral zone. There are indications that sediment discharge was greater during the early Holocene, but the time and maximum seaward extent of the Rio Grande delta during its construction are not known. Furthermore, it is not known precisely when the destructive phase of the abandoned delta was initiated. Although there are indications that sediment discharge was greater during the early Holocene, most Texas streams were in the process of filling their estuaries and were not contributing significant quantities of sand to the littoral currents. In addition to the natural decreases in sediment supply, both the construction of the jetties at Brazos Santiago Pass (1935) and construction of Falcon Dam (1955) have greatly decreased the availability of sediment from the Rio Grande to south Padre Island.

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. 10). During storms, sand may be moved offshore in deeper water or into the lagoons through washover channels; some sand is removed from the beach by eolian processes. 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 Brazos Santiago jetties was initiated in November 1933 and completed February 1935 (U. S. Army Corps Engineers, 1963). The present Mansfield jetties were completed in 1962 (U. S. Army Corps Engineers, 1962a). Projects such as these serve to alter natural processes. 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. Thus, it appears reasonable to expect that any sand trapped by the south jetty is compensated for by removal of sand downdrift, thus increasing local erosion problems.

Falcon Dam has had a profound effect on both the discharge rate and suspended sediment load, which decreased significantly after construction of the dam in 1955 (figs. 8 and 9). Between 1854 and 1937, the accretionary rate of Brazos Island declined sharply and at two stations the trend reversed to an erosional cycle. The trend was initiated prior to dam construction; however, the continued depletion of sediment contributes to the continued erosion on Brazos Island. The erosional rate increased on south Padre Island north of point 16 between 1937 and 1960, the greatest rates occurring between 1960 and 1969-70. This phenomenon may also reflect effects resulting from construction of the dam and jetties.

EVALUATION OF FACTORS

Shore erosion is not only a problem along United States coasts (El-Ashry, 1971) but also a worldwide problem. 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. Lohse (1958) concluded that shoreline retreat in the vicinity of the Rio Grande delta was caused primarily by a deficit in sediment budget. 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 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 logical conclusion drawn from factual information is that the position of shoreline and vegetation line in this region will continue to 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).

Construction pits and borings on south Padre Island (J. H. McGowen, personal communication, 1974; Rusnak, 1960) indicate that sand is about 10 to 15 feet thick under most of the island; the sand is underlain by mud. The sand stored in the barrier island, therefore, is insufficient to prevent future erosion without the addition of sediment to the littoral drift system.

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 (1971b, 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.

REFERENCES

Bascom, W. N., 1951, The relationship between sand size and beach-face slope: Am. Geophysical Union Trans., v. 32, no. 6, p. 866-874.

Bodine, B. R., 1969, Hurricane surge frequency estimated for the Gulf Coast of Texas: U. S. Army Corps of Engineers, Coastal Eng. Research Center Tech. Mem. 26, 32 p.

Braham, R. R., Jr., and Neil, E. A., 1958, Modification of hurricanes through cloud seeding: Natl. Hurricane Research Proj. Rept. 16, 12 p.

Bruun, P., 1962, Sea-level rise as a cause of shore erosion: Am. Soc. Civil Engineers Proc., Jour. Waterways and Harbors Div., WW1, v. 88, p. 117-130.

Bryant, E. A., and McCann, S. B., 1973, Long and short term changes in the barrier islands of Kouchibouguac Bay, southern Gulf of St. Lawrence: Can. Jour. Earth Sci., v. 10, no. 10, p. 1582-1590.

Bullard, F. M., 1942, Source of beach and river sands on Gulf Coast of Texas: Geol. Soc. America Bull., v. 53, p. 1021-1044.

Carr, J. T., 1967, Hurricanes affecting the Texas Gulf Coast: Texas Water Development Board Rept. 49, 58 p.

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

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

Dolan, R., Godfrey, P. J., and Odum, W. E., 1973, Man's impact on the barrier islands of North Carolina: Amer. Scientist, v. 61, no. 2, p. 152-162.

Dunn, G. E., and Miller, B. I., 1964, Atlantic Hurricanes: Louisiana State Univ. Press, 377 p.

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

El-Ashry, M. T., 1971, Causes of recent increased erosion along United States shorelines: Geol. Soc. America Bull., v. 82, p. 2033-2038.

______, and Wanless, H. R., 1968, Photo interpretation of shoreline changes between Capes Hatteras and Fear (North Carolina): Marine Geol., v. 6, p. 347-379.

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

Emory, W. H., 1857, Report of the United States and Mexican boundary survey: House Ex. Doc. 135, 34th Cong., 1st sess., serial 861.

Fisher, W. L., McGowen, J. H., Brown, L. F., Jr., and Groat, C. G., 1972, Environmental Geologic Atlas of the Texas Coastal Zone—Galveston-Houston area: Univ. Texas, Austin, Bur. Econ. Geology, 91 p.

______, Brown, L. F., Jr., McGowen, J. H., and Groat, C. G., 1973, Environmental Geologic Atlas of the Texas Coastal Zone—Beaumont-Port Arthur area: Univ. Texas, Austin, Bur. Econ. Geology, 93 p.

Frazier, D. E., 1974, Depositional-episodes: their relationship to the Quaternary stratigraphic framework in the northwestern portion of the Gulf basin: Univ. Texas, Austin, Bur. Econ. Geology Geol. Circ. 74-1, 28 p.

Garner, L. E., 1967, Sand resources of Texas Gulf coast: Univ. Texas, Austin, Bur. Econ. Geology Rept. Inv. 60, p. 85.

Gould, H. R., and McFarlan, E., Jr., 1959, Geologic history of the chenier plain, southwestern Louisiana: Gulf Coast Assoc. Geol. Socs. Trans., v. 9, p. 261-270.

Gutenberg, B., 1933, Tilting due to glacial melting: Jour. Geology, v. 41, no. 5, p. 449-467.

______ 1941, Changes in sea level, postglacial uplift, and mobility of the earth's interior: Geol. Soc. America Bull., v. 52, p. 721-772.

Hansen, E. A., 1960, Studies of a channel through Padre Island, Texas: Am. Soc. Civil Engineers Proc., Jour. Waterways and Harbors Div., p. 63-82.

Harris, D. L., 1963, Characteristics of the hurricane storm surge: U. S. Weather Tech. Paper 48, 139 p.

Harris, W. D., and Jones, B. G., 1964, Repeat mapping for a record of shore erosion: Shore and Beach, v. 32, no. 2, p. 31-34.

Hayes, M. O., 1964, Grain size modes in Padre Island sands, *in* Depositional Environments, South-Central Texas Coast: Gulf Coast Assoc. Geol. Socs., Field Trip Guidebook, Oct. 30-31, 1964, p. 121-128.

______ 1965, Sedimentation on a semiarid wave-dominated coast (South Texas) with emphasis on hurricane effects: Univ. Texas, Austin, Ph. D. dissert., 350 p.

______ 1967, Hurricanes as geological agents: Case studies of hurricanes Carla, 1961, and Cindy, 1963: Univ. Texas, Austin, Bur. Econ. Geology Rept. Inv. 61, 54 p.

Herbich, J. B., 1970, Comparison of model and beach scour patterns: Proc. 12th Conf. on Coastal Eng., p. 1281-1300.

Hicks, S. D., 1968, Long-period variations in secular sea level trends: Shore and Beach, v. 36, no. 1, p. 32-36.

______ 1972, On the classification and trends of long period sea level series: Shore and Beach, v. 40, no. 1, p. 20-23.

______, and Shofnos, W., 1965, Yearly sea level variations for the United States: Am Soc. Civil Engineers Proc., Jour. Hydraulics Div., v. 91, paper 4468, no. HY 5, p. 23-32.

Inman, D. L., and Brush, B. M., 1973, The coastal challenge: Science, v. 181, no. 4094, p. 20-32.

International Boundary and Water Commission, United States and Mexico, 1931-1944, Flow of the Rio Grande and tributary contributions (Roma Station): Water Bull. No. 1-14.

______ 1945-1946, Flow of the Rio Grande and tributary contributions (Roma Station): Water Bull. No. 15-16.

______ 1952-1970, Flow of the Rio Grande and related data (Roma and San Benito Stations): Water Bull. No. 22-40.

Johnson, J. W., 1959, The supply and loss of sand to the coast: Am. Soc. Civil Engineers Proc., Jour. Waterways and Harbors Div., WW3, v. 85, p 227-251.

______ 1971, The significance of seasonal beach changes in tidal boundaries: Shore and Beach, v. 39, no. 1, p. 26-31.

Lohse, E. A., 1952, Shallow marine sediments of the Rio Grande delta: Univ. Texas (Austin), Ph. D. dissert., 113 p.

_______ 1958, Mouth of Rio Grande: Gulf Coast Assoc. Geol. Socs., Field Trip Guidebook, Oct. 30-Nov. 1, 1958, p. 55-56.

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

Manley, G., 1955, A climatological survey of the retreat of the Laurentide ice sheet: Am. Jour. Sci., v. 253, no. 5, p. 256-273.

Marmer, H. A., 1949, Sea level changes along the coasts of the United States in recent years: Am. Geophysical Union Trans., v. 30, no. 2, p. 201-204.

_______ 1951, Changes in sea level determined from tide observations: Proc. 2d Conf. on Coastal Engineering, p. 62-67.

_______ 1954, Tides and sea level in the Gulf of Mexico, *in* P. S. Galtsoff, coord., Gulf of Mexico, Its origin, waters, and marine life: U. S. Dept. Interior, Fish and Wildlife Serv. Fish. Bull., v. 55, p. 101-118.

McGowen, J. H., and Brewton, J. L., 1975, Historical changes and related coastal processes, Gulf and mainland shorelines, Matagorda Bay area, Texas: Univ. Texas, Austin, Bur. Econ. Geology Rept. Inv.

_______, Groat, C. G., Brown, L. F., Jr., Fisher, W. L., and Scott, A. J., 1970, Effects of Hurricane Celia—a focus on environmental geologic problems of the Texas Coastal Zone: Univ. Texas, Austin, Bur. Econ. Geology Geol. Circ. 70-3, 35 p.

Meixner, R. H., 1948, History of Padre Island: Georgetown, Texas, Southwestern University, Master's thesis.

Morgan, J. P., and Larimore, P. B., 1957, Changes in the Louisiana shoreline: Gulf Coast Assoc. Geol. Socs. Trans., v. 7, p. 303-310.

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

New York Times, Sept. 25, 1973, p. 13, col. 1.

Price, W. A., 1956a, Hurricanes affecting the coast of Texas from Galveston to the Rio Grande: Dept. of the Army, Corps of Engineers, Beach Erosion Board Tech. Memo. no. 78, 17 p.

_______, and Gunter, G., 1943, Certain recent geological and biological changes in south Texas, with consideration of probable causes: Texas Acad. Sci. Proc. and Trans., v. 26, p. 138-156.

Rusnak, G., 1960, Sediments of Laguna Madre, Texas, *in* Am. Petroleum Institute Project 51, Am. Assoc. Petroleum Geologists, p. 152-196.

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

Seelig, W. N., and Sorensen, R. M., 1973, Historic shoreline changes in Texas: Texas A&M Univ. Sea Grant, TAMU-SG-73-206, COE-165, 19 p.

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

Shepard, F. P., 1960a, Gulf Coast barriers, *in* Shepard, F. P., Phleger, F. B., and van Andel, T. H., eds., Recent sediments, northwest Gulf of Mexico: Tulsa, Okla., Am. Assoc. Petroleum Geologists, p. 197-220.

_______ 1960b, Rise of sea level along northwest Gulf of Mexico, *in* Shepard, F. P., Phleger, F. B., and van Andel, T. H., eds., Recent sediments, northwest Gulf of Mexico: Tulsa, Okla., Am. Assoc. Petroleum Geologists, p. 338-344.

Silvester, R., 1959, Engineering aspects of coastal sediment movement: Am. Soc. Civil Engineers Proc., Jour. Waterways and Harbors Div., WW3, v. 85, p. 11-39.

Simpson, J., 1966, Hurricane modification experiments: Hurricane symposium, Am. Soc. for Oceanography Pub. No. 1, p. 255-292.

Simpson, R. H., Ahrens, M. R., and Decker, R. D., 1963, A cloud seeding experiment in Hurricane Esther, 1961: Natl. Hurricane Research Proj. Rept. 60, 30 p.

_______, and Lawrence, M. B., 1971, Atlantic hurricane frequencies along the U. S. coastline: Natl. Oceanic and Atmos. Admin. Tech. Memo NWS SR-58, 14 p.

Stafford, D. B., 1971, An aerial photographic technique for beach erosion surveys in North Carolina: U. S. Army Corps Engineers, Coastal Eng. Research Center Tech. Memo. 36, 115 p.

_______, Bruno, R. O., and Goldstein, H. M., 1973, An annotated bibliography of aerial remote sensing in coastal engineering: U. S. Army Corps Engineers Coastal Eng. Research Center Misc. Paper No. 2-73, 122 p.

Stapor, F., 1973, History and sand budgets of the barrier island system in the Panama City, Florida, region: Marine Geology, v. 14, p. 277-286.

Sugg, A. L., and Pelissier, J. M., 1968, The Atlantic hurricane season of 1967: Monthly Weather Review, v. 96, no. 4, April, p. 242-247.

_______, Pardue, L. G., and Carrodus, R. L., 1971, Memorable hurricanes of the United States since 1873: Natl. Oceanic and Atmos. Admin. Tech. Memo. NWS SR-56, 52 p.

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

Tannehill, I. R., 1956, Hurricanes, their nature and history: Princeton, N. J., Princeton Univ. Press, 308 p.

Texas Board of Water Engineers, 1961, Silt load of Texas streams, a compilation report, June 1889-Sept. 1959 (Roma and Brownsville Stations): Texas Bd. Water Engineers Bull. 6108, p. 221-228.

Texas Water Development Board, 1970, Suspended-sediment load of Texas streams, a compilation report, Oct. 1963-Sept. 1965: Texas Water Devel. Board Rept. 106, p. 54-55.

U. S. Army Corps of Engineers, 1850, Message from the President of the U. S. communicating the report of Lt. Webster of a survey of the Gulf Coast at the mouth of the Rio Grande: S. Ex. Doc. 65, 31st Cong., 1st sess., 12 p.

_______ 1881, Annual Report, Chief of Engineers, Improvement of Rivers and Harbors: House Ex. Doc. 1, 46th Cong., 3d sess., pt. 1, p. 176, pt. 2, p. 1272.

_______ 1888, Annual Report, Chief of Engineers, Improvement of rivers and harbors: House Ex. Doc. 1, 50th Cong., 2d sess., pt. 1, p. 176, pt. 2, p. 1320.

_______ 1895, Annual Report, Chief of Engineers, Improvement of certain rivers and harbors in Texas: House Doc. 2, 54th Cong., 1st sess., pt. 1, p. 265, pt. 3, p. 1819.

_______ 1900, Annual Report, Chief of Engineers, Improvement of harbor at Brazos Santiago, Texas: House Doc. 2, 56th Cong., 2d sess, pt. 1, p. 393, pt. 4, p. 2340.

_______ 1905, Annual Report, Chief of Engineers, Improvement of harbor at Brazos Santiago, Texas: House Doc. 2, 58th Cong., 3d sess., pt. 1, p. 380, pt. 2, p. 2010.

_______ 1913, Improvement of harbor at Brazos Santiago: House Doc. 200, 63d Cong., 1st sess., 25 p.

_______ 1913-1914, Index to reports of Chief of Engineers, 1866-1912, Vol. I, Rivers and Harbors: House Doc. 740, 63d Cong., 2d sess., p. 762.

_______ 1916, Arroyo Colorado, Texas: House Doc. 1731, 64th Cong., 2d sess., 6 p.

_______ 1919, Brazos Island harbor, Texas: House Doc. 1710, 65th Cong., 3d sess., 30 p.

_______ 1928, Annual Report, Chief of Engineers, Improvement of rivers and harbors, p. 1028-1031.

_______ 1936, Annual Report, Chief of Engineers, Improvement of rivers and harbors, p. 783-785.

_______ 1939, Brazos Island harbor, Texas: House Doc. 335, 76th Cong., 1st sess., 14 p.

_______ 1940, Laws of the United States relating to improvement of rivers and harbors from August 11, 1790 to June 29, 1938: House Doc. 379, 76th Cong., 1st sess., v. 1-3.

_______ 1941, Annual Report, Chief of Engineers, Improvement of rivers and harbors, p. 1006-1008.

_______ 1950, Annual Report, Chief of Engineers, Improvement of rivers and harbors, p. 1177-1180.

_______ 1958, Review of reports on Gulf Intracoastal Waterway, tributary channel to Port Mansfield, Texas: Galveston District, May 29, 53 p.

_______ 1960, Annual Report, Chief of Engineers, Improvement of rivers and harbors, p. 704-707.

_______ 1961, Design memorandum on erosion control at inner ends of jetties at Brazos-Santiago Pass, Brazos Island harbor, Texas: Galveston District, April 12, 1961.

_______ 1962a, Annual Report, Chief of Engineers, Improvement of rivers and harbors, p. 782-788.

_______ 1962b, Report on Hurricane Carla, 9-12, Sept. 1961: Galveston District, 29 p.

_______ 1963, Brazos Island harbor, Texas, rehabilitation of north and south jetties: Design Memo. no. 1, 11 p.

_______ 1965, Widen Brownsville channel enlargement of fishing boat harbor, rehabilitation and extension of north jetty: Design Memo. no. 2, 9 p.

_______ 1968a, Laws of the United States relating to rivers and harbors: House Doc. 182, 90th Cong., 1st sess.

_______ 1968b, Report on Hurricane Beulah, 8-21 Sept. 1967: Galveston Dist. Corps Engineers, 26 p.

_______ 1968-1972, Texas Coastal Inlet Studies: Galveston Dist. Corps Engineers.

_______ 1971a, Report on Hurricane Celia, 30 July-5 August 1970: Galveston Dist. Corps Engineers, 13 p.

_______ 1971b, Shore protection guidelines: Washington, D. C., Dept. of the Army, Corps of Engineers, 59 p.

_______ 1971c, National shoreline study, Texas coast shores regional inventory report: Galveston Dist. Corps Engineers, 26 p.

_______ 1972, Report on Hurricane Fern, 7-13 Sept. 1971: Galveston Dist. Corps Engineers, 11 p.

U. S. Department of Commerce, 1930-1974, Tide tables 1930-1974, East Coast of North & South America: Natl. Oceanic & Atmos. Admin.

U. S. Department of Interior, National Park Service-Region Three, 1959, Field Investigation Report, Padre Island, Texas: U. S. Dept. Interior, Natl. Park Service, Field Investigation Report, 23 p.

U. S. Geological Survey, 1927, Surface water supply of U. S., 1923, pt. VIII (Rio Grande—Roma Station), Western Gulf of Mexico Basin: U. S. Geol. Survey Water Supply Paper 568, p. 112-113.

_______ 1928, Surface water supply of U. S., 1924 (Rio Grande—Roma Station), pt. VIII, Western Gulf of Mexico Basin: U. S. Geol. Survey Water Supply Paper 588, p. 189-191.

_______ 1929, Surface water supply of U. S., 1925 (Rio Grande—Roma Station), pt. VIII, Western Gulf of Mexico Basin: U. S. Geol. Survey Water Supply Paper 608, p. 224-225.

_______ 1930, Surface water supply of U. S., 1926 (Rio Grande—Brownsville Station), pt. VIII, Western Gulf of Mexico Basin: U. S. Geol. Survey Water Supply Paper 628, p. 181.

_______ 1932a, Surface water supply of U. S., 1929 (Rio Grande—Roma Station), pt. VIII, Western Gulf of Mexico Basin: U. S. Geol. Survey Water Supply Paper 688, p. 104.

_______ 1932b, Surface water supply of U. S., 1930 (Rio Grande—Roma Station), pt. VIII, Western Gulf of Mexico Basin: U. S. Geol. Survey Water Supply Paper 703, p. 111.

Van Andel, T. H., and Poole, D. M., 1960, Sources of Recent sediments in the northern Gulf of Mexico: Jour. Sed. Petrology, v. 30, no. 1, p. 91-122.

Wiegel, R. L., 1964, Oceanographical Engineering: Englewood Cliffs, N. J., Prentice-Hall Inc., 532 p.

Wilson, B. W., 1957, Hurricane wave statistics for the Gulf of Mexico: Dept. of the Army, Corps of Engineers, Beach Erosion Board Tech. Memo. 98, 61 p.

Appendix A

+ accretion
- erosion

Shoreline Changes

beach segment south Padre - Brazos Island

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	1879-80 1937	0	0	1937 1960	-275	-12.0							1879-80 1960	- 275	-12.0
2	"	- 375	- 6.6	"	-375	-16.3							"	- 750	- 9.4
3	"	- 275	- 4.2	"	-350	-15.2							"	- 625	- 7.8
4	"	- 25	- 0.4	"	-225	- 9.8							"	- 250	- 3.1
5	"	- 200	- 3.5	"	-100	- 4.3							"	- 300	- 3.8
6	"	- 150	- 2.6	"	-150	- 6.5							"	- 300	- 3.8
7	"	- 375	- 6.6	"	-125	- 5.4	1960 1969	0	0				"	- 500	- 5.7
8	"	- 625	-11.0	"	-250	-10.9	"	- 25	- 2.8	1969 1974	- 25	- 5.0	1879-80 1974	- 925	- 9.7
9	"	- 475	- 8.3	"	-300	-13.0	"	-225	-25.0	"	0	0	"	-1000	-10.5
10	"	- 375	- 6.6	"	-325	-14.1	"	-150	-16.7	"	-100	-20.0	"	- 950	-10.0
11	"	- 300	- 5.3	"	-450	-19.6	"	-250	-27.8	"	- 50	-10.0	"	-1050	-11.1
12	"	- 250	- 4.4	"	-425	-18.5	"	-100	-11.1	"	-150	-30.0	"	- 925	- 9.7
13	"	- 650	-11.4	"	+ 50	+ 2.2	"	-225	-25.0	"	- 25	- 5.0	"	- 850	- 8.9
14	"	- 550	- 9.6	"	0	0	"	-325	-36.1	"	- 75	-15.0	"	- 950	-10.0
15	"	- 350	- 6.1	"	-250	-10.9	"	-150	-16.7	"	- 50	-10.0	"	- 800	- 8.4

+ accretion
- erosion

Shoreline Changes

beach segment south Padre - Brazos Island

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
16	1867 1937	- 675	- 9.6	"	- 25	- 1.1	"	-175	-19.4	"	- 75	-15.0	1867 1974	- 950	- 8.9
17	"	- 900	-12.9	"	- 75	- 3.3	1960 1970	-125	-12.5	1970 1974	0	0	"	-1100	-10.3
18	"	-1125	-16.1	"	-175	- 7.6	"	- 50	- 5.0	"	- 50	-12.5	"	-1400	-13.1
19	"	-1250	-17.9	"	- 50	- 2.2	"	- 50	- 5.0	"	0	0	"	-1350	-12.6
20	"	-1200	-17.1	"	+200	+ 8.7	"	+150	+15.0	"	+125	+31.3	"	- 725	- 6.8
21	"	-1125	-16.1	"	+550	+23.9	"	+< 10	+< 1.0	"	+ 50	+12.5	1854 1974	- 75	-< 1.0
22	1854 1937	+ 525	+ 6.3	"	+300	+13.0	"	+ 75	+ 7.5	"			1854 1970	+ 225	+ 2.2
23	"	+ 700	+ 8.4	"	-100	- 4.3	"	-< 10	-< 1.0	1970 1974	+ 25	+ 6.3	1854 1974	+ 625	+ 5.2
24	"	+ 775	+ 9.3	"	+< 10	+< 1.0	"	- 75	- 7.5	"	-100	-25.0	"	+ 600	+ 5.0
25	"	+1425	+17.2	"	-400	-17.4	"	-375	-37.5	"	-125	-31.3	"	+ 525	+ 4.4

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 vegetation line and/or shoreline was used in map preparation.

Date		Source of Photographs
April 1937	*	Tobin Research Inc.
Nov., Dec. 1954		U. S. Dept. Agriculture
Nov. 1955		U. S. Dept. Agriculture
Jan., Feb. 1960	*	Tobin Research Inc.
Oct. 1961		U. S. Army Corps Engineers
June 1967		U. S. Army Corps Engineers
Sept. 25, 1967		Texas Highway Dept.
Sept. 28, 1967	(mouth of Rio Grande)	Intl. Boundary and Water Commission
July 1968		Texas Highway Dept.
Nov. 1969	*	Natl. Oceanic and Atmospheric Admin.
Oct. 1970	*	Natl. Oceanic and Atmospheric Admin.
June 1974	*	Texas Highway Dept.

List of Maps Used in Determination of Shoreline Changes

Date	Description	Source of Maps
Nov. 1854	Topographic map-453	Natl. Oceanic and Atmospheric Admin.
1867	Topographic map-1045	Natl. Oceanic and Atmospheric Admin.
July 1879-80	Topographic map-1476a, 1476b	Natl. Oceanic and Atmospheric Admin.
1917	Topographic map-3673	Natl. Oceanic and Atmospheric Admin.
1934	15-minute quadrangle	U. S. Geological Survey
Oct. 1958	Changes in location of mouth of Rio Grande 1853-1966	Intl. Boundary and Water Commission

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

Mouth of Rio Grande, Texas
Port Isabel, Texas
Port Isabel NW, Texas
North of Port Isabel SW, Texas
North of Port Isabel NW, Texas
South of Portrero Lopeno SE, Texas