GEOLOGICAL CIRCULAR **77-2**

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AN ANALYSIS OF HISTORICAL CHANGES OF THE TEXAS GULF SHORELINE

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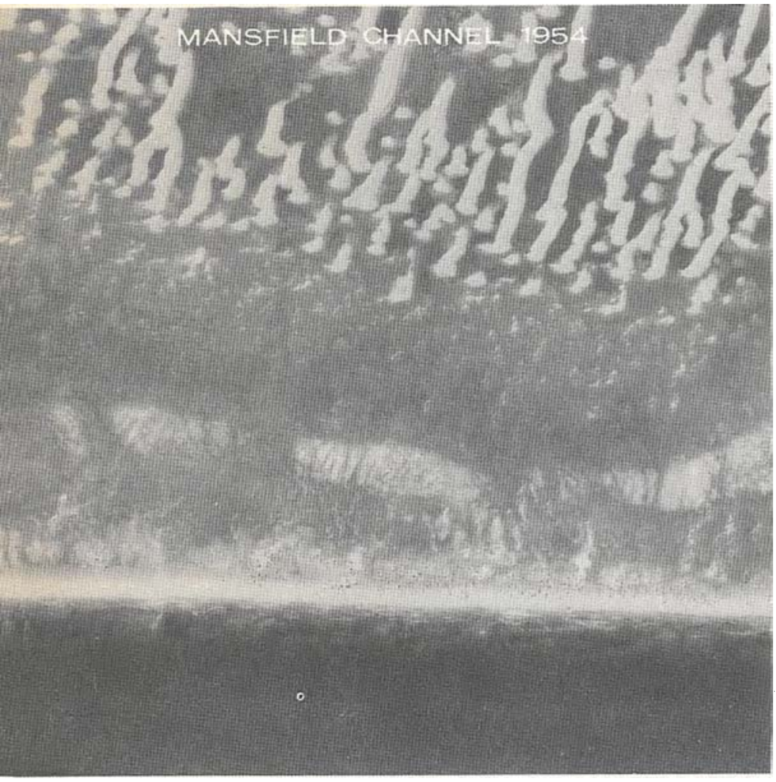

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ABSTRACT

Historical monitoring along central Padre Island 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 1879-81) and aerial photographs (taken in 1937, 1960, 1969, and 1975) indicates short-term changes of accretion and erosion along central Padre Island between Yarborough Pass 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 minor short-term cycles of retreat related to storms (primarily hurricanes) and recovery during intervening years of low storm incidence. Major changes in vegetation along this particular coastal segment result from formation and migration of active dunes and blowouts which are largely controlled by climatic fluctuations.

Long-term trend or direction of shoreline changes averaged over the 96-year time period of this study indicates that net accretion ranging from 25 to 400 feet and averaging 210 feet was predominant from Yarborough Pass to a point 25 miles north of Mansfield Channel. Net accretion along this segment was influenced by substantial accretion between 1879-81 and 1937. Both erosion and accretion occurred from 1937 to 1960, but after 1960, shoreline changes have been erosional.

Net shoreline changes along the southern half of central Padre Island (from Mansfield Channel to a point 19 miles north of the channel) were erosional with net erosion ranging from 25 to 1,150 feet. Maximum net erosion occurred north (downdrift) of Mansfield Channel for 3.5 miles. Average net erosion for this shoreline segment was approximately 795 feet, whereas average net erosion for the remaining shoreline not directly affected by the jetties was about 205 feet.

The shoreline segments experiencing net accretion and net erosion were separated by a transition zone extending for approximately 6 miles. Maximum net shoreline changes within the transition zone were 100 feet, but most net changes were less than 50 feet.

Net rates of change along central Padre Island were low except immediately downdrift from Mansfield Channel where net erosion ranged from 4.9 to 12.0 feet per year. Excluding points adjacent to the jetties, net erosion varied from less than 1 foot per year to 4.2 feet per year and averaged 2.0 feet per year. Net rates of accretion also ranged from less than 1 foot per year to 4.2 feet per year and averaged 2.0 feet per year.

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

Major and minor factors affecting shoreline changes include: (1) climate, (2) storm frequency and intensity, (3) local and eustatic sea-level conditions, (4) sediment budget, and (5) human activities. The major factors affecting shoreline changes along the Texas Coast, including central Padre Island, are relative sea-level rise, compactional subsidence, and changes in sediment supply.

Studies indicate that changes in shoreline and vegetation line on central Padre Island are largely the result of natural processes, perhaps expedited by man's activities. A basic comprehension of these physical processes and their effects is requisite to avoid or minimize physical and economic losses associated with development and use of the coast.

INTRODUCTION

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

Studies indicate that shoreline and vegetation line changes on central Padre Island 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 1879 provide a necessary extension to the time base, an advantage not available through the use of aerial photographs which were not generally available before 1930.

Purpose and Scope

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

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

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

General Statement on Shoreline Changes

Shorelines are in a state of erosion, accretion, or are stabilized either naturally or artificially. Erosion produces a net loss in land, accretion produces a net gain in land, and equilibrium conditions produce no net change. Shoreline changes are the response of the beach to a hierarchy of natural cyclic phenomena including (from lower order to higher order) tides, storms, sediment supply, and relative sea-level changes. Time periods for these cycles range from daily to several thousand years. Most beach segments undergo both erosion and accretion for lower order events, no matter what their long-term trends may be. Furthermore, long-term trends can be unidirectional or cyclic; that is, shoreline changes may persist in one direction, either accretion or erosion, or the shoreline may undergo periods of both erosion and accretion. Thus, the tidal plane boundary defined by the intersection of beach and mean high water is not in a fixed position (Johnson, 1971). Shoreline erosion assumes importance along the Texas Coast because of active loss of land, as well as the potential damage or

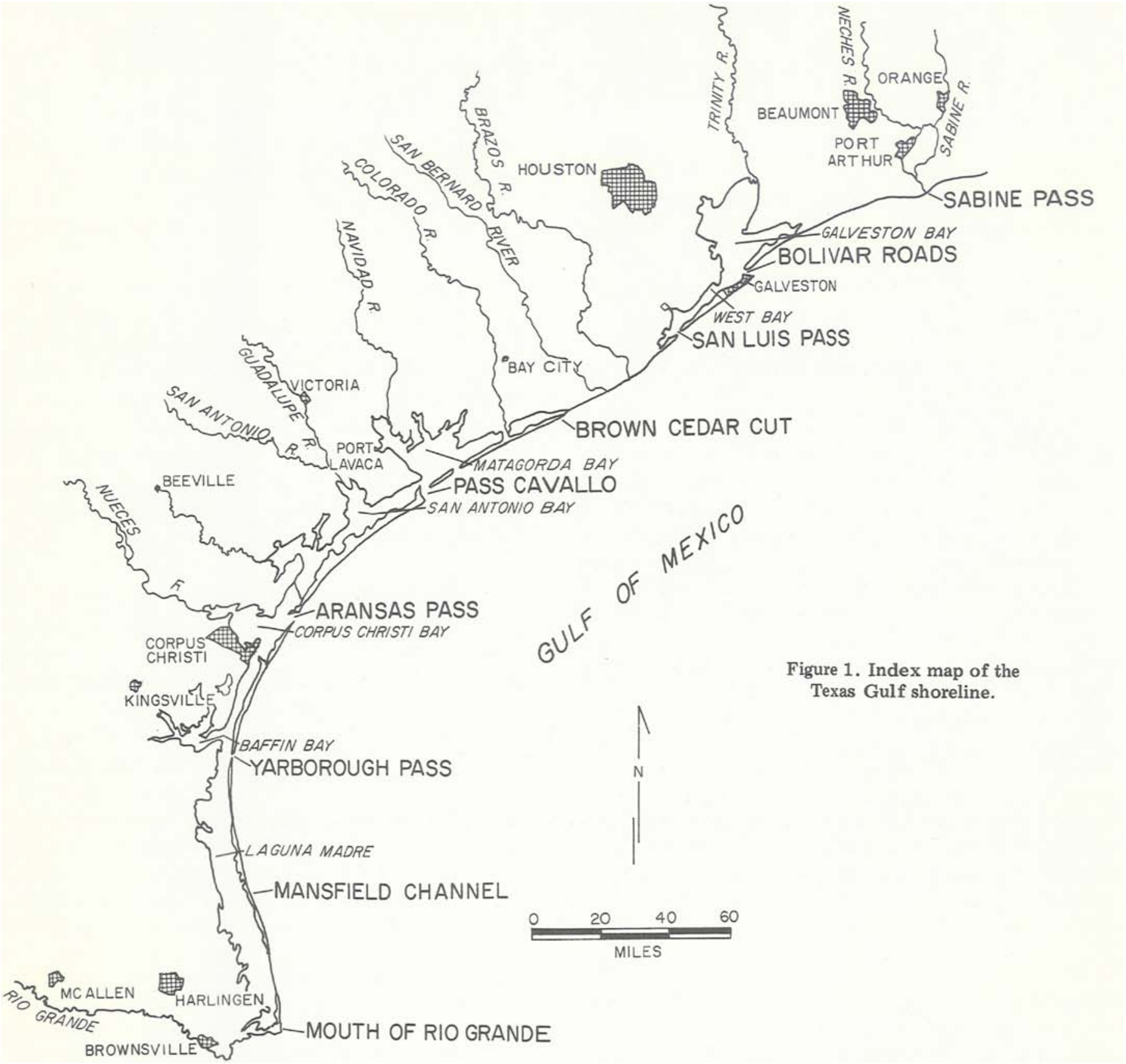

Figure 1. Index map of the Texas Gulf shoreline.

destruction of piers, dwellings, highways, and other structures.

Acknowledgments

Assistance in preparation of this report was provided by L. W. Epps, M. Amdurer, and S. Waisley. Drafting was under the supervision of J. W. Macon. Cartographic work was performed by D. F. Scranton. Critical review was provided by L. F. Brown, Jr., and C. G. Groat. The report was typed by Elizabeth T. Moore and Rosemary Wasson and edited by Kelley Kennedy and Karen White. Composing was under the direction of Fannie M. Sellingsloh.

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

HISTORICAL SHORELINE MONITORING

GENERAL METHODS AND PROCEDURES USED BY THE BUREAU OF ECONOMIC GEOLOGY

Definition

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

Sources of Data

Basic data used to determine changes in shoreline position are near-vertical aerial photographs and mosaics and topographic charts. Accurate topographic charts dating from 1850, available through the Department of Commerce, National Oceanic and Atmospheric Administration (NOAA), were mapped by the U. S. Coast Survey using plane table procedures. Reproductions of originals are used to establish shoreline position (mean high water) prior to the early 1930's. Aerial photography supplemented and later replaced regional topographic surveys in the early 1930's; therefore, subsequent shoreline positions are mapped on individual stereographic photographs and aerial photographic mosaics representing a diversity of scales and vintages. These photographs show shoreline position based on the sediment-water interface at the time the photographs were taken.

Procedure

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

Factors Affecting Accuracy of Data

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

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

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

Original Data

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

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

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

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

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

Interpretation of Photographs

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

Use of mean high-water line on topographic charts and the sediment-water interface on aerial photographs to define the same boundary is inconsistent because normally the sediment-water interface falls somewhere between high and low tide. Horizontal displacement of the shoreline mapped using the sediment-water interface is almost always seaward of the mean high-water line. This displacement is dependent on the tide cycle, slope of the beach, and wind direction when the photograph was taken. The combination of factors on the Gulf shoreline which yield the greatest horizontal displacement of the sediment-water interface from mean high water are low tide conditions, low beach profile, and strong northerly winds. Field measurements indicate that along the Texas Gulf Coast, maximum horizontal displacement of a photographed shoreline from mean high-water level is approximately 125 feet under these same conditions. Because the displacement of the photographed shoreline is almost always seaward of mean high water, shoreline changes determined from comparison of mean high-water line and sediment-water interface will slightly *underestimate rates of erosion* or slightly overestimate rates of accretion.

Cartographic Procedure

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

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

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

Measurements and Calculated Rates

Actual measurements of linear distances on maps can be made to one-hundredth of an inch which corresponds to 20 feet on maps with a scale of 1 inch = 2,000 feet (1:24,000). This is more precise than the significance of the data warrants. However, problems do arise when rates of change are calculated because: (1) time intervals between photographic coverage are not equal; (2) erosion or accretion is assumed constant over the entire time period; and (3) multiple rates ($\frac{n^2-n}{2}$, where n represents the number of mapped shorelines) can be obtained at any given point using various combinations of lines.

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

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

Justification of Method and Limitations

The methods used in long-term historical monitoring carry a degree of imprecision, and trends and rates of shoreline changes determined from these techniques have limitations. Rates of change are to some degree subordinate in accuracy to trends or direction of change; however, there is no doubt about the significance of the trends of shoreline change documented over more than 100 years. An important factor in evaluating shoreline changes is the total length of time represented by observational data. Observations over a short period of time may produce erroneous conclusions about the long-term change in coastal morphology. For example, it is well established that landward retreat of the shoreline during a storm is accompanied by sediment removal; the sediment is eroded, transported, and temporarily stored offshore. Shortly after storm passage, the normal beach processes again become operative and some of the sediment is returned to the beach. If the shoreline is monitored during this recovery period, data would indicate beach accretion; however, if the beach does not accrete to its prestorm position, then net effect of the storm is beach erosion. Therefore, long-term trends are superior to short-term observations. Establishment of long-term trends based on changes in shoreline position necessitates the use of older and less precise topographic surveys. The applicability of topographic surveys for these purposes is discussed by Shalowitz (1964, p. 79) who stated:

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

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

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

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

Sources and Nature of Supplemental Information

Sources of aerial photographs, topographic charts, and topographic base maps used for this report are identified in appendix C. Additional information was derived from miscellaneous reports published by the U. S. Army Corps of Engineers and on-the-ground measurements and observations including beach profiles, prepared as a part of this investigation. Laws relating to the improvement of rivers and harbors are synthesized in House Documents 379 and 182 (U. S. Army Corps of Engineers, 1940, 1968b).

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

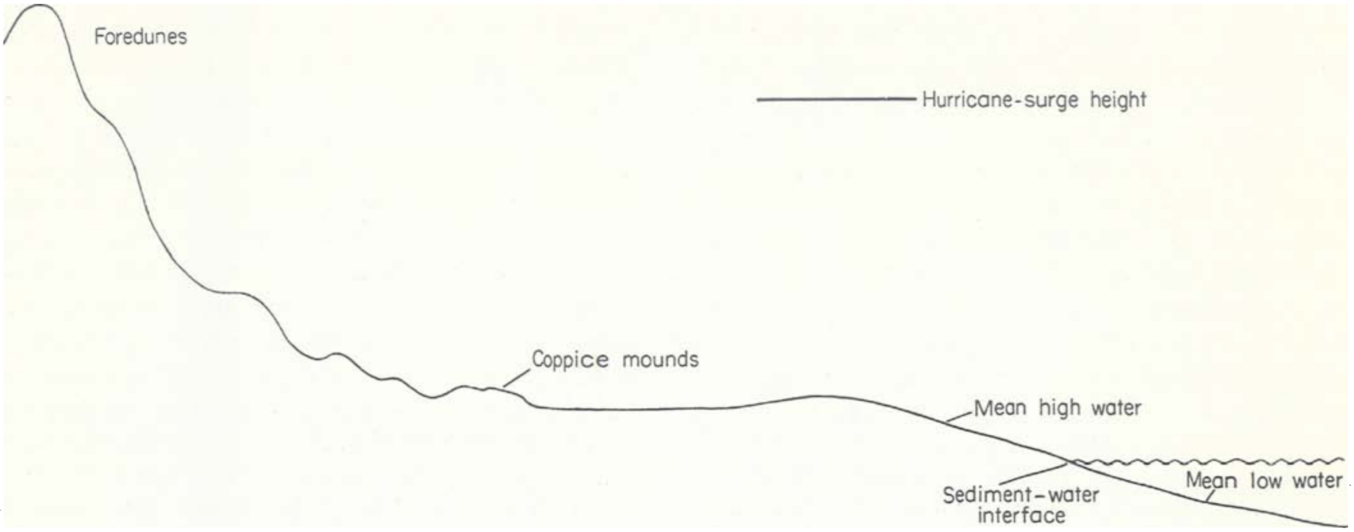

Figure 2. Generalized diagram of beach profile.

effect of meteorological conditions on position of the sediment-water interface (fig. 2).

Monitoring of Vegetation Line

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

PREVIOUS WORK

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

Shoreline changes resulting from jetty construction at Mansfield Channel were discussed by Hansen (1960) and the U. S. Army Corps of Engineers (1958). Beach profiles surveyed by the U. S. Army Corps of Engineers (1968-1974) continued to document short-term shoreline changes in proximity to Mansfield Channel and Yarborough Pass.

A regional inventory of Texas shores was conducted by the U. S. Army Corps of Engineers (1971b). No quantitative data were given, however the study delineated areas of critical and noncritical erosion along the Texas Coast. According to this inventory, there are no areas of critical or noncritical erosion between Yarborough Pass and Mansfield Channel. Hunter and others (1972) compared 1860-1882 topographic surveys with more recent maps and aerial photographs and concluded that no consistently measurable shoreline changes were evident on north and central Padre Island. It was their opinion that relatively stable conditions extended to about the southern limit of Big Shell Beach or approximately 30 miles north of Mansfield Channel.

In a more 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 central 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 erosion in the area of interest determined by Seelig and Sorensen (1973, p. 13-14) range from 0 to -10 feet per year with most values falling between -1 and -3 feet per year. Five points on central Padre Island recorded accretion ranging from 1 to 3 feet per year.

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

PRESENT BEACH CHARACTERISTICS

Texture and Composition

Except for Big Shell and Little Shell Beaches, the shoreline of central Padre Island comprises fine to very fine sand composed primarily of quartz, some feldspar, and heavy minerals. Padre Island can be divided into northern and southern sedimentologic provinces separated by a transition zone of approximately 10 miles. The transition zone is recognized by mixed heavy mineral suites, mixed shell assemblages, and a bimodal grain size distribution (Bullard, 1942; Shepard and Moore, 1955; van Andel and Poole, 1960; Hayes, 1965; Watson, 1971; Foley, 1974). Central Padre Island (Yarborough Pass to Mansfield Channel) falls within the southern sedimentologic province and the transition zone.

Heavy minerals of the southern sedimentologic province include basaltic hornblende and pyroxene from the Rio Grande, whereas the northern sedimentologic province is recognized by more durable heavy minerals such as tourmaline, zircon, garnet, rutile, and staurolite typical of rivers to the north (Bullard, 1942; Shepard and Moore, 1955; van Andel and Poole, 1960; Foley, 1974).

Shell content within the southern sedimentologic province averages about 20 percent, except for higher concentrations along Big Shell Beach, and is characterized by *Eontia ponderosa* Say, *Mercenaria campechiensis* Gmelin, and *Echinochama arcinella* Linne (Watson, 1971). Rock fragments, commonly found on the backbeach of the southern province, decrease in abundance northward from Mansfield Channel. They are derived from relict sediments that crop out on the inner shelf (Hayes, 1967; Thayer and others, 1974).

Shell concentration of the northern province is dominated by *Donax* sp., whereas *Anadara* sp., common to both provinces, increases within the transition zone (Watson, 1971).

Hayes (1965) observed a bimodal grain size distribution within the transition zone consisting of two modes within the fine-sand class: a coarser mode (2.3 to 2.4 ϕ) typical of the southern sedimentologic province and a finer mode (2.9 to 3.0 ϕ) representative of the northern province.

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

Beach Profiles

The beach of central Padre Island between Yarborough Pass and Mansfield Channel is characterized by diverse conditions controlled largely by intermittent vegetated dunes and broad washover channels and by shell content of beach sediment. Beach width varies from 200 to 350 feet; wider beaches are in areas of low discontinuous dunes and washover areas and are typically wider than beaches on south or north Padre Island.

Forebeach slope is dependent primarily on grain size and shell content of beach sediment. Beach slopes where shell content is as much as 50 percent (Watson, 1971) are approximately 6 degrees; whereas slopes where shell content is lower range from 1.5 to 4 degrees. Along much of central Padre Island, the backbeach slopes slightly toward the foredunes (fig. 2). Backbeach slopes vary from 0.5 to 1.5 degrees with greater slopes along Big Shell Beach.

Daily changes in beach appearance reflect changing conditions such as wind direction and velocity, wave height, tidal stage, and the like. Accordingly, beach profiles are subject to change depending on beach and surf conditions that existed when measurements were recorded. In general, the most seaward extent of a beach profile is subjected to the greatest changes because in this area breakpoint bars are created, destroyed, and driven ashore. Under natural conditions, the landward portion of a beach profile is affected only by spring and storm tides of more intense events such as tropical cyclones. With increased use of the beach, however, minor alterations in beach profiles occasionally may be attributed to vehicular traffic and beach maintenance such as raking and scraping.

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

Extant dunes from Yarborough Pass south for 18 miles are continuous and well vegetated except for a large blowout which extends south from Yarborough Pass about 2.75 miles. Individual dunes attain heights up to 50 feet; however, dune heights of 20 to 25 feet are more common. South of this well-developed dune ridge, vegetation is less dense, and dunes are discontinuous and transected by numerous storm channels. Individual stabilized dunes are 30 to 40 feet high, however most dunes in the area range in height from 15 to 20 feet. Approximately 9 miles north of Mansfield Channel, dunes are sparsely vegetated, low, and discontinuous.

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

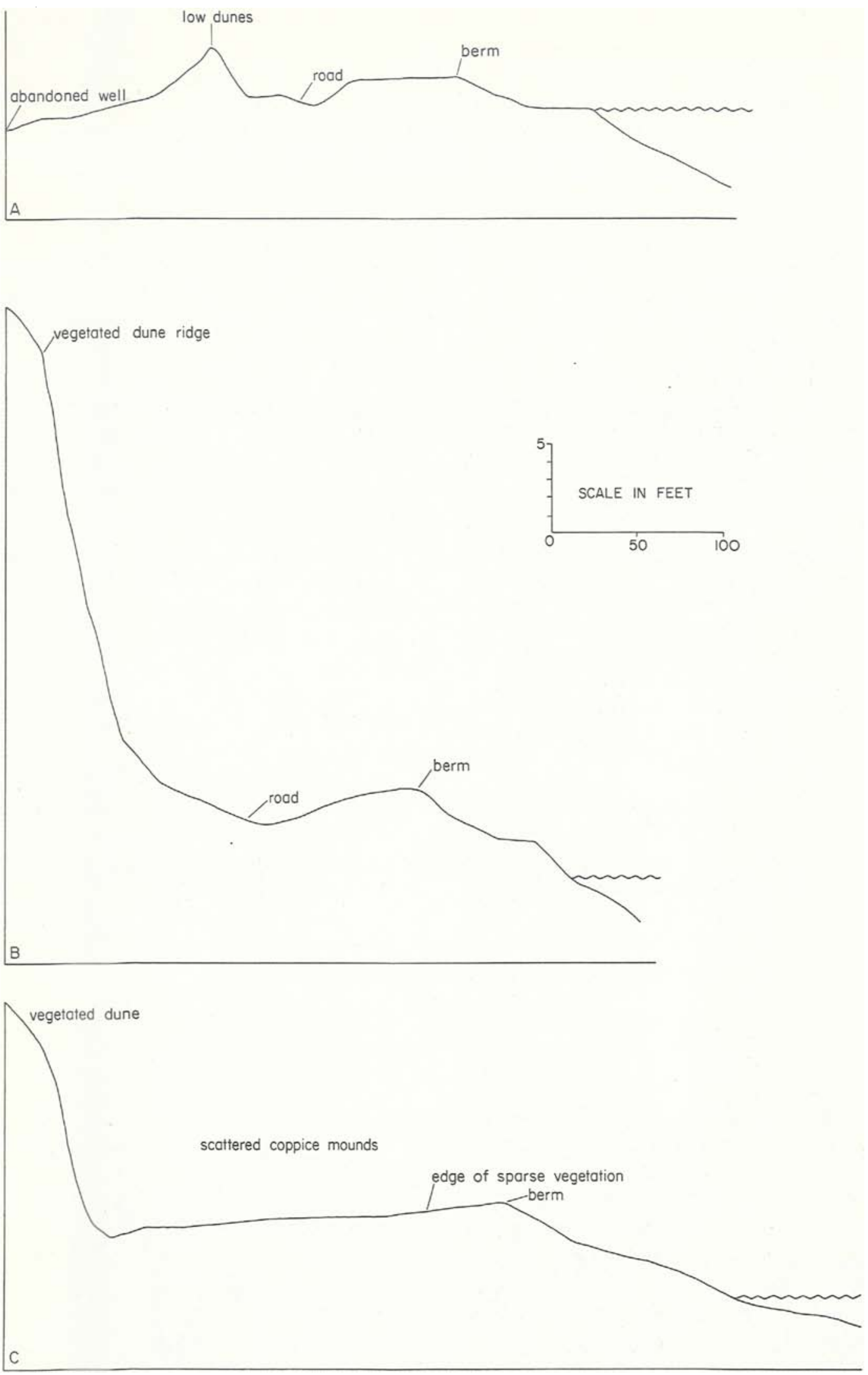

Figure 3. Beach profiles, Yarborough Pass to Mansfield Channel, recorded June 17-18, 1975. Locations plotted on figure 5.

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. Examples of this are evident on the Texas Coast; the beach on south Padre Island is not as wide as the beach on central Padre Island where there is an adequate supply of sand.

HUMAN ALTERATIONS OF NATURAL CONDITIONS

Yarborough Pass

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

Mansfield Channel

Mansfield Channel was dredged through Padre Island by the Willacy County Navigation District in 1957. The channel was initially 10 feet deep and 100 feet wide with the channel entrance protected by two concrete tetrapod jetties. 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, the channel mouth shoaled 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 channel dredging and construction of north and south jetties 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 of Engineers, 1962b).

CHANGES IN SHORELINE POSITION

Late Quaternary Time

Judging from radiocarbon dates of shell material, Fisk (1959) concluded that development of Padre Island was initiated between 4,500 and 5,000 years ago when the shoreline was slightly landward of its present position. Vertical accretion of Padre Island attendant with sea-level rise (fig. 4) was augmented by eolian and washover processes.

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

Historic Time

Shoreline changes and tabulated rates of change between 1879 and 1975, at 47 arbitrary points spaced 5,000 feet apart along the map of central Padre Island (fig. 5), are presented in appendix A. In general, the tabular data document one period of accretion (1879-81 to 1937), two periods of erosion (1960 to 1969 and 1969 to 1975), and one period of both erosion and accretion (1937 to 1960).

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

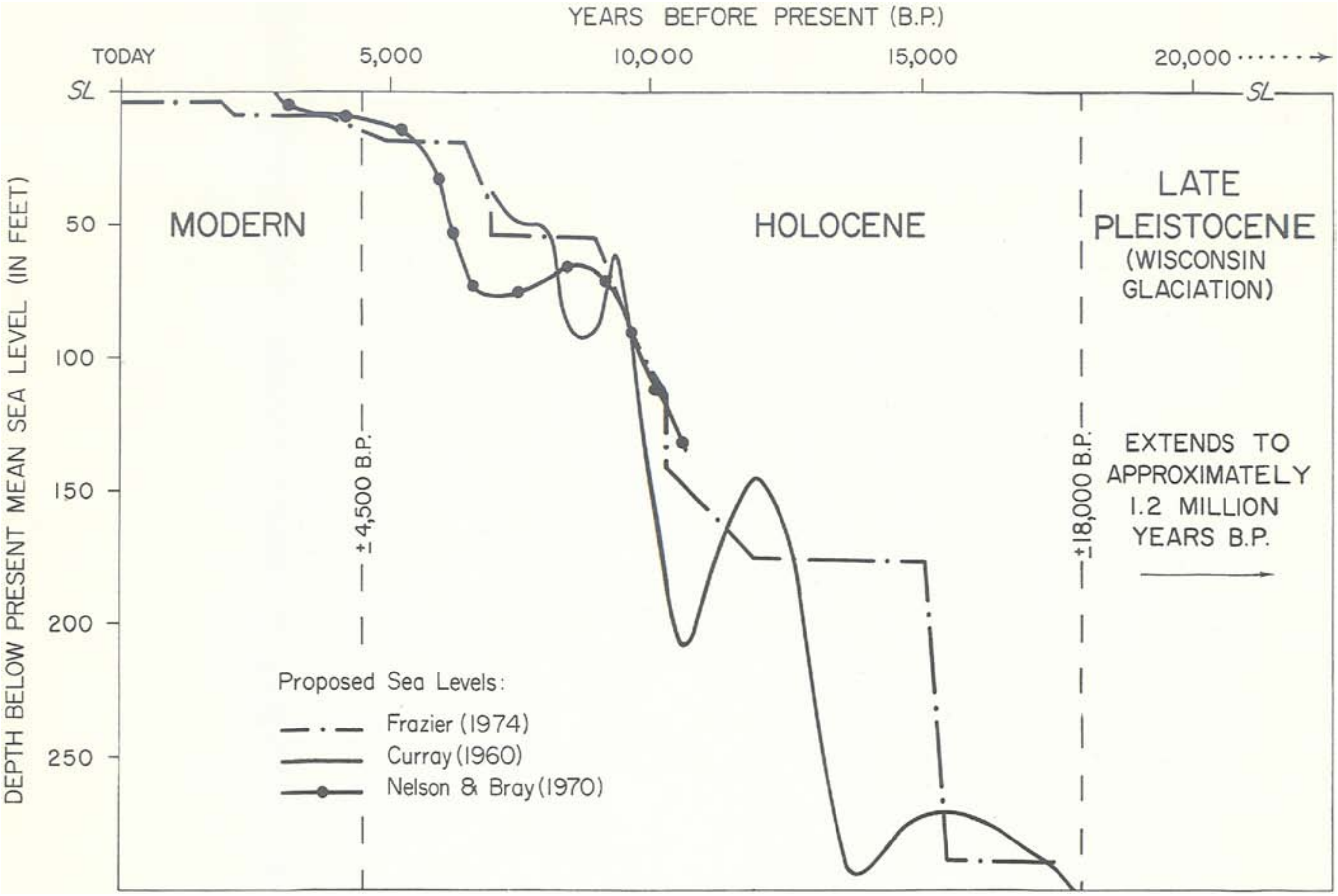

Figure 4. Proposed sea-level changes during the last 20,000 years; sketch defines use of Modern and Holocene. From Fisher and others (1973).

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

1879-81 to 1937.—Of the 47 points monitored for this time interval, 36 experienced accretion, 7 recorded erosion, and 4 recorded no change (appendix A). Substantial shoreline accretion occurred between points 1 and 19 ranging from 500 feet at point 9 to 125 feet at points 1, 5, and 6. Average accretion for this segment was about 295 feet. Except at points 23 and 30 where the shoreline was relatively stable, accretion between points 20 and 32 varied from a maximum of 175 feet at point 26 to a minimum of less than 10 feet at point 28 and averaged about 80 feet. In contrast, shoreline erosion from point 33 to point 37 ranged from 150 to 50 feet and averaged 80 feet.

Points 38 and 45 exhibited relative stability because they were pivot points or the locations of transition from erosion to accretion. The shoreline between points 39 and 44 accreted from 75 to 200 feet and averaged approximately 155 feet. In contrast, shoreline erosion at points 46 and 47, that averaged about 310 feet, was the northern limit of an erosional segment described by Morton and Pieper (1975).

Eleven hurricanes affected central Padre Island during this time interval (table 1). Bailey (1933) supervised a ground survey of Padre Island before and after the July and August storms of 1933 and made an aerial surveillance of the island following the September storm. The July and August storms were of minimal intensity; erosional channels transected low points in the high berm of the backbeach; however, no foredune damage was observed. After the severe September storm, Bailey (1933) reported that dunes on central Padre Island

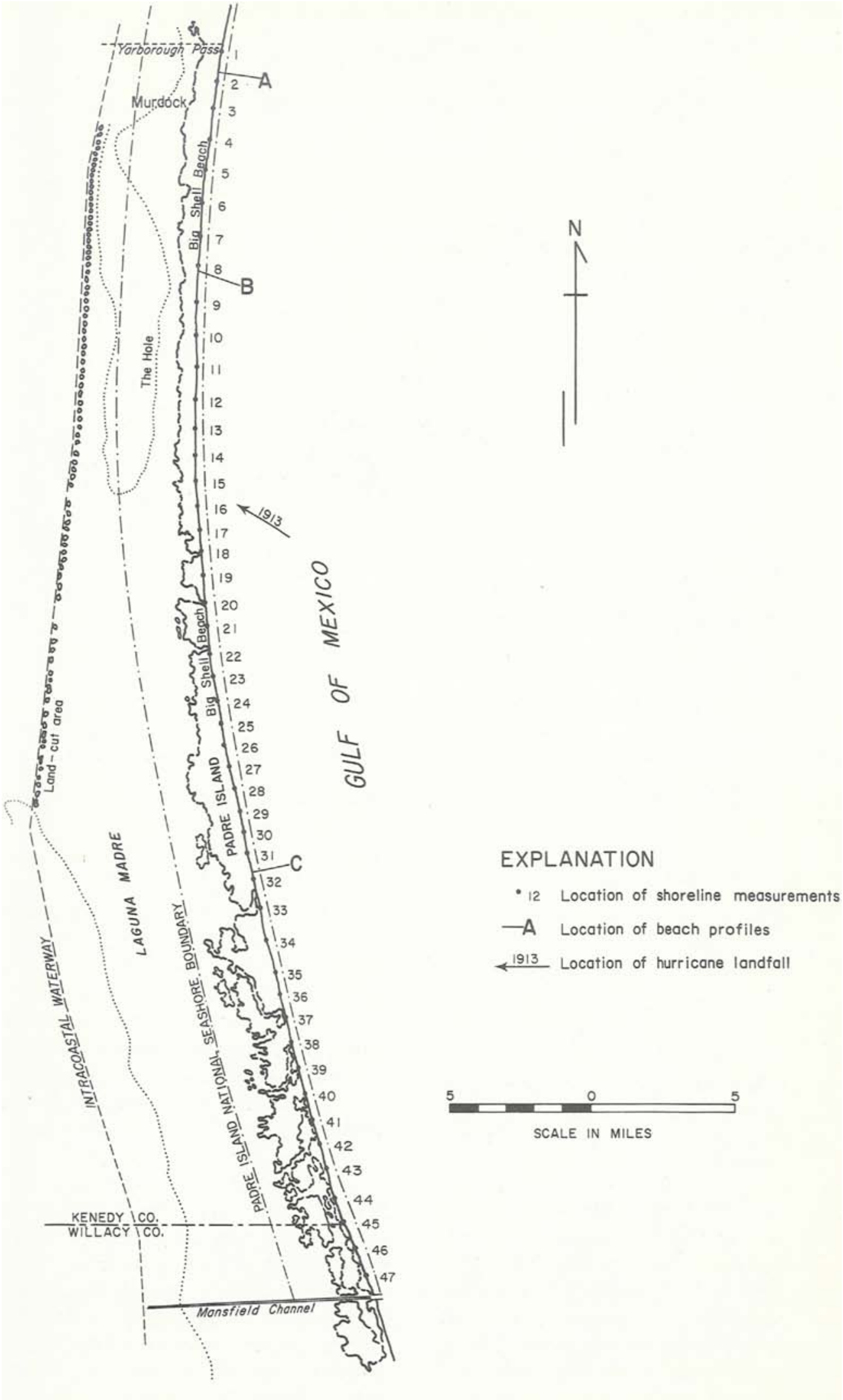

Figure 5. Location map of points of measurement, beach profiles, and hurricane landfall.

Table 1. Maximum hurricane surge height recorded along the south Texas Coast, 1881 to 1975.

Date	Surge Height (feet)	Location	Reference
1881	high	Murdock's Landing	Price, 1956
1887	high	central Padre Island	Bailey, 1933
1909	high	south Padre Island	Price, 1956
1916	9.2	central Padre Island	Cry, 1965
1919	11.5	Port Aransas	Sugg and others, 1971
	8.0	Port Isabel	Price, 1956
1933 (July)	5.5	central Padre Island	Bailey, 193
1933 (Aug.)	5.5	central Padre Island	Bailey, 1933
1933 (Sept.)	8.0	Corpus Christi	Sugg and others, 1971
	12-15	Brownsville	
1945	14.5	Port Aransas	U. S. Army Corps of Engineers, 1953
1961	6-7	central Padre Island	U. S. Army Corps of Engineers, 1962a
1967	8.0	Port Aransas	U. S. Army Corps of Engineers, 1968a
	18.0	lat. 26.4° N	Sugg and Pelissier, 1968

were eroded considerably and numerous washover channels were observed.

1937 to 1960.—Between 1937 and 1960, accretion was no longer the dominant trend as 28 points experienced erosion, 14 experienced accretion, and 5 recorded no change (appendix A). Shoreline accretion between points 1 and 7 varied from a maximum of 350 feet at point 6 to a minimum of 125 feet at point 7 and averaged about 260 feet. Erosion was dominant from point 8 through point 19 ranging from 200 feet at point 14 to less than 10 feet at point 18; average erosion was about 115 feet.

Between point 20 and point 31, the shoreline experienced both minor erosion and accretion reflecting the general stability of this segment. More specifically, points 22, 23, and 30 experienced accretion of 50 feet or less, while points 21, 25, 26, and 29 experienced erosion ranging from 25 to 125 feet. The remaining 5 points (20, 24, 27, 28, and 31) recorded no change. Shoreline accretion from point 32 to point 35 ranged from 25 to 100 feet; however, the remaining segment of central Padre Island (points 36 through 47) experienced erosion ranging from 375 feet at point 47 to 50 feet at point 36 and averaging approximately 180 feet. Dredging of Mansfield Channel was completed in 1957, and the original jetties (later replaced in 1962) were completed shortly thereafter (Hansen, 1960; U. S. Army Corps of Engineers, 1962b). But greater erosion from points 44 through 47 reflects a trend of higher rates of shoreline erosion that extends south of Mansfield Channel (Morton and Pieper, 1975). The storm of August 1945, which made landfall on Matagorda Peninsula and produced high tides along the entire Texas Coast, was the only major storm that affected the area during this time period (table 1).

1960 to 1969.—Shoreline changes along central Padre Island were dominated by erosion between 1960 and 1969. Between points 1 and 24, erosion varied from a minimum of less than 10 feet to a maximum of 175 feet and averaged 95 feet except at point 10 which recorded minor accretion of less than 10 feet. A 1969 overflight was not available from point 25 through point 47, and shoreline changes for this segment of the island between 1960 and 1975 are discussed in a following section.

Two major storms (Carla, 1961, and Beulah, 1967) affected this segment of the Texas Coast between 1960 and 1969. The U. S. Army Corps of Engineers (1962a, plate 4) estimated that storm surge from Carla was about 7 feet along central Padre Island.

Hayes (1967) made a detailed study of Carla's effects on central Padre Island and reported that foredune erosion averaged 100 feet. Storm surge opened Mansfield Channel and 40 storm channels along the island (Hayes, 1967). Erosional effects, however, were restricted mainly to the area north of Mansfield Channel. A series of beach profiles taken in proximity to Mansfield Channel by the U. S. Army Corps of Engineers after Carla indicates shoreline erosion ranging from 60 feet to 160 feet (U. S. Army Corps of Engineers, 1962a).

Hurricane Beulah (1967) crossed the Texas Coast just east of Brownsville. Surge heights were not available along central Padre Island; however, a maximum surge of 18 feet was estimated at latitude 26.4° N (Sugg and Pelissier, 1968); surge heights decreased to 8.0 feet at Port Aransas (U. S. Army Corps of Engineers, 1968a). Scott and others (1969) studied back-island sediment distribution and configuration of storm channels related to Hurricane Beulah, but quantitative data of shoreline and foredune erosion were not presented. Comparison of prestorm and post-storm aerial photographs near Mansfield Channel indicates that, although central Padre Island was extensively flooded by Beulah, shoreline retreat was minimal, probably on the order of 25 to 50 feet. Washover currents caused considerably more dune retreat than scour associated with wave action.

1960-69 to 1975.—Although shoreline changes between 1969 and 1975 were predominantly erosional, the fact that changes were less than 50 feet suggests relative stability. Erosion from point 1 through point 24 ranged from less than 10 feet to 50 feet; however, two points (7 and 13) recorded accretion of 25 feet or less, and 8 points recorded no change. No major storms affected this segment of the Texas Coast between 1969 and 1975.

Aerial photographs for 1969 were not available between points 25 and 47, therefore changes were averaged over the 15 year period from 1960 to 1975. Shoreline changes for this time interval were predominantly erosional with increased erosion southward along the island. The shoreline was relatively stable at points 25 through 27, but between points 28 and 34 erosion ranged from 25 feet (point 28) to 150 feet (point 31) and averaged about 100 feet. South of point 34, increased erosion varied from a minimum of 150 feet to a maximum of 450 feet and averaged about 285 feet. Greatest erosion was limited to the shoreline extending north of Mansfield Channel.

Net Historic Changes (1879-81 to 1975)

Calculations from previously determined changes provide information on the net effect of shoreline retreat and advance along central Padre Island (appendix A and figure 6). Using the earliest shoreline as a base line, the comparison is equal to the difference between the earliest and latest shorelines.

Net shoreline changes along the northern half of central Padre Island (points 1 through 27) were predominantly accretionary, whereas net changes along the southern half (points 28 through 47) were erosional. Between points 1 and 15, net accretion ranged from 125 to 400 feet and averaged approximately 250 feet. Net accretion between points 16 and 27 varied from a minimum of 25 feet to a maximum of 100 feet and averaged about 60 feet. Points 20 and 21 recorded minor net erosion of 50 feet, and points 23 and 24 recorded no change. Net accretion was affected by substantial accretion between 1879-81 and 1937; since 1960, however, shoreline changes have been dominated by erosion.

The shoreline from point 28 to Mansfield Channel has undergone net erosion with greatest net erosion occurring downdrift from Mansfield Channel between points 44 and 47. There erosion ranged from 475 to 1,150 feet; average net erosion was approximately 795 feet. Along the shoreline not in close proximity to the jetties (points 28 through 43), net erosion ranged from 25 to 400 feet and averaged about 200 feet except at point 32 which recorded no change.

Rates of change were also calculated for net change between 1879-81 and 1975; the results are included in appendix A. These figures estimate long-term net effect, but the values should be used

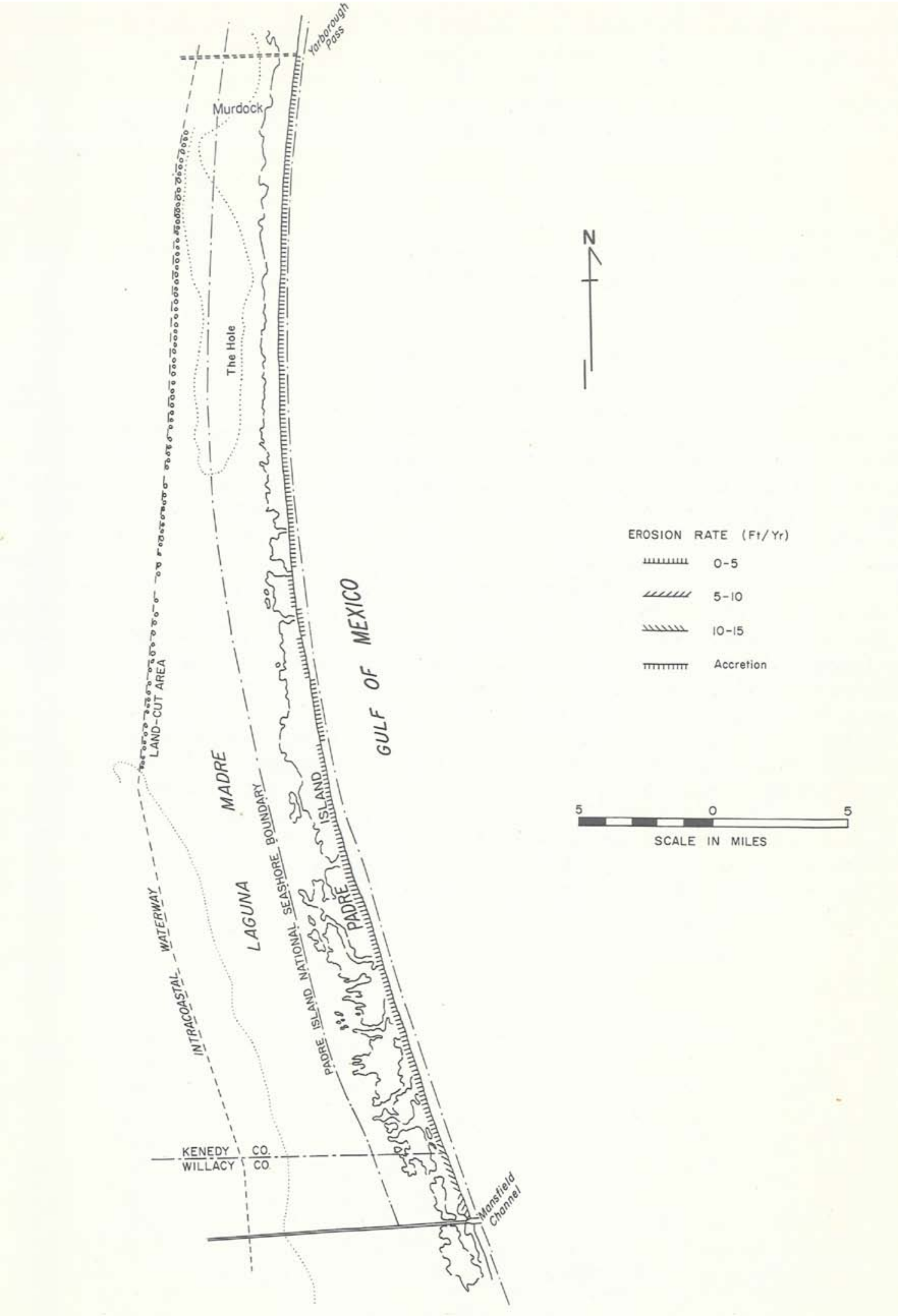

Figure 6. Net shoreline changes from Yarborough Pass to Mansfield Channel based on variable time periods from 1879 to 1975.

in context. The values for rates of net change are adequate for describing long-term trends; however, rates of short-term changes may be of greater magnitude than rates of long-term changes, particularly in areas where both accretion and erosion have occurred.

In general, net rates of change along central Padre Island were low with the exception of net rates of erosion downdrift from the Mansfield jetties where erosion ranged from 4.9 to 12.0 feet per year. Net rates of accretion between points 1 and 27 ranged from less than 1 foot per year to 4.2 feet per year and averaged about 2.0 feet per year. Similarly, net rates of erosion between points 28 and 43 ranged from less than 1 foot per year to 4.2 feet per year with most rates falling between 2 and 3 feet per year. A transition zone exhibiting long-term shoreline stability separating the erosional and accretionary segments extends from point 16 to point 33, with greatest stability between points 20 and 28.

CHANGES IN POSITION OF VEGETATION LINE

Changes in the vegetation line (appendix A) are considered independently from shoreline changes because, in many instances, the nature of change and rate of shoreline and vegetation line recovery are quite dissimilar. Thus, the shoreline and vegetation line should not be viewed as a couplet with fixed horizontal distance; this is illustrated in figure 7. Although response of the shoreline and vegetation line to long-term changes is similar, a certain amount of independence is exhibited by the vegetation line because it reacts to a different set of processes than does the shoreline. Furthermore, documentation of changes in vegetation line for this particular study draws on considerably more data (appendix C) than does documentation of shoreline changes.

Accurate information on position of vegetation line is available neither for the middle 1800's nor for the early 1900's. Accounts of changes in vegetation line are restricted to the time period covered by aerial photographs (1937-1975).

A continuous line of vegetation extends along central Padre Island to point 18. South of this point, however, washover channels and blowouts are large and numerous; consequently, vegetation is restricted to areas of stable dunes. Thus, vegetation line changes along the southern half of central Padre Island are described in general rather than quantitative terms.

1937 to 1960.—Vegetation line changes during this particular time period can be further subdivided with the aid of supplementary aerial photographs taken in 1943 (appendix C). In general, slight increases in vegetation density and minor landward advances of active dunes were recorded between 1937 and 1943. Remnants of washover channels attributed to the storms in 1933

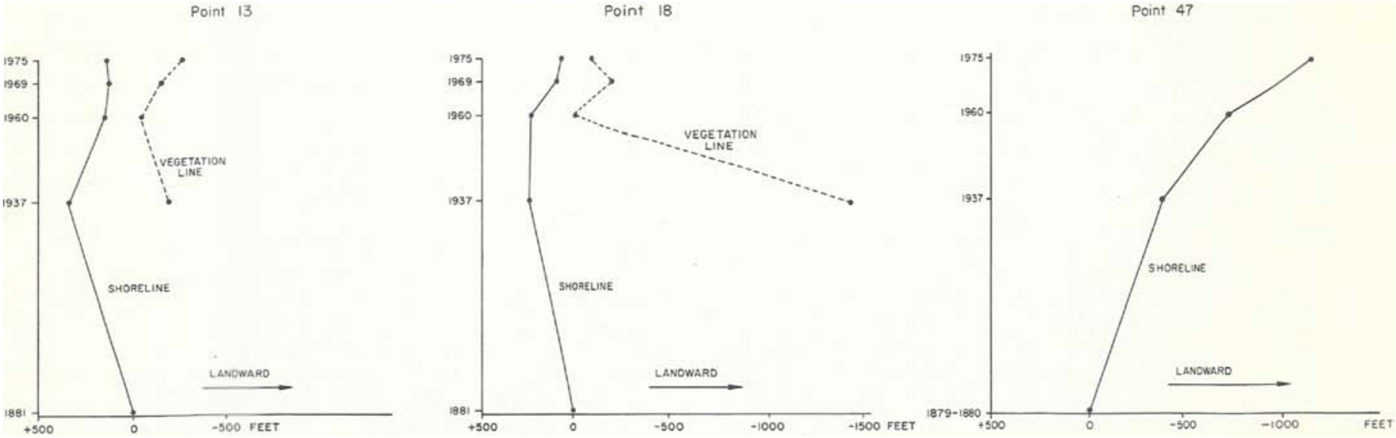

Figure 7. Relative changes in position of shoreline and vegetation line at selected locations, Yarborough Pass to Mansfield Channel.

were nearly filled by newly formed dunes. In the active dunes just north of Mansfield Channel, the density of vegetation remained relatively unchanged.

Trends established during the preceding time period continued between 1943 and 1960 as active dunes that were detached from the foredunes migrated landward and vegetation density increased slightly.

More specifically, the back-island vegetation was continuous but sparse between points 4 and 18; from there to Mansfield Channel, however, central Padre Island was virtually void of vegetation. Between 1937 and 1960, vegetation had advanced 900 feet at point 1, which was located on the margin of a large blowout that was locally revegetated. Between points 2 and 6, blowout migration caused vegetation line retreat of as much as 1,500 feet over the 23 year period.

From point 7 to point 18, the vegetation line was continuous and had advanced, except where retreat ranging from 25 to 50 feet occurred at points 10, 11, and 12; the vegetation line at point 14 was relatively unchanged. Advancement ranged from 50 feet at point 9 to 1,425 feet at point 18 with greatest recovery occurring in previously active blowout areas. Average advancement for the points not experiencing such extreme recovery was about 200 feet.

From point 18 to point 38, sparse and scattered vegetation occupied the dunes, indicating that the vegetation was in an early stage of recovery relative to the lack of vegetation in 1937. But, south of point 38 to Mansfield Channel, the island was virtually void of vegetation.

1960 to 1969.—Between 1960 and 1969, blowouts and active dunes detached from stable foredunes continued to migrate landward while overall density of vegetation increased. Also, washover channels opened by Hurricane Beulah in 1967 had been partially filled by 1969.

Substantial recovery of vegetation was restricted to the large blowout area south of Yarborough Pass (points 2 to 6). Revegetation of the blowout was initiated by 1969 through gradual revegetation of the low foredunes located along the frontal margin of the blowout. The back island, however, was still void of vegetation. The vegetation line south of point 6 experienced both advancement and retreat. Advancements of 50 and 75 feet were recorded at points 9 and 10, and the vegetation line remained relatively unchanged at points 11, 12, and 14. Retreat ranged from 50 to 250 feet and averaged 150 feet. The vegetation south of point 18 was restricted primarily to areas of stabilized dunes separated by washover channels. Vegetation line retreat on central Padre Island between 1960 and 1969 accompanied shoreline erosion associated with hurricanes Carla (1961) and Beulah (1967).

1969 to 1975.—In general, the changes in vegetation were relatively minor during this time period. In some areas vegetation density increased slightly and migration of active back-island dunes was minor; in other areas there was relatively little change from the preceding time period.

Vegetation density continued to increase within the blowout south of Yarborough Pass (points 1 to 6). Vegetation changes from the remaining points (7 to 18) were a mixture of advancement, retreat, and relative stability. But relative stability dominated, and changes were 25 feet or less except at points 9 and 13 that experienced retreat of 50 and 100 feet, respectively, and at point 18 where the vegetation line advanced 125 feet. South of point 18, vegetation was restricted to stabilized dunes. From point 40 to Mansfield Channel, however, Padre Island was virtually void of vegetation.

Between 1937 and 1975 there were substantial increases in vegetation density along central Padre Island. The greatest physiographic changes occurred where the barrier island has remained unvegetated. The least overall changes occurred in the vicinity of Yarborough Pass even though blowouts in that area shifted considerably. In contrast to other segments of the Texas Coast, changes in position of the vegetation line along central Padre Island are related to climatic changes and eolian processes although storms have a minor effect in some areas.

Specific net changes in position of the vegetation line (appendix A) document tremendous net advancement associated with revegetation and stabilization of foredunes. Net advancement decreased southward to point 7 where the vegetation line was relatively stable. The shoreline segment exhibiting relatively little change extended southward to point 15, where greater net advancement was recorded.

In general, the long-term change in position of the vegetation line is similar to that of the shoreline. However, short-term changes in position of the vegetation line reflect climatic conditions and take place independently of shoreline changes. This is demonstrated in figure 7 which illustrates that the horizontal separation between shoreline and vegetation line displays short-term variations.

FACTORS AFFECTING SHORELINE AND VEGETATION LINE CHANGES

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

Climate

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

Changes in stream and bay conditions, as well as migration of certain plant and animal species in South Texas since the late 1800's, were attributed to a combination of overgrazing and more arid climatic conditions (Price and Gunter, 1943). A more complete discussion of the general warming trend is presented in Dunn and Miller (1964). Manley (1955) reported that postglacial air temperature has increased 13°F in the Gulf region. Furthermore, Dury (1965) estimated that many rivers carried between 5 and 10 times greater discharge than present-day rivers. His remarks included reference to the Brazos and Mission Rivers of Texas. Observations based on geologic maps prepared by the Bureau of Economic Geology (Fisher and others, 1972) confirm that many rivers along the Texas Coastal Plain were larger and probably transported greater volumes of sediment during the early Holocene. This, in turn, affected sediment budget by supplying additional sediment to the littoral drift system. Droughts are a potential though indirect factor related to minor shoreline changes via their adverse effect on vegetation. Because dunes and beach sand are stabilized by vegetation, sparse vegetation resulting from droughts offers less resistance to wave attack. Severe droughts have occurred periodically in Texas; the chronological order of severe droughts affecting central Padre Island 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, 1956; Tannehill, 1956; Dunn and Miller, 1964; Cry, 1965), some 62 tropical cyclones have either struck or affected the Texas Coast during this century (1900-1973). The average of 0.8-hurricane per year obtained from these data is similar to the 0.67 per year average reported by Hayes (1967), who concluded that most of the Texas coastline experienced the passage of at least one hurricane eye during this century. He further concluded that every point on the Texas Coast was greatly affected by approximately half of the storms classified as hurricanes.

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

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

Destructive forces and storm damage.—Carla was one of the most violent storms on record because of her extreme size and high storm surge. Although Carla made landfall north of Padre Island, storm tides of approximately 6 to 7 feet inundated the southern half of central Padre Island (U. S. Army Corps of Engineers, 1962a, plate 4); the northern half of central Padre was protected by the well-developed dune ridge. Storm surge associated with Hurricane Beulah (1967) also caused major flooding on central Padre Island and reactivated storm channels, but surge heights were not estimated for the area of study.

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 central Padre Island near Mansfield Channel 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 heights 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 of between 30 and 40 feet once every 50 years for the Brownsville area. Maximum deep-water hurricane wave height predicted for the same location was 45 feet with a recurrence frequency of once every 100 years. Consequently, dissipated energy from breaking storm waves can be tremendous under certain conditions.

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

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

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

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

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

Selective and incomplete removal of vegetation gives rise to the third type of change. Frequently, long, discontinuous, linear dune ridges survive wave attack but are isolated from the post-storm vegetation line by bare sand. Recovery under these circumstances is complicated and also of long duration. The preserved dune ridge does provide a nucleus for dune development; at times, the bare sand is revegetated and the vegetation line is returned to its prestorm position. This type of erosion was not observed on central Padre Island; 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 central Padre Island 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. 8). Their conclusion was based on tide records between 1948 and 1971.

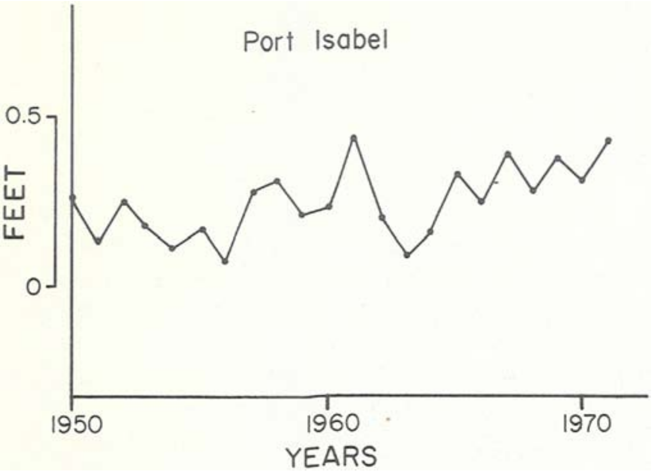

Figure 8. Relative sea-level changes based on tide gage measurements for Port Isabel, Texas. Data from Swanson and Thurlow (1973).

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 foot 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.

Sediment Budget

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

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 central Padre Island probably include sand derived from shelf sediment and the Rio Grande as well as sediment supplied by updrift shoreline erosion. Van Andel and Poole (1960) and Shepard (1960a) suggested that sediments of the Texas Coast are largely of local origin. Shelf sand derived from the previously deposited sediment was apparently reworked and transported shoreward by wave action during the Holocene sea-level rise (fig. 4). The inner continental shelf off the southern extremity of central Padre Island is underlain by fluvial-deltaic and interdeltaic sediments composed predominantly of mud with some interbedded sand. Therefore, reworked shelf sediments in this area provided only minor amounts of sand for barrier island development and beach maintenance. On the other hand, the shelf may have been a source of sediment for Padre Island from Yarborough Pass to 27° N latitude. Evidence for this interpretation comes from McGowen and others (1972) who concluded that the primary source of sediment for Modern sand-rich barrier islands such as north Padre Island was local Pleistocene and early Holocene sources on the inner shelf, based on the spatial relationship of the different age deposits.

Sediment supplied by major streams is transported alongshore by littoral currents. It is generally recognized that the combination of basin configuration and shoreline orientation plus predominant wind direction produce southwesterly littoral drift along the upper and central Texas Coast, whereas littoral drift is northerly along the lower coast (Lohse, 1955). Apparently, the zone of convergence is located near 27° N latitude (Watson, 1971), but seasonal conditions can cause the convergence to shift up the coast toward north Padre Island (Curray, 1960).

Because of seasonal reversals in direction of littoral transport associated with changing wind direction (Blankenship, 1953; Kimsey and Temple, 1962, 1963; Watson and Behrens, 1970; Hunter and others, 1974; Hill and others, 1975), net littoral drift along central Padre Island is perhaps only a fraction of the gross littoral drift. Carothers and Innis (1962) estimated that a net annual volume of 146,000 yd^3 was transported northward at Yarborough Pass along the open coast. Northward transport at Mansfield Channel was also documented by Hansen (1960), who estimated that 250,000 yd^3 of sediment were trapped by the south jetty while 400,000 yd^3 were eroded north of the north jetty in a year and a half following construction.

Substantial net accretion along central Padre Island extends from 15 miles south to about 9 miles north of Yarborough Pass (appendix A and Morton and Pieper, 1977). This shoreline segment exhibiting long-term net accretion nearly coincides with the transition zones established by Bullard (1942), van Andel and Poole (1960), Hayes (1965), and Watson (1971); the only difference is that net accretion extends northward of Yarborough Pass.

Net shoreline changes on central Padre Island support the conclusions of Bullard (1942) and Watson (1971) regarding directions of longshore drift and the location of net drift convergence. Furthermore, they refute the conclusions of van Andel and Poole (1960) that local shelf sediments were the single source of barrier island sand along this coastal segment. Clearly, longshore drift (shoreline erosion and fluvial sediment) as well as landward transport of reworked shelf sediment were important intrabasin sources of barrier island sand in this area.

Sand losses listed by Johnson (1959) do not include sediment removed by deposition from tidal deltas and hurricane washovers; these are two important factors on the Texas Coast (fig. 9). During storms, sand may be moved offshore in deeper water or into lagoons through washover channels. The highest dunes and most extensive dune fields along the Texas Coast occur south of Yarborough Pass, and eolian transport is an important factor in the distribution of sand on central Padre Island. Active blowouts and migrating dune fields (Fisk, 1959) indicate that a substantial volume of sand supplied to beaches by longshore currents is removed from the littoral drift system 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, training of the Mississippi River, 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.

Jetty construction at Mansfield Channel was completed in May 1962 (U. S. Army Corps of Engineers, 1962b). Projects such as this serve to alter natural processes such as inlet siltation, beach erosion, and hurricane surge. Their effects on shoreline changes are subject to debate, but it is an elementary fact that impermeable structures interrupt littoral drift and impoundment of sand occurs at the expense of the beach downdrift of the structure. Therefore, it appears reasonable to expect that any sand trapped by the south jetty is compensated for by removal of sand downdrift, thus increasing local erosion problems.

EVALUATION OF FACTORS

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

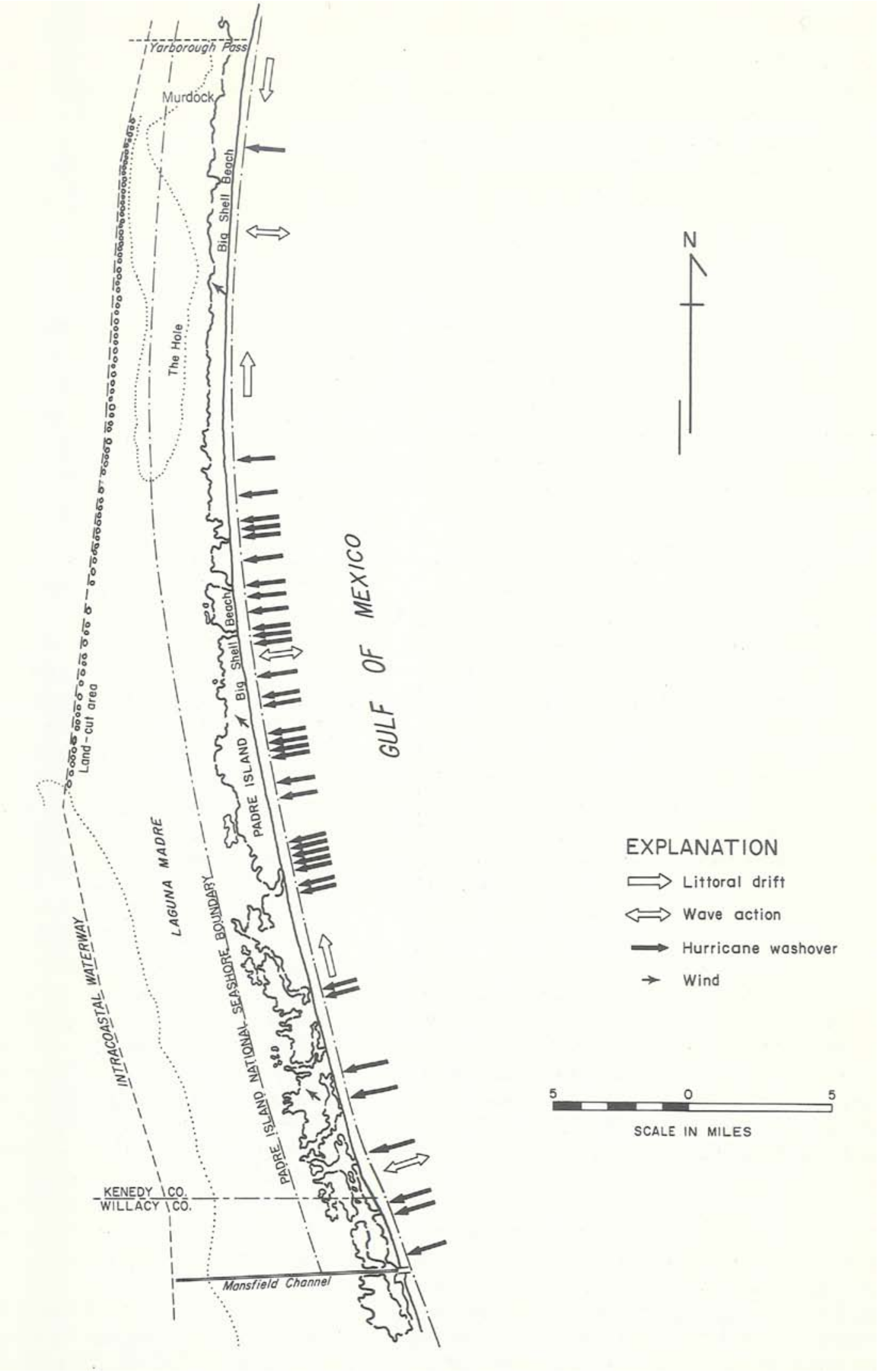

Figure 9. Generalized diagram of sediment transport directions along central Padre Island between Yarborough Pass and Mansfield Channel.

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 prediction of future shoreline changes on central Padre Island is more speculative than along most other segments of the Texas Coast because short-term trends have varied considerably. It appears reasonable to assume that long-term net shoreline changes of the future will occur at relatively low rates except for the beach immediately north of Mansfield Channel.

The shoreline from Yarborough Pass to point 15 has experienced long-term accretion while the shoreline between points 16 and 33 has remained relatively stable. Beach maintenance of these shoreline segments has been partially dependent on littoral drift, which has been recently modified by human alterations to the extent that erosion may occur in areas that were previously stable or accretionary. Shoreline erosion will probably continue between point 34 and Mansfield Channel, perhaps with increased erosion in the vicinity of the north jetty. Moreover, entrapment of sand and disruption of littoral drift by the south jetty may cause greater net shoreline erosion north of point 34.

A critical factor which has not been evaluated fully is sediment budget, especially the balance between sand supplied to central Padre Island by updrift erosion and sand removed by eolian processes. Until sources and sinks of sand along the Texas Coast are known, prediction of future shoreline changes in the zone of convergence is uncertain.

The logical conclusion drawn from factual information is that the position of shoreline and vegetation line in this region will probably retreat landward. 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).

Judging from sparse boring data, sand thickness of central Padre Island increases from between 10 and 15 feet near Mansfield Channel (U. S. Army Corps of Engineers, 1958) to between 35 and 40 feet near the land cut (Fisk, 1959). Future shoreline changes can be predicted to some degree based on sand thickness; for example, where sand is thin (north of Mansfield Channel) future erosion will occur unless sediment is added to the littoral drift system. On the other hand, greater volumes of sand stored in the barrier island should tend to minimize erosion and keep rates relatively low.

The shoreline could be stabilized at enormous expense by a solid structure such as a seawall; however, any beach seaward of the structure would eventually be removed unless maintained artificially by sand nourishment (a costly and sometimes ineffective practice). The U. S. Army Corps of Engineers (1971a, p. 3) stated that "While seawalls may protect the upland, they do not hold or protect the beach which is the greatest asset of shorefront property." Moreover, construction of a single structure can trigger a chain reaction that requires additional structures and maintenance (Inman and Brush, 1973).

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

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

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Appendix A

+ accretion
- erosion

Shoreline Changes

beach segment Yarborough Pass-Mansfield Channel

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	1881 1937	+125	+2.2	1937 1960	+250	+10.9	1960 1969	-125	-13.1	1969 1975	-50	-9.1	1881 1975	+200	+2.1
2	"	+250	+4.5	"	+325	+14.1	"	-175	-18.4	"	0	0	"	+400	+4.2
3	"	+250	+4.5	"	+225	+ 9.8	"	-125	-13.1	"	-25	-4.5	"	+325	+3.4
4	"	+325	+5.8	"	+250	+10.9	"	-150	-15.8	"	-25	-4.5	"	+400	+4.2
5	"	+125	+2.2	"	+300	+13.0	"	- 75	- 7.9	"	-< 10	-<1.0	"	+350	+3.7
6	"	+125	+2.2	"	+350	+15.2	"	-175	-18.4	"	0	0	"	+300	+3.2
7	"	+300	+5.3	"	+125	+ 5.4	"	-150	-15.8	"	+25	+4.5	"	+300	+3.2
8	"	+375	+6.7	"	-125	- 5.4	"	- 50	- 5.3	"	-50	-9.1	"	+150	+1.6
9	"	+500	+8.9	"	-150	- 6.5	"	- 50	- 5.3	"	-<10	-<1.0	"	+300	+3.2
10	"	+375	+6.7	"	-150	- 6.5	"	+< 10	+< 1.0	"	-50	-9.1	"	+175	+1.9
11	"	+475	+8.5	"	-175	- 7.6	"	-< 10	-< 1.0	"	-<10	-<1.0	"	+275	+2.9
12	"	+325	+5.8	"	-100	- 4.3	"	- 50	- 5.3	"	0	0	"	+175	+1.9
13	"	+325	+5.8	"	-175	- 7.6	"	- 25	- 2.6	"	+<10	+<1.0	"	+125	+1.3
14	"	+400	+7.1	"	-200	- 8.7	"	- 25	- 2.6	"	0	0	"	+175	+1.9
15	"	+325	+5.8	"	-100	- 4.3	"	-100	-10.5	"	0	0	"	+125	+1.3
16	"	+225	+4.0	"	- 75	- 3.3	"	-100	-10.5	"	-25	-4.5	"	+ 25	+<1.0
17	"	+250	+4.5	"	- 50	- 2.2	"	-100	-10.5	"	-50	-9.1	"	+ 50	+<1.0
18	"	+250	+4.5	"	-< 10	-< 1.0	"	-150	-15.8	"	-25	-4.5	"	+ 75	+<1.0
19	"	+300	+5.3	"	- 50	- 2.2	"	-100	-10.5	"	-50	-9.1	"	+100	+1.1
20	1879-81 1937	+100	+1.7	"	0	0	"	-125	-13.1	"	-25	-4.5	1879 1975	- 50	-<1.0

+ accretion
- erosion

Shoreline Changes

beach segment Yarborough Pass-Mansfield Channel

Point	Time	Dist. ft	Rate ft per yr	Time	Dist. ft	Rate ft per yr	Time	Dist. ft	Rate ft per yr	Time	Dist. ft	Rate ft per yr	Net Time	Net Dist.	Net Rate
21	1879-81 1937	+125	+2.1	1937 1960	- 25	- 1.1	1960 1969	-150	-15.8	1969 1975	0	0	1879 1975	- 50	-<1.0
22	"	+ 75	+1.3	"	+ 50	+ 2.2	"	- 75	- 7.9	"	-25	-4.5	"	+ 25	+<1.0
23	"	0	0	"	+ 50	+ 2.2	"	- 50	- 5.3	"	0	0	"	0	0
24	"	+ 25	+<1.0	"	0	0	"	- 25	- 2.6	"	0	0	"	0	0
25	"	+150	+2.6	"	-125	- 5.4				1960 1975	0	0	"	+ 25	+<1.0
26	"	+175	+3.0	"	-100	- 4.3				"	+25	+1.7	"	+100	+1.0
27	"	+100	+1.7	"	0	0				"	0	0	"	+100	+1.0
28	"	+< 10	+<1.0	"	0	0				"	-25	-1.7	"	- 25	-<1.0
29	"	+< 50	+<1.0	"	-25	- 1.1				"	-100	-6.7	"	- 75	-<1.0
30	"	0	0	"	+25	- 1.1				"	-100	-6.7	"	- 75	-<1.0
31	"	+ 50	+<1.0	"	0	0				"	-150	-10.0	"	-100	-1.0
32	"	+ 50	+<1.0	"	+75	+ 3.3				"	-125	-8.3	"	0	0
33	"	- 50	-<1.0	"	+100	+ 4.3				"	-100	-6.7	"	- 50	-<1.0
34	"	-100	- 1.7	"	+100	+ 4.3				"	-125	-8.3	"	-125	-1.3
35	"	- 50	-<1.0	"	+25	+ 1.1				"	-250	-16.7	"	-275	-2.9
36	"	- 50	-<1.0	"	-50	- 2.2				"	-275	-18.3	"	-375	-3.9
37	"	-150	-2.6	"	-100	- 4.3				"	-150	-10.0	"	-400	-4.2
38	1879-80 1937	0	0	"	-200	- 8.7				"	-175	-11.7	"	-375	-3.9
39	"	+200	+3.4	"	-175	- 7.6				"	-250	-16.7	"	-225	-2.3
40	"	+150	+2.6	"	-150	- 6.5				"	-275	-18.3	"	-275	-2.9

+ accretion
- erosion

Shoreline Changes

beach segment Yarborough Pass-Mansfield Channel

Point	Time	Dist. ft	Rate ft per yr	Time	Dist. ft	Rate ft per yr	Time	Dist. ft	Rate ft per yr	Time	Dist. ft	Rate ft per yr	Net Time	Net Dist	Net Rate
41	1879-80 1937	+175	+3.0	1937 1960	-125	-5.4				1960 1975	-250	-16.7	1879 1975	-200	-2.1
42	"	+125	+2.1	"	-125	-5.4				"	-225	-15.0	"	-225	-2.3
43	"	+200	+3.4	"	-125	-5.4				"	-350	-23.3	"	-275	-2.9
44	"	+ 75	+1.3	"	-225	-9.8				"	-325	-21.7	"	-475	-4.9
45	"	0	0	"	-275	-12.0				"	-350	-23.3	"	-625	-6.5
46	"	-250	-4.3	"	-225	-9.8				"	-450	-30.0	"	-925	-9.6
47	"	-375	-6.5	"	-375	-16.3				"	-400	-26.7	"	-1150	-12.0

+ accretion
- erosion

Vegetation Line Changes

beach segment Yarborough Pass-Mansfield Channel

Point	Time	Dist. ft	Rate ft per yr	Time	Dist. ft	Rate ft per yr	Time	Dist. ft	Rate ft per yr	Time	Dist. ft	Rate ft per yr	Net Time	Net Dist.	Net Rate
1				1937 1960	+ 900	+39.1	1960 1969	- 100	-10.5	1969 1975	+200	+33.0	1937 1975	+1000	+26.3
2				"	blowout		1937 1969	+2000	+62.5	"	+< 10	+< 1.0	"	+2000	+52.6
3				"	"		"	+1400	+43.7	"	+350	+58.0	"	+1750	+46.0
4				"	"		"	+ 275	+ 8.6	"	+ 25	+ 4.2	"	+ 300	+ 7.9
5				"	"		"	+ 225	+ 7.0	"	+< 10	+< 1.0	"	+ 225	+ 5.9
6				"	"		"	+ 300	+ 9.4	"	+100	+16.7	"	+ 400	+10.5
7				"	+ 300	+13.0	1960 1969	- 175	-18.4	"	+ 25	+ 4.2	"	+ 150	+ 3.9
8				"	+ 150	+ 6.5	"	- 125	-13.2	"	0	0	"	+ 25	+< 1.0
9				"	+ 50	+ 2.2	"	+ 50	+ 5.3	"	- 50	- 9.1	"	+ 50	+ 1.3
10				"	- 50	- 2.2	"	+ 75	+ 7.9	"	- 25	- 4.5	"	0	0
11				"	- 25	- 1.1	"	-< 10	-< 1.0	"	0	0	"	- 25	-< 1.0
12				"	- 50	- 2.2	"	0	0	"	+ 25	+ 4.5	"	- 25	-< 1.0
13				"	+ 150	+ 6.5	"	- 100	-10.6	"	-100	-18.2	"	- 50	- 1.3
14				"	0	0	"	0	0	"	0	0	"	0	0
15				"	+ 150	+ 6.5	"	- 125	-13.2	"	0	0	"	+ 25	+< 1.0
16				"	+ 400	+17.4	"	- 50	- 5.3	"	-< 10	-< 1.0	"	+ 350	+ 9.2
17				"	+ 225	+ 9.8	"	- 225	-23.4	"	+< 10	+< 1.0	"	+< 10	+< 1.0
18				"	+1425	+62.0	"	- 250	-26.3	"	+125	+22.7	"	+1300	+34.2

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
Apr. 1937	*	Tobin Research Inc.
Feb. 1943		U. S. Dept. of Agriculture
Nov. 1954		U. S. Dept. of Agriculture
Feb., Mar., Apr. 1960	*	Tobin Research Inc.
Oct. 1961		U. S. Army Corps of Engineers
June 1967		U. S. Army Corps of Engineers
Sept. 1967		Texas Highway Dept.
Nov. 1967		Intl. Boundary Commission
Oct., Nov. 1969	*	Natl. Oceanic and Atmospheric Adm.
June 1974		Texas General Land Office
July 1975	*	Texas General Land Office

List of Maps Used in Determination of Shoreline Changes

Date	Description	Source of Maps
1879-1880	Topographic map 1477a and 1477b	Natl. Oceanic and Atmospheric Adm.
1879-1881	Topographic map 1676 and 1677	Natl. Oceanic and Atmospheric Adm.
1881	Topographic map 1679 and 1678	Natl. Oceanic and Atmospheric Adm.

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

- Yarborough Pass, Texas
- Portrero Cortado, Texas
- Portrero Lopeno NW, Texas
- Portrero Lopeno SE, Texas
- South of Portrero Lopeno NE, Texas
- South of Portrero Lopeno SE, Texas