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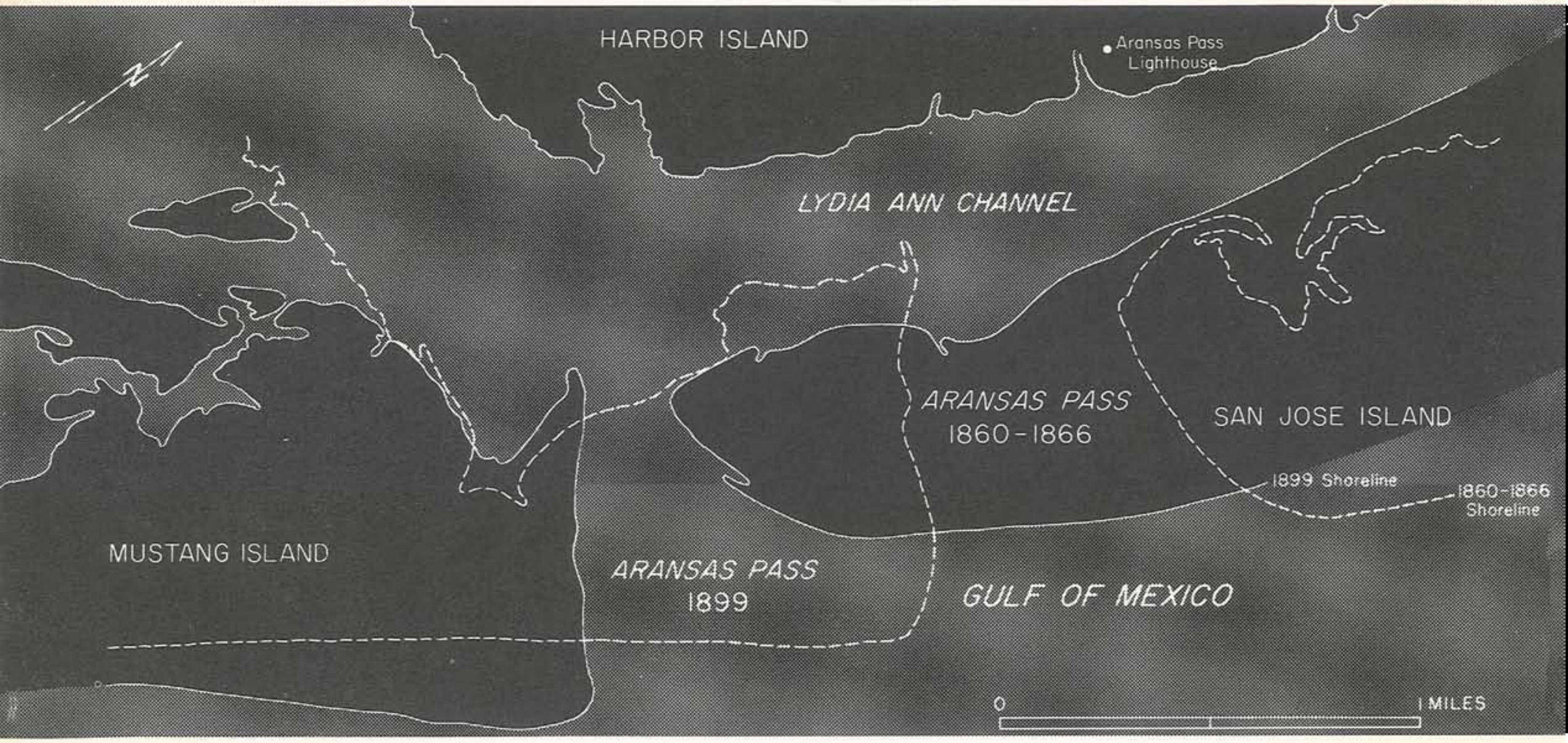
SHORELINE CHANGES ON MATAGORDA ISLAND AND SAN JOSE ISLAND (PASS CAVALLO TO ARANSAS PASS)

AN ANALYSIS OF HISTORICAL CHANGES OF THE TEXAS GULF SHORELINE

BY ROBERT A. MORTON
AND MARY J. PIEPER



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SHORELINE CHANGES ON MATAGORDA ISLAND AND SAN JOSE ISLAND (PASS CAVALLO TO ARANSAS PASS)

AN ANALYSIS OF HISTORICAL CHANGES OF THE TEXAS GULF SHORELINE

by

Robert A. Morton and Mary J. Pieper

ABSTRACT

Historical monitoring along Matagorda Island and San Jose 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 1857-99) and aerial photographs (taken in 1931-37, 1957-58, 1965, and 1974) indicates short-term changes of accretion and erosion along Matagorda and San Jose Islands between Pass Cavallo and Aransas Pass. *Erosion* produces a net loss in land, whereas *accretion* produces a net gain in land. Comparison of the vegetation line based on the aforementioned aerial photographs indicates short-term cycles of erosion related to storms (primarily hurricanes) and recovery during intervening years of low storm incidence.

Long-term trend or direction of shoreline changes averaged over the 117-year time period of this study indicates that net changes on Matagorda Island have been predominantly accretionary with two exceptions. Net erosion of 600 to 2,025 feet occurred in the vicinity of Pass Cavallo owing to reorientation of the shoreline; minor net erosion and accretion along the southernmost 2,500 feet of the island were influenced by the southern migration of Cedar Bayou. The remaining shoreline of Matagorda Island experienced net accretion of 25 to 1,050 feet; average net accretion was 333 feet. Net accretion on Matagorda Island was influenced largely by major accretion which occurred between 1857 and 1937. Net rates of accretion for the southern part of the island were generally less than 1 foot per year, whereas net rates of accretion for the northern half increased from a minimum of 1.1 feet per year to a maximum of 9.1 feet per year. Net erosional rates in the vicinity of Pass Cavallo ranged from 5.1 to 17.3 feet per year.

Net changes on San Jose Island indicate alternating shoreline segments of net accretion and net erosion. In general, net shoreline changes were 75 feet or less, suggesting relative shoreline stability. Extreme net accretion of 750 to 1,400 feet was recorded for the southern portion of San Jose Island where rapid accumulation of sediment occurred in the vicinity of the north jetty at Aransas Pass. Net rates of erosion and accretion on San Jose Island were generally less than 1.5 feet per year.

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

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

Studies indicate that changes in shoreline and vegetation line on Matagorda Island and San Jose 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 Matagorda Island and San Jose 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. Therefore, the utility of the method dictates the type of data used. Topographic maps dating from 1857 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 Pass Cavallo to Aransas Pass (fig. 1) is the fifth in that series.

General Statement on Shoreline Changes

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

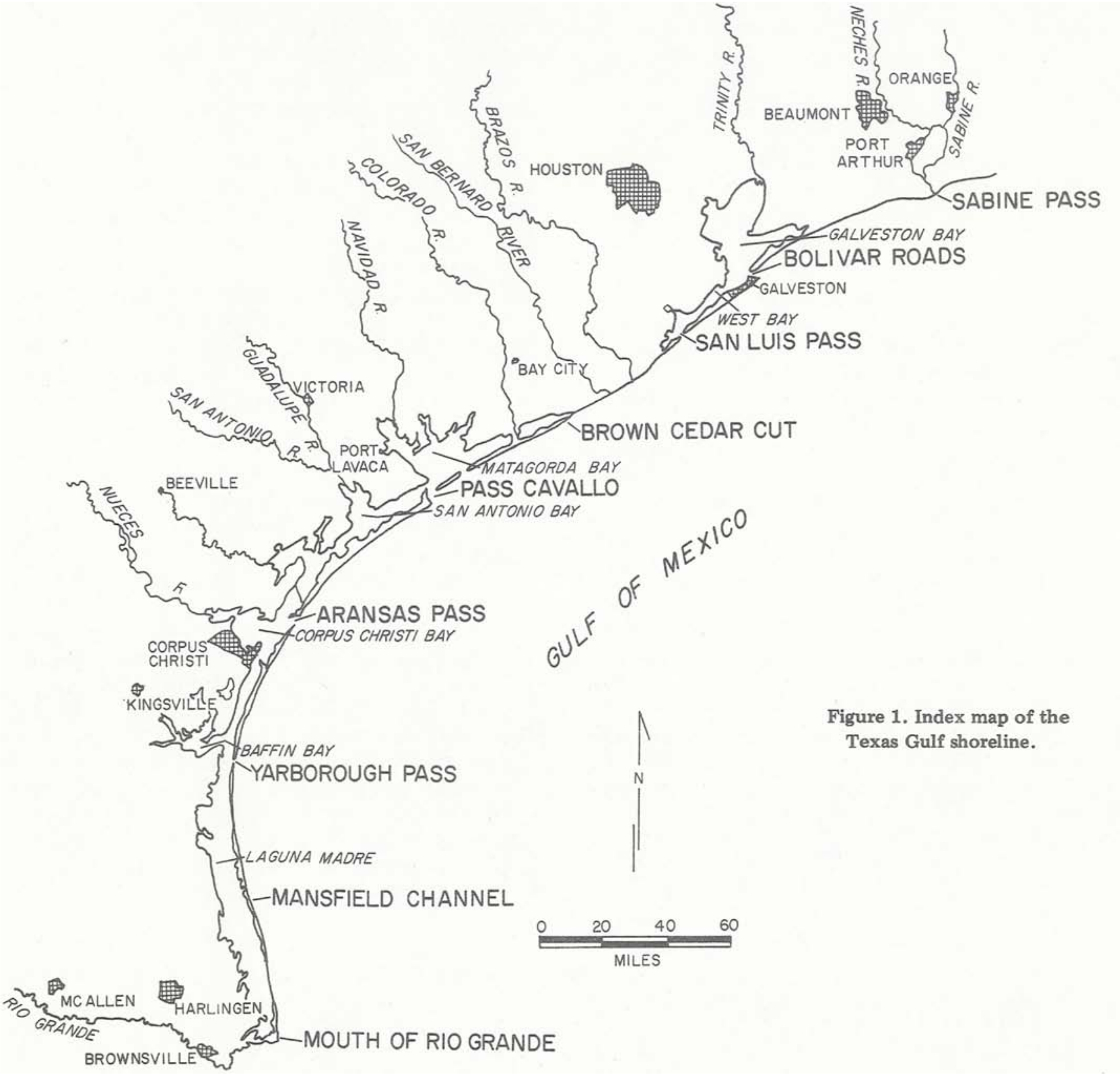

Figure 1. Index map of the Texas Gulf shoreline.

Acknowledgments

Assistance in preparation of this report was provided by M. Amdurer, J. L. Chin, and J. H. McGowen. 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., J. H. McGowen, and C. G. Groat. The report was typed by Elizabeth T. Moore 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, 1968c).

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

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

Monitoring of Vegetation Line

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

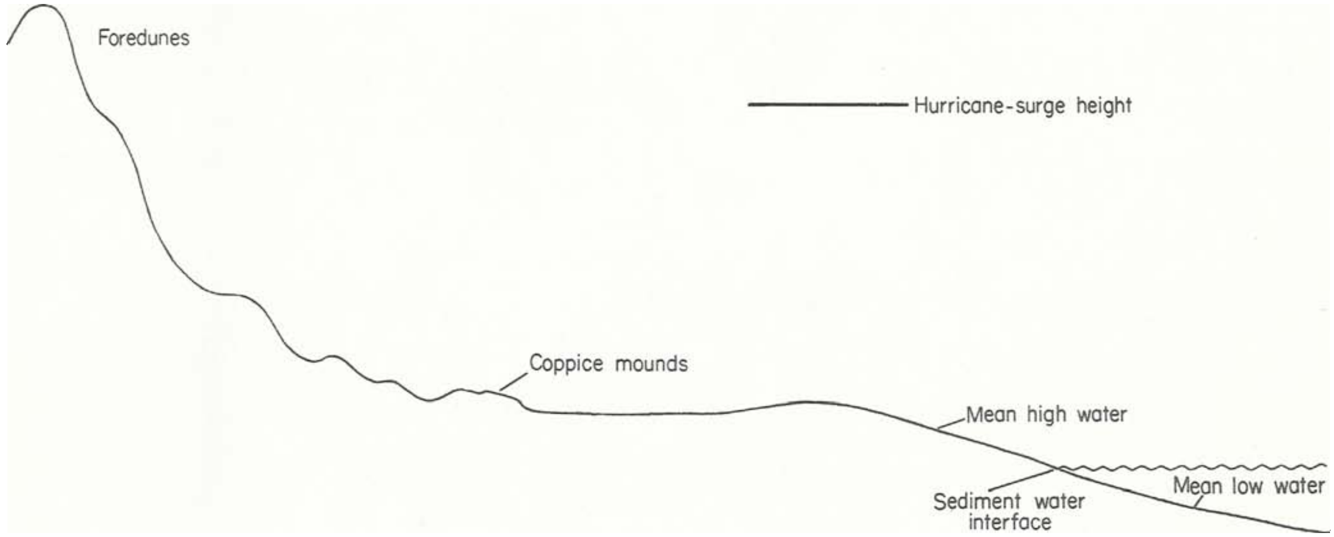

Figure 2. Generalized diagram of beach profile.

PREVIOUS WORK

Originating in the early 1800's and continuing to the present, numerous studies on Aransas Pass and Pass Cavallo have been conducted by the U. S. Army Corps of Engineers. The early studies monitored changes in width of the natural channel, as well as changes in depth of water within the channel and over the channel-mouth bars. Based on these studies, construction of jetties was proposed at Pass Cavallo and Aransas Pass in order to obtain navigable and stable channels.

Beach profiles have been surveyed by the Galveston District, U. S. Army Corps of Engineers (1968-1974) at inlets and midpoints between the inlets along the Texas Coast. These profiles show both erosional and accretionary short-term changes in proximity to the Aransas Pass jetties and at Panther Point on Matagorda Island.

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. The shoreline on Matagorda Island from Pass Cavallo south for a distance of approximately 5 miles was designated as an area of noncritical erosion. Another area of noncritical erosion was delineated on San Jose Island extending approximately 5 miles south from Cedar Bayou.

In a recent study, Seelig and Sorensen (1973) presented tabular data documenting mean low-water shoreline changes along the Texas Coast; values calculated for the rates of shoreline change along Matagorda and San Jose Islands were included in their report. Their technique involved the use of only two dates (early and recent); the change at any point was averaged over the time period between the two dates. Cycles of accretion and erosion were not recognized and few intermediate values were reported; thus, in certain instances, the data are misleading because of technique. Furthermore, data retrieval is difficult because points are identified by the Texas coordinate system. Rates of erosion determined by Seelig and Sorensen (1973, p. 15-16) ranged from 8 to 49 feet per year for the northern portion of Matagorda Island in the vicinity of Pass Cavallo. From this area south, rates of accretion ranging from 1 to 13 feet per year were reported except for the southernmost part of the island where erosion of 1 to 3 feet per year was indicated. Rates of change for San Jose Island were mixed and included areas of no change, areas of net erosion (1 to 6 feet per year), and minor areas of net accretion. Erosion on Matagorda Island was also reported by Harwood (1973) who indicated that Pass Cavallo migrated southwestward from 500 to 1,500 feet between 1887 and 1971.

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

Texture, composition, and other characteristics of beach, dune, barrier-flat, and washover-fan sediments within the study area have been the subjects of numerous investigations (Bullard, 1942; Shepard and Moore, 1954, 1956; Beal and Shepard, 1956; Curray, 1956; Shepard, 1960a; Shepard and Young, 1961; Andrews and van der Lingen, 1969; Andrews, 1970; Nordquist, 1972; Wilkinson, 1973) with several studies attempting to differentiate the various depositional environments on the basis of roundness, heavy mineral abundance, sedimentary structures, or statistical parameters of grain-size distribution. These environments are composed of well-sorted to very well-sorted, fine to very fine sand. Black opaques, hornblende, leucoxene, tourmaline, and zircon are the most common heavy minerals with minor amounts of epidote, garnet, rutile, and staurolite (Bullard, 1942; Shepard and Moore, 1955). Shepard and Moore (1955, 1956) identified traces of glauconite, foraminifera, and echinoid fragments in samples from San Jose and Matagorda Islands. 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. Geyer and Sweet (1973) concluded that these accumulations are natural occurrences attributed to offshore seeps. Price (1933) reported an oil seep on the north end of San Jose Island.

Beach Profiles

The beaches of the central Texas Coast are characterized by a broad (approximately 200 to 350 feet wide), gently seaward sloping (between 1°30′ and 2°30′) sand 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 Matagorda and San Jose Islands, represent beach conditions on June 11, 1974, and March 18, 1975. Beach profiles at Aransas Pass and Panther Point have also been surveyed by the Galveston District, U. S. Army Corps of Engineers (1968-1974). Comparison of beach profiles and beach scour patterns on Galveston Island by Herbich (1970) suggests that beach condition (breaker bar spacing and size) may be similar over a relatively long period of time except during and immediately following storm conditions. Therefore, unless beach profiles are referenced to a permanent, stationary control point on the ground, comparison of profiles at different times may be very similar, but the absolute position of the beach can be quite different. Thus, a beach profile may appear similar (except after storms) for a long period of time but the entire profile may shift seaward (accretion) or landward (erosion) during the same period.

Except in washover and blowout areas, extant dunes on Matagorda and San Jose Islands are high and relatively continuous. Dune heights range up to 50 feet; most fore-island dunes, however, attain elevations of about 15 to 20 feet. Along segments of Matagorda Island, the high fore-island dunes are separated from the beach by an elevated and

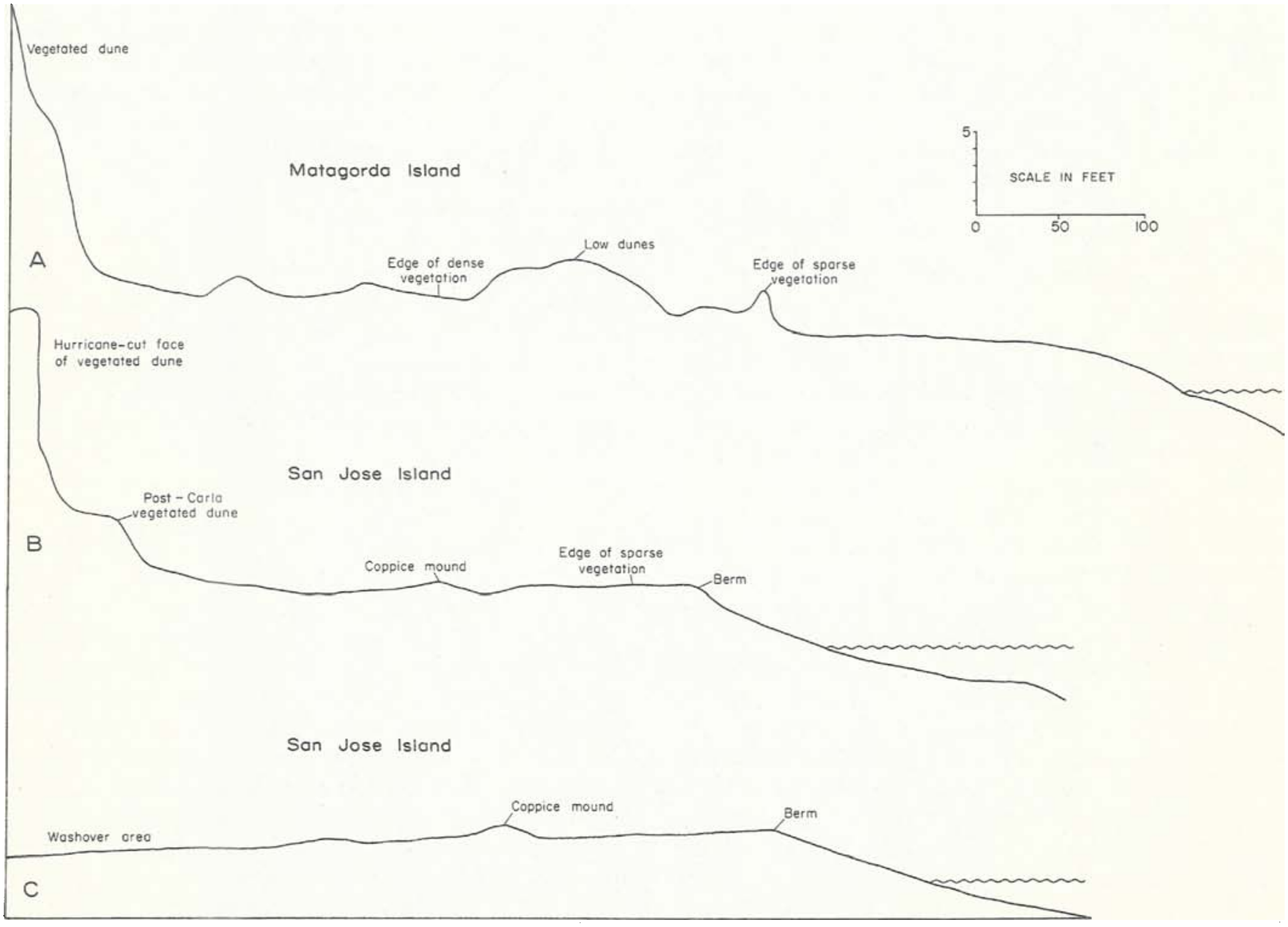

Figure 3. Beach profiles, Pass Cavallo to Aransas Pass, recorded June 11, 1974 (San Jose Island), and March 18, 1975 (Matagorda Island). Locations plotted on figure 6.

vegetated interdune area and low, sparsely vegetated dunes (fig. 3). Apparently the high fore-island dunes represent the equilibrium position of dune formation for a shoreline position preceding the 1857-59 shoreline. The vegetated interdune area, which is about 2.5 feet higher than the present-day backbeach, and the low foredunes were formed contemporaneously with and subsequent to the shoreline accretion. Thus the low dunes represent the equilibrium position of dune formation for the present-day shoreline. The low dunes were overwashed and probably removed by the hurricanes in the 1920's and early 1930's as evidenced by the general coincidence of the 1937 vegetation line with the high fore-island dunes. This relationship, which is easily discerned on 1958, 1965, and 1974 photographs, provides valuable information on natural dune formation attendant with shoreline changes.

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

Pass Cavallo

According to shipping interests in the 1800's, Pass Cavallo was the second best natural pass on the Texas Coast; Galveston was ranked first. A map by Cardenas (Price, 1947) showed that Pass Cavallo had remained in approximately the same location since 1689. Natural water depths varied from 7 to 10 feet over the outer bar; however, the channel over the outer bar changed positions frequently, often rapidly (U. S. Army Corps of Engineers, 1854), and southerly migration was prevalent. Because stabilization of a single channel across the bar was desirable, the suggestion was made to close a portion of the pass, thus increasing current strength through the remaining channel (U. S. Army Corps of Engineers, 1854). While awaiting appropriations, the Corps of Engineers conducted surveys in 1871, 1873, and 1879 in order to monitor short-term changes in the pass (U. S. Army Corps of Engineers, 1871, 1874, 1879).

Changes which occurred between 1853 and 1871 were attributed largely to two major storms which affected the area in 1854 and 1868. The 1854 storm reduced Pelican Island to a low subaerial sandflat, whereas prior to the storm, the island had grass-covered sand dunes up to 20 feet high (U. S. Army Corps of Engineers, 1871). The main channel shifted to the south as a result of the storm and increased to a depth of 13 feet. By 1856, the channel had shoaled to 8 feet (U. S. Army Corps of Engineers, 1871).

The violent storm of 1868 swept away part of Fort Esperanza which was located on Matagorda Island 100 feet from the shoreline and halfway between the lighthouse and Bayou McHenry. No direct reference was made to changes in the channel; however, it was mentioned that since 1856 Pelican Island had shifted to the north approximately three-fourths of a mile (U. S. Army Corps of Engineers, 1871). Whether this shift was the result of the 1868 storm is speculative.

According to the 1873 survey, little change had occurred since the 1871 survey (U. S. Army Corps of Engineers, 1874). Pelican Island shifted northward to a position 3,260 feet closer to Matagorda Peninsula (Decros Point) than in 1871 (U. S. Army Corps of Engineers, 1874).

In 1877, the Corps of Engineers made a formal proposal to close Elizabeth and Decros channels between Pelican Island and Matagorda Peninsula with a 7,000-foot gabionade in order to promote southward accretion of Matagorda Peninsula as far as Pelican Island, thus confining tidal discharge from the bay through the main channel (U. S. Army Corps of Engineers, 1877). Work on this project was never initiated.

The survey of 1879 documented changes resulting from major storms in 1875 and 1877

(U. S. Army Corps of Engineers, 1879). Pelican Island had again shifted, this time approximately 1 mile to the south (U. S. Army Corps of Engineers, 1879). The north end of Matagorda Island had eroded from near Fort Esperanza to the Gulf. At one point, near the site of the old lighthouse, the shoreline receded 1,300 feet. At Fort Esperanza, the shoreline eroded a distance of 600 feet carrying away the remainder of the fort and some houses. Depths over the outer bar were generally increased by the storms. Captain Cross (U. S. Army Corps of Engineers, 1879) observed that by 1878 Matagorda Island was beginning to assume its former shape prior to the storms and consequently it was suggested that a jetty would protect Matagorda Island from further erosion.

A formal proposal for a jetty extending 7,600 feet southeast from Matagorda Island (or to the 18-foot contour) was presented by the Corps of Engineers in 1879. The jetty was to be constructed of brush mattresses covered with mixed ballast of stone and concrete. The proposal also provided for groins to protect the shoreline where necessary (U. S. Army Corps of Engineers, 1880). It was the opinion of the Corps of Engineers that the jetty would also be instrumental in increasing depths over the outer bar. A contract to initiate jetty construction was signed in November 1881 (U. S. Army Corps of Engineers, 1882).

Prior to initial construction of the jetty, another survey was made in 1878. The shoreline on Matagorda Island had advanced approximately 600 feet in line with the proposed jetty and extensive shoaling had occurred near the shore. This event strongly suggested a trend for the shore to regain its pre-1875 position (U. S. Army Corps of Engineers, 1882). The survey also indicated that the channel had ceased its southerly migration.

By July 1882, 1,325 feet of the jetty was completed. With extension of the jetty, the shoreline advanced 400 and 300 feet, respectively, on the north and south side of the jetty; shoaling seaward of the outer end of the jetty also occurred (U. S. Army Corps of Engineers, 1882). By 1884, the jetty extended 5,253 feet; however, work was suspended in July 1885 because of a lack of funds (U. S. Army Corps of Engineers, 1887).

The storm in 1886 damaged the jetty and practically destroyed Indianola. Subsequently, the town was not rebuilt and the need to modify Pass Cavallo declined because Indianola was the only significant port on Matagorda Bay (U. S. Army Corps of Engineers, 1887). No additional work was accomplished on the jetties and the project was abandoned in 1888 (U. S. Army Corps of Engineers, 1888).

Fishing interests, oil companies, and industrial expansion revitalized the need for a deep draft channel connecting Matagorda Bay and the Gulf. But shoaling at Pass Cavallo had increased after 1935 when the Colorado River began discharging directly into the Gulf (McCrone, 1956). Emergency dredging across the bar at the entrance to Pass Cavallo was initiated in August 1949 by the Corps of Engineers and completed in September 1949. The channel was deepened to 17 feet with a bottom width of 135 feet (U. S. Army Corps of Engineers, 1957). The channel shoaled to 10 feet by November 2, 1949, largely because of the October 1949 hurricane (U. S. Army Corps of Engineers, 1957; Rhodes and Boland, 1963). According to Rhodes and Boland (1963) the channel had shoaled to 8 feet by March 1952. No further attempts were made to dredge Pass Cavallo. The feasibility of a jettied entrance into Matagorda Bay was studied, and in 1957 the Corps of Engineers submitted a list of suitable sites for a deep draft channel (Weiser and Armstrong, 1963) that included Pass Cavallo, Matagorda Inlet (a site across Matagorda Peninsula approximately 1 mile southwest of Green's Bayou), and Green's Bayou (U. S. Army Corps of Engineers, 1957). Upon completion of the investigation, the Pass Cavallo site was recommended. Construction of the channel was authorized by the River and Harbor Act of July 3, 1958; however, final designation of the channel site was not made (U. S. Army Corps of Engineers, 1964).

To assist in selection of the most desirable site, authority was given for a model study of the Matagorda Ship Channel. The study was initiated by the Waterways Experiment Station in December 1959 and was completed in September 1962 (Simmons and Rhodes, 1966). On the basis of cumulative data, it was decided that the channel should follow a straight alignment through Matagorda Peninsula in lieu of the Pass Cavallo site (U. S. Army Corps of Engineers, 1964). Dredging of the Matagorda Ship Channel commenced in July 1962 and was completed in September 1963 (U. S. Army Corps of Engineers, 1964). Construction of the jetties began early in 1963 (U. S. Army Corps of Engineers, 1963) and was completed in October 1966 (U. S. Army Corps of Engineers, 1967).

Cedar Bayou

Cedar Bayou, the tidal inlet separating San Jose and Matagorda Islands, has been intermittently open and closed in the past. Simmons and Hoese (1959) suggested that the shoaling of Cedar Bayou in the 1930's and 1950's was due to the droughts and subsequent reduction in discharge of the Guadalupe River. Prentiss (1952), however, stated that Cedar Bayou was closed by the 1929 hurricane. Under normal conditions, the tidal inlet is in equilibrium with the active processes, and it is maintained by tidal currents for extended periods before closing. As is the case with most of the minor tidal inlets along the Texas Coast, Cedar Bayou has a history of migration, shoaling, and breaching by hurricane surge. However, the reactivation of Cedar Bayou after its most recent closings has been by dredging rather than natural forces. The inlet was dredged open by the Texas Game, Fish, and Oyster Commission in 1939 and again in 1959 (Simmons and Hoese, 1959).

Aransas Pass

Aransas Pass was extremely unstable during the middle to late 1880's. Relocation of the channel axis, changes in channel depth of several feet, and shifting of the inlet mouth bars accompanied southerly migration of the inlets. Frequent changes caused navigation problems for trade vessels traveling over the outer bars and through the inlet. Not only were the changes frequent but they occurred rapidly as well. It was reported that during one week in 1853, the channel migrated from the north to the south breakers. The new channel provided 9 feet of clearance but the old channel shoaled to 4 feet (U. S. Army Corps of Engineers, 1853). Between 1851 and 1890, depths over the inlet mouth bars varied from 7 to 10.5 feet (U. S. Army Corps of Engineers, 1890).

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

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

Recommendations following a survey of the pass in 1871 included construction of groins and a revetment on the northern extremity of Mustang Island and a jetty extending into the Gulf from the northeast side of the island (U. S. Army Corps of Engineers, 1871).

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

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

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

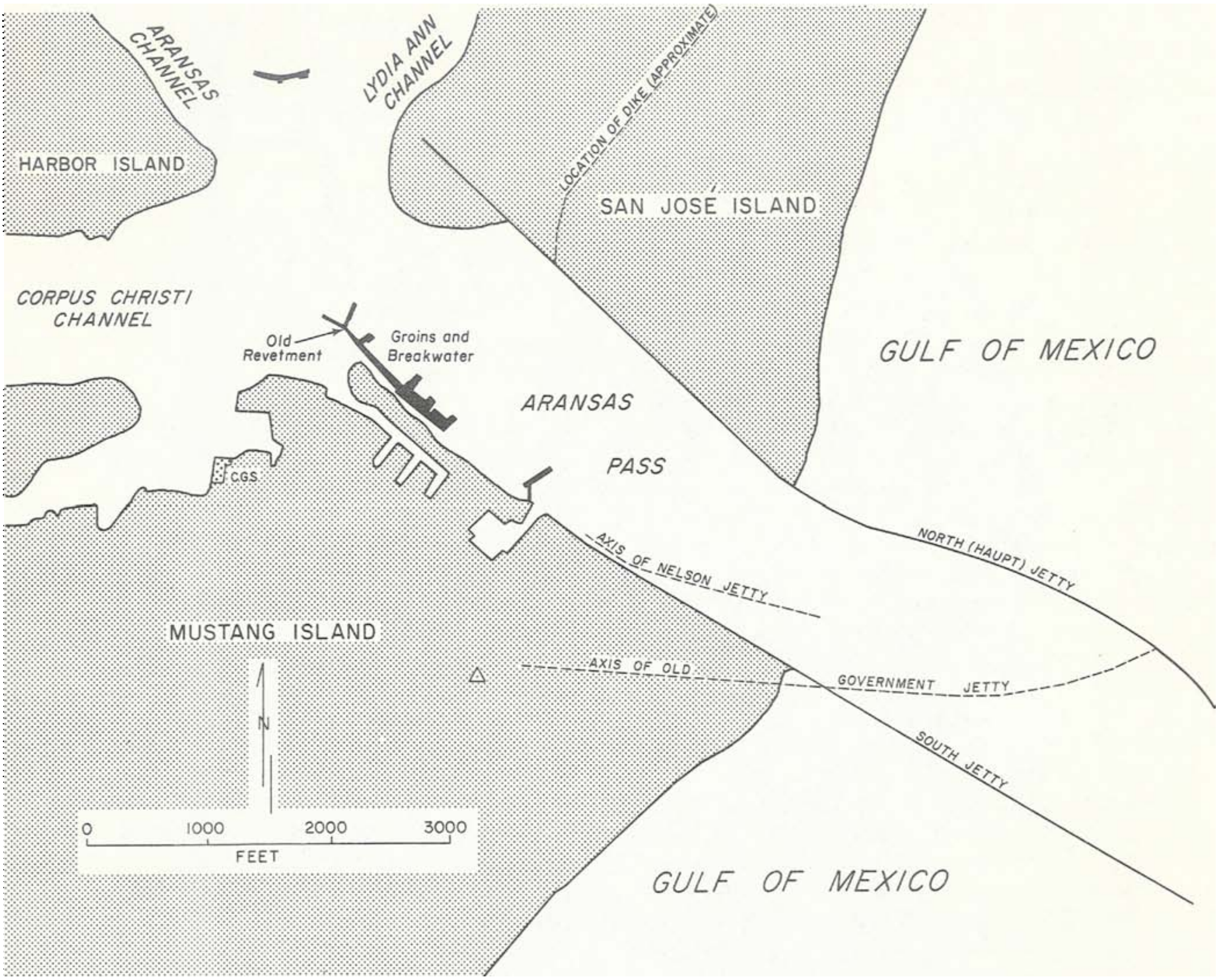

Figure 4. Location of significant coastal structures and alterations of Aransas Pass and adjacent areas.

isolated from the shoreline which had eroded 100 to 200 feet to the south.

During 1888 and 1889, the revetment was lengthened to 2,725 feet and strengthened by an 18-inch-thick wall of riprap from the bottom of the channel to the high-water line. These additions succeeded in stabilizing the northern tip of Mustang Island (U. S. Army Corps of Engineers, 1900). On March 22, 1890, the Aransas Pass Harbor Company was incorporated as a result of the limited annual appropriations and because people believed that proposed improvements for Galveston Harbor would receive any large appropriations. In exchange for certain rights and privileges granted by Congress, the company was to provide a deep-water channel (20 feet) through Aransas Pass by 1899 (U. S. Army Corps of Engineers, 1897-1898). In 1892, the south (or Nelson) jetty was constructed 1,800 feet along the southern edge of Aransas Pass. The north (or Haupt) jetty was constructed between August 1895 and September 1896. This jetty extended 5,750 feet shoreward from the 15-foot contour line to a point 1,500 feet offshore from San Jose Island. Only 1,250 feet of the jetty was completed breakwater with the remainder being either core with partial capping or just core (U. S. Army Corps of Engineers, 1897-1898).

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

The responsibility for the north jetty was transferred to the federal government in 1899 after the Aransas Pass Harbor Company was unable to obtain a 20-foot channel required by contract. Although erosion of the north end of Mustang Island had been eliminated, accretion of San Jose Island continued and the pass narrowed by 300 feet between 1899 and 1900. In turn, flow velocities increased as revealed by the landward and seaward 650-foot shift of both the inner and outer 18-foot contours (U. S. Army Corps of Engineers, 1900).

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

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

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

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

By 1912, a 10,000-foot dike was constructed to prevent channelization of this area. The dike consisted of an 8-foot-high rubble mound which extended from the north jetty along the axis of San Jose (U. S. Army Corps of Engineers, 1912). A 9,100-foot extension of this dike to the edge of high stable dunes on San Jose Island was proposed, and construction of this segment was completed in 1916; total length of the dike was 20,991 feet (U. S. Army Corps of Engineers, 1919). Construction of the 7,385-foot south jetty was also completed in 1916 (U. S. Army Corps of Engineers, 1917). At that time, the channel was 22.5 feet deep (U. S. Army Corps of Engineers, 1916).

The extreme hurricanes in 1916 and 1919 caused extensive damage to the central Texas Coast. The dike on San Jose Island was severely damaged by the 1919 hurricane which breached the island and formed North Pass and Middle Pass (U. S. Army Corps of Engineers, 1922). This storm also caused the channel to shoal from 21 feet to 14.5 feet. The channel had only recovered to 17 feet by June 1920, so during the next year it was redredged to 24.5 feet (U. S. Army Corps of Engineers, 1920). Another hurricane in June 1921 caused widening of North Pass, formation of a new channel along the northern end of the dike, and shoaling of Aransas Pass to 22.5 feet (U. S. Army Corps of Engineers, 1921).

Four spurs projecting at right angles from the north jetty into Aransas Pass were constructed in 1922 in order to straighten the channel and move it southward away from the jetty (U. S. Army Corps of Engineers, 1922). This improvement was relatively successful, but the channel maintained its depth of 22.5 feet for several years (U. S. Army Corps of Engineers, 1924). The Gulf entrances to Middle Pass and North Pass were closed by 1924 but both passes remained open to Lydia Ann Channel.

By 1932, the channel between the jetties had been dredged to 30.7 feet (U. S. Army Corps of

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

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

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

CHANGES IN SHORELINE POSITION

Late Quaternary Time

Significant changes in sea level have occurred along the central Texas Coast during the past 10,000 years (Shepard, 1956, 1960b; LeBlanc and Hodgson, 1959; Wilkinson, 1973, 1975). Prominent ridge and swale topography is visible on aerial photographs and these abandoned beach ridges attest to the fact that accretion was predominant after sea level reached its stillstand position about 3,000 years before present (fig. 5). Radiocarbon methods (Shepard, 1956, 1960b) provide dates for the interpretation of sea-level positions prior to stillstand. Barrier island development was initiated between 5,000 and 3,000 years ago. Vertical accretion of the barrier islands attendant with sea-level rise was augmented by eolian processes.

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

Historic Time

Shoreline changes and tabulated rates of change between 1857 and 1974, at 56 arbitrary points spaced 5,000 feet apart along the map of Matagorda and San Jose Islands (fig. 6), are presented in appendix A. In general, the tabular data for Matagorda Island document one period of accretion (1857-60 to 1937), two periods dominated by erosion (1957 to 1965 and 1965 to 1974), and one period of mixed erosion and accretion (1937 to 1957). San Jose Island experienced three periods dominated by erosion (1931-37 to 1957-58, 1957-58 to 1965, and 1965 to 1974) and one period of accretion (1860-62 to 1937-38).

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

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

1857-62 to 1931-37.—Of the 56 points monitored on San Jose and Matagorda Islands, 50 experienced accretion, 4 recorded erosion, and 2 remained unchanged (appendix A). Accretion was dominant on Matagorda Island with the exception of points 1 through 3 in the vicinity of Pass Cavallo where erosion ranged from 625 to 1,550 feet. The northern third of the island (points 4 through 11) experienced the greatest accretion, ranging from 225 to 1,300 feet. Average accretion for this segment was 925 feet, whereas average accretion for the remaining portion of the island was 288 feet.

Accretion was also dominant on San Jose Island; however, the magnitude was considerably less than that recorded on Matagorda Island. With the exception of points 54 through 56, which were

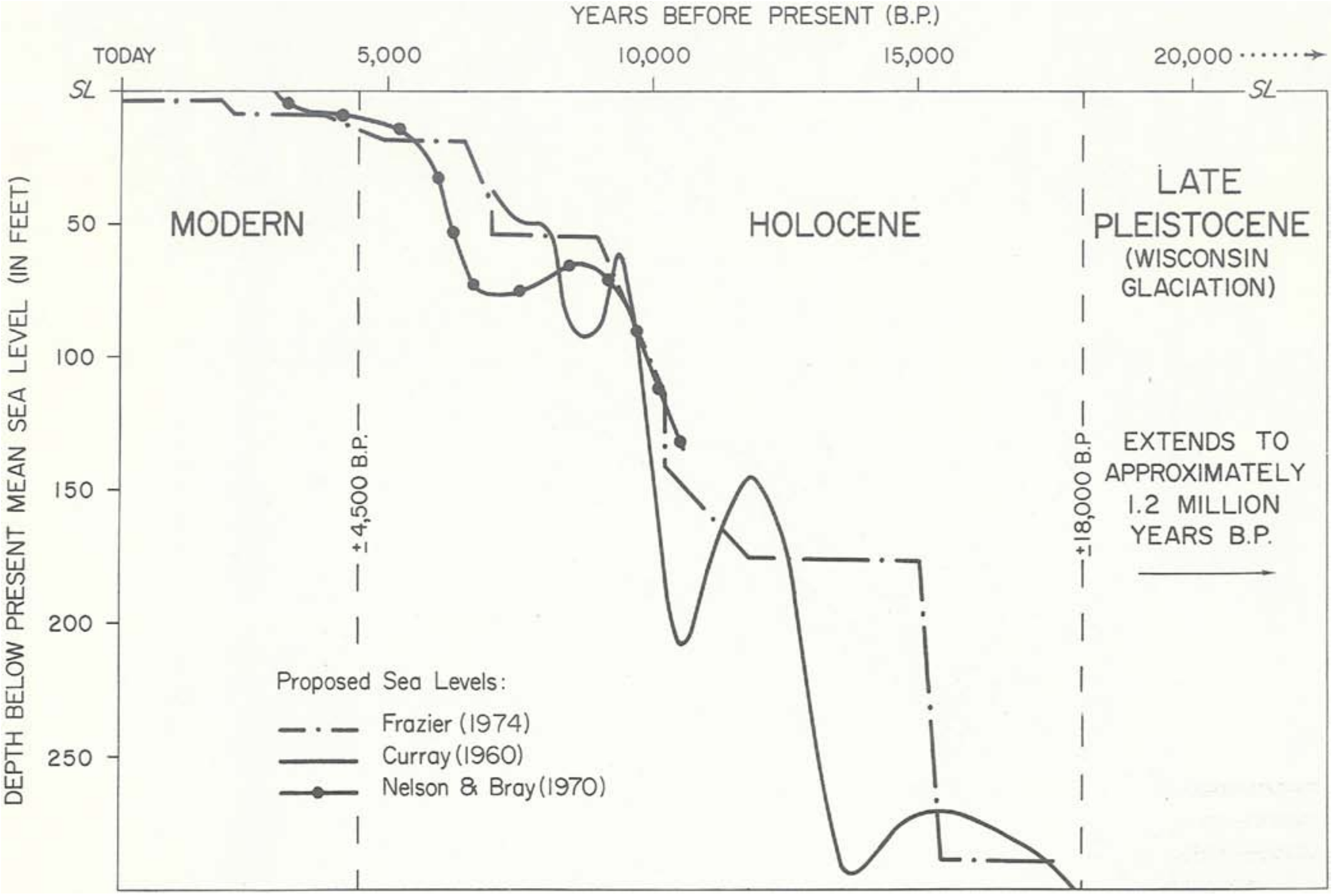

Figure 5. Proposed sea-level changes during the last 20,000 years; sketch defines use of Modern and Holocene. After Fisher and others (1973).

affected by the migration of Aransas Pass and subsequent jetty construction, accretion on San Jose Island ranged from 25 feet (point 43) to 375 feet (point 41) and averaged 225 feet. Between 1899 and 1937, the shoreline at point 56 accreted 1,250 feet as a result of jetty construction at Aransas Pass. Most of the accretion occurred after 1908 when the north jetty was extended landward to connect with the shore. Aransas Pass migrated 5,200 feet to the south between 1862 and 1899 (U. S. Army Corps of Engineers, 1910). Minor erosion was recorded at point 54, and the shoreline remained stable at points 48 and 49.

Eleven hurricanes affected Matagorda and San Jose Islands between 1857 and 1937 (appendix B). Although the 1854 storm did not occur within this time interval, its effects were probably still visible in 1857. Surge data were not available for the earlier storms, but statements made by the U. S. Army Corps of Engineers (1871), Price (1956), and Sugg and others (1971) as to damage incurred at Indianola strongly indicate that a high surge accompanied the 1854, 1857, 1877, and 1886 storms.

1931-37 to 1957-58.—During this time, the shoreline on Matagorda Island experienced mixed accretion and erosion (appendix A), however accretion was predominant. Of the 36 points monitored, 23 points experienced accretion, 10 experienced erosion, and 3 points (7, 8, 23) recorded essentially no change. With the exception of the northernmost portion of the island near Pass Cavallo where point 1 recorded erosion of 175 feet and points 2 and 3 recorded accretion of 225 feet and 200 feet, respectively, the monitored points can be grouped into two segments of erosion and two segments of accretion. Erosion between points 4 and 6 averaged about 125 feet. From point 9 through point 15,

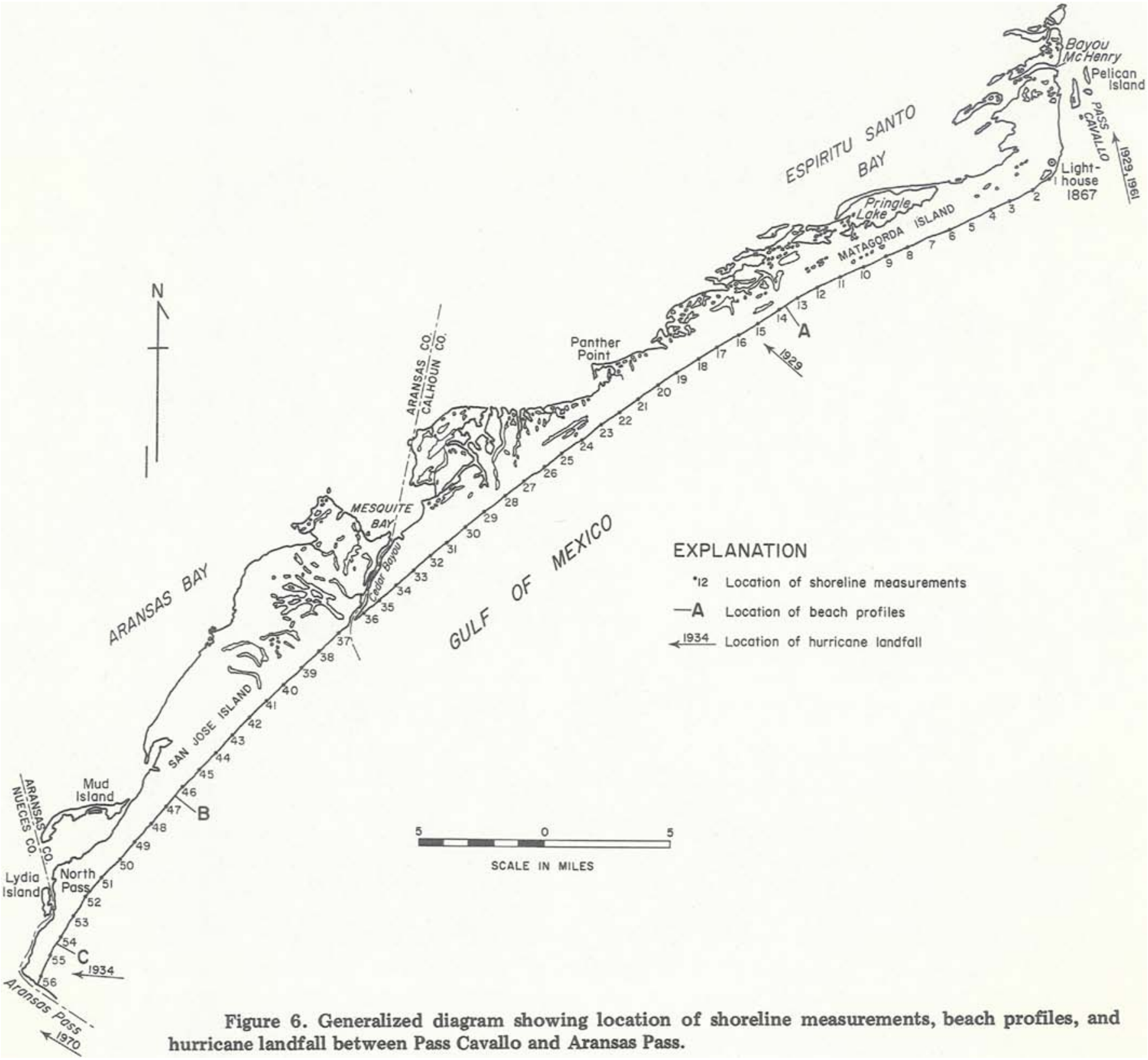

Figure 6. Generalized diagram showing location of shoreline measurements, beach profiles, and hurricane landfall between Pass Cavallo and Aransas Pass.

accretion averaged about 95 feet. Erosion also occurred from point 16 through point 23 and averaged 60 feet (except at point 21 where minor accretion occurred). From point 24 through point 36, accretion averaged 175 feet.

Shoreline changes on San Jose Island documented between 1931 and 1957-58 are nearly opposite those of the preceding time period. Accretion continued at point 37 (200 feet) caused by southward migration of Cedar Bayou and reorientation of the shoreline. Shoreline erosion ranging from 50 to 125 feet occurred from points 38 through 53 with the exceptions of points 42 and 48 where no change and accretion of 50 feet occurred, respectively. Average erosion for those 14 points on San Jose Island was 70 feet. Accretion updrift of the north jetty was 25 feet at point 54 and 100 feet at points 55 and 56.

Hurricane activity was intense during the 1940's. Four major storms made landfall on Matagorda Peninsula, immediately east of Matagorda Island, and generated high tides (table 1). However, no major hurricanes affected this area during the 1950's.

Table 1. Hurricane surge recorded along the central Texas Coast, 1854 to 1974.

Date	Surge height	Location	Reference
1854	high	Matagorda Island	U. S. Army Corps Engineers, 1871
1875	high	Indianola	Price, 1956
1877	10.5 ft	Indianola	Sugg and others, 1971
1886	high	Indianola	Sugg and others, 1971
1919	11.5 ft	Port Aransas	Sugg and others, 1971
1921	7.1 ft	Pass Cavallo	Cry, 1965
1929	3.0 ft	Port O'Connor	Bodine, 1969
1933	5.0 ft	Port Aransas	Price, 1956
1934	10.2 ft	Rockport	U. S. Army Corps Engineers, 1953
1936	3.0 ft	Rockport	Price, 1956
1941	11.0 ft	Matagorda	Sugg and others, 1971
1942	13.8 ft	Port O'Connor	Sugg and others, 1971
1945	8.0 ft	Port O'Connor	Sugg and others, 1971
	14.5 ft	Port Aransas	U. S. Army Corps Engineers, 1953
1949	8.0 ft	Matagorda	Sugg and others, 1971
1957	2.8 ft	Port Aransas	Moore and others, 1957
1961	12.3 ft	Pass Cavallo	U. S. Army Corps Engineers, 1962a
Carla	22.0 ft	Port Lavaca	
	9.3 ft	Port Aransas	
1967	6.1 ft	Matagorda Island	U. S. Army Corps Engineers, 1968a
Beulah	8.0 ft	Port Aransas	
1970	7.7 ft	Matagorda Island	U. S. Army Corps Engineers, 1971c
Celia	9.2 ft	Port Aransas jetty	
1971	5.0 ft	Aransas Pass	Simpson and Hope, 1972
Fern			
1973	3.6 ft	Matagorda	Frank and Hebert, 1974
Delia			

1957-58 to 1965.—During this time interval all points on Matagorda Island recorded erosion with the exception of points 2 and 3, where accretion occurred, and point 19, which experienced no change. Maximum erosion of 850 feet occurred at point 1 where a prominent bulge in the 1957 shoreline was removed; minimum erosion of 25 feet was recorded at points 15, 18, and 20; average shoreline erosion was about 190 feet. Erosion was somewhat greater on the southern half of the island between points 21 and 36. Average erosion for this segment of the shoreline was 240 feet.

Except for the segment between point 54 and the north jetty and anomalous accretion at point 49 (50 feet), the shoreline of San Jose Island suffered erosion between 1957-58 and 1965. Erosion ranged from 25 to 325 feet; average erosion was 125 feet.

Carla, one of the most severe storms of this century, crossed the Texas Coast at Pass Cavallo on September 11, 1961. The U. S. Army Corps of Engineers reported a high water mark of 12.3 feet at Matagorda Island Air Force Base; the tide gage at the Saluria Bayou Coast Guard Station also recorded 12.3 feet (U. S. Army Corps of Engineers, 1962a). Maximum surge height of 22 feet was recorded in Lavaca Bay at Port Lavaca. The amount of shoreline erosion on Matagorda and San Jose Islands was not documented; however, erosion of 850 feet recorded at point 1 adjacent to Pass Cavallo was the result of the storm. No other storm affected this segment of the coast during this time interval.

1965 to 1974.—Shoreline erosion continued to be dominant between 1965 and 1974; however, distances and rates of erosion were considerably less than those of the preceding time interval (appendix A). On Matagorda Island, 27 points recorded erosion, 7 experienced accretion, and 2 remained relatively unchanged. Maximum erosion of 625 feet was recorded at point 2; minimum erosion of less than 10 feet was recorded at points 13, 22, and 34; average erosion was about 75 feet. Of the seven accretionary points, point 1 experienced recovery after erosion suffered during Carla; the remaining six points of accretion, however, were scattered along the island with no apparent pattern.

Of the 20 points monitored on San Jose, 12 points recorded erosion, 2 recorded accretion, and 6 remained unchanged. Accretion of 125 and 50 feet occurred at points 37 and 38, respectively, probably as a result of southward migration of Cedar Bayou. The shoreline remained relatively unchanged between points 42 and 50. On San Jose Island, erosion ranged from 25 to 275 feet. Erosion between points 39 and 41 was 150 feet or less, whereas erosion from points 51 to 55 ranged from 75 to 275 feet; average erosion for this segment was 170 feet. Minor erosion (25 feet) occurred at point 56.

The central Texas Coast was affected by two storms during this time interval (table 1). Wilkinson (1973), who discussed the effects of these storms (Celia and Fern) on Matagorda Island, calculated that approximately 50 million cubic feet of sand was removed from the beaches when Celia cut a steep, wide storm beach between the dune line and the shoreline. He also calculated that approximately 6 million cubic feet of sand was deposited on the back beach near the dunes as the storm beach developed.

During Fern, a less intense storm than Celia, the forebeach was eroded approximately 120 feet. Wilkinson (1973) estimated that 56 million cubic feet of sand was deposited on the beaches to build the new storm berm. At the same time, approximately 210 million cubic feet of sand was eroded from the forebeach by wave action. Wilkinson attributed the difference in amount of erosion resulting from Celia and Fern to higher tides during Celia that permitted erosion across the entire beach area; during Fern, erosion was restricted to the forebeach area. Perhaps the slow forward movement of Celia also contributed to greater erosion (Davis, 1972).

Net Historic Changes (1857-62 to 1974)

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

Perhaps the two most important factors related to the reversal in dominant trend from accretion to erosion are sediment budget and secular sea-level changes. Apparently, long-term changes in climate have resulted in decreased sediment load being transported to the Gulf. There is also the possibility that a natural threshold has been passed whereby sediment that was previously available is no longer being transported. For example, if the shelf profile is an equilibrium profile, then sediment eroded from the shelf may not be as important in shoreline maintenance as it probably was prior to equilibration.

Secular sea-level changes (Hicks, 1968) could also explain some of the reversal from accretion in the 1950's to erosion in the 1960's. A regional lowering of sea level would affect shoreline accretion even though the regional sediment budget may not have been significantly changed. Such a lowering of sea level accompanied drought conditions in the mid 1950's when riverine discharge was low. This is illustrated by tide-gage measurements at Galveston, Freeport, and Port Isabel (Swanson and Thurlow, 1973). Furthermore, inspection of aerial photographs for the same time period (appendix C) also suggests that both bay and Gulf water levels were slightly lower during the mid 1950's.

Excluding the points affected by reorientation of the shoreline in the vicinity of Pass Cavallo, net shoreline changes on Matagorda Island since 1857 were predominantly accretionary. Points 1 through 3 recorded net erosion ranging from 600 feet to 2,025 feet. From point 4 to point 30, the shoreline experienced net accretion ranging from 25 to 1,050 feet; average net accretion for this segment was 333 feet. Points 31 through 36 recorded a combination of minor net erosion and minor net accretion. Overall net accretion on Matagorda Island was influenced largely by the major accretion which occurred between 1857 and 1937. Since the late 1950's or early 1960's the trend has been predominantly erosional.

Of the 20 points monitored on San Jose Island, excluding points 55 and 56 which were affected by the north jetty at Aransas Pass, nine points experienced net erosion, eight experienced net accretion, and one recorded no net change. Net changes on San Jose Island were cyclic and manifested by shoreline segments of net accretion

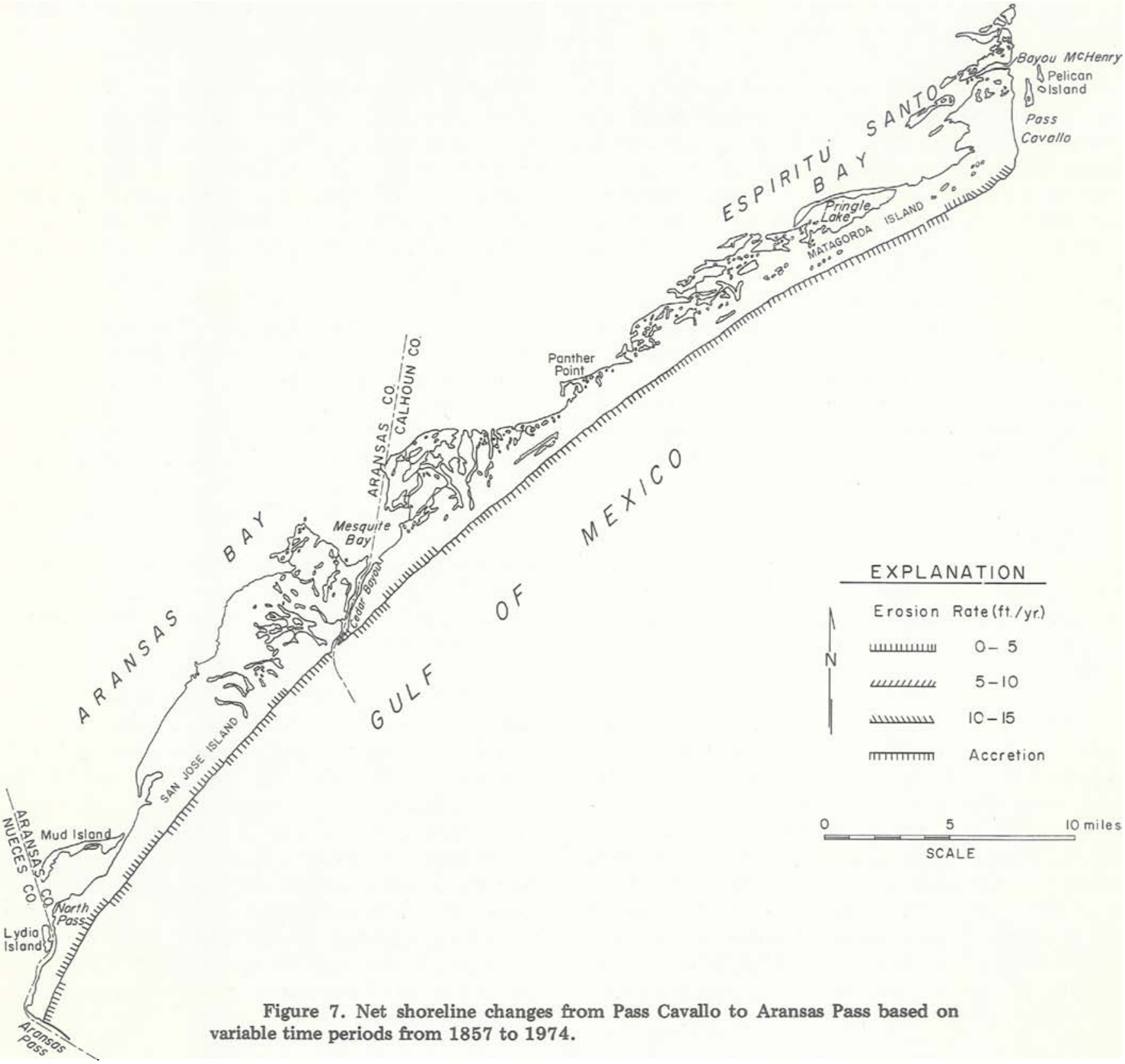

Figure 7. Net shoreline changes from Pass Cavallo to Aransas Pass based on variable time periods from 1857 to 1974.

and net erosion (fig. 7). In general, net shoreline changes were 75 feet or less, suggesting relative shoreline stability.

Rates of change were also calculated for net change between 1857-62 and 1974; the results are included in appendix A. These figures estimate long-term net effect, but the values should be used in context. The values for rates of net change are adequate for describing long-term trends; however, rates of short-term changes may be of greater magnitude than rates of long-term changes, particularly in areas where both accretion and erosion have occurred.

Net rates of shoreline change on Matagorda Island ranged from minor to moderate. Points 1 through 3 experienced net rates of erosion from 5.1 to 17.3 feet per year. Accretionary rates for the remainder of Matagorda Island ranged from less than 1 foot per year to 9.1 feet per year. In general, net rates of change on San Jose Island were minor as most net rates of change were less than 1 foot per year.

CHANGES IN POSITION OF VEGETATION LINE

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

Accurate information on position of vegetation line is neither available for the middle 1800's nor for the early 1900's. Therefore, accounts of changes in vegetation line are restricted to the time period covered by aerial photographs (1931-37 to 1974).

1931-37 to 1957-58.—Between 1931-37 and 1957-58, the vegetation line on Matagorda Island experienced substantial advances. All points monitored between 1937 and 1957 recorded advancement of the vegetation line. Extreme advancement was recorded in areas of previous blowouts, between points 19 and 23 where advances from 3,150 to 4,750 feet were recorded and at points 1 and 2 where advances of 3,525 and 1,425 feet, respectively, occurred. The average advance of the vegetation line for the remaining segment of the island was about 525 feet.

The 1937 photomosaics show the vegetation in a damaged state as exemplified by an irregular frontal margin, wide beaches, and blowout areas. A large expanse of windblown sand was present between points 19 and 23; the northern tip of the island was also barren of vegetation. The beach width was exceptionally wide, ranging from 300 to 500 feet and increasing from 700 to 1,000 feet between points 3 and 9. The condition of the vegetation may be attributed in part to flooding accompanying the 1933 and 1934 storms (table 1). A report by the U. S. Army Corps of Engineers (1871) described a similar incident in 1868 at which time about half of the vegetation on the island was destroyed by salt-water flooding. Drought conditions which affected Matagorda Island between 1937 and 1939 may have reinforced the effects of the 1933 and 1934 storms by impeding recovering of the vegetation. By 1953 the vegetation had recovered a substantial amount despite the effects of hurricanes in 1941, 1942, 1945, and 1949; this recovery continued through the late 1950's.

The vegetation line on San Jose Island advanced an average of 145 feet between 1931 and 1958 despite the fact that major hurricanes affected the area in 1933 and 1945. Perhaps retreat of the vegetation line visible on the 1931 photographs was caused by the 1931 hurricane. Changes were mixed between points 37 and 40, but advance generally increased from 75 feet at point 41 to 400 feet at point 48. The southern end of the island between point 52 and Aransas Pass was barren sand. The low storm incidence in the early and middle 1950's probably accounts for the major recovery of the vegetation.

1957-58 to 1965.—This period was characterized by vegetation line retreat on Matagorda and San Jose Islands, most likely as the result of damage incurred from Hurricane Carla. Of the 35 points monitored on Matagorda Island, 21 points experienced retreat, 11 recorded advancement, and 3 recorded no change. Retreat of the vegetation line along Matagorda Island ranged from less than 10 to 225 feet and averaged about 75 feet. The points experiencing advancement were scattered with no apparent pattern except points 18 through 20 where the vegetation continued to recover in a previous blowout area.

On San Jose Island, comparison of 1958 and 1961 aerial photographs indicates that vegetation line retreat attendant with dune erosion was minimized in areas of large continuous foredunes. However, comparison of 1965 and 1967 photographs suggests that additional retreat of the vegetation line resulted from deterioration of the vegetation probably associated with the salt-water flooding.

Most stations experienced retreat ranging from 50 to 375 feet. Average retreat for these points was about 160 feet. Retreat exceeding 675 feet occurred at point 49 owing to the aforementioned deterioration.

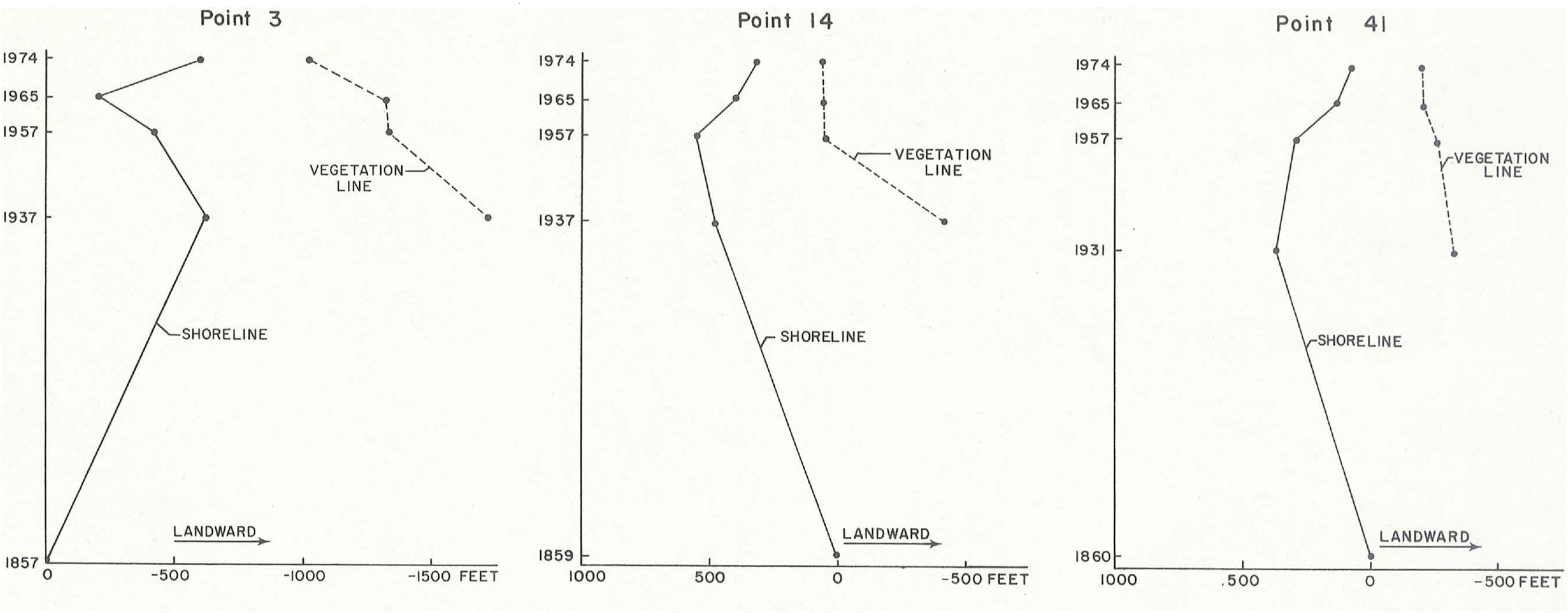

Figure 8. Relative changes in position of shoreline and vegetation line at selected locations, Pass Cavallo to Aransas Pass.

1965 to 1974.—From 1965 to 1974, the vegetation line on Matagorda Island was more stable. Accretion was dominant on the northern third of the island, ranging from 50 feet to 350 feet and averaging about 200 feet. Commencing at point 11 and continuing through point 35, there was mixed retreat and advance with 11 points recording advance and 12 points recording retreat.

Stabilization or advancement of the vegetation line was recorded at most stations on San Jose Island between 1965 and 1974. Of the 15 points monitored, seven showed advancement from 50 to 300 feet with an average accretion of about 120 feet, and seven showed no change. Point 51, in the North Pass washover area, experienced retreat of 300 feet.

Net changes in vegetation line were calculated as they were for shoreline changes. However, it should be emphasized that shifts in vegetation line are related primarily to storms, and the time period over which observations were made was not of sufficient length to establish long-term trends. Nonetheless, the general trend of change in vegetation line has been net accretion (fig. 8), largely because of advances that occurred between 1931-37 and 1957-58. The 1957-58 vegetation line occupied the most seaward position at the greatest number of points monitored on San Jose Island. On Matagorda Island the 1974 vegetation line occupied the most seaward position. Except in blowout areas, where net changes were extreme, net changes on Matagorda Island averaged 570 feet; on San Jose Island net changes in the position of the vegetation line averaged about 100 feet, apparently reflecting greater stability in the vegetation line.

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

FACTORS AFFECTING SHORELINE AND VEGETATION LINE CHANGES

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

Climate

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

Changes in stream and bay conditions, as well as migration of certain plant and animal species in South Texas since the late 1800's, were attributed to a combination of overgrazing and more arid climatic conditions (Price and Gunter, 1943). A more complete discussion of the general warming trend is presented in Dunn and Miller (1964). Manley (1955) reported that postglacial air temperature has increased 13°F in the Gulf region. Furthermore, Dury (1965) estimated that many rivers carried between 5 and 10 times greater discharge than present-day rivers. His remarks included reference to the Brazos and Mission Rivers of Texas. Observations based on geologic maps prepared by the Bureau of Economic Geology (Fisher and others, 1972) confirm that many rivers along the Texas Coastal Plain were larger and probably transported greater volumes of sediment during the early Holocene. This, in turn, affected sediment budget by supplying additional sediment to the littoral drift system. Droughts are a potential though indirect factor related to minor shoreline changes via their adverse effect on vegetation. Because dunes and beach sand are stabilized by vegetation, sparse vegetation resulting from droughts offers less resistance to wave attack. Severe droughts have occurred periodically in Texas; the chronological order of severe droughts affecting Matagorda and San Jose Islands is as follows: 1891-1893, 1896-1899, 1901, 1916-1918, 1937-1939, 1950-52, 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 Matagorda and San Jose Islands has a 13-percent probability of experiencing a tropical storm, a 7-percent probability of experiencing a hurricane, and a 4-percent probability of experiencing a great hurricane.

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

Destructive forces and storm damage.—Carla, one of the most violent storms on record, crossed the Texas Coast at Pass Cavallo and inundated approximately 95 percent of Matagorda and San Jose Islands with a recorded surge of 12.3 feet above mean sea level (U. S. Army Corps of Engineers, 1962a). Flooding also occurred in low-lying areas as a result of Hurricane Beulah (U. S. Army Corps of Engineers, 1968a). The 1919 hurricane caused extensive erosion on the southern end of San Jose Island (Price, 1956). Major hurricanes also affected the area of study in 1854, 1875, 1877, and 1886 (U. S. Army Corps of Engineers, 1877; Price, 1956; Sugg and others, 1971).

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

Hurricane surge is the most destructive element on the Texas Coast (Bodine, 1969). This is particularly true for low lying areas that lack continuous foredunes that can dissipate most of the energy transmitted by wave attack. Because of the role hurricane surge plays in flooding and destruction, the frequency of occurrence of high surge on the open coast has been estimated by Bodine (1969). Included in his report are calculations for Port O'Connor, which suggest that surge height of 11.5 feet can be expected approximately once every 100 years. Maximum hurricane surge predicted was 13 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 40 and 45 feet once every 20 years for Gilchrist (about 25 miles northeast of Galveston on Bolivar Peninsula). Maximum deep-water hurricane wave height predicted for the same location was 55 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). Wilkinson (1973) analyzed the erosional effects of Hurricanes Celia and Fern on the Gulf shoreline of Matagorda Island.

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. However, 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.

Local and Eustatic Sea-Level Conditions

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

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

It should be noted, however, that through geologic time the central Texas Coast, in a regional sense, has been situated over a more stable and positive tectonic element, the San Marcos arch, than the adjacent areas that occupy the Rio Grande embayment to the south and the East Texas embayment to the northeast. Furthermore, stream gradients for the Guadalupe and Nueces Rivers suggest that uplift has been greater in areas updip of the hingeline over the San Marcos arch than in adjacent areas. Releveling data (Brown and others, 1974) also suggest that the central Texas Coast is stable although local subsidence associated with hydrocarbon production and ground-water withdrawal has been documented.

Because Swanson and Thurlow (1973) were interested in the subsidence component reflected in tide-level variations, their data were intentionally adjusted so that the contribution from sea-level rise would be eliminated from their analysis. Nevertheless, tidal data gathered from numerous coastal areas indicate that sea level continues to rise at the rate of approximately 1 foot per century.

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

Sediment Budget

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

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

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

Sediment supplied by major streams is transported alongshore by littoral currents. Net littoral drift along the central Texas Coast appears to be minor probably because of the seasonal reverses in wind direction. Although dominant winds are from the southeast, net littoral drift appears to be to the southwest (fig. 9). The Brazos and Colorado Rivers are the only major rivers in an updrift direction from Matagorda and San Jose Islands that supply sediment directly into the littoral zone. Neither the time nor the maximum seaward extent of the Holocene Brazos-Colorado delta during its construction is known. Furthermore, it is not known precisely when the destructive phase of the abandoned delta was initiated. Although there are indications that sediment discharge was greater during the early Holocene, most Texas streams were in the process of filling their estuaries and were not contributing significant quantities of sand to the littoral currents. In contrast, the Brazos and Colorado Rivers were able to fill their estuaries and debouch directly into the Gulf, therefore contributing substantially to the sediment budget. However, the present-day Brazos and Colorado Rivers contribute little sediment to the littoral drift

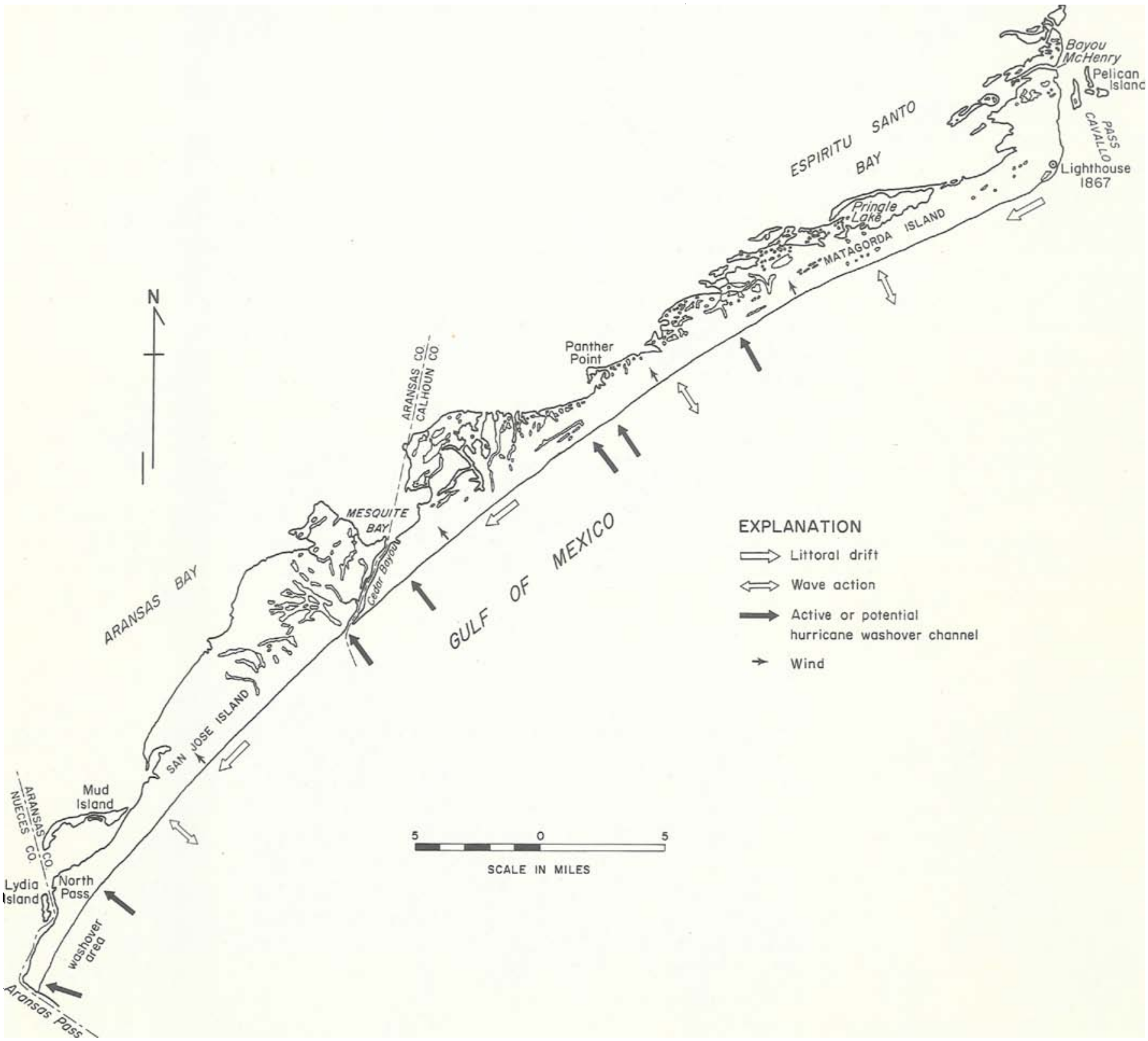

Figure 9. Generalized diagram of active processes from Pass Cavallo to Aransas Pass.

system. The pirated Colorado River did not debouch directly into the Gulf prior to 1936. Furthermore, sediment from the Brazos River is presently being stored in the new Brazos delta. Therefore, these rivers presently are not major sources of sediment for maintenance of beaches on Matagorda and San Jose Islands.

Wilkinson (1975), however, concluded that the Colorado and Brazos Rivers were the primary sources of sediment associated with the initial progradation of Matagorda Island. Although Wilkinson suggested that minor contributions could have been made by updrift shoreline erosion, he summarily dismissed the concept of landward transport of shelf sediment. His conclusions were based on the equivocal assumptions that (1) the extant shoreface slope has persisted since sea-level stillstand, (2) erosion and subsequent deposition on the shoreface is not plausible, and (3) the slope of the Pleistocene-Holocene surface beneath Matagorda Island determined from borings is representative of the slope of the same surface on the inner continental shelf.

If erosion of shelf sediment had been a significant source of barrier island sand, then the offshore slope would be greater today than at the time of stillstand. Furthermore, shelf sand can be eroded and deposited with subsequent shoreline progradation as demonstrated by basic wave tank experiments. These same processes have been operative on the Texas Coast in the recent historical past as illustrated by comparison of hydrographic charts in the vicinity of some of the major inlets with jetties. With regard to the final assumption made by Wilkinson (1975), data on the slope of the Pleistocene-Holocene surface beneath the inner shelf are not available. Thus Wilkinson's arguments are not supported, and it seems certain that the shelf was a significant source of sand during barrier island progradation. Undoubtedly Matagorda and San Jose Islands experienced similar histories as indicated by their juxtaposition and similarity in morphology as well as subsurface sediment characteristics (Shepard, 1956; Bureau of Economic Geology, unpublished data).

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; some sand is blown off the beach by eolian processes. Both Andrews (1970) and Nordquist (1972) studied hurricane washovers on San Jose Island. Historical changes of the North Pass area were studied in detail by Nordquist (1972) who concluded that the origin of North Pass was related to migration of Aransas Pass, the drought of 1915-1918, and the hurricane of 1919. The southern end of San Jose Island, between Aransas Pass and North Pass, was extensively eroded during the hurricane of 1919 (Price, 1956). An estimated 6.3 million cubic yards of sand was deposited with the development and progradation of the washover fan into Aransas Bay (Nordquist, 1972). 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.

Construction of the jetties at Aransas Pass was initiated in 1880. Modifications continued to be made until 1916 when the structures were completed. Construction of Matagorda Ship Channel commenced in 1962 and was completed in 1966. Projects such as these serve to alter natural processes such as inlet siltation, beach erosion, and hurricane surge. Their effects on shoreline changes are subject to debate, but it is an elementary fact that impermeable structures interrupt littoral drift and impoundment of sand occurs at the expense of the beach downdrift of the structure. Therefore, it appears reasonable to expect that any sand trapped by the jetties is compensated for by removal of sand downdrift, thus increasing local erosion problems.

EVALUATION OF FACTORS

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

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

PREDICTIONS OF FUTURE CHANGES

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

Borings on San Jose Island (Morton and Amdurer, 1974; Shepard and Moore, 1955) indicate that sand thickness ranges from 40 to 60 feet under most of the island. The thickness of sand underlying Matagorda Island is 30 to 40 feet (Wilkinson, 1973). Therefore, the 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. 33) stated that "While seawalls may protect the upland, they do not hold or protect the beach which is the greatest asset of shorefront property." Moreover, construction of a single structure can trigger a chain reaction that requires additional structures and maintenance (Inman and Brush, 1973).

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

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

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Appendix A

+ accretion
- erosion

Shoreline Changes

beach segment Pass Cavallo-Aransas Pass

Point	Time	Dist. ft	Rate ft per yr	Time	Dist. ft	Rate ft per yr	Time	Dist. ft	Rate ft per yr	Time	Dist. ft	Rate ft per yr	Net Time	Net Dist.	Net Rate
1	1857 1937	-1100	-13.8	1937 1957	-175	- 8.5	1957 1965	-850	-106.3	1965 1974	+100	+11.8	1857 1974	-2025	-17.3
2	"	-1550	-19.4	"	+225	+11.0	"	+150	+ 18.8	"	-625	-73.5	"	-1800	-15.4
3	"	- 625	- 7.8	"	+200	+ 9.8	"	+225	+ 28.1	"	-400	-47.1	"	- 600	- 5.1
4	"	+ 225	+ 2.8	"	- 25	- 1.2	"	- 50	- 6.3	"	0	0	"	+ 150	+ 1.2
5	"	+ 800	+10.0	"	-150	- 7.3	"	- 75	- 9.4	"	+ 25	+ 2.9	"	+ 600	+ 5.1
6	1859 1937	+1275	+15.9	"	-200	- 9.7	"	-175	- 21.9	"	- 25	- 2.9	1859 1974	+ 875	+ 7.6
7	"	+1225	+15.7	"	-< 10	-< 1.0	"	-350	- 43.8	"	+150	+17.6	"	+1025	+ 8.9
8	"	+1300	+16.6	"	0	0	"	-200	- 25.0	"	- 50	- 5.9	"	+1050	+ 9.1
9	"	+1050	+13.5	"	+125	+ 6.1	"	-175	- 21.9	"	+< 10	+< 1.0	"	+1000	+ 8.5
10	"	+ 950	+12.2	"	+100	+ 4.9	"	-150	- 18.8	"	- 50	- 5.9	"	+ 850	+ 7.4
11	"	+ 575	+ 7.4	"	+100	+ 4.9	"	- 75	- 9.4	"	- 25	- 2.9	"	+ 575	+ 5.0
12	"	+ 325	+ 4.2	"	+150	+ 7.3	"	-300	- 37.5	"	+ 50	+ 5.9	"	+ 225	+ 2.0
13	"	+ 400	+ 5.1	"	+100	+ 4.9	"	-250	- 31.3	"	-< 10	-< 1.0	"	+ 250	+ 2.2
14	"	+ 475	+ 6.1	"	+ 75	+ 3.7	"	-150	- 18.8	"	- 75	- 8.8	"	+ 325	+ 2.8
15	"	+ 525	+ 6.7	"	+ 25	+ 1.2	"	- 25	- 3.1	"	-175	-20.6	"	+ 350	+ 3.0
16	"	+ 550	+ 7.1	"	-125	- 6.1	"	- 75	- 9.4	"	- 50	- 5.9	"	+ 300	+ 2.6
17	"	+ 325	+ 4.2	"	- 75	- 3.7	"	- 75	- 9.4	"	- 50	- 5.9	"	+ 125	+ 1.1
18	"	+ 275	+ 3.5	"	- 50	- 2.4	"	- 25	- 3.1	"	-100	-11.8	"	+ 100	+< 1.0
19	"	+ 275	+ 3.5	"	-100	- 4.9	"	0	0	"	-150	-17.6	"	+ 25	+< 1.0
20	"	+ 375	+ 4.8	"	- 75	- 3.6	"	- 25	- 3.1	"	-175	-20.6	"	+ 100	+< 1.0

\+ accretion
\- erosion

Shoreline Changes

beach segment Pass Cavallo-Aransas Pass

Point	Time	Dist. ft	Rate ft per yr	Time	Dist. ft	Rate ft per yr	Time	Dist. ft	Rate ft per yr	Time	Dist. ft	Rate ft per yr	Net Time	Net Dist.	Net Rate
21	"	+ 325	+ 4.2	"	+ 25	+ 1.2	"	-225	- 28.1	"	- 50	- 5.9	"	+ 75	+< 1.0
22	"	+ 225	+ 2.9	"	- 50	- 2.4	"	-150	- 18.8	"	-< 10	-< 1.0	"	+ 25	+< 1.0
23	"	+ 325	+ 4.2	"	-< 10	-< 1.0	"	-275	- 34.4	"	- 25	- 2.9	"	+ 25	+< 1.0
24	"	+ 400	+ 5.1	"	+100	+ 4.9	"	-225	- 28.1	"	-100	-11.8	"	+ 175	+ 1.5
25	"	+ 475	+ 6.1	"	+ 75	+ 3.6	"	-250	- 31.3	"	- 75	- 8.8	"	+ 225	+ 2.0
26	"	+ 400	+ 5.1	"	+ 50	+ 2.4	"	-250	- 31.3	"	- 75	- 8.8	"	+ 125	+ 1.1
27	"	+ 300	+ 3.8	"	+150	+ 7.3	"	-275	- 34.4	"	-100	-11.8	"	+ 75	+< 1.0
28	1860 1937	+ 275	+ 3.5	"	+150	+ 7.3	"	-175	- 21.9	"	- 75	- 8.8	1860 1974	+ 175	+ 1.5
29	"	+ 175	+ 2.2	"	+225	+10.9	"	-175	- 21.9	"	-125	-14.7	"	+ 100	+< 1.0
30	"	+ 125	+ 1.6	"	+325	+15.8	"	-250	- 31.3	"	-125	-14.7	"	+ 75	+< 1.0
31	"	+ 150	+ 1.9	"	+175	+ 8.5	"	-150	- 18.8	"	-100	-11.8	"	+ 75	+< 1.0
32	"	+ 75	+ 1.0	"	+150	+ 7.3	"	-275	- 34.4	"	+< 10	+< 1.0	"	- 50	-< 1.0
33	"	+ 50	+ 0.6	"	+200	+ 9.8	"	-275	- 34.4	"	+ 25	+ 2.9	"	0	0
34	"	+ 150	+ 1.9	"	+175	+ 8.5	"	-300	- 37.5	"	-< 10	-< 1.0	"	+ 25	+< 1.0
35	"	+ 100	+ 1.3	"	+300	+14.6	"	-225	- 28.1	"	-100	-11.8	"	+ 75	+< 1.0
36	"	+ 125	+ 1.6	"	+200	+ 9.8	"	-375	- 46.9	"	0	0	"	- 50	-< 1.0
37	"	+ 100	+ 1.3	"	+200	+ 9.8	"	-325	- 40.6	"	+125	+14.7	"	+ 100	+< 1.0
38	"	+ 225	+ 2.9	"	- 50	- 2.4	"	-175	- 21.9	"	+ 50	+ 5.9	"	+ 50	+< 1.0
39	1860 1931	+ 325	+ 4.5	1931 1957	-100	- 3.8	"	-100	- 12.5	"	-150	-17.7	"	- 25	-< 1.0
40	"	+ 350	+ 4.9	"	- 50	- 1.9	"	-200	- 25.0	"	- 75	- 8.8	"	+ 25	+< 1.0

+ accretion
- erosion

Shoreline Changes

beach segment Pass Cavallo-Aransas Pass

Point	Time	Dist. ft	Rate ft per yr	Time	Dist. ft	Rate ft per yr	Time	Dist. ft	Rate ft per yr	Time	Dist. ft	Rate ft per yr	Net Time	Net Dist.	Net Rate
41	"	+ 375	+ 5.2	"	- 75	- 2.9	"	-150	- 18.8	"	- 75	- 8.8	"	+ 75	+< 1.0
42	"	+ 350	+ 4.9	"	0	0	"	-125	- 15.6	"	0	0	"	+ 225	+ 2.0
43	1862 1931	+ 25	+< 1.0	1931 1958	- 50	- 1.9	1958 1965	- 75	- 10.0	"	- 50	- 5.9	1862 1974	- 150	- 1.3
44	"	+ 150	+ 2.2	"	-100	- 3.8	"	-100	- 13.3	"	0	0	"	- 50	-< 1.0
45	"	+ 300	+ 4.3	"	-125	- 4.8	"	-100	- 13.3	"	0	0	"	+ 75	+< 1.0
46	"	+ 275	+ 4.0	"	- 50	- 1.9	"	-125	- 16.7	"	- 50	- 5.9	"	+ 50	+< 1.0
47	"	+ 100	+ 1.4	"	- 75	- 2.9	"	- 75	- 10.0	"	0	0	"	- 50	-< 1.0
48	"	0	0	"	+ 50	+ 1.9	"	-100	- 13.3	"	- 25	- 2.9	"	- 75	-< 1.0
49	"	0	0	"	- 50	- 1.9	"	+ 50	+ 6.7	"	0	0	"	0	0
50	"	+ 100	+ 1.4	"	- 50	- 1.9	"	- 25	- 3.3	"	0	0	"	+ 25	+< 1.0
51	"	+ 275	+ 4.0	"	- 50	- 1.9	"	-175	- 25.0	"	- 75	- 8.8	"	- 25	-< 1.0
52	"	+ 250	+ 3.6	"	- 50	- 1.9	"	-100	- 13.3	"	-275	-32.4	"	- 175	- 1.5
53	"	+ 225	+ 3.2	"	-100	- 3.8	"	- 25	- 3.3	"	-175	-20.6	"	- 75	-< 1.0
54	1862 1937	- 25	-< 1.0	1937 1958	+ 25	+ 1.2	"	+100	+ 13.3	"	-225	-26.5	"	- 125	- 1.1
55	"	+ 750	+10.0	"	+100	+ 4.7	"	no 1965 photo		"			"	+ 750	+ 6.7
56	1899 1937	+1250	+20.1	"	+100	+ 4.7	1958 1970	+ 75	+ 6.5	1970 1974	- 25	- 6.3	1899 1974	+1400	+18.7

+ accretion
- erosion

Vegetation Changes

beach segment Pass Cavallo-Aransas Pass

Point	Time	Dist. ft	Rate ft per yr	Time	Dist. ft	Rate ft per yr	Time	Dist. ft	Rate ft per yr	Time	Dist. ft	Rate ft per yr	Net Time	Net Dist.	Net Rate
1	1937 1957	+3525	+171.9	1957 1965	0	0	1965 1974						1937 1974		
2	"	+1425	+ 69.5	"	- 150	- 18.7	"	- 75	- 8.8				"	+1200	+ 32.4
3	"	+ 400	+ 19.5	"	0	0	"	+300	+ 35.2				"	+ 700	+ 18.9
4	"	+ 600	+ 29.3	"	- 25	- 3.1	"	+350	+ 41.1				"	+ 925	+ 25.0
5	"	+ 950	+ 46.3	"	+ 25	+ 3.1	"	+225	+ 26.4				"	+1200	+ 32.4
6	"	+ 800	+ 39.0	"	- 25	- 3.1	"	+300	+ 35.2				"	+1075	+ 29.0
7	"	+ 875	+ 42.7	"	- 125	- 15.6	"	+125	+ 14.7				"	+ 875	+ 23.6
8	"	+ 825	+ 40.2	"	- 50	- 6.2	"	+ 50	+ 5.8				"	+ 825	+ 22.3
9	"	+ 775	+ 37.8	"	- 225	- 28.1	"	+200	+ 23.5				"	+ 750	+ 20.2
10	"	+ 500	+ 24.4	"	+ 50	+ 6.2	"	+ 75	+ 8.8				"	+ 625	+ 16.9
11	"	+1000	+ 48.8	"	- 50	- 6.2	"	-< 10	-< 1.0				"	+ 950	+ 25.6
12	"	+ 525	+ 25.6	"	+ 25	+ 3.1	"	- 50	- 5.8				"	+ 500	+ 13.5
13	"	+ 475	+ 23.2	"	- 100	- 12.5	"	+ 25	+ 2.9				"	+ 400	+ 10.8
14	"	+ 475	+ 23.2	"	-< 10	-< 1.0	"	-< 10	-< 1.0				"	+ 450	+ 12.1
15	"	+ 525	+ 25.6	"	- 25	- 3.1	"	+ 25	+ 2.9				"	+ 525	+ 14.2
16	"	+ 650	+ 31.7	"	- 100	- 12.5	"	-< 10	-< 1.0				"	+ 550	+ 14.8
17	"	+ 550	+ 26.8	"	- 125	- 15.6	"	-< 10	-< 1.0				"	+ 425	+ 11.4
18	"	+ 600	+ 29.3	"	+ 550	+ 68.7	"	-150	- 17.6				"	+1000	+ 27.0
19	"	+4300	+209.8	"	+ 525	+ 65.6	"	-325	- 38.2				"	+4500	+121.6

+ accretion
- erosion

Vegetation Changes

beach segment Pass Cavallo-Aransas Pass

Point	Time	Dist. ft	Rate ft per yr	Time	Dist. ft	Rate ft per yr	Time	Dist. ft	Rate ft per yr	Time	Dist. ft	Rate ft per yr	Net Time	Net Dist.	Net Rate
20	"	+3150	+153.7	"	+ 400	+ 50.0	"	+150	+ 17.6				"	+3700	+100.0
21	"	+4075	+198.8	"	- 25	- 3.1	"	- 50	- 5.8				"	+4000	+108.1
22	"	+4600	+224.4	"	+ 50	+ 6.2	"	- 50	- 5.8				"	+4600	+124.3
23	"	+4750	+231.7	"	- 50	- 6.2	"	- 50	- 5.8				"	+4650	+125.6
24	"	+ 525	+ 25.6	"	- 25	- 3.1	"	+< 10	+< 1.0				"	+ 500	+ 13.5
25	"	+ 425	+ 20.7	"	+ 25	+ 3.1	"	+100	+ 11.7				"	+ 550	+ 14.8
26	"	+ 350	+ 17.1	"	- 75	- 9.4	"	+ 50	+ 5.8				"	+ 325	+ 8.8
27	"	+ 325	+ 15.8	"	- 125	- 15.6	"	+125	+ 14.7				"	+ 325	+ 8.8
28	"	+ 200	+ 9.8	"	+ 150	+ 18.7	"	0	0				"	+ 350	+ 9.4
29	"	+ 300	+ 14.6	"	+ 150	+ 18.7	"	+< 10	+< 1.0				"	+ 450	+ 12.1
30	"	+ 550	+ 26.8	"	+ 50	+ 6.2	"	-175	- 20.6				"	+ 425	+ 11.4
31	"	+ 700	+ 34.1	"	0	0	"	0	0				"	+ 700	+ 18.9
32	"	+ 400	+ 19.5	"	-< 10	-< 1.0	"	- 75	- 8.8				"	+ 325	+ 8.8
33	"	+ 275	+ 13.4	"	- 150	- 18.7	"	+175	+ 20.6				"	+ 300	+ 10.1
34	"	+ 100	+ 4.9	"	- 75	- 9.4	"	+ 75	+ 8.8				"	+ 100	+ 2.7
35	"	+ 225	+ 11.0	"	- 25	- 3.1	"	+100	+ 11.8				"	+ 300	+ 8.1
36	"	Cedar Bayou													
37	"	- 50	- 2.4	"	+ 100	+ 12.5	"	+ 50	+ 5.8				"	+ 100	+ 2.7
38	"	+ 50	+ 2.4	"	- 50	- 6.2	"	0	0				"	0	0

+ accretion
- erosion

Vegetation Changes

beach segment Pass Cavallo-Aransas Pass

Point	Time	Dist. ft	Rate ft per yr	Time	Dist. ft	Rate ft per yr	Time	Dist. ft	Rate ft per yr	Time	Dist. ft	Rate ft per yr	Net Time	Net Dist.	Net Rate
39	1931 1957	0	0	"	0	0	"	0	0				1931 1974	0	0
40	"	- 75	- 2.9	"	+ 100	+ 12.5	"	0	0				"	+ 25	+< 1.0
41	"	+ 75	+ 2.9	"	+ 50	+ 6.3	"	0	0				"	+ 125	+ 2.9
42	"	+ 50	+ 1.9	"	- 50	- 6.3	"	0	0				"	0	0
43	1931 1958	+ 100	+ 3.8	1958 1965	- 50	- 6.7	"	0	0				"	+ 50	+ 1.2
44	"	+ 175	+ 6.6	"	- 175	- 23.3	"	+ 50	+ 5.9				"	+ 50	+ 1.2
45	"	+ 50	+ 1.9	"	- 150	- 20.0	"	+ 75	+ 8.8				"	- 25	-< 1.0
46	"	+ 225	+ 8.5	"	- 225	- 30.0	"	0	0				"	0	0
47	"	+ 200	+ 7.5	"	- 375	- 50.0	"	+300	+ 35.3				"	+ 125	+ 2.9
48	"	+ 400	+ 15.1	"	- 150	- 20.0	"	+ 50	+ 5.8				"	+ 300	+ 7.1
49	"	+3975	+150.0	"	- 675	- 90.0	"	+200	+ 23.5				"	+3500	+ 82.4
50	"			"	0	0	"	+100	+ 11.8				"		
51	"	+ 150	+ 5.6	"	- 250	- 35.7	"	-300	- 35.3				"	- 400	- 10.8
52	"				washover area										
53	"				"	"									
54	1937 1958				"	"									
55	"				"	"									
56	"				"	"									

APPENDIX B

Tropical Cyclones Affecting the Texas Coast 1854-1973
(compiled from Tannehill, 1956; Dunn and Miller, 1964; and Cry, 1965).

Intensity Classification from Dunn and Miller

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

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

APPENDIX C

List of Materials and Sources

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

Date		Source of Photographs
Oct. 1931, March-April 1937	*	Tobin Research Inc.
Feb., Dec. 1953		U. S. Dept. Agriculture
Jan., March, April 1956		U. S. Dept. Agriculture
Nov., Dec. 1957	*	Tobin Research Inc.
Jan., Dec. 1958	*	Tobin Research Inc.
Sept. 1961		U. S. Army Corps Engineers
Sept. 1961		Natl. Oceanic and Atmospheric Adm.
Oct. 1965	*	Natl. Oceanic and Atmospheric Adm.
June 1967		U. S. Army Corps Engineers
Oct. 1971		Tobin Research Inc.
June 1974	*	General Land Office

List of Maps Used in Determination of Shoreline Changes

Date	Description	Source of Maps
Apr.-May 1857	topographic map 644	Natl. Oceanic and Atmospheric Adm.
1859	topographic maps 766 and 1030	Natl. Oceanic and Atmospheric Adm.
Jan.-Apr. 1860	topographic map 787	Natl. Oceanic and Atmospheric Adm.
1860-61 - 1866	topographic map 823	Natl. Oceanic and Atmospheric Adm.
Feb. 1899	topographic map 2354	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.

Pass Cavallo SW, Texas
Long Island, Texas
Panther Point NE, Texas
Panther Point, Texas
Mesquite Bay, Texas
St. Charles Bay SE, Texas
St. Charles Bay SW, Texas
Allyn's Bight, Texas
Estes, Texas
Port Aransas, Texas