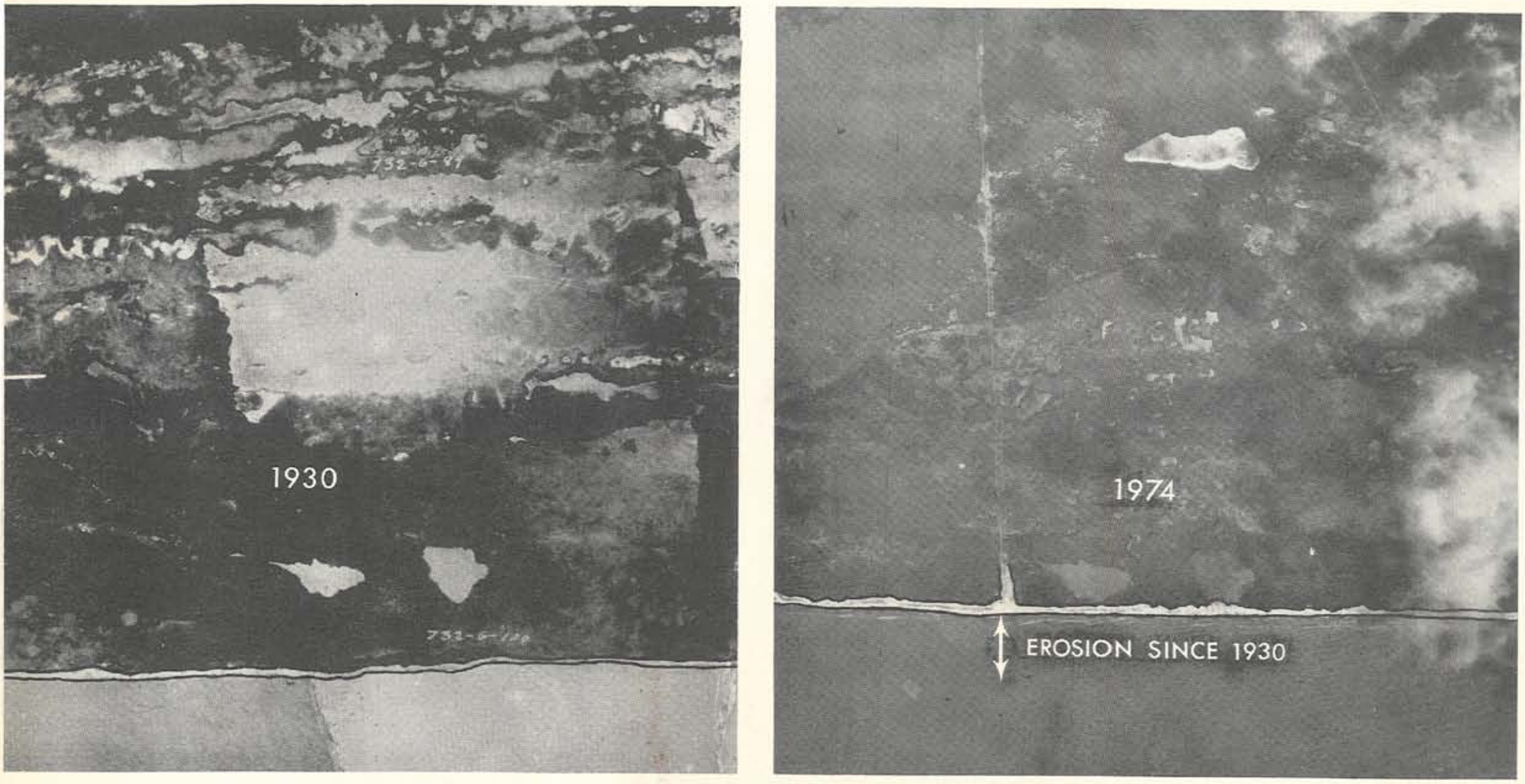
GEOLOGICAL CIRCULAR 75-6

SHORELINE CHANGES BETWEEN SABINE PASS AND BOLIVAR ROADS

AN ANALYSIS OF HISTORICAL CHANGES OF THE TEXAS GULF SHORELINE

BY ROBERT A. MORTON



BUREAU OF ECONOMIC GEOLOGY
THE UNIVERSITY OF TEXAS AT AUSTIN
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CONTENTS

LIST OF ILLUSTRATIONS

Figures—

Table—

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by Robert A. Morton

ABSTRACT

Historical monitoring between Sabine Pass and Bolivar Roads 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 1882-83) and aerial photographs (taken in 1930, 1955-57, 1965, and 1974) indicates short-term changes of accretion and erosion along the Gulf shoreline between Sabine Pass and Bolivar Roads. *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 92-year time period of this study indicates that net accretion was 2,225 feet at Sabine Pass although there was no net change 2 miles west of Sabine Pass. Except for minor accretion associated with shoreline adjustment where the major change in orientation of the coast occurs west of Sabine Pass, net erosion dominated the shoreline from the preceding segment to approximately 3 miles east of Crystal Beach. Maximum net erosion was 2,900 feet or 31.5 feet per year; minimum net erosion was 100 feet or 1.1 feet per year. Net erosion for this segment over the 92-year time interval averaged 775 feet or 8.4 feet per year. Net accretion or equilibrium was recorded along the remaining beach westward from Crystal Beach to the east jetty at Bolivar Roads. Maximum net accretion for this segment, 2,575 feet, occurred just east of the east jetty; minimum net accretion for this segment was 25 feet.

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 the shoreline between Sabine Pass and Bolivar Roads, 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 between Sabine Pass and Bolivar Roads are largely the result of natural processes, perhaps expedited by man's activities. The only exceptions are accretion associated with the jetties at Sabine Pass and Bolivar Roads as well as erosion aggravated by the opening of Rollover Pass. 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 between Sabine Pass and Bolivar Roads 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 1882 provide a necessary extension to the time base, an advantage not available through the use of aerial photographs which were not generally available before 1930.

Purpose and Scope

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

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

In 1973, the Texas Legislature appropriated funds for the Bureau of Economic Geology to conduct historical monitoring of the entire 367 miles of Texas Gulf shoreline during the 1973-1975 biennium. 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 Sabine Pass to Bolivar Roads (fig. 1) is the fourth 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.

Acknowledgments

Assistance in preparation of this report was provided by L. W. Epps, M. J. Pieper, J. L. Chin,

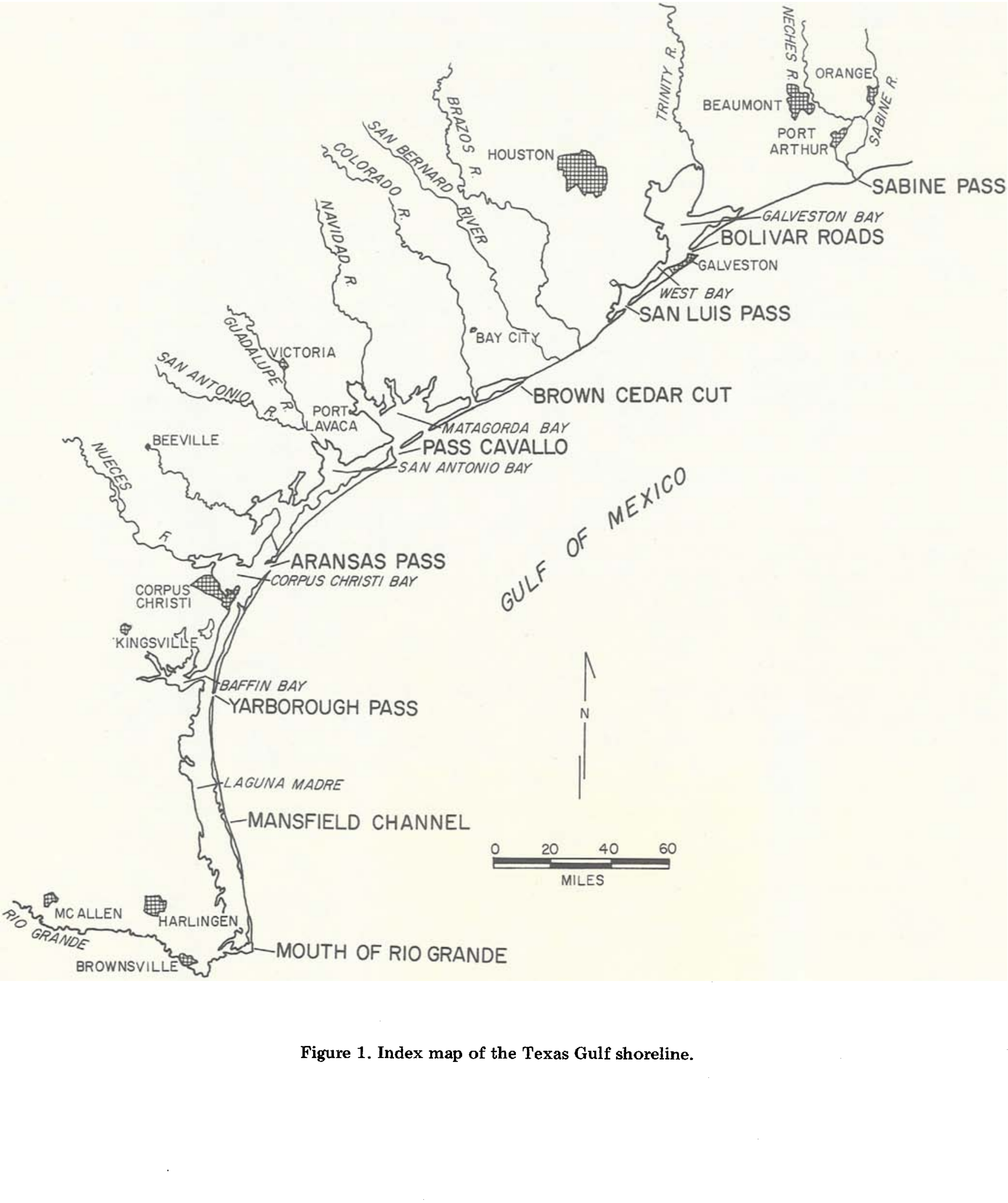

Figure 1. Index map of the Texas Gulf shoreline.

W. E. Jones, and M. Amdurer. Drafting was under the supervision of J. W. Macon. Cartographic work was performed by D. F. Scranton. Critical review was provided by W. L. Fisher and L. F. Brown, Jr. Manuscript preparation was by Elizabeth T. Moore and Sharon Polensky. The report was edited by Kelley Kennedy. Composing was under the direction of Fannie M. Sellingsloh.

Cooperation of personnel with the U. S. Army Corps of Engineers, Galveston District 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 was 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 was established, it would take considerable time (20 to 30 years) before sufficient data were available for determination of long-term trends.

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

Original Data

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

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

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

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

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

Interpretation of Photographs

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

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

Cartographic Procedure

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

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

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

Measurements and Calculated Rates

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

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

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

Justification of Method and Limitations

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

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

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

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

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

Sources and Nature of Supplemental Information

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

Relative wave intensity, estimated from photographs, and the general appearance of the beach dictate whether or not tide and weather bureau records should be checked for abnormal conditions at the time of photography. Most flights are executed during calm weather conditions, thus eliminating most of this effect. On the other hand, large-scale changes are recorded immediately after the passage of a tropical storm or hurricane. For this reason, photography dates have been compared with weather bureau records to determine

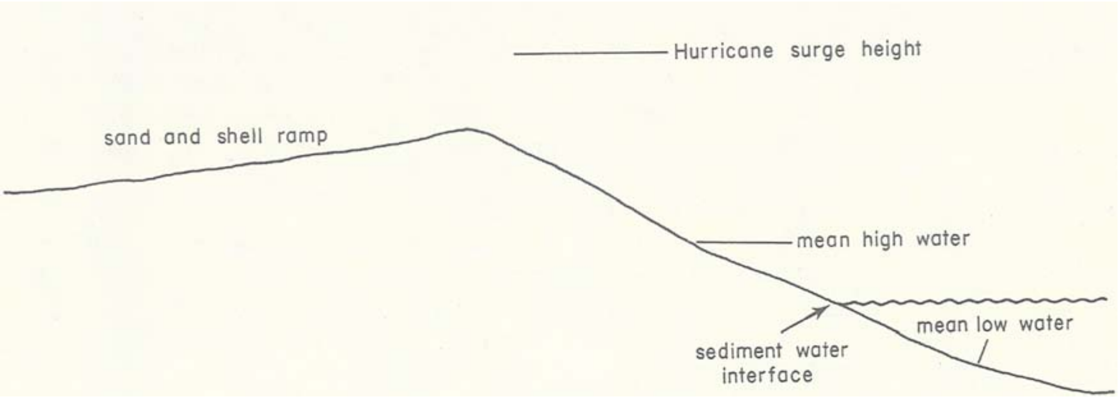

Figure 2. Generalized diagram of beach profile.

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.

PREVIOUS WORK

Beach erosion between Sabine Pass and Bolivar Roads has been the subject of numerous reports and investigations which originated as early as 1947 when Sheets (1947) commented on the beach erosion of 400 feet near High Island and subsequent relocation of State Highway 87. LeBlanc and Hodgson (1959) also described shoreline recession west of Sabine Pass and the subsequent relocation of State Highway 87. They speculated that during the past several thousand years, the shoreline west of Sabine Pass had eroded several thousand feet.

More quantitative data from tables and maps depicting shoreline changes between 1850 and 1956 for the coastal segment extending from High Island to Bolivar Roads were presented as part of a beach erosion study in the vicinity of Rollover Pass (U. S. Army Corps Engineers, 1959b). In general, the maps show continuous erosion except along the coast east of Bolivar Roads where accretion occurred. Net erosion in the vicinity of Rollover Pass reported by the U. S. Army Corps of Engineers (1959b) ranged from 230 to 525 feet.

Shoreline changes a mile on either side of Rollover Pass between 1930 and 1961 (post-Carla) were summarized by Feray (1963) who reported net erosion of 347 and 430 feet northeast and southwest, respectively, of the fish pass.

Short-term accretion and erosion at Sabine Pass, High Island, and Bolivar Roads have been recorded by beach surveys conducted by the U. S. Army Corps of Engineers (1968-1974). Beach profile changes at Rollover Pass between 1963 and 1971 were presented by Prather and Sorensen (1972) who concluded that the beach in that area was stabilized and changes occurred only seasonally or in response to storms. Additional data presented herein indicate that the beach near Rollover Pass is not stable but erosional.

According to Jaworski (1971), the rate of shoreline erosion between Sabine Pass and Bolivar Roads is approximately 5 feet per year. His conclusions were based on various sources of information including the relocation of State Highway 87, personal communication with local residents, a report by the U. S. Army Corps of Engineers, and comparison of maps published by the U. S. Coast and Geodetic Survey. Other than this generalization, no quantitative data on shoreline changes were presented.

A regional inventory of Texas shores was conducted by the U. S. Army Corps of Engineers (1971b). No quantitative data were given and only two categories of erosion were utilized. The shoreline from Sabine Pass to High Island was classified as noncritical erosion, whereas the shoreline from High Island to Crystal Beach was identified as an area of critical erosion.

In a more recent study, Seelig and Sorensen (1973) presented tabular data documenting mean low-water shoreline changes along the Texas Coast; values calculated for the rates of shoreline change between Sabine Pass and Bolivar Roads 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. Seelig and Sorensen (1973) reported accretion west of Sabine Pass and east of Bolivar Roads with erosion prevailing along the remaining shoreline. Rates of accretion west of Sabine Pass and east of Bolivar Roads determined by Seelig and Sorensen range from 2 to 30 feet per year. Maximum rate of erosion reported for the remaining shoreline was 44 feet per year; minimum rate of erosion was 1 foot per year.

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

PRESENT BEACH CHARACTERISTICS

Texture and Composition

The beach between Sabine Pass and Bolivar Roads varies in texture and composition from mud or thin sand veneer over mud with high concentrations of caliche nodules and shell material to dominantly sand with minor shell material. Shell material is comprised of whole and broken surf zone, shelf, and bay species, with bay species (*Crassostrea virginica*, *Rangia cuneata*, and *Mercenaria*) being most abundant in certain areas. Shell content ranges up to 83 percent (U. S. Army Corps Engineers, 1958a). The sand fraction is comprised of well-sorted, fine to very fine sand (Bullard, 1942; Richardson, 1948; U. S. Army Corps Engineers, 1958a; Bridges, 1959; Hsu, 1960; Garner, 1967; Prather and Sorensen, 1972) composed primarily of quartz, feldspar, shell material, and heavy minerals. Analysis of heavy minerals (Bullard, 1942; Richardson, 1948) indicates that black opaques, hornblende, leucoxene, garnet, zircon, tourmaline, and epidote are most common with minor amounts of kyanite, staurolite, rutile, pyroxene, and basaltic hornblende also present.

Beach Profiles

Beach width varies from 50 to 75 feet between Sabine Pass and High Island whereas beach width increases to about 150 feet on Bolivar Peninsula. In general, beach width and beach slope are related. Narrow beaches are relatively steep (about 4 degrees), whereas wider beaches have a more gentle seaward slope. 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 the coast between Sabine Pass and Bolivar Roads, represent beach conditions on March 25, 1975. High tide mark was identified by sand wetness and position of debris line. Beach profiles have also been surveyed by the Galveston District, U. S. Army Corps of Engineers (1968-1974). Comparison of beach profiles and beach scour patterns by Herbich (1970) suggests that beach condition (breaker bar spacing and size) may be similar over a relatively long period of time except during and immediately following storm conditions. Therefore, unless beach profiles are referenced to a permanent, stationary control point on the ground, comparison of profiles at different times may be very similar, but the absolute position of the beach can be quite different. Thus, a beach profile may appear similar (except after storms) for a long period of time but the entire profile may shift seaward (accretion) or landward (erosion) during the same period.

Extant dunes between Sabine Pass and Bolivar Roads are low, generally less than 5 feet in height, and discontinuous. Many areas have virtually no dunes. East of High Island and west of Sea Rim State Park, the dunes are artificially maintained by the Texas Highway Department in order to minimize flooding of State Highway 87.

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

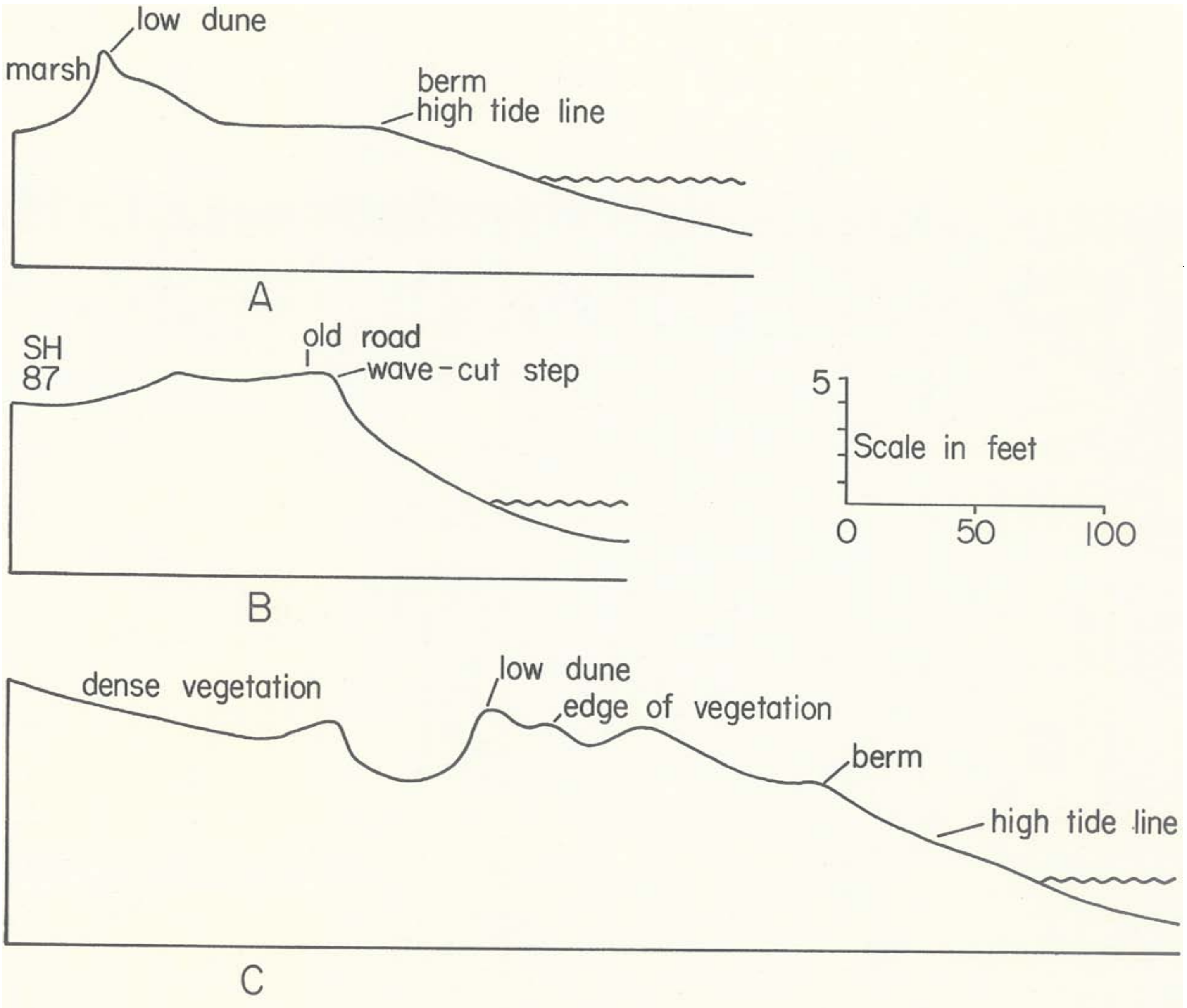

Figure 3. Beach profiles, between Sabine Pass and Bolivar Roads, recorded March 25, 1975. Locations plotted on figure 6.

HUMAN ALTERATIONS OF NATURAL CONDITIONS

Sabine Pass

Recommendations for improvement of Sabine Pass were based on initial hydrographic surveys in 1853 which indicated natural water depths of 7 feet over the channel-mouth bar at Sabine Pass (U. S. Army Corps Engineers, 1853). No harbor improvements were made until another survey was conducted in 1874 to determine the feasibility of dredging at the mouth of Sabine Pass (U. S. Army Corps Engineers, 1875b). Dredging was begun in 1875 but the company performing the work balked on the contract (U. S. Army Corps Engineers, 1877b). Channel depths of 12 to 15 feet were obtained for about half of the project by a government-owned dredge before mechanical problems and the sinking of another government dredge caused a temporary discontinuance in the operation (U. S. Army Corps Engineers, 1878b). Dredging was resumed in 1878 and by 1879, the channel was 12 feet deep and 75 feet wide at the narrowest point; maximum channel width was 140 feet (U. S. Army Corps Engineers, 1879a). Intermittent channel dredging and mechanical problems continued for the next two years, but the dredging was insufficient to prevent shoaling (U. S. Army Corps Engineers, 1882). By 1881, the channel had shoaled to 5.5 feet in some places and by 1882, the channel was nearly closed (U. S. Army Corps Engineers, 1915c). Recommendations for the construction of jetties at Sabine Pass followed another survey conducted in 1882 (U. S. Army Corps Engineers, 1882).

Approval was obtained for two brush and stone jetties, and construction on the east and west jetties was begun in 1883 and 1885, respectively. The project also called for a channel 100 feet wide and 20 feet deep between the jetties. Dredging and jetty construction continued, and by 1896 the east jetty was 19,500 feet long (17,000 feet completed) and the west jetty was 14,875 feet long (6,609 feet finished). The dredged channel between the jetties was 100 feet wide and 24 feet deep (U. S. Army Corps Engineers, 1915c). The channel was deepened and the jetties were extended between 1897 and 1900. By 1900, the channel was 25 feet deep with the east jetty 25,100 feet long (21,540 feet completed) and the west jetty 22,000 feet long (15,250 feet completed).

The hurricane in September 1900 caused considerable damage to the harbor improvements including gaps 600, 450, and 300 feet wide in the east jetty. Subsidence of the east jetty averaged 8 feet. Damage to the west jetty was restricted to the movement and removal of numerous capping blocks (U. S. Army Corps Engineers, 1901). The channel was about 17 feet deep prior to the storm; however, after the storm, minimum depth was 22 feet.

Dredging continued between 1901 and 1903 when 25-foot depths at the pass and in the channel were attained. The jetties were repaired and increased in height when funds were available. By 1915, work was in progress to obtain channel depths of 28 feet over the channel bar and 26 feet between the jetties (U. S. Army Corps Engineers, 1915a). At that time, the east jetty was 25,270 feet long and the west jetty was 21,860 feet long. The east jetty was completed, and channel depths were maintained in 1920. Measurements showed that the channel at the pass was 26.2 feet deep (U. S. Army Corps Engineers, 1920a).

In 1923, the channel between the jetties was deepened to 30 feet as work continued on the west jetty to obtain an elevation of 4 feet. At that time, the outer bar channel was 30.5 feet deep and 200 feet wide (U. S. Army Corps Engineers, 1923a). In 1925, the main channel was dredged to 30 feet, but the outer bar channel was deepened to 33 feet and widened to 450 feet; channel width between the jetties remained at 200 feet (U. S. Army Corps Engineers, 1925a). During the next few years, work continued on the west jetty though the east jetty still needed repairs. At the same time, recommendations were made to widen the channels (U. S. Army Corps Engineers, 1927). The west jetty was completed in 1929 and repairs to the east jetty, begun in 1930, were completed in 1931 (U. S. Army Corps Engineers, 1928a, 1930, 1931a). In 1932, repairs were made to the west jetty and channel depths over the outer bar were increased to 34 feet. Similarly, the channel between the jetties was deepened to 33 feet; the channels to Sabine Pass and Port Arthur were 30 feet deep. Repairs were made to the east jetty in 1934 (U. S. Army Corps Engineers, 1932, 1934a). All channels in the area were enlarged by dredging, and by 1935 the channel over the outer bar and between the jetties was 35 feet deep, whereas the channels to Sabine Pass and Port Arthur were 32 feet deep (U. S. Army Corps Engineers, 1935a).

Between 1937 and 1938, additional repairs to the east jetty were completed and channel depths were increased. By 1938, the outer bar channel was 38 feet deep, the channel between the jetties was 36 feet deep, and the channels to Sabine Pass and Port Arthur were deepened to 34 feet (U. S. Army Corps Engineers, 1937a, 1938a). The channels were also widened to 800 feet (outer bar) and 500 feet (between jetties); the channels to Sabine Pass and Port Arthur were 500 and 400 feet wide, respectively (U. S. Army Corps Engineers, 1939a). Throughout the 1940's, channel and jetty maintenance continued as minor repairs were needed and the channels required dredging (U. S. Army Corps Engineers, 1941a, 1945, 1946, 1949). Apparently little work was done on the harbor improvements during the early 1950's. Repairs to the jetties and dredging operations were conducted between 1957 and 1961 (U. S. Army Corps Engineers, 1957, 1958b, 1960, 1961).

Channel dimensions were increased between 1963 and 1964. By 1964, the channel over the outer bar was 800 feet wide and 42 feet deep; the channel between the jetties was 500 to 800 feet wide and 40 feet deep (U. S. Army Corps Engineers, 1963a, 1964b). During the latter half of the 1960's, maintenance dredging and jetty repairs continued (U. S. Army Corps Engineers, 1965, 1966). In 1971, the east jetty was 25,310 feet long, the west jetty was 21,905 feet long, and channel depths were 42 feet (U. S. Army Corps Engineers, 1971d).

Galveston Harbor

In 1874, an experimental jetty was constructed using concrete-covered wickerwork or brush structures filled with sand (gabions). Channel scour caused the gabions to settle, and plans were formulated to stop the scour by using side jetties. In 1875, an attempt was made to obtain a 15-foot channel with the south jetty (U. S. Army Corps Engineers, 1875a). The severe storm of 1875 caused considerable damage in the Galveston area and noticeable changes in the shoals and channels, but apparently the jetty was not damaged. The channel over the bar was 16.5 feet deep at low tide in 1876, whereas before jetty construction the channel was only 12 feet deep (U. S. Army Corps Engineers, 1876). Construction on the north jetty was initiated in 1876 but work was slowed owing to a lack of funds. The south jetty (Fort Point gabionade) was extended 1,000 feet in 1877. The channel over the bar was 20 feet deep and 200 feet wide in 1878. Storms in 1877 and 1879 caused damage to both jetties. At this time, the north jetty was over the outer bar (7,332 feet), and 121 gabions, washed ashore by the storms, were allowed to dry rot (U. S. Army Corps Engineers, 1877a, 1878a, 1879b).

In 1880, the plans were modified to include a stone and brush mattress jetty from Bolivar Peninsula in order to obtain 25-foot depths over the outer bar. The Rivers and Harbors Act provided for construction of north and south jetties extended to the 30-foot Gulf contour. The plan also included channel dredging to 25 feet over both the inner and outer bars. Channel depths at that time (1886) were 20 feet over the inner bar and 15 feet over the outer bar (U. S. Army Corps Engineers, 1915b). By 1900, the dredged channel was 26 feet deep over the inner and outer bars, the south jetty was 35,306 feet long, and the north jetty was 25,907 feet long; the jetties were 7,000 feet apart at the outer edge (U. S. Army Corps Engineers, 1915b). Jetty repairs related to storm damage suffered in 1900 were begun in 1902 and completed in 1906. Additional changes to the project design, adopted in 1907, called for the extension of stone jetties 25,907 feet and 35,900 feet from Bolivar Peninsula and Galveston Island, respectively. By 1915, the project was completed and the channel had been deepened by scour and dredging to approximately 31 feet over the outer bar. The inner bar was entirely removed. The channel between the jetties was 32.5 feet deep and 800 feet wide from the Gulf to Bolivar Roads (U. S. Army Corps Engineers, 1915b).

High labor costs prevented work on the jetties for several years. Dredging continued, however, and channel depths had been increased to 33.75 feet in the outer channel and 33.25 feet in the inner channel. Channel widths had decreased to 400 feet and 250 feet for the outer and inner channels, respectively. The 1919 storm caused shoaling in the outer channel; the old channel at the outer end of the south jetty was closed to navigation (U. S. Army Corps Engineers, 1920b). The channels continued to be enlarged by dredging, and by 1923 the outer channel was 500 feet wide and the inner channel was 700 feet wide. Channel depths at the same time were 35.5 feet and 32.5 feet for the outer and inner channels, respectively (U. S. Army Corps Engineers, 1923b). Jetty repairs and channel maintenance and enlargement continued from 1925 to 1931 when the outer bar channel was 800 feet wide and 36 feet deep, and the inner bar channel was 700 feet wide and 34 feet deep (U. S. Army Corps Engineers, 1925b, 1926, 1928b, 1931b). Siltation remained a problem throughout the 1930's as indicated by the continued dredging. Frequent repairs to the jetties were also necessary. During this same time period, the ferry channel between Galveston and Bolivar Peninsula was dredged (1934) and other projects such as groin construction along the Galveston seawall were also active (U. S. Army Corps Engineers, 1933, 1934b, 1935b, 1936, 1937b, 1938b). In 1939, the channel depths over the inner and outer bars had decreased to 32.5 feet (U. S. Army Corps Engineers, 1939b). The records indicate that activities during the 1940's were similar to those of the 1930's. Jetty repairs and maintenance dredging continued until 1948 when dredging operations were initiated to deepen the inner and outer bars to 36 feet and 38 feet, respectively (U. S. Army Corps Engineers, 1940b, 1941b, 1942, 1948). After the deepening operations were completed in 1950, channel depths were 37 feet and 39 feet for the inner bar and outer bar channels, respectively (U. S. Army Corps Engineers, 1950). Project maintenance continued throughout the 1950's. In 1959, the recommendation was made to deepen the channel to 42 feet from the Gulf to 2 miles west of the end of the north jetty (U. S. Army Corps Engineers, 1959a). Dredging and jetty maintenance continued through the mid-1960's (U. S. Army Corps Engineers, 1963b, 1964a), and by 1968 the project was completed. The entrance channel and outer bar channel were 800 feet wide and 42 feet deep while the inner bar channel and Bolivar Roads channel were 800 feet wide and 40 feet deep (U. S. Army Corps Engineers, 1968c).

Rollover Pass

Construction of the fish pass at Rollover extended from October 1954 to February 1955 (U. S. Army Corps Engineers, 1959b) under the direction of the Texas Game and Fish Commission. The original design called for a channel 80 feet wide and 8 feet deep but tidal currents caused scouring which increased the channel to 30 feet deep at the Texas Highway 87 bridge and 500 feet wide at the Gulf entrance (U. S. Army Corps Engineers, 1959b). Protective works employed to prevent further bank erosion included additional pilings, a steel sheet pile and timber groin, and assorted rubble. Despite these efforts, erosion continued until November 1955 when a steel bulkhead was placed across the pass reducing the effective depth of the channel to 2 feet (U. S. Army Corps Engineers, 1959b) by lowering alternate pairs of pilings below the depth of mean low tide (McCrone, 1956). Subsequently, the pass was reopened by driving all the pilings 5 feet below mean low water (Prather and Sorensen, 1972).

CHANGES IN SHORELINE POSITION

Late Quaternary Time

Significant shoreline changes resulting from littoral processes have occurred along the shoreline between Sabine Pass and Bolivar Roads during the past several thousand years (Bernard and others, 1959; LeBlanc and Hodgson, 1959). 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 (fig. 4). Prior to stillstand of sea level, sedimentation was occurring predominantly in the former valleys of the Sabine-Neches and Trinity Rivers (LeBlanc and Hodgson, 1959; Kane, 1959; Nelson and Bray, 1970). Furthermore, contemporaneous accretion in the vicinity of Sabine Pass and on Bolivar Peninsula was initiated approximately 3,000 to 2,800 years B.P. (before present) (LeBlanc and Hodgson, 1959; Gould and McFarlan, 1959). Gould and McFarlan used radiocarbon dates and physiography to interpret shoreline positions near Sabine Pass between 2800 and 600 years B.P. (fig. 5). Their data document considerable seaward accretion. During this time, Bolivar Peninsula also grew seaward by accretion and southwestward in the direction of prevailing longshore drift by lateral spit migration.

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

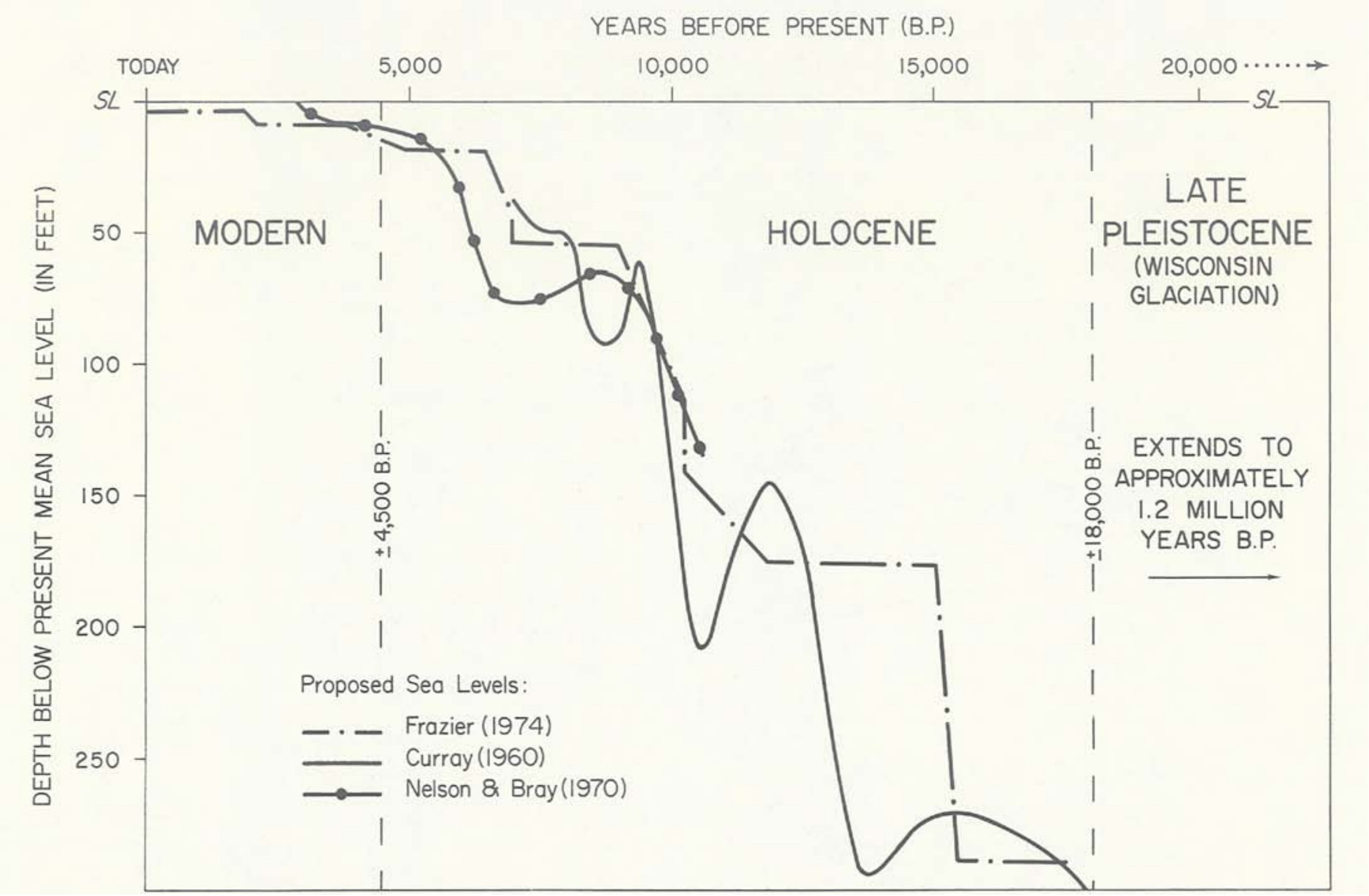

Figure 4. Proposed sea-level changes during the last 20,000 years; sketch defines use of Modern and Holocene used in text. From Fisher and others (1973).

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 1882-83 and 1974, at 62 arbitrary points spaced 5,000 feet apart along the shoreline map from Sabine Pass to Bolivar Roads (fig. 6), are presented in appendix A. In general, the tabular data document two periods of erosion (1882-83 to 1930, 1955-57 to 1974), one period of accretion (1930 to 1955-57), and an intermediate period of erosion (1956-57 to 1965). Thus, excluding points on the western end of Bolivar Peninsula which have experienced accretion, the data document shoreline erosion for all time periods except 1930 to 1955-57 when shoreline accretion or equilibrium predominated.

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

1851 to 1882.—Shoreline changes between 1851 and 1882 are only available from point 54 to point 62 because of the limited extent of the 1851 shoreline published on Topographic Map 329 (appendix C). However, shoreline changes for points 54 through 62 are important because they represent a record of shoreline changes prior to construction of the jetties at Galveston Harbor.

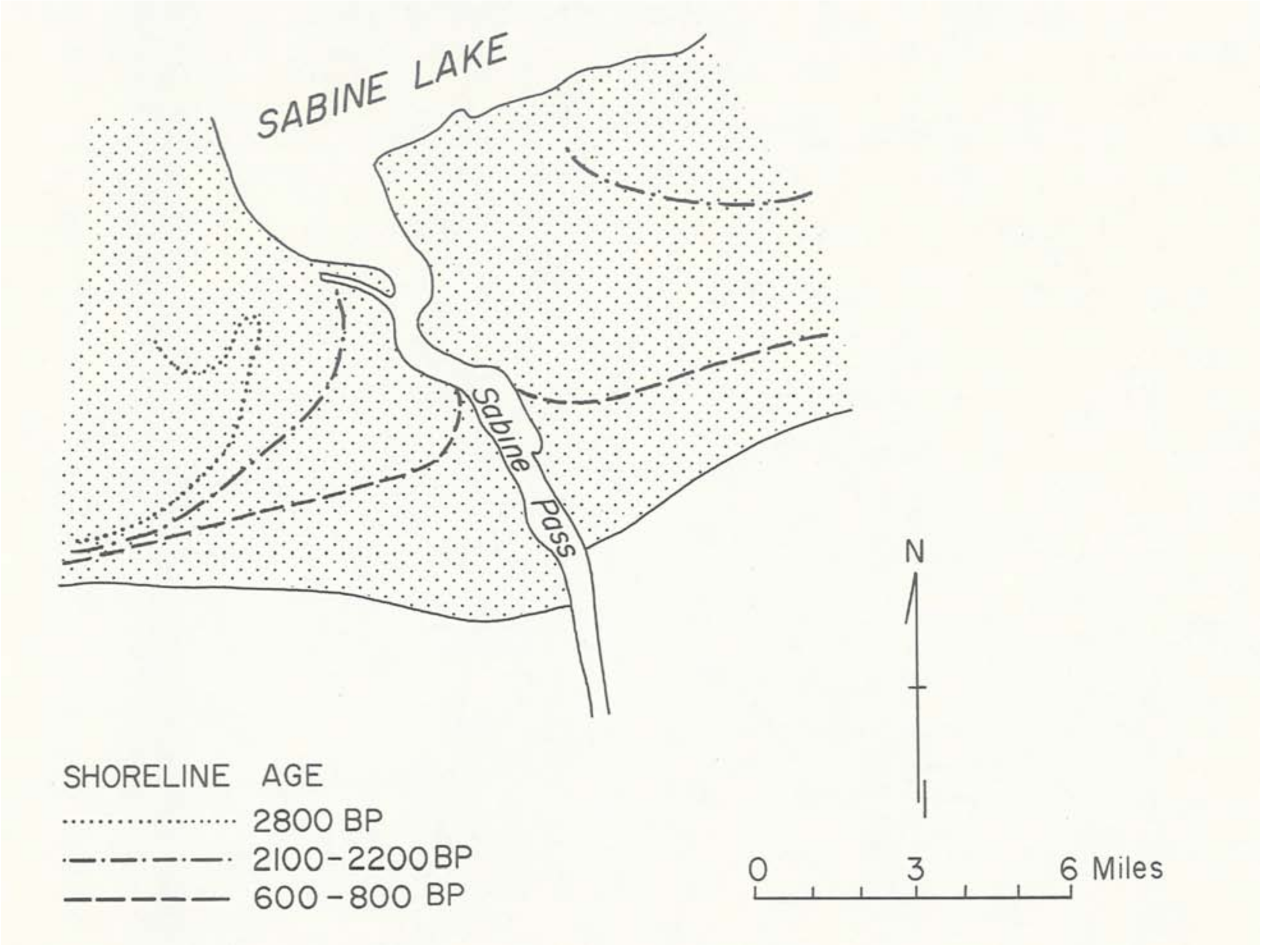

Figure 5. Previous shoreline positions near Sabine Pass interpreted from physiography and radiocarbon dates. From Gould and McFarlan (1959).

During the 31 years between 1851 and 1882, the western shoreline along Bolivar Peninsula (points 54-62) experienced extreme erosion ranging from 125 to 710 feet; average erosion for the 9 points monitored was 525 feet. Minor to extreme hurricanes affected Bolivar Peninsula in 1854, 1867, 1875, and 1879 (appendix B). The hurricanes in 1854 and 1875 caused storm tides of 8.2 feet at Galveston (table 1).

1882-83 to 1930.—Nearly two-thirds of the shoreline experienced erosion from 1882-83 to 1930. Erosion occurred at all points except 1-4, 12-15, and 48-62 where the shoreline position either remained unchanged or accreted. Apparently erosion predominated throughout this time interval as indicated by interim changes determined by the 1923 shoreline for the first 27 points. With few exceptions, the trends established from 1882-83 to 1923 and from 1923 to 1930 are the same as those determined for the entire time period. Shoreline erosion between 1882 and 1930 ranged from 25 to 1,325 feet and averaged 520 feet. Accretion decreased from 2,075 feet at point 1 to 250 feet at point 4. The shoreline was relatively stable between points 12 and 13, whereas the shoreline accreted 250 feet and 175 feet at points 14 and 15, respectively. Shoreline stability was also documented between points 48 and 54; shoreline accretion between points 55 and 62 ranged from 100 to 1,100 feet except for points 58 and 59 which remained unchanged. Excluding points 58 and 59, accretion from points 55 to 62 averaged 355 feet.

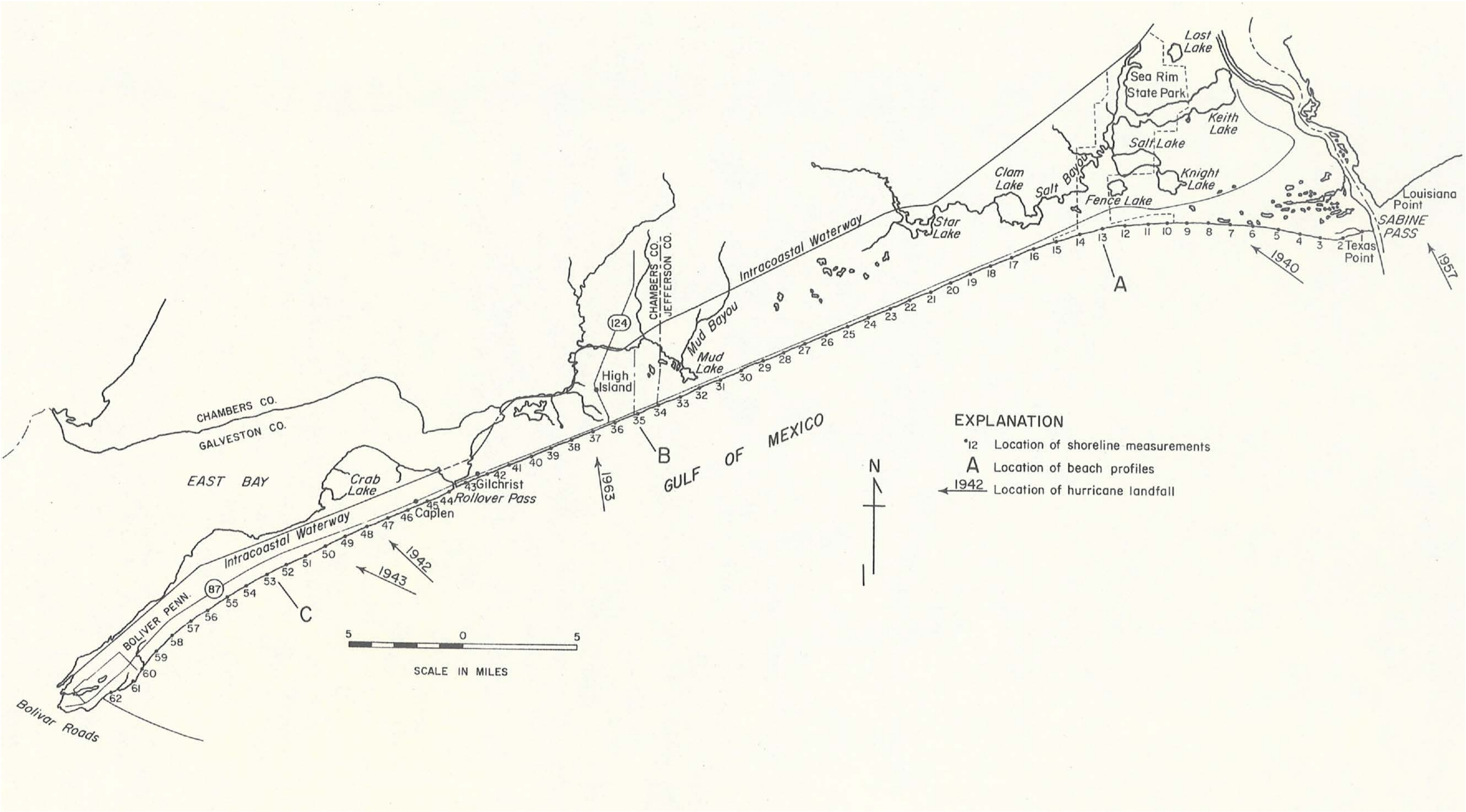

Figure 6. Location map of points of measurement and beach profiles.

Table 1. Maximum storm tides at Galveston exceeding 4.5 feet, 1847-1974.

Date	Surge Height (feet)	Reference
1847	7.7	U. S. Army Corps Engineers, 1959b
1854	8.2	"
1867	5.3	"
1875	8.2	"
1886	7.7	"
1886	5.2	"
1900	14.5	"
1909	5.2	"
1915	12.7	"
1919	7.6	"
1932	4.5	"
1933	4.6	"
1934	6.0	"
1941	5.7	"
1942	6.3	"
1949	5.7	"
1957	6.1	"
1961	9.3	" 1962
1971	5.5	Simpson and Hope, 1972

Twice in 1886, the upper Texas Coast was the site of hurricane landfall with surge heights of 9.0 and 12.4 feet recorded at Sabine Pass (U. S. Army Corps Engineers, 1953). Extreme hurricanes also affected this coastal segment in 1900, 1915, and 1919; the hurricane in 1909 was classified as a major storm.

1930 to 1955-57.—The dominant erosional trend of the preceding time period reversed between the early 1930's and the mid-1950's. Of the 62 points monitored for this time interval, 36 points experienced accretion, 17 experienced erosion, and 9 points remained relatively unchanged. Except for point 4 which remained unchanged, erosion extended from point 2 to point 13. Erosion along this segment ranged from 50 to 1,225 feet and averaged 650 feet. Minor to moderate erosion also extended from point 27 to point 31. Accretion predominated between points 14 and 26 except at point 17 which remained unchanged. Accretion at the other 11 points along this segment ranged from 25 to 225 feet and averaged 125 feet. Minor accretion and equilibrium conditions were recorded between points 32 and 57; accretion increasing from moderate to extreme was recorded from point 59 to point 62.

1956-57 to 1965.—The 1965 shoreline was mapped on aerial photographs available only between points 37 and 62. During this time period, the dominant shoreline changes again reversed to an erosional trend. The shoreline segment extending from point 37 to point 60 experienced erosion ranging from 25 to 350 feet; average erosion for these 23 points was about 150 feet. The opening of Rollover Pass contributed to local erosion in that area (point 45). An accretionary trend was recorded southwestward from point 60 which exhibited no change. Accretion at points 61 and 62 was 175 and 200 feet, respectively.

1955-57 to 1970-74.—The erosional trend apparently established by the late 1950's or early 1960's and documented in the preceding section continued to 1974. Of the 62 points monitored, 56 points experienced erosion, 3 points (1, 17, and 18) remained unchanged, and three points (60 to 62) continued to record accretion. Maximum erosion for this time period was recorded at point 3 (775 feet); minimum erosion was 50 feet. Average erosion was about 240 feet. Shoreline segments from points 2 to 12, 34 to 47, and 55 to 58 experienced greatest erosion.

Storm frequency did not diminish during this period but perhaps shoreline erosion was only aggravated by the tropical storms and hurricanes. Hurricanes and tropical storms made landfall in the area in 1957 (Audrey), 1963 (Cindy), 1970 (Felice), and 1973 (Delia). With the exception of Felice, these storms caused tides in excess of 4 feet along the upper Texas Coast. Hurricane surge near Sabine Pass was 6 to 8 feet during Audrey (Ross and Blum, 1957; Moore and others, 1957); a stillwater elevation of 7.1 feet was measured at Rollover Pass. Consequently, the Gulf shoreline in the vicinity of Rollover Pass eroded 50 to 60 feet during that storm (U. S. Army Corps Engineers, 1959b). Although Carla (1961) did not make landfall within the coastal segment covered by this report, associated storm tides in excess of 8 feet were recorded between Sabine Pass and Galveston (table 1). Prestorm and post-storm beach profiles indicate that the shoreline in the vicinity of Rollover also eroded about 60 feet during Carla (U. S. Army Corps Engineers, 1962).

Undoubtedly, there is some relationship between storm characteristics and beach erosion, but the role of tropical storms and minimal hurricanes may be underestimated because of a lack of detailed measurements of beach changes. This is substantiated by field observations following tropical storm Delia in September 1973. During that storm, approximately 60 cubic feet of sand per linear foot of beach was removed by erosion of a wave-cut step in the vicinity of Rollover Pass. Some sand was completely removed from the beach-littoral drift system between High Island and Sabine Pass by washover and deposition of sand in the adjacent marsh.

Net Historic Change (1882 to 1974)

Calculations from previously determined changes provide information on the net effect of shoreline retreat and advance between Sabine Pass and Bolivar Roads (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.

Between 1882-83 and 1970-74, net erosion predominated from point 3 to point 50. Maximum net erosion at point 11 (2,900 feet) is attributed to long-term erosion substantially increased by straightening of the shoreline. Average net erosion for the 43 points was 760 feet. Major net accretion occurred at points 1 and 2; only minor net accretion occurred at points 14 and 15 owing to reorientation of the shoreline. There was essentially no net change at points 51 and 52 as accretion and erosion were equal; the shoreline between points 53 and 58 was also relatively stable as indicated by net changes of 50 feet or less. Net accretion, however, increased from 150 feet at point 59 to 2,575 feet at point 62.

Construction of the Galveston Harbor and Sabine Pass jetties with attendant reorientation of the shoreline and impoundment of large quantities of sand account for the tremendous net accretion just west of Sabine Pass and east of Bolivar Roads.

Rates of change were also calculated for net change between 1882-83 and 1970-74; 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 between Sabine Pass and Bolivar Roads are minor or moderate except for extreme net accretion of 26 and 28 feet per year at points adjacent to the jetties at Sabine Pass and Galveston Harbor and extreme net erosion between points 8 and 11 that averaged 28 feet per year. Net erosion at the remaining points ranged from 1 foot per year to 17.4 feet per year and averaged 6.4 feet per year.

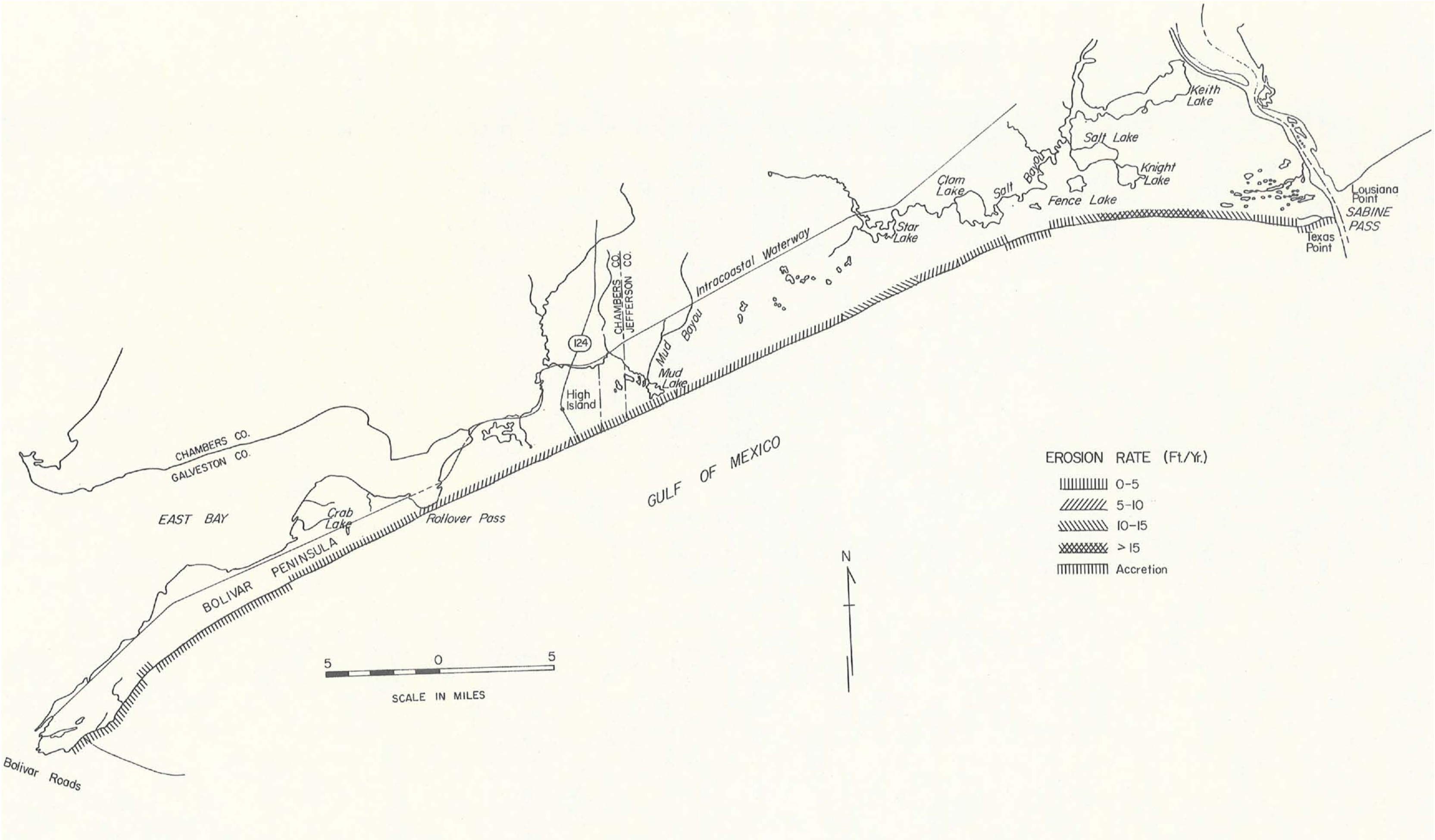

Figure 7. Net shoreline changes from Sabine Pass to Bolivar Roads based on the time period from 1882-83 to 1970-74.

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.

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 (1930-1974). Changes in position of the vegetation line west of point 59 were not documented because of the transitional nature of the vegetation line in that area.

1930 to 1955-57.—Between 1930 and 1955-57, changes in position of the vegetation line were nearly equally divided between erosion and accretion or equilibrium. Of the 57 stations monitored, 30 points experienced retreat while 22 points experienced advancement; at 5 points, the vegetation line remained unchanged. The vegetation line advanced 225 feet at point 1; however, landward retreat of the vegetation line was predominant between points 2 and 13 (fig. 8). Excluding point 4, which remained essentially unchanged, retreat along this segment ranged from 25 to 1,250 feet and averaged about 690 feet. Retreat of the vegetation line in this area was closely associated with shoreline erosion as indicated by the similarity in the magnitude of both shoreline and vegetation line changes.

Changes in the vegetation line were mixed between points 14 and 17. Points 14 and 15 experienced advancement, whereas retreat was recorded at points 16 and 17. Between points 18 and 28, the vegetation line advanced except at points 18, 23, and 27 where the vegetation line remained unchanged. Advancement for this segment ranged from 25 to 125 feet and averaged 85 feet. Changes in position of the vegetation line along this segment were similar to shoreline changes during the same period.

Vegetation line retreat between points 29 and 46 ranged from 25 to 225 feet and averaged 140 feet. Beach width was increased significantly between points 32 and 46 because the shoreline accreted while the vegetation line retreated.

Advancement of the vegetation line was predominant between points 46 and 59. Much of the vegetation line advance was associated with contemporaneous shoreline accretion. In contrast, the shoreline was stable between points 47 and 50; therefore, beach width was reduced. An increase in density of the vegetation between 1930 and 1955 was partially responsible for the advance in the vegetation line along this segment.

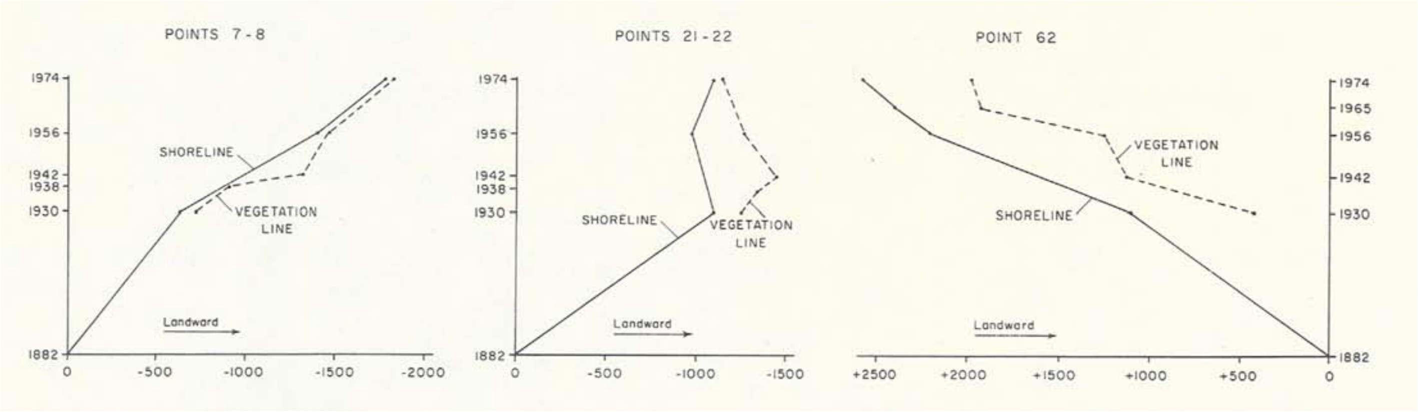

Figure 8. Relative changes in position of shoreline and vegetation line at selected locations.

The 1942 hurricane caused retreat of the vegetation line especially in the vicinity of High Island as indicated by inspection of photographs taken in 1938 and 1942 (appendix C). This erosion could account for the discrepancies between shoreline changes and vegetation line changes between points 32 and 46. Apparently, the effects of the storm were masked by shoreline changes for the remaining segments between Sabine Pass and Bolivar Roads.

1956-57 to 1965.—Documentation of changes in position of the vegetation line between 1956 and 1965 is limited to points 37 through 59 because of the lack of 1965 photography previously mentioned. In general, this was a period of vegetation line retreat. Except for anomalous advance at point 48 and relative stability at points 39, 49, 54, and 55, the vegetation line retreated from 25 to 150 feet; average retreat was 70 feet. Detailed comparison of 1961 and 1965 aerial photographs indicates that retreat of the vegetation line during Hurricane Carla was of greater magnitude than that recorded; however, partial recovery of the vegetation line had occurred by 1965, thus minimizing the retreat measured. Retreat associated with Hurricane Audrey may have been a minor contributing factor to the overall retreat.

1955-57 to 1974.—Changes in the position of the vegetation line were mixed between 1955-57 and 1974. Of the 54 points monitored, 31 experienced retreat, 17 experienced advancement, and 6 remained unchanged. Retreat of the vegetation line between points 5 and 15 ranged from 25 to 600 feet; average retreat for this segment was about 285 feet. Advancement or equilibrium conditions were prevalent between points 20 and 24 (fig. 8). The vegetation line advanced as much as 100 feet along this segment. In contrast, average retreat of about 115 feet occurred between points 25 and 29. Minor advances or equilibrium were recorded between points 30 and 36. With the exception of point 42, the vegetation line from point 37 to point 47 retreated from 25 to 175 feet; average retreat for this segment was 90 feet. No definite trend was established between points 48 and 59 as changes in the vegetation line were mixed.

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. Net retreat of the vegetation line was generally recorded between points 5 and 17 and from point 25 to point 47; net advance of the vegetation line generally prevailed for the remaining segment between points 48 and 59. It should be emphasized that the position of the vegetation line is artificially maintained where State Highway 87 is in close proximity to the beach. This condition extends from approximately point 16 to High Island. Sand washed over the road during storms is removed and placed as artificial dunes on the seaward side of the road. The vegetation, which becomes established in a short period of time, tends to stabilize the artificial dunes.

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 the Texas Coast between Sabine Pass and Bolivar Roads is as follows: 1891-1893, 1896-1899, 1916-1918, 1937-1939, 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 (1900-1974). 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.

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 (1962, 1968b, 1971c, 1972).

Destructive forces and storm damage.—Carla was one of the most violent storms on record because of her extreme size and high storm surge; the entire coastal area from Sabine Pass to Bolivar Roads was inundated with still-high water elevations ranging from 8.8 to 9.3 feet above mean sea level (U. S. Army Corps of Engineers, 1962). Flooding also occurred in low-lying areas as a result of Hurricane Beulah (U. S. Army Corps of Engineers, 1968b). However, the most intense storms to strike the upper Texas Coast were the hurricanes of 1900 and 1915.

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 the upper Texas Coast because of low elevations and lack of continuous foredunes that can dissipate most of the energy transmitted by wave attack. Because of the role hurricane surge plays in flooding and destruction, the frequency of occurrence of high surge on the open coast has been estimated by Bodine (1969). Included in his report are calculations for Sabine Pass, which suggest that surge height of 10 feet can be expected approximately six times every 100 years. Maximum hurricane surge predicted was 17.5 feet. These estimates were based on the most complete records of hurricane surge elevations available for the Texas Coast. Surge for specific storms was compiled by Harris (1963). Wilson (1957) estimated deepwater 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 deepwater 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 either (1) transported and stored temporarily in an offshore bar, (2) transported in the direction of littoral currents, and/or (3) washed across the peninsula 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).

Morgan and others (1958) described the characteristics and changes in beach conditions along the western Louisiana Coast associated with Hurricane Audrey. Their beach profiles document shoreline retreat and landward migration of the sand and shell ramp that is often developed on erosional, sand-deficient beaches similar to the shoreline segment between Sabine Pass and Rollover Pass.

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 steps 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 the coast between Sabine Pass and Bolivar Roads are (1) sea-level changes, and (2) compactional subsidence. Shepard (1960b) discussed Holocene rise in sea level along the Texas Coast based on C^{14} data. Relative sea-level changes during historical time are deduced by monitoring mean sea level as determined from tide observations and developing trends based on long-term measurements (Gutenberg, 1933, 1941; Marmer, 1949, 1951, 1954; Hicks and Shofnos, 1965; Hicks, 1968, 1972). However, this method does not distinguish between sea-level rise and land-surface subsidence. More realistically, differentiation of these processes or understanding their individual contributions, if both are operative, is an academic question; the problem is just as real no matter what the cause. A minor vertical rise in sea level relative to adjacent land in low-lying coastal areas causes a considerable horizontal displacement of the shoreline in a landward direction (Bruun, 1962).

Swanson and Thurlow (1973) attributed the relative rise in sea level at Galveston to compactional subsidence. Their conclusion was based on tide records between 1950 and 1971. However, continuous tide data are available from 1904 (Gutenberg, 1933; Marmer, 1951), and the trend has indicated rising sea level since that time (fig. 9). Interpreted rates of sea-level rise depend a great deal on the specific time interval studied; thus, short-term records can be used to demonstrate most any trends. On the other hand, long-term records provide a better indication of the overall trend and are useful for future prediction. Rates of relative sea-level rise determined by previous workers range from 0.013 to 0.020 feet per year or 1.3 to 2.0 feet per century. It is readily apparent that rises in sea level of this order of magnitude may cause substantial changes in shoreline position.

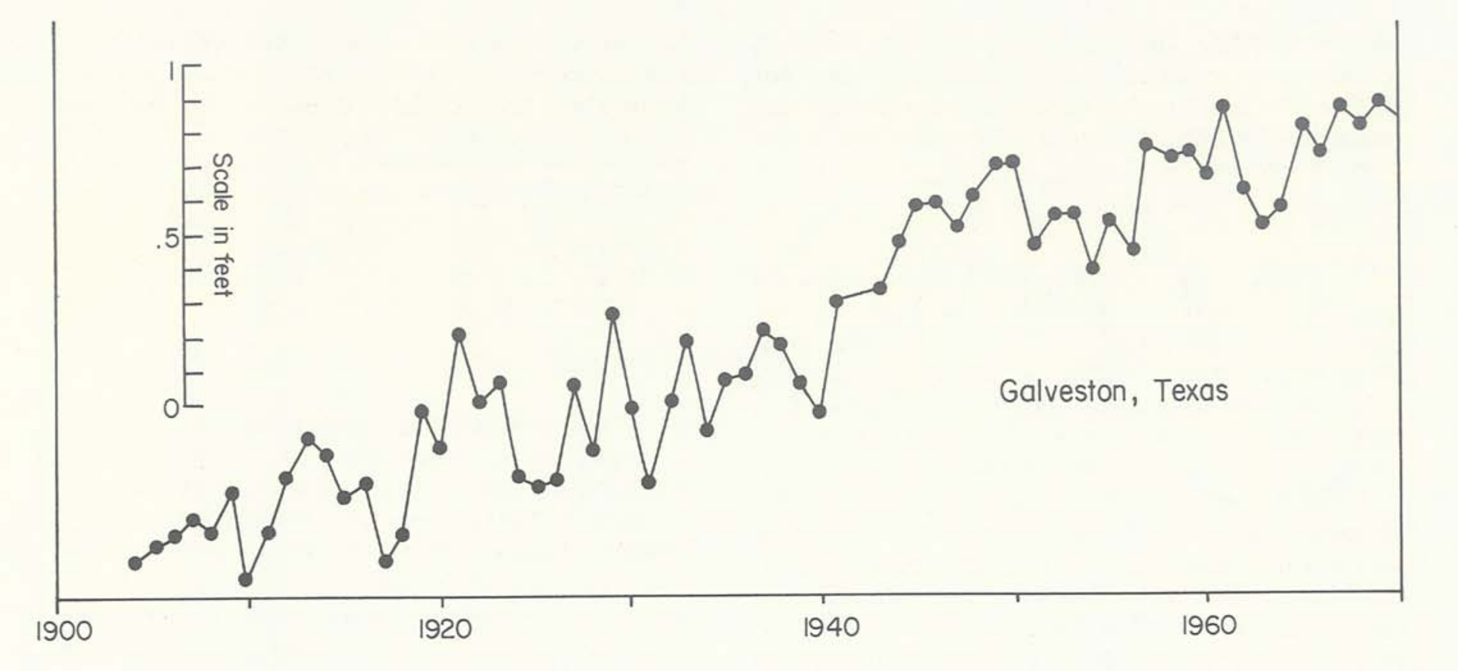

Figure 9. Relative sea-level changes based on tide gage measurements for Galveston, Texas. Data from Gutenberg (1941), Marmer (1951), and Swanson and Thurlow (1973).

There is increasing concern regarding land-surface subsidence in the Houston-Galveston area associated with production of oil (Pratt and Johnson, 1926) and withdrawal of ground water (Winslow and Doyel, 1954; Gabrysch, 1969). Total land subsidence recorded for the Sabine area, however, has been less than 1 foot (Brown and others, 1974). Although the shoreline along the upper Texas Coast does not appear to be affected significantly at the present, continued withdrawal and concomitant decline in fluid pressure could eventually affect this coastal segment as the cone of depression spreads outward from the area of principal withdrawal. Such would augment the effects of compactional subsidence and lead to future loss of land at the land-water interface.

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 Bolivar Peninsula. Although there has been shoreline accretion near Sabine Pass, the sand associated with that accretion is relatively minor in comparison to the volume of mud deposited.

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 Bolivar Peninsula probably include both sand derived from shelf sediment and the Mississippi River. Van Andel and Poole (1960) and Shepard (1960a) suggested that sediments of the Texas Coast are largely of local origin. Shelf sand derived from the previously deposited sediment was apparently reworked and transported shoreward by wave action during the Holocene sea-level rise (fig. 4). McGowen and others (1972) also concluded that the primary source of sediment for Modern sand-rich barrier islands and peninsulas such as Galveston Island and Bolivar Peninsula was local Pleistocene and early Holocene sources on the inner shelf, based on the spatial relationship of the different age deposits.

Unfortunately much of the shelf between Sabine Pass and Rollover Pass is underlain by clay, thus precluding the reworking and landward transport of substantial amounts of sand. A notable exception is the shoreline segment along Sea Rim State Park where the sand beach is attributed to reworking of Pleistocene fluvial sands now exposed on the shelf.

Sediment supplied by major streams is transported alongshore by littoral currents. Because of the orientation of the shoreline between Sabine Pass and Bolivar Roads, south and southwest winds also promote drift to the northeast. Under the influence of dominant southeast winds, littoral drift is from east to southwest along the upper Texas Coast (figs. 10 and 11). The only major river in an updrift direction from this segment of the Texas Coast that supplies sediment directly to the littoral zone is the Mississippi River. 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.

Bernard and others (1959) presented data, which indicated that Galveston Island was in an accretionary state between 6,000 and 1,600 years B.P. (before present). Radiocarbon data from Gould and McFarlan (1959) suggested that shoreline accretion in the Sabine Pass area was initiated approximately 2,800 years ago. This was also the time period when the Mississippi River was debouching sediment into the Gulf of Mexico under shoal water conditions (Morgan and Larimore, 1957; Frazier, 1967). In this situation, wave action and longshore currents would be better able to transport fine sand. For the past 300 to 400 years (Morgan and Larimore, 1957), the Mississippi River has deposited its load in the deep water off the present birdfoot delta lobe, and consequently, the sand, which subsides in the water-saturated prodelta clays, is stored therein and does not become part of the littoral drift system.

Shoreline erosion at rates from 7.5 and 62.0 feet per year has been documented along the Louisiana Coast between 1812 and 1954 (Morgan and Larimore, 1957). Some of the eroded material is added to the littoral system, but this does not represent a significant contribution to the upper Texas Coast owing to the low percentage of sand in the sediment and the fact that most of this material is trapped by the jetties at Sabine Pass (Morgan and Larimore, 1957). The same holds true for most of the eroded sediment west of Sabine Pass, which is trapped by the jetties at the entrance to Galveston Harbor.

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. Minor amounts of sand may be moved offshore in deeper water during storms and some sand is blown off the beach by eolian processes, but the high rainfall and dense vegetation preclude removal of large quantities of sand by wind. Sand removed by man-made structures and for construction purposes is discussed in the following section on human activities.

The U. S. Army Corps of Engineers (1959b) estimated that prior to opening of Rollover Pass an annual sediment deficit of 200,000 cu yds existed for the beach segment between High Island and a point seven miles east of the entrance to Galveston Harbor. Additional losses estimated at 18,000 cu yds annually were attributed to opening of the pass (U. S. Army Corps Engineers, 1959b). The beach immediately west of Rollover Pass was artificially nourished with 6,000 cu yds of fill in February 1957, by the Texas Game and Fish Commission; however, this material was removed by erosion within four months.

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,

Figure 10. Littoral drift along upper Texas Coast (Sabine Pass-Galveston Island). Reproduction from NASA ERTS E-1180-16194-401, January 1973.

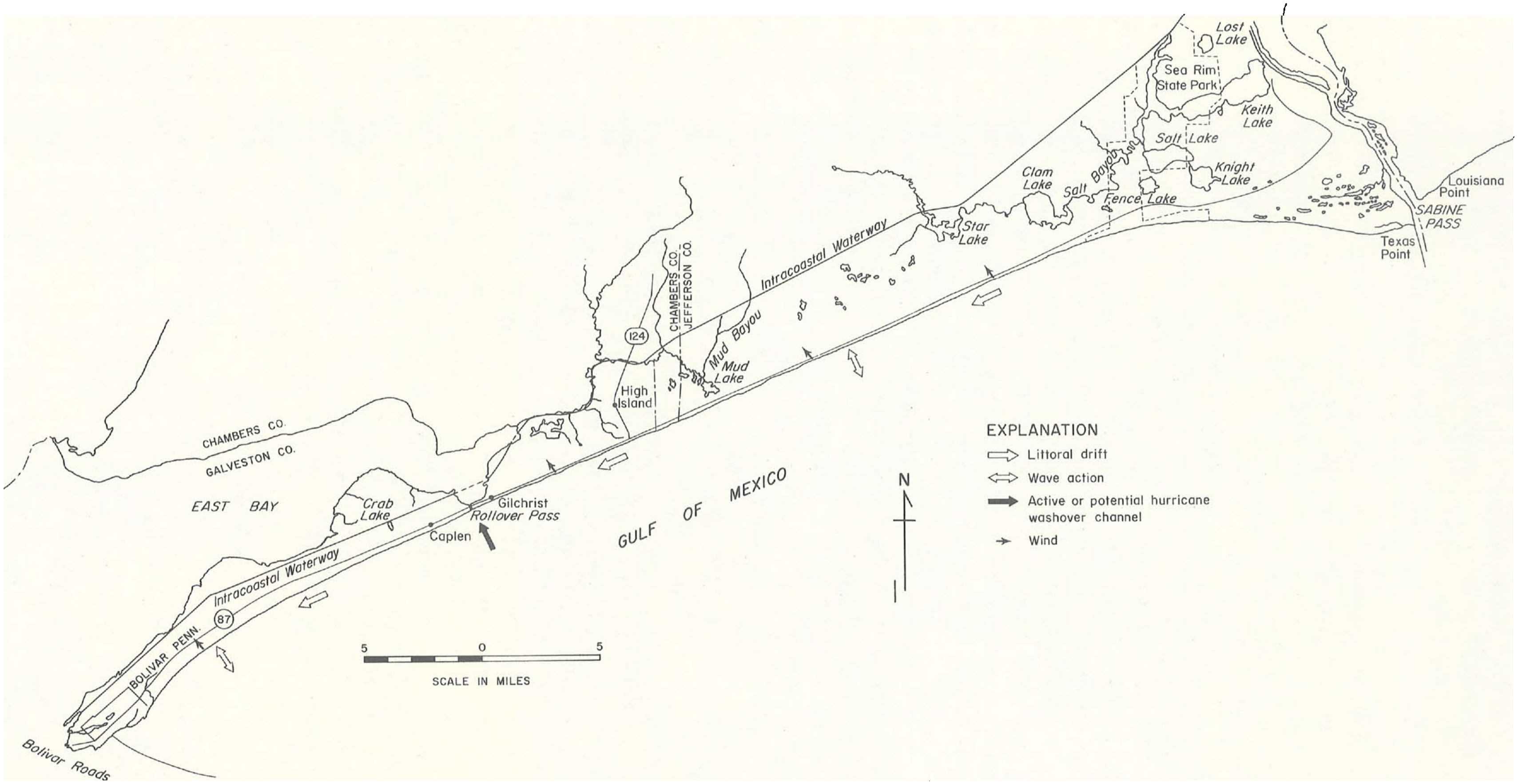

Figure 11. Generalized diagram of sediment transport directions between Sabine Pass and Bolivar Roads.

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 in Galveston Harbor was initiated in 1874 and completed in 1894. Jetty construction at Sabine Pass extended from 1883 to 1900. Construction of Rollover Pass was completed in 1955. Projects such as these serve to alter natural processes such as inlet siltation, beach erosion, and hurricane surge. Their effect on shoreline changes is subject to debate, but it is an elementary fact that impermeable structures interrupt littoral drift and impoundment of sand occurs at the expense of the beach downdrift of the structure. Thus, it appears reasonable to expect that any sand trapped by the jetties is compensated for by removal of sand downdrift, thus increasing local erosion problems.

Until recently, sand was excavated from the beach at High Island by the Texas Highway Department (Bridges, 1959) for construction purposes. Such activities tend to increase the deficit in sediment supply.

The deltaic plain of the Mississippi River is characterized by both minor and major distributaries, most of which have been blocked off from the main river and thus prevented from transporting major quantities of sediment to the Gulf. Levee construction in 1868 eliminated flow through Bayou Plaquemine; discharge through Bayou Lafourche was controlled in 1904 (Gunter, 1952). But the main controls placed on the river system occurred when locks were constructed to prevent increased discharge into the Atchafalaya River, which would have eventually caused diversion of the Mississippi River because of the shorter Gulf route. The impact of these controls in modifying sediment budget is not documented, but any increase in sediment supply to the littoral system would be helpful under natural conditions. However, the presence of jetties and the proposed extension of some into deeper water would virtually guarantee the exclusion of most sand transported by littoral currents for beach nourishment.

EVALUATION OF FACTORS

Shore erosion is not only a problem along United States coasts (El-Ashry, 1971) but also a worldwide problem. Even though some local conditions may aggravate the situation, major factors affecting shoreline changes are eustatic conditions (compactional subsidence on the Texas Coast) and a deficit in sediment supply. 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).

Field observations as well as investigations by Nelson and Bray (1970) indicate that the beach sand between High Island and Sabine Pass is only a thin veneer over the Holocene marsh and Pleistocene Beaumont clays. Apparently sand on Bolivar Peninsula is at least 30 feet thick (U. S. Army Corps Engineers, 1950) and perhaps greater than 50 feet thick (LeBlanc and Hodgson, 1959). Moreover, sand thickness decreases to the east. The sand stored in Bolivar Peninsula should tend to minimize erosion and keep rates of erosion relatively low. Conversely, where clay substrate predominates, rates of erosion will probably continue to be higher.

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 Sabine Pass-Bolivar Roads

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	1883 1930	+2075	+ 44.2	1930 1955	+ 150	+ 5.8	1955 1970	0	0				1883 1970	+2225	+ 26.6
2	"	+1750	+ 37.2	"	- 550	- 21.6	"	-600	- 41.4				"	+ 600	+ 6.9
3	1882 1930	+1025	+ 21.4	"	- 375	- 14.7	"	-775	- 53.4				1882 1970	- 125	- 1.4
4	"	+ 250	+ 5.2	"	0	0	"	-675	- 46.6				"	- 425	- 4.8
5	"	- 675	- 14.1	"	- 50	- 2.5	1955 1974	-400	- 20.5				1882 1974	-1125	- 12.0
6	"	- 400	- 8.9	"	- 400	- 15.7	"	-375	- 19.2				"	-1175	- 12.8
7	"	- 700	- 14.6	"	- 500	- 19.6	"	-400	- 20.5				"	-1600	- 17.4
8	"	- 975	- 20.3	"	- 850	- 33.3	"	-600	- 30.8				"	-2375	- 25.8
9	"	-1050	- 21.9	"	- 975	- 38.2	"	-500	- 25.6				"	-2525	- 27.4
10	"	- 975	- 20.3	"	-1225	- 48.0	"	-350	- 17.9				"	-2550	- 27.7
11	"	-1325	- 27.6	1930 1956	-1200	- 46.2	1956 1974	-375	- 20.8				"	-2900	- 31.5
12	"	+ 25	+< 1.0	"	- 775	- 29.8	"	-200	- 11.1				"	- 950	- 10.3
13	"	0	0	"	- 275	- 10.6	"	-125	- 6.9				"	- 400	- 4.3
14	"	+ 250	+ 5.2	"	+ 100	+ 3.8	"	-175	- 9.7				"	+ 175	+ 1.9
15	"	+ 175	+ 3.6	"	+ 225	+ 8.7	"	-175	- 9.7				"	+ 225	+ 2.4
16	"	- 100	- 2.1	"	+ 100	+ 3.8	"	-100	- 5.6				"	- 100	- 1.1
17	"	- 325	- 6.8	"	0	0	"	0	0				"	- 325	- 3.5
18	"	- 625	- 13.0	"	+ 100	+ 3.8	"	0	0				"	- 525	- 5.7
19	"	- 775	- 16.1	"	+ 150	+ 5.8	"	- 75	- 4.2				"	- 700	- 7.6
20	"	- 825	- 17.2	"	+ 150	+ 5.8	"	-200	- 11.1				"	- 875	- 9.5

+ accretion
- erosion

Shoreline Changes

beach segment Sabine Pass-Bolivar Roads

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	"	- 925	- 19.3	"	+ 150	+ 5.8	"	-150	- 8.3				"	- 925	- 10.1
22	"	-1050	- 21.9	"	+ 125	+ 4.8	"	-125	- 6.9				"	-1050	- 11.4
23	"	-1000	- 20.8	"	+ 100	+ 3.8	"	-150	- 8.3				"	-1050	- 11.4
24	"	- 775	- 16.1	"	+ 125	+ 4.8	"	-125	- 6.9				"	- 775	- 8.4
25	"	- 650	- 13.5	"	+ 125	+ 4.8	"	-200	-11.1				"	- 725	- 7.9
26	"	- 500	- 10.4	"	+ 25	+< 1.0	"	-125	- 6.9				"	- 650	- 7.1
27	"	- 475	- 9.9	"	- 50	- 1.8	"	-100	- 5.6				"	- 625	- 6.8
28	"	- 250	- 5.2	1930 1957	- 175	- 6.4	1957 1974	- 50	- 2.9				"	- 475	- 5.2
29	"	- 200	- 4.4	"	- 200	- 7.3	"	- 75	- 4.4				"	- 475	- 5.2
30	"	- 250	- 5.2	"	- 200	- 7.3	"	- 50	- 2.9				"	- 500	- 5.4
31	"	- 325	- 6.8	"	- 125	- 4.5	"	-100	- 5.9				"	- 550	- 6.0
32	"	- 350	- 7.3	"	+ 50	+ 1.8	"	-100	- 5.9				"	- 400	- 4.3
33	"	- 275	- 5.7	"	+ 50	+ 1.8	"	-150	- 8.8				"	- 375	- 4.1
34	"	- 200	- 4.2	"	+ 100	+ 3.6	"	-250	-14.7				"	- 350	- 3.8
35	"	- 75	- 1.6	"	- 75	- 2.7	"	-200	-11.8				"	- 350	- 3.8
36	"	- 150	- 3.1	"	+ 50	+ 1.8	"	-350	-20.6				"	- 450	- 4.9
37	"	- 350	- 7.3	"	+ 50	+ 1.8	"	-350	-20.6				"	- 650	- 7.1
38	"	- 250	- 5.2	"	+ 100	+ 3.6	"	-425	-25.0				"	- 575	- 6.3
39	"	- 350	- 7.3	"	+ 75	+ 2.7	"	-275	-16.2				"	- 550	- 6.0
40	"	- 400	- 8.3	"	+ 75	+ 2.7	"	-300	-17.6				"	- 625	- 6.8
41	"	- 450	- 9.4	"	+ 25	+< 1.0	"	-300	-17.6				"	- 725	- 7.9

+ accretion
- erosion

Shoreline Changes

beach segment Sabine Pass-Bolivar Roads

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
42	"	- 575	- 12.0	"	0	0	"	-175	-10.3				"	- 750	- 8.2
43	"			"	0	0	"	-275	-16.2				"		
44	"			"	+ 100	+ 3.6	"	-250	-14.7				"		
45	"			1930 1956	0	0	1956 1974	-300	-16.7				"		
46	"	- 200	- 4.2	"	+ 50	+ 1.9	"	-250	-13.9				"	- 400	- 4.3
47	"	- 25	- 0.5	"	0	0	"	-200	-11.1				"	- 225	- 2.4
48	"	0	0	"	0	0	"	-175	- 9.7				"	- 175	- 1.9
49	"	0	0	"	0	0	"	-150	- 8.3				"	- 150	- 1.6
50	"	0	0	"	0	0	"	-175	- 9.7				"	- 175	- 1.9
51	"	0	0	"	+ 100	+ 3.8	"	-100	- 5.6				"	0	0
52	"	0	0	"	+ 125	+ 4.8	"	-125	- 6.9				"	0	0
53	"	0	0	"	+ 150	+ 5.8	"	-100	- 5.6				"	+ 50	+< 1.0
54	"	0	0	"	+ 150	+ 5.8	"	-125	- 6.9				"	+ 25	+< 1.0
55	"	+ 100	+ 2.1	"	+ 150	+ 5.8	"	-225	-12.5				"	+ 25	+< 1.0
56	"	+ 175	+ 3.6	"	+ 150	+ 5.8	"	-300	-16.7				"	+ 25	+< 1.0
57	"	+ 175	+ 3.6	"	+ 100	+ 3.8	"	-250	-13.9				"	+ 25	+< 1.0
58	"	0	0	"	+ 300	+ 11.5	"	-325	-18.1				"	- 25	-< 1.0
59	"	0	0	"	+ 275	+ 10.6	"	-125	- 6.9				"	+ 150	+ 1.6
60	"	+ 125	+ 2.6	"	+ 400	+ 15.4	"	+ 50	+ 2.8				"	+ 575	+ 6.3
61	"	+ 450	+ 9.4	"	+ 600	+ 23.1	"	+275	+15.3				"	+1325	+ 14.4
62	"	+1100	+ 22.9	"	+1075	+ 41.3	"	+400	+22.2				"	+2575	+ 28.0

+ accretion
- erosion

Vegetation Changes

beach segment Sabine Pass-Bolivar Roads

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	1930 1955	+ 225	+ 8.8							1955 1974			1930 1974		
2	"	- 625	- 24.5							"			"		
3	"	- 450	- 17.6							"			"		
4	"	+< 10	+< 1.0							"			"		
5	"	- 25	- 1.0							"	-450	-23.7	"	- 475	- 10.8
6	"	- 475	- 18.6							"	-325	-17.1	"	- 800	- 18.2
7	"	- 550	- 21.6							"			"		
8	"	- 850	- 33.3							"	-600	-31.6	"	-1450	- 33.0
9	"	-1025	- 40.2							"	-500	-26.3	"	-1525	- 34.7
10	"	-1250	- 49.0							"	-250	-13.2	"	-1500	- 34.1
11	1930 1956	-1200	- 46.2							1956 1974	-450	-25.0	"	-1650	- 37.5
12	"	- 775	- 29.8							"	-125	- 6.9	"	- 900	- 20.5
13	"	- 350	- 13.5							"	- 75	- 4.2	"	- 425	- 9.7
14	"	+ 100	+ 3.8							"	- 25	- 1.4	"	+ 75	+ 1.7
15	"	+ 75	+ 2.9							"	- 75	- 4.2	"	0	0
16	"	- 50	- 1.9							"	0	0	"	- 50	- 1.1
17	"	- 125	- 4.8							"	+100	+ 5.6	"	- 25	- 0.6
18	"	0	0							"	+ 50	+ 2.8	"	+ 50	- 1.1
19	"	+ 125	+ 4.8							"	+ 50	+ 2.8	"	+ 175	+ 4.0
20	"	+ 100	+ 3.8							"	0	0	"	+ 100	+ 2.3

+ accretion
- erosion

Vegetation Changes

beach segment Sabine Pass-Bolivar Roads

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	"	+ 100	+ 3.8							"	- 75	- 4.2	"	+ 25	+< 1.0
22	"	+ 25	+ 1.0							"	+ 75	+ 4.2	"	+ 100	+ 2.3
23	"	0	0							"	+ 75	+ 4.2	"	+ 75	+ 1.7
24	"	+ 25	+ 1.0							"	+ 25	+ 1.4	"	+ 50	+ 1.1
25	"	+ 125	+ 4.8							"	-175	- 9.7	"	- 50	- 1.1
26	"	+ 100	+ 3.8							"	-150	- 8.3	"	- 50	- 1.1
27	"	0	0							"	-100	- 5.6	"	- 100	- 2.3
28	1930 1957									1957 1974	-100	- 5.9	"		
29	"	- 225	- 8.2							"	- 50	- 2.9	"	- 275	- 6.3
30	"	- 150	- 5.5							"	+ 50	+ 2.9	"	- 100	- 2.3
31	"	- 150	- 5.5							"	+ 50	+ 2.9	"	- 100	- 2.3
32	"	- 125	- 4.5							"	+125	+ 7.4	"	0	0
33	"	- 100	- 3.6							"	+ 50	+ 2.9	"	- 50	- 1.1
34	"	- 150	- 5.5							"	0	0	"	- 150	- 3.4
35	"	- 200	- 7.3							"	+ 50	+ 2.9	"	- 150	- 3.4
36	"	- 150	- 5.5							"	0	0	"	- 150	- 3.4
37	"	- 200	- 7.3	1957 1965	- 50	- 6.3				1957 1974	- 25	- 1.5	"	- 225	- 5.1
38	"	- 150	- 5.5	"	- 50	- 6.3				"	- 50	- 2.9	"	- 200	- 4.5
39	"	- 200	- 7.3	"	0	0				"	- 50	- 2.9	"	- 250	- 5.7
40	"	- 25	- 0.9	"	- 50	- 6.3				"	-100	- 5.9	"	- 125	- 2.8
41	"	- 100	- 3.6	"	- 50	- 6.3				"	- 25	- 1.5	"	- 125	- 2.8

+ accretion
- erosion

Vegetation Changes

beach segment Sabine Pass-Bolivar Roads

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
42	"	- 100	- 3.6	"	- 25	- 3.1				"	+ 25	+ 1.5	"	- 75	- 1.7
43	"	- 100	- 3.6	"	- 75	- 9.4				"	-125	- 7.4	"	- 225	- 5.1
44										"	-125	- 7.4	"	- 175	- 4.0
45	1930 1956	- 100	- 3.8	1956 1965	- 150	- 16.7				1956 1974	-175	- 9.7	"	- 275	- 6.3
46	"	+ 50	+ 1.9	"	- 100	- 11.1				"	-175	- 9.7	"	- 125	- 2.8
47	"	+ 25	+ 1.0	"	- 50	- 5.6				"	- 50	- 2.8	"	- 25	-< 1.0
48	"	+ 50	+ 1.9	"	+ 75	+ 8.3				"	+ 75	+ 4.2	"	+ 125	+ 2.8
49	"	- 25	- 1.0	"	0	0				"	+125	+ 6.9	"	+ 100	+ 2.3
50	"	+ 100	+ 3.8	"	- 125	- 13.9				"	- 75	- 4.2	"	+ 25	+< 1.0
51	"	+ 200	+ 7.7	"	- 75	- 8.3				"	- 25	- 1.4	"	+ 175	+ 4.0
52	"	+ 75	+ 2.9	"	- 25	- 2.8				"	0	0	"	+ 75	+ 1.7
53	"	0	0	"	- 25	- 2.8				"	+ 75	+ 4.2	"	+ 75	+ 1.7
54	"	+ 150	+ 5.8	"	0	0				"	0	0	"	+ 150	+ 3.4
55	"	+ 50	+ 1.9	"	0	0				"	+ 25	+ 1.4	"	+ 75	+ 1.7
56	"	+ 25	+ 1.0	"	- 75	- 8.3				"	- 75	- 4.2	"	- 50	- 1.1
57	"	+ 50	+ 1.9	"	- 150	- 16.7				"	- 50	- 2.8	"	0	0
58	"	+ 150	+ 5.8	"	- 100	- 11.1				"	- 25	- 1.4	"	+ 125	+ 2.8
59	"	+ 250	+ 9.6	"	- 25	- 2.8				"	+175	+ 9.7	"	+ 425	+ 9.7
60										"	+ 300	+16.7			

APPENDIX B

Tropical Cyclones Affecting the Texas Coast 1854-1973

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

Intensity Classification from Dunn and Miller

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

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

APPENDIX C

List of Materials and Sources

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

Date		Source of Photographs
April-May 1930	*	Tobin Research Inc.
Dec. 1938		U. S. Dept. Agriculture
Dec. 1941		U. S. Dept. Agriculture
Sept. 1942		U. S. Army Corps Engineers
Nov. 1955-Oct. 1957	*	Tobin Research Inc.
Sept. 1961		Natl. Oceanic and Atmospheric Admin.
Oct. 1965	*	Natl. Oceanic and Atmospheric Admin.
July 1967		U. S. Army Corps Engineers
June 1974	*	Texas General Land Office

List of Maps Used in Determination of Shoreline Changes

Date	Description	Source of Maps
Jan.-May 1851	topographic map 329	Natl. Oceanic and Atmospheric Admin.
1882-83	topographic maps 1633, 1634, 1635, and 1636	Natl. Oceanic and Atmospheric Admin.
Mar.-June 1923	topographic maps 4057 and 4058	Natl. Oceanic and Atmospheric Admin.

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

Texas Point, Texas
Sabine Pass, Texas
Clam Lake, Texas
Star Lake, Texas
South of Star Lake, Texas
Mud Lake, Texas
High Island, Texas
Frozen Point, Texas
Caplen, Texas
Flake, Texas
The Jetties, Texas