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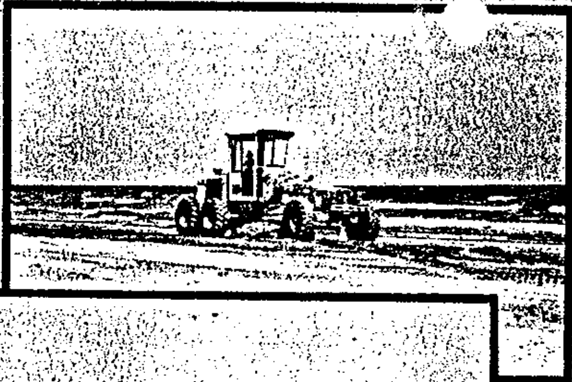
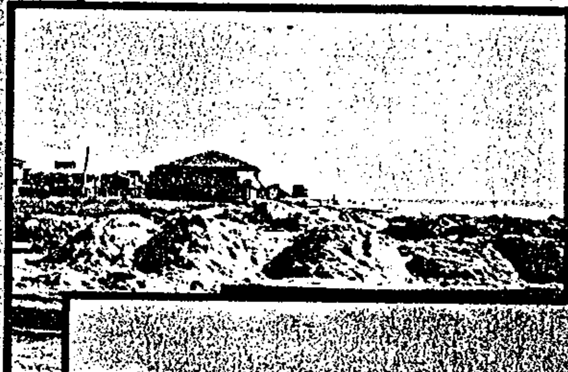
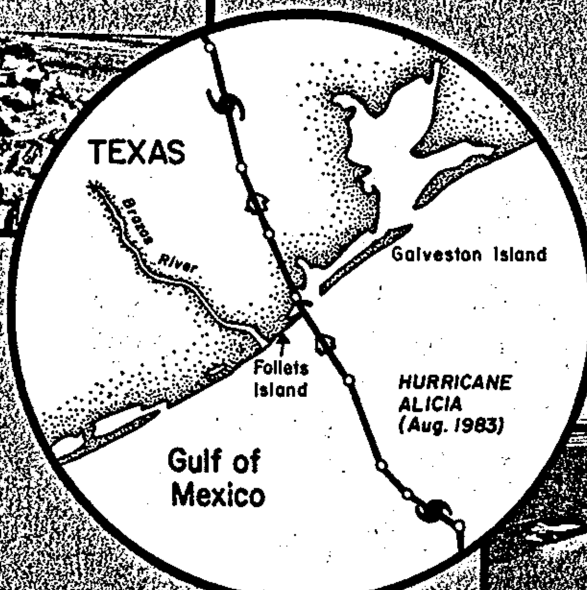




Beach and Vegetation-Line Changes at Galveston Island, Texas:
Erosion, Deposition, and Recovery from Hurricane Alicia



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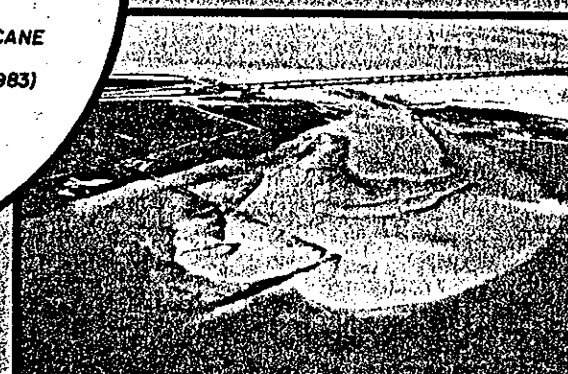

Bureau of Economic Geology
W. L. Fisher, Director
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Austin, Texas 78713

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Beach and Vegetation-Line Changes at Galveston Island, Texas:

Erosion, Deposition, and Recovery from Hurricane Alicia

by
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assisted by
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CONTENTS

ABSTRACT 1
INTRODUCTION 2
Purpose and objectives 2
General descriptions 2
METHODS 5
Aerial photographs 5
Beach profiles 6
Beach elevations 7
PRE-ALICIA SHORELINE STABILITY 7
Long-term trends 7
Short-term trends 7
HURRICANE ALICIA 8
Formation and development 8
Landfall 8
COASTAL EFFECTS OF HURRICANE ALICIA 9
Erosion 9
SHORELINE RETREAT 9
VEGETATION-LINE RETREAT 10
Natural beaches 12
Developed beaches 12
Unbulkheaded areas 12
Bulkheaded areas 13
ESTIMATED VOLUME OF SEDIMENT LOSS 13
Estimates from aerial photographs 14
Area of vegetation retreat 14
Depth of erosion 14
Volume of sediment loss (between vegetation lines) 14
Estimates from beach profiles 14
Washover deposition 14
NATURAL AREAS 15
DEVELOPED AREAS 16
VOLUME OF WASHOVER SEDIMENT DEPOSITED BY HURRICANE ALICIA 18
Storm-sediment budget 18
Post-storm runoff 18
POST-ALICIA BEACH CHANGES 19
Natural recovery 19
SAND TRANSPORT 20
Central zone 20
Eastern zone 20
Western zone 22
Volume of sand returned 22
VEGETATION CHANGES 22
Colonization of washover deposits 22
Vegetation-line changes 23
Human alterations 23
SAND REPLENISHMENT 23
SHORELINE PROTECTION 24
DUNE CONSTRUCTION 24
Effects of the Alvenus *oil spill* 25

COMPARISONS WITH OTHER STORMS 26
Storm surge 26
SURGE HEIGHT 26
SURGE DURATION 27
Vegetation-line retreat 27
Washover deposition 29
POTENTIAL FOR BEACH RECOVERY AFTER HURRICANE ALICIA 31
Phases of recovery 31
Factors that influence recovery 32
SEVERITY OF DAMAGE CAUSED BY HURRICANE ALICIA 32
STORM RECURRENCE AND STRENGTH 32
SHORELINE STABILITY 32
CLIMATIC VARIATIONS 33
HUMAN INTERFERENCE 33
Predictions for West Beach 34
ACKNOWLEDGMENTS 35
REFERENCES 36
APPENDIX A: Date, landfall location, and approximate tide height of tropical cyclones affecting Galveston Island, 1900 to 1984 37
APPENDIX B: List of aerial photographs used to document shoreline and vegetation-line changes and extent of washover deposition on Galveston Island 38
APPENDIX C: Movement of the vegetation line, 1958 to 1983, and inland extent of washover deposition caused by Hurricanes Carla (1961), Allen (1980), and Alicia (1983) at West Beach, Galveston Island 38

Figures

1. Location of study area 3
2. Generalized pre-storm profile of West Beach 4
3. Measuring stations, beach-profile sites, subdivisions, and stability of Gulf shoreline, Galveston Island 6
4. Gulf tidal elevations at Pleasure Pier, Galveston Island, during Hurricane Alicia 9
5. Undermined beach home landward of failed bulkhead, Sea Isle subdivision 10
6. a. Pre-Alicia vegetation line and b. post-Alicia erosional escarpment and vegetation line, West Beach 11
7. Vegetation-line retreat caused by Hurricane Alicia, West Beach 13
8. Remnants of a reinforced concrete bulkhead destroyed by Hurricane Alicia, Sea Isle subdivision 13
9. Thin layer of light-colored sand (Alicia washover deposits) covering dark, organic-rich soil zone 16
10. Profile of typical Alicia washover deposit along West Beach 16
11. Inland extent of washover deposition from Hurricane Alicia, West Beach 17
12. Storm-runoff drainage channel on Follets Island 1 week after Hurricane Alicia 19
13. Profile of dune ridge on Follets Island 19
14. Pre- and post-Alicia beach profiles 21
15. Sprigs of vegetation colonizing the backbeach near Indian Beach 23
16. Post-Alicia view of Jamaica Beach subdivision 24
17. Highest monthly tides observed at Pier 21 on the bay side of Galveston Island, 1908 to 1983 26
18. Storm surge height and duration, Galveston Island 27
19. West Beach vegetation-line retreat caused by Hurricanes Carla, Allen, and Alicia 28
20. Incremental and cumulative West Beach vegetation-line changes, 1958 to 1983 30
21. Inland extent of Carla, Allen, and Alicia washover deposition, West Beach 31
22. Sequential movement of vegetation line from 1961 to 1985 in a developed area 34
23. Sequential movement of vegetation line from 1961 to 1985 in an undeveloped area 34
24. Sequential movement of vegetation line from 1942 to 1985 in an undeveloped area east of Pirates Beach 35

Tables

1. Vegetation-line retreat between June 10, 1982, and August 22, 1983, along West Beach 12
2. Loss of ground elevation due to Hurricane Alicia at West Beach 14
3. Volumes of sand erosion and subsequent depositional recovery of West Beach 15
4. Inland extent of washover deposits in natural, recreational, developed, and bulkheaded areas along West Beach 17
5. Comparison of vegetation-line retreat and inland washover extent caused by Hurricanes Carla, Allen, and Alicia along West Beach 29

ABSTRACT

On August 18, 1983, Hurricane Alicia crossed the upper Texas Gulf Coast and caused extensive property damage, especially along West Beach of Galveston Island. Aerial photographs taken before and after Alicia and field measurements made during the first 2 yr after the storm provide a basis for determining nearshore changes associated with a major hurricane and for predicting potential beach recovery. Alicia caused substantial landward retreat of both the shoreline and the vegetation line. Retreat of the vegetation line ranged from 20 to 145 ft and averaged about 80 ft. Erosion was generally greatest near the Sea Isle and Bay Harbor subdivisions, where storm processes were most intense; beach erosion generally decreased away from San Luis Pass, which is near the site of storm landfall. Surface elevations were lowered as much as 4.5 ft, and many Gulf-front houses were undermined and exposed on the beach after the storm.

Alicia eroded more than 2 million yd^3 of sand from West Beach. About one-tenth of that sand was deposited on the adjacent barrier flat as a washover terrace. Washover penetration was greatest to the east of the storm's eye and along developed shoreline segments. The remaining eroded beach sand was deposited offshore as shoreface bars or as storm deposits on the inner shelf. The shoreface deposits promoted rapid forebeach accretion during the first post-storm year; at the same time the backbeach elevation remained about 2.5 to 3 ft lower than before the storm, and the natural post-Alicia vegetation line remained essentially unchanged. Recovery of the vegetation line 2 yr after the storm was insignificant, mainly because the depth of beach erosion exceeded root depth, thus eliminating plants from some areas that were densely vegetated before the storm.

Natural seaward advancement of the forebeach after Alicia was accompanied by diverse and widespread human alteration of the backbeach in developed communities. These modifications principally involved spreading sand fill, repositioning storm rubble, constructing bulkheads, building artificial dunes, planting dune grasses, watering and fertilizing the grass, and erecting sand fences. These human modifications tended to obscure the natural vegetation line and to narrow the beach.

Hurricane Alicia (1983) caused more beach erosion than did Hurricane Allen (1980) but less than Hurricane Carla (1961). Although the vegetation line returned to its pre-Carla position in some West Beach areas, it did not fully recover along most segments because of long-term beach erosion. As in the past, future recovery of the vegetation line will depend on severity of storm damage, storm recurrence and strength, shoreline stability, and coastal climate. This study shows that beach erosion caused by Alicia was substantial, that the Gulf beach of Galveston Island is frequently influenced by storms, and that much of West Beach is eroding. Therefore, natural recovery of the vegetation line to its pre-storm position is unlikely along eroding segments, and substantial seaward advancement even along relatively stable shoreline segments will take several years. Some human activities in developed areas have artificially raised the backbeach and advanced the vegetation line nearly to its pre-storm position. Such manipulation will be difficult to detect as dunes grow and vegetation density increases.

Historical records clearly show that Galveston beachfront property will receive minor storm damage every few years and extreme storm damage about every 20 yr. Frequent storms and long-term beach erosion are important considerations when planning for future use of the beach and barrier island.

Keywords: barrier islands, beach profiles, coastal geology, Galveston Island, Hurricane Alicia, shoreline changes, storm processes, Texas Gulf Coast, vegetation-line changes

INTRODUCTION

On August 18, 1983, Hurricane Alicia crossed the upper Texas Gulf Coast (fig. 1), causing unsurpassed economic losses. Alicia was neither the first storm to strike Galveston Island (appendix A) nor the first to emphasize the hazards of building on a barrier island. The 1900 hurricane was larger and more deadly than Alicia, but Alicia was the first Texas storm in recent history that damaged or destroyed much of the beachfront property in its path. Strong winds, waves, and currents devastated residential and commercial buildings while reshaping the island's sandy surface. As a result of the widespread destruction, the nation's attention was briefly turned to the dramatic beach changes and attendant legal issues that confronted the State and littoral property-owners.

The tremendous physical energy released by the storm was surpassed only by the human energy spent to rebuild the island and to resolve the flood of legal controversies that accompanied retreat of the beach and vegetation line. This litigation will undoubtedly set precedents for future disputes concerning ownership and use of Texas Gulf beaches. However, similar dilemmas will probably recur as long as public and private property rights are partly defined by shifting littoral boundaries that respond to the dynamic forces of nature.

Purpose and Objectives

A previous study of the Gulf coast along Galveston Island (Morton, 1974) briefly described the influence of tropical cyclones on the shoreline and vegetation line. Coastal boundaries mapped on post-storm aerial photographs were excluded from that report so that time-averaged boundary movement documented for nonstorm periods would be reasonably accurate. In contrast, the current report focuses on nearshore changes caused by storms and post-storm responses of the beach and vegetation line. Although the study area includes the upper Texas coast from High Island to Sargent Beach (fig. 1), emphasis is placed on the changes that occurred along West Beach of Galveston Island.

The purposes of this circular are (1) to document Alicia's impact on Galveston Island and Follets Island (fig. 1), (2) to place those changes in the context of storm history and shoreline stability, (3) to establish the magnitude of beach erosion, washover deposition, and vegetation-line retreat for a specific storm, (4) to record the initial phases (first 2 yr) of post-storm recovery, and (5) to discuss the factors that will influence future movement of the vegetation line. In a broader sense, this publication serves as a basis for comparing future changes in the co-extensive geological and legal boundaries that border the Texas Gulf shoreline.

High-density beach communities along other segments of the Texas coast are at least as vulnerable to storm damage. Therefore, conclusions drawn from data presented here are applicable to other coastal areas where protection from high winds, large waves, and strong currents is inadequate.

General Descriptions

References to the beach and vegetation line in this report conform to standard geological definitions (Bates and Jackson, 1980). The beach encompasses the area of barren sand between mean low water and the vegetation line (fig. 2). Beaches that are in equilibrium with the local wave climate can be subdivided into forebeach and backbeach on the basis of surficial slope and physical processes. The forebeach includes the area covered by water during the normal tidal cycle; thus it is also commonly known as the wet beach. The forebeach is influenced by wave uprush and spring tides that produce a slightly steeper slope on the forebeach than on the backbeach. The flatter backbeach is also known as the dry beach because its surface elevation (approximately 3 to 5 ft) prevents inundation except by abnormally high tides or storm waves.

The frequency of erosional and depositional cycles along the beach depends on the surface elevation and proximity to waves. Forebeaches are low, form near the water, and consequently change position throughout the year as wind and wave conditions fluctuate. In contrast to forebeaches, backbeaches are slightly higher, farther from the water, and less exposed to waves and nearshore currents. Dunes have the highest elevations along the beach and therefore are not susceptible to minor fluctuations in water level and wave energy.

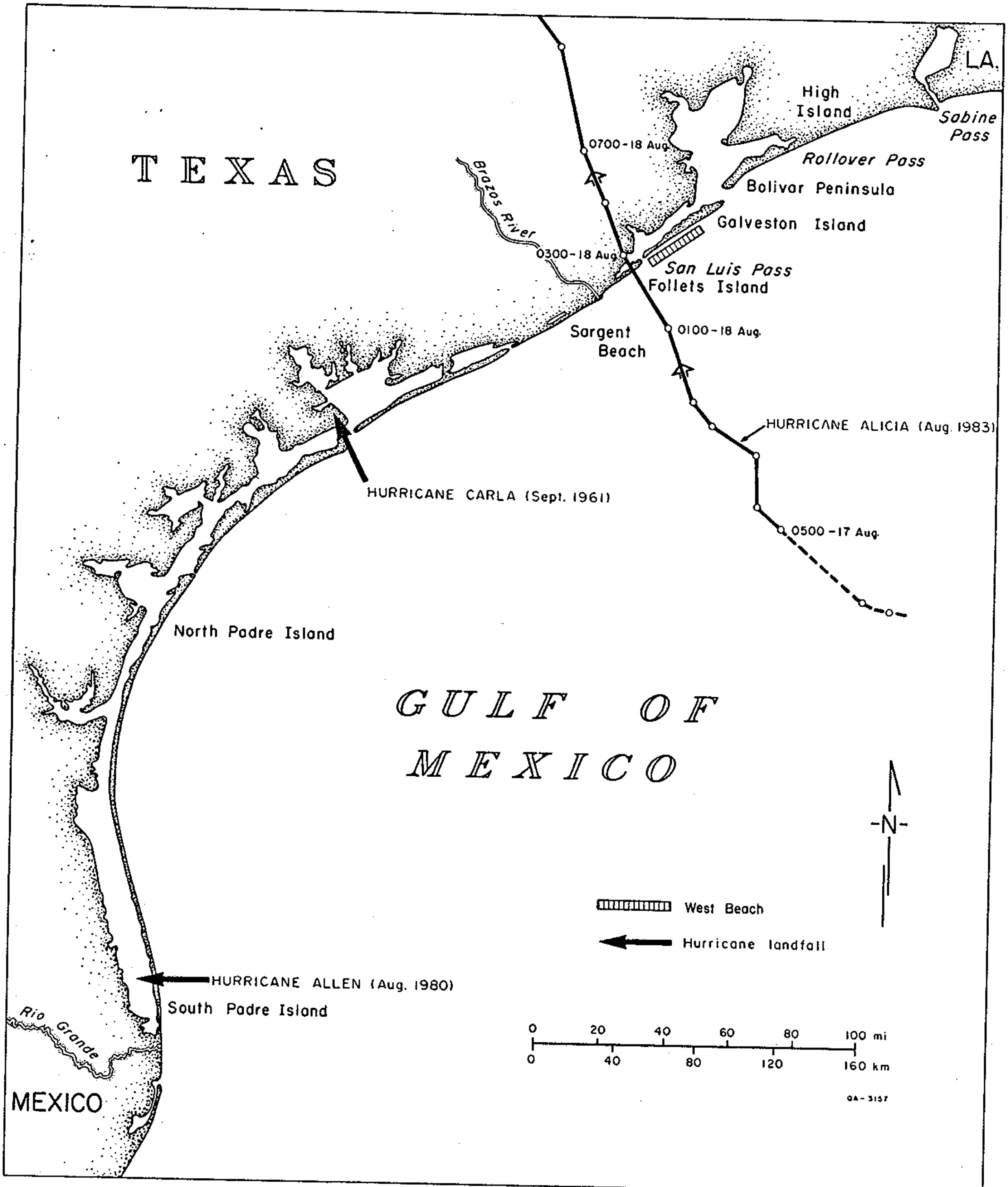

Figure 1. Location of study area (West Beach), geographic features, and sites of recent hurricane landfall along the Texas Gulf Coast.

Normally storm surges must exceed 4 ft, an infrequent event, before dunes are severely eroded by Gulf waters. Washover occurs when the terrain landward of the backbeach is overtopped by breaking storm waves. During this inundation, strong currents flow landward and form fans composed mainly of sand and shell. In this context, washover refers both to the process and to the sedimentary deposit.

The position of the vegetation line (fig. 2) also depends on elevation and frequency of beach flooding. Indigenous dune vegetation, mostly perennial grasses, tolerates some salt spray but dies after prolonged exposure to salt water. Consequently, the line of natural vegetation that spreads continuously inland usually coincides with the foredunes, if any exist, or with other elevated areas landward of the backbeach, such as washover terraces.

Vegetative ground cover landward of the backbeach can be either sparse or dense, depending on previous storm history, climatic cycle, and human activities. Also, the amount of ground cover may vary from one site to another at a given time or can change through time at a given site. Immediately after a storm, the vegetation line may be poorly defined because of burial by washover sand, or it may be an abrupt, distinct boundary that coincides with the erosional escarpment. In periods of low storm frequency, the seaward limit of vegetation tends to be irregular because the vegetation is restricted to sparse, isolated clumps growing on low sand mounds. These coppice mounds (fig. 2), or embryonic dunes, form in the backbeach and eventually broaden and gain elevation if sediment supply and eolian processes encourage dune growth. Because coppice mounds occupy the transition zone of the backbeach, they may be swept away by waves and strong currents during storms, or they may be relatively stable during nonstorm periods. Under the former conditions, the coppice mounds may be partly or entirely destroyed, whereas under the latter conditions they may coalesce to form more stable dune ridges. Because sparse vegetation may or may not be present and because dense vegetation is present in most areas and under most circumstances, mapping the seaward limit of natural continuous vegetation maintains consistency from area to area and from one time period to another.

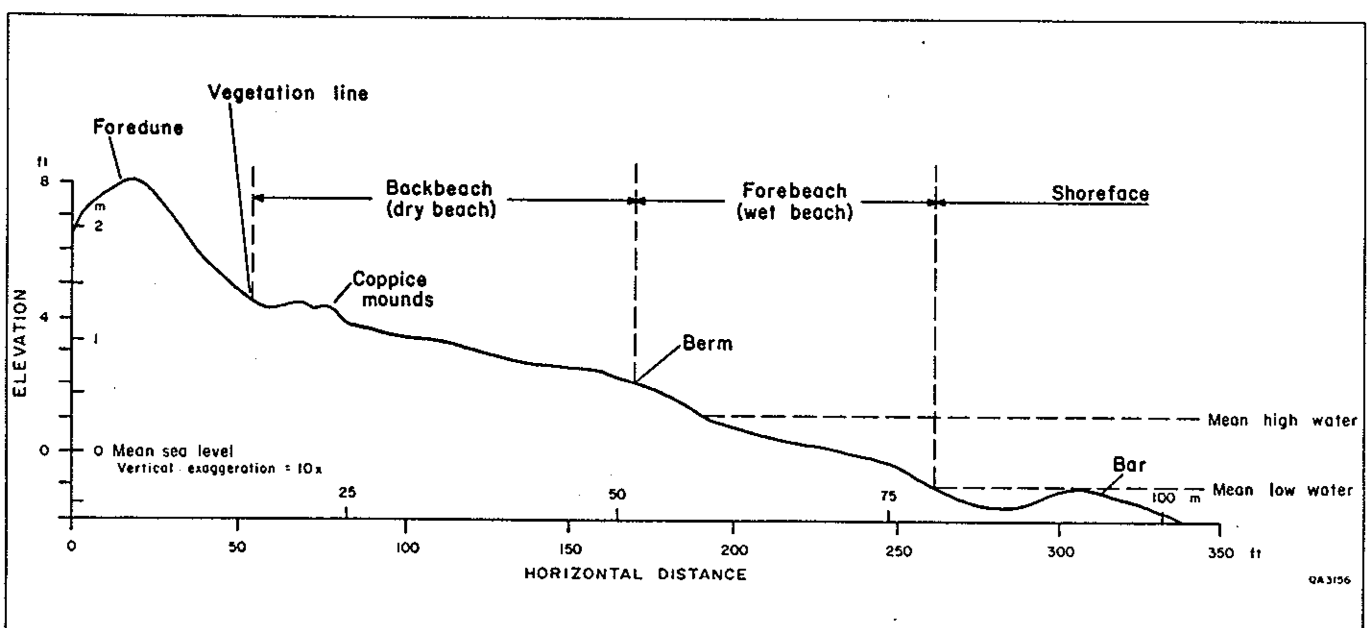

Figure 2. Generalized pre-storm profile of West Beach showing morphological subdivisions of the beach and related tidal and physiographic boundaries.

METHODS

Aerial photographs, beach profiles, and site-specific beach elevations were used to document beach and vegetation-line changes caused by Hurricane Alicia. Aerial photographs were also used to compare Hurricane Alicia with other storms that have affected the upper Texas coast. Each type of information has a unique set of advantages, disadvantages, and sources of error.

Aerial Photographs

Aerial photographs of West Beach (and some adjacent areas) were used to establish the position of the shoreline and vegetation line and the areal extent of storm washover. Many photographic missions have been flown over Galveston Island since 1930; photographs selected for this study were taken around the dates of major storms. Hurricane Alicia was the primary focus of the study, but understanding the consequences of Alicia necessarily involves assessment of other events affecting the area, including in particular Hurricanes Carla (1961) and Allen (1980). Ideally, an area of interest would be photographed immediately before a storm to establish baseline conditions, immediately after a storm to document the effects of the storm, and at some regular interval until the next storm to allow documentation of coastline recovery.

Aerial photographs used in this study were obtained from various sources (appendix B). Features were mapped and measurements were made on photographs taken before Carla (1958), immediately after Carla (1961), before Allen (1979), immediately after Allen (1980), before Alicia (1982), and immediately after Alicia (1983). Other photographs were used to document local changes and intermediate vegetation-line positions.

All the photographs used for mapping were enlarged to a common scale (approximately 1:6,000, or 1 inch = 500 ft). Transparent overlays were attached to individual prints and relevant features were mapped. Position of the vegetation line, landward and seaward boundaries of washover deposits, and in some areas the landward edge of the wet beach were mapped on post-storm photographs. Washover deposits do not appear and were not mapped on pre-storm photographs.

To compare vegetation lines among sets of photographs, all lines were optically transferred (with a Saltzman projector) to overlays on the post-Alicia photographs. This technique compensates for scale changes across a single photograph (caused by lens aberration or airplane tilt) and between photographs by changing the scale of the projected image until it precisely matches the image onto which the projection is made.

Vegetation-line changes between periods and washover extent on post-storm photographs were calculated in two ways. The first method allowed determination of vegetation-line changes or washover width at a given point along the shoreline. Measuring points (fig. 3 and appendix C) were spaced approximately 1,250 ft apart along West Beach, and measurements were made between successive positions of the vegetation line at each point. Additionally, the distance between the landward and seaward edges of washover deposition was measured on post-storm photographs. In the second method, the area between vegetation lines of different periods (as in the area between the pre-storm and post-storm vegetation lines) and the area of washover deposition mapped on post-storm photographs were determined.

The microrule used to measure distances can be read to 0.001 inch. At the photographic scale used in this study, 0.001 inch corresponds to 0.5 ft. Measurements could conceivably be made to that precision; practically, the accuracy of the measurements is much lower. Measurements were rounded to the nearest 5 ft because of boundary uncertainty, minor mislocation during optical transfer, and the thickness of the mapped lines. Considering these uncertainties, measurements made at points along West Beach (appendix C) should be accurate to within 10 ft.

Areas were measured directly by a two-arm planimeter. Planimetering errors include those mentioned for the first method as well as differences in path of the planimeter from the region's perimeter. Repeated measurements of a known area show that areas can be determined to within an accuracy of about 5 percent.

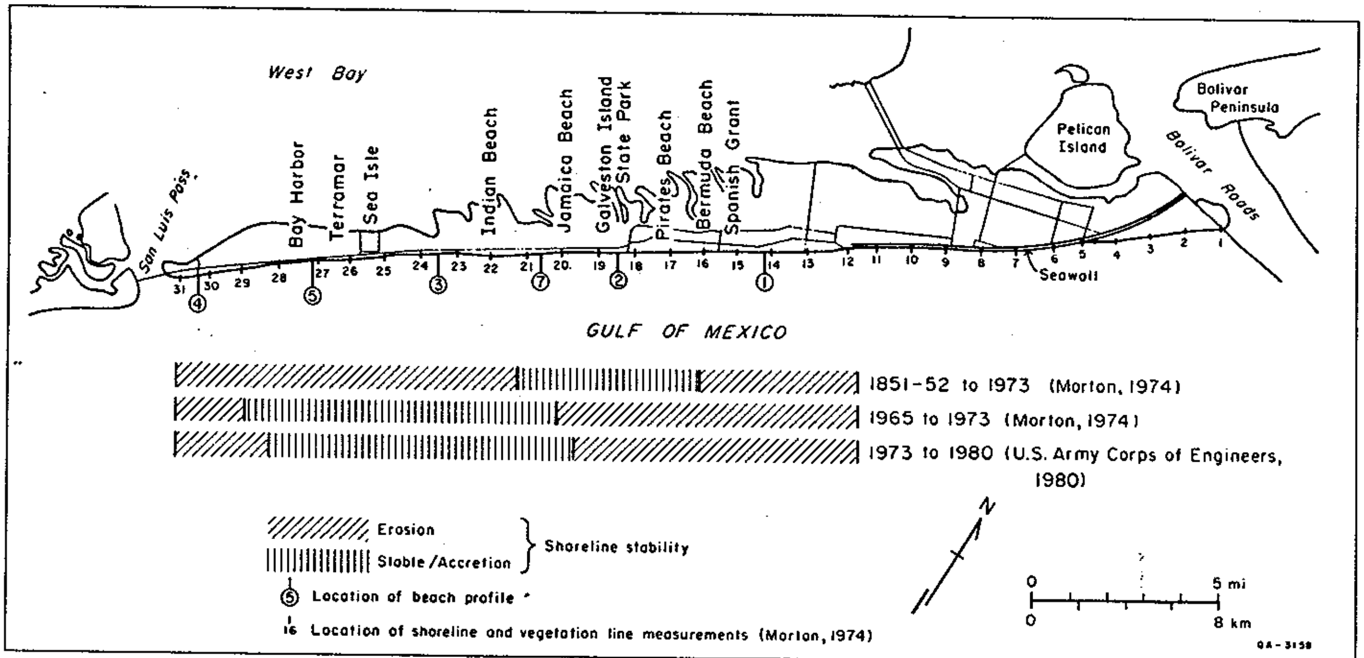

Figure 3. Measuring stations, beach-profile sites, subdivisions, and stability of Gulf shoreline, Galveston Island. Numbered measuring stations (appendix C) spaced approximately 5,000 ft apart; intermediate stations, spaced approximately 1,250 ft apart, are not shown here but are included in appendix C.

Point measurements give site-specific information, facilitate the recognition of trends along the shoreline, and, when integrated, allow crude area approximations. The planimeter provides more accurate area estimates and is thus desirable for volume calculations.

Beach Profiles

Beach changes can be calculated from profiles measured at the same location on different dates. Changes in cross-sectional area then can be multiplied by shoreline length to obtain an estimate of sand-volume change between the dates of the profiles.

Six profile sites were established on West Beach (fig. 3) to monitor beach changes after Hurricane Alicia. The sites were first visited in December 1983 and were subsequently revisited in February, May, August, and December 1984 and February, May, and August 1985. The December 1983 profiles were completed more than 3 mo after landfall of Alicia. Sand deposited during this initial recovery phase was estimated by comparing the December profiles with post-storm profiles conducted by Louisiana State University in August 1983.

Estimates of sand volume eroded from West Beach by Hurricane Alicia were obtained by comparing the post-storm profiles with nearby pre-Alicia profiles completed by the U.S. Army Corps of Engineers (1980). Minor uncertainties in the comparison arise from two sources. First, U.S. Army Corps of Engineers profiles were selected to correspond as closely as possible to the location of post-Alicia profiles; however, none of the profiles occupied exactly the same location. The differences visible in pre-storm profiles from one location and post-storm profiles from a slightly different location could be caused by actual beach changes or by the variability in beach morphology between locations. Because pre- and post-storm profiles were close (ranging from 200 to 2,900 ft apart) and because beach morphology is similar for short distances along West Beach, the comparisons appear valid. Second, the most recent Corps of Engineers profiles were completed in February 1980; therefore, comparisons between those profiles and post-Alicia profiles also include the effects of Hurricane Allen (August 1980) and may slightly overestimate erosion attributable to Alicia. The overestimation, if any, probably is small because (1) Allen made landfall near Brownsville, causing relatively minor erosion along

Galveston Island, and (2) 3 yr elapsed between Allen and Alicia, allowing sufficient time for much of the eroded material to return to West Beach.

Beach Elevations

Beach-elevation measurements are similar to beach profiles in that they record vertical beach changes. Profiles document elevation changes along a line, whereas beach-elevation measurements only provide elevation changes at a point. Elevation measurements were made on West Beach structures that were landward of the vegetation line before Hurricane Alicia but were at least partly seaward of the post-Alicia vegetation line.

Most beachfront structures are supported by pilings buried several feet in the sand. The depth of erosion by Hurricane Alicia was estimated by measuring the vertical distance between the post-storm beach and the pre-storm ground level, which was visible on many of the exposed pilings.

If the depth of erosion in an area is known, then the volume of sand lost can be calculated and compared to the estimate obtained from pre- and post-storm profiles. Beach-elevation measurements, however, can be used only to estimate the volume eroded between the pre- and post-storm vegetation lines because all the structures on which elevation measurements were made were landward of the pre-Alicia vegetation line. Beach-elevation measurements also contributed site-specific information about magnitude of backbeach deposition during the recovery from Hurricane Alicia.

PRE-ALICIA SHORELINE STABILITY

The impact of Hurricane Alicia on Texas beaches and the potential for recovery of those beaches are best understood in the context of shoreline stability during the preceding 20-yr period, when few storms affected Galveston Island. Morphology of the post-storm beach profile and the magnitude of beach change differ among eroding, accreting, and stable beaches.

Long-Term Trends

Shoreline positions compiled from topographic maps and aerial photographs spanning more than 120 yr (1851 to 1973) delineate three shoreline segments (fig. 3) exhibiting different long-term movement. These prominent segments reflect the net changes in shoreline position during the period for which accurate records are available. Both distances and rates of long-term erosion were greatest (10 ft/yr) in the easternmost segment just west of the seawall; erosion rates within this segment diminished westward to about 1 ft/yr at Bermuda Beach, which was transitional with the stable shoreline segment. Rates of change recorded in the middle segment were all less than 1 ft/yr, which suggests a relatively stable shoreline. Long-term erosion rates in the westernmost segment were 1 to 2 ft/yr (Morton, 1974).

Short-Term Trends

Two independent sources of data provide a basis for comparing sequential shoreline movement along Galveston's West Beach between 1965 and 1980. Morton (1974) used aerial photographs taken in 1965 and 1973 to determine short-term shoreline movement along West Beach (fig. 3). These photographs identify an erosional segment extending 8 mi west of the seawall, a stable or slightly accretionary 8-mi segment between Jamaica Beach and Bay Harbor, and a highly erosional segment extending 2.5 mi east from San Luis Pass. Subsequent surveys by the U.S. Army Corps of Engineers (1980) document shoreline changes using beach profiles along West Beach taken from 1973 to 1980. These profiles also show three zones of shoreline movement (fig. 3) that agree closely with those described above. The profiles show differences not only in shoreline position but also in elevation. For example, the stable shoreline segment was characterized by breaker-bar migration, deposition of sand on the backbeach, and vertical aggradation of 2 ft or less, whereas movement of the shoreline at the mean sea level (m.s.l.) datum was negligible.

A qualitative assessment of physical coastal processes and sediment budget explains the pattern of shoreline movement on West Beach. Persistent erosion near the seawall is attributed to insufficient sediment supply and abundant energy; the energy is generated by breaking waves and littoral currents that are capable of suspending and transporting a substantial volume of sand. The absence of a wide sand beach along the seawall means that sand eroded from the nearest unprotected beach, which is adjacent to the western end of the seawall, will not be replaced by longshore processes (Morton, 1974). Littoral currents transport this sand southwestward where it supplies downdrift beaches and helps maintain a stable shoreline between Jamaica Beach and Bay Harbor. Beach erosion near San Luis Pass may also contribute minor amounts of sand to mid-island beaches by periodic littoral-drift reversals.

The stable beach segment also coincides with an arcuate offshore trend of coarse clastic sediment that delineates a submerged ancestral shoreline (Morton and Winker, 1979). This coarser sediment and the substantial thickness of underlying barrier-core sand (Bernard and others, 1970; Morton and Nummedal, 1982) may minimize erosion along the middle part of West Beach by contributing sand to the littoral system. However, the zone of beach stability or minor accretion cannot be maintained indefinitely because shore alignment and wave refraction would eventually cause recession of the formerly stable segment. If a stable or accreting beach is flanked by eroding beaches, a protuberance would eventually form; wave energy focused on the protuberance ultimately would cause beach erosion and straightening of the shoreline. Progressive westward shifting of the stable shoreline segment (fig. 3) probably reflects realignment of the shoreline in response to long-term erosion of adjacent segments. Therefore, the most recent stable trends experienced along the middle part of West Beach may not be indicative of future responses to existing natural conditions.

Average rates of shoreline change convey the incorrect impression of uniform movement, and they depend on the time period for which they are calculated. Because of these limitations, rates of change are subordinate to directions as indicators of actual shoreline fluctuations. Despite their limitations, calculated rates of change are useful for making comparisons and for determining the relative magnitude of change. Average rates of shoreline erosion reported for an earlier period (1965-1973) from analysis of aerial photographs (Morton, 1974) compare reasonably well to erosion rates calculated for the later period (1973-1980) from beach profiles (U.S. Army Corps of Engineers, 1980). Both data sets show shoreline retreat of 20 ft/yr near the western end of the seawall, diminishing to a few ft/yr near Jamaica Beach and erosion of greater than 20 ft/yr east of San Luis Pass. Because the previously reported directions and rates of change compare favorably with subsequent independent measurements, it is assumed that both data sets accurately depict shoreline movement for the 15-yr period (1965-1980) of low storm frequency that preceded Hurricanes Alicia and Allen.

HURRICANE ALICIA

Formation and Development

In the afternoon of August 15, 1983, the National Weather Service reported the formation of a tropical depression in the north-central Gulf of Mexico. By 5 p.m. c.d.t. on the same day, this depression became Tropical Storm Alicia, located 375 mi east of Corpus Christi. Maximum sustained winds were 45 mph; the storm was moving westward at 10 mph.

By 5 p.m. on August 16, reports of sustained winds up to 80 mph caused Alicia to be reclassified as a category 1 hurricane, capable of minimal damage (Simpson and Riehl, 1981). Alicia moved toward the Texas coast during the night of the 16th, but did not intensify appreciably. On the morning of the 17th, maximum sustained winds were still 80 mph and the center of the storm was 90 mi south-southeast of Galveston (fig. 1) and moving west-northwest. At that time the National Hurricane Center predicted tides of 5 ft above normal for the upper Texas coast. Alicia again strengthened during the morning of the 17th and by 1 p.m. became a category 2 hurricane (capable of moderate damage) having sustained winds of 100 mph and a central pressure of 974 millibars (mbar). Tide estimates were increased to 10 ft above normal for the landfall area. Alicia was stationary for most of the day but resumed its northwesterly track in the evening. Intensification continued throughout the evening of the 17th; maximum tides were estimated to be to 12 ft above normal near landfall.

Landfall

Before landfall, maximum sustained winds increased to 115 mph and central pressure dropped to 963 mbar, making Alicia a category 3 hurricane (capable of extensive damage).

Early in the morning of August 18, the center of Alicia crossed the Texas coast near San Luis Pass (fig. 1), causing winds of up to 102 mph in Galveston and 80 mph in Houston.

Counterclockwise air circulation of northern hemisphere hurricanes increases water levels to the right of the storm's path. Because the center of Alicia passed southwest of Galveston, the island was subjected to higher tides and sustained more damage than other coastal areas. Predictions of tides 12 ft above normal near landfall were accurate; a still-water elevation of 12.7 ft above m.s.l. was measured at San Luis Pass, and water elevations of 6.5 to 11.0 ft above m.s.l. were measured along the gulf side of Galveston Island (U.S. Army Corps of Engineers, 1983a). Flood elevations (fig. 4) were generally lower west of the storm (5 to 9 ft above m.s.l. along most of Follets Island) and farther from the center (7 to 9 ft above m.s.l. along Bolivar Peninsula).

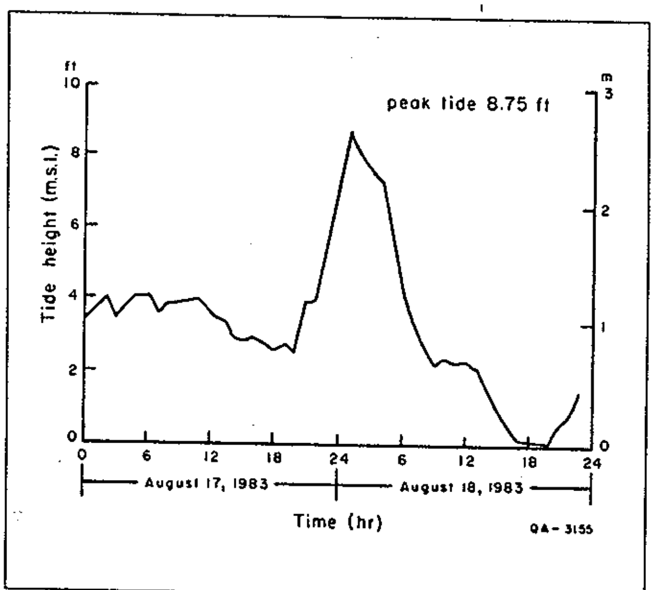

Figure 4. Gulf tidal elevations at Pleasure Pier, Galveston Island, during Hurricane Alicia. Data from National Ocean Service.

COASTAL EFFECTS OF HURRICANE ALICIA

The approach and passage of Hurricane Alicia brought high winds and tides, powerful waves, and strong water currents to Galveston Island. Winds caused extensive damage to structures; however, tides, waves, and attendant nearshore currents more effectively moved unconsolidated beach sand and reshaped the island. The most notable morphological changes occurred along the Gulf shore of the island, where the storm eroded sand from the beach, pushed the seaward limit of vegetation landward, transported beach sand offshore to calmer waters, and moved sand across the vegetation line to form washover deposits.

Erosion

Erosion of sand from the beach during Hurricane Alicia caused both shoreline and vegetation-line changes. Both lines moved landward during the storm; however, at most points vegetation-line retreat and shoreline retreat were unequal. The net result of unequal shoreline and vegetation-line changes is a change in beach width. If the vegetation line retreats less than the shoreline, the beach temporarily narrows; conversely, if the vegetation line retreats more than the shoreline, the beach temporarily widens.

Two types of information (aerial photographs and beach profiles) were used to quantify beach erosion caused by Hurricane Alicia. Pre- and post-storm shorelines and vegetation lines were visible on aerial photographs, allowing measurement of retreat at any point along Galveston Island. Additionally, aerial photographs allowed the calculation of the total area of vegetation-line retreat. Beach profiles also can be used to calculate vegetation-line and shoreline retreat at a point, but they primarily allow the detection of vertical beach changes. Combining the two types of information allows calculations made from one set of data to be verified independently by the other.

Because vegetation-line changes and shoreline changes are not necessarily the same at any point and because data were derived mainly from aerial photographs, shoreline and vegetation-line changes are described separately. The position of the vegetation line is more easily and accurately determined than is the position of the shoreline; consequently, the vegetation line was studied in more detail.

SHORELINE RETREAT

The greatest loss of sand occurred on the beach, lowering elevations considerably (fig. 5) and removing part of the vegetated zone (figs. 6a and b). The generally lower beaches

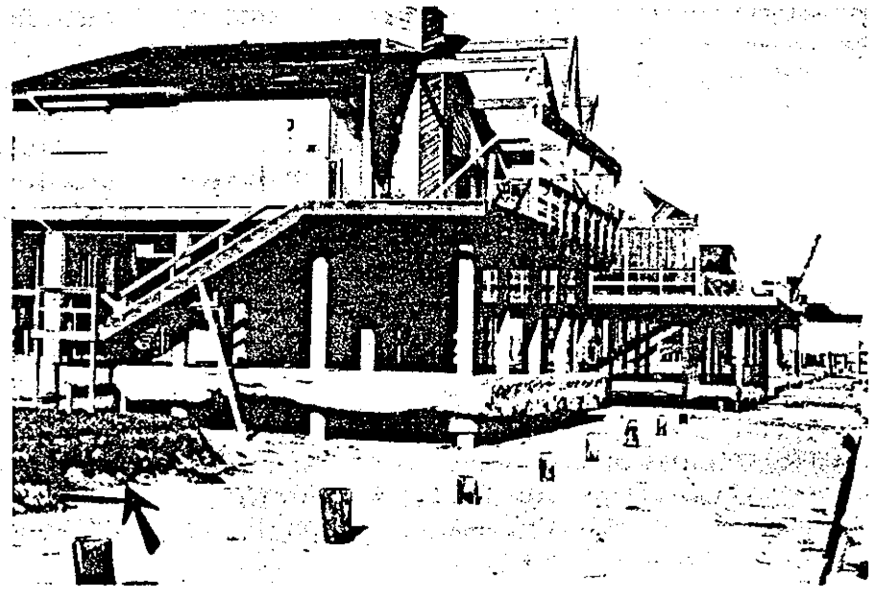

Figure 5. Undermined beach home landward of failed bulkhead, Sea Isle subdivision. Erosional escarpment visible at lower left (see arrow).

allowed normal high tides to reach farther inland than they did before the storm. Indeed, many West Beach structures that were landward of the continuous vegetation line before the storm were on the beach and within reach of normal tides after the storm (fig. 5).

Amount of shoreline retreat is difficult to determine precisely from aerial photographs for several reasons. First, the tidal stage is normally different on different sets of photographs; thus even a stable beach has varying shoreline positions at different times. Second, the flatter post-storm beach profile results in a greater range of shoreline positions for normal tides. Third, several distinct lines appear on aerial photographs in the beach zone from the vegetation line seaward. These lines include wave-uprush-debris lines, the landward edge of the wet beach, and the water's edge. Probably the most consistent and recognizable beach boundary is the landward edge of the wet beach (fig. 2). This boundary separates the forebeach from the backbeach and marks the position of the most recent high tide. Comparing the edge of the wet beach on photographs requires the assumption that the last high tide on both sets was similar. This assumption is not completely valid because of minor differences in beach slope, wave runup, and water level.

The landward edge of the wet beach was mapped on two sets of Galveston Island aerial photographs; one set was taken before Hurricane Alicia (June 10, 1982) and the other was taken after the storm (August 22, 1983). The wet beach is much wider on the post-storm photographs (owing to the flatter profile), but in both sets of photographs the landward edge is visible. The approximate distance between the 1982 wet-beach edge and the post-storm wet-beach edge was determined at 74 locations between the west end of the Galveston seawall and San Luis Pass.

Pre- and post-storm photographs reveal wet-beach retreat of 10 to 250 ft between the seawall and San Luis Pass. Severe shoreline erosion (150 ft) occurred near San Luis Pass, 150 ft or less having been observed between the pass and Bay Harbor. Wet-beach retreat was greatest (150 to 250 ft) near the Bay Harbor, Sea Isle, and Terramar subdivisions. From there eastward, erosion generally decreased with distance from storm landfall. Wet-beach retreat near the seawall ranged from 50 to 100 ft.

VEGETATION-LINE RETREAT

The boundary on or near the beach that is consistent regardless of the tide or season is the vegetation line (figs. 6a and 6b). Like the shoreline, it is also a dynamic boundary; however, it changes imperceptibly from day to day under normal conditions. Under extreme conditions, such as during a hurricane, it can move rapidly landward tens or hundreds of feet as a result of beach erosion. In the aftermath of a hurricane, several years may pass as coastal processes gradually increase backbeach

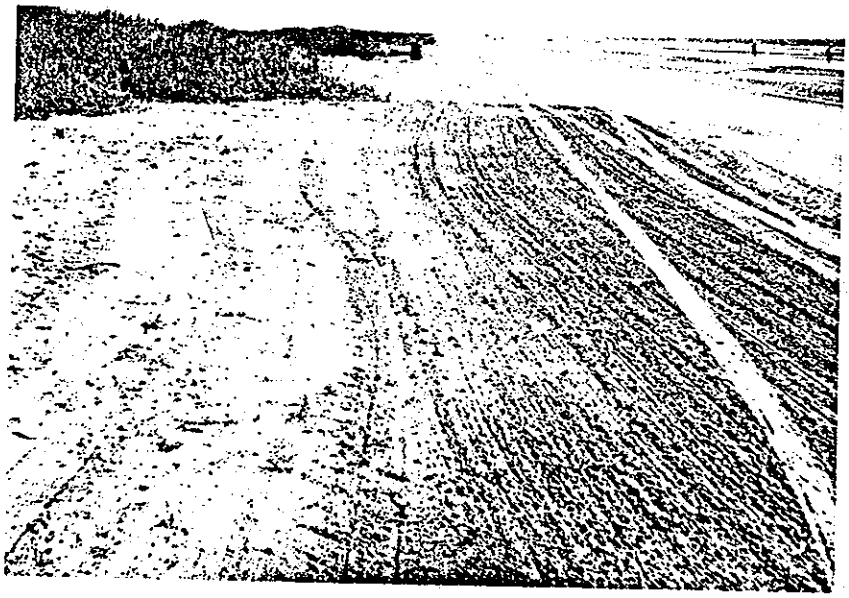

Figure 6a. Pre-Alicia vegetation line, West Beach.

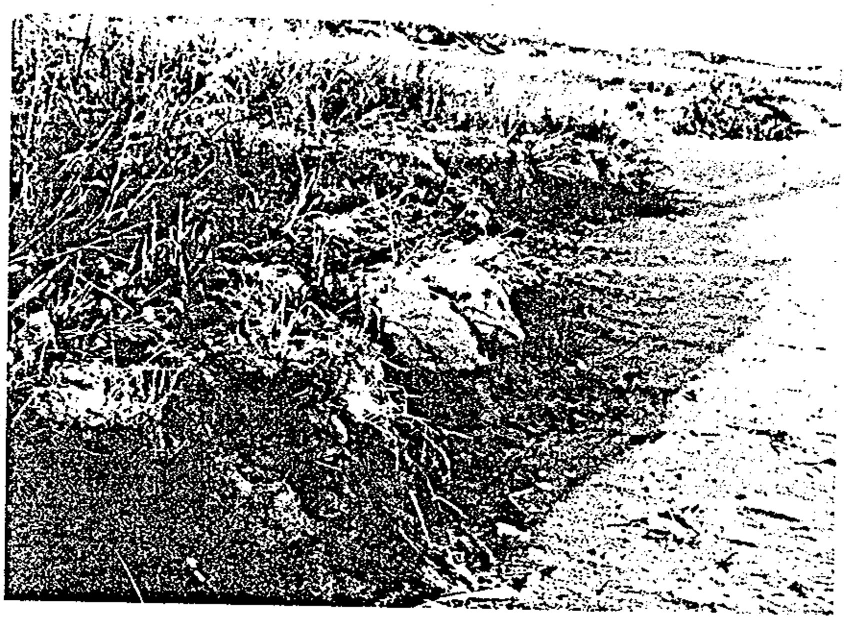

Figure 6b. Post-Alicia erosional escarpment and vegetation line, West Beach. Shoreline to right of area shown.

elevation, allowing vegetation to encroach on the bare beach and move the vegetation line seaward.

Comparison of vegetation lines shown on aerial photographs taken in June 1982 and August 1983 reveals that Hurricane Alicia moved the vegetation line on West Beach landward an average of 78 ft (table 1 and appendix C). Measured vegetation-line retreat ranged from 20 to 145 ft and generally decreased away from San Luis Pass (fig. 7). The most retreat (145 ft) was observed both at Sea Isle subdivision and along a natural stretch west of Bay Harbor subdivision.

Galveston Island beaches can be divided into two categories, those in natural areas and those in developed areas. Included in the broad category of natural areas are undeveloped beaches as well as beaches fronting recreational parks such as the Galveston Island State Park and several county parks along West Beach. Developed areas include beaches along communities such as Sea Isle, Pirates Beach, and numerous other small island subdivisions.

Table 1. Vegetation-line retreat between June 10, 1982 (pre-Alicia), and August 22, 1983 (post-Alicia), along West Beach. Compiled from appendix C.

	Number of Stations	Mean Vegetation Retreat (ft)	Standard Deviation (ft)
Mostly natural areas			
Natural beaches	40	78	26
Recreational beaches	8	69	10
Developed areas			
Unbulkheaded	22	85	28
Bulkheaded	4	62	38
All West Beach stations	74	78	26

Natural Beaches

Slightly more than half the West Beach measurements were of beaches in essentially undeveloped areas (table 1). Vegetation-line retreat in these areas varied considerably, ranging from a low of 25 ft to a high of 145 ft, but retreat at most West Beach stations was between 50 and 100 ft. Average vegetation-line retreat at West Beach was 78 ft. Despite significant local variation, vegetation-line retreat along natural beaches on Galveston Island tended to decrease with distance from San Luis Pass (fig. 7).

Surprisingly, vegetation along the stretch of shoreline closest to San Luis Pass (points 30.25 to 30.75, appendix C) retreated 35 to 105 ft; the vegetation line at the station closest to San Luis Pass retreated only 35 ft. The apparent peak of vegetation-line retreat in natural areas occurred 1 or 2 mi east of San Luis Pass, where retreat ranged from 100 to 145 ft (stations 29.25 to 30.00). This may indicate that part of the relatively calm "eye" of Alicia passed over the western tip of Galveston Island, subjecting the remainder of the island to higher winds and more powerful waves.

The vegetation-line retreat measured at stations on recreational beaches such as those at Galveston Island State Park and Galveston County parks averaged 9 ft less than that at stations in natural areas of West Beach (69 ft compared with 78 ft, table 1). Most of the recreational beaches, however, are on the eastern half of West Beach (fig. 7). Because Galveston Island vegetation-line retreat generally decreases eastward, the discrepancy between truly natural beaches and recreational beaches is insignificant. In fact, vegetation-line retreat on recreational beaches falls entirely within the range of retreat observed at natural stations occurring both east and west of the recreational areas.

Developed Beaches

Residential development of West Beach is sporadic but locally intense. The boundary between undeveloped, natural areas and moderately dense residential developments is quite distinct, making the task of differentiating natural from developed beaches fairly simple.

Various dune- and home-protection schemes, found in almost every subdivision, range from simple sand traps to concrete or wooden bulkheads hundreds of feet long. Of all these schemes, bulkheads had probably the most significant impact on the style and magnitude of vegetation retreat during Hurricane Alicia. Remains of the bulkheads were visible on aerial photographs; it was thus possible to differentiate bulkheaded and unbulkheaded areas within subdivisions.

Unbulkheaded Areas.—Nearly one-third of all West Beach measuring points were located in unbulkheaded developed areas (table 1). Vegetation-line retreat in these areas ranged from a low of 30 ft to a high of 145 ft (appendix C). Retreat in the Sea Isle subdivision between and including points 25.25 and 25.75 (120 to 145 ft) was generally higher than retreat in other developed areas.

Average vegetation-line retreat was 7 ft more in unbulkheaded developed areas than in natural areas (85 to 78 ft, respectively) even though the vegetation line in developed areas retreated less than that in adjacent natural areas (fig. 7). The west part of West Beach has fewer developments than the east; consequently, more stations are in natural areas in the west part than in the east part. Developed areas, then, were more concentrated on a stretch of the island farther from hurricane landfall. It is significant that the average vegetation-line retreat in unbulkheaded developed areas is higher than that in natural areas despite their distance from the storm.

Bulkheaded Areas.—Many bulkheads, including those of concrete, wood, or metal, were constructed on Galveston Island both before and after Hurricane Alicia. Most bulkheads constructed before Alicia were built at or landward of the vegetation line and thus were obstructions for rising storm tides and waves during Alicia. Some had considerable impact on vegetation retreat during the storm.

Average vegetation-line retreat at the four bulkheaded points was about 62 ft, or 16 ft less than in natural areas, 7 ft less than in recreational areas, and 23 ft less than in unbulkheaded developed areas (table 1). However, retreat at only two of the bulkheaded stations was significantly less than in adjacent unbulkheaded and natural areas (fig. 7). Field investigations suggest that construction materials and bulkhead design correlate with effectiveness in reducing vegetation-line retreat. Low wooden or metal bulkheads did little to reduce vegetation retreat; the substantial concrete bulkhead fronting the eastern part of Sea Isle subdivision (points 24.75 and 25.00 and fig. 8), although destroyed by the storm, reduced vegetation-line retreat by 75 to 100 ft compared with adjacent unbulkheaded parts of the development, and by 20 to 50 ft relative to adjacent natural areas. These bulkheads only reduced vegetation-line retreat and not shoreline erosion; consequently, bulkheaded beaches were generally narrower than adjacent unbulkheaded beaches after the storm.

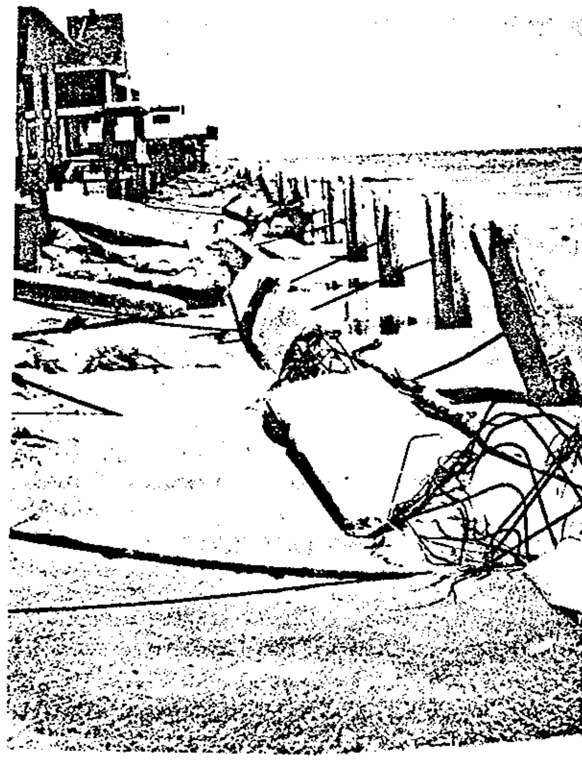
Figure 8. Remnants of a reinforced concrete bulkhead destroyed by Hurricane Alicia, Sea Isle subdivision.

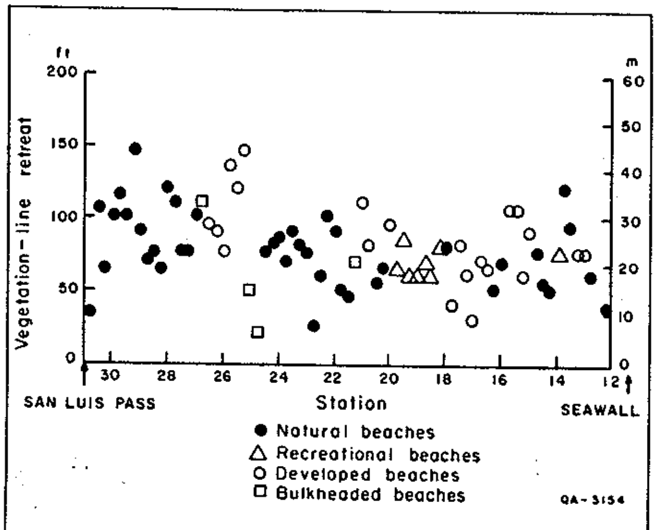

Figure 7. Vegetation-line retreat caused by Hurricane Alicia, West Beach. Station locations shown in figure 3.

ESTIMATED VOLUME OF SEDIMENT LOSS

Data collected for this and other (U.S. Army Corps of Engineers, 1980) studies were used to estimate the volume of sediment eroded from beaches during Hurricane Alicia. From aerial photographs alone, it is possible to determine only areal changes. To calculate volumetric changes, a third dimension (depth of erosion or thickness of deposition) must be known. Fortunately, landmarks on the beach indicate the position of the pre-storm ground level (fig. 5), allowing calculation of the approximate depth of erosion.

The volume of sediment eroded between the pre- and post-storm vegetation lines does not represent the total volume eroded from the beach during Hurricane Alicia. Beach profiles were used in making volumetric estimates that included the amount eroded seaward of the pre-storm vegetation line.

Estimates from Aerial Photographs

Volumetric estimates from aerial photographs were restricted to the volume of sediment lost from between the pre- and post-storm vegetation lines. This is because shoreline positions were highly variable and because landmarks, necessary for estimating depth of erosion, were available only in the area between the vegetation lines.

Area of Vegetation Retreat.—The area between the pre- and post-Alicia vegetation lines, amounting to approximately 7,575,000 ft^2 along West Beach, was estimated by planimeter using 1982 and 1983 aerial photographs. The accuracy of this estimate can be checked by dividing it by the length of West Beach from the seawall to San Luis Pass (approximately 95,000 ft). The resultant average vegetation-line retreat (79.7 ft) compares favorably with the average vegetation-line retreat calculated in table 1 (78.0 ft).

Depth of Erosion.—Pre-storm ground elevations (fig. 5) were indicated by the discoloration of exposed pilings, the presence of concrete slabs perched above the post-storm beach, and the height of the Alicia erosional escarpment at the vegetation line (fig. 6b). Elevation loss varied among subdivisions, houses, and even pilings on the same house, but most of the measurements were between 2 and 5 ft (table 2). Average elevation loss in the zone between the pre-Alicia and post-Alicia vegetation lines on West Beach was slightly more than 3 ft.

Volume of Sediment Loss (Between Vegetation Lines).—An estimate of the volume of sand removed by Hurricane Alicia landward of the pre-storm vegetation line on West Beach can be calculated by multiplying the estimated area (7,575,000 ft^2) by the average thickness of sediment removed (3.15 ft). This value (23,861,250 ft^3, or 883,750 yd^3) must be added to the amount of sand removed seaward of the pre-storm vegetation line to accurately estimate the total volume of sand removed from West Beach of Galveston Island.

Table 2. Loss of ground elevation due to Hurricane Alicia at West Beach subdivisions, Galveston Island. Measurements were made on house pilings and do not imply that every location within a subdivision experienced the same elevation loss.

Area	Elevation Loss (inches)
Spanish Grant	53
Bermuda Beach	40
Pirates Beach	27
Jamaica Beach	26
Acapulco Village	17
Texas Campgrounds	36
Sea Isle	38
"	54
"	36
Terramar	51
Number of measurements	10
Mean elevation loss (inches)	38

Estimates from Beach Profiles

After Alicia, the Bureau of Economic Geology established six profile sites on West Beach, between the seawall and San Luis Pass (fig. 3). Comparison of these post-storm profiles with pre-storm profiles allows an estimate of total volume of sediment eroded between mean low tide and the post-storm vegetation line.

Comparisons of profiles taken in February 1980 (U.S. Army Corps of Engineers, 1980) and after Alicia indicate that a total of about 2,020,000 yd^3 of sand was removed from West Beach in that period (table 3). The estimate may be slightly high because the pre-storm profiles were completed before Hurricane Allen (1980), which had a small but measurable impact on Galveston Island. The estimate includes all beach changes between February 1980 and August 1983, including erosion from Allen, subsequent recovery, and erosion from Alicia.

Washover Deposition

Some of the sand eroded from the beach and vegetated areas was deposited landward of the post-storm vegetation line. These sand deposits commonly start at the post-storm erosional escarpment (vegetation line) and stretch inland tens to hundreds of feet. Because the washover sands were deposited landward of the vegetation line, they directly overlie

Table 3. Volumes of sand erosion and subsequent depositional recovery of West Beach in the aftermath of Hurricane Alicia. Volumes were calculated from beach profiles. February 1980 profiles (U.S. Army Corps of Engineers, 1980) are pre-Alicia profiles; others were conducted after Alicia by the Bureau of Economic Geology.

Period	Change (yd^3)	Cumulative Return (yd^3)	% Returned
Feb. 1980 to Aug. 1983	-2,020,000	--	--
Aug. 1983 to Dec. 1983	+369,000	+369,000	18
Dec. 1983 to Feb. 1984	+92,000	+461,000	23
Feb. 1984 to May 1984	+100,000	+561,000	28
May 1984 to Aug. 1984	+238,000	+799,000	40
Aug. 1984 to Dec. 1984	-46,000	+753,000	37
Dec. 1984 to Feb. 1985	-45,000	+708,000	35
Feb. 1985 to May 1985	+115,000	+823,000	41
May 1985 to Aug. 1985	+152,000	+975,000	48

vegetation that existed before the storm. Trenches through washover deposits revealed a dark, organic-rich horizon a few inches to a few feet below the top of the sands. This horizon represents the pre-storm vegetated surface (fig. 9). The distance between the darkened horizon and the top of the washover sand represents the thickness of the storm deposit at that point.

Washover thickness was measured at 62 locations on West Beach. These locations included areas of maximum deposition on the western end of the island and minimum deposition near the seawall. The greatest thickness (27 inches) was measured east of San Luis Pass on a broad washover deposit consisting of sand and coarser shell fragments. Measurements in other West Beach areas ranged from less than 1 inch to 17.5 inches. The average measured thickness of washover deposits was about 9 inches.

Washover deposits were typically lens- or sheet-like in cross sections measured perpendicular to the shoreline. Trenches along beach and washover profiles showed that washover deposits are thin (less than 1 inch) at the top of the erosional escarpment and at the landward limit of the deposits. Thickest accumulations of sand were in the middle of the deposits; the maximum thickness was nearer the vegetation line than the landward limit of deposition (fig. 10). Washover sands were commonly structureless but locally exhibited small-scale laminations and vertical grain-size changes. The deposits underwent minor redistribution by winds before extensive plant colonization.

Areal extent of washover deposition was mapped on post-Alicia aerial photographs. The seaward boundary was the vegetation line or erosional escarpment; the landward boundary was the most landward occurrence of unvegetated sand. Trenches landward of barren sand confirmed the presence of additional washover deposits; however, these deposits represented the feather edge of washover and everywhere were less than an inch thick.

Washover width (the distance between the post-storm vegetation line and the landward limit of unvegetated sand) averaged about 85 ft but varied considerably along the island (appendix C). Some areas experienced virtually no washover deposition; in contrast, washover sands extended 355 ft landward of the vegetation line at station 26.50 in the Terramar subdivision and even farther inland (at least 1,000 ft) between measuring points in the same subdivision. The measuring points were located in natural areas, recreational areas, developed areas without bulkheads, and developed areas with bulkheads. Land use strongly influenced the landward extent of storm-washover deposition (fig. 11 and table 4).

NATURAL AREAS

Washover deposition in natural areas generally did not extend inland as far as in other areas. The distance between the landward and seaward edges of storm washover deposits in natural areas ranged from 0 ft (no deposition) to 125 ft, a smaller range than for other types of beaches. Average washover width in natural

Figure 9. Thin layer of light-colored sand (Alicia washover deposits) covering dark, organic-rich soil zone. Dark zone (see arrow) represents prestorm ground surface.

areas (60 ft) was also considerably less than the average for all measuring points (85 ft).

Extent of storm washover at stations located in recreational areas (Galveston Island State Park and other developed parklands) was indistinguishable from that in undeveloped areas. Indeed, washover widths along recreational beaches were similar to washover widths in adjacent natural areas (fig. 11). The distance between the landward and seaward limits of subaerial storm deposition at the eight measuring points along recreational beaches averaged 56 ft (table 4).

Although washover widths in recreational areas were similar to widths in natural areas, weakened vegetative cover in high-use areas (such as near picnic tables) caused local increases in extent of washover. For example, several stations were located along Galveston Island State Park (stations 18.25 through 19.75, appendix C). The widest washover deposit (160 ft at station 18.50) occurred at the visitors center, whereas washover widths at other stations in the park ranged from 35 to 65 ft.

DEVELOPED AREAS

Inland extent of washover deposition was significantly greater in developed areas than in undeveloped areas. Average washover width at the 22 developed but unbulkheaded stations was 125 ft, nearly 70 ft more than the average in natural areas (table 4). Nearly all developed areas underwent more extensive washover deposition than did adjacent natural areas (fig. 11). Washover deposits extended landward of the post-storm vegetation line from 30 to 355 ft at measuring points in developed areas, and as much as 1,000 ft in specific areas between measuring points. The widest washover deposits in unbulkheaded developed stations were found at the westernmost subdivisions on Galveston Island; one station in Terramar recorded 355 ft, and two stations in Bay Harbor recorded 215 ft each.

Bulkheaded areas also experienced more extensive washover deposition than did natural

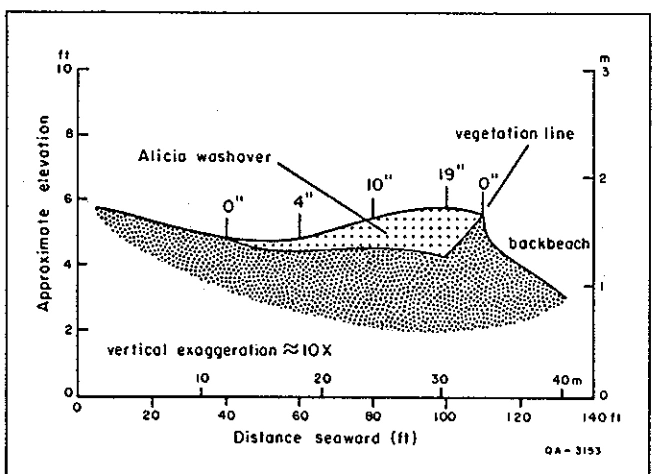

Figure 10. Profile of typical Alicia washover deposit along West Beach. Profile constructed from trenches along profile 3.

Table 4. Inland extent of washover deposits (measured from the Alicia vegetation line to the landward edge of barren sand) in natural, recreational, developed, and bulkheaded areas along West Beach. Compiled from appendix C.

	Number of Stations	Mean Washover Width (ft)	Standard Deviation (ft)
Mostly natural areas			
Natural beaches	40	60	34
Recreational beaches	8	56	46
Developed areas			
Unbulkheaded	22	125	70
Bulkheaded	4	173	74
All West Beach stations	74	85	61

areas (average of 173 ft; 100 ft more than the average washover in natural areas). The average washover in bulkheaded areas also was much greater than that in unbulkheaded developed areas, but the small sample (four stations) prevented determining the significance of those differences. Bulkheaded areas did not sustain appreciably more washover than adjacent unbulkheaded developments (fig. 11).

There are several possible explanations for the apparent correlation between type of beach and the amount of storm deposition landward of the vegetation line. One is that increased human activities in developed areas tend to disturb sand-binding vegetation, resulting in increased erosion and more sand available for transport landward of the vegetation line. Although vegetation lines along unbulkheaded developed areas retreated slightly more than in adjacent natural areas, the average difference (7 ft, table 1) was insignificant when compared with the great difference in washover extent. Furthermore, bulkheaded areas received as much or more washover deposition than did unbulkheaded developed areas, yet well-constructed bulkheads actually decreased vegetation-line retreat compared with that in adjacent natural areas.

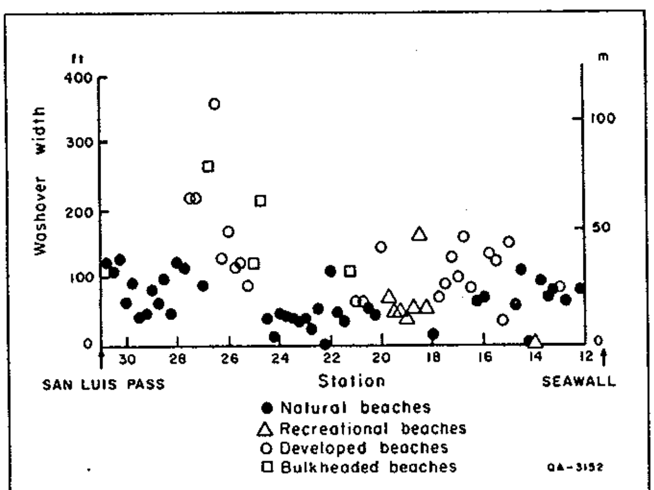

Figure 11. Inland extent of washover deposition from Hurricane Alicia, West Beach. Station locations shown in figure 3.

A more reasonable explanation involves the popular waterfront practice of dune construction. Tides along Galveston Island were high enough during Hurricane Allen (1980) to cause significant vegetation-line retreat, dune damage, and washover deposition. The interval between Allen and Alicia (roughly 3 yr) was insufficient to allow formation of dunes in natural areas. Therefore, the supply of sand available for washover deposition was somewhat diminished in natural areas. In developed areas, however, vegetation-line retreat and dune destruction during Allen were probably quickly nullified by landfilling, sodding and planting, and artificial dune construction. This additional sand in developed areas was thus available for washover when Alicia made landfall. Washover deposition was also increased by artificial dunes that are commonly nothing more than loose mounds of sand covered with vegetation. Natural dunes grow more slowly through the continual vegetal binding of sand as the dune grows from small vegetated mounds, and are therefore more resistant to erosion.

VOLUME OF WASHOVER SEDIMENT DEPOSITED BY HURRICANE ALICIA

The area of washover deposits created by Alicia between the west end of the Galveston seawall and San Luis Pass (8,599,250 ft^2) was planimetered on the post-storm aerial photographs. This number is approximately that calculated by multiplying the average washover deposit width (85 ft) by the length of West Beach (95,000 ft), resulting in an area of 8,094,000 ft^2.

Average thickness of washover deposits is slightly more than 9 inches (0.76 ft). Multiplying this average thickness by the planimetered area (8,599,250 ft^2) gives an estimate of the volume of material transported and deposited landward of the post-Alicia vegetation line on West Beach, approximately 6,563,380 ft^3 (243,090 yd^3).

Storm-Sediment Budget

Sand eroded from the beach by Hurricane Alicia was either transported landward of the post-storm vegetation line and left there as washover deposits or deposited an unknown distance offshore. Some of the deposition occurred directly offshore from Galveston Island, and beach profiles conducted periodically after the storm indicate that some of the sand transported offshore returned to the beach. Apparently, much of the eroded sand was carried away from Galveston Island by southwesterly wind-driven currents as Alicia approached San Luis Pass. Some of this sand contributes to the sediment budget southwest of San Luis Pass (including Follets Island) and may not return to Galveston Island.

The volume of sand carried offshore from West Beach can be estimated by subtracting the amount lost from the littoral system through washover deposition (243,090 yd^3) from the total eroded volume (2,020,000 yd^3); the remainder (1,776,910 yd^3, or 88 percent of the amount eroded) was carried offshore. Sand offshore of Galveston Island will probably contribute to both immediate and short-term (months to years) beach recovery, whereas sand carried southwestward across San Luis Pass may only contribute to the longer term (years) recovery of West Beach. An unknown fraction of the offshore component was carried below normal wave base and is permanently lost from the littoral system.

Post-Storm Runoff

Alicia's counterclockwise wind pattern, landward storm movement, and hydrologic influence spanning several high tides caused multiple stages of erosion and deposition as well as multiple directions of sediment transport. In the storm's right-front quadrant (Galveston Island), onshore wind- and wave-driven currents resulted in flood-oriented washover deposits. Ebb-oriented erosion features were predominant in the left-front quadrant (Follets Island), as predicted by the hurricane model devised by McGowen and others (1970).

Clusters of short, narrow channels that served as conduits for receding flood waters were scoured along the Gulf beach of Follets Island (fig. 12). These channels drained back-island marshes and barrier flats that were inundated by water raised nearly 10 ft above sea level (Savage and others, 1984). Water funneled southwestward through Christmas Bay and Drum Bay and impounded by the fore-island dunes created flood depths of 3.5 to 5 ft (fig. 13). The drainage channels originated at breaches in the dunes, such as beach-access roads. Once formed, the channels grew by headward (bayward) erosion. The channel thalwegs either merged landward with dendritic gullies or terminated abruptly at the coastal highway, which washed out at several sites.

The channels were 25 to 150 ft wide, 100 to 350 ft long, and several feet deep. Channel morphology was largely controlled by the discharge, which depended on water-level differences between the Gulf and adjacent bay. Measured elevations of Gulf and bay drift lines (fig. 13) indicate that the minimum difference in water levels was 1.3 ft. However, the maximum difference at peak runoff was probably much greater because Gulf flooding generally preceded bay flooding. If, as expected, Gulf flood levels began receding before bay flood levels peaked, then the hydraulic differential may have been several feet. The flood elevations, narrow thalwegs, and moderate scour depths indicate that strong, partially confined, gravity-induced currents formed the ebb channels. Late-stage ebb currents flowing across the beach were deflected northward by longshore currents in response to the post-

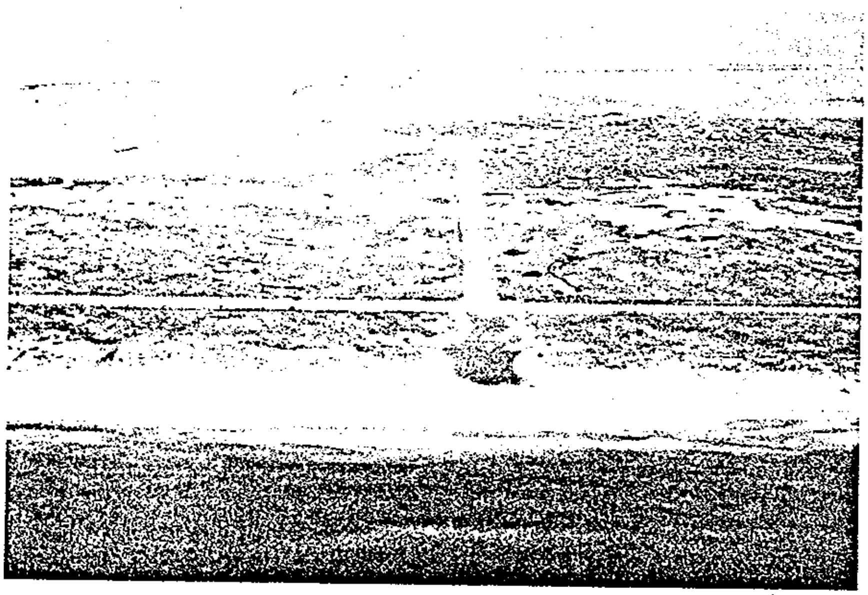

Figure 12. Storm-runoff drainage channel on Follets Island 1 week after Hurricane Alicia. The washout is about 150 ft wide, 310 ft long, and 3 ft deep.

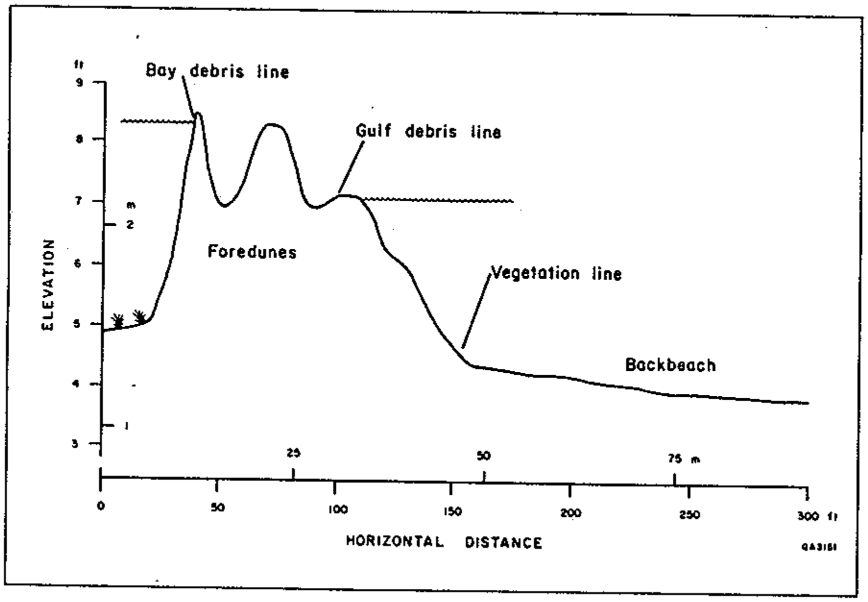

Figure 13. Profile of dune ridge on Follets Island (fig. 1) showing Gulf and bay debris-line elevations. Profile location is adjacent to a large storm-runoff drainage channel.

landfall wind direction. The strength and jetlike flow of the ebb currents were confirmed by the seaward offset and discontinuity of offshore bars immediately after Alicia.

POST-ALICIA BEACH CHANGES

Natural recovery from severe storms begins as storm tides recede and winds and waves weaken. Both nature and human activities have had a major impact on the recovery of West Beach.

Natural Recovery

All aspects of natural recovery involve either sand transport or vegetation changes. The first natural changes included reestablishment of offshore bars, return of some eroded sand to the forebeach, and deflation of unvegetated washover deposits. With time, vegetation began to encroach the washover deposits and to descend the erosional escarpment. Onshore winds and periodic high tides began moving some forebeach sand to the backbeach, increasing its elevation.

SAND TRANSPORT

West Beach recovery after Alicia was monitored quarterly using beach profiles (fig. 3) and measurements of beach width and elevation. Three of the six profiles were chosen to represent the three distinct West Beach shoreline segments (figs. 3 and 14A, B, and C). One profile is located along the dominantly erosional stretch of shoreline southwest of the seawall, another within the central stable zone, and the third just east of San Luis Pass along another erosional stretch.

Central Zone

A profile (fig. 14A) from within the most stable zone of West Beach shows substantially more sand deposition during the early recovery period (August 1983 to August 1984) than do the other profiles. The shoreline at profile 3 had recovered (returned to its pre-storm position) by August 1984, even though only 52 percent of the sand eroded by Alicia had returned to that segment. The forebeach recovered, but the backbeach remained much lower (about 3 to 5 ft m.s.l.) than before the storm. Sand deposited in the backbeach was transported landward by wind and trapped against the erosional escarpment. During the first post-storm year, recovery along the most stable West Beach shoreline was confined to seaward migration of the forebeach, and no large elevation gains were made in the backbeach.

During the first half of the second post-storm year (August 1984 to February 1985), the forebeach retreated about 50 ft. Much of the eroded sand was transported landward by winter storm waves and tides, raising backbeach elevations by as much as 1 ft and steepening the beach. By undergoing both forebeach erosion and backbeach deposition during this period, the site was still gaining volume, but at a reduced rate. Between August 1983 and February 1984 (the first six months after Alicia), about 38 percent of the amount of sand eroded by Alicia had returned to the beach; during the same period in the second post-storm year (August 1984 to February 1985), only 8 percent of the sand eroded by Alicia returned to the site. The most likely explanation for this reduction in accumulation is that most of the accessible sand stored offshore after the storm had returned to the site by August 1984.

Significant accretion between February 1985 and the end of the second post-storm year (August 1985) left the shoreline near its pre-storm position and brought cumulative recovery at this site to 90 percent. Additional accretion is likely only during favorable periods, such as summer months.

Eastern Zone

Profile 1 depicts an area located about 2 mi southwest of the end of the seawall along an erosional shoreline. Pre- and post-storm profiles (fig. 14B) indicate that the shoreline retreated 50 to 75 ft, whereas the vegetation line moved 75 to 85 ft landward. Consistent recovery was observed at this site during the first post-storm year, and, as at profile 3, the August 1984 shoreline had nearly attained its pre-storm position, but backbeach elevation was several feet below the pre-storm elevation. Some windblown sand was deposited along the base of the erosional escarpment, and some oily sand was dumped on the backbeach during the cleanup of the *Alvenus* oil spill in the summer of 1984. About 59 percent of the sand eroded from the beach near profile 1 during Alicia had returned by August 1984.

Between August 1984 and February 1985, the shoreline at profile 1 eroded approximately 50 ft. Although some of the eroded sand was deposited on the backbeach, raising backbeach elevation by as much as 1 ft, net beach erosion occurred because more sand was eroded from the forebeach than was deposited on the backbeach. After a peak recovery of 59 percent of the amount eroded by Alicia, subsequent sand losses reduced the recovery to 23 percent by February 1985. About two-thirds of the winter erosion occurred between December 1984 and February 1985. The sand eroded between August 1984 and February 1985 was equivalent to about 36 percent of the amount eroded during Alicia; during the same period in the first post-storm year (August 1983 to February 1984), 20 percent of the sand eroded by Alicia returned to the beach. As in the central stable zone, sand deposited offshore by Alicia was insufficient to offset winter erosion in the second post-storm year.

Beach recovery by the end of the second post-storm year (53 percent by August 1985) was less than that observed at the end of the first post-storm year. This net sand loss during the second year may indicate that the eastern zone has again become erosional.

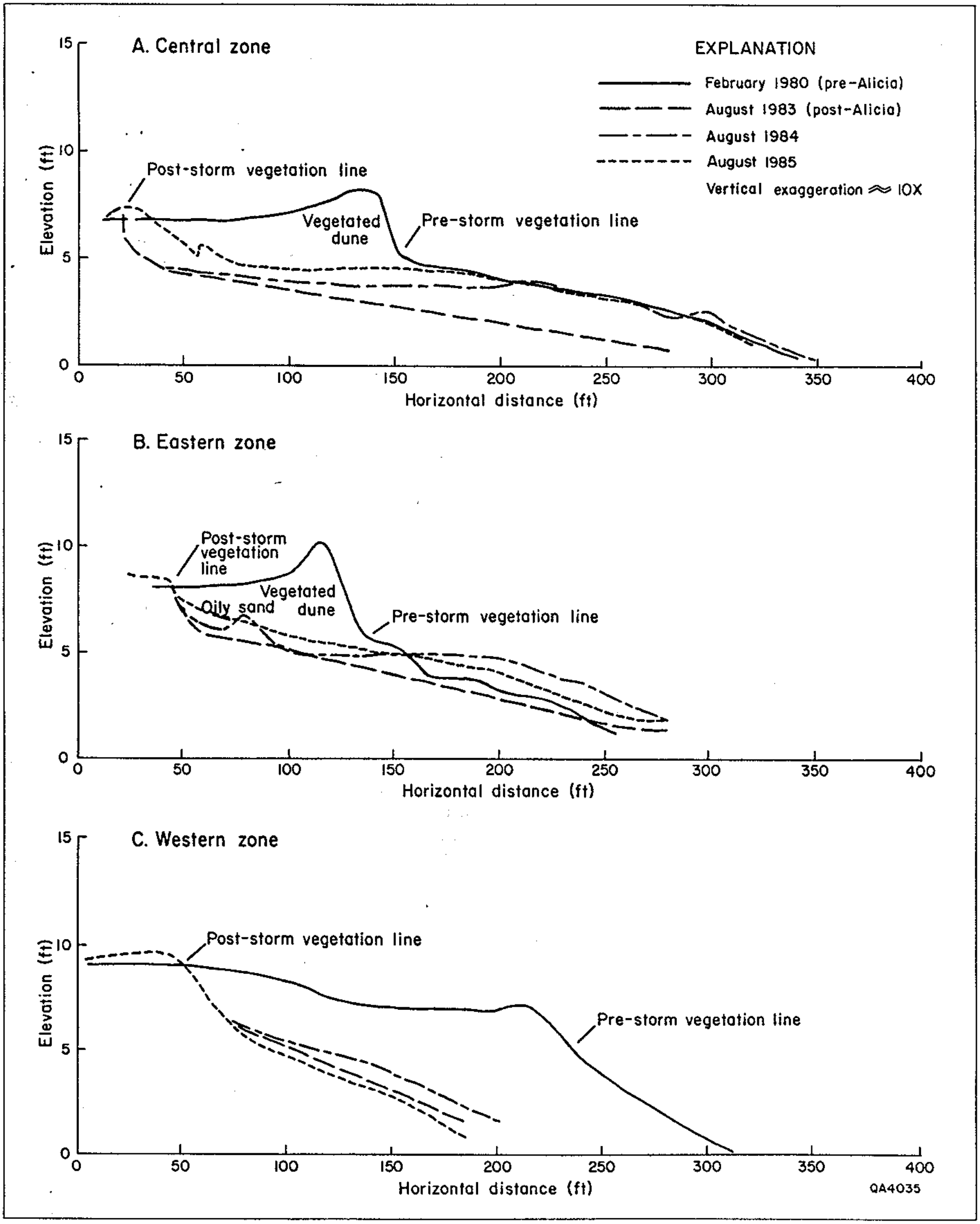

Figure 14. Pre- and post-Alicia beach profiles from (A), the central stable zone of West Beach (profile 3); (B), the eastern erosional zone near West Beach tower base (profile 1); and (C), the western erosional zone near San Luis Pass (profile 4). February 1980 profiles by U.S. Army Corps of Engineers (1980).

Western Zone

Profile 4 is located along the highly erosional shoreline just east of San Luis Pass and is closest to the site of Alicia's landfall. Here Alicia caused about 100 ft of shoreline erosion and about 150 ft of vegetation-line retreat. The recovery profiles are strikingly different from those farther east along the island (fig. 14C). In the western zone, little sand returned to the beach during the first post-storm year; during the period most favorable for beach recovery (May to August 1984), the shoreline accreted only about 15 ft. Slight recovery occurred between August 1983 and February 1984 (amounting to a little more than 6 percent of the total amount eroded), but erosion between February and May 1984 removed more sand than was deposited in the previous period and left the shoreline near its post-Alicia position. Minor accretion between May and August 1984 brought the recovery at the end of the first post-storm year to only 7 percent of the total sand eroded.

Slight erosion at profile 4 between August and December 1984 decreased recovery to 6 percent of the volume eroded by Alicia. However, severe erosion between December 1984 and February 1985 removed the equivalent of 15 percent of the sand eroded by Alicia. This winter erosion caused net shoreline retreat and lowered the backbeach as much as 1 ft below its elevation after Alicia. Erosion to the end of the second post-storm year pushed the shoreline farther landward of its post-storm position (fig. 14C).

Volume of Sand Returned

Volume calculations integrated from all six beach profiles illustrate the broad trends of recovery 2 yr after Alicia. The greatest volume of sand (369,000 yd^3, or about 18 percent of the total amount eroded, table 3) returned to West Beach by early December 1983 (table 3). The quarterly rate of sand accumulation diminished between December 1983 and February 1984 (5 percent), and between February and May 1984 (5 percent). However, light onshore winds and calm waves between May and August 1984 increased the rate to 12 percent, two-thirds that of the period immediately after the storm.

By the end of the second post-storm year, about 975,000 yd^3 of sand, representing approximately 48 percent of the total amount eroded by Hurricane Alicia, had returned to the West Beach of Galveston Island. This maximum recovery indicates that nearly 40 percent of the sand eroded by Alicia (802,000 yd^3) was neither incorporated in washover deposits (12 percent) nor returned to the beach (48 percent) and either was lost from the littoral system, will feed future West Beach recovery, or has been transported elsewhere.

After reaching a peak in August 1984, recovery declined until February 1985 (table 3). Sand losses were recorded during the first quarter (-46,000 yd^3, or 2 percent of Alicia erosion) and second quarter (-45,000 yd^3, or 2 percent) of the second post-storm year. Seasonal gains during the last 6 mo of the second post-storm year pushed recovery to 48 percent, but rates of sand return were not as great as during the same period of the first post-storm year. These losses during the winter and diminished gains during the summer of the second year represent a return to near-normal conditions, but they stand in sharp contrast to substantial (799,000 yd^3) deposition in the equivalent 12-mo period immediately after Alicia.

VEGETATION CHANGES

Erosion of the vegetation line during Hurricane Alicia was accomplished by the removal of a 2- to 5-ft-thick layer of sand from within the vegetated zone. The thickness of sand removed was sufficient to carry away all traces of plants, including root systems. Erosion left an escarpment at the edge of the bare beach; in many places, vegetation landward of the escarpment was covered by washover deposits.

Colonization of Washover Deposits

During the first year of recovery from Hurricane Alicia, vegetation recolonized most of the sand deposits landward of the post-storm vegetation line. In areas of thin washover deposition, underlying vegetation was able to grow through the deposits. In areas of thicker deposition, colonization began at the landward and seaward edges of the deposits then progressively moved toward the centers of thickest accumulation.

Colonization primarily occurred between late February 1984 (6 mo after landfall) and August 1984. Minor eolian reworking of storm washover deposits occurred before February 1984.

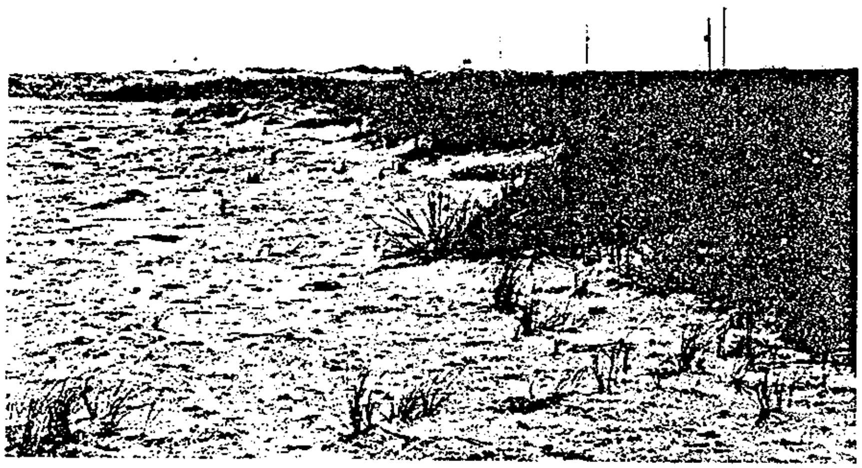

Figure 15. Sprigs of vegetation colonizing the backbeach near Indian Beach.

Vegetation-Line Changes

Field surveys indicate that the seaward limit of vegetation in natural areas did not change appreciably in the first 2 yr after landfall. The only notable, widespread change was that vegetation colonized the area between the base and top of the erosional escarpment, whereas it had been present only at the top immediately after the storm (compare figs. 6b and 15). Widespread colonization of the bare backbeach was hampered by its low elevation, which allowed inundation by high tides. Colonization of the backbeach and concomitant seaward migration of the vegetation line will probably not occur until backbeach elevations have increased sufficiently through the transport of sand from the forebeach by eolian processes or minor storms.

Human Alterations

Human activities were responsible for the greatest increase in sediment volume and changes in backbeach morphology after Hurricane Alicia. These activities, conducted both on individual first-row lots and within entire beachfront communities, were intended to replace the sediment eroded beneath foundations, restore support for exposed pilings, and protect structures and surrounding areas from further damage by minor storm waves.

The most common human alterations consisted of filling individual beachfront lots, grading the fill to the pre-storm elevation, and planting sprigs of grass or sodding the fill to reestablish lawns. Additional activities in some communities included construction of bulkheads and artificial sand dunes. In densely developed areas, these activities collectively reduced the effective beach width by an average of 100 ft (fig. 16).

SAND REPLENISHMENT

Although storm debris was used as landfill at some sites, the ground surface was raised at most sites with a mixture of sand and clay. Most of the fill is tan to reddish-brown Pleistocene sand and mud transported from the mainland, but some fill is light-tan Holocene barrier sand reclaimed from washover deposits in nearby drainage ditches or scraped from adjacent beaches. In many lots, the seaward limit of backbeach fill coincides with the position of the pre-storm vegetation line.

The sand volume that was returned to West Beach as a result of human activities can be estimated as follows: If an average beachfront lot required 800 yd^3 of fill to regain its pre-storm elevation and if approximately 200 lots were filled, then about 160,000 yd^3 were added to the backbeach in developed areas of Galveston Island.

Figure 16. Post-Alicia view of Jamaica Beach subdivision. Fill extends approximately 110 ft seaward of the natural post-storm vegetation line.

SHORELINE PROTECTION

In some subdivisions (for example, areas of Spanish Grant, Bermuda Beach, Pirates Beach, Jamaica Beach, and Sea Isle), additional measures have been taken to protect the fill and prevent undermining by abnormally high tides. These measures include construction of bulkheads and placement of riprap or other low-cost materials on the backbeach. The narrow wooden bulkheads normally protrude 2 to 3 ft above the surface of the beach and serve as retaining walls for the fill. Locally, property-owners have used other shoreline protection methods that cost less and are probably much less effective than bulkheads. In Jamaica Beach, Seven Seas, and Sea Isle, crude revetments were constructed from wooden storm debris, broken concrete slabs, and other riprap. These materials were placed on the beach landward of the normal high-tide line, but they lack coherence and are easily undermined by moderate waves. In 1985, the rubble embankments were mostly covered with sand and acted as rigid cores for artificial dunes.

DUNE CONSTRUCTION

Artificial dune ridges were created in various ways along segments of the upper Texas coast after Hurricane Alicia. One simple but seldom used technique involved lining the backbeach with sand fences, creating wind shadows that cause deposition of windblown sand and that form low dune ridges. Bundled Christmas trees were also placed on the dry beach to trap sand blown landward by prevailing onshore winds. At the end of the second post-storm year, the volume of accumulated sand was insignificant, especially compared with the volume eroded from the beach.

Dune ridges were constructed along segments of Jamaica Beach, Acapulco Village, Sea Isle, and Terramar subdivisions on Galveston Island and at scattered localities on Bolivar Peninsula (fig. 1). In these areas, heavy equipment was used to form linear sand ridges about 6 ft wide at the base and 2 ft above the beach surface. These sand berms are trapezoidal in cross section.

The barren surfaces of most sand ridges, covered bulkheads, and buried rubble revetments were stabilized with sprigs of native dune grasses (bitter panicum) or coastal Bermudagrass and other grasses grown from seed. Some residents encouraged growth by periodically watering and fertilizing the grass.

Artificial dunes of loose sand offer the advantage of providing immediate protection from abnormally high tides. However, these cohesionless dunes are vulnerable to attack by storm waves; ample evidence of this weakness was provided by the artificial dunes built at Sea Isle in 1982 that were destroyed and incorporated into the Alicia washover deposits.

Another disadvantage of artificial dunes is their tendency to prevent aggradation of the backbeach if they are constructed substantially seaward of the vegetation line. As elevation of the backbeach increases by minor flooding and sand deposition, the area between the vegetation line and the artificial dune ridge remains a topographic low that ponds water. Artificial dune ridges at Sea Isle and Terramar caused this type of interference with backbeach recovery.

Artificial dunes that offer the greatest resistance to erosion achieve their height by enlarging in concert with plant growth. These dunes have a network of roots that minimize erosion. The erosional resistance of planted experimental dunes was demonstrated by Dahl and others (1982) along north Padre Island (fig. 1) after Hurricane Allen.

During periods of low storm frequency, eolian processes can deposit substantial volumes of sand along the backbeach as both natural and artificially nourished dunes. This sand accumulation has buried bulkheads, fences, and posts, which have subsequently been uncovered by Hurricane Alicia or other major storms.

Effects of the Alvenus *Oil Spill*

Unusual circumstances in early August 1984 altered the course of storm recovery along Galveston Island. At that time the British tanker *Alvenus* ran aground in the Gulf of Mexico east of Sabine Pass (fig. 1), spilling more than 45,000 bbl of crude oil. A broad oil slick originating at the ruptured tanker drifted southwestward with the littoral currents and began coming ashore 5 days later along the upper Texas coast between High Island and San Luis Pass (fig. 1). Most of the spilled oil evaporated, sank to the seafloor, or was dispersed by wave energy; the remaining oil washed onto Texas beaches, where it was removed primarily by grading equipment. After the initial cleanup of heavily contaminated sand, small patches of oily forebeach sand were graded and raked to mix the lightly contaminated and uncontaminated sand.

Oily sand was removed from Pirates Beach, Galveston Island State Park, Jamaica Beach, and Indian Beach (fig. 3). These areas of sand removal lie within the transition zone between eroding and stable beach segments. As previously stated, these beach segments have also undergone net losses of sand caused by Hurricane Alicia. Thus, the sand removed during cleanup represents an additional net loss of beach sand. About 90,000 yd^3 of oily forebeach sand was moved to landfill sites on the island (C. R. Miertschin, Texas Department of Water Resources, personal communication, 1984); a lesser volume of lightly contaminated sand was scraped from the forebeach and spread along the backbeach immediately seaward of the vegetation line. Neither beach scraping nor backfilling altered the position of the natural vegetation line. The 90,000 yd^3 estimate was based on the number of truckloads removed; therefore, it probably represents a maximum value because scraped sand occupies a larger volume than does naturally compacted beach sand. For comparison, the net annual littoral drift is approximately 60,000 yd^3 near the west end of the seawall (U.S. Army Corps of Engineers, 1983b).

Some of the sand removed by scraping was rapidly replaced by normal processes such as seasonal onshore bar migration. Field measurements showed vertical forebeach accretion of 3 to 5 inches after the oil spill. Furthermore, the beach scraping did not surpass normal beach accretion nor did it drastically alter beach morphology (figs. 14A and B). Beach profiles outside the spill area also displayed summer accretion; therefore, the onshore sand transport was related to the summer buildup and post-storm recovery and was not a result of beach grading.

Before the oil spill occurred, a technique for scraping the forebeach and transferring sand to the backbeach was proposed as a method for mitigating shoreline erosion and rebuilding the dunes on Galveston's West Beach. In principle, beach slope is reduced so that sand is transported onshore and deposited by uprushing waves. According to theory, sand from the inner shelf would replenish sediment removed from the forebeach, causing a net gain of beach sand. Apart from the economics, several physical considerations may limit the practical application of this technique: (1) many erosional beaches do not have an adequate supply of offshore sand, (2) retreat of highly erosional beaches would be accelerated, (3) sand taken from the littoral system could deprive downdrift beaches or interfere with the normal post-storm recovery process, and (4) sand backfilled in the dune area would eventually be transported offshore by storm

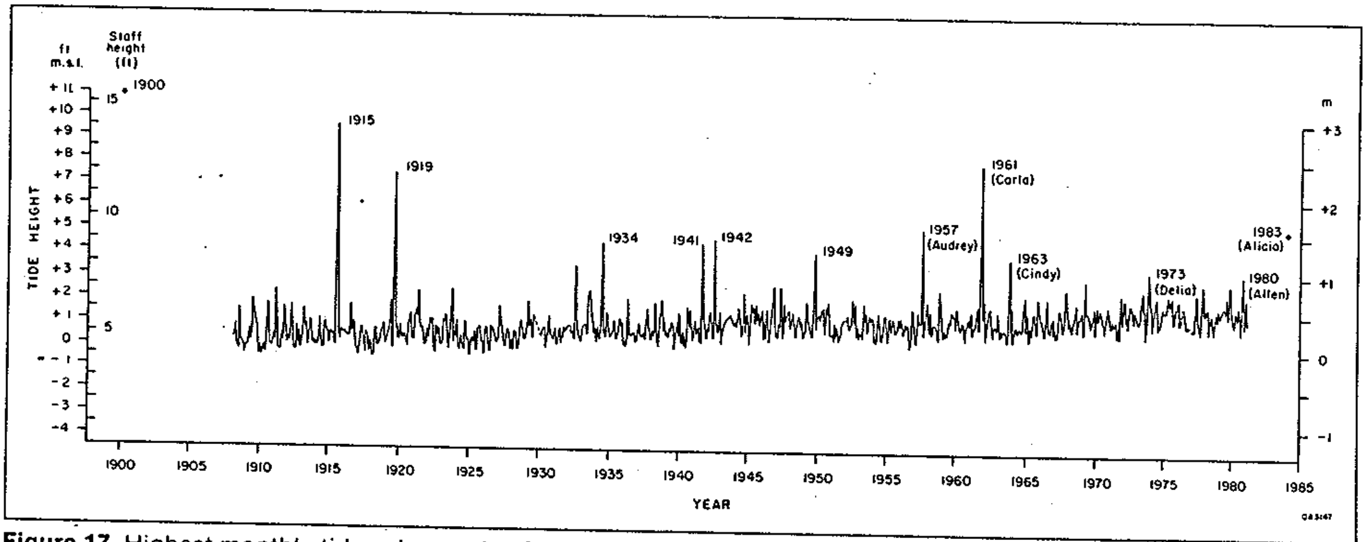

Figure 17. Highest monthly tides observed at Pier 21 on the bay side of Galveston Island, 1908 to 1983. Mean sea level (m.s.l.) calculated from 1960 through 1978 hourly tide heights. Tide heights of earlier storms may not equal heights mentioned in text because of periodic adjustments to mean sea level. Modified from U.S. Army Corps of Engineers (1983b). Data from National Ocean Service.

waves, thus making any local benefit only temporary. In addition, the scrape-and-transfer technique does not alter the primary causes of shoreline erosion.

A beach-scraping project like the one proposed for West Beach was conducted at Myrtle Beach, South Carolina, to provide temporary relief from dune recession along a developed recreational beach (Kana and Svetlichny, 1982). This stable to slightly eroding storm-dominated coast has undergone long-term erosional rates (1.5 ft/yr) that are comparable to or lower than those of Galveston Island's Gulf shoreline. Detailed field surveys during the project revealed that the 100,000 yd^3 of backfill scraped from the beach remained in the dune area less than a year (Kana and Svetlichny, 1982).

COMPARISONS WITH OTHER STORMS

Storm Surge

Tropical cyclones are characterized by their central pressure, highest sustained winds, large storm diameter, and above-average tide height (storm surge). The parameter that correlates best with the amount of sediment transported in coastal areas is storm surge. Storm surge is influenced by all measures of storm strength as well as by position relative to the storm. For a given storm crossing the Texas coast, surge is typically higher in the right-front quadrant of the storm and in areas having a broad, shallow continental shelf. For a given area on the Texas coast, surge tends to increase with lower central pressures, higher sustained winds, larger storm diameter, and rapid storm movement toward land.

SURGE HEIGHT

Higher storm surge generally causes greater beach erosion. The most severe beach erosion occurs in areas near hurricane landfall; however, because hurricanes are typically very large (up to hundreds of miles in diameter) they can cause elevated tides and concomitant beach erosion great distances from landfall. Although many of the highest tides observed on Galveston Island were from storms that crossed the coast at or near the island (the storms of 1900, 1915, and 1983, for example) (fig. 17), other storms making landfall far from Galveston Island have also caused high tides and beach erosion at Galveston (the 1919 and 1961 storms made landfall south of Corpus Christi and near Port O'Connor, respectively).

Tide data on Galveston Island from the National Oceanic and Atmospheric Administration indicate that since 1958, only Hurricane Carla (1961) had a higher open-coast surge than Hurricane Alicia. Comparable open-coast surge heights of storms affecting Galveston Island before 1958 were unavailable,

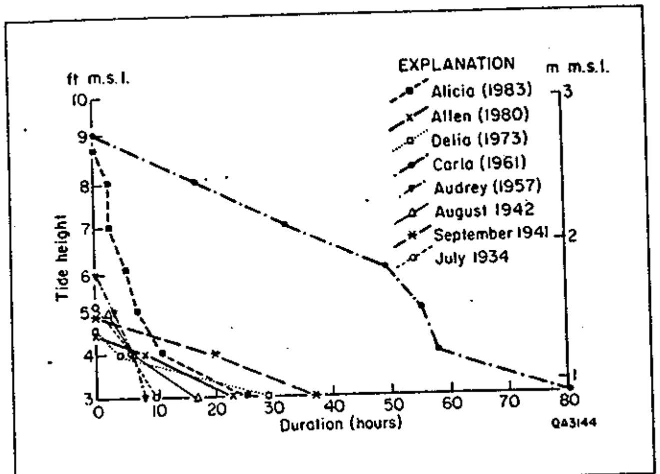

Figure 18. Storm surge height and duration, Galveston Island. Carla (1961) and later storms were recorded at Pleasure Pier (gulf gauge); earlier storms were recorded at Pier 21 (bay gauge). Data from National Ocean Service.

so comparison with these storms is based on tides recorded on the bay side of the island. Just as tide heights of the same storm vary at different points along the Gulf coast, so do they also vary between Gulf and bay waters. Bay and Gulf water levels can differ by several feet in the same storm owing to restricted tidal exchange, storm runoff, wind direction, and bay bathymetry. For example, Alicia's high tide reported at Pleasure Pier on the open coast (8.8 ft m.s.l.) was more than 3 ft higher than high tide at Pier 21 on the Galveston Channel (5.7 ft m.s.l.). Given the possible tide-height variation across Galveston Island for the same storm, Gulf tide heights are better indicators of potential shoreline erosion.

The tide record began in 1908 at Pier 21 (on the bay side of Galveston Island), allowing comparison of all storms after 1908 at the same gauge. A summary of monthly high tides at this gauge (fig. 17) shows that several storms have caused tides higher than Alicia's 5.7-ft peak, including the storms of 1915 (10.5 ft), 1919 (8.4 ft), 1957 (5.9 ft), and 1961 (8.4 ft). The 1900 storm tide was estimated to be 11.2 ft. Several other storms registered tides only slightly lower than Alicia's tides, notably storms in 1932, 1934, 1941, 1942, 1949, 1963, 1973, and 1980. In comparison, highest monthly tides in non-hurricane months average about 2 ft (U.S. Army Corps of Engineers, 1983b).

SURGE DURATION

Beach erosion depends not only on surge height but also on surge duration. Primary factors controlling surge duration are astronomical tides and storm path, speed, size, and strength.

Alicia's open-coast tide measured at Pleasure Pier was essentially the same as Hurricane Carla's. On the basis of tide height alone, about the same shoreline erosion would be expected from both storms. However, water levels during Hurricane Carla remained high much longer (fig. 18), allowing more beach erosion. Alicia's storm tides remained above 5 ft m.s.l. for about 7 hr, whereas Carla pushed water levels over 5 ft m.s.l. at the same location for about eight times longer (55 hr). In fact, Carla's water levels were over 7 ft m.s.l. for more than a day. Surge durations of the severe storms affecting Galveston early in this century (1900, 1915, and 1919) were unavailable; their tides were comparable to or higher than those of Hurricane Carla and possibly had equal or longer durations.

Hurricanes Allen (1980) and Carla (1961) were chosen for detailed comparisons with Alicia in regard to West Beach deposition and erosion. Of the three storms, only Alicia crossed the coastline near Galveston Island (fig. 1). The effects of Hurricane Allen, making landfall near Brownsville, were considerably diminished along the upper Texas coast. Open-coast tide height at Pleasure Pier during Allen was only 4.5 ft m.s.l. Tides remained above 3 ft for about 24 hr, causing minor beach erosion.

Vegetation-Line Retreat

Comparison of storm effects on the West Beach vegetation line was accomplished with pre- and post-storm photographs for Hurricanes Carla, Allen, and Alicia. If surge height and duration were primary factors controlling vegetation-line retreat, then Hurricane Alicia, even with its nearby landfall, should have caused more vegetation-line retreat than Allen, but less than Carla. Comparisons of vegetation lines mapped on aerial photographs verify the prediction.

Vegetation-line retreat along West Beach ranged to as much as 315 ft for Carla, 95 ft for Allen, and 145 ft for Alicia (fig. 19 and appendix C). Carla caused average vegetation-line retreat of 164 ft (table 5), or more than twice that caused by Alicia (78 ft) and almost five times that caused by Allen (34 ft). Areal measurements made from pre- and post-storm photographs also indicate that Carla eroded about twice as much vegetated area as did

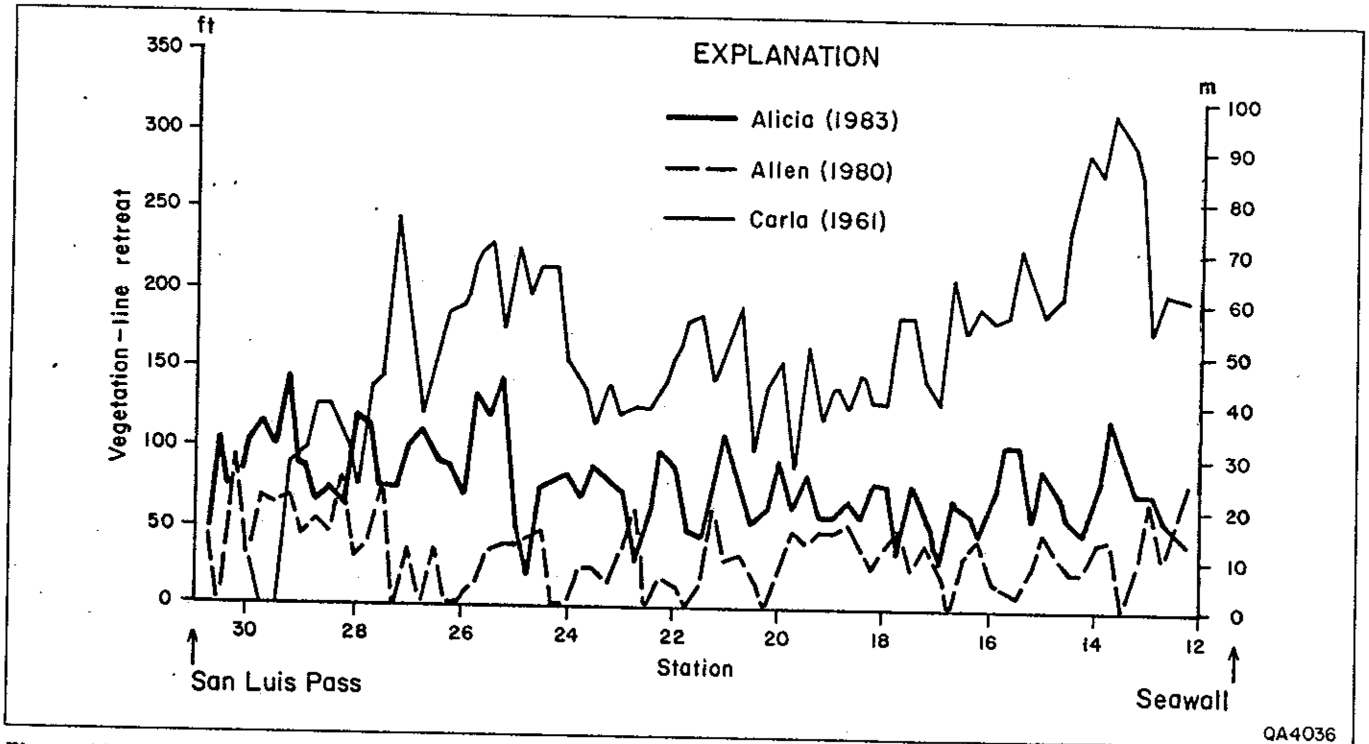

Figure 19. West Beach vegetation-line retreat caused by Hurricanes Carla, Allen, and Alicia. Station locations shown in figure 3.

Alicia (15,000,000 ft^2 to 7,575,000 ft^2) and more than four times as much as did Allen (3,570,000 ft^2).

Greatest retreat measured for Allen was near San Luis Pass (95 ft at station 30.25, appendix C) and near the west end of the seawall (90 ft at station 12.2). Vegetation-line retreat attributed to Allen varied from place to place (fig. 19) but was considerably less than that caused by Alicia at most stations. Variation in retreat along the beach was more pronounced for Carla; more retreat occurred between Spanish Grant and the western end of the seawall (175 to 315 ft), between Jamaica Beach and Indian Beach (145 to 190 ft), and between Bay Harbor and Sea Isle subdivisions (120 to 245 ft). Carla caused more vegetation-line retreat than did Allen and Alicia except near San Luis Pass (fig. 19).

Storm surge from Hurricane Allen at Galveston Island was nearly equal in duration but only half as high as that of Alicia (fig. 18), an indication that vegetation-line retreat lasted about as long during both storms. More erosion was caused by Alicia's higher surge and more powerful waves near landfall. Surge heights of Hurricanes Carla and Alicia at Galveston Island were similar, but the extremely long duration of Carla's surge resulted in greater vegetation-line retreat.

Cumulative effects of these storms and the intervening recovery periods on vegetation-line position were documented by comparing the earliest vegetation-line position with positions taken from later photographs (appendix A). In this study, 1958 photographs served as the pre-Carla baseline, 1961 photographs showed the effects of Hurricane Carla, 1979 photographs indicated both the extent of recovery from Carla and pre-Allen conditions, 1980 photographs documented Allen erosion, 1982 photographs showed both post-Allen changes and pre-Alicia conditions, and 1983 photographs showed Alicia erosion. Each vegetation line was compared with (1) its predecessor, to ascertain vegetation-line changes during the previous storm or recovery period, and (2) the 1958 vegetation line, to better understand longer-term changes.

From 1958 and 1961 aerial photographs, it is clear that virtually all of West Beach underwent vegetation-line retreat during Carla. After Carla, the vegetation line advanced as part of the storm recovery process. During the approximately 18 yr between photographs taken in 1961 (after Carla) and 1979, the only

Table 5. Comparison of vegetation-line retreat and inland washover extent caused by Hurricanes Carla, Allen, and Alicia along West Beach. Fewer stations were used for Carla because shoreline reorientation near San Luis Pass caused misleading values. Compiled from appendix C.

		Vegetation-Line Retreat (ft)		Washover Width (ft)	
Storm	Stations	Mean	sd	Mean	sd
Alicia (1983)	74	78	26	85	61
Allen (1980)	74	34	23	41	49
Carla (1961)	72	164	61	317	214

areas not showing post-storm vegetation-line advancement were a mile-long segment west of the seawall and the western tip of the island from station 29.5 westward (fig. 20, post-Carla changes). The segment west of the seawall remained near its post-Carla position, whereas the vegetation line near San Luis Pass continued to retreat, even in the absence of major storms. Only in a relatively small portion of West Beach (primarily between Jamaica Beach and Bay Harbor) did the vegetation line attain or move seaward of its 1958 (pre-Carla) position (fig. 20, 1958 to 1979).

Hurricane Allen caused additional vegetation-line retreat on West Beach (fig. 20, Allen erosion). Its effect was to leave a smaller portion of the West Beach vegetation line within 100 ft of its 1958 position (fig. 20, 1958 to 1980). Less than 2 yr passed between post-Allen photographs and pre-Alicia photographs; thus few vegetation-line changes occurred during the period (fig. 20, post-Allen changes).

Hurricane Alicia moved the vegetation line landward of its pre-Carla position at all measuring points along West Beach (fig. 20, 1958 to 1983). The most retreat since 1958 was found from station 29 westward to San Luis Pass, and from station 17 eastward to the seawall.

Washover Deposition

Of the three major storms compared in this study, Hurricane Carla was the most severe. Although landfall occurred farther from West Beach near Pass Cavallo, Carla caused much more vegetation-line retreat and washover deposition on Galveston Island than did either Allen or Alicia (table 5).

The inland extent of washover deposition varied considerably with location and storm strength. For example, Carla deposits reached 85 ft to 1,250 ft inland from the post-storm vegetation line, Allen deposits 0 to 200 ft inland, and Alicia deposits 0 to 355 ft inland (fig. 21 and appendix C). These are the ranges measured at West Beach stations; ranges measured between stations were slightly greater. Average washover extent at all stations (table 5) corroborates the relative ranking of these storms, ranging from greatest deposition (Carla deposited washover sands an average of more than 315 ft inland of the post-storm vegetation line) to moderate deposition (average Alicia deposition extended about 85 ft inland), to least deposition (average Allen deposition extended just over 40 ft inland). The greatest inland extent of washover deposition caused by all three storms is along the western end of the island between stations 24 and 30, and a well-defined maximum occurs between stations 26 and 27 (near the Terramar subdivision).

Some of the widest Alicia washover deposits are partly attributed to human activities, including dune building. However, extensive Carla washover deposits between Sea Isle subdivision and San Luis Pass before development indicate that the western portion of the island is naturally more susceptible to overwash, possibly due to lower elevations.

Hurricane Allen washover deposits on West Beach covered approximately 3,570,000 ft^2. In comparison, Alicia deposits covered 8,599,250 ft^2 and Carla deposits covered 28,635,000 ft^2. The more than threefold difference between Alicia and Carla washover deposition was apparently caused by the tremendous difference in surge duration (fig. 18).

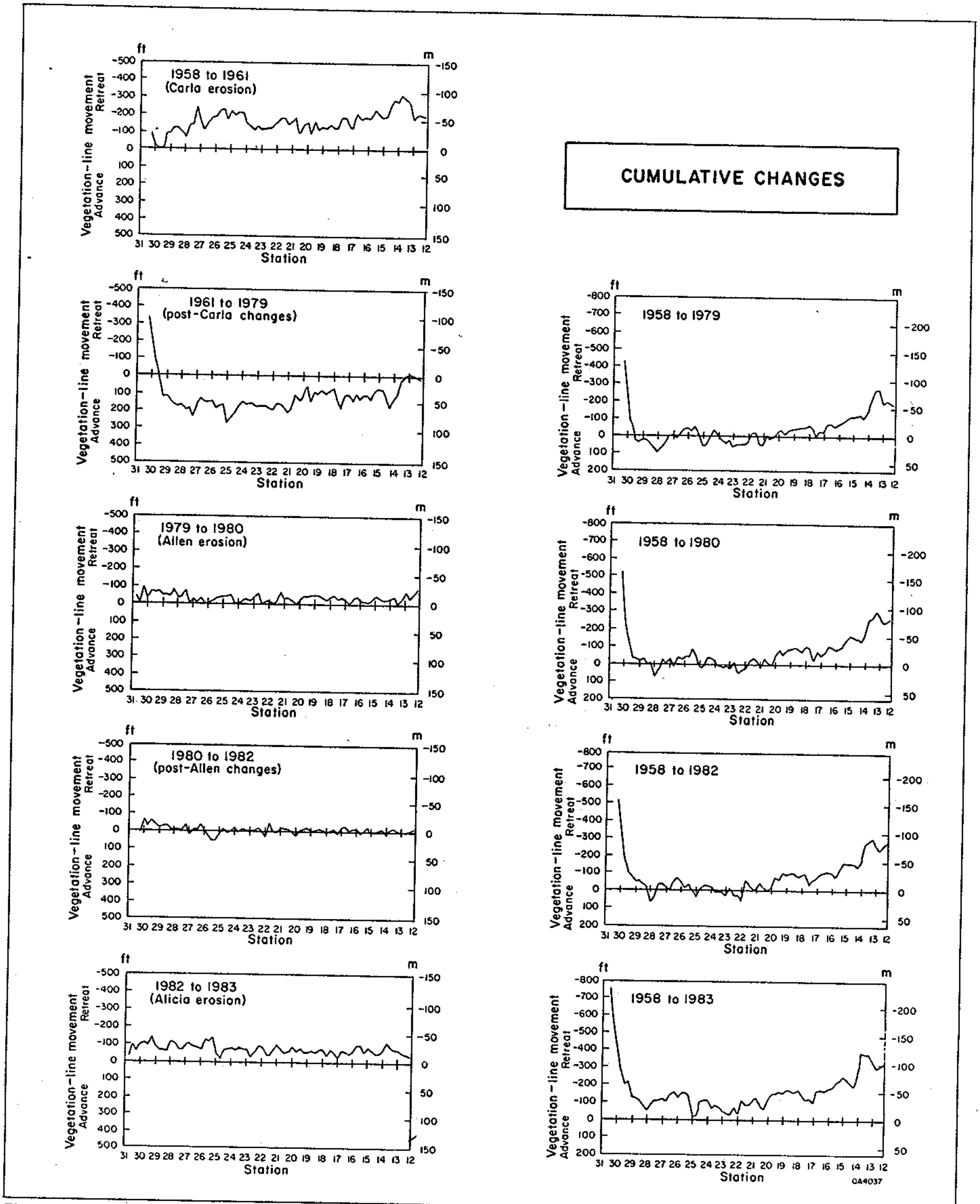

Figure 20. Incremental and cumulative West Beach vegetation-line changes, 1958 to 1983. Left column: vegetation-line changes during Hurricanes Carla, Allen, and Alicia and during intervening recovery periods. Right column: cumulative vegetation-line changes since 1958.

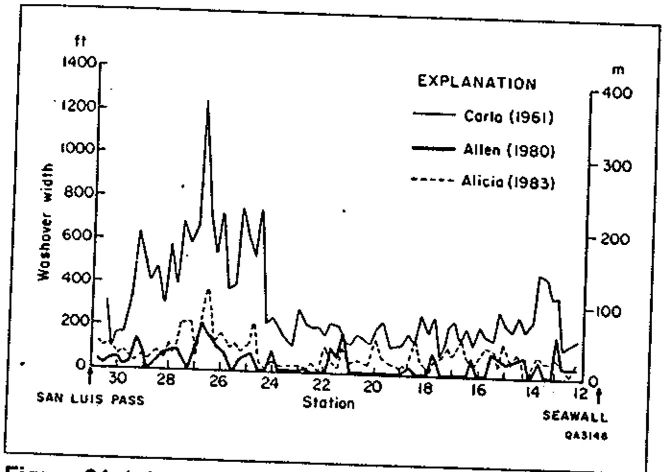

Figure 21. Inland extent of Carla, Allen, and Alicia washover deposition, West Beach. Station locations shown in figure 3.

POTENTIAL FOR BEACH RECOVERY AFTER HURRICANE ALICIA

Both the shoreline and the vegetation line are nearshore physiographic features, but their short-term movements are independent of one another because each responds at different rates to different sets of coastal processes. A physical link between the two features is storm response. Episodic movement of these coastal boundaries on Galveston Island (Morton, 1974) and elsewhere clearly demonstrates that the line of continuous vegetation is neither stable nor permanently positioned with respect to the earth's surface. Long-term movement of the vegetation line is similar to long-term movement of the shoreline; however, immediate post-storm responses of the shoreline and vegetation line are quite different and allow recognition of distinct recovery phases.

Phases of Recovery

Post-storm recovery of the beach and vegetation line occurs in four time-dependent phases (Morton, 1974); each of the last three phases relies partly on the preceding phase. Onshore transport of sand, vertical aggradation and forebeach steepening, and berm construction characterize the first phase of beach recovery, which begins shortly after the storm and continues through the first post-storm year. This phase progresses relatively rapidly as the equilibrium beach profile is reestablished. Beach morphology following the initial phase is generally similar to pre-storm conditions with the exception that backbeach elevation is commonly lower than that before the storm (fig. 14). This failure to attain pre-storm elevations is attributed to the height of subaqueous deposition controlled by the limits of wave uprush and spring tide water levels. In contrast, the second phase of recovery is characterized by eolian processes (subaerial deposition) and minor flooding of the backbeach that promote accumulation of sand seaward of the vegetation line. High winter waves associated with passage of cold fronts narrow and steepen the beach by eroding the forebeach and transporting sand both landward and seaward. Sand removed from the forebeach and deposited in the backbeach creates a high (winter storm) berm and increases the backbeach elevation. After these storms, low-energy waves form a lower berm and reestablish the forebeach. Higher elevations and concomitant greater protection from salt-water flooding during the second phase of recovery encourage colonization of the incipient dunes by native vegetation, forming coppice mounds. This recovery phase normally begins during the second post-storm summer along coasts, such as West Beach, that have limited eolian transport and severe storm damage.

The second and third phases of recovery are transitional as coppice mounds grow and merge with fore-island dunes. The accumulation of eolian sand and propagation of vegetation partly obscure the former erosional escarpments and wave-cut dunes.

On wide post-storm beaches, such as West Beach after Alicia, the area of optimum dune growth may be slightly seaward of the erosional escarpment (vegetation line). Topographic lows between the erosional escarpment and new dunes may be partly filled with washover and eolian deposits or they may be preserved as fresh-water swales. In either case, increases in vegetative cover accompany dune growth as plants stabilize the barren sand and cause sparsely vegetated areas to become densely (continuously) overgrown. Plant colonization and infilling advance the vegetation line seaward; this advancement constitutes the fourth phase of recovery.

Initial advances of the vegetation line are irregular because newly formed dunes are low and hummocky. If recovery continues, the vegetation line eventually becomes straighter as interdune lows are filled and vegetated.

Factors that Influence Recovery

Many factors affect the degree and rate of beach and vegetation-line recovery, including time, storm damage, subsequent storms, shoreline stability, climatic variations, and human alteration of the natural processes. Some of these variables are independent, whereas others are interactive. Predicting responses to these variables is further complicated by the uncertainty associated with each variable; some are easily characterized (storm damage), but others are largely unknown (impending storms). Ironically, the extreme short-term (months) and long-term (tens of years) responses are easier to predict than responses in intermediate periods (less than 10 to 15 yr). Unless otherwise specified, the following discussion pertains to natural recovery in undeveloped areas without human interference.

SEVERITY OF DAMAGE CAUSED BY HURRICANE ALICIA

Tropical cyclones represent upper limits in the continuum of physical forces affecting coastal areas. The energy released and the sediment transported during a few storm hours equal a few years of work performed by non-storm processes. Consequently, severe storm damage prolongs recovery of the beach and vegetation line.

The extent of beach erosion by Hurricane Alicia ensures that natural recovery of the vegetation line will be slow. A prolonged recovery period is predicted because wave erosion substantially lowered the backbeach elevation and exceeded the depth of root penetration. Elimination of the dune and backbeach root systems means that colonization by perennial vegetation will be necessary to advance the vegetation line. Colonizing barren sand takes years, a slow process compared with the seasonal sprouting new leaves from old roots. Two years after Hurricane Alicia, the backbeach surface was 3 to 5 ft below its pre-storm elevation and devoid of incipient dunes. The lack of coppice mounds (second phase of recovery) indicates that several more years will elapse before the vegetation line advances seaward appreciably.

STORM RECURRENCE AND STRENGTH

Historical records were used to establish storm frequency for particular coastal areas. According to data presented by Hayes (1967), the Texas coast is influenced by approximately two tropical cyclones every 3 yr. This high frequency demonstrates that tropical storms and hurricanes are not anomalous events but are simply less common occurrences in the geological spectrum. Despite high storm frequency, the annual probability of a storm striking Galveston (about 18 percent) is fairly low (Simpson and Lawrence, 1971). However, the probability of landfall at, or near, Galveston increases to 100 percent given enough time.

The most recent shoreline conditions persisted for at least 15 yr (1965-1980), a period when the beaches of Galveston Island were not measurably affected by major storms. However, since 1980 two storms have eroded the beach and have contributed to net losses of sand from the littoral system. Hurricane Allen (1980) caused minor erosion, whereas Hurricane Alicia (1983) caused substantial retreat of the shoreline and vegetation line.

The 19-yr period between Carla and Allen was unprecedented for recorded length of time without abnormally high waves eroding Galveston beaches; tide records from 1908 to 1983 indicate that about every 5 yr, water levels exceeded elevations of 4 ft (fig. 17). Storm surges of this magnitude cause beach and dune erosion, landward washover, and offshore transport of sand. These cumulative losses of sediment in the absence of sand replenishment ultimately translate into shoreline erosion.

SHORELINE STABILITY

Sediment supply and attendant shoreline stability profoundly affect post-storm beach recovery. Where sand is abundant and shorelines are either stable or accreting, the beach and vegetation line will eventually recover to their pre-storm positions. Conversely, where sand supply is deficient and shorelines are undergoing long-term erosion, the beach and vegetation line will not entirely recover. Indeed, on highly erosional coasts, the vegetation line may remain in its most landward position until the next erosional event causes further landward retreat.

Shoreline trends since 1965 (fig. 3) provide a preliminary basis for evaluating potential post-Alicia recovery of the vegetation line along West Beach. Frequent beach scour and inundation of the backbeach probably will retard dune growth and prevent complete recovery of the vegetation line along those segments having long-term (tens of years) erosion. More stable segments have a better chance for short-term (few years) complete recovery of the vegetation line if subsequent storms do not cause additional retreat and if sediment supply is not greatly diminished by washover and offshore transport. Net losses of littoral sand are especially critical along Galveston Island and Follets Island where the littoral drift system is compartmentalized and lacks outside sources of sand. The long jetties and deep-draft channels at Galveston and Freeport Harbors effectively prevent sand from entering this compartment from adjacent littoral drift cells. Consequently, repeated storm losses cause a deficit in the littoral sand budget. The natural processes balance this sediment deficit by eroding the beach.

Another potential contributor to shoreline erosion is the long-term relative rise in sea level, which has been recorded at most Gulf coast and Atlantic coast tide gauges (Hicks, 1972). Relative sea-level rise along the Gulf Coast is attributed principally to compactional subsidence (Swanson and Thurlow, 1973) rather than to eustatic increases caused by thermally expanding oceans or melting polar ice caps. Atmospheric warming (the greenhouse effect) may influence sea-level rise and shoreline stability in the future if it is as significant as some researchers predict.

Regardless of the cause, relative sea-level at Galveston has risen more than 1 ft since 1904, when long-period tide records began. The most recent (1979) adjustment at Galveston's Pleasure Pier gauge increased the tidal datum 0.12 ft above the datum for the previous 18-yr period (1960-1978). Reduced sediment supply and increased sea level have little influence on short-term changes in the vegetation line. However, they contribute to long-term retreat of the vegetation line by inducing shoreline erosion.

CLIMATIC VARIATIONS

The balance between precipitation and evapotranspiration can cause shoreline and vegetation-line changes. Periods of above-average rainfall may raise ground-water levels and increase vegetative cover. Conversely, periods of below-average rainfall may lower ground-water levels and decrease vegetative cover. Wet and dry cycles commonly alter the vegetative cover, but their influence on the Gulf shoreline is generally negligible. Of the two extremes, droughts cause the greatest changes in the vegetation line. Droughts can also adversely affect post-storm recovery by minimizing the vegetative cover and allowing active dune migration.

The first growing season after Alicia was characterized by below-average rainfall. This deficit did not adversely affect indigenous barrier island vegetation, which can tolerate relatively low rainfall. The same grass species grow in coastal South Texas, where average rainfall is considerably less than that along the upper coast. Thus, recovery of the vegetation line would be inhibited only by a severe drought, which is impossible to predict.

HUMAN INTERFERENCE

Anthropogenic activities can both hinder and promote post-storm recovery of the beach and vegetation line. Activities that alter littoral drift or sediment supply mainly affect beach restoration. Sand removal or placement of coastal structures that cause or increase sand losses may hinder beach recovery. Conversely, sand replenishment and coastal structures that trap sand or minimize erosion may locally enhance beach recovery.

Activities that alter plant density and robustness normally affect the position of the vegetation line. Intense or frequently repeated activities such as construction may weaken or destroy vegetation and may temporarily alter or permanently obliterate segments of the natural vegetation line. Heavy vehicular traffic may also retard advancement of the vegetation line by interfering with dune growth and plant recolonization. However, normal traffic, beach maintenance, and public recreation after Hurricane Carla did not prevent advancement of the vegetation line in either developed or undeveloped areas (figs. 22 through 24).

Increasing backbeach elevation, blocking eolian sand transport, changing backbeach morphology, planting native species, and watering and fertilizing plants are all conducive to vegetation-line advancement. Many owners of developed West Beach Gulf-front property

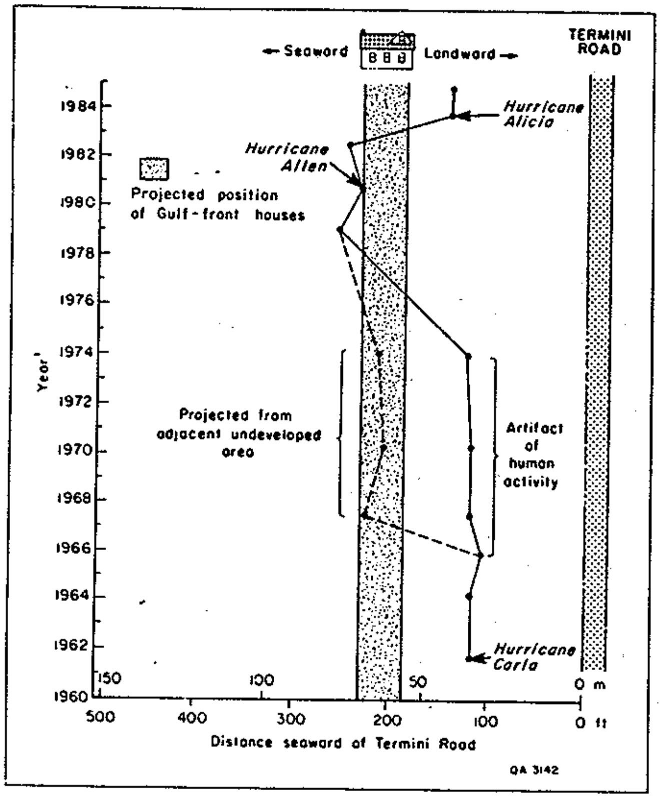

Figure 22. Sequential movement of vegetation line from 1961 to 1985. Profile is within the Sea Isle subdivision (fig. 3). Shading represents the position of Gulf-front houses.

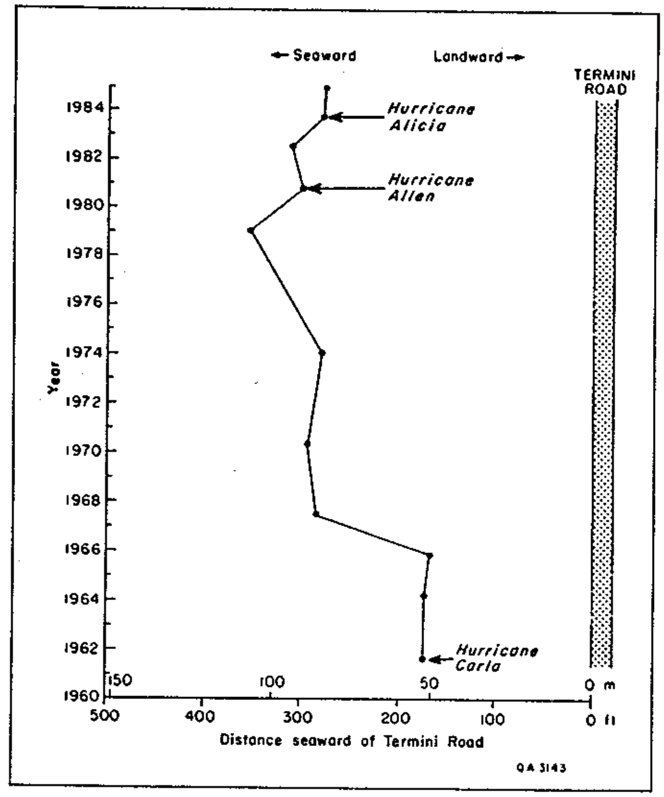

Figure 23. Sequential movement of vegetation line from 1961 to 1985. Profile is within an undeveloped area just east of Sea Isle subdivision (fig. 3).

used these techniques to artificially reestablish a vegetation line in its pre-storm position or to promote its recovery. Nearly 80 percent of the beachfront lots with buildings were filled and sodded after Hurricane Alicia. The fill replaced approximately 160,000 yd^3 of sand eroded from the backbeach, or slightly less than the amount that accumulated as washover deposits. Artificial sand dunes built with heavy equipment or created by wind shadows also changed the backbeach shape and raised the land surface. Native grasses planted on these sand mounds will eventually flourish, making the lines separating artificial and natural vegetation less distinct.

Widespread manipulations of the backbeach and vegetation line were observed in developed areas and were detected by comparing beach width and beach shape in developed and adjacent undeveloped areas. Measurements at unaltered lots within subdivisions showed that artificial dunes, sand fences, and other obstructions were placed 75 to 130 ft seaward of the natural post-storm vegetation line. In some areas, such as Sea Isle subdivision, these modifications covered about half of the beach width in 1985.

Predictions for West Beach

Advancement of the vegetation line after Hurricane Carla provides evidence of the processes, sequences, and probable duration for post-Alicia beach changes. The lack of photographs taken immediately before Hurricane Carla (1961) hampers recovery analysis; nevertheless, photographs taken in 1958 (appendix B) reasonably represent the pre-Carla nonstorm period. Comparison of the 1958 and 1979 photographs indicates that the vegetation line from the seawall to Indian Beach experienced incomplete recovery ranging from 30 to 200 ft. Except near San Luis Pass, the vegetation line west of Indian Beach either completely recovered or advanced seaward of its 1958 position. This complete

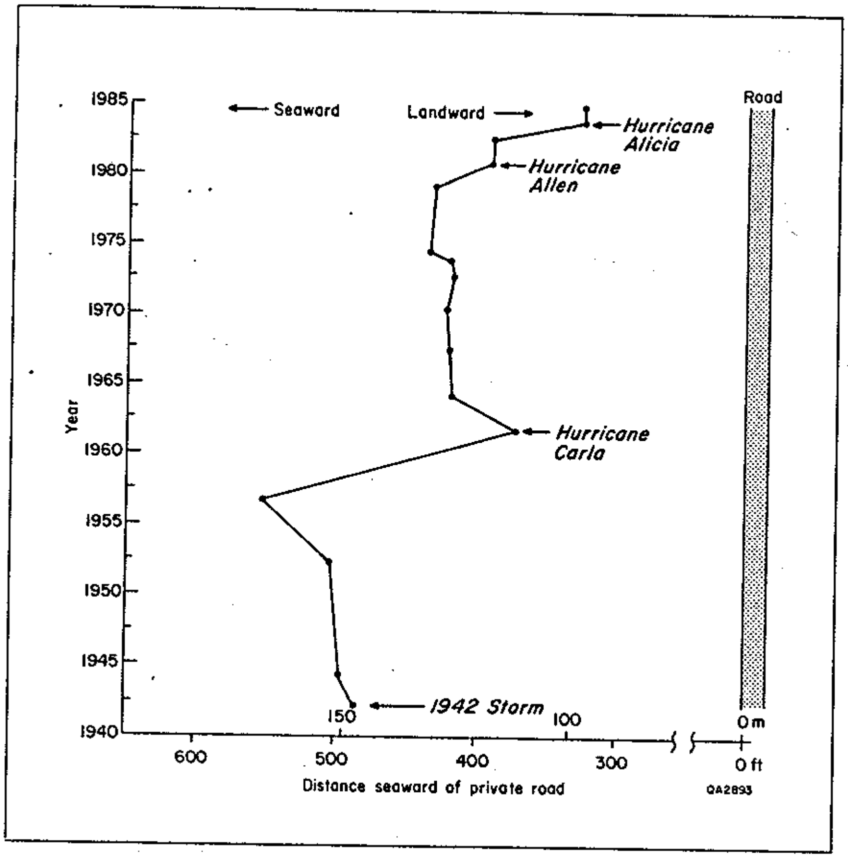

Figure 24. Sequential movement of vegetation line from 1942 to 1985. Profile is within an undeveloped area east of Pirates Beach (fig. 3).

recovery or net advancement is anomalous and may not be generally applicable to predicting post-Alicia recovery even though Carla caused greater retreat of the vegetation line than did Alicia.

A significant reason for doubting that the vegetation line will recover completely after Alicia is the substantial reduction of sand available for natural backbeach restoration. Before 1970, wide beaches existed along the seawall, but continued erosion has eliminated that source of sand. Additional net losses of sand caused by Alicia or future storms will add to the deficit, exacerbate existing rates of shoreline retreat, and probably cause erosion of beaches that were formerly stable.

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APPENDIX A

Date, landfall location, and approximate tide height of tropical cyclones affecting Galveston Island, 1900 to 1984. Peak tide heights are for Pier 21 on the Galveston Channel (unpublished data from National Ocean Service). Landfall and approximate storm rank compiled from Dunn and Miller (1964), Price (1956), Simpson and Riehl (1981), Tannehill (1956), and U.S. Army Corps of Engineers (1979).

The Saffir/Simpson Damage-Potential Scale (from Simpson and Riehl, 1981):

Rank	Central Pressure (mb)	Winds (mph)	Surge (ft)	Damage
1	≥980	74-95	4-5	Minimal
2	965-979	96-110	6-8	Moderate
3	945-964	111-130	9-12	Extensive
4	920-944	131-155	13-18	Extreme
5	<920	>155	>18	Catastrophic

Tropical storms below rank 1 are designated as TS.

Year	Landfall Area	Rank	Peak Tide (ft) at Galveston
1900	Galveston Island	4	11.2 (est)
1908	Brownsville	?	2.5
1909	Velasco	3	?
1909	Brownsville	2	2.9
1910	Lower coast	2	2.7
1912	Lower coast	1	1.8
1915	Upper coast	4	10.5 (est)
1916	Lower coast	3	2.7
1918	Southeastern Louisiana	3	1.0
1919	Corpus Christi	4	8.4
1921	Palacios	2	3.3
1931	Port O'Connor	1	1.0
1932	Freeport	4	3.9
1933	Lower coast	2	2.5
1933	Brownsville	3	2.8
1934	Rockport	2	5.1
1936	Port Aransas	1	0.9
1938	Western Louisiana	1	1.7
1938	Freeport	TS	2.5
1940	Sabine Pass	2	0.7
1940	Western Louisiana	TS	2.1
1941	Upper coast	TS	1.9
1941	Freeport	3	4.9
1942	Bolivar Peninsula	1	>2.0
1942	Matagorda Peninsula	3	5.1
1943	Bolivar Peninsula	2	4.0 (gauge out)
1945	Middle coast	>2	2.3
1947	Galveston Island	1	2.0
1949	Freeport	2	4.6
1957	Sabine Pass	4	5.6
1958	Middle coast	TS	3.0
1959	Galveston	1	2.1
1960	South Padre Island	TS	1.6
1961	Port O'Connor	4	8.5
1963	High Island	1	4.4
1964	Matagorda	TS	1.9
1967	Brownsville	3	3.1
1968	Port Aransas	TS	2.5
1970	Port Aransas	3	1.8
1970	High Island	TS	2.1
1971	Middle coast	1	2.9
1973	Upper coast	TS	3.9
1974	Louisiana	3	1.9
1977	Northern Mexico	4	3.4
1978	Louisiana	TS	2.1
1979	Upper coast	TS	3.3
1979	Matagorda	TS	2.6
1980	South Padre Island	3	3.8
1980	Galveston Bay	TS	2.9
1983	Galveston Island	3	5.7

APPENDIX B

List of aerial photographs used to document shoreline and vegetation-line changes and extent of washover deposition on Galveston Island. Asterisk denotes photographs used in appendix C.

Date	Source	Date	Source
March and April 1942	National Archives	June 1967	U. S. Army Corps of Engineers
September 1942	"	April 1970	Texas Highway Department
April 1944	Stern (1948)	August 1972	"
March and April 1952	U. S. Department of Agriculture	December 1973	Texas Forest Service
August 1956	Tobin Research, Inc.	June 1974	Texas Highway Department
February to May 1958	*U. S. Department of Agriculture	February 1979	*Texas General Land Office
September 1961	*U. S. Coast and Geodetic Survey	September 1980	* "
February 1964	Texas Highway Department	June 1982	* "
October 1965	U. S. Coast and Geodetic Survey	August 1983	* "

APPENDIX C

Movement of the vegetation line, 1958 to 1983, and inland extent of washover deposition caused by Hurricanes Carla (1961), Allen (1980), and Alicia (1983) at West Beach, Galveston Island. Station locations given in figure 1.

		Vegetation-Line Movement (ft)					Inland Extent of Washover (ft)		
Station	Status‡	1958 to 1961	1961 to 1979	1979 to 1980	1980 to 1982	1982 to 1983	Carla	Allen	Alicia
12.20	N	-195	10	-90	-15	-40	175	40	75
12.75	N	-200	-10	-30	0	-60	130	40	60
13.00	D	-175	-15	-70	0	-75	375	170	80
13.25	N	-275	0	-30	0	-75	365	0	75
13.50	N	-300	35	0	-20	-95	455	0	65
13.75	N	-315	100	-45	-10	-120	475	70	90
14.00	NRP	-275	130	-40	10	-75	250	0	0
14.25	N	-290	185	-25	-10	-50	210	95	0
14.50	N	-250	125	-25	-5	-55	275	80	105
14.75	N	-195	75	-35	0	-75	205	60	55
15.00	D	-185	70	-50	5	-90	235	65	145
15.25	D	-205	90	-25	-25	-60	300	60	30
15.50	D	-230	135	-10	0	-105	165	105	120
15.75	D	-185	105	-15	15	-105	185	0	130
16.00	N	-180	110	-20	-20	-70	220	0	65
16.25	N	-190	135	-45	-15	-50	135	70	60
16.50	D	-175	100	-35	0	-65	210	0	80
16.75	D	-210	140	0	-30	-70	150	0	155
17.00	D	-130	105	-25	-20	-30	245	0	95
17.25	D	-145	110	-40	10	-60	215	0	125
17.50	D	-185	185	-25	-10	-80	85	0	85
17.75	D	-185	135	-50	0	-40	265	95	65
18.00	N	-130	65	-40	10	-80	195	0	10
18.25	NRP	-130	80	-25	-5	-80	265	0	50
18.50	NRP	-150	100	-40	-15	-60	130	0	160
18.75	NRP	-125	80	-55	-5	-70	185	40	50
19.00	NRP	-140	100	-50	-5	-60	135	0	35
19.25	NRP	-120	85	-50	-20	-60	130	0	45
19.50	NRP	-165	150	-40	-10	-85	125	0	45
19.75	NRP	-90	55	-50	0	-65	235	0	65
20.00	D	-155	125	-25	30	-95	205	0	140

Appendix C (cont.)

Station	Status‡	Vegetation-Line Movement (ft) 1958 to 1961	1961 to 1979	1979 to 1980	1980 to 1982	1982 to 1983	Inland Extent of Washover (ft) Carla	Allen	Alicia
20.25	N	-140	140	0	0	-65	135	0	40
20.50	N	-100	110	-20	-10	-55	160	0	50
20.75	D	-190	185	-35	-10	-80	180	0	60
21.00	D	-165	210	-30	-20	-110	135	0	60
21.25	DB	-145	185	-65	10	-70	160	180	105
21.50	N	-185	160	-15	0	-45	215	70	30
21.75	N	-180	160	0	-45	-50	230	105	45
22.00	N	-160	195	-15	35	-90	165	0	105
22.25	N	-140	185	-20	0	-100	205	0	0
22.50	N	-125	170	0	-15	-60	200	0	50
22.75	N	-125	170	-60	0	-25	225	15	20
23.00	N	-120	180	-35	0	-75	290	0	35
23.25	N	-140	160	-15	0	-80	115	0	30
23.50	N	-115	155	-25	-10	-90	150	0	35
23.75	N	-140	165	-25	5	-70	185	0	40
24.00	N	-155	145	0	-20	-85	245	90	45
24.25	N	-215	180	0	0	-80	225	0	10
24.50	N	-215	220	-50	15	-75	750	0	35
24.75	DB	-195	245	-45	-10	-20	530	80	210
25.00	DB	-225	280	-40	20	-50	615	75	115
25.25	D	-175	165	-40	55	-145	750	55	85
25.50	D	-230	175	-35	55	-120	390	0	120
25.75	D	-220	190	-15	30	-135	380	40	110
26.00	D	-190	145	-5	0	-75	725	95	165
26.25	D	-185	150	0	-35	-90	545	115	125
26.50	D	-155	145	-35	0	-95	725	150	355
26.75	DB	-120	130	0	-5	-110	1250	200	260
27.00	N	-180	175	-35	20	-100	660	70	85
27.25	D	-245	240	0	-35	-75	585	0	215
27.50	D	-145	185	-75	0	-75	680	40	215
27.75	N	-135	200	-40	-5	-110	400	100	110
28.00	N	-75	170	-30	0	-120	565	65	120
28.25	N	-105	175	-80	-10	-65	305	75	45
28.50	N	-125	165	-45	-30	-75	470	25	95
28.75	N	-125	145	-55	-20	-70	415	0	60
29.00	N	-95	115	-45	-20	-90	520	55	80
29.25	N	-90	125	-70	-40	-145	625	125	45
29.50	N	0	25	-65	-60	-100	315	40	35
29.75	N	0	-75	-70	-25	-115	170	20	90
30.00	N	-30	-215	-30	-60	-100	170	60	60
30.25	N	-95	-340	-95	15	-65	100	50	125
30.50	N	*	-635	0	-20	-105	*	25	105
30.75	N	*	*	-45	0	-35	*	50	120

‡"Status" refers to type of beach as of August 1983, including N (undeveloped), NRP (recreational parks), D (unbulkheaded development), and DB (bulkheaded development). Negative values for vegetation-line movement refer to landward changes; positive values denote seaward changes. Vegetation-line changes between 1961 and 1979 are taken as Carla recovery, between 1979 and 1980 as Allen erosion, between 1980 and 1982 as Allen recovery, and between 1982 and 1983 as Alicia erosion.
*misleading numbers due to shoreline reorientation near San Luis Pass