# Airphoto Analysis of the Impact of Hurricane Alicia on Galveston Island

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Texas A&M University Sea Grant College Program
College Station, TX 77843

# AIRPHOTO ANALYSIS OF THE IMPACT OF HURRICANE ALICIA ON GALVESTON ISLAND

by

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## ABSTRACT

The advent of Hurricane Alicia at Galveston Island in August 1983 brought not only widely reported structural damage but significant, less-publicized shoreline erosion as well. The purpose of this study was to quantify the erosional impact of Alicia and to determine whether that impact was a departure from, or merely a continuation of, the ongoing pattern of mid- to long-term shoreline movement on the island.

The study compared aerial photography taken shortly after Alicia's passage with similar photographic sequences taken in 1979, 1977, 1967 and 1952 as well as a number of individual photos from 1970 and 1980. Measurements were made on each set of photos between fixed landmarks and the seaward edge of the line of natural vegetation to determine how far and in which direction that line had moved between photographic dates. Vegetation-line position provides a better index of erosion or accretion than the actual shoreline because it is not subject to anomalous diurnal or seasonal movement which might confuse the results. The vegetation line also has an important legal significance in Texas.

Structural damage from Alicia, which seems to have been a major hurricane but not an extreme one like Carla, Celia or Allen, was concentrated along the beachfront and on the southwestern half of the island. Erosion from 1979 to 1983, most of which was due to Alicia, was fairly uniform: close to 100 feet over most of West Beach except for a short stretch near the southwest tip of the island where it exceeded 200 feet. Shoreline change at West Beach was more erratic during the 1952-1967 and 1967-1979 periods: 1952-1967 saw mostly moderate erosion except for some accretion at the southwest tip; from 1967 to 1979

there was modest accretion over most of West Beach but rapid erosion at the southwest tip.

The vegetated bluffs along undeveloped beaches withstand erosional events better than developed beachfronts. Bulkheading does not appear to significantly inhibit erosion resulting from direct hits by major storms such as Hurricane Alicia.

The Texas Open Beaches Act defines the public beach as the area between the vegetation line and the low water line, stipulating that no structures are allowed in that zone. Scores of beachfront homes which were behind the vegetation line prior to Alicia ended up either partially or wholly on this public-access area in the storm's wake. This initiated legal proceedings which have apparently not yet been fully resolved.

It is quite unlikely that the West Beach vegetation line will move seaward significantly over the years to come. The sand source which had provided some nourishment to that area in the past has apparently been depleted. Even East Beach, which has steadily accreted since the 1890's when the Galveston jetties were built, is showing signs of an erosional future.

Considering the implications of the Texas Open Beaches Act and the probability of continued long-term erosion along West Beach, purchase of a beachfront home in that area is a chancy proposition at best. We suggest that any new waterfront structure be set back sufficiently far from the vegetation line to accommodate at least thirty years of projected erosion for the particular stretch of beach on which it is to be built.

# ACKNOWLEDGEMENTS

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We also wish to thank Mike Kieslich of the Galveston District, U. S. Army Corps of Engineers, for making available the Corps' 1967 aerial photography to augment the 1952 and 1983 Galveston photos already on hand.

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# INTRODUCTION

Hurricane Alicia formed in the middle of the Gulf of Mexico in mid-August 1983. Strengthening as it moved slowly westward and northward, the storm reached hurricane intensity shortly before crossing the southwest tip of Galveston Island on the morning of August 18. Alicia was apparently not an extremely powerful hurricane; nevertheless, there was significant structural damage at Galveston because the island lay in the path of the storm's highest velocity winds. A less-publicized impact of Alicia was shoreline erosion.

Immediately after Alicia's passage, debris blocked roads leading to what is locally known as West Galveston, a scattering of residential enclaves in the relatively undeveloped southwestern two-thirds of the island. Lacking access to this hard-hit area, earliest newspaper accounts focused on property damage within the city of Galveston (see Figure 1, page 2). Since a seawall extending along the northeastern third of the island protects the city shoreline, there was initially no erosion story to tell. But reporters who later flew over West Galveston were able to describe not only the widespread structural damage that had occurred, but also the obvious and extensive erosion beyond the end of the seawall.

Structural damage along a populated coastline is mostly the result of very high winds, exacerbated near the beach by abnormally high waves riding on a significant storm surge. Shoreline erosion, however, comes about whenever the surf-surge combination is sufficiently developed to scour the dune base. Major structural damage at Galveston is infrequent and almost exclusively the result of tropical storms and hurricanes which hit the island directly or close by. Conversely, erosion is somewhat of an ongoing process triggered by less publi-

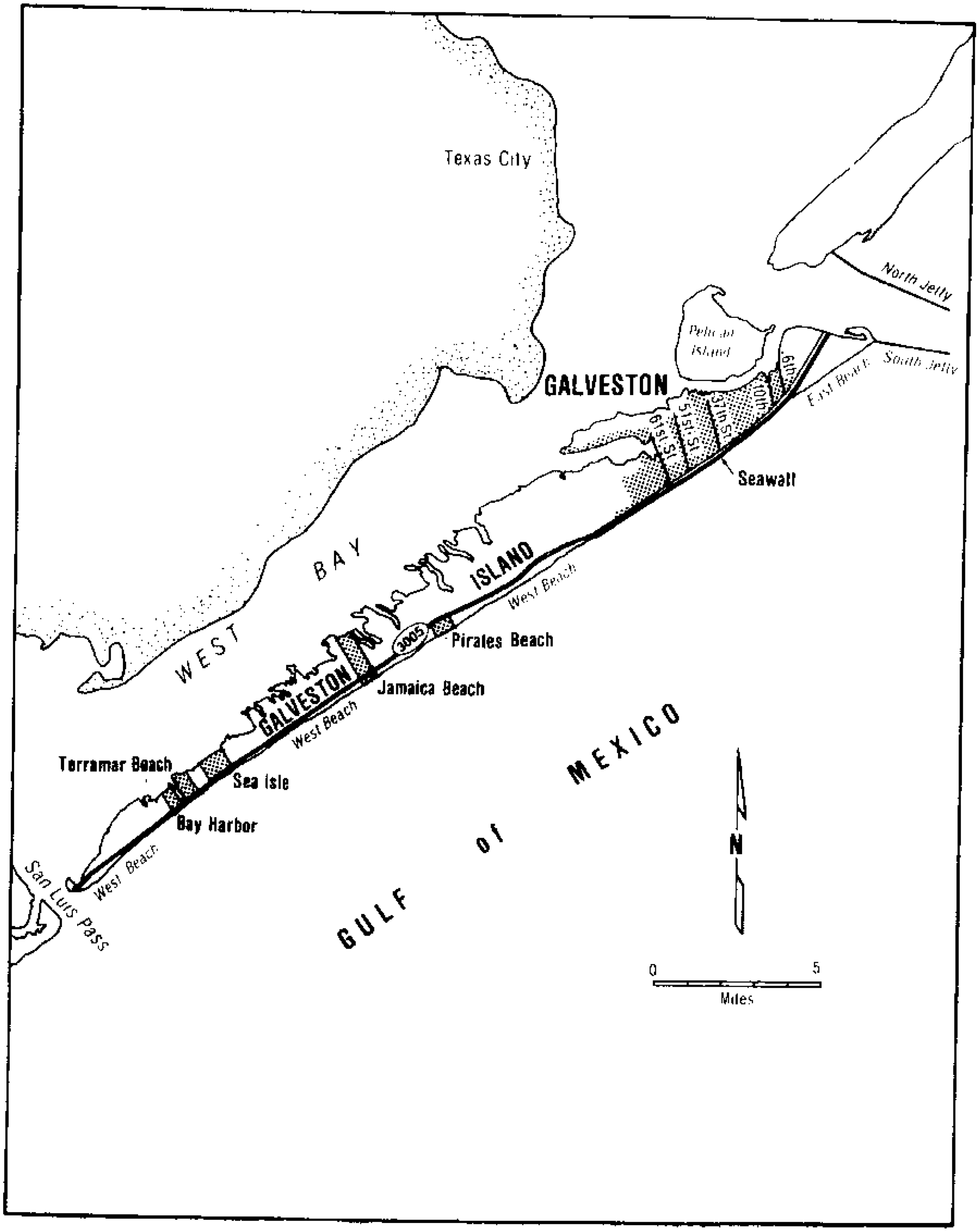


Figure I. Galveston Island

cized events such as modest local storms or major storms which make landfall some distance away.

If erosional impacts are to be analyzed and documented, it is important to evaluate not only the aftermath of a single storm such as Hurricane Alicia, but also the cumulative effects of the normal succession of erosional events. That is the purpose of this study.

## Overview

Hurricane records for Texas date back to the 1870's when the first of two intense storms struck the seaport of Indianola and brought about its eventual abandonment. Henry et al. [3] list 102 hurricanes or tropical storms affecting Texas since 1871. The tracks and coastal crossing points of those storms indicate that most of them had perceptible erosional impact on Galveston Island.

Investigators have been periodically measuring and reporting erosion at Galveston Island for nearly a century. An 1895 study by the Corps of Engineers [11] found fairly steady erosion at the northeast end of the island prior to completion of the South Jetty in 1893, after which there was rapid accretion immediately adjacent to the jetty. However, erosion continued along the beach at the city of Galveston a few miles to the southwest. That study recommended that no funds be committed to shoreline protection until the long-term effect of the jetty could be determined.

Further evaluation of erosion along the city's beachfront was hindered by the Great Hurricane of 1900 and by the subsequent construction of several miles of seawall by the county. A 1920 Corps study [12] concluded that the shoreline adjacent to the South Jetty (East Beach) had advanced over a mile since the jetty was built but that the beach in front of the newly built seawall further to the southwest was receding. A 1919 storm had scoured the northeastern end of the seawall, so the 1920 study recommended extending the seawall all the way to the South Jetty. That project was finished in 1926.

A 1934 Corps of Engineers study [13] found continued erosion in front of the seawall and called for a groin field to halt the process, a project that was completed in 1939. A 1949 Corps study [14] recommended extension of the seawall to the southwest. This work was subsequently funded and the seawall extended to its present position in 1963. A 1953 Corps study [15] examined beach profile changes on East Beach, along the front of the seawall, and at West Beach (the West Galveston beachfront), concluding that erosion rates were not high enough to justify further stabilization measures. In a subsequent shoreline study completed in 1971 [16], the Corps of Engineers determined that East Beach was accreting and that West Beach was eroding, the most critical erosion occurring at the the southwest tip of the island and along the beach just beyond the southwest end of the seawall.

Although these early Corps studies undoubtedly fulfilled their purpose, they were essentially qualitative. Later investigators were able to quantify erosion rates for various coastal segments. Seelig and Sorensen [9] compared shoreline locations on 19th Century planetable surveys with those on modern photogrammetric surveys. They found accretion of 25 feet per year adjacent to the South Jetty, with erosion beginning a short distance to the southwest and increasing slowly with increased distance from the jetty, then peaking rapidly to 11 feet per year near San Luis Pass.

The Seelig and Sorenson study was limited by its use of just two sets of cartographic data acquired about 100 years apart. Morton [6], on the other hand, compared shoreline positions on many different sets of cartographic and photographic sources. A problem with Morton's data set was the unavoidable gap between the 1850's topographic maps and the first aerial photography, taken in

1930. Subsequent photography was available for a number of dates through 1973. Thus, Morton was able to document several long-term rates of shoreline change as well as a number of short- to mid-term rates. His long-term rates were close to those of Seelig and Sorenson [8] but he found that in recent years there have been some intervals of relatively widespread accretion within the overall long-term trend toward erosion on most of the island. Morton attributed short-term erosion or accretion to periods of stormy or calm weather.

In 1976 Mathewson and Minter [5] looked at beach erosion at the old Brazos River delta some 15 miles southwest of Galveston Island. Referring to the Seelig and Sorensen [9] figures for their study area, they state that the rate has accelerated since the 1930's, attributing the increase to man's activities.

Benton et al. [2], using 1970 and 1977 photography for a baseline land-use study of Galveston Island, reported instances of moderate erosion and moderate accretion on West Beach, but high recent rates of erosion at the southwest tip of the island and immediately beyond the southwest end of the seawall. Their 1977 photography, which consisted of several flights taken quarterly, showed the impact of a single erosional event, Hurricane Anita, which hit land 120 miles south of the Rio Grande in late August 1977.

The Corps of Engineers, in its 1983 Galveston County Shore Erosion Study [17], compared its own cartographic and photographic records with the results of Seelig and Sorensen [9] and Morton [6]. The Corps study only looked at the shoreline in front of the seawall and at the beach at the southwest end of the island. Compared to the other two studies, the Corps claimed to have found less erosion--and even some accretion--in front of the seawall, but was more in agreement concerning erosion rates at the southwest end.

## Shoreline Definition

Discrepancies in reported erosion rates at Galveston Island occur in part because different investigators define erosion in different ways. At first glance it would seem that the most straightforward definition of erosion would be the displacement of the shoreline landward in a direction perpendicular to the mean shoreline. Accretion, on the other hand, would be shoreline movement in a seaward direction. The shoreline, however, is usually considered to be the land-sea interface. Its location, whether it be the low water line, the high water line or mean sea level, is difficult to pin down.

Other factors being equal, the springtime shoreline lies landward of the fall shoreline. This is because wave action from winter storms moves sand to offshore bars and steepens the beach profile. Gentler summer waves bring the stored sand back onto the beach and produce a more gradually sloping beach. Thus, shoreline position taken from a given aerial photo is a function of the time of year the photo sequence was taken. Comparison of different-year photos taken at different seasons can thus distort the actual erosion rate.

This problem can be avoided by using the seaward edge of the natural vegetation line as the measurement point. In an erosional situation, this line will normally mark the inshore limit of a recent erosional event. With accretion, seaward migration of vegetation will occur in clumps, making for an irregular, mottled pattern on the photos which is in marked contrast to the hard-edged, usually linear boundary of a very recently eroded bluffline. It is assumed that the mean annual shoreline will track the movement of the vegetation line.

Use of the vegetation line is particularly relevant since the enactment in 1959 of the Texas Open Beaches Act. That act, following the common law easement right, defines the public beach as the area between mean low water and the line of continuous vegetation. That portion of the public beach lying seaward of the mean high water line is state-owned by definition. The party lying landward of mean high water is usually privately owned; however, normal use of this area by the landowner is severely limited because the Act guarantees unlimited public easement. Moreover, the Act forbids erection of any obstruction within the public easement and authorizes the Attorney General to remove any obstruction situated thereon. The Attorney General holds that a dwelling, bulkhead, riprap, fence or sandfill constitutes an "obstruction" within the meaning of the Act, inclusive of existing structures which originally lay landward of the vegetation line.

Retreat of the vegetation line after a storm can place beachfront houses on the public easement, a circumstance that has occurred often in recent years on Galveston Island. Enforcement of the Act subsequent to Hurricane Alicia has resulted in suits by and against the Attorney General. The initial judgment in the first case completed, now in appeal, affirmed the Attorney General's contention that structures which now lie on the public beach as a result of vegetation-line retreat are subject to removal. The ultimate resolution of this and related cases will have a decided impact on future beachfront construction.

## Study Concept and Scope

Most previous studies have based erosion rate measurements on mid- to long-term movement of the cartographic or photographic waterline, a boundary which is hard to locate and which has less legal relevance than the vegetation line. Further, recent aerial photographic sequences suggest that erosion rates on Galveston Island are accelerating. Finally, it would be well to assess the erosional impact of a single significant storm event, a factor which was not discernible on the widely spaced data sets of previous investigations.

With that in mind, this study looks into short- to mid-term erosion rates on the Island over the past three decades. It establishes erosion rates by measuring movement of the vegetation line in successive photo sets. It adds two new photographic sequences, including post-Hurricane Alicia photography for the final update and for quantifying the erosion caused by a direct hit from a large storm.

The areas studied were East Beach and West Beach (see Fig. 1), there being little remaining sand beach along the waterfront portion of the seawall; none whatever southwest of the groin field.

## PROCEDURES

Change-analysis studies involving interpretation of multi-date photography are relatively simple in concept. They entail locating sources of archival photography, taking current-year photography if relevant or necessary, doing sufficient ground truth to authenticate the photointerpretation, making the actual measurements on photo overlays, then, if applicable, documenting results in map form using fairly straightforward photocartographic techniques.

### Archival and Current-Year Photography

The major impetus for this study was the occurrence of Hurricane Alicia, and the original intent was simply to document its impact on the shoreline of Galveston Island. It was later decided, after viewing the splendid photography showing Alicia's aftermath, to compare it with earlier photo sets in order to determine corresponding short- to mid-term erosion rates between photographic sequences. The study budget, adequate for the original study concept, was too austere to cover acquisition of extensive photography. We had to settle for what was on hand or readily available.

The earliest sequence used in this study was taken in April 1952 for the Agricultural Stabilization and Conservation Service (ASCS) and flown along the ASCS's standard north-south orientation. These 1:20,000-scale black and white prints are available at relatively low cost from the ASCS distribution center in Salt Lake City.

The 1965 ASCS photography of Galveston County was limited to the mainland portion of the county, ASCS having decided that the island was no longer sufficiently agricultural to warrant photo coverage. Fortunately we were able to borrow from the Corps of Engineers a set of good 1:9,600-scale black and white prints from a 1967 overflight oriented along the Galveston Island shoreline.

Photography for 1977 and 1979 was already on hand. Both sets are in the form of color infrared transparencies and in both cases the photo lines were flown along the longitudinal axis of the island, generally parallel to the Gulf shoreline. The 1977 photos, all at 1:32,000 scale, were taken in March, July, September and December by the Remote Sensing Center as part of a land-use study of the island [2]. The 1979 photography was flown at a scale of 1:24,000 as a follow-up to a September tropical storm. That overflight, also made by the Remote Sensing Center, was funded by the Kempner Foundation of Galveston.

The post-Alicia sequence was taken by the Remote Sensing Center on 22 September 1983. This photography, also color infrared, comprises two flight lines at different scales: 1:24,000 along the axis of the island and 1:12,000 along the shoreline. The larger-scale photography, taken as an afterthought simply because the photo aircraft had to descend in order to refuel, turned out to be the more valuable sequence because of its detail.

Three incomplete sets of post-Hurricane Allen photography, taken in color infrared at different scales in 1980 and 1981 by NASA, became available during the closing days of this study. All aerial photography was taken with 9-inch-by-9-inch-format mapping cam-eras. Remote Sensing Center photography was taken from a Cessna TU-206 turbo-charged aircraft using Kodak Type 2443 Aerochrome Infrared Film in a Wild RC-8 calibrated mapping camera.

Erosion measurements were made on photography from 1952, 1967, 1977, 1979 and 1983. The values tabulated in this report are from 1952, 1967, 1979 and 1983 only, since those sets provide better time intervals and are all of larger scale. The 1977 photos are referred to less often. As none of the 1980 and 1981 series constituted a continuous flight line along the island, they could not be incorporated into the primary measurement process. However, those photos were used for measurements at discrete points along the shoreline in order to isolate the impact of Hurricane Alicia.

## Ground Truth

Field verification of remote sensing imagery can be done in two ways: at the time of the overflight (a difficult logistical problem) or at a later date when the success of the overflight has been established. Same-day verification has the obvious advantage of currency, but the field party is often unsure of what to check. Latter-day verification affords the opportunity of first examining the photos, then going to the field to answer questions and resolve imagery anomalies that have surfaced during the preliminary analysis. If the process or phenomenon being studied is not subject to too-rapid change, delayed ground truth is significantly more advantageous than concurrent ground truth.

This was certainly the case on this project, since we wished to determine the line of post-storm vegetational retreat, something that would remain essentially the same for some time to come. For that reason a fairly thorough pre-ground truth photoanalysis was made, during which the locations of points of interpretive uncertainty were carefully inked and coded on transparent overlays taped to color prints made expressly for field use.

Field verification on Galveston Island was carried out between 11 and 13 November 1983, nearly three months after Alicia and approximately a month and a half after the photography. Since the project budget and other considerations pre-cluded more than one trip to Galveston, it was necessary that field work be as thorough as possible. Field records consisted of record-book notation, inked annotations on the field-print overlays, and a large number of ground-level color photos. With the field records at hand, final analysis could begin.

## Photoanalysis

Erosion and accretion were determined by measuring successive vegetation-line locations along selected transects whose positions could be located on every set of photos. Measurements were made at transect points from roads lying near the beach or, where roads lay some distance inland, measurements were made from other nearshore landmarks which were discernible on all photo sets. Highway 3005, which runs close to the vegetated bluffline along the greater length of West Beach, did not extend all the way to the southwest end of the island in 1952. Its location was drawn on the 1952 photo overlays by measuring its distance from fixed landmarks on later photos.

Measurements were made using a Finescale Magnifying Comparator on which was mounted a transparent scale having 0.005-inch divisions. Interpolation to 0.2 division, or 0.001 inches, was easily done. The 0.001-inch measurement capability is essentially the same as the resolution of metric color infrared photography, or about 40 line pairs per mm for contrasting images. For photography of 1:24,000 scale, this is about 2 feet on the ground.

Ninety-five transects were chosen which were relatively evenly spaced and whose locations were identifiable on all photo sets. Of these, 13 were on East Beach and 82 on West Beach. Differences in distance from the measurement reference to the vegetation line along a given transect established the movement of that line between aerial photographic sequences. Measured differences were tabulated for all transects and for all time intervals relevant to this study. Difference measurements are listed in the Appendix for the periods 1952-1967, 1967-1979, 1979-1983 and 1952-1983.

## Photocartography

Transect positions were located on base maps of Galveston Island compiled at 1:24,000 scale, the same as that used on the U. S. Geological Survey 7 1/2-minute quadrangle maps. Measured differences in vegetation-line location were plotted on a separate erosion-vs-shoreline position graph below the map, with y-value being erosion in feet and x-value being location of the transect along the island shoreline. Best-fit curves of periodic erosion amounts were then drawn on the x-y plots (see figures in RESULTS section).

## RESULTS

This study assesses the erosional impact of Hurricane Alicia on Galveston Island in the context of the longer-term impact of a normal succession of less spectacular erosional events occurring over several years. Thus, it is well to consider just how strong a storm Alicia may have been.

### Relative Intensity of Hurricane Alicia

If Alicia is to be ranked in terms of its relative strength, some frame of reference or standard of comparison is needed. Tropical cyclones, the generic name for tropical storms and hurricanes of both minor and major proportion, come in different sizes and there are at least two methods of classifying them. The system with which most people are familiar begins with Tropical Depression (sustained winds less than 39 mph) and continues with Tropical Storm (sustained winds from 39 to 74 mph), Hurricane (sustained winds 74 to 100 mph), Major Hurricane (maximum winds 101 to 135 mph AND a minimum central pressure of 28.01 to 29.00 inches of mercury [Hg]) and Extreme Hurricane (maximum winds of 136 mph or higher AND a minimum central pressure of 28.00 inches Hg or less)[3].

Alicia was an unusual tropical cyclone in that it developed wholly within the Gulf of Mexico. It was first observed about 175 nautical miles south of New Orleans on the morning of August 15. By noon it had become a Tropical Storm with winds of 46 mph and a central pressure of 29.71 inches of mercury. By the evening of the 16th it had moved halfway to the Texas coast from its area of formation and was rated a Hurricane with sustained winds of 75 mph and central pressure of 29.27 inches Hg. Just before reaching Galveston Island on the morning of August 18 its maximum winds had reached 115 mph and its central pressure had dropped to 28.41 inches Hg. Based on the National Weather Service's widely known hurricane warning scale, Alicia falls midway in the range listed for a Major Hurricane [7].

The rather broad scale used by the National Weather Service for its storm warnings may be somewhat imprecise for the purpose of this study. In contrast, the NWS Hurricane Disaster-Potential Scale, better known as the Saffir-Simpson scale, breaks hurricane-force tropical cyclones into five discrete ranges of wind velocity and storm surge, correlating each one with a specific level of structural damage or lowland flooding [3]. Scale No. 1 has a 74 to 95 mph windspeed (damage to trees, shrubs and unanchored mobile homes) or 4- to 5-foot surge range (small craft in exposed areas torn from their moorings). Scale No. 5 is for winds above 155 mph (some total building failures and some small buildings blown away) or surge higher than 18 feet (major damage to lower floors of all structures less than 15 feet above sea level and within 500 yards of shore). The Saffir-Simpson scale, designed as a potential-damage index for incoming storms, also provides improved after-the-fact assessment of hurricane strength.

The Fujita scale, designed for classifying tornadoes, also relates wind velocity to structural damage. The F0, F1 and F2 values on the Fujita scale indicate winds of 40 to 72 mph, 73 to 112 mph and 113 to 157 mph, respectively, with a different level of anticipated structural damage for each velocity range.

From either the Saffir-Simpson or the Fujita scale, we should be able to estimate the relative strength of Alicia by examining the level of damage seen in post-storm aerial and ground photography and by obtaining surge levels from tide gauge records for the storm date.

Structural damage was greatest immediately adjacent to the West Beach shoreline, with roofs and walls missing from many of the beachfront homes and in some cases the entire structure of the house gone from its pile-supported foundation. A much smaller number of homes further in from the beach suffered structural failure and in many such cases similar-appearing homes next door were relatively unscathed. Few homes in the West Galveston area were unaffected, though. The common denominator for damaged homes was loss of roofing material; sometimes small patches, sometimes most of a roof plane.

The pattern of apparent damage to mobile homes was also irregular. There were only isolated signs of significant damage to individual units within the many trailer parks in the city of Galveston or among the large number of mobile homes randomly located well back from the beach in West Galveston. Conversely, there was great structural damage to many trailers parked close to the shore at West Beach and to most of the trailers in a large East Beach mobile home park lying between the seawall and the water. In the latter case, nearly all units appeared damaged, perhaps half were demolished, their pieces scattered about.

Considering the rapid movement of Alicia and the brief period available to take action, evacuation of large numbers of mobile homes from the island prior to the storm's arrival was a logistic impossibility. It is assumed that most of the mobile homes visible in the September photography were on the island at the time of the hurricane. It is also reasonable to assume that, as in the case of the houses on the island, mobile homes suffering significant hurricane damage would for the most part not have been repaired before the aerial photos were taken.

Why the almost random pattern of major structural damage from Alicia? Two explanations come to mind. First, houses and mobile homes situated near the beach were probably hit by waves as well as wind, thus negating the correlation between structural damage and wind velocity. Second, much of the sporadic damage further in from the beach could have resulted from tornadoes spawned by the hurricane--the photos show some isolated, narrow debris swaths. There were widespread reports of tornadoes from witnesses further inland [7]. However, although many people stayed on Galveston Island throughout the storm, it was dark at the time when hurricane-related tornadoes were most likely to occur [3]. Alicia's center, some 50 miles offshore at dusk on the 17th of August, made landfall just before 2 a.m. CST on the 18th and had moved 40 miles inland by morning [7]. Potential eyewitnesses would likely not have ventured outdoors during the night.

Storm surge data came from the National Ocean Survey tide gauge at the Flagship Hotel pier on the Galveston beachfront, about 25 miles northeast of where Alicia crossed the coastline. This would be near the point of maximum storm surge for a moderate hurricane. Gauge levels at the time of Alicia's passage were provided by personal communication from Milton Rutstein, Chief of the National Ocean Survey's Tidal Liaison Unit at the National Oceanic and Atmospheric Administration headquarters in Rockville, Maryland.

Maximum tidal height, referenced to zero on the tide staff, was 12.43 feet at 0118 CST on 18 August 1983, a time close to that of predicted high tide. Staff zero at the Flagship pier gauge is 2.77 feet below mean lower low water, putting the surge at 12.43 - 2.77 = 9.66 feet above MLLW. Predicted high tide on the morning of the 18th was 2.4 feet above the MLLW reference, which makes the surge height 9.66 - 2.4, or between 7.2 and 7.3 feet above normal tide level. According to the National Ocean Survey Tide Tables, the mean tidal range at the Flagship pier is 2.0 feet, or a 1.0-foot range either side of mean sea level. The surge with respect to mean sea level was therefore between 8.2 and 8.3 feet.

Considering storm surge alone, Alicia could be rated at the upper end of Saffir-Simpson Scale No. 2 (6-8 ft above normal) or the bottom of Scale No. 3

(9-12 ft above normal), depending on the definition of "normal." Alicia's maximum recorded winds of 115 mph also place it in the low end of Scale No. 3. With respect to wind damage, Alicia falls into Scale No. 3 ("Winds of 111-130 mph... Some damage to roofing materials...some structural damage to small build-ings. Mobile homes destroyed.") or even Scale No. 4 ("Winds of 131-155 mph...Extensive damage to roofing materials...Complete failure of roofs on many small residences. Complete destruction of mobile homes."). [3]

Similarly, the Fujita tornado scale would rate wind damage as F2 ("...113-157 mph...surfaces peeled off roofs...Mobile homes pushed off foundations or overturned.").

Note that both the Saffir-Simpson and Fujita scales give higher ratings to Alicia than it would merit on the basis of either its recorded windspeed or its recorded storm surge. Three explanations come to mind. First, by far the largest number of cases of structural failure occurred along the beach or in the immediate vicinity; thus, much of this damage was probably due to waves rather than winds. Second, at least some instances of major structural damage which occured well away from the beach could have come from tornadoes. Third, the West Beach area contains many vacation homes which are not particularly well built and are thus more susceptible to wind damage. Many new, well-built homes on West Beach came through the storm with no apparent damage, and some of those are directly on the beach. In the city of Galveston itself, structural damage was limited almost exclusively to beachfront situations.

The relatively higher proportion of structural damage at West Galveston could be due in part to quality of construction. Although West Galveston and the city are now both subject to the same building code, this has not always been the case. Further, strict, uniform observance of codes has quite probably not been as well enforced in West Galveston's summer-home environment.

All things considered, Alicia should probably be classed as Scale No. 3 on the Saffir-Simpson scale, despite the fact that its storm surge was just below the range of a Scale No. 3 hurricane. Of the hurricanes striking the Texas coast between 1871 and 1980, Neumann et al. [8] have determined that 58 percent were weaker than Scale No. 3 and 19 percent were stronger. Thus, Alicia was well short of the strength of Celia (1970), Carla (1961) or the Great Hurricane of 1900, all of which were Scale No. 4 hurricanes.

## Quantitative Values of Erosion and Accretion

Alicia, then, was a reasonably strong, but far from extreme hurricane. This is the context in which its erosional impact should be considered. The following is a detailed discussion of the effects of Alicia and of the short- to mid-term erosion rates now occurring on the island. Since erosion rates vary considerably over the length of the island, the discussion will be broken into six separate zones, beginning with East Beach and continuing to the southwest tip of the island.

East Beach - The area at the northeast end of the island lying between the seawall and the Gulf is locally known as East Beach. It is nearly all new land which accreted since the South Jetty was built in the early 1890's. The primary source of accretionary sediment seems to have been the beach and nearshore zones extending several miles southwest from the Jetty. A secondary source is dredge material deposited over the years from maintenance of the navigational channel at Bolivar Roads immediately northeast of the South Jetty.

Figure 2 shows the northeastern three quarters of East Beach in September 1979. The beach area adjacent to the South Jetty had advanced some 4000 feet since the 1890's; almost all the land area in the photograph did not exist when jetty construction began. The South Jetty, running from top left to the lower

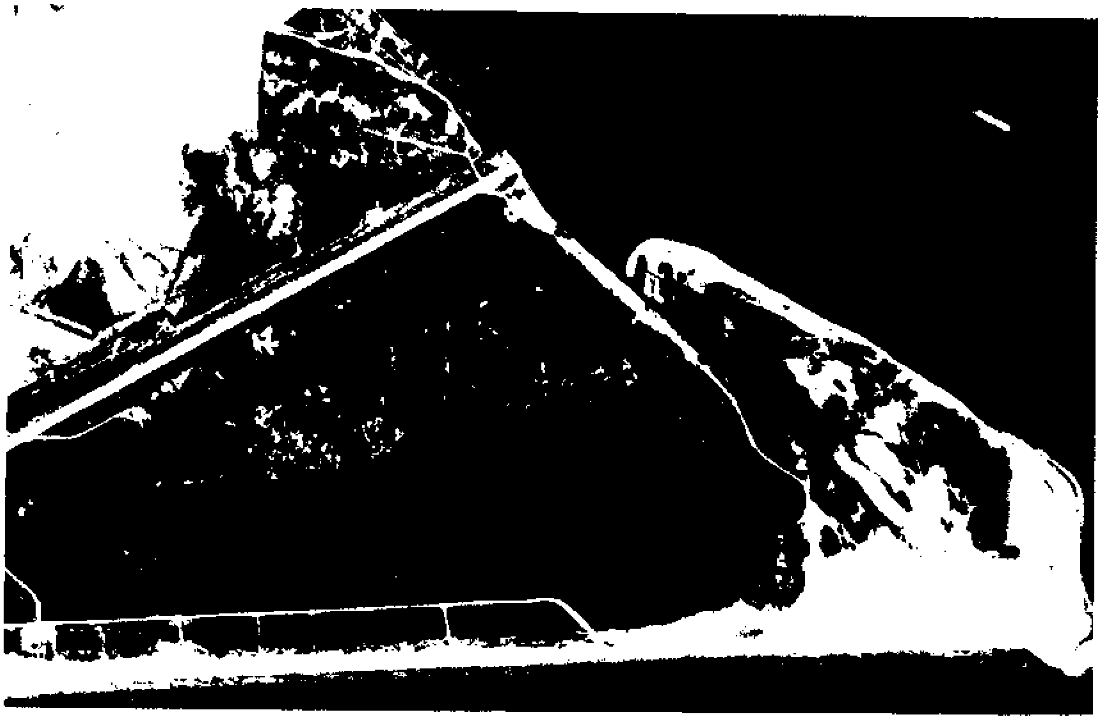


Figure 2. East Beach, September 1979. Remote Sensing Center CIR photo.

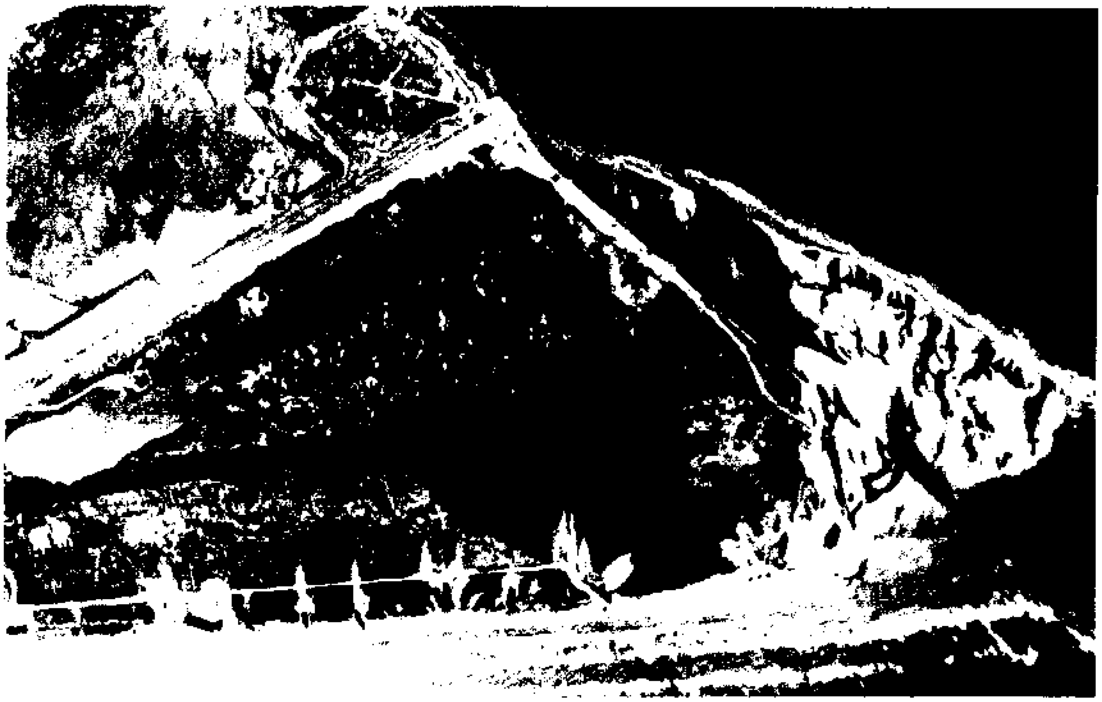


Figure 3. East Beach, September 1983. Remote Sensing Center CIR photo.

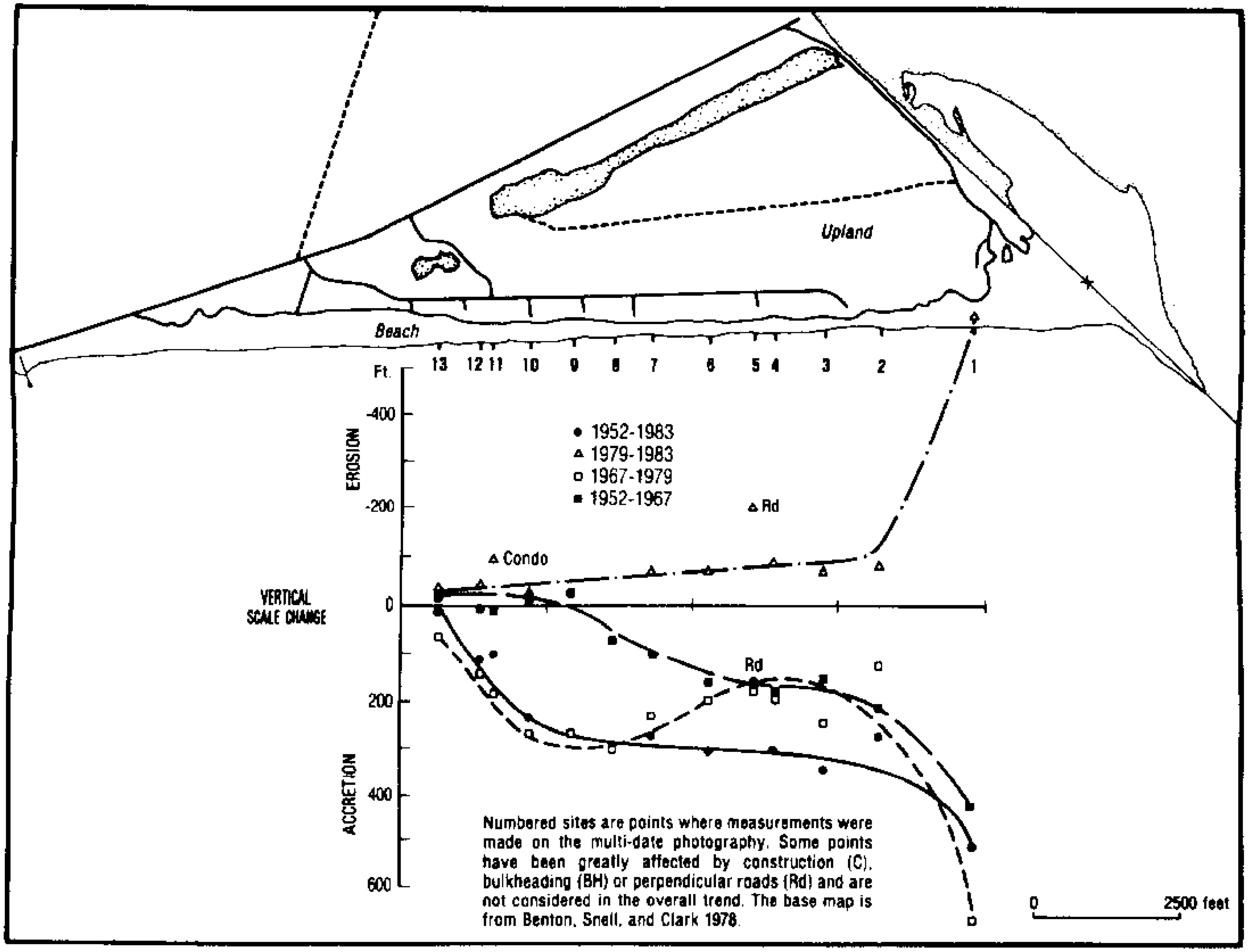
right corner of Figure 2, is met by the seawall just above photo center. The partially vegetated peninsula overlapping the channel at right is Big Reef, composed of sand washed over the South Jetty from East Beach, usually during winter storms.

The beach was still accreting in 1979. This is apparent from the mottled appearance of the edge of the vegetation line in the photo. The light-colored area at upper left is freshly deposited dredge spoil, the other constituent of the East Beach land mass. Public beach access is provided by the gravel road paralleling the beach in the lower left half of the photo.

Figure 3 shows the same area on 22 September 1983, slightly more than a month after Hurricane Alicia. The most obvious change was the loss of 600 feet of sand from East Beach at the South Jetty. Note that Big Reef was also significantly diminished by the storm. The greatest loss of beach was in the unvegetated area immediately adjacent to the jetty. Moving left (southwest) from the jetty area, erosion of the vegetation line was from 40 to 90 feet, the greater amount occurring in the area shown in the righthand two-thirds of this photo.

Note the sand plumes extending back behind the beach from the roads which ran perpendicular to the beach in the 1979 photo. Throughout East and West Beach, sand scour was greatest along this type of road, since there was no vegetation to maintain the backbeach dunes and bluffs against the forces of wind and sea. The long, narrow, dark patches centered on the beach side of each plume are water-filled ponds created by scour currents.

The new condominium at lower left is flanked by washover fans, the result of vegetation being stripped from adjacent dunes during construction. Compare with the minimal erosion around the older condominium at extreme lower left, where vegetation had been left reasonably intact prior to the storm. Note also the additional dredge spoil deposited at upper left since 1979.



Numbered sites are points where measurements were made on the multi-date photography. Some points have been greatly affected by construction (C), bulkheading (BH) or perpendicular roads (Rd) and are not considered in the overall trend. The base map is from Benton, Snell, and Clark 1978.

Figure 4. Shoreline Changes, East Beach, 1952-1983

The curves in Figure 4 show short- to mid-term erosion at East Beach since 1952. Points 1 though 13 are transects along which vegetation-line distances were measured on the 1952, 1967, 1979 and 1983 aerial photography. The curves show that East Beach was accreting during all periods except for 1979 to 1983. It remains to be seen whether East Beach will again recrete in the coming years.

Southwest end of seawall to Bermuda Beach - There was still a good deal of sand beach fronting the seawall at the time it was built: our January 1970 photography shows about 100 feet between the seawall and the winter shoreline in the vicinity of 37th Street (see Figure 1). By the late 1970's, however, the bulk of the visible sand remaining in front of the seawall in that area was in the form of cusps against the bases of the groins.

Figure 5 on the next page shows the southwest end of the seawall in June 1967, not long after that final segment of seawall construction had been completed. The seawall ramped down to the sand at this point, providing paved-road access to the beach for the motorists of that day. The dark rectangles just inshore on the left half of the photo are borrow pits from which fill was taken to slope the behind-the-seawall ground level up to the elevation of the top of the seawall. There was about 75 feet of beach in front of the seawall in this late-spring photo.

Figure 6 on the next page, taken in September 1983, shows the same beach area after Hurricane Alicia. This late-summer photo shows that the shoreline had retreated about 275 feet since 1967, a mean erosion rate of some 17 feet per year. Note that two of the borrow pits, well back from the shoreline in 1967, fronted on the Gulf after Alicia. Note also that four of the five beachfront houses in the 1967 photo were gone by 1983 and the fifth was standing out in the surf swash zone. As will be discussed further along, the erosion rate in this area has apparently accelerated since the mid-1970's.

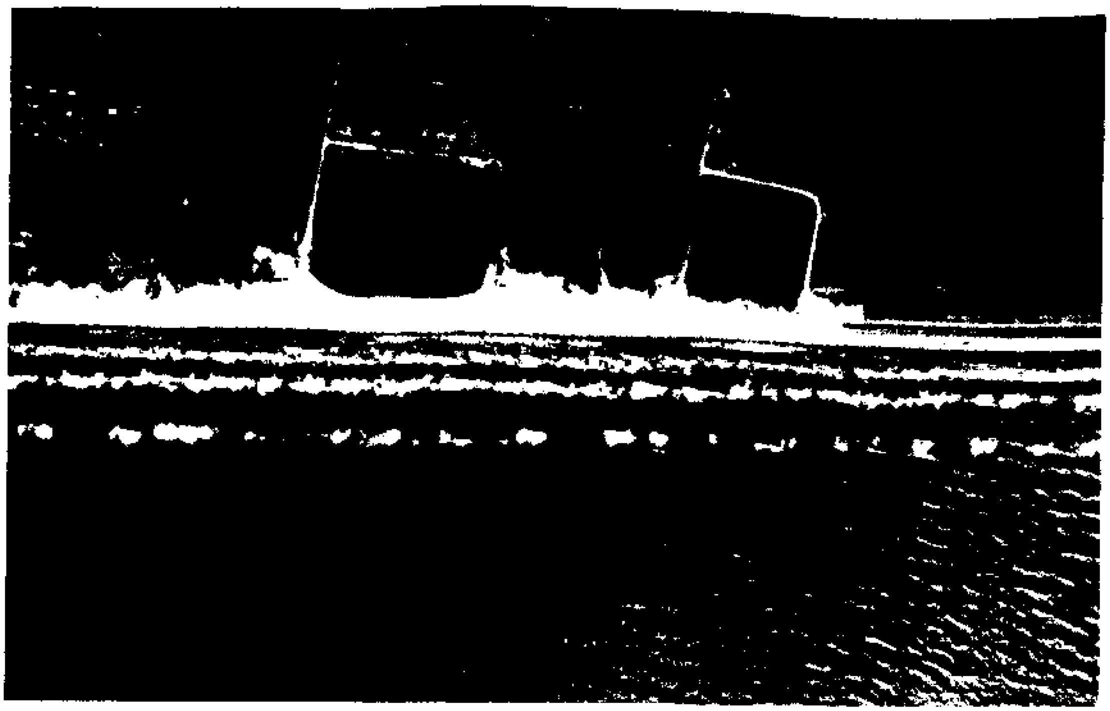


Figure 5. End of Seawall, 1967. Corps of Engineers photo.

Figure 6. End of Seawall, 1983. Remote Sensing Center photo.

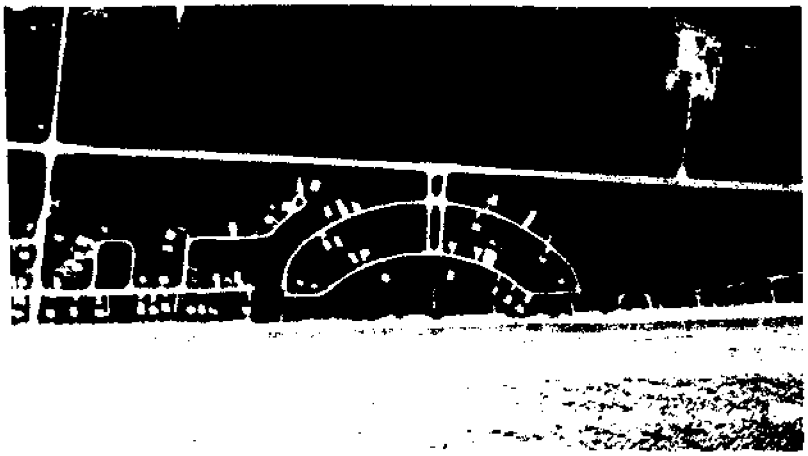


Figure 7. Spanish Grant Subdivision, 1977. Remote Sensing Center photo.

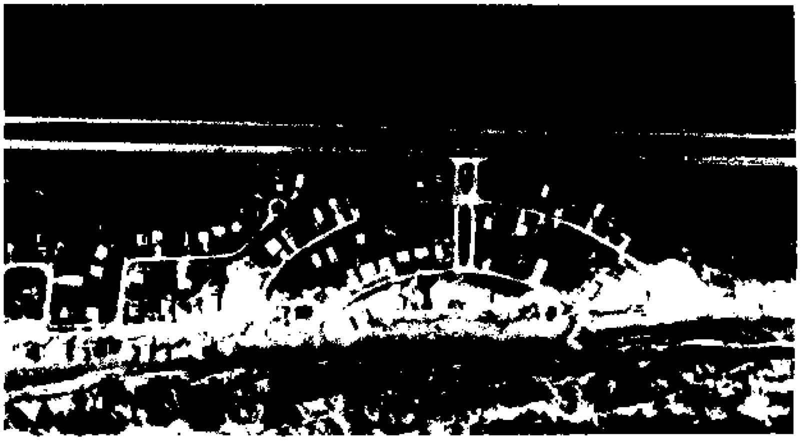


Figure 8. Spanish Grant Subdivision, 1983. Remote Sensing Center photo.

Figures 7 and 8 show Spanish Grant, the first beachfront subdivision beyond the seawall, in September 1977 and September 1983, respectively. The vegetated bluffline, quite distinct in Figure 7, is seen in Figure 8 as a thin, irregular dark line separating the beach from the sand lens washed onto the top of the bluff by the storm. In 1977 all beachfront homes were comfortably back from the edge of the bluff, although the yard of the one farthest on the right jutted onto the beach slightly, its edge protected by rip-rap (see Figure 9). After Alicia that house was standing in the surf swash zone. The homes at left have fared somewhat better, but they, too, found themselves on the public-beach side of the vegetated bluffline after passage of Alicia.

Figure 9. "Karisma" at Spanish Grant, 1977 Remote Sensing Center photo.

Figure 10. "Karisma" at Spanish Grant, 1983 Remote Sensing Center photo.

Figures 9 and 10 show the home discussed on the previous page. Although it seems well built and well cared for, it is apparently a vacation home rather than a year-round residence. A sign on the front of the house says "Karisma." Figure 9, taken on a foggy March morning in 1977, shows the winter shutters still in place. Yard fencing comes to the top edge of the neatly placed rip-rap. Figure 10, taken three months after Alicia, shows the house from about the same angle, a new coat of paint on the walls, the rip-rap gone, the sheet piling exposed, and the slab base undermined about three feet. The cylindrical piling, which forms the true foundation for this building, appears intact in the photograph.

Considering its beachfront location and the extensive scouring that had taken place under the slab base, the house is in quite reasonable condition. This is just one of many beachfront homes that came through Hurricane Alicia relatively intact, although subject to very significant erosional impacts. As can be seen in Figures 8 and 10, neither the rip-rapping nor the sheet piling were protection against erosional scour from Alicia's seas.

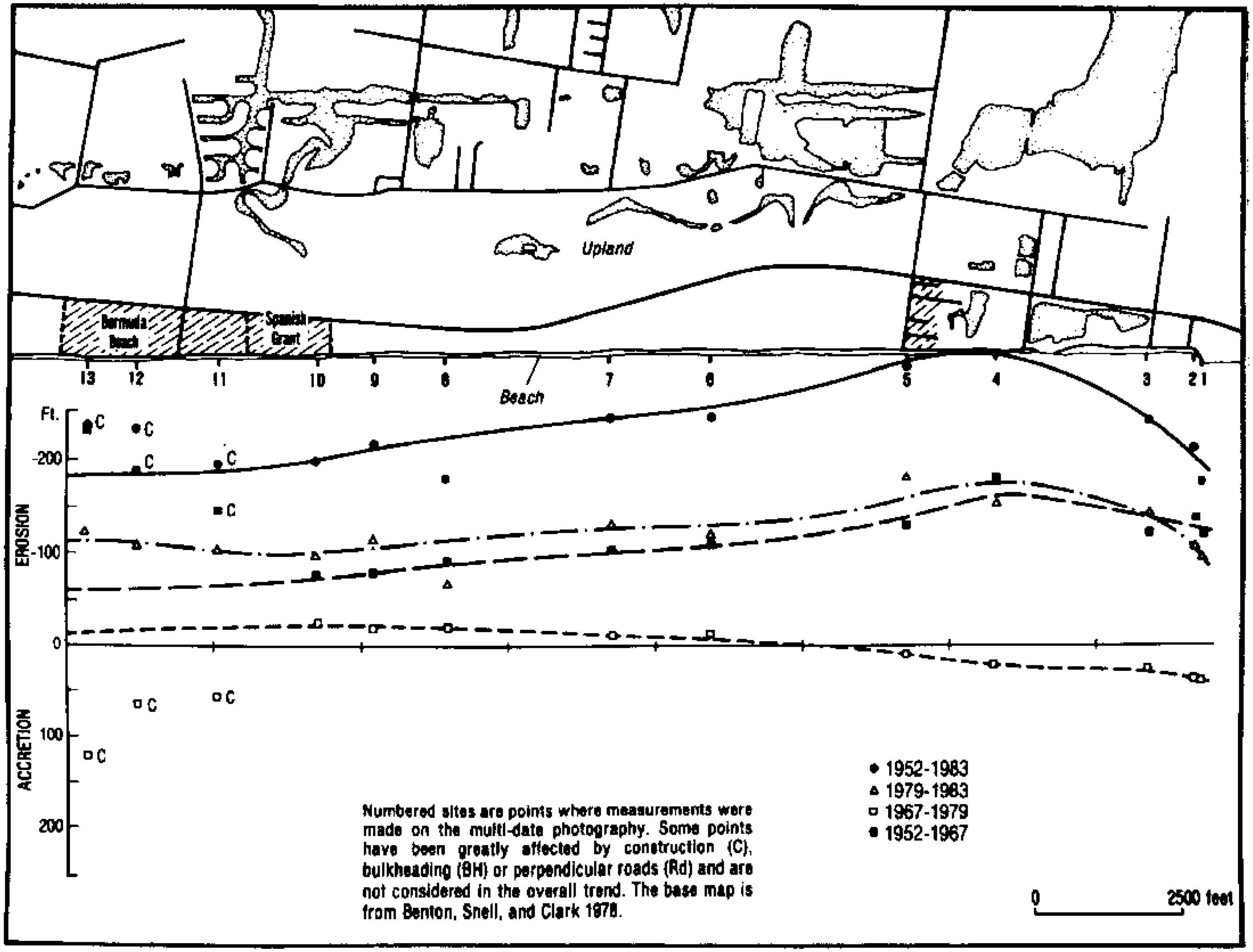
Figure 11 on the next page shows damage to underground utilities at the southwest edge of the Spanish Grant subdivision, about 1200 feet southwest of

Figure 11. Undermined Utilities at Spanish Grant, 1983. RSC photo.

the house in Figures 9 and 10. The homes on the left are actually in Bermuda Beach, the next development to the southwest. Although beachfront property tends to be snapped up rather quickly, what we see here is a case of developed frontage being eroded away before houses could be built on it.

Note that there is no evident structural damage to any of the homes in the photo despite the very extensive damage to the lightly paved street and to the utilities buried under it. Dwellings in these two relatively new subdivisions seem better built than those in older areas on West Galveston, and this could account for the modest amount of apparent damage in the immediate area.

Figure 12 is the set of curves showing erosion amounts over four different timespans for the area just discussed. Half a mile from the seawall the loss of beach from 1952 to 1983 was over 300 feet, a rate of about 10 feet per year. Of that 300 feet, just over half eroded away in the interval between 1979 and 1983,



Numbered sites are points where measurements were made on the multi-date photography. Some points have been greatly affected by construction (C), bulkheading (BH) or perpendicular roads (Rd) and are not considered in the overall trend. The base map is from Benton, Snell, and Clark 1978.

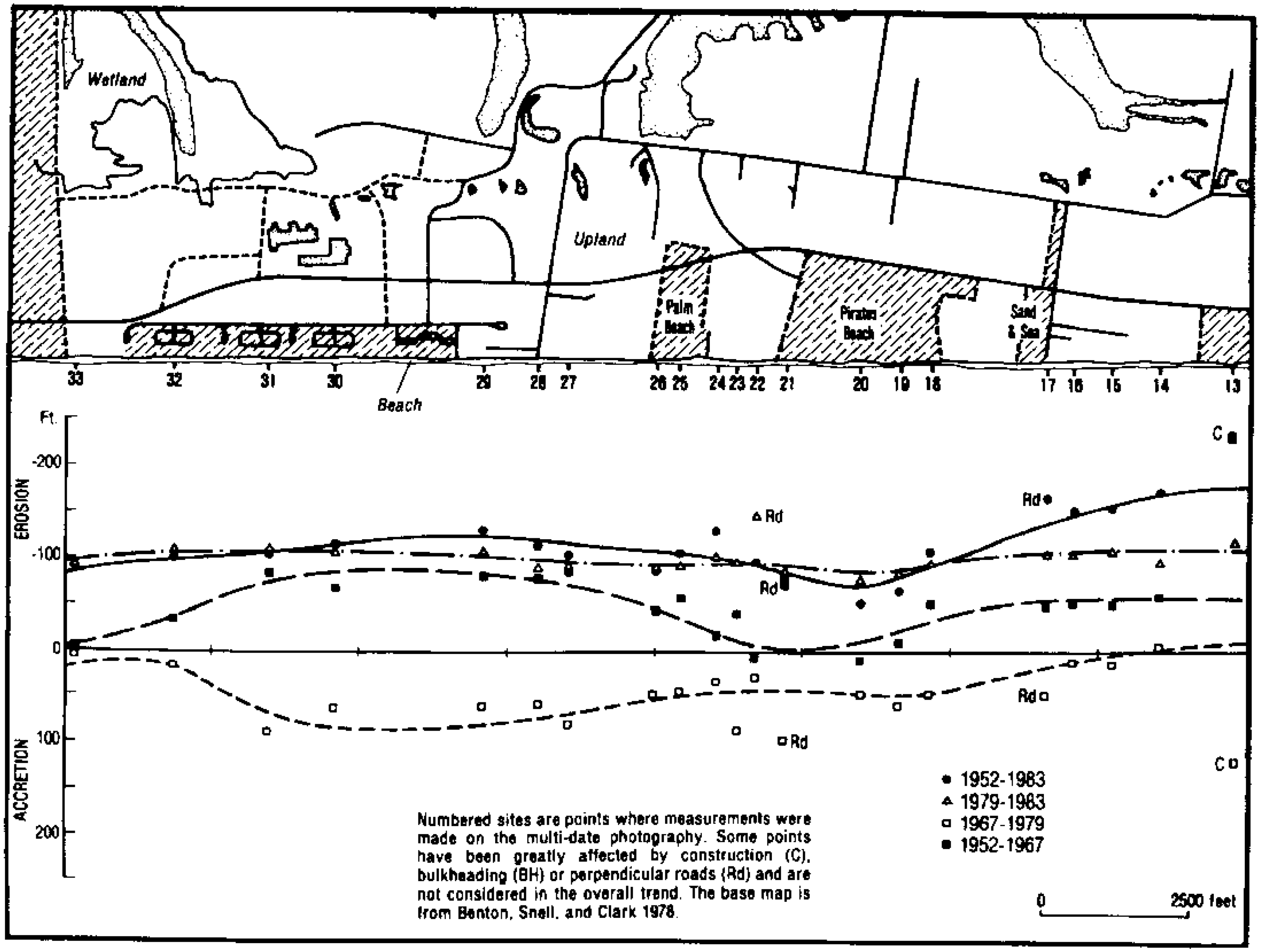
Figure 12. Shoreline changes, end of Seawall to Bermuda Beach, 1952-1983

the bulk of that accruing to Alicia. The 1979-1983 rate has thus been nearly 40 feet per year.

The indicated level of accretion between 1967 and 1979 is a possible artifact of the measurement method. In 1967 the beachfront vegetation just past the end of the seawall had probably not recovered from the effects of recent seawall construction activity. It is, therefore, quite possible that for the first half mile or so from the seawall (West Beach transects 1 through 4), the 1952 to 1967 erosion could be overstated and the modest accretion measured between 1967 and 1979 might actually have been erosion.

Further to the left (southwest) in Figure 12, erosion amounts diminish for all periods except the questionable 1967 to 1979 timeframe. This decrease is to be expected because southwest-moving longshore currents now come around the end of the seawall in a sediment-deficient state, resulting in rapid erosion of the shoreline just beyond. As that line has become deeply indented, the point of maximum erosion has moved to the southwest. This process will undoubtedly continue in the years to come, with the point of maximum erosion moving slightly southwestward with each erosional event. After the first three quarters of a mile or so from the end of the seawall, erosion rates decrease rapidly as the southwest-moving longshore currents approach their sand-carrying capacities.

Bermuda Beach to Jamaica Beach - Figure 13 (next page) is the set of shoreline-change curves for the next beach segment to the southwest, the beginning of a long stretch of West Beach shoreline where there was an accretionary trend between 1967 and 1979. Mid-term shoreline change during the 1952-to-1979 period was very near zero, erosion from 1952 to 1967 being generally balanced by accretion from 1967 to 1979. This is evident from comparing the 1952-to-1983 curve with the 1979-to-1983 curve: except for the slight divergence toward the right edge of the figure, 1952 to 1983 is closely matched with 1979 to 1983.



Numbered sites are points where measurements were made on the multi-date photography. Some points have been greatly affected by construction (C), bulkheading (BH) or perpendicular roads (Rd) and are not considered in the overall trend. The base map is from Benton, Snell, and Clark 1978.

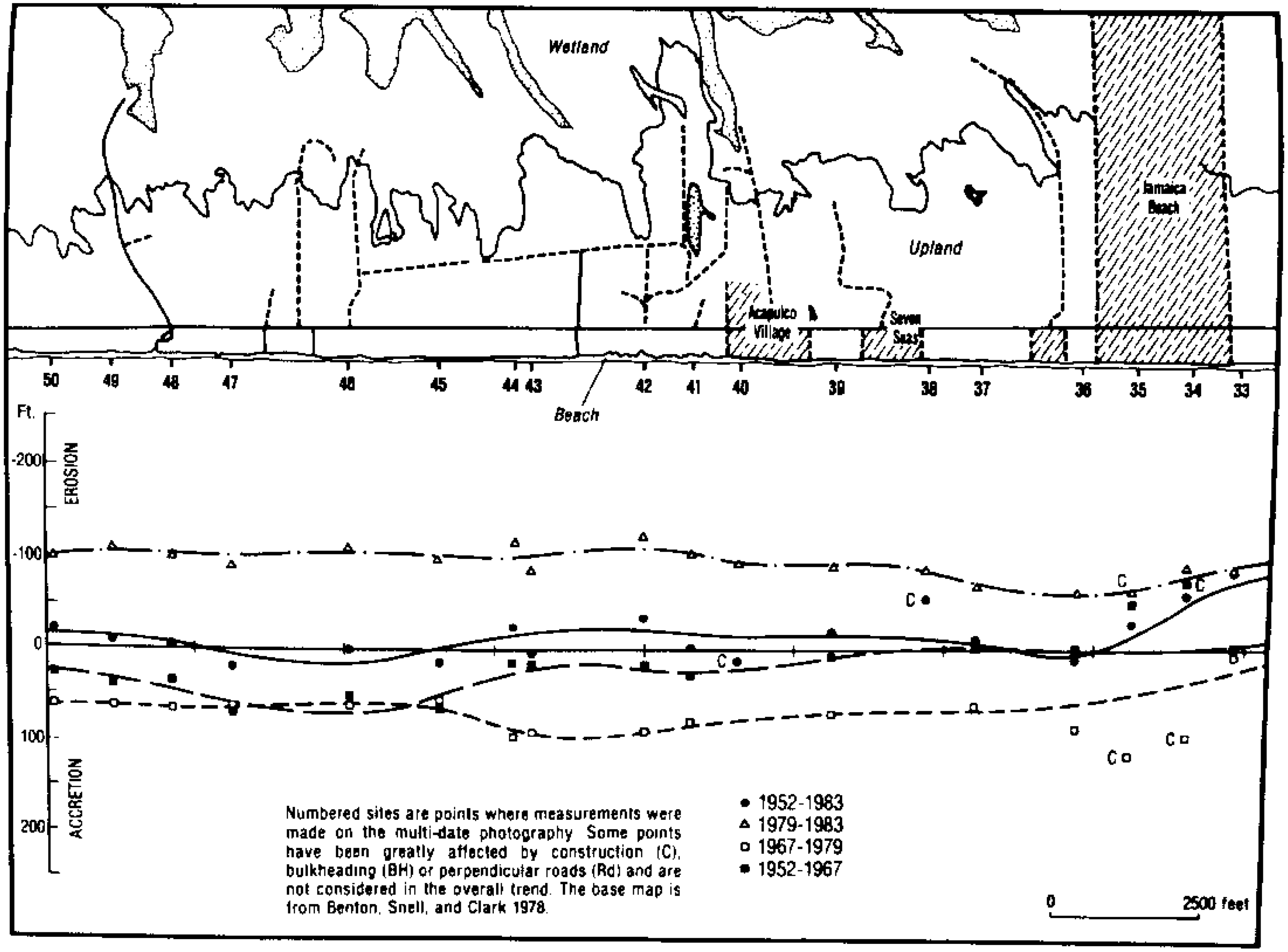
Figure 13. Shoreline Change, Bermuda Beach to Jamaica Beach, 1952-1983

Note that for 1979 to 1983 there was a near-constant 100 feet of erosion. Comparison with post-Hurricane Allen photography shows that most of the 1979 to 1983 erosion was the result of Hurricane Alicia.

Post-Alicia photography shows the vegetated bluffline as a fairly regular feature along those stretches of shoreline where there is no beachfront construction. The Pirates Beach and Palm Beach blufflines, for example, are very irregular compared to the bluffline at the undeveloped portion of Galveston Island State Park just to the southwest. The park takes up the left half of Figure 13. In the developed portion of the park, where campsites and picnic areas abut the edge of the bluff, there are some of the same bluffline irregularities.

Another interesting contrast on the post-storm photography is the large volume of beach sand lying inshore from the bluffs in developed areas versus the much smaller volume coming over the bluffs in undeveloped areas. The difference seems to be a function of the relative vigor and density of native vegetation in the two situations: where native grasses are thick and healthy, the volume of washed-over sand is generally significantly less. Developed beachfronts contain the more easily erodable surfaces such as unpaved roads, barren ground and lawn grasses whose roots are comparatively shallow. Conversely, the structures themselves, including bulkheads, may inhibit erosion somewhat.

Vicinity of Acapulco Village - Figure 14 shows vegetation-line change values from Jamaica Beach southwestward (West Beach Transect Nos. 33 to 50). Here, for all time periods except 1979 to 1983, there was accretion rather than erosion. Accretion averaged about 10 feet per year over most of this stretch from 1967 to 1979 but less than 5 feet per year from 1952 to 1967. The 1979 to 1983 change was a fairly even 100 feet, the bulk of that due to Alicia, as is the case over most of West Beach.



Numbered sites are points where measurements were made on the multi-date photography. Some points have been greatly affected by construction (C), bulkheading (BH) or perpendicular roads (Rd) and are not considered in the overall trend. The base map is from Benton, Snell, and Clark 1978.

Figure 14. Shoreline Change, Acapulco Village Beachfront Area, 1952-1983

On the post-Alicia photography, waterfront homes along Jamaica Beach were generally not affected as badly as those elsewhere along West Beach. The vegetated bluffline seemed more intact, fewer houses stood seaward of that line, and less sand had been thrown over the bluffs. In the small development immediately to the southwest of Jamaica Beach, on the other hand, the entire front rank of houses was out in the swash zone and a proportionally greater volume of sand had come over the bluffs.

Post-storm conditions at Acapulco Village were about the same as at the small development discussed above. Along the long, undeveloped beach beyond Acapulco Village, the bluffline was generally more regular and the volume of washed-over beach sand behind the bluffs was significantly less. Even so, the amount of storm erosion along this stretch was about the same in undeveloped areas as at the subdivisions, an indication that a greater proportion of the eroded beach sand in undeveloped areas must have remained in the coastwise drift or moved to bars offshore.

<u>Vicinity of Sea Isle</u> - This next stretch of West Beach, between Transect Nos. 50 and 68, centers on the Sea Isle community, one of the first on the west end of the island to be developed. The spine of the island is generally lower here, the average elevation decreasing as the end of the island is approached. The erosional impact from Alicia increases slightly in this area and the volume of sand thrown over these low bluffs is also proportionally greater, along both developed and undeveloped beaches. The three miles of unoccupied shoreline southwest of Acapulco Village ends half a mile short of Sea Isle. From that point to the southwest side of Terramar Beach, two or more ranks of homes had been built between the road and the bluffs. Most of these were fairly recent.

The entire front rank of homes in front of and adjacent to Sea Isle were in the surf swash zones on the date of the post-Alicia photography. Bulkhead-

Figure 15. Undermined Foundation at Sea Isle Subdivision, 1983. RSC photo.

ing in front of those homes had been circumvented completely and the vegetation line, which stood well in front of the houses before Alicia, had retreated, in most cases to an irregular line between the first and second ranks. Figure 15 shows a beachfront home at Sea Isle three months after the storm, its concrete slab-and-pile foundation still two feet above the sand and the bluffline well into the background. (The house was actually level; the camera was tilted).

Figures 16 and 17 on the next page are before and after aerial views of Terramar Beach subdivision, next southwest from Sea Isle and about four and a half miles from the end of the island. Figure 16, taken in September 1979, shows an orderly situation with beachfront homes some 20 to 40 feet back from the edge of a fairly linear bluffline. Figure 17 shows the same area a month after Alicia, the front rank of houses all well down into the swash zone and a broad plume of sand cast well inland. Note that the direction of the sand plume is no longer normal to the shoreline, instead it angles to the left. This is because Terramar Beach was actually in the eye as the storm crossed the coast;

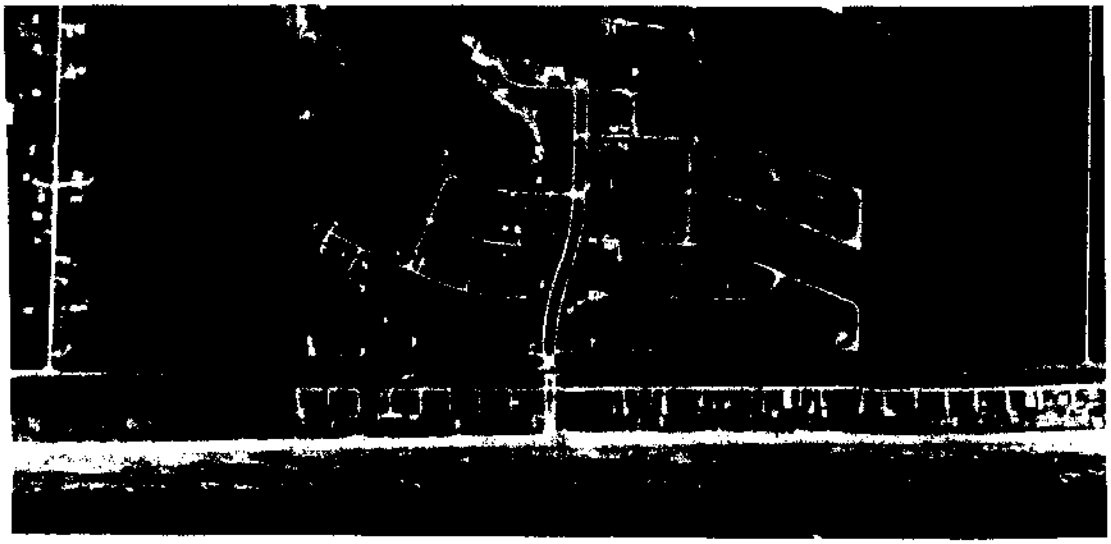


Figure 16. Terramar Beach, 1979. Remote Sensing Center photo.

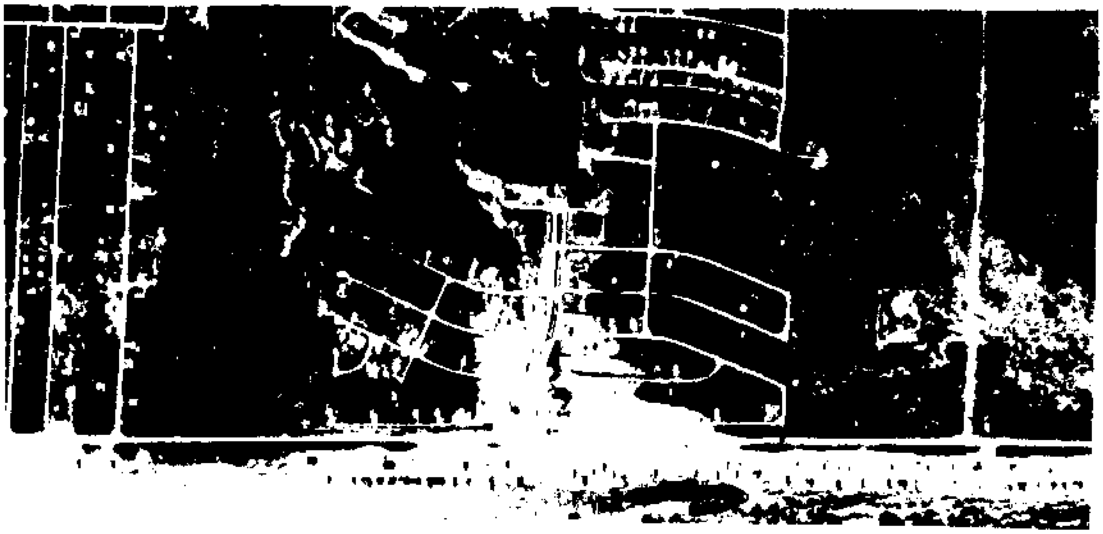
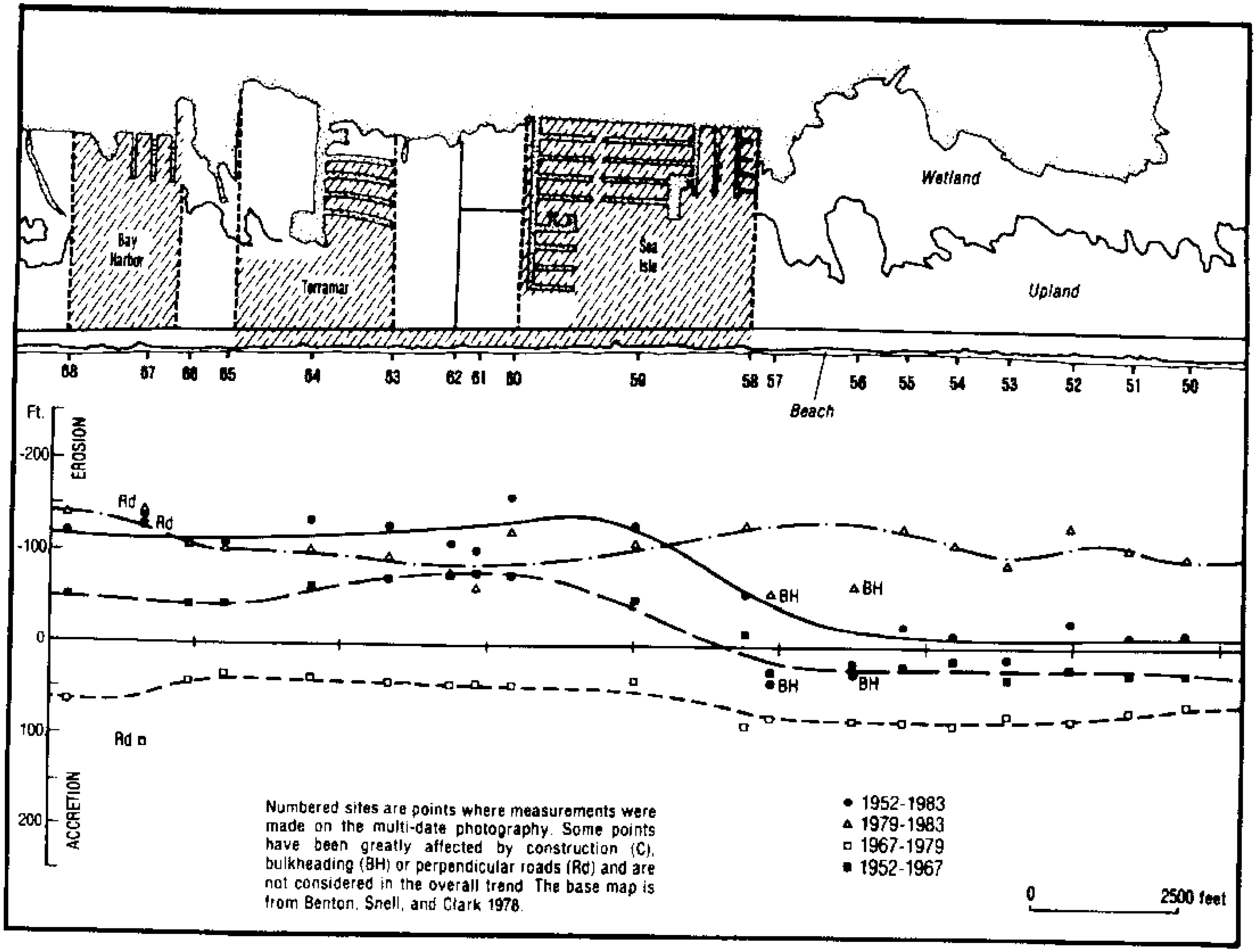


Figure 17. Terramar Beach, 1983. Remote Sensing Center photo.

therefore, the peak winds occurred here when the eye was still offshore. Note also that far more sand was thrown up along the developed beachfront than in the undeveloped area at left.

Figure 18 on the next page shows the vegetation-line change curves for this section of West Beach. The 1967 to 1979 plot still shows accretion, although less than occurred further northeast. The 1952 to 1967 curve, on the other



Numbered sites are points where measurements were made on the multi-date photography. Some points have been greatly affected by construction (C), bulkheading (BH) or perpendicular roads (Rd) and are not considered in the overall trend. The base map is from Benton, Snell, and Clark 1978.

Figure 18. Shoreline Changes, Sea Isle Beachfront Area, 1952-1983

hand, changes rapidly from accretion to erosion at the northeast side of Sea Isle. The 1979 to 1983 curve, as before, continues to show erosion of 100 feet and more.

Were it not for Hurricane Alicia, or perhaps the combination of Alicia and Allen, this segment of West Beach might have averaged either a slight accretion or a zero change since 1952. It is along the beach fronting Sea Isle and Terramar that the 1967 to 1979 accretion was offset by a strong trend toward erosion during the 1952 to 1967 period. The remainder of this stretch of shoreline had either outright accretion (right side of Figure 18) or minimal erosion (left edge of Figure 18) from 1952 to 1967.

The southwest end of the island has been subject to a good deal of erosion in the past 30 years--more so than anywhere else--and the only other area of West Beach with a consistent erosional pattern is the stretch just southwest of the end of the seawall. Along the broad center of West Beach the mid-term shoreline change from the early 1950's through the late 1970's has been quite definitely in the direction of accretion. The question now is whether or not the erosional trend of the last several years will continue.

Bay Harbor to southwest tip - The shape of the southwest end of Galveston Island has changed significantly since the early 1950's. Figure 19 (on the next page) is a March 1952 photo showing a prominent beachfront dune structure with a low, rolling upland interspersed with palustrine wetlands behind it. The sand beach broadened significantly at the tip of the island in what appears to have been a still-developing situation. The sand feature was probably of recent origin since there is no sign of pioneer vegetation.

The photo does indicate that there had been a relatively recent seaward advance of the vegetation line. The thin, dark crescent forming the seaward boundary of the slightly lighter main body of vegetation was a newly evolved

Figure 19. Southwest Tip of Island, 1952. ASCS photo.

Figure 20. Southwest Tip of Island, 1970. NASA photo.

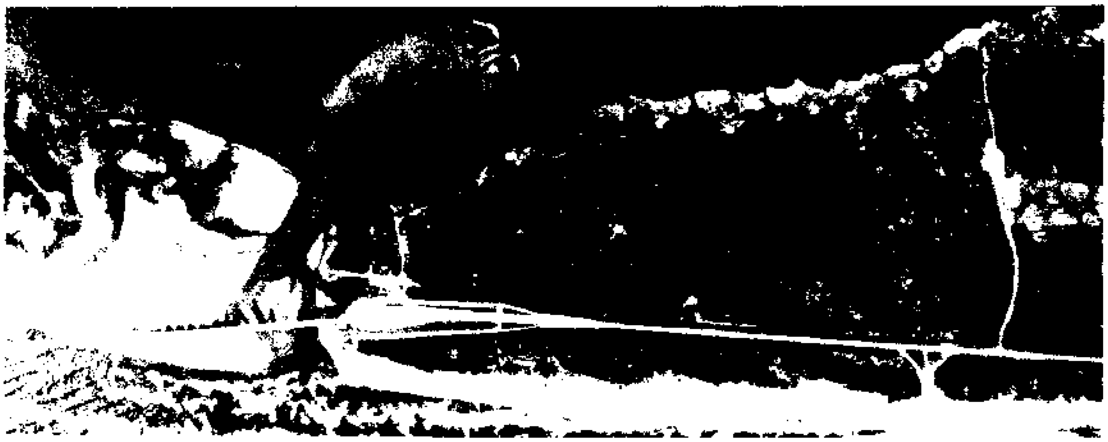


Figure 21. Southwest Tip of Island, 1983. RSC photo.

dune-and-swale system which had been around long enough for expanding grassbeds to fill in the empty spaces and provide a fairly regular, hard-edged vegetation line.

Later photography showed a further seaward advance of the vegetation line, but a general retreat of the shoreline. It appears that the mechanism which created the large sand feature or, more likely, the source of its sand, no longer exists.

Figure 20 shows the same area in January 1970. The vegetation line had by then advanced still further from the 1952 boundary but the grasses in the newly vegetated area give the irregular, mottled appearance of still-expanding plant beds. However, the shoreline bulge at the tip of the island had receded since 1952.

Note the newly built bridge and the associated toll-plaza turnaround area at photo center. It is nearly 800 feet from the rounded, southwest end of the turnaround to the short road connecting the turnaround lanes. Using that as a measuring scale, the perpendicular distance from the parallel roadway at the southwest end of the turnaround area to the edge of the vegetation line appears to be well over 800 feet. The measured distance was actually 940 feet [2].

Figure 21, taken one month after Alicia in 1983, shows that very significant erosion had occurred between the two dates. The new channel just southwest of the end of the turnaround is a recurring feature which appeared briefly in 1979 after Tropical Storm Elena and again in 1980 after Hurricane Allen. The 1983 occurrence was fairly long lasting; it was still in evidence in November 1983 but had closed again by late spring of 1984. With each of the recent erosional events, this channel has been a little wider, a little deeper, and a little slower to fill. Given the normal continuance of such events, the channel could become a permanent feature before long.

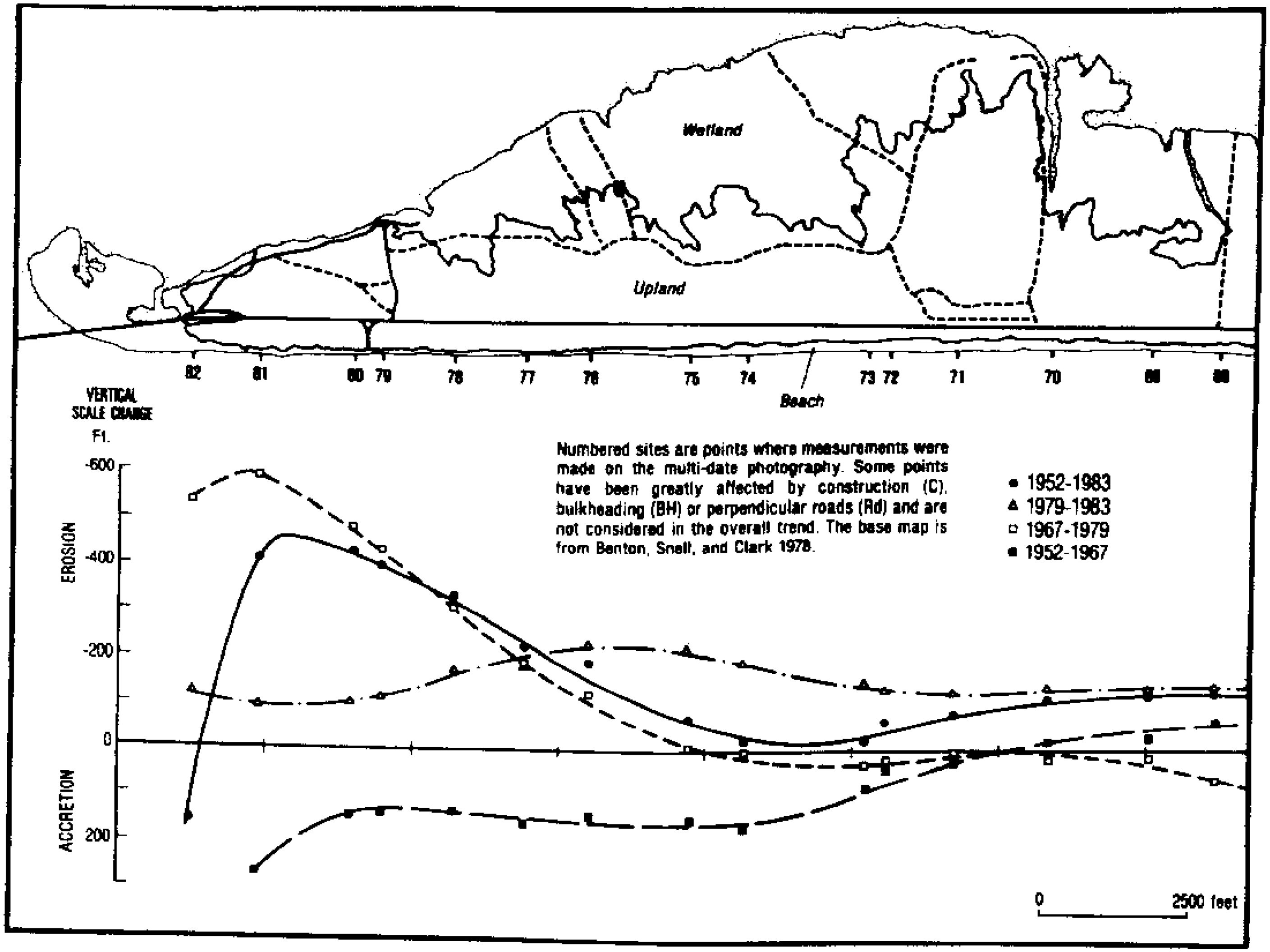
An equally noteworthy feature of this September 1983 photo is the radical retreat of the vegetated bluffline from its January 1970 position. This did not occur all at once, The minimum perpendicular distance from the turnaround road to the vegetation line had been reduced to 440 feet by December 1977 [2], and by September 1980 the distance had been cut to 270 feet. Measurement of the Figure 21 photo shows the September 1983 distance to have been 180 feet.

Figure 22 (next page) is the vegetation-line-change diagram for the southwest end of Galveston Island. Because of the extreme amount of erosion here, the vertical scale factor in Figure 22 is twice that of the comparable diagrams for other sections of West Beach.

The maximum measured amount of 1979 to 1983 erosion along West Beach was 216 feet at Transect No. 76, most of which was due to Alicia. The erosional impact of Alicia diminished near the tip of the island because that area was within the eye at time of passage and the maximum winds blew parallel to the beach rather than angling onshore; thus, the sea direction was such that an extreme wave-and-current scour could not develop.

There was a maximum vegetation-line retreat of nearly 600 feet at the tip of the island (Transect 81) from 1967 to 1979; but from 1952 to 1967 the vegetation line advanced some 270 feet at that point while the shoreline receded. This significant countermovement, illustrated by Figures 19 and 20, was apparently unique to the island tip. Other photos show that between nearby Transects 71 and 80 the vegetation line and shoreline advanced together from 1952 to 1967.

Examination of Figures 19 to 22 clearly shows the high rates of short- and mid-term erosion at the end of the island. From 1967 to 1979 the rate was 50 feet per year, while it was 25 feet per year from 1979 to 1983. Had Alicia crossed the coast a few miles further southwest, much greater scour would probably have occurred at the tip, with greater beach loss at the bridge.



Numbered sites are points where measurements were made on the multi-date photography. Some points have been greatly affected by construction (C), bulkheading (BH) or perpendicular roads (Rd) and are not considered in the overall trend. The base map is from Benton, Snell, and Clark 1978.

Figure 22. Shoreline Changes, Southwest End of Island, 1952-1983

## Photointerpretation of Shoreline-Change Direction

To identify an object, a condition or an ongoing process on a photograph, interpreters must rely on the characteristics of shape, size, pattern, tone (or color), texture and context. Vegetated blufflines are somewhat linear features with dark tones on one side and light tones on the other, and they are situated in proximity to a seashore. Color infrared film provides the added advantage that dark tones will have a reddish hue (if the photography was taken during the growing season) and the white sand and blue water will provide reasonably conclusive evidence that what is being interpreted is indeed a seashore vegetation boundary.

But the above is actually a rather cursory analysis that relies on just shape, size, tone and context. If pattern and texture are also examined, an interpreter can usually determine whether the vegetation line was advancing or retreating at the time the photograph was taken. This is possible because of the manner in which the dune and bluff plants propagate.

Different species of such vegetation have differing habitat requirements. Unlike wetlands plants, the dune and bluff species are intolerant of periodic saline inundation and therefore need a higher-elevation substrate. Some of the classic dunetop grasses will not prosper on low bluffs, and plants that will grow on low bluffs will ordinarily not survive in even the upper elevations of an intertidal situation.

For a given species of bluff vegetation to spread seaward, there must be an influx of sand which expands its habitat boundary in a seaward direction; i.e., the new sand must be built to a viable elevation. Once that occurs, the propagules move onto the new territory in a random fashion and with random success. The new plant assemblages are not regular, linear extensions of the old boundary; rather, they colonize intermittently as clumps and elongate configurations whose position and shape have only a tenuous relationship to previous boundaries.

To the photointerpreter, these expanding plant communities, typical of an accreting shoreline condition, appear as mottled areas which are somewhat less dense than the older vegetation systems from which they have sprung. In the terminology of the interpreter, the texture of the feature is mottled, its pattern is an assemblage of random small shapes, and its context is the zone of occurrence between the solid line of older vegetation and the sand beach. The new boundaries will be usually be softer, less linear, often cumuloform.

Examples of accretionary appearance abound in the earlier photographic sequences used in this study. The vegetation line was actively advancing in 1952 along a broad segment of the middle of West Beach. In 1967 this advance was essentially continuous. Figures 19 and 20, showing the tip of the island in 1952 and 1970, have already been discussed in this context. The same mottled, irregular vegetation boundary is seen in 1967 in Figure 5.

This trend, which was so obvious in 1967, had by 1977 come to a halt. The vegetation line on the March 1977 photography showed that since 1967 there had been an erosional event, or series of events, which reversed the long-term advance. The trend of the bluffline in that sequence was relatively regular and the cutoff of bluff vegetation was fairly abrupt. From the end of the seawall to Jamaica Beach there was only scattered evidence of an earlier advance, but from Jamaica Beach to within two or three miles of the southwest tip it was quite apparent that there had been widespread, significant accretion in prior years. Over the last two or three miles to the end of the island, however, the evidence of an earlier advance was essentially missing. From March 1977 to the present there has been no indication of further accretion on West Beach.

Along East Beach, on the other hand, every photo sequence but the last one shows an ongoing advance of the vegetation line. The left half of Figure 2, for example, shows a typical accretionary condition. There was little indication of this in the right half of the photo, but that is because of trail bike and dune buggy traffic on and across the dunes in that area. Along the beach area in the left half, the local government had erected barricades and posted signs in a partially successful attempt to restrict this practice and preserve the newly developed dune vegetation. Figure 3, however, shows that Alicia had removed almost all indication of recent advance.

## Impact of Beachfront Construction on Erosion Patterns

Healthy dune and bluff vegetation should be considered the first line of defense against erosion. Conversely, any activity that diminishes plant cover will increase the likelihood and extent of erosion. The native, deep-rooted grasses which withstand winds and seas so well are actually rather fragile and cannot survive traffic. Once stripped away, they are slow to return.

Public access to beaches seems to require the building of roads crossing the vegetation line in order for beachgoers to drive down onto the sand. The roads are generally nothing more than gravel or shell covering the devegetated rights of way. When storms come along, these barren strips are eroded rapidly. Figure 3 is a spectacular illustration of the impact of storm winds and seas on beach access roads. The roadways were undermined to depths of several feet and their sand bases sluiced hundreds of feet inland, while adjacent grass-covered dunes receded only slightly under the same onslaught.

Figure 3 also shows the effect of the standard construction practice of stripping away vegetation in the process of erecting buildings. As has been pointed out earlier, there was very significant erosion adjacent to the new condominium left of photo center because of the barren soil left in the wake of its recent construction.

Beachfront homes on Galveston Island are often planted with Bermudagrass or similar lawn species which can withstand moderate foot traffic but which have short roots compared with less traffic-tolerant native grasses. These lawn species have far less resistance to high-riding storm waves than the native vegetation they replace.

The presence of beachfront homes tends to exacerbate the erosional situation. Although the structure itself, including its foundation and any associated bulkheading that happens to be present, may inhibit for a time the onset of erosion at the structure's location, the blufflines between such structures tend to be more affected by storm forces. In Figure 10, the bluff immediately behind the beach home on the right protrudes slightly from the mean bluffline in that area; however, the adjacent between-the-homes bluff is significantly indented with respect to the mean. Similar features abound on West Beach, their manifestations readily visible under magnification on the post-Alicia photography. Where beachfront structures, bulkheading, or a combination of the two provide this sort of localized lessening of erosion, there seems almost invariably to be a compensating erosional increase close by.

Bulkheading, though, does not necessarily provide even this minimal protection for beachfront homes. At Sea Isle the vegetation line receded almost as much where there was extensive bulkheading as it did where there was none.

Figure 17 would seem to show that the presence of a large number of adjacent beachfront structures worked to a mutual disadvantage. Bluffline retreat and sand loss from the beach were significantly greater over much of Terramar Beach than along the undeveloped shorelines on either side. The fact that many of those homes were built recently may have been a contributing factor.

# DISCUSSION

## Impact of Texas Open Beaches Act

The Texas Open Beaches Act codifies the common-law concept of the public's right of access to beaches. The Act defines the public access as the area between the line of mean low tide and the line of continuous vegetation, allowing the visitor to determine easily and precisely where he may or may not go; i.e., everything seaward of the vegetation line is either public property (the area between the mean low waterline and the mean high waterline) or an unrestricted public easement across private property (the area between the mean high waterline and the vegetation line). The the Act also stipulates that no private structure is allowed on the public beach, a provision which (a) denies the private owner any practical current use of that portion of the property lying seaward of the vegetation line and (b) diminishes the current resale value of the property accordingly.

Now consider the physical processes involved in the retreat or advance of the vegetation line. A major erosional event will cause an immediate shoreward displacement of the vegetation line (e.g., the 100-foot displacement along most of West Beach following Alicia) with most of the eroded beach sands stored in offshore bars at least temporarily. Low, long-period, constructive waves will subsequently return most of the stored sand to the beach, a process which produces a much broader and more gently sloping beach in the short- to mid-term than existed just prior to the storm. If relative quiescence continues over a few years' time, berms will form which are high enough to allow the growth and spread of plants, moving the vegetation line seaward. One result of the berm-forming process is resumption of a more normal mean beach slope, and therefore a subsequent return to the pre-storm mean beach width. Except for relatively brief periods following erosional episodes, the tendency is for the shoreline and the vegetation line to move shoreward or seaward somewhat in unison. Consideration of coastal dynamics leads to this conclusion; the aerial photography available to this study confirms it.

In the long-term, as the vegetation line retreats the public beach moves landward; as it advances the public beach will move seaward. Regardless of where the vegetation line may be for a given, possibly aberrant, year, its average distance from mean low water is relatively constant, although the late winter beach is usually narrower than in late summer. Thus, although erosional ar accretional processes move the public beach significantly landward or seaward, its seasonal width tends to remain about the same.

These processes directly involve both the beach-going public and the owne of beachfront property. The Act protects both the public right of access and the area of public access no matter which way the beach moves. The impact of the Act on the beachfront property owner, however, is much less benign. When the vegetation line retreats, the owner loses most of the use of that portion the property which has fallen into the public easement. When the vegetation line retreats sufficiently to place a structure (i.e., bulkheading, riprapping or the dwelling itself) in the public easement area, the Texas Open Beaches Act makes the owner liable for the cost of removal of such "obstruction, barrier or restraint of any nature" from the public beach.

When the vegetation line subsequently advances, the property owner regain full use of the seaward-moving portion. Given the likelihood of another futur retreat, however, erection of a new structure on the newly regained land would be a chancy proposition at best. The Attorney General has been willing to enforce relevant provisions of the Act.

In the recently concluded Matcha case, a West Beach property owner rebuilt a virtually destroyed beachfront house that ended up on the public easement after Hurricane Alicia. The Attorney General filed an enforcement suit and obtained an injunction to prevent reuse of the dwelling. Despite the legal proceedings, the property owner also brought in sandfill in an attempt to reestablish the vegetation line seaward of the rebuilt dwelling. Although the court decision is being appealed, the judgment affirmed the attorney General's position that (a) an existing dwelling that becomes situated on the public easement is by definition an illegal obstruction to that easement and (b) the act requires that the dwelling be removed from said easement.

Many West Beach property owners, finding their otherwise-livable dwellings on the public beach after passage of Alicia, had sand trucked in, planted grass, and, in effect, attempted to reestablish the vegetation line in its pre-storm position. But the Act defines the inshore limit of the public beach as the natural vegetation line and explicitly prohibits any artificial addition of fill or turf whose purpose is to extend the vegetation line seaward. Thus, the recent court decision puts such private or corporate owners on notice that the earlier location of the vegetation line has no bearing on present rights of property use and raises the spector of further prosecution.

The argument might be made, based on historic aerial photography such as that used in this study, that there could be equivalent accretional periods along West Beach that would again place the vegetation line seaward of the houses in question. Such an argument would be irrelevant since a structure that exists on the public beach easement, even for a relatively short time, is an illegal obstruction subject to removal. Further, data from this study, and expert testimony given in the Matcha case, indicate that it is unlikely that the vegetation line will regain the ground lost due to Hurricane Alicia and that any recovery would be swallowed up in what now seems to be the long-term erosion process on West Beach.

The key point is that archival aerial photographs can delineate the location of the vegetation line on a given date. Properly used, they can provide clues to erosional or accretional trends. Such photos determine for the office of the State Attorney General whether or not a given house lies seaward of the vegetation line on the photographic date. But they cannot, in themselves, establish beyond doubt what will happen at some future time with respect to erosion or accretion on Galveston Island.

## Future Shoreline Movement at Galveston

Photography from the past seven years clearly establishes that the shoreline at West Beach is retreating and that this retreat has in all probability been going on somewhat longer than seven years. Thus, Hurricane Alicia was just one more in a continuing series of near-term erosional events affecting the island. The occurrence of erosional events is nothing new; they come about with regularity. Their effects, however, are not always lasting. During the decade from 1964 through 1973, for example, there were four hurricanes and four tropical storms of potentially significant impact on Galveston Island [3]. Three such hurricanes and five tropical storms occurred during the next decade [3]. All other things being equal, it would appear that the potential for erosion was about the same during both periods. Yet there was a net accretion over the earlier interval but net erosion over the latter one.

So it would seem that all things are not necessarily equal, that something other than the occurrence or non-occurrence of hurricanes and tropical storms must be involved. Consider now the availability of sand-sized particles. In order for accretion to occur there must be a sediment supply in the offing.

There has not been a ready supply of sand for some time now. In the last century, sand arrived at Galveston in the coastwise drift which then, as now, had a mean movement from northeast to southwest. It seems most unlikely that new sand is arriving at Galveston Island from this previous source because it would have to bypass the jetties; i.e., it must move seaward along the North Jetty, thence southwestward across the dredged channel to the South Jetty, then finally upslope along the south side of the South Jetty to the vicinity of East Beach. It is difficult to conceive of the mechanism or set of mechanisms which would produce this remarkable feat in water of that depth. Moreover, it would appear that the bulk of the sand moving southwestward along Bolivar Peninsula toward the North Jetty has become trapped in the buildup or the sizeable accretionary Gulf-front feature now known as Bolivar Flats.

Since almost no new sand seems to be arriving, it must be assumed that the sand which was at Galveston at the time the jetties were completed is about all the sand that will be there for the foreseeable future. That being the case, erosional-accretional patterns since the jetties have been in place could simply have been manifestations of the manner in which the sand that was already there was being shuffled about.

Consider now the mechanism for that redistribution. Longshore currents generated by waves angling in toward the beach are the primary means for moving sand in the nearshore zone. The mean sea direction at Galveston is such as to normally generate a net flow of sand from northeast to southwest. But the jetties block development of a southwestward-moving coastwise drift in the East Beach area. Once beyond the shadowing effect of the jetties, such as midway along the present seawall, seas angling in from the east can once again begin to generate southwestward-moving longshore currents of sufficient velocity to move sand-sized particles. In effect, then, the present mean longshore current structure along Galveston Island comprises a divergence zone situated at mid-seawall with net northeasterly sediment transport northeast of there and net southwesterly transport southwest of there. Lacking a supply of sand feeding into the divergence zone, the end result is a net long-term loss of sand from that area.

Thus, sand may not ordinarily be moved out of East Beach, but it may be moved in on the occasional northeastward-moving drift as long as the updrift source remains. The primary source of replenishment for West Beach was once this same area in front of the seawall. The situation was complicated in the late 1930's by construction of the groin field near the middle of the current divergence zone. As noted earlier, the purpose of the groin field was to retard erosion. It has done just that, acting to slow the departure of sand to the northeast and to the southwest. The groin field, then, has served to delay the inevitable.

All of this means that East Beach has become the repository for much of the sand from the beach and from the nearshore zone in front of the seawall. Most of the remainder of the sand which once resided in that area has been moved to the southwest. That portion of this source which fed into the southwesterly transport now seems to be depleted. Some time in the early 1970's the last of the visible sand remaining in front of the southwestern third of the seawall was scoured away by the southwest-moving drift. This led to the accelerated erosion observed just beyond the end of the seawall. It remains to be seen whether or not the accretion at East Beach has ended. Lacking a viable source, the previously observed buildup cannot be sustained.

The East Beach situation may continue for a time as an accretional aberration. For West Beach, the sand source has been depleted. At the West Beach end of the seawall and at the southwest end of the island, continued, severe erosion seems assured. Along the middle of West Beach there may be occasional, perverse blips of accretion in the short- to mid-term, but it is most unlikely that the natural processes will again produce a consistent, broad advance of the vegetation line. On the contrary, West Beach can probably look forward to continuing, and probably increasing, long-term erosion.

## Impact of Sea Level Rise and Land Subsidence on Erosion Rates

The case has been made in the above discussion that erosion problems on Galveston Island are primarily the result of localized sediment depletion. But there is also the possibility that what we are seeing is merely symptomatic of rising sea level, land subsidence or a combination of the two. Swanson and Thurlow [10] have compared the long-term record from the Galveston primary tide gauge with that from the Pensacola gauge and have determined that the higher rate of sea level rise at Galveston may be attributed to the known subsidence rate at the Galveston gauge site. Their data show a sea level rise rate of about 2.4 feet per century between 1930 and 1970, the period during which significant, known subsidence has taken place. The earlier rise rate, prior to the heavy groundwater pumping at Houston which caused the subsidence, was about 1.5 feet per century.[10]

Considering the two percent slope of an average summer beach, the effect of a 2.4-foot per century rise in sea level would be a 1.2-foot per year horizontal component. However, the 2.4-foot rate occurs at the site of the Galveston primary tide gauge, located at the 20th Street Pier on the bay side of downtown Galveston. According to subsidence maps [10], Galveston lies on the fringe of the subsidence zone, with the 20th Street Pier located at about the maximum point for the island and San Luis Pass lying in the zone of zero subsidence. Thus, the subsidence at West Beach is significantly less than in downtown Gal veston. Furthermore, the rate of subsidence east of Houston, which affects Galveston, has slowed significantly of late while picking up on the west side of Houston. As this trend continues, long-term sea level rise relative to the Galveston primary gauge should return to the apparent natural rate of around 1.5 feet per year.

The rate of sea level rise at West Beach has never departed significantly from the lower value. Given the two percent beach profile, this comes to three quarters of a foot of horizontal shoreline movement per year. From data developed over the course of this study and presented earlier, the short-term rate of erosion near the southwest end of the seawall is about 30 feet per year and the 30-year rate there is around 10 feet per year. Erosion at the southwest tip of the island is even more rapid, about 15 feet per year over the past 30 years. The sea-level-rise component is quite small in comparison.

## Projections and Recommendations

Summing up, the mid- to long-term trend for West Beach is toward continued erosion, possibly with some localized accretion of modest extent and relatively brief duration. The situation on East Beach is probably no different except that there may be continued short- to mid-term accretion before the inevitable long-term erosion sets in.

The cause of the long-term erosional trend is depletion of the sand source which remained after the jetties were built. That legacy is mostly gone and the hard evidence of its departure is visible along the front of the seawall. The consequence of the trend is continued slow loss of Gulf frontage, mostly from West Beach for the present, but ultimately from East Beach as well.

What, if anything, should be done about this? The choices seem limited to (1) maintenance of the existing shoreline location through periodic replenishment of beach sand; (2) maintenance of the existing shoreline with an engineering solution such as extending the seawall; or (3) simply letting nature take its course. The main beneficiaries of holding to the present mean shoreline would be the beachfront property owners; as already discussed, an eroding shoreline is of no immediate concern to the beachgoing public. If the seawall were to be extended, on the other hand, property would be protected but the inevitable loss of sand from in front of the seawall would eliminate the public beach. Since relatively few people (or corporate entities) would benefit, it is hard to justify using public monies for either of these high-cost solutions.

The remaining alternative is to simply let it all happen. That is, maintain the riprap protection at the base of the seawall as long as it is economically feasible to do so but allow the shorelines at West Beach and East Beach to migrate where they will. This do-nothing policy requires that owners of existing beachfront dwellings simply continue to take the consequences of their original calculated risk. This is not necessarily a heartless concept. It has long been the expectation on West Beach that owners of houses in the second rank will eventually, due to the eroding away of the first rank of properties, enjoy first-rank benefits themselves.

Despite this expectation, it would not be surprising if provision were to be made for at least token recompense to existing owners for loss of dwelling and land. If this were to occur, however, it would be appropriate if owners of beachfront houses built after some reasonable future cutoff date were required to bear the loss when their erosion-depleted property reverts to the state. To protect unsuspecting buyers, future beachfront houses should have a required setback from the vegetation line which would allow for projected loss of bluff frontage over a stipulated reasonable-use lifetime of the structure.

What must be defined are projected loss rate and reasonable-use lifetime.

Thirty years might seem a reasonable life. If for no other reason, that period coincides with the length of the most popular mortgage; lenders would be provided with some assurance of at least a pro-rata collateral value in case of default.

Given a 30-year life, the required setback along a given stretch of West Beach shoreline should be equal to the projected 30-year average erosion plus some nominal buffer distance, such as 50 feet. For the segment of West Beach lying between the end of the seawall and Bermuda Beach, the required setback would be around 250 feet. From Bermuda Beach to Jamaica Beach it would drop to something such as 175 feet. For the Sea Isle-Terramar-Bay Harbor area the defined setback would also be about 175 feet.

The impact of instituting such a policy at this time would be that the developers who own the property would have fewer lots on which to build or to sell. The bulk of this potential loss would be made up in the usual manner by simply charging more for the larger pieces of land involved. The purchaser would then buy property which, over the normal course of events, would be incrementally eaten away in a very real illustration of depreciation. At length, the structure itself would go the same way.

For most owners, this would not be as staggering a loss as it might seem. According to the State Attorney General's office, owners of West Beach properties are most often individuals or groups whose primary purpose of ownership is the derivation of income from that property. As such, they enjoy tax advantages unavailable to the minority who use beachfront houses as principal residences or as personal vacation homes.

The above proposal may or may not be feasible. The key point in all of this is the impact of erosional events on Galveston Island. Hurricane Alicia was not a freak happening. It was just one more episode in a continuing, probably worsening situation whose far-reaching ramifications must be addressed.

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# APPENDIX

The following table shows movement of the vegetated bluffline as measured along fixed transects which were identifiable on aerial photographs taken at selected time intervals between 1952 and 1983. Distances are in feet, with accretion designated "+" and erosion designated "-". The letter R, B or C means that the precision of a measurement so designated may have been affected by the presence of a road, bulkheading, or construction scars, respectively.

## EAST BEACH

| TRANSECT NUMBER | MOVEMENT IN FEET OF THE VEGETATED BLUFFLINE NORMAL TO THE SHORELINE | | | | |
|---|---|---|---|---|---|
| | 1952-1967 | 1967-1979 | 1952-1979 | 1979-1983 | 1952-1983 |
| 1 | +436 | +688 | +1124 | -600 | +524 |
| 2 | +216 | +136 | +352 | - 70 | +282 |
| 3 | +161 | +252 | +413 | - 60 | +353 |
| 4 | +189 | +204 | +393 | - 80 | +313 |
| 5 | +181 | +182 | +363 | -190 R | +173 |
| 6 | +164 | +204 | +368 | - 60 | +308 |
| 7 | +104 | +236 | +340 | - 65 | +275 |
| 8 | + 74 | +304 | +378 | ---- C | ---- C |
| 9 | - 24 | +272 | +248 | ---- C | ---- C |
| 10 | - 13 | +266 | +253 | - 10 | +243 |
| 11 | + 13 | +184 | +197 | - 95 | +102 |
| 12 | + 9 | +148 | +157 | - 40 | +117 |
| 13 | - 16 | + 68 | + 52 | - 40 | + 12 |

## WEST BEACH

| TRANSECT NUMBER | MOVEMENT IN FEET OF THE VEGETATED BLUFFLINE NORMAL TO THE SHORELINE | | | | |
|---|---|---|---|---|---|
| | 1952-1967 | 1967-1979 | 1952-1979 | 1979-1983 | 1952-1983 |
| 1 | -121 | + 38 | - 83 | - 95 | -178 |
| 2 | -139 | + 36 | -103 | -109 | -212 |
| 3 | -123 | + 26 | - 97 | -145 | -242 |
| 4 | -182 | + 22 | -160 | -155 | -315 |
| 5 | -128 | + 8 | -120 | -180 | -300 |
| 6 | -109 | - 16 | -125 | -122 | -247 |
| 7 | -103 | - 12 | -115 | -130 | -245 |
| 8 | - 89 | - 24 | -113 | - 70 | -183 |
| 9 | - 81 | - 22 | -103 | -115 | -218 |
| 10 | - 77 | - 24 | -101 | -100 | -201 |

# APPENDIX

## WEST BEACH (Continued)

| TRANSECT | MOVEMENT IN FEET OF THE VEGETATED BLUFFLINE NORMAL TO THE SHORELINE | | | | |
|---|---|---|---|---|---|
| NUMBER | 1952-1967 | 1967-1979 | 1952-1979 | 1979-1983 | 1952-1983 |
| 11 | -146 C | + 54 C | - 92 | -105 | -197 |
| 12 | -187 C | + 64 C | -123 | -110 | -233 |
| 13 | -232 C | +122 C | -110 | -125 | -235 |
| 14 | - 65 | - 12 | - 77 | -100 | -177 |
| 15 | - 55 | + 8 | - 47 | -115 | -162 |
| 16 | - 56 | + 6 | - 50 | -110 | -160 |
| 17 | -107 R | + 44 R | - 63 | -110 | -173 |
| 18 | - 56 | + 44 | - 12 | -100 | -112 |
| 19 | - 16 | + 54 | + 38 | - 85 | - 47 |
| 20 | + 6 | + 44 | + 50 | - 82 | - 32 |
| 21 | - 81 R | + 94 R | + 13 | - 90 | - 77 |
| 22 | + 4 | + 26 | + 30 | -150 R | -120 |
| 23 | - 44 | + 84 | + 40 | -100 | - 60 |
| 24 | - 21 | + 32 | + 11 | -104 | - 93 |
| 25 | - 59 C | + 44 | - 15 | - 95 | -110 |
| 26 | - 46 C | + 46 | 0 | - 92 | - 92 |
| 27 | - 87 | + 76 | - 11 | - 94 | -105 |
| 28 | - 79 | + 56 | - 23 | - 90 | -113 |
| 29 | - 80 | + 58 | - 22 | -110 | -132 |
| 30 | - 71 | + 64 | - 7 | -110 | -117 |
| 31 | - 86 | + 68 | + 2 | -110 | -108 |
| 32 | - 34 | + 44 | + 10 | -110 | -100 |
| 33 | - 2 | + 4 | + 2 | - 92 | - 90 |
| 34 | - 77 C | +112 C | + 35 | - 97 | - 62 |
| 35 | - 52 C | + 92 C | + 40 | - 70 | - 30 |
| 36 | - 3 | + 80 | + 77 | - 70 | + 7 |
| 37 | - 3 | + 60 | + 57 | - 75 | - 18 |
| 38 | ---- C | ---- C | + 37 | - 95 | - 58 |
| 39 | + 5 | + 68 | + 73 | - 95 | - 22 |
| 40 | ---- C | ---- C | +103 | - 95 | + 8 |
| 41 | + 27 | + 76 | +103 | -105 | - 2 |
| 42 | + 16 | + 86 | +102 | -125 | - 23 |
| 43 | + 17 | + 90 | +107 | - 90 | + 17 |
| 44 | + 13 | + 94 | +107 | -120 | - 13 |
| 45 | + 61 | + 52 | +113 | -100 | + 13 |
| 46 | + 50 | + 60 | +110 | -110 | 0 |
| 47 | + 68 | + 62 | +130 | - 90 | + 40 |
| 48 | + 35 | + 66 | +101 | -103 | - 2 |
| 49 | + 40 | + 62 | +102 | -110 | - 8 |
| 50 | + 28 | + 62 | + 90 | -100 | - 10 |
| 51 | + 29 | + 68 | + 97 | -110 | - 13 |
| 52 | + 25 | + 80 | +105 | -135 | - 30 |
| 53 | + 34 | + 74 | +108 | - 95 | + 13 |
| 54 | + 16 | + 84 | +100 | -115 | - 15 |
| 55 | + 23 | + 82 | +105 | -130 | - 25 |

# APPENDIX

## WEST BEACH (Continued)

| TRANSECT NUMBER | MOVEMENT IN FEET OF THE VEGETATED BLUFFLINE NORMAL TO THE SHORELINE | | | | |
|---|---|---|---|---|---|
| | 1952-1967 | 1967-1979 | 1952-1979 | 1979-1983 | 1952-1983 |
| 56 | + 19 | + 78 | + 97 | - 70 B | + 27 |
| 57 | + 27 | + 76 | +103 | - 65 B | + 38 |
| 58 | - 17 | + 84 | + 67 | -129 | - 62 |
| 59 | - 51 | + 38 | - 13 | -115 | -128 |
| 60 | - 77 | + 40 | - 37 | -125 | -162 |
| 61 | - 77 | + 40 | - 37 | - 65 | -102 |
| 62 | - 77 | + 44 | - 33 | - 79 | -112 |
| 63 | - 73 | + 40 | - 33 | - 99 | -132 |
| 64 | - 68 | + 36 | - 32 | -106 | -138 |
| 65 | - 45 | + 32 | - 13 | -104 | -117 |
| 66 | - 45 | + 38 | - 7 | -110 | -117 |
| 67 | -125 R | +128 R | + 3 | -145 R | -142 |
| 68 | - 52 | + 64 | + 12 | -135 | -123 |
| 69 | - 12 | + 24 | + 12 | -125 | -113 |
| 70 | - 8 | + 30 | + 22 | -130 | -108 |
| 71 | + 36 | + 12 | + 48 | -122 | - 74 |
| 72 | + 45 | + 28 | + 73 | -130 | - 57 |
| 73 | + 87 | + 38 | +125 | -146 | - 21 |
| 74 | +167 | - 2 | +165 | -188 | - 23 |
| 75 | +150 | 0 | +150 | -211 | - 61 |
| 76 | +144 | -118 | + 26 | -216 | -190 |
| 77 | +157 | -192 | - 35 | -190 | -225 |
| 78 | +143 | -306 | -163 | -170 | -333 |
| 79 | +145 | -428 | -283 | -114 | -397 |
| 80 | +147 | -474 | -327 | -100 | -427 |
| 81 | +269 | -586 | -317 | - 90 | -407 |
| 82 | +810 | -532 | +278 | -120 | +158 |