BUREAU OF ECONOMIC GEOLOGY
The University of Texas at Austin
W.L. Fisher, Director
In cooperation with Texas Coastal and Marine Council

NATURAL HAZARDS OF THE TEXAS COASTAL ZONE

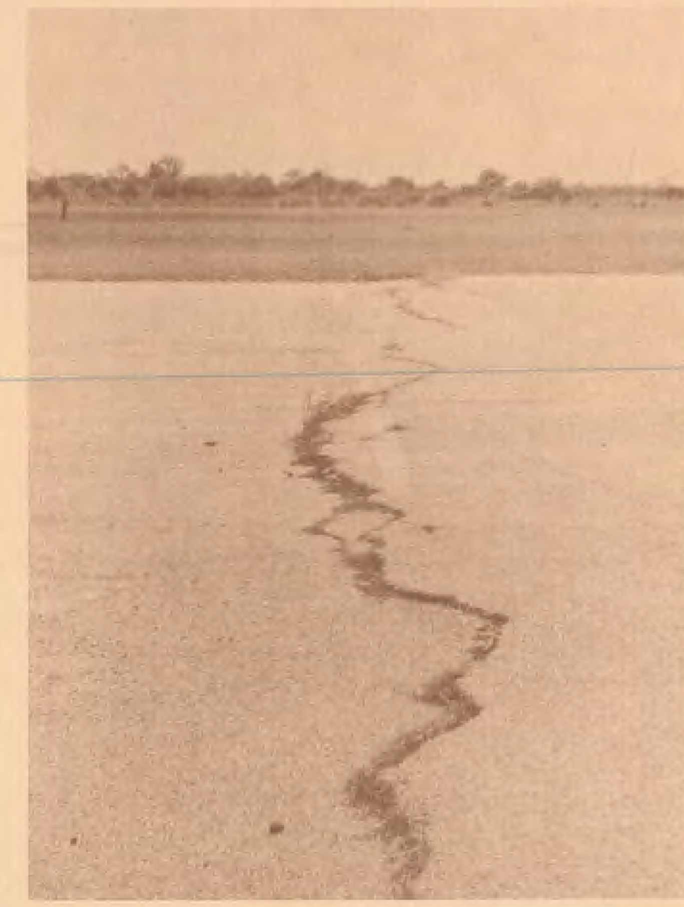
Distribution and Occurrence
Processes and Causes
Impacts
Mitigation and Reduction

1974

By
L. F. Brown, Jr.
Robert A. Morton
Joseph H. McGowen
Charles W. Kreitler
W. L. Fisher


SHORELINE EROSION


SUBSIDENCE


FAULTING


STREAM FLOODING

HURRICANE FLOODING


HURRICANE WINDS

● NATURAL HAZARDS OF THE ● TEXAS COASTAL ZONE

SYNOPSIS

The Texas Coastal Zone is a dynamic and changing natural environment. It is also the home of a fourth of the State's population and the site of a third of the State's industry. Accordingly, many natural processes become natural hazards by posing threats to both life and property. The principal natural hazards in the Texas Coastal Zone are (1) hurricanes, (2) flooding, (3) shoreline erosion, (4) land-surface subsidence, and (5) faulting. This atlas, "Natural Hazards of the Texas Coastal Zone," is composed of a series of Natural Hazards Maps and a text describing hazard distribution and occurrence, processes and causes, impacts, mitigation, and reduction. Most hazard-prone elements and areas are based on observed, historically documented information. They are hazards that have occurred or are currently active.

HURRICANES

Because of meteorological conditions, most hurricanes (winds greater than 74 miles per hour) strike Texas during August; lesser tropical storms are also common during summer months. A total of 27 hurricanes have struck Texas since 1900. Hurricane approach and landfall may change the shoreline significantly and may damage or destroy man-made structures. Large, steep waves riding the crest of a storm surge will erode beaches, dunes, and cliffed bay shores, and may destroy inadequately designed structures. Maximum hurricane winds and tidal surge are concentrated a few miles to the right of the hurricane eye. Tidal surge breaches barrier islands and peninsulas and extensively erodes and floods low-lying coastal areas.

Hurricanes *Carla*, *Beulah*, and *Celia* serve as examples of storms that are characterized by intensive storm surge, rainfall, and wind, respectively. The effects of these storms provide data for evaluating the potential impact of future hurricanes that strike the Texas Coast. The destructiveness of a hurricane depends also upon the population density and the degree of development at the point of landfall. Hurricanes *Carla*, *Beulah*, and *Celia* inflicted (according to the U. S. Army Corps of Engineers) \$408,290,000, \$145,544,000, and \$467,311,000 damage to the Coastal Zone, respectively. A total of 60 people died as a result of these three Texas storms.

FLOODING

Storm-surge flooding and aftermath-rainfall flooding and ponding are the most destructive aspects of hurricanes. Storm-surge tides of 10 feet above mean sea level have occurred repeatedly this century; high storm-tide levels up to 22 feet have been recorded in restricted, shallow bays. The physical character of the Texas Coast—barrier islands, lagoons, bays, headlands, peninsulas, and narrow funnel-shaped bays—contributes significantly to the degree of tidal flooding that will occur under various storm conditions. Heavy rainfall that accompanies and follows hurricane passage causes streams on the coastal plain to flood extensively; low, depressed areas are also flooded by ponded waters. Frontal-related storms produce extensive flooding on the coastal plain.

Data on areas of flooding by Hurricanes *Carla* and *Beulah*, provided by the U. S. Army Corps of Engineers, are used to delineate flood-prone areas. Areas of *Beulah* rainfall flooding and ponding provide an historic record of potential fresh-water flooding along the southwestern Texas Coast. Geologic/geomorphic interpretation of floodplains defines flood-prone areas along the northeastern coastal plain. Approximately 3,164 square miles were flooded by Hurricanes *Carla* and/or *Beulah*, and 2,187 square miles of the southwestern Coastal Zone were flooded by *Beulah* rainfall. At least 2,073 square miles along the northeastern coastal plain are flood prone.

Mitigation of hurricane destruction includes an array of engineering structures (dikes, seawalls) to prevent flood-surge damage. Natural defenses such as well-vegetated barrier islands and dense marshes and grassflats also provide protection from extensive erosion and damage from storm surges. Protection from hurricanes may, in some cases, be best accomplished by land-use planning. Flood-prone areas may be best suited for activities that will preclude extensive damage and loss of life.

SHORELINE EROSION

Texas shorelines are in a natural state of erosion, accretion, or equilibrium, or are stabilized artificially. Erosion produces a net loss in land, accretion produces a net gain in land, and equilibrium conditions produce no net change. Shorelines change in response to tides, storms, sediment supply, and relative sea-level changes. Long-term erosion during the past 74 to 132 years has subjected 46 linear miles (13 percent) of the Texas shoreline to severe erosion (greater than 10 feet per year), and 154 miles (42 percent) to moderate erosion (up to 10 feet per year). Short-term erosion during the past 7 to 23 years has subjected 153 linear miles (42 percent) of the Texas shoreline to severe erosion (greater than 10 feet per year), and 101 miles (28 percent) to moderate erosion (up to 10 feet per year).

Long-term shoreline change is commonly the net effect of a myriad of short-term variations. Short- and long-term changes are determined by historical monitoring of shoreline position using sequential maps and aerial photographs. Documentation of long-term erosion indicates a definite trend toward reduction of land area in the Texas Coastal Zone because the sediment budget of the Texas coastal system is trending toward a deficit in long-term supply. Sediment compaction, regional subsidence (tectonic), and worldwide (eustatic) sea-level rise are also long-term factors of consequence in shoreline stability.

A variety of man-made structures (seawalls, groins) have been constructed to protect some developed coastal areas from shoreline erosion. In some instances, such methods are both necessary and proper. The extensive use of artificial shorelines in Texas should be examined for the potential aggravating effect on shoreline stability and on the basis of cost.

LAND-SURFACE SUBSIDENCE

Land-surface subsidence, primarily as a consequence of ground-water pumping and withdrawal that began in Texas in the early part of this century, affects to varying degrees a substantial part of the Coastal Zone. The extent and amount of subsidence have been well defined by leveling surveys begun in 1905-06 by the National Geodetic Survey. Likewise, the cause of subsidence is well documented; since 1929, the U. S. Geological Survey has carried on extensive monitoring of water wells.

Subsidence and decline of water level and aquifer pressure are coextensive. Undercompacted, water-saturated clays are dewatered and, hence, irreversibly compacted, during and following the production of water from interstratified aquifer sands. Variations in the sand-clay ratios, as well as in clay compressibility, may result in regional differences in degree of potential subsidence.

By 1974, more than 1,300 square miles of coastal plain covered by this Atlas had undergone more than 1 foot of subsidence; 227 square miles had subsided more than 5 feet; and maximum land subsidence had reached 9 feet. Subsiding coastal areas yearly subject more and more land to potential impact by hurricane-tidal surge. Mitigation of the impact of subsidence will involve some modification of historic use of ground water, in volume, in well density, and in well spacing and location.

Although ground water is less costly than surface water, the offsetting cost of land loss and potential hurricane damage are also factors to be considered. A detailed analysis and mapping of both the geologic and hydrologic character of the coastal aquifer may permit delineation of preferred production areas and pumpage levels (or natural carrying capacity).

FAULTING

Additional active faults are being recognized yearly in the Houston metropolitan area of the Texas Coastal Zone. Active faults severely damage houses, apartments, and industry buildings; some streets and highways require continual repairs. Coastal plain faults move slowly, however, and are *not* accompanied by any recognizable seismic activity. Almost 100 miles of active faults have been recognized to date in the area covered by this atlas; in the future, other faults will certainly be recognized.

Faults in the region can be identified by breaks in structures, by linear topographic scarps, by sharp breaks in rates of subsidence on cumulative topographic profiles, and by aerial photographic tonal anomalies. These faults may be caused by variations in consolidation of sediments resulting from either (1) differential sand-clay compaction or differential ground-water withdrawal caused by the fault serving as a hydrologic barrier within the aquifer; and/or (2) by landslide-type failure resulting from seepage pressure.

The coincidence of active faults concentrated in areas of land subsidence and ground-water decline points empirically to subsidence as an important factor in the activation of many of the coastal plain faults. Some faults, however, were active before ground-water pumping began and these certainly were initiated by natural processes. If ground-water pumping is an important factor in current fault activation, faulting may be best controlled or reduced by planning controlled ground-water use. Recognition of known faults (or zones of potential faulting) can lead to avoidance and special engineering required to mitigate their impact on man-made structures.

CONCLUSIONS

The first step in mitigating the effects of natural hazards is adequate and comprehensive description of hazard-prone lands. This atlas, "Natural Hazards of the Texas Coastal Zone," is the first step in delineating these lands and in attempting to explain, with current knowledge, the processes leading to the hazard. Mitigation of natural hazards certainly must involve cost-to-benefit analysis to evaluate the economic and technological requirements and cost of hazard control.

● CONTENTS ●

FIGURES

MAPS

TABLES

CAPTIONS FOR COVER PHOTOGRAPHS

Shoreline erosion: Erosion of relict (Pleistocene) deltaic deposits along the western shoreline of Lavaca Bay, Texas. Principal erosion along bay shorelines occurs during hurricanes, tropical storms, and polar fronts (northers). Photograph by J. H. McGowen, 1971.

Subsidence: Flooding of low-lying area in the Brownwood subdivision, Baytown, Texas, as a result of land-surface subsidence. Subsidence causes Galveston Bay waters to inundate nearshore property. Photograph by C. W. Kreitler, 1974.

Faulting: Active faulting in the Greater Houston area results in damage to man-made structures such as this break in the parking lot at Ellington Air Force Base, Texas. Movement of the earth along such faults causes damage to many rigid structures. Photograph by C. W. Kreitler, 1974.

Stream flooding: High rainfall during and following the passage of Hurricane *Beulah* resulted in extensive stream flooding and ponding, such as this example from Falfurrias, Texas, a few miles west of the Kingsville map area. More than 30 inches of rain were reported from stations in South Texas. Photograph taken in September 1967, by U. S. Army Corps of Engineers (1968). Reproduced with the permission of the District Engineer, Galveston District, U. S. Army Corps of Engineers.

Hurricane flooding: Storm-surge tide moving along 21st Street in Galveston, Texas, during landfall of Hurricane *Carla*. A tidal-surge level of 9.3 feet (MSL) was recorded at the seawall in Galveston during this storm. Photograph by Houston Chronicle, September 1961. Reproduced with the permission of the Managing Editor, Houston Chronicle, Houston, Texas. From U. S. Army Corps of Engineers (1962).

Hurricane winds: Devastating winds in excess of 120 miles per hour struck the Corpus Christi area as the eye of Hurricane *Celia* made landfall near Port Aransas. Damaged home in Port Aransas is typical of devastation in the path of *Celia*. Photograph taken in August 1970, by U. S. Army Corps of Engineers (1971a). Reproduced with the permission of the District Engineer, Galveston District, U. S. Army Corps of Engineers.

NATURAL HAZARDS OF THE TEXAS COASTAL ZONE

L. F. Brown, Jr., Robert A. Morton, Joseph H. McGowen, Charles W. Kreitler, and W. L. Fisher

● INTRODUCTION ●

GENERAL STATEMENT

The Texas Coastal Zone is marked by diversity in geography, resources, climate, and industry. It is richly endowed with extensive petroleum reserves, sulfur and salt, seaports, intracoastal waterways, mild climate, good water supplies, abundant wildlife, rich agricultural lands, commercial fishing resources, unusual recreational potential, and large tracts of uncrowded land. The Coastal Zone, as herein defined, is a vast area of about 18,000 square miles, including approximately 2,075 square miles of bays and estuaries, 367 miles of Gulf coastline, and 1,100 miles of bay, estuary, and lagoon shoreline (table 1). About a quarter of the State's population and a third of its economic resources are concentrated in the Coastal Zone, an area including about 6 percent of the total area of the State.

Table 1. Statistical information for the area covered by the Natural Hazards Maps. All data by Texas Bureau of Economic Geology, except areas of Hurricanes *Carla* and *Beulah* salt-water flooding and areas of *Beulah* rainfall flooding. After U. S. Army Corps of Engineers (1962, 1968).

Number of hurricane landfalls, 1900-1972	27
Area (square miles) of salt-water flooding, Hurricanes *Carla* and *Beulah*	3,164
Area (square miles) of fresh-water flooding, Hurricane *Beulah*	2,187
Area (square miles) of fresh-water flooding by hurricane rainfall (floodplains), northern part of Coastal Zone only	2,073
Area (square miles) below elevation of 20 feet (MSL): subject to salt-water flooding by tidal surge	5,787
Number of active or potential hurricane washover channels	137
Number of miles of Gulf beach erosion: greater than 10 feet per year (long term)	47
Number of miles of Gulf beach erosion: from 5 to 10 feet per year (long term)	50
Number of miles of Gulf beach erosion: from 0 to 5 feet per year (long term)	104
Number of miles of bay and lagoon shoreline erosion	408
Area (square miles) of land subsidence: greater than 5 feet	227
Area (square miles) of land subsidence: from 1 to 5 feet	1,080
Area (square miles) of land subsidence: from 0.2 to 1 foot	5,422
Number of miles of known active surface faults	96
Number of miles of Gulf shoreline	367
Number of miles of bay-lagoon shoreline	1,100
Area (square miles) of bays and lagoons	2,075
Area (square miles) of land in map area	18,000

The Texas shoreline is characterized by interconnecting natural waterways, restricted bays, lagoons, and estuaries, low to moderate fresh-water inflow, long and narrow barrier islands, and extremely low astronomical tidal range. Combined with these natural coastal environments are bayside and intrabay oil fields, bayside refineries and petrochemical plants, dredged intracoastal canals and channels, and satellite industries. Exploration and development of offshore oil and gas resources are also under way.

The Texas Coastal Zone has become an attractive area for industrialization, urbanization, and recreational development. The zone is characterized by a variety of dynamic natural physical, biological, and chemical processes. Of critical concern to Texans, however, are those natural processes which constitute hazards, both to property and life in the Texas Coastal Zone. This atlas is dedicated to a better understanding of these natural hazards, their processes, impact, and possible mitigation.

Texas is subjected to a diversity of natural hazards, most of which impact upon the dynamic Coastal Zone and immediately adjacent inland areas. Principal among these natural hazards are (1) shoreline erosion, (2) land-surface subsidence, especially in the upper Coastal Zone, (3) frequent and damaging hurricanes, (4) flooding from streams and hurricane-tidal surges, and (5) active surface faulting. Each of these hazards results in substantial physical and monetary losses; hazards such as flooding and hurricane impact also have resulted in the loss of many lives. In addition, the areal extent of certain of the hazards, such as subsidence and active faulting, is increasing in size each year. In all cases, more extensive development in the Coastal Zone means that there will be greater impact from natural hazards in the future unless adequate mitigation is undertaken.

The most effective and, in some cases, the only mitigation of natural hazards and resulting damage is to avoid certain uses of hazard-prone lands. Mitigation by selected use requires, however, that the extent, frequency, and impact of natural hazards be known. The basic goal of this atlas, "Natural Hazards of the Texas Coastal Zone," is identification of the principal natural hazards of the Coastal Zone (fig. 1), delineation of hazard occurrence and distribution, recognition of the natural and man-induced causes of these hazards, and evaluation of measures that may lead to mitigation of hazard impact.

The Bureau of Economic Geology, The University of Texas at Austin, has conducted a variety of research programs in the Texas Coastal Zone. The primary program has been the preparation of an extensive "Environmental Geologic Atlas of the Texas Coastal Zone." The Environmental Geologic Atlas is a series of seven individual atlases designed to provide a comprehensive inventory of the land, water, and natural resources of the Texas Coastal Zone. Further, the 63d Legislature of the State of Texas, through a special line appropriation, directed the Bureau of Economic Geology to conduct a program involving the historical monitoring of the Texas Gulf shoreline. By mapping the shoreline position at selected historical intervals using available, controlled aerial photographs and coastal charts, along with surveyed beach profiles, the historical rate of change of the Gulf shoreline and related natural features has been determined. Recognition of the major natural hazards of the Coastal Zone and consequent impact was an outgrowth of these investigations of shoreline change, as well as the result of mapping and analysis as a part of the "Environmental Geologic Atlas of the Texas Coastal Zone." Various natural hazards in the Texas Coastal Zone have been evaluated in a number of reports already published or currently in preparation. This report is intended primarily to summarize in a general way the current knowledge of the distribution, nature, and impact of these natural coastal hazards.

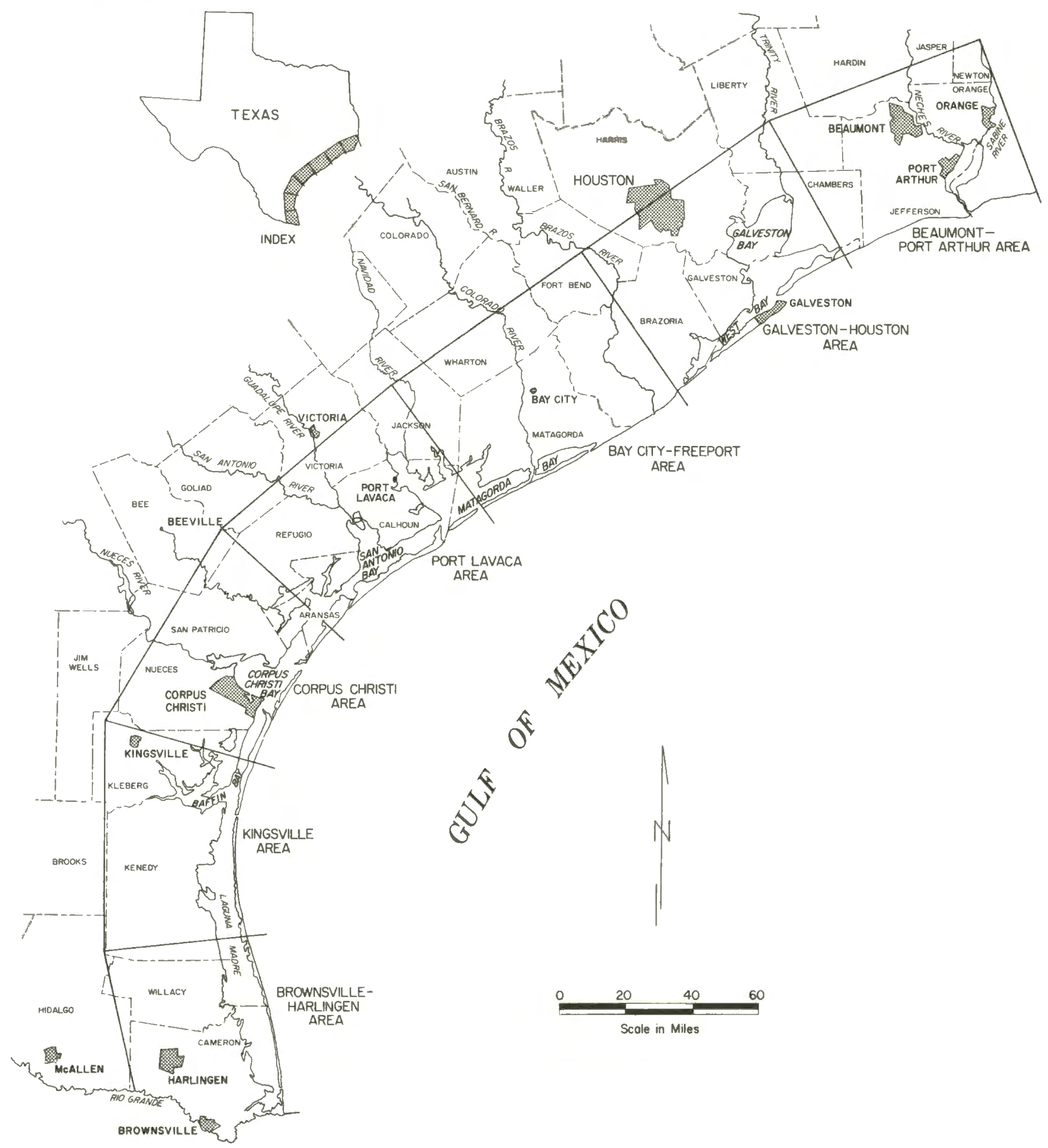


Figure 1. Index of Natural Hazards Maps of the Texas Coastal Zone.

NATURAL HAZARDS AND LAND USE

The subject of land use, and especially any consideration of land-use management, is complex. In the case of lands subjected to hazardous coastal processes, however, the application of any measures, whether voluntary or obligatory, structural or nonstructural, that lead to the reduction and mitigation of damage caused by these natural hazards, is beneficial. Nevertheless, a number of problems are involved in proper mitigation. First, an adequate effort must be expended in delineating hazard-prone lands and in determining the economic impact of selected use of hazard-prone lands. Second, the economic incentive for mitigation is largely negative; it is unlike the positive incentives for the effective management of agricultural lands. Finally, the kinds of cost-to-benefit ratios involved for various, specific uses of hazard-prone lands must be determined. In some cases, damages and losses sustained in utilizing certain hazard-prone lands may be offset by significant economic gain. For example, the agricultural use of floodplains may result in periodic crop damage and loss by flooding, but the overall high yield from these fertile lands justifies their continued use. Clearly, a different cost-to-benefit ratio exists in the use of floodplains for residential development. In another example, the use of ground water in the Coastal Zone results in substantial annual savings over the cost of transport and treatment of surface water. The withdrawal of ground water, however, causes subsidence and some associated problems which result in property damage and land loss. Natural hazards and measures for reduction of losses should be considered logically in the context of both costs and benefits for specific uses of hazard-prone lands.

NATURAL HAZARDS OF THE TEXAS COASTAL ZONE

Natural hazards in the Texas Coastal Zone and immediately adjacent land areas can be classified into two general categories. Some of these hazards are dynamic, relatively *short-term* events, such as hurricanes and flooding; the more obvious impacts are known, even if not always fully respected. Other hazards, such as shoreline erosion, land-surface subsidence, and active surface faulting, are relatively *long-term* processes; they are commonly less dramatic and, for the most part, are neither widely recognized nor appreciated.

In this atlas, natural hazards are discussed in terms of distribution and occurrence, processes and causes, impacts, and mitigation and reduction. This text, as well as the figures and tables, is intended to provide a perspective which will enable the reader to better understand and interpret the maps of the atlas. Inclusion of areas of coastal hazards, except for the flood-prone areas of the upper Texas Coastal Zone, is based on actual, recent occurrences that have been observed, monitored, or measured. The hazards are defined on the basis of data available in 1974; additional information in the future certainly may permit improvement of the accuracy of the maps.

The seven maps of the atlas (fig. 1) each contain a descriptive legend, as well as other conventional map symbols. The base map was constructed from 350 U. S. Geological Survey 7.5-minute quadrangle maps by the cartography section of the Bureau of Economic Geology. The scale of the maps is 1:250,000 or 4 miles per inch. Sources of map data, as well as credits, are listed in the legend of each map and are further documented in the following text. Although this atlas is the collective product of the listed writers, each individual writer assumed principal responsibility for preparation of one or more sections: Introduction and Conclusions—W. L. Fisher and L. F. Brown, Jr.; Hurricanes—J. H. McGowen; Flooding—L. F. Brown, Jr.; Shoreline Erosion—R. A. Morton; Land-Surface Subsidence—W. L. Fisher; and Faulting—C. W. Kreitler.

Information and data for several of the natural hazards reported herein are available in more detailed form and on more detailed base maps; these sources are cited in this report. In addition, more detailed information on shoreline erosion exists on work maps on file at the Bureau of Economic Geology.

ACKNOWLEDGMENTS

Many staff members of the Bureau of Economic Geology contributed to the preparation of this report. Cartographic preparation of the maps was by R. L. Dillon, Barbara Hartmann, and D. F. Scranton under the direction of J. W. Macon, chief cartographer. Research assistance was provided by the following staff members: M. Amdurer, J. L. Brewton, C. L. Burton, A. C. Funk, M. K. Pieper, and P. M. Walters. The manuscript was typed by Sharon E. Polensky and Jamie L. Tillerson. The report was edited by Kelley Kennedy, Elizabeth T. Moore, Leslie Jones, and Karen M. White. Camera-ready copy was prepared by Fannie M. Sellingsloh and Dawn M. Weiler.

The manuscript was reviewed by E. G. Wermund and M. K. Pieper, Bureau of Economic Geology; R. O. Kehle, Department of Geological Sciences, The University of Texas at Austin; and J. C. Moseley, Executive Director, Texas Coastal and Marine Council.

● HURRICANES ●

GENERAL STATEMENT

Hurricane approach and landfall may drastically change the shoreline and damage or destroy man-made structures. Large, steep waves riding the crest of a storm surge erode beaches, dunes, and cliffed bay shores and destroy inadequately designed buildings. The storm surge inundates low-lying areas along Gulf and mainland shorelines with salt water, and severe storm-surge flooding may destroy large areas of natural vegetation and agricultural crops. Fresh-water flooding produced by torrential hurricane rainfall may be particularly destructive along natural drainage systems. Hurricane winds may damage or destroy man-made structures, with mobile homes particularly vulnerable to wind damage. Because of the direct and pervasive relationship of hurricanes and many natural coastal hazards, an understanding of hurricanes is important.

DEVELOPMENT OF TROPICAL CYCLONES

A hurricane is a storm of tropical origin with a cyclonic wind circulation of 74 miles per hour or higher (Dunn and Miller, 1964). The cyclonic atmospheric system is characterized by decreasing barometric pressure toward the center and by surface winds. In the northern hemisphere, these surface winds spiral counterclockwise upward, lifting the air and eventually producing clouds and precipitation.

The hurricane is the devastating end member of the tropical cyclone class of storms. The classification that is commonly used in the Atlantic region (table 2) is as follows: (1) *tropical disturbance*—rotary circulation slight or absent on the surface; no closed isobars (contours of equal pressure) or strong winds; common throughout the tropics; (2) *tropical depression*—one or more closed isobars; wind equal to or less than Beaufort 7; (3) *tropical storm*—closed isobars; wind greater than Beaufort 7 but less than 12; and (4) *hurricane*—wind force of Beaufort 12, or 74 mph or greater.

Table 2. Beaufort scale of wind force. After Dunn and Miller (1964).

Beaufort No.	MPH	Knots	U. S. Weather Bureau Classification
0	1	1	
1	1-3	1-3	Light
2	4-7	4-6	
3	8-12	7-10	Gentle
4	13-18	11-16	Moderate
5	19-24	17-21	Fresh
6	25-31	22-27	Strong
7	32-38	28-33	
8	39-46	34-40	Gale
9	47-54	41-47	
10	55-63	48-55	Whole Gale
11	64-73	56-63	
12	74 or >74	64 or >64	Hurricane

The precise details of physical processes that produce hurricanes are not well understood. It is known, nevertheless, that the mechanism producing hurricanes must supply (1) low-level atmospheric convergence of sufficient strength to lift the moist layer; (2) high-level atmospheric divergence to remove accumulated air and yield a pressure drop at the surface; and (3) energy to maintain the atmospheric circulation.

Conditions favorable for tropical cyclone development exist in the North Atlantic Ocean, the Caribbean Sea, and the Gulf of Mexico from June through October (fig. 2). Tropical storms and hurricanes that strike the Texas Coast occur most frequently in August and September (fig. 3). The mean storm track and the area of most frequent origin change from month to month during the hurricane season. Storms spawned at a particular time and place have a preferred landfall area (Dunn and Miller, 1964). The most frequent landfall area for storms that develop in the northwestern Caribbean or the Gulf of Mexico in June is the Texas Coast. The Texas Coast is rarely struck by hurricanes after the middle of September.

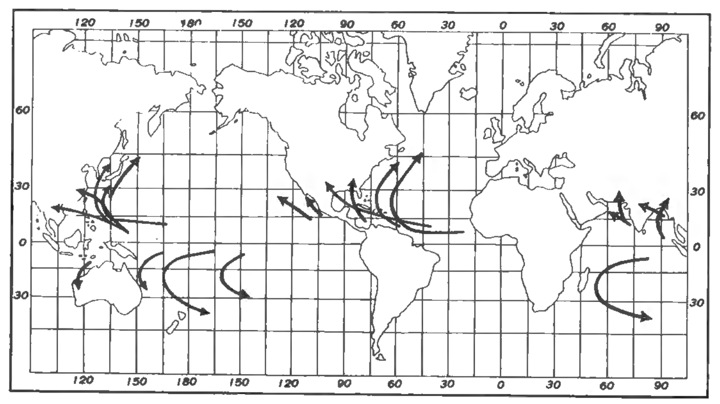


Figure 2. Areas of tropical cyclone development. After Dunn and Miller (1964).

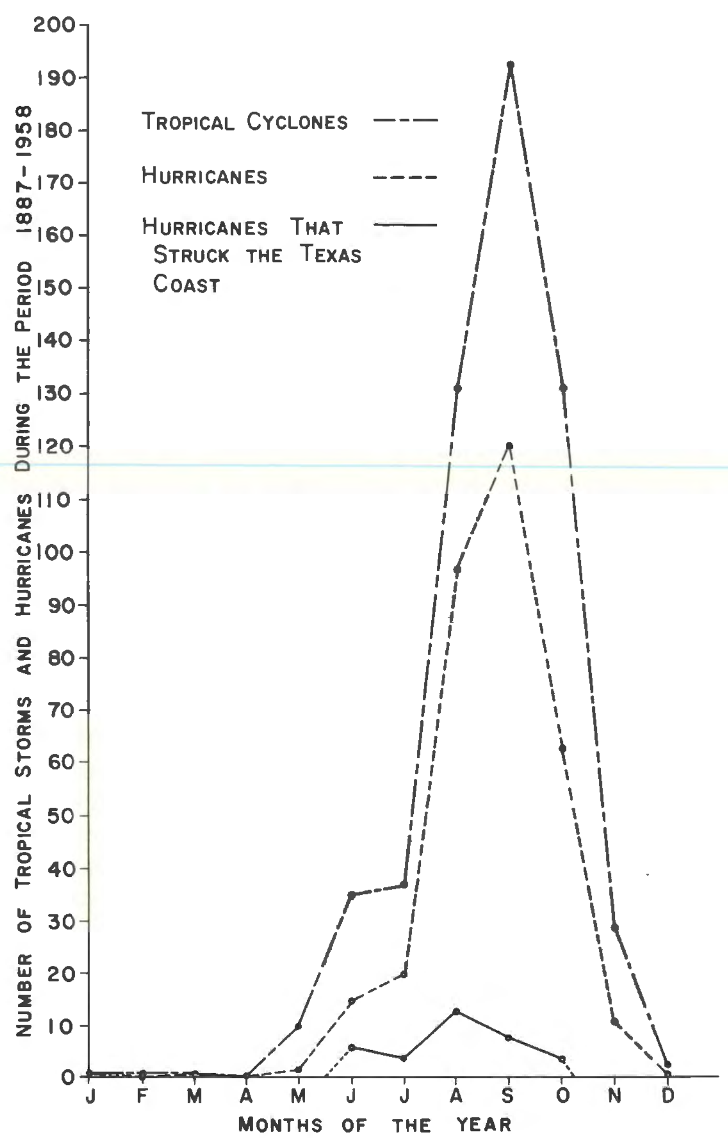


Figure 3. Frequency of Atlantic tropical cyclones and hurricanes and the number of hurricanes that struck the Texas Coast between 1887 and 1958. Data from Dunn and Miller (1964).

Atmospheric conditions or elements that directly or indirectly contribute to the formation of tropical cyclones are (1) the Azores-Bermuda High, (2) easterly waves, (3) the Intertropical Convergence Zone, and (4) polar troughs. The Azores-Bermuda High is a large anticyclone extending from the Iberian Peninsula to the southeastern United States (fig. 4). It is the dominant atmospheric system for the Atlantic during summer and early fall when the High oscillates from north to south (Dunn and Miller, 1964). Persistent departures from normal position have a significant effect on hurricane frequency and paths. The easterly wave is a low-pressure trough which is imbedded in the easterly current lying south of the Azores-Bermuda High. A stable wave may move from east to west as much as 3,000 miles without any change. Deviation from the norm indicates that the wave is developing a hurricane vortex. The Intertropical Convergence Zone is the area where winds from the North and South Atlantic converge. When the ICZ moves north or south of the equator, the Earth's rotation imparts a spin to converging currents, thereby developing tropical cyclones. In the North Atlantic this occurs near Cape Verde. A polar trough is a low-pressure zone which migrates from west to east within the prevailing westerlies. The westerlies lie north of the Azores-Bermuda High. When the polar trough is very strong or when the Azores-Bermuda High is weak, the trough may penetrate the tropics. Its influence on the development of tropical cyclones is greatest either early or late in the hurricane season.

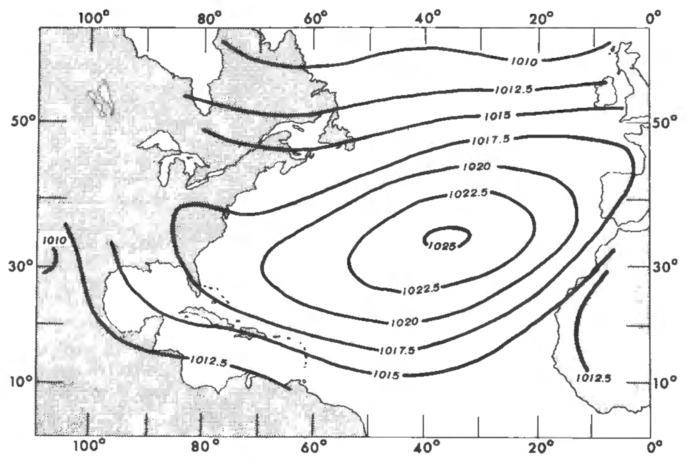


Figure 4. Mean position of the Azores-Bermuda High during the month of August. Mean sea-level pressure in millibars. After Dunn and Miller (1964).

A hurricane runs on heat. Its formation and maintenance depend upon energy derived from the ocean surface. Hurricanes form over comparatively warm water with a temperature above 79°F. Warm moist air moves across the ocean surface spiraling inward into the hurricane circulation. As it rises to higher elevations, it expands under reduced pressure. When the air becomes saturated, moisture condenses and releases heat to the surrounding atmosphere. Energy is partly dissipated in the upper anticyclonic flow by surface and internal friction.

CHARACTERISTICS OF HURRICANES

The principal features of a hurricane are (1) the eye, surrounded by convective clouds; (2) low-level cyclonic winds; (3) upper level anticyclonic winds; and (4) a vertical circulation system in which air flows into the eye at low levels, flowing upward within the convective clouds, outward in the upper levels, and downward in the outer parts of the storm (fig. 5).

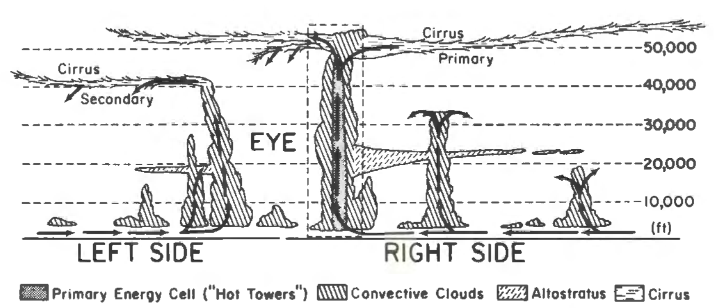


Figure 5. Hurricane model. The primary energy cell (convective chimney) is located in the area enclosed by the broken line. After Carr (1967).

The eye of the hurricane is a low-pressure area where wind velocities are only 10 to 20 mph. The eye may be relatively small, only 4 miles in diameter, or large, up to 25 miles in diameter. Average diameter is about 14 miles (Dunn and Miller, 1964).

Air flows from high-pressure areas toward the low-pressure storm center. The pressure differential results primarily from temperature differences. Strongest hurricane winds are near the storm center because this is the area with the steepest pressure gradient (fig. 6). Lower level winds have sustained velocities ranging from 74 to 200 mph; the velocity of gusts may exceed sustained winds by 30 to 50 percent. Winds are stronger on the right side of the hurricane eye (fig. 5) because the forward motion of the storm is added to the rotational wind velocities.

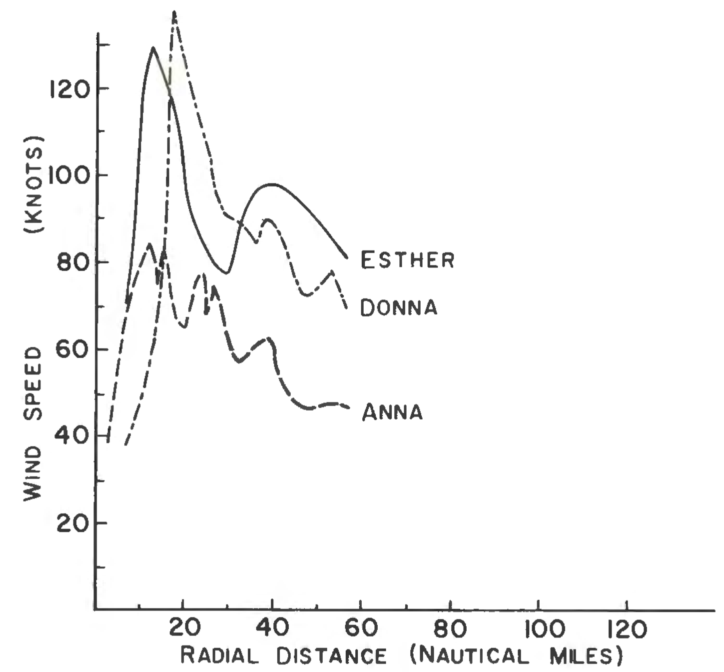


Figure 6. Wind profiles in Hurricanes *Donna*, 1960, *Esther*, 1961, and *Anna*, 1961. After Colón (1966).

Hurricane size is commonly expressed in terms of diameter of hurricane and gale winds or by diameter of the outer closed isobar. Average diameters of hurricane and gale winds are about 100 and 400 miles, respectively. There is a wide range in the size of hurricanes. The Great Atlantic Hurricane of 1944 had hurricane winds with a diameter of 600 miles (Dunn and Miller, 1964). Hurricane *Carla*, in 1961, had hurricane-force winds with a diameter of about 300 miles (Colón, 1966; Hayes, 1967), and in 1970, *Celia's* hurricane wind diameter was about 80 miles.

Table 3. Hurricane classification. After Dunn and Miller (1964).

Classification	Maximum winds (mph)	Minimum central pressure (inches Hg)
Minor	Less than 74	More than 29.40
Minimal	74 to 100	29.03 to 29.40
Major	101 to 135	28.01 to 29.00
Extreme	136 and higher	28.00 or less

Hurricane size and intensity are not directly related. The most intense hurricanes are not necessarily the largest; for example, the diameter of cyclonic circulation tends to increase during the decaying stage (Colón, 1966). Low barometric pressure and relatively high wind velocity are common to all tropical disturbances (table 3), and these parameters are more suitable for classifying hurricanes (Dunn and Miller, 1964).

Average life of a hurricane, determined by time and place of origin and rate of forward movement, is about nine days. Most hurricanes move forward at a rate of about 12 mph. The forward speed of hurricanes that have struck the Texas Coast in August and September has averaged 8 to 12 mph. Hurricanes that struck the Texas Coast between 1900 and 1972 exhibit a wide variety of characteristics (table 4).

Table 4. The nature of hurricanes striking the Texas Coast between 1900 and 1972. Dash indicates that data are unavailable. Data from National Oceanic and Atmospheric Administration—National Hurricane Center (1900-1974). Note that data do not necessarily agree with that provided by U. S. Army Corps of Engineers (1962, 1968, 1971a).

Hurricane	Date & location of landfall	Approach speed	Wind velocity maximum	Pressure at eye	Storm surge height	Dollar value of damage	Deaths
1900 Not named	Sept. 8 Galveston	10 mph	125 mph	27.64"	20' Galveston	$30,000,000	6,000
1909 Not named	July 21 Velasco	12 mph	120 mph	29.00"	10' Galveston	$2,000,000	41
1910 Not named	Sept. 14 Padre Island (south)	–	120 mph	–	–	minimal	–
1912 Not named	Oct. 15 Mustang Island	–	100 mph	–	–	$28,000	–
1913 Not named	June 27 Padre Island (central)	–	100 mph	–	12.7' Galveston	–	–
1915 Not named	Aug. 17 Freeport	11 mph	120 mph	28.06"	16' Galveston Causeway	$50,000,000	275
1916 Not named	Aug. 18 Padre Island (north)	11 mph	130 mph	28.00"	9.2' Central Padre	$1,800,000	20
1919 Not named	Sept. 14 Corpus Christi	10 mph	120 mph	27.99"	16' Corpus	$20,270,000	300 600
1921 Not named	June 22 Port O'Connor	–	110 mph	–	7.1' Pass Cavallo	minimal	–
1929 Not named	June 28 Port O'Connor	17 mph	90 mph	28.62"	3' Port O'Connor	$675,000	3
1932 Not named	Aug. 13 Freeport	17 mph	110 mph	27.83"	6.1' Freeport	$7,500,000	40
1933 Not named	Sept. 4-5 Brownsville	8 mph	100 mph	28.02"	13' Brownsville	$12,000,000	40
1934 Not named	July 25 Rockport	–	70 mph	–	10.2' St. Joseph Island	$4,500,000	11
1936 Not named	June 27 Port Aransas	–	80 mph	–		$550,000	–
1940 Not named	Aug. 7 Port Arthur	8 mph	80 mph	28.87"	2.1' Sabine Pass, High Island	$1,750,000	–
1941 Not named	Sept. 23 Freeport	13 mph	90 mph	28.31"	9.9' Sargent	$6,000,000	4
1942 Not named	Aug. 22 Gilchrist	–	72 mph	29.35"	7' High Island	$601,000	0
1942 Not named	Aug. 29-30 Matagorda Bay	14 mph	110 mph	28.10"	14.7' Matagorda	$26,500,000	8
1943 Not named	July 27 Port Bolivar	9 mph	100 mph	28.78"	3' Port Bolivar	$16,550,000	19
1945 Not named	Aug. 27 Matagorda Bay	4 mph	130 mph	28.57"	15' Port Lavaca	$20,133,000	3
1947 Not named	Aug. 24 Galveston	–	80 mph	29.30"	3.6' Sabine Pass	$200,000	1
1949 Not named	Oct. 3 Freeport	13 mph	135 mph	28.88"	11.0' Freeport	$6,700,000 mainly crops	2
1959 Debra	July 25 Galveston	6 mph	80 mph	29.07"	2.8' Galveston	$7,000,000	0
1961 Carla	Sept. 11 Port O'Connor	6 mph	150 mph	27.49"	22' Port Lavaca	$408,000,000	46
1963 Cindy	Sept. 17 High Island	8 mph	60 mph	29.41"	4.2' High Island	$11,700,000 incl. Louisiana	3
1967 Beulah	Sept. 20 E. of Brownsville	8 mph	140 mph	27.98"	12' Port Isabel	$200,000,000	15
1970 Celia	Aug. 3 Corpus Christi	–	130 mph	27.80"	9.2' Port Aransas	$453,000,000	11
1971 Fern	Sept. 10 Between Freeport and Matagorda	–	78 mph	29.04"	6' Freeport	$30,000,000	2

RELATED STORM EFFECTS

Hurricanes produce striking changes in the sea; huge waves and storm tides are generated. Hurricanes also trigger heavy rainfall, create high-velocity winds, and spawn tornadoes. As the storm approaches and makes landfall, each of these related phenomena becomes increasingly more important because hurricanes have the potential to alter the shoreline by erosion or deposition, to flood low-lying areas, and to damage or destroy man-made structures.

Changes in Water Level

A slow rise in water level occurs when oceanic swells generated by a distant storm approach the coast. This rise in water level is known as the *forerunner*. A rise in water level of 3 to 4 feet, produced by the forerunner, can affect several hundred miles of coast (Dunn and Miller, 1964). *Storm surge*, on the other hand, is a rapid rise in water level generated by onshore hurricane winds and decreasing barometric pressure. Maximum storm surge generally occurs 10 to 20 miles to the right of the storm track, but it may occur to the left of the storm if counterclockwise north winds stack water against an obstruction, such as the back side of a barrier island.

Maximum surge height is commonly associated with a storm which has a track perpendicular to the shoreline. It is also greatest along coasts, such as the Texas Gulf Coast, that are concave and adjacent to wide, gently sloping shelves. If the hurricane landfall coincides with the astronomical high tide, surge height will be even greater.

The rare "hurricane wave" or seiche has caused some of the world's greatest natural disasters (Dunn and Miller, 1964). It may result from resonance that produces a huge wave, or it may be a rapidly rising and abnormally high storm surge. The hurricane that struck Galveston on 8 September 1900 may have been accompanied by such a hurricane wave. During the Galveston storm, water level rose steadily from 3:00 to 7:30 p.m., at which time there was an abrupt rise of about 4 feet in as many seconds (Dunn and Miller, 1964).

Development of Washover (Breach) Channels

One of the principal effects of the storm surge is the development of washover channels that breach barrier islands or peninsulas. These channels readily develop at the sites of eolian erosion (blowouts) or in areas with poorly developed fore-island dune ridges and beach ridges. Tidal waters flow landward through the channels, scouring sand and depositing the sediment in washover fans within the adjacent bay or lagoon. Following passage of the hurricane, the channels serve to return the elevated waters of the bays and lagoons to the open Gulf. The surge channels are active only during the brief period of hurricane approach, landfall, and immediate aftermath; storms tend to reactivate the same washover channels. Marine shoreline processes close the gulfward end of the channel within a few days. Water may stand in the abandoned channel for months following the storm.

In general, the density of washover channels increases southwestward along the Texas Coast. This regional increase in channels results principally from the southwestward decrease in vegetational stability of barrier islands and fore-island dunes. A total of 137 washover channel sites have been recognized and are shown on the Natural Hazards Maps. The location of these sites is based on interpretation of aerial photographs, low-level aerial reconnaissance, and field work undertaken as part of the "Environmental Geologic Atlas of the Texas Coastal Zone." Construction within or immediately adjacent to hurricane breach or surge channels may lead to property damage in the event of a hurricane landfall.

Waves

Principal damage to man-made structures and severe erosion of shorelines are produced by storm waves superimposed on the storm surge. The power generated by a breaking wave can be visualized by considering that a cubic yard of water weighs about 1,500 pounds and that waves may be moving at a velocity of about 70 to 80 feet per second. Breaking waves alone can destroy many buildings, but their destructive potential is significantly increased by tree trunks, pilings, and other debris that act as battering rams. Appropriately designed structures, nevertheless, can withstand flooding associated with the forerunner and storm surge.

The shoreline may retreat several hundred feet during a few hours when under attack by storm waves (Shepard, 1973; McGowen and Brewton, 1975). Between hurricanes, accretion may restore much of the shoreline lost during the storm.

Rainfall

Some of the greatest rainfalls recorded in Texas have resulted from hurricanes. Upon striking a landmass and moving inland, the forward movement of a hurricane is reduced, and the rate of rainfall increases. Maximum rainfall occurs in front of and along the right side of slowly moving tropical storms. Rainfall is equally distributed in the front and rear halves of storms whose forward motion has stalled.

Wind

Hurricane winds rank third behind waves and rainfall flooding in destructive potential. Width of the area of destructive winds may range from about 14 to 300 miles (Dunn and Miller, 1964). Wind velocities of 100 to 135 mph are common. Severe storms have velocities of 135 to 160 mph; the most violent hurricanes have wind velocities of 200 mph or greater. Damage to structures results from sudden pressure changes associated with gusts. Damage begins when pressure reaches approximately 15 to 20 pounds per square foot (wind velocity of about 60 mph).

The highest velocity winds associated with hurricanes are contained in tornadoes having estimated velocities of 400 to 500 mph. Tornadoes may occur at any time during and immediately following hurricane passage; their most frequent occurrence is in the forward half of the storm.

GENERALIZED HURRICANE MODEL

Historical records indicate that successive hurricanes may differ markedly (table 4). One hurricane may generate a large storm surge, another may be characterized by torrential rainfall, while exceptionally high wind velocities may define a third type. From these records and from previous studies, a general hurricane model (fig. 7) was developed (Price, 1956; Hayes, 1967; McGowen and others, 1970). The following is a description of a model hurricane as it approaches the Texas Coast, makes landfall, and moves inland.

Storm Approach

Storm approach (fig. 7B) is marked by rising tides (forerunners) and increased wind velocities. When the storm strikes the coast, the storm surge and associated waves erode the normal beach and foredunes to form a broad, flat hurricane beach. Storm-surge flooding often scours washover channels across barrier islands and peninsulas. Sediment is transported through the storm channels and is deposited on barrier flats and along bay margins as washover fans. Mainland shorelines receive muddy sediment that is derived from the bay bottom and carried ashore by storm-surge floods. Storm-surge tides are commonly higher in the bays than on the Gulf beaches, although the flooding and the effects of the accompanying waves are pronounced in both areas.

Landfall

At landfall (fig. 7C), when the storm passes over the shoreline, the direction of current movement and wave approach shifts into compliance with the change in wind direction. Highest intensity winds are felt as the storm comes ashore. On the left side of the storm, water and sediment are moved from the bays back into the Gulf through inlets and breaches in the island, while water and sediment are still being pushed into the bays on the right side. Waves strike the Gulf shoreline at a low angle as the back side of the storm passes, creating currents that transport sediment northeastward alongshore in the same manner that the front-edge winds and currents had moved materials toward the southwest.

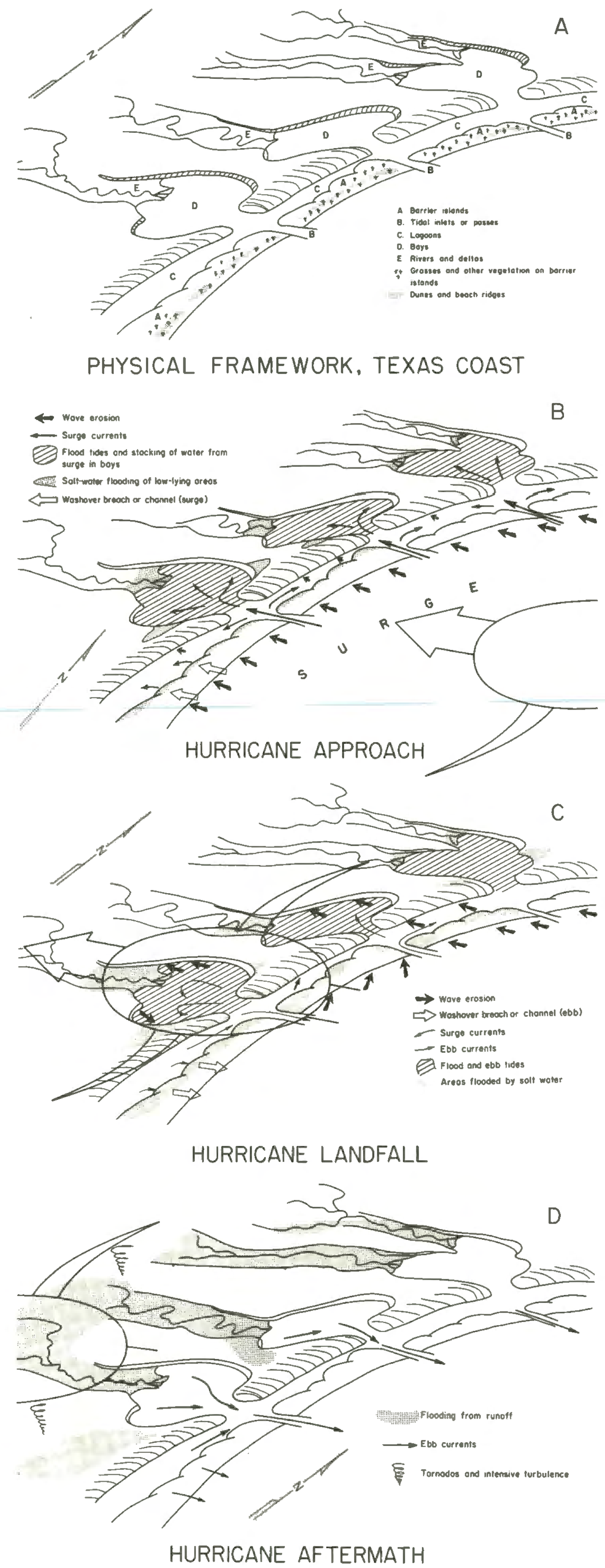


Figure 7. Schematic model of hurricane effects on the Texas coastline. (A) Physical features characterizing the Texas Coast, (B) Effect of approaching hurricanes, (C) Effect of hurricanes upon impact with coast, (D) Aftermath effects of hurricanes. After McGowen and others (1970).

Hurricane Aftermath

Hurricane aftermath (fig. 7D) is the period following passage of the storm inland from the coastal area. As the storm moves inland, it becomes weaker and more diffuse, and commonly spawns numerous tornadoes. Excessive water in the bays drains gulfward through storm breach channels and passes, depositing sediment within the channels and in the nearshore Gulf. Heavy rains that commonly accompany hurricanes produce runoff of flood proportion, inundating low-lying areas along stream courses and bay margins. The influence of strong winds and heavy rains may accompany the storm inland for considerable distances.

Longshore currents begin to build bars that eventually close off the mouths of hurricane channels, and waves begin to restore the normal beach profile. Hurricane deposits are reworked by subsequent rains and wind. Some of the sand that is exposed in breach channels is blown landward onto the barrier flat, and washover fans are reworked by bay and lagoon waves and currents.

TYPES OF HURRICANES

During the past 70 years, most coastal areas in Texas have experienced severe weather resulting from direct impact or nearby passage of a hurricane. No area, however, has experienced each of the hurricane types which can strike during the hurricane season. Using meteorological and hurricane data accumulated over the past several decades, it is possible to recognize at least three general kinds of hurricanes and to predict their impact on different parts of the Texas Coast (table 4). Predictability of hurricane effects is based on (1) bay-estuary shape, (2) Gulf shoreline configuration, (3) track of the hurricane relative to the coastline, (4) nature and distribution of physical and biological environments, and (5) population density. Three recent, well-documented hurricanes, *Carla*, *Beulah*, and *Celia*, illustrate the nature of hurricane variations (table 5; fig. 8). The reader should be aware that observations such as storm-surge elevation, hurricane wind velocity, and pressure values, may vary among observers. For this reason, the sources of the data are noted in this atlas; any inconsistencies in wind velocity or storm surge, for example, result from the use of several data sources.

Hurricane *Carla*

Hurricane *Carla* was spawned in the western Caribbean on or about 3 September 1961. She became a hurricane on 5 September and moved into the Gulf of Mexico between Cuba and the Yucatan Peninsula on 7 September (Hayes, 1967). *Carla* moved toward the Texas Coast at about 9 mph, making landfall (fig. 8) near Port O'Connor on 11 September (Port Lavaca map). Her travel time over the warm waters of the Caribbean and Gulf of Mexico was about nine days. Maximum sustained winds at landfall were about 175 mph, and pressure in the eye was about 931 millibars

Table 5. The characteristics of basic types of hurricanes striking the Texas Coastal Zone. After McGowen and others (1970).

Variables	*Beulah* type	*Carla* type	*Celia* type
Wind	Moderate	Moderate	High
Storm-surge tides	Moderate	High	Low
Rainfall	High	Moderate	Low
Size of destructive core	Medium	Large	Small
Length of aftermath effects	Extended	Intermediate	Brief
Character of coastline affected	Port Mansfield: poorly vegetated, low relief, broad unrestricted bay	Port O'Connor: well vegetated, local relief to 30 feet, funnel-like Lavaca Bay	Port Aransas: moderate vegetation, local relief to 30 feet, funnel-like Nueces Bay

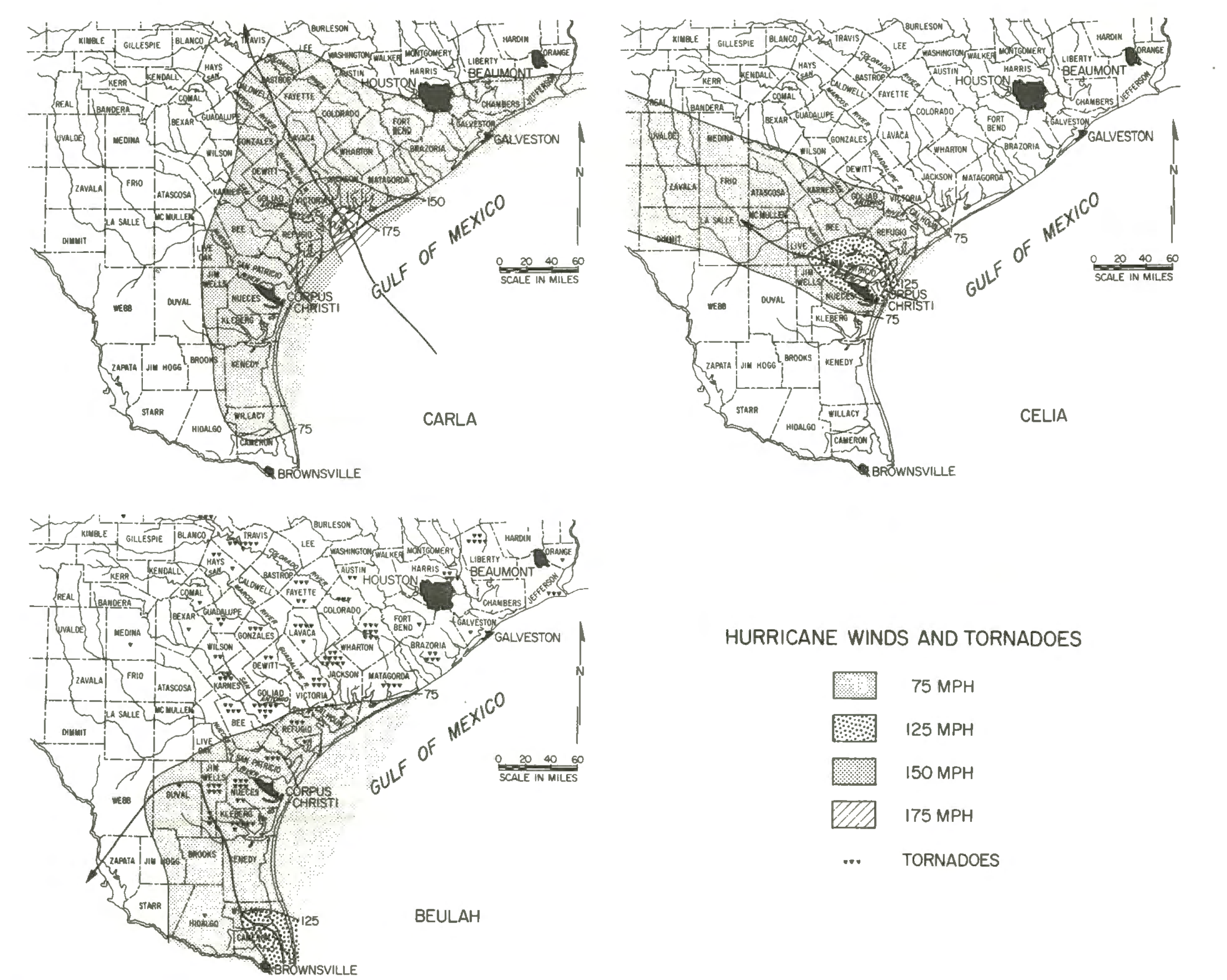


Figure 8. The track of the eyes of Hurricanes *Carla*, *Beulah*, and *Celia*, and the area covered by hurricane-level winds, Texas Coastal Zone. Based on data from Cooperman and Sumner (1961), Orton and Condon (1970), Orton (1970), and U. S. Army Corps of Engineers (1968). After Texas Coastal and Marine Council (1974).

(mb). The Galveston weather station was under effects of gale-force winds for 49 hours (Colón, 1966). Corpus Christi, only 50 to 60 miles from the storm center, experienced peak gusts of 85 mph and pressure of 977 mb. Hurricane wind diameter was approximately 300 miles (fig. 8). *Carla* was probably the largest Atlantic hurricane for which there are reliable data (Colón, 1966).

Carla was characterized by extensive storm-surge flooding (fig. 9) and severe shoreline erosion. Surge height in the Port O'Connor area was in excess of 10 feet above mean sea level (MSL), and at Port Lavaca, the surge reached a maximum of 22 feet above MSL (U. S. Army Corps of Engineers, 1962). Parts of Matagorda Peninsula were breached by storm channels, and shorelines were eroded as much as 800 feet (Shepard, 1973; McGowen and Brewton, 1975). Dunes on Mustang Island were eroded landward as much as 150 feet (Hayes, 1967).

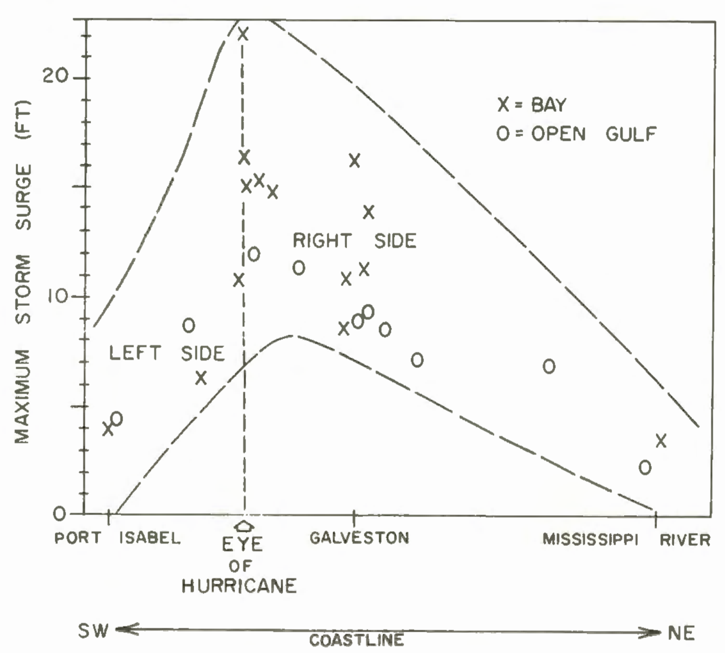


Figure 9. Maximum storm surge that occurred during Hurricane *Carla*, 1961, at 14 bay and 10 open Gulf localities along the northwest Gulf of Mexico. Note that the right side of *Carla* generated greater storm surge than the left side of the storm. Based on tide data collected by the U. S. Army Corps of Engineers, Galveston and New Orleans Districts, and presented by Cooperman and Sumner (1961) and Harris (1963). After Hayes (1967).

Carla's track across the Gulf of Mexico was northwestward. After landfall, her course curved to the northeast, and she crossed the United States and entered Canada in the Great Lakes area.

Hurricane *Beulah*

Hurricane *Beulah* was spawned in the Atlantic, becoming a hurricane on 7 September 1967 (Scott and others, 1969). She moved west-northwestward into the Caribbean, lost considerable energy in the mountains of Haiti, re-formed and assumed a more westerly course crossing the Yucatan Peninsula on 17 September. She made landfall (fig. 8) in Mexico, just south of Brownsville, on 20 September (Brownsville-Harlingen map). After becoming a hurricane, her travel time over the Caribbean Sea and Gulf of Mexico was 13 days. Maximum wind velocity at landfall was 125 to 160 mph. In Texas, winds of hurricane force extended from the Rio Grande northward approximately 250 miles (fig. 8). Storm surge was about 10 feet above MSL at Brazos Santiago, and tides were 6 to 7 feet between Port Mansfield and Port Aransas and 5 feet near Cedar Bayou (Behrens, 1969; Scott and others, 1969).

After making landfall, *Beulah* traveled north-northwestward inland into Duval County, changed her course to the southwest, and moved back into Mexico. The long path overland slowed the storm, resulting in heavy rainfall and the generation of at least 115 tornadoes (fig. 8). *Beulah* was characterized by exceptionally heavy rainfall; in some areas, rainfall was in excess of 30 inches during the four or five days of aftermath storms.

Hurricane *Celia*

Hurricane *Celia* was spawned in the Caribbean Sea near Cuba. A tropical squall struck the western part of Cuba on 31 July 1970. On the morning of 1 August, the disturbance became a tropical storm, and on the afternoon of 1 August, *Celia* became a hurricane (McGowen and others, 1970). *Celia's* course was west-northwest toward the Texas Coast, and her rate of forward movement was 10 to 15 mph. She made landfall at Port Aransas on 3 August (Corpus Christi map); her travel time over the Gulf of Mexico was only three days. At about the time she made landfall, the eye decreased in size by about 40 percent, and wind velocity increased from 90 to 130 mph with gusts of 160 to 180 mph. The width of *Celia's* destructive path was about 15 miles, and her hurricane winds had a diameter of about 80 miles (fig. 8). *Celia's* inland path was west-northwest to Del Rio where her progress became irregular. The storm expired in the mountains near Chihuahua, Mexico.

Celia was accompanied by high-velocity winds and a few tornadoes. Rainfall was minimal and storm surge was restricted to a very narrow zone. Maximum surge (determined from debris lines and, therefore, not indicative of still-water level) was about 9 feet along the Gulf shore near the Aransas Pass jetties, 12 to 14 feet along the bay shore at Aransas Pass, and up to 9 feet at Corpus Christi. Surge height in the North Pass and Corpus Christi Pass areas was only 4 feet. Hurricane *Celia* was characterized by her destructive winds; storm-surge flooding and rainfall were relatively insignificant.

FACTORS INFLUENCING SEVERITY OF HURRICANE IMPACT

The severity of hurricanes can be expressed in various terms, such as damage to man-made structures, monetary losses, and loss of human life. The nature of the storm, population density, and shoreline characteristics determine the number of lives lost, the extent of shoreline erosion, and damage to or destruction of man-made structures. The nature of the storm dictates whether storm surge, fresh-water flooding, or wind will be the dominant destructive element. The loss of human life and the amount of property damage is directly affected by population density. Shoreline characteristics will either amplify or diminish some of the hurricane processes.

Nature of the Storm

Three destructive elements are associated with hurricanes. In order of decreasing destructive potential, these are (1) storm surge and attendant breaking waves, (2) fresh-water flooding, and (3) wind. Assuming a common point of landfall, *Carla*-type hurricanes have the greatest destructive potential of the three basic hurricane types, *Beulah*-type storms rank second, and *Celia*-type storms are the least destructive. A *Celia*-type storm, nevertheless, can become highly destructive when it strikes a highly developed area (table 4).

Large, intense hurricanes, which create high storm-surge flooding with attendant wave erosion, can be expected when a storm moves slowly across the ocean without being impeded by landmasses en route to the Texas shoreline (*Carla*-type hurricane). The path that a hurricane takes after making landfall, the rate of forward movement, and the topography of the landmass over which it moves have an effect on rainfall rate, which dictates the magnitude of fresh-water flooding. A long route over the ocean by a slowly moving storm significantly increases the moisture content of the storm clouds. Slow forward movement overland, coupled with considerable topographic relief, is conducive to high rainfall rates (*Beulah*-type hurricane). A hurricane that is spawned in the Gulf of Mexico and travels rapidly across the open Gulf will most likely be accompanied by high-velocity wind, minimal rainfall, and minimal storm surge. These storms are generally small, but intense (*Celia*-type hurricane).

Shoreline Characteristics

The Texas Coast is characterized by an outer Gulf shoreline and an inner bay shoreline (fig. 7A). *Gulf shorelines* exhibit three principal morphological types: (1) deltaic headlands, (2) peninsulas, and (3) barrier islands. *Bay shores* consist of a variety of shoreline types; among these are (1) relatively high cliffs, (2) low-lying marshes, (3) bayhead deltas and river valleys, and (4) areally restricted sand and shell beaches. The shoreline type determines, in many instances, the extent of storm-surge flooding and wave erosion.

Deltaic headlands occur between Sabine Pass and Bolivar Peninsula, Follets Island and Brown Cedar Cut, and the Rio Grande and Brazos Santiago Pass. The two easternmost headlands (Beaumont-Port Arthur and Bay City-Freeport maps) are morphologically similar. Physiographic subdivisions of these two headlands include (1) forebeach, (2) erosional escarpment, and (3) shell apron or ramp (fig. 10). A shell ramp, which is about 5 to 7 feet above MSL, is commonly backed by marshes with attendant lakes and tidal creeks. These low-relief shoreline features are readily breached by storm surge and adjacent marshes are commonly flooded. With the exception of part of the Modern Brazos delta, the Texas coastal headlands erode rapidly under normal sea conditions and erode excessively during storms. Incipient dunes occur along the headlands; most dunes are destroyed by storm surge and breaking waves.

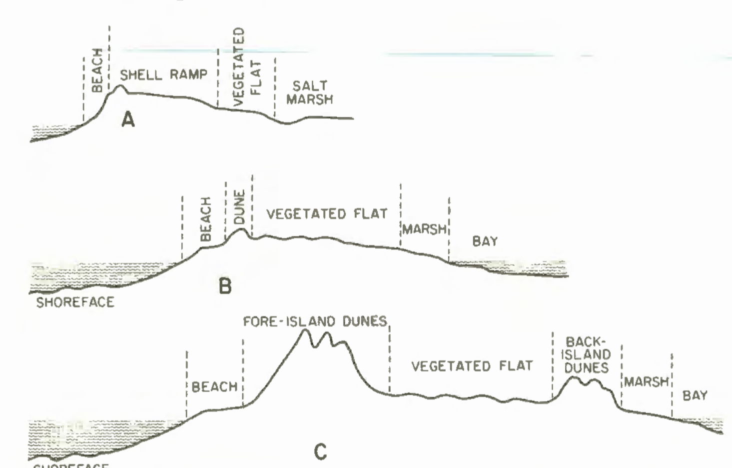


Figure 10. Generalized profiles of types of Texas Gulf Coast shorelines. (A) Headlands, (B) Peninsulas, (C) Barrier islands.

The Rio Grande deltaic headland (Brownsville-Harlingen map) is characterized by sand beaches and fore-island dunes. The vegetated dunes locally are 30 feet high. Breaks in the fore-island dune ridge may be a few hundred feet to a mile wide. The storm-tidal surge commonly breaches and scours the low areas between dunes and floods the Rio Grande delta plain and adjacent lowlands. Shoreline erosion is excessive even under normal sea conditions, but under storm conditions, shorelines may retreat a few hundred feet within a few hours. Post-storm processes may accrete the shoreline to its approximate prestorm position.

Peninsulas, which resemble offshore islands, are elongate strips of sand and shell that are attached to headlands and extend in the direction of longshore drift. Three peninsulas on the Texas Coast are Bolivar Peninsula, Matagorda Peninsula, and south Padre Island. A generalized profile across a peninsula is illustrated in figure 10.

Bolivar Peninsula (Galveston-Houston map) is about 23 miles long, is densely vegetated, and consists chiefly of fine-grained sand. It is characterized by well-developed ridge-and-swale topography, and there is no evidence of recent storm erosion or breaching of Bolivar Peninsula by storm washover channels. Maximum elevation along the seaward edge of Bolivar Peninsula is about 10 feet above MSL. Several storm-surge floods have flooded the peninsula, but dense vegetation has prevented the scouring of channels and development of active washover fans.

Matagorda Peninsula (Bay City-Freeport map) is about 51 miles long. The easternmost three miles of the peninsula is separated from the western segment by Brown Cedar Cut, a tidal pass created by a hurricane breach channel. Greens Bayou, similar to Brown Cedar Cut, is open only during and shortly following the passage of hurricanes.

The elevation of Matagorda Peninsula averages 5 to 7 feet above MSL. Continuous low dunes, 8 to 12 feet above MSL, extend from the mouth of the Colorado River eastward for about 8 miles, and from Greens Bayou westward to within a mile or two of Pass Cavallo. Storm washover channels are common along the peninsula. Spring high tides and forerunner tides associated with distant storms frequently overwash beaches adjacent to storm channels. Most of Matagorda Peninsula is overwashed by 5- to 7-foot storm surges. Continuous dunes with heights greater than about 10 feet afford some protection from storm surge.

During major storms such as Hurricane *Carla* (1961), two types of washover deposits are developed along Matagorda Peninsula: shell ramps and washover fans. Shell ramps are long berms that parallel the elongate peninsula. Individual ramps are a few miles long and 180 to 2,180 feet wide. Washover fans are lobate sand-shell bodies that accumulate at the bay terminus of storm channels that transect the peninsula. Small storm surges reactivate the channels and sometimes construct a washover fan along the bay margin. Large storms with 10 to 11 feet of storm surge cut the peninsula into numerous small islands separated by channels up to 1,700 feet wide. These same storms also may erode the shoreline as much as 800 feet (Shepard, 1973).

In South Texas, the gulfward part of the Rio Grande delta grades northward into south Padre Island (Brownsville-Harlingen map). South Padre Island, which originated as a peninsula, is now separated from the deltaic headland of the Rio Grande by Brazos Santiago Pass. South Padre Island is characterized by sand and shell beaches, sparse vegetation, and poorly developed fore-island dunes. Its morphology is the product of combined wind and storm activity. There is little natural defense to prevent breaching of south Padre Island by storms of the magnitude of *Carla* (1961) and *Beulah* (1967). Flow across the island is virtually unconfined during principal hurricanes; for example, south Padre Island was highly segmented by washover channels during Hurricane *Beulah*. Active dunes on south Padre Island range in height from 5 to 25 feet above MSL, but they present little resistance to tidal flow once a storm breach has been opened. Width of storm breach channels ranges from about 0.2 to 1.0 mile.

Barrier islands are elongate, detached sand bodies that are separated from the mainland by bays or lagoons and from each other by tidal passes. The five barrier islands of the Texas Coast are Galveston, Matagorda, St. Joseph, Mustang, and Padre. A generalized profile combining the features of Mustang Island is shown on figure 10.

Galveston Island (Galveston-Houston map) is wide and densely vegetated and is characterized by numerous sand ridges and swales. Average elevation is about 5 feet above MSL; maximum elevation of poorly developed fore-island dunes is about 15 feet above MSL. Hurricane erosion on Galveston Island is confined primarily to beaches and dunes.

Matagorda Island (Port Lavaca map) like Galveston Island is a broad, sandy island with well-defined ridge-and-swale topography and more or less continuous fore-island dunes (Wilkinson, 1974). Average elevation is about 5 feet above MSL. Fore-island dunes on Matagorda Island average about 10 feet with some peaks up to 30 feet above MSL. In historical times, hurricanes have not scoured washover channels across the island, but because of the development of several blowouts during the past few decades, breaching may occur in the near future.

St. Joseph Island (Corpus Christi map) also displays prominent ridge-and-swale topography. Vegetation on the island is less dense, and blowouts are more numerous than on islands to the east. Average elevation of St. Joseph Island is slightly more than 5 feet above MSL. Vegetated fore-island dunes average about 15 feet above MSL; there are some dunes that extend to 35 feet above MSL. Active washover channels occur at the extreme northeastern and southwestern ends of the island (Price, 1956; Andrews, 1970; Nordquist, 1972). North Pass was formed by a major hurricane in 1919 (Price, 1956; Nordquist, 1972). Approximately 9.3 million cubic yards of sediment accumulated along the bayward terminus of the washover channel as a consequence of hurricane activity, beginning with the 1919 hurricane and continuing through 1971.

Mustang Island (Corpus Christi map) is a broad barrier which has an average elevation of about 7 feet. It does not display ridge-and-swale topography. Vegetated fore-island dunes have an average elevation of about 15 feet above MSL and a maximum elevation of about 50 feet above MSL. Vegetation is less dense on Mustang than on islands to the northeast; consequently, blowouts, hurricane breaches, and washover channels are more numerous. Two factors contribute to the increased frequency of storm channel breaching on southern Mustang Island. First, there is a southwestward decrease in vegetation along the Texas Gulf Coast, and consequently, fore-island dunes are more susceptible to blowouts by wind erosion. Second, a major tidal pass existed in the southern Mustang Island area until the early 1900's. Hurricanes tend to readily breach those barrier segments that are adjacent to, and on the upcurrent (longshore current) side of, tidal inlets such as North Pass on St. Joseph Island and southern Mustang Island (Price, 1952, 1956).

Padre Island (Corpus Christi and Kingsville maps) is distinctively different from barrier islands of the central and upper Texas Coast. Vegetation on Padre Island is less dense, but fore-island dunes are generally well developed southward along north Padre Island almost to Mansfield Channel. Average dune elevation is about 15 feet above MSL; maximum elevations reach about 50 feet above MSL. Near Mansfield Channel, fore-island dunes are low and discontinuous; hence, along central Padre Island, storm-surge flooding is virtually unimpeded and many breach or washover channels are concentrated in the area. Northern Padre Island beaches are generally low and broad and consist of terrigenous sand. Southward, beaches become shelly, narrow, and high. The height of back beaches increases to about 7 feet above MSL, thereby providing some protection to fore-island dunes during storms.

Bay shoreline and inland areas are severely affected by storm-surge flooding, wave erosion, and fresh-water flooding from hurricanes. Severity of storm-surge flooding and destruction of man-made and natural features by waves is chiefly a function of bay size and configuration, presence or absence of cliffs, and location of hurricane landfall. Severity of fresh-water flooding is determined by local topography and storm characteristics.

Storm-surge flooding and wave damage are greatest along the shores of large, funnel-shaped bays with relatively high cliffs at the bayhead, which lie to the right of the landfall area. As onshore winds within the right side of the hurricane strike the Coastal Zone, storm-surge height increases toward the heads of bays as the surface area of the bay decreases and cliff height increases. Flooding along Matagorda Bay and Lavaca Bay shores during Hurricane *Carla*, 1961, is an example of hurricane impact within funnel-shaped Texas bays (Bay City-Freeport and Port Lavaca maps).

Bays that lie to the left of the storm track are not as severely flooded by storm surge as those lying to the right because storm tides and waves are driven toward the Gulf of Mexico on the left side of the counterclockwise wind systems. In this situation, most of the surge and wave attack is directed toward the back side of peninsulas and barrier islands.

Low-lying areas, such as marshes, delta plains, and river floodplains, are commonly flooded by storm surge. River floodplains and flat upland areas also may be extensively flooded by rainfall associated with a hurricane that moves slowly inland. Unless these areas are inhabited, little damage occurs; salt to brackish marshes are temporarily freshened. Floodplains may pond water for months.

Population Density

Storm-surge flooding, breaking waves, wind, and fresh-water flooding may cause considerable destruction in areas that are sparsely populated, but because of the low population density, this kind of natural damage does not significantly affect man. Perhaps the severity of a hurricane should, therefore, be measured in terms of its impact on man and man-made structures or developments—according to this viewpoint, the greater the population density, obviously the greater the severity of the storm.

Hurricane *Celia* was a small hurricane with high-velocity winds, which damaged or destroyed many man-made structures in the populated Corpus Christi region. In monetary terms, *Celia* was a severe storm. Had *Celia* made landfall on deserted central Padre Island and moved westward over the sparsely populated eolian sandplain, there would have been very little loss of life or damage to man-made structures. In such a setting, *Celia* would not have been a severe storm.

PREDICTION OF SEVERE HURRICANE DAMAGE

The most severe storm damage can be expected when large hurricanes of the *Carla* type make landfall (1) where barrier islands or peninsulas are of low relief (fore-island dunes are poorly developed or absent), (2) where sands constituting barrier islands or peninsulas are relatively thin, (3) where elongate bays lie to the right of the hurricane track, and (4) where the landfall area is densely populated. Examples of situations (1) and (2) are Matagorda Peninsula and south Padre Island. Funnel-shaped or elongate bays that may be the sites of extreme storm-surge flooding (situation 3) are Trinity, Galveston, Lavaca, San Antonio, Corpus Christi, and Nueces Bays. Densely populated areas and areas that are currently experiencing rapid development (situation 4), which can be expected to be severely damaged by a *Carla*-type hurricane, are the south Padre Island area, the Corpus Christi area (including the smaller cities adjacent to the bays), the Port Lavaca area, the Galveston-Houston area, and the Beaumont-Port Arthur area.

The *Beulah*-type hurricane causes extensive flooding. Man-made structures (i.e., residences, farm buildings, recreational facilities) situated on floodplains and adjacent to creeks and rivers can be expected to be damaged or destroyed. A storm such as *Beulah* in 1967, or *Carmen* in 1974, does not necessarily have to make landfall along the Texas Coast to cause flooding along Texas creeks and rivers. For example, *Carmen* struck the Louisiana coastline during the first week of September in 1974. She was still influencing weather in Texas as late as the second week in September, triggering excessively heavy rainfall in the Coastal Zone between Port Lavaca and Sinton. During the early morning of 13 September 1974, up to 17 inches of rain fell on the Papalote Creek drainage, a tributary to Aransas River. Flooding of Papalote Creek from this heavy rainfall was greater than the flooding experienced during the earlier Hurricane *Beulah* rains.

MITIGATION OF HURRICANE IMPACT

Hurricanes cost the people of Texas millions of dollars (table 6). Several methods have been employed to reduce the destructive potential of hurricanes. Mitigation of the hurricane hazard is in part accomplished by (1) reliable forecasting and prediction, (2) formulating evacuation procedures, (3) strengthening natural defenses such as fore-island dunes, and (4) erecting rigid structures to withstand wave attack or to retard waves and prevent storm-surge flooding. Another possible method of reducing the destructive potential of a storm lies in altering the storm itself. Finally, the most certain means of reducing storm damage is avoidance. Need for mitigation throughout the Atlantic and Gulf coasts becomes progressively more urgent since there was a 40-percent increase in beach residents between 1960 and 1970 (Frank, 1974). Although numerous problems arise from such rapid growth in the Coastal Zone, perhaps the most critical problem is the lack of hurricane experience of many of the new coastal residents.

Forecasting and prediction are now very sophisticated. Hurricanes are carefully monitored by electronic methods, by air surveillance, and by weather satellite. Residents in the vicinity of predicted landfall generally have sufficient time to evacuate the area. On the other hand, the time may be approaching when it will be impossible to entirely evacuate some coastal areas, e.g., barrier islands. A mass exodus of hundreds of thousands of people by automobile across congested causeways may not be physically possible. Two alternatives may be considered in order to reduce the number of people that would be required to flee the islands. First, with better forecasting, it may become possible to determine with even greater accuracy the "direct hit" and "fringe" areas. Evacuation of residents in the direct hit areas would be required; those in fringe areas would remain. A second alternative to evacuation would be the utilization of specially structured high rises (hotels, motels, condominiums, and apartments) as vertical refuges (Frank, 1974).

Fore-island dunes if present form the first line of natural defense against storm surge and breaking waves. The ability of dunes to withstand hurricane attack is dependent upon the density of stabilizing vegetation cover. Many dunes have been weakened or destroyed through devegetation. This occurs naturally during droughts and as a result of man's activities. Attempts have been made to strengthen dunes through artificial stabilization by increasing the vegetation density. Most notable of these ventures has been on the barrier islands of North Carolina (Dolan and Godfrey, 1973; Dolan and Odum, 1973). Artificial dune stabilization in North Carolina, however, has aggravated shoreline erosion.

Table 6. Losses from recent hurricanes. (A) Hurricane *Carla*, (B) Hurricane *Beulah*, (C) Hurricane *Celia*. Values in thousands of dollars. Data from U. S. Army Corps of Engineers (1962, 1968, 1971a). Note that data do not necessarily agree with that provided by National Oceanic and Atmospheric Administration (1900-1974).

A. HURRICANE CARLA

Type of loss	Tidal flooding	Wind and Rain	Total
Agriculture	19,544	41,314	60,858
Residential	105,779	66,441	172,220
Commercial buildings and contents	39,148	25,658	64,806
Industrial plants	11,683	3,349	15,032
Transportation	9,207	3,141	12,348
Utility	1,198	8,787	9,985
Miscellaneous	13,636	6,801	20,437
Services	–	–	52,604
Total	200,195	155,491	408,290

Lives lost: 32 persons

B. HURRICANE BEULAH

Type of loss	Tidal flooding	Wind and wind-driven rain	Stream flooding and ponding	Total
Agriculture	0	6,835	31,019	37,854
Commercial	2,241	1,192	6,370	9,803
Residential	615	21,457	25,463	47,535
Services	2,097	12,781	35,474	50,352
Total	4,953	42,265	98,326	145,544

Lives lost: 15 persons in Texas

C. HURRICANE CELIA

Type of loss	Wind damages	Tidal flooding	Total
Agriculture	19,220	13	19,233
Residential	199,652	3,523	203,175
Commercial	44,375	917	45,292
Industrial	75,980	8,705	84,685
Public	33,633	150	33,783
Transportation	540	1,186	1,726
Utilities	21,922	187	22,109
Marine	3,100	7,029	10,129
Automobiles	18,944	620	19,564
Services	22,372	5,243	27,615
Total	439,738	27,573	467,311

Lives lost: 13 persons

Estimated losses from hurricanes since 1900: $1,271,983,000

The Galveston seawall is an example of an engineering approach to retard hurricane damage, but as a result of stabilizing the shoreline, the beach has been lost. The seawall was erected specifically to protect the city against overflows from the sea (Davis, 1961). Sand, excavated from western Galveston Island, was used to fill part of the low area behind the seawall. Bulkheads and revetments are also commonly used to protect some bay shores from hurricane wave attack. Other proposed methods to alleviate potential storm surge and wave damage to bay-shore property include the use of breakwaters constructed within the bays specifically to reduce wave action, and the construction of a system of locks which, in the event of a hurricane, could close off the tidal and navigation channels.

Two other means of lessening damage potential are to avoid those areas that are prone to storm-surge and fresh-water flooding and to enact appropriate building codes; areas that have been flooded by storm surge and fresh water are shown on Natural Hazards Maps. Buildings can be constructed to withstand the high-velocity winds and sudden pressure changes associated with hurricanes. Elevation of buildings by utilizing pilings can eliminate most of the damage from storm-surge flooding, but will not eliminate damage or destruction from breaking waves.

Attempts have been made to alter the hurricane itself, and research is being conducted to determine the feasibility of altering tropical storms (Dunn and Miller, 1964; Simpson, 1966). The object of hurricane modification is to decrease the steep pressure profile (hence decrease the wind velocity) and to convert the hurricane to a tropical storm. Profiles through hurricanes and tropical storms (fig. 11) show that wind velocity and pressure gradient are greatest near the eye of a hurricane. The tropical storm, which has no eye, has a much lower wind velocity than hurricanes. At present, cloud seeding appears to be a promising method to reduce wind speed and eliminate the eye. The seeding method may never lead directly to useful modification, however, because hurricanes are so large and their energy is so enormous (Simpson, 1966). A hurricane with moderate strength releases as much condensation heat energy in a day as the nuclear fusion energy of four hundred 29-megaton hydrogen bombs. Significant modification of hurricanes may be impossible. It also may prove to be undesirable to destroy a hurricane or to alter its course, since these storms supply a quarter to a third of the rainfall in critical areas of the world.

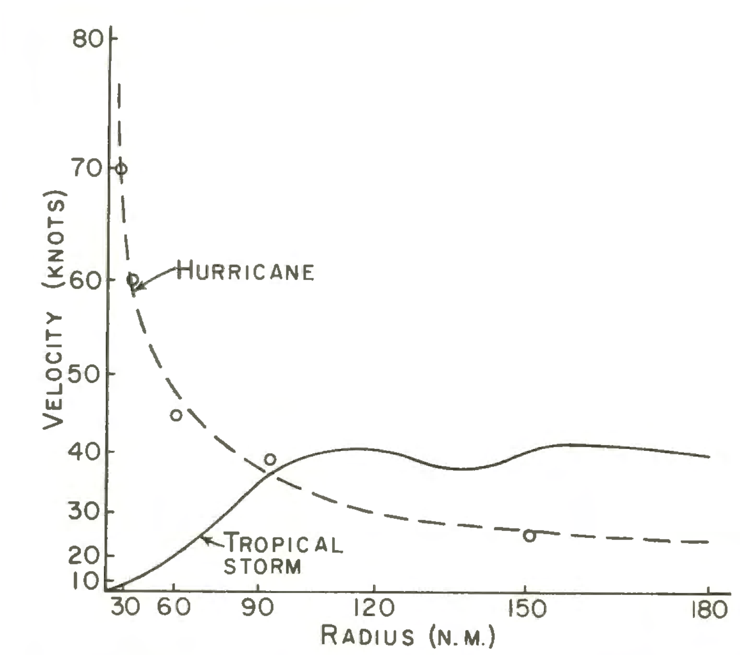


Figure 11. Velocity profiles characteristic of hurricanes and tropical storms. After Simpson (1966).

● FLOODING ●

GENERAL STATEMENT

Two principal types of flood hazards exist in the Texas Coastal Zone: storm-surge tidal flooding and fresh-water flooding. During the passage of hurricanes and tropical storms, storm-surge tides may flood low-lying coastal areas up to elevations above 20 feet (fig. 7). Fresh-water flooding, on the other hand, results from hurricane-aftermath rainfall, as well as from severe thunderstorms and frontal-related storms. Fresh-water flooding may occur as stream flooding of floodplains or as rainfall flooding of broad areas of the coastal plain. On the flat coastal plain, the runoff is ponded in natural depressions or dammed behind highways, railroads, and other man-made structures.

Shoreline erosion and land subsidence, both natural factors that can be accelerated by human impact, are increasing the hazard of storm-surge and fresh-water flooding in the Coastal Zone. As shorelines retreat, or as lands subside, greater areas of the Coastal Zone are exposed to storm-surge tides. Similarly, land subsidence, whether due to natural compaction and subsidence or to ground-water withdrawal, produces broad irregular depressions that can pond substantial volumes of rainfall on the impermeable muddy substrates of much of the lower coastal plain. Ship channels, irrigation ditches, and extensive dikes, related both to agriculture and industrial/commercial development, may also serve to aggravate the impact of the storm-surge tide and to impede rainfall runoff.

Those areas actually flooded by the storm-surge tides that accompanied Hurricanes *Carla* and/or *Beulah* (3,164 square miles) are shown on the Natural Hazards Maps. Likewise, areas flooded by Hurricane *Beulah* aftermath rainfall (2,187 square miles) define the extent of fresh-water flooding (stream flooding, ponding, and damming) in the Texas Coastal Zone between Bay City and Brownsville. Data on Hurricanes *Carla* and *Beulah* were obtained from the U. S. Army Corps of Engineers (1962, 1968) and are based on aerial photographs, drift-line observations, and a variety of recording gages. The reader is referred to the above reports, as well as to a report on Hurricane *Celia* (U. S. Army Corps of Engineers, 1971a) and a report on hurricane-surge frequency estimated for the Texas Coastal Zone (Bodine, 1969). Maps and text which were distributed as part of the Texas Hurricane Awareness Program by the Texas Coastal and Marine Council (1974) also provide information on flooding.

In the northeastern part of the Coastal Zone, where adequate hurricane-aftermath flood data are generally unavailable, areas of possible stream flooding (2,073 square miles) shown on the Natural Hazards Maps are based upon the distribution of floodplain sediments and upon the geomorphic character of the stream systems. Areas that will be flooded by ponding of excessive rainfall were not delineated for the northeastern part of the Texas Coastal Zone because the necessary mapping of subtle topographic variations is beyond the resolution of regionally available topographic maps. In addition, the degree of ponding is also related to the efficiency of highway and railroad drainage systems, which may be blocked by driftwood and other debris.

The flood-prone areas shown on the Natural Hazards Maps are, therefore, based principally upon historical or geologic evidence and not upon theoretical prediction and extrapolation methods.

FLOODING PROCESSES

Hurricanes and Tropical Storms

As previously described, the most destructive aspect of hurricanes that have struck the Texas Coast (table 4) is the impact of the storm-tidal surge; widespread forerunner tides of lesser magnitude may precede the storm-surge tides. Storm surge, which is generated within the storm by the low barometric pressure and the intense, counterclockwise winds, strikes the coast as the storm makes landfall and spreads across the low coastal plain with lethal results. Most property damage and, more critically, most deaths result from the surge of ocean water across exposed, low-lying barrier islands and mainland shorelines (table 6). Nine out of ten deaths as a result of hurricanes are caused by drownings (Texas Coastal and Marine Council, 1974). As the hurricane moves ashore, floating debris propelled by the storm surge adds to the damage inflicted by the rising water and pounding waves. The greatest property losses result both from flooding and from the battering effect of water-carried debris. The devastation imposed upon Mississippi in 1969 by Hurricane *Camille* was caused principally by a storm surge of nearly 25 feet above MSL. Most seawalls and hurricane protection dikes along the Texas Coast are less than 20 feet above sea level.

Storm-Surge Tides

A general model that illustrates the nature of storm-surge tidal flooding along the Texas coastline during approach and passage of a hurricane has been previously described (fig. 7). The elevation of the storm-surge tide generated by a hurricane is generally less on the Gulf shoreline (barrier islands, peninsulas, headlands) than along the shorelines of constricted bays and estuaries where storm-tidal surge may be significantly elevated. A storm surge greater than 10 feet above MSL, therefore, may occur within constricted bays because of superelevation of the tide on the gently sloping bottoms and on the adjacent coastal plain (fig. 9). The frequency of storm-tidal surge greater than 10 feet is consistently and substantially greater for bays than for open Gulf beaches (fig. 12).

Rainfall Flooding

Rains may precede the landfall of a hurricane, but as the storm center moves inland, heavy rainfall, often accompanied by tornadoes, generally strikes the coastal plain (fig. 7). If the hurricane moves directly inland, the period of heavy rainfall may be limited to three or four hours. If the storm moves parallel to the coastline or repeatedly changes its forward direction, excessive rains may continue for many hours or even several days. For example, in 1967 Hurricane *Beulah* remained in the South Texas area for almost three days; up to 32 inches of rain fell in the region during the five or six days following landfall (fig. 8). Stream flooding and ponding inundated 1.4 million acres of land while only 630,000 acres were flooded by storm-surge tides (U. S. Army Corps of Engineers, 1968).

Hurricane-aftermath rainfall is generally so excessive that coastal streams inundate floodplains. Floodwaters are discharged into the various Texas bays, which are already experiencing high tides. As a result, combined storm-surge tides and overbank stream flooding may devastate vast areas of the flat, lower coastal plains. As the hurricane moves inland, rainfall runoff continues to flood drainage systems; streams may discharge floodwaters into bays for many days following storm passage.

Ponding of rainfall on the coastal plain may inundate more area than stream flooding. Most of the lower 50 miles of the coastal plain is underlain by flat-lying, poorly drained, moderately to highly impermeable sediments (refer to "Environmental Geologic Atlas of the Texas Coastal Zone," Fisher and others, 1972, 1973; also Fisher, 1973); rainfall runoff is high because of this relatively impervious substrate.

Although lives may be lost in hurricane-aftermath flooding, more commonly the principal loss is to property such as bridges, highways, and homes. Thousands of persons may be left temporarily homeless by the stream flooding and ponding; transportation systems may be destroyed or blocked. Flooding also damages water and sewerage facilities, leading to the threat of epidemic diseases.

Frontal-Related Storms

Storms associated with more normal meteorologic circulation also produce flood hazards in the Coastal Zone. Although thunderstorms are generated during the summer months in the coastal region by convection, most severe weather, excluding hurricanes and tropical storms, is related to frontal systems that move eastward and southeastward across the North American continent. In the winter, polar fronts may move rapidly into the coastal area suddenly bringing low temperatures, rain, and strong northerly winds. These storms may last for two or three days, during which time some locally heavy rainfall can occur. The northerly winds may generate flood tides that inundate wind-tidal flats and other low areas, especially along the southern margins of the bays and the back sides of barrier islands. Wind-tidal flooding is slow, and it does not present a serious hazard.

During spring and fall, when polar fronts diminish in strength, the cooler air mass of the frontal system is unable to maintain its momentum against warmer Gulf air; stationary fronts (sometimes called warm fronts) result. These broad fronts, which lift warm Gulf air aloft, may remain in the coastal region for many days while generating widely distributed rainfall. Serious flooding of coastal streams may occur but rarely to the degree experienced during hurricanes and tropical storms.

FLOOD-PRONE AREAS

Storm-Surge Tidal Flooding

Between 1900 and 1972, 27 hurricanes (winds greater than 74 mph) and many less severe tropical storms (winds greater than 39 mph and less than 74 mph) struck the Texas Coast (table 4), generally in August or September (fig. 3). This constitutes a rate of one hurricane every 2.5 years. Very few areas of the Texas Coast have escaped hurricane impact during this century. Each hurricane is a rather unique storm in terms of the nature and degree of winds, storm surge, and aftermath rainfall. Every bay, barrier island, peninsula, and headland exhibits some unique physical variations which can serve to modify the impact of storm-surge tides.

Two recent well-documented hurricanes (*Carla*, 1961 and *Beulah*, 1967) have been used in this atlas to define known limits of storm-surge flooding and aftermath-rainfall flooding (table 5). Flood-surge elevations and area of flooding are based on studies by the U. S. Army Corps of Engineers (1962, 1968); flood elevations are based on drift line and various gage measurements. Although *Carla* and *Beulah* flooded 3,164 square miles, they probably do not represent ultimate hurricanes. One must assume, nevertheless, that storms such as *Carla* or *Beulah* may eventually strike other parts of the coast. For instance, should a *Carla*-type storm directly strike the Galveston area (such as the 1900 storm, table 4), the area of tidal flooding could be much greater than the actual flooding that occurred when *Carla* struck Port O'Connor. With storm flood tides of 15 feet above MSL possible on the Gulf beaches and with more than 20 feet of storm tide possible within restricted bays (fig. 12), the potential flood-prone area of the Texas Coast may be significantly greater than the net area reported for *Carla* and *Beulah* flooding.

A total of 5,787 square miles of Texas coastal plain lies below an elevation of 20 feet above MSL (table 1). Much of this land below an elevation of 20 feet may be flooded locally when maximum storm-surge conditions are focused on the specific section of the Texas shoreline.

In the *Beaumont-Port Arthur map area*, *Carla* floodwaters moved inland from the Gulf beaches for 15 to 20 miles and reached up the Neches River valley to the vicinity of Beaumont. Tidal levels ranged from 6.8 feet above MSL at Orangefield to 10.5 feet above MSL northwest of High Island. Flood levels reached 8.5 feet above MSL at the mouth of the Neches River, 7.9 feet near Port Neches, 5.0 feet near Port Acres, 7.6 feet at Port Arthur, 9.4 feet along the northern shore of Sabine Pass, 8.6 feet near Big Hill, and 8.9 feet at High Island.

A total of 583 square miles of coastal lands in the Beaumont-Port Arthur map area were flooded by Hurricane *Carla*. If the center of a *Carla*-level storm struck the Sabine Lake area, tidal flooding might inundate areas up to elevations of 15 to 20 feet, hence covering 20 to 30 percent more land than indicated on the Natural Hazards Map. Although only two hurricane washover channels have been recognized near High Island, Hurricane *Carla* floodwaters apparently crossed the low-lying shoreline at many points to flood the broad marshlands along the Intracoastal Canal.

In the *Galveston-Houston map area*, *Carla* flooding extended inland for 15 miles in the Angleton area, covered most of Galveston Island and Bolivar Peninsula, most of Smith Point area, and extended up the Trinity and San Jacinto river valleys. Flooding along the western side of Galveston Bay extended up Dickinson Bayou and Clear Creek to Interstate 45. On the Gulf beaches, maximum tidal levels of 9.6 and 12.1 feet above MSL were recorded on Bolivar Peninsula and central Galveston Island, respectively. Tide levels reached 14.0 feet above MSL at Wallisville, 13.4 feet at Anahuac, 9.8 feet at Smith Point, 14.1 feet at Baytown, 15.0 feet at Morgan Point, 14.2 feet at the mouth of Clear Creek, 12.7 feet at Dickinson, 11.0 feet at Texas City, and 14.7 feet at Chocolate Bayou.

Hurricane *Carla* tidal waters flooded 694 square miles of the Galveston-Houston map area. If tidal flooding were to approach 15 to 20 feet in the Galveston Bay vicinity as a result of the direct impact of the center of a *Carla*-level storm, perhaps 10 to 20 percent more land area would be flooded than indicated on the Natural Hazards Map. Seven potential washover channels occur on Galveston and Follets Islands; other channels may develop during severe hurricanes.

Continued land subsidence centered in the Baytown region is yearly subjecting greater areas to potential tidal flooding. If the flood levels that occurred in Galveston Bay during Hurricane *Carla*, in 1961, were to strike Galveston Bay today, it is estimated that approximately 70 additional square miles would be subjected to flooding because of land subsidence (Texas Coastal and Marine Council, 1974).

In the *Bay City-Freeport map area*, tidal flooding by Hurricane *Carla* extended inland approximately 10 miles from the Gulf beach. Most of Matagorda Peninsula and the Colorado River delta were inundated and flood tides moved from 3 to 8 miles inland from the shoreline of east and west Matagorda Bay. Flood-tidal levels were measured at 10.9 feet above MSL at the mouth of the Brazos River and 5.2 feet above MSL at the Freeport channel; other levels include 13.8 feet above MSL at a site on the Brazos River about 7 miles inland, 11.0 feet near the mouth of the San Bernard River, 13.7 feet about 10 miles inland along the San Bernard River, 14.1 feet on Lake Austin, 13.7 feet along the Intracoastal Canal on the north side of East Matagorda Bay, 15.3 feet near the town of Matagorda, and 15.4 feet at Palacios.

Hurricane *Carla* tidal surge flooded 564 square miles of coastal lands in the Bay City-Freeport map area. The Bay City-Freeport map area was situated to the right of *Carla's* center when the hurricane made landfall. This location, relative to the hurricane's eye, received some of the most intense winds and storm tides experienced along the entire coast. If tidal-flood levels were to approach 15 to 20 feet in the area, perhaps 10 percent more land area would be flooded than indicated on the Natural Hazards Map. Numerous hurricane washover sites occur along Matagorda Peninsula.

The eye of Hurricane *Carla* crossed the Texas coastline at Pass Cavallo, located in the *Port Lavaca map area*. Flood tides were highly elevated in Carancahua Bay, Keller Bay, and Lavaca Bay. Tidal waters moved from 10 to 18 miles up Garcitas Creek and the Lavaca River, respectively. Most of the land area between Seadrift and Port Lavaca was flooded; very little of Matagorda Island remained emergent. Extensive flooding occurred in the Green Lake-Guadalupe delta area, along Blackjack Peninsula, and in the vicinity of St. Charles Bay.

Measured *Carla* tidal-flood levels in the Port Lavaca map area include 18.4 feet above MSL on the west side of Carancahua Bay, 20.1 feet at the State Highway 35 bridge over the upper part of Carancahua Bay, 16.3 feet in Keller Bay, 17.3 feet at Point Comfort, 22.0 feet at Port Lavaca, 15.4 feet near Port O'Connor, 10.3 feet at the ship channel on Matagorda Peninsula, 12.3 feet along the west side of Pass Cavallo, 12.1 feet at Matagorda Island Air Force Base, 11.2 feet at Seadrift, 10.3 feet on the west side of San Antonio Bay, and 7.3 feet at the State Highway 35 bridge over Copano Bay. Hurricane *Carla* tidal surge flooded 495 square miles in the Port Lavaca map area. Tidal-flood levels generally coincided with the 20-foot-elevation contour line along and to the right of *Carla's* landfall. Had *Carla* made landfall at St. Joseph Island, perhaps an additional 5 to 10 percent of the western part of the Port Lavaca area would have been inundated by tidal floodwaters. Two hurricane washover channels have been recognized near the western end of Matagorda Peninsula; Vinson Slough on St. Joseph Island is a major washover channel.

In the *Corpus Christi map area*, land inundated by tidal flooding by Hurricane *Carla* in 1961 slightly exceeded the area flooded by Hurricane *Beulah*, which made landfall near the Rio Grande in 1967. *Carla's* tidal surge flooded most of southern St. Joseph Island, Mustang Island, and northern Padre Island, except for elevated areas comprising fore-island dunes and stabilized blowout dunes. Tidal flooding extended for 10 miles up the Mission, Aransas, and Nueces river valleys. Low-lying areas surrounding Port Bay were similarly inundated. Minor tidal flooding occurred along the landward sides of Corpus Christi Bay and northern Laguna Madre. Measured *Carla* tidal-flood levels include 7.3 feet above MSL at the mouth of the Aransas River, 7.9 feet on the east side of Port Bay, 7.5 feet near Key Allegro, 9.3 feet at Port Aransas, and 5.9 feet at the southeast end of Live Oak Peninsula near Ingleside. Measured *Beulah* tidal-flood elevations in the Corpus Christi map area include 8.0 feet above MSL on northern Mustang beach, 7.3 feet at Portland, 7.3 feet near the bay bridge at Corpus Christi, 8.2 feet at the Corpus Christi Naval Air Station, 6.8 feet at the Flour Bluff bridge, and 8.8 feet in upper Oso Bay.

The elevation of *Carla's* tidal surge significantly diminished southwestward across the Corpus Christi map area; this region was located on the left or low-intensity side of *Carla's* storm center (fig. 9). Hurricane *Carla's* tidal flooding inundated 203 square miles in the Corpus Christi map area; Hurricane *Beulah* flooded only slightly less area. If the center of a *Carla*-level storm made landfall at Port Aransas, tidal levels might reach 15 to 20 feet above MSL and an additional 10 to 15 percent of the land area would be flooded by the surge, particularly in the Port Bay and Laguna Larga-Oso Bay areas. Broad hurricane washover channels occur at the southeastern end of St. Joseph Island and in the Packery-Newport-Corpus Christi channel area on southern Mustang and northern Padre Islands.

Storm-surge tides generated by Hurricane *Beulah* in the *Kingsville map area* far exceeded *Carla's* tidal flooding in the area. Hurricane *Beulah* storm tides inundated much of Padre Island, all tidal flats and low-lying areas along the landward side of Laguna Madre, large areas adjacent to Baffin Bay, and the lower reaches of Olmos Creek, San Fernando Creek, and Petronilla Creek. Hurricane *Beulah* tidal flooding inundated 288 square miles in the Kingsville map area. Measured *Beulah* flood-tide elevations include 8.7 feet above MSL at Malaquite Beach (Padre Island National Seashore), 5.6 feet at Penascal Point at the mouth of Baffin Bay, 8.8 feet near Loyola Beach, and 10.9 feet along the lower reaches of San Fernando Creek.

If the center of a *Beulah*- or *Carla*-level storm were to make landfall along north-central Padre Island, 10 to 15 percent more land would probably be inundated by tidal flooding, especially in the Baffin Bay region, on Padre Island, and within low areas associated with the extensive sand dune fields. Much of Padre Island near the land-cut area was breached by hurricane washover channels.

In the *Brownsville-Harlingen map area*, Hurricane *Beulah* tidal flooding inundated most of southern Padre Island and all of the extensive tidal flats, particularly in the Arroyo Colorado area and in the vicinity of the Brownsville ship channel. Hurricane *Beulah* did not strike the south Texas Coast head-on, but moved into the region from Mexico, almost parallel to the coastline. For this reason, the Brownsville region may have experienced lower storm tides than it would if the hurricane had moved directly westward out of the Gulf of Mexico.

Measured *Beulah* tidal elevations include 6.9 feet above MSL at Port Mansfield, 3.5 feet on the Gulf beach south of Mansfield jetty, 5.3 feet along the Intracoastal Canal at the mouth of Arroyo Colorado, 3.9 to 7.4 feet on southernmost Padre Island, 7.5 feet on the Gulf beach at Boca Chica, 6.3 feet near Port Isabel, and 8.5 feet along State Highway 48, halfway between Boca Chica and Brownsville. Sugg and Pelissia (1968) reported a high-water mark of 12 feet above MSL in a house at south Port Isabel. Hurricane *Beulah* tidal surge flooded 336 square miles in the Brownsville-Harlingen map area; much of this flooded area consists of low tidal flats. If the center of a *Beulah*- or *Carla*-level storm were to strike the south Texas Coast while moving westward or southwestward, a significantly greater land area than indicated on the Natural Hazards Maps might be flooded.

Stream Flooding and Ponding

On the Natural Hazards Maps, flood-prone areas resulting from rainfall associated with tropical storms, hurricanes, and frontal systems are based on two sources: (1) data on Hurricane *Beulah* flooding (U. S. Army Corps of Engineers, 1968) served as a guide to flood-prone areas in South Texas between the Rio Grande and the Lavaca/Navidad River system; and (2) aerial photographs, topographic maps, and field observations were used to delineate flood-prone areas (based on geologic/geomorphic evidence) between the Lavaca/Navidad River system and the Sabine River where regional rainfall flood data are unavailable. The use of *Beulah* stream flooding and ponding data provides an actual historical example of flooded areas. It should be realized, however, that the fresh-water flood area shown on the Natural Hazards Maps is probably a conservative estimate below the maximum flood levels which can occur in the region. Northeast of the Lavaca/Navidad River basin, flood-prone areas are underlain by floodplain sediments, which are geologic evidence of flooding.

In the *south coastal areas*, Hurricane *Beulah* delivered approximately 30 inches of rainfall in less than one week. It is one of the best documented flood events in the region. Although *Beulah*-related rainfall was general in the region, certain areas received anomalous quantities of precipitation. For this reason, one must recognize that the fresh-water flood limits on the Natural Hazards Maps are not based upon uniform rainfall within each stream system.

Every stream between the Rio Grande and the Lavaca/Navidad Rivers experienced flooding; the general limits of flooding are shown on the Natural Hazards Maps. Flooding inundated 2,187 square miles (table 1). Extensive ponding occurred between Baffin Bay and the North Floodway/Arroyo Colorado area, where stream drainage is essentially nonexistent within the broad fields of sand dunes. Impervious substrates, which occur locally beneath the dunes, coupled with the hummocky sand ridges and blowout depressions, ponded the rainfall and inhibited its runoff to the Gulf of Mexico. Earthen embankments along State Highway 77 and the Missouri Pacific Railroad locally retarded runoff. Ponded water remained for months before evaporation and slow percolation combined to lower water levels.

In the *northeast coastal area* between the Lavaca/Navidad Rivers and the Sabine River, *Beulah* rainfall was insufficient to produce stream flooding and ponding. Because of the absence of regional historic rainfall data for the upper region of the Texas Coastal Zone, flood-prone areas on the Natural Hazards Maps are based on geologic and geomorphic evidence. On the Natural Hazards Maps, these areas, which cover 2,073 square miles (table 1), are called "potential areas of fresh-water flooding by hurricane rainfall." The areas are underlain by floodplain sediments, which verify their flood potential. This flood category is comprised chiefly of river or stream valleys and adjacent depressed, poorly drained areas that occasionally may be flooded by overbank discharge of the stream, as well as by intensive hurricane rainfall. Such flood-prone areas can be delineated with reasonable accuracy, but they do *not* represent flooding by a single, observed flood event similar to that caused by *Beulah* rainfall.

Delineation of potential areas of ponding are not included for the northeastern part of the Coastal Zone. Ponding results from a complex interplay of subtle topographic depressions, water-table elevations, man-made structures, and available drainage systems. For this reason, the precise limits of ponding can best be determined by actual experience. Ponding rarely leaves a distinctive geologic deposit that can be used to determine its limits.

Predicting Flood-Prone Areas

Meteorologists and engineers have correctly placed a high priority on learning to predict the level of tidal surge caused by hurricanes. When enough is known about tidal levels, wind direction and intensity, atmospheric pressure, and other factors, it may be possible to construct reasonably accurate hurricane prediction models. Hurricanes strike Texas an average of once every 2.5 years. Meager quantitative data are available on most of these storms, especially data at many sites along the Gulf beaches and within the bays. For this reason, insufficient data exist at this time to develop a truly accurate and statistically valid model (Bodine, 1969). A dense network of tidal gages and other recorders are needed throughout the region. Even if such a data system were now available, it would take many years to sample a sufficient number of hurricanes to generate highly reliable prediction models.

By using a combination of observational information and logic, some progress has been made in predicting the level of storm-tidal surge. One such method (Bodine, 1969) is based on a hypothetical hurricane with a central pressure index frequency probability of once in 100 years (fig. 12). This hypothetical hurricane is the Standard Project Hurricane of the U. S. Army Corps of Engineers, if it generates maximum surge at a specific, selected location.

Because the Gulf beaches are relatively straight and offshore bathymetry generally uniform, estimates of surge elevations are probably significantly more accurate on the Gulf shoreline than within the highly complex and variable bays. The variety of bathymetry, shoreline configuration, and other factors make accurate prediction of surge within bays much more difficult. Estimates of the frequency of surge heights on the Gulf shore at Freeport and within Galveston Bay at Baytown are shown on figures 12A and 12B; figure 12C shows predicted Gulf beach tidal elevations along the entire Texas Gulf Coast.

Hurricane-tidal levels will be predicted with increasing accuracy, especially along the Gulf beaches. Because of the variability of the Gulf hurricane, its path, and its interaction with the highly variable configuration of Texas bays, precise prediction of maximum flood levels will take many years to perfect. In the meantime, the charting of observed flood events provides a valuable guide to flood-prone areas.

MITIGATION AND AGGRAVATION OF FLOODING

Before man settled the Texas Coastal Zone, hurricane processes, along with all coastal and marine processes, were generally in equilibrium with the natural coastal environments. Hurricanes are but one of a large number of natural phenomena that probably have operated for tens of thousands of years in the Texas coastal region. Before man arrived, the storms expended much of their great energy in the coastal system and brought about, in a natural way, certain physical and biologic changes. The slow evolution of the Texas Gulf Coastal Zone has been affected by the tropical cyclone.

Tropical storms and hurricanes have effected certain changes in the region; barrier islands were modified and, perhaps, even their origin was, in part, controlled by such storms. Bays were flushed and supplied with marine nutrients; sediment was eroded and redistributed. When man became part of the coastal system, however, hurricanes became disastrous because man does not necessarily live in equilibrium with the natural environment. Hurricanes have become severe problems today because they strike man's habitation and development. It is important during this period of growing population and development in the coastal region that man strive to live in harmony with the hurricane, while at the same time developing safeguards to prevent loss of life and to minimize loss of property.

Many natural features of the coastal area tend to mitigate the impact of hurricane flooding on man-made structures and developments. In addition, man has attempted to alleviate the danger and destruction caused by the hurricane floods in a variety of ways, most of which involve protective structures. It is probable that man can significantly improve his safety and can reduce storm damage by careful development of building codes and construction methods. In some

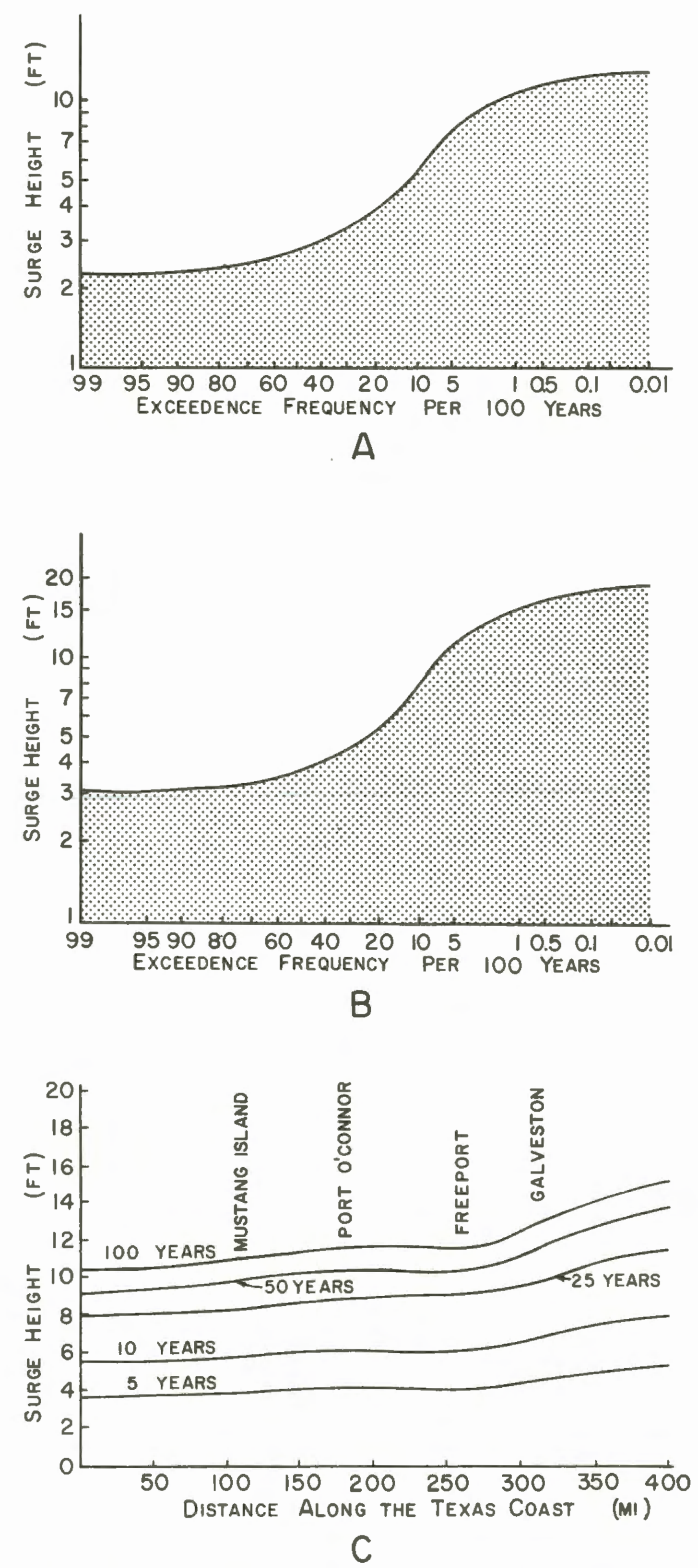


Figure 12. Estimation of storm-surge height and frequency, Texas Gulf Coast. Based on mathematical methods. After Bodine (1969). (A) Gulf beaches at Freeport, (B) Bay shoreline at Baytown, Galveston Bay, (C) Predicted tidal elevations (in terms of exceedence frequency) along entire open Gulf Coast.

areas, nevertheless, it may prove to be thoroughly impractical for man to try to control the impact of storm surge. In these flood-prone areas, it may be more profitable to avoid a potential disaster by utilizing the areas for more compatible uses than habitation.

Natural Flood Protection

In the coastal region, the first natural defense against hurricane surge is the barrier island, which constitutes a barrier to waves generated on the inner shelf. The fore-island dune ridge is an important element which allows the barrier island to block effectively some of the storm-surge energy. The barrier islands, however, are effective in absorbing some of the storm's energy only if they are well stabilized by vegetation. Along the shoreline of the bays, extensive marshes and shallow grassflats provide a buffer or baffle which dampens some of the erosive power and wave energy generated by tropical storms. Marshes, like vegetated barrier islands, are resistant to storm erosion. Elongate oyster reefs, which grow upward from the bay bottom to within 1 to 3 feet of the water surface, provide a natural baffling system that aids in reducing tidal surge and that reduces the effective fetch of waves within the bays.

Land Use and Coastal Flooding

A number of man's activities may aggravate the destructive power of the storm-tidal surge and fresh-water flooding. Any activity that destroys stabilizing vegetation will weaken and subject a barrier island or a bay shoreline to increased storm-tidal erosion. Additional hurricane washover channels may develop if fore-island dunes are destroyed. Navigation passes constructed through barrier islands provide additional routes by which storm-surge tides may enter the restricted bays. Construction of channels, dikes, or any other modification which can serve to divert or focus storm tides may lead to acceleration of natural shoreline erosion. Land subsidence resulting from use of ground water exposes greater areas of the coast to the impact of tidal surge and flooding. Modification of stream courses to provide better drainage can also lead to accelerated erosion and, perhaps, even expose new areas to stream flooding and ponding. Structures that cross stream courses may impede the flow of flood-waters; similarly, ponding may develop because runoff is impeded by man-made structures.

Flood Prevention Structures

Under the pressure of growing population and industrialization, man has impinged upon more and more flood-prone areas; for example, homes and businesses are constructed within areas that have historically flooded. Dikes, berms, levees, seawalls, groins, and bulkheads have been constructed to protect life and property in flood-prone coastal areas.

Every reasonable effort should be made to protect life and property from the threat of hurricane flooding. Maximum use of premium coastal lands will require that more extensive flood protection structures be engineered and built. New and innovative methods of construction, along with improved building codes, should be effective means of diminishing flood damage. It is important, nevertheless, to consider the rational limits on coastal construction aimed at flood prevention. More importantly, at some point, man must decide how far he can afford to go to eliminate flooding in low-lying coastal areas. Areas that are repeatedly and severely flooded might best be utilized for activities that preclude extensive property damage and safety hazards.

● SHORELINE EROSION ●

GENERAL STATEMENT

Shorelines are in a state of erosion, accretion, or equilibrium, either naturally or artificially. Erosion produces a net loss in land, accretion produces a net gain in land, and equilibrium conditions produce no net change. Shoreline changes are the response of the beach to a hierarchy of natural cyclic phenomena including (from lower to higher order) tides, storms, sediment supply, and relative sea-level changes. Time periods for these cycles range from one day to several thousand years. Most beach segments undergo both erosion and accretion in response to lower order events no matter what their long-term trends may be. Furthermore, long-term trends can be unidirectional or cyclic; that is, shoreline changes may persist in one direction, either accretion or erosion, or the shoreline may undergo repetitive periods of erosion and accretion. Shoreline erosion assumes importance along the Texas Coast because of active loss of land, as well as the potential damage or destruction of piers, dwellings, highways, and other structures.

SHORELINE MONITORING PROGRAM

In 1972, the Bureau of Economic Geology initiated a program in historical monitoring for the purpose of determining, on a quantitative basis, long-term shoreline changes in the Texas Coastal Zone. The recent acceleration in Gulf-front real estate and industrial development has provided the incentive for adequate evaluation of shoreline characteristics. Of special concern has been the documentation of those shorelines undergoing erosion and accretion, as well as those that are in equilibrium.

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

In 1973, the Texas Legislature appropriated funds for the Bureau of Economic Geology to conduct historical monitoring of the entire 367 miles of Texas Gulf shoreline during the 1973-1975 biennium. Results of the project will be published ultimately in the form of detailed, cartographically precise shoreline maps. Work versions of these maps (scale 1:24,000) will be on open file at the Bureau of Economic Geology until publication. In advance of the final report and maps, a series of preliminary interim reports (e.g., Morton, 1974; Morton and Pieper, 1975) is being published.

GENERAL METHODS AND PROCEDURES

Definition

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

Sources of Data

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

Procedure

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

Factors Affecting Accuracy of Data

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

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

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

Original Data

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

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

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

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

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

Interpretation of Photographs

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

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

Cartographic Procedure

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

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

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

Measurements and Calculated Rates

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

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

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

Justification of Method and Limitations

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

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

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

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

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

RESULTS OF HISTORICAL MONITORING PROGRAM

Gulf Shoreline Erosion

Long-term erosion during the past 74 to 132 years (table 1) has subjected 47 linear miles, or 13 percent, of the Texas Gulf shoreline to severe erosion and shoreline retreat (greater than 10 ft per year); 154 linear miles, representing 42 percent of the Texas Gulf shoreline, similarly has been affected by moderate long-term erosion and shoreline retreat (up to 10 ft per year). Long-term accretion has occurred along 35 percent of the Texas Gulf shoreline; 10 percent of the Gulf coastline has been in long-term equilibrium.

Short-term erosion during the past 7 to 23 years has subjected 153 linear miles, or 42 percent, of the Texas Gulf shoreline to severe erosion and shoreline retreat (greater than 10 ft per year); similarly 101 linear miles, representing 28 percent of the Texas Gulf shoreline, has been affected by moderate short-term erosion and shoreline retreat (up to 10 ft per year). Only 13 percent of the Texas Gulf shoreline is undergoing short-term accretion, while 17 percent is in short-term equilibrium.

The Gulf shoreline, as previously classified, is composed of deltaic headlands, peninsulas, and barrier islands. Areas undergoing shoreline erosion can be related to this physiographic classification on a regional scale. Deltaic headlands are comprised predominantly of mud with relatively low percentages of sand, a factor that contributes to high rates of severe shoreline erosion. Eroded mud is carried seaward where it is deposited and, hence, removed from the sediment supply system. Brazos Island and south Padre Island of the Rio Grande delta (Brownsville-Harlingen map) and the beach between San Luis Pass and Brown Cedar Cut of the Brazos-Colorado delta (Port Lavaca map) are Holocene deltaic headlands. The Gulf shore from Sabine Pass to Rollover Pass (Beaumont-Port Arthur map) is developed on a relict (Pleistocene) deltaic headland overlain by Modern marsh and strandplain sediments. Bolivar Peninsula (Galveston-Houston map) and Matagorda Peninsula (Bay City-Freeport map) are also undergoing erosion as a result of their close association with the sand-deficient deltaic headlands.

Barrier islands of the Texas Coast, which include Galveston, Matagorda, St. Joseph, Mustang, and north and central Padre Islands (Galveston-Houston, Bay City-Freeport, Port Lavaca, Corpus Christi, and Kingsville maps, respectively) are elongate bodies of fine-grained sand from 20 to 60 feet thick. Rates of shoreline erosion along barrier islands are generally lower because of the increased availability of sand. Apparently, the shoreline along central Padre Island (Kingsville map) is relatively stable because sand is supplied to this segment of the coast by longshore currents that converge in the general vicinity of 27 degrees North latitude (Lohse, 1955). Although considerable sand is removed from the beach by eolian processes along central Padre Island, sufficient sediment to replenish the losses is transported by net longshore currents flowing northward from the southern part of the coast and southwestward from the upper part of the coast.

Bay Shoreline Erosion

Of the 1,100 miles of bay and estuarine shoreline, 408 linear miles or 37 percent of the total bay-estuarine shoreline is undergoing varying rates of shoreline erosion (table 1). At present, research on precise rates of bay-shore erosion has not been completed; bay shorelines undergoing erosion have been interpreted qualitatively. Bay shoreline erosion is related principally to the dominant wind regimes of the region, but hurricanes and tropical storms may inflict bay shores with severe erosion during brief periods of landfall.

Southeasterly winds persist throughout the spring, summer, and fall months, whereas northerly winds of less duration but greater strength persist during the winter months. Wind strength and duration, fetch, depth of water, and orientation of bay shorelines are some of the important factors controlling bay shoreline erosion. In areas where fetch is measured in miles, the southwesterly winds generate waves and currents that impinge and erode shoreline segments along northwestern bay margins; examples occur in Trinity and Galveston Bays (Galveston-Houston map), Matagorda Bay (Bay City-Freeport map), San Antonio Bay (Port Lavaca map), Aransas and Corpus Christi Bays (Corpus Christi map), and Baffin Bay (Kingsville map), as well as in Laguna Madre (Brownsville-Harlingen map). Similarly, northerly winds generate waves that strike and erode southern and southwestern shoreline segments in Galveston, Matagorda, San Antonio, Corpus Christi, and Baffin Bays. Bay shoreline erosion along Matagorda, St. Joseph, and Mustang Islands and Matagorda Peninsula is also caused by waves and currents generated by northerly winds. Sand eroded from bay shorelines is deposited within the bay; some mud derived from shorelines may reach the Gulf, but much of it gradually fills the bay.

FACTORS AFFECTING SHORELINE CHANGES

Studies indicate that shoreline changes along the Texas Gulf Coast are largely the result of natural processes, although in some instances the changes may have been aggravated by human activities. Geologic processes and, more specifically, coastal processes are complex dynamic components of large-scale systems. Coastal processes are dependent upon the intricate interaction of a large number of natural variables such as wind velocity and duration, fetch, rainfall, storm frequency and intensity, tidal range and characteristics, and littoral currents. It is difficult, therefore, if not impossible, to isolate at this time all the specific factors causing shoreline changes.

Climate

Climatic changes during the 18,000 years since the end of the Pleistocene ice age have been documented by various methods. In general, air temperature was lower and precipitation was greater at the end of the Pleistocene than at the present; the warmer and drier conditions, which now prevail, affect other factors such as vegetal cover, runoff, sediment concentration, and sediment yield. Observations based on geologic maps prepared by the Bureau of Economic Geology ("Environmental Geologic Atlas of the Texas Coastal Zone") confirm that many rivers along the Texas coastal plain were larger and probably transported greater volumes of sediment thousands of years ago (early Holocene). This, in turn, affected the sediment budget of the Texas Coast by supplying additional sediment to the littoral drift system.

Severe droughts that occur periodically are a potential, though indirect, factor related to minor shoreline changes because of the adverse effect of low rainfall on vegetation. Because dunes and beach sand are stabilized by vegetation, sparse vegetation resulting from droughts offers less resistance to wave attack. Regional variations in rainfall and wind dominance along the Texas Coast also must exert some differential effect on shoreline stability.

Storm Frequency and Intensity

The frequency of tropical cyclones is dependent on cyclic fluctuations in temperature; increased frequency of hurricanes occurs during warm cycles (Dunn and Miller, 1964). Because of their frequent occurrence, devastating force, and catastrophic nature, tropical cyclones have received considerable attention in recent years. The significance of hurricanes as geologic agents was emphasized by Hayes (1967) who concluded that most of the Texas coastline experienced the passage of at least one hurricane eye during this century. The general nature of tropical storms and hurricanes, as well as their relationship to flood hazard, has been described in this report. The specific relationship between these storms and shoreline stability in Texas also is important in understanding the nature of rapid changes in shorelines.

As previously described, high-velocity winds with attendant waves and currents of destructive force scour and transport large quantities of sand during hurricane approach and landfall (fig. 7). The amount of damage suffered by the beach and adjoining areas depends on a number of factors including angle of storm approach, configuration of the shoreline, shape and slope of Gulf bottom, wind velocity, forward speed of the storm, distance from the eye, stage of astronomical tide, decrease in atmospheric pressure, and longevity of the storm. Beach profiles adjust themselves to changing conditions in an attempt to maintain a profile of equilibrium; shorelines experience their greatest short-term changes during and after storms. Storm surge and wave action commonly plane off preexisting topographic features and produce a featureless, uniformly seaward-sloping beach. Eroded dunes, wave-cut steps, and washover fans are common products of the surge; the sand removed by erosion is (1) transported and stored temporarily in an offshore bar, (2) transported in the direction of littoral drift, and/or (3) washed across the barrier island through hurricane channels. Sediment transported offshore and stored in the nearshore zone is eventually returned to the beach by bar migration under the influence of normal post-storm wave action. The processes involved in beach recovery are discussed by Hayes (1967) and McGowen and others (1970).

Foredunes are an important line of defense against wave attack and, thus, afford considerable protection against hurricane surge and washover. Dunes also serve as a reserve of sediment from which the beach can recover after a storm. Sand that is removed from the dunes and beach, transported offshore, and returned to the beach, provides the material from which small coppice mounds and eventually the large fore-island dunes rebuild. Dune removal, therefore, eliminates sediment reserve, as well as a natural defense mechanism established for beach protection.

Whether the beach returns to its prestorm position depends primarily on the amount of sand available. If net sand is lost, the beach profile will not reestablish itself at the prestorm position; thus, net shoreline erosion or retreat has occurred. The beach profile readjusts to normal prestorm conditions much more rapidly than does the vegetation line. Generally speaking, the sequence of events is as follows: (1) return of sand to beach and profile adjustment (accretion), (2) development of low sand mounds (coppice mounds) seaward of the foredunes or vegetation line, (3) merging of coppice mounds with foredunes, and (4) migration of vegetation line to prestorm position. The first step is initiated within days after passage of the storm and adjustment is normally attained within several weeks or a few months. The remaining steps require months or possibly years and, in some instances, complete recovery is never attained.

Local and Worldwide Sea-Level Conditions

Two factors of major importance relevant to land-sea relationships are sea-level changes and compactional subsidence. Shepard (1960b) discussed Holocene or post ice-age (Pleistocene) rise in sea level along the Texas Coast based on C^{14} age determinations. During historical time, relative sea-level changes are deduced by geodetic engineers who monitor mean sea level using tide observations to develop trends based on long-term measurements. This method, however, does not distinguish between sea-level rise and land-surface subsidence. A minor vertical rise in sea level relative to adjacent land in low-lying coastal areas causes a considerable horizontal, landward displacement of the shoreline.

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

Sediment Budget

Sediment budget refers to the amount of sediment in the coastal system and the balance among quantity of material introduced, temporarily stored, or removed from the system. Beaches are nourished and maintained by sand-size sediment contributed by major streams, updrift shoreline erosion, and onshore movement of shelf sand by wave action. Sand losses are attributed to (1) transportation offshore into deep water, (2) accretion along and against natural littoral barriers and man-made structures, (3) deposition in tidal deltas and hurricane washover fans, (4) excavation for construction purposes, and (5) eolian processes.

Sediment supplied by major streams is transported along the shore by littoral currents. The Brazos River, Colorado River, and Rio Grande are the only major Texas rivers that debouch directly into the Gulf of Mexico, but discharge data indicate that these rivers currently contribute very little sediment to the littoral drift system. The Mississippi River was a possible source of beach sediment prior to its shift to the eastern part of the delta about 400 years ago.

Van Andel and Poole (1960) and Shepard (1960a) suggested that sediments of the Texas Coast are largely of local origin. Sands derived from previously deposited sediment on the floor of the continental shelf were apparently reworked and transported shoreward by wave action during the post ice-age (Holocene) sea-level rise. McGowen and others (1972) also concluded that the primary source of sediment for Modern sand-rich barrier islands, such as Galveston, Matagorda, and St. Joseph Islands, was local Pleistocene and early Holocene sources on the adjacent inner shelf.

FACTORS AGGRAVATING EROSION

Shoreline changes induced by man are difficult to quantify because human activities promote alterations and imbalances in the sediment budget of the Coastal Zone. Furthermore, ground-water withdrawal increases land subsidence. Construction of dams, erection of seawalls, groins, and jetties, artificial stabilization of the Mississippi River, and removal of sediment for building purposes all contribute to changes in quantity and type of beach material delivered to the Texas Coast. Even such minor activities as vehicular traffic and beach scraping can contribute to the overall changes, although they are in no way controlling factors. Erection of impermeable structures and removal of sediment have an immediate, as well as a long-term effect, whereas a lag of several to many years may be required to evaluate fully the effect of other changes such as river control, dam construction, and subsurface fluid withdrawal.

Jetty construction along the Texas Coast was initiated in the late 1800's. These projects serve to alter natural processes such as inlet siltation, beach erosion, and hurricane surge. Their effect on shoreline changes is subject to debate, but it is an obvious fact that impermeable structures interrupt littoral drift, and impoundment of sand occurs at the expense of beach nourishment downdrift of the structure. It appears reasonable to expect that any sand trapped by the jetties is compensated for by removal of sand downdrift, thus increasing local erosion problems.

Factors which have contributed to the deficit in sediment budget include: (1) removal of sand from the fore-island dunes, (2) dredging of sand from the Gulf, (3) excavation of sand from barrier islands and peninsulas, (4) construction of dams on the Rio Grande and Brazos River, and (5) artificial maintenance of the current position of the Mississippi River.

LONG-TERM TRENDS IN SHORELINE POSITION

Shore erosion is not only a problem along United States coasts but also is a problem worldwide. Even though some local conditions may aggravate erosion, major factors affecting shoreline changes are sea-level variation, including compactional subsidence, and a deficit in sediment supply. A deficit in sand supply may be related to climatic changes, human activities, and the exhaustion of the shelf supply through subsequent burial of shelf sand by finer sediments to a depth below wave scour.

A logical conclusion that can be drawn from available information is that shoreline position will continue to change, and landward retreat (erosion) will be the long-term trend. The combined influence of interrupted and decreased sediment supply, relative sea-level rise, and tropical cyclones is insurmountable except in very local areas such as river mouths. There is no evidence to suggest that a long-term reversal may occur in the foreseeable future to change the present trends of shoreline change.

POTENTIAL MITIGATION OF SHORELINE EROSION

The best defense against the hazard of shoreline erosion is recognition and subsequent adjustment in land use. Other alternatives include artificial beach nourishment or artificial stabilization by dune vegetation and structures.

It should be noted, however, that dune stabilization, while appearing to be environmentally sound, can be counterproductive and may have a definite impact on beach steepness and erosion. This was demonstrated on the North Carolina coastline where vegetated dunes resisted storm wave attack so well that the normal exchange of sand between the dunes and beach was eliminated; increased beach steepness and beach erosion resulted from this effort to stabilize the dunes (Dolan and Godfrey, 1973).

The shoreline in Texas could be stabilized at enormous expense by a solid structure such as a seawall. Any beach seaward of such a structure would eventually be removed unless maintained artificially by sand nourishment (a costly and sometimes ineffective practice). The U. S. Army Corps of Engineers (1971b, p. 33) stated: "While seawalls may protect the upland, they do not hold or protect the beach which is the greatest asset of shorefront property." Moreover, construction of a single structure may trigger a chain reaction that will require additional structures and maintenance.

When development plans are being formulated, careful consideration must be given to the evidence that shoreline erosion will continue into the foreseeable future. While beach-front property may demand the highest prices, it may also carry with it the greatest risks.

● LAND-SURFACE SUBSIDENCE ●

GENERAL STATEMENT

Land-surface subsidence, primarily a consequence of ground-water pumping and withdrawal that began in the Texas Coastal Zone in the early part of this century, affects to varying degrees a substantial part of the lower Texas coastal plain. Most serious subsidence is in the Greater Houston area, where some localities show recorded subsidence up to 8.5 feet (Galveston-Houston map). Significantly, both the rate of land subsidence, in terms of lost land elevation, and the area of impact are progressively increasing and have increased dramatically in the past two decades (fig. 13).

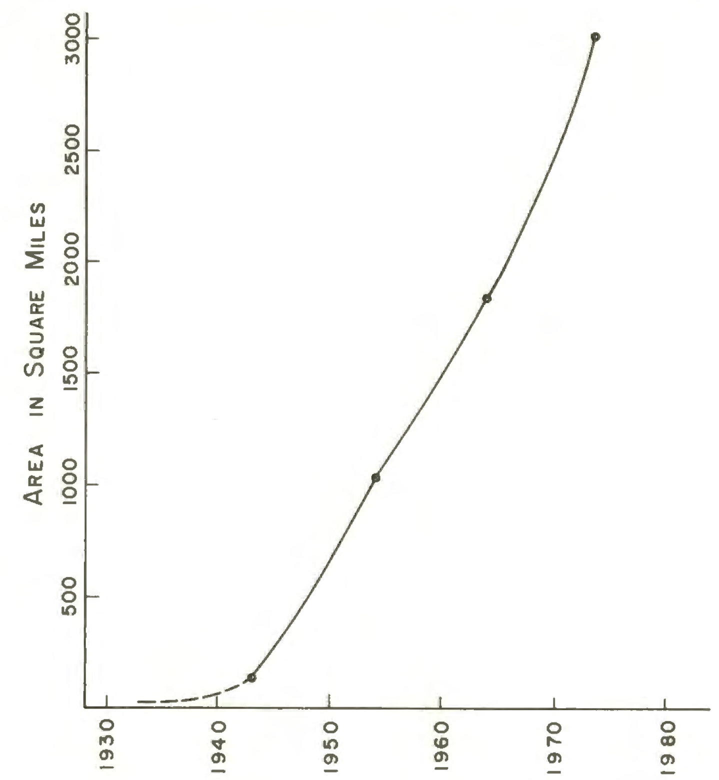


Figure 13. Area in the Texas Coastal Zone impacted by land-surface subsidence in excess of 1 foot between 1943 and 1973. Values are cumulative.

The extent and amount of subsidence are well defined and known through a series of elevation benchmarks established and resurveyed or leveled at selected intervals by the National Geodetic Survey (formerly the U. S. Coast and Geodetic Survey) of the Department of Commerce. The first leveling program was a first-order line from Smithville to Galveston surveyed in 1905 and 1906. In 1918, a first-order line was established from Sinton, Texas, to New Orleans, Louisiana. During the period between 1932 and 1936, several other first- and second-order lines were established, and the two original lines were releveled. In 1942 and 1943, a large number of second-order lines were established and most of the older lines were releveled. Following the leveling program of 1942-1943, subsidence in the Houston area was first documented. Subsequently, releveling surveys were completed in 1951, 1953-54, 1958-59, 1964, and

1973. These surveys clearly establish the extent and amount of subsidence in the lower Texas coastal plain.

Likewise, the cause of subsidence is well documented, primarily through the extensive monitoring of water-well levels, which was started in 1929 by the Water Resources Division of the U. S. Geological Survey. Comparison of areas of water level and piezometric decline with areas of land-surface subsidence clearly shows that they are coextensive. Results of monitoring by the U. S. Geological Survey have been reported in several papers; refer especially to those reports by Gabrysch (1969, 1972), Gabrysch and McAdoo (1972), and Gabrysch and Bonnet (1974) as well as to reports by Marshall (1973) and Turner, Collie, and Braden, Inc. (1966). Portions of this section of the atlas have been drawn from these previously published reports.

Although the principal cause of subsidence is ground-water withdrawal, a minor amount of subsidence can be attributed to natural compactional subsidence, to tectonic subsidence, and locally, to the withdrawal of oil, salt, and sulfur. Subsidence resulting from mineral extraction has been restricted largely to areas of production on and adjacent to certain coastal salt domes. More than 3 feet of subsidence at the Goose Creek oil field was caused by oil production, resulting chiefly from poor production practice in the early history of the field (Pratt and Johnson, 1926).

While the extent, amount, and mechanisms of land-surface subsidence are well documented, methods for mitigating the problem, short of massive curtailment of ground-water pumping, are not evident. Variations in the lithologic composition of the aquifers, as well as local difference in hydrologic behavior, suggest that certain areas are more prone to subsidence than are others.

CAUSE AND MECHANISMS OF LAND SUBSIDENCE

Most of the ground-water production in the Texas coastal plain is from aquifers occurring from near the surface to depths as great as 3,000 feet. The geologic formations involved are composed of varying amounts of alternating sands (the aquifers) and interstratified clays. Significantly, the clays are water saturated and undercompacted; clays nearer the surface are commonly less compacted than those at greater depths. The aquifer sands and interbedded clays dip gently toward the coast; they crop out in a general coastwise-trending belt extending from about 30 to 50 miles inland from the coastline. It is in the zone of outcrop that the aquifers are recharged by infiltration of fresh water. Principal water production is from the Lagarto and Goliad Formations (Evangeline Aquifer), and from the Willis, Lissie, and Beaumont Formations (comprising the Chicot Aquifer). Earlier authors referred to these two aquifers simply as the Principal Aquifer. Similarly, in certain areas of the northeast part of the Coastal Zone, sands above the Principal Aquifer were referred to as the Alta Loma sands or the Alta Loma Aquifer.

Prior to 1900, before heavy pumping commenced, water wells in the artesian aquifers flowed naturally; that is, the aquifers were under sufficient pressure to force water to the land surface within open wells. Subsequent pumping, especially in the past three decades, has resulted in a continuing decline in artesian pressure or piezometric surface over wider and wider areas. Geologists and engineers of the U. S. Geological Survey, who started monitoring water levels in coastal plain wells in 1929, have charted the long-term decline in the pressure levels. In 1943, maximum decline of the water level was about 150 feet; by 1954, the piezometric level had dropped to about 300 feet; by 1964, it had declined to about 350 feet; and in 1974, it locally has declined to 400 feet. Comparison of areas of pressure-level decline and areas of subsidence show clearly their coextensive nature (figs. 14, 15).

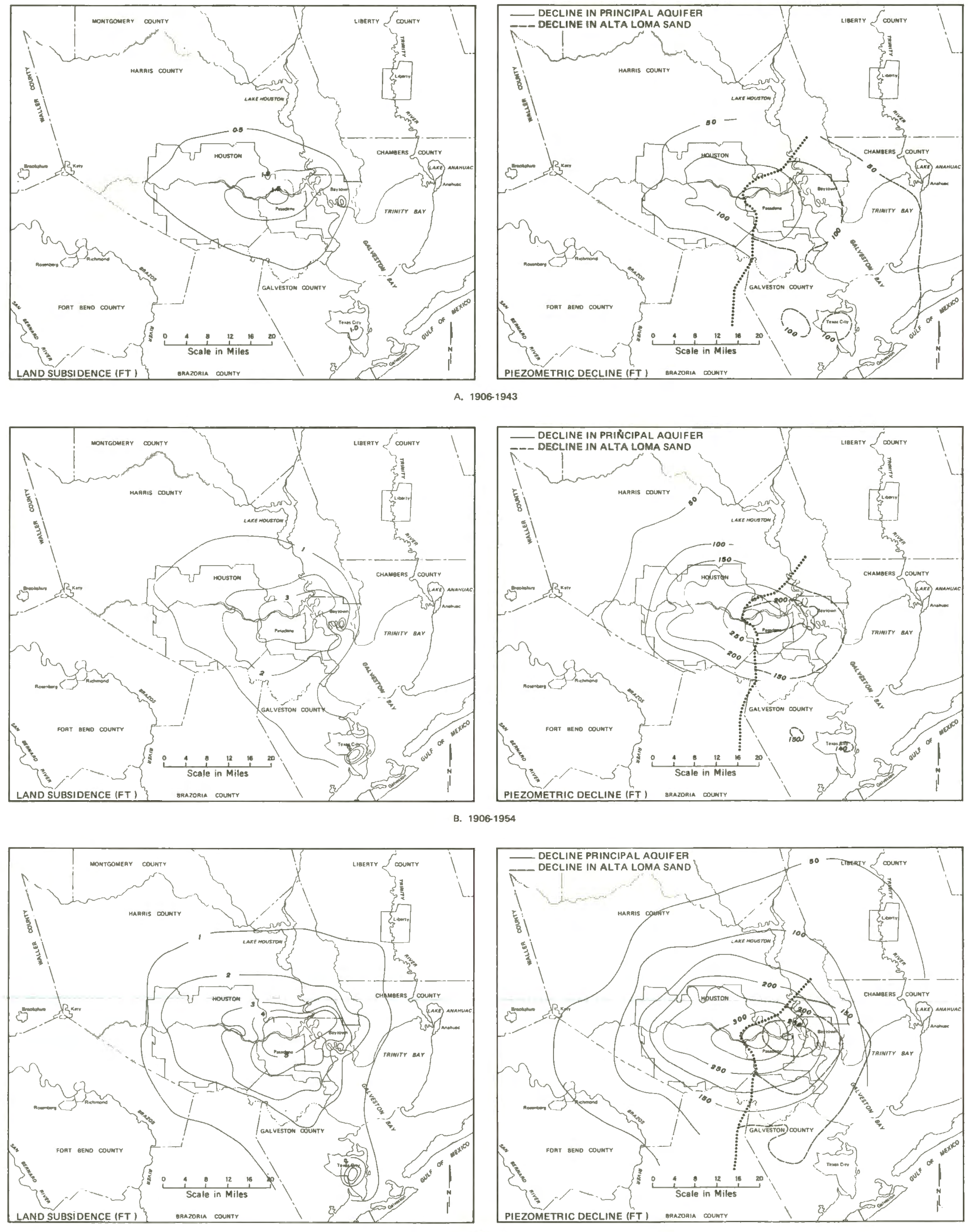


Figure 14. Land-surface subsidence and decline of piezometric (ground-water) surface within Principal and Alta Loma Aquifers, 1906-1963, Greater Houston area. Modified after Marshall (1973).

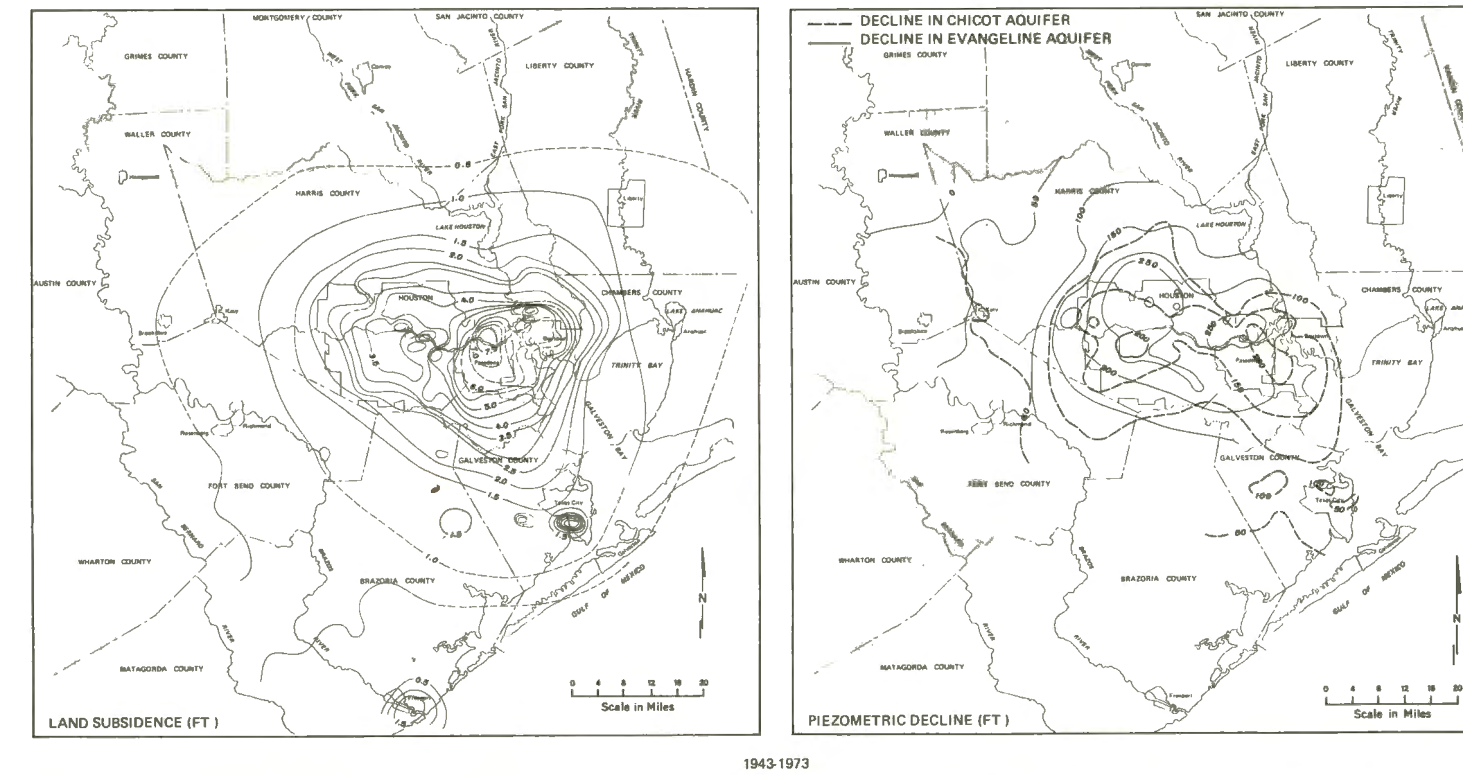


Figure 15. Land-surface subsidence and decline of piezometric (ground-water) surface within Evangeline and Chicot Aquifers, 1943-1973, Greater Houston area. After Gabrysch and Bonnet (1974).

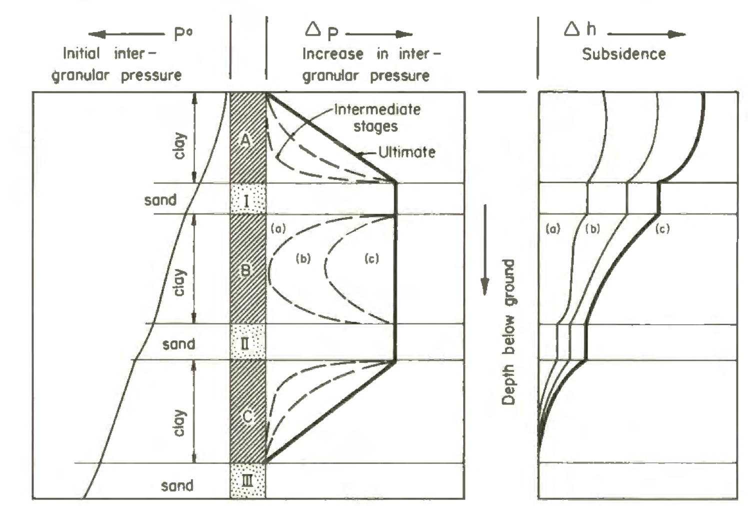


Figure 16. Effects of ground-water withdrawal on intergranular pressure, with consequent volume reductions and surface subsidence. After Turner, Collie, and Braden, Inc. (1966).

The water-saturated clays that occur interstratified with the aquifer sands are compressible and become compacted when subjected to increased load. This reduction in volume of the compressible clays is translated to surface subsidence. Reduction in artesian pressure from pumping causes a loss of buoyant support to the granular structure of the aquifer sands (decreased pore pressure), and each layer is, therefore, subjected to a corresponding increase in effective vertical pressure. This decreased pore-pressure effect is immediately transferred to the contact surface with interbedded clays, but, because of the low permeability of the clays, the clays drain more slowly (fig. 16). The clay layers compress vertically and become thinner; consequently, the overlying sediments and the ground surface subside.

The amount of subsidence that will occur is directly related to the decline in piezometric level, which is a function of the volume of water withdrawn from the aquifer. The amount of subsidence, however, will vary further depending upon the amount of clay within the aquifer section, the vertical distribution of the clay, the compressibility of the clay, and finally, the degree of undercompaction of the clay in its natural state. The amount of clay in the aquifer and the number of clay beds within the aquifer sands, as well as the compressibility of the beds, vary areally; certain areas are more prone to subsidence than others, even with the same amount of ground-water withdrawal and comparable levels of piezometric decline.

Compaction of the clays and resulting subsidence are nearly 100 percent irreversible (a small rebound may be possible). Further, additional subsidence may occur even if ground-water withdrawal is reduced and the decline in piezometric levels is arrested. This is because of a lag between the addition of the load and ultimate compaction of the clays. Computations by Marshall (1973) indicated that additional subsidence after water-level decline ceases will be at least 50 percent and possibly as much as 150 percent of the subsidence experienced prior to that time. Gabrysch and Bonnet (1974) state that only 15 to 20 percent of additional subsidence will occur. R. O. Kehle (personal communication, 1974), however, suggests that subsidence may stop immediately if piezometric decline is arrested. Variation in the percentage of eventual subsidence, even after arrest of piezometric decline, is also a function of the amount and nature of clays occurring within and associated with the aquifer. Eventual subsidence, therefore, should be variable and will depend on the geologic nature of the aquifer.

EXTENT OF LAND SUBSIDENCE

Land subsidence, both in amount of land elevation lost and in area affected, has been increasing significantly during the past three decades. Coincident with accelerating subsidence have been increases in the volume of water withdrawn and decline of artesian pressure levels. In 1943, when releveling recorded the first measurable subsidence, a little more than 140 square miles of land in the Houston region had subsided 1 foot or more, with maximum subsidence of about 1.5 feet. By 1954, about 1,000 square miles of land had experienced subsidence in excess of 1 foot, with maximum subsidence up to 4 feet. In 1964, more than 1,800 square miles of land had subsided more than 1 foot, with maximum subsidence up to 6 feet. By 1974, more than 3,000 square miles of land on the lower Texas coastal plain had undergone more than a foot of subsidence, and maximum subsidence had reached 8.5 feet (Galveston-Houston map). The area of lands impacted by subsidence of 1 foot or more has doubled approximately each decade for the past 30 years. At the present time, about 230 square miles of land, centering on Pasadena, has subsided more than 5 feet.

Measurable subsidence, defined herein as 0.2 foot and greater, now impacts three areas of the lower Texas coastal plain: (1) an extensive area of the upper Texas coastal plain extending from Bay City northward into Louisiana and inland as much as 60 miles (Bay City-Freeport, Galveston-Houston, and Beaumont-Port Arthur maps); this zone includes the critically impacted Greater Houston area; (2) a large part of Jackson County (Port Lavaca and Bay City-Freeport maps); and (3) an area in Nueces and San Patricio Counties centered near the community of Odem (Corpus Christi map). Maximum subsidence in the Corpus Christi area is in excess of 1 foot, with the distribution of subsidence showing a pattern remarkably similar to that of the Houston area in 1943.

Subsidence values shown on the Natural Hazards Maps were calculated with data derived from various releveling surveys conducted by the National Geodetic Survey. Periodic releveling data are limited; therefore, the boundaries between subsidence zones are *approximate*. Three subsidence zones, (1) 0.2 foot to 1 foot, (2) 1 foot to 5 feet, and (3) greater than 5 feet, are based on *maximum recorded subsidence* for any particular benchmark or level station. In some areas, the "total" amount of subsidence has been determined from elevation differences recorded at a benchmark for relatively short periods of time (for example, 1951 to 1973); in other areas with more data, the measured subsidence includes elevation differences recorded for longer periods of time (for example, 1905-1973). This approach of using net or maximum elevation variation at each benchmark provides a map that displays maximum recorded subsidence.

Land subsidence is minimal in the zone of 0.2-foot to 1.0-foot subsidence and has progressed substantially in the zone defined by subsidence in the range of 1 foot to 5 feet. Within the zone of maximum subsidence (greater than 5 feet and, currently, less than 8.5 feet), land subsidence is a factor that requires careful consideration both in urban and industrial development and in maintenance of public facilities. The three zones provide a perspective of the land-subsidence problem consistent with the map scale and goals of the Natural Hazards Maps. The reader may wish to refer to specific studies on land subsidence; e.g., Marshall (1973) and Gabrysch and Bonnet (1974).

PROBLEMS CAUSED BY LAND SUBSIDENCE

The most obvious consequences of land subsidence in coastal areas are actual loss of lands in low-lying tidal areas and submergence of structures along these subsiding coastlines. Equally threatening is the loss of ground elevation and the potential subjection of more land to the natural hazard of flooding, either by hurricane surge or stream runoff. For example, assuming an ultimate subsidence of 10 to 12 feet in the Greater Houston area, it is estimated that approximately 20,000 acres (about 31 square miles) of land may be lost by the year 2000; substantially more land could be lost if ultimate subsidence is greater. Furthermore, if storm tides with the same surge height as those generated by Hurricane *Carla* in 1961 were to strike upper Galveston Bay today (1974), an additional 70 square miles of subsiding lands, much of it extensively developed, would be flooded by hurricane-surge waters.

Depending upon original topography, subsidence can result in change of land slopes, stream gradients, and stream drainage patterns. Changes and reversals in land slope can and have caused problems in such gravity transport systems as water and sewerage lines.

Although land subsidence is regional in pattern and is regionally expressed as "bowls" of subsidence, recent studies by the Bureau of Economic Geology indicate that, in detail, subsidence tends to occur in blocks. Such movements are shown by abrupt changes in detailed land-subsidence profiles (fig. 17); a great number of the downward-subsiding blocks shown on these profiles are bounded by active faults. Such faults are posing additional problems for areas of subsidence.

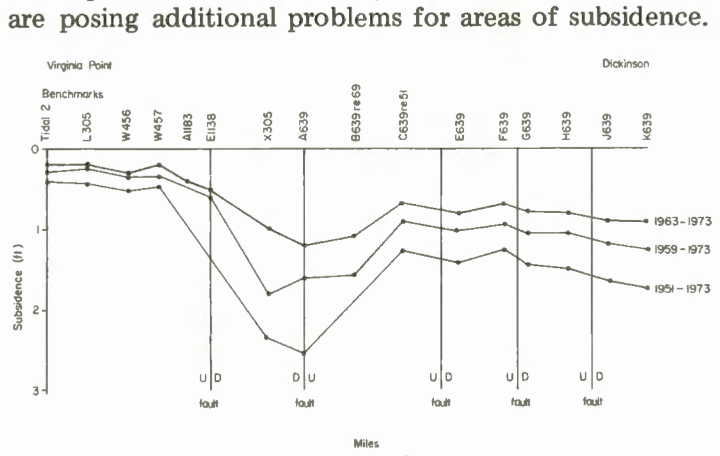


Figure 17. Correlation of active faults with sharp breaks in land-subsidence profiles. Elevation data from National Ocean Survey (formerly U. S. Coast and Geodetic Survey). Profile parallels State Highway 3 south of Dickinson, Texas, Galveston-Houston map area.

The particular hazard of surface faulting and associated problems is discussed in the chapter, *Faulting*. Subsidence of shoreline lands along the open Gulf and bay shorelines, which can measurably increase the already critical natural hazard of shoreline erosion, has been discussed under *Shoreline Erosion*.

MITIGATION OF LAND SUBSIDENCE AND ASSOCIATED PROBLEMS

Although the withdrawal of ground water in the lower Texas coastal plain is the principal cause of subsidence and associated problems, use of ground water has proved to be a significant economic benefit. At the present time, for example, about 650 million gallons per day are withdrawn from aquifers in the Greater Houston area. The cost of ground water is significantly less than the cost involved in transporting and treating surface water. Ground water is, therefore, an important natural resource in the coastal area of the State and its use results in substantial savings to the users. A recent report on the economics of subsidence (Warren and others, 1974) suggests that the total cost of land loss and damage to structures may exceed the cost difference between surface water and ground water. The problems caused by subsidence and ground-water withdrawal must be evaluated in the context of the economic alternatives.

Land subsidence that has occurred in the Coastal Zone is irreversible and, due to lag time in clay compressibility, may continue to a substantial degree, even if pressure-level declines are arrested. Mitigation of the impact already experienced and that which will inevitably be experienced in the future can only be accomplished either by vacating the impacted lands or by constructing protective structures. Of principal concern is the maintenance of lands subject to water encroachment, particularly those subject to flood inundation. Construction of protective structures is the only means of mitigating the problems of flooding in areas already developed. Several dikes and levees have already been built in critically impacted areas; the elevation of many of these will have to be raised and others constructed. The U. S. Army Corps of Engineers has investigated the possibility of constructing an extensive hurricane barrier system across the southern end of Galveston Bay; the costs of constructing and maintaining this system can be weighed against its benefits in protection from flooding and inundation. For other areas where subsidence is occurring but where development has not yet taken place, nonstructural methods such as zoning for certain uses might be more feasible.

Finally, the modification of the historical pattern of ground-water withdrawal in the Texas coastal plain can effectively mitigate subsidence and its associated problems. Such a plan will necessarily involve significantly less withdrawal of ground water, but a variety of other mitigating factors should be considered. Different levels of subsidence and associated problems may be tolerated; for example, subsidence is clearly a much greater problem in low-lying, developed areas than it is in less developed areas or in areas at higher elevations. The aquifers, of course, are homogeneous neither in geologic nor in hydrologic character; aquifers with a minimum of intercalated muds can sustain more withdrawal than aquifers containing a large number of undercompacted clay beds. Other mitigating factors include the extent to which associated clays are compressible and the extent to which compression and consolidation have already taken place, both naturally and as a result of ground-water production. Hydrologic variations indicate that certain aquifers can sustain greater ground-water production with less severe declines in artesian pressure than can others. Accordingly, detailed analysis and mapping of the geologic and the hydrologic character of the coastal aquifers might permit delineation of preferred production areas and pumpage levels (natural carrying capacity). This approach could provide the necessary base for determining the maximum amount of withdrawal and the density of producing wells that can exist within prescribed acceptable levels of subsidence. Ultimately, acceptable levels of subsidence or nonsubsidence could be defined, depending on such factors as present state of development and original or present topography or land elevation.

Ground water in the Texas coastal plain is and should be considered a very valuable natural resource. Nevertheless, if subsidence and the several associated problems are to be mitigated, use of ground water, both in water volume and well density, must be adjusted to the carrying capacity of the aquifers. This will require a modification of historical use patterns and most certainly some reduction in the amount of ground water used in given areas, but it need not involve a complete curtailment of ground-water use and withdrawal.

● FAULTING ●

GENERAL STATEMENT

Active surface faults in the Texas Coastal Zone have become an important geologic hazard which daily affects the economic well-being of the people in this area. Active faults severely damage houses, apartment complexes, and industrial plants. Some city streets, farm-to-market roads, and interstate highways must be continually repaired because of fault damage; faults also cross the runways of Hobby Airport and Ellington Air Force Base. Active faults intersect the extensive railroad network at several places, weakening rails, ties, and roadbed, and creating a potential for future derailments.

EXTENT OF ACTIVE FAULTING

Active surface faults are relatively common in parts of the Texas Coastal Zone. Most active faults that have been recognized occur in the Galveston-Houston map area, where 95 linear miles of faulting are shown on the Natural Hazards Map. Many other active faults exist inland from the map area. An active surface fault about 4 miles long also occurs in the Corpus Christi map area. There are 96 miles (table 1) of known active faults in the entire area covered by this report; locations of the faults have been compiled from studies by other workers (Weaver and Sheets, 1962; Van Siclen, 1967; Sheets, 1971; Reid, 1973; Clanton and Amsbury, 1974) and as the result of recent mapping in this region by the Bureau of Economic Geology. More detailed mapping in the future will undoubtedly locate more faults, and possibly may discount some faults already mapped. In addition, new faults may be generated in areas of land-surface subsidence.

IDENTIFICATION OF ACTIVE FAULTS

Active faults are defined as faults which have had movement since the end of the Pleistocene (ice age) about 20,000 years ago. Most of the faults shown on the Natural Hazards Maps, however, have moved in the last 30 years.

Four lines of evidence have been used in this atlas to identify active faults: (1) breaks in street pavements, foundations, highways, airport runways, and swimming pools involving vertical displacement (cover photograph); (2) topographic scarps defined by an abrupt steepening of land surface along uniform slopes or flat areas; (3) sharp breaks in rates of subsidence as determined from cumulative topographic profiles; and (4) linear tonal anomalies on black-and-white and on color-infrared aerial photographs. All active faults shown on the Natural Hazards Maps have been verified by ground observation; most of these features have not been subjected to subsurface analysis.

The presence of cracks in highways and structures, coupled with evidence of continual repaving of highways or repairing of buildings, is an excellent guide for locating active faults. This type of evidence is considered the most reliable because it shows the precise location of the surface expression of the fault and indicates that the fault is presently active. A fault crossing a parking lot at Ellington Air Force Base is shown on the cover of this atlas; this fault also extends across the runways, causing extensive, continuing damage to the landing surfaces.

Changes in the elevation of survey benchmarks can also be used to delineate location and amount of movement along faults. Topographic profiles break sharply across active faults. A subsidence profile, based on cumulative, first-order topographic leveling data from Virginia Point to League City (along State Highway 3 in Galveston County), is one of several such profiles that shows changes in topographic slope at the intersections of level lines and faults (fig. 17). This technique is capable of pinpointing very slight changes in differential subsidence; the only drawback to the method is that the benchmarks are generally located a mile apart; this distance precludes a precise location of the active fault with the level profile.

Low topographic scarps may show the exact location of a fault, but it is difficult to determine if the fault is presently active or inactive. The continuation of such topographic scarps into a continually cracking highway pavement nearby does confirm, however, the recent activity of the fault.

The least confirmatory method for locating faults is the identification of linear tonal anomalies on black-and-white and on color-infrared photographs. Nearly all active faults can be identified on aerial photographs, but not all linear tonal anomalies are active faults. Aerial photographs are a very important tool, however, because they identify areas where more intensive ground study should be conducted. Several of the active faults on the Galveston-Houston area map were initially identified by this technique and later substantiated by field work.

GEOLOGIC CONTROLS OF FAULTING

Mapped surface faults and the surface trace of subsurface faults that are projected to the land surface exhibit a strong parallelism. At this time, however, there are only a few cases for which sufficient data are available to reliably connect the surface-expressed fault with a verified subsurface fault. Two such examples are the Addicks fault in the Fairbanks oil field northwest of Houston (Van Siclen, 1967) and the Clarksville fault in the Saxet oil field west of Corpus Christi (Poole, 1940). Both of these faults can be traced to depths of 7,000 feet. The Saxet fault is shown on the Natural Hazards Map of the Corpus Christi area. The Addicks fault occurs immediately northwest of the Natural Hazards Map of the Galveston-Houston area.

Several linear tonal anomalies, along which there has been no perceptible fault movement, also correlate with subsurface faults. Subsurface faults extrapolated to the land surface in the Angleton oil field, the Blessing oil field, and the West Columbia oil field generally coincide with both location and orientation of linear tonal anomalies. The lack of detailed well control and seismic data, however, prevents a definitive conclusion that, in these cases, the surface lineation and subsurface fault are in fact coincident.

The similarity in trend of surface and subsurface faults indicates that most surface faults are probably genetically related either to long-trending coastwise fault systems extending upward from several thousand feet below surface and/or to faults associated with the numerous salt domes of the area. Faults radiating from salt domes may explain why some surface faults trend perpendicular to the common coastwise trend. Where verified, the association between surface and subsurface faults indicates that some surface faults are products of natural geologic processes.

Faults of the Coastal Zone have been explained by a number of processes: (1) deposition of sediments (Carver, 1968); (2) upward movement of salt masses to form salt domes (Quarles, 1953); (3) gulfward creep of the coastal landmass (Cloos, 1968); and (4) bending of the landmass due to regional tectonics. Sediment loading, salt movement, and gulfward creep are probably the dominant causes for fault development in the Coastal Zone. Sediment accumulation in the present-day Gulf Coastal Zone, however, is occurring principally in the area of the Mississippi delta; there is little evidence to document continued growth in the salt domes or a natural gulfward creep of unconsolidated sediments.

METHODS OF FAULT ACTIVATION

Faults in the Texas Coastal Zone are products of natural geologic phenomena. Geologic evidence suggests that fault activity today should be a relatively minor process. The frequency and activity of fault movement, nonetheless, is increasing. There are clear indications that certain of man's activities, such as ground-water withdrawal and oil and gas production, are causing this increase in fault activation. In the Houston-Galveston-Baytown area, where there has been heavy withdrawal of ground water, oil, and gas and extensive concomitant subsidence, several faults have become active. Nearly all faulting has occurred in areas where the potentiometric surface (piezometric surface) has dropped over 100 feet and where there has been at least 1 foot of land-surface subsidence (Galveston-Houston map). Of course, these areas of heavy ground-water usage are also the areas of greatest land use and, hence, the presence of active surface faults and their effect is more likely to be noticed than in areas of less intense use.

The monitoring of movement on the Long Point fault and the Eureka Heights fault in western Houston shows a direct correlation between vertical fault displacement and change in the potentiometric (piezometric) surface of the Chicot Aquifer (fig. 18). In March of each year, when the potentiometric surface begins to drop, movement along the Long Point fault becomes more rapid. In October, when ground-water pumpage decreases, the potentiometric surface rises and the rate of fault movement decreases. Some rebound even occurs on the Eureka Heights fault.

Faults are being activated by natural as well as man-induced phenomena. The Long Point fault in western Houston appears to be moving for normal geologic reasons and because of man-induced phenomena. A topographic map with a 1-foot contour interval, surveyed before 1920, shows a topographic scarp coinciding with the location of the Long Point fault (Van Siclen, 1967). The curve of the fault displacement for the Long Point fault (fig. 18) at section *a-a'* shows movement even though there is decreased ground-water production and a rising potentiometric surface, possibly indicating a natural method of activation.

Man-induced fault movement may occur by two different mechanisms: differential consolidation of sediments and landslide-type failure caused by vertical

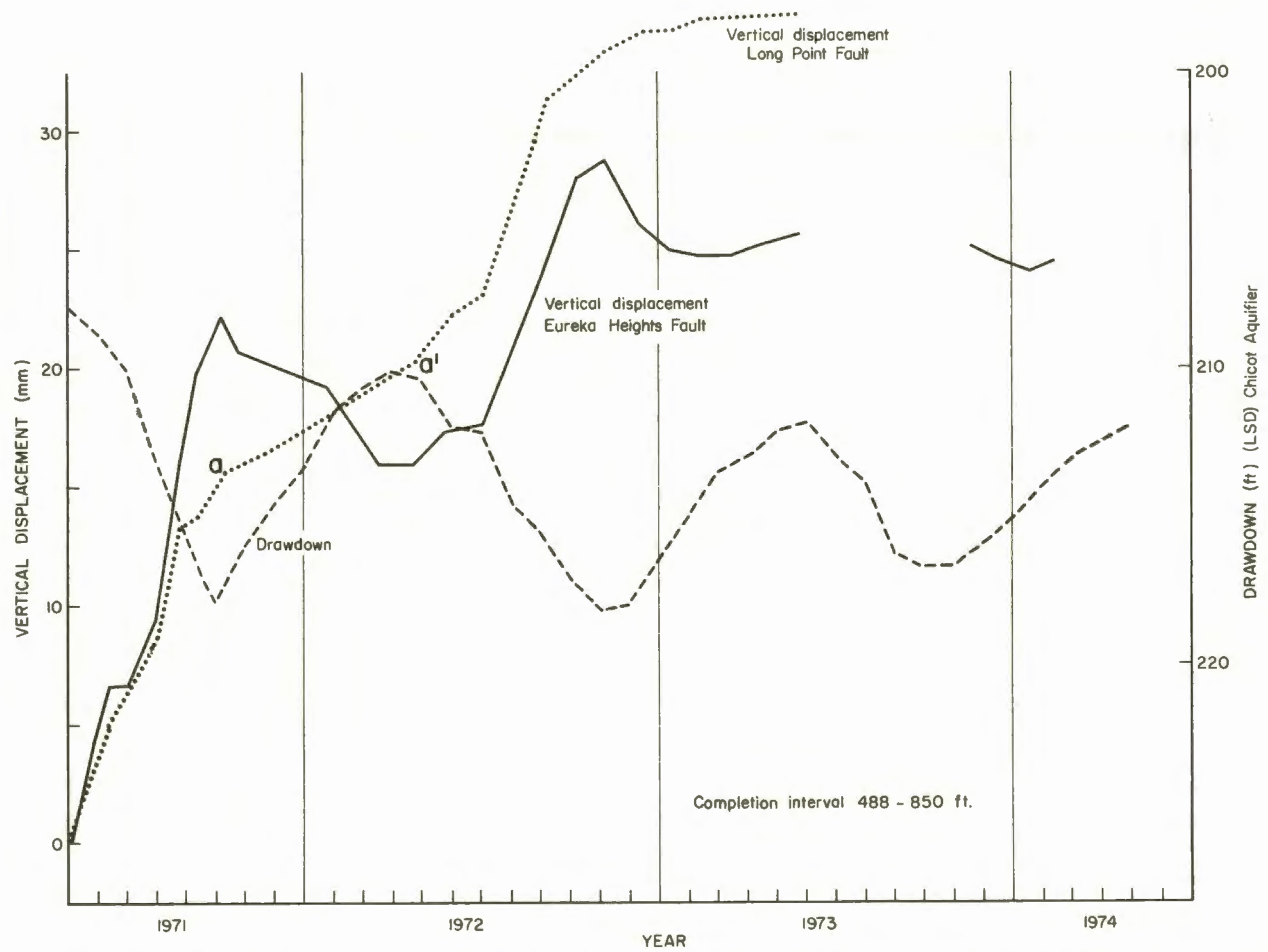


Figure 18. Vertical displacement on Long Point and Eureka Heights faults in western part of Houston compared to drawdown of piezometric surface of Chicot Aquifer. Displacement data for April 1971 to April 1972 from Reid (1973); displacement data for May 1972 to January 1974 and drawdown data for piezometric surface for federal observation well LJ-65-13-408 from R. Gabrysch (personal communication, 1974).

seepage forces. *Differential consolidation of sediments* can occur (1) if there is more mud on one side of a fault than on the other because of a *facies change*, or (2) if the fault acts as a *hydrologic barrier* to fluid migration. The amount of land-surface subsidence by consolidation of sediments depends, in part, on the amount of compressible clay associated with a sand aquifer. Many growth faults in the subsurface of the Gulf Coast area are located at major *facies boundaries*, separating, for example, prodelta muds from deltaic sands. If growth faults were active during the Pleistocene, they may have caused appreciable facies variations in the Chicot Aquifer. An equal lowering of the potentiometric surface across a fault with different clay-sand ratios (facies) on either side will result in different amounts of consolidation and differential land subsidence.

The amount of land subsidence at any particular point is also controlled by the amount of decline in the potentiometric surface, as well as by the amount of mud within the aquifer system. If a fault acts as a *hydrologic boundary* and causes the potentiometric surface to be at different elevations on either side of the fault, there will be different amounts of consolidation that may be expressed as fault movement at the land surface.

Vertical displacement on the Eureka Heights fault demonstrates fault activation by differential consolidation of sediment (fig. 18). The rebound of vertical displacement shown on the graph can be explained by the slight expansion of elastic sand bodies within the aquifer on only one side of the fault. Rebound can occur if there is a hydrologic boundary or if there is a significant lateral change in the composition (facies) of the aquifer.

Faults may also be activated by increasing the overburden pressures (vertical effective stress), resulting in a *landslide-type failure*. If the Gulf Coast sediments are treated as a large landslide, they are unstable with a factor of safety less than 1.0 (Reid, 1973). The Coastal Zone theoretically should be slowly sliding into the Gulf of Mexico. An increase in effective overburden pressures (analogous to loading at the head of a landslide) should cause the unstable mass of sediments to move more rapidly toward the Gulf of Mexico and initiate an increase in active faulting.

An increase in effective overburden pressure is accomplished by dropping the potentiometric surface in an artesian aquifer. The downward flow of water from a shallow, unconfined aquifer and overlying aquitards to the artesian aquifer transfers some of its energy to the sediments through frictional lag, causing an increase in the effective stress in the direction of ground-water flow. This increase in stress is known as "seepage pressure." The effective overburden pressure in a static system at any particular point in the subsurface is approximately equal to the bouyant weight of the sediments. The additional seepage is equal to the decline in the potentiometric surface times the unit weight of water (Lofgren, 1968). For example, at a depth of 400 feet, the effective overburden pressure is equal to approximately 170 pounds per square inch (psi). A drop in the potentiometric surface of 200 feet will cause an additional effective overburden pressure of 86 psi or a 50-percent increase in the effective overburden pressures, which would be the same as depositing an additional 200 feet of saturated sediment over the Houston and Baytown area. In some places in the Houston area, the potentiometric surface has dropped over 400 feet. This increase in overburden pressure may be enough to activate some faults in the Gulf Coast sediments.

Natural movement, differential consolidation, and landslide-type failure are all important mechanisms for fault activation; their relative importance in the Texas Coastal Zone has not yet been determined. Fault activation by oil and gas exploitation has also been documented in the Texas Coastal Zone. Pratt and Johnson (1926) observed fault activation in the Goose Creek oil field. The Clarkwood fault west of Corpus Christi, which exhibits a 4.5-foot scarp, was probably caused by oil production from the Saxet oil and gas field. The extensive faulting over the Clear Lake oil field also may have been caused by oil production.

MITIGATION OF PROBLEMS ASSOCIATED WITH FAULTING

One of the purposes of including the trace of active faults on the Natural Hazards Maps of this atlas is to help explain the reason for continual repair problems in particular areas (e.g., highways, city streets, and train tracks) and to delineate those areas where special care may be required in future development. It stands to reason that man-made structures should be built with full knowledge of potential foundation problems.

Another related problem is the distance a structure should be built from a fault. Along some faults, the scarp (the topographic expression) is narrow, perhaps less than 30 feet wide, such as the fault in the town of Hitchcock. Structures can be located safely in close proximity to these kinds of faults, especially when special engineering techniques are applied. Other faults have relatively wide scarps. For example, the topography in the area of the Long Point fault where it crosses Memorial Drive in western Houston appears to be altered up to 150 feet on either side of the fault (Reid, 1973). Construction of large, heavy structures should be carefully designed for or perhaps even eliminated from this wide zone, whereas light structures, such as houses, may not be adversely affected. The width of these hazardous zones needs to be evaluated for each fault. Because the coastal plain is so flat, unlevel land adjacent to an active fault is probably an indication that the area is being affected by recurring fault movement. Subtle variations in topography can best be determined by measuring the change in slope with surveying equipment. These slight variations can also be determined by detailed analysis of benchmark-level data.

The rate of movement along a Coastal Zone fault is another factor of importance to the people of the region. The sudden movement along a California-type fault produces earthquakes and does extensive damage to areas not even close to the active fault. Fault movement in the Texas Coastal Zone, however, is gradual, and earthquakes are *not* a hazard. The amount of surface displacement that can be recognized on the Coastal Zone surface faults ranges up to as much as 40 feet at the Hockley scarp northwest of Houston. This accumulated displacement has, however, occurred over a long period of time predating man's settlement of the Coastal Zone. Most fault scarps in the Coastal Zone are no more than a few feet high. In Houston, the average rate of displacement has been estimated to be 1.3 inches per year (Reid, 1973). It is feasible to build structures across these faults as long as they are designed so that engineering techniques can compensate for differential offset.

Faults of the Texas Coastal Zone need not be a problem. Future construction on faults can be avoided, and where this is impossible, the awareness of faults will permit architects and engineers to design structures that can accommodate the low rates of differential movement. Decreased ground-water usage may tend to deactivate many of the faults (fig. 18). Technically, this method of fault mitigation is possible.

CONCLUSIONS

A number of natural hazards affect the Texas Coastal Zone. Some of these hazards are actually increasing in magnitude, but the impact of all hazards obviously becomes more critical with increased development in the Coastal Zone. The degree of impact and the damage and loss resulting from natural hazards depends upon the particular use made of hazard-prone lands. Mitigation of the impact of natural hazards can lead to significant reduction of losses currently sustained or likely to be sustained in the future.

Clearly, the first step in mitigating the effects of natural hazards is adequate and comprehensive delineation of hazard-prone lands and of processes that give rise to the hazard. "Natural Hazards of the Texas Coastal Zone" is a first effort in delineating hazard-prone lands and in attempting to explain, with current knowledge, the processes leading to the hazard. Second, the present and projected use of hazard-prone lands needs to be determined and inventoried. Third, hazard impact, in terms of frequency, extent, and severity, can be assessed in terms of the relation of costs to benefits. Special attention needs to be directed to those natural hazards that may pose a threat to life or property. Cost-to-benefit analysis can also be applied to determine whether it is feasible to undertake technological and engineering programs aimed at mitigation. For hazard-prone lands already developed, the construction of hazard prevention structures is the only recourse in hazard mitigation; for hazard-prone lands that have not been developed, a variety of alternative measures may prove to be both economical and appropriate.

In a recent study by the California Division of Mines and Geology (Alfors and others, 1973), the total projected loss to the State of California from natural hazards over the period 1970 to 2000 is estimated to be $55 billion. While California has some hazards not common to Texas, such as earthquakes, Texas experiences some natural hazards that do not occur in California. Importantly, the California report estimates that $38 billion of the $55 billion loss, or about 70 percent, can be prevented by applying current state-of-the-art loss reduction or hazard mitigation measures. These measures include technological and engineering approaches, as well as methods involving zoning and preventative planning. Further, these hazard mitigation measures can be applied at a cost of $6 billion over the 30-year period. A comparable overall cost-to-benefit ratio generally would be applicable in the Texas Coastal Zone. In addition to satisfying the need for increased public safety and fulfilling the social and political requirements, natural hazard reduction and mitigation is simply good business.

● SELECTED REFERENCES ●

Alfors, J. T., Burnett, J. L., and Guy, T. E., Jr., 1973, Urban geology master plan for California: The nature, magnitude, and costs of geologic hazards in California and recommendations for their mitigation: California Div. Mines and Geology, Bull. 198, 112 p.

Andrews, P. B., 1970, Facies and genesis of a hurricane-washover fan, St. Joseph Island, central Texas coast: Univ. Texas, Austin, Bur. Econ. Geology Rept. Inv. 67, 147 p.

Behrens, E. W., 1969, Hurricane effects on a hypersaline bay, *in* Castañares, A. A., and Phleger, F. B., eds., Lagunas Costeras, Un Simposio: Mexico, D. F., Universidad Nac. Autónoma de Mexico, UNAM-UNESCO, Mem. Simposio Internat. Lagunas Costeras, p. 301-312.

Bodine, B. R., 1969, Hurricane surge frequency estimated for the Gulf Coast of Texas: U. S. Army Corps Engineers, Coastal Eng. Research Center Tech. Mem. 26, 32 p.

Bryant, E. A., and McCann, S. B., 1973, Long and short term changes in the barrier islands of Kouchibouguac Bay, southern Gulf of St. Lawrence: Canadian Jour. Earth Sci., v. 10, no. 10, p. 1582-1590.

Carr, J. T., Jr., 1967, Hurricanes affecting the Texas Gulf Coast: Texas Water Devel. Board Rept. 49, 58 p.

Carver, R. F., 1968, Differential compaction as a cause of regional contemporaneous faults: Am. Assoc. Petroleum Geologists Bull., v. 52, no. 3, p. 414-419.

Clanton, E. S., and Amsbury, D., 1974, Open fissures associated with subsidence and active faulting in the Houston area, Texas (abs.): Geol. Soc. America, Abs. with Programs, v. 6, no. 7, p. 688-689.

Cloos, E., 1968, Experimental analysis of Gulf Coast fracture patterns: Am. Assoc. Petroleum Geologists Bull., v. 52, no. 3, p. 420-444.

Colón, J. A., 1966, Some aspects of Hurricane Carla (1961), *in* Hurricane Symposium: Am. Soc. Oceanography Pub. No. 1, Oct. 10-11, 1966, Houston, Texas, p. 1-33.

Cooperman, A. I., and Sumner, H. C., 1961, North Atlantic tropical cyclones, September 1961: Climatological Data, Natl. Summ., v. 12, no. 9, p. 468-477.

Davis, A. B., 1961, Galveston's bulwark against the sea—history of the Galveston seawall: U. S. Army Corps Engineers, Galveston Dist., 19 p.

Dolan, R., and Godfrey, P., 1973, Effects of Hurricane Ginger on the barrier islands of North Carolina: Geol. Soc. America Bull., v. 84, p. 1329-1334.

———, and Odum, W. E., 1973, Man's impact on the barrier islands of North Carolina: Am. Scientist, v. 61, no. 2, p. 152-162.

Dunn, G. E., and Miller, B. I., 1964, Atlantic hurricanes: Baton Rouge, La., Louisiana State Univ. Press, 377 p.

El-Ashry, M. T., and Wanless, H. R., 1968, Photo interpretation of shoreline changes between Capes Hatteras and Fear (North Carolina): Marine Geology, v. 6, p. 347-379.

Fisher, W. L., 1973, Land-surface subsidence in the Texas Coastal Zone: Texas House of Representatives, testimony presented to Committee on Natural Resources.

———, Brown, L. F., Jr., McGowen, J. H., and Groat, C. G., 1973, Environmental geologic atlas of the Texas Coastal Zone—Beaumont-Port Arthur area: Univ. Texas, Austin, Bur. Econ. Geology, 93 p.

———, McGowen, J. H., Brown, L. F., Jr., and Groat, C. G., 1972, Environmental geologic atlas of the Texas Coastal Zone—Galveston-Houston area: Univ. Texas, Austin, Bur. Econ. Geology, 91 p.

Frank, N., 1974, The hard facts about hurricanes: Natl. Oceanic and Atmospheric Adm., NOAA Mag., July 1974, p. 4-9.

Gabrysch, R. K., 1969, Land-surface subsidence in the Houston-Galveston region, Texas: Tokyo, Japan, Internat. Symposium on Land Subsidence, Proc. 1969, p. 43-54.

——— 1972, Development of ground water in the Houston district, Texas, 1966-69: Texas Water Devel. Board Rept. 152, 24 p.

———, and Bonnet, C. W., 1974, Land-surface subsidence in the Houston-Galveston region, Texas: U. S. Geol. Survey open-file rept., 23 p.

———, and McAdoo, G. D., 1972, Development of ground-water resources in the Orange County area, Texas and Louisiana, 1963-71: Texas Water Devel. Board Rept. 156, 47 p.

Harris, D. L., 1963, Characteristics of the hurricane storm surge: U. S. Weather Bur. Tech. Paper No. 48, 139 p.

Harris, W. D., and Jones, B. G., 1964, Repeat mapping for a record of shore erosion: Shore and Beach, v. 32, no. 2, p. 31-34.

Hayes, M. O., 1967, Hurricanes as geological agents: Case studies of Hurricanes Carla, 1961, and Cindy, 1963: Univ. Texas, Austin, Bur. Econ. Geology Rept. Inv. 61, 56 p.

Lofgren, B. E., 1968, Analysis of stresses causing land subsidence: U. S. Geol. Survey Prof. Paper 600-B, p. B219-B225.

Lohse, E. A., 1955, Dynamic geology of the modern coastal region, northwest Gulf of Mexico, *in* Finding ancient shorelines—a symposium: Soc. Econ. Paleontologists and Mineralogists Spec. Pub. 3, p. 99-105.

Marshall, A. F., Jr., 1973, How much more will Houston sink? The disturbing problem of land surface subsidence: Houston Eng. & Sci. Society, The Slide Rule, v. 33, no. 2, 6 p.

McGowen, J. H., and Brewton, J. L., 1975, Historical changes and related coastal processes, Gulf and mainland shorelines, Matagorda Bay area, Texas: Univ. Texas, Austin, Bur. Econ. Geology Rept. Inv. 84.

———, Garner, L. E., and Wilkinson, B. H., 1972, Significance of changes in shoreline features along Texas Gulf Coast (abs.): Am. Assoc. Petroleum Geologists Bull., v. 56, no. 9, p. 1900-1901.

———, Groat, C. G., Brown, L. F., Jr., Fisher, W. L., and Scott, A. J., 1970, Effects of Hurricane Celia—a focus on environmental geologic problems of the Texas Coastal Zone: Univ. Texas, Austin, Bur. Econ. Geology Geol. Circ. 70-3, 35 p.

Morgan, J. P., and Larimore, P. B., 1957, Changes in the Louisiana shoreline: Gulf Coast Assoc. Geol. Socs. Trans., v. 7, p. 303-310.

Morton, R. A., 1974, Shoreline changes on Galveston Island (Bolivar Roads to San Luis Pass): Univ. Texas, Austin, Bur. Econ. Geology Geol. Circ. 74-2, 34 p.

———, and Pieper, M. K., 1975, Shoreline changes on Brazos Island and south Padre Island (Mansfield Channel to mouth of the Rio Grande): Univ. Texas, Austin, Bur. Econ. Geology Geol. Circ. 75-1.

National Geodetic Survey, 1974, Report: 1973 releveling of the Houston-Galveston area, Texas: U. S. Dept. Commerce, 49 p.

National Oceanic and Atmospheric Administration, National Hurricane Center, 1900-1974, Various sources of published data.

Nordquist, R. W., 1972, Origin, development, and facies of a young hurricane washover fan on southern St. Joseph Island, central Texas Coast: Univ. Texas, Austin, Master's thesis, 103 p.

Orton, R. B., 1970, Tornadoes associated with Hurricane *Beulah* on September 19-23, 1967: Monthly Weather Review, v. 98, no. 7, p. 541-547.

———, and Condon, C. R., 1970, Hurricane Celia, July 30-August 5: U. S. Dept. Commerce, NOAA, Environmental Data Service, Climatological Data, National Summary, v. 21, no. 8, p. 403-418.

Petitt, B. M., Jr., and Winslow, A. G., 1957, Geology and ground-water resources of Galveston County, Texas: U. S. Geol. Survey Water-Supply Paper 1416, 157 p.

Poole, J. C., 1940, Saxet oil and gas field, Nueces County, Texas: Am. Assoc. Petroleum Geologists Bull., v. 24, no. 10, p. 1805-1835.

Pratt, W. E., and Johnson, D. W., 1926, Local subsidence of the Goose Creek oil field: Jour. Geology, v. 34, p. 577-590.

Price, W. A., 1952, Reduction of maintenance by proper orientation of ship channels through tidal inlets: Houston, Texas, Proc., 2d Conf. Coastal Eng., Chpt. 22, p. 243-255. *Reprinted in* Texas A&M College, Contr. in Oceanography and Meteorology, v. 1, no. 12, p. 101-113.

——— 1956, North Beach study for the City of Corpus Christi: Corpus Christi, Texas, Zoning and Planning Dept., City Hall, Rept. on file, 120 p.

Quarles, M., Jr., 1953, Salt-ridge hypothesis on origin of Texas Gulf Coast type of faulting: Am. Assoc. Petroleum Geologists Bull., v. 37, no. 3, p. 489-508.

Reid, W. M., 1973, Active faults in Houston, Texas: Univ. Texas, Austin, Ph.D. dissert., 122 p.

Scott, A. J., Hoover, R. A., and McGowen, J. H., 1969, Effects of Hurricane Beulah, 1967, on Texas coastal lagoons and barriers, *in* Castañares, A. A., and Phleger, F. B., eds., Lagunas Costeras, Un Simposio: Mexico, D. F., Universidad Nac. Autónoma de Mexico, UNAM-UNESCO, Mem. Simposio Internat. Lagunas Costeras, p. 221-236.

Shalowitz, A., 1964, Shore and sea boundaries: U. S. Dept. Commerce Pub. 10-1, v. 2, 749 p.

Sheets, M. M., 1971, Active surface faulting in the Houston area, Texas: Houston Geol. Soc. Bull., v. 13, no. 7, p. 24-33.

Shepard, F. P., 1960a, Gulf Coast barriers, *in* Shepard, F. P., Phleger, F. B., and van Andel, T. H., eds., Recent sediments, northwest Gulf of Mexico: Tulsa, Okla., Am. Assoc. Petroleum Geologists, p. 197-220.

——— 1960b, Rise of sea level along northwest Gulf of Mexico, *in* Shepard, F. P., Phleger, F. B., and van Andel, T. H., eds., Recent sediments, northwest Gulf of Mexico: Tulsa, Okla., Am. Assoc. Petroleum Geologists, p. 338-344.

——— 1973, Submarine geology: New York, Harper and Row, 517 p.

———, and Moore, D. G., 1960, Bays of central Texas coast, *in* Shepard, F. P., Phleger, F. B., and van Andel, T. H., eds., Recent sediments, northwest Gulf of Mexico: Tulsa, Okla., Am. Assoc. Petroleum Geologists, p. 117-152.

Simpson, J., 1966, Hurricane modification experiments, *in* Hurricane Symposium: Am. Soc. Oceanography, Pub. No. 1, p. 255-292.

Stafford, D. B., 1971, An aerial photographic technique for beach erosion surveys in North Carolina: U. S. Army Corps Engineers, Coastal Eng. Research Center Tech. Memo. 36, 115 p.

———, Bruno, R. O., and Goldstein, H. M., 1973, An annotated bibliography of aerial remote sensing in coastal engineering: U. S. Army Corps Engineers, Coastal Eng. Research Center Misc. Paper No. 2-73, 122 p.

Stapor, F., 1973, History and sand budgets of the barrier island system in the Panama City, Florida, region: Marine Geology, v. 14, p. 277-286.

Sugg, A. L., and Pelissia, J. M., 1968, The hurricane season of 1967: Monthly Weather Review, v. 96, no. 4, p. 247.

Swanson, R. L., and Thurlow, C. I., 1973, Recent subsidence rates along the Texas and Louisiana coasts as determined from tide measurements: Jour. Geophys. Research, v. 78, no. 15, p. 2665-2671.

Texas Coastal and Marine Council, 1974, Hurricane awareness briefings, 1974: Austin, Texas, Texas Coastal and Marine Council, unpaged.

Turner, Collie, and Braden, Inc., Consulting Engineers, 1966, Comprehensive study of Houston's municipal water system for the City of Houston, Phase I, Basic studies, 50 p.

U. S. Army Corps of Engineers, 1962, Report on Hurricane Carla 9-12 September 1961: U. S. Army Corps Engineers, Galveston Dist., 29 p.

——— 1968, Report on Hurricane Beulah 8-21 September 1967: U. S. Army Corps Engineers, Galveston Dist., 26 p.

——— 1971a, Report on Hurricane Celia 30 July-5 August 1970: U. S. Army Corps Engineers, Galveston Dist., 13 p.

——— 1971b, Shore protection guidelines: Washington, D. C., Dept. of the Army, Corps Engineers, 59 p.

Van Andel, T. H., and Poole, D. M., 1960, Sources of Recent sediments in the northern Gulf of Mexico: Jour. Sed. Petrology, v. 30, p. 91-122.

Van Siclen, D. C., 1967, The Houston fault problem, *in* Proc., 3d Ann. Mtg., Texas Sec., Am. Inst. Prof. Geologists, p. 9-29.

Warren, J. P., Jones, L. L., Griffin, W. L., and Lacewell, R. D., 1974, Cost of land subsidence due to groundwater withdrawal: Texas A&M Univ., Texas Water Resources Inst., Tech. Rept. 57, 79 p.

Weaver, P., and Sheets, M. M., 1962, Active faults, subsidence, and foundation problems in the Houston, Texas, area, *in* Rainwater, E. H., and Zingula, R. P., eds., Geology of the Gulf Coast and Central Texas and guidebook of excursions: Houston, Texas, Houston Geol. Soc. Field Excursion Guidebook, p. 254-265.

Wesselman, J. B., 1972, Ground-water resources of Fort Bend County, Texas: Texas Water Devel. Board Rept. 155, 176 p.

Wilkinson, B. H., 1974, Matagorda Island—the evolution of a Gulf Coast barrier complex: Univ. Texas, Austin, Ph.D. dissert., 178 p.

Winslow, A. G., and Doyel, W. W., 1954, Land-surface subsidence and its relation to the withdrawal of ground water in the Houston-Galveston region, Texas: Econ. Geology, v. 49, no. 4, p. 413-422.

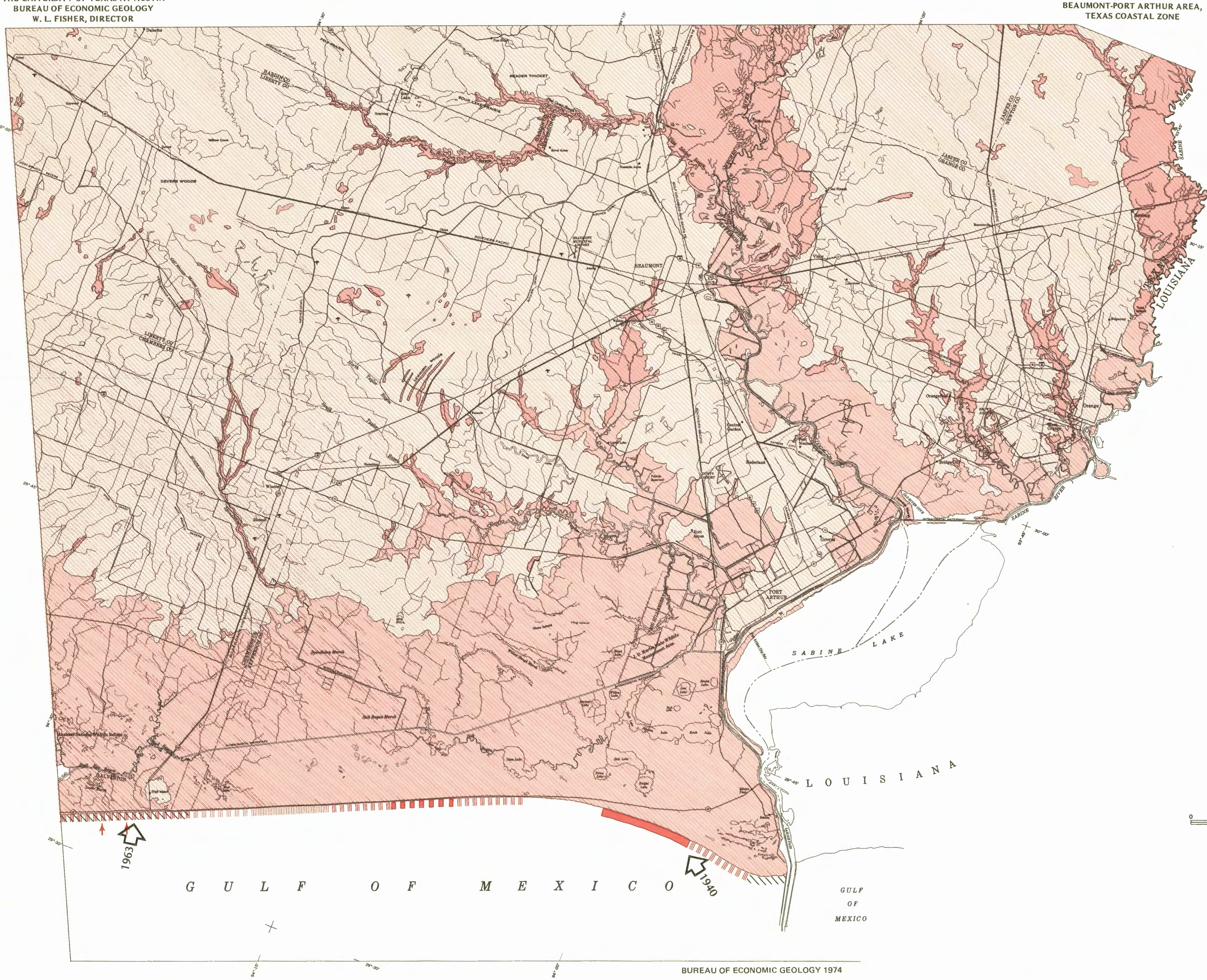
———, and Wood, L. A., 1959, Relation of land subsidence to ground-water withdrawals in the upper Gulf Coast region, Texas: Am. Inst. Mining, Metall., Petroleum Engineers Trans., v. 214, p. 1030-1034.

Wood, L. A., Gabrysch, R. K., and Patten, E. P., Jr., 1965, Analog model study of ground water in the Houston district, Texas: Texas Water Comm. Bull. 6508, 103 p.

NATURAL HAZARDS MAPS

THE UNIVERSITY OF TEXAS AT AUSTIN
BUREAU OF ECONOMIC GEOLOGY
W. L. FISHER, DIRECTOR

BEAUMONT-PORT ARTHUR AREA,
TEXAS COASTAL ZONE



EXPLANATION

HURRICANE FLOODING

1900 Hurricane landfall 1900-1971

Saltwater flooding by Beulah or Carla

Potential freshwater flooding by hurricane rainfall

Active or potential hurricane washover channel

SHORELINE EROSION (APPROXIMATE)

GULF SHORELINE (Based on various time intervals)

Dashed where temporary accretion has occurred

More than 10 feet per year

5-10 feet per year

0-5 feet per year

Recent rates more than 10 feet per year

MAXIMUM LAND SUBSIDENCE (APPROXIMATE)

0.2-1.0 foot

Mapping and cartography by Bureau of Economic Geology
Geology and shoreline changes mapped on aerial photographs, Edgar Tobin Aerial Surveys and National Oceanic and Atmospheric Administration
Base adapted from U.S.G.S. topographic maps
Level data from National Oceanic and Atmospheric Administration
Flood elevations (Hurricane Carla and Beulah), U. S. Army Corps of Engineers
Hurricane landfall from National Hurricane Center

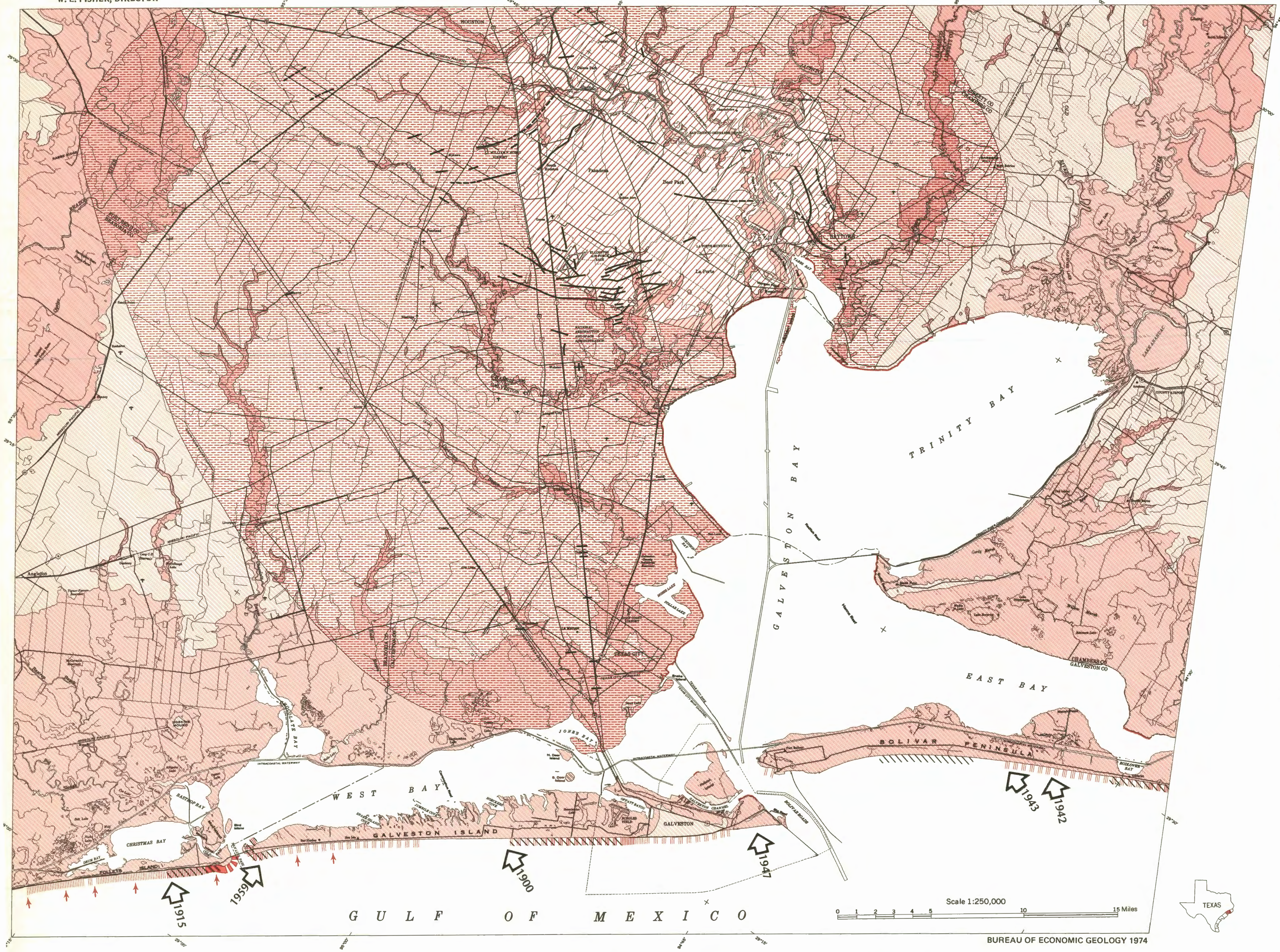
TEXAS

Scale 1:250,000

0 1 2 3 4 5 10 15 Miles

NATURAL HAZARDS, TEXAS COASTAL ZONE, BEAUMONT-PORT ARTHUR AREA

THE UNIVERSITY OF TEXAS AT AUSTIN
BUREAU OF ECONOMIC GEOLOGY
W. L. FISHER, DIRECTOR



EXPLANATION

HURRICANE FLOODING

1900 Hurricane landfall 1900-1971

Saltwater flooding by Beulah or Carla

Potential freshwater flooding by hurricane rainfall

Active or potential hurricane washover channel

SHORELINE EROSION (APPROXIMATE)

BAY SHORELINE
Variable rates and amounts

GULF SHORELINE (Based on various time intervals)
Dashed where temporary accretion has occurred

More than 10 feet per year

5-10 feet per year

0-5 feet per year

Recent rates more than 10 feet per year

MAXIMUM LAND SUBSIDENCE (APPROXIMATE)

More than 5 feet

1-5 feet

0.2-1.0 feet

SURFACE FAULTS

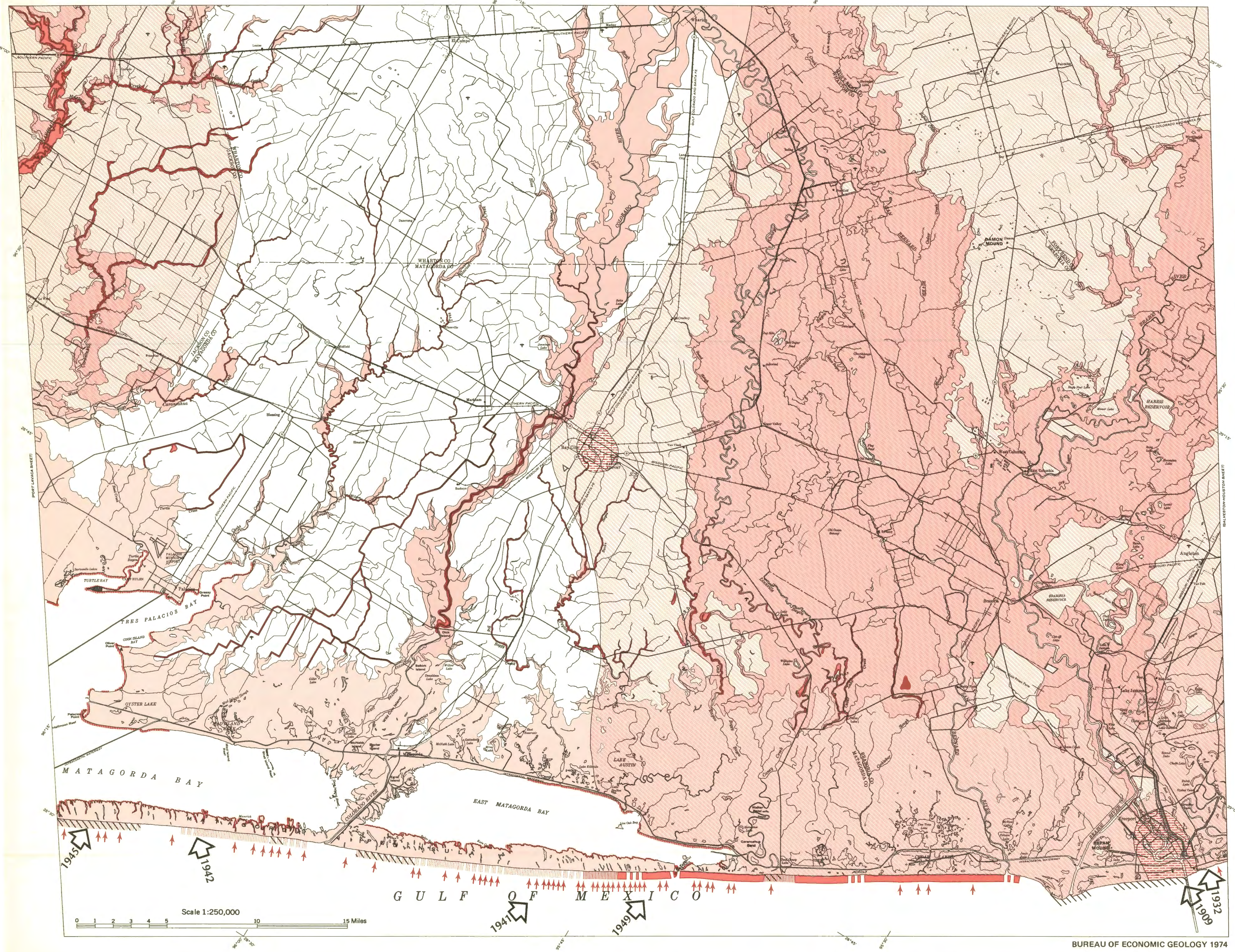
Active surface faults (Dashed where inferred)

Mapping and cartography by Bureau of Economic Geology
Geology and shoreline changes mapped on aerial photographs, Edgar Tobin Aerial Surveys and National Oceanic and Atmospheric Administration
Base adapted from U.S.G.S. topographic maps
Level data from National Oceanic and Atmospheric Administration
Flood elevations (Hurricane Carla and Beulah), U. S. Army Corps of Engineers
Hurricane landfall from National Hurricane Center

BUREAU OF ECONOMIC GEOLOGY 1974

NATURAL HAZARDS, TEXAS COASTAL ZONE, GALVESTON-HOUSTON AREA

THE UNIVERSITY OF TEXAS AT AUSTIN
BUREAU OF ECONOMIC GEOLOGY
W. L. FISHER, DIRECTOR



EXPLANATION

HURRICANE FLOODING

1900 Hurricane landfall 1900-1971

Saltwater flooding by Beulah or Carla

Freshwater flooding by Beulah

Potential freshwater flooding by hurricane rainfall

Active or potential hurricane washover channel

SHORELINE EROSION (APPROXIMATE)

BAY SHORELINE

Variable rates and amounts

GULF SHORELINE (Based on various time intervals)

Dashed where temporary accretion has occurred

More than 10 feet per year

5-10 feet per year

0-5 feet per year

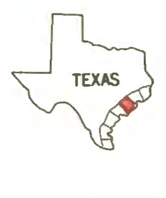
Recent rates more than 10 feet per year

MAXIMUM LAND SUBSIDENCE (APPROXIMATE)

1-5 feet

0.2-1.0 foot

Mapping and cartography by Bureau of Economic Geology
Geology and shoreline changes mapped on aerial photographs, Edgar Tobin Aerial Surveys and National Oceanic and Atmospheric Administration
Base adapted from U.S.G.S. topographic maps
Level data from National Oceanic and Atmospheric Administration
Flood elevations (Hurricane Carla and Beulah), U. S. Army Corps of Engineers
Hurricane landfall from National Hurricane Center

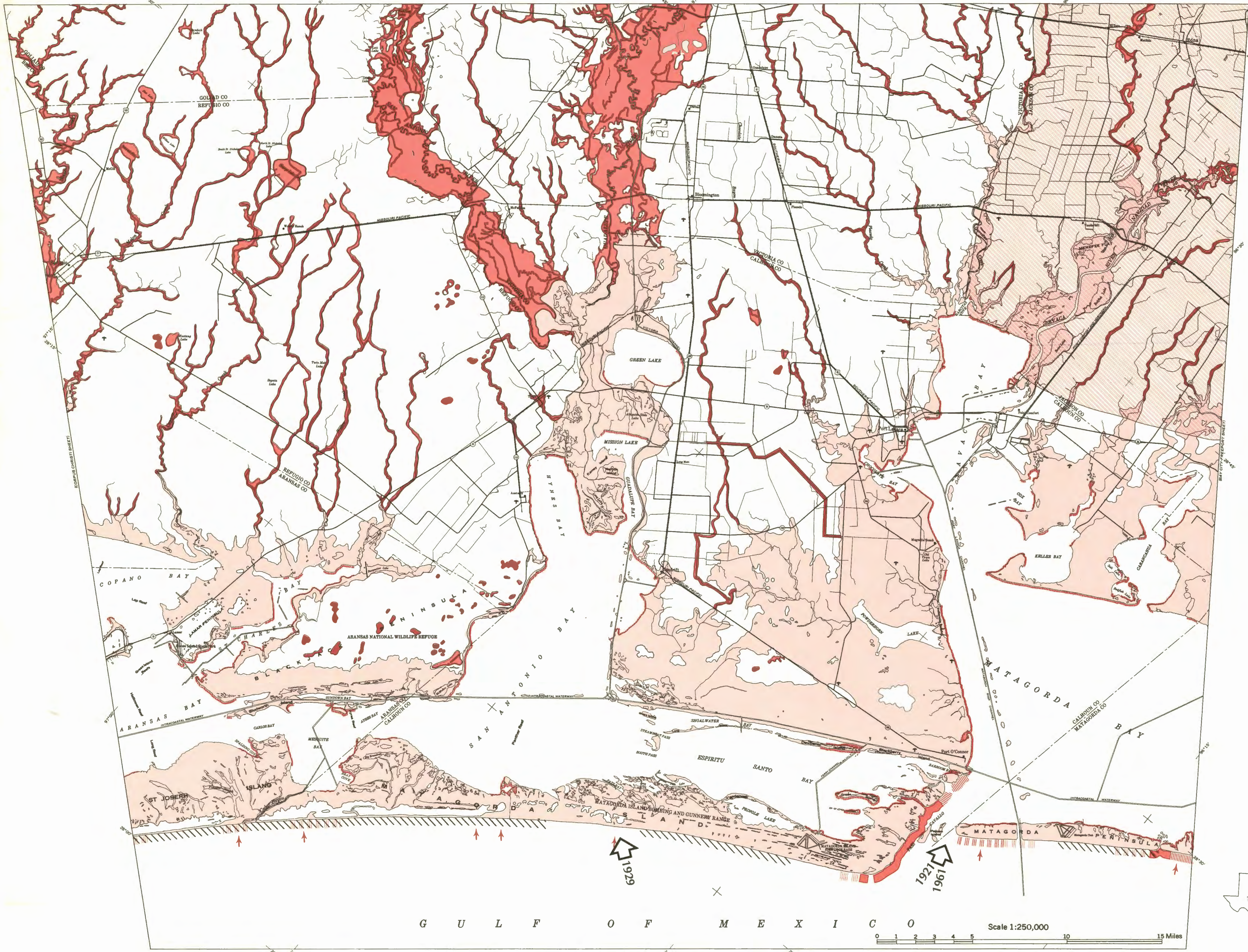


BUREAU OF ECONOMIC GEOLOGY 1974

NATURAL HAZARDS, TEXAS COASTAL ZONE, BAY CITY-FREEPORT AREA

THE UNIVERSITY OF TEXAS AT AUSTIN
BUREAU OF ECONOMIC GEOLOGY
W. L. FISHER, DIRECTOR

PORT LAVACA AREA,
TEXAS COASTAL ZONE



EXPLANATION

HURRICANE FLOODING

1900 Hurricane landfall 1900-1971

Saltwater flooding by Beulah or Carla

Freshwater flooding Beulah rainfall

Active or potential hurricane washover channel

SHORELINE EROSION (APPROXIMATE)

BAY SHORELINE

Variable rates and amounts

GULF SHORELINE (Based on various time intervals)

Dashed where temporary accretion has occurred

More than 10 feet per year

5-10 feet per year

0-5 feet per year

Recent rates more than 10 feet per year

MAXIMUM LAND SUBSIDENCE (APPROXIMATE)

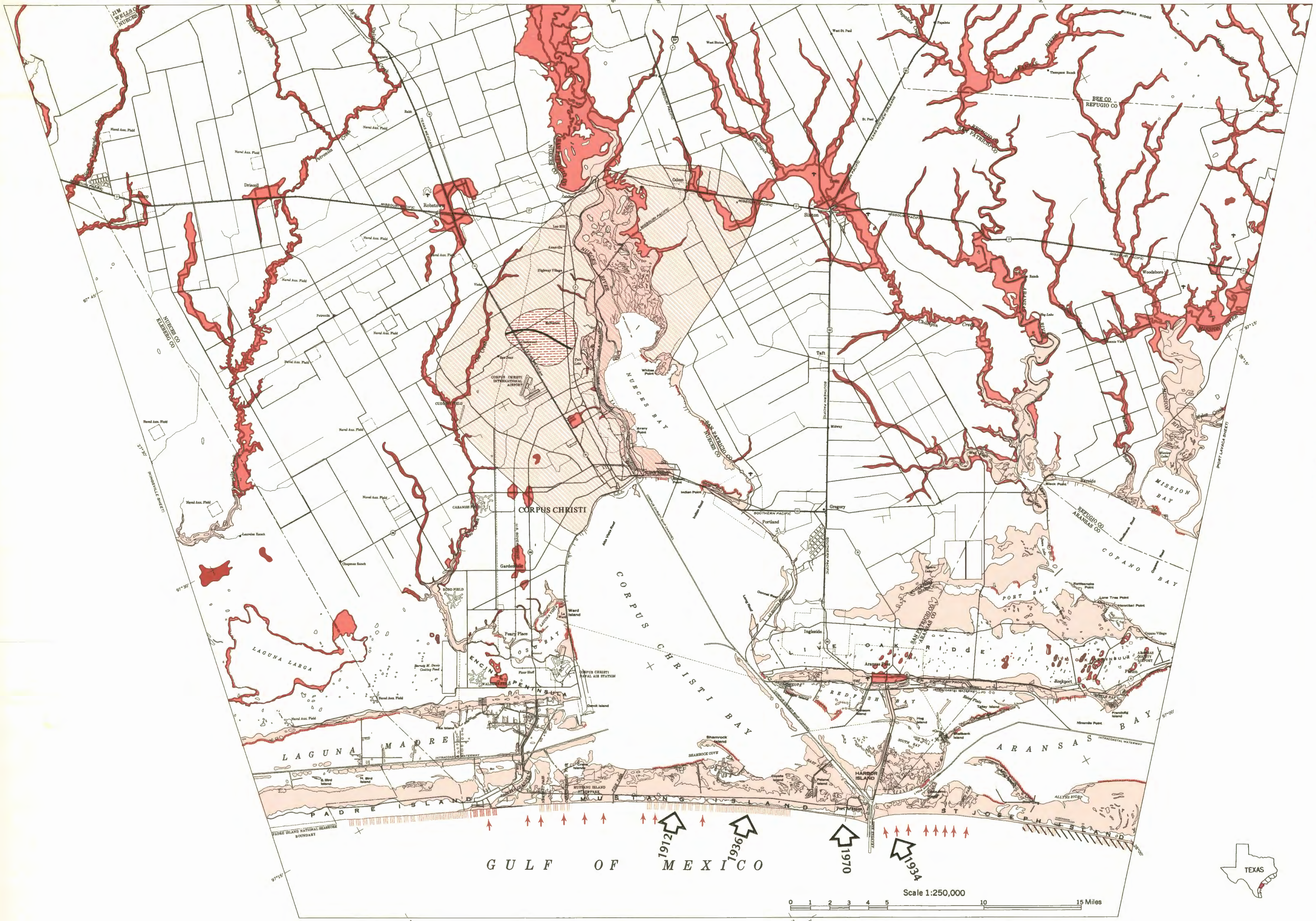
0.2-1.0 foot

Mapping and cartography by Bureau of Economic Geology
Geology and shoreline changes mapped on aerial photographs, Edgar Tobin Aerial Surveys and National Oceanic and Atmospheric Administration
Base adapted from U.S.G.S. topographic maps
Level data from National Oceanic and Atmospheric Administration
Flood elevations (Hurricane Carla and Beulah), U. S. Army Corps of Engineers
Hurricane landfall from National Hurricane Center

BUREAU OF ECONOMIC GEOLOGY 1974

NATURAL HAZARDS, TEXAS COASTAL ZONE, PORT LAVACA AREA

THE UNIVERSITY OF TEXAS AT AUSTIN
BUREAU OF ECONOMIC GEOLOGY
W. L. FISHER, DIRECTOR



EXPLANATION

HURRICANE FLOODING

1900 — Hurricane landfall 1900-1971

Saltwater flooding by Beulah or Carla

Freshwater flooding by Beulah

Active or potential hurricane washover channel

SHORELINE EROSION (APPROXIMATE)

BAY SHORELINE

Variable rates or amounts

GULF SHORELINE (Based on various time intervals)

Dashed where temporary accretion has occurred

5-10 feet per year

0-5 feet per year

Recent rates more than 10 feet per year

MAXIMUM LAND SUBSIDENCE (APPROXIMATE)

1-5 feet

0.2-1.0 feet

SURFACE FAULT

Active surface faults (Dashed where inferred)

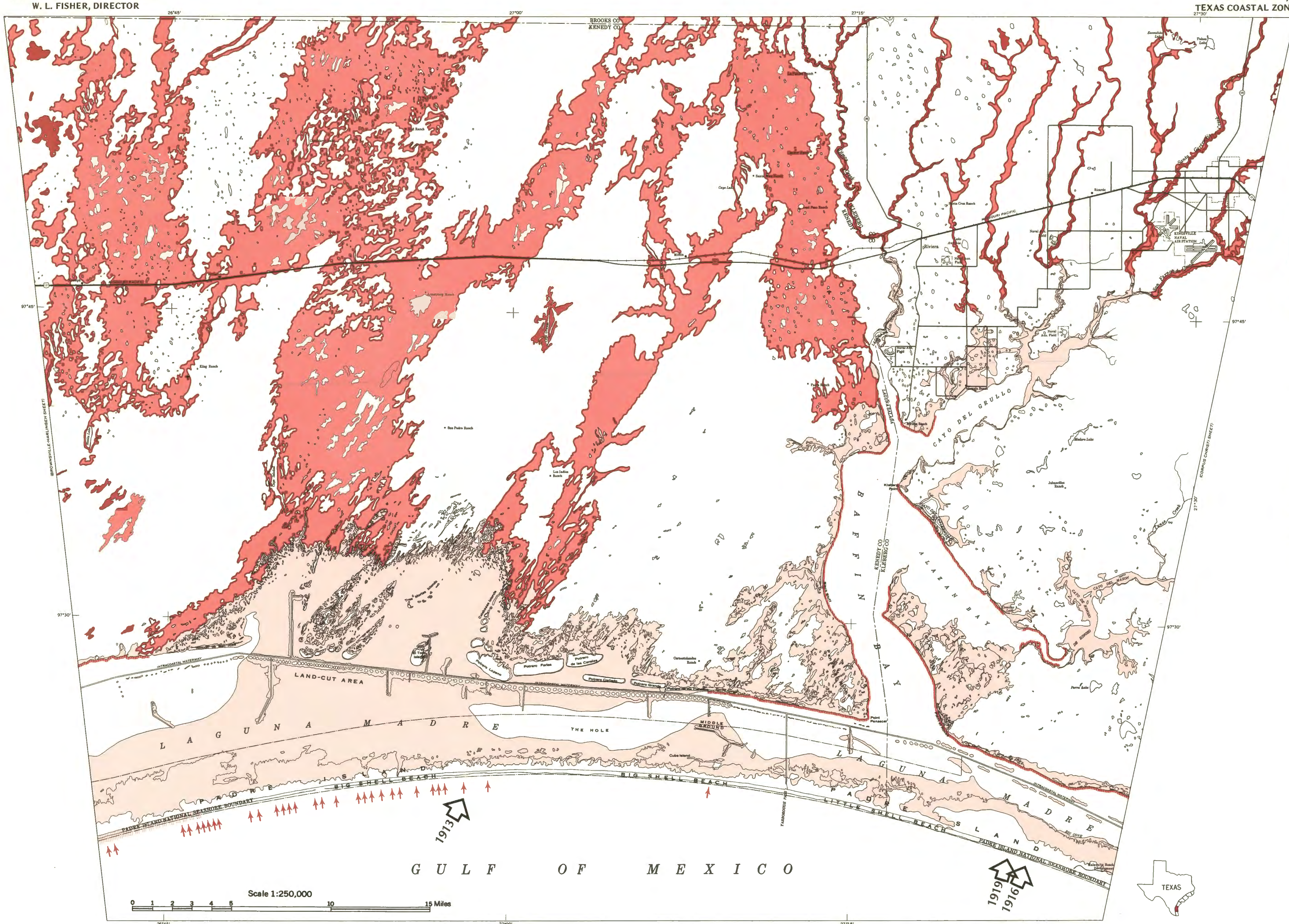
Mapping and cartography by Bureau of Economic Geology
Geology and shoreline changes mapped on aerial photographs, Edgar Tobin Aerial Surveys and National Oceanic and Atmospheric Administration
Base adapted from U.S.G.S. topographic maps
Level data from National Oceanic and Atmospheric Administration
Flood elevations (Hurricane Carla and Beulah), U. S. Army Corps of Engineers
Hurricane landfall from National Hurricane Center

BUREAU OF ECONOMIC GEOLOGY-1974

NATURAL HAZARDS, TEXAS COASTAL ZONE, CORPUS CHRISTI AREA

THE UNIVERSITY OF TEXAS AT AUSTIN
BUREAU OF ECONOMIC GEOLOGY
W. L. FISHER, DIRECTOR

KINGSVILLE AREA,
TEXAS COASTAL ZONE



EXPLANATION

HURRICANE FLOODING

1900 Hurricane landfall 1900-1971

Saltwater flooding by Beulah or Carla

Freshwater flooding by Beulah

Active or potential hurricane washover channel

SHORELINE EROSION (APPROXIMATE)

BAY SHORELINE

Variable rates and amounts

GULF SHORELINE (Based on various time intervals)

Dashed where temporary accretion has occurred

0-5 feet per year

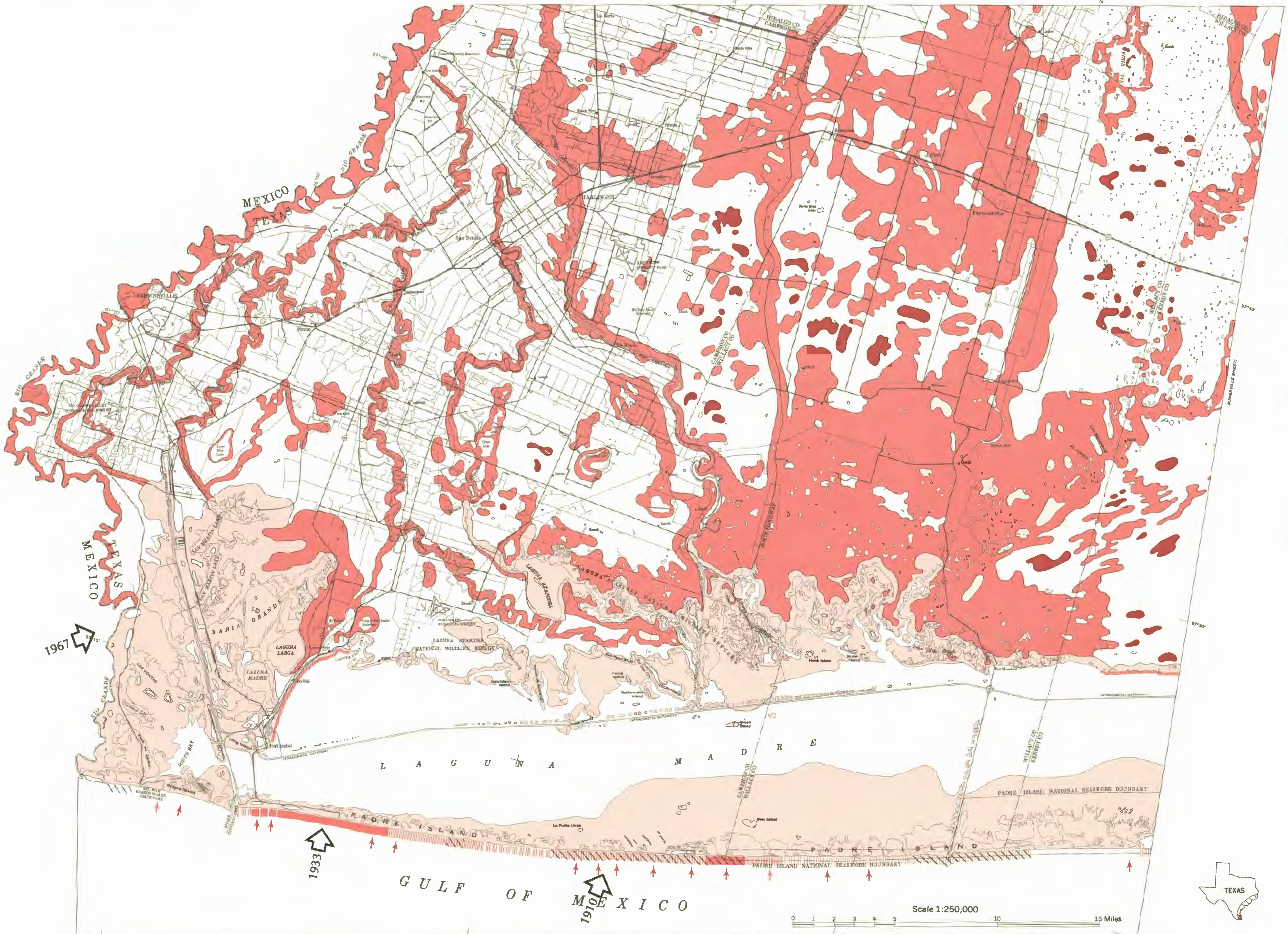
Mapping and cartography by Bureau of Economic Geology
Geology and shoreline changes mapped on aerial photographs, Edgar Tobin Aerial Surveys and National Oceanic and Atmospheric Administration
Base adapted from U.S.G.S. topographic maps
Level data from National Oceanic and Atmospheric Administration
Flood elevations (Hurricane Carla and Beulah), U. S. Army Corps of Engineers
Hurricane landfall from National Hurricane Center

BUREAU OF ECONOMIC GEOLOGY 1974

NATURAL HAZARDS, TEXAS COASTAL ZONE, KINGSVILLE AREA

THE UNIVERSITY OF TEXAS AT AUSTIN
BUREAU OF ECONOMIC GEOLOGY
W. L. FISHER, DIRECTOR

BROWNSVILLE-HARLINGEN AREA,
TEXAS COASTAL ZONE



EXPLANATION

HURRICANE FLOODING

1900 Hurricane landfall 1900-1971

Saltwater flooding by Beulah or Carla

Freshwater flooding by Beulah

Active or potential hurricane washover channel

SHORELINE EROSION (APPROXIMATE)

BAY SHORELINE

Variable rates and amounts

GULF SHORELINE (Based on various time intervals)

Dashed where temporary accretion has occurred

More than 10 feet per year

5-10 feet per year

0-5 feet per year

Recent rates more than 10 feet per year

Mapping and cartography by Bureau of Economic Geology
Geology and shoreline changes mapped on aerial photographs, Edgar Tobin Aerial Surveys and National Oceanic and Atmospheric Administration
Base adapted from U.S.G.S. topographic maps
Level data from National Oceanic and Atmospheric Administration
Flood elevations (Hurricane Carla and Beulah), U. S. Army Corps of Engineers
Hurricane landfall from National Hurricane Center

Scale 1:250,000

0 1 2 3 4 5 10 15 Miles

BUREAU OF ECONOMIC GEOLOGY 1974

NATURAL HAZARDS, TEXAS COASTAL ZONE, BROWNSVILLE-HARLINGEN AREA