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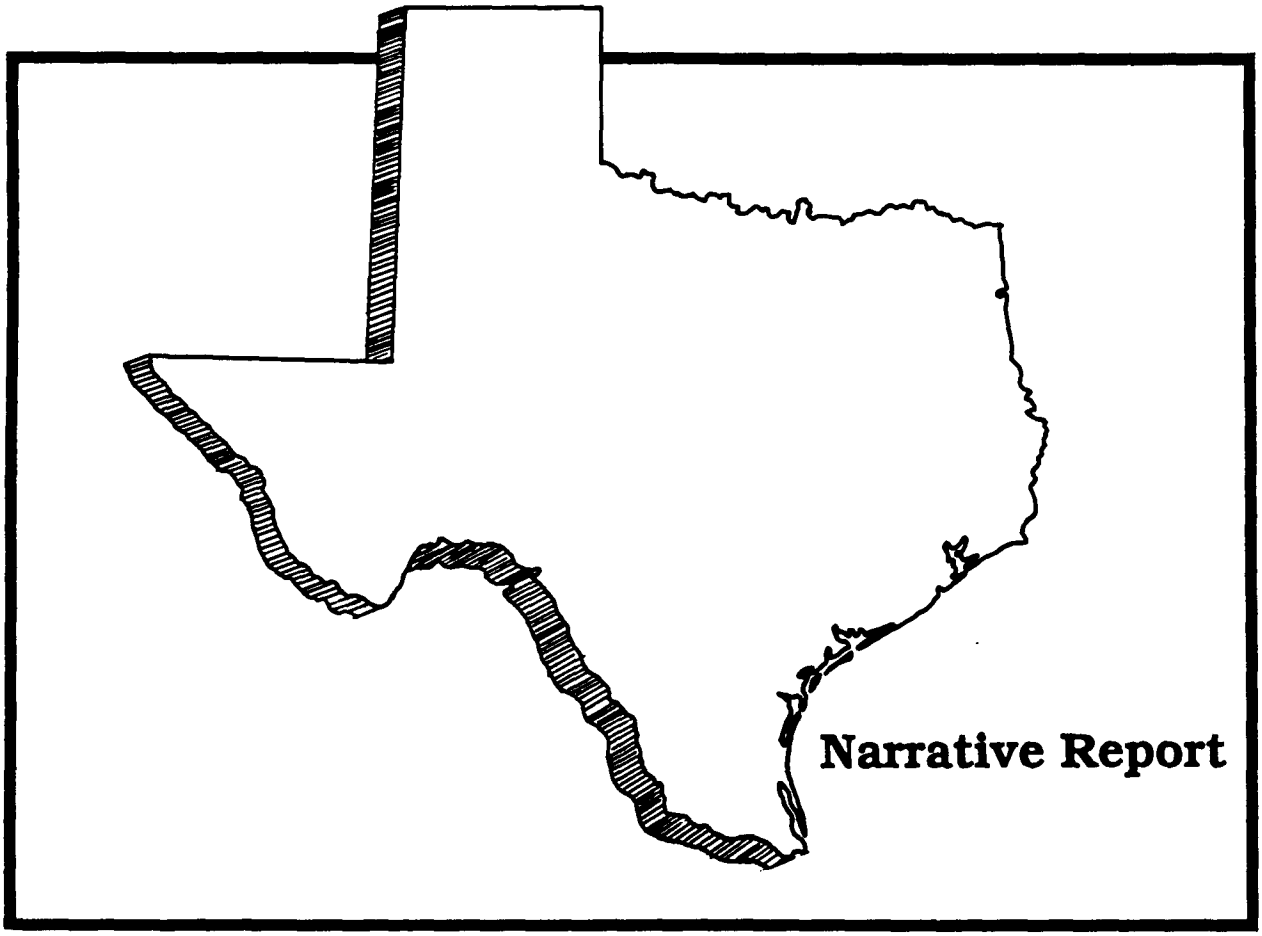
TEXAS BARRIER ISLAND REGION CHARACTERIZATION



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TEXAS BARRIER ISLAND REGION CHARACTERIZATION
Narrative Report

by

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DISCLAIMER

This final report is printed largely as first received from the authors in 1983, therefore, some of the data and interpretations are dated. In particular, the socioeconomic data are from the late 1970's and do not accurately reflect current trends in coastal Texas. These sections of the report should be considered only in the context that they were written.

The ecosystem models in this report are conceptual. They are supported by data and published references, and may be of some use to persons making field evaluations. However, because of the model's generic nature, site-specific information must also be considered before the models and supporting data can validly be used in decision-making. The opinions and interpretations expressed in this report are those of the authors and do not necessarily reflect the views of the U.S. Fish and Wildlife Service, the Minerals Management Service, or the Texas General Land Office.

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SUMMARY

This narrative report is a synthesis of information about the Texas Barrier Island Region. The report treats the area from three scales of view, region, hydrologic basins, and habitats. The organization of each section and the topics covered were guided by set of conceptual models, which are included in the appendix.

Chapter I - User's Guide - describes the content of the report and SRtprovides guidance to the reader in how to use the report.

SRt Chapter II - The Texas Barrier Island Region - describes the entire SRtregion and gives information about the processes that created its form and SRtcharacteristics. This section also contains some historical information about SRtthe pattern of economic development in the region.

Chapter III - Basins in the Texas Barrier Island Region - contains a SRtdiscussion of hydrologic and sedimentary processes that have affected the SRtregion over the past 50 million years and continue to affect it, with man as SRtan additional agent. This chapter includes a detailed description of each SRtbasin emphasizing habitats and hydrology. Economic data and resource demand SRtinformation is also included for each basin. At the conclusion of the chapter SRtis a section comparing the natural processes, economic systems, and resource SRtdemands in the basins.

Chapter IV - Habitats of the Texas Barrier Island Region - contains SRtdescriptions of eighteen habitat types found in the region. Each habitat SRtdescription includes information about its area, physical appearence, SRtoperation, flora and fauna, adjacent habitats, economic uses, and the impacts SRtwrought by man.

ABBREVIATIONS

ac	acre
ac-ft	acre-foot
BOD	biochemical oxygen demand
BP	before present
C	Centigrade
cm	centimeter
cu ft	cubic foot
cu m	cubic meter
deg	degrees
ft	feet
gm ash-free dry wt	gram dry weight on an ash-free basis
gm dry wt	gram dry weight
gm	gram
ha	hectare
hr	hour
in	inch
kg	kilogram
km	kilometer
kw	kilowatts
l	liter
lb	pound
m	meter
mi	mile
mg per l	milligrams per liter
MHW	mean high water
MSL	mean sea level
pH	log of the positive hydrogen ion concentration
ppt	parts per thousand
sq km	square kilometer
sq m	square meter
sq mi	square mile
TDWR	Texas Department of Water Resources
TWDB	Texas Water Development Board
yr	year

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Dr. Dale Sawyer of the University of Texas at Austin supplied information about the Gulf Coast Geosyncline and Dr. Jim Davenport with the Texas Department of Water Resources supplied data about waste loads in the region. Dr. Charles M. Woodruff reviewed some of the geologic interpretation and models, and made a number of useful suggestions. Sally Davenport provided a number of hard-to-find facts from her files and was a convenient sounding board for many ideas. Mike Hightower and Steve Stubbs provided administrative assistance and help over the period of this study. Dr. Hal Irby kindly prepared six figures for the narrative report and several others for the appendix.

The Texas Department of Health supplied information about areas closed to shellfishing as well as other health-related statistics. The staff of the Texas Natural Resources Information System provided a variety of information and materials ranging from the area of lakes used for irrigation, to a digitized map of shorelines, rivers, and streams that served as a base map for the plates. The staff of the Texas Department of Water Resources library were also very helpful in finding documents and research materials.

This report was edited in full by Muriel Wright. Rebecca Green and Sally Davenport assisted in reviewing a number of portions of the written material.

USER'S GUIDE

This report is a descriptive narrative characterizing the Texas Barrier Island Region, an arc-shaped band approximately 50 miles wide that abuts the Chenier Plain of southwestern Louisiana and the eastern Texas coast and extends southwestward to the international boundary with Mexico. The region comprises sedimentary coastal plain, islands and peninsulas, and a portion of the continental shelf.

The report examines the Texas Barrier Island Region from the perspective of systems analysis, employing graphic models as a framework for the integration of diverse information about the region. The region is viewed as a hierarchy of systems, illustrated by models at three levels: region, basin, and habitat (Figure 1).

The models are based on the physical and biological processes at work within the region. They depict the principal components of each system and the interrelationships among components, primarily flows of materials and energy. Man and human activities are part of the coastal ecosystem, but for the purposes of this study human systems are viewed as being superimposed upon natural systems. Man is represented as a major agent of change in the natural environment. The nature and extent of changes brought about by man can be determined only if the operation of the natural systems upon which human systems depend is understood.

Because they show the interconnections that cause alteration of one part of a system to alter other parts, the models have predictive, as well as descriptive, value. They allow us to foresee the probable environmental effects of contemplated projects: the building of dams or levees; the

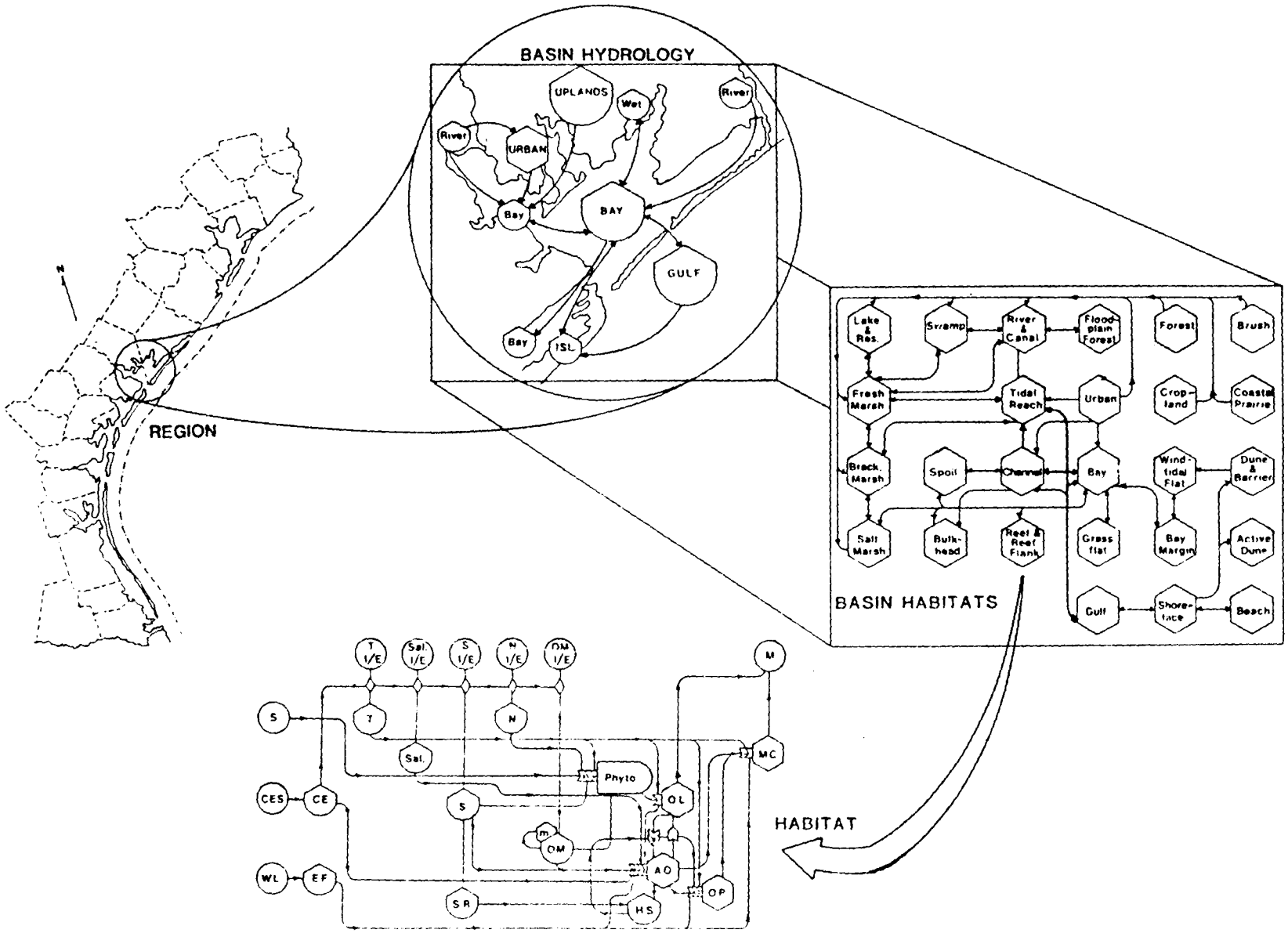


Figure 1. Three levels for modeling of the Texas Barrier Island Region.

extraction of water, hard minerals, oil, or gas; the dredging of harbors or channels; the conversion of agricultural land to urban use; and other actions that may interrupt or redirect flows within or between natural systems.

The regional model concentrates on the long-term, far-reaching processes that shaped the Texas Barrier Island Region and that determine its present makeup. These include geologic processes, climatic gradients, dramatic weather patterns, tidal forces, and major wind and current regimes. The basin model shows the geologic and hydrologic patterns that led to the development of three types of basins on the Texas coast: the classic estuary, the tidal river mouth, and the lagoon. Separate models have been constructed for 25 coastal habitats, distinguished by locational features, biotic communities, sediment types, salinity, and small-scale circulation patterns.

The connections between human systems and natural systems are depicted in two socioeconomic models. One of these models links the six major sectors of the coastal economy to driving forces within the external economy and to coastal resources that sustain and are affected by the economic sectors. The second model, overlaid on a pictorial diagram of river basins, shows the points where man intervenes in the ecosystem to alter components and flows.

ORGANIZATION

This report is one of a series that make up the Texas Barrier Island Ecological Characterization Study, sponsored by the Biological Services Program of the U.S. Fish and Wildlife Service. The other components of the series are a two-volume socioeconomic study consisting of synthesis papers and a data appendix (Liebow et al. 1980); a set of environmental synthesis papers (Shew et al. 1981); an ecological atlas prepared by Texas A&M University; and

a computerized bibliography of environmental references, compiled by the Office of Biological Services of the U.S. Fish and Wildlife Service.

Historical, geological, biological, chemical, hydrological, climatic, and socioeconomic data drawn from these and other information sources are consolidated in this report to produce a unified picture of the Texas Barrier Island Region. The report consists of two volumes: the narrative description and an appendix containing the graphic system models. The two volumes discuss first the region as a whole, then the basins within the region, and finally the habitats within the basins.

USE

The models in this report show the most important features and processes that characterize ecological systems of the Texas Barrier Island Region at each level of observation. The reader should bear in mind that some features and processes present in the systems are omitted from the models. These are conceptual models--simple representations of complex systems. They depict functional relationships among system components but not specific measurements of distance, of quantity or velocity of flows, or of biological populations.

The narrative report shows how system models can be used as a guide to the description, and thus to the understanding, of natural systems. The models should be useful to planners and managers in industry and government, particularly in combination with specific data about an area for which a project is proposed. Because they permit the effects of a system alteration to be traced throughout the altered system and to other systems, the models enable planners to estimate the geographic extent and probable severity of a project's environmental impacts. And, by promoting a comprehensive view of

resources, the models encourage awareness of the cumulative effects of alterations in the natural environment.

TEXAS BARRIER ISLAND REGION

DESCRIPTION OF THE TEXAS BARRIER ISLAND REGION

Location and Orientation

Location. The Texas Barrier Island Region defined by the U. S. Fish and Wildlife Service reaches from the northeastern tip of East Bay in the Galveston Bay complex south to the Rio Grande. The region extends inland about 68 km (40 mi) from the Gulf of Mexico shoreline, encompassing all bays and estuaries, tidally influenced streams, and bordering wetlands. The eastern limit of the region is the demarcation line between state and federal offshore areas, three leagues (16.68 km or 10.35 miles) seaward of the gulf shoreline.

Physiography and climate. The region lies within the coastal plain formed by Pleistocene fluvial-deltaic deposits along the edge of the geologic basin known as the Gulf Coast geosyncline. The land surface is of low relief with a maximum elevation of 44 m (145 ft) above mean sea level and slopes gently toward the continental shelf.

Nine major river systems cut across the coastal plain within the region's boundaries. Three rivers--the Brazos, the Colorado, and the Rio Grande--flow directly into the Gulf of Mexico and display broad delta plains. The Trinity, San Jacinto, Lavaca, Guadalupe, San Antonio, and Nueces rivers empty into shallow bays separated from the open gulf by long, narrow barrier islands and peninsulas.

The barrier formations, interrupted by natural and man-made passes, lie in a chain that parallels the mainland for more than 480 km (300 mi). They consist of highly permeable sand and range in elevation from sea level to 15 m

(50 ft). The largest barrier islands are Galveston Island, Matagorda Island, San Jose Island, Mustang Island, and Padre Island. The major peninsulas are Bolivar Peninsula, which encloses most of East Bay, and Matagorda Peninsula, along Matagorda Bay and East Matagorda Bay.

The climate of the Texas Barrier Island Region, dominated by moist air from the Gulf of Mexico, is generally humid subtropical but ranges from humid on the upper coast to semiarid on the lower coast.

Large, densely vegetated salt marshes border the bays of the upper coast. The coastal prairie adjacent to the marshes is fertile, poorly drained grassland interspersed with forest communities. An extensive pine and hardwood forest belt touches the northern boundary of the region, and floodplain forests occupy the drainage basin of the Colorado and Brazos rivers, stream bottoms, and freshwater marsh areas. Small wooded areas, primarily oak mottes, occur on the mainland in the central region and on some barrier islands of the upper and central coast.

River flow and bay size diminish from the upper to the lower coast, and the coastal prairie grades from grassland to dry, brush-covered savannahs. Salt marshes become narrower and less continuous from northeast to southwest, ultimately giving way to sparsely vegetated salt flats along the lower Laguna Madre. The lower coast is characterized by mobile, wind-blown sand sheets; hot, dry prevailing winds carry sand from well developed, active barrier dunes far inland onto the Rio Grande plain.

Economic resources. The resources of the Texas Barrier Island Region support a variety of economic activities. The region has rich oil and gas fields and contains half of the nation's petrochemical industry and more than one quarter of its refining capacity. With ten deep-draft ports, numerous

barge facilities, and 686 km (426 mi) of intracoastal waterway, Texas leads the nation in volume of marine commerce. Finfish and shellfish sustain profitable commercial fisheries and sportfishing.

Most of the region is devoted to agricultural production: grain sorghum and cotton on the central and lower coast, fruits and vegetables in irrigated portions of the lower Rio Grande Valley, and rice in the marshy upper coastal area. Cattle production is widespread throughout the region, from pastures and barrier islands of the upper coast to the ranges of the Rio Grande plain.

The mild climate and the recreational opportunities offered by the bays, barrier island beaches, and extensive hunting grounds bring millions of tourists to the region each year from both within and outside the state. More than one-third of the state's permanent population lives in the two tiers of counties bordering the coast, and this number is rapidly increasing.

Population growth and increasing development in the Texas Barrier Island Region make examination of the interaction of human and natural systems in the region essential. Some adverse effects of coastal development are already apparent; for example, the extraction of groundwater for municipal and industrial use has accelerated subsidence in some areas; large areas of marsh have been destroyed or disrupted by dredging and filling; and development on the barrier islands has aggravated erosion and increased the danger of hurricane damage. The competition for land and water resources to support a growing population is intensifying.

Geologic History of the Region

Elevation in the Mississippian Period. The last buildup from materials and forces beneath the earth's crust in the Texas Barrier Island Region

occurred during the Mississippian Period (340 million to 300 million years BP) when metamorphic, igneous, and sedimentary rock formed from Precambrian and earlier Paleozoic sediments uplifted and began to erode. Mountain weathering and the transport of weathered sediment into a central basin in the region persisted throughout the Pennsylvanian, Permian, and Triassic periods. By the beginning of the Jurassic Period (180 million to 130 million years BP), the region's high areas had been worn down to low plains.

Gulf Coast geosyncline. The Texas Gulf Coast began to assume its present concave configuration in the early Jurassic, when downwarp within the earth's crust caused the surface of the coastal plain to subside, forming the Gulf Coast geosyncline. The geosyncline is an elliptical basin more than 1167 km (725 mi) in length that extends southwestward from Alabama to northeastern Mexico. The landward margin of Jurassic subsidence was about 193 km (120 mi) inland of the present gulf shoreline.

As the coastal plain sank during the late Jurassic, seas invaded from the east, depositing sand and mud in the basin. During the early Cretaceous Period (130 to 65 million years BP) all the land area within the present state of Texas was flooded by shallow inland seas that left large deposits of limy mud. Until the late, or upper, Cretaceous the basin received only moderate amounts of terrigenous sediment. Carbonate sediments of biologic origin and salt deposits (the Louann Salt layer) accumulated in far greater quantities than sediment from upland sources.

Sediment transport to the region in the Tertiary. As the Cretaceous Period ended and the Tertiary began, material and uplift forces caused the Larimide revolution, the raising of the Rocky Mountains. Vast amounts of weathered sediment and plains sediment were transported to the coastal basin

in spurts, governed by the local amount of downwarping and by brief periods of uplift to the northwest. The weight of the layers of accumulated mud and sand caused faulting that forced Jurassic salt deposits upward thousands of feet into the overlying sediments. Hydrocarbons trapped in faults at the sides of these salt domes form many of the present-day Gulf Coast oil and gas fields.

The gulfward transport of sediment from distant areas of uplift continued throughout the Paleocene and Eocene epochs; by the end of the Oligocene and throughout the Tertiary, the primary sources of transported sediment were the western and central portions of the state. By the beginning of the Pleistocene Epoch, the gulf shoreline was built out to approximately the inland boundary of the present Texas Barrier Island Region.

Final landform. Sea level dropped dramatically with the glaciations of the Quaternary Period. Sediment at the edge of the basin became plains sediment as the sea retreated. Atmospheric moisture increased, and heavy stream and river flow cut wide valleys across the coastal plain, depositing large volumes of sediment into deeper portions of the basin. Wide river deltas extended far out on the continental shelf. During warmer interglacial stages, sea level rose and the sites of deposition moved inland. The river valleys were drowned, and the coastal plain was built up by fluvial deposition. Deltaic deposition added sediment to the estuaries and gulf (Figure 2, from Hunt, 1967).

Sea level rose and fell several times during the Pleistocene before stabilizing around 4000 years BP. At the time of stabilization, fluvial and deltaic deposition had built the shoreline 40 to 80 miles gulfward, forming the mainland of the present-day barrier island region. The barrier islands

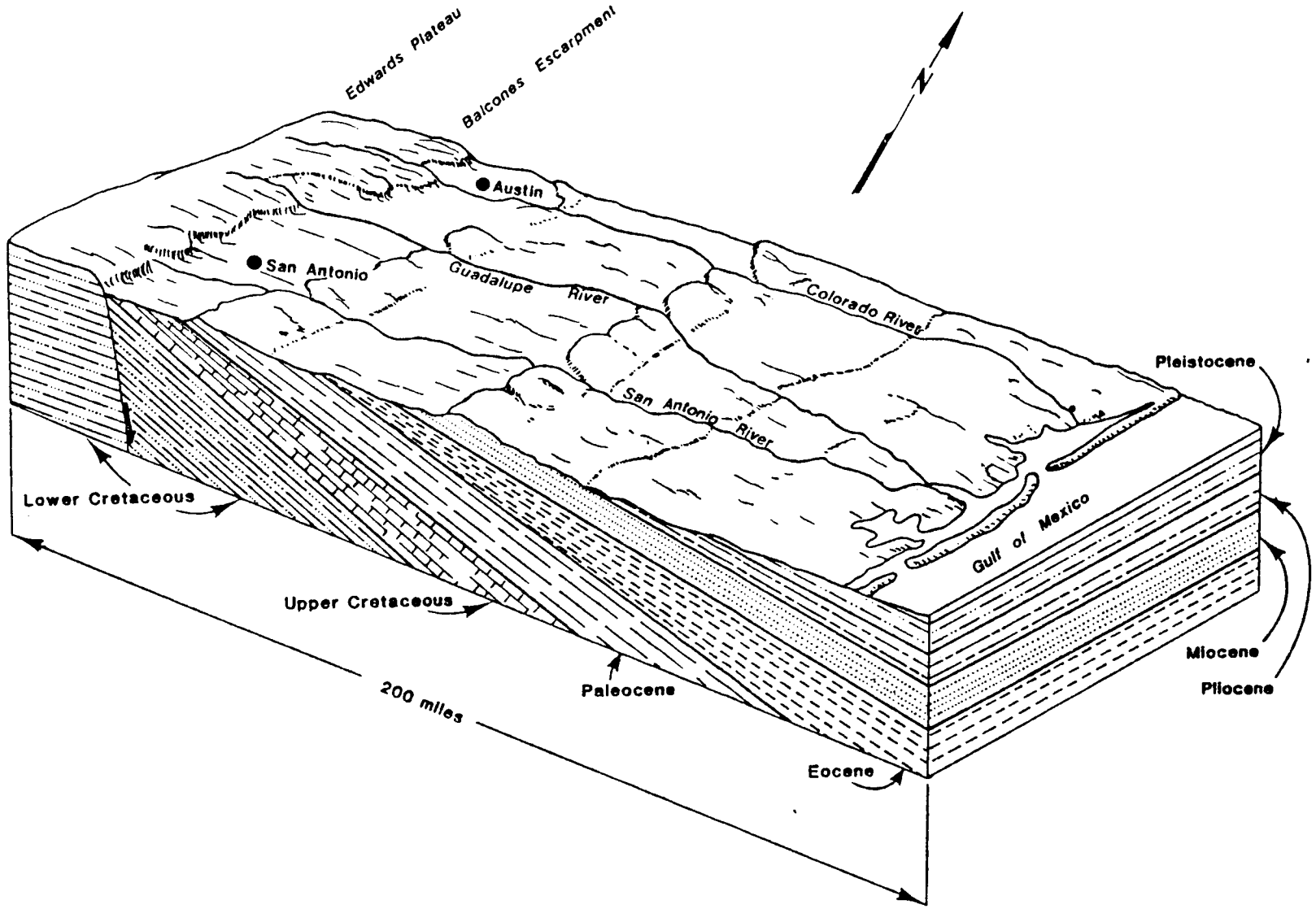


Figure 2. Geologic cross section of Texas.

and peninsulas, formed by reworked Pleistocene depcsits on the inner shelf, achieved their present position only within the last 2000 years.

PATTERNS OF VARIATION IN THE NATURAL ENVIRONMENT

The regional model of the Texas Barrier Island Region (see appendix) illustrates the development of the region over geologic time. The patterns of fluctuation of some driving forces and components of the region do not vary enough to note differences within short time periods. The driving forces and regional system components discussed here are those that have recognizable long-term patterns and that continue to influence the form and organization of the region. The patterns of variation that will be discussed are downwarp, subsidence, and eustacy; topography and bathymetry; weather patterns; temperature variation; rainfall; broad hydrologic patterns; erosion, sediment transport, and offshore sediment movement; and substrates and soils.

Downwarp, Subsidence, and Eustatic Sea Level Change

Gulf Coast geosyncline. The major axis of the Gulf Coast geosyncline is parallel to the Texas coastline and has been moving gulfward since the geosyncline developed. As the area deflected downward, Cretaceous, Tertiary, and Quaternary sediments accumulated on top of the Jurassic materials within the depression. Figure 3 (from Hardin 1962) shows the thickness of the Cenozoic deposits. In some places Cenozoic sediments are more than 50,000 ft deep. Williams et al. (1976) noted that the sediments covering the geosyncline surface are as deep as 60,000 to 65,000 ft in the Houston area. Hardin (1962) estimated that more than 10,000 ft of Cenozoic sediments are present over an area of 250,000 sq mi.

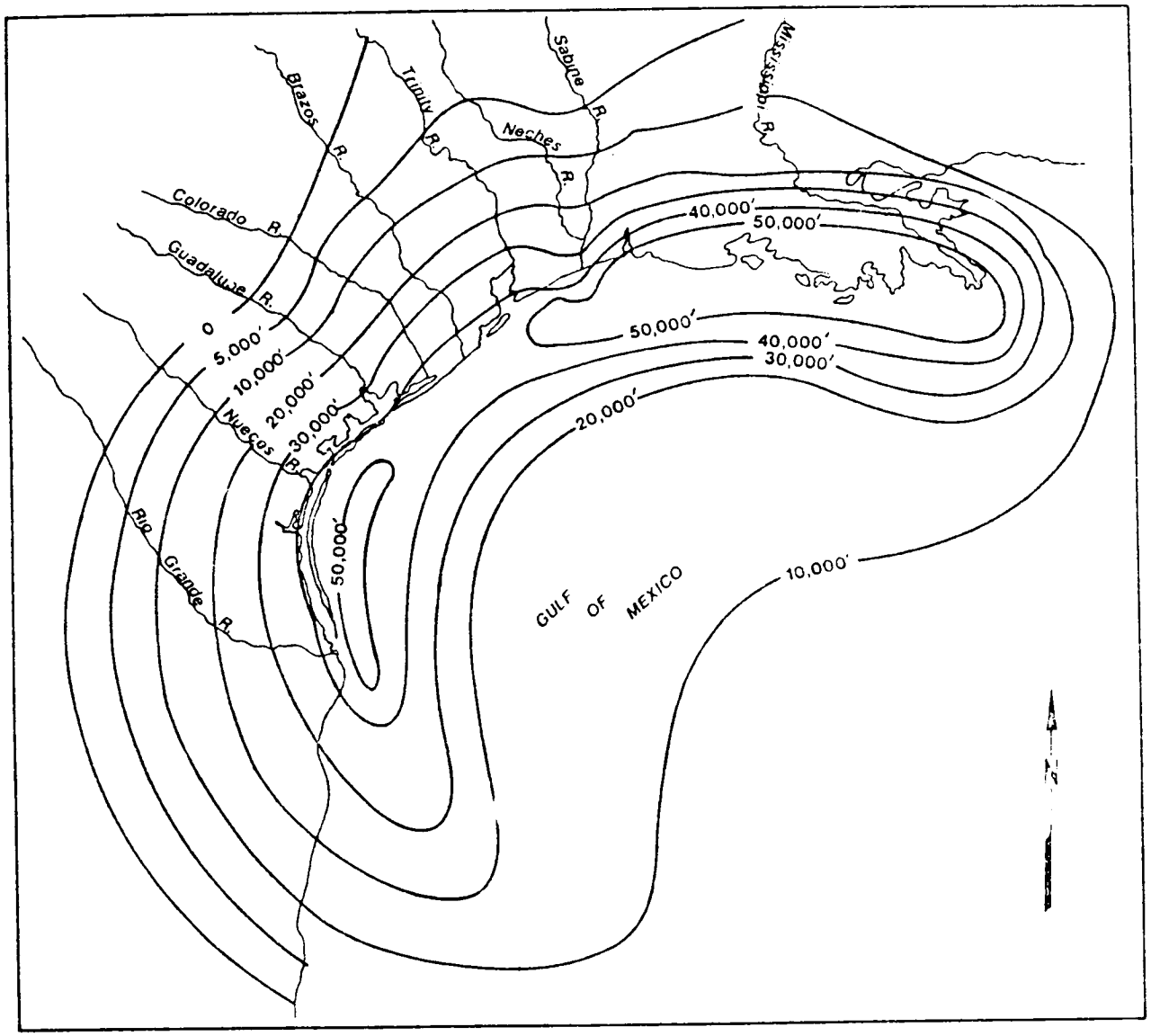


Figure 3. Depths of Cenozoic deposits within the Texas Barrier Island Region.

The slope of the geosyncline is not constant. At the edges of the depression, the slope of the base layer is gentle (0.2 to 1.9 percent per mile); closer to the major axis, the slope of the base layer increases (5 to 100 percent per mile, Hardin 1962).

The Gulf Coast geosyncline, an active force for more than 150 million years, has been the major factor shaping the coastal region. It has provided an elevation gradient over which the force of gravity acts to produce water movement, sediment transport, and deposition. These processes and an abundant sediment supply have given the region its general slope. The concave shape of the Texas coastline mirrors the contours of the geosyncline.

Maximum sedimentation rates, indicative of the rate of flexure of the geosyncline, have generally increased with time, ranging from a low of 0.3 cm per century in the Cretaceous to 15 to 20 cm per century in the Pleistocene and Recent epochs (Hardin 1962).

Instantaneous measurements of the rates of sinking of the geosyncline range from 0.1 to 0.15 mm/yr (Winker 1979). The continued sinking of the geosyncline indicates that this will be an important driving force far into the future.

Eustatic sea level change. Relative sea level change and local subsidence have also provided elevation gradients, although their effects have been of shorter duration. During the late Wisconsin (20,000 years BP) sea level dropped to about 400 ft below its present level. It rose to an elevation 3 to 4.5 m (10 to 15 ft) below its present level by 4500 years BP (McGowen et al. 1976). The rate of sea level rise during this time was about 0.8 cm (0.026 ft) per year. Sea level has risen 4.5 m (15 ft) in the ensuing 4500 years, a rate of 0.1 cm (0.0033 ft) per year. Over the past 40 years,

mean sea level has risen globally at a rate of 0.3 cm (0.01 ft) per year (Etkins and Epstein 1982). Although short-term changes in sea level occur, sea level is currently rising at a rate equal to about 40 percent of the average rate during the Holocene.

Subsidence. Localized subsidence in the coastal region is related to the extraction of groundwater, oil, gas, and sulfur (Gustavson and Kreitler 1976, Ratzlaff 1980). Withdrawal of liquids from coarse sand beds causes an immediate reduction of pore pressure in the bed. Changes in pore pressure in beds of fine-grained deposits, however, is not instantaneous. The resulting pressure differential between clays and sands causes water to move from the saturated clay beds, and the clays compact under the weight of the overlying sediments. The vertical compression of the formations is seen at the ground surface as subsidence, which deepens the existing basins, lowers subaerial land, or causes subaerial land to become subaqueous.

Figure 4 (Brown et al. 1974) shows areas of localized subsidence in the region. About 30 percent of the area of the coastal counties from the Louisiana border to the Rio Grande has subsided 6 to 25 cm (0.2 to 1.0 ft) since 1906; about 7 percent has subsided 1 to 5 ft (0.3 to 1.5 m); and less than 2 percent has subsided more than 1.5 m (5 ft) (from Brown et al. 1974). The locations where the most subsidence has occurred include portions of Houston, greater than 2.6 m (8.5 ft); Swan Lake near Texas City, 1.5 m (5.0 ft); Moss Bluff salt dome near the Trinity River (sulfur mining), 4.6 m (15 ft); and the Saxet oil and gas field near Corpus Christi, 1.6 m (5.3 ft) (Ratzlaff 1980). In the Houston area, Clear Lake and portions of upper Galveston Bay have deepened substantially.

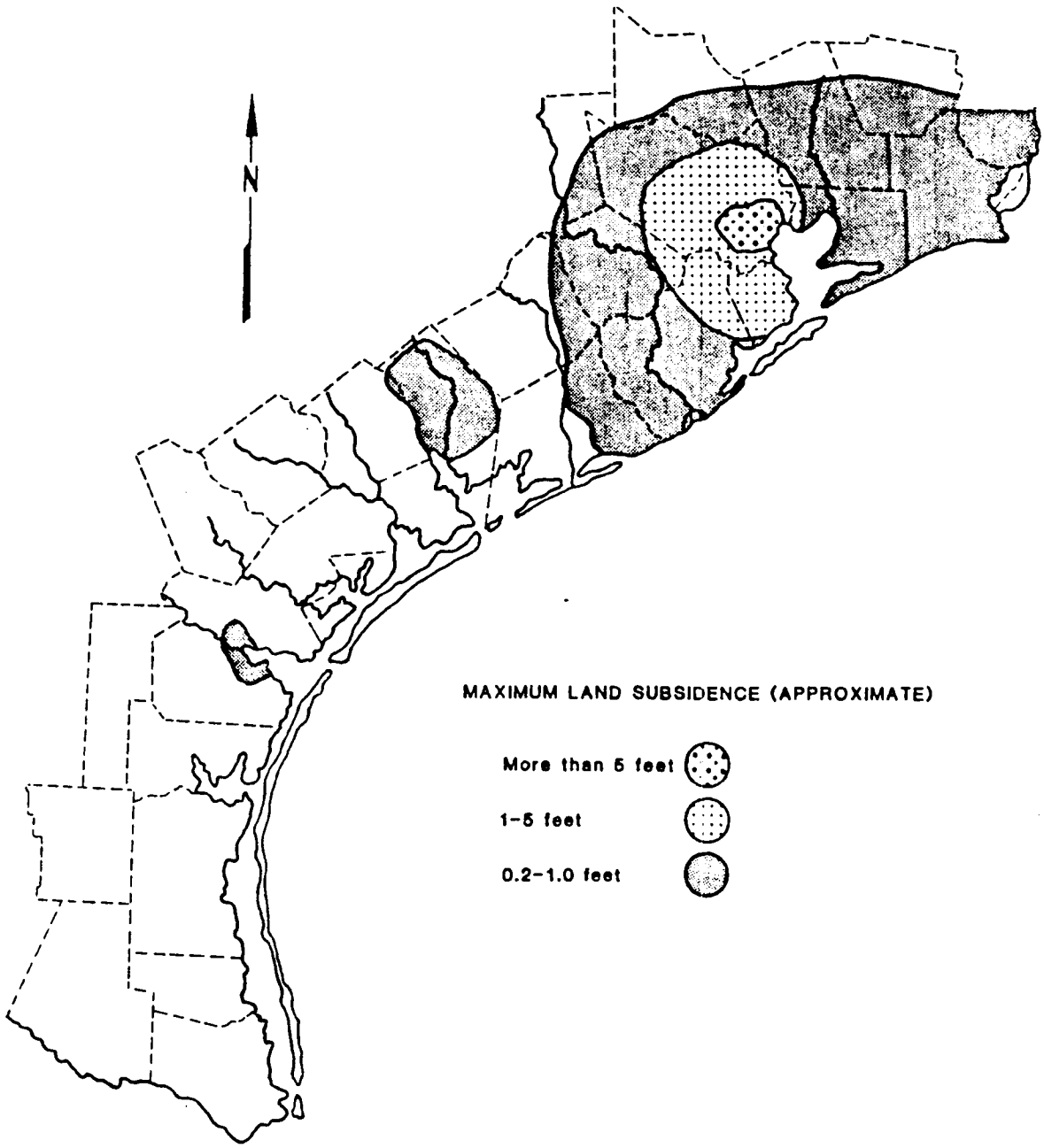


Figure 4. Areas of subsidence within the Texas Barrier Island Region. (1906-1973)

Topography and Bathymetry

The pattern of topography and bathymetry in the region displays the influence of the Gulf Coast geosyncline (Figure 5). A few features diverge slightly from the shape imparted to the land surface by the geosyncline. The wide continental shelf off the upper coast and the protuberances on the shelf opposite river mouths are the result of deposition of large amounts of sediment. However, since the sediment was directed to the coast by the dipping of the land surface, even these features are indirectly related to geosyncline development. The downwarp from geosyncline development is the major link connecting subsurface processes with surface physiography in the region.

Topography. The map in Figure 5 shows that the gulfward slope of the land is not constant; it is greatest in the most inland parts and flattens toward the gulf. The coastal plain is widest in the upper coastal region, narrows in the area between Lavaca Bay and Corpus Christi Bay, and widens again toward the Rio Grande. The similarity between the map of topographic features and the map showing depths of the geosyncline (Figure 3) clearly illustrates the influence of the geosyncline on upland topography.

The gulfward slope of the uplands is obvious; however, between the Guadalupe River valley and the Nueces River valley is a topographically high area called the San Marcos arch. This arch separated the Sabine and the Rio Grande embayments during the late Jurassic. Remnants of the arch are evident in the inset diagram in Figure 5, which depicts the range of slopes to the gulf shoreline for six segments of the Texas Barrier Island Region. The slopes were measured from the highest and lowest upland elevations at the inner boundary of the region (measurements from Fisher et al. 1972; Brown et

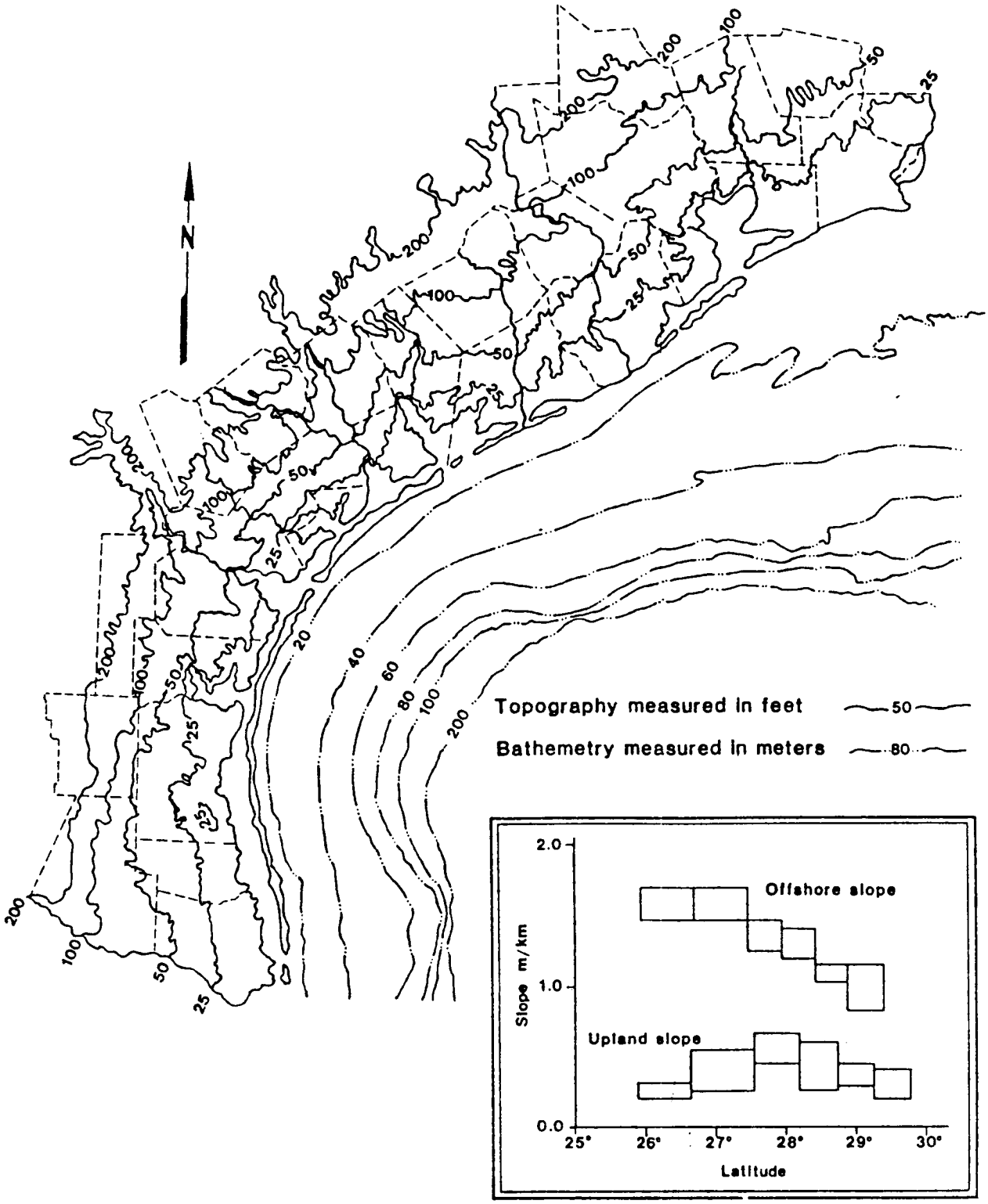


Figure 5. Topography and bathymetry of the Texas Barrier Island Region.

al. 1976; McGowen et al. 1976a, 1976b; Brown et al. 1977; and Brown et al. 1980). The elevations were measured outside the floodplains of rivers that flow to the coast. The middle two blocks in the upland slope portion of the inset diagram show land slope from the Corpus Christi area to the Port Lavaca area. These are the areas with the highest slopes; areas of the region to the northeast and southwest have progressively lower slopes. Consequently there is a lateral elevation gradient with its highest point in the central coast in addition to a gradient toward the gulf.

Bathymetry. The bathymetric portion of Figure 5 shows the shape of the subaqueous land surface. The continental shelf varies in width from about 80 km (50 mi) along the southern coast to more than 161 km (100 mi) along the upper portion of the region. The influence of material carried from the Rio Grande is evident from the convex bathymetric contours at the river mouth. The bathymetric contours are parallel to the geosyncline contours in the lower coastal area, above the Rio Grande. At a point opposite San Antonio Bay, however, the bathymetric contours turn sharply eastward and the shelf widens. The thick, wide shelf in this area is the result of deposition of very large quantities of Miocene, Pliocene, and Pleistocene and Recent sediment (Hardin 1962). Much of the large supply of sediment came from erosion of the Rocky Mountains.

Periodic bumps at the edge of the continental shelf indicate the location of old Colorado and Brazos-Colorado deltas (Curray 1960). The bathymetry of much of the continental shelf has only recently been mapped in detail (1:250,000 bathymetric sheets available from the Minerals Management Service, U.S. Department of the Interior).

Figure 5 shows the offshore land slope measured from the gulf beach to the highest and lowest bathymetric contours three leagues (10.35 mi) from the shoreline (the line of state-federal demarcation). At three leagues the depth varies from 14 to 28 m (45 to 93 ft). The slope of the nearshore subaqueous areas is similar to the larger bathymetric pattern; that is, low along the upper coastline and increasing toward the south.

Weather Patterns

Seasonal differences in weather patterns. Weather patterns in the Texas Barrier Island Region are strongly influenced by the season of the year. During the summer the greatest influences on the region are strong southeasterly winds, humidity, and tropical cyclones (tropical storms or hurricanes) from the Gulf of Mexico. Tropical storms and hurricanes are concentrated weather events that usually occur during the summer months (July, August, September) (Figure 6). Only about 25 percent of the 92 tropical cyclones in the past 112 years have occurred at times other than the summer months (Henry et al. 1975). During the remainder of the year, weather patterns oscillate under the alternating influences of polar or arctic fronts from the north and northwest and warm moist air from the gulf.

Wind patterns. Figure 7 shows wind roses for six areas of the Texas Barrier Island Region (from Fisher et al. 1972; Brown et al. 1976; McGowen et al. 1976a, 1976b; Brown et al. 1977; and Brown et al. 1980). The wind roses indicate the percent frequency of surface winds. The long vectors indicate the dominance of winds from the gulf; shorter vectors from the northern quadrants show frontal passage.

The wind roses also show that the dominant wind direction changes slightly from the upper to the lower coast. On the upper coast, which lies on

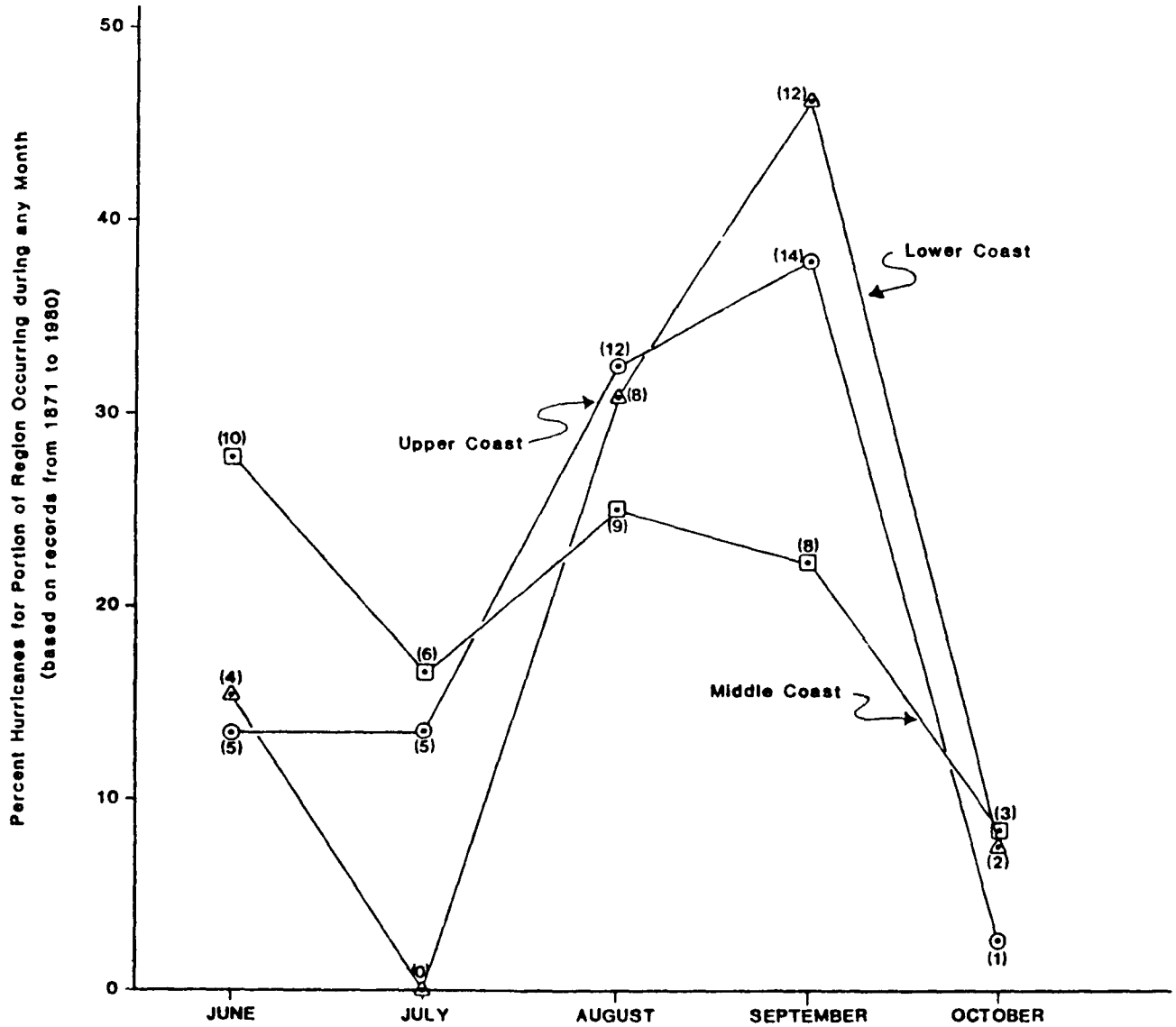


Figure 6. Tropical cyclone incidence for upper, middle, and lower Texas coast.

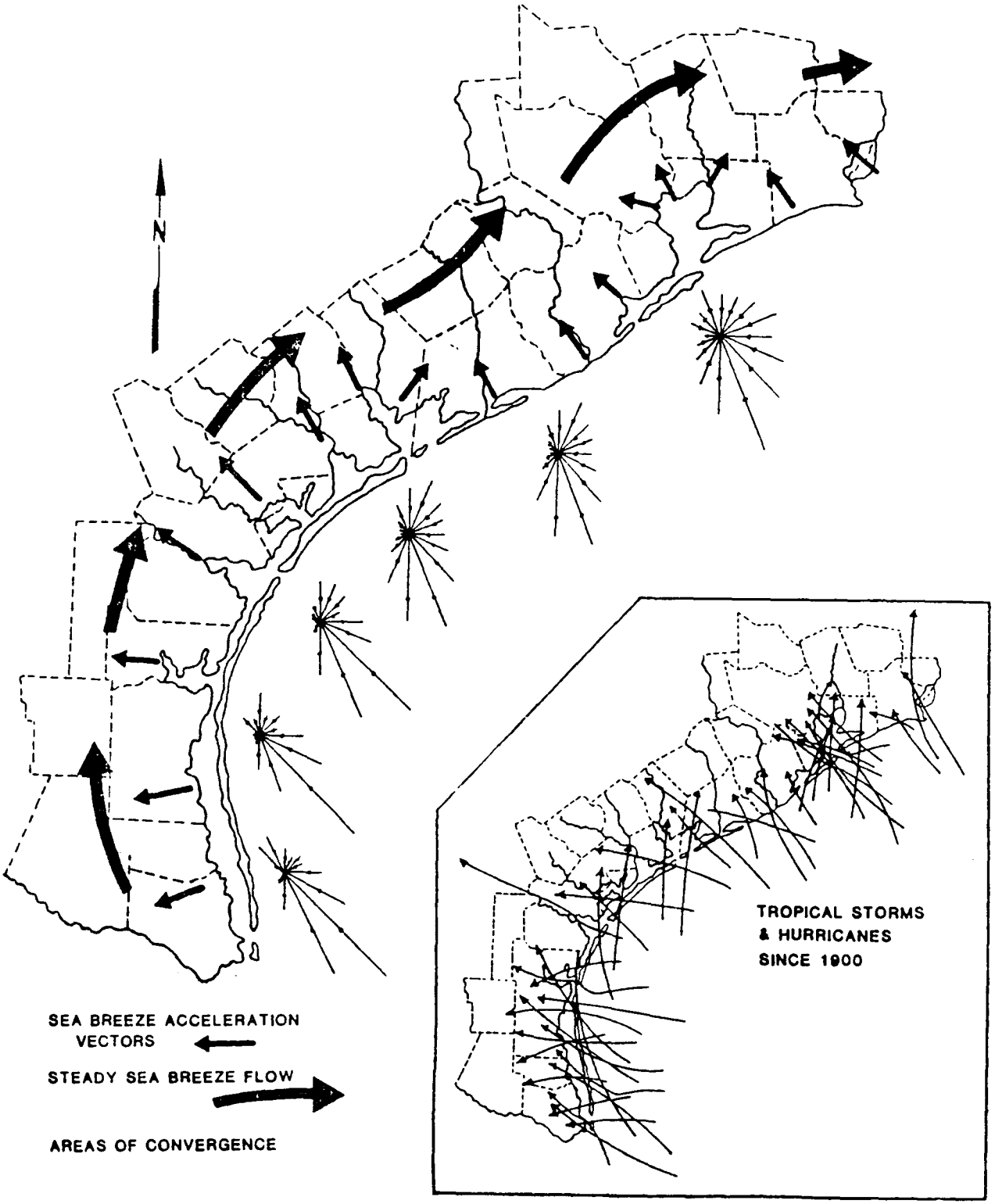


Figure 7. Wind and storm patterns.

a northeast to southwest axis, winds are more southerly than on the lower coast. The shoreline of the lower coast runs approximately north and south, and the dominant winds are more easterly.

Sea breeze. When not affected by frontal passage, the wind patterns over land in the region are governed by the sea breeze. The sea breeze is a wind force generated by the differential heating and cooling of air masses over land and water. During the day the land absorbs heat more rapidly than the shallow water in bays, the gulf, or marshes. The air above the land becomes less dense and rises, which pulls moist air from over the water to the land. The moist air also rises, is cooled, and forms clouds that are pushed inland and become taller. If they are cooled enough, the clouds will produce rain showers inland throughout the region (Williams et al. 1976).

Zones of convergence. The direction of air flow from the sea breeze is perpendicular to the shoreline between the upland and the adjacent water body or wetland. The small arrows in Figure 7 show the direction of sea breeze acceleration vectors that result from the shape of the coastline. In three places along the Texas coast the acceleration vectors focus upon common geographic areas. These zones of convergence (Figure 7) are the sites of higher-than-expected precipitation. The zones of convergence are due to an interaction of land shape and climatic processes.

Pattern of airflow. At altitudes where the friction between the land surface and air movement dissipates, winds are rotated to the right by the Coriolis effect. This causes a general pattern of air movement up the coast roughly paralleling the coastline. The large arrows in Figure 7 show the trend of this air movement.

Tropical cyclone characteristics. Tropical cyclone paths since 1900 are illustrated in Figure 7 (Davenport 1978). Cyclones are spawned in the Gulf of Mexico, the Caribbean Sea, or the equatorial Atlantic Ocean as far away as the African coast. They generally travel westward but begin to turn more northward as they enter the gulf. Tropical cyclones that strike the Texas Coast tend to cross the gulf shoreline at angles between 10 and 90 degrees to the coastline as viewed from the south. It is unusual for a tropical cyclone to cross the shoreline in a southwest direction.

Tropical cyclones rotate counterclockwise. Because cyclones usually move to the northwest or west-northwest, winds to the north and east of the eye are the strongest. Storm surge and winds are usually higher to the north of the storm track on gulf beaches and the mainland shoreline (Brown et al. 1974). On the back side of barriers and peninsulas, however, storm surge and winds may be highest to the south of the storm line because of the counterclockwise winds.

The major effects of hurricanes are storm surge (producing short-term changes in water level), waves, heavy rainfall, and high winds. Storm surge is caused by hurricane winds and by decreased barometric pressure. Since 1900 storm surge from hurricanes has ranged from 0.6 to 7.6 m (2.1 to 22 ft) on the Texas coast. Severe shoreline erosion is produced by high-energy waves; it is increased by the high water levels associated with storm surge. Beaches and dunes on barrier islands and peninsulas may be eroded several hundred feet by wave action (McGowen and Brewton 1976).

Rainfall accompanying tropical cyclones. Rainfall normally accompanies tropical storms. As the storms slow over land, rainfall increases. Rainfall from hurricane Beulah in 1967 was greater than 76 cm (30 inches) in areas

where storms lingered (Brown et al. 1974). Heavy rainfall causes high levels of runoff from the uplands. Flooding of lowland areas around rivers and bays by runoff often exceeds the flooding caused by storm surge.

Differences in tropical cyclone activity in the region. Figure 6 shows the temporal pattern of cyclones striking or affecting the Texas coast over the past 112 years. The upper coast has been affected by 37 percent of the cyclones, the central coast by 36 percent, and the lower coast by 26 percent. About 75 percent of the tropical cyclones have occurred during the summer; 62 percent have occurred during the months of August and September. The temporal patterns in the upper and lower coast are very similar; the middle region, from Corpus Christi Bay to East Matagorda Bay, has had the greatest number of cyclones strike during June, early in the hurricane season.

Rainfall

Rainfall and evapotranspiration are the major processes linking water in the atmosphere and on the land surface. Rainfall patterns are particularly significant because they show the relative influence of frontal passage, gulf moisture, and hurricanes upon the region's precipitation. Precipitation influences runoff, which is important in controlling sediment transport.

Influences of frontal passage and the gulf on rainfall. Figure 8 (Williams et al. 1976) shows 30-year rainfall averages in inches for the summer months (June through October) and for the period of frontal passage (November through May). During the summer months, rainfall isohyets are generally parallel to the coastline. Rainfall decreases with distance inland from the shoreline. While this pattern is somewhat complicated by the three zones of convergence (at the Rio Grande, at the mouth of the Brazos, and near

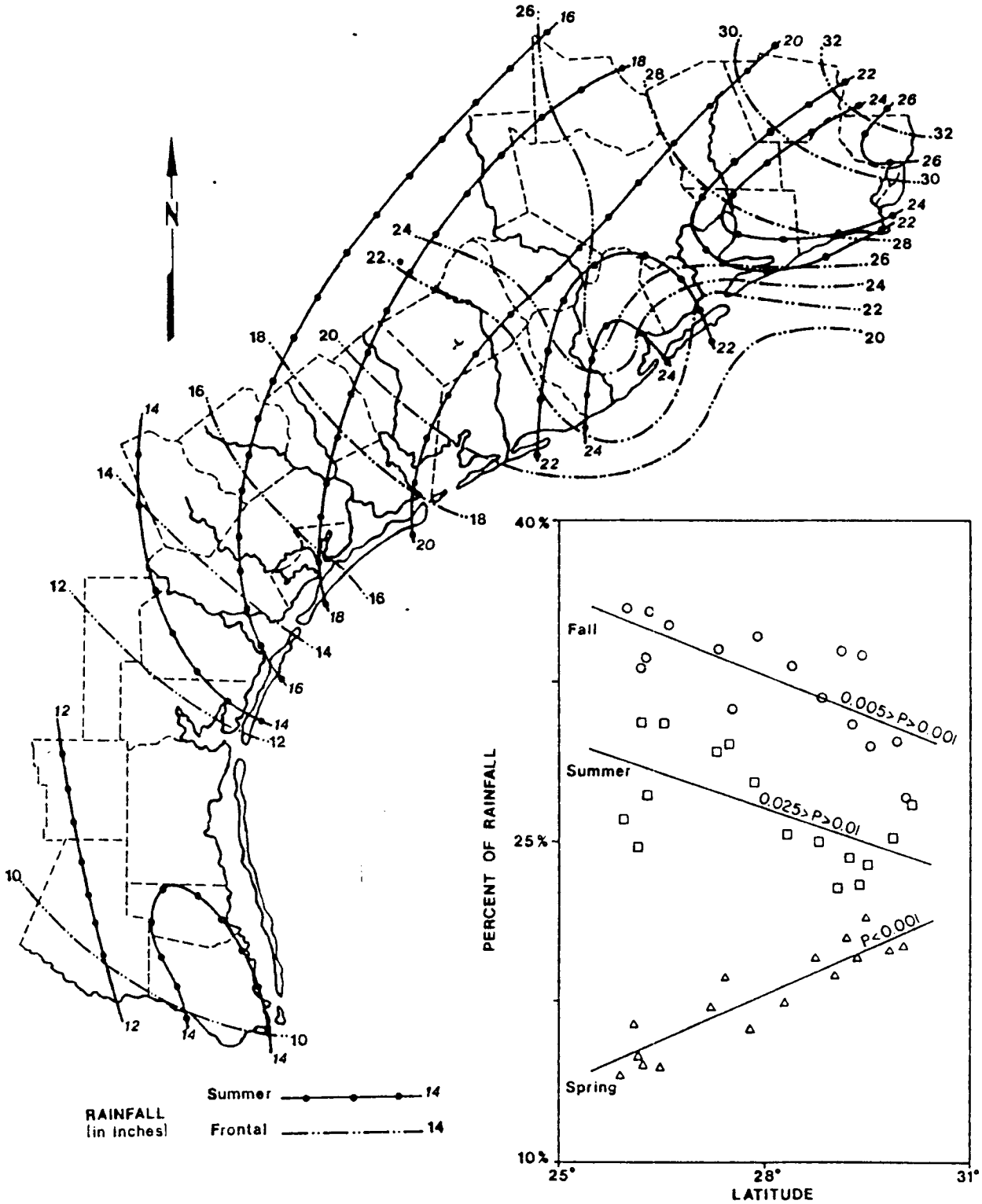


Figure 8. 30-year rainfall averages: seasonal distribution.

the Texas-Louisiana border), it shows that rainfall during the summer months is associated with thunderstorms and hurricanes that move inland from the gulf.

Frontal isohyets indicate the amount of rainfall associated with the passage of polar continental, polar maritime, and arctic fronts (Orton 1964). Frontal isohyets generally run east and west and are perpendicular to the coast at the coastline. The contours show a decrease in rainfall from north to south because the source of the frontal energy is to the north.

Seasonal rainfall patterns. Rainfall patterns within the coastal region exhibit marked seasonal variation. The inset graph in Figure 8 shows the percent total rainfall occurring during spring, summer, and fall at each of 16 weather stations at different latitudes (based upon 30-year average rainfall data; National Climatic Center 1973). The data were separated into 3-month seasons and the percent total rainfall plotted against latitude.

Seasonal distribution of rainfall is uneven. Spring has less rainfall than any other season (17.8 percent coastwide). Average winter rainfall is slightly higher (22.5 percent); summer is higher still (26.6 percent), and fall has the highest proportion of rainfall (33.0 percent). The percent rainfall within a season varies with latitude for all seasons but winter. In spring a larger proportion of the season's precipitation falls on the upper coast than on the lower coast. Just the reverse is true for summer and fall. The regression lines on the inset graph (Figure 8) show statistically significant linear regressions of percent rainfall upon latitude.

Spring and fall rainfall are associated with frontal movement. It appears that spring frontal passage results in a larger proportion of precipitation on the upper coast than on the lower coast. During fall the

lower coast receives a larger proportion of rainfall from frontal passage than the upper coast. Summer weather patterns, including hurricanes, are predominantly from the gulf. The inset in Figure 8 suggests that gulf weather processes are more important in producing rainfall on the lower coast than on the upper coast. The largest proportion of rainfall on the lower coast is associated with gulf-generated storms or hurricanes in the summer and with fronts in the fall. Rainfall on the upper coast is less dependent upon frontal passage in the fall and gulf weather patterns in the summer, but more dependent upon spring frontal movement.

Yearly rainfall pattern. Figure 9 (Williams et al. 1976) shows the 30-year average pattern of rainfall for the region. The influence of landform in the three zones of convergence is clearly visible. The yearly average isohyets show a rainfall gradient running from the upper coast to the lower coast. At the northern boundary of the region, average rainfall is about 127 cm (50 inches) per year; at the southern boundary, average rainfall is about 51 cm (20 inches) per year. This gradient influences the surface water flow and affects the makeup of the biotic communities over the entire region.

Variation in rainfall quantity. Average rainfall for the 16 stations is 90.7 cm (35.7 inches) per year (National Climatic Center 1973). A rainfall variation probability graph (Portig 1962) shows that average rainfall may vary from 64 to 122 cm (25 to 48 inches) per year 30 percent of the time in the region. Some investigators report a regular rainfall/drought cycle, but its predictability is poor.

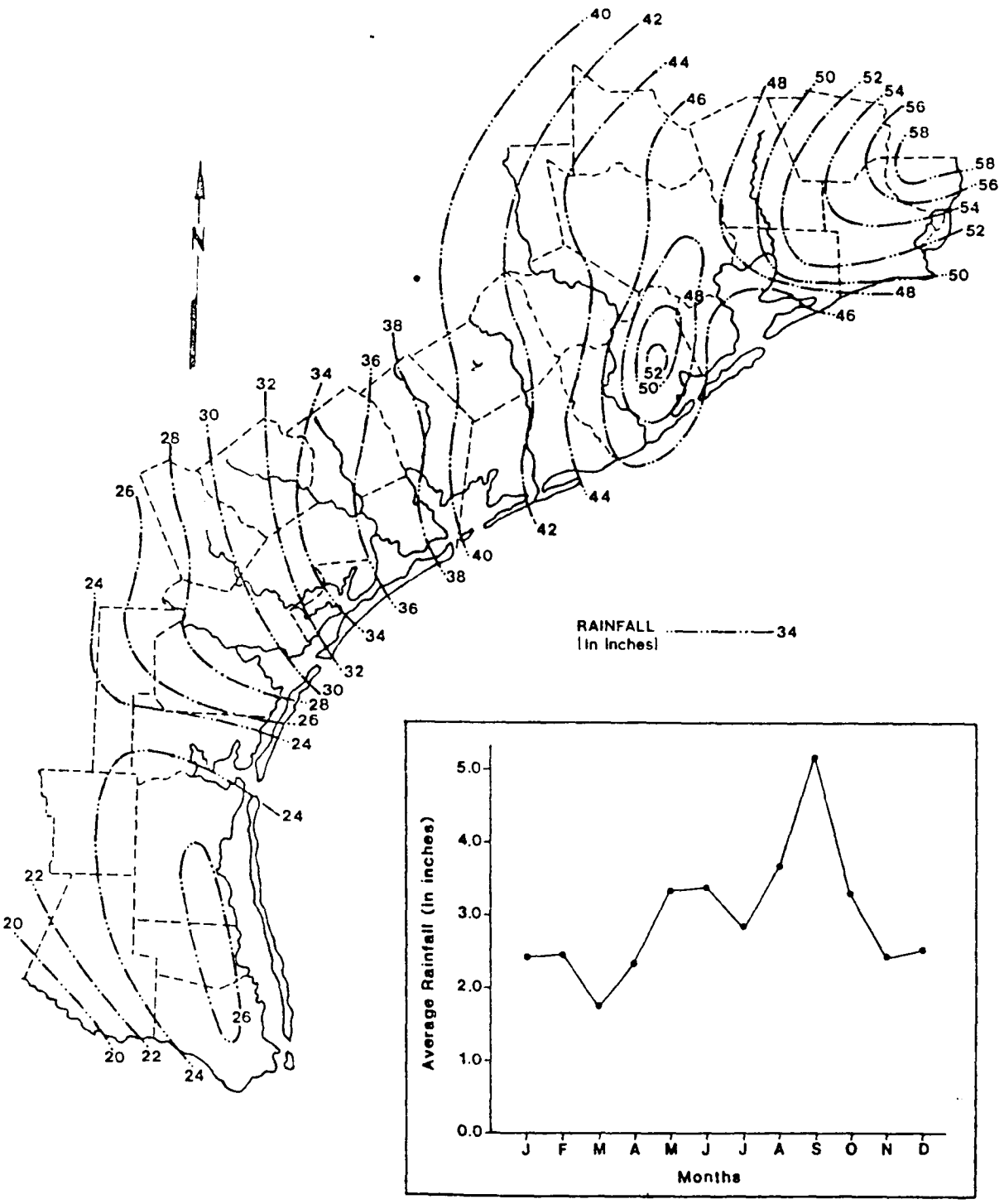


Figure 9. 30-year rainfall averages: annual distribution.

Temperature

Heat, indicated by temperature variation at the regional scale, affects the coastal region through two major processes: interaction with biota and interaction with hard substrates. Metabolic rates and metabolic functions of organisms are regulated by environmental temperature. They are elevated in warmer months for most organisms, although metabolic adaptation to seasonal thermal regimes is not unusual in poikilotherms. Plants and bacteria accelerate rock weathering; rooted plants, however, tend to retard the transport of sediments. In areas with rock substrates, thermal expansion may cause stress cracking in solids, but this is probably of little importance in the sedimentary environment of the Texas Barrier Island Region. Through these processes temperature variation has both direct and indirect effects upon sediment production and transport.

Frontal passage and gulf influence on temperature. Figure 10 (Williams et al. 1976) shows the patterns of average summer high temperatures and average winter low temperatures. The summer highs show the influence of the gulf; the isotherms are somewhat parallel to the coastline, indicating that temperature increases with distance inland from the shoreline.

Average winter low temperature isotherms are generally parallel to lines of latitude, since cold fronts move in from the north or northwest. There is an increasing temperature gradient in the region from north to south. Temperature increases at the rate of about 1.4 deg C (2.5 deg F) per degree of latitude.

Temperature extremes. Average high and low values for environmental parameters are indicative of typical conditions. Survival and distribution of organisms, however, are influenced more by periodic extremes of environmental

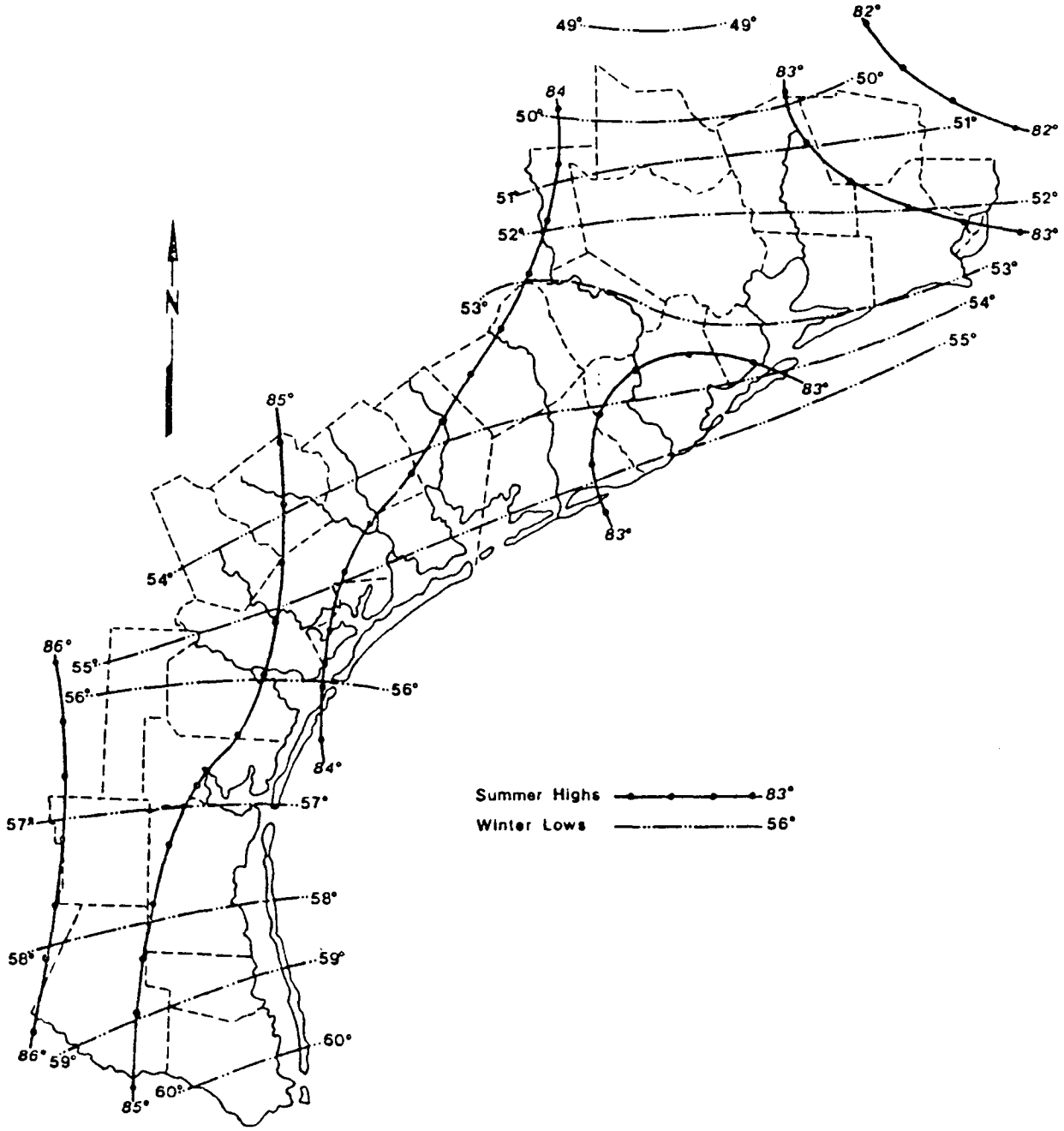


Figure 10. Seasonal temperature extremes.

parameters than by average conditions (Taylor 1934). Extremely high or low temperatures are rare in the upland environments of the Texas Barrier Island Region, but extreme temperatures and rapid temperature changes do occur in aquatic environments. Temperatures up to 44 degrees C have been measured in shallow Laguna Madre waters (Simmons 1957). Temperatures at or very close to freezing have been observed in Laguna Madre and Redfish Bay near Harbor Island, Texas (Gunter 1967; Moore 1976). Since the specific heat of water decreases with increasing salinity (Copeland 1967), shallow euhaline and hyperhaline aquatic systems are even more susceptible to wide temperature variations over short periods than lower-salinity environments.

Yearly temperature averages. Figure 11 shows the yearly average temperature over the entire region. There is a definite temperature gradient, although its magnitude is only about 0.8 deg C (1.5 deg F) per degree of latitude. The temperature and rainfall gradients reinforce one another. The area of highest temperature (southern portion of the region) is also the area of lowest rainfall. The area of greatest rainfall (northern portion of the region) is also the area with the most moderate temperatures.

Hydrologic Patterns

Surface water flow mediates the transport and distribution of sediment throughout the region. Hydrologic patterns exist on the land surface and in the large water bodies. From a regional scale of view, circulation in the gulf, the storage of water in reservoirs, and the flow of water to the region are of interest.

River flow. Ten hydrologic basins carry fresh water from river flow, rainfall, and return flows into the Texas Barrier Island Region. The area

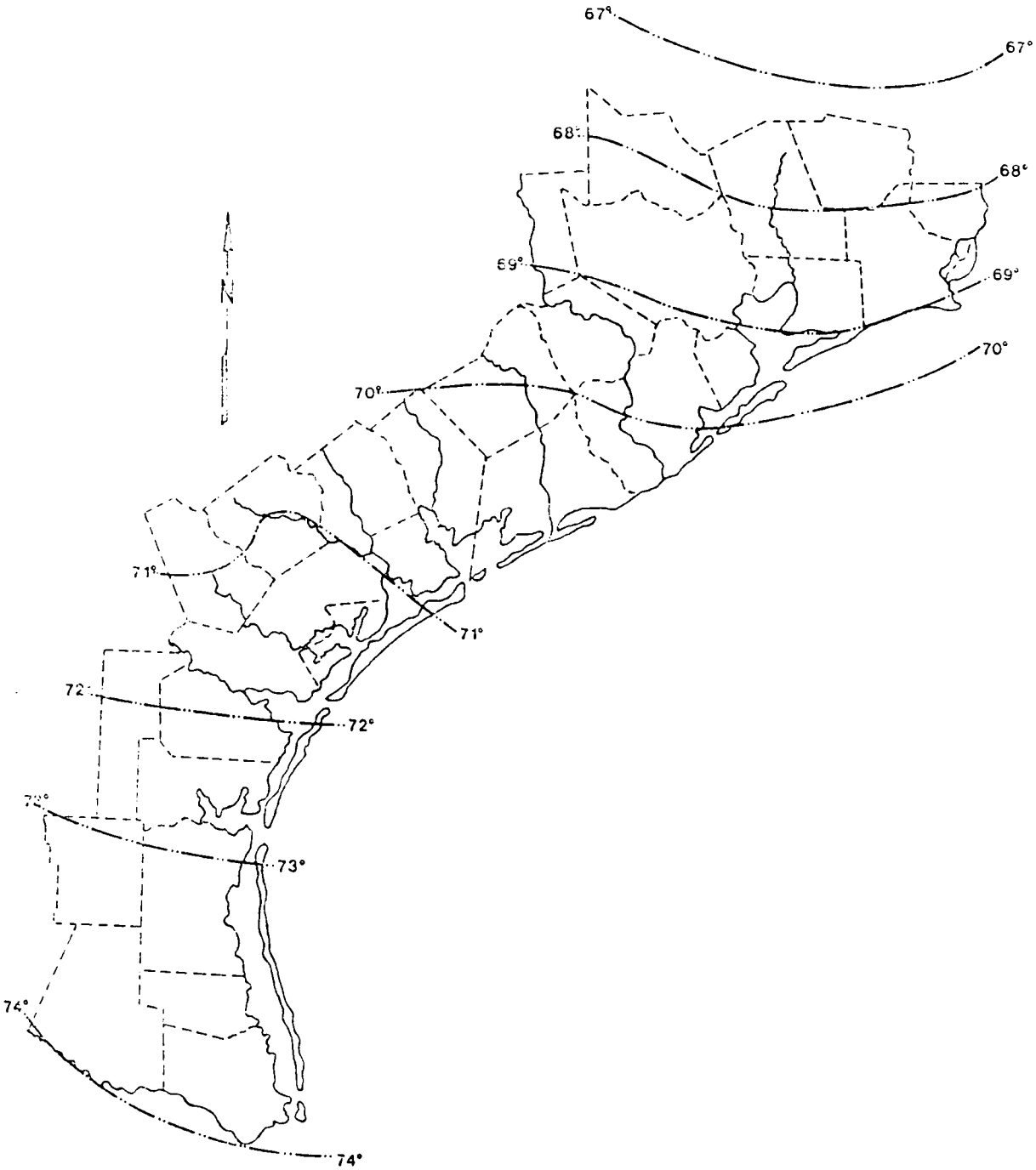


Figure 11. Yearly average temperatures.

drained by these basins is 92 million ha (228 million ac). This is a much larger area than the upland portion of the region itself (2.9 million ha or 7.2 million acres) and is 29.5 percent larger than the entire state of Texas. Some of the hydrologic basins extend far beyond state boundaries. The Colorado and Brazos river basins extend into New Mexico. Only 49 percent of the Rio Grande basin is in the United States, and nearly half of that is in New Mexico and Colorado.

The average yearly flow of streams, return flows, and precipitation into the region is 27.9 billion cu m (22.6 million ac-ft) (data from Texas Water Development Board 1967; Texas Water Development Board 1970; Texas Department of Water Resources 1977; Texas Department of Water Resources 1979). It is difficult to compare actual water flow figures from one basin to another because of large differences in watershed area, but flows into the Texas Barrier Island Region are greatest in the northern basins and decrease to the south (Figure 12).

Gulf surface circulation. Figure 13 shows seasonal surface circulation patterns in the Gulf of Mexico. Surface water current patterns have been estimated by several investigators in compilations of information about the Gulf of Mexico (Leipper 1954; Curray 1960; Watson and Behrens 1970). The patterns shown, taken from Temple and Martin (1979), combine information from two different years into one figure. The surface water patterns indicate that wind direction is of prime importance in determining the flow direction, as noted by Smith (1978). Surface currents may not be entirely accurate indicators of the forces acting upon submerged sediment, however. Smith (1980) showed that bottom currents at a station 6 km (3.7 mi) offshore displayed somewhat different patterns of flow direction than surface currents.

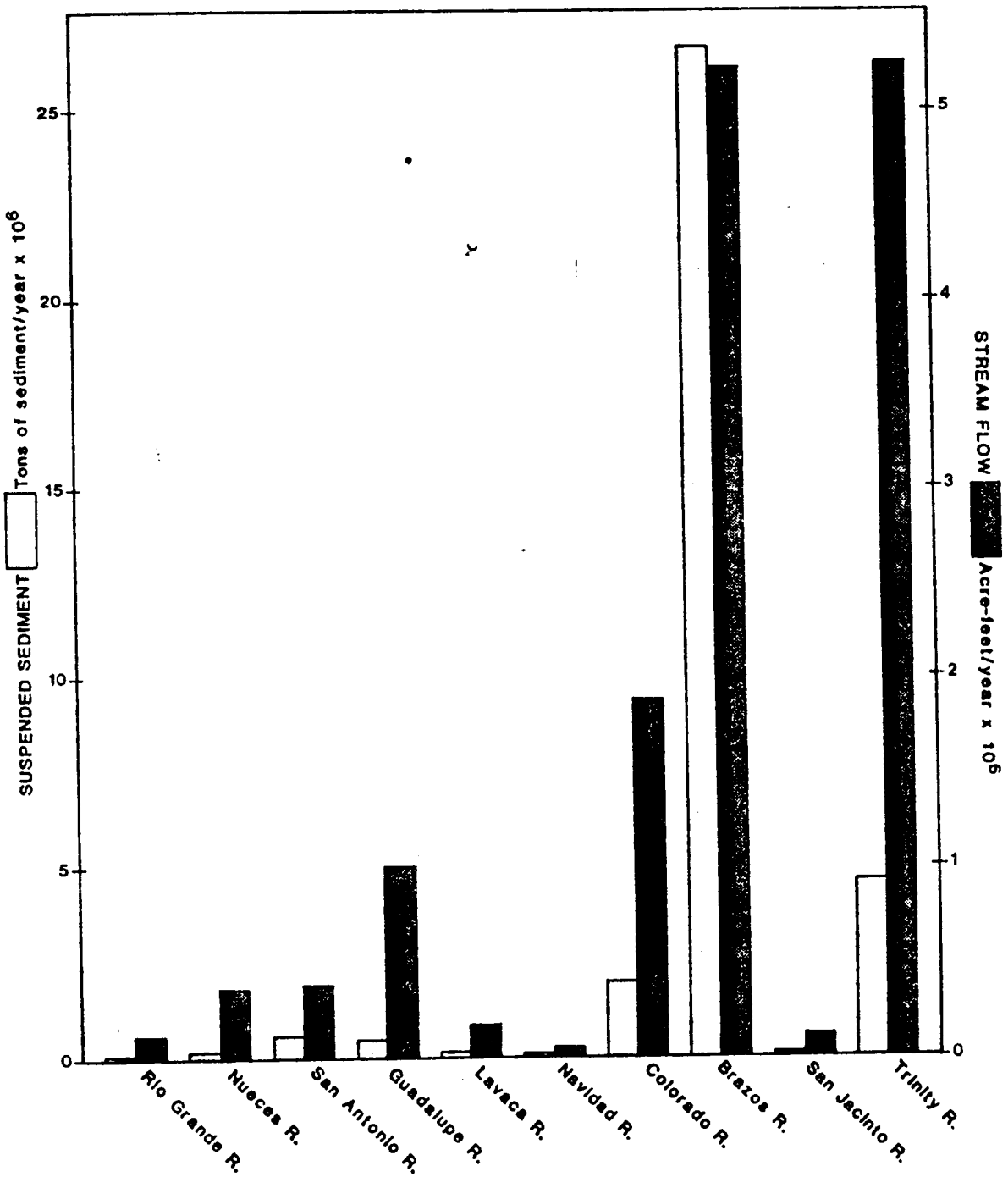


Figure 12. Yearly river flow volumes and suspended sediment loads.

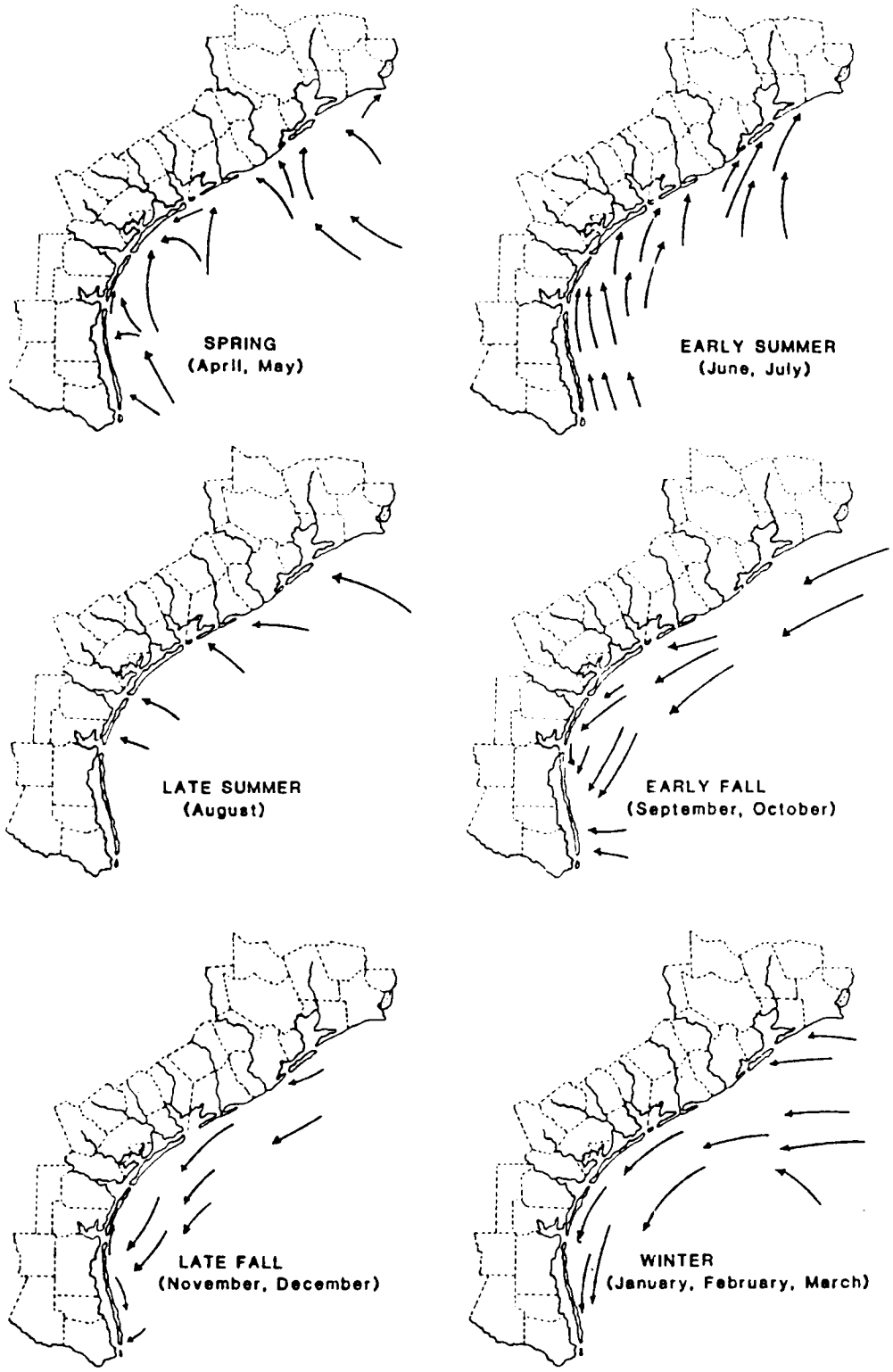


Figure 13. Seasonal surface circulation patterns in the Gulf of Mexico.

Figure 13 shows that northerly surface flow predominates during the early summer, but that flow direction reverses to the southwest in late summer. This southwesterly flow prevails through the winter until spring, when there may be a lengthy period of confused flow as the predominant direction changes back to the summer pattern. There is a definite yearly variation to surface circulation in the region, but the average annual water movement in the nearshore area is approximated in Figure 14. Below the central portion of Padre Island there is an average net flow to the north; above that area there is an average net flow to the south (Watson and Behrens 1970).

Impoundments in the region. Stock tanks and reservoirs in the Texas Barrier Island Region total more than 116,000 acres (from Fisher et al. 1972; Brown et al. 1976; McGowen et al. 1976a, 1976b; Brown et al. 1977; Brown et al. 1980; Texas Department of Water Resources 1983). Figure 14 shows the location of 19 reservoirs in the region. Most of the large reservoirs are located in the upper half of the region. Lake Conroe (21,000 acres in area), Lake Houston (12,200 acres), Sheldon Reservoir (1700 acres), Palmetto Bend (11,000 acres), and Lake Corpus Christi (21,900 acres) are some of the larger reservoirs (Texas Department of Water Resources 1983). There are many smaller reservoirs and stock tanks not included on the figure.

Modifications in land surface flow. The Texas Barrier Island Region contains more than 2849 mi of drainage ditches and irrigation canals. Liberty, Chambers, Harris, Galveston, Brazoria, Matagorda, Wharton, Jackson, Victoria, Cameron, and Hidalgo counties have extensive networks. Much of the water carried by irrigation canals is used for farming of rice, cotton,

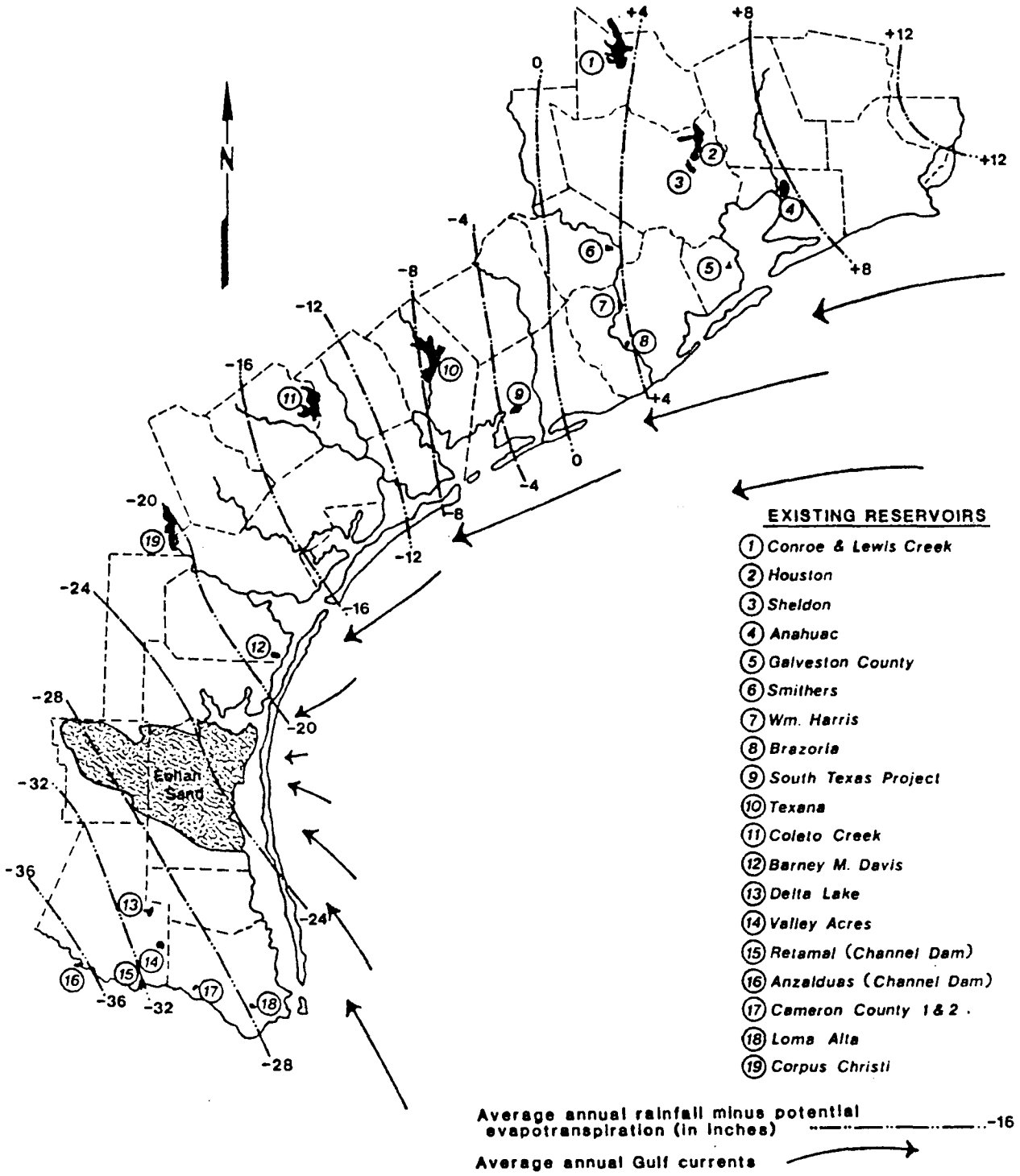


Figure 14. Surface water supply, potential evapotranspiration, annual average water movement, and aeolian sand.

sorghum, and other crops. The greatest concentration of irrigation canals is in the lower coast; there are more than 1448 km (900 mi) of canals in Cameron County. On the upper coast, the large flow from the Trinity, Brazos, and Colorado rivers supports the canal network. On the lower coast, nearly all of the flow to irrigated agriculture is surface water diverted from the Rio Grande (Texas Department of Water Resources 1983). Projected demand figures indicate that the supply of surface water in this area may not be sufficient to meet future municipal and agricultural demand (Texas Department of Water Resources 1983).

The irrigation canals and drainage ditches in the region generally follow the land physiography, but they form networks that alter natural drainage patterns. Highways also interrupt existing drainage patterns. Although highway designers use culverts, bridges, and other means to minimize alteration of water flow, the hydrologic effect of highways in the region may be substantial because of their high density. In 1976 highways in the region were reported to total 63,481 km (39,445 mi) (Liebow et al. 1980). The mileage has probably increased considerably since that estimate was made.

Modifications in estuarine circulation. Bays, lagoons, and some rivers within the Texas Barrier Island Region have been altered by dredging and channelization. The region contains more than 1376 km (855 mi) of dredged channel, of which 1123 km (698 mi) is federally dredged. No estimate of the length of small private channels is available. The Gulf Intracoastal Waterway runs from Louisiana to Brazos Santiago Pass just north of the Rio Grande. Other channels have been dredged perpendicular to the intracoastal waterway to serve port and industrial facilities. The Brownsville Ship Channel, Port Mansfield Channel, Corpus Christi Ship Channel, Aransas Channel, Victoria

Barge Canal, Matagorda Ship Channel, Dow Barge Canal, Chocolate Bayou Channel, Texas City Channel, Houston Ship Channel, and Trinity River Channel are major dredged navigation channels in the region.

Deep navigation channels allow saltwater intrusion; they provide a wide, deep trough through which tidal forces may be transmitted upstream. They may also direct freshwater flow rapidly outward rather than allowing it to mix with other bay waters. Spoil dredged from channels may alter flow directions within hydrologic basins. Long spoil dikes such as the Texas City Dike may markedly alter estuarine circulation. The volume of spoil to be generated in the region during the 10-year period of 1976 to 1986 has been estimated at 385 million cu m (312,262 ac-ft) (Belaire and Alexander 1976). Disposal sites for a number of channels are already approaching depletion. The establishment of new sites for the disposal of maintenance spoil will further alter estuarine circulation patterns.

Surface water surplus or deficit. Figure 14 shows isopleths of average annual rainfall minus potential evapotranspiration. Transpiration (the passage of water vapor from plants to the atmosphere) and evaporation act to remove water from the soil; rainfall adds moisture. The balance between the addition and removal of moisture is a measure of the availability of water for agriculture and other uses, and of an area's suitability for natural plant communities. Figure 14 shows that the equilibrium point is reached slightly to the east of the Colorado River. The deficit increases to the south with decreasing rainfall and increasing temperature. Between Baffin Bay and the Rio Grande the deficit ranges from 61 to 91 cm (24 to 36 inches). In this area the coastal influence is apparent; at the same latitude isopleths of

rainfall minus evapotranspiration show smaller deficits closer to the coastline than farther inland.

Sediment Transport

The sediment transport and deposition processes that formed the coastal plain and the continental shelf during the Cenozoic Era continue today, though much less sediment is being carried to subaqueous basins, bays and lagoons, and the gulf now than in the Tertiary Period and the Pleistocene Epoch. Sediment carried into the gulf has not remained static; upper layers have been redistributed by major gulf water movements.

Erosion. Both wind and water erosion are severe in some upland portions of the Texas Barrier Island Region. Upland water erosion may be of three types: sheet, rill, or gully erosion (Texas State Soil and Water Conservation Board 1981). Sheet erosion is the removal of a fairly uniform layer of soil from the land surface by rainfall and surface runoff (U.S. Department of Agriculture 1981). Rill erosion is the removal and transport of sediment by numerous small channels a few inches deep that are formed by surface runoff (U.S. Department of Agriculture 1981). Gully erosion is the carving out or enlargement of deep trenches by water movement.

The natural topsoil formation rate nationwide varies from 3.4 to 9.0 metric tons per ha (1.5 to 4 tons per acre) per year (Risser 1978; Scott 1978). The average loss of topsoil from agricultural lands nationwide has been estimated at 11.7 to 19.3 metric tons per ha (5.2 to 8.6 tons per acre) per year (Brink et al. 1977), 20.2 metric tons per ha (9 tons per acre) per year (Risser 1978), and 26.9 metric tons per ha (12 tons per acre) per year (Pimentel et al. 1976). Recent studies give the following estimates of average sheet and rill erosion rates for land uses in Texas: cropland, 7.3

metric tons per ha (3.3 tons per acre) per year; pastureland, 2.9 metric tons per ha (1.3 tons per acre per year); rangeland, 8.5 metric tons per ha (3.8 tons per acre) per year; urban, 2.7 metric tons per ha (1.2 tons per acre) per year; and forestland, 0.8 metric tons per ha (0.34 tons per acre) per year (U.S. Department of Agriculture 1980; Texas State Soil and Water Conservation Board 1981). One cubic yard of topsoil weighs about one ton; one acre-inch of topsoil weighs about 134 tons. The number of years required to lose one inch of topsoil may be calculated by dividing 134 by the erosion rate in tons per acre per year.

Detailed erosion estimates are not available for the Texas Barrier Island Region. County acreage estimates from the Texas State Soil and Water Conservation Board (1981) and the statewide average erosion rates above, however, indicate that sheet and rill erosion in the region amounts to 36,069,415 metric tons (39,767,823 tons) per year. Estimated average annual erosion on streambanks, gullies, roads, roadsides, and construction sites in the region is about 1.7 metric tons per ha (0.77 tons per acre) per year, or 11,056,686 metric tons (12,190,392 tons) per year (U.S. Department of Agriculture 1980). The amount of soil lost to wind erosion in the region cannot be estimated accurately from available information. Rates as high as 33.2 metric tons per ha (14.8 tons per acre) per year may occur on cropland in the state (U.S. Department of Agriculture 1980). More than 9.1 million ha (22.6 million ac) of cropland and rangeland in Texas have wind erosion rates greater than 11.2 metric tons per ha (5 tons per acre) per year (U.S. Department of Agriculture 1980).

Erosion problem areas. No county-specific quantitative information showing variation in upland wind and water erosion throughout the region has been collected; however, soil and water conservation districts have provided qualitative estimates by ranking and rating the importance, extent, and severity of various soil and water conservation problems as part of a long-range planning effort (Texas State Soil and Water Conservation Board 1981). From this information it is possible to estimate the percent of the area of each county in the region experiencing moderate-to-severe upland water erosion or moderate-to-severe wind erosion (Figure 15). While the soil and water conservation districts only estimated the areal extent of problems and did not have uniform definitions of problem severity, the estimates were made by individuals who had excellent first-hand knowledge of the problems and lands involved.

Upland water erosion. The water erosion map in Figure 15 shows the extent of upland water erosion problems reported by the Texas State Soil and Water Conservation Board for the Texas Barrier Island Region. Counties very close to the gulf tend to have fewer water erosion problems than their neighbors further inland. This difference may be related to the land slope since the average slope is greater in the more inland counties than in the coastal counties. With the exception of Fort Bend County, counties reporting the highest degree of water erosion were located in the lower portion of the central coastal region, from San Antonio Bay to Baffin Bay. It is not clear why these counties report higher proportions of moderate-to-severe water erosion than counties to the north and south of them.

Wind erosion. The wind erosion map in Figure 15 shows the extent of wind erosion reported for counties in the region. Only counties on the lower coast

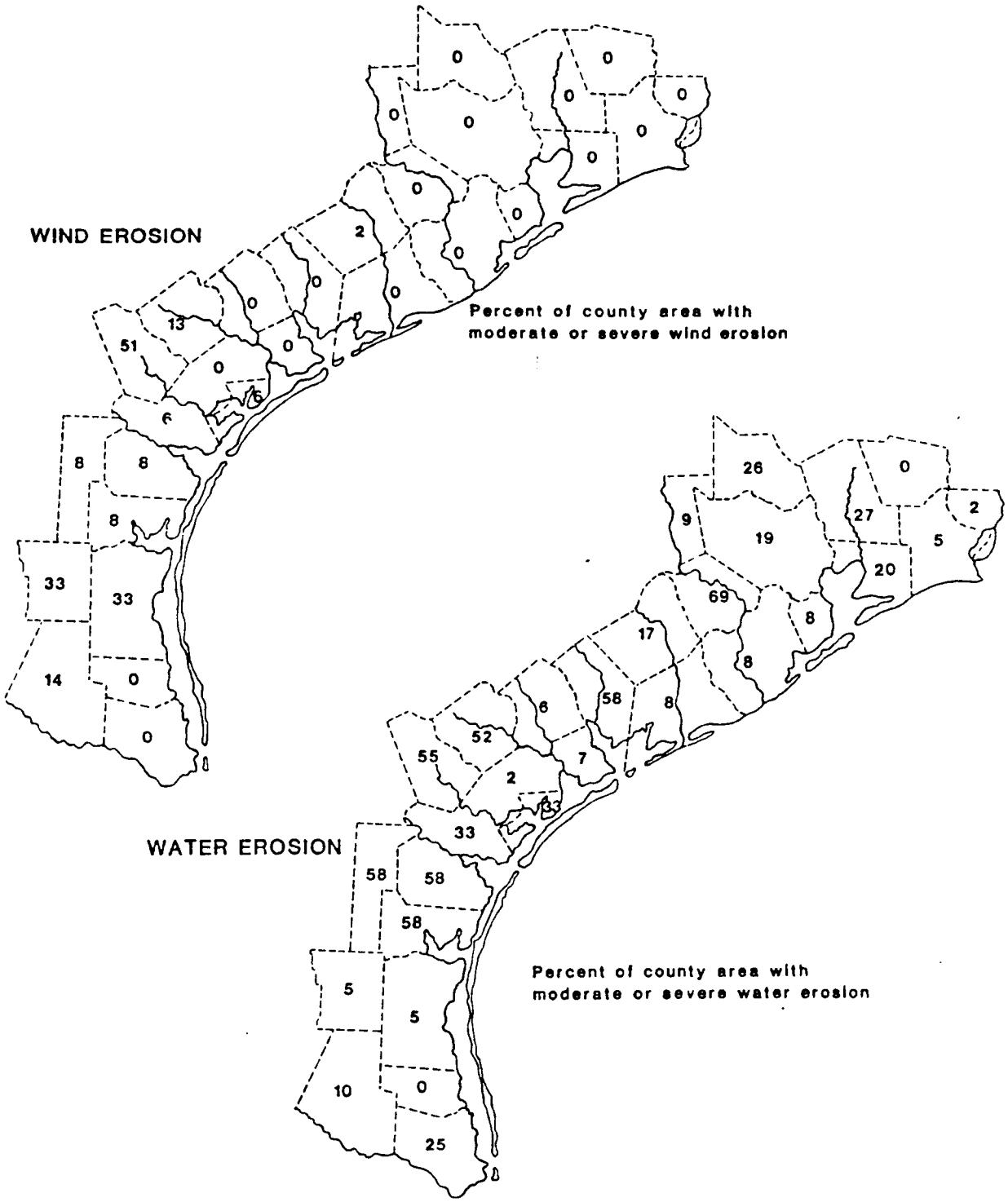


Figure 15. Wind and water erosion reported by coastal counties.

and part of the middle coast reported wind erosion problems. Wind erosion is most prevalent on sandy and sandy loam soils, such as are found in the middle and lower coast (Texas State Soil and Water Conservation Board 1981). These counties are also in an area of relative surface water deficit that ranges from 41 to 91 cm (16 to 36 inches) per year, which aggravates the erosion problem. Wind tends to separate the finest soil particles (silt, clay, and organic matter) and differentially remove them from soil. Because these are the components that contribute most to soil fertility, their removal affects the quality of vegetative cover, which is important in preventing wind erosion.

Sediment load carried by rivers and streams. More than 31.4 million metric tons (34.6 million tons) of suspended sediment is carried by river systems and deposited in the Texas Barrier Island Region annually (data from Texas Water Development Board 1967, 1970). Using a figure of 1132 kg per cu m (70 lb of suspended sediment per cu ft, Texas Department of Water Resources 1967), the volume of suspended load carried into the region is 2.8 million cu m (100 million cu ft) per yr. Since these estimates do not include bedload material, they are not total transport measures. Several estimates of bedload transport are available for the Brazos River (Welborn, cited in Mathewson and Minter 1976; estimates by Mathewson and Minter 1976). These estimates range from less than 2 percent to 30 percent of the suspended sediment load. Bedload quantities could substantially increase the sediment transport figures for the region.

Figure 12 shows the relative amounts of suspended sediment carried by individual rivers. Although the quantity of sediment carried is related to

the amount of water flow, the pattern of sediment movement does not follow the north to south decline that is shown for water flow in the same figure.

Mathewson and Minton (1976) noted a decline in water and sediment volume on the Brazos River over the period 1920 to 1970. They attributed this decline to water resource development within the Brazos River basin. Morton (1977) also noted this decline and attributed it both to river basin development and to natural decreases in supply. This may be the general trend on other river systems as water resource development continues.

Offshore sediment. Offshore sediment movement is not well documented. Morton (1977) stated that there was more landward movement of shelf sediment in the past than at the present time, and that the importance of the shelf as a sediment source has diminished because the inner shelf has been reaching an equilibrium profile. However, he noted the lack of detailed information for a comprehensive sediment budget. Some sediment is moving onshore in a few areas of accretion, such as the zone of littoral convergence in the gulf just south of Baffin Bay.

Substrates

Sediment transported to the coast in the past 65 million years has created the upland and submerged substrates in the Texas Barrier Island Region. Some Ancient substrates in the region were deposited millions of years ago. Other materials are of Recent origin since transport and depositional processes have continued throughout the Cenozoic Era.

Figure 16 (from Woodruff 1975) shows 10 substrates in the Texas Barrier Island Region. Ancient river systems, Ancient river-delta systems, Ancient barrier systems, and Ancient eolian systems account for most of the upland substrates in the region. The Modern upland and aquatic substrate systems

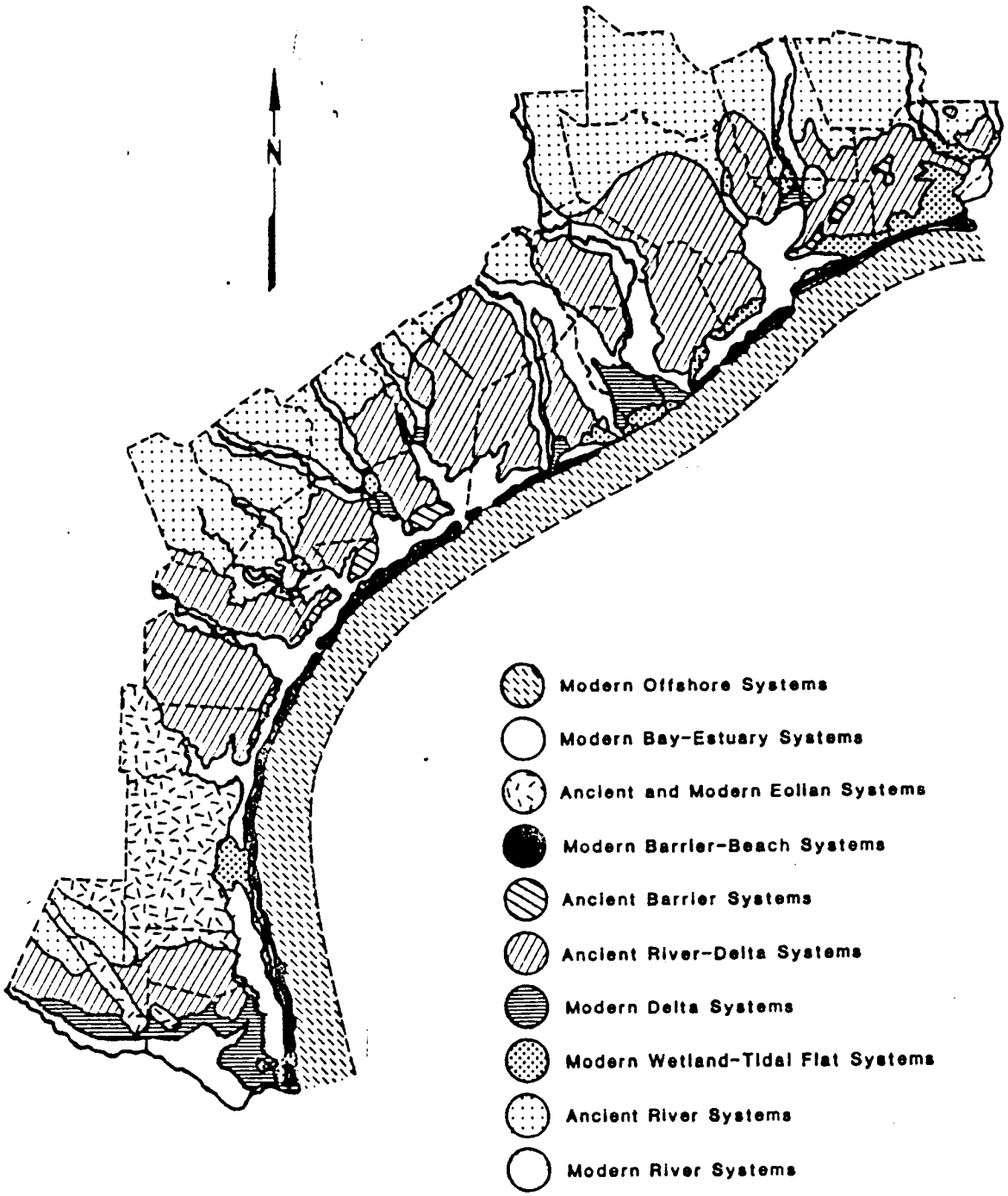


Figure 16. Substrates of the Texas Barrier Island Region.

have been formed by geologic processes that have acted over the past 5000 years and are still active today.

Ancient river systems. The most inland portions of the region are remnants of Ancient river systems. Materials deposited in these areas came from meanderbelt sands and associated floodplain deposits of Ancient rivers (Fisher et al. 1972). This system extends more than half the length of the region southwestward from the northern border. There is a small area of Ancient river systems in the southern portion of the region.

Ancient river-delta systems. Ancient river-delta systems were sites of delta formation where rivers emptied into estuaries. These deltas grew so large that rivers later flowed upon them and deposited river sediments. Delta and river deposition processes became so intertwined in these large areas that it is difficult to differentiate fluvial and deltaic deposits. This substrate occurs gulfward of the Ancient river systems and borders many existing bays.

Ancient barrier systems. Remnants of Ancient barrier systems form a thin band along the edge of the mainland between major bay systems. Ancient barrier systems are deposits of sand resting above Ancient river-delta systems. They are old barrier islands and strandplains that existed in the Peorian interglacial stage more than 55,000 years BP. On the upper coast the Ancient barrier systems are located 16 or more km (10 or more mi) inland of the present coastline. On the lower coast they are 9.7 or more km (6 or more mi) inland.

Ancient and Modern eolian systems. An extensive area of eolian deposits covers more than 3885 sq km (1500 square mi) of South Texas (Brown et al. 1977). In Figure 16 this area is identified as Ancient and Modern eolian

systems. Much of the surface of these eolian systems is from recent sediment transport; however, there are early Holocene deposits, and it is likely that Pleistocene eolian deposits occur in the subsurface (Brown et al. 1977). The materials that make up this system are not uniform. Transported materials may range from Pleistocene to Modern sediments. Silts and clays have been deflated from the gulfward portions of the eolian system and transported inland to form loess sheets. These areas have been mapped more than 97 km (60 mi) inland of the coastline (Brown et al. 1977).

Modern river systems. The Modern river systems shown in Figure 16 are the floodplains of existing river systems that have been in place since sea level rose at the end of the Late Wisconsin glaciation. Modern river system floodplains for rivers flowing into existing bays are relatively narrow. Modern delta systems are usually located at the bay end of Modern river systems. In the southern portion of the region, Modern river system substrates consist of deposits left by floodwaters in abandoned channels of the Rio Grande, called resacas, and adjacent meanderbelt sands.

Modern delta systems. The Brazos, Colorado, and Rio Grande are Modern river systems with wide floodplains. A large Modern delta system developed where the Brazos and Colorado rivers flowed close to each other. The rivers filled their estuary with sediment about 1800 yr BP and began to flow directly into the gulf (McGowen et al. 1976). The large quantities of water and sediment transported down these two rivers flooded wide areas above their deltas and built broad floodplains.

About 1000 years BP a headward-eroding stream captured the flow of the Colorado River near Wharton, Texas (McGowen et al. 1976). Since then the flow of the Colorado has been directed into the eastern arm of Matagorda Bay. The

remnant of the Colorado running in the old river bed is now called Caney Creek. In 1929 a log jam was removed jam from the Colorado. The river immediately built a large delta across Matagorda Bay to Matagorda Peninsula. Later cuts by dredges have allowed the river to flow partially into Matagorda Bay and the Gulf of Mexico.

The Rio Grande has been a major stream throughout Pleistocene, Holocene, and Modern history. Modern-Holocene deposits have nearly filled the Rio Grande river valley which was carved out during the Pleistocene. A Modern delta system has created delta plains in the lower end of this valley (Brown et al. 1980). The flow of the Rio Grande into this region is very low due to water resource developments upriver; today, the river floods only during major storms (Brown et al. 1980).

Modern bay-estuary systems. Modern bay-estuary systems are the substrate types found in the bays and lagoons of the coast. The upper ends of these areas, located near Modern deltas, contain sediments of Recent origin transported by rivers. Closer to the gulf, these materials grade into sediments carried into the bays from offshore by tidal fluctuation or eolian transport.

Modern wetland and tidal flat systems. The Land Cut just to the south of Baffin Bay is a Modern tidal flat system connecting Padre Island with the mainland (the Gulf Intracoastal Waterway has been dredged through it). Its surface materials consist of wind-transported sand and sediments deposited by storm surge (Brown et al. 1977). The area is rarely submerged and contributes materials to the Ancient and Modern eolian system to the west.

Modern wetland systems exist from the area around Nueces Bay northward. At the lower end of this range, Modern wetland systems are found mostly in association with Modern river deltas and as small areas on the bayside of Modern barrier-beach systems. Sediments forming these Modern wetland systems come from river flow, washovers, or flood-tidal deltas.

On the upper coast, wetlands are also found in association with Modern river deltas and Modern barrier-beach systems. In addition, brackish wetlands develop on low areas subject to frequent or occasional tidal inundation. These may be broad areas of land on the mainland shorefront where sediment from tidal flow or upland drainage is trapped.

Modern offshore system. In the gulf the substrate is the Modern offshore system, which consists largely of mud and muddy sand that has been extensively reworked by burrowing organisms. Underlying Holocene and Pleistocene deposits have contributed to the Modern offshore system sediments (Brown et al. 1976); however, the system also contains materials that have been transported from offshore, from rivers, and from estuaries. At the Brazos River mouth there is a delta and prodelta of sand, silt, and mud. These sediments are largely Recent material transported by the river. At some passes there are well-formed ebb and flood deltas that combine shelf, shoreface, and estuarine sediments.

Modern beach-barrier system. The Modern barrier-beach system makes up the barrier islands, the peninsulas, and a thin band of beach along the mainland areas that contact the Gulf of Mexico. The Modern beach-barrier system is derived from the Modern offshore system since it has been built by materials transported from the upper shoreface.

Soil Resources

A generalized soil resource map is shown in Figure 17 (U.S. Department of Agriculture 1977). This map contains six soil resource units that represent areas characterized by similarities of soil, topography, climate, and vegetation.

Texas blackland prairie. The Texas blackland prairie is a very small area in the northernmost portion of the region. The soil ranges from brown clay of medium acidity to moderately alkaline sticky clay.

Southern coastal plain. The southern coastal plain is a gently rolling area with acid soils that are largely sandy loam. The substrates giving rise to this soil were Ancient river systems.

Gulf Coast marsh. The Gulf Coast marsh occupies the area of Modern wetland systems along the upper coast. Gulf Coast marsh soils are wet clay with high organic content. The high level of organic matter in brackish marshes may be the result of limited export of organic matter from the marsh surface, as shown by Borey et al. (1983).

Texas claypan area. The Texas claypan area occupies the most inland portions of the region. Claypan soils developed from Ancient river system substrates. They consist of a thin, slightly acid layer of sandy loam lying above dense clayey subsoil. The upper layer is droughty, and the clayey subsoil discourages deep root development.

Gulf Coast prairie. The largest soil resource unit is Gulf Coast prairie. This unit rests largely on Ancient river delta substrates. The topography is very flat, and the soils are mostly calcareous clay and clay loams that become slightly acid and sandier inland. River bottomland bisects Gulf Coast prairie perpendicular to the coastline.

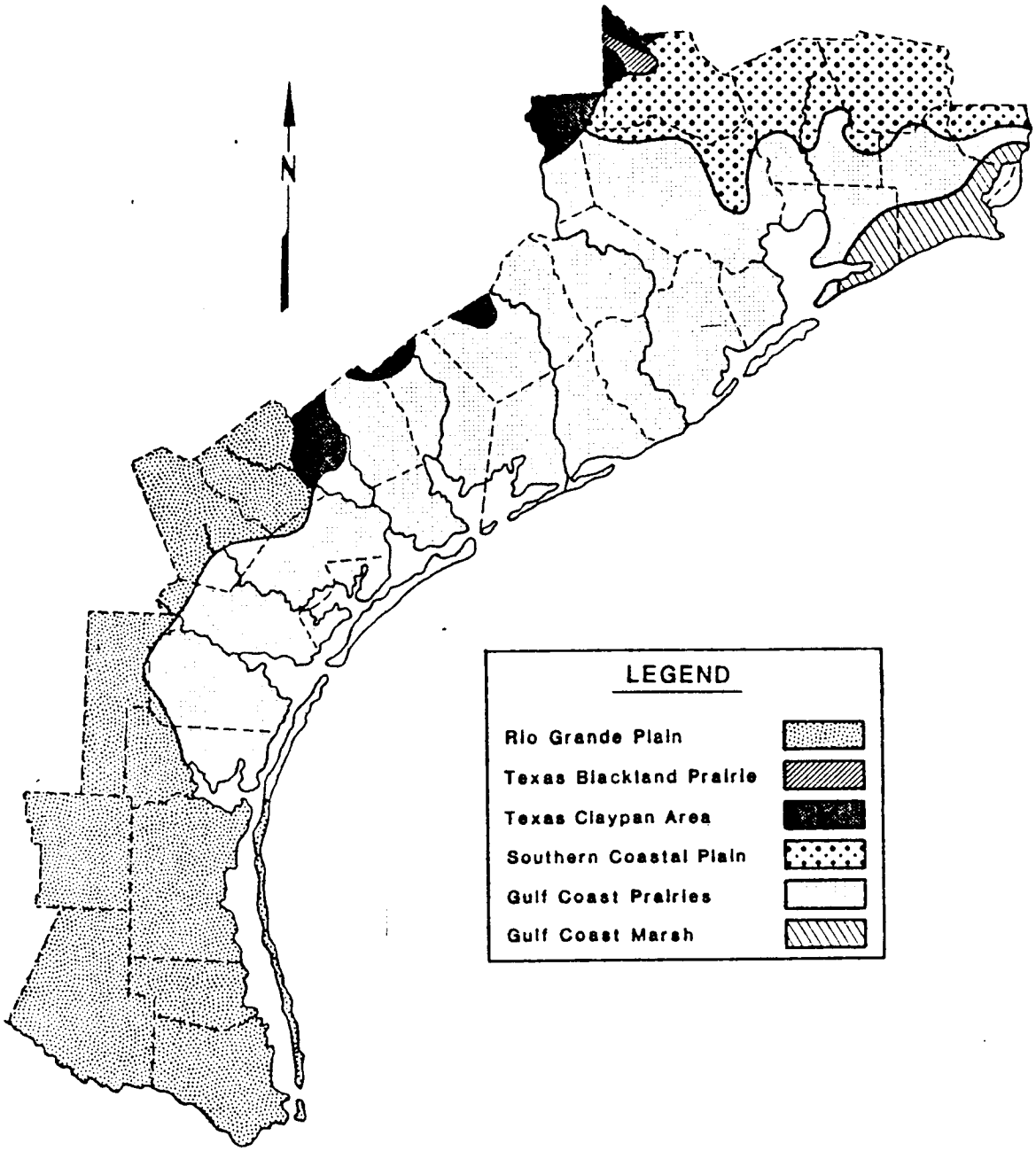


Figure 17. Soils of the Texas Barrier Island Region.

Rio Grande plain. The Rio Grande plain has developed on Ancient river system, Ancient river-delta system, Ancient and Modern eolian system, Modern delta system, and Modern river system substrates. All these substrates are sandy, and in most places the soils have developed on a caliche layer that is characteristic of arid or semiarid regions (U.S. Department of Agriculture 1977). The soils range from slightly acid to neutral.

BIOTIC COMMUNITIES

Potential Natural Vegetation

Biotic communities on the uplands are indicated by plant assemblages. The distribution of plant assemblages is determined by a combination of environmental factors; among the most important are soil, substrate, and climate. Figure 18 (Williams et al. 1976) is a modification of Kuchler's (1964) potential natural vegetation map of the U.S. This classification shows the climax vegetation that would be expected to occur if man's influences and land uses were not present.

The native American tribes in the Texas Barrier Island Region were mainly nomadic hunters and trappers (Newell and Gambrell 1949; Sewell and Rogers 1973). The Spanish and Mexicans who ruled the region from about 1690 to 1836 made only sporadic attempts to colonize the coast (Hudson 1978). Because neither the Indians nor the Spaniards significantly altered the land, the biotic community map is a fairly accurate representation of the biomes in the region up to the early 1800's, when settlers began to enter Texas.

The biomes in Figure 18 are of three types: forests, grasslands, and savannahs. The savannahs depicted here are different from typical tropical savannahs, which are adapted to a regime of moist, hot summers and dry, mild

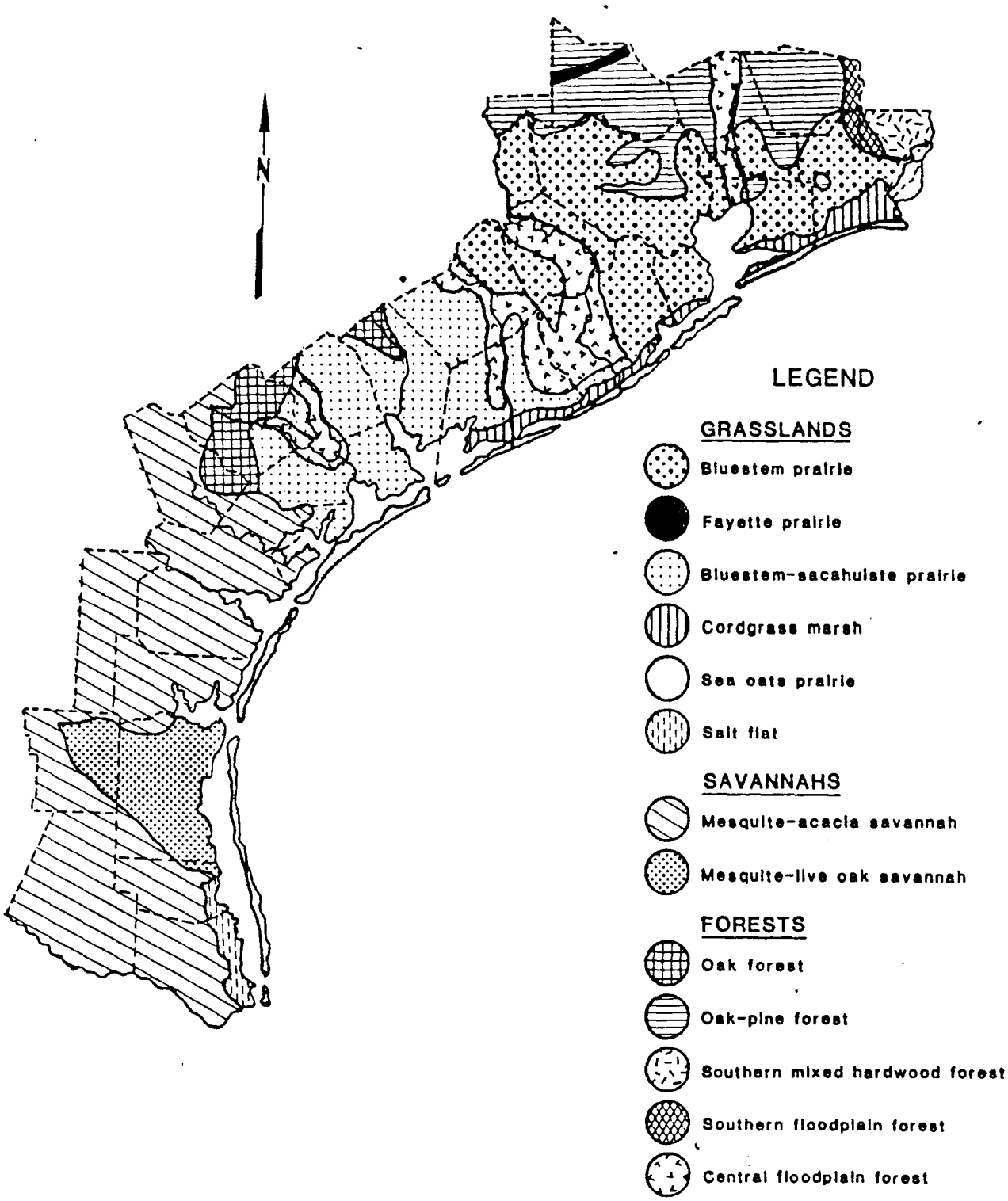


Figure 18. Potential natural vegetation.

winters. The South Texas savannahs are adapted to long, hot, relatively dry summers and short, mild, relatively wet winters (Bailey 1978). Bailey classified South Texas savannahs as prairies since their low rainfall and drought conditions are typical of grasslands rather than savannahs. South Texas savannahs look like tropical savannahs; both have woody plants interspersed among grasses. However, the woody plants of South Texas savannahs--mesquite, live oak, acacia, and hackberry--are species that grow well on sandy soils, that grow deep root systems to find water and survive the hot dry summer, and that are tolerant of salt in the soil and air.

Forest biomes. Oak-pine, southern mixed hardwood, and southern floodplain forest are found in the northernmost portions of the Texas coast, where rainfall is greatest. Belts of central floodplain forest are associated with Modern river systems and Modern delta systems (see Figure 16 and Figure 17). A small area of oak forest appears as far south as Victoria. This biome unit, commonly called the post oak belt, closely follows the Texas claypan area and contains post oak, blackjack oak, and yaupon (U.S. Department of Agriculture 1977).

Grassland biomes. The grassland biomes include cordgrass marsh, which closely follows the Modern wetland system substrate of Figure 16, and sea oats prairie, found almost exclusively on Modern beach-barrier system substrate. The largest areas of grasslands--bluestem prairie and bluestem-sacahuista prairie--closely correspond to the Ancient river-delta system substrate unit (Figure 16) and the Gulf coast prairie soil resource unit (Figure 17). However, the bluestem-sacahuista prairie ends at Copano Bay, while the Gulf Coast prairie and the Ancient river-delta system extend all the way to Baffin

Bay.

Savannah biomes. Two types of savannahs reach from Copano Bay south to the Rio Grande. Authorities do not agree whether the brushy savannahs are natural or are the result of overgrazing and fire control. The largest area, running from the Rio Grande to Copano Bay, is described as mesquite-acacia savannah. Seacoast bluestem, mesquite, and hackberry are the dominant grasses and woody plants in this unit. The mesquite-live oak savannah has a distribution similar to the Ancient and Modern eolian system substrate found inland of the point of offshore littoral convergence. Live oak mottes and brush, seacoast bluestem, and mesquite trees are dominant. It seems likely that the deep sandy soils resulting from eolian processes are an important factor in the distribution of this community.

Biome Pattern in the Region

The biomes in the Texas Barrier Island Region vary in type from north to south. In the north, forest lands are present; their distribution is closely associated with high rainfall and slightly acid soils. Rainfall declines to the south and the soils contain more clay, supporting a large area of bluestem prairie. At about the point where rainfall and evapotranspiration balance (just east of the Colorado River), the bluestem community becomes a bluestem-sacahuista prairie. This community ends at Copano Bay, where the savannahs that extend to the southern boundary of the region begin. Soils become sandier below Corpus Christi, but changes in the plant community do not exactly mirror differences in soil throughout the rest of the region.

The distribution of biotic communities in the region is determined by a set of environmental factors that all act simultaneously. The influence of these factors does not fit a simple pattern, however; some factors that appear

to control one end of the distribution of a community do not appear to control the opposite end. The distribution of biotic communities is complicated by gradients of rainfall, storm patterns, river flow, salinity, temperature, and land slope.

Some gradients vary with latitude; many are related to hydrologic relationships in the region. The yearly average rainfall over land and the frequency of tropical storms or hurricanes striking the coast increase with latitude. In general, the amount of fresh water flowing through the region increases with increasing latitude (although this is partially a function of drainage basin size and man's withdrawal of fresh water for other uses). The average surface salinity in estuaries generally decreases with increasing latitude. The rainfall-evapotranspiration ratio, a measure of hydrologic balance, shifts from a substantial deficit of rainfall to a surplus with increasing latitude. In addition, the average yearly temperature on land decreases with increasing latitude, an indication of the decrease in annual solar radiation from south to north in the region. At right angles to these gradients is the major physical gradient of the region, the slope of the land.

Other environmental factors in the region--soil and local topography, for example--result in heterogenous areas that do not have gradual gradients. The combination of heterogeneous factors, environmental gradients in several directions, and fluctuating conditions or intermittent extremes (seasonal climatic change, storms, drought, cold, and fire) produces a diverse landscape. Boundaries between communities fluctuate, and the factors determining the boundary location may differ from one area to another.

Areal measurements of biologic assemblage units made by the Bureau of

Economic Geology (BEG) for the Texas coast were used to estimate the proportionate areas of the potential natural vegetation biomes mapped in Figure 18 (Fisher et al. 1972, 1973; Brown et al. 1976; McGowen et al. 1976a, 1976b; Brown et al. 1977; and Brown et al. 1980). The area studied by the BEG--approximately the first tier of coastal counties--corresponds closely with the Texas Barrier Island Region study area but is smaller than the area shown in Figure 18, which includes most of the second tier of counties as well. The BEG defined 33 subaerial biologic assemblages. Various BEG units were combined to produce estimates for the relative proportions of the six mapped biomes. The BEG assemblages did not distinguish between grassland and savannah assemblages in the same manner as Figure 18. Therefore bluestem prairie, Fayette prairie, bluestem-sacahuista prairie, and both types of savannah were grouped into one estimate. These units make up 79.1 percent of the coastal region from Galveston Bay to the Rio Grande. Percentages for the other biome units are: forest, 12.9 percent; cordgrass, 3.3 percent; sea oats prairie (barrier islands and peninsulas) 3.3 percent; and salt flats, 1.4 percent.

EFFECTS OF MAN

Settlement of the Texas Barrier Island Region

No permanent settlements were established within the Texas Barrier Island Region until the early 1800's. The Indians native to the region--including the Arkokisas, Karankawas, and Coahuiltecans--were nomadic hunters, gatherers, and fishermen (Connor 1971; Hudson 1978). Their influence on subsequent settlement patterns was principally that their presence decided the location

of Spanish missions and presidios and often led to the abandonment of early colonization sites.

European exploration of the region began in 1519, when the Spaniard Alvarez de Pineda mapped the coastline and islands of the Gulf of Mexico (Miller 1972). In the 1530's, Alvar Nunez Cabeza de Vaca, shipwrecked off the Texas coast in 1528 (probably at Galveston Island), traveled across Texas and northern Mexico (Steen 1939; De Vaca's route is disputed). His account of his adventures stimulated further exploration, but it was not until the French began to make inroads into Texas that the Spanish were moved to occupy the territory.

After Rene Cavelier, Sieur de la Salle, established Fort Saint Louis on Garcitas Creek west of the Lavaca River in 1685, the Spanish began to establish missions and small garrisons to protect their frontier (Fehrenbach 1968). The first mission, San Francisco de los Tejas, was founded near the Neches River in 1690 but was occupied only until 1693, when hostile Indians forced the missionaries to withdraw. When the French began to occupy Louisiana, the Spanish revived their effort to secure their claim to Texas. In 1716 and 1717, six missions were established in East Texas, and in 1718, a mission and presidio were established at the present site of San Antonio as a halfway post between the East Texas missions and the Spanish presidios in northern Mexico.

French explorers and traders continued to penetrate into Texas (Figure 19). Francois Simars de Bellisle, marooned in Galveston Bay in 1719, made a second expedition to the bay in 1721. In that same year, the Marquis de Aguayo acted to reassert the Spanish presence in the coastal region, reoccupying and relocating garrisons and missions there (Steen 1939). In

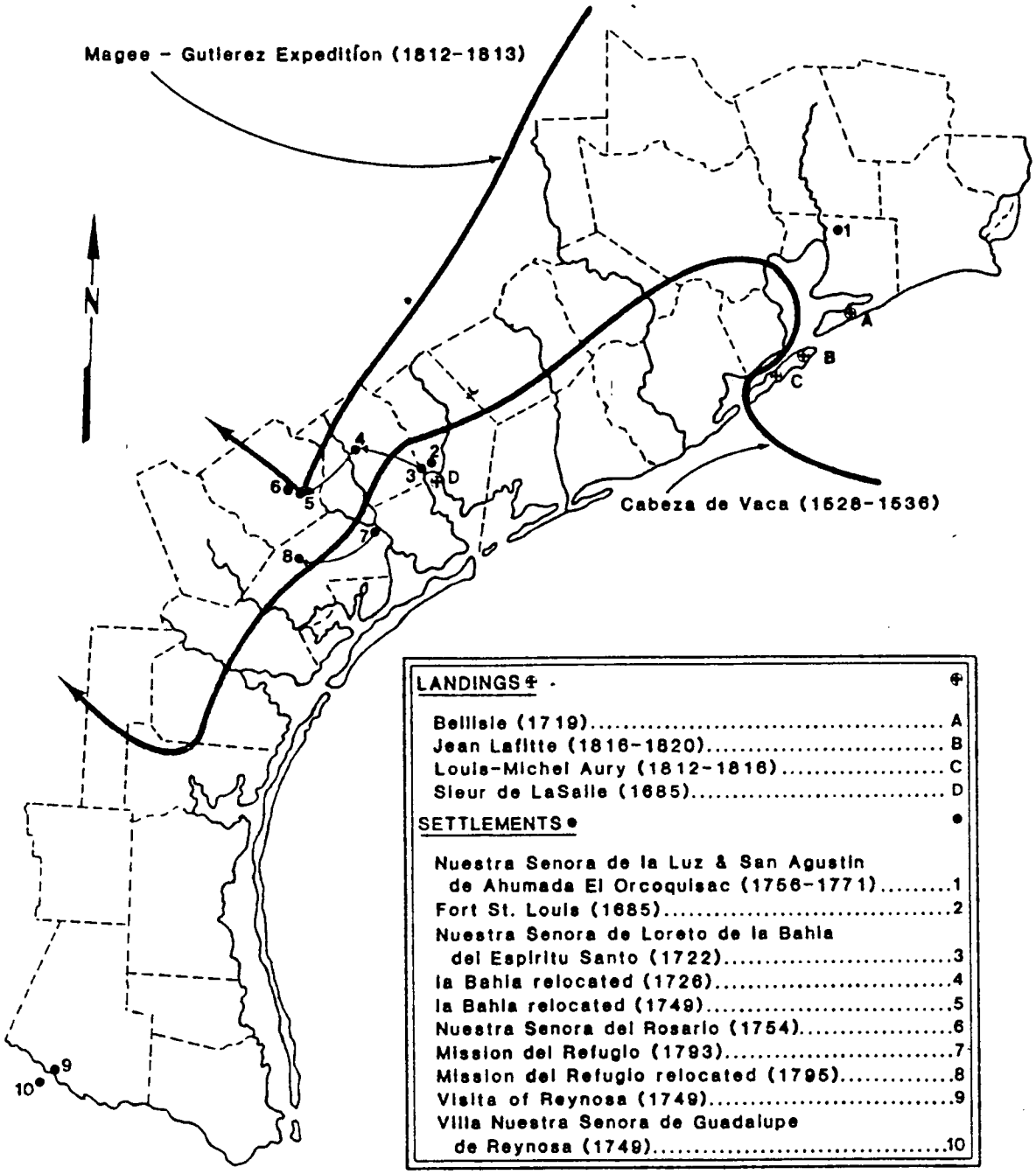


Figure 19. Landings, settlements, and expeditions in the Texas Barrier Island Region during the Spanish period.

1722, he built a mission and presidio, Nuestra Senora de Loreto de la Bahia del Espiritu Santo (La Bahia), on Matagorda Bay near the site of the old Fort Saint Louis (Brown et al. 1982). Because the area was occupied by hostile Karankawas, the mission and presidio were relocated in 1726 on the Guadalupe River near the current site of Victoria. In 1749, the mission was moved to the San Antonio River, where the town of Goliad was established. A second mission, Nuestra Senora del Rosario, was founded nearby to serve the Karankawas.

Between 1749 and 1755, Jose Escandon, a Mexican governor, established colonies between the mission settlement of San Juan Bautista on the Rio Grande (near the present-day city of Eagle Pass) and the mouth of the river. In 1756, a mission and presidio were established at a village of Orcoquisac (Arkokisa) Indians near the Trinity River delta to guard the routes to East Texas from Louisiana.

In 1762, France ceded western Louisiana to Spain, eliminating the threat of French invasion but introducing a fear of British invasion from the north. The Spanish turned their attention to the protection of their northern frontier and gulf settlements, and the East Texas settlements were abandoned. Some settlers returned to the Trinity River in 1779, however, and established the town of Nacogdoches at an old mission site. In 1793, the last Spanish mission, Mission del Refugio, was founded at the confluence of the Guadalupe and San Antonio rivers. It was relocated in 1795 at the present site of the town of Refugio (Ellis et al. 1976).

By 1800, Anglo-Americans were becoming interested in Texas; this interest increased with the Louisiana Purchase of 1803. The Spanish tried to build a

buffer against Anglo-American invasion by encouraging settlement by Catholics, but Spain's hold on Mexico and Texas began to deteriorate. Among the republicans who conducted filibustering expeditions into Texas were Augustus Magee and Bernard Gutierrez (Figure 19). They captured Nacogdoches and Goliad, where Magee was killed; Gutierrez went on to capture San Antonio (Steen 1939). These victories were overturned by the Spanish, as were the later victories of Dr. James Long at Nacogdoches in 1819 and La Bahia in 1821. But persistent revolutionary acts culminated in Mexican independence in 1824.

By 1821, the only permanent settlement in the coastal region remaining from Spanish occupation was La Bahia (Goliad). But the Spanish had laid the groundwork for the later settlement of Texas: they established travel routes; towns and cities eventually developed at many of their mission sites; and the presence of Spanish outposts of culture in the wilderness probably encouraged Anglo-American settlers.

In December of 1821, Stephen F. Austin brought 300 families to settle 200,000 acres between the Brazos and Colorado rivers that had been granted to his father, Moses F. Austin, by the Spanish government. The land grant extended inland of the Texas Barrier Island region from a line 10 leagues landward of the coastline (Ellis et al. 1976; Meinig 1969). By 1831, Austin had settled more than 1500 families, concentrated around Columbus, Washington-on-the-Brazos, and Hempstead (Fehrenbach 1968).

The success of Austin's colony inspired the Mexican government to offer large grants to other empresarios and individual settlers. Other empresarios who received coastal grants were Martin de Leon, who settled a number of families at Victoria; Green DeWitt, who settled several hundred families west of the Colorado River and founded the town of Gonzales in 1825; Joseph

Vehlein; McMullen and McGloin; and Lorenzo de Zavala (Ellis et al. 1976). Austin was granted three more colonies in 1825, 1827, and 1828; the last grant was the segment of land between the shoreline and the 10-league boundary of his 1821 grant (Figure 20).

The population of Texas increased dramatically during the empresario period; an estimated 50,000 settlers moved into Texas between 1831 and 1836. Settlers entered the coastal region both by sea and by overland routes. Overland settlers followed a road from Louisiana through the middle of the Austin colony. Most who immigrated by sea entered at Galveston or at Indianola, 200 miles to the south. A few landed at the town of Copano on Copano Bay and at Velasco at the mouth of the Brazos River (Newton and Gambrell 1949). It was possible to travel up the Brazos River to Brazoria, up the Colorado River to Columbia, and up the Trinity River to Liberty. At some times of the year, the Trinity was navigable to Magnolia Point, near Palestine. By the time of the Texas Revolution in 1835, a number of steamships traveled the rivers, carrying settlers and supplies.

The Republic of Texas, which won its independence in 1836, was heavily in debt. To settle war debts, provide money for the operation of the government, and encourage immigration, the government of the republic sold and granted thousands of acres of public land. But because skirmishes with Mexico continued to drain the treasury, Texas sought statehood and was annexed in 1845. More than 7,000 new residents were added to the Texas population between 1836 and 1846.

Low land prices continued to attract large numbers of settlers throughout the Civil War period. By 1870, the population of Texas was 818,574. The

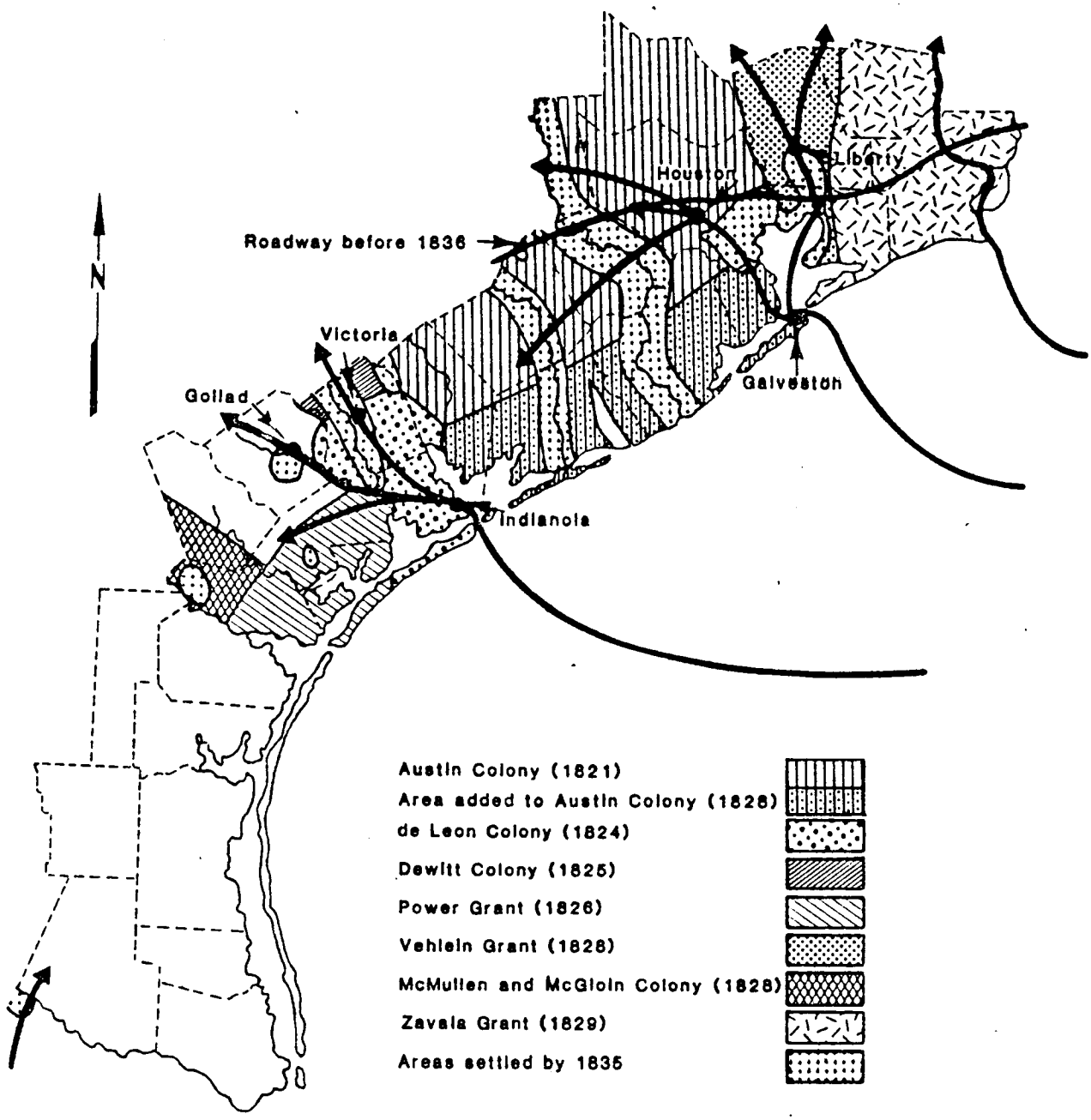


Figure 20. Colonization of the Texas Barrier Island Region during the Empresario period.

state's economy was mainly agricultural. Open-range cattle ranching spread rapidly, and cotton became the state's chief crop. The value of crops in the state was about $45,000,000 per year, and the annual value of manufactured goods was about $12,000,000, only 2 percent of the national total (Connor 1971). The largest industry was flour and grist milling, and the state contained only 400 miles of railroad track.

Economic Development

By 1900, the state's population had grown to 3,048,710, largely because of heavy immigration during the 1870's and early 1880's. The value of crops had risen to $240,000,000, and there were about six times as many farms as in 1870. Manufacturing had become a larger economic sector, valued at about $120,000 per year, and railroad mileage had increased to 10,000 miles (Connor 1971). Lumber, cottonseed oil production, and cake pressing for cattle feed replaced flour and grist milling as the most important industries. Thus, by the turn of the century, the manufacturing and industrial base of the state's economy was established.

The turning point in the development of the state's economy was the discovery of the Spindletop oil field near Beaumont in 1901. This and the subsequent discovery of other oil and gas fields throughout the state gave rise to the tremendous oil and gas industry in Texas and were a major impetus to the expansion of the industrial and manufacturing segments of the economy.

Oil and gas development radically altered the character of the coastal region. The early settlements along the bays and rivers of the Texas coast served interior districts and had little communication with each other (Meinig 1969). This pattern changed irrevocably with the discovery of the Spindletop oil field. The northern coastal areas were soon linked by pipelines,

railroads, and coastal shipping; with further discoveries, this network extended further down the coast, increasing population in most coastal counties.

Pipelines, waterborne commerce, and refining complexes have given the Texas Gulf Coast a lateral unity and growth pattern. Though growth has been concentrated in the larger cities (Houston, Victoria, and Corpus Christi within the Texas Barrier Island Region), a number of sprawling urban areas have sprung up, and industrial centers have developed outside the major urban centers. The coastal highway system has contributed to this diffuse pattern of development.

The discovery of oil and gas fields in the coastal region created a need for expanded transportation and new equipment and led to the development of a diversity of related industries. Today, manufacturing of chemicals from local supplies of petroleum and natural gas as well as salt, sulfur, and lime; synthetics; and electronics form a regional industrial complex along the Texas coast from Port Arthur (north of the Texas Barrier Island Region boundary) to Corpus Christi.

But the industrialization and urbanization of the Texas coast did not come about at the expense of the region's agricultural production. The agricultural system continued to expand and grow more sophisticated as small farms were replaced by large-scale operations employing more productive methods. Cattle and crop production remain principal economic sectors that, like the oil and gas industry, have contributed to the growth of related industries and to the wealth of the coastal region and the state.

Other sectors that have flourished and occupy a position of great importance in the region's economy are commercial finfishing and shellfishing, with related processing and distribution industries, and recreation and tourism, including sportfishing, boating, hunting, and beach use.

Growth of Ports and Transportation Systems

Inland waterways. Until the mid-1800's, when shallow connecting channels and canals were dug, ships had to enter the Gulf of Mexico to travel between Texas bays. As the growing coastal economy became more dependent upon waterborne transportation, deep-draft channels were dredged to ports to accommodate larger cargo ships, and shallow-draft waterways were constructed for barge traffic.

Construction of the intracoastal waterway began in 1905, with the dredging of canals 1.5 m (5 ft) deep and 12.2 m (40 ft) wide along some areas of the coastline. In 1925, the federal government authorized construction of the upper portion of the Gulf Intracoastal Waterway connecting Texas with the Mississippi River. A 2.7 m (9 ft) by 30.5 m (100 ft) channel from the Sabine River to Corpus Christi was completed in 1941. In 1949, the waterway was enlarged to dimensions of 3.7 m (12) ft by 38.1 m (125 ft) and extended to Brownsville. The total length of the Texas segment of the waterway is approximately 868 km (426 mi).

The Gulf Intracoastal Waterway and a series of deep-draft and shallow-draft channels permit shipment of large volumes of liquid and bulk cargo at relatively low cost and link Texas ports with the commercial markets of the East, Midwest, and South. This transportation network stimulated coastal development and continues to attract new industries to coastal sites.

Within the Texas Barrier Island Region, nine deep-draft channels and 26 shallow-draft channels connect port and industrial facilities with the intracoastal waterway. The deep-draft channels are the Houston, Bayport, Texas City, Galveston, Freeport, Matagorda, Corpus Christi, La Quinta, and Brownsville ship channels.

The Houston Ship Channel extends approximately 84 km (52 mi) from Galveston Harbor to Houston. Its principal commodity flows include petroleum and coal products, crude petroleum, chemicals, and farm products. The Bayport Ship Channel, about 8 km (5 mi) in length, branches off the Houston Ship Channel and serves a complex of refineries and petrochemical plants. The Texas City channel extends approximately 12.9 km (8 mi) from Galveston Harbor to Texas City on the southern shore of Galveston Bay, where the major industries are refining, petrochemical production, and manufacturing of fertilizers. The chief commodities carried on this channel are crude petroleum, petroleum and coal products, and chemicals. The 8-kilometer (5-mile) Galveston Ship Channel is used primarily for the transport of farm products, nonmetallic minerals excluding fuel, and crude petroleum.

The Freeport Ship Channel, extending about 17.7 km (11 mi) from the gulf to a diversion dam on the Old Brazos River, serves a large complex of chemical plants. Commodities transported in greatest volume on this channel are crude petroleum, chemicals, and petroleum and coal products. The Matagorda Ship Channel, approximately 40.2 km (25 mi) long, serves aluminum manufacturing plants at Point Comfort. Metallic ores are the main commodity carried on this channel, but chemicals and nonmetallic minerals excluding fuels are also transported in large volumes.

On the Corpus Christi Ship Channel, about 51.5 km (32 mi) in length, and on the 9.7-kilometer (6-mile) La Quinta Channel that branches from it in Corpus Christi Bay, the major cargoes are crude petroleum, petroleum and coal products, metallic ores, and farm products. The Brownsville Ship Channel, extending about 30.6 km (19 mi) from the gulf to port facilities near Brownsville, carries mainly petroleum and coal products, chemicals and allied products, nonmetallic minerals excluding fuels, farm products, and primary metal products.

Major ports. Houston was founded on Buffalo Bayou off Galveston Bay in 1836, was incorporated in 1837, and served as the capital of the Republic of Texas from 1837 to 1839. It became a prosperous railroad center in the early 20th century (when Galveston was debilitated after the hurricane of 1900), but its dramatic growth is attributable to the construction (1912-1914) of the ship channel on Buffalo Bayou and Galveston Bay that linked it to the Gulf of Mexico and made it a deepwater port. Its expanding economy was fed by the development of coastal oil fields; by the production of natural gas, sulfur, salt, and limestone that supported its chemical industry; and by shipbuilding during World War II. Today, Houston is the nation's fifth largest city, and its port is the third largest in the nation. Its industries include huge oil refineries; one of the world's largest concentrations of petrochemical works; steel mills; shipyards; grain elevators; paper, rice, and cotton mills; and numerous manufacturing industries. The city's 1980 population was 1,594,086, and the population of the larger metropolitan area was 2,905,350.

Galveston was settled in the 1830's and the city was incorporated in 1839. Before that time, the island was visited by Indians, explorers, revolutionists, and buccaneers. It was first occupied by Europeans under

Louis-Michel Aury in 1816 (Figure 19). The pirate Jean Laffitte took over Aury's location and occupied it until 1820. In 1825, the Congress of Mexico designated Galveston as a provisional port and customs entry point and established a protective garrison there. It was made a port of entry for the Republic of Texas in 1837 and was the republic's shipping, commercial, financial, and cultural center as well as its largest city. The port declined during the Civil War but was reopened to world trade in 1865 and flourished as shipping routes connected it with New York and other East Coast cities via New Orleans. The development of railroad connections accelerated growth of the port, and in 1890, the federal government appropriated funds for the construction of a 8-kilometer (5-mile) jetty system and for channel deepening. Despite competition from Houston, Galveston has remained a major port of entry and the world's foremost cotton port. Its major industries are oil refining and ship building, and it houses grain elevators, cotton compresses, chemical plants, and large fishing and shrimping fleets. Galveston is also a popular beach and fishing resort. It is protected by a 16 km (10 mi) seawall, constructed after the devastating hurricane of 1900. The city's 1980 population was 61,902. The population of the Galveston-Texas City area in 1980 was 195,940.

Freeport, located on the Brazos River, has been a port since the 1820's but became prominent only when sulfur began to be mined in the early 1900's. It was incorporated in 1913 and is part of the nine-city Brazosport industrial community. Its chemical and petrochemical industries developed during World War II, and new port facilities were opened in 1955. The Freeport area is also a recreational area for both coastal and deep-sea fishing. The

population of the city of Freeport in 1980 was 13,444, and the population of the Brazosport industrial and port area was 52,453.

Port Lavaca, the Calhoun County seat, was founded on the site of Linnville, a town destroyed by Comanches in 1840. It was an important deepwater port until the late 19th century, when it declined. The discovery of oil revived the city's growth, and it wasincorporated in 1907. Today, Port Lavaca is a port of entry and shipping point for grain, cotton, rice, and cattle. Its industries include commercial seafood operations and manufacturing of chemicals, offshore drilling rigs, and aluminum. The city is also a recreational fishing center. The 1980 population of the city of Port Lavaca was 10,911.

The city of Victoria, seat of Victoria County, developed at the site of the Mexican settlement Nuestra Senora de Guadalupe de Victoria on the Guadalupe River. It prospered after Texas independence and attracted many German settlers. Today, the city is an agribusiness center connected with the Gulf Intracoastal Waterway by the Victoria Barge Canal, completed in 1962. Its industries include manufacturing of petrochemicals, aluminum, steel products, oilfield equipment, concrete, and boats. The city's 1980 population was 50,695.

Corpus Christi, the seat of Nueces County, is located on the west end of Corpus Christi bay at the entrance to Nueces Bay. Its first settlers came from the Rio Grande Valley in the 1760's. In 1839, a trading post was established, and a colony of traders and adventurers developed. It prospered as a port and terminus for overland wagon-train traffic during the Mexican War and later served as a supply and shipping point for sheep and cattle. The city was incorporated in 1852. It became an industrial center after oil was

discovered in the area and after the completion in 1926 of the deepwater channel past Mustang Island. Corpus Christi is a major seaport and agricultural trade center. The principal cargoes handled by the port are cotton, oil, grain, and chemicals. It is heavily industrial, with oil refineries, smelting plants, chemical works, and food-processing plants, and houses a large shrimping fleet and important fishing industry. It is also a tourist center for sportfishing and beach use and is the gateway to the Padre Island National Seashore. The city is partially protected by a 3,749 m (12,300 ft) seawall built between 1939 and 1941. Its 1980 population was 231,999.

Brownsville, the county seat of Cameron County, is located on the Rio Grande about 27.4 km (17 mi) from the river mouth. It grew around Fort Texas, which was established by General Zachary Taylor in 1846 and, renamed Fort Brown, remained active until 1944. The town was incorporated in 1850 and was a cattle shipping port in the late 19th century. Brownsville is an important port of entry and a trade, processing, and distribution center for agricultural products of the Rio Grande Valley. The deepwater channel connecting the port of Brownsville with the Gulf of Mexico was completed in 1939. Brownsville has many oil- and gas-related industries and manufacturing plants. It is a popular resort and recreation center for fishing, hunting, and water sports, and a causeway at nearby Port Isabel provides access to South Padre Island. Brownsville's 1980 population was 84,997.

Railroads. Figure 21 and Figure 22, showing railroad construction in the region, indicate how rapidly the Texas Barrier Island Region was developed from the Civil War to modern times (from Potts et al. 1966; Connor 1971; Ellis

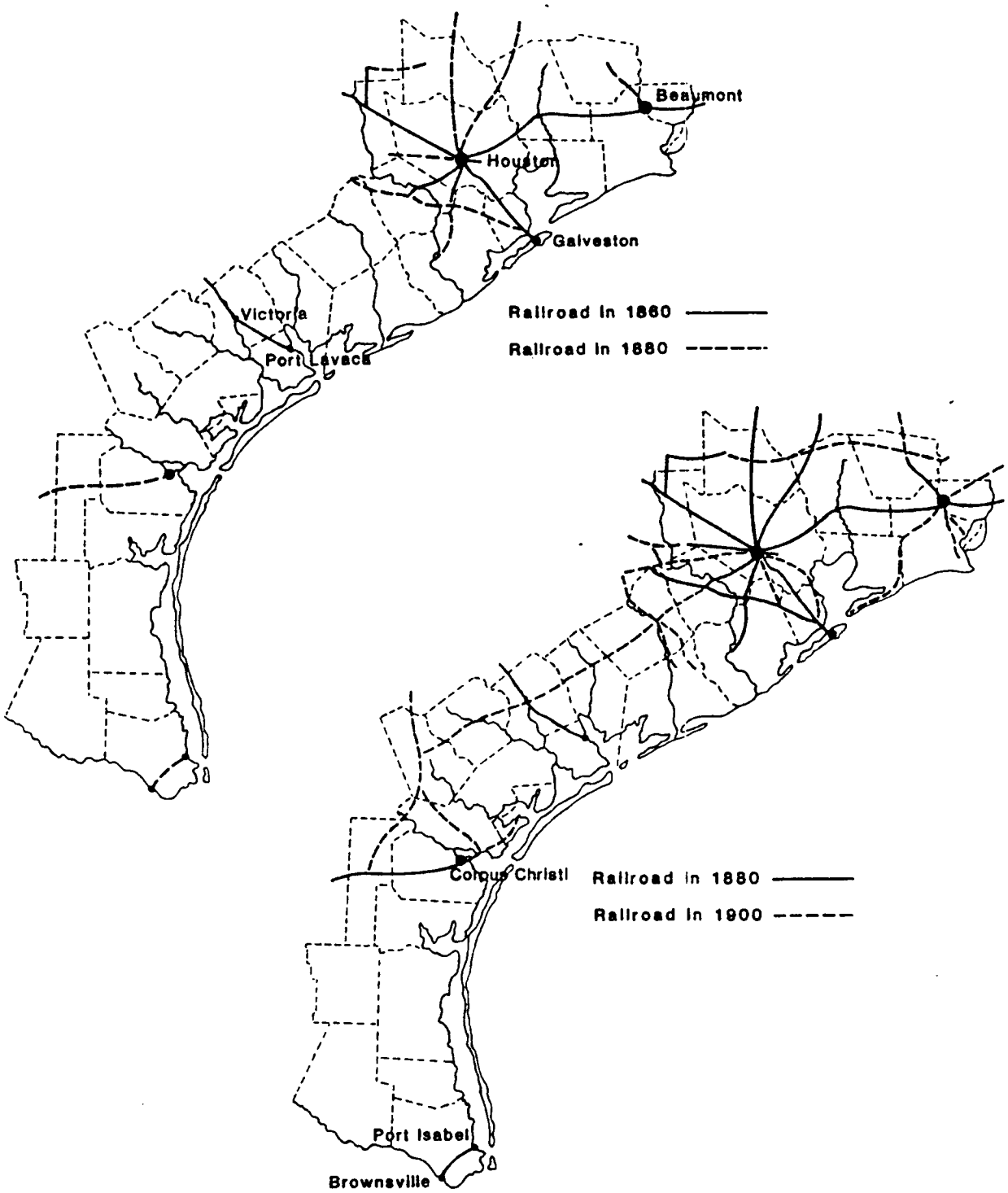


Figure 21. Development of railroad lines, 1860 to 1900.

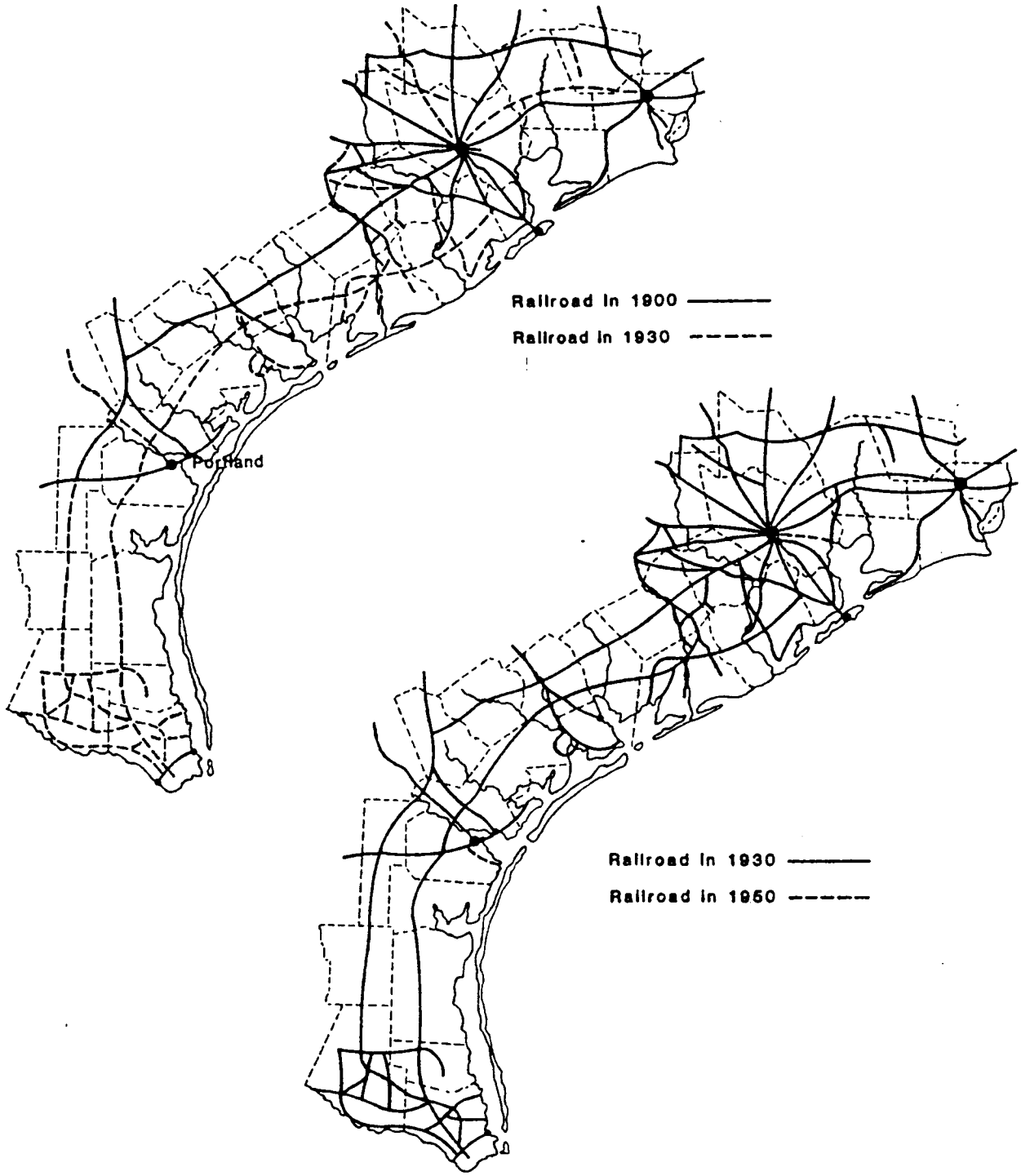


Figure 22. Development of railroad lines 1900 to 1950.

et al. 1976). Houston has always been the hub of railroad activity in the region. In 1860, lines ran from Houston to the port at Galveston and to Beaumont; additional lines from Houston branched to populated areas along the Brazos, connecting Houston with other parts of the nation. A line from Port Lavaca to Victoria was also completed by 1860. By 1880, a line connected Port Isabel and Brownsville, and small lines ran from other ports to nearby cities. The network around Houston had spread north, east, and west (Figure 21).

By 1900 the network around Houston was denser; added lines connected Houston with Corpus Christi and with the agricultural and cattle ranching areas of the central coast (Figure 22). By 1930 more railroad more lines ran to the lower portion of the region, and a web of small lines had been constructed in the Rio Grande Valley to serve the intensive agriculture that was developing there. Railroad construction peaked by 1930. The map of railroad lines in 1950 shows only two small additions, one at Houston and one at Corpus Christi. By this time an extensive highway system had developed and railroads were on the wane.

Population Growth

Population figures illustrate the rate of urbanization and suggest the level of demands made upon natural resources. Population has been measured in the Texas Barrier Island Region since 1850 as part of the regular U.S. census. Population numbers taken from census reports were used to calculate the population densities graphed in Figures 23, 24, and 25. Aransas, Brazoria, Brooks, Cameron, Fort Bend, Hidalgo, Jim Wells, Kleberg, Liberty, Montgomery, Nueces, Refugio, Waller, Wharton, and Willacy counties were either created or changed substantially in area over the period 1850 to 1940. The population

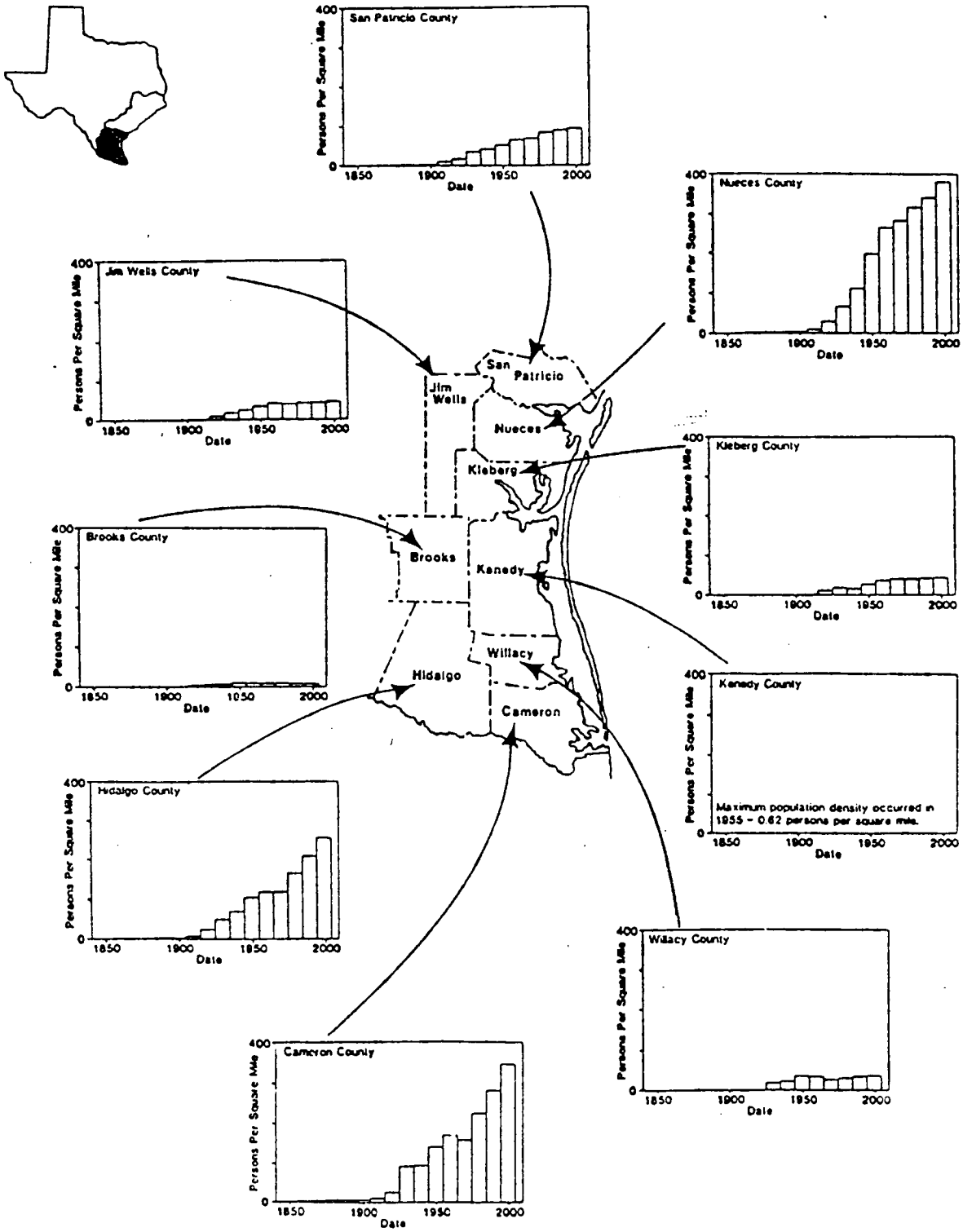


Figure 23. Population growth on the lower Texas coast, 1850 to 2000.

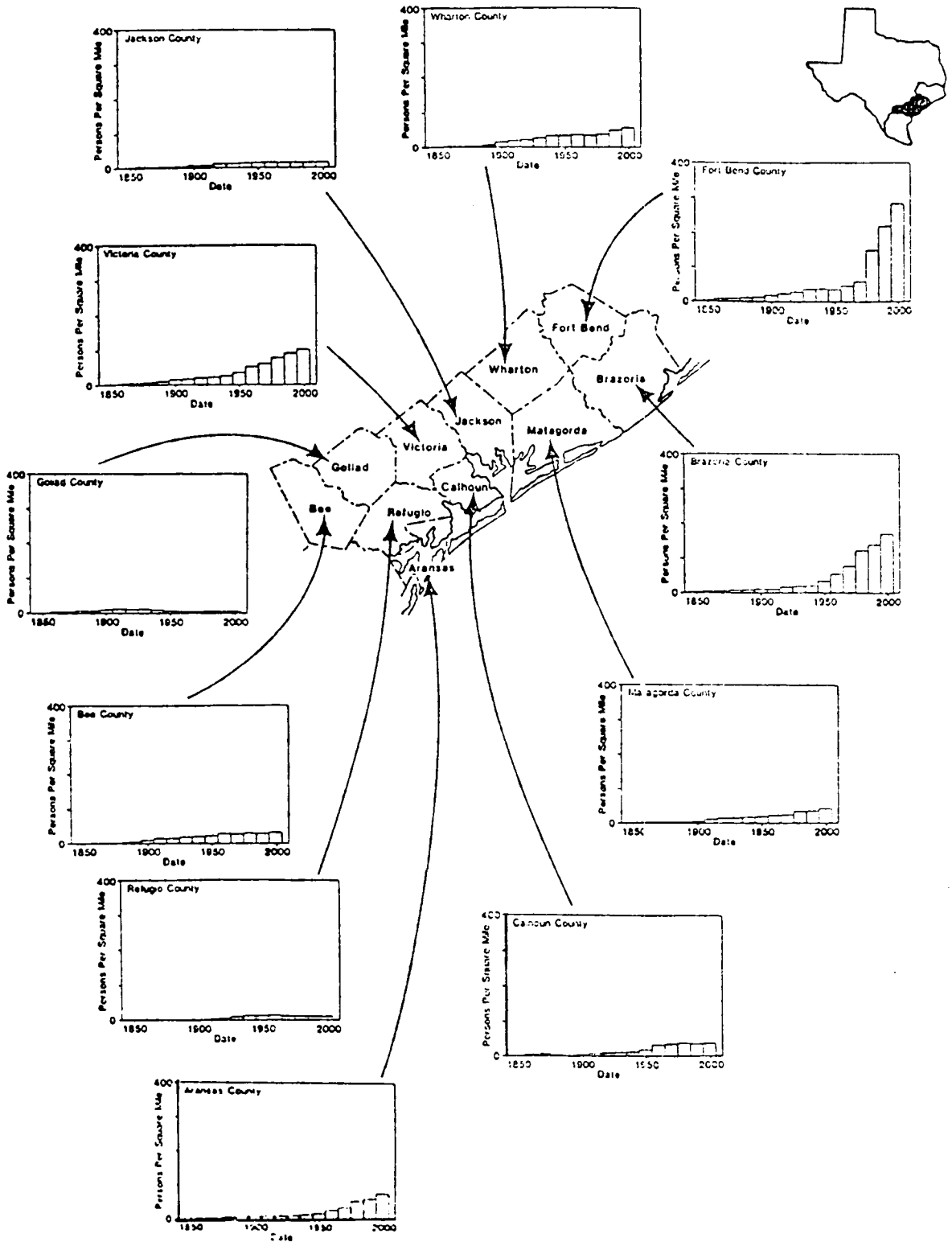


Figure 24. Population growth on the central Texas coast, 1850 to 2000.

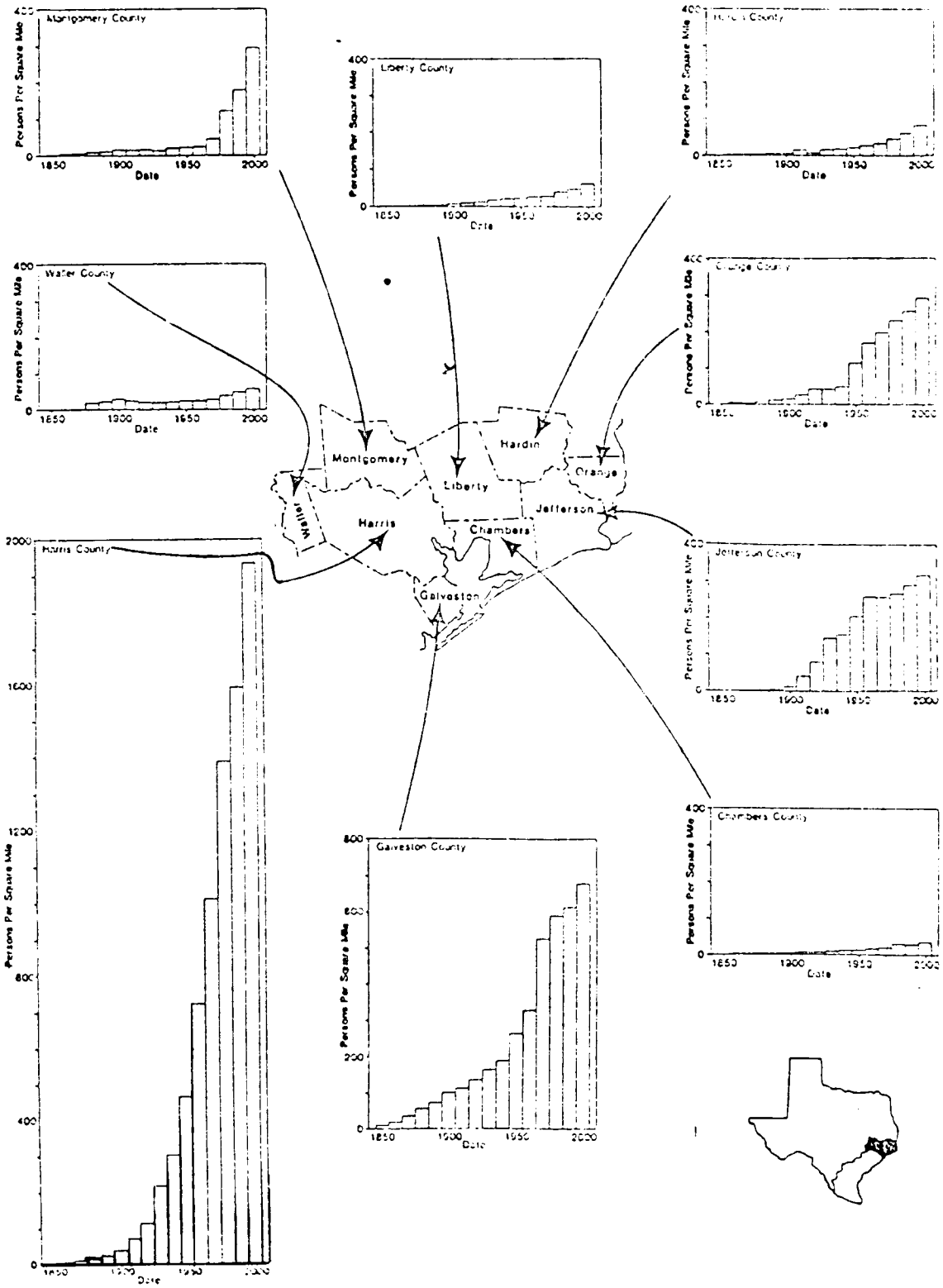


Figure 25. Population growth on the upper Texas coast, 1850 to 2000.

density estimates take these areal changes into account. Population projections for 1990 and 2000 are also graphed (Texas Department of Water Resources 1980).

Population growth on the lower coast. Figure 23 shows population trends in the counties of the lower coastal region. Several counties, including Jim Wells and Kleberg, were not created until 1920. Others, such as Nueces County, have been in existence since Texas became a state. Cameron, Hidalgo, Nueces, and San Patricio counties contain metropolitan areas: Brownsville, Harlingen, Edinburg, McAllen, Corpus Christi, Portland, and Sinton. Population growth in these four counties has been steady and moderate since 1920, and continued growth is projected through the year 2000. Cameron and Nueces counties are expected to have population densities between 300 and 400 persons per square mile by 2000. In the other counties of the lower coast, population has remained at a low and relatively constant level since 1950. Kenedy County reached a maximum density of 0.62 persons per square mile in 1950.

Population growth on the central coast. Most of the counties in the southern portion of the central coast have maintained low population densities over the past 50 years (Figure 24), and little growth is projected for them in the next 20 years. Aransas and Victoria counties are the exceptions. Aransas County, smallest in area of all the counties in the region, has a large bay shoreline. Most recent growth in this county is due to residential and commercial development along the shoreline. Victoria County, containing the city of Victoria, had an increase in growth rate in 1960 which is expected to continue through the year 2000. Bee, Refugio, Calhoun, Jackson, Wharton, and

Matagorda counties have had relatively little increase in population density since 1900. The population of Goliad County has declined since its peak in 1930.

Recent and projected population growth in Fort Bend and Brazoria counties is high. By 2000, the population density is expected to reach between 200 and 300 persons per square mile in both counties. Until 1960 population density in these counties remained fairly low and constant. Both counties began to experience spillover growth from the Houston-Galveston area in the 1950's. Brazoria County has a long history of oil and gas development and substantial chemical and petrochemical manufacturing industries. It is clear that these counties are in the process of changing from rural to more urban environments.

Population growth on the upper coast. Figure 25 shows population growth for counties in the upper portion of the Texas coast. Population growth in Harris County far exceeds growth in the rest of the coastal region. Dramatic growth has taken place in this county since 1910, and growth since the 1950 census has been exponential. Projections put the population density of Harris County at nearly 1950 persons per square mile by the year 2000. For the entire nation the population density of urban areas was 2760 persons per square mile in 1970 (U.S. Department of Commerce 1981). Since half the land in Harris County is cropland, rangeland, pasture, or forest, the present population density of 1400 persons per square mile for the county as a whole indicates that the county's urban population may already surpass the nationwide urban average.

Galveston County had a steady population increase for nearly a century, from 1850 to 1940. The censuses of 1950 and 1970 showed substantial increases. Most recent projections (600 to 700 persons per square mile by

2000) suggest a continued increase, but at a lower rate. Galveston County has absorbed some of the population associated with the expansion of Houston.

The population of Montgomery County, just to the north of Harris County, has increased five-fold since 1960. Considerable residential development has occurred in Conroe and other small communities in Montgomery County because of their proximity to Houston. Before 1960 the population of Montgomery County had remained remarkably constant since 1880.

Orange County had major population increases in 1920, 1950, and 1960; since 1960 there has been steady growth. The discovery of oil fields in 1913, 1950, and 1951 and industrial development associated with the petroleum industry have been major influences.

Between 1900 and 1960 the population of Jefferson County increased at a steady rate of about 38,500 persons per decade. Jefferson County has been a center of petroleum development since the Spindletop oil field was discovered in 1901. Much of the later growth, particularly in 1950 and 1960, has been associated with the expansion of the petrochemical industry.

Waller, Chambers, and Liberty counties are adjacent to Harris County, but they have not had the substantial population increases that Montgomery, Galveston, Brazoria, or Fort Bend counties have experienced.

Summary of growth patterns. The counties in the Texas Barrier Island Region show five different patterns of population change (Figure 26). Galveston and Harris counties have a long history of growth with very high recent increases. These two counties contain 56.6 percent of the population of the counties shown in Figure 25 (using 1980 census figures). Montgomery County to the north and Fort Bend and Brazoria counties to the south have

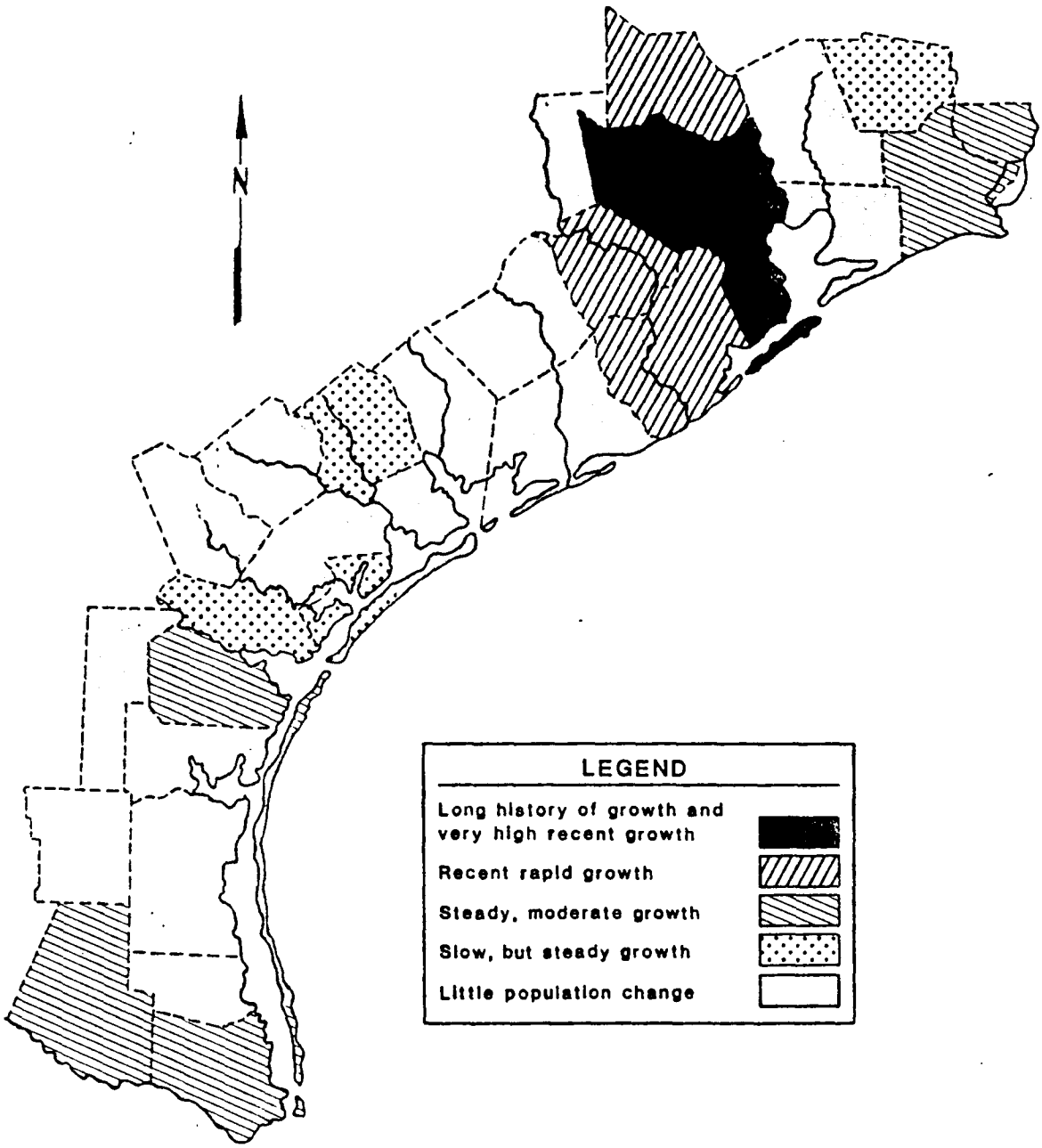


Figure 26. Patterns of population change.

exhibited high growth only recently, largely because of their proximity to Galveston and Harris counties. These five counties contain 65.9 percent of the coastal population and 21.2 percent of the state's population. The five-county area is the major population center and urban growth area in the region.

Cameron, Hidalgo, Nueces, Orange, and Jefferson counties have had steady, moderate growth since 1920 and are projected to grow at the same pace for the next 20 years. These counties contain 22.9 percent of the population of the counties shown in Figure 26. The populations of Aransas, Hardin, San Patricio, and Victoria counties (3.9 percent of the region) have also increased over the past 50 years, although at a lower rate.

The four population growth areas in the region are separated by groups of counties that historically and presently have low population densities and low growth rates. These counties, designated as areas of "little population change" in Figure 26, constitute 53.5 percent of the land area but contain only 7.2 percent of the population.

Land Use

Current land use in the Texas Barrier Island Region is shown in Figure 27 (Caran 1978). This map depicts six very general land use units: croplands, woodlands, grazing lands, wetlands, urban areas, and barrier islands.

Croplands, grazing lands, and urban areas are the units most easily recognizable as designations for land uses superimposed upon natural systems. "Woodlands" is not as clearly a land use classification as, for example, "timber" would be; but woodlands in the region are not areas of uniform land use. Timber harvesting is a minor industry within the region's boundaries. Some coastal woodland areas are sites of residential development; others are

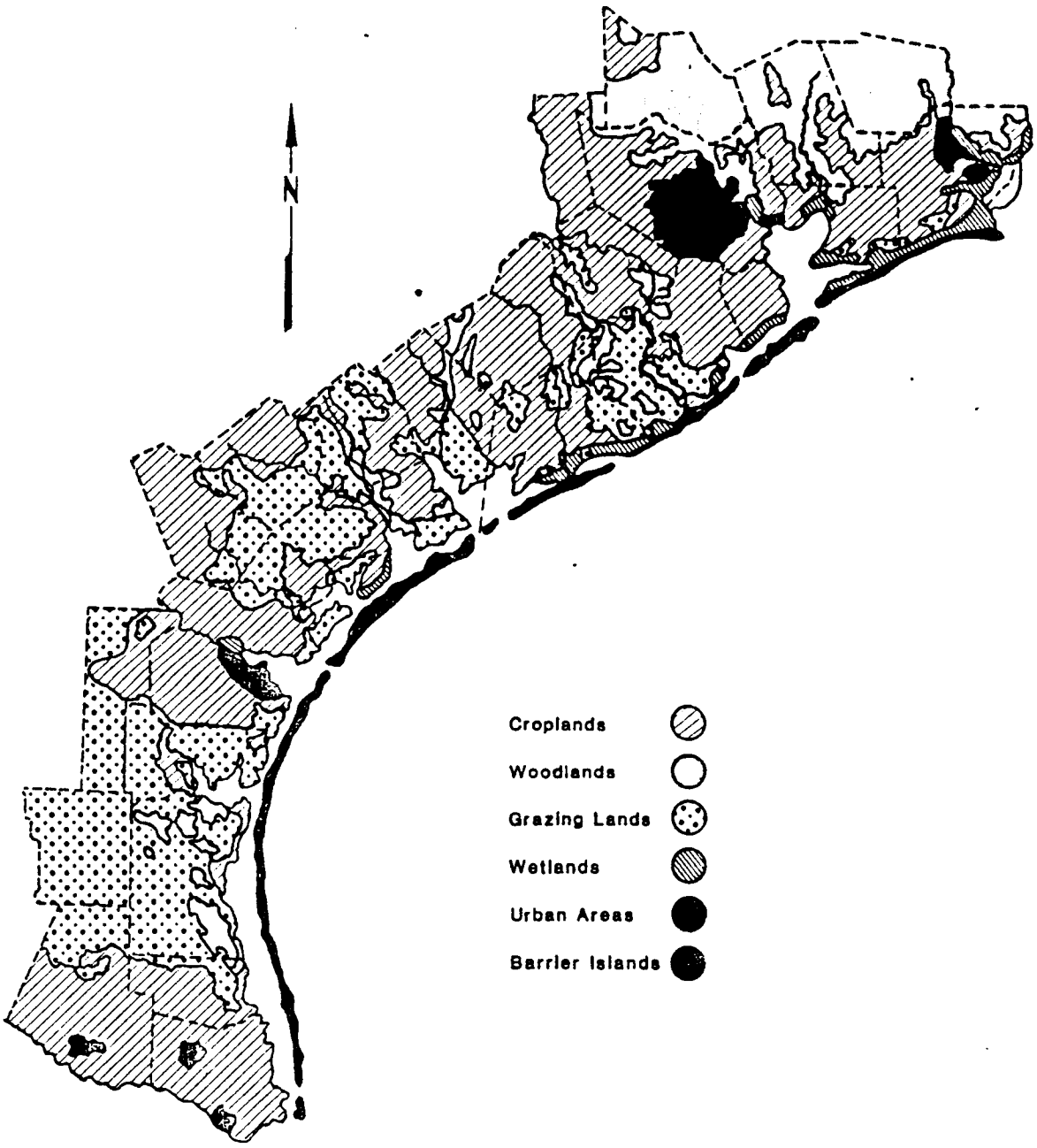


Figure 27. Current land use in the Texas Barrier Island Region.

areas of no significant land use. The same is true of the wetlands land use unit: the region contains large areas of undeveloped wetlands, important because they have not been subject to significant alteration. Some of them are privately owned, some are publicly owned, and many are within parks and refuges. Wetlands sustain a variety of uses, including recreation, grazing, transportation, and oil and gas production.

The barrier unit is used here because the scale of the comparative maps of the region in this chapter makes it impossible to distinguish most other land use units on the barrier islands, peninsulas, and strandplain. The only other unit shown on the barriers is the large urban area on Galveston Island. Principal uses of the barrier islands, peninsulas, and strandplain include recreation and cattle grazing. Developed areas and areas protected from development by inclusion in parks and refuges are described in the discussion of this unit below.

Woodland. The northernmost land use unit is a large area of woodlands. This is primarily oak-pine forest, some of which is harvested commercially; 3.5 percent of the statewide income from timber in 1978 came from this area (Liebow et al. 1978). Some woodland near Houston is being thinned for residential development. Small belts of forest remain in the Brazos, Colorado, Lavaca-Navidad, and Guadalupe river basins. The live oak groves shown in the lower coastal region were not recognized as separate forest areas on the biologic community map (Figure 18), but were considered part of the mesquite-live oak savannah biome.

Urban areas. Eight large urban concentrations are shown in Figure 27. The urban centers on the upper coast are, from north to south, Beaumont, Port Arthur, Houston, and Galveston. The area covered by the city of Houston is

as large as some counties. Since this map is based on 1978 data, the Houston area is probably larger than shown. Corpus Christi is the next major urban area to the south. In the southern coastal region near the Rio Grande are Brownsville, Harlingen, and McAllen, from east to west. This map shows only the largest urban areas; smaller urban centers such as Freeport, Port Lavaca, and Victoria are not depicted. Land-use data collected by the Texas State Soil and Water Conservation Board indicate that there are about 2450 square miles of urban land in the 29-county area of Figure 26.

Cropland. About a third of the region is cropland, more than one-third of which is irrigated (calculated from Texas State Soil and Water Conservation Board 1978). A large area of nearly uninterrupted cropland stretches from Beaumont to Matagorda Bay, approximately half the length of the coast. Rice and soybeans are abundant throughout this area. Corn is grown in the lower portion, and a substantial amount of cotton is produced in Wharton and Fort Bend counties (Liebow et al. 1980a).

The counties with cropland near Corpus Christi (Bee, Refugio, San Patricio, Nueces, and Jim Wells) grow sorghum and flaxseed. Cotton is grown in Nueces and San Patricio counties, and Bee County produces corn. The last area of extensive cropland is in the Rio Grande Valley--in Cameron, Willacy, and Hidalgo counties. These areas are important producers of vegetables, citrus, and corn, but also produce sorghum and cotton.

Grazing land. A large area of grazing land is located in the central coastal region between Copano Bay and Matagorda Bay. A smaller area is located to the northeast near the Brazos River. The largest area of grazing land, in the lower coastal region, includes Brooks, Kenedy, Kleberg, Jim

Wells, Hidalgo, and Willacy counties. In 1978 most of these counties reported herds in excess of 60,000 head (Liebow et al. 1980).

Wetlands and barrier islands. Undeveloped wetlands, concentrated in the upper half of the region, remain despite the demand for land for agricultural and urban use.

Though most of the land area of the barrier islands, peninsulas, and strandplains is undeveloped, development has accelerated during the past decade. About half of Galveston Island is urbanized. Other barrier features experiencing urbanization are Bolivar Peninsula, the beach ridge and interridge area of the mainland near Freeport and the Brazos River, a large portion of Mustang Island, and the northern and southern tips of Padre Island. Large areas of the barrier islands are preserved as parks and refuges. Half of Matagorda Island is a wildlife refuge under federal and state management. There are state and federal wildlife refuges in the upper coastal region that extend onto the barrier flat. About 60 percent of Padre Island is a National Seashore, and there are a few county and state parks on Galveston, Mustang, and Padre islands. The half of Matagorda Island outside the refuge, San Jose Island, and a substantial portion of Matagorda Peninsula are privately owned. Since transportation to these areas is very limited, it is unlikely that they will be developed in the near future.

Changes in Land Use

Comparison of the original biotic communities of Figure 18, potential natural vegetation before man's influences, with the current land uses of Figure 27 shows the extent and nature of the changes man has brought to the region.

Land uses with no change in function. There were no "land uses" before man began to manage the lands in the Texas Barrier Island Region; all plant and animal communities were integrated functional units and man had a minor role or none at all. Today, man's influence pervades the region. Even areas that remain undeveloped are subject to some kind of land use, though it may be inconspicuous. Some land-use units operate in the same manner as their biotic community counterparts shown in Figure 18. For example, the components of woodland--several strata of vegetation, herbivores, omnivores, carnivores, and abiotic constituents--function the same way today as they have for thousands of years. Undeveloped wetlands and barrier island land-use units operate in the same fashion as the cordgrass marsh and sea oats prairie biotic communities.

Cropland, a new functional unit. Cropland units operate differently than the natural units from which they were derived. The energy stages of development of croplands and urban areas in human history have been examined by Odum (1983). Man began to use croplands by taking advantage of pulses in production in natural systems, at first by gathering grain, fruits, and nuts when they appeared, and then by sewing seed, tilling, or eliminating competing species at critical times to improve production. As agriculture developed, man changed the ecosystem so that he was no longer one of many consumers--he became the major consumer. Man used several strategies to increase the net primary production for human use: he excluded other consumer species; he used husbandry practices to select plant species that would divert energy formerly used in self-maintenance to yield; and he learned to control many of the components of the now-altered ecological system. Weeding, tilling, fertilizing, watering or irrigating, and adding pesticides are some of the

ways man controls the components of agricultural ecosystems. However, controlling system components through these means and supporting genetic strains selected for high yields is an energy-intensive process.

As high-quality energy sources became more available, agriculture was increasingly based upon the energy subsidies of fossil fuels, synthetic fertilizers, and pesticides, and less dependent upon the environmental energies of sun, wind, rain, and soil (Odum 1983). The controlling forces in agricultural ecosystems became the inputs of the farmer; the organization and structure of the agricultural ecosystem changed drastically from those of forest, prairie, or savannah. The plant and animal communities of cropland, as well as soil components, microorganisms, nutrients, water, and physiography, are all unlike the parent biotic communities.

Urban land, a new functional unit. Urban land-use systems, like cropland, are highly dependent upon the import and export of fossil fuels, goods and services, and a variety of control pathways from outside the system--government regulation, tourism, and investment (Odum 1983). Urban systems require some natural components to operate successfully (Odum and Odum 1972). However, the functioning of urban systems is largely independent of the original biotic community on which they are built. The organisms--man, dogs, cats, squirrels, rats, and introduced plants--are often those that adapt well to many ecosystems or that are especially associated with urban systems. Many of the abiotic components--roads, sidewalks, water and sewer lines, electric cables, private homes, and commercial buildings--are imported and were never part of the original system. It is clear that both urban and cropland systems are substantially different from the biotic communities on

which they were built; they are entirely dependent upon man's management and energy inputs.

Grazing land, a natural but managed system. Grazing land is neither a completely man-managed system nor a completely natural system. The native grassland communities in the Texas Barrier Island Region were bluestem prairie, Fayette prairie, bluestem-sacahuista prairie, mesquite-acacia savannah, and mesquite-live oak savannah (Figure 18). The diversity of the flora in these grassland communities was low, but productivity was high. Avian faunal diversity was limited, but invertebrates, particularly insects, were abundant. The faunal community included herbivores, and omnivores such as reptiles, birds, squirrels, gophers, mice, rats, opossum, raccoon, skunks, and rabbits; most were burrowing species. Carnivores that fed on these smaller animals included coyotes, bobcats, foxes, predaceous birds, and snakes.

A characteristic of grassland communities was large herds of mobile herbivores (Smith 1966; Whittaker 1975). Historical information indicates that deer, antelope, and wild horses were abundant in the grasslands of the Texas coastal region between 1690 and 1850 (Inglis 1964). The existence of buffalo in the region is less certain. Hudson (1978) noted that Karankawas in the upper coastal region followed game which included deer, bison, bear, and peccary. De Leon encountered buffalo in Victoria County in 1689 (Inglis 1964), and Webb (1952) stated that buffalo occasionally migrated to the Gulf Coastal plains. When Western man brought cattle and horses to the grasslands, these domesticated animals replaced the buffalo, antelope, and deer as the large mobile herbivores. Deer retreated to the brushy areas in the grasslands

but have been successful in adapting to areas of new land uses introduced by man.

Some models of grazing ecosystems are nearly identical to models of natural systems (Odum 1971). Other grazing ecosystem models, like models of cropland and urban land-use systems, include outside inputs of fuel, supplies, labor, supplementary feeds, and government subsidies (Odum 1983). The grazing lands in the Texas coastal region probably range from nearly natural systems to those that receive some supplementary feeds (feedlot operations are not considered here). Many of the grasses--for example, bluestem and gulf cordgrass--are the same species that would occur naturally, but their distribution and productivity are probably different from the natural communities. Many consumers and carnivores are the same as those in the grassland biomes, although the large herbivores are now primarily cattle. While there are similarities, there are also differences. Brush has expanded into grasslands in the southern region (Inglis 1964); this has largely been attributed to overgrazing (Bogusch 1952). To summarize, grazing systems are not completely natural systems, but they look and function more like the natural systems from which they came than man-made or other man-managed land-use systems.

Locations of altered land uses. Land use changes are presented in Figure 28. This figure shows differences in land uses and biotic communities from Figure 18 and Figure 27; the contrasts occur in system operation. Wetlands, the nonurbanized parts of barrier islands, and woodland land-use units operate in the same fashion as cordgrass marsh, sea oats prairie, and forest systems. Urban and cropland units operate in an entirely different fashion from their parent natural biotic communities. Grazing lands operate in essentially the

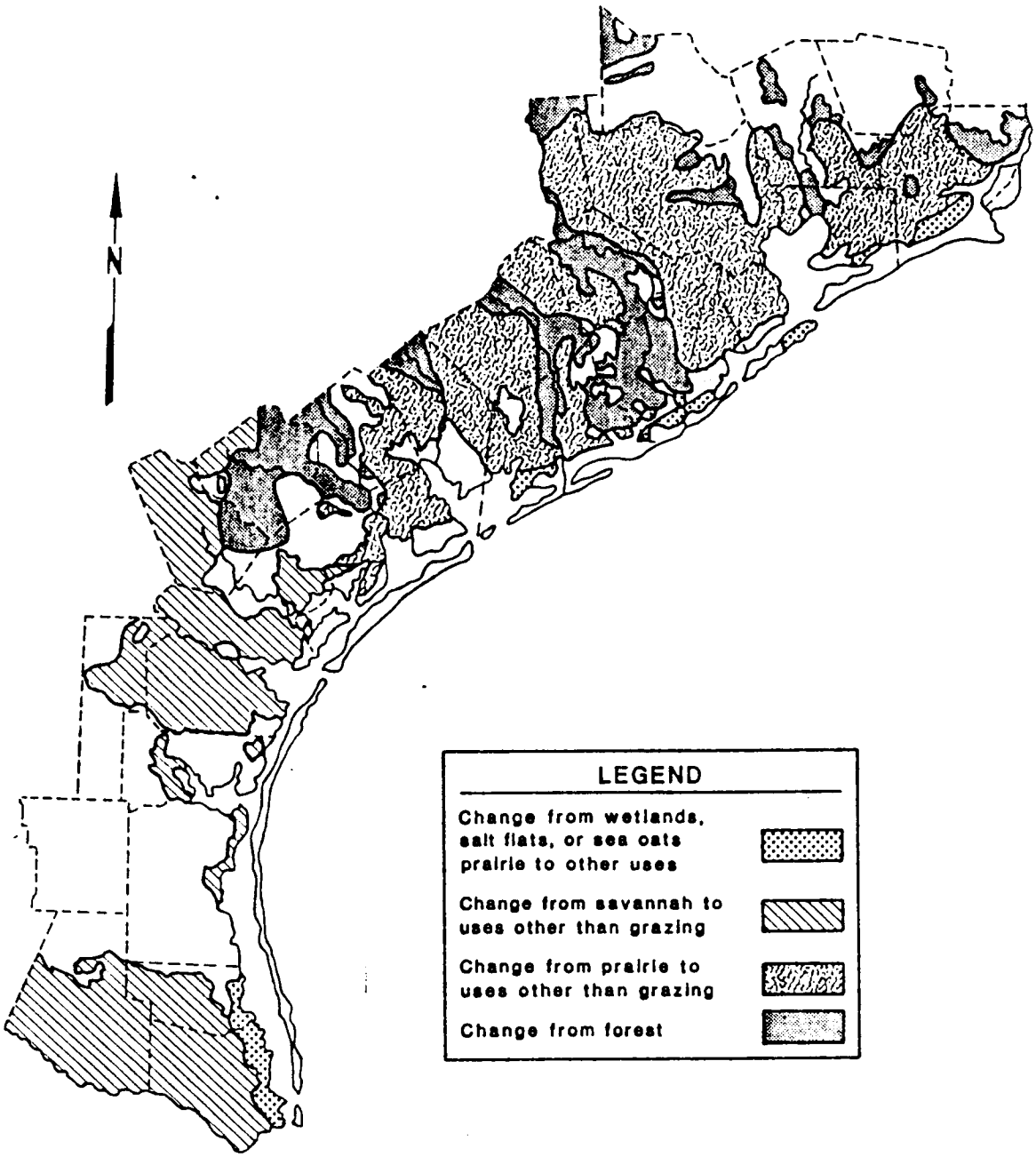


Figure 28. Land use changes in the Texas Barrier Region.

same fashion as mesquite-acacia savannah, mesquite-live oak savannah, bluestem prairie, Fayette prairie, and bluestem-sacahuista prairie. Changes other than the compatible land-use conversions described above constitute a major alteration in system operation and are noted as land use changes.

Units in Figure 28 that lack any shading are areas where the current ecosystem function does not differ markedly from that of the biotic community found there before man influenced the region. The most northern area of no change is nearly all forest. There is a small central area with no change; most of this area was bluestem-sacahuista prairie that is currently used for grazing. The largest unchanged area includes Kleberg, Kenedy, and Brooks counties and most of Jim Wells County. The original natural communities were mesquite-acacia and mesquite-live oak savannah. Most of this area is now used for grazing. The remaining portion of the region experiencing relatively little change is the barrier island system. Although there are urban developments in a few spots, much of the barrier islands remain undeveloped. Based upon shoreline length estimates, 69.3 percent of the barrier islands are undeveloped (Hees et al. 1978; Barrier Islands Coalition 1982).

Figure 28 shows areas that have changed from wetlands, salt flats, or sea oats prairie to other land uses. On the upper Texas coast some wetlands have become grazing land and croplands. Many other areas too small to be shown at this map scale have become urban land. It has been estimated that as much as 53,000 acres of coastal wetland in the region has been filled or drastically altered (Texas Coastal Management Program 1976). Direct measurements in the Galveston Bay region show a loss of 12,509 acres of wetland from 1956 to 1979 (Johnston and Ader 1983).

A large urban area exists on the eastern portion of Galveston Island, and residential development is taking place on the rest of the island. Farther down the coast, wetlands near Freeport and on Matagorda Bay now support grazing. The salt flat area in the southern Laguna Madre supports crops and grazing (Brown et al. 1980).

Figure 28 shows areas that have changed from savannah and from prairie to uses other than grazing and supporting grassland communities. The areas of savannah that have changed have for the most part become croplands. These include the valley of South Texas and the croplands of the coastal bend area around Corpus Christi. Some of the savannah has become urban area. Prairie that has been put to uses other than grazing is found around Matagorda Bay and in the areas immediately adjacent to and including Harris County. In the Matagorda Bay area, all of the prairie has become cropland. In the Harris County area, most of the prairie has become cropland, but a large portion has become urban area--Houston, Beaumont, and Port Arthur.

The changes from forest to other uses are shown on Figure 28. Although the urbanization of the Houston area has certainly altered some forest areas, conversion of the floodplain forest areas of the Brazos, Colorado, Guadalupe, and San Antonio rivers to cropland and grazing land has changed a much larger area. Portions of oak-pine forest in the Texas claypan area have been converted to cropland, and parts of the oak forest on the upper Rio Grande plain and lower Texas claypan area have been converted to cropland and grazing land.

Quantitative changes in land uses. Areal measurements of environments, biologic assemblages, and land uses available from Bureau of Economic Geology publications are based on photographs from the late 1950's and early 1960's

(Brown et al. 1976, 1977, 1980; Fisher et al. 1972, 1973; McGowen et al. 1976a, 1976b). Although these measurements do not indicate changes that have occurred in the last 20 years, they do illustrate the degree of change resulting from development of the region (Table 1).

For comparison, biologic assemblage units were grouped into four classifications: forest; prairie, savannah, or salt flats; sea oats prairie; and cordgrass marsh. Similarly, land use units were classified as woodland, grazing land, cropland, wetland, barrier island, and urban land. Area totals were calculated on a county basis for the whole coastal region. When total areas for both classification systems were compared for completeness, totals differed by less than 0.5 percent. The data is presented in Table 1 in terms of percent rather than absolute acreage figures. The area covered by these measurements closely approximates the upland and wetland portion of the Texas Barrier Island Region.

Visual inspection of maps placed side-by-side allowed rough estimates to be made of which new land uses came from individual biotic communities. Cropland and urban land have been created from each of the four groups of biotic communities. About a fourth of the forest in the region has been converted to other uses. Most of the forest land has been changed to cropland or grazing land, in about equal proportions. The conversion of forest to urban land has been much smaller.

Prairie, savannah, and salt flats made up 80.5 percent of the upland biotic communities in the Texas Barrier Island Region before development began. Grazing land now constitutes 47.1 percent of the upland area of the Texas Barrier Island Region. Most of the change in these biotic communities

Table 1. Land use changes in the Texas Barrier Island Region.

Original biotic community	Measured total area (percent)	Present land use	Measured area that is unchanged (percent)	Estimated area that is changed (percent)
Forest	12.9	Woodland	9.4	
		Cropland		> 1
		Grazing land		> 1
		Urban land		< 1
Prairie, savannah and salt flats	80.5	Grazing land	47.1	
		Cropland		> 25
		Urban		< 5
		Woodland		< 2
Sea oats prairie	3.3	Barrier island	3.0	
		Urban		< 1
Cordgrass marsh	3.3	Wetland	2.7	
		Cropland		< 1
		Grazing land		< 1
		Urban land		< 1
Percent of land area	100.0		62.2	37.8

has come about through their conversion to cropland, but conversion to urban land has also been important. Areal measurements indicate that nearly 33.6 percent of the upland in the region is cropland and about 4.1 percent is urban land.

About a tenth of the sea oats prairie has been converted to urban land. A slightly greater proportion of wetland has been changed to cropland, grazing land, and urban land. Overall, 37.8 percent of the upland ecological systems in the region are now intensively managed by man as cropland and urban area according to BEG measurements.

More recent land use figures indicate that this proportion has increased. In its long-range plan, the Texas State Soil and Water Conservation Board (1981) estimated the acreage of cropland, rangeland and pasture, forest, and urban areas for all soil and water conservation districts. Their figures for the counties in the Texas Barrier Island Region are: grazing land, 44.5 percent; woodland, 9.1 percent; cropland, 33.9 percent; and urban land, 12.5 percent. These proportions indicate that 46.4 percent of the upland ecological systems in the region are now intensively managed by man.

Other Measures of Economic Development

The population of the Texas Barrier Island Region in 1977 was 1,722,912, about 28 percent of the population of the state; employment was 790,172. The total area of the region (including submerged lands) is 6.6 million ha (12.9 million ac), about 7.4 percent of the land area of the state.

The economy makes a number of resource demands upon the region's environment. These include the demand for space, materials, energy, and biota. As previously noted, 38 percent and possibly as much as 46 percent of the land area in the region is intensively managed for crops or urban uses.

The water systems in the region--more than 1.8 million ha (4.5 million ac) acres of bay, lagoon, river, and nearshore gulf--are used for fisheries, recreation, navigation, and processing or transporting societal wastes. The intensity of use and the degree of management varies, however. As with grazing lands, the overall intensity of management activities in aquatic systems is low, but noticeable. Table 2 indicates the areal extent of land uses.

Fresh water is used for agricultural, municipal, and industrial purposes. The total freshwater use in the region is 6035 million cu m per year (Texas Water Development Board 1977). Currently, three cubic meters of surface water are used for every two cubic meters of groundwater water (Table 2). Municipal use accounts for 13.6 percent of the freshwater consumption in the region; manufacturing consumes 16.5 percent; and irrigation consumes 65.8 percent. Steam-electric power generation, mining, livestock, and other uses make up the remaining 4.1 percent of freshwater use (from Texas Water Development Board 1977). Return flows for municipal and manufacturing use equal 54.5 percent of the freshwater used from both surface and groundwater sources. Irrigation returns 18.2 percent of the total water used. About 28 percent of all fresh water consumed in the region is returned to the water systems after use (from Texas Water Development Board 1977).

The economy uses the natural biotic production of the region to obtain fishery and agricultural products. More than 42 million kg (94 million lb) of fishery products are landed in the region (Table 3). About 28.2 million kg (62.1 million lb) are shrimp fished from the gulf. Some of the gulf shrimp catch may come from outside the Texas Barrier Island Region; however, since

Table 2. Demands for space and freshwater in the Texas Barrier Island Region.

Resource demand	Economic or resource demand indicator	Quantity
Space		
Relatively unchanged upland or wetland systems	Barrier island	1163.4 sq km
	Wetland	1008.5 sq km
	Woodland	2825.2 sq km
Moderately changed upland systems	Grazing land	16,023.0 sq km
Highly Changed upland systems	Cropland	11,395.2 sq km
	Urban land	1432.5 sq km
Total area of uplands and wetlands		34,211.5 sq km
Total area of Texas Barrier Island Region		52,426.8 sq km
Fresh water		
For agriculture, municipal, industrial, and miscellaneous uses	Surface water	3626 million cu m
	Ground Water	2409 million cu m

Table 3. Biomass production in the Texas Barrier Island Region.

Resource type	Economic or resource demand indicator	Quantity
Fishery products	Bay shrimp	6.1 million kg
	Gulf shrimp	28.2 million kg
	Oysters	1.2 million kg
	Crabs	3.5 million kg
	Finfish and other	3.4 million kg
Total harvest		42.4 million kg
Direct commercial value		$127.6 million
Agricultural products	Grain: corn, wheat, oats, sorghum, and soybeans	2,305,344 kiloliters
	Cotton	434,796 bales
	Hay	263,479 metric tons
	Rice	624,404 metric tons
	Cattle and calves sold	359,515
Total market value		$393.4 million

shrimp spend part of their life cycle in the estuaries it is appropriate to attribute this production to the region. The total value of the catch was $127.6 million in 1976.

Agriculture is a major resource use in the Texas Barrier Island Region. The market value of livestock and cropland production in the region was $393.4 million in 1974. The importance of agriculture in influencing land uses is very high since cropland and grazing land occupy more than 78 percent of the region's area (from Texas State Soil and Water Conservation Board 1981).

The demand for minerals in the Texas Barrier Island Region, particularly natural gas and petroleum, is high. The region supplies 16 percent of the crude oil and more than 33 percent of the natural gas produced in the state (Table 4). Condensate, other gaseous products, and a variety of other minerals are also produced. The market value of the minerals produced in the region is nearly $3 billion, and the indirect benefits to the rest of the economy are substantial.

Industrial and residential development is a large sector of the coastal economy that adds value to resources through manufacturing and building. The value added by this sector of the economy was more than $12 billion in 1977 (Liebow et al. 1980b).

Recreation is a rapidly developing sector of the coastal economy. Demands on the natural environment for recreational use include space, biotic production (for fishing and hunting), clean waters, and an attractive environment. Table 4 shows the relative value of recreation to the coastal economy. The recreation industry generates far more revenue than agriculture.

The other major economic sector is transportation. The major demand that transportation makes on the coastal environment is for space. However, it

Table 4. Mineral production, recreation, and transportation in the Texas Barrier Island Region.

Resource demand	Economic or resource demand indicator	Quantity
Oil and gas production	•Crude oil	19,229 million liters
	Liquid condensate	1084 million liters
	Natural gas and casinghead gas	45,040 million cu m
	Value of production	$2.99 million
Recreation and tourism	Travel-related employment	34,373
	Area available for recreation	126,113 ha
	Expenditures for travel	$971.5 million
Transportation	Highways length	34,930 km
	Total railroad length	2,169 km
	Waterway length	1,323 km
	Water tonnage	211,849,000 metric tons

also causes changes in waterflow patterns and results in the introduction of waste loads and materials detrimental to public health. The transportation network through the region is very large. There are more than 37,000 km of roads and railroads in the region (Table 4) and more than 1300 km of channels, of which more than 1100 km are federal navigation projects. Over a 10-year period, about 280,000 cu m of spoil must be removed to keep a single mile of channel operational (calculated from Belaire and Alexander 1976). About 50 percent more material must be removed for channel maintenance than flows into the region from all the major river systems each year.

The region has major deepwater port facilities at Houston, Texas City, Galveston, Freeport, Corpus Christi, and Brownsville. Three quarters of all goods that are shipped from Texas to other states travel by water (Texas Coastal Management Program 1975) and more than 211,849,000 metric tons were shipped in 1977 (Table 4).

The coastal economy requires the natural environment to process wastes (Table 5). Waste loads affect the esthetic aspects and public health of the region, especially in highly urbanized areas. Emissions such as hydrocarbons and particulates from automobiles and industries have been high in the region and have exceeded national standards at times in the Houston, Galveston, Freeport, and Corpus Christi areas (Williams et al. 1976).

More than 62 percent of the point-source discharges into the region's water systems are from municipal sanitary treatment facilities (Liebow et al. 1980b). Industrial, agricultural, and retail establishments make up the rest of the point-source discharges. Williams et al. (1976) reported that about 53 percent of the stream segments in their study area (larger than the Texas

Table 5. Demands upon natural environment to process societal wastes.

Resource demand	Economic or resource demand indicator	Quantity
Public health	Total length of stream segments in region	3045 km
	Total length of fishable and swimmable segments in the region	2780 km
	Percent length of segments that are fishable and swimmable	91 percent
Waste loads	Airborne particulate matter	191,741 metric tons
	Airborne hydrocarbons	853,188 metric tons
	5-day BOD oxygen total	15.7 million kg
	Number of permitted discharges	915
	Cumulative industrial solid waste amount	36.6 million metric tons

Barrier Island Region) were fit for human contact. There appears to have been improvement, however, since their study was made. The Texas Department of Water Resources (1983a) reported that about 91 percent of the stream segments in the region met state water quality standards were fishable and swimmable.

REGION SUMMARY

The greatest natural influences on the physiographic development of the Texas Barrier Island Region were the Gulf Coast geosyncline and sedimentary processes. These geologic forces continue to shape the region. The greatest natural influence on the biotic development of the region has been climate, governed by predominant weather patterns from the Gulf of Mexico and seasonal frontal weather patterns from the northwest. Geologic processes have given the region a low, flat land surface; climatic influences have produced an environment that varies substantially from subhumid in the north to semiarid in the south. The region has been inhabited for thousands of years, but development is very recent: nearly all man-made changes have occurred in the last 150 years. These changes have been not only rapid, but extensive. Nearly half of the region's land is intensively managed by man as cropland and urban area. The remainder, the largest portion of which is grazing land, is not intensively managed, but is affected by man's activities.

Areas of population concentration on the Texas coast developed at port sites that served as points of entry for early settlers, trade centers, and shipping points for agricultural products. These areas prospered with the expansion of railroads and the waterborne transportation system. The catalyst for rapid growth in the 20th century was the discovery of coastal oil and gas

fields, which enlarged and diversified the economic base of the region. Three of the four population centers on the Texas coast lie within the Texas Barrier Island Region. They are separated by large areas of cropland and grazing land, where the human population density is low. Population growth is explosive in the counties surrounding the Houston area, which is the focal point of population growth, economic development, and change in the region.

BASINS IN THE TEXAS BARRIER ISLAND REGION

INTRODUCTION

Basin Arrangement in the Region

Basins are areas with a common drainage whose boundaries are determined by land topography. Ten basins have been delineated for the Texas Barrier Island Region study: Rio Grande, Laguna Madre, Corpus Christi, Aransas-Copano, San Antonio, Matagorda, Colorado, Brazos-Colorado, Brazos, and Galveston (Figure 29). All extend further inland than the inner boundary of the study area. The Colorado and Brazos basins extend into New Mexico. The Rio Grande basin extends into New Mexico and Colorado and more than half of the Rio Grande Basin is in Mexico.

Other basins are wholly contained within the state. The Galveston Basin extends more than 320 km (200 mi) inland and includes the metropolitan areas of Dallas and Fort Worth within its drainage area. The San Antonio Basin extends into Central Texas as far as Kerr County and includes the city of San Antonio. The Corpus Christi Basin extends into Central Texas and South Texas as far as Edwards County, just west of Kerr County. The remaining basins--Laguna Madre, Aransas-Copano, Matagorda, and Brazos-Colorado--extend only a little further inland from the coastline than the study area boundary.

The river systems of most of the basins empty into bays. Only three basins that extend beyond the state's boundaries--the Rio Grande, Colorado, and Brazos basins--have rivers that empty directly into the gulf. At one time the rivers of these large basins emptied into bays, but riverborne sediment completely filled their estuaries and narrowed the river basins.

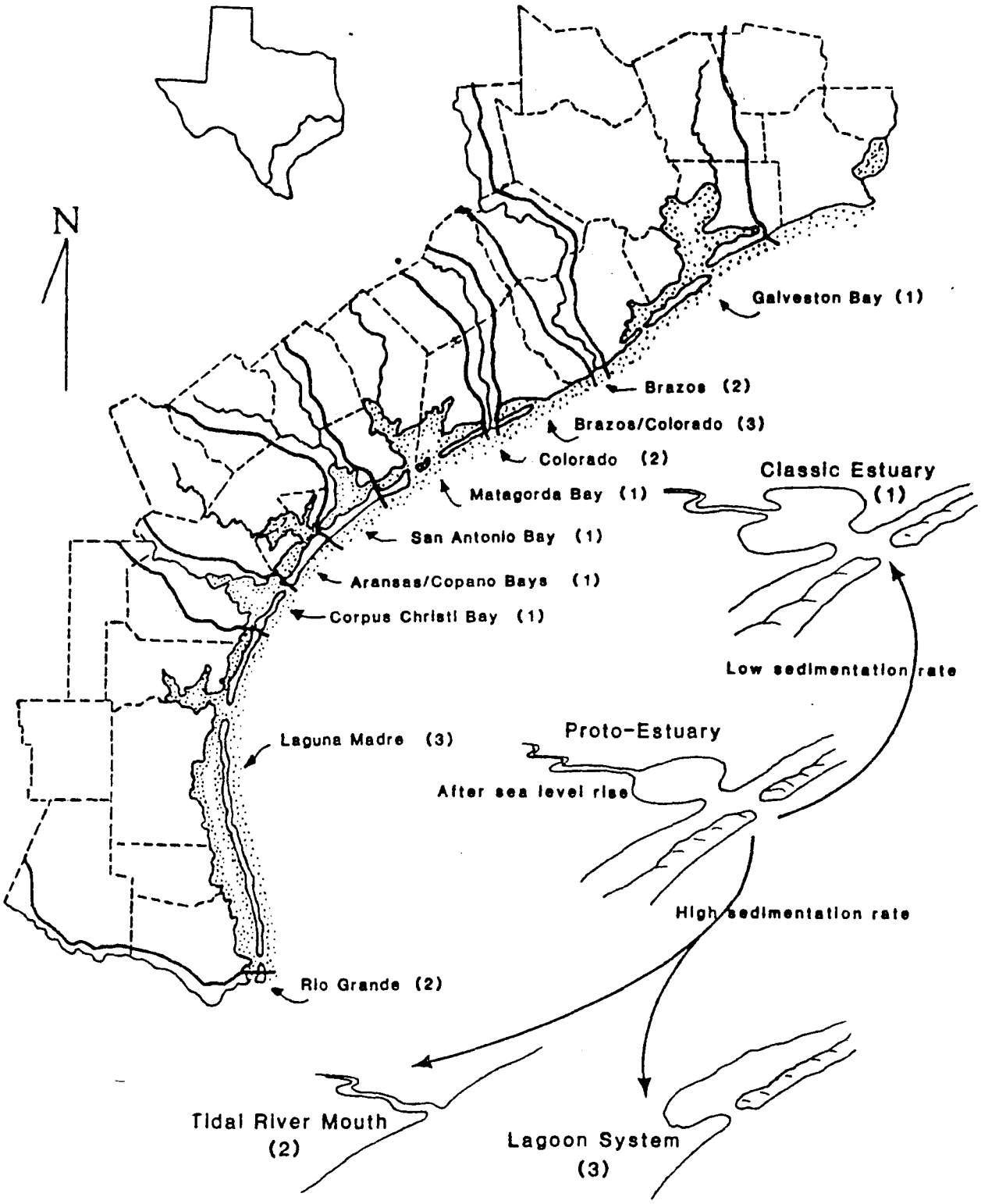


Figure 29. Map of Texas Barrier Island Region.

The Texas Department of Water Resources (TDWR) has defined standard geographic boundaries for river basins and coastal basins (Texas Water Development Board 1977). These boundaries, based upon topography, are defined by law and are used by the TDWR for planning and management of water resources. In this study no distinction is made between river basins and coastal basins; a basin is any of the major drainage units that passes through the region. In general, the hydrologic boundaries of basins in this study follow the statutory boundaries defined by TDWR except where the latter divide a bay among two or more distinct basins. In these cases, basin boundaries have been redrawn to include entire bay systems. Topographic maps with drainage features and maps with component drainage basin boundaries (Woodruff 1975) were used to redefine the basin boundaries.

Concepts for Basin Analysis

Time scale for basin processes. The basins described in this chapter have developed in a geologic cycle that began at the beginning of the most recent ice age, the Late Wisconsin glaciation (50,000 to 60,000 yr B.P.), and that continues today. The morphology of some basins--particularly those with small drainage areas--has changed slowly during this period as the result of processes extending over tens of thousands of years. Other basins--particularly those emptying directly into the gulf--have undergone major morphological changes in just a few thousand years.

Hydrologic relationships. Water is the main unifying element in the consideration of basins. The transmission of energy and transport of materials by water formed the basins and continues to drive their operation. Except for geologic processes occurring at great depths in the sediments, water and water movement influence every aspect of the natural environment.

The flows of water within basins provide the pathways for material, energy, and biota transport among habitats. Water also strongly influences many parts man's socioeconomic system.

Habitats. Basins contain an arrangement of habitats, both natural and man-made systems. The pattern of habitats that develops in basins is largely the result of long- and short-term hydrologic processes. The long-term interaction between climate and substrate provides the landform upon which natural habitats develop. Water is the key ingredient in this interaction and shapes the substrate by picking up, transporting, and depositing sediment. Characteristics determined by long-term hydrologic processes include elevation, slope, surface sediment type, and soil type.

Short-term hydrologic conditions influence the balance among basin habitats and provide the environmental conditions that separate one habitat from another. Relative humidity, precipitation, soil moisture, current velocity, salinity, and frequency of inundation are examples of short-term hydrologic conditions that are determinants of habitat distribution and boundaries.

Socioeconomic activities and basins. A few socioeconomic activities are visible at the regional scale of view as land-use changes. These include spoil placed adjacent to major navigation channels, water impoundments, large-scale agricultural developments, and areas of industrial and residential development. But it is necessary to focus on the basin level of organization before the consequences of socioeconomic activities can be analyzed in terms of cause-and-effect relationships upon basins and the habitats within them.

Appendix B contains a description of the socioeconomic structure within basins. Six major socioeconomic sectors were defined by Liebow et al. (1980): oil and gas production, recreation and tourism, commercial fishing, industrial and residential development, transportation systems, and agriculture. For continued operation of the socioeconomic system, each of these sectors requires inputs from or produces outputs for habitats in the basin. These inputs and outputs, termed "resource demands," are the requirements or stresses on habitats that produce environmental impacts. Resource demands from the habitats include requirements for space or portions of particular habitats, minerals, biomass, esthetic qualities, water quality acceptable for public health, and fresh water flows. Resource demand outputs that must be accepted by habitats include waste produced by transport systems, industries, residential development, and municipal sewage facilities; subsidence caused by extraction of groundwater and petroleum; and water flow modifications--changes in both quantity and patterns of flow--caused by industrial, residential, transportation, and agricultural uses.

Chapter Organization

This chapter is divided into five sections. The first identifies the hydrologic, climatic, and sedimentary inputs that formed the basins and describes the development of the basins. The second section shows how resource demands from the socioeconomic system affect basins as a whole. The third section concentrates on habitats within basins, describing how they are linked and how they are changed by socioeconomic activities.

The fourth section consists of comprehensive descriptions of the 10 basins in the Texas Barrier Island Region. These descriptions include information on both the natural and socioeconomic systems as well as

identifiable basin problems. The last section in this chapter is a comparison of the basins, emphasizing the similarities and differences of the 10 systems.

GEOLOGIC DEVELOPMENT OF BASINS

Modern conditions gradually developed during the Cenozoic era (4,500 to 70 million yr B.P.). The land mass that had submerged in the coastal area during the Mesozoic was buried by deposited sediments to depths as great as 65,000 ft (Williams et al. 1976). Large quantities of sediment were transported, and a series of transgressions and regressions between the sea and the land caused the shoreline to advance and retreat scores of miles.

At least four principal glacial episodes (Brown et al. 1976) took place during the Pleistocene period close to the end of the Cenozoic (18,000 to 1.2 million yr B.P.). Figure 30 illustrates periods of glaciation and the changes in sea level associated with the Pleistocene. The substrate characteristics and present landform of the Texas Barrier Island Region are largely due to the depositional processes that occurred during the Pleistocene.

Figure 31 through 36 show the sequence of development of present coastal features. The dashed outline in the figures shows the present location of various coastal features. These features are labeled in Figure 36.

Sangamon Interglacial Stage

The landform near the present coastline was particularly influenced by the last two glacial intrusions. Figure 31 represents the coastal region about 150,000 yr B.P. The uplands in area "F" resulted from fluvial processes. They were formed mainly by meanderbelt sand from shifting river channels and by mud and silt deposited by river flooding.

ERA	PERIOD	EPOCH	LIFE FORMS	MILLIONS OF YEARS B.P.	GRAPHIC SCALE
	THE FORMATION OF THE EARTH				
Precambrian			Plants, animals with soft body tissues; few fossils	4600	
Paleozoic	Cambrian		Many marine invertebrates	570	
	Ordovician		Primitive fish	480	
	Silurian		First land plants/animals	435	
	Devonian		Amphibians; fish abundant	405	
	Mississippian		Sharks abundant	340	
	Pennsylvanian		First reptiles	300	
	Permian		Conifers	260	
Mesozoic	Triassic		Dinosaurs	225	
	Jurassic		First birds; small mammals	180	
	Cretaceous		End dinosaurs	130	
Cenozoic	Tertiary	Paleocene	First placental mammals	65	
		Eocene	Flowering plant	55	
		Oligocene	Large browsing mammals	38	
		Miocene	Apes, grazers	27	
		Pliocene	Big carnivores	10	
	Quaternary	Pleistocene	Early man	2	
		Holocene		0.01	

Figure 30. Geologic timescale.

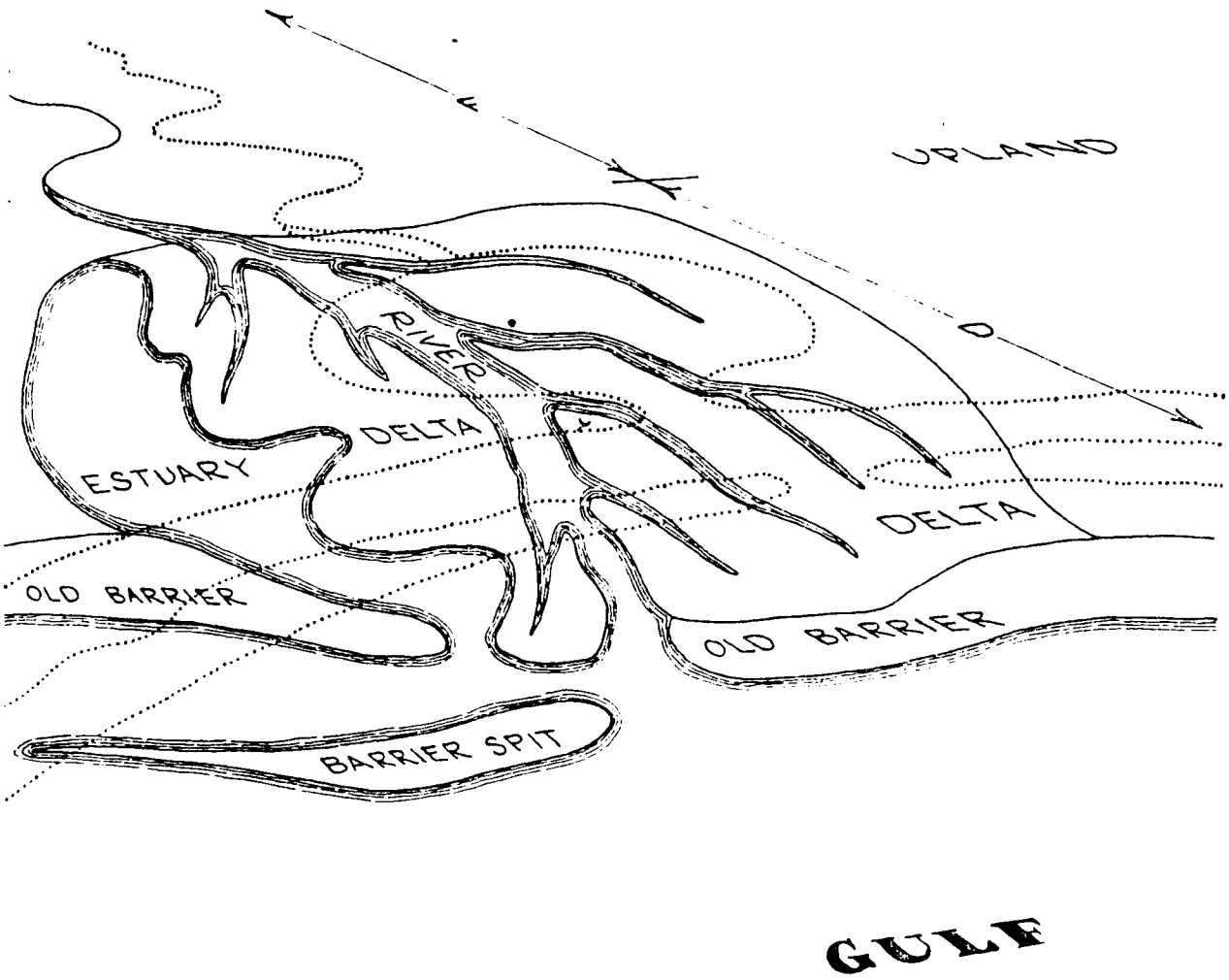


Figure 31. Landform during the Sangamon Interglacial Stage.

The upland in area "D" was formed by a combination of fluvial and deltaic processes. Deltas were built by the deposition of sand and mud at the mouths of distributaries. Overbank flooding spread mud and silt into the interdistributary areas. The deltas were built far into the ancient embayments until they became overextended. Changes upstream caused water and sediment to flow through new channels with higher gradients (Brown et al. 1976). Distributaries were abandoned and reoccupied again and again while the embayment filled with sediment. Occasionally, major river courses were abandoned due to events far upstream. The entire process of delta formation and estuary filling occurred both north or south of abandoned river mouths.

Early Wisconsin Glaciation

The fall in sea level accompanying glaciation began slowly at first and then accelerated. As sea level declined, the entire sequence of coastal land and water areas--uplands in the coastal plain, river mouths and deltas, estuaries, offshore bars, and barriers--moved seaward. Areas that had been formed by delta processes received sediment from fluvial processes only. By the time the glaciation had reached its maximum extent, sea level was 91 to 121 m(300 to 450 ft) below its present level. Deltas were still being built, but now at a shoreline 80 km (50 mi) or more out on the continental shelf.

Figure 32 (approximately 100,000 yr B.P.) shows the processes occurring in the same geographic location at the time of the lowest sea elevation. The entire area had become upland and was a source of sediment for transport downstream. Erosion became the dominant sedimentary process as river valleys widened and deepened. Tributaries developed, draining adjacent areas and carrying water and sediment to the river system.

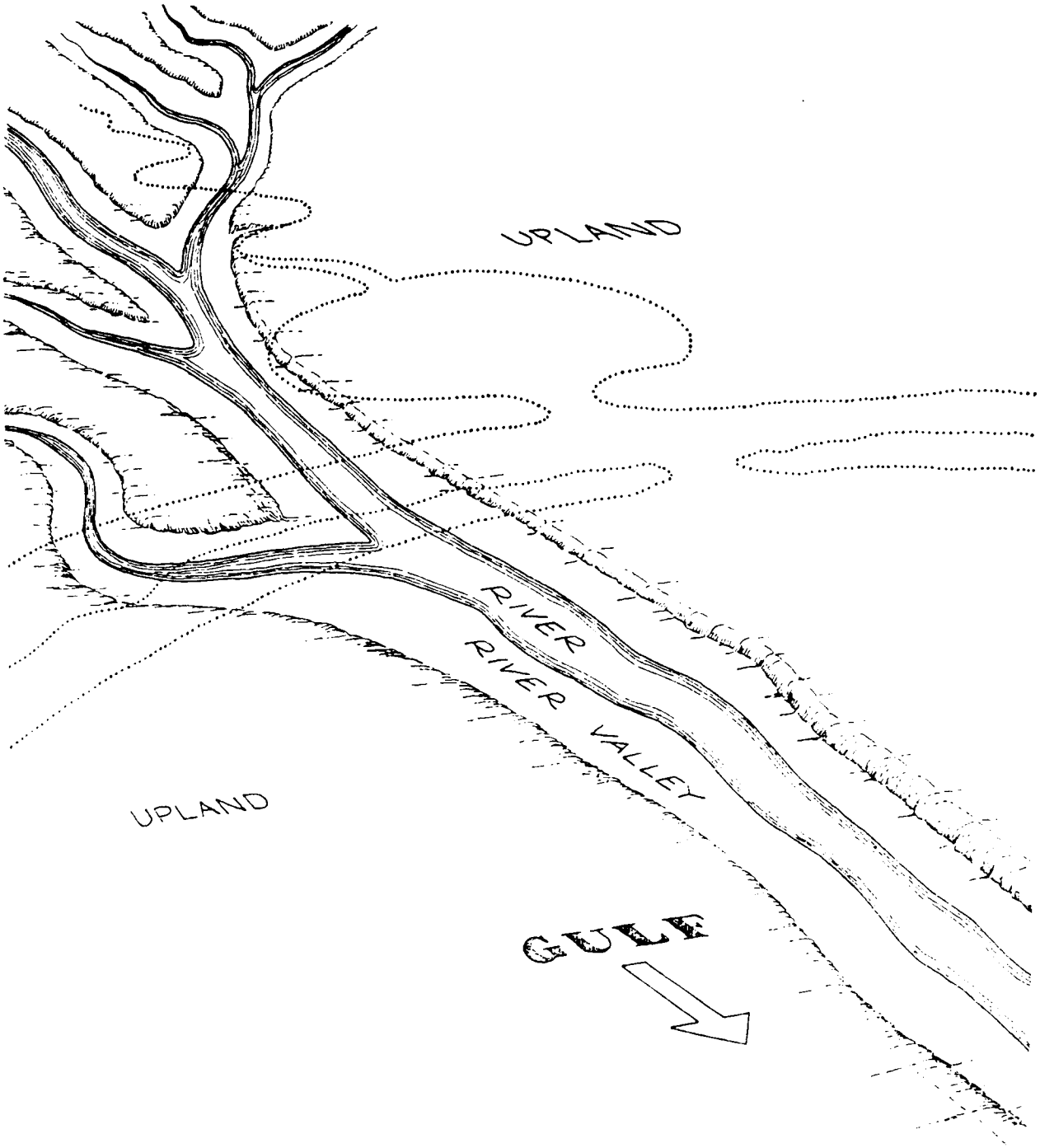


Figure 32. Landform during the Early Wisconsin Glaciation.

Peorian Interglacial Stage

Sea level rose rapidly during the Peorian interglacial stage. It reached a level slightly above its present level, but did not remain there long. Figure 33 shows the land features at that time. Most rivers did not build extensive deltas. They discharged sediment directly into the nearshore areas. The sediment was carried alongshore and onshore to form a strandplain (McGowen et al. 1976a). The strandplain prograded seaward for several miles, as far as the present barrier islands (Brown et al. 1976). Some water bodies developed behind the strandplain, though they were usually brackish lakes or lagoons largely cut off from circulation with the gulf.

Along upper portions of the coast, the sand supply for building the strandplain was riverborne sediment, older Pleistocene delta deposits, and sediment imported from the western lobes of the Mississippi River. Minor fluctuations in sea level and looal changes in land elevation caused erosion of some strandplain areas and burial of others by fluvial and delta-building processes. By the time the final glacial episode occurred, the strandplain was wide but not continuous along the coast.

Late Wisconsin Glaciation

Sea level began to drop again 50,000 to 60,000 yr B.P. Figure 34 shows the processes and land areas during the period of lowest sea level elevation, approximately 40,000 yr B.P. The conditions within the Texas Barrier Island Region during this glaciation were similar to those of the early Wisconsin glaciation 60,000 yr before.

Holocene Period

Meltwater from the retreating glaciers began to reach the oceans and cause sea level to rise during the Holocene Period (4,500 to 18,000 yr B.P.)

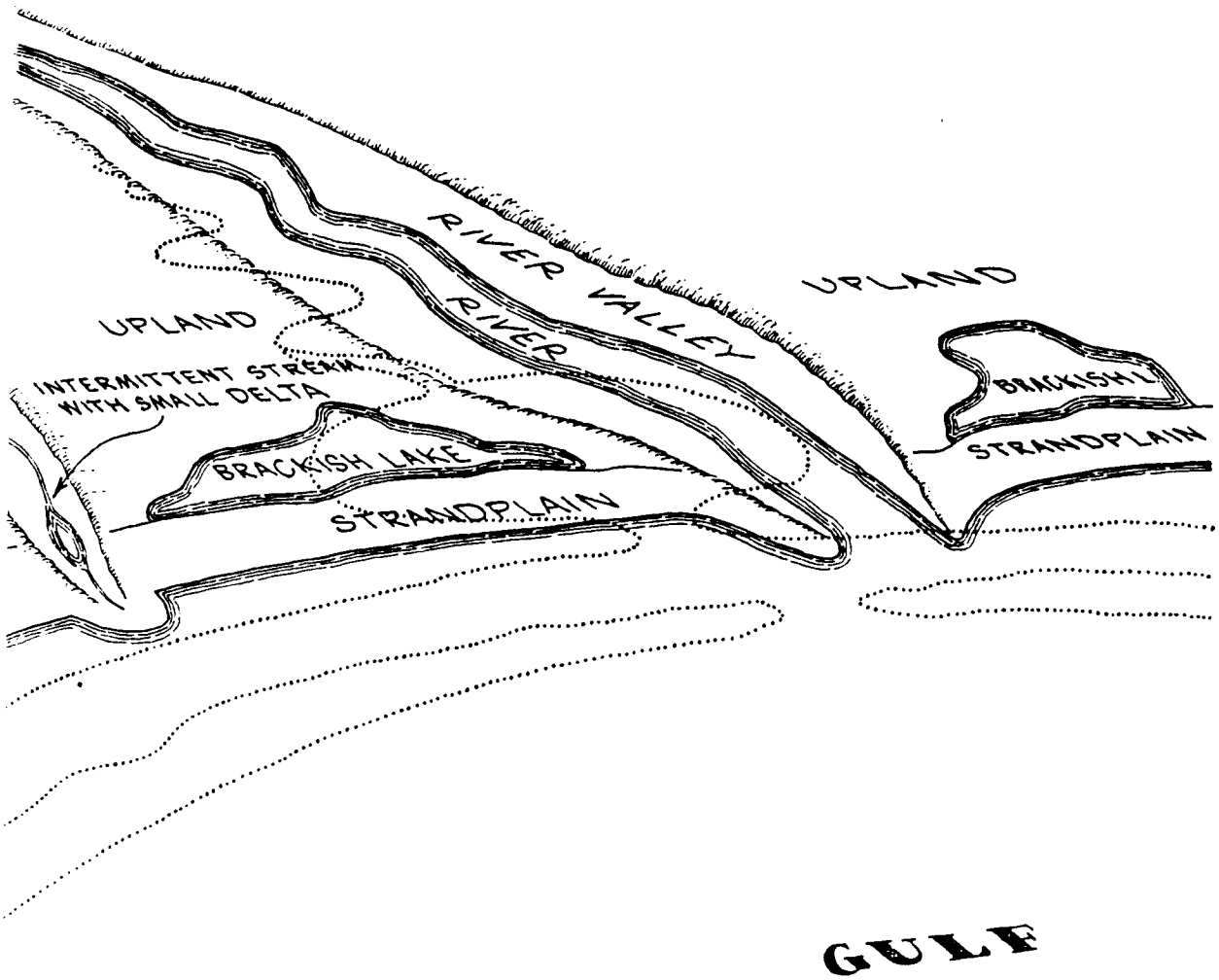


Figure 33. Landform during the Peorian Interglacial Stage.

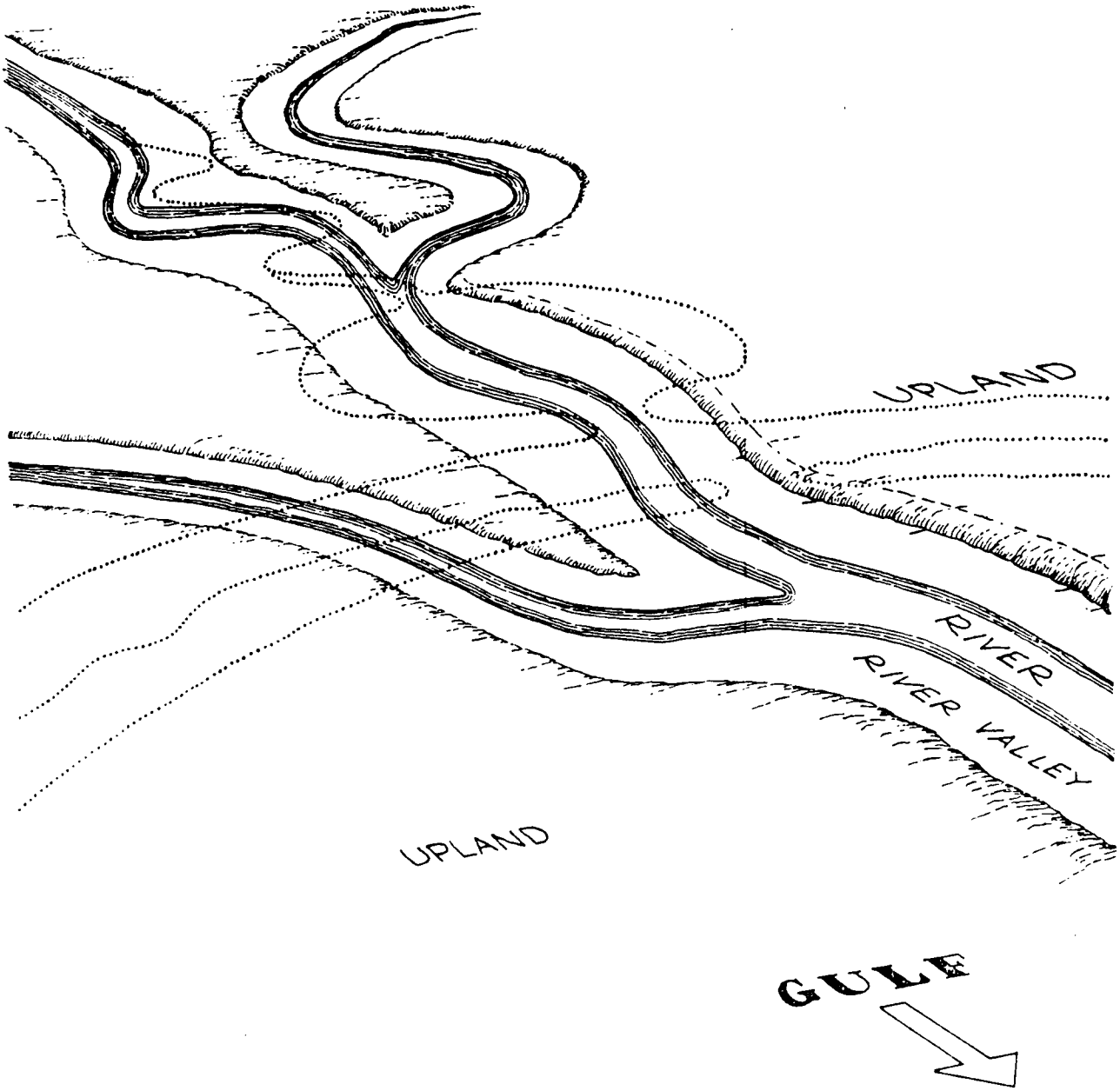


Figure 34. Landform during the Late Wisconsin Glaciation.

of the late Cenozoic Era. The rise was slower than before and the gradient for river flow not as steep. Rivers meandered within their incised valleys and deposition commenced again. Sea level did not rise smoothly; there were several incidents of small rises and falls.

Modern History

Final landform morphology. The Modern Period began 4,500 yr B.P. Relative sea level changes have been less than 4.5 m (15 ft) (Brown et al. 1976) during this time. The estuaries became deep drowned river valleys as sea level rose during the Holocene. They began to fill with sediment carried in by the rivers, eroded from the river valley walls, transported by the wind from the beach barrier islands or strandplains, and transported from the gulf into flood-tidal deltas.

On the gulf shoreline between the major river valleys, sand from the previous Pleistocene strandplain, eroded Pleistocene headlands, and submerged Pleistocene deposits on the inner shelf was transported along the coast by longshore currents and carried onshore during storms. This material formed bars and shoals just seaward of the headlands, and these formations eventually became the emergent barrier island and peninsula chain. Some rivers, such as the Brazos and Colorado, quickly filled their river basins and began to contribute sand directly to longshore transport (McGowen et al. 1976b). This material supplemented the Pleistocene sand forming the barrier chain. The mouths of the major river courses remained open as long as there was sufficient water flow; the location of location of the opening itself, however, often shifted as deltas formed and storms opened new drainage paths with less resistance to flow.

By 2000 yr B.P. the coastal region had achieved its present form as seen in Figure 35. Since then, many short-term changes have occurred: changes in pass location; erosion of shorelands; delta formation; headward erosion of streams; and accretion and erosion of the barrier chain. The general pattern of the land areas, however, has not changed.

Surface expression of sedimentary history. Figure 36 shows the origin of the present surface lands in the coastal region. The barrier chain, lagoon, and modern marsh-lagoon margin are very recent landforms. They have developed in their present locations within the last 4000 to 5000 yr. The floodplain (Modern-Holocene fluvial deposits) developed over the past 18,000 yr. Most rivers have remained within the same river valleys since the previous interglacial stage (60,000 yr B.P.). Estuaries are within the old river valleys but each has developed a distinctive shape through erosion since sea level stabilized.

The most inland portions of the coastal plain were formed by Pleistocene fluvial deposits. Toward the gulf, the coastal plain consists of Pleistocene deltaic and fluvial deposits. The areas that lie parallel to the present lagoon shoreline are Pleistocene strandplains formed in the previous interglacial stage. They are not entirely continuous because of local erosion or direct deposition of deltaic material. Local areas of Modern-Holocene deposits may partially or completely fill the brackish lakes or lagoons that developed in some places behind the Pleistocene strandplains.

MAN'S EFFECTS ON BASINS

The hydrologic and geologic processes that formed and reformed the Texas Barrier Island Region over thousands of years are still active today, but now

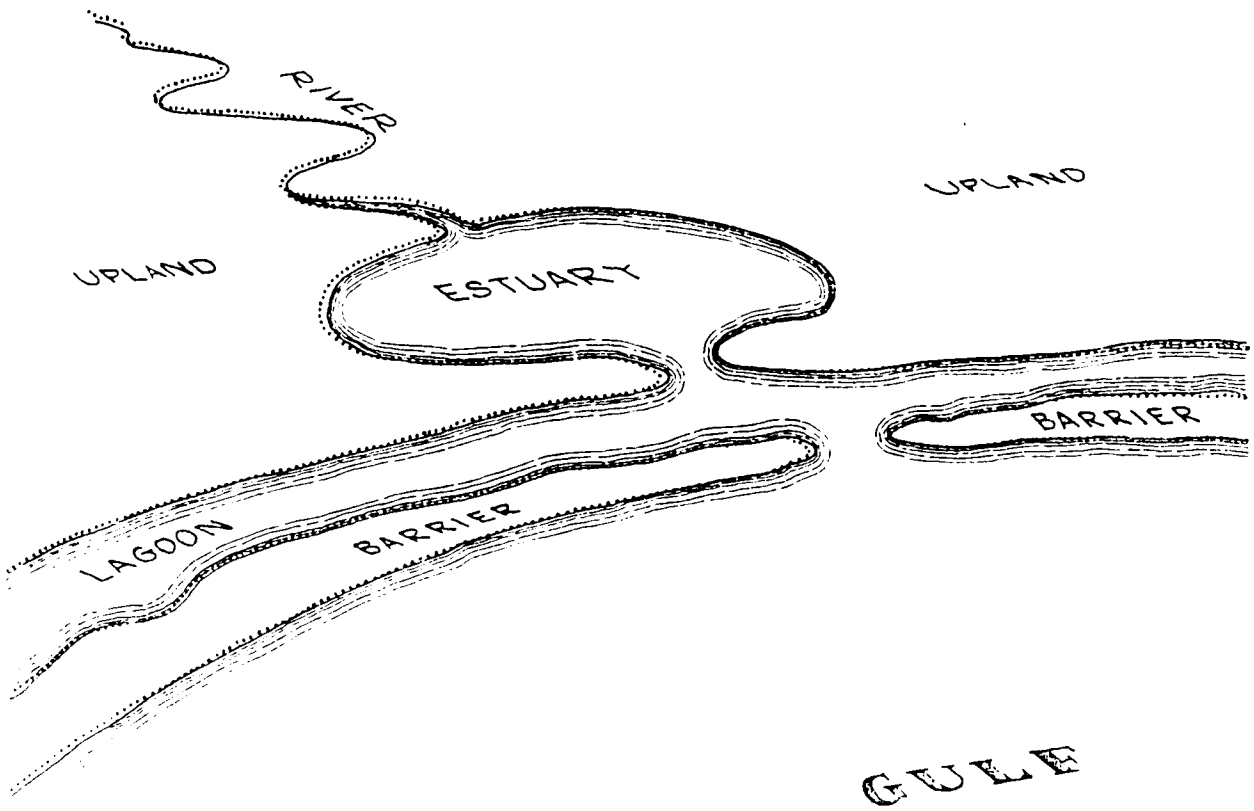


Figure 35. Modern landform of a typical basin.

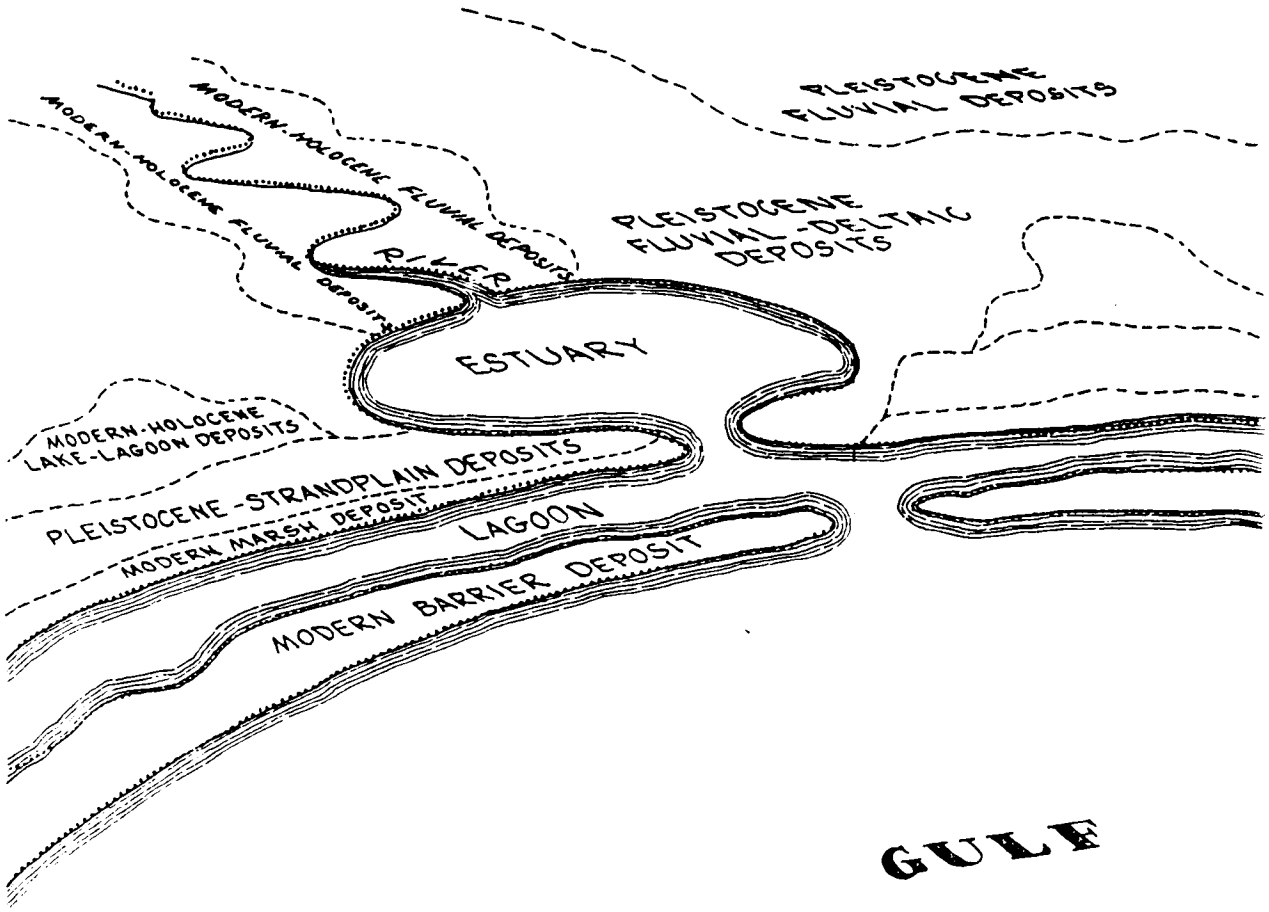


Figure 36. Origins of surface lands in the coastal region.

they are strongly influenced by man. Man makes alterations in the coastal environment to meet three major needs: to control natural forces such as floods that might cause catastrophic damage; to use components of the natural environment for support of the human population; and to improve navigation for commerce.

Human influence on the operation of natural systems in the Texas Barrier Island Region is most evident at the basin level of observation. Alteration of a specific habitat is of interest in itself, but the effects of such an alteration extend beyond the boundaries of the habitat, particularly in the coastal region, where habitats are linked over long distances by water and sediment movement. Human activities that interrupt, redirect, or accelerate flows of water and sediment produce changes in system function that are not only widespread, but lasting. Substantial human alteration of the Texas Barrier Island Region has occurred only within the last 100 years, but has produced hydrologic and geologic changes that can be overridden only by changes in climate and sea level of the magnitude that accompany glacial episodes.

Figure 37, a modification of the basin model, shows the places where man intervenes in the basin system to control or alter system components and flows of energy, water, and sediment among them. The numbered stick figures represent changes brought about by various kinds of human intervention: use of machinery, erection of structures, and other actions. A detailed explanation of the mechanics of this model appears in the appendix to this report.

Production of Soil

Intervention number 1 shows man's effects on the production of sediment in the uplands. In Texas the natural topsoil formation rate varies between

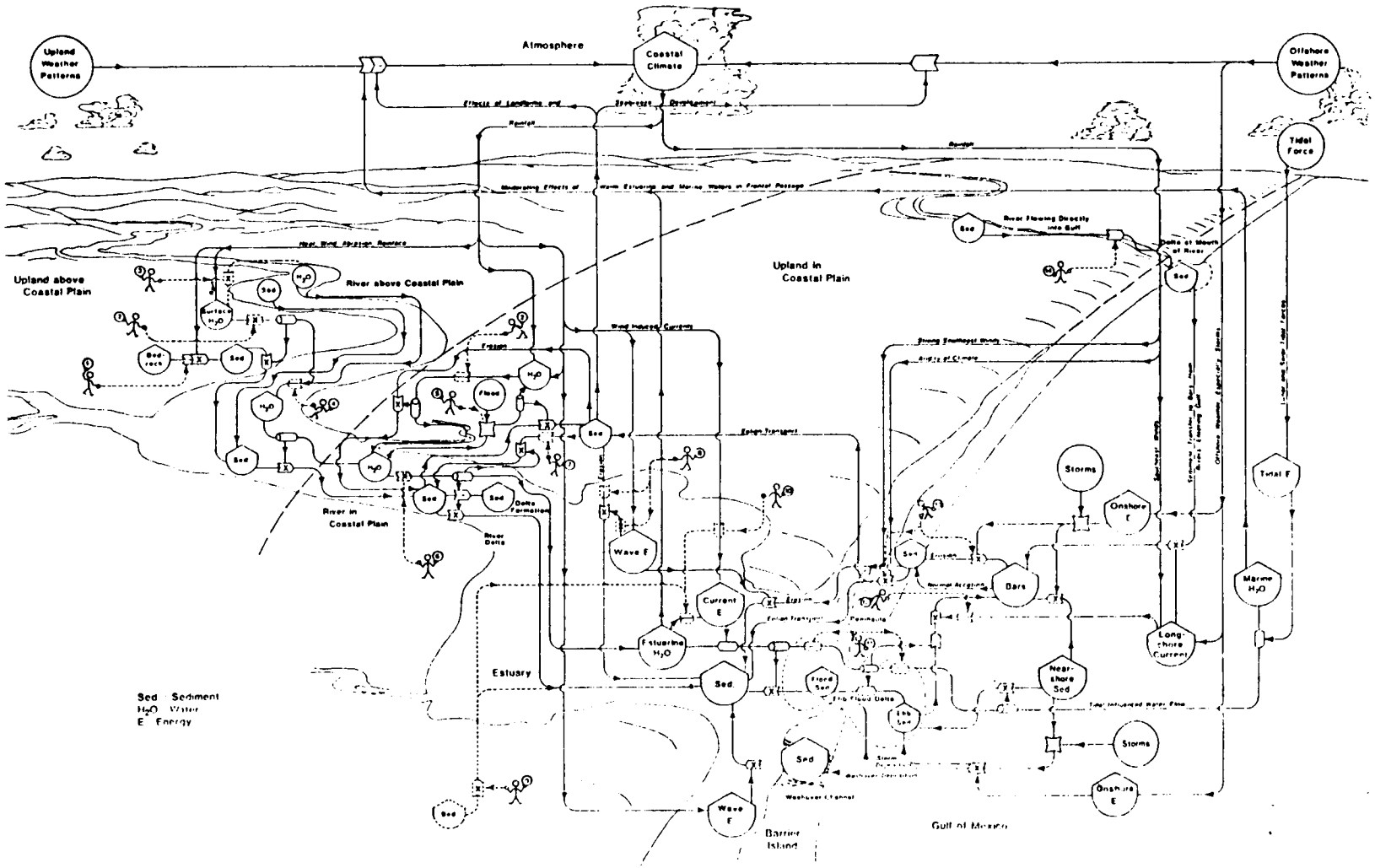


Figure 37. Man's effects on basin operation.

0.5 to 1.4 metric tons per ha (1.5 to 4 tons per acre) (Scott 1978; Risser 1978). Land use practices that bare the soil, increasing its exposure to sun and rainfall, increase the sediment susceptible to erosion. Revegetation of denuded or sparsely vegetated areas decreases the amount of sediment that can be transported. Urbanization of prairie or forest, may inhibit soil movement and decrease the rate of soil production by reducing the exposure of sediment to the weather and by preventing the accumulation of organic material.

Modification of Runoff from Uplands into Rivers

Intervention number 2 represents changes in runoff that are due to man's activities. Paving in urban areas, poor agricultural practices, drainage projects, and removal of surface vegetation increase runoff into the rivers and change the pattern of water flow. When the land surface is denuded or tributaries are channelized and straightened, the quantity of flowing water during and after rains increases. The water runs off more rapidly and, where sediment is available, can carry a larger sediment load.

Soil conservation programs have helped to slow the rate of topsoil loss, although nationwide the erosional loss from agricultural lands ranges from 1.8 to 4.2 metric tons per ha (5.2 to 12 tons per acre) per year (Pimentel et al. 1976; Brink et al. 1977). Statewide, the rate of soil loss from erosion is about 1 metric ton per ha (3 tons per acre) per year (calculated from Texas State Soil and Water Conservation Board 1981). Six counties in the Texas Barrier Island Region have reported water erosion on cropland to be a critical problem.

Diversion of Water from Rivers to Upland Uses

Diversion of water for municipal, industrial, and agricultural use is shown by intervention number 3. These uses decrease the quantity of water flowing down the rivers, even though some diverted water is eventually returned. Texas Department of Water Resources (1977) planning documents give an indication of the proportion of water diverted for some societal uses that is released in return flows. In coastal basins having approximately 50 percent of their area within the Texas Barrier Island Region, three units of water are returned as return flows for every two that are diverted. This occurs because return flows include both surface and subsurface water. In the same geographic area, agricultural return flows are only about 25 percent of the diversions of surface water. These return flows also include both surface and subsurface water.

Control of Flow in Rivers Above the Coastal Plain

Intervention number 4 illustrates the changes in river flow that are due to dams above the coastal plain. These structures change both the quantity and pattern of downstream water flow. Since water movement is responsible for sediment transport, the sediment supply to downstream areas is also affected. The control man exerts on water flow by means of dams is complex and, because of periodic releases, cannot be characterized as a simple decrease. The magnitude of the effect varies with many factors including the distance from the coastal plain, flow volume, and characteristics of the transported sediment.

Control of Overbank Flooding in the Coastal Plain

Human intervention number 5 represents the control of overbank flooding in the coastal plain through placement of flood control structures such as

levees. In urban areas, overbank flooding damages public and private property. In rural areas where land near rivers is used for agriculture, overbank flooding can damage crops and equipment. However, there are benefits as well: floodwaters transport sediment and nutrients onto the land, and river bottom areas provide fertile lands for agriculture.

Flood control levees indirectly control the extent of movement of rivers within their river valleys. When water is confined within levees, the areas outside the levees are rarely subject to the water flow forces that create new river channels, oxbow lakes, or sand deposits from old river bars. Upland areas in the coastal plain that are adjacent to levees rarely receive inputs of sediment and other materials from the river.

Influence of River Flow in the Coastal Plain

Human intervention number 6 represents the effect that straightening and channelization of rivers and streams have on flow velocity. These modifications are usually made to hasten runoff so local flooding may be avoided; watercourses are also modified to allow navigation. Both types of modification increase flow velocities, thus enabling watercourses to pick up more sediment from the bed and banks of the waterway and carry it downstream. As material is eroded, the waterway deepens and widens, and flow velocity decreases. Until a new equilibrium is reached, more sediment will be transported to the estuary and less deposited in the delta.

Channelization and straightening increases the flow velocity during extreme events such as major storms and hurricanes. Though infrequent, these are often the periods of greatest sediment transport to the estuary.

Controlling Bank Erosion in Rivers in the Coastal Plain

To protect land bordering rivers and streams from erosion, littoral owners may erect concrete slabs, rip-rap, or sheet piling at the edge of the banks (intervention number 7). This type of bank protection is often used where the flow velocity of the watercourse has been increased by channelization and straightening as well as in places where there is substantial natural erosion.

Erosion control structures prevent waterways from reaching the natural equilibrium between sediment transport and hydrologic forces. Where such structures are used, this equilibrium cannot be reached unless the waterway changes course dramatically or unless people cease to maintain the structures. As long as the erosion control structures operate as planned, the disruption of the natural equilibrium between river flow and sediment transport will be compensated for by the structure. Erosion control structures may fail under increased hydrologic forces during periods of heavy river flow. When the structures are undermined, the bank areas are again subjected to erosional forces.

Control of Shoreline Erosion in Estuary

Human intervention number 8 shows the effects of protection of estuarine shorelines. These shorelines erode naturally, as the tendency of Texas estuaries is to widen and become shallower. Erosion is particularly noticeable along the higher bluffs in some bays. Erosion control structures used along shorelines are similar to those used in rivers, although the purpose is protection against wave action rather than against unidirectional water flow.

The model shows that the protection measures decrease the amount of sediment contributed by the shoreline banks. Since many bulkheads are flat and vertical, they reflect much of the wave energy directed at the shoreline rather than absorbing and damping the wave action as a sloping beach would. Thus localized wave energy is higher than on unprotected shoreline. Erosion protection devices are designed to withstand this effect.

As in the case of river bank protection, control of shoreline erosion in the estuary prevents the equilibrium condition that would occur naturally if the control structure were not present. This is advantageous to the landowner whose property is adjacent to the estuary; the amount of land that will be available over a particular time period and the uses to which it can be put are more predictable.

Bulkheads may fail and be undermined during storms, allowing the exposed shoreline areas to erode to reach a new equilibrium. By preventing continuous, incremental natural adjustments in the shoreline, both shoreline and river bank erosion control structures make reaching equilibrium more dependent upon catastrophic events.

Direct Alteration of the Estuary by Filling

Human intervention number 9 illustrates the effect of direct placement of sediment in the estuary. Filling wetlands to create dry land for development and using wetland areas as spoil disposal sites are examples of this human intervention. Since Texas estuaries tend to fill with sediment naturally, the direct placement of sediment simply hastens the process.

The long-term effect of spoil placement can be widespread since it alters the flow patterns in the estuary. The Texas City Dike in Galveston Bay is an example of a filled and stabilized area. Hydrologic models of Galveston Bay

(Texas Department of Water Resources 1979) show that the dike directs flow from the upper portions of the bay through Bolivar Roads or back to upper Galveston Bay rather than into West Bay.

Change of Current Energy in Estuary

Deep-draft channels alter the current energy in the estuary. The effects of the Houston Ship Channel on the flow patterns in Galveston Bay are very evident from hydrologic models of the bay (Texas Department of Water Resources 1979). Deep channels provide pathways for high-velocity flow from wind-induced currents, river flow, and tidal exchange. When substantial salinity differences exist between the estuarine and marine waters, large salinity gradients may be found between surface and bottom waters in the channels. This may result in salinity wedges intruding far up the channel into areas of low salinity.

Hydrologic changes in estuaries due to channel dredging are not limited to the immediate channel; the effects extend over a wide area, although they decrease with distance from the channel. As the channel naturally fills with sediment, the hydrologic effects of the channel decrease. Filling occurs rapidly in the Texas coastal area; only continual maintenance dredging allows prolonged existence of deep channels.

Stabilization of Passes or Cuts in Barrier Islands and Peninsulas

Human intervention number 11 represents the effects of channelizing and stabilizing natural passes and artificial cuts through barrier islands and peninsulas. Each major bay system has a natural opening to the gulf. A few of these passes are open only intermittently because of insufficient flow from bay waters into the gulf. The unstabilized passes migrate north and south

depending upon sediment availability and a complex interaction of water flow between the estuary and the gulf. Shoal areas in the natural passes change almost daily, making navigation with large vessels hazardous. To promote commerce, passes or artificial cuts have been dredged and stabilized at seven locations on the coast.

Stabilization and deepening of the passes increases the bidirectional water flow between the estuary and the gulf if there is sufficient hydrostatic head from freshwater inflow. The increased flow velocity and volume cause more sediment to be transported in both directions through stabilized passes.

Although design of passes may minimize shoaling within them, ebb- and flood-tidal deltas and portions of the passes do collect sediment. In time, without continued dredging of the bars and inner portions of the passes, flow would be restricted.

Direct alteration of the estuary by filling, channel dredging, and stabilization of passes and cuts often occur together. For example, construction of a major navigation channel requires the provision of access through a pass to the gulf, dredging of the channel itself, and disposal of the dredged material. When these actions occur together, the result is a synergistic combination of the individual effects.

Change in Longshore Current Patterns by Man-made Structures

Longshore drift transports sediment parallel to the gulf shoreline. While the direction of longshore drift changes seasonally, there is a net yearly direction of sediment movement. From the Texas-Louisiana state boundary to the Land Cut in the Laguna Madre the net direction of movement is south; on the lower coast, from the U.S.-Mexico Border to the Land Cut the net movement is north.

On some segments of the gulf shoreline longshore drift causes erosion. To counter the erosional effects of longshore drift, structures extending out into the surf zone are erected perpendicular to the shoreline (human intervention number 12). These are often groins, narrow walls of pilings and heavy timbers, positioned to disrupt the longshore current and reduce its velocity. The slowed water deposits some of its sediment load. Where there is an adequate sediment supply, groins can be used to either retard erosion or build beaches seaward.

If there is a basic deficiency in sediment supply, groins or other structures may not function as expected. If placement of structures is not carefully planned, taking into account the hydraulics of the site, the amount of sediment trapped may be insufficient to counteract the shoreline erosion, and downdrift shoreline deprived of current-borne sediment may erode severely (U.S. Coastal Engineering Research Center 1977). Groins and similar structures are expensive both to build and to maintain. Because they are subject to continual, strong hydraulic forces, maintenance of the structures is critical to their operation. In a single day, the power in the waves of a storm can undermine a groin and erode all of the area that may have accreted over a period of several years.

Alteration of Sediment Balance on Barriers and Peninsulas

Most of the sediment that forms barrier islands and peninsulas comes from offshore sources or river mouths that empty directly into the gulf. Normally, waves carry sediment from the surf zone to the beach, and wind transports it to the dunes and barrier flats. The dunes and beaches are reservoirs of sediment, eroded by severe storms and built back over longer periods (Davis

1972). Some of the sediment that collects on the barriers and peninsulas is carried by the wind to the uplands or estuaries further inland. Human activities on the beach or in the dune area (human intervention 13) can alter the sediment balance between the surf zone, dunes, and barrier flat.

Cattle grazed on dunes and barrier flats have impeded the growth of vegetation both by trampling it and by feeding directly upon it. When foredunes are denuded, blowout dune fields may develop. These active sand dunes bury vegetation and allow sediment normally trapped on the beach and in the dunes to travel to the bays or mainland areas. South of the Corpus Christi area, where dune and barrier flats were heavily overgrazed, low rainfall has inhibited the reestablishment of vegetation. Baccus and Horton (1979) noted that effects of overgrazing that took place a hundred years ago were still evident in some places on Padre Island. To the north, higher rainfall has permitted more rapid revegetation.

Recreational use of dune buggies began in the 1960's. The results of this use are similar to overgrazing, but the effects occur more rapidly and are more severe. Vehicular traffic on the beach and in the foredune area decreases the standing crop of stabilizing vegetation, so less sediment is trapped and held in the dune and beach sediment reservoirs (Behrens et al. 1974; McAtee and Drawe 1974). In addition, vehicular traffic loosens beach sand and facilitates its eolian transport. During storms, it is evident that beaches and foredunes that have been heavily used by vehicles are less stable than similar areas that have had little traffic (Baccus and Horton 1979).

Activities that destabilize the beaches and dunes of barrier islands and peninsulas reduce their buffering effect on storm action. During severe storms, blowout dune fields and weakened dune areas may become washover

channels, threatening areas landward with flooding. Washover waters may carry greater amounts of sediment than usual to shallow estuarine environments. The effects of washover development may be short-lived or long-term, depending upon how quickly the beach and foredunes can rebuild.

Decrease in Sediment Contribution from Rivers into the Gulf

Human intervention number 14 represents the reduction of sediment loads in rivers directly entering the gulf. Dams and water diversion are in part responsible for the decrease.

Part of the sediment that rivers carry into the gulf is transported by longshore currents and is incorporated into the beach and dune erosion and accretion cycle. When the sediment supply from the river is reduced, less sediment is available for beach replenishment, and erosion may occur. Sealy and Ahr (1975) attributed a portion of the accelerated beach erosion near Sargent, Texas, to a 50 percent decrease in Brazos River bedload since 1929 due to dam construction.

Human interventions 13 and 14 may occur together. Decreases in sediment from the rivers result in erosion downstream from river mouths. To combat the erosion, man-made structures such as groins are placed into the gulf to trap sediment. If beach traffic increases, the sediment balance between the beach, dunes, and upper shoreface may be further disrupted.

Persistence of the Effects of Human Interventions

Reduction of soil production, modification of runoff from uplands to rivers, diversion of water from rivers to uplands, control of flow in rivers above the coastal plain, direct filling of estuaries with sediment, alteration of sediment balance on barrier islands and peninsulas, and decrease in

sediment contribution from rivers to the gulf are the effects of human interventions which persist for a long period of time with little energetic or economic cost to man beyond the original expense. Other human alterations require continuous maintenance by society to combat natural forces. These include control of overbank flooding in the coastal plain, control of river flow in the coastal plain, control of bank erosion in rivers in the coastal plain, control of shoreline erosion in estuaries, channelization in estuaries, stabilization of passes or cuts through barrier islands and peninsulas, and interruption of longshore current patterns by man-made structures. While both groups of interventions produce noticeable changes in the region, the former group are long-lived once undertaken. In time, changes in the region caused by the latter group tend to return to preintervention conditions in the absence of regular human maintenance efforts.

HABITAT INTERACTIONS

Each basin contains a set of habitats which has developed a particular spatial arrangement as a result of the basin's natural forces and man's activities. Habitats are of interest at this level of organization since they provide organic production to basins and are also qualitatively different from each other. It is the relative amount and spatial arrangement of habitats that gives each basin its character.

Habitats are complete systems that depend upon exchanges of materials, energy, and biota for their continued operation. In many instances the exchanges are mediated by water flow or by the transport pathways afforded by water systems. The discussions of geologic development and man's effects have shown that water systems and water flows are the central integrating factors

in the formation and continued operation of basins. To understand how habitats function together as the elements of a basin system, it is necessary see the pattern of water-mediated movements of materials, energy, and biota within a basin.

Superimposed upon this pattern is an additional complication: habitats are not static; they evolve and change through the natural process of succession, or they are altered through man's direct or indirect actions. When habitats change from one type to another their flow patterns also change.

Figures 38 through 43 graphically depict the water-dependent pathways for materials, energy, and biota. The alteration of habitats by natural succession or man-made causes is also shown. For completeness, the figures illustrate both ecosystems (hexagonal symbols) and habitats (dashed polygons encompassing more than one ecosystem unit). Where an ecosystem hexagon is not included within a dashed habitat polygon, the habitat unit consists only of that ecosystem. The figures are generic models. The interactions they depict are generally applicable to the Texas Barrier Island Region but may or may not occur at specific sites.

Water-dependent Flow Pathways Among Habitats

Transport between habitats through water systems. Almost matter transported between habitats in Texas coastal basins is waterborne. Sediments, organic detritus, nutrients, pesticides, and phytoplankton are some of the most important materials transported by water. Figure 38 shows the typical water pathways between habitats. These are also the routes of the major waste loads from human activities. The bolder lines indicate pathways with large flows.

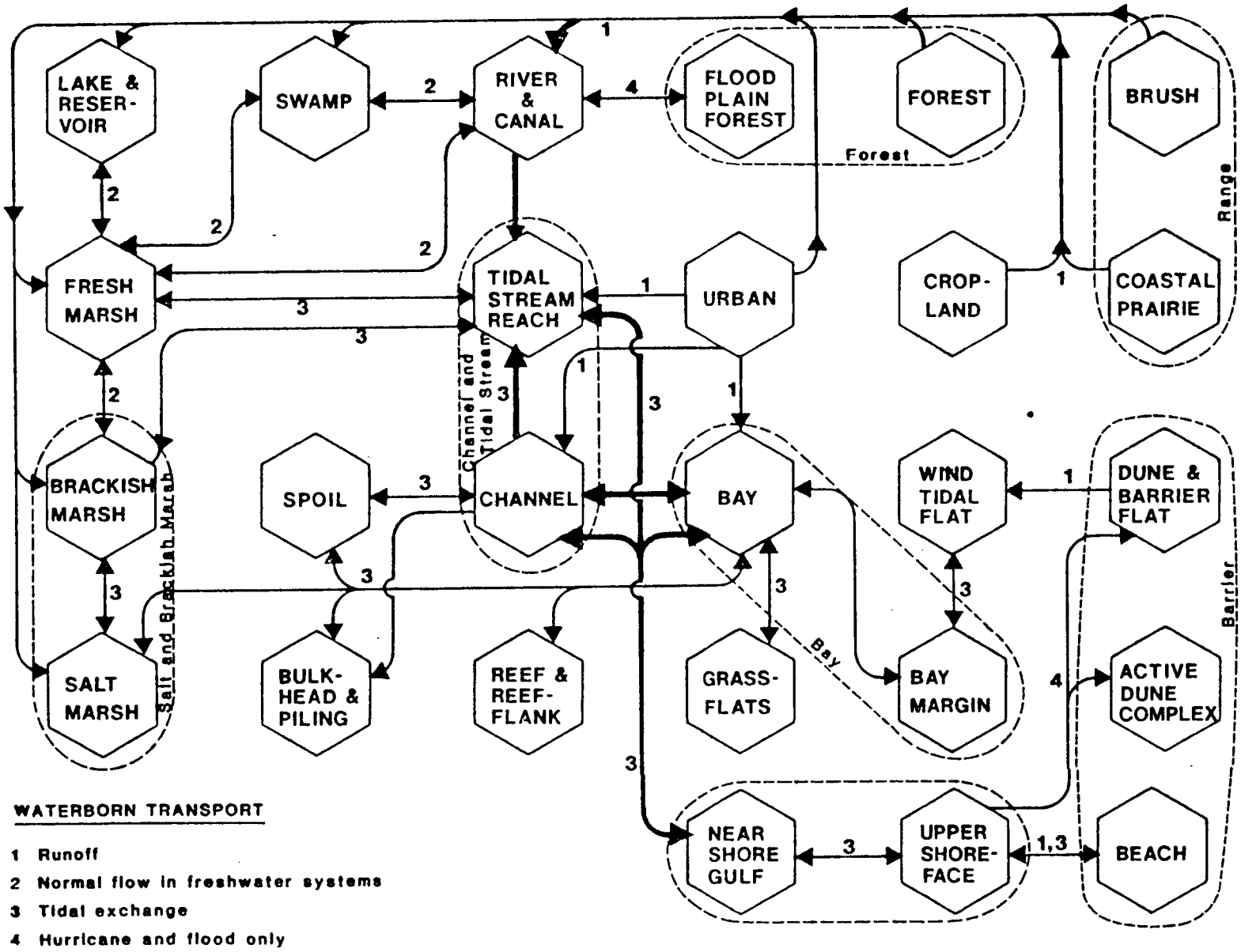


Figure 38. Transport of materials between habitats through water systems.

Materials from the upland habitats, urban systems, and inland portions of the basins are transported by runoff to river and canal systems. Runoff also carries lesser amounts of materials directly to lake and reservoir systems and wetland habitats. The rivers flow to the tidal stream reach and thus into the bay or channel systems, or in the cases of the Brazos, Colorado, and Rio Grande rivers, directly to the nearshore gulf.

Materials transported from marine habitats include saline water, suspended solids, and organisms. As shown in Figure 38, the only habitats exchanging water and materials directly with the nearshore gulf are bay, channel, and in some cases tidal stream reach. The barrier islands effectively minimize the exchange between estuarine systems and the gulf. On the lower coast, where freshwater input is low, restricted water exchange with the gulf leads to long residence times for water in the estuarine systems. This obstruction of flow by the barriers is also beneficial, however; pollutants originating in the Gulf of Mexico, such as oil spills, tend to influence the beach systems much more than the estuarine systems.

Figure 38 clearly shows that bay and channel systems are the major transport pathways by which upland runoff materials and marine materials reach estuarine systems such as salt marsh, bulkhead and piling, spoil, reef and reef flank, and bay margin.

In general, the bay and channel systems show net accumulation of suspended solids, although channels are routinely redredged to remove this accumulated sediments. Historical records (Shepard, 1953) indicate that Texas bays are filling at rates of 0.3 to 0.5 (1.0 to 1.5 ft) per century. It is likely that there is net accumulation of suspended solids in the salt marsh, reef, and grassflat habitats also, but there is little data on this for the

Texas coast. In addition to slowly filling in the bays, the accumulating sediments also trap organic matter, nutrients, and toxic materials.

Current energy transport. Current energy is generated by astronomical tides in the Gulf of Mexico, by wind, and by runoff from the land. The paths of exchange of current energy between habitats are the same as the "waterborne transport" paths.

Wave energy movement. Although some wave energy is locally generated in all aquatic habitats, the most intense wave energy is generated by wind acting over expanses of open water such as the lake and reservoir, bay, and nearshore gulf habitats. These systems export large amounts of wave energy to neighboring habitats, as shown in Figure 39. Because the blockage of wave energy transport by barrier islands and peninsulas is nearly complete, the figure shows no wave energy transfer between marine and estuarine systems.

Aquatic organism movement. Figure 40 depicts typical pathways of aquatic organism migration. As with the waterborne transport diagram, the channel and bay habitats provide the major pathways. Organisms harvested from aquatic habitats may have been dependent on other habitats in earlier stages of their life cycles. Though terrestrial organisms may use water transport pathways, thay are usually not dependent upon them and can move freely from one terrestrial system to another.

Transformations of Habitats

The three major causes of habitat transformation in the coastal area are natural succession (Figure 41), subsidence (Figure 42), and the activities of man (Figure 43).

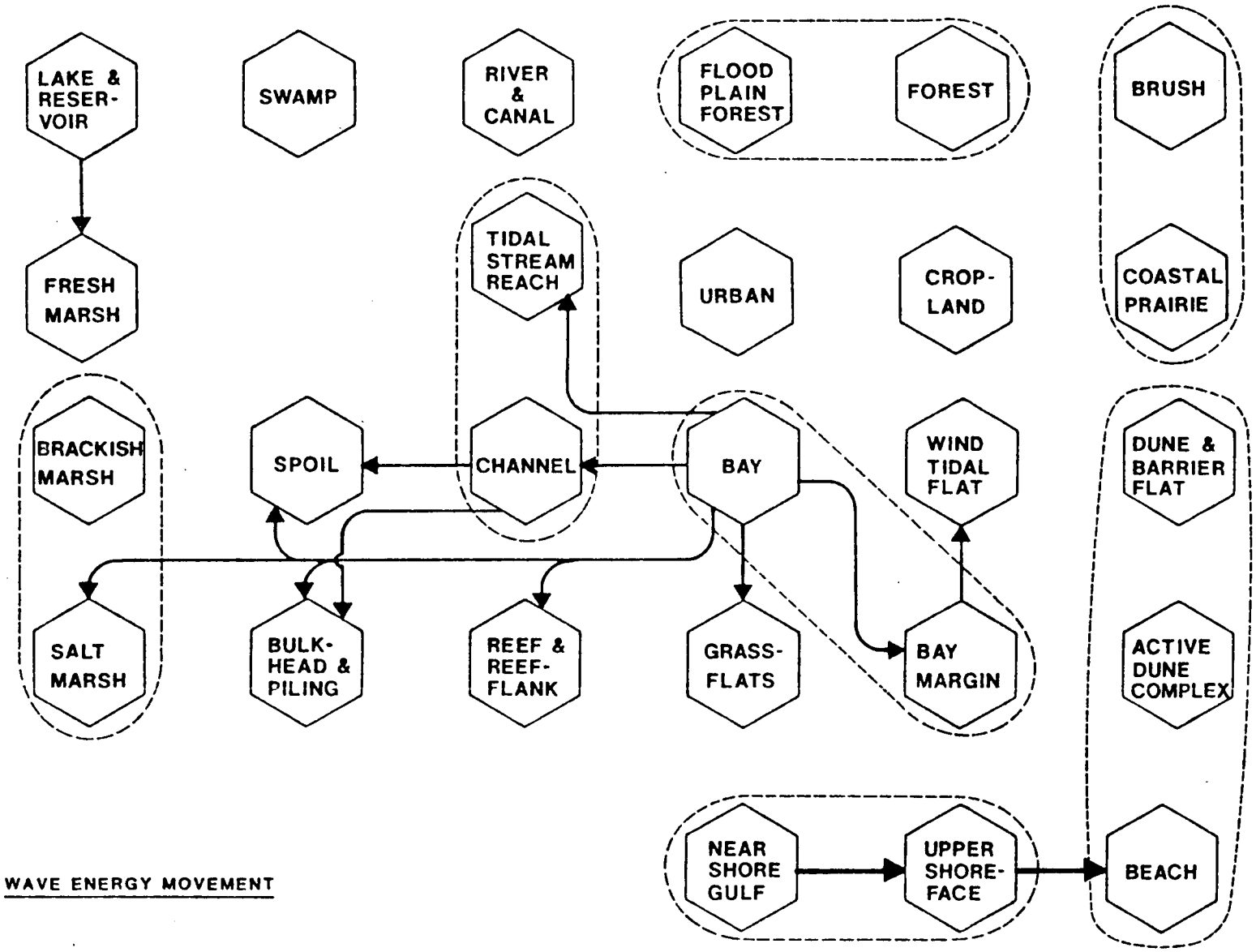


Figure 39. Transfer of wave energy between habitats.

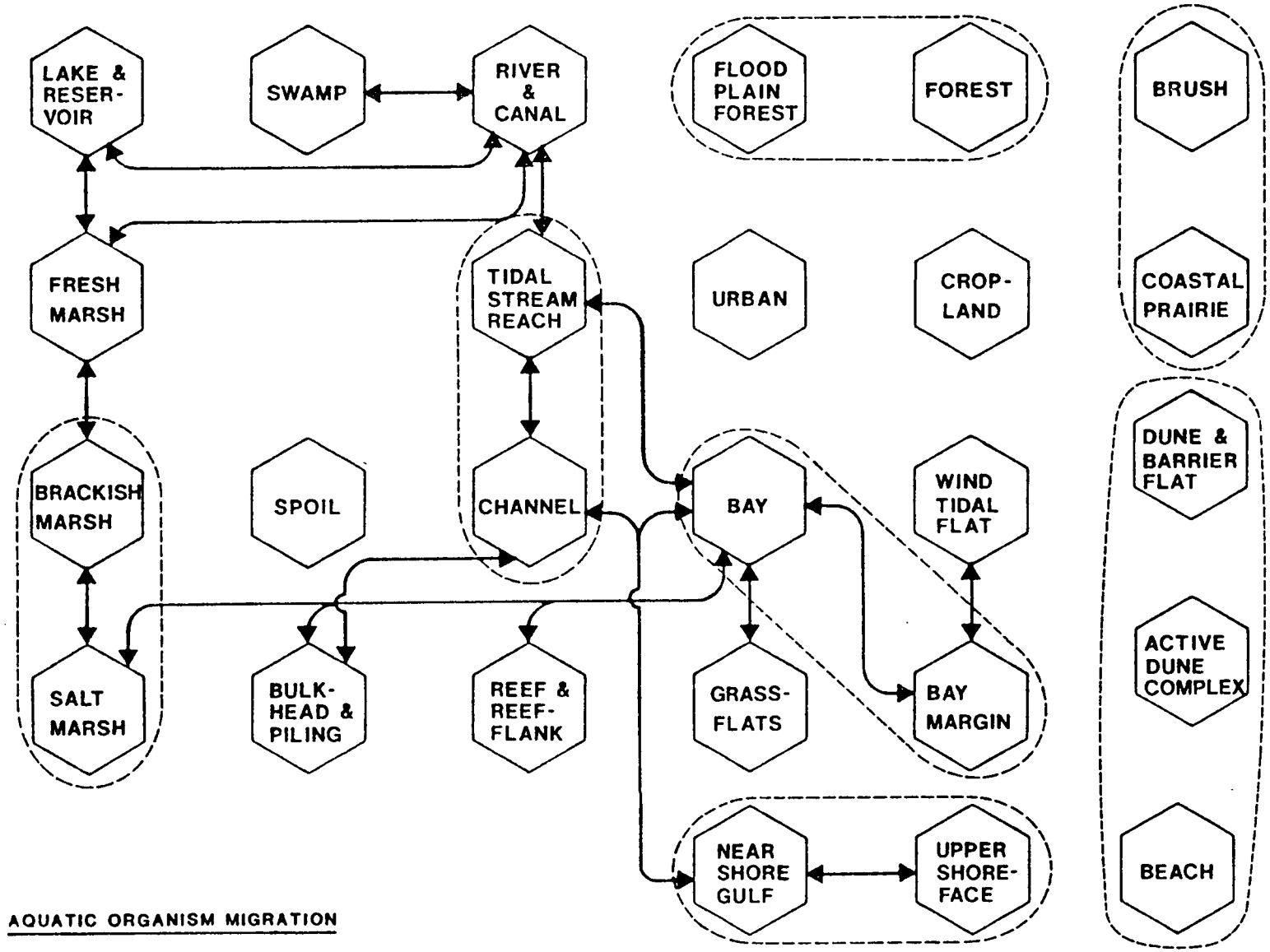


Figure 40. Aquatic organism movement between habitats.

Natural succession. The natural succession transformations are due to erosion and sedimentation, biological community changes, or changes in water flow or salinity. Erosion converts tidal stream reaches and bay margins to bays and may convert dune and barrier flat to wind-tidal flat or active dune complex. Active dunes may be converted to beach, and beach may be converted to upper shoreface through erosion.

Accretion works in the opposite manner. It may cause upper shoreface to become beach, beach to become active dune complex, and dune and barrier flat to be formed from active dune complex or wind-tidal flat. Along the gulf shoreline, the beach habitat and the dune and barrier flat habitat advance or retreat according to the balance of erosion and deposition.

In freshwater areas, the accumulation of sediment may allow freshwater marsh to develop within a lake, floodplain forest to develop from swamp, and upland forest to develop from floodplain forest.

Biological community changes are the most familiar form of succession. A number of examples are given in Figure 41. Swamp may develop on freshwater marsh through community changes. Newly placed spoil deposits progress through several seral stages and may become forest, brush, or coastal prairie depending upon local climatic conditions. There is a balance among forest, coastal prairie, and brush habitats that is controlled by rainfall, fire, and grazing. In estuarine systems, the development of reefs in bays and grassflats on bay margins are two examples of natural succession.

Water flow or salinity change, the third major major cause of natural succession, is best illustrated by changes in wetlands, habitats particularly sensitive to variations in these factors. For example, increases in

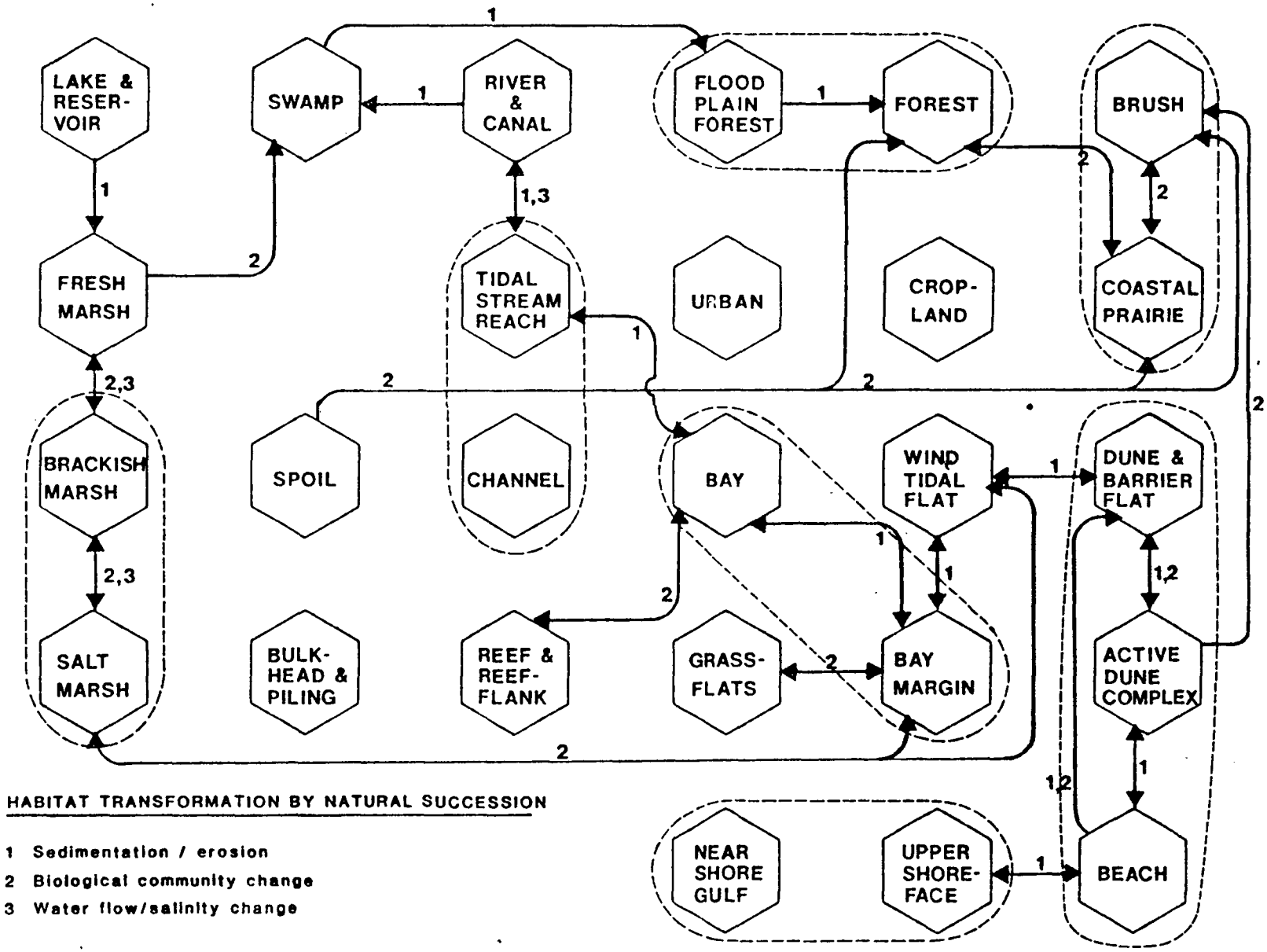


Figure 41. Changes in habitats through natural succession.

freshwater flow to salt marshes may result in their conversion to brackish marshes or even freshwater marshes.

Subsidence. Subsidence in the study area is almost entirely induced by pumping of fresh water, oil, gas, and brine. When the land surface is lowered relative to the local water level, the physical conditions in habitats are changed, and changes in the biota soon follow (Figure 42). In coastal systems, these changes tend to reverse the effects of sedimentation and natural succession. The extent to which this is occurring in the Texas Barrier Island Region varies from basin to basin. The Houston-Galveston area, Freeport region, and a small portion of the Corpus Christi area have had the greatest amount of man-induced subsidence. The basin trend from subsidence illustrated in Figure 42 is the conversion of upland systems to aquatic systems, and the conversion of fresh or brackish systems to more saline systems.

Activities of man. Man's activities usually convert natural systems to human-oriented uses. The transformations shown in Figure 43 are those commonly found in the study area. Dredging, urban construction, and water impoundment are probably the most significant processes at the present time in terms of area converted. Earlier in the history of man's exploitation of the coast, conversion to agricultural uses was the major transformation.

Dredge and fill activities result in complete, rapid conversion of one habitat to another habitat type; for example, grassflat areas become channel, brackish marsh areas become spoil, and bay margin areas become bulkhead.

Urbanization may alter floodplain forest, forest, cropland, brush, coastal prairie, dune and barrier flat, active dune complex, freshwater marsh, brackish marsh, and salt marsh.

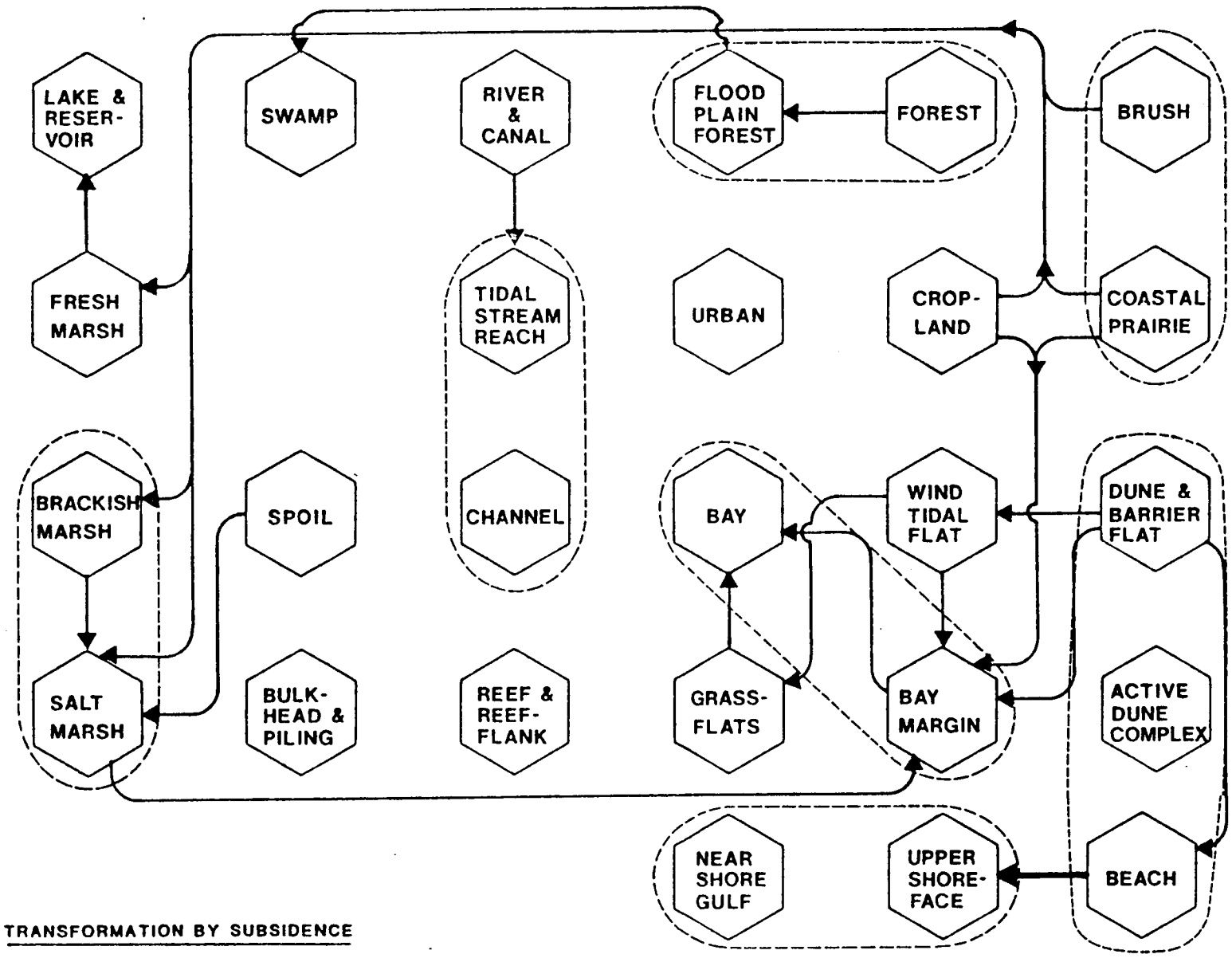


Figure 42. Changes in habitats due to subsidence.

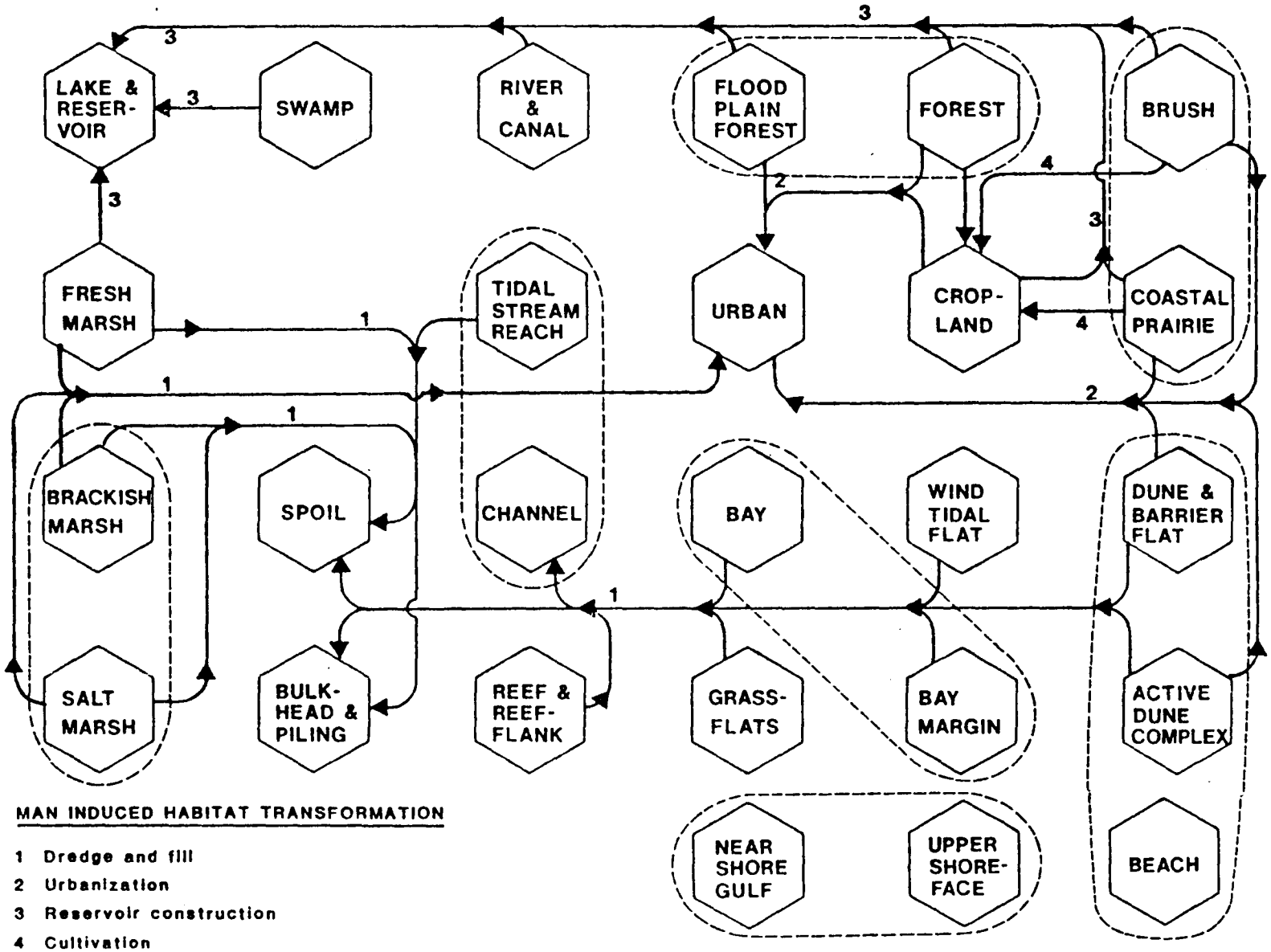


Figure 43. Changes in habitats due to man's activities.

Like urbanization, reservoir construction converts a variety of upland and freshwater habitats to a single unit. Two differences, other than the final form of the habitats, are evident in the transformation. Conversion to lake and reservoir is a complete change; no vestige of the original habitats remains after conversion. Urban habitats may retain some characteristics of their predecessors; for example, native vegetation may remain in parks converted from forest or prairie. The second difference is the speed of the change. Reservoir construction and the attendant transformation of habitats occurs over a short time span--a period of a few years; urbanization is a long-term process that occurs incrementally.

BASIN DESCRIPTIONS

Section Organization

The following section describes each of the ten coastal basins of the Texas Barrier Island Region. Each basin description is divided into five parts: a description of prominent features; a short discussion of geologic development; information about the climate and hydrology; a brief discussion of the basin's economy; and a characterization of the demands the economy makes upon the natural systems and populations in the basin.

Location and description. The basin descriptions delineate only the lateral boundaries of each basin. For purposes of this study the landward and seaward boundaries of all basins are the same. The landward boundary is the inland limit used for mapped information in the Bureau of Economic Geology's environmental geologic atlas of the Texas coastal zone (Brown et al. 1976, 1977, 1980; Fisher et al. 1972; McGowen et al. 1976a, 1976b). This boundary, which lies about 64 km (40 mi) inland of the gulf shoreline, does not

correspond to the natural hydrologic boundaries defined for basins along the Texas coast by the Texas Department of Water Resources (1977). Most of the natural hydrologic systems extend further inland than the study area and are much larger than the basins defined here. The seaward boundary is the boundary of state-federal demarcation located 16.68 km (10.36 mi) from the gulf shoreline.

A description of the basin's land physiography, land features, and substrate is followed by a discussion of the areal extent and arrangement of habitats in the basin. The areal measurements given for habitats or groups of habitats are based on measurements contained in the Bureau of Economic Geology atlases cited above. Details about the method used to calculate these areas are found in the introduction to the chapter on habitats in this report. In general, habitat measurements were compiled by county from the Bureau of Economic Geology's studies; basin totals were compiled by calculating the proportion of county areas found within a basin, multiplying that proportion by the area of habitat in the county, and summing this product for all counties found in the basin. No direct measurements were made other than the proportions of counties in each basin. As a result, there is a margin of error in the area estimates, but it is thought to be small.

Geologic development. The brief discussion of the geologic development of each basins emphasizes the processes that gave the basin land its present features, shape, and sediments.

Basin climate and hydrology. In the discussion of the climate of each basin, only information relating to basin hydrology is discussed in detail. The description of the surface hydrology of the uplands includes the sources

and distribution of surface water. The major estuarine areas are described with respect to their shape, bathymetry, surface sediment type, tidal forces, circulation patterns, salinity characteristics, and bay shoreline erosion. The nearshore gulf area is characterized with respect to gulf bathymetry, surface sediment type, circulation, and shoreline erosion.

Basin economy. The discussion of each basin's economy includes both population patterns and economic sectors. Population trends are presented using census data and population projections. The relative values of six major economic sectors--mineral production, recreation and tourism, commercial fishing, industrial and residential development, transportation, and agriculture--identified by Liebow et al. (1980) are discussed for each basin. Indicator statistics that illustrate the level of economic activity for each sector are given in the text and summarized in tables. These statistics are used in the comparison of basins in the final section of this chapter.

Basin resource demands. The economy makes demands upon the natural systems in each basin for space, raw materials, and waste processing. In addition, significant hydrologic changes accompany most economic activities. The discussion of resource demands in each basin presents direct or indirect measurements of these demands, waste loads, and changes. Some of the measurements seem similar to the quantities given in the basin economy section; there is a significant difference, however. The economic data is presented in terms of numbers of persons, jobs, profits, or expenditures--some measure of the economy that is related to trade or consumption. Economic data rarely defines the level of demands made upon the natural system. In contrast, resource demand data is given in terms of the amount of area or volume of material required, volume or weight produced, amount of waste that

must be assimilated, public health effects on the human population, or density of disruptions to hydrologic flow.

An example illustrates the difference between these indicators. The market values of farm production from the Rio Grande and San Antonio basins were both about $8 million in 1977; from the economic viewpoint these levels of production seem equivalent. However, the Rio Grande basin produced 18 times as much cotton as the San Antonio basin but only 50 percent as much grain, and 40 percent as many cattle and calves; no rice was produced in the Rio Grande basin. These differences in agricultural products, not identifiable by economic data, reflect large differences in the demands upon the natural systems: water and land uses in the two basins differ greatly. The agriculture in the Rio Grande basin required 309 million cu m of irrigation water; the San Antonio basin used only 34 million cu m. The Rio Grande basin supplied 33,658 ha of land for agriculture, 68 percent of which was cropland; the San Antonio basin supplied 114,812 ha of land for agriculture, 28 percent of which was cropland. These differences are not apparent from market-value statistics.

Resource demand indicators have been assembled for all of the kinds of demands made by the economy. Some of these indicators are: quantity of upland used for cropland, range, and urban land; volumes of minerals produced; volumes or weights of agricultural and fishery products harvested; mortality from diseases that may have some relationship to air or water quality; the amount of freshwater streams that are fishable and swimmable; the amount of airborne particulate and hydrocarbons placed in the atmosphere; the amount of waste material placed in the basin's waters measured as the amount of oxygen

used to meet the metabolic needs of aerobic aquatic microorganisms (biochemical oxygen demand, or BOD); the number of waste discharges in a basin; the areal extent and depth of subsidence in a basin; the total and individual amounts of surface water and groundwater used for municipal, industrial, and agricultural purposes; the amount of return flow; the density of roads, railway roadbed, irrigation and drainage canals; the density of dredged channels; and the volume of maintenance spoil that is disposed each year. Resource demand indicators are used to compare basins in the final section of this chapter.

Rio Grande Basin

Location and description. The Rio Grande basin is a long, narrow river basin that follows the course of the Rio Grande River, which drains parts of Mexico, Texas, New Mexico, and Colorado. The total area of the basin is 471,935 sq km (182,215 sq mi). The portion that lies within the boundaries of the Texas Barrier Island Region is 739 sq km (285.3 sq mi) in area; the uplands in this portion are less than 0.1 percent of the total drainage area of the Rio Grande. The northern boundary of the basin follows a drainage division parallel to the Rio Grande River and 6.4 km (4 mi) to 20.1 km (12.5 mi) north of it. The southern boundary of the basin area described here is the international border between the United States and Mexico, coinciding with the southern boundary of the Texas Barrier Island Region; it is not a natural drainage boundary. The basin includes only a narrow portion of Cameron County along the Rio Grande and a very small area of Hidalgo County.

Upland and barrier island habitats account for 56 percent of the basin's area. The gulf constitutes 20 percent; estuarine habitats make up 12 percent;

lakes and freshwater wetlands comprise 11 percent. About 1 percent of the basin is subaerial spoil.

The elevation of this basin at its inland extreme is 18 m (60 ft). Since the basin is a narrow river valley, its greatest slope is toward the river. However, the land also slopes toward the coast over a much longer distance, decreasing in elevation until it reaches a low, flat area within 10 km of the coastline where the elevation is less than 1.5 m (5 ft). Most of this low area is wind-tidal flat except for South Bay, a natural estuarine water body. South Bay is located next to Brazos Island, the barrier island that lies between Brazos Santiago Pass and a natural pass 7 km (4.3 mi) to the south that is open only intermittently.

The river is the most prominent feature in the basin. It is highly convoluted; the length of the river channel between the river mouth and its inland boundary is more than three times the straight-line distance between these points. The Brownsville Ship Channel, a long straight dredged navigation channel, connects Port Brownsville with the gulf through Brazos Santiago Pass. Numerous reservoirs are located in the upper two-thirds of the basin; many small resacas and oxbows are also present.

Sediments along the Rio Grande and resacas are dominantly clayey sands and silts with moderate permeability and water-holding capacity. Sediments in the interdistributary areas between rivers and resacas are clay and mud with low permeability and high water-holding capacity (Brown et al. 1980).

Fifteen habitats are shown on the basin map (Plate 1). Cropland makes up 227.1 sq km (87.7 sq mi), or 30.7 percent of the basin. It is the largest habitat in the basin and extends from the inland boundary to a point about 23 km from the coastline. The largest expanse of cropland surrounds several

urban areaa including the city of Brownsville and the Rio Grande Valley International Airport. A small amount of cropland is located closer to the coastline along the Rio Grande River.

A belt of range habitat, about 12 km (7.5 mi) wide and adjacent to the eastern edge of the major cropland area, extends the width of the basin. Range is the second largest upland habitat, comprising 109.3 sq km (42.2 sq mi), or 14.8 percent of the basin. Some of the range extends all the way to the barrier habitat at the shoreline, but most is located inland of or around wind-tidal flats.

The flats are lower in elevation than the range and lie even closer to the coastline; the largest wind-tidal flat area is adjacent to South Bay. Large grassflats occur in the estuarine bay system and near the opening of Brazos Santiago pass to the gulf.

Channel and tidal stream habitat in the basin consists almost entirely of the Brownsville Ship Channel and a connecting portion of the intracoastal waterway. River and canal habitat has a length of more than 257 km. This estimate includes only the major river channels and drainage or irrigation canals; photographs and land use maps (Brown et al. 1980) show a dense pattern of irrigation canals in the cropland area of this basin, so the total length of river and canal habitat including smaller ditches is probably considerably greater.

Table 6 summarizes the areas and lengths of habitats in the Rio Grande basin. The basin has a smaller proportion of range and a larger proportion of cropland than the region as a whole (Figure 44). It has about one-third of the region-wide proportion of bay area but more than four times the region's

Table 6. Habitat areas, lengths, and proportions in the Rio Grande basin.

Habitat	Area (sq km)	Length (km)	Percent of basin area
Barrier	55.2		7.5
Bay	18.4		2.5
Bulkhead	< 0.1		< 0.1
Channel and tidal stream		19.7	
Cropland	227.1		30.7
Forest	0.0		0.0
Freshwater marsh	0.3		< 0.1
Grassflat	39.1		5.3
Gulf	144.8		19.6
Lake and reservoir	83.7		11.3
Range	109.3		14.8
Reef	0.0		0.0
River and canal		257.4	
Salt and brackish marsh	0.3		< 0.1
Spoil	4.7		0.6
Swamp	0.0		0.0
Urban	22.8		3.1
Wind-tidal flat	33.4		4.5

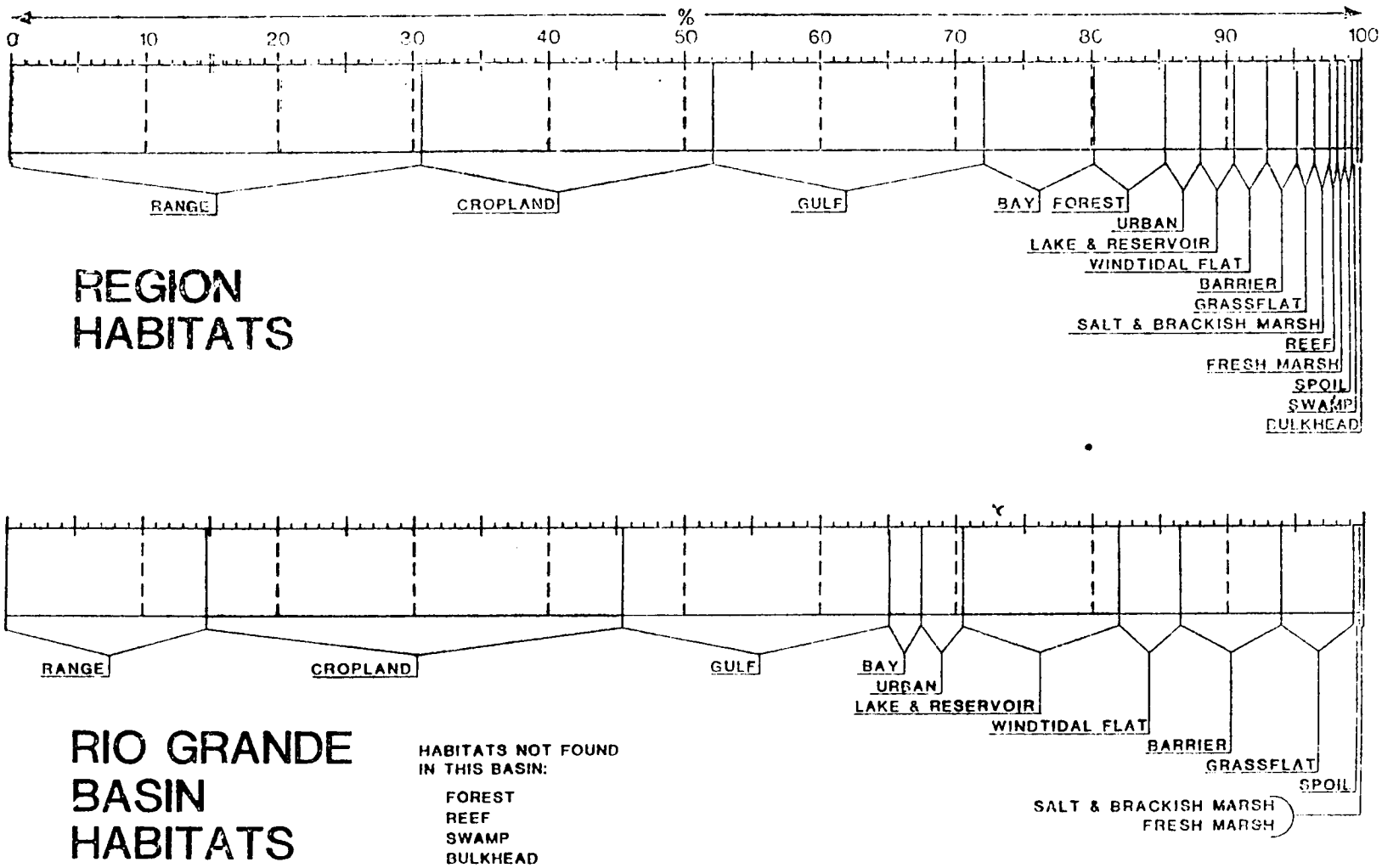


Figure 44. Habitat proportions of the Rio Grande basin and the Texas Barrier Island Region.

proportion of lake and reservoir. The relative amounts of wind-tidal flat, barrier, and grassflat habitats are greater than for the region; the relative amounts of urban, gulf, and spoil are about the same. The Rio Grande basin does not contain swamp or forest habitat. There are small clumps of oysters in this basin, but no large reef areas.

Most of the past land use changes have involved clearing woodland and brush for cropland and urban land (Brown et al. 1980). The barrier habitat and range adjacent to Port Isabel is currently undergoing significant urbanization; more inland areas of range have been less directly affected by urban development. The wind-tidal flats, bay, and grassflats have been directly and indirectly affected by dredging and maintenance of the Brownsville Ship Channel.

Geologic development. During the Pleistocene Epoch, up to the beginning of the Peorian interglacial stage, streams that flowed through the southern basins of the coast eroded and deposited materials over a wide area. For example, a fluvial-deltaic system was deposited near Raymondville in the Laguna Madre basin, probably by the ancient Rio Grande; the location of this deposit is 30 to 60 km (19 to 38 mi) north of the present Rio Grande River. When sea level dropped during the late Wisconsin glaciation 50,000 to 60,000 yr BP, a deep, broad valley was eroded into older fluvial and deltaic deposits where today's uplands exist. The deepest portion of this valley was probably about 30 m (100 ft) below present sea level. Its exact location has not yet been determined, but it was within 60 km of the present Rio Grande River channel (Brown et al. 1980).

As sea level rose during the early Holocene, 18,000 to 7000 yr BP, the river valley was drowned, and fluvial and deltaic materials were deposited in

its upper portions. Wave action eroded the walls of the river valley, forming a wider but shallower estuary. In addition, marine sediments were transported and deposited in the lower reaches of the estuary. The lateral extent of the erosion and deposition during this period was narrower than before, no more than about 20 km (12 mi) north of the present Rio Grande channel.

In the mid to late Holocene, as the rate of sea level rise slowed, the Rio Grande began to prograde its delta seaward. Three delta lobes protruded into the present Gulf of Mexico more than 16 km (10 mi) east of the present coastline. During this period of high sediment flow, the subaerial portion of the river valley was filled with point-bar sand and flood-basin mud (Brown et al. 1980). These and later deposits from river flooding form the surface sediments present today along most of the Rio Grande basin.

The sediment flow through the basin began to slow about 3500 yr BP, and delta-building into the gulf ceased. This coincided with a climatic change to more arid conditions. Offshore sediments were transported landward and formed a north-projecting peninsula connected to the retreating Rio Grande delta. This peninsula eventually ined with the barrier islands further to the north to form Padre Island (Brown et al. 1980).

Basin climate and hydrology. The Rio Grande basin is at the southern extreme of a temperature gradient in the Texas Barrier Island Region. The yearly average temperature in the basin is 23.3 deg C (74 deg F); the average winter low temperature is 15.6 deg C (60 deg F) and the average summer high temperature is 29.4 deg C (85 deg F) (Williams et al. 1976).

The basin climate is arid. Average rainfall is 61 to 66 cm (24 to 24 in) per year. The majority of the rainfall occurs in late summer and early fall;

September has the highest rainfall followed by October and August; March has the lowest rainfall (Bomar 1983). Evapotranspiration is significantly higher than rainfall so there is a precipitation deficit of 71 cm (28 in) per year (Woodruff 1975). Habitats that store fresh or slightly brackish water (lakes, reservoirs, and marshes) constitute nearly 17 percent of the area of all habitats above mean sea level.

The 42-year average river flow in the Rio Grande basin, measured near Brownsville, is 1960 million cu m per year (Texas Department of Water Resources 1979). This flow measurement includes diversions from and return flows to the river. Extreme high and low flows measured during this period have ranged from 2 to 411 percent of the average flow volume. The pattern of Rio Grande water flow parallels the basin's rainfall pattern; the highest flows occur from August through October, with peak flows in September (Woodruff 1975). Figure 45 shows a hydrograph for river flow and also illustrates the hydrologic distribution pattern in the basin. There is a significant amount of river diversion for agriculture, and a small diversion for municipal use; return flows are also small. During periods of flooding from very high river flow or hurricane rainfall, some of the water in the basin may exit across the northern basin boundary and enter the adjacent Laguna Madre basin through floodwater channels (Texas Department of Water Resources 1983a).

The amount of sediment transported to the gulf has decreased over the past 50 years because of irrigation diversion and upstream dam construction (Brown et al. 1980). The four-year average sediment flow calculated from Cook (1967, 1970) is 29,185 metric tons of sediment per year.

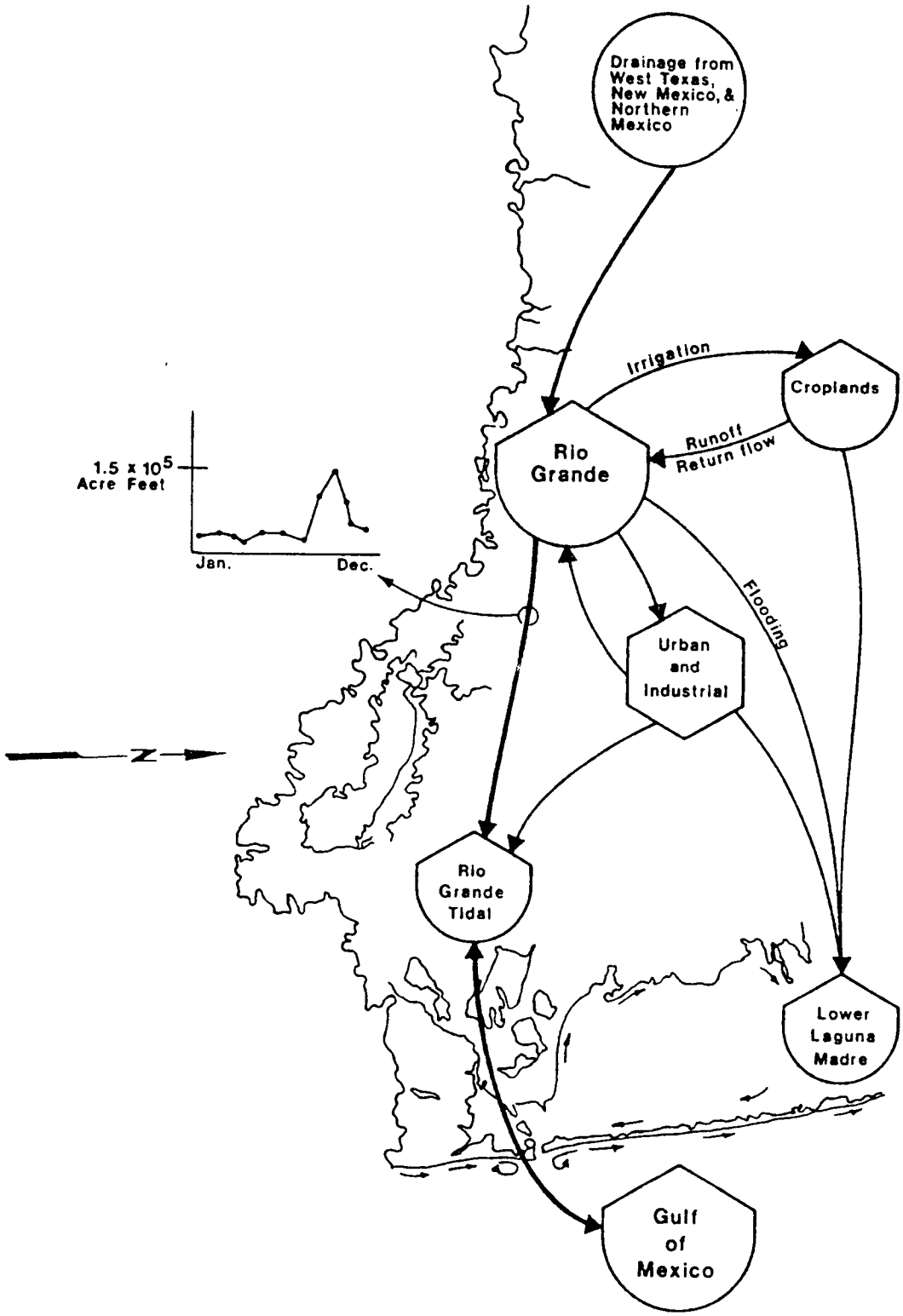


Figure 45. Hydrology of the Rio Grande basin.

The estuarine systems in the basin include South Bay, the channel to Port Brownsville, and the tidal portion of the Rio Grande. The diurnal tidal range at Port Isabel is 0.4 m (1.3 ft) (U.S. Department of Commerce 1983). Tidal forces at the turning basin of the Brownsville Ship Channel are low.

South Bay is very shallow, less than 1 m (3 ft) deep. It contains scattered oysters and grassflats. Salinity in South Bay ranges from 27.1 to 40.5 ppt and averages 32.3 ppt (Texas Department of Water Resources 1983a). Spoil from the Brownsville Ship Channel has largely cut off South Bay from free circulation with the Laguna Madre. Spoil piles have blocked the hydrostatic head from wind tides in the Laguna Madre which kept Boca Chica Pass open and water circulating through South Bay (Breuer 1962). Commercial fishing and sportsfishing effectively ceased because of the change in hydrology. Spoil has spread across the bay and the sediments are mostly mud with a small amount of sandy mud near Brazos Island (McGowen and Morton 1979).

The Brownsville Ship Channel was dredged to a depth of 10.7 m (35 ft). It is more than 17 km (12 mi) long and receives little drainage to force flow out the channel. Salinity in the channel ranges from 10.1 to 37.6 ppt and averages 29.5 ppt (Texas Department of Water Resources 1983a). The channel was dredged through Bahia Grande and Vadia Ancha, both shallow brackish water bodies. Spoil placement and later road development along the channel cut off water flow to these areas from the ship channel and eliminated them as estuarine nursery grounds.

The mouth of the Rio Grande River is tidally influenced for a length of 79 km (49 mi). The salinity of this tidal segment ranges from 0.2 to 4.3 ppt and averages 1.0 ppt (Texas Department of Water Resources 1983a).

Offshore the gulf floor slopes steeply for the first kilometer and then more gently to the three-league line. The water depth at the outer basin boundary is 29.3 m (96 ft). Gulf sediments are sandy close to the beach and vary from mud to sandy mud to shelly sandy mud offshore. Circulation in the gulf is complicated and changes seasonally in response to wind forces. The yearly average pattern is a northward surface flow especially during spring and summer; fall and winter circulation direction may be reversed part of the time in response to frontal passage and large scale gulf circulation influences (Watson and Behrens 1970; Temple and Martin 1979).

Sediment transported out of the Rio Grande River is no longer adequate to balance wave erosion associated with storm impact on the Modern Rio Grande delta. Consequently Brazos Island and the lower portion of Padre Island are slowly retreating landward (Brown et al. 1980). Morton et al. (1983) reported beach erosion along the gulf shoreline that ranged from 2.5 to 6 m (5 to 20 ft) per year. There is high flood and washover potential for nearly the entire gulf shoreline in this basin.

Basin economy. Table 7 presents a summary of economic indicators that can be compared with other basins. The population of the Rio Grande basin in 1980 was 31,060 (U.S. Department of Commerce 1981). The basin has just experienced a growth of 49 percent since 1970 and population projections indicate the growth will be large during the next two decades (Table 7, calculated from Texas Department of Water Resources 1980d). By the year 2000 the population is expected to be 46 percent larger than today.

Mineral production in the Rio Grande basin is of minor economic importance; the value of oil and gas produced in 1977 was $1.25 million (Liebow et al. 1980). Tourism and recreation is a more profitable sector. In

Table 7. Economic data for the Rio Grande basin.

Data type	Quantity
1970 Population	20776
1977 Population	26130
1980 Population	31060
1990 Population projection	36837
2000 Population projection	45387
Mineral production (X $1000)	1250
Deer harvest	22
Travel expenses (X $1000)	13500
Travel employment	473
Sportfishing spending (X $1000)	0
Commercial fishing spending (X $1000)	0
Electrical generating capacity (kw)	46879
Total employment	9329
Number of building permits	160
Length of railroad track (km)	26
Length of highways (km)	621
Number of vehicles registered	20052
Commodity flows (1000 metric tons)	2117
Number of farms	198
Market value of products (X $1000)	8878
Area of irrigated land (ha)	17716

1978, travel expenditures in the region were $13.5 million and travel-related employment was 473, about 5 percent of the total employment (Liebow et al. 1980).

Commercial fishing information indicates that this activity has little economic impact on the basin. A harbor was built off the ship channel for fishing vessels, but most fishing occurs in the gulf or adjacent basins.

Rapid residential and industrial development has accompanied the recent population growth in the basin. In 1977 the total employment was 9329 and 160 building permits were issued (Liebow et al. 1980).

Transportation is an important part of the basin's economy. The 414 sq km of upland have 621 km of roads and highways; more than 20,000 vehicles were registered in 1978 (Liebow et al. 1980). The port has been particularly significant; in 1977 more than 2.1 million metric tons of commodities were transported through the Brownsville Ship Channel (RPC Inc. 1980).

Nearly 200 farms were located in the basin in 1974, and the total market value of their production in that year was nearly $9 million (Liebow et al. 1980). Most agriculture in the basin depends upon irrigation. The area of irrigated cropland, 17,716 ha (Pfluger et al. 1981), accounted for about three-quarters of the cropland in the basin.

Resource demands. The importance of agriculture can be seen from the demand for space for cropland: 22,724 ha, or nearly 55 percent of all the basin's upland, is devoted to cropland; 10,934 ha, or 26 percent, is range (Table 8). Urban areas currently occupy 2280 ha, or 5.5 percent, of the upland. With the projected rapid population growth, urban expansion is certain.

Table 8. Resource demands in the Rio Grande basin.

Resource demands	Quantity
Cropland area (ha)	22724
Range area (ha)	10934
Urban area (ha)	2280
Recreation area (ha)	3130
Crude oil production (kiloliters)	131
Natural and casinghead gas (million cu m)	32
Condensate (thousand liters)	420
1902-1978 oil production (million liters)	470
Grain production (kiloliters)	48917
Cotton production (bales)	18482
Hay produced (metric tons)	2374
Peanuts produced (kg)	0
Rice produced (metric tons)	0
Cattle and calves sold	6521
Bay shrimp harvested (kg)	0
Bay oysters harvested (kg)	0
Bay crabs harvested (kg)	0
Bay commercial fish harvested (kg)	0
Bay sportfish landed (kg)	0
Total commercial fish harvested (kg)	0
Total commercial shellfish harvested (kg)	0

Table 8 (continued). Resource demands in the Rio Grande basin.

Resource demands	Quantity
Digestive cancer mortality	6
Lung cancer mortality	6
Pneumonia and influenza mortality	4
Emphysema, bronchitis, and asthma mortality	1
Length fishable, swimmable stream segments (km)	63
Percent fishable, swimmable stream segments (%)	80
Airborne particulates (metric tons)	2313
Airborne hydrocarbons (metric tons)	1714
Waste discharge measured as 5-day BOD (kg)	113498
Number of discharges	1
Cumulative industrial solid waste (metric tons)	0
Subsidence of land surface (m)	None
Municipal surface water use (million cu m)	35
Municipal groundwater use (million cu m)	12
Manufacturing surface water use (million cu m)	0
Manufacturing groundwater use (million cu m)	1
Irrigation surface water use (million cu m)	243
Irrigation groundwater use (million cu m)	66
Total surface water use (million cu m)	281
Total groundwater use (million cu m)	103
Municipal, manufact. return flow (million cu m)	26
Agricultural return flow (million cu m)	36
Obstructions to runoff, roads + railroads (km)	647
Major drainage ditches and canals (km)	76
Maintenance spoil, historical average (cu m)	769562
Length of dredged channels (km)	20

The demand on the mineral resources in the basin has been small. Oil and gas has been produced since 1934, but less than 400 million liters have been produced since that time. Table 8 contains other indicators of the low level of oil and gas production in this basin.

Biomass production in the basin is almost entirely agricultural, with special emphasis on grain and cotton. In 1978, 48,917 kiloliters of grain and 18,482 bales of cotton were produced. The number of cattle and calves sold was 6521. Using the area estimate for range (Table 8) 59.6 cattle and calves were sold for every hectare of range land in the basin.

Public health indicators show a low incidence of environmentally related cancers and respiratory diseases in the basin (National Center for Health Statistics 1981). About 80 percent of the freshwater stream segments in the basin are fishable and swimmable (Texas Department of Water Resources 1983a). The only public health problems in the basin are minor, localized high bacterial concentrations associated with urban runoff and municipal waste treatment.

Waste materials released to the atmosphere are low; 2313 metric tons of airborne particulates and 1714 metric tons of hydrocarbons were released in 1974 (Texas Air Control Board 1977). Permits have been issued for seven discharges in basin waters; six of the discharges are from domestic waste treatment plants and five of these empty into the Brownsville Ship Channel. Five-day BOD, a measurement of the organic waste load placed in natural waters for biological processing, is high: 113,498 kg per year (Texas Department of Water Resources 1984).

Total water use in 1974 in the Rio Grande basin was 384 million cu m. Twenty-seven percent of the water demand was satisfied by groundwater. Of the

309 million cu m were used for irrigation in 1974, more than 90 percent was from surface sources. Municipal water use accounted for 47 million cu m, while manufacturing use was only about 1 million cu m. Return flows totaled 62 million cu m. About 55 percent of the municipal and industrial water was returned for reuse; only 12 percent of the agricultural water was returned. Table 8 provides complete statistics of basin water use (Texas Department of Water Resources 1977).

Land surface hydrology has been altered by the placement of roads, railway beds, drainage canals, and the Brownsville ship channel. Six hundred forty-seven miles of roads and railroad beds (Liebow et al. 1980) are present in the basin. This is a density of nearly 1.6 km of road or railway for every sq km of upland area. More than 76 km of major drainage and irrigation ditches are also present. The total dredged channel length in the basin is nearly 20 km. Most of this is the Brownsville Ship Channel. About two-thirds of the length of the ship channel crosses the range habitat. Large spoil piles on either side of the channel have altered upland, wind-tidal flat, and bay hydrology. The historical average annual maintenance material volume for the basin is 1,005,549 cu m, which is disposed both on land and in the estuarine areas (Belaire 1976).

Laguna Madre Basin

The Laguna Madre basin is the largest basin in the Texas Barrier Island Region, comprising 16,973 sq km (6553 sq mi) within the region's boundaries. It is a portion of a larger coastal basin, the Nueces-Rio Grande basin, which has an area of 27,045 sq km (10,442 sq mi) (Texas Department of Water

Resources 1977). The portion of the basin discussed here constitutes about 63 percent of the natural hydrologic unit.

The southern boundary of the basin is the natural drainage division that lies 6.4 to 21.1 km (4 to 12.5 mi) north of the Rio Grande. The northern boundary follows a topographic ridge that protrudes seaward from the area near Robstown, Texas, and separates the drainage areas of Oso Creek to the north and Petronila Creek to the south. The northern boundary is approximately 15.3 km (9.5 mi) south of the southern shoreline of Corpus Christi Bay. The basin includes all or part of Brooks, Cameron, Hidalgo, Kenedy, Kleberg, Nueces, and Willacy counties.

Upland and barrier island habitats occupy 60 percent of the area of this basin; the gulf constitutes 23 percent. Estuarine habitats make up 13 percent of the basin, and lakes and freshwater wetlands comprise 4 percent. Slightly less than 1 percent of the basin is spoil.

The physiography of the Laguna Madre basin is not uniform. The southern half of the basin is a low, flat coastal plain gently sloping to sea level. The elevation at the inland boundary ranges from 12 to 15 m (40 to 50 ft). Just south of area around Baffin Bay the elevation at the inland boundary begins to increase. Much of the land at the inland boundary of the northern portion of the basin is 24 to 30 m (40 to 100 ft) in elevation; a few places are higher than 40 m (131 ft). The land generally slopes toward the coastline, although small creeks that drain toward Baffin Bay alter this pattern somewhat. The average land slope increases from the south to the north; however, within 10 km of the bay shoreline the land elevation rarely exceeds 8 m.

Baffin Bay and three secondary bays that join it--Alazan Bay, Cayo del Grullo, and Laguna Salada--protrude inland at a point about two-thirds of the distance from the southern to the northern boundary of the basin. These bays extend inland about 29 km (18 mi). The land adjacent to the bays is very low, generally less than 3 m (10 ft) above sea level. Two long, narrow lagoons parallel the mainland coast. These are the southern Laguna Madre and the northern Laguna Madre. The southernmost portion of the northern Laguna Madre is an isolated water body known as The Hole.

The two lagoons are separated by a 19-km wide area of wind-tidal flat known as the land cut. Before the intracoastal waterway was dredged, it would have been possible to walk from the mainland to Padre Island across the wind-tidal flat.

Padre Island is a long barrier island that stretches from Brazos Santiago Pass on the south to Packery Channel, the dividing line between Padre and Mustang islands. It is 174 km (108 mi) long and ranges in width from 0.5 km (0.3 mi) to 3.7 km (2.3 mi). Dunes on Padre Island vary in height from 1.5 to 7.6 m (5 to 25 ft). In the northern portion of the island dunes are low but continuous; toward the south the dunes become discontinuous and are interespersed with wide washover areas. Brown et al. (1974) noted 46 active or potential washover channels on Padre Island; Morton et al. (1983) noted that at least 60 washovers had opened as the result of hurricanes Beulah (1967) and Allen (1980).

Mansfield Channel was cut through Padre Island to Port Mansfield in 1958 and is maintained for pleasure boats and fishing vessels. Yarborough Channel was dredged across Padre Island in 1941 and reopened on four separate occasions over a span of 10 years. It never remained open for more than a few

months before refilling with sediment and has been closed since 1952 (Simmons 1957).

The wide expanse of open land without major drainages to the coastline is the most prominent feature in this basin. This unbroken expanse is the result of the arid conditions of the basin. The other most notable features are the long, continuous barrier island chain and Baffin Bay, which has no major river system draining into it. These features are also consistent with the basin's hydrologic conditions. A final distinctive feature of this basin is the linear piles of spoil adjacent to the intracoastal waterway. These spoil areas are more prominent in the northern Laguna Madre.

The upland sediments vary greatly over the basin. In the southern third, the surface sediments are clayey sand and silt interspersed with clay and mud deposits. The sand and silt is characterized by moderate permeability and water-holding capacity; the clay and mud has low permeability and high water-holding capacity. Upland sediments of the middle third of the basin, including the area immediately west of Baffin Bay, are eolian sands with some areas of active mainland dunes or loess sheets (windblown silt). They have moderate to high permeability and low to moderate water-holding capacity. Surface sediments in the upper third of the basin, from Baffin Bay to the northern boundary, are similar to the sediments in the bottom third. Long narrow areas of clayey sand and silt are former distributary channels; between these sediments are clays and muds, probably left by interdistributary deposition. Close to the lagoon shoreline are sandier sediments remaining from delta and strandplain sediments deposited there during glacial episodes.

Seventeen habitats are present in the Laguna Madre basin (Table 9). Range, by far the largest of all the habitats, constitutes 37.9 percent of the basin area. The entire middle portion of the basin, from the inner boundary to the bay shoreline, and about half the area between Baffin Bay and the northern boundary of the basin are range (Plate 2).

Cropland is the second largest upland unit, comprising 16.9 percent of the basin. There ate three major cropland areas: the most southern portion of the basin, the most northern portion of the basin, and an area just northwest of Baffin Bay near the city of Kingsville. Several urban habitats are found within the cropland; the largest urban areas include San Benito, Harlingen, Raymondville, Kingsville, and Bishop. Urban habitat makes up 313.4 sq km, or 1.9 percent, of the basin's area.

The barrier habitat, Padre Island, comprises 485.9 sq km, or 2.9 percent of the basin's area. A large expanse of wind-tidal flats lies landward of the barrier island and in some places stretches more than 8 km (5 mi) from the barrier to the intracoastal waterway. Except for some wind-tidal flat at the edge of Alazan Bay and Cayo del Grullo, and on the mainland shore near the Arroyo Colorado, all of this habitat lies behind the barrier island and remains dry much of the time because the predominant southeast winds push waters to the west side of the Laguna. The total area of wind-tidal flat in this basin is 994 sq km (383.8 sq mi), which constitutes 5.9 percent of the basin and 44 percent of the estuarine habitats.

The Laguna Madre basin contains 527.8 sq km (203.8 sq mi) of grassflat. This accounts for 3.1 percent of the basin's area, 23 percent of its estuarine habitats, and 78 percent of all the grassflats in the region. Grassflats in the Laguna Madre covers almost as much area as wetlands for all of the other

Table 9. Habitat areas, lengths, and proportions in the Laguna Madre basin.

Habitat	Area (sq km)	Length (km)	Percent of basin area
Barrier	485.9		2.9
Bay	742.0		4.4
Bulkhead	3.4		< 0.1
Channel and tidal stream		419.4	
Cropland	2872.3		16.9
Forest	7.5		< 0.1
Freshwater marsh	45.1		0.3
Grassflat	527.8		3.1
Gulf	3836.8		22.6
Lake and reservoir	600.1		3.5
Range	6433.3		37.9
Reef	3.6		< 0.1
River and canal		1891.6	
Salt and brackish marsh	7.5		< 0.1
Spoil	100.0		0.6
Swamp	0.0		0.0
Urban	313.4		1.9
Wind-tidal flat	994.0		5.9

basins combined. The grassflats are particularly large near the northern and southern boundaries of the basin. They become sparse in the middle portion of the basin where wind-tidal flat predominate. Salt and brackish marsh occupies only 7.5 sq km (2.9 sq mi) in the basin.

Available measurements indicate that the Laguna Madre basin contains 419.4 km of dredged channels, including the intracoastal waterway, Mansfield Channel, a dredged portion of the Arroyo Colorado, and many small access channels, most of which lead to oil and gas wells. Subaerial spoil adjacent to the channels occupies 100 sq km (38.6 sq mi). Channels are found throughout the length of the lagoon, and many additional small channels have been dredged since the mapped information was gathered.

The basin contains 1891.6 km of rivers and canals. The majority of this measurement is canal located in the large cropland area near the southern boundary. Since only the major irrigation and drainage canals have been measured, it is likely that the true length of canals in the basin is significantly greater.

Overall the basin has a higher proportion of range than the region as a whole. Other habitats that occur in higher proportions in the basin than in the region as a whole include gulf, wind-tidal flat, barrier, and grassflat (Figure 46). The basin has smaller proportions of cropland, urban area, and fresh marsh than the region. Because the Laguna Madre is so long and thin, the basin has less bay area than would be expected from the region average. Swamp is not found in this basin, presumably because of the arid conditions.

Major land use changes in this basin include the dredging of canals and placement of spoil and the conversion of rangeland to cropland by clearing

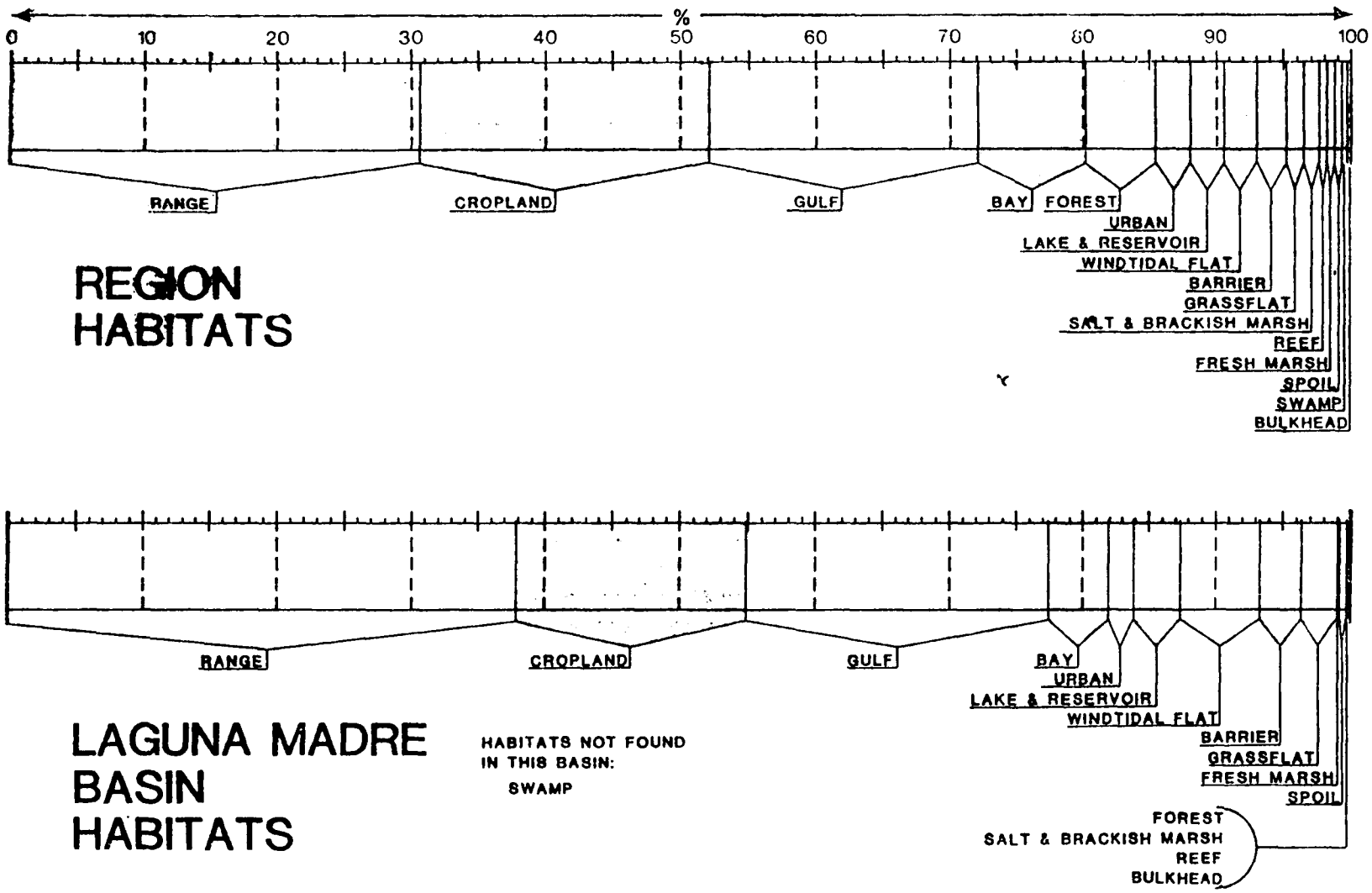


Figure 46. Habitat proportions of the Laguna Madre basin and the Texas Barrier Island Region.

land and building networks of irrogation pipelines and canals. The southern part of Padre Island and the mainland near Port Isabel is currently undergoing rapid urbanization with condominium and vacation home construction.

Geologic development. The middle portion of the mainland of this basin, from the area around Port Mansfield to the northern shore of Baffin Bay, developed as an older Pleistocene fluvial system probably during the Sangamon interglacial stage more than 150 million yr BP (Brown et al. 1977). Ancient rivers transported sediment to this area; it has since received additional sediment layers from eolian deposition but has also lost layers through erosion. As sea level declined during the Early Wisconsin period, rivers in the area eroded deep river valleys. Brown et al. (1976) state that the Nueces River valley was approximately in its present location. The location of the Rio Grande at that time is not certain.

As sea level rose, the Rio Grande estuaries eroded and filled. The rivers meandered and left younger Pleistocene fluvial deposits on the southern portion of the mainland, below the latitude of Port Mansfield, where a delta had been built out to what is presently the gulf. In the northern area, above Baffin Bay, the Nueces River built a delta with overlying fluvial deposits nearly as far as the present location of Baffin Bay (Brown et al. 1976). During the Peorian period, when sea level was slightly above its current elevation, a Pleistocene barrier-strandplain system was formed along the edge of what is now the mainland, although there is disagreement whether it was a true barrier system or not (Brown et al 1976).

The Late Wisconsin glaciation lowered sea level for the last time and the Nueces and Rio Grande rivers flowed through incised river valleys in their present locations. During the glaciation, conditions were much wetter and

Olmos, San Fernando, and Petronila creeks eroded what is now the Baffin Bay system.

As sea level rose a final time, the walls of today's Baffin Bay eroded, sediment was transported in from the gulf and the flowing streams, and eventually a string of barrier islands coalesced to form Padre Island. Baffin Bay was cut off from direct connection with the gulf about 2500 to 2800 yr BP, although Breuer (1957) notes that experts have found evidence of inlets opposite the mouth of Baffin Bay that may have been open at various times.

Basin climate and hydrology. The average yearly temperature in the Laguna Madre basin is 23 deg C (73 deg F). The average winter low temperature is 15 deg C (59 deg F), and the average summer high temperature is 29 deg C (85 deg F) (Williams et al. 1976).

The climate of the basin is arid. Rainfall varies from 61 to 66 cm (24 to 26 inches) per year. About 35 percent of the yearly rainfall occurs in the fall; slightly less than 30 percent occurs during the late summer (National Climatic Center 1973). This rainfall pattern is usually associated with the fall passage of tropical cyclones rather than with frontal passage. Evapotranspiration substantially greater than rainfall in the basin creates an annual deficit of 56 to 71 cm (22 to 28 in) (Wcodruff 1975). The Texas Department of Water Resources (1979) reported that evaporation from the Laguna Madre was about four times the amount of the estimated combined inflows to the system. Although there is a significant precipitation deficit throughout the basin, 6 percent of the land area above mean sea level contains habitats which store fresh or brackish water.

Freshwater flows are carried to the bay system by the Arroyo Colorado and the North Floodway which enter Laguna Madre, and by Los Olmos Creek and San Fernando Creek which enter Baffin Bay. Gaged flow has averaged 413 million cu m per year (Texas Department of Water Resources 1983a), but has ranged from 5 to 606 percent of the average flow (Dougherty 1980). The Texas Department of Water Resources estimated that the total inflow through streams (including ungaged portions, return flows, and diversions) was 850 million cu m per year. When rainfall and evaporation were included, the net freshwater inflow was 947 million cu m, a large deficit for Laguna Madre waters.

The gaged flows into the Laguna Madre are spread over a wide area. Overall the greatest flows occur during the months of September and October (Dougherty 1980), although in some streams the flows are very erratic (Woodruff 1975). Figure 47 illustrates the hydrologic distribution pattern for the Laguna Madre basin. The Arroyo Colorado flow depends upon municipal and industrial discharges, and upon agricultural return flows (Texas Department of Water Resources 1983a). It also receives floodwaters from the southern portion of the basin and spillover from the Rio Grande basin that results from heavy rains or Rio Grande River flooding.

The sources of flows into Baffin Bay are natural land drainage and return flows of urban and industrial water diverted from the Nueces River and used by industries and cities in the northern part of the basin (Texas Department of Water Resources 1977). Because of the limited drainage into the basin, estimates are not available for the sediment transported by streams. The entire basin is subject to eolian sediment transport from the gulf which may be greater may be greater than from the waterborne transport from the uplands. Breuer (1957) reported that sediments in the bottom of Cayo del Grullo are 1

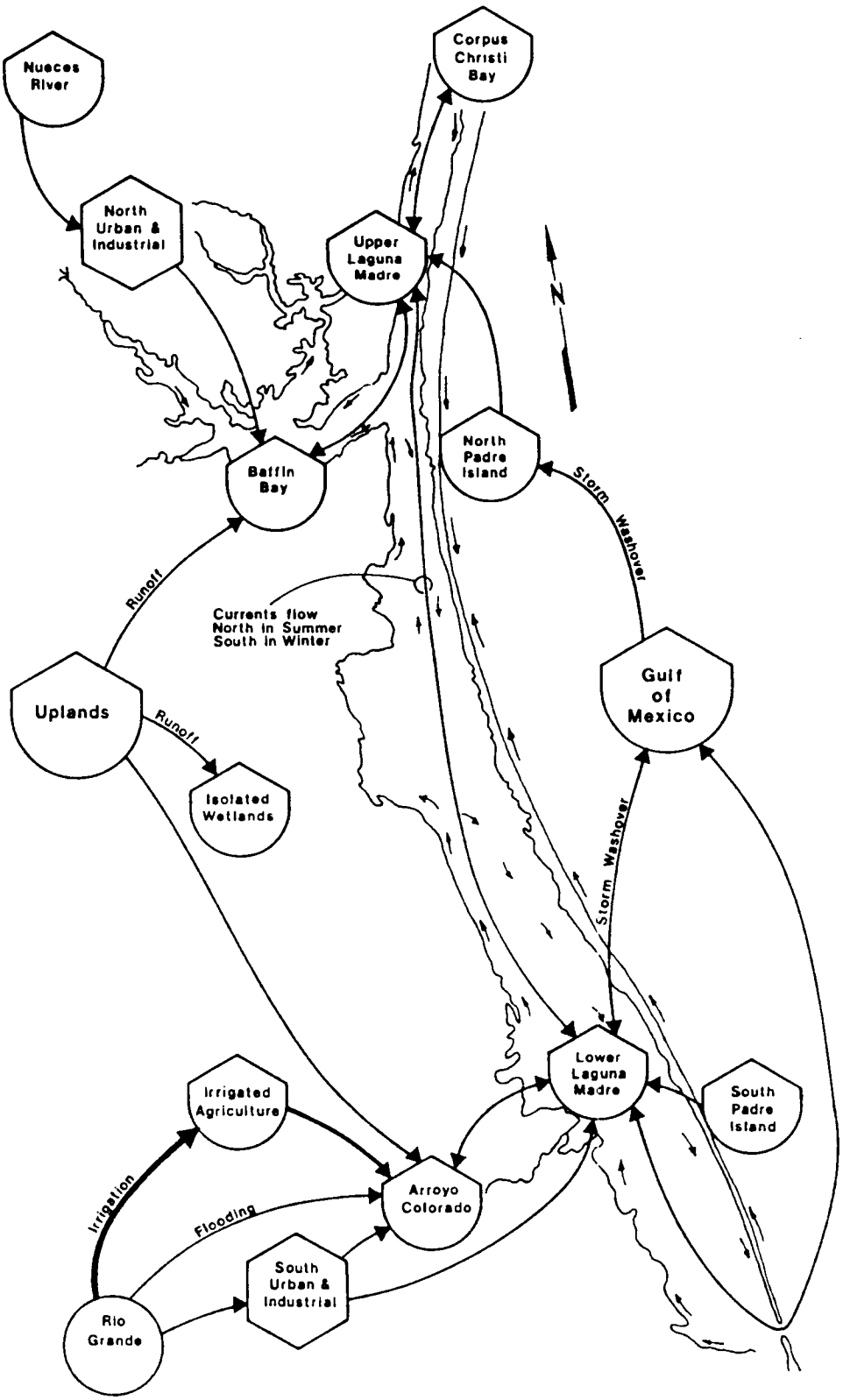


Figure 47. Hydrology of the Laguna Madre basin.

to 2.5 m (3 to 8 ft) of soft mud that may be the residue of heavy siltation several hundred years earlier. Archaeological information (cited by Breuer) suggests that oysters once grew in Cayo del Grullo. If this is true, rainfall, freshwater inflow, and sediment transport into the basin may have been much greater at some periods in the past few centuries.

The estuarine systems in the basin are affected more by meteorologic forces than by tidal forces. Solar and lunar tidal effects are moderate near the openings to the gulf and are damped with distance from the gulf influence. The diurnal tidal fluctuation given in tide tables is only 0.1 m (0.3 ft) at Riviera Beach in Baffin Bay (U.S. Department of Commerce 1983). In a recent study, Gill (1983) reported that the interval between mean higher high water and mean lower low water at three stations in the southern Laguna Madre averaged 0.08 m (0.27 ft). This value was based upon more than 3 years of intensive data collection and calculated over the 1960-1978 National Tidal Datum Epoch. Because of the weakness of the solar and lunar tidal influences, meteorologic influences, especially wind-tides dominate water movement.

Most of the southern Laguna Madre is 1 m (3 ft) or less in depth. Only near Brazos Santiago Pass and the Land Cut are depths greater than 1 m (3 ft) found. The depth of the northern Laguna Madre is about the same, although there are more areas with depths of 1 to 2 m (3 to 6 ft). Depths in the Hole are less than 1 m (3 ft), but between the Hole and the mouth of Baffin there is an area where the depth is 2 to 3.5 m (6 to 12 ft). Nearly half of Baffin Bay is 2 to 3.5 m (6 to 12 ft); while the depth in the secondary bays is less than 2 m (6 ft).

Sediments in the southern and northern Laguna Madre are very sandy; in areas of seagrasses the sediments may be sandy mud or may also contain quantities of shell. Baffin Bay sediments are largely mud. The difference in sediment type is the result of different sediment sources. Baffin Bay sediments come from upland drainage. Northern and southern Laguna Madre sediments are sand derived from the gulf that has been transported to the Laguna through washovers and by eolian processes.

Surveys of Baffin and Alazan Bays (Breuer 1957), northern Laguna Madre (Simmons 1957), and southern Laguna Madre (Breuer 1962) are the only large-scale observations of circulation in the lagoon complex. Wind is the strongest influence on circulation patterns. During the summer, prevailing winds drive water in through Brazos Santiago Pass and push it up the southern Laguna Madre and through the Land Cut. Mansfield Pass acts as an overflow valve through which the excess water passes into the gulf (Breuer 1962). Waters flowing through the Land Cut have marine salinities (about 35 ppt) and may stabilize higher northern Laguna Madre salinities. During the winter, north winds blow water in the other direction. Higher salinity waters from the northern Laguna Madre are pushed south, diluted with marine waters entering through Mansfield Pass, and eventually flow through Brazos Santiago Pass to the gulf.

Circulation in the northern Laguna Madre is restricted by both the Land Cut and a causeway across the northern opening of the northern Laguna Madre. Simmons (1957) reported that winds produced currents parallel to the predominant wind direction. He also noted that the increased flow resulting from the dredging of the intracoastal waterway did not always bring about greater mixing of waters of different salinities; he observed that a plug of

high salinity water moved back and forth in the northern Laguna Madre without substantially increasing the mixing.

Circulation in Baffin Bay is not well documented. Dead serpulid reefs restrict water flow between the bay and the northern Laguna Madre. In the past Baffin Bay was subject to very high salinities. Hedgpeth (1953) reported a high salinity of 113.9 ppt between 1946 and 1948 and noted that 70 ppt was common. Breuer (1957) reported salinities in the range of 1.4 to 75.1 ppt, with an average of 51.7 for the period 1951 to 1953. Salinities between 30 and 70 ppt were measured by Behrens (1966) over the period 1964 to 1966. Over the past four years the average has been 30.5 ppt within a range of 4.5 to 48.3 (Texas Department of Water Resources 1983a).

Salinities in the northern Laguna Madre have been lower than in Baffin Bay. Simmons (1957) reported a range of 22.1 to 79.2 ppt; Behrens (1966) measured values in the range of 30 to 60 ppt. Southern Laguna Madre salinities have ranged from less than 10 to more than 50 ppt (Breuer 1962); usually the salinity is close to marine conditions. Figure 48 shows typical salinity contours in the Laguna Madre and Baffin Bay during periods of high and low flow (from Brown et al. 1976; Brown et al. 1977; Brown et al. 1980).

In the Laguna Madre, bay shoreline erosion is limited to the western portion of the lagoon except for places where wide areas of wind-tidal flats are present. Much of the shoreline of Baffin Bay is oriented to receive wave action generated by frequent strong southeast winds or northwest winds associaed with northers. Most of the shoreline of this bay is subject to wave erosion (Brown et al. 1976, 1977, 1980).

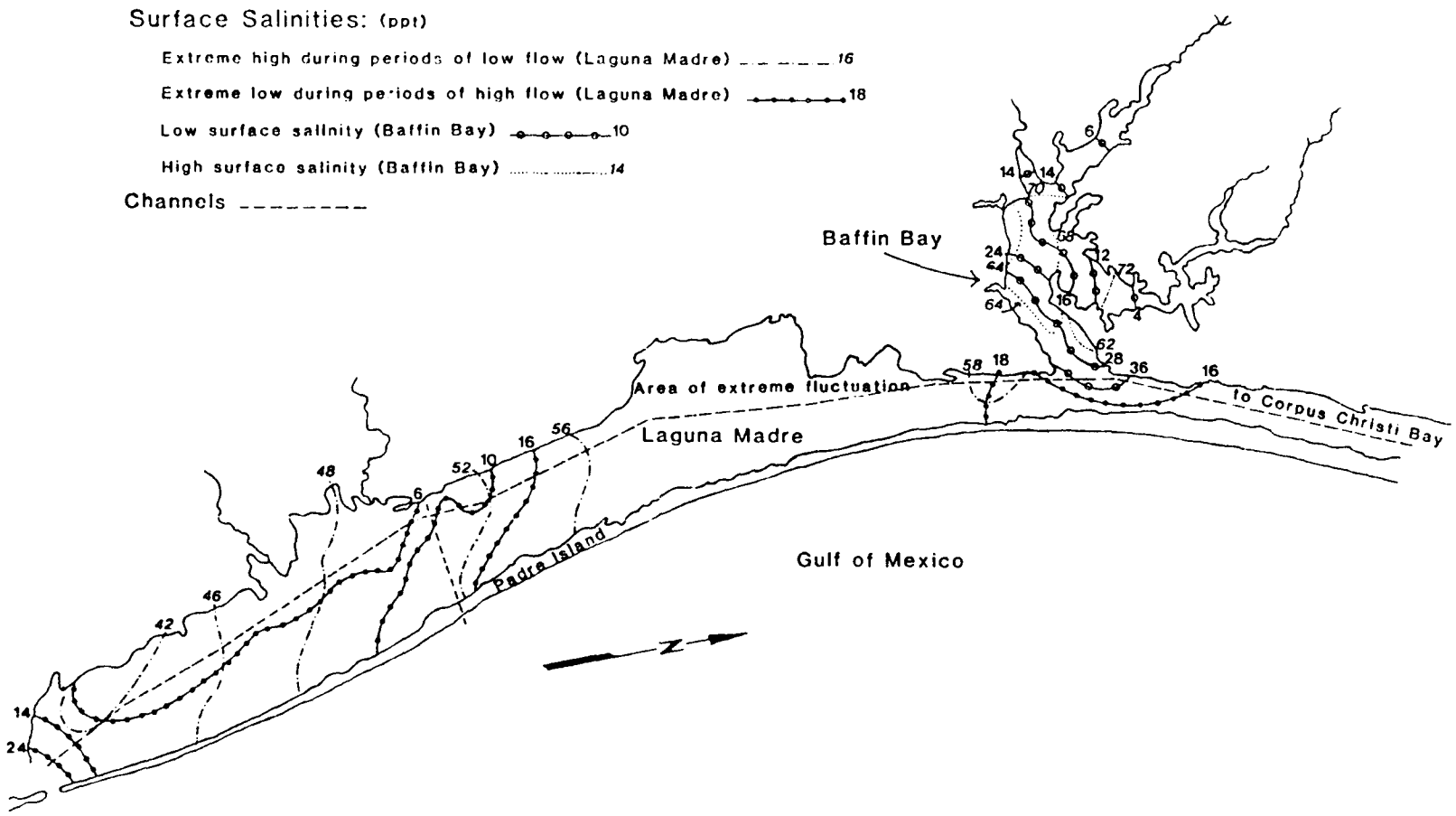


Figure 48. Salinity variation in the Laguna Madre basin.

Offshore the floor of the gulf slopes steeply for the first kilometer and then gently to the three-league line. In the southern portion of the basin, the depth at the seaward boundary is 27 m (90 ft); at the northern end, the depth is 24.3 m (80 ft). Within 2 km of the shoreline, sand is the dominant sediment. The sand belt widens south of the Land Cut area and is sometimes 10 km wide. In the southern portion of the basin, sediments seaward of the sandy area are a mixture of sand, mud, and shell. To the north, there is a more regular progression offshore of sand, sandy mud, muddy sand, and mud (McGowen and Morton 1979).

Near the area of the Land Cut there are several offshore deposits of shell and rock fragment gravel. From the Land Cut to Yarborough Pass the gulf beach is known as Big Shell Beach because of the preponderance of large shell fragments in the beach sediment. North of Yarborough Pass, for a distance of about 15 km, the beach is known as Little Shell Beach because of the preponderance of small clam shells on the foreshore (Andrews 1971).

Gulf currents and longshore drift vary seasonally; however, the net direction of wind and resulting water flow on a yearly basis is to the north in the southern part of basin and to the south in the northern portion of the basin. There is a zone of convergence as demonstrated by Lohse (1955 cited in Weise and White 1980), Watson and Behrens (1970), and Watson (1971) at about latitude 27 deg north, in the area of Big Shell Beach. This area is noted on Figure 13, where the arrows denoting the average direction of littoral drift converge. Watson (1971) showed that the location of Big Shell and Little Shell beaches at the zone of convergence is not coincidental. Sand and shells moved by littoral drift converge at this point and are funneled ashore by

hydrologic forces. Once ashore, the sand shell mixture is separated by eolian transport. The sand is blown landward, leaving the shell on the beaches.

Morton (1977) further confirmed this hydrologic and sediment movement pattern in long-term studies of Texas gulf shoreline changes. Over a 120-year period the zone of convergence was an area of net accretion while much of the rest of the coastline displayed a long-term erosional trend. Morton and Pieper (1975, 1977a, 1977b) measured long-term erosion rates of 1.5 to 4.5 m (5 to 15 ft) per year from Brazos Santiago Pass to Mansfield Channel, and 0.0 to 1.5 m (0.0 to 5 ft) per year from Mansfield Channel to the Land Cut Area. The beach was accreting above the Land Cut to a point 20 km (12.5 mi) north of Yarborough Pass. Northward to the northern boundary of the basin there were areas of accretion and erosion.

Laguna Madre basin economy. Conparative measures of the Laguna Madre economy are given in Table 10. The population of the Laguna Madre basin in 1980 was 346,453 persons, an increase of 24 percent over the 1970 (Bureau of the Census 1982). A 35 percent increase in the population is expected by the year 2000 (Texas Department of Water Resources 1980d). The basin's population is concentrated in several urban areas and portions of two populous counties, Cameron and Nueces. Population densities in these counties will be nearly 255 per sq km (400 per sq mi) by the year 2000. In contrast, population densities in Willacy and Kleberg counties are expected to be only 22.1 per sq km (35.7 per sq mi) and 26.3 per sq km (42.3 per sq mi) by 2000. The population density of Kenedy County is presently 0.2 per sq km (0.4 per sq mi) and is expected to decrease by the year 2000.

Mineral production is probably the most important aspect of the basin's economy. In 1977 the value of produced minerals was $625 million (Liebow et

Table 10. Economic data for the Laguna Madre basin.

Data type	Quantity
1970 Population	279015
1977 Population	317456
1980 Population	355795
1990 Population projection	402829
2000 Population projection	470896
Mineral production (X $1000)	624578
Deer harvest	1963
Travel expenses (X $1000)	147822
Travel employment	5305
Sportfishing expenditures (X $1000)	8686
Commercial fishing value (X $1000)	2669
Electrical generating capacity (kw)	945565
Total employment	122167
Number of building permits	1961
Length of railroad track (km)	367
Length of highways (km)	8142
Number of vehicles registered	267509
Commodity flows (1000 metric tons)	652
Number of farms	2184
Market value of products (X $1000)	118065
Area of irrigated land (ha)	122394

al. 1980). Recreation and tourism is also a strong economic sector in the basin. Hunting and sportfishing are significant recreational industries (Table 10). More than 4 percent of the basin's work force is employed in travel-related jobs, and expenditures on travel within the basin amounted to $148 million in 1977 (Liebow et al. 1980).

The basin's commercial fishing industry is small. The direct economic value of the commercial fushery catch in the basin was $2.7 million in 1977 (Texas Department of Water Resources 1983b). Finfish have been an important part of the commercial catch in the basin, but since severe limitations were placed upon commercial netting, finfish harvest has become less important than shellfish harvest. Stokes (1974) notes that there is a sizable shrimp fishery in the southern Laguna Madre, and Liebow et al. (1980) report a significant shrimp catch from the gulf, although it may not be landed in the basin.

There is a moderate level of commercial and industrial development in the basin, mostly associated with the growing urban areas in Cameron County. Total employment in 1977 was 122,167 persons, and 1961 building permits were issued (Liebow et al. 1980).

Transportation figures for this basin, reflect personal transportation needs rather than commercial traffic. There are 0.85 vehicles registered per person in the basin. Highway and railroad length (8142 and 367 km or 5059 and 228 mi respectively) reflect the large size of this basin and not the level of commerce. Commodity flow on waterways, 652,000 metric tons, is low and is mostly related to oil and gas production in the region (Liebow et al. 1980).

Agriculture is a major economic sector. The total annual market value of all products sold from the basin's 2184 farms in 1974 was $118 million (Liebow

et al. 1980). The area of irrigated land in 1979 was 1224 sq km (472 sq mi), 43 percent of the cropland area (Pfluger et al 1981).

Resource demands in the Laguna Madre basin. Resource demand information is given in Table 11. Agriculture's importance to the basin is evident from the amount of land allocated to agricultural use: cropland occupies 28 percent of the upland area and range constitutes 64 percent. Recreational land in the Laguna Madre basin, which may partially be included in the areas for range, windtidal flat, and barrier, constitutes 737 sq km (285 sq mi), or 58 percent of all the recreational lands in the region.

Mineral production in the Laguna Madre basin is high. Since 1926, when mineral development began in the basin, 169 million kiloliters of crude oil have been produced. In 1977 the crude production was 972,429 kiloliters, nearly 0.6 percent of the cumulative production. Natural gas and casinghead gas production is also high; 15,667 million cu m were produced in 1977 (Liebow et al. 1980).

While some fishery products are harvested in the basin, most biomass produced comes from farming and cattle production. More than 825,000 kiloliters of grain are harvested from the basin annually. In 1977, 56 percent of the cotton grown in the region, or 241,926 bales, was produced in this basin, and the hay harvest was 38,903 metric tons. In the same year 107,196 cattle and calves were sold. The density of cattle and calves on the basin's rangeland is 16.7 animals per sq km. This low density suggests that cattle and calves are allowed to graze the range and are not kept in feedlots (U.S. Department of Agriculture 1980).

Fishery products from the estuarine area are mainly blue crabs (442,250 kg) and fish (589,667 kg). The sportfishing catch averaged 291,613 kg over a

Table 11. Resource demands in the Laguna Madre Basin.

Resource demands	Quantity
Cropland area (ha)	287352
Range area (ha)	643602
Urban area (ha)	31352
Recreation area (ha)	73740
Crude oil production (kiloliters)	972429
Natural and casinghead gas (million cu m)	15667
Condensate (million liters)	160
1902-1978 oil production (million kiloliters)	169
Grain production (kiloliters)	825751
Cotton production (bales)	241926
Hay produced (metric tons)	38903
Peanuts produced (kg)	0
Rice produced (metric tons)	0
Cattle and calves sold	107196
Bay shrimp harvested (kg)	0
Bay oysters harvested (kg)	4082
Bay crabs harvested (kg)	442250
Bay commercial fish harvested (kg)	589667
Bay sport fish landed (kg)	291613
Total commercial fish harvested (kg)	1800000
Total commercial shellfish harvested (kg)	396500

Table 11 (continued). Resource demands in the Laguna Madre Basin.

Resource demands	Quantity
Digestive cancer mortality	125
Lung cancer mortality	137
Pneumonia and influenza mortality	91
Emphysema, bronchitis, and asthma mortality	38
Length fishable, swimmable stream segments (km)	0
Percent fishable, swimmable stream segments (%)	0
Airborne particulates (metric tons)	54910
Airborne hydrocarbons (metric tons)	56116
Waste discharge measured as 5-Day BOD (kg)	706026
Number of discharges	58
Cumulative industrial solid waste (metric tons)	1090578
Subsidence of land surface (m)	None
Municipal surface water use (million cu m)	67
Municipal groundwater use (million cu m)	9
Manufacturing surface water use (million cu m)	8
Manufacturing groundwater use (million cu m)	1
Irrigation surface water use (million cu m)	1230
Irrigation groundwater use (million cu m)	25
Total surface water use (million cu m)	1311
Total groundwater use (million cu m)	43
Municipal, manufact. return flow (million cu m)	49
Agricultural return flow (million cu m)	0
Obstructions to runoff, roads + railroads (km)	8509
Major drainage ditches and canals (km)	1673
Maintenance spoil, historical average (cu m)	2087181
Length of dredged channels (km)	416

two-year period (Liebow et al. 1980). The total commercial fish catch (lagoon plus gulf) was 1.8 million kg of fish and 396,500 kg of shellfish (Texas Department of Water Resources 1983b).

Public health statistics show that there were 125 deaths from digestive cancers and 137 deaths from lung cancer in the basin in 1977. This is less than the mortality rate that occurs for the state as a whole or for the Texas Barrier Island Region. Mortality due to pneumonia and influenza (91) and emphysema, bronchitis, and asthma (38) is about the same as for the state as a whole.

The major freshwater stream segment monitored by the Texas Department of Water Resources is the Arroyo Colorado. Since flows in this segment depend upon municipal, industrial, and agricultural return flows and storm runoff, water quality problems often occur. High coliform counts pose potential health problems and make the entire segment unfishable and unswimmable.

Waste materials released into the atmosphere in 1973 included 54,910 metric tons of airborne particulates and 56,116 metric tons of hydrocarbons (Texas Air Control Board 1977). There are 57 waste discharges into basin waters: 20 into the Laguna Madre, 14 into Baffin Bay, and 23 into the Arroyo Colorado; 44 of these discharges are from municipal waste treatment plants (Texas Department of Water Resources 1984). The waste delivered to the basin's waters, measured as 5-day BOD levels, was high and totaled 706,026 kg for 1983. In addition to high coliform levels, the Arroyo Colorado is occasionally eutrophic because of high nitrogen and phosphorus levels. It also receives pesticide residues and heavy metals in excess of recommended safe levels (Texas Department of Water Resources 1983a). A cumulative total

of more than one million metric tons of solid wastes have been disposed in this basin.

Water use in the basin is shown in Table 11. Nearly 97 percent of the basin's water comes from surface sources; nearly 93 percent is used for irrigation of cropland. The majority of the water consumed in the basin comes from the Rio Grande River; most diversion points are upstream of the Rio Grande basin. The total volume of agricultural water use in the basin is 1255 million cu m per year. While more than 50 million cu m flows back into streams, it is of high enough salinity that it is not useable as fresh water. Consequently the return flow from agriculture is considered to be zero (Texas Department of Water Resources 1977).

Land surface hydrology has been altered by placement of roads, railways, and canals. Road and railway obstructions to flow amount to more than 8509 km (Liebow et al. 1980); drainage and irrigation canal length is 1673 km although it is probably higher since only major water systems were measured. Over the entire basin the density of these obstructions is 156 km per 100 sq km for roads and railroads, and 18 km per 100 sq km for ditches and canals. Most of the area containing these features is in the southern third of the basin.

Estuarine hydrologic modification is attributable to 416 km of dredged channels. The average annual maintenance of channels in the basin produces 2,087,181 cu m of spoil each year. Spoil piles in some areas--the northern Laguna Madre, for example--cause major changes in the flow patterns of the shallow estuarine system.

Corpus Christi Basin

Location and description. The Corpus Christi basin has an area of 2189 sq km (845 sq mi). It contains parts of three hydrologic systems defined by

the Texas Department of Water Resources (1977), but is much smaller than the main contributing hydrologic unit known as the Nueces Basin (43,900 sq km or 16,950 sq mi) which stretches northwest more than 210 km (130 mi) to the Balcones Escarpment.

The southern boundary of the basin is a natural drainage divide that separates Petronila Creek and Oso Creek about 15 km south of the southern shoreline of Corpus Christi Bay. The northern boundary is a line that parallels and is about 5 km (3.2 mi) north of the edge of the Nueces River valley and the northern boundary of Nueces and Corpus Christi bays. This boundary line separates drainage areas that flow into the Nueces River from those that drain into Copano Bay. The northern boundary includes the southern half of Redfish Bay. It follows a line of spoil disposed from the dredging of a channel to the city of Aransas Pass and the construction of a highway across Harbor Island to Port Aransas. The basin contains about one-half of Nueces County and one-third of San Patricio County. About two-thirds of the basin is upland, 16 percent is estuarine habitat, and 15 percent is gulf. Lake and freshwater wetland areas and spoil areas each constitute about 1 percent of the basin.

The Corpus Christi basin is half as wide as it is long and is a classic estuarine system with a single river that flows through the uplands and enters the bay through a delta. At its inland boundary the upland portion of the basin is 27 to 30 m (90 to 100 ft) in elevation. A deep, narrow river valley with steep walls separates the fluvial area from the uplands. The Nueces River delta is 4 to 5 km wide and opens into Nueces Bay, a secondary bay that joins Corpus Christi Bay. Like the river valley, the uplands adjacent to the

bay are high with steep slopes. Bluffs overlooking Nueces Bay are 12 to 18 m (40 to 60 ft) in elevation.

At the point where Nueces Bay opens into Corpus Christi Bay, the upland elevation is about 10 m (32 ft) and the land slopes seaward. The opening into Corpus Christi Bay is about half the width of Nueces Bay and is spanned by an elevated causeway and an old railroad trestle. Corpus Christi Bay has approximately four times the area of Nueces Bay and is about twice as wide and long. Oso Bay, a smaller secondary bay, opens into Corpus Christi Bay at the south and receives drainage from Oso Creek. The land reaches a low point in the area of Oso Bay on the southern shore of Corpus Christi Bay and at a point almost directly opposite along the northern shore. This low area is about 4 or 5 km from the mainland shoreline which parallels the gulf along the northern Laguna Madre and Redfish Bay. Seaward of this area, the land elevation rises several meters then falls to sea level at the mainland shoreline. This long, narrow strip of elevated land--known as Encinal Peninsula on the south side of Corpus Christi Bay and as Live Oak Ridge on the north--was a barrier island or strandplain on the gulf during a previous interglacial period.

Mustang Island separates the bay and gulf, but Aransas Pass, a dredged and stabilized channel, permits water exchange between them. This pass also provides water exchange with the Aransas-Copano basin immediately to the north.

An inlet tidal delta, Harbor Island, is located just east of Aransas Pass. Plate 3 shows it as an area of spoil, urban land, and wind-tidal flat near the northeastern corner of the map. This delta is barely above mean sea level and shelters grassflats and shallow bay areas behind it.

Upland sediments in the Nueces River valley are clayey silt and sand with moderate permeability and water-holding capacity. Other areas on the uplands that were once ancient fluvial and distributary systems have the same sediment type. The surface sediments between these old river and stream channels are clay and mud with low permeability and high water-holding capacity. More than half of the upland sediments are muds and clays. Sediments on the mainland shore along Encinal Peninsula and Live Oak Ridge and on Mustang Island are sand with high permeability and low water-holding capacity.

Plate 3 shows 17 habitats in the Corpus Christi Basin. The largest single habitat is cropland, which constitutes 957.5 sq km (369.7 sq mi), or 43.7 percent of the basin's area. It stretches from the inland boundary of the basin to the area of Oso Bay along the southern shore, and from the inland boundary to a parallel position along the northern shoreline of Corpus Christi Bay. On the northern side of Nueces Bay and the Nueces River valley, cropland extends to the edge of the bluff overlooking the bay. On the southern side of Nueces and Corpus Christi bays, urban land is immediately adjacent to the bay system. The entire southern shoreline of both bays is urban area comprising 5.4 percent of the basin's area, or 118.4 sq km (45.7 sq mi).

Range, which occupies 303.5 sq km (117.2 sq mi), or 13.9 percent of the basin's area, is located in the Nueces River valley and in the area between the cropland and the mainland shoreline along the northern Laguna Madre and Redfish Bay. There are two areas of forest in this basin: the Nueces River valley and Live Oak Ridge. Live oak mottes are the predominant vegetation in the latter forest area. Small areas of freshwater wetlands are located to the

south of Oso Bay, in the Nueces River marsh, and adjacent to the Live Oak Ridge.

Barrier habitat within the basin occupies 56.5 sq km (21.8 sq mi). It includes the northern end of Padre Island and all of Mustang Island. Plate 3 shows urban habitat on the extreme northern and southern portions of Mustang Island. Today there is a high level of development over the entire island; condominiums, resort hotels, and single family residences are being built behind the foredunes and on the barrier flat.

The largest area of estuarine habitat, bay, covers 266 sq km (102.7 sq mi) within the basin. Wind-tidal flat (24.3 sq km or 9.4 sq mi) is located between the bay and the barrier habitat; there is also a small area of wind-tidal flat in the Nueces delta. The Corpus Christi basin is the most southern basin that contains a significant quantity of salt and brackish marsh; nearly 12 sq km of marsh are located on the Nueces delta. The basin contains 41.7 sq km (16.1 sq mi) of grassflat, most of which is located in the northern Laguna Madre. There is some grassflat in Redfish Bay west of Harbor Island. Grassflats, salt and brackish marsh, and the shallow bay areas in Nueces Bay are especially valuable nursery areas for juvenile shrimp and fish.

Some oyster reef is present in Corpus Christi and Nueces bays; however, many dead reefs were dredged for shell in Nueces Bay in the 1960's. Although some of the reefs still contain live oysters, there is no commercial oyster fishery as there was 25 years ago. Subaerial spoil accounts for 15.5 sq km (6 sq mi) of area in the basin. Most of the spoil shown in Plate 3 is located along the Corpus Christi Ship Channel, the intracoastal waterway, the Aransas Channel, and the causeway connecting Padre Island with the southern shore of the mainland. Spoil placed in this bay system has significantly altered the

hydrology. Some urban land at the edge of Nueces Bay has been built upon spoil dredged from the 138.1 km (85.8 mi) of dredged channel in the basin.

A complete list of the habitats present in this basin and their areas is given in Table 12. The Corpus Christi basin has more than twice the relative amount of cropland as the Texas Barrier Island Region as a whole (Figure 49). It also has relatively more bay, urban land, and grassflat than the region. It has about half the proportionate amount of range and smaller proportions of gulf, forest, lake and reservoir, and wind-tidal flat. The basin contains no swamp habitat. Its remaining habitats are small and occur in proportions similar to those for the whole region.

Geological development. Most of the uplands in the Corpus Christi basin come from fluvial-deltaic sediments that were deposited during the Sangamon interglacial period when the Nueces River carried a heavy load of sediment and frequently flooded its banks (Brown et al. 1976). Some of the deposits in the northwest corner of the uplands of the basin (Plate 3) may have been part of a relict delta lobe deposited by the San Antonio River during earlier periods.

During the Early Wisconsin glaciation (125,000 to 75,000 yr BP) following the Sangamon interglacial period, the Nueces River eroded a deep valley along the path of its present river valley. When sea level rose during the Peorian interglacial stage, the Nueces River emptied directly into the gulf, and a barrier strandplain developed on either side of the river mouth. This barrier strandplain is still visible today as the sandy, elevated Encinal Peninsula and Live Oak Ridge.

When the last glaciation, the Late Wisconsin (55,000 to 18,999 yr BP), lowered sea level again, the river cut a deep valley at about the same

Table 12. Habitat areas and lengths in the Corpus Christi basin.

Habitat	Area sq km	Length km	Percent of basin area
Barrier	56.5		2.6
Bay	266.0		12.2
Bulkhead	4.1		0.2
Channel and tidal stream		138.1	
Cropland	957.5		43.7
Forest	27.5		1.3
Freshwater marsh	11.1		0.5
Grassflat	41.7		1.9
Gulf	329.7		15.1
Lake and reservoir	17.4		0.8
Range	303.5		13.9
Reef	4.4		0.2
River and canal		191.5	
Salt and brackish marsh	11.9		0.5
Spoil	15.5		0.7
Swamp	0.0		0.0
Urban	118.4		5.4
Wind-tidal flat	24.3		1.1

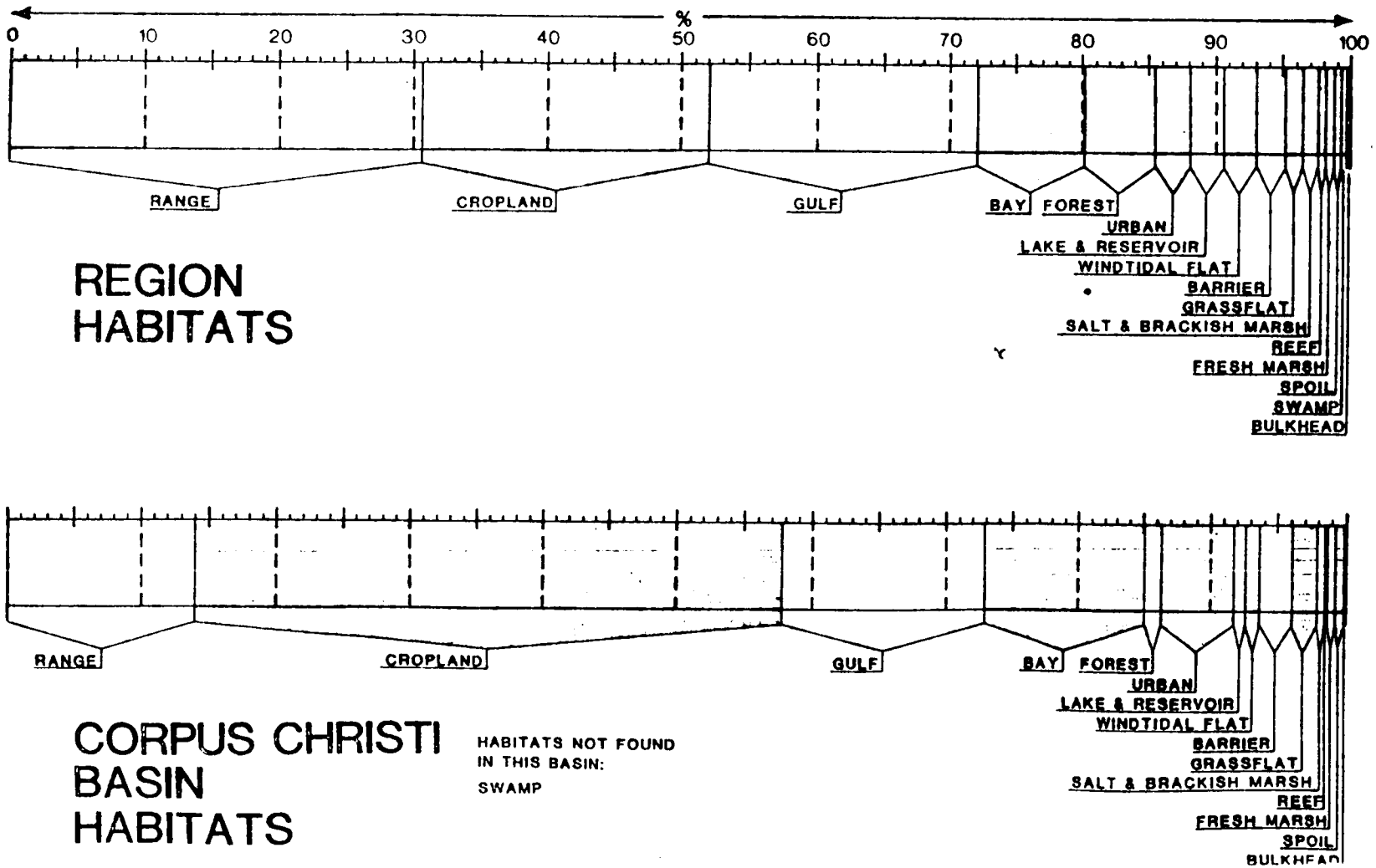


Figure 49. Habitat proportions of the Corpus Christi basin and Texas Barrier Island Region.

location as before. As the sea rose during the Holocene, sediment was carried into the river valley by fluvial processes. As sea level approached its present position, sediment eroded from the river valley walls was added to that carried by the river. By 2500 yr BP gulf sediment was being transported toward the bay to form the barrier island, and eolian processes were moving sediment inland. The combination of all these erosion and transport forces over the last 2000 years has given the basin the shape it has today.

Basin climate and hydrology. The climate of the Corpus Christi basin is warm and dry but more moderate than that of the Laguna Madre basin to the south. The average yearly temperature is 22 deg C (72 deg F); the average summer high and winter low temperatures are 29 deg C (84 deg F) and 13 deg C (56 deg F) respectively (Williams et al. 1976).

Average rainfall in the basin is 76 cm (30 in) per year (Williams et al. 1976). September has the highest average rainfall, 15 cm (6 in); August and October each usually have slightly more than half that amount. May and June also have high rainfall amounts, averaging about 8 cm (3 in) (Bomar 1983). Evapotranspiration causes a deficit of about 46 cm (18 in) of precipitation each year (Woodruff 1975). Evaporation from the bay equals 56 percent of the total freshwater inflow to the system from river flow and rainfall (Texas Department of Water Resources 1983a).

Most of the freshwater flow into the basin comes from the Nueces River; Oso Creek flow equals only about 3 percent of the Nueces flow (Dougherty 1980). The average gaged flow is 775 million cu m per year (Texas Department of Water Resources 1983a); extreme low and high flows vary from 13 to 402 percent of the average flow volume (Dougherty 1980). The sum of gaged, ungaged, and return flows, less the amount diverted, amounts to 850 million cu

m per yr. When evaporation is included, the net annual freshwater inflow is 509 million cu m (Texas Department of Water Resources 1983a). Sediment carried by the inflowing water is low, 18,744 metric tons per yr (Cook 1967, 1970).

The pattern of water flow is bimodal. The greatest river flow typically occurs during September and the second highest flow during October. May and June each have about two-thirds of the flow of September and October, but much higher flows than the winter and early spring months.

Freshwater flow down the Nueces River is controlled at Lake Corpus Christi, a large reservoir just west of the basin. This reservoir catches water from a large area of south Texas. Water diverted from the Nueces River is sent to urban and industrial users in Corpus Christi and in the Laguna Madre basin to the south. The flow of water released to the Nueces River is occasionally high enough to inundate the Nueces Delta (Figure 50). Some water drains back into the river and tidal portions from the surrounding uplands, but the flow from the dam is the most important water source.

Return flows, mostly from municipal and manufacturing uses, enter Nueces and Corpus Christi bays and mix with the estuarine waters there; the return flows are much smaller than the gaged flows. Figure 50 illustrates the hydrologic distribution pattern in the basin.

Nueces Bay is long, narrow, and shallow, generally less than 1.5 m (5 ft) deep. Sediment in the deeper middle portions of the bay is mud but is sandier toward the shallow edges (McGowen and Morton 1978). The river enters the bay at the southern side of the delta, which floods only during periods of extreme river flow. Circulation in Nueces Bay is wind-driven with some river

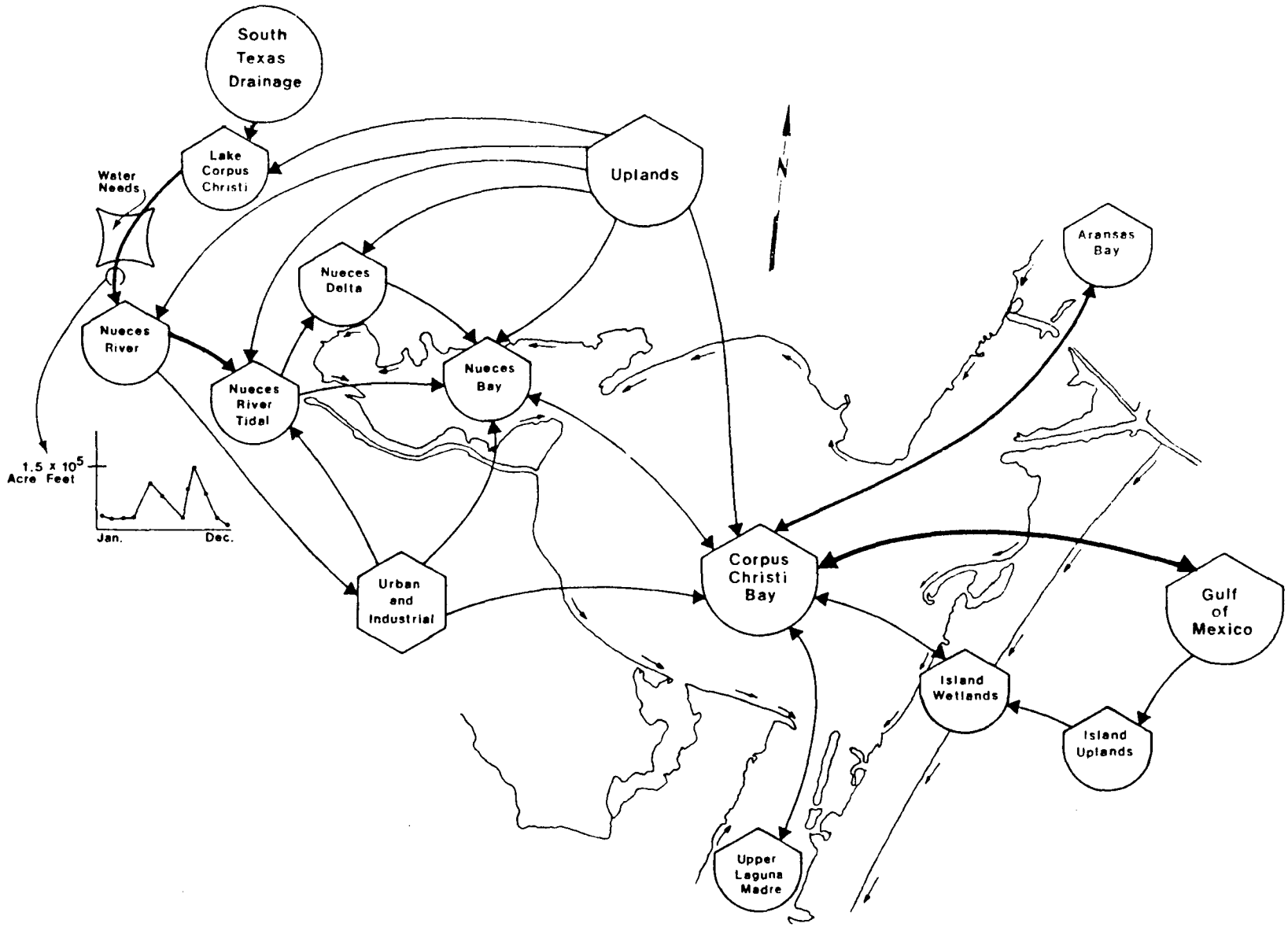


Figure 50. Hydrology of Corpus Christi Bay.

influence; tidal influence is very low. During periods of normal southeast winds there is counterclockwise circulation in the lower portion of Nueces Bay. Under high flow conditions the general flow direction is toward Corpus Christi Bay (Texas Department of Water Resources 1980a). Areas of both erosion and accretion occur along the northern shoreline of Nueces Bay; erosion rates are not currently available (Brown et al. 1976; Texas Department of Water Resources 1980a).

Salinity in the basin is highly variable. The average salinity over the past four years has been 23.3 ppt within a range of 1.5 to 37.9 ppt (Texas Department of Water Resources 1983a). Figure 51 shows some typical salinity contours for Nueces Bay and the other water bodies of this basin (Brown et al. 1976).

Corpus Christi Bay is somewhat circular in shape and relatively deep (Figure 52). The depth of much of the bay exceeds 4.3 m (14 ft). Most of the bottom sediments are mud (McGowen and Morton 1978), but there are a few areas of shelly mud, and the shallow edges of the bay are sandy.

Tidal influence in Corpus Christi Bay varies with distance from the tidal pass. Close to the tidal pass and some distance along the channel to Corpus Christi, tidal influence is strong (Texas Department of Water Resources 198Ca). At the western end of Corpus Christi Bay, tidal influence is weak and freshwater inflows and wind circulation patterns dominate. The Texas Department of Water Resources (1982) hydrologic models show two circulation vortices in the bay: a clockwise pattern in the southern area off Oso Bay, and a counterclockwise pattern between the ship channel and the northern shore of the bay. Currents near the connection with the Laguna Madre are strong and generally move from the Laguna to Corpus Christi Bay. The hydrologic models

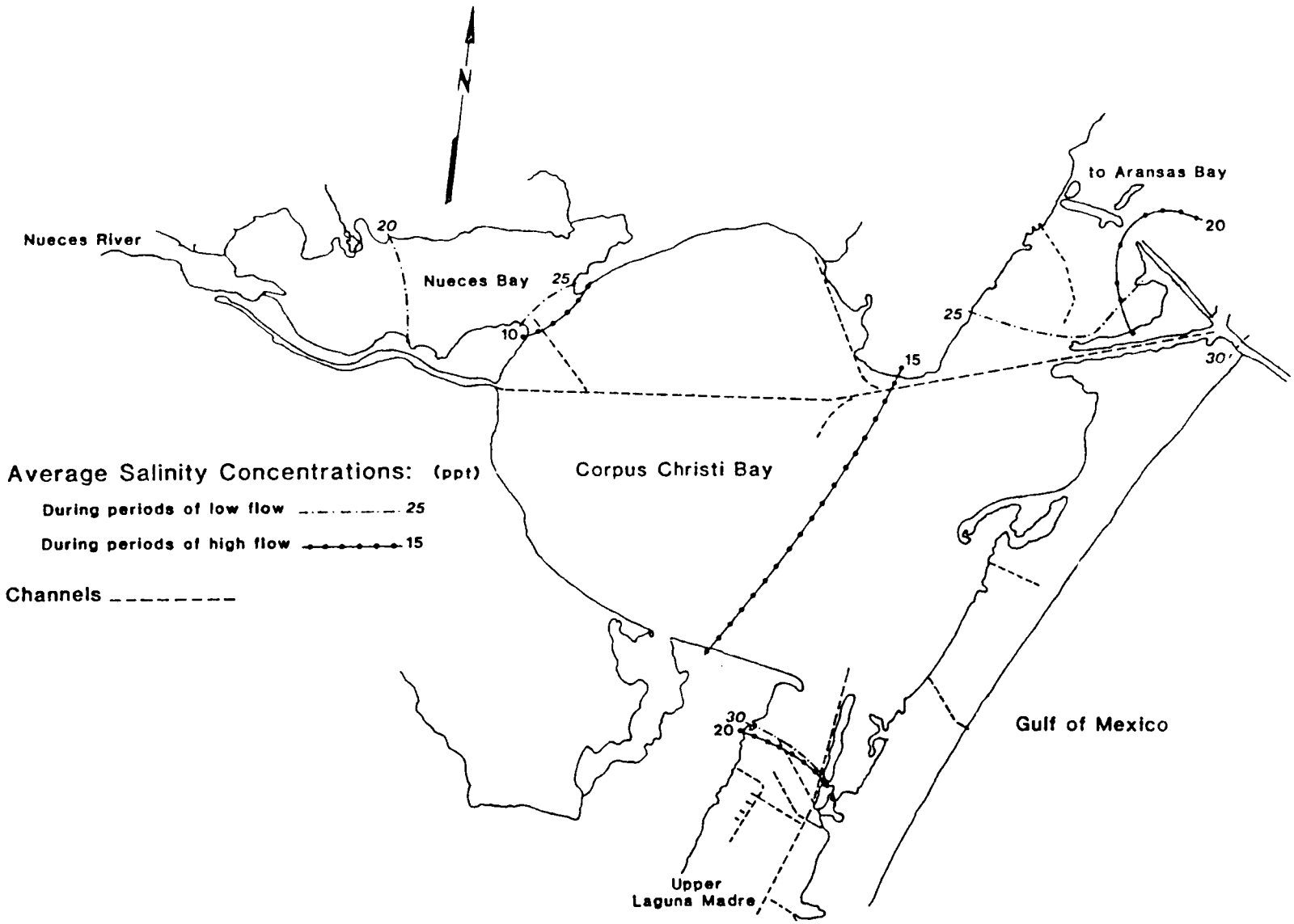


Figure 51. Salinity variation in the bays of the Corpus Christi basin.

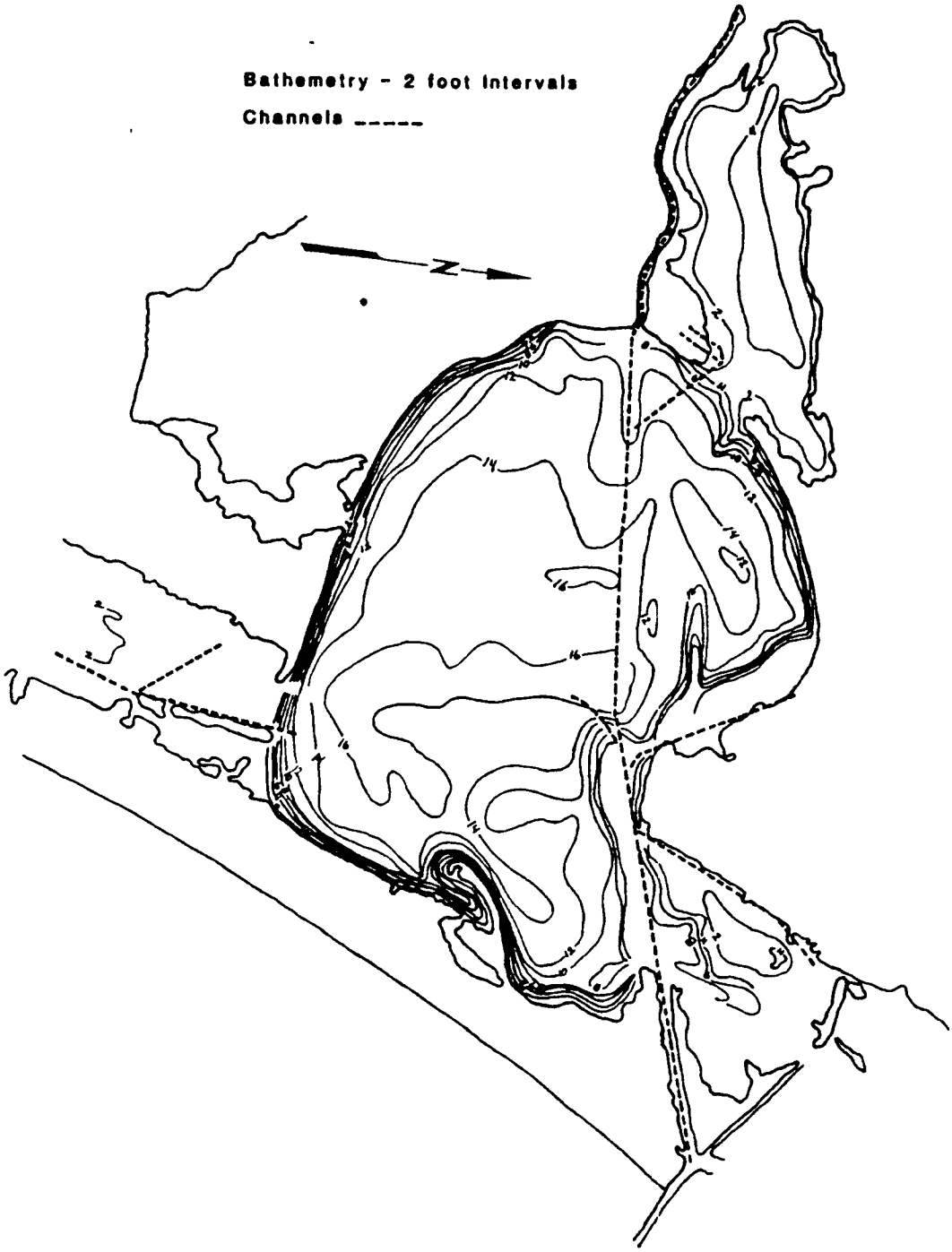


Figure 52. Bathymetry of bays in the Corpus Christi basin.

show that water flows into the Laguna only during September, when there is high flow down the Nueces River.

Erosion is a problem along the north and south shores of Corpus Christi Bay because of the long fetch across the bay. Bulkheads have been erected for erosion control in some places.

The southern half of Redfish Bay is 0.6 to 1.2 m (2 to 4 ft) deep except for an area off the Corpus Christi Ship Channel that is 3 m (10 ft) deep. Sediments in this bay are a mixture of sand and mud, shell and mud, or all three. Water usually flows north through Redfish Bay and passes through Morris and Cummins Cut and Corpus Christi Bayou, two openings in the spoil and highway fill that bisects Redfish Bay.

The stabilization of Aransas Pass, the dredging of the ship channel, and the placement of spoil along the ship channel and across Redfish Bay have contributed to a major change in the hydrologic pattern of the bay. Before these modifications were made, Packery Channel, Newport Pass, and Corpus Christi Pass were the natural outlets for flow between Corpus Christi Bay and the gulf (natural passes are usually located on the southeastern portion of bays). Aransas Pass received some flow from Corpus Christi Bay, although it functioned more for Aransas and other bays to the north than for Corpus Christi Bay.

When Aransas Pass was stabilized and the ship channel dredged, the major direction of flow changed from the southern passes to Aransas Pass. The presence of the pass and the deep channel probably increased the overall mixing of bay and gulf waters and the tidal flux in the bay. In the early 1970's a fish pass was dredged across Mustang Island to provide a second

outlet for passage of estuarine species that spend part of their life cycle in the gulf; the pass was also supposed to increase circulation in the southeastern end of the bay. It served neither purpose, however, because it continuously filled with littoral sediment. Studies by Watson and Behrens (1976) showed that the fish pass was dominated by flood tides and its channel was so long that the sediment was deposited before it could reach the flood-tidal inlet delta.

Within the Corpus Christi basin, the floor of the gulf slopes sharply near the beach and then more gently to the gulf boundary. Depth at the three-league line ranges from 21 to 24 m (72 to 79 ft). The sediments are sandy within 5 km of the gulf shoreline. They become progressively muddier offshore and are predominantly mud at the gulfward boundary. Circulation in the gulf varies seasonally and is strongly influenced by the wind (Watson and Behrens 1970; Temple and Martin 1979). Over a year's period, the average direction of flow in the gulf is to the south, although obstructions such as jetties may alter the flow direction locally.

Erosion is the dominant pattern on the gulf beach (Morton and Pieper 1976, 1977). Except for accreting areas immediately adjacent to the jetties at Aransas Pass, and another spot opposite Packery Channel, long-term erosion is occurring at rates of 0 to 1.5 m (0 to 5 ft) per year.

Corpus Christi basin economy. The 1980 population of the Corpus Christi basin was 156,939 persons. Population growth of 19 percent is expected by the year 2000. Population growth during the last decade was 14 percent, so the growth rate is slowing somewhat. Population projections are given in Table 13.

Table 13. Economic data for the Corpus Christi basin.

Data type	Quantity
1970 Population	137818
1977 Population	146195
1980 Population	156939
1990 Population projection	168554
2000 Population projection	187227
Mineral production (X $1000)	129543
Deer harvest	272
Travel expenses (X $1000)	76584
Travel employment	2729
Sportfishing spending (X $1000)	17029
Commercial catch value (X $1000)	23736
Electrical generating capacity (kw)	782423
Total employment	62618
Number of building permits	1223
Length of railroad track (km)	114
Length of highways (km)	2776
Number of vehicles registered	139170
Commodity flows (1000 metric tons)	50963
Number of farms	589
Market value of products (X $1000)	36150
Area of irrigated land (ha)	249

Mineral production is an integral part of the basin's economy. The basin has many oil and gas wells, and some production from offshore comes into the basin. The value of minerals produced in the basin was nearly $130 million in 1977 (calculated from Liebow et al. 1980).

Tourism and recreation is a profitable sector of the economy. In 1977 travel expenditures in the basin amounted to nearly $77 million, although only 2 percent of the population is employed in travel-related jobs. Sportfishing expenditures were greater than $17 million in 1977, and hunters harvested 272 deer in an area with only 303.5 sq km of range (calculated from Liebow et al. 1980).

Commercial fishing makes a significant contribution to the basin's economy, although the figures calculated from Texas Department of Water Resources (1980a) combine the direct commercial value of fisheries in this basin and in the Aransas-Copano basin to the north. The combined total, calculated from 4-year catch statistics, was nearly $24 million in 1976.

Total employment in the basin in 1977 was 62,618, about 43 percent of the population. A significant amount of construction occurred in 1977, with 1223 building permits issued (calculated from Liebow et al. 1980).

Waterborne transportation is also a major feature of the economy. While the basin has 114 km (71 mi) of railroad track and 2776 km (1725 mi) of highways, shipping is the most significant part of the transportation sector. In 1977 nearly 51 million metric tons of commodities passed through the basin's navigation channels on barges and ships (RPC, Inc. 1980).

Since 43.7 percent of the basin is agricultural land, farm production also contributes heavily to the basin's economy. The market value of production from the 589 farms in the basin was more than $36 million in 1974.

Most of the production was from nonirrigated fields since less than 250 ha of land was irrigated.

Resource demands. The demand for land in the basin is strong. More than 65 percent of the basin's land is cultivated, almost 21 percent is range, and 8 percent is urban (see Table 14). Although there are a number of areas with large quantities of recreational land in adjacent basins, only about 1400 ha of land in the Corpus Christi basin is available for recreational use.

The demand for minerals in the basin is high. Most of the production is crude oil; more than 400,000 kiloliters was produced in 1977. About 2500 million cu m of natural and casinghead gas was produced in 1977 (Table 14). The cumulative amount of oil produced from this basin since production began in 1928 is 115 million kiloliters.

Agricultural biomass produced in 1978 was chiefly grain (272,722 kiloliters) and cotton (58,771 bales). Some hay was also grown (12,877 metric tons), and 17,768 cattle and calves were sold in 1978 (Bureau of the Census 1980). Biomass production from the bays and gulf was dominated by commercial shellfish harvest. The combined catch from the Corpus Christi and Aransas-Copano basins was more than 7 million kg using average figures for 1972 to 1976 harvests (Texas Department of Water Resources 1980a). The 1977 fishery yield from the basin's estuarine waters was 546,576 kg of shrimp, 181,436 kg of commercial fish, and 46,720 kg of crab (calculated from Liebow et al. 1980).

Public health indicators show some incidence of mortality from cancers and respiratory diseases (National Center for Health Statistics 1981). Mortality from emphysema, bronchitis, and and asthma is about 50 percent

Table 14. Resource demands in the Corpus Christi basin.

Resource demands	Quantity
Cropland area (ha)	95793
Range area (ha)	30368
Urban area (ha)	11841
Recreation area (ha)	1355
Crude oil production (kiloliters)	400073
Natural and casinghead gas (million cu m)	2455
Condensate (million liters)	90
1902-1978 oil production (million kiloliters)	115
Grain production (kiloliters)	272722
Cotton production (bales)	58771
Hay produced (metric tons)	12877
Peanuts produced (kg)	0
Rice produced (metric tons)	0
Cattle and calves sold	17768
Bay shrimp harvested (kg)	546576
Bay oysters harvested (kg)	0
Bay crabs harvested (kg)	46720
Bay commercial fish harvested (kg)	181436
Bay sport fish landed (kg)	79605
Total commercial fish harvested (kg)	866600
Total commercial shellfish harvested (kg)	7200000

Table 14 (continued). Resource demands in the Corpus Christi basin.

Resource demands	Quantity
Digestive cancer mortality	91
Lung cancer mortality	108
Pneumonia and influenza mortality	43
Emphysema, bronchitis, and asthma mortality	36
Length fishable, swimmable stream segments (km)	80
Percent fishable, swimmable stream segments (%)	100
Airborne particulates (metric tons)	24036
Airborne hydrocarbons (metric tons)	86482
Waste discharge measured as 5-Day BOD (kg)	1606281
Number of discharges	47
Cumulative industrial solid waste (metric tons)	1299815
Subsidence of land surface (m)	0.0-1.5
Municipal surface water use (million cu m)	52
Municipal ground water use (million cu m)	32
Manufacturing surface water use (million cu m)	33
Manufacturing ground water use (million cu m)	4
Irrigation surface water use (million cu m)	85
Irrigation ground water use (million cu m)	495
Total surface water use (million cu m)	176
Total ground water use (million cu m)	563
Municipal, manufact. return flow (million cu m)	33
Agricultural return flow (million cu m)	12
Obstructions to runoff, roads + railroads (km)	2890
Major drainage ditches and canals (km)	370
Maintenance spoil, historical average (cu m)	777837
Length of dredged channels (km)	109

higher than for the state as a whole, and mortality from lung cancer is 14 percent higher than the state average. However, 100 percent of the 80 km of freshwater stream segments in the basin have excellent water quality and are fishable and swimmable; the only occasional problem is high nutrient levels in the tidal portion of the Nueces River (Texas Department of Water Resources 1983a).

The estuarine water quality is generally acceptable, although Nueces Bay has a moderate problem with heavy metals, and the Corpus Christi inner harbor sometimes has elevated nutrient and bacterial levels.

The quantity of waste materials carried in the air in this basin is relatively high. In 1974, airborne particulates totaled 24,036 metric tons; hydrocarbon quantity was 86,482 metric tons (Texas Air Control Board 1977). Waste loads placed into basin waters are also high. Five-day BOD measurements total more than 1.6 million kg of oxygen per year for 47 waste discharges (Texas Department of Water Resources 1984). Sixteen of these discharges are from domestic waste treatment plants. In addition to this waste load, the basin has received a total of nearly 1.3 million metric tons of industrial solid wastes (calculated from Liebow et al. 1980).

Some subsidence has been documented in the basin. The area most affected is the Saxet oil and gas field, where the maximum subsidence has been 1.5 m (5ft). Subsidence of 0.15 m (0.5 ft) or more has occurred over an area 12 km (7.5 mi) wide to the south of Nueces Bay. Because the subsiding area is centered on an oil and gas field with no water wells nearby, the subsidence is probably related to the withdrawal of minerals (Ratzlaff 1982).

Water use in the basin totals 739 million cu m per year (calculated from Texas Department of Water Resources 1977). Twenty-four percent of the water

comes from surface sources, the rest from groundwater.

The basin has a high density of land obstructions to drainage in the form of roads, railway beds, and drainage canals. Nearly 2900 km (1800 mi) of roads and railway beds are present, and there are 370 km (230 mi) of canals. In the bays, hydrologic modification has also been significant: 109 km of channel has been dredged in 348 sq km (134.5 sq mi) of estuarine habitat. The average annual maintenance spoil volume in the basin is slightly more than 777 thousand cu m (Belaire 1976).

Aransas-Copano Basin

Location and description. The Aransas-Copano basin is located north-northeast of Corpus Christi Bay and south-southwest of San Antonio Bay. The basin has an area of 4985 sq km (1925 sq mi) and contains about 73 percent of the area of the San Antonio-Nueces hydrologic unit defined by the Texas Department of Water Resources (1977). It includes most of Aransas and Refugio counties and part of Bee, Goliad, Nueces, and San Patricio counties.

The lower boundary of the basin is a line that parallels and is about 5 km (3.2 mi) north of the edge of the Nueces River valley and the northern boundary of Nueces and Corpus Christi bays. This line separates drainages that flow into the Nueces River from those that drain into Copano Bay. The lower boundary takes in the northern half of Redfish Bay, following a line of spoil that was disposed from the dredging of a channel to the city of Aransas Pass and the construction of a highway across Harbor Island.

The upper boundary follows a drainage divide that is south of but parallel to the San Antonio River valley. The boundary begins about 4 km (2.5 mi) southwest of the abrupt edge of the San Antonio River valley near the

basin's inland boundary. It runs southeast to Blackjack Peninsula and then turns to the south-southwest and follows the topographic high to the peninsula's southwestern tip. The upper boundary separates streams that drain into Mission, Copano, St. Charles, and Aransas bays from those that drain into San Antonio Bay.

The Aransas-Copano basin has a very high proportion of land compared to water. Seventy-six percent of the area of this basin is upland; only 12 percent is estuarine and 9 percent is gulf. A little less than 3 percent of the basin's area is lakes or freshwater wetlands, and there is hardly any subaerial spoil. This basin contains the highest elevations found near the coast. One area in Bee County has an elevation of 44 m (145 ft); a second area, in Goliad County, has land as high as 41 m (135 ft). Most of the land near the inland boundary is 24 to 30 m (80 to 100 ft) in elevation. For the first 16 km (10mi) from the inland boundary toward the coast, the land slope is greater in this basin than in all others. However, an area about 10 km (6 mi) wide inland from Copano and Mission Bay has a gentle slope like the rest of the coastal region. Live Oak Peninsula between Copano and Aransas bays on the south, Lamar Peninsula between Copano and St. Charles bays, and Blackjack Peninsula east of St. Charles Bay all have elevated ridges parallel to the coast and are higher than the lands just inland of them. These peninsulas are all relict barrier-strandplain deposits formed on the gulf during a previous interglacial period. Their height is the result of sand collected in dunes and dune fields.

The Aransas-Copano basin does not have a major river system like the Corpus Christi basin to the south or the San Antonio basin to the north. It

is part of a relatively small natural drainage basin with a number of small creeks and rivers.

The basin contains five bay systems and several creeks that drain into them. In the southern portion of the basin, Port Bay runs parallel to and just west of Live Oak Peninsula. Port Bay drains a small area through McCampbell Slough and opens into Copano Bay on its southern edge.

Chiltipin Creek and the Aransas River join just before entering Copano Bay at its southwest corner; Chiltipin Creek drains the city of Sinton. On the northwest side of Copano Bay, the Mission River empties into Mission Bay, which in turn drains into Copano Bay. Copano Creek drains the north-central portion of the basin and empties into the northern part of Copano Bay.

Copano Bay opens into Aransas Bay, the largest water body in the system. St. Charles Bay is located at the northern end of Aransas Bay and splits Lamar and Blackjack peninsulas. Aransas Bay is a long, thin bay that narrows at its southern end and connects with the stabilized Aransas Pass through Lydia Ann Channel. This pass is the dividing point between San Jose Island on the north and Mustang Island on the south.

Both the northern and southern ends of San Jose Island are very low and are prone to washover by hurricane tides and bay floodwaters that follow hurricane rainfall. Except for a portion of the southern tip, San Jose Island is privately owned and accessible only by boat.

Between the basin's lower boundary and the Aransas River, the sediments are predominantly clay and mud. There are some areas of clayey sand and silt, but they make up less than half the surface sediments in this southern portion. The area between Live Oak Peninsula and Port Bay is predominantly clayey sand and silt, and the peninsulas themselves have sandy soils.

North of the Aransas River the clayey sand and silt predominates and there is relatively less clay and mud. Clayey sand and silt sediments have moderate permeability and moderate water-holding capacity. They are often found along old distributary channels. The clays and muds have low permeability and high water-holding capacity. They are usually interdistributary deposits from previous land flooding. The difference in sediment types of the northern and southern halves of the basin demarcate differences in the river systems that contributed soil to form the land surface. The difference in surface sediment types also divides the two major land habitats, range and cropland. Most range is located in the northern portion on the clayey sand and silt, while cropland is largely located in the southern portion on the mud and clay.

Eighteen habitats are represented in this basin (Plate 4). Table 15 lists the areas of the habitats and the percentages of the total basin area occupied by each. Range is the dominant habitat and comprises 2523.7 sq km (974.4 sq mi), or 50.6 percent of the basin's area. Range stretches from the inland boundary to Copano Bay and from the upper boundary to Chiltipin Creek. Except for two areas of cropland near Mission Bay and St. Charles Bay, the expanse of range is almost unbroken. South of Chiltipin Creek, cropland stretches from the inland boundary of the basin to Live Oak Peninsula. This large area of cropland is interrupted only by a few small areas of urban land and range. The basin contains 871.0 sq km (336.3 sq mi) of cropland, which makes up 17.5 percent of the total area.

A number of small urban areas are scattered throughout the basin. The inland urban areas are centers for farming and ranching; the major coastal

Table 15. Habitat areas, lengths, and proportions in the Aransas-Copano basin.

Habitat	Area sq km	Length km	Percent of basin area
Barrier	118.1		2.4
Bay	407.9		8.2
Bulkhead	0.3		< 0.1
Channel and tidal stream		206.5	
Cropland	871.0		17.5
Forest	184.9		3.7
Freshwater marsh	42.2		0.9
Grassflat	16.6		0.3
Gulf	437.2		8.8
Lake and reservoir	90.6		1.8
Range	2523.7		50.6
Reef	32.1		0.6
River and canal		313.0	
Salt and brackish marsh	78.0		1.6
Spoil	10.4		0.2
Swamp	1.6		< 0.1
Urban	99.7		2.0
Wind-tidal flat	72.5		1.5

urban area on Aransas Bay--Rockport and Fulton--is a center for recreational activities and contains many vacation and retirement homes. The urban habitat comprises 99.7 sq km (38.5 sq mi).

A significant amount of forest is located on the high sandy peninsulas and along many of the streams that flow into Copano Bay. Forest occupies 184.9 sq km (71.4 sq mi), or 3.7 percent of the basin's area.

The bay habitat comprises 407.9 sq km (157.5 sq mi), or 8.2 percent of the basin's area. Scattered at the edge of the bay are a number of salt and brackish marshes (78 sq km or 30.1 sq mi). The marshes are located in a number of small sloughs and creeks, on deltas of the Aransas and Mission rivers and Copano Creek, and along the edges of the peninsulas. There is a small amount of grassflat (16.6 sq km or 6.4 sq mi) in Redfish Bay.

There are a number of oyster reefs (32.1 sq km or 12.4 sq mi), largely located in Copano and Aransas bays. The magnitude of reef development is evidence that conditions conducive to reef expansion have existed in these areas for a long time.

A large area of wind-tidal flat (72.5 sq km or 30.0 sq mi) is located behind the barrier habitat. It is extensive in the southern portion but begins to diminish in the northern portion.

Compared to habitat proportions for the region as a whole, the Aransas-Copano basin contains two-thirds more range and slightly more salt and brackish marsh (Figure 53). The basin contains only about two-thirds as much cropland, half as much gulf, and three quarters as much forest. Most of the other habitats for which areal measurements are available occupy about the same proportion of area in the basin as in the entire region.

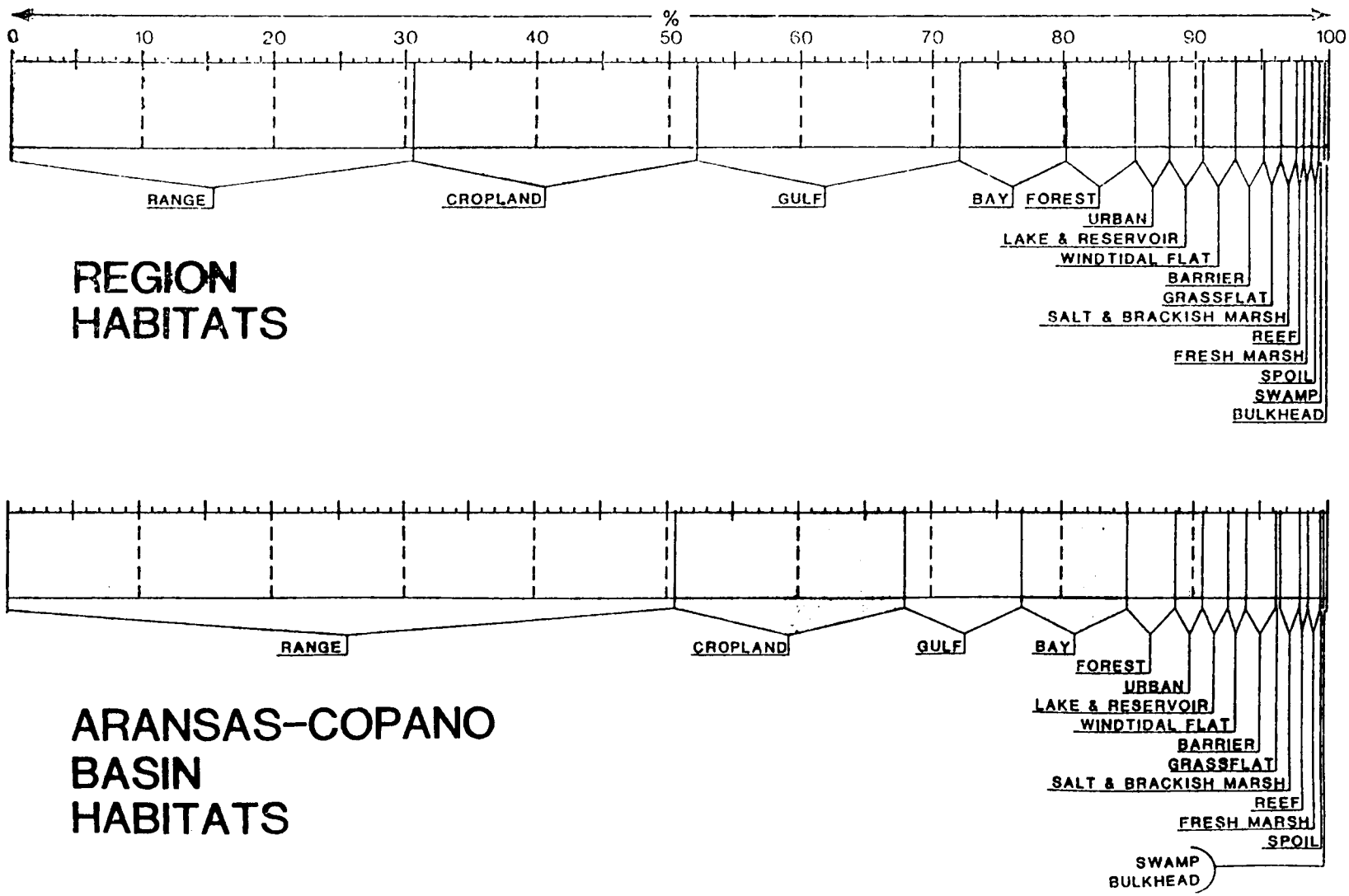


Figure 53. Habitat proportions of the Aransas-Copano basin and Texas Barrier Island Region.

The major land-use changes in this area have involved the conversion of natural brush and coastal prairie to cropland; there has been some urbanization. One of the larger land-use changes involves an area shown as lake and reservoir to the west of Port Bay. This was an area of range but was converted to a bauxite storage site for an aluminum plant located in the Corpus Christi basin. The dikes surrounding the storage area catch and hold rainwater.

Geologic development. The Aransas-Copano basin was formed by the deposition of sediment from the Nueces River to the south and the San Antonio-Guadalupe River system to the north. During the Sangamon interglacial period, the Nueces and San Antonio-Guadalupe river systems built large deltas into the present Gulf of Mexico. Fluvial sediments were later deposited on these deltas. Brown et al. (1976) note that the area from Port Bay to Sinton south of Chiltipin Creek probably originated from sediments carried by the Nueces River. The area west of Sinton and all of the land to the north except for Live Oak, Lamar, and Blackjack peninsulas were emplaced as fluvial-deltaic or fluvial deposits by the San Antonio-Guadalupe system (Brown et al. 1976; McGowen 1976a).

During the Early Wisconsin period, sea level dropped and the delta sediments eroded and were reworked. When sea level rose again, the shoreline was about 10 km (6 mi) inland of its present location. The rivers did not build large deltas during this period; instead, waves and currents striking the coast carried sediment along the shoreline and built a barrier-strandplain. The strandplain accreted and may have been built seaward as far as the present barrier islands (Brown et al. 1976).

When sea level began to drop 50,000 to 60,000 yr BP, the exposed sediments eroded. Core records and subbottom profiling reveal that deep river valleys were cut into the surface. The erosion breached the barrier-strandplain system that had formed in the previous interglacial period. Port Bay, Copano Bay, and Mission Bay were initially cut during this glacial period; St. Charles Bay divided what is now Lamar and Blackjack peninsulas from each other. McGowen et al. (1976) reported that the ancient Mission River valley extends 24 m (80 ft) below mean sea level across Aransas Bay into the gulf.

As sea level began to rise 25,000 to 18,000 yr BP, sediment filled the deep river valleys. McGowen et al. (1976) noted that sea level stopped rising 10,000 to 7500 yr BP about 16 m (54 ft) below its present elevation and that barrier islands developed 5 km (3 mi) seaward of their present location.

When sea level stabilized at its present level 2500 yr BP, sand was transported landward from offshore deposits. This material plus other sand from the Pleistocene barrier-strandplains formed the present barrier islands.

Harbor Island, a large inlet-tidal delta, developed opposite Aransas Pass, which migrated back and forth along the southern portion of San Jose Island in response to storm and flood conditions. Harbor Island was formed during the past 2000 yr as storm flood tides carried large volumes of sediment into the bay system through the pass and washovers (Brown et al. 1976).

A tidal channel running out of Aransas Bay opposite the mouth of Copano Bay and through San Jose Island remained active for a long period. Eventually a large flood-tidal delta formed, closing the channel. Remnants of this delta are still visible today.

Basin hydrology and climate. The basin climate is warm and dry. The average temperature of the basin is 22 deg C (71.5 deg F); the average summer high is 29 deg C (84 deg F) and the average winter low is 13 deg C (55.5 deg F) (Williams et al. 1976).

Average rainfall in the basin is 86.4 cm (34 in) (Williams et al. 1976). The greatest rainfall occurs in the month of September, with August, October, and June rainfall following in descending order. March is typically the driest month (National Climatic Center 1973). Evapotranspiration is higher than basin rainfall and produces a net deficit of 35.5 cm (14 inches) of precipitation (Woodruff 1975). Habitats that store fresh or brackish water constitute 133 sq km (51 sq mi), or 3.4 percent of the basin area above mean sea level.

Fresh water flows into the basin via the Aransas and Mission rivers and Chiltipin and Copano creeks. The Mission River has about twice the flow of the other streams, which all have about equal flows. Flows have been recorded on the streams for periods of 5 to 36 years, and the annual gaged flows average 128 million cu m. During periods of low and high flow, the flow volume ranges from 8 to 323 percent of the average flow (Dougherty 1980). Adding ungaged flows, return flows, and diversions increases the inflow volume to 476 million cu m; but even with direct rainfall added in, evaporation reduces the net inflow to 190 million cu m (Texas Department of Water Resources 1979). Sediment transport data is unavailable for this basin; however, the relatively low inflow into the bay suggests that sediment input is also low.

Freshwater inflow into this basin occurs sporadically. The hydrograph in Figure 54 shows that the period of highest inflow is September with smaller

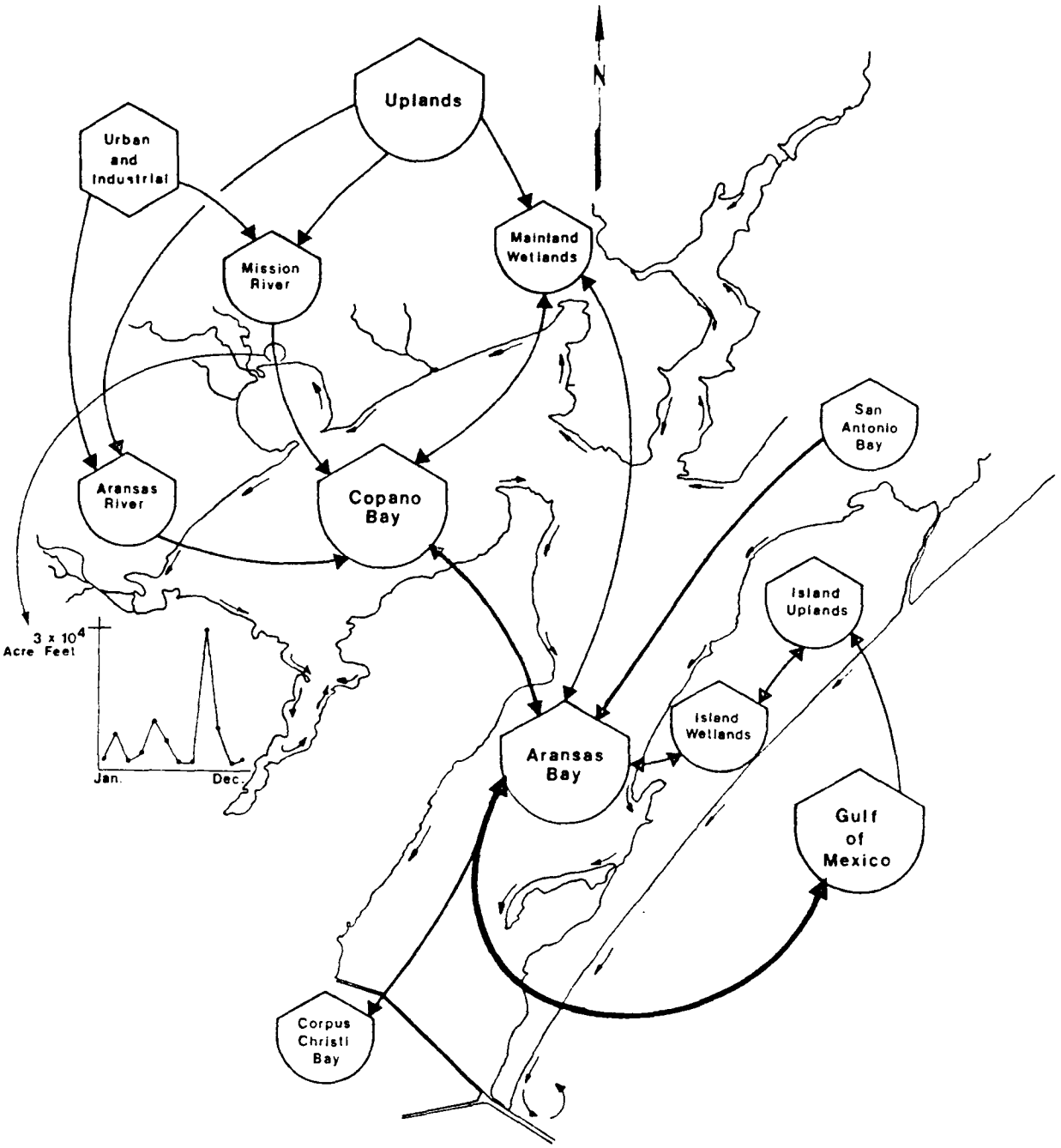


Figure 54. Hydrology of the Aransas-Copano basin.

peaks during May and February (Woodruff 1975). Since the drainage area for the river systems in this basin is relatively small, local weather patterns and storms are reflected in monthly inflow totals more than they are in basins that have very large drainage areas.

Figure 54 shows the hydrologic distribution pattern for the basin. Runoff from the uplands and the small return flows enter the main streams that drain into Copano Bay. Aransas Bay receives flow from Copano Bay, St. Charles Bay, and San Antonio Bay. Cedar Bayou, a natural pass at the southern tip of San Antonio Bay, opens only during storms and closes within a few months.

Port, Mission, and St. Charles bays are all shallow, with depths less than 1.5 m (5 ft). Port and St. Charles bays are long and thin with minor streams entering them. Mission Bay was once a longer estuary than it is today; its present shape is the result of Mission River delta progradation which is slowly filling the bay. The bottom sediments of these bays are muddy sand or sandy mud, and circulation is determined by local winds and runoff.

Copano Bay depths reach to 3 m (10 ft), although most of the bay is about 2 m (6.6 ft) deep. The bottom of Copano Bay is not a smooth basin but is interrupted by at least four large reef systems that nearly cross the width of the bay. Brown et al. (1976) state that relict reefs are buried beneath bay deposits. Most of the bottom sediment is mud with muddy shell near the reefs and muddy sand near the shore (McGowen and Morton 1978). Reefs that protrude above the bottom probably influence the bay's circulation patterns.

The northern half of Redfish Bay is very shallow, less than a meter in depth, and is isolated from Aransas Bay by a chain of islands that mark the edge of the large Harbor Island flood-tidal delta. Sediments in the portion

of Redfish Bay that contains grassflats are sandy and shelly with less mud than the surrounding bays. Redfish Bay circulation is wind-driven, but tidal influence is strong close to the pass.

Most of Aransas Bay is 3 m (10 ft) or more in depth (Figure 55). Most bottom sediment is mud, but there are areas of sand or sandy mud near the shorelines. Near the mouth of Copano and St. Charles bays several reefs span the width of Aransas Bay; they probably influence the circulation of the bay system.

Brown et al. (1976) and McGowen et al. (1976a) described generalized flow patterns that would be expected in the Aransas-Copano bay system under average conditions of wind, freshwater flow, and tidal influence. These flow patterns, indicated by arrows in Figure 54, are based on observation of the basin's hydrologic features. The Texas Department of Water Resources (1979b) simulated net steady-state flows using a hydrologic model of the bay system. This model calculates the long-term net flow and direction at selected points in the bay; it does not purport to show actual currents. These two circulation descriptions are not entirely comparable. Moreover, they show different hydrologic patterns: the simulation model's flows are all to the north, while the flows subjectively estimated by Brown et al. and McGowen et al. are to the south. This underscores the complexity of circulation patterns in this system; circulation is highly dependent upon wind and freshwater inflow conditions, and further studies will be required to characterize it more precisely.

The natural channel at the southern end of Aransas Bay is swept by currents between the gulf and Aransas Bay. Tidal influence is strong here, and the naturally deep channel connects with a dredged alternate route of the

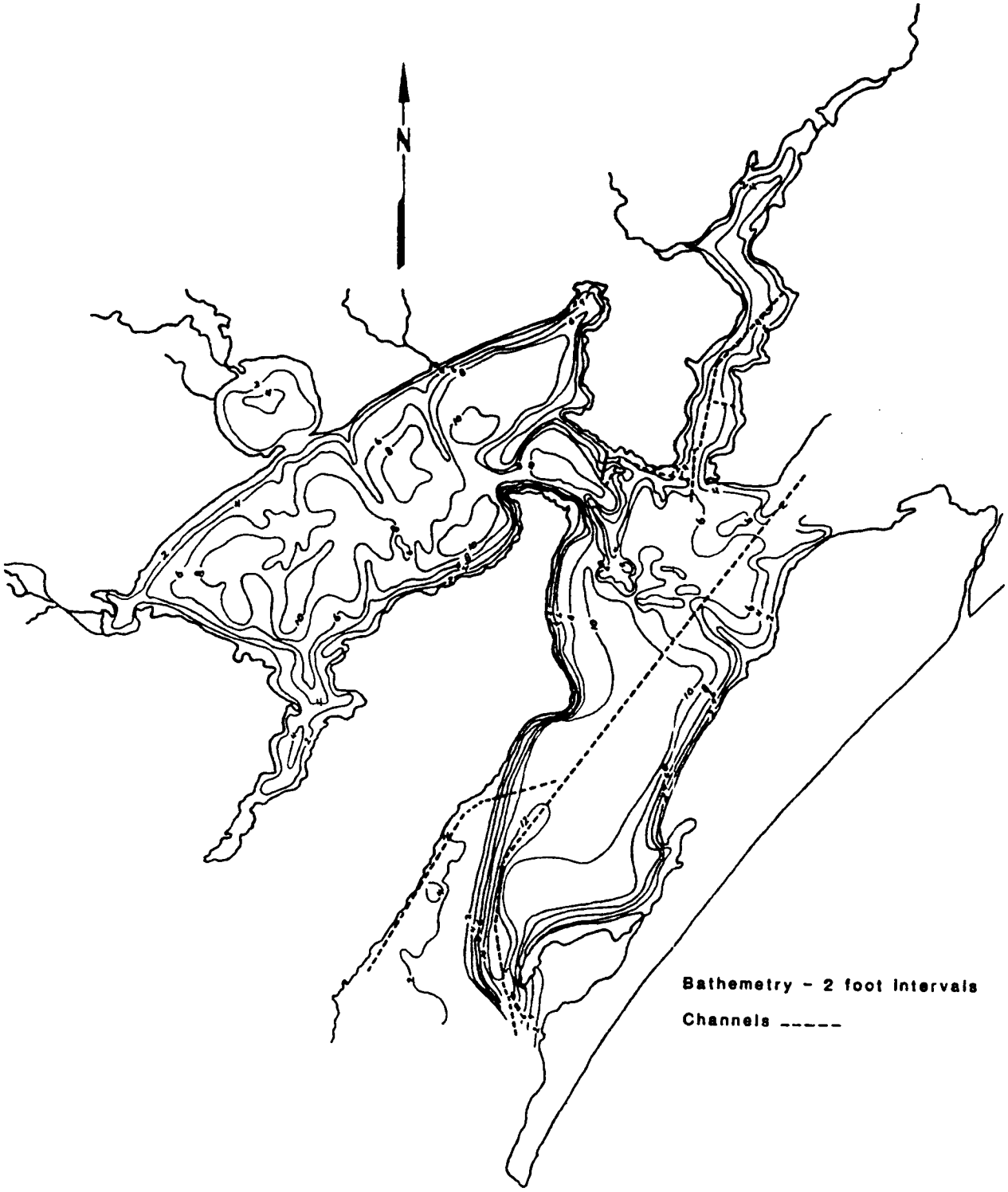


Figure 55. Bathymetry of bays in the Aransas-Copano basin.

intracoastal waterway that joins the main intracoastal waterway leading north. This waterway is dredged to about 3.5 m (12 ft) and runs northeast through shallower portions of Aransas Bay. It cuts through Long Reef in Aransas Bay and passes east of Blackjack Peninsula. The intracoastal waterway provides a deep and wide channel for water flow between San Antonio Bay and Aransas Bay.

Bay salinities reflect the sources of fresh water and proximity to marine influence (Figure 56). Copano Bay, which receives fresh water from several rivers and creeks, has an average salinity of 11.0 ppt with extremes of 0.6 to 24.4 ppt. The average salinity of Aransas Bay is 22.7 ppt with extremes of 8.8 to 36.1 ppt. Redfish Bay, closest to marine influence and furthest from freshwater inflows, has an average salinity of 26.5 ppt with extremes of 9.8 and 39.4 ppt (Texas Department of Water Resources 1983a).

Within 2 km (1.3 mi) of the gulf shoreline, the gulf floor rapidly descends to a depth of 9 m (30 ft) and then slopes more gently to the offshore boundary at a depth of 20 m (66 ft). Near the shoreline, sediments are sand but grade to muddy sand, sandy mud, and mud offshore. The dominant currents offshore vary seasonally, but the yearly average flow direction is to the south. Sediment carried by littoral drift moves toward Aransas Pass (Watson 1971). The basin's gulf shoreline has areas of erosion and accretion. Overall, about half of the San Jose Island shoreline is eroding while the other half is accreting (Morton and Pieper 1976).

Basin economy. The Aransas-Copano basin contained 58,999 persons in 1980 (Table 16), a 19 percent increase over its 1970 population. Population projections, however, estimate a growth rate of only 15 percent during the next 20 years (Texas Department of Water Resources 1980).

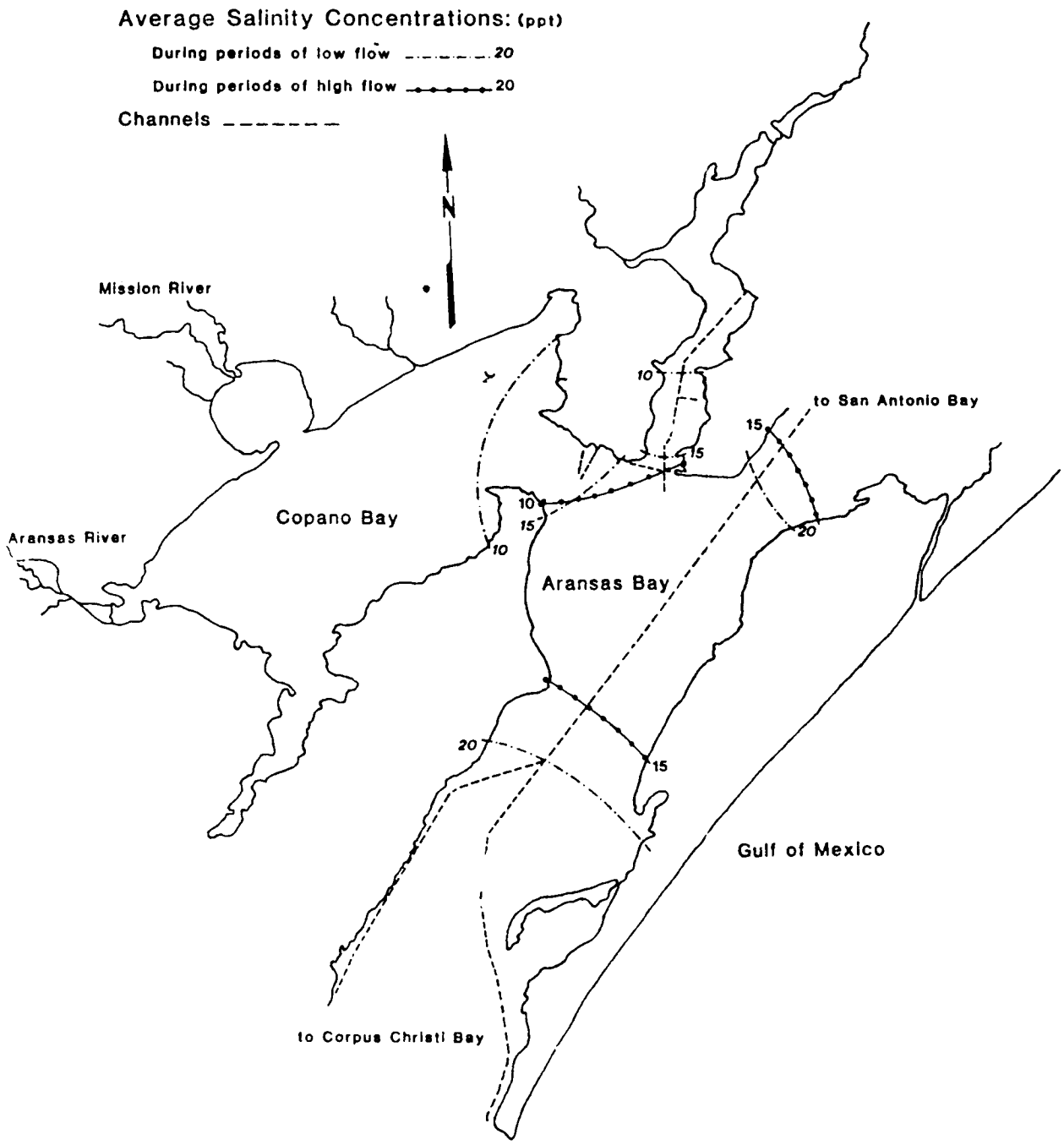


Figure 56. Salinity variation in the Aransas-Copano basin.

Table 16. Economic data for the Aransas-Copano basin.

Data type	Quantity
1970 Population	45264
1977 Population	49696
1980 Population	55877
1990 Population projection	58999
2000 Population projection	64392
Mineral production (X $1000)	445055
Deer harvest	2054
Travel expenses (X $1000)	32464
Travel employment	1146
Sportfishing spending (X $1000)	0
Commercial catch value (X $1000)	6000-12,000
Electrical generating capacity (kw)	0
Total employment	15962
Number of building permits	407
Length of railroad track (km)	174
Length of highways (km)	2916
Number of vehicles registered	49313
Commodity flows (1000 metric tons)	105
Number of farms	708
Market value of products (X $1000)	36417
Area of irrigated land (ha)	511

The mineral resources of this basin are very important to the economy. The value of minerals produced in 1977 was over $445 million, which puts this basin among the leaders in mineral production (Liebow et al. 1980).

Recreation also has a significant share of the economy. More than 2000 deer were harvested in the basin in 1977; travel expenditures amounted to more than $32 million in 1977, and more than 7 percent of the jobs (1146) were travel-related (Liebow et al. 1980). Sportfishing was important part of the recreational economy. Sportfishing expenditures (Texas Department of Water Resources 1980a) for this basin were combined with the Corpus Christi basin totals. Using sportfishing catch (Liebow et al. 1980) from the two basins to allocate sportfishing expenditures, nearly $8.5 million was spent in the basin.

Commercial fishing is also important to the economy. Commercial fishing expenditures are combined with the Corpus Christi basin statistics and cannot easily be disaggregated. If one-quarter to one-half of the expenditures are allocated to this basin, the commercial fishery catch value for 1976 would range from $6 to $12 million (from Texas Department of Water Resources 1980a).

Although the basin is a big producer of oil and gas, it imports its electricity from other basins. There are few industries in the Aransas-Copano basin, and adjacent basins have excess capacity. Other measures of industrial and residential development suggest that the economy is focused upon mineral production and recreation. Employment in 1977 was 15,962 persons, or 32 percent of the population. This low figure may indicate a high level of retired persons in the population. Development as measured by the number of building permits in 1977 is low; 407 permits were issued (Liebow et al. 1980). This amounts to about 4 permits per sq km of urban area.

Transportation is not a large factor in the basin's economy. The basin had 174 km of railroad track and 2916 km of roads in 1976 (Liebow et al. 1980). Vehicle registrations in 1978 were were 49,313 (Liebow et al. 1980); only 16 vehicles were registered for every km of road in the basin. Shipping was of little importance to the economy; only 105,000 metric tons of commodities moved through the channels of this basin in 1977 (RPC, Inc. 1980).

In 1974 there were 708 farms in the basin. The market value of their production was more than $36 million. Grain and cotton were the major crops; cattle and calf production on the range was also high (Bureau of the Census 1980). The value of farm production was about the same as travel expenditures but an order of magnitude less than the value of minerals produced.

Resource demands. Twenty-three percent of this basin's upland area is cropland, 67 percent is range, and less than three percent is urban. The basin has a large quantity of recreational land, 181 sq km, or nearly 5 percent of the land area (Liebow et al. 1980). The large proportion of range suggests that many resource demands in the basin are low.

In 1977 more than 5 million kiloliters of crude oil were produced in the basin (Table 17). This was nearly 3 percent of all the crude oil produced in the basin since 1928, when production began (Liebow et al. 1980). More than 4000 million cu m of gas were also produced in 1977 (Liebow et al. 1980).

Biomass yield from farms in the basin included 332,588 kiloliters of grain and 57,170 bales of cotton in 1974. A small quantity of hay was also produced, and 48,929 cattle and calves were sold during the year. Biomass production from the estuary and gulf was also significant. Liebow et al. (1980) reported that about 1 million kg of shrimp, 30 thousand kg of oysters,

Table 17. Resource demands in the Aransas-Copano basin.

Resource demands	Quantity
Cropland area (ha)	87138
Range area (ha)	252476
Urban area (ha)	9976
Recreation area (ha)	18110
Crude oil production (kiloliters)	5198691
Natural and casinghead gas (million cu m)	4039
Condensate (million liters)	132
1902-1978 oil production (million kiloliters)	181
Grain production (kiloliters)	332588
Cotton production (bales)	57170
Hay produced (metric tons)	22575
Peanuts produced (kg)	0
Rice produced (metric tons)	0
Cattle and calves sold	48929
Bay shrimp harvested (kg)	1049607
Bay oysters harvested (kg)	29937
Bay crabs harvested (kg)	975219
Bay commercial fish harvested (kg)	259907
Bay sport fish landed (kg)	78380
Total commercial fish harvested (kg)	0
Total commercial shellfish harvested (kg)	0

Table 17 (continued). Resource demands in the Aransas-Copano basin.

Resource demands	Quantity
Digestive cancer mortality	22
Lung cancer mortality	31
Pneumonia and influenza mortality	10
Emphysema, bronchitis, and asthma mortality	3
Length fishable, swimmable stream segments (km)	146
Percent fishable, swimmable stream segments (%)	100
Airborne particulates (metric tons)	9043
Airborne hydrocarbons (metric tons)	12199
Waste discharge measured as 5-Day BOD (kg)	98285
Number of discharges	21
Cumulative industrial solid waste (metric tons)	49732
Subsidence of land surface (m)	None
Municipal surface water use (million cu m)	5
Municipal groundwater use (million cu m)	9
Manufacturing surface water use (million cu m)	16
Manufacturing groundwater use (million cu m)	1
Irrigation surface water use (million cu m)	0
Irrigation groundwater use (million cu m)	8
Total surface water use (million cu m)	22
Total groundwater use (million cu m)	21
Municipal, manufact. return flow (million cu m)	11
Agricultural return flow (million cu m)	1
Obstructions to runoff, roads + railroads (km)	3090
Major drainage ditches and canals (km)	8
Maintenance spoil, historical average (cu m)	258378
Length of dredged channels (km)	97

1 million kg of crabs, and 300 thousand kg of fish were harvested commercially from the estuarine systems of the basin in 1977 (Table 17). They also reported that 78 thousand kg of fish were caught by sportsmen. The figures for biomass from total commercial catch from the Texas Department of Water Resources (1980a) are combined with Corpus Christi Bay statistics, but it is likely that the gulf harvest is at least double the bay's biomass harvest total.

Public health indicators show a low incidence of cancers and respiratory diseases in the basin (Table 17) (National Center for Health Statistics 1981). The basin's waters generally have good water quality. Of the 146 km of freshwater streams, all are fishable and swimmable (Texas Department of Water Resources 1983a). Redfish Bay and some small areas in Aransas and Copano bays are closed to shellfish harvest, but the restricted area is less than 10 percent of the basin's estuarine waters (Texas Department of Health 1983).

Waste materials added to the atmosphere are low in the Aransas-Copano basin; the airborne particulate and hydrocarbon loads in 1974 were 9043 and 12,199 metric tons respectively (Texas Air Control Board 1977). Twenty-one discharges are permitted in basin waters; 12 of these are from domestic waste treatment plants. Five-day BOD measurements of organic wastes placed in basin waters total 98,285 kg for 1983 (Texas Department of Water Resources 1984).

Subsidence in this basin is very low. Only one small area, the Refugio Heard Oil and Gas Field near the city of Refugio, had measurable subsidence of 0.15 m (0.5 ft) over the period 1918-1951. The area affected is about 3 km (2 mi) wide (Ratzlaff 1982).

Water use in the basin is low, totaling 43 million cu m annually (Texas Department of Water Resources 1977). Water supply is almost equally divided

between surface water and groundwater; the largest single water user is the small industrial community in the basin. Approximately 35 percent of the total water used for municipal and manufacturing uses is returned to the basin for reuse.

The amount of hydrologic change on the land surface and in the estuarine area is low. The basin contains 3090 km of roads and railroads (Liebow et al. 1980), an average of only about 0.8 km per sq km of upland area; most of the roads are concentrated in the urban and cropland areas. Less than 10 km of drainage and irrigation canals are located in the basin. The basin has 97 km of dredged channels, and the average annual maintenance spoil volume is 258,378 cu m. Slightly less than 2700 cu m of spoil must be removed for each km of channel length.

San Antonio Basin

Location and description. The San Antonio basin has an area of 2265.2 sq km (874.6 sq mi) within the boundaries of the Texas Barrier Island Region. It contains portions of four natural hydrologic units defined by the Texas Water Development Board (1977): the Guadalupe and San Antonio river basins and two coastal basins--the Lavaca-Guadalupe and the Guadalupe-Nueces. The San Antonio basin is much smaller than either of the two river basins systems which extend inland as far as Kerr County in central Texas.

The lower boundary follows a drainage divide that is south of and parallel to the San Antonio River valley, beginning about 4 km (2.5 mi) southwest of the abrupt edge of the San Antonio River valley near the basin's inland boundary. The boundary runs southeast to Blackjack Peninsula and then turns to the south-southwest and follows the topographic high to the

peninsula's southwestern tip. From there it turns southwest and crosses San Jose Island. This boundary separates streams that drain into San Antonio Bay from those that drain into Mission, Copano, St. Charles, and Aransas bays. The boundary includes Mesquite Bay and Cedar Bayou, which is the natural pass separating San Jose and Matagorda islands.

The upper boundary approximately follows the railroad tracks and State Highway 185 from the inland boundary through Bloomington to Seadrift. From Seadrift, the boundary continues southeast, dividing Espiritu Santo Bay and the lower portion of San Antonio Bay and crossing Matagorda Island. The upper boundary separates the streams and creeks that drain into the San Antonio basin from those that drain into the Matagorda basin to the north. The basin contains portions of five counties: Aransas, Calhoun, Goliad, Refugio, and Victoria. About 58 percent of the basin's area is upland, 3 percent is freshwater habitat, 21 percent is estuarine habitats, and 18 percent is gulf. A small amount of emergent spoil covers much less than 1 percent of the basin's area.

The San Antonio basin is fairly narrow through the uplands and upper portion of the bay; its lower portion broadens to include more than half of Blackjack Peninsula, Ayres Bay, Mesquite Bay, and Carlos Bay (Plate 5). The San Antonio River enters the basin to the south and the Guadalupe River enters to the north. The two rivers join about 30 km (19 mi) from the gulf shoreline and pass through the Guadalupe delta, a large delta that extends into the bay system. The river systems have separate river valleys at the inland boundary of the basin. The San Antonio River valley is about 2 km (1.3 mi) wide, and the Guadalupe River valley is about 9 km (5.6 mi) wide. The upland portions of the basin range from 24 to 33 m (80 to 110 ft) in elevation. The land

slopes evenly to the coast, and the river valleys have steeply-sloped sides. The upland surrounding the bays ranges in elevation from 9 m (30 ft) near the most inland portion of the bay to sea level near the intracoastal waterway. Matagorda Island, a low barrier island, completely separates San Antonio Bay from the gulf. Cedar Bayou, the natural pass, is usually closed except after hurricanes or major storms; it usually remains open for just a few weeks or months.

The intracoastal waterway crosses the lower portion of San Antonio Bay. A second dredged channel, Victoria Channel, extends from the intracoastal waterway inland more than 52 km (32 mi). This channels follows the northern shorelines of the bay, of Mission Lake, and of Green Lake in the Guadalupe delta and ends near the town of Dernal.

Basin sediments are predominantly clayey sand and silt with moderate permeability and moderate water-holding capacity. These sediments are the result of meanders and flooding of the two river systems that flow into the basin. Interspersed among them are clays and muds that are largely the result of fluvial deposition in interdistributary areas. The clays and muds have low permeability but high water-holding capacity. Blackjack Peninsula along the southern edge of San Antonio Bay, the corresponding area to the north, and Matagorda Island have sandy soils as the result of their formation as barrier or strandplain systems.

All habitats except bulkhead are present in this basin (Table 18). Range comprises 801.1 sq km (319.3 sq mi), or 36.5 percent of the basin's area. Range extends from the inland boundary all the way to the bay shoreline but is broken by a few areas of cropland. The range area is also split by the

Table 18. Habitat areas, lengths, and proportions in the San Antonio basin.

Habitat	Area sq km	Length km	Percent of basin area
Barrier	65.0		2.8
Bay	360.8		15.9
Bulkhead	0.0		0.0
Channel and tidal stream		106.9	
Cropland	320.6		14.2
Forest	99.7		4.4
Freshwater marsh	29.5		1.3
Grassflat	10.1		0.5
Gulf	396.0		17.5
Lake and reservoir	43.5		1.9
Range	801.1		36.5
Reef	22.3		1.0
River and canal		260.4	
Salt and brackish marsh	37.8		1.7
Spoil	6.7		0.3
Swamp	1.8		0.1
Urban	19.4		0.9
Wind-tidal flat	24.9		1.1

natural drainages of the rivers and habitats associated with them. Range predominates on Blackjack Peninsula, which is the site of the Aransas National Wildlife Refuge.

Cropland occupies 320.6 sq km (123.8 sq mi), or 14.2 percent of the basin's area. Cropland is located on the clay and mud sediments in the basin, and the largest areas are adjacent to the upper end of the bay system.

Three areas of forest exist in this basin. Two are floodplain forests along the San Antonio and Guadalupe River systems. The third area Blackjack Peninsula, where live oak mottes occur in clumps and along ridges of the old barrier-strandplain deposits.

The San Antonio basin has a significant amount of freshwater marsh, 29.5 sq km (11.4 sq mi), or 1.3 percent of the basin's area. Some of this marsh is found in swales on the relict barrier-strandplain deposits. Most is located in the San Antonio-Guadalupe delta around the edges of the freshwater lakes and adjacent to Mission Lake. A small area of swamp is located in the same vicinity.

The barrier habitat, Matagorda Island, comprises 65 sq km (25.1 sq mi) in the basin. The barrier is completely undeveloped. The southern portion belongs to a private owner, and the northern portion is a wildlife management area jointly managed by the state and the federal government.

The bay habitat is the largest of the estuarine systems in the basin. It occupies 360.8 sq km (139.3 sq mi), or 15.9 percent of the basin's area. An extensive area of oyster reefs is located in the central and lower part of the bay system; reefs comprise 22.3 sq km (8.6 sq mi), or 1 percent of the basin area.

The back side of Matagorda Island has several areas of wind-tidal flat, more extensive in the southern than in the northern portion. Wind-tidal flat comprises 24.9 sq km (9.6 sq mi), or 1.1 percent of the basin area. Large areas of salt and brackish marsh are found bayward of the flats, along the southeastern edge of Blackjack Peninsula, along the northern edge of San Antonio Bay, and on the protruding delta that separates Hynes and Guadalupe bays. Salt and brackish marsh occupies 37.8 sq km (14.6 sq mi), or 1.7 percent of the basin's area. Small areas of grassflat, totaling 10.1 sq km (3.9 sq mi), are found between the bay and the salt and brackish marsh habitats. These are mostly located on the barrier-island side of San Antonio Bay.

Figure 57 compares the proportions of habitats in the San Antonio basin to the proportions in the region. Range and barrier habitats are slightly more abundant in the basin. Bay, salt and brackish marsh, reef, and freshwater marsh also occur in greater quantities in the basin than in the region as a whole. In contrast the region contains greater proportions of cropland and urban habitats than the basin. Wind-tidal flat and grassflat are proportionally higher in the region, but the preponderance of these areas in the Laguna Madre basin skews the comparisons with other basins.

This basin has had relatively little land-use change. The conversion of range to cropland, the dredging of channels, and the dredging of dead oyster reef for construction materials in the late 1960's and early 1970's are among the few changes that have taken place.

Geologic development. The San Antonio basin was formed by the deposition of sediment from the San Antonio-Guadalupe river system. During the Sangamon interglacial period, the San Antonio and Guadalupe rivers built large deltas

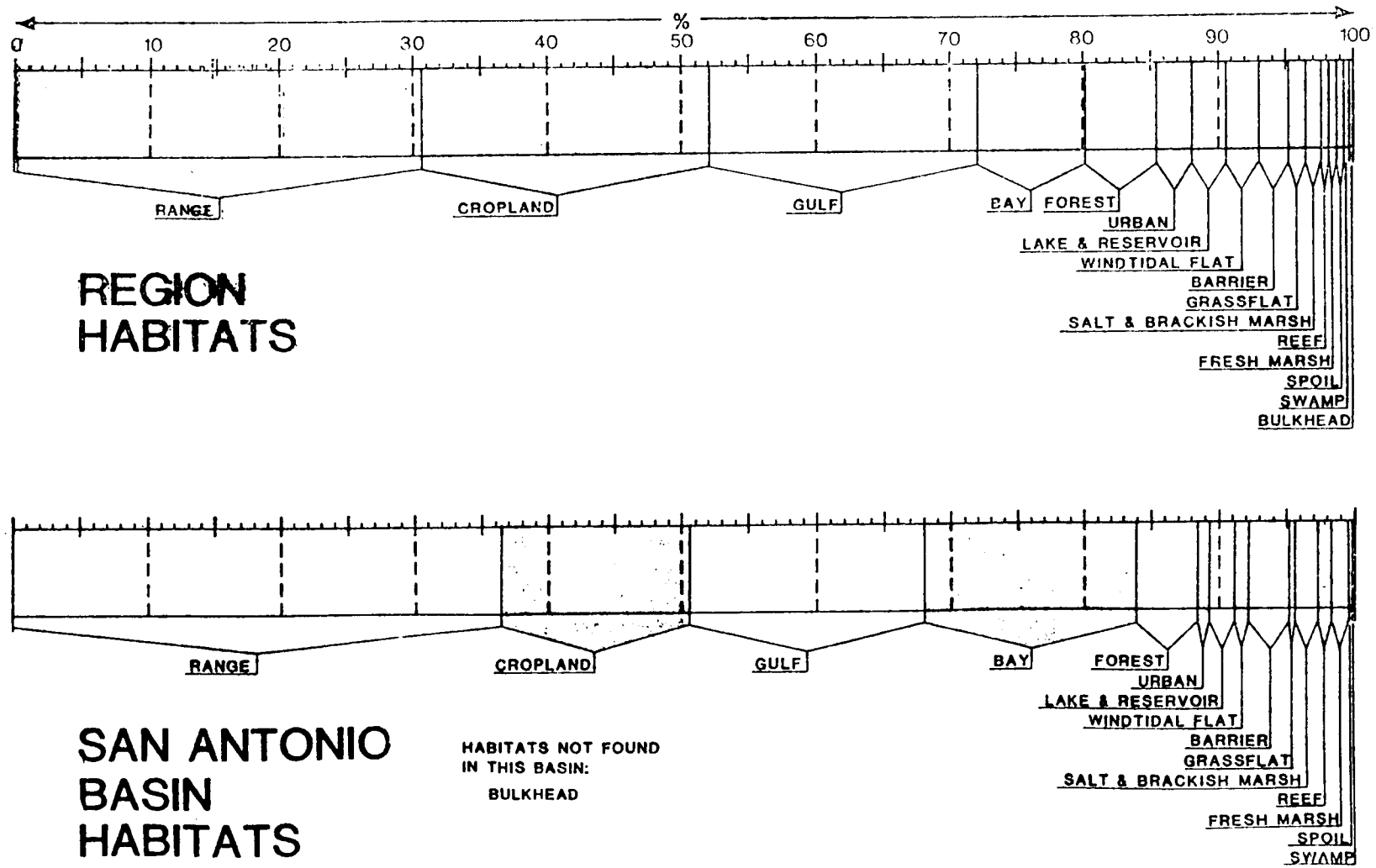


Figure 57. Habitat proportions of the San Antonio basin and Texas Barrier Island Region.

into the present Gulf of Mexico. All of the land inland of Blackjack Peninsula and the corresponding area on the north side of the bay were built by fluvial-deltaic or fluvial deposition on top of the deltas (McGowen 1976a).

Sea level dropped during the early Wisconsin Period. When it rose again to its approximate former location, about 10 km (6 mi) inland of the present shoreline, the rivers carried sediment to the coast. Waves and currents striking the coast carried sediment along the shoreline and built a barrier-strandplain which accreted seaward as least as far as the present barrier islands (McGowen et al. 1976a).

When sea level began to drop 50,000 to 60,000 yr BP, and erosion of the exposed sediments widened the breach in the barrier-strandplain system and cut deep river valleys into the surface. The San Antonio-Guadalupe river valley was scoured to about 24 m (80 ft) below mean sea level across San Antonio Bay into the gulf (McGowen et al. 1976).

When sea level rose 25,000 to 18,000 yr BP, the river valleys were filled by sediment from headward-eroding streams, river valley wall erosion, estuary bank erosion, and sediments transported from the gulf. McGowen et al. (1976) noted that sea level stopped rising several times during the Holocene, most recently at 10,000 to 7500 yr BP about 16 m (54 ft) below its present elevation. A sand body that may have been a barrier or peninsula developed 10 km (6 mi) seaward of Matagorda Island's present location.

As sea level reached at its present level 2800 to 2500 yr BP, sand transported landward from offshore deposits and sand from the Pleistocene barrier-strandplains formed the present barrier islands.

A tidal channel running through Matagorda Island south of the mouth of San Antonio Bay remained active for a long period, until a large flood-tidal delta formed which eventually closed it. The delta, which separates San Antonio and Mesquite bays, is still visible.

The Guadalupe delta began prograding into San Antonio Bay about 2000 yr BP (McGowen et al. 1976a) from a point nearly 24 km (15 mi) inland of its present location. Since then some of the more inland Modern delta deposits have been covered with Modern fluvial sediments carried by the river systems.

Basin climate and hydrology. The San Antonio basin has an annual average temperature of 21.7 deg C (71 deg F). The average winter low temperature is 12.8 deg C (55 deg F), and the average summer high is 29 deg C (84 deg F) (Williams et al 1976).

Average rainfall in the basin is 94 cm (37 in) (Williams et al 1976). The greatest rainfall occurs in the month of September (14 cm or 5.6 in). Other months with high rainfalls are, in descending order, August, October, and June; March has the least rainfall, 4.3 cm (1.7 in) (National Climatic Center 1973). Potential evapotranspiration is higher than basin rainfall and there is a net deficit of 30.5 cm (12 in) of precipitation (Woodruff 1975). This basin has a significant area of freshwater marshes and lakes that store fresh water. These areas constitute 5.3 percent of the area above mean sea level.

Fresh water enters the San Antonio basin from the San Antonio and Guadalupe rivers. The average gaged flow (40 yr average) into the basin is 2230 million cu m per year; the extreme low and high flows have ranged from 7 to 256 percent of the yearly average (Texas Department of Water Resources 1979). Gaged flows , ungaged flows, return flows, and diversions total 2798

million cu m per year; when rainfall to and evaporation from the bay are included, the net inflow to the system is 2545 million cu m per year (Texas Department of Water Resources 1979). Total suspended sediment flow transported through the basin by the two rivers (30-year average) is estimated at 905,438 metric tons per year (Dougherty 1979).

The seasonal pattern of freshwater inflow to the bay system changes between the San Antonio basin and the Aransas-Copano basin to the south. In the Aransas-Copano basin and in all other basins to the south, a majority of the inflow occurs during the late summer and early fall. In the San Antonio basin and in all basins to the north, the greatest proportion of the inflow occurs in the spring. Figure 58 contains a hydrograph (Woodruff 1975) of San Antonio and Guadalupe river inflow. The highest flow occurs during May; June flow is almost as high. July and August have the lowest flows, but volume increases again in the period September through November with a peak in October. This shift signals a change in the weather patterns controlling rainfall; to the north the effects of mid-to-late spring cold fronts are more important than gulf-spawned storms, which occur with greatest frequency in late summer and early fall.

Figure 58 illustrates the hydrologic distribution pattern for the basin. The majority of the basin's fresh water enters from the combined river flows. Some water flows onto the Guadalupe delta from the river or from the estuary during periods of flooding or storm. Floodwaters pick up and transport nutrients and accumulated organic matter to the bay system (Texas Department of Water Resources 1980b). Flow from the river and delta reaches San Antonio Bay, which also receives water from local upland and wetland drainage and from

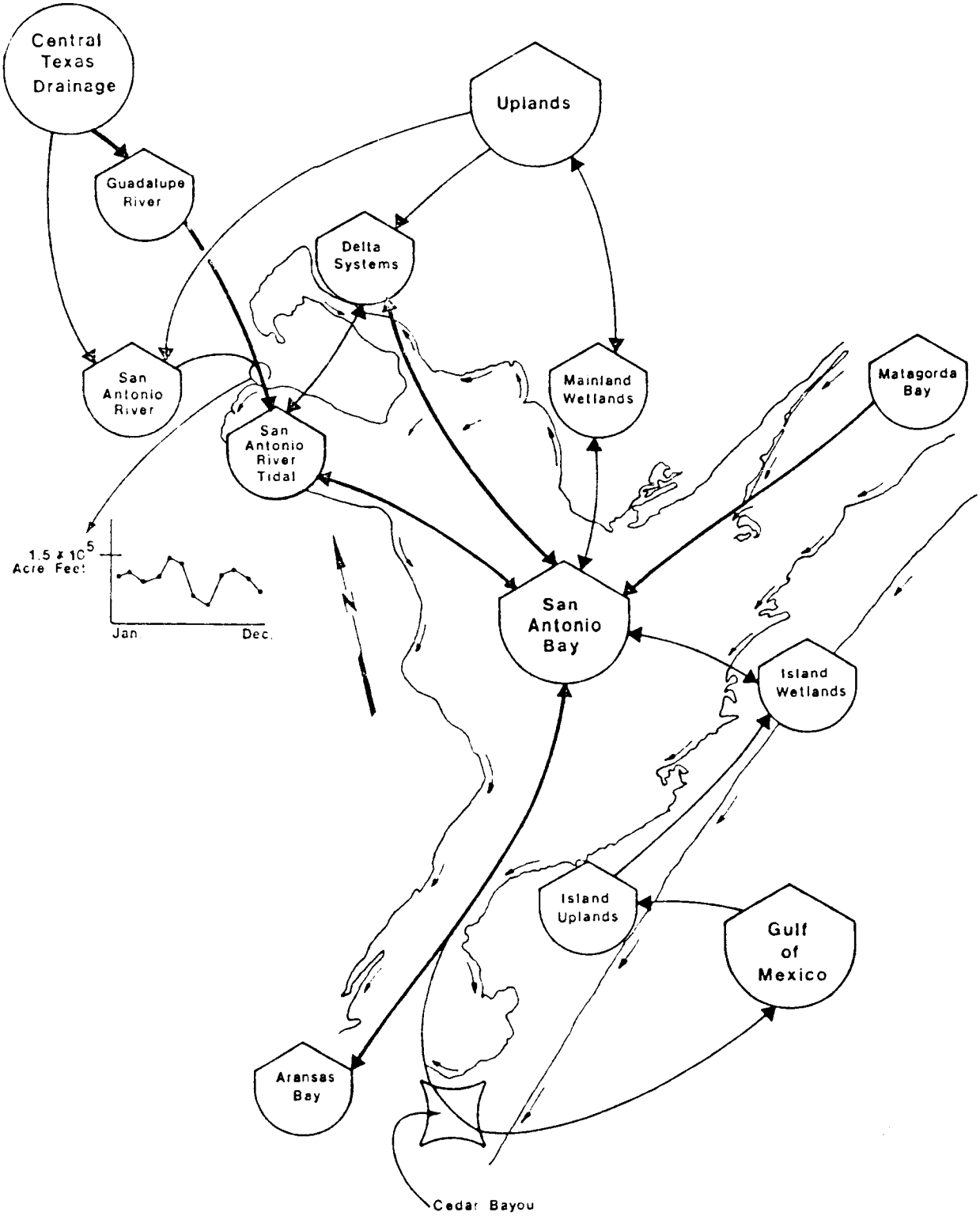


Figure 58. Hydrology of the San Antonio basin.

Matagorda Bay. Hydrostatic pressure from flood conditions opens Cedar Bayou for passage of water out of the bay. High waters in the gulf may allow water to enter San Antonio Bay from the gulf through several washover channels. San Antonio Bay is connected with Aransas Bay through the shallow Ayres, Mesquite, and Carlos bays, and also through the intracoastal waterway along the Blackjack Peninsula shoreline.

The bays and estuarine lakes surrounding the Guadalupe delta are very shallow, generally 1 m (3.3 ft) or less in depth (Figure 59). Hynes and Mesquite bays are a little deeper, and most of San Antonio Bay ranges from 2 to 2.5 m (6 to 8 ft). The many oyster reefs in San Antonio Bay interrupt the bathymetry. Reefs often protrude above the bottom and in many places come close to the water's surface. Except for the reefs, most of the bottom sediment in San Antonio Bay, Hynes Bay, and Mission Lake is mud. Guadalupe Bay receives sand from the delta and river system. Sediments in Mesquite Bay and the lower portion of San Antonio Bay near Matagorda Island are sandy mud (McGowen and Morton 1979).

Generalized flow patterns from McGowen et al. (1976a) suggest a counter-clockwise circulation in upper San Antonio Bay and a general flow direction to the south in the lower portion of the bay (Figure 58). A hydrologic model (Texas Department of Water Resources 1981c) simulates net flow and direction at selected points in the bay. It shows a complex pattern in the upper portion of the bay consistent with the presence of oyster reefs. In the lower portion of the bay the net direction of circulation is shown to be north, and Cedar Bayou is a net contributor of water to the bay system. The inconsistencies between the emphasize the complexity of circulation in this bay system. Circulation varies with freshwater inflow, wind strength, and

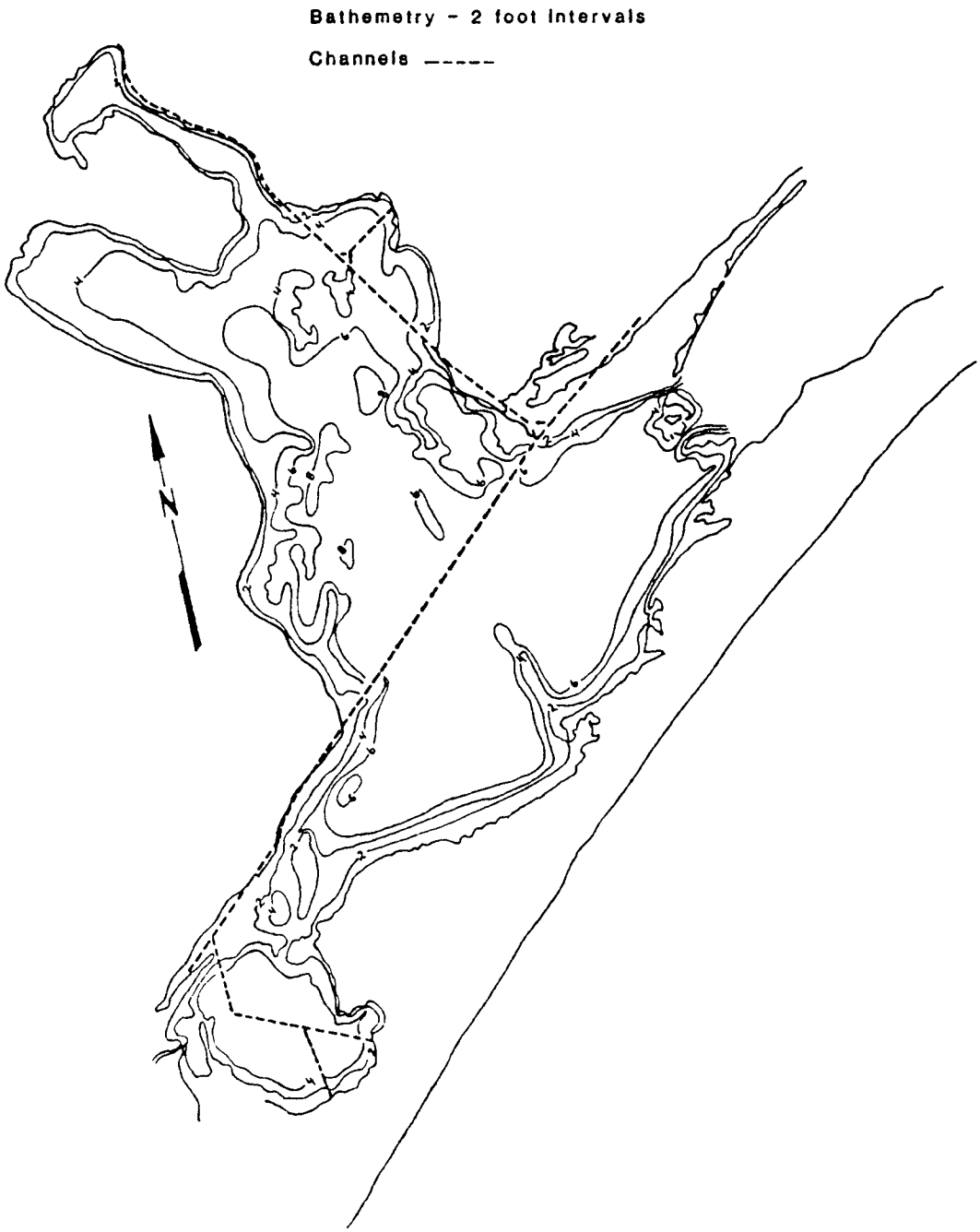


Figure 59. Bathymetry of bays in the San Antonio basin.

direction; further study will be required to characterize the pattern accurately.

Salinities of the water bodies form a gradient through the estuary depending upon the proximity to freshwater or marine influence (Figure 60). The tidal portion of the Guadalupe River has an average salinity of 0.2 ppt, with extremes over the past four years of 0.1 to 0.5 ppt. The average salinity of Guadalupe, Hynes, and San Antonio Bay was 10.0 ppt with extremes of 0.4 to 23.0 ppt. Mesquite Bay, closest to gulf waters through Cedar Bayou or Aransas Bay had an average salinity of 15.0 ppt with extremes of 4.9 to 28.9 ppt.

The gulf floor slopes rapidly to a depth of 7.3 m (24 ft) and then dips gently to a depth of 20 m (66 ft) at the offshore boundary. Near the shoreline the sediment is sand and becomes progressively muddier offshore (McGowen and Morton 1979). Some areas of sandy mud protrude further offshore than in most other basins and may be remnants of offshore barriers present before the sea reached its final stable level. Morton et al. (1976) identified the dominant flow direction by noting that the net littoral drift is to the south along the Matagorda Island Shoreline. Except for a small area seaward of Mesquite Bay, the gulf shoreline is accretionary along the island's length.

Basin economy. The population of this basin is small. In 1980 the basin contained 26,244 persons. Population projections estimate a slow but steady growth over the next two decades (Table 19) with an expected increase of about 24 percent.

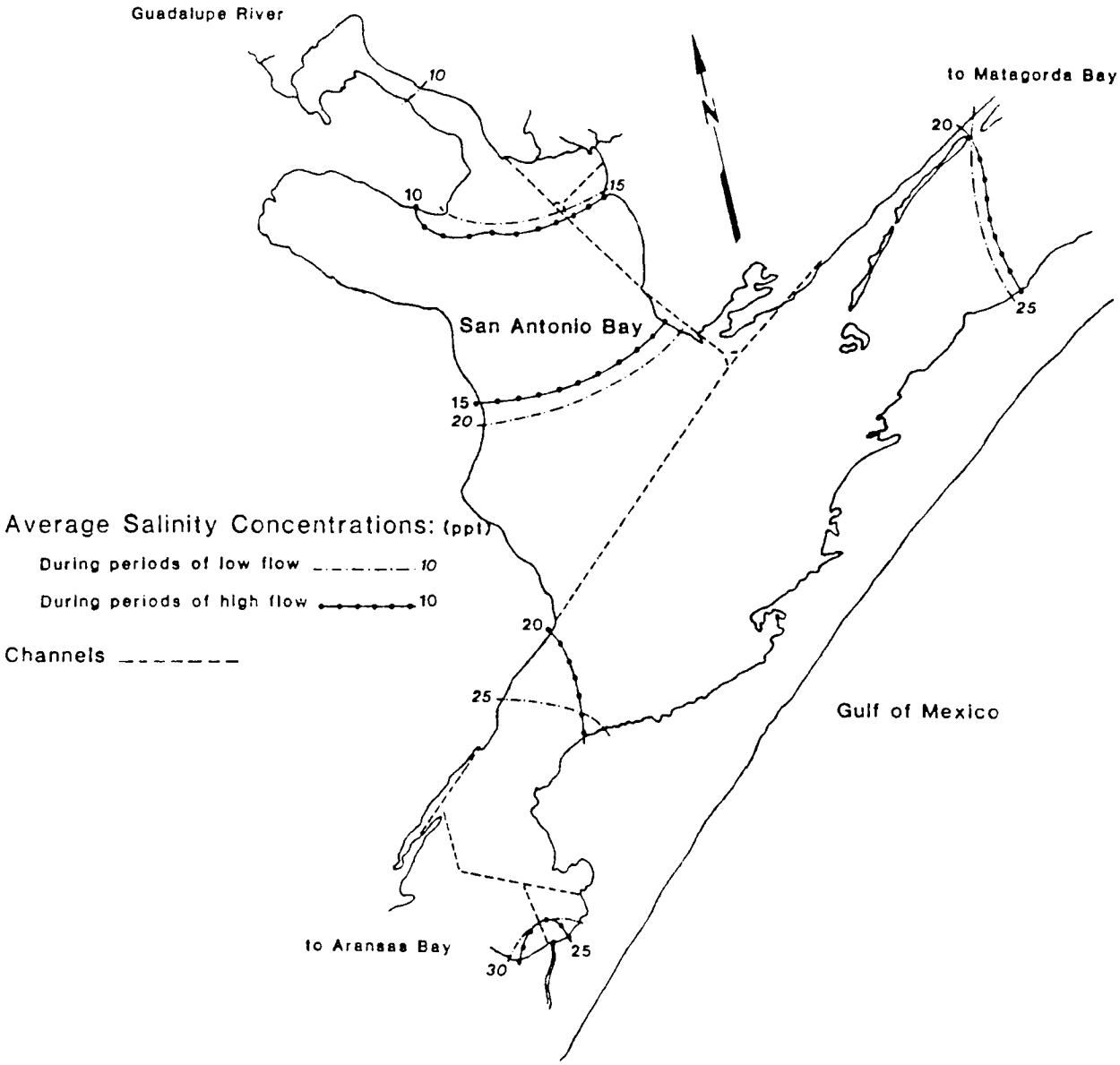


Figure 60. Salinity variation in bays of the San Antonio basin.

Table 19. Economic data for the San Antonio basin.

Data type	Quantity
1970 Population	21131
1977 Population	23218
1980 Population	26224
1990 Population projection	29008
2000 Population projection	32429
Mineral production (X $1000)	87136
Deer harvest	944
Travel expenses (X $1000)	12005
Travel employment	500
Sportfishing spending (X $1000)	1937
Commercial catch value (X $1000)	18264
Electrical generating capacity (kw)	1549949
Total employment	10549
Number of building permits	283
Length of railroad track (km)	64
Length of highways (km)	1036
Number of vehicles registered	25920
Commodity flows (1000 metric tons)	2326
Number of farms	331
Market value of products (X $1000)	8362
Area of irrigated land (ha)	2237

The mineral resources of the basin are moderately important to the economy. The value of minerals produced in 1977 was slightly more than $87 million (Liebow et al. 1980).

Recreation and tourism is also of moderate importance to the economy. Hunters harvested nearly 1000 deer in 1977, and travel expenditures in the basin totaled $12 million. Nearly 5 percent of the jobs were travel-related and nearly $2 million was spent on sportfishing (Liebow et al. 1980).

Commercial fishing was very valuable to the region. The Texas Department of Water Resources (1980b) calculated that the direct value of commercial fisheries in the basin was more than $18 million based upon 1976 dollars and using 1972 to 1976 average production figures.

In 1977, total employment in the basin was 10,549 persons and the number of building permits issued was 283. When the moderate population gains projected for the next 20 years are considered, the number of new building permits seems unusually high.

Transportation is of low to moderate importance in this basin. There are approximately 64 km (40 mi) of railroad track that lead to a few industries and 1036 km (644 mi) of roads. Road length is low since there is so little urban habitat in the basin. The intracoastal waterway and Victoria Channel transport 2.3 million metric tons of commodities each year. Much of the material passes through the region but some moves to and from industries that have developed along the Victoria Channel inland.

Agriculture is relatively important to the basin. There were 331 farms in 1974, and the total market value of the farm production was more than $8 million. Cattle production on range was moderately important; the most important product was grain.

Resource demand. Sixty-one percent of the upland area in the San Antonio basin is range, 24 percent is cropland, and 1 percent is urban. Most of the suitable cropland is under cultivation. The demand for space for urbanization and industry has been very low.

Crude oil production in this basin in 1977 was slightly more than 800,000 kiloliters (Table 20). This was only about 1 percent of the total production since oil and gas began to be produced in 1928. Natural and casinghead gas was also produced in low amounts; production in 1977 was 973 million cu m (Liebow et al. 1980).

Biomass production from farms yielded 98,367 kiloliters of grain and 1024 bales of cotton in 1978 (Bureau of the Census 1980). Hay production, less than 10,000 metric tons, and rice production, 12,536 metric tons, were fairly low. The rice fields are irrigated and there has been a trend of slightly increased irrigation in the basin since 1958. The number of cattle and calves produced in the basin was 15,416.

Biomass production from the estuary and the gulf is high. The 1977 bay catch was: shrimp, 753,413 kg; oysters, 198,672 kg; bay crabs, 1,031,917 kg, and bay finfish, 85,275 kg (Liebow et al. 1980). The landed catch of sport fish averaged over a two-year period was also high, 93,893 kg (Liebow et al. 1980). The total commercial finfish catch--bay and gulf--was 244,863 kg; the total catch for shellfish was 5,641,727 kg (Texas Department of Water Resources 1980b).

Public health indicators for the basin showed that 30 persons died from digestive cancers in 1977, and 24 died from lung cancer (National Center for Health Statistics 1981). Other measures of mortality for respiratory-related

Table 20. Resource demands in the San Antonio basin.

Resource demands	Quantity
Cropland area (ha)	32078
Range area (ha)	82734
Urban area (ha)	1943
Recreation area (ha)	4207
Crude oil production (kiloliters)	822658
Natural and casinghead gas (million cu m)	973
Condensate (million liters)	19
1902-1978 oil production (million kiloliters)	77
Grain production (kiloliters)	98367
Cotton production (bales)	1024
Hay produced (metric tons)	9789
Peanuts produced (kg)	0
Rice produced (metric tons)	12536
Cattle and calves sold	15416
Bay shrimp harvested (kg)	753413
Bay oysters harvested (kg)	198672
Bay crabs harvested (kg)	1031917
Bay commercial fish harvested (kg)	85275
Bay sport fish landed (kg)	93893
Total commercial fish harvested (kg)	244863
Total commercial shellfish harvested (kg)	5641727

Table 20 (continued). Resource demands in the San Antonio basin.

Resource demands	Quantity
Digestive cancer mortality	30
Lung cancer mortality	24
Pneumonia and influenza mortality	7
Emphysema, bronchitis, and asthma mortality	3
Length fishable, swimmable stream segments (km)	612
Percent fishable, swimmable stream segments (%)	91
Airborne particulates (metric tons)	3646
Airborne hydrocarbons (metric tons)	17433
Waste discharge measured as 5-Day BOD (kg)	212406
Number of discharges	19
Cumulative industrial solid waste (metric tons)	95304
Subsidence of land surface (m)	None
Municipal surface water use (million cu m)	5
Municipal ground water use (million cu m)	26
Manufacturing surface water use (million cu m)	36
Manufacturing ground water use (million cu m)	4
Irrigation surface water use (million cu m)	12
Irrigation ground water use (million cu m)	22
Total surface water use (million cu m)	64
Total ground water use (million cu m)	65
Municipal, manufact. return flow (million cu m)	47
Agricultural return flow (million cu m)	2
Obstructions to runoff, roads + railroads (km)	1100
Major drainage ditches and canals (km)	179
Maintenance spoil, historical average (cu m)	911512
Length of dredged channels (km)	81

deaths were low (Table 20). Some water quality problems have been reported in the basin. High levels of nutrients from agricultural runoff, high suspended solids, and localized high bacterial counts are sometimes problems in basin waters (Texas Department of Water Resources 1983a). Shellfish harvest is currently restricted to the middle and lower portions of San Antonio bays. Harvest in Hynes Bay, Guadalupe Bay, Mission Lake, and adjacent to Seadrift is prohibited (Texas Department of Health 1983).

The quantity of waste materials added to the atmosphere is fairly low in the basin; in 1973 the load of airborne particulates was 3646 and the hydrocarbon load was 17,433 metric tons in 1974 (Texas Air Control Board 1977). Nineteen waste discharges are permitted in the San Antonio basin; 13 of these are from municipal waste treatment facilities. Five-day BOD measurements of the organic materials introduced into basin waters show that a waste load of 212,406 kg was disposed for natural system processing in 1983 (Texas Department of Water Resources 1984).

Total water use in the basin was 129 million cu m in 1974 (Texas Department of Water Resources 1977). Barely more than half the water (65 million cu m) came from groundwater sources. Industrial water use was slightly greater than municipal and agricultural use (Table 20). However, the distribution of surface and ground use was very different. Most industrial water came from surface sources; about two-thirds of the irrigation water and most of the municipal water was from groundwater. About two-thirds of the water used by municipalities and manufacturing was returned for reuse; however, almost all of the agricultural water was consumed.

The amount of hydrologic change on the land surface is relatively low. There are 1100 km (684 mi) of roads and railroads in the basin; this amounts

to 0.8 km per sq km of upland. About 179 km (111 mi) of canals and drainage ditches are also found in the basin. The length of dredged channels in the estuary is 81 km (50 mi), a density of 16 km per 100 sq km of estuary. The basin's historical average maintenance spoil volume is 911,512 cu m. For every km of channel 11,253 cu m must be removed annually to keep the channel open.

Matagorda Basin

Location and description. The Matagorda basin is located in the central portion of the Texas coast and occupies an area of 6771 sq km (2614 sq mi). The basin constitutes about 62 percent of the area of the three natural hydrologic units defined by the Texas Water Development Board (1977) that drain into Matagorda Bay: the Colorado-Lavaca coastal basin, the Lavaca River basin, and the Lavaca-Guadalupe coastal basin.

The lower boundary approximately follows the railroad tracks and State Highway 185 from the inland boundary through Bloomington, to Seadrift. At Seadrift the boundary continues southeast across the bay and Matagorda Island, and separates Espiritu Santo Bay from the lower portion of San Antonio Bay.

The upper boundary of the Matagorda basin coincides with the boundary line between the Colorado River basin and the Colorado-Lavaca coastal basin defined by the Texas Water Development Board (1977). This boundary is 3.2 to 24 km (2 to 15 mi) west of the Colorado River and follows a slight ridge near the towns of Markham and Buckeye. The boundary separates areas that drain into Matagorda Bay from those that drain into the Colorado River.

The Matagorda basin has a high proportion of land compared to water. Almost 69 percent of the basin's area is upland; 17 percent is estuarine

habitats, 11 percent is gulf, and three percent is freshwater habitats. Less than one percent of the basin's area is subaerial spoil. The basin contains more than two-thirds of Calhoun and Jackson counties, nearly half of Matagorda County, and a fraction each of Victoria and Wharton counties.

The Matagorda basin is wide. If a cross section were made of the inland boundary, it would begin at the southwest corner at an elevation of 27 m (90 ft) and would gradually drop to about 18 m (60 ft) near Garcitas Creek; the creek bottom is at an elevation of 14 m (45 ft). On the northern side of the creek the elevation rises to 21 m (70 ft) but is interrupted by the Lavaca and Navidad river valleys. The incised river valleys drop to about 14 m (45 ft) where the rivers flow but rise to the 21 m (70 ft) upland elevation on the north side of the Navidad River. The land then slowly rises to elevations of 29 to 30 m near the northeast corner of the inland boundary. Except for the river and creek bottoms, the profile is concave. The highest areas are found along the upper and lower basin boundaries. Consequently water in all parts of the basin tends to drain toward the basin's center.

The headlands at the upper part of Lavaca Bay are 6 to 8 m (20 to 25 ft) in elevation. Most other areas adjacent to bay waters have elevations ranging from 3 to 4.5 m (10 to 15 ft), especially in the vicinity of the small secondary bays that open into Matagorda Bay. The northern portion of Matagorda Island, in the southeastern portion of the basin, has dunes higher than 4.5 m (15 ft); much of the central portion is 1.5 to 3 m (5 to 10 ft). The Matagorda Peninsula, which separates Matagorda Bay and the gulf, is lower, with most of the land less than 2 m (6.6 ft) high.

The Lavaca and Navidad rivers join in the Lavaca River delta and flow into Lavaca Bay. Garcitas Creek also drains into Lavaca Bay. Three tertiary

bays--Chocolate Bay, Cox Bay, and Keller Bay--open into Lavaca Bay. Lavaca Bay opens into Matagorda Bay. Powderhorn Lake and Carancahua, Turtle, and Tres Palacios bays all have small drainages within the basin and open into Matagorda Bay. Espiritu Santo Bay, south of Matagorda Bay, is separated from the other water bodies. It has a marine character because of its proximity to the gulf and because it receives very little freshwater flow from upland drainage. Tidal channels through the low islands at the northern end of Matagorda Island provide circulation with the gulf.

Before 1929, Matagorda Bay included what is now East Matagorda Bay and the Colorado River delta that separates Matagorda and East Matagorda bays. In 1929 a large log jam on the Colorado River was cleared through a combination of human efforts and floods. By 1941 sediment carried down the river had built the across the width of Matagorda Bay to the gulf (Ward and Armstrong 1980).

Matagorda Bay is connected to the gulf by Pass Cavallo, a natural pass between Matagorda Peninsula and Matagorda Island, and by 1963 the Matagorda Ship Channel. The ship channel, north of Pass Cavallo, was cut through the peninsula in 1963 to accommodate deep-draft vessels.

Sediments in the basin are clayey sands and silts, clay and mud, and sand. The clayey sand and silt is located along some of the larger existing streams and along areas that were once streams and distributary channels. The linear structure of these deposits can often be seen in the southern half of the basin. In the northern half of the basin, the area of clayey sand and silt is more amorphous and occurs in large blocks rather than as long, narrow deposits. Clays and muds form about 40 percent of the sediments in this

basin. Clays and muds are predominantly found north, northwest, and west of Lavaca Bay, but large pockets of these finer sediments are interspersed among the sandier sediments. The clays and muds are less permeable and have higher water-holding capacity than the clayey sands and silts. In general, cropland is associated more with the clay and mud sediments than with the clayey sands. Sandy sediments in the basin include Matagorda Island, Matagorda Peninsula, and the peninsula between San Antonio and Matagorda bays.

All habitats except bulkhead are represented in Plate 6; Table 21 contains measurements and proportions of these habitats in the basin. The bulkhead habitat in the basin is too small to be observed and measured accurately at the mapped scale. Range comprises the largest area of all the habitats in the basin, 2381.2 sq km (919.4 sq mi), or 35.2 percent of the basin's area. Most of the range habitat in the region lies just inland and north of the Matagorda Bay system for a distance of 24 to 40 km (15 to 25 mi). The peninsula between San Antonio and Matagorda bays and an area east of Lavaca Bay are also range. Cropland, which occupies 1485.6 sq km (573.6 sq mi), or 21.9 percent of the region, is predominant west of Lavaca Bay and inland of the region of range previously described. There are many small tracts of cropland within the large range area.

Forest is a large habitat unit in this basin, comprising 608.1 sq km (234.8 sq mi), or 9.0 percent of the basin's area. All forest in the basin is floodplain forest, situated along the larger creeks and rivers that drain into Matagorda Bay. The forest areas end several miles from the bay shoreline, close to the point of tidal influence in the streams.

Urban land occupies 54.4 sq km (21.0 sq mi), or 0.8 percent of the basin's area. The largest urban areas are Port Lavaca and Wharton. The

Table 21. Habitat areas, lengths, and proportions in the Matagorda basin.

Habitat	Area (sq km)	Length (km)	Percent of basin area
Barrier	138.6		2.1
Bay	943.5		13.9
Bulkhead	0.0		0.0
Channel and tidal stream		233.8	
Cropland	1485.6		21.9
Forest	608.1		9.0
Freshwater marsh	72.5		1.1
Grassflat	17.1		0.3
Gulf	717.9		10.6
Lake and reservoir	124.1		1.8
Range	2381.2		35.2
Reef	37.3		0.6
River and canal		609.0	
Salt and brackish marsh	125.4		1.9
Spoil	25.1		0.4
Swamp	5.4		0.1
Urban	54.4		0.8
Wind-tidal flat	37.3		0.6

cities of El Campo, Edna, and Palacios are also found in the basin. Only Port Lavaca and Palacios are located on the bay.

The lake and reservoir habitat unit comprises 124.1 sq km (47.9 sq mi), or 1.8 percent of the basin. The lakes in the basin are fresh or barely brackish and are associated with deltas or small embayments where there is significant freshwater flow. Freshwater marshes occupy 72.5 sq km (28.0 sq mi), or 1.1 percent of the basin. A few are adjacent to the freshwater lakes in the Lavaca delta; most are located on the peninsula between San Antonio and Matagorda bays in swales between higher sandy deposits.

The area of bay habitat in the Matagorda Bay system is 943.5 sq km (369.3 sq mi), or 13.9 percent of the basin's area. The bay types range from the large, deep open bays (Matagorda Bay) to small and shallow sheltered systems.

Salt and brackish marsh occupies 125.4 sq km (48.4 sq mi), or 1.9 percent of the basin's area. Many areas of salt and brackish marsh exist in deltas or along the edges of the small secondary and tertiary bays that drain into Lavaca and Matagorda bays. Salt and brackish marsh is located along the mainland adjacent to Espiritu Santo Bay, on the back side of Matagorda Island and MAtagorda Peninsula, and on the islands on the northern border of Matagorda Island.

Wind-tidal flat is limited in the Matagorda basin. It occupies 0.6 percent of the basin and has an area of 37.3 sq km (14.4 sq mi). Wind-tidal flat is found only on the bay side of Matagorda Island and Matagorda Peninsula. Grassflat habitat is also limited in area, occupying 17.1 sq km (6.6 sq mi). Small areas of grassflat are located on the bay side of the island and peninsula and in a few protected locations in secondary bays,

especially adjacent to salt and brackish marshes. Grassflat distribution patterns mapped by Ward and Armstrong (1980) in a study of Matagorda Bay and based on more recent field investigations are similiar to those presented here.

Oyster reefs are present in both Lavaca and Matagorda bays. The basin contains 37.3 sq km (14.4 sq mi) of reefs, but many small clumps of oysters too small to map and measure occur in Keller, Cox, Chocolate, and other bays in the system.

Comparing the proportion of habitats in the Matagorda Bay basin to the region as a whole, the basin has slightly more range and nearly twice as much bay as the Texas Barrier Island Region (Figure 61). The relative proportions of forest and freshwater marsh are also higher. In contrast, the relative areas of gulf, urban, and lake and reservoir habitats are smaller than for the region as a whole. Wind-tidal flat and grassflat areas are also proportionally smaller though the preponderance of these areas in the Laguna Madre basin--83 and 77 percent respectively--skew the proportions for all other basins.

The major land use changes in this basin have been the conversion of grasslands to cropland and the development of a few urban areas. One change currently in progress is the construction and filling of Lake Texana--earlier known as Palmetto Bend Reservoir. This reservoir will cover an area of 74.9 sq km (28.9 sq mi) at conservation stage. The area impounded is part of the Navidad River about 6 km (4 mi) upstream of its confluence with the Lavaca River. Habitats that will be inundated include forest, cropland, and range. The areas of these habitats in the basin will decrease by a small proportion; the area of lake and reservoir will increase by 60 percent.

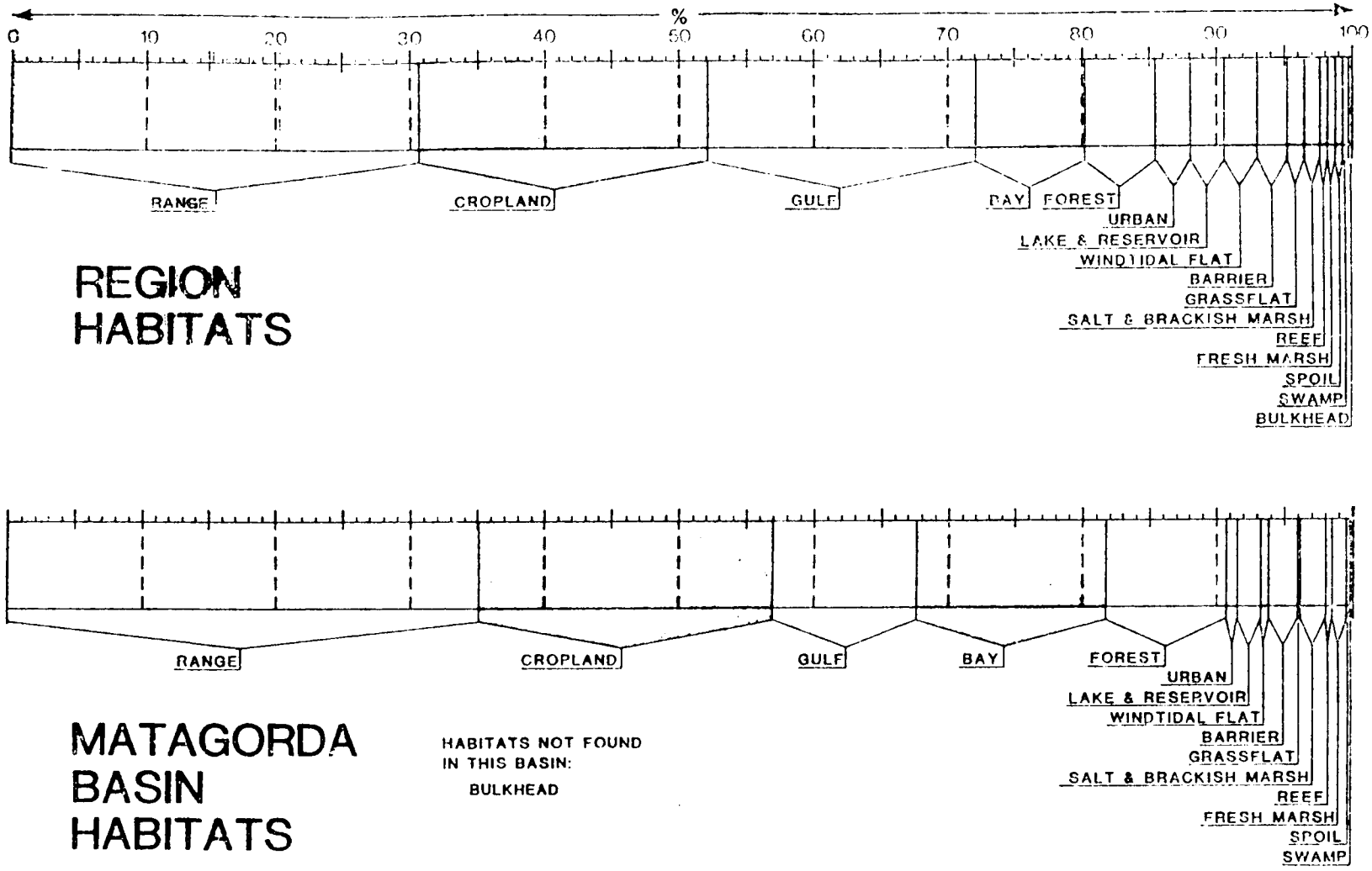


Figure 61. Habitat proportions of the Matagorda basin and Texas Barrier Island Region.

The marshes in the Lavaca River delta will also be affected by the building of this impoundment and by water management. Research during the past decade has shown that occasional inundation of the delta by pulses of fresh water is necessary to bring sediment and nutrients into the marsh to maintain its elevation and nutrient levels. In addition, the occasional inundation sweeps accumulated duff, micronutrients, and reduced inorganic materials produced from anaerobic decomposition of marsh vegetation to the estuary (see salt and brackish marsh habitat description, next chapter). These materials contribute directly and indirectly to plant, chemoautotroph, and consumer production in the estuary, though the relative importance of these inputs to the maintenance of productivity in the system is a point of disagreement among interest groups and some experts. The necessity, quantity, and timing of inflows for these marshes are currently being considered by the Texas Water Commission.

Geologic development. The Matagorda basin was formed by the deposition of sediment from the San Antonio-Guadalupe river systems and the Colorado River system. The area east of the Guadalupe River and west of Garcitas Creek was formed by fluvial-deltaic deposits from the San Antonio and Guadalupe rivers during the Sangamon interglacial period (McGowen et al. 1976a).

The area east of Garcitas Creek and extending east the basin boundary is a Pleistocene fluvial-deltaic deposit also of Sangamon age (McGowen et al. 1976a, 1976b). This large area was deposited by the Colorado River as the result of many large river-course changes.

The present peninsula between San Antonio Bay and Matagorda Bay, from Powderhorn Lake to Espiritu Santo Bay, is the remaining inland portion of a

relict barrier-strandplain that developed in the Peorian interglacial stage. No relict barrier-strandplain system has been found to the northeast for 161 km (100 mi) until the western edge of Chocolate Bay in the Galveston basin is reached. There is no reason to doubt that the same process occurred where relict systems are absent; barrier-strandplains in this area were probably obliterated by some large-scale process.

When sea level began to drop 50,000 to 60,000 yr BP exposed sediments over a wide area in Matagorda Bay eroded. Transects taken across Matagorda Bay reveal that five river valleys were cut into the subsiding Pleistocene delta which now lies below the Holocene and Modern sediments that form the Matagorda Bay floor (McGowen et al. 1976a). McGowen et al. also noted that the river valleys were as deep as 38 m (125 ft) below mean sea level in the vicinity of Port O'Connor.

When sea level rose 25,000 to 18,000 yr BP, sediment filled the deep river valleys. McGowen et al. (1976b) noted that up until 4000 yr BP, Matagorda Bay was largely open to the sea, judging from the composition of shell berms. Reworking of Pleistocene delta sediment along the north shore may have occurred during this interval.

With the final rise in sea level 2800 to 2500 yr BP sand transported landward from offshore deposits and other sand from the Pleistocene barrier-strandplains or deltas formed Matagorda Island. At the same time, shoals and a discontinuous chain of islands developed across the mouth of Matagorda Bay. About 1800 yr BP the Colorado-Brazos estuary filled completely and debouched sediment into the gulf. A spit was built at the headlands of the filled estuary; fed by sediment from the river systems, it developed across the entire width of Matagorda Bay to form the present Matagorda Peninsula.

Basin hydrology and climate. The yearly average temperature in the Matagorda Basin is 21.4 deg C (70.5 deg F); the average summer high temperature is 28.6 deg C (83.5 deg F), and the average winter low temperature is 12.5 deg C (55.5 deg F) (Williams et al. 1976).

Average rainfall in the basin is 101.6 cm (40 in) (Williams et al. 1976). The greatest proportion of yearly rainfall occurs in September (17 percent in Port Lavaca) with June, October, and August following in descending order. March is the month with the lowest average rainfall (Bomar 1983). Potential evapotranspiration is slightly higher than rainfall in the basin; consequently there is a net precipitation deficit of 15.3 cm (6 in) (Woodruff 1975). Those habitats that store freshwater on the land's surface constitute about 4 percent of the area above mean sea level; when Lake Texana is filled this percentage will rise to 5.6 percent.

Freshwater flows into this basin through a number of rivers, creeks, and streams. The Lavaca and Navidad rivers and Garcitas Creek have records of gaged flow. The annual average gaged flow through the basin is 2155 million cu m (Texas Department of Water Resources 1979). Low and high flows vary from 18 to 341 percent of the average flows (Dougherty 1980). When diversions, return flows, and flows calculated for drainages without gages are added, the average annual flow is 3620 million cu m (Texas Department of Water Resources 1979). This includes 1580 million cu m from the Colorado River that enters Matagorda Bay through the intracoastal waterway, Culver Cut, and Tiger Island Cut (73.3 percent of flow from the Colorado; calculated from Dougherty 1980 and Texas Department of Water Resources 1980a). When direct rainfall and evaporation are included, the total falls to 3242 million cu m (Texas

Department of Water Resources 1979). The suspended sediment load carried to the coast was partially estimated by Ward and Armstrong (1980), who gave separate values for sediment volumes for the Lavaca-Navidad system and for the Colorado River. Using the 73.4 percent inflow from the Colorado and converting the volume to weight (70 lb sediment per cu ft, Cook, 1967), the sediment inflow to the basin totals 81,540 metric tons per year.

The greatest freshwater inflow through the rivers into Matagorda Bay occurs during the late spring and early summer. May and June constitute the major inflow period; flows for September and October form a second though minor peak (hydrograph in Figure 62, Woodruff 1975). The hydrologic distribution pattern in this basin is also shown in Figure 62. The majority of water flowing through the basin enters Lavaca Bay through the Lavaca and Navidad rivers; Lavaca Bay empties into Matagorda Bay. Not all the water from the Lavaca and Navidad rivers enters the bay directly; there are some withdrawals for municipal, industrial, and agricultural use, with return flows.

Matagorda Bay also receives flow from the Colorado River--about one-third of the basin's inflow. There is also drainage from small watersheds within the basin such as the Carancahua Creek or Tres Palacios subbasins. Matagorda Bay has a strong exchange with the gulf and a strong flow in most months through the intracoastal waterway and Espiritu Santo Bay toward San Antonio Bay.

The small secondary and tertiary bays have depths of less than 1.5 m (5 ft). The depth of Lavaca Bay depth is less than 2 m (6.6 ft), and Espiritu Santo Bay is less than 2.5 m (8 ft) (Figure 63). A large portion of the center of Matagorda Bay is 3.5 m (12 ft). A few areas, including Pass Cavallo

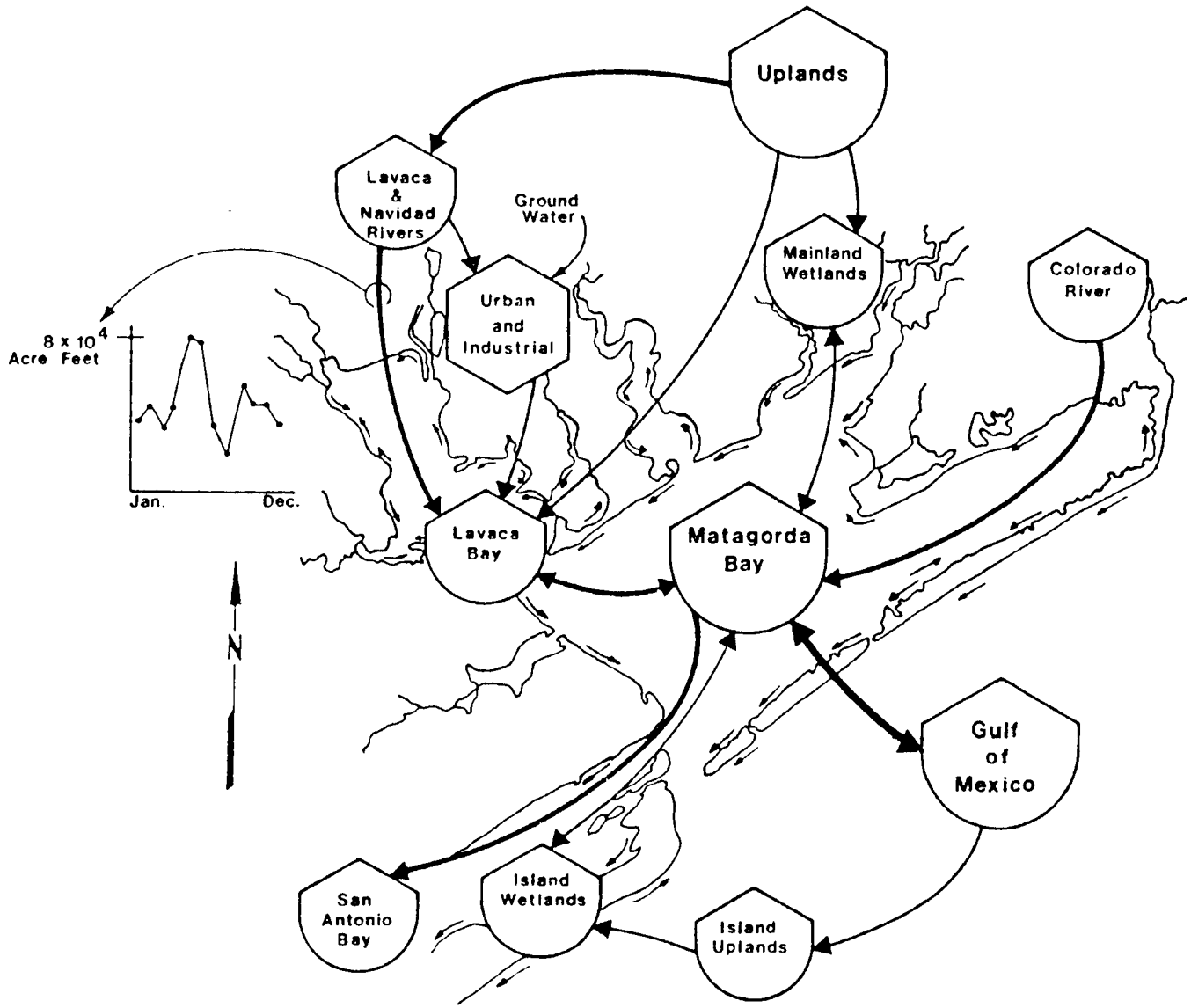


Figure 62. Hydrology of the Matagorda basin.

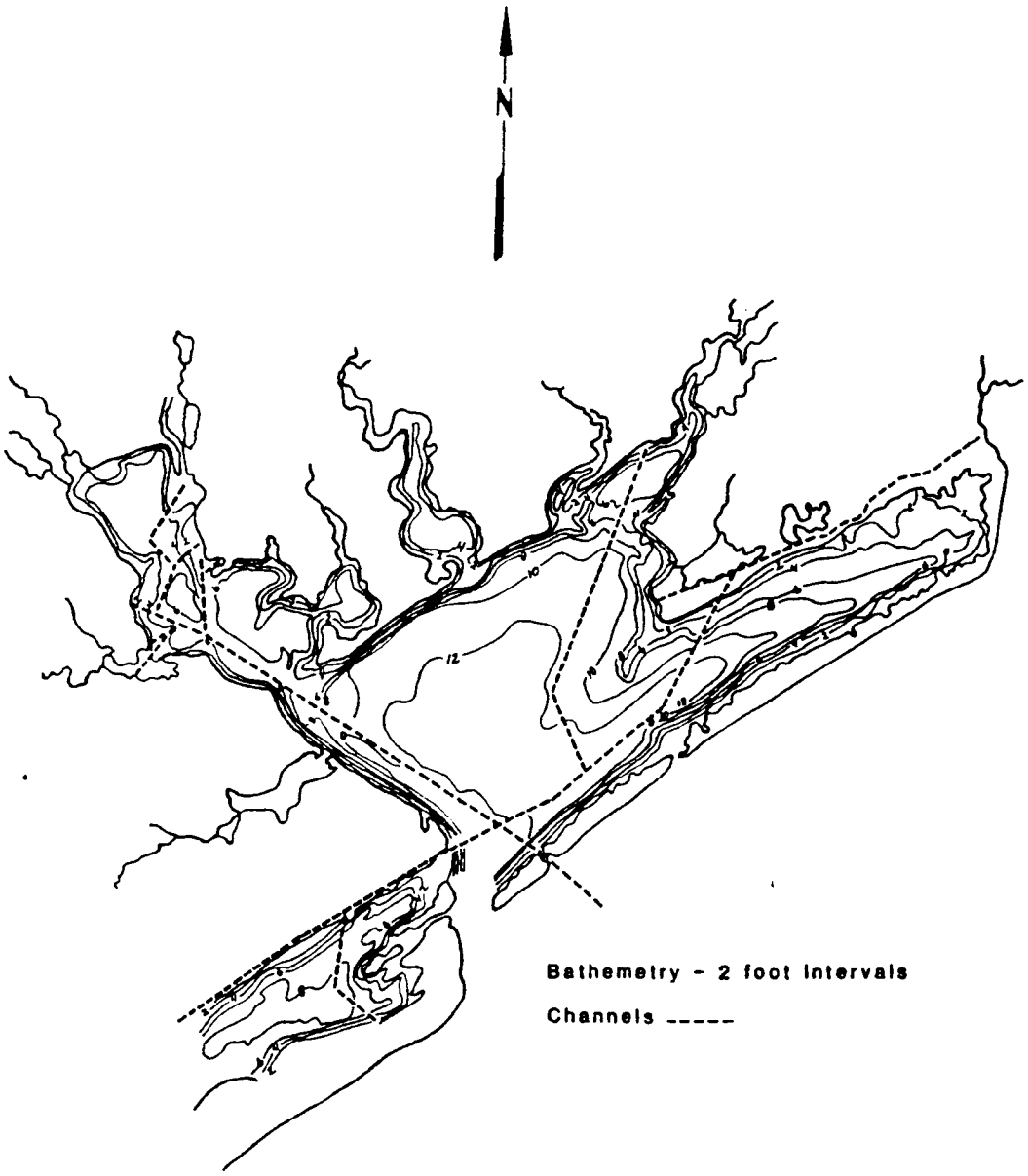


Figure 63. Bathymetry of bays in the Matagorda basin.

and the ship channel through Matagorda Peninsula, are deeper becasue they are scoured through tidal exchange with the gulf. The most eastern portion of Matagorda Bay is a shoal with depths of less than 1.5 m (5 ft). The intracoastal waterway which crosses the breadth of Matagorda Bay, is dredged to a depth of 3.7 m (12 ft). The Matagorda Ship Channel is dredged to a depth of about 10 m (33 ft) and a width of 90 m (295 ft). There is also a channel to Palacios of about the same dimensions and a shallower channel up the Lavaca River. The ship channel to Port Lavaca and Point Comfort is dredged to a depth of about 10 m (33 ft) and a width of about 90 m.

The sediment in the small bays is largely sandy mud or muddy sand with mud in some of the deepest portions. Sediments are sandier in the Espiritu Santo Bay toward Matagorda Island and the relict barrier-strandplain. They are also sandy near the mouth of the Lavaca River and Garcitas Creek in Lavaca Bay. Sediments in the remainder of Lavaca Bay and nearly all of Matagorda Bay are muds. Matagorda Bay has a few reefs near the north shore in its eastern end, and Lavaca Bay contains several reefs in its upper reaches (McGowen and Morton 1979).

McGowen et al. (1976a, 1976b) described generalized circulation patterns that might be expected under average conditions of wind, freshwater inflow, and tidal influence. The general pattern was water movement from the inflow areas toward the passes. The Texas Department of Water Resources (1981c) simulated steady-state flows using a hydrologic model of the bay system based on monthly inflow and weather patterns determined over a 35-year period. Results from the model indicate long-term net flows rather than actual currents. Patterns of circulation are very complicated and display large

variations from month to month. Central areas in Matagorda Bay showed complex gyres, and the flux of water through Pass Cavallo was particularly strong.

Bay shorelines are affected by wave action and the nearshore circulation patterns. McGowen and Brewton (1975) found that almost all of the bay shorelines in the Matagorda basin were eroding except for a few that were accreting at deltas and near passes.

Bay salinities in the Matagorda basin are variable. Figure 64 illustrates salinity patterns that are typical of high and low flow conditions (McGowen et al. 1976a, 1976b). Average salinities with extreme lows and highs for bays in this basin are: Lavaca and Chocolate bays, 15.2 ppt (1.5 to 26.4 ppt); Cox Bay, 17.2 ppt (3.1 to 26.9 ppt); Keller Bay, 19.1 ppt (5.4 to 28.9 ppt); Carancahua Bay, 5.0 ppt (0.2 to 14.3 ppt); Tres Palacios Bay, 19.9 ppt (10.0 to 27.6 ppt); Matagorda Bay, 15.0 ppt (3.2 to 32.5 ppt); and Espiritu Santo Bay, 23.1 ppt (10.0 to 33.6 ppt) (Texas Department of Water Resources 1983a).

The gulf shoreline slopes to a depth of 7 m (24 ft) within 1.6 km of the gulf shoreline. The bottom then slowly descends to a depth of 19 to 24 m at the offshore boundary. The sediments in the gulf near Matagorda Island are sandy for several kilometers; they then become a mixture of mud and sand that grades to mud progressively toward the outer boundary. Off Matagorda Peninsula the sandy sediments are very narrow and mud is found close to the shoreline. There are some local deposits of shell and rock offshore, and there are many areas of mixtures of mud, sand, and shell (McGowen and Morton 1979). Circulation in the gulf is not well studied, but there is a yearly net flow to the south in the littoral area (Morton and Pieper 1976; Morton et al. 1976). Nearly all the gulf shoreline of Matagorda Island is accretionary

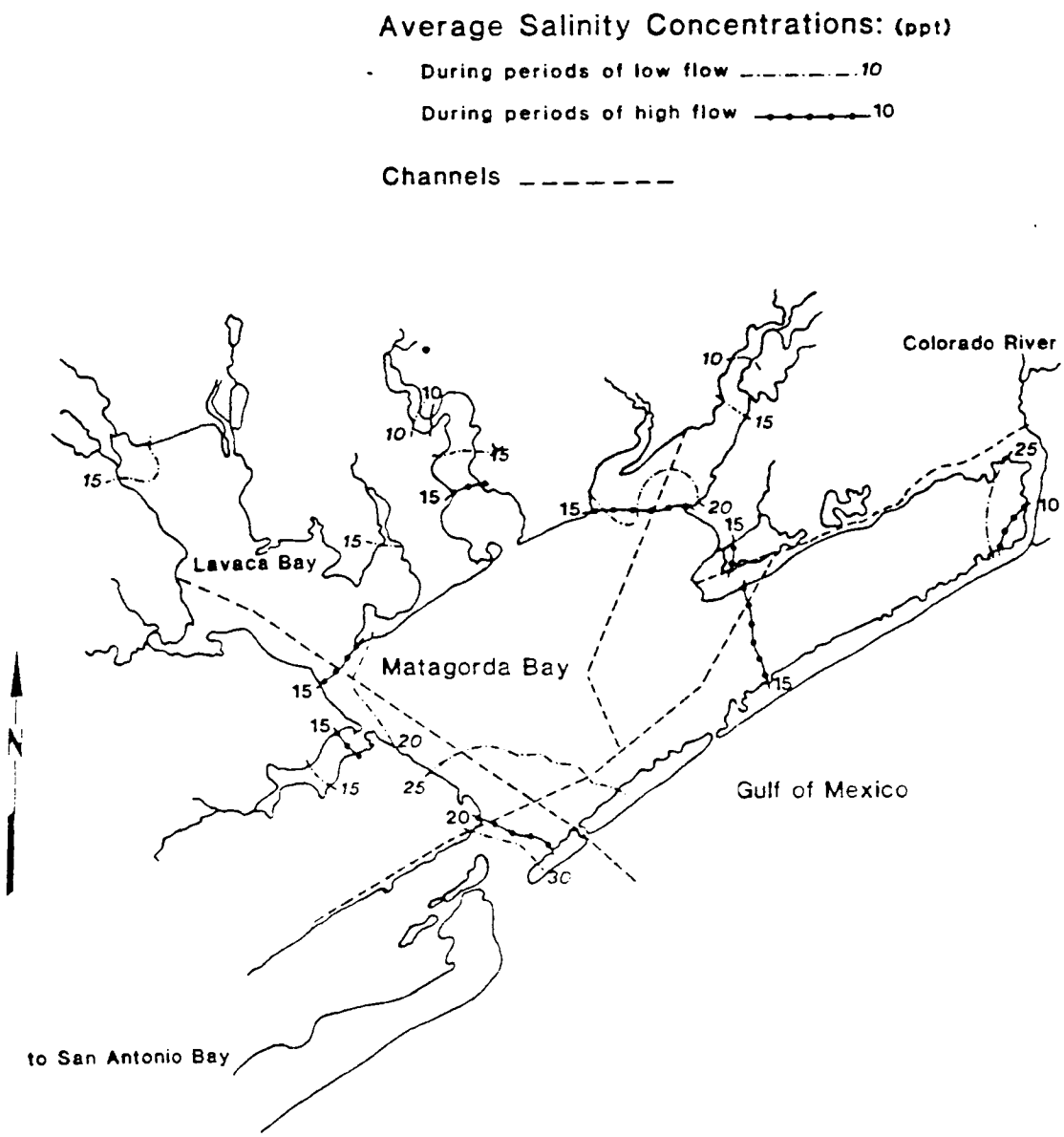


Figure 65. Salinity variation in bays of the Matagorda basin.

except at the island's northern tip, where erosion rates range from 0 to 4.5 m (0 to 15 ft) per yr (Morton and Pieper 1976). Most of Matagorda Peninsula is eroding at the same range of rates, but there is one area of accretion north of the Matagorda Ship Channel (Morton et al. 1976).

Basin economy. In 1980 the Matagorda basin contained 65,330 persons (Table 22). In the decade since 1970 the basin population grew at a rate of 19 percent; population projections to the year 2000 predict growth of 22 percent over the 20-year interval (Texas Department of Water Resources 1980).

The production of oil and gas is an important sector in the basin's economy. In 1977 the total value of oil and gas production was more than $266 million (Liebow et al. 1980).

Recreation and tourism makes a contribution to the economy although it is not nearly as important as oil and gas production. Expenditures for travel were nearly $16 million in 1978, and 650 jobs in the basin were travel-related (Liebow et al. 1980). Hunting and sportfishing were important to the recreation and tourism sector. Nearly 2000 deer were harvested by sportsmen in 1978 (Liebow et al. 1980) and the expenditures by sports fishermen were nearly $6 million (Texas Department of Water Resources 1980a).

Direct value of the commercial catch in the basin was more than $23 million in 1976 (Texas Department of Water Resources 1980a). This was a significant value, and the indirect and induced benefits within the basin contributed even more to the economy.

There were 27,287 persons employed in the basin in 1977; this amounted to 46 percent of the basin's population. There was a modest level of building and construction in 1977. Four hundred fifty-nine building permits were

Table 22. Economic data for the Matagorda basin.

Data type	Quantity
1970 Population	54781
1977 Population	58126
1980 Population	65330
1990 Population projection	70951
2000 Population projection	79424
Mineral production (X $1000)	266332
Deer harvest	1955
Travel expenses (X $1000)	15866
Travel employment	650
Sportfishing spending (X $1000)	5948
Commercial catch value (X $1000)	23261
Electrical generating capacity (kw)	1843549
Total employment	27287
Number of building permits	459
Length of railroad track (km)	257
Length of highways (km)	3762
Number of vehicles registered	64687
Commodity flows (1000 metric tons)	3621
Number of farms	1510
Market value of products (X $1000)	65741
Area of irrigated land (ha)	31964

issued that year; however, this amounted to only 10 permits per 100 sq km of upland basin area (Liebow et al. 1980).

Transportation was also of only moderate importance to the basin's economy. There were 257 km of railroad track and 3762 km of roads in 1977 (Liebow et al. 1980). The number of vehicles registered was 64,687 and the basin had only 17 vehicles registered for each km of road, a low vehicular density. More than 3.6 million metric tons of commodities were transported through the basin's channels in 1977 (RPC Inc., 1980); on a per capita basis, 62 metric tons of commodities were shipped per basin resident.

The Matagorda basin is strong in agriculture. In 1974, 1510 farms produced agricultural products with a market value of nearly $66 million. About 22 percent of the cropland was irrigated, mostly for rice.

Resource demands. Table 23 contains resource demand information for the Matagorda basin. Nearly 32 percent of the upland in the basin is cropland; 51 percent of the upland is range; and slightly more than 1 percent of the upland area is urban land. With completion of construction and filling of Lake Texana a new demand--space for lake and reservoir habitat--will require 1.6 percent of the basin's upland area.

The petroleum extracted within this basin is chiefly crude oil; 1977 production of crude was nearly 2 million kiloliters, or 1.4 percent of the cumulative total production since 1904. Natural and casinghead gas production amounted to 3609 million cu m in 1977 (Liebow et al. 1980).

The demand for biomass production in the Matagorda basin was high for all agricultural products. Over 390 thousand kiloliters of grain were produced in 1978; 12,822 bales of cotton, and more than 54 thousand metric tons of hay and 190 thousand metric tons of rice were grown (Bureau of the Census 1980).

Table 23. Resource demands in the Matagorda basin.

Resource demands	Quantity
Cropland area (ha)	148625
Range area (ha)	238225
Urban area (ha)	5441
Recreation area (ha)	1053
Crude oil production (kiloliters)	1992450
Natural and casinghead gas (million cu m)	3609
Condensate (million liters)	85
1902-1978 oil production (million kiloliters)	138
Grain production (kiloliters)	391328
Cotton production (bales)	12822
Hay produced (metric tons)	54346
Peanuts produced (kg)	0
Rice produced (metric tons)	190155
Cattle and calves sold	56257
Bay shrimp harvested (kg)	2029362
Bay oysters harvested (kg)	63503
Bay crabs harvested (kg)	242671
Bay commercial fish harvested (kg)	73935
Bay sport fish landed (kg)	121290
Total commercial fish harvested (kg)	154045
Total commercial shellfish harvested (kg)	7224045

Table 23 (continued). Resource demands in the Matagorda basin.

Resource demands	Quantity
Digestive cancer mortality	28
Lung cancer mortality	25
Pneumonia and influenza mortality	13
Emphysema, bronchitis, and asthma mortality	10
Length fishable, swimmable stream segments (km)	276
Percent fishable, swimmable stream segments (%)	100
Airborne particulates (metric tons)	11655
Airborne hydrocarbons (metric tons)	64234
Waste discharge measured as 5-Day BOD (kg)	200810
Number of discharges	38
Cumulative industrial solid waste (metric tons)	540087
Subsidence of land surface (m)	0.0-0.5
Municipal surface water use (million cu m)	2
Municipal groundwater use (million cu m)	13
Manufacturing surface water use (million cu m)	32
Manufacturing groundwater use (million cu m)	6
Irrigation surface water use (million cu m)	258
Irrigation groundwater use (million cu m)	470
Total surface water use (million cu m)	299
Total groundwater use (million cu m)	492
Municipal, manufact. return flow (million cu m)	24
Agricultural return flow (million cu m)	268
Obstructions to runoff, roads + railroads (km)	4019
Major drainage ditches and canals (km)	206
Maintenance spoil, historical average (cu m)	2637813
Length of dredged channels (km)	140

Cattle and calf production was also high with 56,257 cattle and calves sold in 1978 (Bureau of the Census 1980).

Biomass production from the estuary and gulf is also high. In 1977 the bay systems in the Matagorda basin produced more than 2 million kg of shrimp, nearly 64 thousand kg of oysters, more than 242 thousand kg of crabs, and nearly 74 thousand kg of fish (Liebow et al. 1980). The two-year average of the sportfishing catch for 1974-1975 and 1976-1977 was more than 121 thousand kg. The four-year average of total catch from 1972 to 1976 combining estuarine and gulf harvest is 154 thousand kg for commercial fish and more than 7 million kg for commercial shellfish (Texas Department of Water Resources 1980a).

Public health indicators for this basin show that the mortality from digestive cancers, lung cancer, and pneumonia and influenza are about the same as the statewide averages. The incidence of emphysema, bronchitis, and asthma was a little higher (National Center for Health Statistics 1981). These statistics do not indicate mortality related to environmental causes throughout the basin.

Stream segments monitored by the Texas Department of Water Resources for water quality have a length of 276 km in this basin. One hundred percent of these waterways are fishable and swimmable today although Tres Palacios Creek has occasional high coliform bacterial counts Texas Department of Water Resources (1983a). Areas restricted for shellfish harvesting have been delineated by the Texas Department of Health (1983). They include Chocolate Bay, the area of Lavaca Bay immediately adjacent to Port Lavaca, and area adjacent to Magnolia Beach. Also included is the shoreline of Lavaca Bay for

a width of about 0.8 km (0.5 mi) from Garcitas Creek to Cox Point on the western edgo of Cox Creek. This comprises about 20 percent of the Lavaca Bay complex. In Matagorda Bay restricted areas include Indianola, most of Carancahua Bay, Turtle Bay, Tres Palacios Bay, and waters adjacent to Port O'Connor. Less than 10 percent of Matagorda Bay is restricted.

Waste loads in the air were surprisingly high in 1973 the Matagorda basin; 11,655 metric tons of airborne particulates and 64,234 metric tons of airborne hydrocarbons (Texas Air Control Board 1977). In the natural waters of this basin 38 discharges are allowed under permit. Fifteen of these discharges are from municipal waste treatment plants. The five-day BOD measurements of organic wastes placed into basin waters total 200,810 kg, an oxygen demand to process wastes of nearly 10 kg per day per person.

The Matagorda basin has experienced subsidence, measured over the period 1918 to 1973 (Ratzlaff 1982). The subsiding areas include both areas with water wells and sites of major oil and gas fields. Ratzlaff attributes the majority of the subsidence in the basin to groundwater withdrawal rather than mineral extraction. Maximum land subsidence is 0.5 m in two areas near Blessing. About 25 percent of the basin area has experienced subsidence of 0.15 m (0.5 ft) or less; less than 10 percent of the basin has had subsidence as great as 0.3 m (1 ft).

The total 1974 water use in the basin was 791 million cu m (Texas Department of Water Resources 1977). Sixty-two percent of the water used in the basin was groundwater; 92 percent of the water, or 728 million cu m, was used for agriculture. Return flows from agriculture totaled 268 million cu m, or 37 percent of the total use. This is much higher than return flows from

agriculture for the region and is probably a result of a large return from rice field drainage.

The degree of hydrologic change on the land surface is relatively low. The total length of roads and railroads that could obstruct drainage is 4019 km (Liebow et al. 1980), a density of 86 km of road and railroad per 100 sq km of upland. The measured area of ditches and canals is 206 km, which seems low in light of the irrigated farming in the basin. The calculated ditch and canal density is low, only 4 km per 100 sq km of upland.

The estuary contains 140 km of channel, or 12 km of channel per 100 sq km of estuary. The annual average maintenance spoil volume is 2,637,813 cu m (Belaire 1976). The spoil load for each kilometer of channel is high and amounts to 24,643 cu m per km.

Colorado basin

Location and description. The Colorado basin is located northeast of the Matagorda basin and southwest of the Brazos-Colorado basin. The basin is long and narrow and consists of the coastal portion of a natural hydrologic unit, the Colorado River Basin (Texas Water Development Board 1977). The natural hydrologic unit is very large (108,166 sq km or 41,763 sq mi) and extends across the entire state and into New Mexico. The Colorado basin defined for this study is relatively small, 1572.1 sq km (607 sq mi), or about 1.5 percent of the area of natural hydrologic unit.

The lower boundary of the Colorado basin coincides with the boundary line between the Colorado River Basin and the Colorado-Lavaca Coastal Basin, natural hydrologic units defined by the Texas Water Development Board (1977). This boundary is 3.2 to 24 km (2 to 15 mi) west of the Colorado River and follows a slight ridge near the towns of Markham and Buckeye.

The upper boundary of the Colorado basin coincides with the boundary line between the natural hydrologic units, the Colorado River Basin and Brazos-Colorado Coastal Basin (Texas Water Development Board 1977). This boundary is 1.6 to 7.2 km (1 to 4.5 mi) east of the Colorado River and separates watersheds draining into Big Boggy Creek, Peyton Creek, and Caney Creek, from those draining into the Colorado River.

About two-thirds of this basin is upland; 2 percent is freshwater habitats, 10 percent is estuarine habitats, 21 percent is gulf, and less than 1 percent is spoil. At its widest point the basin is 22.5 km (14 mi) in breadth. Most of the basin is narrower, usually about 8.9 km (5.5 mi).

At its inland boundary, between the cities of Wharton and El Campo, the basin's elevation is 30 m (100 ft). The basin slopes to the mainland shoreline where elevations are less than 1.5 m (5 ft). A low, wide delta crosses Matagorda Bay separating East Matagorda Bay from the larger bay. In most places the delta is less than 1.5 m (5 ft) in elevation, the same height as Matagorda Peninsula with which it merges. The Colorado River flows through the basin and the delta and discharges directly into the gulf. A portion of the flow reaches Matagorda Bay through channels in the delta including the intracoastal waterway, Culver Cut, and Tiger Island Cut.

About two-thirds of the sediments in the basin are clayey sands and silts placed in ancient deltas or distributary channels, or deposited more recently by meandering rivers, primarily the Colorado. Clays and muds form most of the rest of the basin sediments except for an area of sandy sediments located on Matagorda Peninsula.

Seventeen habitats are represented in this basin (Plate 7); the area or length of each habitat and its percentage of the basin's area are given in Table 24. The largest habitat in the region is range, which occupies 505.8 sq km (195.3 sq km), or 32.2 percent of the basin's area. It is found throughout the basin but occurs in greater quantity in the central and lower portions than in the inland one-third. Cropland comprises 332.0 sq km (128.2 sq mi), or 21.1 percent of the basin's area. Most of the cropland is located close to the inland boundary of the region, although some small parcels are found in the bottom third of the mapped area, near the mainland shore. The cropland parcels often correspond to the areas of clay and mud sediments.

Forest constitutes 170.4 sq km (65.8 sq mi), or 10.8 percent of the basin. The forest in the basin is floodplain forest lying in a relatively narrow band immediately adjacent to the river. The only barrier habitat is a small area on Matagorda Peninsula near the river mouth. The land here is undergoing rapid urbanization as vacation homes are built along the levee of the Colorado delta and on the barrier. Other areas of urban land include the city of Matagorda at the mouth of the Colorado River and the cities of Wharton and El Campo at the inland boundary. Urban land constitutes about 17.1 sq km (6.6 sq mi), or 1.1 percent of the basin.

The estuarine habitats present in this basin include bay, grassflat, reef, salt and brackish marsh, and wind-tidal flat. (Because of the method of calculation and the small size of this basin, the area of these habitats in Table 24 is slightly overestimated; in addition, some areas were too small to be mapped.) The largest estuarine habitat in the basin, salt and brackish marsh, occurs on the extensive Colorado River delta and in the area of Robbins Lake to the west of the Colorado River. The salt and brackish marsh on the

Table 24. Habitat areas, lengths, and proportions in the Colorado basin.

Habitat	Area (sq km)	Length (km)	Percent of basin area
Barrier	17.9		1.1
Bay	122.2		7.8
Bulkhead	0.0		0.0
Channel and tidal stream		53.6	
Cropland	332.0		21.1
Forest	170.4		10.8
Freshwater marsh	1.6		0.1
Grassflat	3.4		0.2
Gulf	330.2		21.0
Lake and reservoir	29.5		1.9
Range	505.8		32.2
Reef	3.6		0.2
River and canal		363.7	
Salt and brackish marsh	26.2		1.7
Spoil	4.9		0.3
Swamp	2.1		0.1
Urban	17.1		1.1
Wind-tidal flat	5.2		0.3

delta is relatively new since the delta has existed only since 1930; McGowen and Brewton (1975) reported that the area of new marsh was 14.7 sq km (5.7 sq mi). The amount of bay habitat in the basin is relatively small. The basin includes only a portion of Matagorda Bay and a portion of East Matagorda Bay. Some reef habitat, Dog Island Reef, occurs near the delta adjacent to the openings of Culver Cut and Tiger Island Cut into the eastern arm of Matagorda Bay.

Numerous land-use changes have occurred or are currently taking place in the basin. Houston Lighting and Power Company (no date) reported that areas of forest along the Colorado River had been treated with the plant hormones 2,4-D and 2,4,5-T over a period of several years. The hormone, which selectively kills woody plants, has been used in a program of land clearing to increase the amount of range in the basin.

The South Texas Project--a nuclear generating plant--is currently under construction 10 km (6.2 mi) north of the intracoastal waterway, to the west of the Colorado River. A cooling pond for the plant occupies 28.3 sq km (10.9 sq mi) (Houston Lighting and Power Company 1978). When it is filled, the cooling pond will substantially increase the total area of lake and reservoir habitat in the basin.

The most dramatic change in habitats in the Colorado River basin was the progradation of the Colorado delta across Matagorda Bay. A detailed account of the actions leading to the delta growth is given in Ward and Armstrong (1980). Following actions to weaken a 24-km (15-mi) long log jam on the Colorado River above Matagorda, a large storm in 1929 swept most of the logs into Matagorda Bay, and the sediment that had accumulated was transported to

the mouth of the Colorado River. By 1930 the delta stretched halfway across the bay; by 1936 the delta had joined Matagorda Peninsula and the river flowed directly into the gulf. By 1941 the delta, much of it wetland, covered 28.7 sq km (11.1 sq mi) (McGowen and Brewton 1975).

A project to improve navigation facilities and divert Colorado River flow--the Mouth of the Colorado Project--is currently underway within the delta. As a part of this effort, Colorado River flow will be partially diverted into the eastern arm of Matagorda Bay. The low-salinity water will improve the salinity gradient in Matagorda Bay, but the sediment load will increase the size of the delta and probably cover what remains of Dog Island Reef (Ward and Armstrong 1980).

Geologic development. Sediments underlying the Colorado basin are derived from delta and fluvial-delta deposits left by the ancient Colorado River system during the Sangamon interglacial period (McGowen et al. 1976b).

Sea level dropped during the Early Wisconsin period, and when it rose again, the shoreline was 10 km (6 mi) inland of its present location. A barrier-strandplain system may have been built across the mainland from Port O'Connor to Chocolate bay, although no traces of it exist today.

Sea level began to drop 50,000 to 60,000 yr BP and erosion of the exposed sediments occurred over a wide area; many small streams eroded river valleys in the Pleistocene fluvial-deltaic sediments. This erosion occurred in what is now the Modern Colorado River valley, but it is probable that a stream other than the Colorado River created this valley during the last glaciation.

When sea level rose 25,000 to 18,000 yr BP, sediment from headward-eroding streams, river valley wall erosion, estuary bank erosion, and transport of sediments from the gulf partially filled the river valleys. Up

until 4000 yr BP, Matagorda Bay was largely open to the sea (McGowen et al. 1976b). Pleistocene delta sediment along the mainland shoreline of the basin may have been reworked at this time.

Sea level arrived at its present level 2800 to 2500 yr BP. Shoals and a discontinuous chain of islands developed across the mouth of Matagorda Bay. About 1800 yr BP the Colorado-Brazos estuary--a large area east of the Colorado basin--completely filled and debouched sediment into the gulf; the Colorado River flowed in what is now Caney Creek. A spit, fed by sediment from the river systems, built out from the headlands of the old Colorado across the entire width of Matagorda Bay to form the present Matagorda Peninsula.

About 1000 yr ago the headward-eroding stream that had created the Modern Colorado River valley met the Colorado River near Wharton and pirated the flow down the Modern Colorado River (McGowen et al. 1976b). After that time, enough sediment flowed down the river to fill much of the lower portion of the estuary. This allowed the river to empty directly into the eastern arm of Matagorda Bay. Sometime after the delta was built to the mainland shoreline, the log jam that was instrumental in creating the modern delta across Matagorda Bay began to form.

Basin hydrology and climate. The average temperature of the basin is 21.4 deg C (70.5 deg F); the average summer high is 28.6 deg C (83.5 deg F) and the average winter low is 12.5 deg C (54.5 deg F) (Williams et al. 1976).

Average rainfall in the basin is 107 cm (42.1 in) (Williams et al. 1976). The greatest rainfall occurs during the month of September (15.1 percent at Bay City) with June, May, and August rainfall following in descending order.

March has the lowest quantity of rainfall (Bomar 1983). Potential evapotranspiration only slightly higher than basin rainfall produces a net precipitation deficit of 5 cm (2 in) (Woodruff 1975).

Surface water flowing through this basin comes from the Colorado River. The 27-yr average flow at the Bay City gage is 2155 million cu m per year (Dougherty 1980). Variation during periods of low and high flow have ranged from 18 to 341 percent of the average flow (Dougherty 1980). The sediment carried by the Colorado was estimated by Ward and Armstrong (1980) to be 300,000 cu m per year.

The greatest flow through the basin occurs during the spring. May has the highest flows, and June has the second-highest. Smaller flow peaks occur during the months of February, October, and November; August and July are the periods of least flow through the basin. Figure 65 presents a hydrograph of Colorado River flow and shows the hydrologic distribution pattern for the basin. Most of the water in the river comes from drainage areas further inland. There is a small amount of drainage from the basin into the Colorado. Upland flooding may occur during periods of high water flow. The South Texas Nuclear plant will be a net consumer of water from the Colorado River. The plant will remove 45 to 79 million cu m of water each year and return about 20 million cu m directly (Houston Lighting and Power Company 1978).

Some flow from the tidal portion of the Colorado enters the Brazos-Colorado basin and East Matagorda Bay through the intracoastal waterway and small channels into the bay. The volume of water is low and only enters during high flow conditions. A significant quantity of water enters the eastern arm of Matagorda Bay through Tiger Island Cut and Culver Cut. Ward and Armstrong (1980) note that estimates of flow through the cuts have ranged

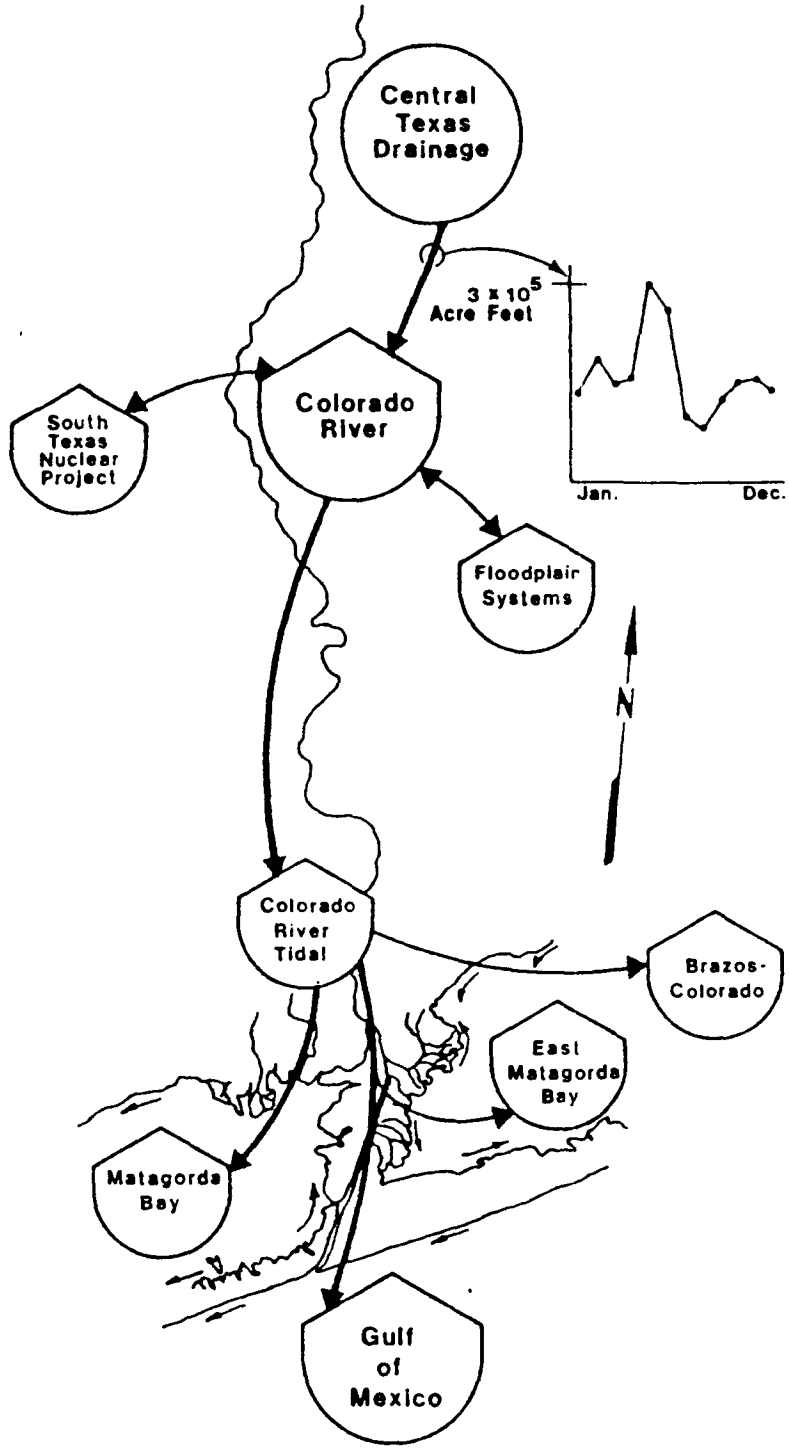


Figure 65. Hydrology of the Colorado basin.

from 25 to 80 percent of the river flow volume and are a function of river flow volume. The Texas Department of Water Resources (1980a) computed a 25-year average of 1580 million cu m per year. This is 73 percent of the flow measured by the Bay City gaging station.

The small areas of Matagorda and East Matagorda bays in this basin are very shallow, less than 1 m (3.3 ft). The sediments of both areas are about evenly divided between sandy mud and mud, with sandy mud closest to the delta (McGowen and Morton 1979). Circulation is highly influenced by the wind, but is dominated by inflows from the river during periods of high flow.

Long-term detailed measurements of the salinities of the small bay areas in the basin are not available. In a short-term study, Diener (1973) measured salinities of 17.4 to 31.2 ppt in the eastern arm of Matagorda Bay and 17.5 to 28.1 ppt in East Matagorda Bay. The average salinity of the tidal portion of the Colorado River is 0.7 ppt with extreme low and high measurements of 0.1 and 2.2 ppt.

Offshore, the floor of the gulf drops rapidly to a depth of 7 m (24 ft) and then slopes gently to a depth of 19 m (63 ft) at the three-league line. Nearshore sediments are sandy and bordered by a narrow band of mud. Further offshore there is a complex mixture of sandy mud and muddy sandy (McGowen and Morton 1979).

Morton et al. (1976) noted that the dominant direction of flow in the littoral zone is to the southeast. Temple and Martin (1979) showed that offshore surface circulation patterns fluctuated seasonally, although the net flow direction appeared to be to the south or southwest. The part of Matagorda Peninsula within the basin has been undergoing long-term erosion at

the rate of 0 to 1.5 m (0 to 5 ft) per year (Morton et al. 1976). Areas just downstream from the Colorado mouth have both accreted and eroded recently, although erosion has outweighed accretion since 1937 (Morton et al. 1976). Even though the Colorado River now discharges part of its sediment into the gulf, this addition does not offset other losses.

Basin economy. The population of the basin in 1980 was 14,583 persons (Table 25). Over the decade from 1970 to 1980, the basin experienced a 21 percent growth in population. Population projections from the Texas Department of Water Resources (1980) predict a growth of 37 percent by the year 2000.

Oil and gas production has been moderately important to the economy of the basin. The value of minerals produced in 1977 was nearly $54 million, or $34 thousand per sq km of basin area (Liebow et al. 1980).

In contrast, recreation has been relatively unimportant. Travel expenditures in 1978 were less than $3 million and the number of travel-related jobs was only 114 (Liebow et al. 1980); only 19 jobs per 1000 persons employed were travel-related. The importance of hunting and fishing to recreation and tourism was also low. Since the basin has almost no estuarine area and a limited gulf area, commercial fishing is an unimportant part of the basin's economy.

Total employment in the basin was 5837 in 1977; 46 percent of the population was employed. In 1977, 43 building permits were issued; this was an average of 41 per 100 sq km (Liebow et al. 1980). The South Texas Project has been a major impetus to the residential and industrial development sector of the basin's economy since construction began more than a decade ago.

Table 25. Economic data for the Colorado basin.

Data type	Quantity
1970 Population	12009
1977 Population	12639
1980 Population	14583
1990 Population projection	17057
2000 Population projection	19938
Mineral production (X $1000)	53940
Deer harvest	217
Travel expenses (X $1000)	2866
Travel employment	114
Sportfishing spending (X $1000)	0
Commercial catch value (X $1000)	0
Electrical generating capacity (kw)	0
Total employment	5837
Number of building permits	43
Length of railroad track (km)	71
Length of highways (km)	906
Number of vehicles registered	14049
Commodity flows (1000 metric tons)	283
Number of farms	399
Market value of products (X $1000)	21391
Area of irrigated land (ha)	10635

Transportation has been of minor importance to the economy. There were 71 km (44 mi) of railroad track and 906 km (563 mi) of roads in the basin in 1976. The number of vehicles registered was 14,049 in 1978, and the vehicular density was only 15 vehicles per 100 km of highways--the lowest in the region. Commodity flows are also of minor importance. In 1977 only 283 thousand metric tons of commodities were carried over the basin's waterways (RPC, Inc. 1980). This amounted to 22 tons per person, a minor contribution to the economy.

The agricultural sector is one of the most valuable portions of the economy of the Colorado basin. The basin contained nearly 400 farms in 1974, and their market value of the production was more than $21 million (Liebow et al. 1980).

Resource demands. There has been a high demand for space for agriculture. Almost 49 percent of the basin's area is range and nearly 32 percent is cropland (Table 26). Less than 2 percent of the basin's area is urban land.

The majority of the petroleum found in the basin is crude oil. In 1978, 180,816 kiloliters of crude oil were produced. This was 1.5 percent of the cumulative total since oil and gas production first began in 1904 (Liebow et al. 1980). The amount of natural gas and casinghead gas produced was low, totaling 997 million cu m.

Biomass production in the basin was high. In 1978 more than 86,661 kiloliters of grain, 7721 bales of cotton, and 13,627 metric tons of hay were produced. Rice production, 63,557 metric tons, was also high, and rice was one of the most important crops. The number of cattle and calves sold in 1978

Table 26. Resource demands in the Colorado basin.

Resource demands	Quantity
Cropland area (ha)	33218
Range area (ha)	50604
Urban area (ha)	1710
Recreation area (ha)	45
Crude oil production (kiloliters)	180816
Natural and casinghead gas (million cu m)	997
Condensate (million liters)	25
1902-1978 oil production (million kiloliters)	12
Grain production (kiloliters)	86661
Cotton production (bales)	7721
Hay produced (metric tons)	13627
Peanuts produced (kg)	0
Rice produced (metric tons)	63577
Cattle and calves sold	11102
Bay shrimp harvested (kg)	0
Bay oysters harvested (kg)	0
Bay crabs harvested (kg)	0
Bay commercial fish harvested (kg)	0
Bay sport fish landed (kg)	0
Total commercial fish harvested (kg)	0
Total commercial shellfish harvested (kg)	0

Table 26 (continued). Resource demands in the Colorado basin.

Resource demands	Quantity
Digestive cancer mortality	6
Lung cancer mortality	4
Pneumonia and influenza mortality	4
Emphysema, bronchitis, and asthma mortality	1
Length fishable, swimmable stream segments (km)	43
Percent fishable, swimmable stream segments (%)	100
Airborne particulates (metric tons)	1914
Airborne hydrocarbons (metric tons)	1986
Waste discharge measured as 5-day BOD (kg)	6508
Number of discharges	5
Cumulative industrial solid waste (metric tons)	141874
Subsidence of land surface (m)	0.0-0.3
Municipal surface water use (million cu m)	82
Municipal groundwater use (million cu m)	22
Manufacturing surface water use (million cu m)	10
Manufacturing groundwater use (million cu m)	2
Irrigation surface water use (million cu m)	72
Irrigation groundwater use (million cu m)	47
Total surface water use (million cu m)	190
Total groundwater use (million cu m)	84
Municipal, manufact. return flow (million cu m)	54
Agricultural return flow (million cu m)	25
Obstructions to runoff, roads + railroads (km)	977
Major drainage ditches and canals (km)	87
Maintenance spoil, historical average (cu m)	436169
Length of dredged channels (km)	29

was 11,102 (Bureau of the Census 1980). Livestock density suggested that cattle grazed on range land rather than being placed in feed lots.

Public health statistics show that the incidence of respiratory diseases that might be environmentally related is low in the Colorado basin and is comparable to the statewide average (National Center for Health Statistics 1981). Forty-three kilometers of freshwater streams and rivers in the basin are monitored for water quality. All of these areas are fishable and swimmable according to water quality criteria (Texas Department of Water Resources 1983a). The tidal portion of the Colorado River has moderate public health problems as the result of high bacterial levels. The tidal portion of the river receives point-source discharges and agricultural runoff; in addition, the Colorado River channel between the intracoastal waterway and the gulf receives poorly treated sewage from vacation homes on the banks. It has been closed to shellfishing by the Texas Department of Health (1983).

The basin receives 1914 metric tons of airborne particulates and 1986 metric tons of airborne hydrocarbons per year (Texas Air Control Board 1977). On an areal basis this is about 1 ton each of particulates and hydrocarbons per sq km of upland per year, a very low figure.

The basin receives effluent from five permitted waste discharges, one of which is a municipal waste treatment facility. In 1983 the 5-day BOD load was 6508 kg of oxygen per year; on an areal basis this was 6 kg of oxygen per sq km of upland per year, the lowest waste load of all the basins.

Land-surface subsidence has been measured in the Colorado basin over the period 1918 to 1973; most has occurred in the vicinity of Bay City, about halfway between the mainland boundary and the inland boundary. Ratzlaff (1982) attributed the subsidence to the extraction of fresh groundwater, oil,

gas, and groundwater produced with oil and gas. The area affected by the maximum subsidence (0.3 m or 1 ft) is about 5 percent of the basin.

The total water use in the basin in 1974 was 274 million cu m, 69 percent of which came from surface sources. The agricultural use of groundwater was 119 million cu m, or 43 percent of the total use. Nearly 61 percent of the water used for agriculture was surface water. The return flow from agriculture was 25 million cu m, a return rate of 21 percent. The total municipal and manufacturing use of water accounted for 116 million cu m; return flow from these uses was 47 percent (Texas Department of Water Resources 1977).

The amount of hydrologic change on the land surface is low. The basin contains 977 km of roads and railroads, and 87 km of canals and drainage ditches. The density of these obstructions to water flow was 93 and 8 km per 100 sq km of uplands respectively. The amount of estuarine area in the basin is small and contains only 29 km (18 mi) of dredged channel. The average annual maintenance spoil volume is 436,169 cu m (Belaire 1976), and each km of dredged channel requires the removal of 15,040 cu m of spoil.

Brazos-Colorado Basin

Location and description. The Brazos-Colorado basin described hereis located in the upper coastal region, between the Colorado and Brazos rivers. The basin is wholly contained within the Brazos-Colorado Coastal Basin, a natural hydrologic unit defined by the Texas Department of Water Resources (Texas Water Development Board 1977). The basin within the Texas Barrier Island Region study area comprises 3608.6 sq km (1393.3 sq mi), about 75 percent of the area of the natural hydrologic unit.

The lower boundary of the Brazos-Colorado basin coincides with the boundary line between the Brazos-Colorado Coastal Basin and a second natural hydrologic unit, the Colorado River Basin (Texas Water Development Board 1977). This boundary is 1.6 to 7.2 km (1 to 4.5 mi) east of the Colorado River and separates watersheds draining into Big Boggy Creek, Peyton Creek, and Caney Creek from those draining into the Colorado River. It includes most of Bay City and bisects Wharton.

The upper boundary of the Brazos-Colorado basin coincides with the boundary line between the Brazos-Colorado Coastal Basin and the Brazos River Basin (Texas Water Development Board 1977). This boundary is 2 to 25.5 km (1.2 to 15.8 mi) west of the Brazos River and separates the streams that drain into the basin--the San Bernard River, for example--from those that drain into the Brazos River. The boundary passes through or close to the cities of Jones Creek, Brazoria, West Columbia, Damon, and Needville.

The Brazos-Colorado basin is narrower at its inland boundary than at the seaward boundary. Consequently the relative area of gulf included in the basin, 29 percent, is large. The estuarine area is smaller than in many basins and constitutes about 10 percent of the basin's area. Uplands occupy 58 percent of the basin, and freshwater habitats occupy 3 percent. Spoil constitutes less than 0.5 percent of the basin's area.

At the inland boundary, the elevation of the basin is 30.5 m (100 ft) on the west and 27 m (90 ft) on the east. The elevation dips toward the center of the inland boundary and is 21 to 24 m (70 to 80 ft) where the San Bernard River flows. This concave depression continues through the top third of the basin but becomes less evident toward the coast, where other streams and creeks drain the uplands.

The lower half of the uplands, closest to the coast, has four distinct subbasins that drain into small creeks and streams. The westernmost subbasin contains Big Boggy Creek, which drains into the intracoastal waterway, and Peyton Creek, which drains into Lake Austin, a fresh to brackish lake inland of East Matagorda Bay. The next subbasin contains Live Oak Bayou, Boggy Bayou, and Caney Creek; it drains into East Matagorda Bay and the intracoastal waterway. The third subbasin contains Cedar Lake Creek, which drains into Cedar Lakes, and the easternmost subbasin contains the lower portion of the San Bernard River, which drains into the intracoastal waterway and the gulf.

East Matagorda Bay is the major estuarine system in this basin. Lake Austin, Cedar Lakes, Cow Trap Lake, and several other small water bodies are fresh to brackish since they receive fresh water from adjacent land runoff and a small amount of estuarine water from the intracoastal waterway.

Sediments in the eastern two-thirds of the basin are predominantly clayey sands and silts characterized by moderate permeability and water-holding capacity. Clay and mud sediments are located in the western third, between the area of Caney Creek and the Colorado River, and along the edge of the mainland shoreline just inland of salt and brackish marshes. These soils have low permeability and high water-holding capacity.

All 18 habitats are represented in the Brazos-Colorado basin (Plate 8). Table 27 shows the extent of each habitat and its percentage of the basin's area. A large area of forest in the central portion of the basin extends nearly to the coastline (Plate 8). This is floodplain forest that has developed on a wide area of clayey sands and silts deposited by meandering rivers and streams during the past thousand years. Although sizable areas of

Table 27. Habitat areas, lengths, and proportions in the Brazos-Colorado basin.

Habitat	Area (sq km)	Length (km)	Percent of basin area
Barrier	38.8		1.1
Bay	248.9		6.9
Bulkhead	1.0		<0.1
Channel and tidal stream		154.3	
Cropland	693.1		19.2
Forest	403.5		11.2
Freshwater marsh	9.6		0.3
Grassflat	6.7		0.2
Gulf	1045.3		29.0
Lake and reservoir	83.4		2.3
Range	930.6		25.8
Reef	2.0		0.2
River and canal		363.7	
Salt and brackish marsh	69.4		1.9
Spoil	14.5		0.4
Swamp	7.8		0.2
Urban	39.6		1.1
Wind-tidal flat	9.3		0.3

forest have been cut and cleared for range and cropland in the last 200 years, much forest still remains.

The largest proportion of the upland area of the basin is range. Range is found along the western and southern portions of the basin. In addition, a large area of range has been carved out of the forest land. Cropland is scattered throughout the basin, but the greatest concentration occurs near the inland boundary. More cropland is found along the western side of the basin, where there are mud and clay sediments suitable for crop production, than along the eastern side.

Several small habitats are scattered within the uplands. At least eight areas of swamp are located within the forest habitat. They occur near streams or in depressions and are usually some distance from the shoreline. Several freshwater wetlands are located in the lower portion of the uplands where the land is relatively low. The basin contains a few small urban areas, including Bay City, a portion of of Wharton, Boling, Old Ocean, and Jones Creek.

The principal barrier habitat in the basin is Matagorda Peninsula, which is partially separated from the mainland by Brown Cedar Cut, a pass from the gulf to East Matagorda Bay that remains open for long periods of time after major storms (Ward and Armstrong 1980). Barrier habitat is also located along the mainland shoreline from Brown Cedar Cut to the Brazos River delta. In this area the barrier habitat consists of beach and low dunes.

The estuarine habitats in the basin include bay, reefs in East Matagorda Bay, and a small area of grassflats near the Colorado River delta. Large areas of salt and brackish marsh occur on the mainland shoreline in an elevation gradient that contains the complete sequence of plant communities from upland to salt marsh. Wind-tidal flat, bounded by salt and brackish

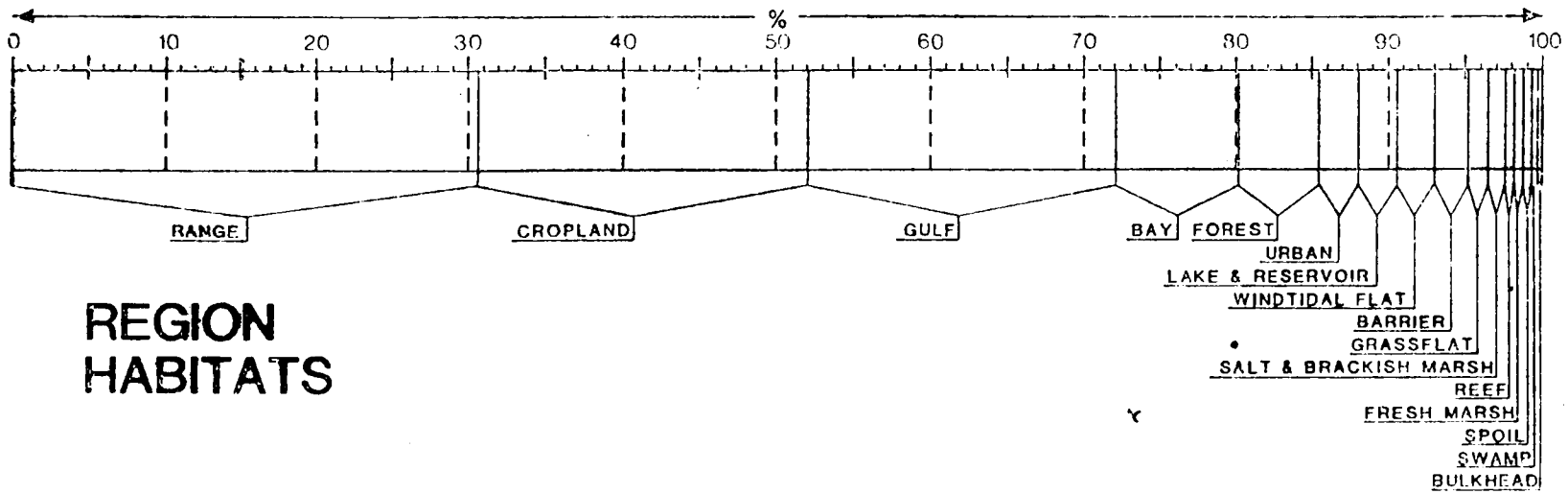
marsh, is present on the bay side of the barrier, but is too small to be mapped.

Channel and tidal stream habitat and spoil habitat are significant in this basin, not because of their area, but because of their hydrologic influence. When the intracoastal waterway was dredged across the basin, spoil was placed immediately adjacent to the channel. As a result, saline water was able to penetrate some areas that had previously received only freshwater flows. In addition, continuous subaerial spoil piles blocked freshwater flows in other areas.

The Brazos-Colorado basin contains a larger proportion of gulf, forest, and salt and brackish marsh habitats than the region as a whole (Figure 66). The proportions of range, cropland, urban land, and barrier habitats are slightly smaller in the basin than in the region. The basin also contains smaller proportions of bay, grassflat, reef, and wind-tidal flat. The remaining habitats occupy about the same percentage of the basin's area as they do of the region's area.

Geologic development. The surface sediments in the Brazos-Colorado basin range in age from Pleistocene to Recent. Underlying the entire basin are fluvial-deltaic sediments deposited by the Colorado River and to a lesser extent by the Brazos River during the Sangamon interglacial stage of the Pleistocene (McGowen et al. 1976b).

When sea level rose again after the Early Wisconsin glaciation, a barrier-strandplain system may have been built parallel to today's shoreline along this basin; however, no traces of a strandplain exist today between Port O'Connor and Chocolate Bay.



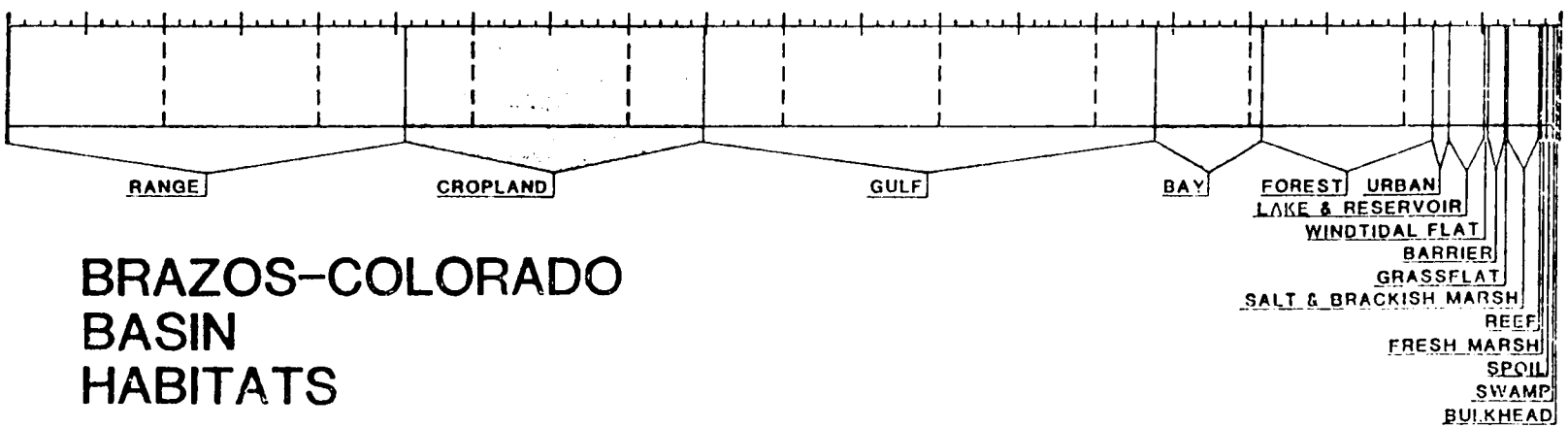


Figure 66. Habitat proportions of the Brazos-Colorado basin and Texas Barrier Island Region.

Sea level dropped again 50,000 to 60,000 yr BP. Exposed sediments eroded, and the Colorado and Brazos rivers formed wide, deep river valleys that joined and formed a common river valley within the basin. McGowen et al. (1976b) noted that the bottoms of the river valleys in the vicinity of today's shoreline were 30.5 m (100 ft) below mean sea level.

When the sea rose 25,000 to 18,000 yr BP, sediment from headward-eroding streams, river valley wall erosion, estuary bank erosion, and the gulf began to fill the eroded valleys. By the time sea level stabilized 2800 yr BP, the headlands of the common estuary into which both river systems flowed were 35 km (22 mi) inland of the present shoreline near Cedar Lakes. The mainland north of Matagorda Bay was open to the gulf, and delta sediments along this mainland shoreline were probably reworked by gulf wave action. Eventually, shoals and a discontinuous chain of islands developed across the mouth of Matagorda Bay.

Over a period of 1200 yr after sea level stabilized, the Colorado and Brazos rivers built a delta across their estuary to the sea. The delta grew at the rate of about 29.6 m (97 ft) per year and completely filled the estuary (McGowen et al. 1976b). As a result, both the Colorado and Brazos rivers deposited their sediment directly into the gulf. A spit, fed by sediment from the river systems, developed to the southwest from the headlands of the old Colorado. It built across the entire width of Matagorda Bay, forming the present Matagorda Peninsula.

For some period after the estuary filled, the waters of the Colorado flowed along Caney Creek rather than down its present course. About 1000 yr BP, the headward-eroding stream that had created the Modern Colorado River valley met the Colorado River near Wharton and pirated the flow down the

Modern Colorado River (McGowen et al. 1976b). The Brazos wandered over a wide area east of this basin but came no further west than the present mouth of the Brazos. Consequently the upland portion of this basin became an established hydrologic unit about 1000 yr BP.

Sediment that was transported down the Modern Colorado River filled the small estuary which the original headward-eroding stream had created. This estuary was about 8 km (5 mi) long. The delta prograded to the mainland shore and out into Matagorda Bay by the year 1856 (McGowen et al. 1976b). After Matagorda Peninsula developed, the area now known as East Matagorda Bay was simply a portion of the eastern arm of Matagorda Bay. In 1929 a log jam that had formed over several hundred years was loosened and was swept out of the Colorado River into Matagorda Bay. The increased flow resulting from removal of the log jam transported accumulated sediment, and in a span of seven years the Colorado delta prograded across the entire bay, isolating East Matagorda Bay from the rest of the bay system (Ward and Armstrong 1980).

Basin hydrology and climate. The basin climate is warm and humid. The average temperature in the Brazos-Colorado basin is 21.4 deg C (70.5 deg F); the average summer high temperature is 28.3 deg C (83 deg F) and the average winter low temperature is 12.5 deg C (54.5 deg F) (Williams et al. 1976).

Average rainfall in the basin is 117 cm (46 in) (Williams et al. 1976). The greatest proportion of rainfall occurs during September (15.6 percent), followed by July, August, and June; March has the lowest precipitation (3.7 percent) (data for Freeport from Bomar 1983). Evapotranspiration is lower than rainfall in the Brazos-Colorado basin and produces a slight excess of 10.2 cm (4 in) of precipitation (Woodruff 1975). Habitats that store fresh or

slightly brackish water constitute 93 sq km (36 sq mi), or 4.2 percent of the area above mean high water.

Fresh water flows through this basin via the San Bernard River and many small creeks and streams that drain into the fresh-to-brackish lakes or the intracoastal waterway. Flow records for the San Bernard River and Big Boggy Creek show that the average gaged flow was 454 million cu m over a 21-yr period. During times of extreme low and high flow, gaged flow ranged from 9 to 269 percent of the average (Dougherty 1980). Since the basin described in this study is wholly included within the larger Brazosos-Colorado Coastal Basin, the total flow calculated for the latter may be indicative of the net freshwater inflow to the basin. The product of the average runoff and basin area is 1018 million cu m, more than twice the gaged flow (Texas Water Development Board 1977). No information is available on sediment flow through the basin.

The inflow from gaged streams into the basin has peaks in three different months (Figure 67). Late spring flow, in May and June, brings the largest proportion of water into the basin; September, October, and February have minor flow peaks. The lowest flow occurs during August (Dougherty 1980).

Figure 67 shows the hydrologic distribution pattern for the basin. The uplands supply water to the San Bernard River, small creeks, and streams. Urban and industrial return flows supplement the natural freshwater flows. The San Bernard River sends water directly into the gulf, although some of this flow passes into the intracoastal waterway. The intracoastal waterway receives water from some of the small creeks and streams and serves as a distribution channel for water from the Brazos and Colorado rivers. Flow from the Brazos and Colorado rivers is partially controlled by flood gates that are

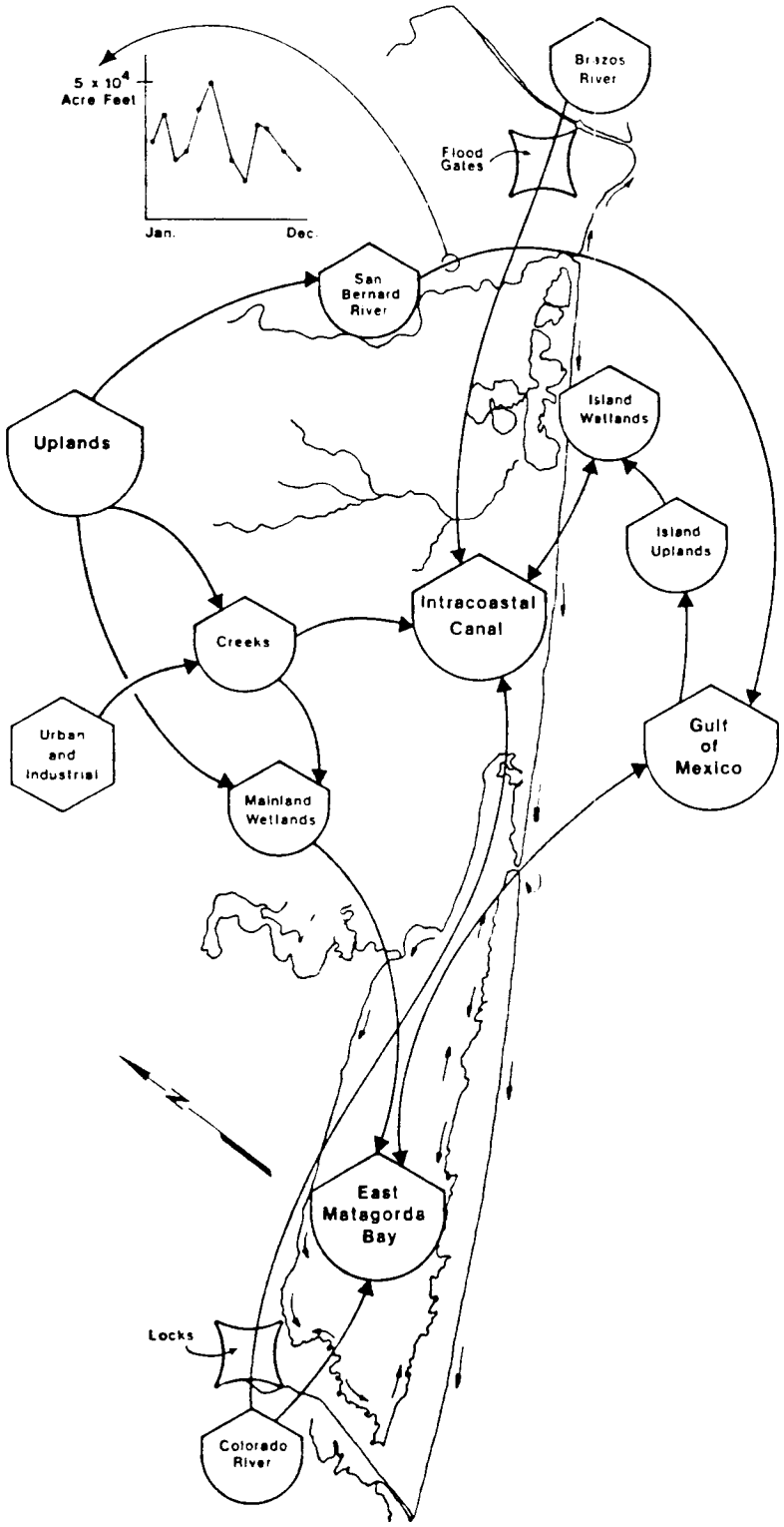


Figure 67. Hydrology of the Brazos-Colorado basin.

closed when the rivers flood to prevent shoaling in the intracoastal waterway. Water channeled through the intracoastal waterway supplies wetlands throughout the basin, especially those between the eastern tip of East Matagorda Bay and the opening of the San Bernard River.

East Matagorda Bay receives fresh water intermittently from flooding on the Colorado; it also receives water from Live Oak Bayou, Chinquapin Bayou, Caney Creek, and the intracoastal waterway through breaks in some of the spoil piles. Marine waters enter and exit East Matagorda Bay through Brown Cedar Cut.

Most of East Matagorda Bay is 1 m (3.3 ft) or less in depth. Bottom sediments are generally mud, although near the barrier island and adjacent to the opening of Live Oak Bayou the sediments are sandy mud, muddy sand, or sand (McGowen and Morton 1979). The other natural water bodies in the region are all uniformly shallow. Johnson (1975) reported depths in Cedar Lakes and Cow Trap Lake of less than 1 m (3.3 ft). He also noted that bottom sediments were silts, clays, and muds with small amounts of sand. The intracoastal waterway that passes through the basin is dredged to a depth of 3.7 m (12 ft) and a width of 38 m (125 ft). Because of the width and depth of the waterway, the volume of water it carries is sizable compared to the volume of some of the brackish lakes it passes by.

Circulation in East Matagorda Bay has not been studied. Because the bay is so shallow, circulation is certainly governed by predominant winds. McGowen et al. (1976b) surmised that under normal conditions water would flow generally counter-clockwise in the bay (Figure 67). Circulation through the rest of the basin is also unknown.

The salinity of East Matagorda Bay (4-year average) is 15 ppt; extreme high and low measurements during the period have ranged from 3.2 to 32.5 ppt (Texas Department of Water Resources 1983a). Salinity was measured in Cedar Lakes, Cow Trap Lake, and the intracoastal waterway by Johnson (1975). Averages and extreme measurements were: Cedar Lakes, 18.7 ppt (2.2 to 30.0 ppt); Cow Trap Lake, 16.2 ppt (2.8 to 26.6 ppt); and the intracoastal waterway, 18.5 ppt (8.9 to 27.8 ppt).

Offshore, the bottom recedes to a depth of 7.3 m (24 ft) within 1.5 km (1 mi) of the shoreline; at the three-league line the depth is about 18 m (60 ft). Sediments close to shore are sandy; offshore sediments are muddy. Some offshore sediments are mixtures of sand, mud, and shell, and several locations have large concentrations of shell or gravel (McGowen and Morton 1979).

Offshore circulation varies, but the general water pattern offshore in this basin is from northeast to southwest (SEADOCK, Inc. 1974). While in the long term the area of convergence of currents along the Texas Barrier Island Region's gulf shoreline is off Padre Island south of Baffin Bay, the convergence zone shifts seasonally and may occur as far north as Freeport in early summer (SEADOCK, Inc. 1974). Drift bottle measurements of offshore current velocities usually ranged from 0.15 to 0.41 m per second; maximum velocities of 0.55 to 1.03 m per second were observed on a few occasions.

Morton and Pieper (1975a) and Morton et al. (1976) examined long-term accretion and erosion on Matagorda Peninsula and the mainland shore between East Matagorda Bay and the Brazos River. They found that erosion had occurred over the entire region over a period of more than a century. Near the mouth of the Colorado, erosion rates were 0 to 1.5 m (0 to 5 ft) per year. South of

Brown Cedar Cut and all the way to the San Bernard River, erosion rates varied from 1.5 to 4.6 m (5 to 15 ft) per year.

Basin economy. The Brazos-Colorado basin had a population of 59,495 in 1980 (Table 28). This was a 54 percent increase over the 1970 population. A population increase of 43 percent is projected for the 20-year period from 1980 to the year 2000 (Texas Department of Water Resources 1980).

Oil and gas production is an important economic sector in the Brazos-Colorado basin. In 1977 the value of oil and gas produced was more than $206 million (Liebow et al. 1980). On a per-capita basis the value of production was $4391 per person; about $57 thousand of minerals were produced per sq km of basin area.

Recreation and tourism contributes much less to the the basin's economy than oil and gas production. In 1977, travel expenditures were slightly more than $20 million, and there were 519 travel-related jobs--only 19 out of every 1000 jobs (Liebow et al. 1980). No statistics exist for sport fishery expenditures, but they are probably low since the estuarine area is small and not easily accessible. Hunting was of moderate importance to this economic sector. In 1978, 518 deer were killed, a harvest rate of 24 per 100 sq km of upland.

No statistics for commercial fish landings attributed to this basin are available. Commercial fishing is of little economic importance in this basin today, although Johnson (1975) noted that there was commercial oyster production near Cow Trap Lake at one time, and that a substantial value had been placed upon oysters that were destroyed by a well blowout in Cedar Lakes. Johnson also reported that the small creeks, bayous, and lakes served as significant nursery habitat for shrimp and finfish.

Table 28. Economic data for the Brazos-Colorado basin.

Data type	Quantity
1970 Population	38511
1977 Population	47056
1980 Population	59495
1990 Population projection	69690
2000 Population projection	85273
Mineral production (X $1000)	206600
Deer harvest	518
Travel expenses (X $1000)	20321
Travel employment	519
Sportfishing expenditures (X $1000)	0
Commercial catch value (X $1000)	0
Electrical generating capacity (kw)	103069
Total employment	20141
Number of building permits	625
Length of railroad track (km)	150
Length of highways (km)	1865
Number of vehicles registered	52497
Commodity flows (1000 metric tons)	376
Number of farms	684
Market value of products (X $1000)	29056
Area of irrigated land (ha)	17589

Forty-two percent of the basin's population, 20,141 persons, is employed. In 1977, 625 building permits were issued, a rate of 30 per 100 sq km of upland (Liebow et al. 1980). When considered with the population growth in the basin, this rate of construction suggests a moderate rate of residential and industrial development.

Transportation is not a major component of the basin's economy. The Brazos-Colorado basin had 150 km (93 mi) of railroad and 1865 km (1159 mi) of highway in 1976 (Liebow et al. 1980), a density of 7 km of railroad track and 88 km of highway for each 100 sq km of uplands. The number of vehicles registered in 1978 was 52,497; vehicular density was 28 vehicles per km of road (Liebow et al. 1980). Waterborne transport is of low importance to the basin's economy. The volume of commodities that passed through the basin's waterways in 1977 was 376,000 metric tons. The basin has no port facilities for deep-draft vessels and only one inland channel--the San Bernard River--with barge loading facilities (RPC, Inc. 1980).

The number of farms in the basin in 1974 was 684. The total market value of production was $29 million (Liebow et al. 1980). In terms of basin area and population, the value of production was $17 thousand per sq km of agricultural area (cropland plus range) and the market value of crops was $617 per person. About 25 percent of the cropland was irrigated (Pfluger et al. 1981). The value of agriculture to the basin was moderately high, probably less than mineral production but more than recreation and tourism.

Resource demands. Cropland occupies nearly one-third of the upland area of the basin; rangeland occupies slightly more than 40 percent (Table 29). The quantity of urban area is small, comprising only about 1.9 percent of the

Table 29. Resource demands in the Brazos-Colorado basin.

Resource demands	Quantity
Cropland area (ha)	69338
Range area (ha)	93098
Urban area (ha)	3964
Recreation area (ha)	3242
Crude oil production (kiloliters)	1227877
Natural and casinghead gas (million cu m)	2840
Condensate (million liters)	69
1902-1978 oil production (million kiloliters)	49
Grain production (kiloliters)	82670
Cotton production (bales)	10654
Hay produced (metric tons)	26227
Peanuts produced (kg)	24227
Rice produced (metric tons)	94926
Cattle and calves sold	22835
Bay shrimp harvested (kg)	0
Bay oysters harvested (kg)	0
Bay crabs harvested (kg)	0
Bay commercial fish harvested (kg)	0
Bay sport fish landed (kg)	0
Total commercial fish harvested (kg)	0
Total commercial shellfish harvested (kg)	0

Table 29 (continued). Resource demands in the Brazos-Colorado basin.

Resource demands	Quantity
Digestive cancer mortality	20
Lung cancer mortality	13
Pneumonia and influenza mortality	12
Emphysema, bronchitis, and asthma mortality	4
Length fishable, swimmable stream segments (km)	518
Percent fishable, swimmable stream segments (%)	100
Airborne particulates (metric tons)	5197
Airborne hydrocarbons (metric tons)	7592
Waste discharge measured as 5-day BOD (kg)	1430779
Number of discharges	24
Cumulative industrial solid waste (metric tons)	649673
Subsidence of land surface (m)	0.0-0.3
Municipal surface water use (million cu m)	0
Municipal groundwater use (million cu m)	10
Manufacturing surface water use (million cu m)	10
Manufacturing groundwater use (million cu m)	4
Irrigation surface water use (million cu m)	188
Irrigation groundwater use (million cu m)	76
Total surface water use (million cu m)	206
Total groundwater use (million cu m)	96
Municipal, manufact. return flow (million cu m)	6
Agricultural return flow (million cu m)	102
Obstructions to runoff, roads + railroads (km)	2015
Major drainage ditches and canals (km)	243
Maintenance spoil, historical average (cu m)	469818
Length of dredged channels (km)	81

upland area. About 1.5 percent of the upland area is available as recreational land (Liebow et al. 1980).

Petroleum production in this basin is chiefly crude oil. In 1977 more 1.2 million kiloliters of crude were extracted; this is about 2.5 percent of the cumulative total of crude produced in the basin since 1902 (Liebow et al. 1980). The crude oil production in the basin amounts to 340 thousand liters per sq km of basin. Natural gas and casinghead gas production was 2840 million cu m in 1977 (Liebow et al. 1980).

Biomass production from basin farms in 1978 yielded 82,670 kiloliters of grain and 94,926 metric tons of rice. Cotton production was 10,654 bales, and 26,227 metric tons of hay were harvested (Bureau of the Census 1980). In 1977, 22,835 cattle and calves were sold in the basin.

Statistics on public health show that mortality from digestive cancers and lung cancer for the Brazos-Colorado basin is not significantly different from the statewide mortality (National Center for Health Statistics 1980). Mortality from other respiratory diseases that might be be related to environmental quality is also no higher than the statewide average. More than 500 km of streams are found in this basin and the larger natural hydrologic unit. All stream segments in the basin are classified as being swimmable and fishable by the Texas Department of Water Resources (1983a). The Texas Department of Health has closed some estuarine areas in the basin. The intracoastal waterway, Live Oak Bayou, Caney Creek, McNeal Lake, Pelican Lake, Jones Lake, Jones Creek, and the San Bernard River are restricted for shellfish harvest. All other estuarine areas are open (Texas Department of Health 1983).

In 1973, 5197 metric tons of airborne particulates and 7592 metric tons of airborne hydrocarbons were released to the basin's atmosphere (Texas Air Control Board 1977). This is an airborne waste load of 2 and 3 metric tons per sq km respectively. Twenty-four waste discharges into the basin's waters were authorized in 1983; 17 were from municipal waste treatment plants. The quantity of material to be processed by natural systems as measured by the 5-day BOD test is high, more than 1.4 million kg. This amounts to about 30 kg per person per year or 679 kg per sq km per year (Texas Department of Water Resources 1984), a high waste load on a per-capita basis. The basin has also accumulated nearly 650 thousand metric tons of industrial solid wastes.

Subsidence has occurred in the vicinity of Bay City in the western portion of the basin and around the Old Ocean Oil and Gas Field in the eastern portion. Subsidence in the Bay City area (0 to 0.3 m or 0 to 1 ft) is due to the withdrawal of fresh groundwater, oil, gas, and petroleum-related groundwater; less than 5 percent of the uplands are affected. Subsidence in the Old Ocean area is more extensive, affecting 15 to 20 percent of the upland area, but reaches a maximum of only 0.15 m (0.5 ft). Ratzlaff (1982) attributed the subsidence in this area to fresh groundwater extraction.

The demand for fresh water in the Brazos-Colorado basin totaled 312 million cu m in 1974. Nearly 32 percent was supplied by groundwater (Table 29). Agriculture accounted for almost 85 percent of the total water use. Seventy-one percent of the water used in agriculture is from surface sources, and 38 percent of the agricultural water is returned for reuse--a very high return rate for agriculture (Texas Water Development Board 1977).

The amount of hydrologic change on the land surface of this basin is low. The land-surface obstruction presented by roads and railroads totals 2015 km

(1252 mi); this is a density of less than 95 km of road or railroad per 100 sq km of upland. There are 243 km (151 mi) of ditches and canals, a density of 11 km per 100 sq km of upland.

The amount of hydrologic change in the estuarine area is moderately high. The basin has a total of 81 km of channel, a density of 23 km of channel per 100 km of estuarine area. The average annual maintenance spoil volume is 469,818 cu m (Belaire 1976); the average volume of spoil that must be removed per km of channel is 5800 cu m, a fairly low figure. The effect of spoil placement in this basin is large since spoil has been placed in long, continuous piles across the entire basin, perpendicular to the major axis of flow. Spoil placement has isolated East Matagorda Bay and much of Cedar Lakes by blocking freshwater flow from the uplands.

Brazos Basin

Location and description. The Brazos basin is located in the upper Texas coast between the Brazos-Colorado basin and the Galveston basin. The Brazos basin described here includes the lower portion of a natural hydrologic unit, the Brazos River Basin, but is a little wider and includes Oyster Creek within its bounds. The Brazos basin within the Texas Barrier Island Region has a total area of 2485.9 sq km (959.8 sq mi) and occupies only about 2 percent of the area of the natural hydrologic unit, which is very large and stretches across the state into New Mexico (Texas Water Development Board 1977).

The lower boundary of the Brazos-Colorado basin coincides with the boundary line between the Brazos-Colorado Coastal Basin and the Brazos River Basin (Texas Water Development Board 1977). This boundary is 2 to 25.5 km (1.2 to 15.8 mi) west of the Brazos River and separates those streams that

drain into the Brazos-Colorado basin from those that drain into the Brazos River.

The upper boundary parallels Oyster Creek, a former course of the Brazos River. This boundary lies 1.2 to 15 km (0.8 to 9.3 mi) east of Oyster Creek and divides the areas that drain into this creek from those that drain into the Galveston basin.

At its widest portion the Brazos basin is about 37 km (23 mi) in breadth; at the shoreline the basin is narrower, only about 20 km (12.4 mi). The Brazos basin has a very high proportion of upland compared to the total basin area. Upland habitats comprise 70 percent of the area. Both estuarine and freshwater habitats occupy about 3 percent of the basin's area, and the gulf constitutes 24 percent. Subaerial spoil occupies less than 0.5 percent of the basin.

At its inland limit, the elevation of the Brazos basin is 27 m (90 ft) at its lower boundary, dips to 21 m (70 ft) where the Brazos River flows, and rises slightly to 24 m (80 ft) at the upper boundary. The land slope decreases toward the coast, and near the shoreline is a broad area about 7 km (4 mi) wide where the land elevation ranges from 0 to 1.5 m (0 to 5 ft).

The basin contains the Brazos River, Oyster Creek, and a number of natural lakes and artificial reservoirs. The lower end of the Brazos River that empties into the gulf west of Freeport is not a natural channel. The river was diverted to its present course just north of Freeport so its natural river mouth could be used as a harbor.

Bryan Mound, an elevated area above a natural salt dome, is located immediately to the east of the relocated channel. Bryan Mound is currently being developed as part of the nation's strategic petroleum reserve.

Clayey sand and silt, with moderate permeability and water-holding capacity, is the dominant sediment type. Only a few isolated patches of clays and muds are found in the western and southern portions of the basin.

The distribution of habitats is shown in Plate 9; Table 30 presents the areal extent or length of each habitat unit in the basin and its percentage of the basin area. The upland habitat with the greatest area is cropland, whcih occupies 775.5 sq km (299.5 sq mi), or 31.2 percent of the basin's area. The distribution of cropland is closely tied to the location of clay and mud sediments. Consequently much of the cropland habitat is located in the western portion of the basin; other parcels of cropland are found in isolated pockets throughout the basin.

Forest occupies 384.1 sq km (148.3 sq mi), 15.5 percent of the basin. Forest is located on the clayey sand and silt sediments left by meandering rivers throughout the basin. From the configuration of boundaries between forest and cropland or range, and by comparison with biologic assemblage information showing the location of potential natural vegetation (McGowen et al. 1976b), it is clear that many areas of forest have been cut to provide additional cropland or range for agriculture.

Range constitutes 528.9 sq km (204.2 sq mi), or 21.3 percent of the basin's area. Although range is distributed throughout the basin, the largest portion is in the upper western portion. Some range is found between salt and brackish marsh at the shoreline and forest about 10 km (6 mi) inland.

Swamp covers 11.1 sq km (4.3 sq mi) in the basin. Swamp areas are small and are scattered throughout the length of the basin within forests. Freshwater marsh comprises 9.6 sq km (3.7 sq mi). It is found in the lower

Table 30. Habitat areas, lengths, and proportions in the Brazos basin.

Habitat	Area (sq km)	Length (km)	Percent of basin area
Barrier	7.8		0.3
Bay	30.8		1.2
Bulkhead	1.6		< 0.1
Channel and tidal stream		102.0	
Cropland	775.7		31.2
Forest	384.1		15.5
Freshwater marsh	9.6		0.4
Grassflat	0.8		< 0.1
Gulf	594.7		23.9
Lake and reservoir	66.0		2.7
Range	528.9		21.3
Reef	0.5		< 0.1
River and canal		343.4	
Salt and brackish marsh	28.7		1.2
Spoil	7.5		0.3
Swamp	11.1		0.5
Urban	38.1		1.5
Wind-tidal flat	1.6		< 0.1

half of the basin, often adjacent to natural lakes and ponds. The lake and reservoir habitat (66.0 sq km or 25.5 sq mi) is scattered throughout the basin; more than half of the total area of this habitat is in man-made impoundments. Urban habitat occupies 38.1 sq km (14.7 sq mi). The largest urban areas are Freeport, Lake Jackson, Clute, and West Columbia.

The estuarine areas are very limited in size. The largest is the salt and brackish marsh that surrounds the mouth of the Brazos River and Bryan Mound. This wetland has an area of 28.7 sq km (11.1 sq mi).

The Brazos basin has a slightly greater proportion of lake and reservoir habitat and gulf habitat than the region as a whole (Figure 68). The proportion of cropland is substantially greater, and the proportion of forest in the basin is about three times as great as in the region. Range occupies about a third less area in the Brazos basin than in the region as a whole; bay, urban, wind-tidal flat, and reef are also smaller in relative proportion. Other habitats--barrier, freshwater marsh, spoil, swamp, and salt and brackish marsh--occupy about the same relative area in the basin as in the region.

Changes in forest areas have already been noted; changes in other habitats are presently occurring at a high rate. Since the Brazos basin is adjacent to the Galveston basin--the major growth area on the Texas coast--a significant amount of change resulting from growth spillover is predictable. The baseline information used to define the basin's habitat units is circa 1956 and 1957 although it has been selectively updated with newer land-use information (Fisher et al. 1972; McGowen et al. 1976b); consequently it shows some but not all of the major changes that have occurred in the last 25 years. However, some comparative maps and area measurements were available from the U.S. Fish and Wildlife Service National Coastal Ecosystems Team for 1956 and

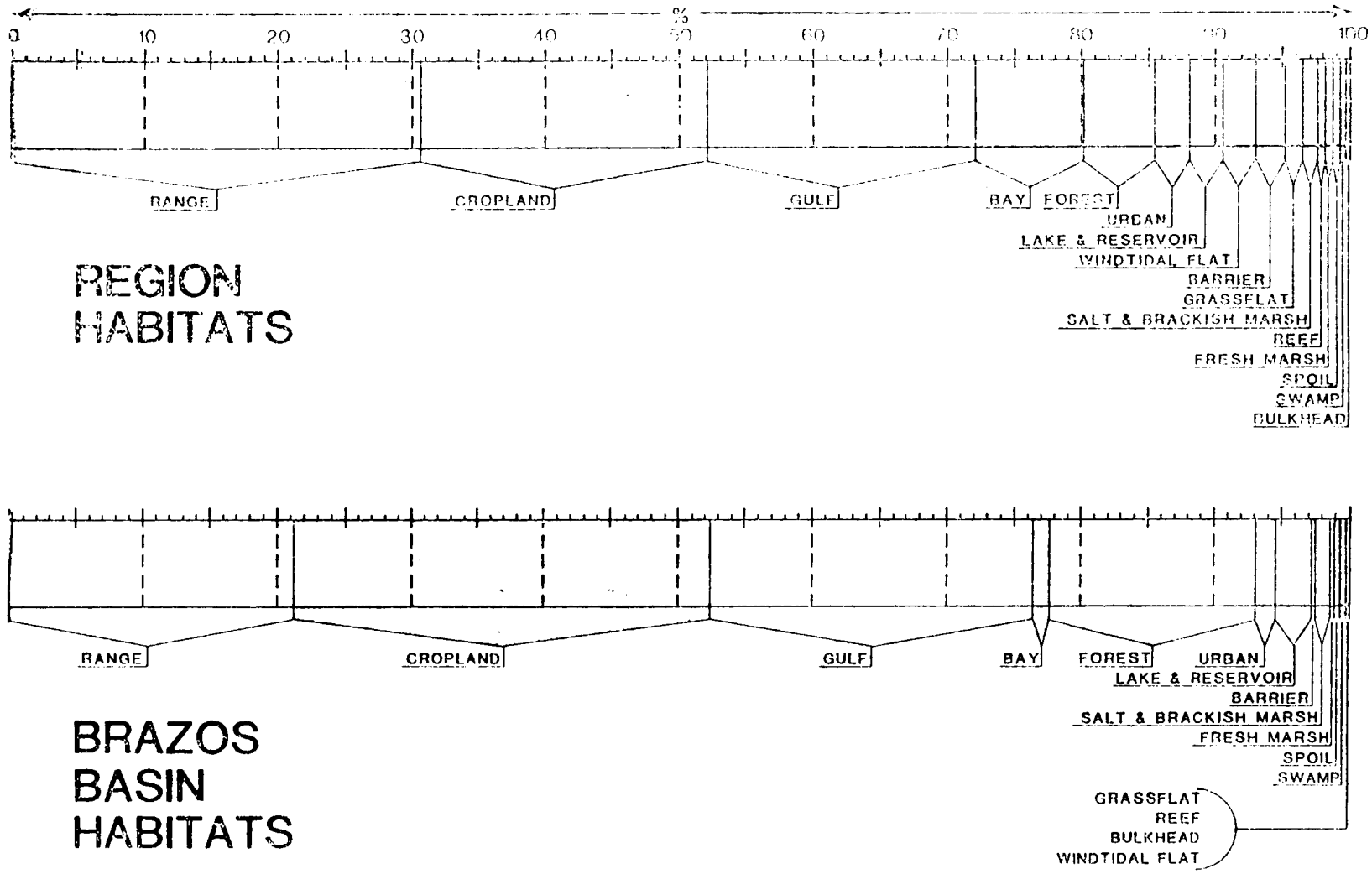


Figure 68. Habitat proportions of the Brazos basin and Texas Barrier Island Region.

1979. The mapped areas were the Freeport and Jones Creek 7.5 minute U.S. Geological Survey quadrangles; the mapped units were a modified set of the wetland units used for the National Wetland Inventory Program (Cowardin et al. 1979).

The Freeport and Jones Creek quadrangles, in which the cities of Freeport and Clute are found, include business and industrial sites, residential communities, and port facilities. This area is experiencing sizable population growth and has undergone significant subsidence in the past 70 years; Ratzlaff (1982) reported that maximum subsidence was more than 0.6 m (2 ft) over the period 1906 to 1973. Table 31 shows changes in the areas of nine resource unit types between 1956 and 1979. The U.S. Fish and Wildlife Service map units based on the Cowardin system were grouped into this smaller number of categories, similar to some of the habitat units, for simplification.

Between 1956 and 1979, more than half the beach in the basin was converted to other habitats types. In 1956, the major area of beach was east of the Brazos delta; a narrow beach ran to the northeast. By 1979, the wide beach near the Brazos delta disappeared. Some was eroded or submerged, and some portions became salt and brackish marsh.

Forested wetlands--which include some floodplain forest and swamp--occupied only 0.3 sq km in 1956. By 1979 this unit had expanded to 5.6 sq km. Almost all of the expansion occurred adjacent to the Brazos River at least 27 km (17 mi) inland from the shoreline in an area classified as upland in the 1956 mapping. The expansion of this land type is closely linked to increased soil moisture from fresh water. While subsidence was only 0.15 m (0.5 ft) in

Table 31. Changes in resource unit areas from 1956 to 1979 for Freeport and Jones Creek U.S. Geological Survey 7.5 minute quadrangles.

Land type	1956 area (sq km)	1979 area (sq km)	Change in area (sq km)	Percent change
Beach/bar	2.8	1.1	- 1.6	- 59.6
Forested wetlands	0.3	5.6	+ 5.4	+ 2048.1
Freshwater marsh	17.1	20.5	+ 3.5	+ 20.0
Freshwater ponds and lakes	3.1	9.3	+ 6.2	+ 200.9
Salt and brackish marsh	72.0	60.8	- 11.3	- 15.6
Upland	148.0	143.3	- 4.7	- 3.2

this area (Ratzlaff 1982), it may have been instrumental in the expansion of this land unit.

Freshwater marsh increased by 3.5 sq km, a change of 20 percent. There was some loss of freshwater marsh to freshwater lakes and ponds in the Freeport area, to upland in the Freeport area, and to salt and brackish marsh in the western portion of the basin. The largest gain resulted from conversion of two large areas of salt and brackish marsh to freshwater marsh. One of these areas was affected by the presence of a flood control dike which probably impounded fresh water. The other occurred at the upper end of a salt and brackish marsh; several nearby areas of upland also became freshwater marsh.

The quantity of freshwater ponds and lakes tripled from 3.1 to 9.3 sq km. Because of their shape it was clear that most of these water bodies were man-made. About half of the newly impounded areas were located on upland; most of the remaining impoundments had been built in salt and brackish marsh.

The area of salt and brackish marsh decreased by 15.6 percent, from 72.0 to 60.8 sq km. Close to Freeport, salt and brackish marsh was converted to upland or was impounded to produce freshwater lakes and ponds. In addition, some estuarine water bodies within the salt and brackish areas widened at the expense of the marshes. To the west some new areas of salt and brackish formed on what had been upland.

The area of upland decreased by 4.7 sq km, or 3.2 percent. Upland was involved in practically every type of land change. In most cases, changes to upland and changes from upland to lake and reservoir or to estuarine water bodies were the result of deliberate alteration by dredging, filling, and impoundment. Other changes--conversion of upland to freshwater marsh or salt

and brackish marsh--may have been related to subsidence or wetter conditions in the basin.

Geologic development. The surface sediments in the Brazos basin range in age from Pleistocene to Recent. Underlying the entire basin are fluvial-deltaic sediments deposited by the Brazos River during the Sangamon interglacial stage of the Pleistocene (McGowen et al. 1976b).

Sea level dropped during the Early Wisconsin period; when it rose again, barrier-strandplains were constructed in the Texas Barrier Island Region that still have remnants in some other basins. No trace of a strandplain exists today in the Brazos basin, although a small relict exists on the west side of Chocolate Bay in the Galveston basin, 14 km (8.7 mi) to the northeast.

When sea level dropped again 50,000 to 60,000 yr BP and wide-spread erosion of the exposed sediments occurred, the Brazos river formed a wide, deep river valley that joined a similar valley carved by the Colorado River to form a common river valley in the Brazos-Colorado basin.

When the sea rose 25,000 to 18,000 yr BP, sediment from headward-eroding streams, river valley wall erosion, estuary bank erosion, and the gulf began to fill the eroded valleys. By the time sea level stabilized 2800 yr BP, the headlands of the common estuary into which both river systems flowed was about 35 km (22 mi) inland from the present shoreline, in the Brazos-Colorado basin to the southwest.

Over the next 1200 years, the Brazos and Colorado rivers built a delta across their estuary to the sea. The delta prograded at the rate of about 29.6 m (97 ft) per year and completely filled the estuary (McGowen et al. 1976b). Both the Brazos and Colorado rivers deposited their sediment directly

into the gulf, where it was transported by littoral currents to build peninsulas and barriers to the southwest.

While much of the large sediment load carried by the Brazos was deposited in the delta, some was deposited in the modern fluvial system that forms the surface sediments in the eastern portion of the basin; these are the sediments upon which the extensive forests of this basin developed.

After the Brazos filled its estuary, the river course changed. McGowen et al. (1976a) noted that the mouth of the Brazos River meandered and formed at least three deltas into the gulf: near San Luis Pass; at the mouth of Oyster Creek; and in the area of Freeport Harbor. The river mouth was diverted in 1929, and a fourth delta has been forming over the past 50 years at its present location.

Basin hydrology and climate. The climate of the Brazos basin is warm and humid. The average temperature of the basin is 21.1 deg C (70 deg F); the average summer high temperature is 28.3 deg C (83 deg F) and the average winter low is 12.2 deg C (54 deg F) (Williams et al. 1976).

The basin is located in a zone of rainfall convergence. The average rainfall in the basin is 121.9 cm (48 in) (Williams et al. 1976). September is the month with the highest rainfall (15.6 percent). In descending order, the other months with high rainfall are July, August, and June; March has the lowest rainfall average (Bomar 1983). Rainfall is higher than potential evapotranspiration in this basin; as a result there is a precipitation surplus of about 10.2 cm (4 in) (Woodruff 1975). Habitats that store fresh or brackish water comprise 86.8 sq km (33.5 sq mi), or 4.8 percent of the area above mean sea level.

Nearly all the water that passes through the Brazos basin is carried by the Brazos River. From the gage at Richmond the 53-year average flow of the Brazos is 6538 million cu m. The variation during periods of low and high flow has ranged from 17 to 268 percent of the average flow (Dougherty 1980). The Brazos has the highest sediment transport of all the rivers flowing through the Texas Barrier Island Region. The 51-year average suspended sediment load is 21,680,106 metric tons per year (Dougherty 1979).

The greatest proportion of river flow occurs during late spring, as shown in the hydrograph in Figure 69 (Woodruff 1975). May has the highest flow, although there is a secondary peak during November; August is the period of lowest flow. The hydrologic distribution pattern is shown in Figure 69. The Brazos carries water from the drainage further inland into the basin. Diversion from the Brazos to lakes and reservoirs provides water for agricultural and manufacturing use. Return flows include water from both surface and groundwater sources. Brazos River water and return flows eventually reach the tidal portion of the Brazos, which discharges into the gulf. The tidal Brazos also exchanges water with the nearby wetlands and adjacent basins through the intracoastal waterway.

The tidal portion of the Brazos River has a relatively low salinity. The 4-yr average value is 6.9 ppt with extreme low and high measurements of 1.5 and 23.3 ppt (Texas Department of Water Resources 1983a). At the intersection of the intracoastal waterway and the Brazos River is a set of floodgates that are closed when the Brazos River floods to minimize shoaling of the intracoastal waterway. Johnson (1975) reported that the salinity in the intracoastal waterway over a two-year period averaged 14.0 ppt with extreme low and high measurements of 1.7 and 26.6 ppt.

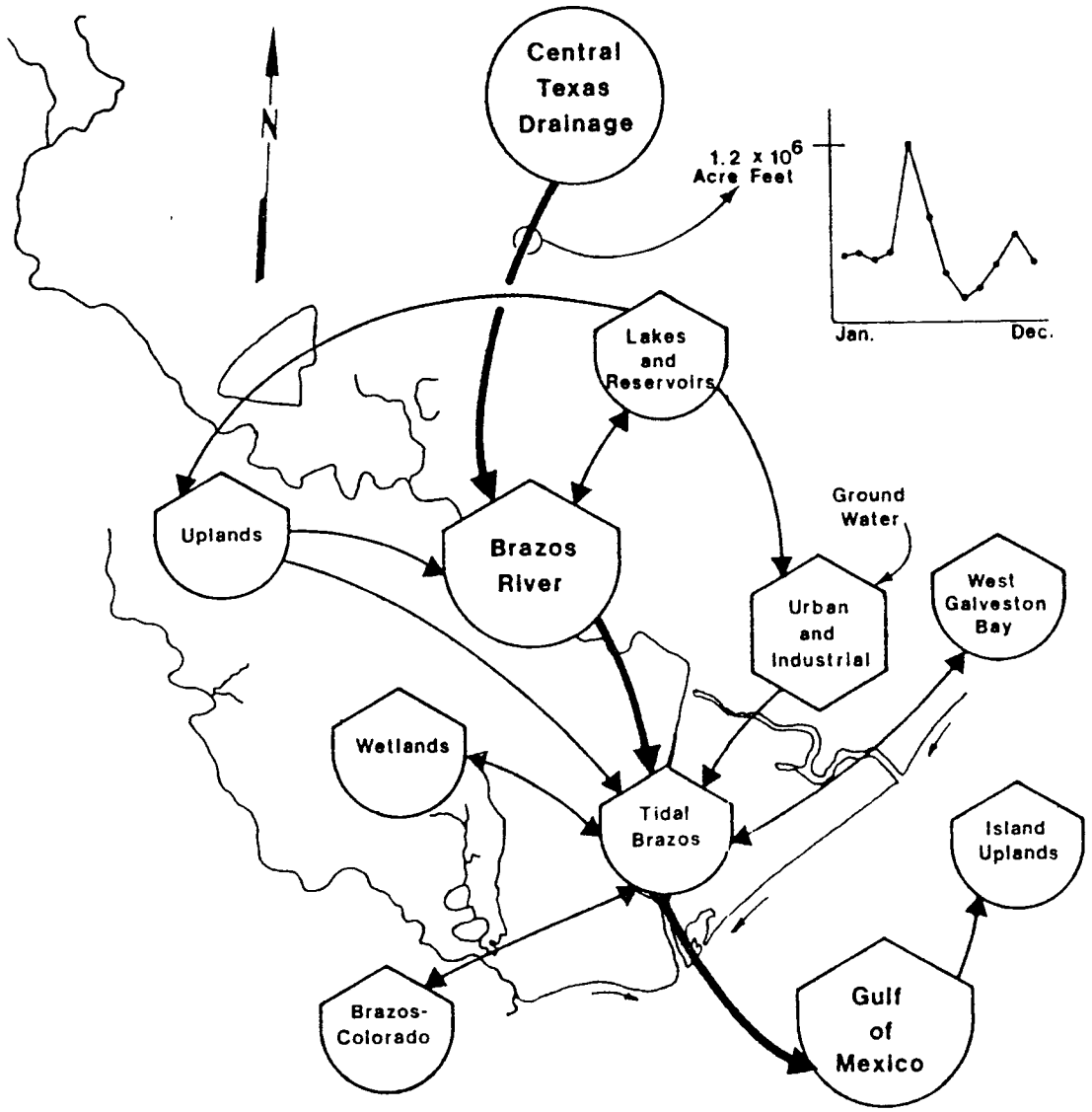


Figure 69. Hydrology of the Brazos basin.

In the vicinity of the Brazos River delta, the floor of the gulf slopes at a fairly constant rate to the three-league line, where the depth is about 18 m (60 ft). There is a wide band of sand immediately offshore for a distance of 2 km (1.2 mi). Further offshore the bottom sediments are muddy. McGowen and Morton (1979) reported several large areas of shell and rock-fragment gravel as well as mixtures of sand, mud, and shell or gravel.

The general pattern of flow offshore in this basin is from northeast to southwest (SEADOCK, Inc. 1974). While the area of convergence of currents along the Texas gulf shoreline is off Padre Island near Baffin Bay over the long term, the convergence zone shifts seasonally and may occur as far north as Freeport in early summer (SEADOCK, Inc. 1974). Measurements of offshore current velocities have usually ranged from 0.15 to 0.41 m per second although higher velocities of 0.55 to 1.03 m per second have been observed.

Morton and Pieper (1975a) examined long-term accretion and erosion on the mainland shore between East Matagorda Bay and San Luis Pass. In the area between the San Bernard River and Oyster Creek, accretion was the general pattern for more than a century. Since 1965, however, only the area immediately south of the opening of the Brazos River has accreted; the area to the north has exhibited annual erosion rates of 22 to 67 ft per year.

Basin economy. The 1980 population of the basin was 93,388 (Table 32). During the previous decade, the basin experienced rapid growth and a 92 percent increase in population. Population projections for the next 20 years suggest that the population will increase by 64 percent, or more than 60,000 persons (Texas Department of Water Resources 1980).

Table 32. Economic data for the Brazos basin.

Data type	Quantity
1970 Population	48631
1977 Population	68265
1980 Population	93388
1990 Population projection	121612
2000 Population projection	153375
Mineral production (X $1000)	232948
Deer harvest	534
Travel expenses (X $1000)	52145
Travel employment	1021
Sportfishing expenditures (X $1000)	0
Commercial catch value (X $1000)	0
Electrical generating capacity (kw)	618430
Total employment	26816
Number of building permits	1010
Length of railroad track (km)	159
Length of highways (km)	1891
Number of vehicles registered	74507
Commodity flows (1000 metric tons)	13907
Number of farms	730
Market value of products (X $1000)	17064
Area of irrigated land (ha)	11368

Oil and gas production is important to the economy of the basin. In 1977 the value of minerals produced was nearly $233 million (Liebow et al. 1980). On an areal basis this was $93 thousand per sq km of basin.

Recreation and tourism are also fairly important to the economy. Travel expenditures were more than $52 million in 1978, and 1021 jobs were travel-related (Liebow et al. 1980). Travel-related employment accounted for 38 of every 1000 jobs in the basin. Hunting and fishing were less important to this sector than other recreational activities. No economic statistics specific to the basin were available for either sportfishing or commercial fishing.

Employment in 1977 was 26,816, which was 39 percent of the population (Liebow et al. 1980). Residential development, as measured by the number of building permits issued, was relatively high: 1010 permits were issued in 1977, or 58 permits per 100 sq km of uplands. The basin has a few large industries located in Freeport that produce petrochemicals and process primary metals. Coupled with the high population growth of the last decade and projected future growth, industrial and residential development is a strong part of the basin's economy.

Transportation is important to the economy, especially to industrial development. The basin had 159 km (99 mi) of railroads and 1891 km (1175 mi) of roads in 1976; 74,507 vehicles were registered, a density of 39 vehicles per km of road. Almost 14 million metric tons of commodities were shipped over the basin's waterways (RPC, Inc. 1977); more than 200 metric tons were shipped for every person in the basin. This high level of commodity flow indicates that waterborne transport is of considerable importance to the basin's economy.

Agriculture also contributes to the economy, although the value of its production is less than that of many other sectors. In 1974 there were 730 farms in the basin; the total market value of crops in 1974 was slightly more than $17 million.

Resource demands. About 45 percent of the upland area in the basin was used for crop production in 1979; range occupied about 30 percent (Table 33). Urban areas occupied about 2 percent of the land area in the basin, and recreational lands comprised about 3 percent (Liebow et al. 1980).

Crude oil was the principle mineral produced in 1977. More than 1.9 million kiloliters of crude oil were pumped; this was a little more than 2 percent of the cumulative production in this basin since exploration began in 1902 (Liebow et al. 1980).

Biomass produced in 1978 included 64,507 kiloliters of grain, 19,472 bales of cotton, and 23,001 metric tons of hay. Rice production totaled 54,520 metric tons, and the number of cattle and calves sold was 19,070 (Bureau of the Census 1980). None of the production figures per area of cropland were exceptionally high. The number of cattle and calves sold per sq km of rangeland was 36; this is a higher ratio than in most areas where cattle are range-fed. Liebow et al. (1980) do not report any feedlots in the upper Texas coast; perhaps better range conditions resulting from greater rainfall allow a higher stocking rate in this basin.

Public health indicators for the basin do not show any significant mortality from digestive tract or respiratory diseases that might be environmentally related (National Center for Health Statistics 1981). The mortality figures in Table 33 are not significantly different from statewide averages.

Table 33. Resource demands in the Brazos basin.

Resource demands	Quantity
Cropland area (ha)	77603
Range area (ha)	52910
Urban area (ha)	3809
Recreation area (ha)	4885
Crude oil production (kiloliters)	1901860
Natural and casinghead gas (million cu m)	2165
Condensate (million liters)	40
1902-1978 oil production (million kiloliters)	90
Grain production (kiloliters)	64507
Cotton production (bales)	19472
Hay produced (metric tons)	23001
Peanuts produced (kg)	33267
Rice produced (metric tons)	54520
Cattle and calves sold	19070
Bay shrimp harvested (kg)	0
Bay oysters harvested (kg)	0
Bay crabs harvested (kg)	0
Bay commercial fish harvested (kg)	0
Bay sport fish landed (kg)	0
Total commercial fish harvested (kg)	0
Total commercial shellfish harvested (kg)	0

Table 33 (continued). Resource demands in the Brazos basin.

Resource demands	Quantity
Digestive cancer mortality	22
Lung cancer mortality	18
Pneumonia and influenza mortality	16
Emphysema, bronchitis, and asthma mortality	6
Length fishable, swimmable stream segments (km)	587
Percent fishable, swimmable stream segments (%)	95
Airborne particulates (metric tons)	4381
Airborne hydrocarbons (metric tons)	20154
Waste discharge measured as 5-day BOD (kg)	1363156
Number of discharges	79
Cumulative industrial solid waste (metric tons)	530806
Subsidence of land surface (m)	0.0-0.6
Municipal surface water use (million cu m)	0
Municipal groundwater use (million cu m)	11
Manufacturing surface water use (million cu m)	241
Manufacturing groundwater use (million cu m)	6
Irrigation surface water use (million cu m)	25
Irrigation groundwater use (million cu m)	37
Total surface water use (million cu m)	281
Total groundwater use (million cu m)	57
Municipal, manufact. return flow (million cu m)	0
Agricultural return flow (million cu m)	23
Obstructions to runoff, roads + railroads (km)	2050
Major drainage ditches and canals (km)	185
Maintenance spoil, historical average (cu m)	394588
Length of dredged channels (km)	39

Five hundred eighty-seven kilometers of freshwater streams are found in this basin. Ninety-five percent of the freshwater stream segments are classified as being swimmable and fishable by the Texas Department of Water Resources (1983a); bacterial and oxygen depletion problems occur in several sections of Oyster Creek. In addition, the Texas Department of Health has closed all estuarine water bodies between the San Bernard River and Drum Bay to shellfishing (Texas Department of Health 1983).

In 1973, 4381 metric tons of airborne particulates and 20,154 metric tons of airborne hydrocarbons were added to the basin's atmosphere (Texas Air Control Board 1977). This is an airborne waste load of 2 and 11 metric tons per sq km respectively. Some of the hydrocarbon load probably came from the basin's petrochemical plants as well as from storage and loading facilities for petroleum products.

In 1983, 44 waste discharge permits were authorized in the basin's waters; 29 of the permits were for municipal waste treatment plants. The amount of waste materials from municipal and industrial sources processed by natural systems was measured by the 5-day BOD test and totaled almost 1.4 million kg (Texas Department of Water Resources 1984). This is about 20 kg of oxygen for waste processing per person and almost 800 kg per sq km of upland. In addition to these annual waste loads, the Brazos basin has received a cumulative total of more than 530 thousand metric tons of industrial solid wastes.

Land surface subsidence as great as 0.6 m (2 ft) was measured in the Brazos basin over the period 1906 to 1973 (Ratzlaff 1982). Most of the basin has experienced less subsidence than the maximum, but the whole basin has been

affected to some degree. The greatest subsidence has taken place in the immediate vicinity of Freeport, where groundwater is withdrawn from shallow subsurface deposits for municipal and industrial use (Ratzlaff 1982).

Freshwater demand in the basin was 338 million cu m in 1974 (Texas Water Development Board 1977). About 17 percent of the water demand was satisfied by groundwater sources. Only 18 percent of the freshwater used went to agriculture; 40 percent of that water was from surface water sources, and agriculture returned 37 percent of the combined total of surface and groundwater used. The primary freshwater user in this basin was industry; it used 73 percent of the water in the basin, almost all of which came from surface sources. Neither industry nor municipalities returned any fresh water that could be reused for other freshwater needs.

The amount of hydrologic change on the land surface of this basin is low to moderate. The amount of obstruction to hydrologic flow presented by roads and railroads totals 2050 km (1274 mi). Comparing this total to the amount of upland in the basin, there is 118 km of road and railroad for each 100 sq km of upland. The basin also has 185 km (115 mi) of ditches and canals; the density of these collection points for drainage is 10 km per 100 sq km of upland.

The amount of hydrologic change in the estuarine area is very high, largely because the basin has very little estuarine area. There is 39 km of channel in only 62 sq km of estuarine area, a density of 63 km per 100 sq km. The average annual maintenance spoil volume is 394,588 cu m (Belaire 1976), or 6264 cu m per km of channel.

Because port, manufacturing, and residential areas are located so close to the gulf at low elevations, flood control dikes and canals have been built.

These and facilities such as ponds and reservoirs have altered the hydrology of the low-lying areas greatly. Subsidence in the basin has exacerbated the flooding problem, forcing additional flood control measures to be taken.

Galveston basin

Location and description. The Galveston basin is the northernmost basin in the Texas Barrier Island Region. It is located northeast of the Brazos basin and includes all of Galveston Bay and its tributaries. The Galveston basin receives drainage from five natural hydrologic units: the Neches-Trinity Coastal Basin, the Trinity River Basin, the Trinity-San Jacinto Coastal Basin, the San Jacinto River Basin, and the San Jacinto-Brazos Coastal Basin (Texas Water Development Board 1977). The total area of the Galveston basin is 10,849.1 sq km (4188.9 sq mi), less than one-sixth the area drained by the natural hydrologic units; one of the units, the Trinity River Basin, stretches to Archer County 150 km (93 mi) west of Fort Worth.

The lower boundary of the basin parallels Oyster Creek, which lies 1.2 to 15 km (0.8 to 9.3 mi) to the west. The boundary divides the areas that drain into Oyster Creek in the Brazos basin from those that drain into the Galveston basin. Some of the creeks and bayous near the boundary that drain into the Galveston basin are Bastrop Bayou, Chocolate Bayou, and Clear Creek.

The upper boundary lies to the east of Trinity Bay and East Bay. It crosses the shoreline just west of High Island and runs approximately north to the inland boundary. The upper boundary passes about 11 km (8 mi) west of the city of Winnie, and east of the cities of Devers and Daisetta. There are many creeks and streams in this area, although none is very large. The boundary

roughly divides those that eventually drain into Trinity Bay or East Bay from those that drain into the marshes and intracoastal waterway to the east.

The Galveston basin, about 110 km (69 mi) wide is the second largest basin in the Texas Barrier Island Region. The most prominent features in this basin are Galveston and Trinity bays, which stretch inland 40 km (25 mi), about two-thirds of the distance from the gulf shoreline to the inland boundary. The land surrounding Galveston and Trinity bays slopes toward them, so the area is bowl-shaped. East and West bays parallel the gulf shoreline, and the mainland slopes evenly toward them.

At its inland limit the elevation of the basin at the lower boundary is 24 m (80 ft). Moving toward the upper boundary, the land gently slopes downward to about 12 m (40 ft) in the Buffalo Bayou drainage area. At the San Jacinto River valley the land slopes sharply downward; the swamp located in the river bottom is at an elevation of 1.5 to 4.5 m (5 to 15 ft). The land rises again to about 20 m (66 ft) and then slopes sharply downward in the Trinity River Valley, where the elevation of the extensive floodplain forest is 4 to 8 m (13 to 26 ft). North of the river valley the land elevation rises to about 20 m (66 ft).

Between the gulf and East and West bays are two barrier formations, Bolivar Peninsula and Galveston Island. Bolivar Peninsula is low, with land elevations to only 3 m. It has low dunes and a wide area of salt and brackish marsh behind it built upon old washover fans. Galveston Island is higher, with elevations to 5 m (16 ft). It has been extensively modified through urban development.

The dominant sediment type in the basin is fine-grained clay and mud. This sediment has low permeability and high water-holding capacity and was deposited

from overbanking fluvial and deltaic streams and channels during the Pleistocene (Fisher et al. 1972). A wide expanse of this sediment type runs from the lower boundary to the area just west of the San Jacinto River, and from just east of the San Jacinto River to just west of the Trinity River. A second smaller area is located on the mainland just east of Trinity Bay. Areas having these sediments are used extensively as cropland.

Long, sinuous strips of clayey sands and silts are found throughout the area of clays and muds. These narrow strips were deposited as distributary channel silts and sands during the Pleistocene, probably from the Brazos River. On the mainland shoreline of West Bay there is a wide area of clayey sands and silts just inland of the mainland wetlands; this area is exposed Pleistocene delta-front sand. Wide bands of clayey sands and silts flank the San Jacinto and Trinity rivers. These are meanderbelt sands and silts deposited by the rivers (Fisher et al. 1972).

Sandy sediments are located on Galveston Island, Bolivar Peninsula, the mainland adjacent to Chocolate Bay and Dollar Bay, and in a long band running northeast from Smith Point. The sandy areas on the mainland are relict barrier strandplains deposited in a previous interglacial period.

The Galveston basin has significant areas of marsh and swamp soils. The marsh soils are located along the edges of the bays or inland of salt and brackish marshes, on large river deltas, and in river-bottom areas further upstream in river valleys.

The distribution of habitats is shown in Plate 10; Table 34 lists areas, lengths, and percentages of basin area. Cropland occupies a larger area than any other upland unit. It comprises 2860.1 sq km (1104.3 sq mi), or 26.4

Table 34. Habitat areas, lengths, and proportions in the Galveston basin.

Habitat	Area sq km	Length km	Percent of basin area
Barrier	179.7		1.7
Bay	1090.9		10.1
Bulkhead	28.5		0.3
Channel and tidal stream		689.4	
Cropland	2860.1		26.4
Forest	939.4		8.7
Freshwater marsh	43.0		0.4
Grassflat	18.1		0.2
Gulf	2647.2		24.4
Lake and reservoir	237.8		2.2
Range	1479.7		13.6
Reef	220.9		2.0
River and canal		1438.8	
Salt and brackish marsh	247.1		2.3
Spoil	49.0		0.5
Swamp	82.1		0.8
Urban	709.9		6.6
Wind-tidal flat	15.7		0.1

percent of the basin area. Practically all of the land in the western portion of the basin is cropland. A large area of cropland lies between the San Jacinto and Trinity Rivers, and extends from the eastern boundary of the basin to Trinity Bay and the forest bordering the Trinity River. Except for the areas of urban habitat, practically all of the land which is dominantly clay and mud sediments is cropland.

Range constitutes 1479.9 sq km (571.3 sq mi), or 13.6 percent of the basin's area, and is found in pockets scattered throughout the basin. Many range habitats are located on clayey sand and silt sediments which are less favorable for crops, although a belt of range surrounding the Houston metropolitan area rests upon clay and mud sediments. Range is also found on the mainland shoreline of the basin. This is an area of saline silts and sands, not well suited for crops. Cattle graze on these range areas and often roam out onto the brackish marsh.

Forest occupies an area of 939.4 sq km (361.7 sq mi), 8.7 percent of the basin's area; the mapped units do not distinguish among forest types. The largest area of forest is the floodplain forest immediately flanking the Trinity River. Other areas with this type of forest include Cedar Bayou between the San Jacinto and Trinity rivers, Clear Creek and the tributaries to Clear Lake, Dickinson Bayou, Halls Bayou, and Chocolate Bayou (Fisher et al. 1972). Areas of mixed pine-hardwood forest are found in the northeastern portion of the basin, on the east side of Lake Anahuac, on the west side of the Trinity River, west of the San Jacinto River, and adjacent to the City of Houston.

Urban land comprises 709.9 sq km (274.1 sq mi), or 6.1 percent of the basin. The largest concentration of urban land is the Houston metropolitan area

in the northwestern portion of the basin. This urban area is spreading in all directions, particularly toward Galveston. The corridor between Houston and Galveston had already begun to develop at the time this information was originally mapped. Because of the high rate of growth, the city of Houston is today significantly larger than shown in Plate 10 and the corridor between Houston and Galveston is almost solid urban land.

The city of Galveston occupies about a third of Galveston Island in Plate 10. It has spread further westward and today additional residential developments have been built on the western portion of the island. Pelican Island, immediately adjacent to Galveston Island, is urban land and was almost entirely built with material dredged from the many channels in nearby bays. Other urban areas are shown on Bolivar Peninsula; they have also expanded, although not as much as the Houston-Galveston corridor.

The uplands contain several smaller habitats of interest. Almost 75 percent of all the swamp in the Texas Barrier Island Region is located in the Galveston basin and occupies 82.1 sq km (31.7 sq mi), or 0.8 percent of the basin's area. Swamp occurs in the San Jacinto and Trinity river valleys; several isolated areas occur in old oxbows from former Trinity River courses. Freshwater marsh occupies 43.0 sq km (16.6 sq mi). Most of the inland freshwater marsh is found in association with swamp and fresh to brackish lakes.

Lakes and reservoirs constitute 237.8 sq km (91.8 sq mi), or 2.2 percent of the basin's area. Lake Anahuac, Lake Charlotte, and Lake Surprise are natural . Most of the small lakes or reservoirs are man-made and are used for

municipal, industrial, and agricultural purposes. Many lakes and reservoirs were too small to show on the map in Plate 10.

Bulkhead habitat comprises 28.5 sq km (11.0 sq mi) in the Galveston basin. The jetties around Bolivar Roads, the Texas City Dike, and the seawall along the gulf shoreline in the city of Galveston are mapped as bulkhead. Many small bulkheads are located throughout the basin--along Buffalo Bayou and the Houston Ship Channel in its upper reaches, in numerous residential developments with canals for pleasure boats, and along the mainland shoreline within the western portion of Galveston Bay.

Galveston Bay, Trinity Bay, East Bay, West Bay, and the small secondary and tertiary bays constitute the largest contiguous area of bay in the Texas Barrier Island Region, a total of 1090.9 sq km (421.2 sq mi) comprising 10.1 percent of the basin's area. The bay system is highly productive and provides habitat for a large and rich group of plants and animals. Contained within the bay system is a large area of oyster reefs that occupies 220.0 sq km (85.3 sq mi). Two-thirds of all the oyster reef habitat in the region is located in the Galveston basin.

The basin contains 247.1 sq km (95.4 sq mi) of salt and brackish marsh; this is almost 40 percent of the marsh area in the Texas Barrier Island Region. One of the largest areas of marsh is located on the Trinity River delta; a smaller area is located on the San Jacinto River delta. Several small marsh areas are present along the edges of secondary bays, small creeks, and bayous. Many of the latter areas are too small to be shown in Plate 10.

The largest proportion of marsh is located along the mainland shoreline. The marsh types vary with elevation, with salt marsh at the lowest elevations and fresh marsh at the highest elevations, merging into upland grassland. An

additional area of marsh is present along the back side of the barrier habitat. Two particularly large areas are present on the bay side of Bolivar Peninsula. Here the marsh has grown upon washover fans, places where large quantities of sediment have washed over the barrier to form bay-side deltas. The washovers probably occurred during large hurricanes.

A small amount of wind-tidal flat is located between the barrier and the salt and brackish marsh areas. The area of wind-tidal flat totals 15.7 sq km (6.1 sq mi), and is too small to be mapped. Bayward of the salt and brackish marshes on the backside of Galveston Island are several areas of shallow grassflats.

The Galveston basin contains 689.4 km (428.4 mi) of channel and tidal stream, nearly one third of the total of this habitat in the region. Major channels include the intracoastal waterway, Houston Ship Channel, Chocolate Bayou Channel, Texas City Channel, Dickinson Channel, Clear Creek Channel, Trinity River Channel, Double Bayou Channel, Bayport Channel, Anahuac Channel, Cedar Bayou Channel, and Barbours Cut. Dredging and maintenance of channels has produced 49.0 sq km (18.9 sq mi) of spoil. Much of the spoil in this basin was disposed in unconfined, subaqueous disposal sites. Since the bays are relatively deep, the amount of subaerial spoil is only about half that of the Laguna Madre basin even though the channel length is 64 percent greater.

The Galveston basin has a slightly greater proportion of cropland, gulf, bay, and forest than the region as a whole and more than twice the relative area of urban land and salt and brackish marsh (Figure 70). The relative areas of reef, swamp, and bulkhead are also much greater in this basin than in the region.

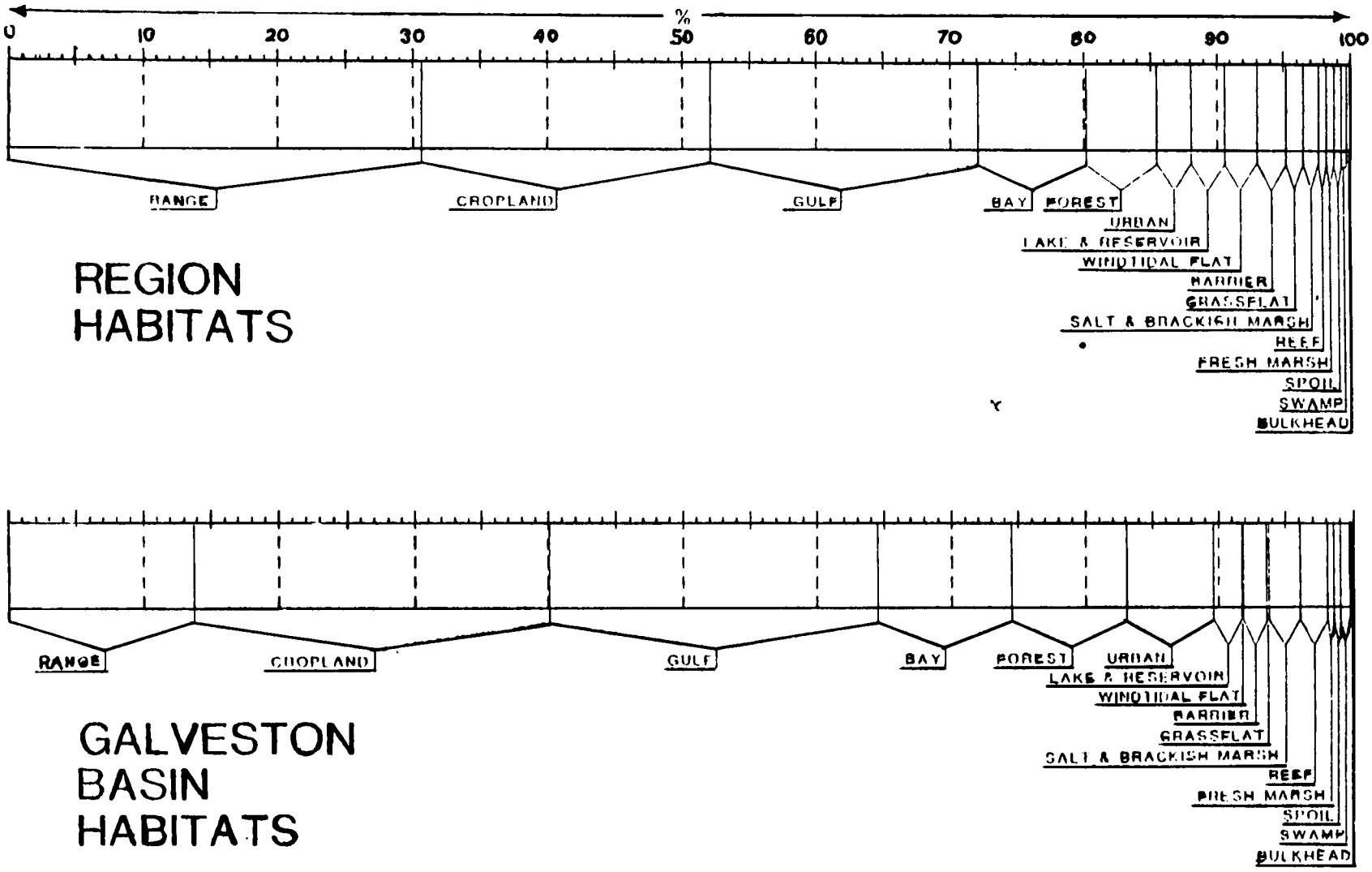


Figure 70. Habitat proportions of the Galveston basin and Texas Barrier Island Region.

The basin contains a slightly smaller fraction of wind-tidal flat and grassflat than the region and less than half the relative area of range. Barrier, lake and reservoir, fresh marsh, and spoil habitats occur in about the same proportion in the basin as in the region overall.

Baseline information in the 7-volume Environmental Geologic Atlas of the Texas Coastal Zone, used to define the basin's habitat units, is circa 1956 and 1957 but has been selectively updated to include more modern land-use information (Fisher et al. 1972; Fisher et al. 1973; McGowen et al. 1976b). Consequently, it shows some but not all of the major changes that have occurred in the last 25 years. No recent data source is as comprehensive or comparable over the entire coast as the Environmental Geologic Atlas from which the habitat maps for this study are drawn. However, comparative maps and area measurements for 29 U.S. Geological Survey 7.5 minute quadrangles for the period 1956 to 1979 were available from the U.S. Fish and Wildlife Service National Coastal Ecosystems Team. These were used to identify habitat changes. The units on these maps are a modified set of the wetland units used for the National Wetland Inventory Program (Cowardin et al. 1979).

The 29 quadrangles encompass about 4900 sq km, nearly 45 percent of the basin's area. In the 23-year period between 1956 and 1979 this area has experienced extensive population growth and land development. In addition, it has undergone significant subsidence since 1906. Ratzlaff (1982) reported that the range of subsidence for the area covered by these maps is 0.15 to 1.5 m (0.5 to 5 ft). Table 35 shows changes in the total area occupied by various resource unit types between 1956 and 1979. To simplify the many different units mapped using the Cowardin system, units were grouped into six categories, similar to some of the habitat units in this study.

Table 35. Changes in land areas from 1956 to 1979 for 29 U.S. Geological Survey 7.5 minute quadrangles in the Galveston basin.

Land type	1956 area (sq km)	1979 area (sq km)	Change in area (sq km)	Percent change
Beach/bar	10.8	6.5	- 4.3	- 39.8
Forested wetlands	21.5	30.5	+ 9.0	+ 41.7
Freshwater marsh	190.7	127.5	- 63.2	- 33.2
Freshwater ponds and lakes	47.4	82.7	+ 35.3	+ 74.5
Salt and brackish marsh	471.1	429.6	- 41.5	- 8.8
Upland	1684.5	1691.0	+ 6.5	+ 0.4

USGS 7.5 minute quadrangles included in the measurements:

Anahuac
Bacliff
Caplen
Christmas Point
Cove
Dickinson
Flake
Frozen Point
Galveston
High Island
Hitchcock
Hoskins Mound
Lake Como
Lake Stephenson
La Porte
League City
Morgan Point
Oak Island
Oyster Bayou
Oyster Creek
Port Bolivar
San Luis Pass
Sea Isle
Smith Point
South Christmas Point
Texas City
The Jetties
Umbrella Point
Virginia Point

The area of beach in the Galveston basin decreased by 4.3 sq km (1.7 sq mi) between 1956 and 1979, a loss of 39.8 percent. A sizable spit at the southern tip of Galveston Island disappeared, and the beach narrowed over the length of the island. In addition, some of the accumulated sand on the gulf side of Bolivar Peninsula at the north jetty eroded and some of the remaining beach was replaced by salt and brackish marsh.

Forested wetlands increased by 9.0 sq km (3.5 sq mi), a gain of 41.7 percent. Near Bastrop Bay, some forested wetlands were lost, but others developed over the 23-year period. There were both losses and gains in the swamps of the Trinity River; overall, the amount of swamp in this area remained about the same. Gains in forested wetlands were registered in an area near Morgan Point and east of Trinity Bay; upland was converted to forested wetland in these areas. A few spoil islands in East Bay also developed forested wetlands at the expense of salt and brackish marsh. Detailed maps of the spoil island changes are given in Coastal Zone Resources Corporation (1977).

Freshwater marsh area decreased drastically according to the U.S. Fish and Wildlife Service maps. The maps indicate a loss of 63.2 sq km (24.4 sq mi), or 33.2 percent of the unit's area. The total area of freshwater marsh was calculated to be 190.7 sq km for 1956, 4.4 times as large as the area of freshwater marsh for the basin given in Table 34. This large discrepancy is the result of differences in the definitions of map units for the area. The units from the latter works (Fisher et al. 1972, 1973 and McGowen et al. 1976b) were land-use units, based upon potential uses; range included areas of high marsh, and cropland included areas out of cultivation that might naturally have

wetland vegetation. The fresh marsh unit from the U.S. Fish and Wildlife Service maps included portions of range, cropland, freshwater marsh, and salt and brackish-water marsh from the maps in Plate 10.

Around Bastrop Bay, Chocolate Bay, along the mainland of West Bay, and near Dickinson and Dollar bays, much of the area shown as freshwater marsh in 1956 is shown as upland on the 1979 maps. The reason for this change is not clear. West of the Trinity River delta, a large area of freshwater marsh was converted into a large open-water body. This is a cooling pond for a large electric generating plant that now contains brackish water.

To the east, a large area of freshwater marsh on the bay side of the Trinity River channel changed to salt and brackish marsh. It is likely that hydrologic alterations within the Trinity River delta for navigation and impoundment of Lake Wallisville (currently under construction) have modified the supply of fresh water to this marsh area and caused the habitat change. In the upper portion of the Trinity River delta some freshwater marsh has become an estuarine open water body. The reason for this change is not clear.

East of Trinity Bay, in the Smith Point area, some new freshwater marsh developed in areas that were formerly upland. On the mainland north of East Bay, several large areas of freshwater wetland developed on what had been salt and brackish marsh; a smaller freshwater wetland area developed upon upland in the same part of the basin.

The declines in freshwater marsh area are in part due to human influences. In some areas the differences may be the result of short-term land use changes--the use of marginal wetland for crops or range in dry years, for example. The reasons for other losses and gains are not clear.

There was a sizable increase in the area of freshwater lakes and ponds; this unit gained 35.3 sq km (13.6 sq mi), a 74.5 percent increase over the 1956 area. In the vicinity of Bastrop Bay there were gains and losses of freshwater lakes and ponds, with little overall change. On the mainland around Chocolate and West bays, there was a net gain of lake and pond area; some came from upland, but most came from salt and brackish marsh. Most of the areas of increase appear to be new impoundments.

Near Dickinson and Dollar bays and Morgan Point, the area of freshwater lakes and ponds increased becasue of additional impoundments on the uplands. At Morgan Point most of Black Duck Bay was impounded, creating a freshwater pond. The impoundment is a spoil containment area for the Houston Ship Channel. Around Clear Lake there was some loss of natural freshwater lakes and ponds to estuarine open-water bodies. Both subsidence and development in this area probably contributed to the change.

Above the large cooling pond at the edge of the Trinity River delta the area of lakes and ponds increased slightly. Some upland, freshwater marsh, and estuarine water bodies were converted into freshwater ponds and lakes. On the uplands the conversions were obviously man-made; in the delta the cause of the change is unclear.

East of the Trinity delta, Lake Anahuac increased in size due to loss in freshwater marsh in the lake. Near Smith Point and along the East Bay mainland there was some increase in freshwater lakes and ponds at the expense of salt and brackish marsh; the 1979 maps several man-made impoundments were evident in this area.

Newly impounded areas appeared on Pelican Island and at Fort Point on Galveston Island, the northernmost portion of the island behind the seawall.

Both areas are spoil containment sites and capture rainfall so the presence of freshwater ponds is incidental.

The majority of the increase in freshwater lakes and ponds is the result of impoundment of areas for water supply or spoil containment. However, in Clear Lake and the Trinity Delta changes may be either natural or indirectly due to man's activities such as through subsidence.

Salt and brackish marsh in the Galveston basin lost 41.5 sq km (16.0 sq mi), or 8.8 percent of its area over the period 1956 to 1979. The area of salt and brackish marsh calculated for 1956 by the U.S. Fish and Wildlife Service was 471.1 sq km (181.9 sq mi), 90.7 percent larger than the area presented in Table 34, calculated from Environmental Geologic Atlas (Fisher et al. 1972, 1973; McGowen et al. (1976b). This discrepancy is also the result of differences in the definitions of map units. The land-use units in the atlas were based upon potential uses and did not include areas of high marsh and wet grasslands that might be used occasionally as range or cropland. The salt and brackish marsh unit from the U.S. Fish and Wildlife Service maps included portions of areas shown as range, cropland, salt and brackish-water marsh, spoil, and wind-tidal flat on the maps in Plate 10.

Near Christmas and Bastrop bays there was some expansion of salt and brackish marsh onto upland and freshwater marsh areas. There were also decreases caused by spoil placement and conversion to upland. The expansion of salt and brackish marsh slightly outweighed the decreases. Near Chocolate Bay there was a slight decrease in marsh area; the 1979 maps show that some marsh was replaced by upland.

Along the West Bay mainland significant decreases in salt and brackish marsh occurred between the mappings. Much of the marsh at higher elevations was transformed into upland. Human actions altered some marsh areas; at least three land developments with dredged canals and several freshwater impoundments converted salt and brackish marsh area to upland and to freshwater lake and pond. Tiki Island off Virginia Point was completely converted from marsh to fingerfill development, for example. The largest change was the appearance of sizable estuarine open-water bodies in the low marsh areas. This change was probably due to subsidence in this area, which ranged from 0.3 to 0.6 m (1 to 2 ft between 1906 and 1973 (Ratzlaff 1982).

On the eastern side of Virginia Point, the marshes at Swan Lake were almost completely converted to impounded freshwater ponds or estuarine open-water bodies. Subsidence in this area has also-ranged from 0.3 to 0.6 m (1 to 2 ft).

Along the western shoreline of Galveston Bay, salt and brackish marsh almost disappeared from Dollar and Dickinson bays and Clear Lake. Dollar and Dickinson bays are now surrounded by a storm control levee and have subsided at least 0.6 m (2 ft); Clear Lake has subsided at least 1.2 m (4 ft).

Losses and gains in marsh area have occurred near the entrance of the Houston Ship Channel to upper Galveston Bay. Conversion of marsh to estuarine waters is attributable to subsidence ranging from 1.2 to 1.8 m (4 to 6 ft), and gains were cause by the development of marshes on maintenance spoil placed in confined areas. It appears that the loss of salt and brackish marshes which subsided to become estuarine open-water bodies has been nearly balanced by the formtion of new marshes on subsiding uplands and dredge spoil.

At the Trinity River delta there was a large gain in salt and brackish marsh area through conversion of an area of freshwater marsh south of the Trinity River channel and adjacent to Trinity Bay. This alteration was probably the result of man-made hydrologic changes in the delta such as blocking freshwater flow to the wetlands.

At Smith Point there was a significant net increase in salt and brackish marsh; most of the new marsh was upland on the 1956 maps. Only small losses were observed in this area, mostly due to an impounded freshwater pond. On the East Bay mainland, there was a net loss of salt and brackish marsh. A little was transformed into upland; some was lost to additional estuarine open-water bodies and an impounded freshwater pond. The greatest loss was to a large area of new freshwater marsh at a higher elevation than the surrounding wetlands. Near the mainland shoreline there were some salt and brackish marsh gains from areas classified as uplands on the 1956 maps.

Between Rollover Pass and High Island, filling for land development converted some marsh into upland. However, an even larger area of marsh changed to estuarine open water body throughout this wetland area. Balancing these losses, the strandplain flat behind the gulf beach narrowed, with some of it becoming salt and brackish marsh.

On the back side of Bolivar Peninsula, marsh areas have been dredged or filled at least 10 land developments and canals (Texas A&M University 1978) have filled or dredged marsh areas on the backside of the peninsula. There was a small net loss of marsh area on the spoil piles, probably due to smothering by new spoil. Salt and brackish marshes in swales and depressions between beach ridges near Port Bolivar and the north jetty expanded over the 23-year period. The largest marsh change on the peninsula was on the northernmost washover fan,

known as Marsh Point; about one-third of the salt and brackish marsh was replaced by estuarine open water.

Galveston and Pelican islands displayed sizable losses of salt and brackish marsh. Most of the areas of change on Pelican Island and at Fort Point on Galveston Island are spoil disposal sites; their conversion to upland is related to maintenance dredging. On the bay side of Galveston Island at least six developments have filled or dredged salt and brackish marsh to create land for residences or canals for pleasure vessels (Marvin Springer and Associates 1978). The back side of the island near the southern tip changed from marsh to upland between 1956 and 1979; reasons for the change are not obvious. Finally, a large portion of the bayside marshes on Galveston Island have become estuarine open water areas lake their counterparts on the mainland side of West Bay.

A significant portion of the change in salt and brackish marsh area is the result of human activities: the construction of channels, filling for land development, impoundment or spoil disposal or water storage, and alteration of natural hydrologic flow for navigation. Changes in other area that changed do not appear to have a direct man-made cause, however. The development of estuarine open-water areas from salt and brackish marsh along West Bay, on the west side of Galveston Bay, between Rollover Pass and High Island, and on Marsh Point of Bolivar Peninsula may be the result of subsidence. New open- water areas appear to develop in a manner similar to those forming through the subsidence of interdistributary marshes on deltas described by Morgan (1972). West Bay sites and the west side of Galveston Bay have experienced significant

subsidence. Marsh Point and the area from Rollover Pass to High Island, however, have had only minor subsidence according to Ratzlaff (1982).

The loss of high-elevation salt and brackish marshes to uplands on the West Bay mainland does not have an obvious explanation. Land uses may have changed on the West Bay mainland marshes, although the mapped information can neither confirm nor disprove this point. The difference is probably not the result of natural variation in wetland areas due to wet and dry years. The winter of 1978-1979 and the fall of 1979, when photographs of the entire Texas Barrier Island Region were taken, ranged from slightly wetter to much wetter than normal (Bomar 1979). The gain in salt and brackish marsh from uplands around Smith Point might be the result of the wetter conditions, since the area received more than 125 percent of its normal rainfall.

Geologic development. Surface sediments in the Galveston basin range in age from Pleistocene to Recent. Underlying the entire basin are fluvial-deltaic sediments deposited by major river systems during the Pleistocene through the Sangamon interglacial stage.

Sea level dropped during the Early Wisconsin period; when it rose again, the rivers deposited their sediment in the gulf where it was reworked along with older delta-front sand to create barrier-strandplains along the shoreline. Relicts of these strandplains are present near the mouth of Chocolate Bay, along the southern edge of Dollar Bay, and along Smith Point for a distance of 32 km (20 mi) to the northwest (Fisher et al. 1972).

The major streams in the area meandered during this interglacial period and deposited deltas behind the barrier-strandplains (Fisher et al. 1972). In the area north of West Bay, the river system--probably the Brazos--deposited delta material over or around the discontinuous strandplain but stopped at about

the present mainland shoreline. To the east of Galveston Bay and north of East Bay, a late Pleistocene delta--probably from the Trinity River-- buried the barrier strandplain or built around it. Here the delta front may have extended as much as 20 km (12 mi) gulfward of the barrier-strandplain.

When sea level dropped again 50,000 to 60,000 yr BP, the San Jacinto and Trinity rivers incised deep valleys across what is now Galveston Bay. The two rivers joined between Smith Point and San Leon and formed a single deep valley that extended southward through Bolivar Roads and across the continental shelf (Fisher et al. 1972).

Sea level rose 25,000 to 18,000 yr BP, and by the time it stabilized, the upper portions of the estuaries had received much sediment from headward-eroding streams, river valley wall erosion, and estuary bank erosion. The lower portions received gulf sediment from flood-tidal currents. In addition, large oyster reefs developed, adding to the mass of material filling the bays.

The Trinity and San Jacinto river developed deltas the prograded seaward at a relatively slow rate; Fisher et al. (1972) reported that the Trinity River delta had extended only about 16 km (10 mi) since sea level stabilized.

Headward-eroding streams cut into the Pleistocene fluvial-deltaic deposits and created some of the smaller subbasins seen today, including Chocolate Bayou and Clear Creek.

Sand from the Late Pleistocene deltaic headlands and earlier submerged Pleistocene deposits northeast of the Galveston basin was transported to the southwest by the dominant littoral currents. The sand built a spit, Bolivar Peninsula, across East Bay and supplied the much of the material for Galveston and Follet islands further to the southwest.

Basin hydrology and climate. The climate of the Galveston basin is warm and humid. The average temperature is 20.6 deg C (69 deg F); the average summer high temperature is 28.3 deg C (83 deg F), and the average winter low is 11.6 deg C (53 deg F) (Williams et al. 1976).

The average rainfall in the basin is 121.9 cm (48 in) (Williams et al. 1976). The distribution of rainfall is relatively even throughout the year; September has the highest rainfall (13.1 percent), followed by June, July, and May. The lowest rainfall, which occurs in March deviates less from the mean monthly figure than does the September rainfall amount (Bomar 1983). Rainfall is higher than potential evapotranspiration; consequently this basin has a net precipitation surplus of about 15 cm (6 in) (Woodruff 1975).

The Galveston basin receives inflows from the Trinity River and the San Jacinto River, two major rivers that have significant drainage areas outside of the basin. A large number of small streams and bayous drain areas that extend only slightly outside the basin or that lie wholly within the basin. Some of these waterways are Buffalo Bayou, White Oak Bayou, Brays Bayou, Sims Bayou, Clear Creek, and Chocolate Bayou. The average inflow from gaged streams in this basin is 8742 million cu m per year (Texas Department of Water Resources 1979). Variation during periods of low and high flow has ranged from 19 to 233 percent of the average flow (Dougherty 1980). Estimates of total inflow including gaged and ungaged flows, return flows, and diversions is 12,054 million cu m per year (Texas Department of Water Resources 1978). When direct rainfall and evaporation are also added, the net inflow into the basin is 12,284 million cu m per year (Texas Department of Water Resources 1979). Sediment inflow information is available only for the Trinity River, which contributes about 87 percent of the

gaged flow into the basin. The sediment load from the Trinity is 3,557,774 metric tons per year.

The greatest proportion of river water enters the basin during the late spring. The hydrograph in Figure 71 shows that the peak flow occurs in May and high flows occur in the adjacent months, April and June. Slightly more than 42 percent of the river flow occurs during this three-month period (Dougherty 1980). The period of lowest flow is August, with less than 2 percent, followed closely by September, with only slightly more than 2 percent. Estimates from the Texas Department of Water Resources (1981b) for total inflow to the bay show the same pattern even when ungaged flow, precipitation, and evaporation are added. This is of interest since September, the month with the next-to-lowest fresh water inflow, has the highest rainfall; freshwater inflow into the Galveston basin is highly influenced by hydrologic conditions outside of the basin.

Figure 71 shows the hydrologic distribution pattern for the basin. The Trinity supplies about 53 percent of the water for the basin (Texas Department of Water Resources 1979; Dougherty 1980). Some of the water it contributes to Trinity Bay is local runoff from uplands. Upland runoff enters all of the major bays in the basin. In the less urbanized areas, runoff enters the bays via streams such Chocolate Bayou. Some runoff flows to mainland wetlands such as those along East and West bays.

In the urbanized area some runoff directly or indirectly enters the Houston Ship Channel from adjacent land or from the many bayous and drainage ditches which are tributaries of Buffalo Bayou. In addition to these natural flows, return flows from municipal and industrial facilities empty directly or indirectly into the Houston Ship Channel through drainage ditches and bayous;

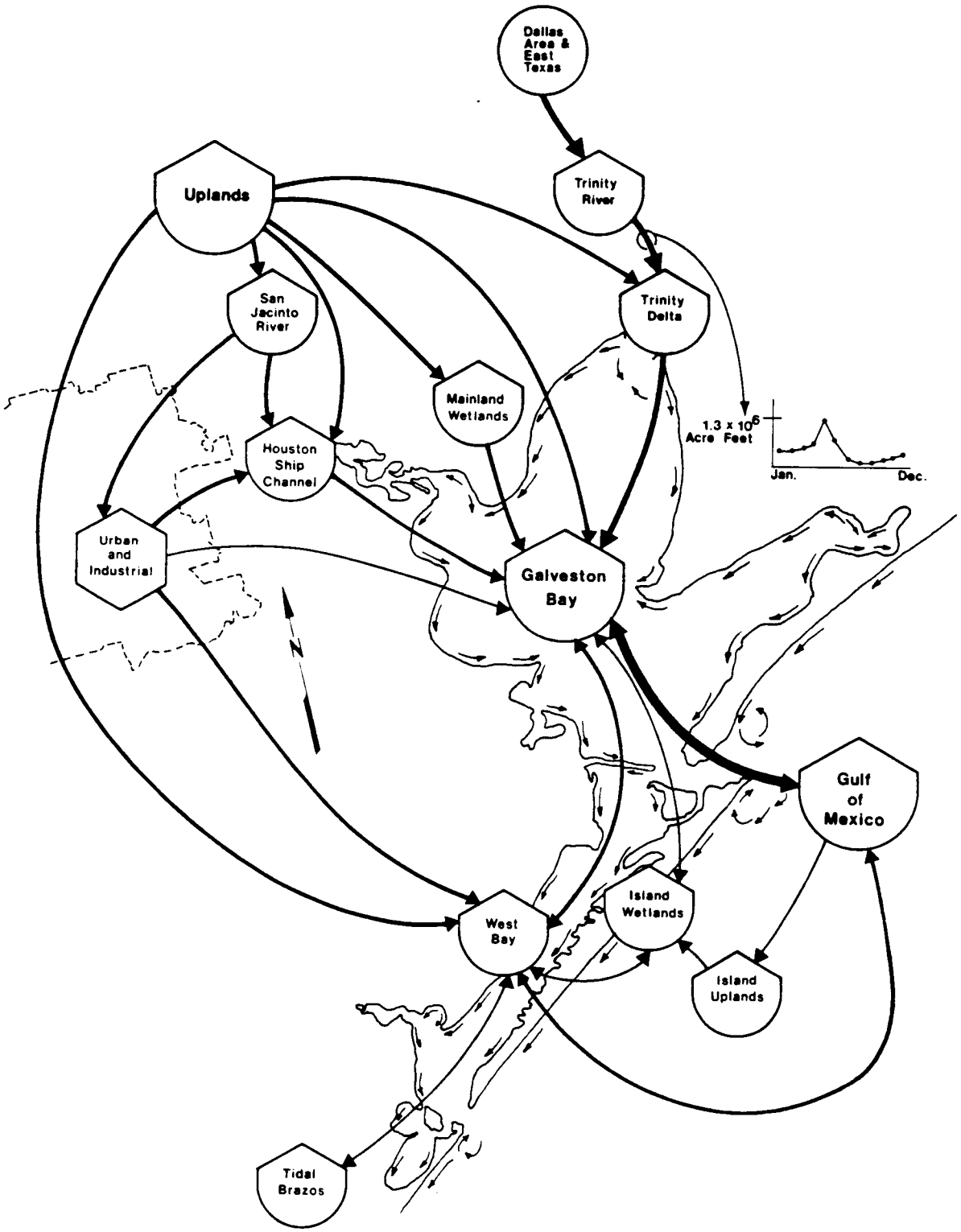


Figure 71. Hydrology of the Galveston basin.

urban flows also enter Galveston and West bays from urban areas built adjacent to them.

Galveston Bay and the gulf exchange water largely through Bolivar Roads. West Bay exchanges some water with the gulf through San Luis Pass, and with the Brazos basin through the intracoastal waterway. Water from Galveston, East, and West bays is exchanged with mainland and island wetlands. The island wetlands sometimes receive gulf storm water directly from washovers.

The major bay systems in the Galveston basin are upper and lower Galveston Bay, Trinity Bay, East Bay, and West Bay. Clear Lake and Dickinson Bay are of interest because of their heavy use for recreation. Drum, Christmas, Bastrop, and Chocolate bays are relatively inaccessible and less affected by man's actions than many areas in the basin. Tabbs, Black Duck, San Jacinto, Scott, and Burnet bays have all been g~eatly affected by water quality problems, by dredging from the Houston Ship Channel, and by extreme amounts of subsidence.

Trinity Bay slopes from the Trinity River delta to upper Galveston Bay. Most of Trinity Bay is about 2.4 m (8 ft) deep. The depth of upper Galveston Bay ranges to 3 m (10 ft) except in the Houston Ship Channel which bisects the bay (Figure 72). The depth of the channel is 12.2 m (40 ft), but adjacent spoil may be subaerial or at shoal depths. Sediment in these bays is mostly mud, but some oyster reefs are located in the southern area (McGowen and Morton 1978). The 4-year average salinity of Trinity Bay is 7.3 ppt with extremes of 0.1 and 18.0 ppt (Figure 73); the 4-year average salinity of upper Galveston Bay is 16.9 ppt with extremes of 1.3 and 30.7 ppt (Texas Department of Water Resources 1983a). The influence of the Houston Ship Channel on upper

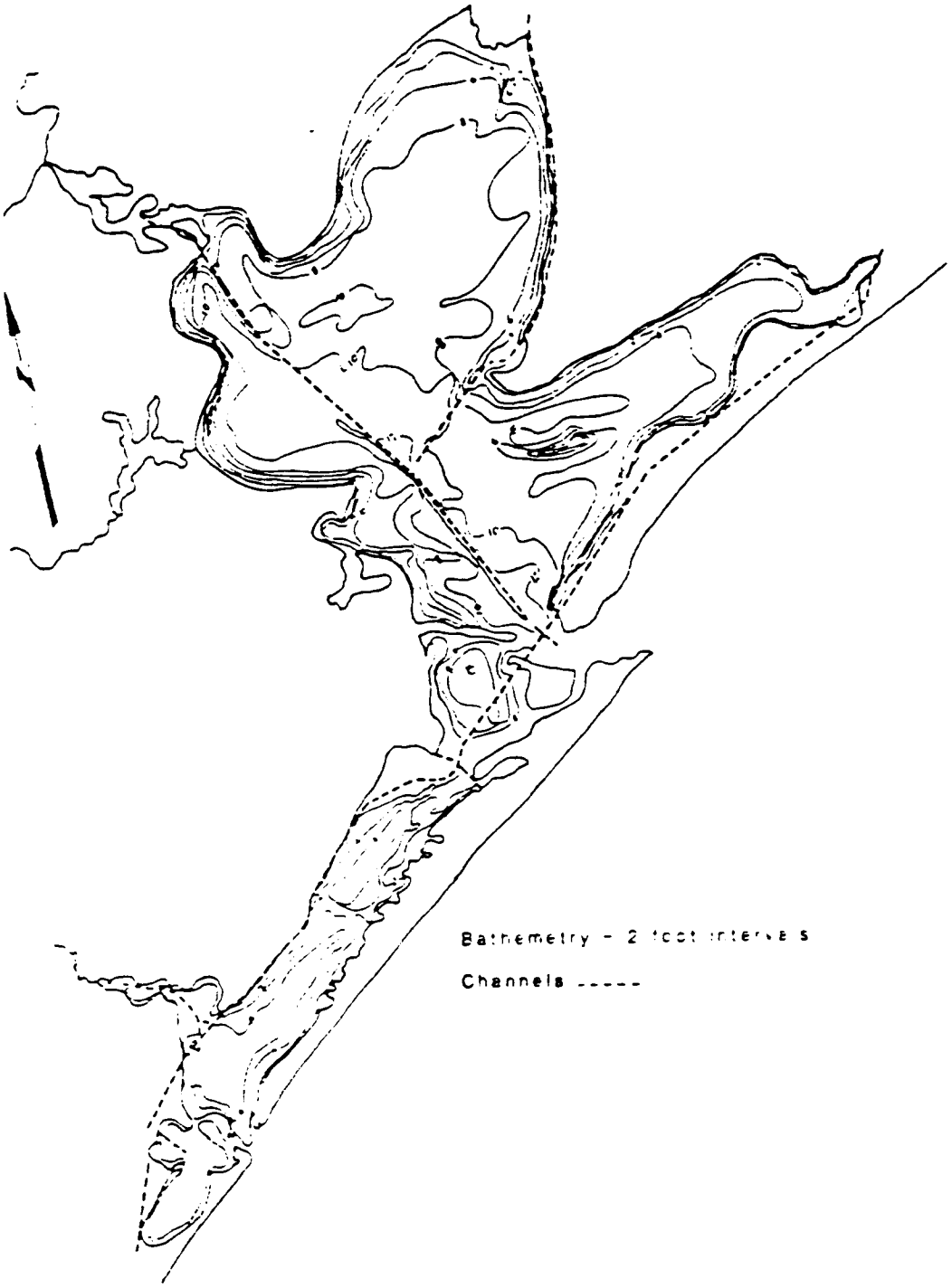


Figure 72. Bathymetry of bays in the Galveston basin.

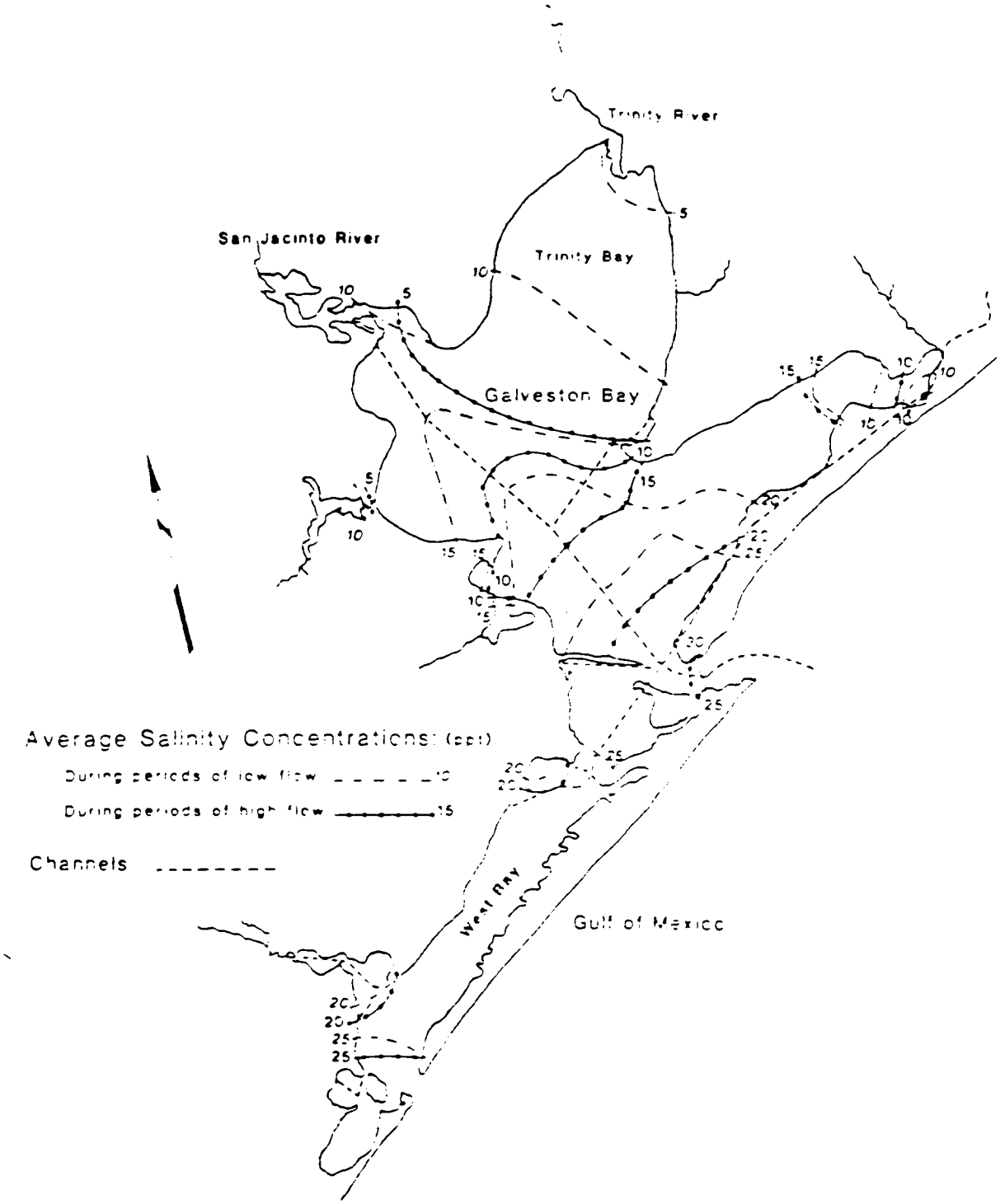


Figure 73. Salinity variation in bays of the Galveston basin.

Galveston Bay salinities is very strong. Belaire (1976) noted the importance of density currents in directing the flow of higher salinity gulf water up channels into low salinity areas.

East Bay ranges in depth from 1.2 to 2.4 m (4 to 8 ft). Lower Galveston Bay is 2.4 to 3 m (8 to 10 ft) with a few areas 3.7 m (12 ft) deep (Figure 72); the Houston Ship Channel also runs through this bay. At the entrance to Bolivar Roads, the bay depth increases; depths of 8 to 10 m (26 to 33 ft) are not unusual. The protected area between Pelican Island, the Texas City Dike, and Virginia Point on the mainland has depths to 3 m (10 ft).

East Bay sediments are generally muds except in areas of reefs. Lower Galveston Bay also contains mud sediments and reef material. At Dollar Point near Dollar Bay, and near the entrance to Bolivar Roads, the sediments are sand, muddy sand, and sandy mud. The bay area adjacent to Bolivar Roads, which has high current velocities, is shell or rock fragment gravel. The protected area between Pelican Island, the Texas City Dike, and Virginia Point has mud, sand, and shell sediments in various combinations (McGowen and Morton 1978). The 4-year average salinity of East Bay is 14.5 ppt with extremes of 3.2 and 24.4 ppt. The 4-year average salinity of lower Galveston Bay is 17.1 ppt with extremes of 1.5 and 32.0 ppt (Texas Department of Water Resources 1983a).

Most of West Bay is 1.2 to 1.8 m (4 to 6 ft) deep (Figure 72). Sediments are largely mud except along the back side of Galveston Island where they are sandy. Several reefs are located in West Bay and the sediments around the reefs are shell, muddy shell, and shelly mud (McGowen and Morton 1978). The 4-year average salinity of West Bay is 23.9 ppt with extremes of 3.2 and 50.8 ppt (Texas Department of Water Resources 1983a).

Depths in Drum, Christmas, Bastrop, Chocolate, and Dickinson bays range from 0.6 to 1 m (2 to 3 ft), although several of these bays have 2.4 m (8 ft) channels running though them. Sediments are mostly mud. Christmas Bay has some sand and Chocolate Bay contains some areas of sandy mud and muddy sand (McGowen and Morton 1979). Four-year average salinity measurements and extremes are: Bastrop Bay, 22.0 ppt (0.3 to 32.9); Christmas Bay, 22.5 ppt (1.6 to 31.8 ppt); Chocolate Bay, 14.2 ppt (0.7 to 27.1 ppt); Drum Bay, 22.2 ppt (4.0 to 28.7 ppt).

The depth of Clear Lake has recently increased because of subsidence (1.2 m or 4 ft, Ratzlaff 1982). Depths of 1.2 to 1.8 m (4 to 6 ft) are not unusual in the area. Bottom sediments are mostly mud (McGowen and Morton 1979) and the 4-year salinity average is 10.3 ppt with extremes of 0.1 and 21.3 ppt (Texas Department of Water Resources 1983a).

Tabbs, Black Duck, San Jacinto, Scott, and Burnet bays are all located at the upper end of upper Galveston Bay. Subsidence in this area has been 1.2 to 1.5 m (4 to 5 ft) so the depth of these bays has also increased; recent nautical charts have not been updated to reflect these changes. Bottom sediment in these bays is mud (McGowen and Morton 1979). The 4-year average salinities are: Black Duck Bay, 11.8 ppt (2.6 to 18.8); Burnet Bay, 8.6 ppt (0.5 to 16.5 ppt); Scott Bay, 9.6 (0.6 to 17.2 ppt); Tabbs, 11.2 ppt (2.3 to 19.2 ppt).

Circulation in the small bays is dominated by wind and pulses of fresh water. Circulation in Clear Lake is strongly influenced by an electric generating plant in Webster, Texas. The plant draws water from an intake canal on Clear Creek, several kilometers upstream from the opening into Clear

Lake and each day discharges an amount which is 18 to 34 percent of lake's volume. The daily freshwater flow of Clear Creek is only 16 to 23 percent of the volume the power plant draws through the intake canal. Consequently water flows upstream, from the lake through the creek to the power plant, and then back to the lake (Lohse 1973; U.S. Army Corps of Engineers 1974).

Generalized flow patterns that might be expected under average flow conditions were given by Fisher et al. (1972) and are presented in Figure 71. There is a general movement of water from Trinity and upper Galveston Bay to the opening of Bolivar Roads.

Detailed studies have been made of the hydrology of Galveston Bay, based upon mathematical and physical models. Espey, Huston and Associates (1978) prepared hydrologic models and a description of flow in the bay for a proposed port expansion project in Galveston. Using sustained seasonal flow conditions, they presented diagrams showing net velocities and directions of flow in 1-nautical-mile compartments for Trinity Bay, upper and lower Galveston bays, East Bay, West Bay, Chocolate Bay, San Luis Pass, and Bolivar Roads. These are long-term average movements rather than instantaneous flow patterns. There is a net movement of water from Trinity Bay toward the constriction between Smith Point and San Leon. The Cedar Bayou electric generating plant north of Trinity Bay causes water to move from the northern portion of Trinity Bay near the outlet of the cooling pond, travel clockwise around Houston Point separating Trinity and upper Galveston bays, and flow up Cedar Bayou through the power plant, into the cooling pond, and back to Trinity Bay. The influence is strong and reverses the natural direction of flow in Cedar Bayou and part of upper Galveston Bay.

The seasonal net movements in upper Galveston Bay are small and randomly directed except near the opening to lower Galveston Bay and at one point near the western shore. A second electric generating plant, located on the western shore of the mainland, draws bay water from Dickinson Bay up Salt Bayou, through the generating plant, and back to upper Galveston Bay north of San Leon. This circulation is also clockwise and reverses the natural flow of the bayou.

The constriction at Smith Point is an obvious narrowing of the land area. Less obvious are the hydrologic constrictions caused by numerous oyster reefs and spoil piles. Two other hydrologic obstructions have a large effect upon flow in the lower part of the bay system: the Texas City Dike and Hannah Reef.

The Texas City dike was constructed in 1915 to control siltation of the Texas City Channel, which was dredged perpendicular to the natural direction of flow. The dike directs all flow from upper and lower Galveston Bay either to Bolivar Roads or back up the western shoreline of lower Galveston Bay. Hannah Reef is 6 km long (3.7 mi) and, with the constriction at Smith Point and near other reefs, effectively isolates most of the East Bay open circulation with lower Galveston Bay. The flow in lower Galveston Bay under the sustained seasonal conditions imposed by the hydrologic model was strongly to the southeast, out of Bolivar Roads.

Net flow in East Bay is small in magnitude and without well-defined direction except where water enters at Smith Point and exits south of Hannah Reef. In contrast, flow velocities in West Bay are strong, and the pattern of flow is from San Luis Pass to Bolivar Roads around both sides of Pelican Island.

The Texas Department of Water Resources (1979) modeled the Galveston basin under conditions of monthly steady-state flows. Flow diagrams from this study reveal the variation in circulation under different freshwater inflow regimes. During May, the month with the extreme high freshwater inflow, 5.4 times more water enters the basin than during August, the month with the lowest average inflow (Texas Department of Water Resources 1981b). The most obvious difference is in flow along the Houston Ship Channel. In periods of low freshwater inflow, there is a strong movement of water up the channel; with high inflow there is a strong flow out the channel. Under conditions of low flow the net flow velocity in all areas except the ship channel and upper Galveston Bay west of the ship channel is low and generally without definite direction; there is a counterclockwise flow of moderate strength in upper Galveston Bay. Under high flow conditions, a strong southwest flow occurs in Trinity Bay, a strong northwest flow pattern is apparent in West Bay, upper Galveston Bay west of the ship channel has a clockwise flow pattern, and lower Galveston Bay water is directed to the northwest, counter to the southeast movement of ship channel water.

The ship channel is the single major hydrologic influence on bay hydrology during most of the year. Isohalines--contour lines showing the salinity distribution pattern--generally display a bulge of higher salinity water protruding into upper Galveston Bay. However, even this hydrologic intrusion can be completely disrupted by large freshwater inflows, which require 20 to 30 days to establish a new equilibrium salinity gradient.

The gulf bottom in this basin slopes to a depth of 7.3 m (24 ft) within 2 km (1.2 mi) of the shoreline. Seaward the bottom slope is less rapid; depth at the three-league line is 19.2 m (63 ft) at the lower boundary but only 13.4 m

(44 ft) at the upper boundary. Bottom sediments near the beach are sandy. Most of the offshore sediments are mud, and sandy mud the next most abundant type. Offshore of the western portion of Galveston Island the sediment is sandier than in most other locations. There are also deposits of sand, shell or gravel, and combinations of all sediment types. McGowen and Morton (1978) consider these to be relict beach deposits.

Over a yearly cycle, offshore surface and bottom currents move to the southwest off of the Galveston basin (Espey, Huston and Associates 1978). The movement is weakest in the summer but strong during the other seasons. Surface currents average nearly 0.5 m per second (1 knot) but decrease with depth; deeper currents flow at only about half the surface velocity. Erosion has been a general trend although there has been some variation. Over the period 1852 to 1974, erosion was the general trend between Oyster Creek and San Luis Pass; erosion rates were as high as 3.0 m (10.0 ft) per year. Since 1965 erosion has generally been higher, occurring at rates of 2.5 to 10 m (8.3 to 33.3 ft) per year except in the area immediately adjacent to San Luis Pass (Morton and Pieper 1975a).

On Galveston Island the trend from the 1850's to the 1970's has been increasing erosion except for the accreting area near the south jetty. Erosion rates have ranged up to 3 m (10 ft) per year. The rate of accretion near the jetty has been as high as 15 m (49 ft) per year. Over the period 1956 to 1970, most of the island shoreline eroded with rates as high as 21 m (68 ft) per year (Morton 1974).

On Bolivar Peninsula between 1882 and 1974 erosion dominated the area from High Island to a point 14 km (9 mi) from Bolivar Roads. Long-term erosion rates

ranged from 0.5 to 2.5 m (1.6 to 8.2 ft) per year. From the midpoint to Bolivar Roads accretion was the usual pattern with rates ranging to 8.5 m (28 ft) per year. Between 1956 and 1974, erosion was the general pattern for the peninsula. Erosion rates varied from 1.7 to 6.3 m (5.6 to 20.6 ft) per year except near the jetty, where accretion of 0.9 to 6.8 m (2.8 to 22.2 ft) per year was measured (Morton 1975).

Basin economy. The Galveston basin contained 1,087,254 persons in 1980 (Table 36). The basin sustained a population growth of 35 percent over the previous decade, an increase of almost 285,000 individuals. Population projections predict a growth of 39 percent over the period 1980 to 2000, with an increase of more than 425,000 (Texas Department of Water Resources 1980).

The value of oil and gas produced in the basin is very high; in 1977 the total value was almost $946 million (Liebow et al. 1980). On an areal basis the value of minerals produced was $87 thousand per sq km; on a per capita basis the value of production was $971 per person.

Recreation and tourism is an important economic sector in the Galveston basin. Travel expenditures for the basin in 1978 were nearly $598 million (Liebow et al. 1980). The number of travel-related jobs was 21,916, or 44 jobs for every 1000 employed (Liebow et al. 1980). Travel expenditures on a per area basis were $96 thousand per sq km of upland. While sportfishing and hunting contributed to the value of the recreation and tourism sector, their contribution was relatively low; sportfishing expenditures were slightly more than $4 million and the number of deer harvested was 1089, only 17 per 100 sq km of upland (Liebow et al. 1980).

Table 36. Economic data for the Galveston basin.

Data type	Quantity
1970 Population	802522
1977 Population	974131
1980 Population	1087254
1990 Population projection	1266669
2000 Population projection	1515072
Mineral production (X $1000)	945967
Deer harvest	1089
Travel expenses (X $1000)	597886
Travel employment	21916
Sportfishing expenditures (X $1000)	4006
Commercial catch value (X $1000)	59689
Electrical generating capacity (kw)	4012829
Total employment	489466
Number of building permits	12045
Length of railroad track (km)	787
Length of highways (km)	11015
Number of vehicles registered	994121
Commodity flows (1000 metric tons)	137499
Number of farms	1746
Market value of products (X $1000)	52231
Area of irrigated land (ha)	41874

Commercial fishing contributed significantly to the basin economy. The direct commercial value of the fishery catch was almost $59 million in 1976 (Texas Department of Water Resources 1981b).

Residential and industrial development is probably the largest and most important sector of the basin's economy. In 1977, 489,466 persons were employed, 50 percent of the population in the basin (Liebow et al. 1980). The number of building permits in 1977--a measure of the level of new construction--was 12,045, or 194 permits per 100 sq km of uplands (Liebow et al. 1980).

Transportation is important to all segments of the economy. In 1976, there were 787 km of railroad track in the basin providing materials and links to markets in other parts of the state and nation (Liebow et al. 1980). The basin had 11,015 km of highway and 994,121 vehicles registered (Liebow et al. 1980); slightly more than 90 vehicles were registered for each km of road, a very high vehicular density.

Commodity flows though the basin's ports are also high. In 1977 more than 137 million metric tons of commodities moved through the basin's waterways (RPC, Inc. 1980). This was 141 tons of commodities for each individual in the basin, and more than 442 thousand metric tons of commodities per km of dredged channel.

While agriculture added significantly to the basin's economy, it was not on a par with oil and gas development or industrial development. In 1974, 1746 farms were located in the basin, and the market value of their total production was more than $52 million (Liebow et al. 1980).

Resource demands. There is a heavy demand for upland space in the Galveston basin (Table 37). More than 11 percent of the upland is occupied by

Table 37. Resource demands in the Galveston basin.

Resource demands	Quantity
Cropland area (ha)	286134
Range area (ha)	148029
Urban area (ha)	71022
Recreation area (ha)	16346
Crude oil production (kiloliters)	6531575
Natural and casinghead gas (million cu m)	12263
Condensate (million liters)	464
1902-1978 oil production (million kiloliters)	614
Grain production (kiloliters)	101833
Cotton production (bales)	6754
Hay produced (metric tons)	59760
Peanuts produced (kg)	273078
Rice produced (metric tons)	208690
Cattle and calves sold	54421
Bay shrimp harvested (kg)	1719560
Bay oysters harvested (kg)	883593
Bay crabs harvested (kg)	791968
Bay commercial fish harvested (kg)	125191
Bay sport fish landed (kg)	353392
Total commercial fish harvested (kg)	375440
Total commercial shellfish harvested (kg)	18500000

Table 37 (continued). Resource demands in the Galveston Basin.

Resource demands	Quantity
Digestive cancer mortality	790
Lung cancer mortality	968
Pneumonia and influenza mortality	331
Emphysema, bronchitis, and asthma mortality	225
Length fishable, swimmable stream segments (km)	455
Percent fishable, swimmable stream segments (%)	75
Airborne particulates (metric tons)	74646
Airborne hydrocarbons (metric tons)	585278
Waste discharge measured as 5-day BOD (kg)	9992602
Number of discharges	624
Cumulative industrial solid waste (metric tons)	32237984
Subsidence of land surface (m)	0.0-2.6
Municipal surface water use (million cu m)	90
Municipal groundwater use (million cu m)	339
Manufacturing surface water use (million cu m)	274
Manufacturing groundwater use (million cu m)	305
Irrigation surface water use (million cu m)	417
Irrigation groundwater use (million cu m)	198
Total surface water use (million cu m)	796
Total groundwater use (million cu m)	885
Municipal, manufact. return flow (million cu m)	721
Agricultural return flow (million cu m)	253
Obstructions to runoff, roads + railroads (km)	11802
Major drainage ditches and canals (km)	1718
Maintenance spoil, historical average (cu m)	6977035
Length of dredged channels (km)	311

residences, businesses, and the transportation network; this proportion is expanding rapidly.Cropland which occupies more than 46 percent of the upland, and range, which occupies nearly 24 percent, are diminishing in size because of urban growth.

In 1978 the basin produced 6.5 million kiloliters of crude oil; this is slightly more than 1 percent of the cumulative total produced in this basin since production began in 1902 (Liebow et al. 1980). Natural gas and casinghead gas was also produced in large quantities; the 1978 production was more than 12,263 million cu m (Liebow et al. 1980).

Biomass produced by basin farms in 1978 included 101,833 kiloliters of grain, 59,760 metric tons of hay, and 273,078 kg of peanuts. Rice production, 208,690 metric tons, was high, but cotton production was relatively low, only 6754 bales. Livestock production was also significant; more than 54,000 cattle and calves were sold during the year (Bureau of the Census 1980).

Biomass production from the bays and gulf was sizable (Table 37). In 1977, more than 1.7 million kg of shrimp, 883,000 kg of oysters, 791,000 kg of blue crabs, and 125,000 kg of commercial fish were harvested from the basin's bay systems (Liebow et al. 1980). In addition, an average of more than 353,000 kg per yr of sport fish were caught in the Galveston basin over the period 1974 to 1977. The yearly average biomass from the combined gulf and bay commercial catch for the period 1972 to 1976 was 375 thousand kg for fish and 18.5 million kg for shellfish (Texas Department of Water Resources 1981b).

Public health statistics for mortality from cancers and respiratory illnesses that might be environmentally related are listed in Table 37 (National Center for Health Statistics 1981). While the mortality levels appear high,

they are not significantly different from statewide mortality rates for the same diseases when the basin's population is taken into account.

The basin contains 455 km (283 mi) of streams monitored for water quality; 340 km (211 mi), or 74.8 percent, are classified as fishable and swimmable (Texas Department of Water Resources 1983a). About 115 km (71.4 mi) of the streams have occasional to frequent high concentrations of fecal coliform bacteria or high levels of nickel, mercury, lead, arsenic, manganese, silver, zinc, cadmium, copper, oil and grease, Dieldrin, Aldrin, or toxaphene in their sediment or waters (Texas Department of Water Resources 1983a). Some of the problem areas are Cedar Bayou, the Houston Ship Channel from Morgan Point to the turning basin, Clear Creek, Dickinson Bayou, Bastrop Bayou, and Chocolate Bayou.

About 50 percent of the estuarine waters in Galveston Bay are closed to shellfishing because of public health problems (Texas Department of Health 1983). Restricted areas include: Bastrop Bayou; Chocolate Bay; the intracoastal waterway; all of West Bay and lower Galveston Bay in the vicinity of the city of Galveston and Texas City; the western shoreline of lower and upper Galveston Bay as well as all secondary and tertiary bays located along the western shore; all of the shoreline and the upper two-thirds of Trinity Bay; and East Bay from Marsh Point eastward. The areas remaining open are most of West Bay and the portions of lower Trinity, lower Galveston Bay, and western East Bay that contain commercial reefs. Hofstetter (1977) compared areas open to oyster harvest in 1951, 1955, and 1972 by map. Comparing these areas with the 1983 map, it is apparent that a large portion of the bay remains closed to shellfish harvest. However, the closed area is not much different from the area closed

in 1951 and subsequent years. Deteriorating conditions do not appear to have spread.

The quantity of materials added to the atmosphere in the Galveston basin is large; in 1973 the load of airborne particulates was 74,646 metric tons and the quantity of airborne hydrocarbons was 585,278 metric tons (Texas Air Control Board 1977). At the time these measurements were made, 42 percent of the hydrocarbons came from chemical industries, 20 percent from transportation, 19 percent from storage and loading facilities, 14 percent from the petroleum industry, and the rest from miscellaneous sources (Texas Air Control Board 1976).

Permits have been issued for 624 waste discharges into basin waters. The number of permitted municipal waste discharges is 420, two-thirds of all the permitted waste facilities (Texas Department of Water Resources 1984). Five-day BOD measurements of the oxygen consumed to process the added organic waste total 9,992,602 kg per year. This amounts to more than 1600 kg per sq km per year. Stream and bay segments that have elevated nitrogen and phosphate levels include Trinity Bay, Cedar Bayou (tidal), Tabbs Bay, Black Duck Bay, San Jacinto Bay, Scott Bay, Burnet Bay, San Jacinto River (tidal), Clear Creek (tidal and above tidal), and Bastrop Bayou (tidal). The 41 km (25 mi) portion of the Houston Ship Channel from Morgan Point to the turning basin contains 447 waste discharges that contribute 82 percent of the basin's organic waste load measured as BOD (Texas Department of Water Resources 1984).

Subsidence, significant throughout the entire basin, is attributed mainly to groundwater withdrawl. The subsidence range is 0.2 to 2.6 m (0.5 to 8.5 ft), and about 90 percent of the basin's area has subsided at least 0.3 m (1 ft). Nearly 40 percent of the basin has subsided 0.6 m (2 ft), and about 10 percent has subsided 1.5 m (5 ft) (Ratzlaff 1982).

Total water use in the basin in 1974 was 1681 million cu m, 47 percent of which came from surface sources. Agriculture was the largest freshwater user, consuming 615 million cu m, or 37 percent of the basin's total; 68 percent of agricultural water came from surface sources. Manufacturing required the second highest volume, 579 million cu m, or 34 percent of the basin's freshwater. Forty-seven percent of the manufacturing water came from surface sources. About 26 percent of the water supply, 429 million cu m, went to municipal uses; only 21 percent of this water came from surface water sources. Return rates are high. Agriculture returned 41 percent of total water used in 1974. Manufacturing and municipal users returned nearly 72 percent of their total water use (Texas Water Development Board 1977).

The amount of hydrologic change on the land surface and in the estuaries is high in the Galveston basin. There are 11,802 km (7333 mi) of roads and railroads that may obstruct surface flow (Liebow et al. 1980). On an areal basis this is 190 km of roads and railroads for every 100 km of uplands. The basin also has 1718 km of drainage and irrigation ditches, or 27 km per 100 sq km of upland. There are 311 km (193 mi) of dredged channel in the basin, or 16 km of dredged channel for every 100 sq km of estuarine area. Historical maintenance dredging has amounted to 6,977,035 cu m per year; 3812 cu m of maintenance material must be removed for each km of channel.

COMPARISON OF THE BASINS

Natural Systems

The dominant difference among the basins in the Texas Barrier Island Region is climate. The average temperature of the southernmost basin, the Rio Grande basin, is 3 to 4 deg C warmer than the average for the Galveston basin, the northernmost basin. The average rainfall of the Rio Grande basin is 60 cm less than that of the Galveston basin, or about half the Galveston basin's total; rainfall minus potential evapotranspiration produces a deficit of 71 cm of precipitation in the southernmost basin but an excess of 20 cm in the northernmost basin. In short, the southern basins are hotter and drier than the northern basins. The differences are the result of a climatic gradient related to latitude.

The differences in rainfall affect the flow of streams and the inflow of water to the estuaries in the basins. Low freshwater inflows in the southern basins result in high average salinity levels in the bays. Higher freshwater inflows produce lower average salinty levels in basins of the upper coast.

The habitats in the basins reflect these climatic differences. The southernmost basins contain vast areas of brush-covered land used for low-density cattle grazing, and much of the cropland is irrigated. Basins of the central and upper coast are characterized by grasslands that are now extensively cultivated. The amount of forest and swamp increases northward in response to the increasing availability of water. The Rio Grande basin contains no swamp or forest, whereas these habitats occupy 9.5 percent of the Galveston basin.

Variations in estuarine habitats are also a function of water flow. Broad areas of wind-tidal flat are found in the southernmost basins. In basins to

the north, wind-tidal flats are narrow with salt and brackish marshes on their bay sides. Large salt and brackish marshes occur along the bays of the northernmost basins. Large grassflats are found in the southern basins of the region; the largest expanse is in the Laguna Madre. The northern basins contain only small, scattered grassflats.

Economic System

Population. In 1977 the Galveston basin had the largest population of any basin. It was followed by the Laguna Madre, Corpus Christi, and Brazos basins; the Colorado basin had the smallest population. The population density of the Galveston basin was also the highest (157 persons per sq km), and was followed by the Corpus Christi basin (100 persons per sq km) and the Rio Grande basin (63 persons per sq km). The Aransas-Copano basin (13 persons per sq km) and the Matagorda and Colorado basins (12 persons per sq km) were the least densely populated (Table 38).

Growth projections indicate that the Brazos basin population will increase by 64 percent by the year 2000. The Rio Grande basin population should increase by 54 percent, the Brazos-Colorado basin by 43 percent, the Galveston basin by 39 percent, and the Colorado basin by 37 percent. The Aransas-Copano basin is expected to have the smallest increase in the next 20 years, 15 percent. Although the Galveston basin will not increase at the greatest rate, the number of additional persons will be more than 400,000, an increment larger than the total 1980 populations of any of the other basins. The projected increases in the Brazos, Brazos-Colorado, and Colorado basins are undoubtedly related to the tremendous growth of the Galveston basin.

Table 38. Comparative economic measurements for basins.

Economic measure	Rio Grande	Laguna Madre	Corpus Christi	Aransas-Copano	San Antonio
1977 population per sq km upland	63	31	100	13	18
Projected % population increase 1980-2000	46	32	19	15	24
Mineral value ($) per person	48	1967	886	8955	3753
Mineral value ($1000) per sq km basin	1	36	59	89	38
Deer harvested per 100 sq km upland	5	19	18	54	72
Travel expenditure ($1000) per sq km upland	32	14	52	8	9
Travel-related jobs per 1000 employed	50	43	44	71	47
Sportfish. expend. ($1000) per sq km estuary	0	3	18	(combined with Corpus Christi)	4
Commer. fish expend. ($1000) per sq km (estuary + gulf)	0	< 1	14	(combined with Corpus Christi)	20
Watts generating capacity per person	1794	2978	5351	0	66756
% employed	35	38	42	32	45
Building permits per 100 sq km upland	39	19	214	11	22
Km railroad per 100 sq km upland	6	3	7	4	4
Km highway per 100 sq km upland	150	80	189	76	79
Vehicles registered per km highway	32	32	50	16	25
Commod. flow (metric ton) per person	81	2	348	2	100
Commod. flow (metric ton) per km dredged channel	105850	1567	467550	1082	28716
Market value ($1000) per sq km (cropland + range)	26	12	28	10	7
Market value ($) per person	340	372	247	733	360

Table 38 (continued). Comparative economic measurements for basins.

Economic measure	Matagorda	Colorado	Brazos-Colorado	Brazos	Galveston
1977 population per sq km upland	12	12	22	39	157
Projected % population increase 1980-2000	22	37	43	64	39
Mineral value ($) per person	4582	4268	4391	3412	971
Mineral value ($1000) per sq km basin	39	34	57	93	87
Deer harvested per 100 sq km upland	41	20	24	30	17
Travel expenditure ($1000) per sq km upland	3	2	9	30	96
Travel-related jobs per 1000 employed	23	19	25	38	44
Sportfish. expend. ($1000) per sq km estuary	5	0	0	0	2
Commer. fish expend. ($1000) per sq km (estuary + gulf)	12	0	0	0	13
Watts generating capacity per person	31716	0	2190	9059	4119
% employed	46	46	42	39	50
Building permits per 100 sq km upland	10	41	30	58	194
Km railroad per 100 sq km upland	5	6	7	9	12
Km highway per 100 sq km upland	80	86	88	108	177
Vehicles registered per km highway	17	15	28	39	90
Commod. flow (metric ton) per person	62	22	7	203	141
Commod. flow (metric ton) per km dredged channel	25864	9758	4641	356589	442118
Market value ($1000) per sq km (cropland + range)	17	25	17	13	12
Market value ($) per person	1131	1692	617	250	54

Mineral production. The value of mineral production in 1977 was highest in the Galveston basin ($946 million) and lowest in the Rio Grande basin ($1.3 million). On a per capita basis, however, mineral value was highest in the Aransas-Copano basin ($8955 per person), followed by Matagorda ($4582 per person), Brazos-Colorado ($4391 per person), and Colorado ($4268 per person). The per-capita value is low in the Galveston, Corpus Christi, and Rio Grande basins. While mineral production is significant in almost every basin, its importance to the economies of the Aransas-Copano, Matagorda, Brazos-Colorado, and Colorado basins, is much higher than for the Galveston, Corpus Christi, and Rio Grande basins (Table 38).

Recreation and tourism. In 1978, travel expenditures and travel-related employment were highest in the Galveston basin and lowest in the Colorado basin. Travel expenditures per sq km of upland indicate the relative amount of spending for travel without regard to basin area (Table 38). Travel expenditures were highest in the Galveston basin ($96 thousand per sq km) followed by Corpus Christi ($52 thousand per sq km), Rio Grande ($32 thousand per sq km), and Brazos ($30 thousand per sq km). Travel-related employment was highest in the Aransas-Copano basin (71 jobs per thousand employed), followed by Rio Grande (50 jobs per thousand employed), San Antonio (47 jobs per thousand employed), and Galveston and Corpus Christi (44 jobs per thousand employed).

Overall, recreation and tourism occurred at a significant level in the Galveston, Corpus Christi, and Rio Grande basins where travel expenditures were high and travel-related employment was relatively high. Recreation and tourism was also important to the Aransas-Copano basin where travel-related employment was high, and sport fishing and hunting activities were significant.

Commercial fishing. The direct commercial value of fishery products for 1976 was highest in the Galveston basin and lowest in the Laguna Madre basin (there was no data for four basins). When direct commercial value is adjusted for the different areas of bay and gulf in each basin, commercial harvest does not differ much (Table 38). On this areal basis, the annual direct commercial value of fishery products per sq km of estuary and gulf is about one quarter the annual value of minerals per sq km of basin.

Residential and industrial development. The number of building permits in 1977--a measure of residential development--was higher in Galveston than in any other basin, 12,045. When put on an equal upland area basis (Table 38), Corpus Christi lead the region with 214 permits per 100 sq km, followed by Galveston with 194 permits per 100 sq km. Other basins had far fewer permits per area, and the Matagorda basin had the fewest (10 permits per 100 sq km).

With the greatest number of jobs, highest proportion employed, second highest number of building permits per upland area, and the largest number of building permits, the Galveston basin had the highest level of industrial and residential development in the region. The Corpus Christi basin had the second highest population density but only a moderate projected population growth. It is therefore surprising that the number of building permits issued in the basin is so high. The Brazos basin, which is anticipating twice the number of new residents in the next 20 years as Corpus Christi, had 200 fewer building permits in 1977 and a much lower number of permits per 100 sq km of uplands.

Transportation. In 1976, the Galveston basin had the greatest length of railroad track (787 km) while the Rio Grande basin (26 km) had the least. The density of track (Table 38) is a measure of the importance of commercial transportation and probably the degree of industrial development in a basin. The Galveston basin had the highest density (12 km of track per 100 sq km), followed by the Brazos basin (9 km of track per 100 sq km), and the Brazos-Colorado and Corpus Christi basins (7 km per 100 sq km). The Galveston, Brazos, and Corpus Christi basins all have significant industrial development and shipping. The railroad track density in the Brazos-Colorado basin is moderately high since it is a junction point for several different railroad lines at Bay City.

In 1976 the Galveston basin had the greatest highway length (11,015 km) while the Rio Grande basin had the smallest (621 km). However, the Corpus Christi basin had the highest density of roads (189 km per 100 sq km) followed by the Galveston basin (177 km per 100 sq km), the Rio Grande basin (150 km per 100 sq km), and the Brazos basin (108 km per sq km). The lowest densities were in the range of 76 to 80 km per 100 sq km and were shared by the Laguna Madre, Aransas-Copano, San Antonio, and Matagorda basins.

The Galveston basin had more than 90 vehicles registered per km of road; the Corpus Christi basin had 50 vehicles registered per km and the Brazos basin 39 vehicles per km. Other basins had lower vehicular densities; the Aransas-Copano, Matagorda, and Colorado basins had the lowest vehicular densities, 15 to 17 vehicles per km.

The Galveston basin led the region in tonnage of commodities transported through the waterways, 137 million metric tons in 1977. All other basins were far behind the Galveston basin in total tonnage. Commodity flows on a per-

capita basis indicate the relative economic importance of waterborne transportation and port development to a basin. The economy of the Corpus Christi basin had the highest benefit from shipping (348 metric tons per person); it was followed by Brazos (203 metric tons per person), Galveston (141 metric tons per person), San Antonio (100 metric tons per person).

On the basis of the commodity flows per km of channel, Corpus Christi waterways are the busiest (467,550 metric tons per km), followed by Galveston (442,118 metric tons per km), Brazos (356,589 metric tons per km), and Rio Grande (105,850 metric tons per km).

The transportation segment of the economy operates at high levels in the Galveston, Corpus Christi, and Brazos basins; all have high or moderately high road network densities, high traffic density, high flows of commodities per person, and heavy use of their navigation channels. Transportation is significant in the Rio Grande basin although traffic density on roads and commodity flows per person are a little lower than in the other three basins mentioned.

Agriculture. The market value of agricultural production in 1974 was highest in Laguna Madre ($122 million) but significantly less in other basins. Per-capita market value illustrates the relative strength of agricultural production to the basin's economy. The Colorado basin had the highest value ($1692 per person), followed by Matagorda ($1131 per person), Aransas-Copano ($733 per person), and Brazos-Colorado ($617 per person). The value was low in the Brazos ($250 per person), Corpus Christi ($247 per person), and Galveston ($54 per person) basins. Although these basins had significant total market

values for agricultural production, the population was supported to a greater extent by economic activities other than agriculture.

Resource Demands

Demand for space. Estimates of space used as cropland from the 1950's and 1960's showed that the greatest demand for cropland was in the Laguna Madre (2874 sq km) and Galveston (2861 sq km) basins, with Matagorda (1486 sq km) and Nueces (958 sq km) in succeeding order. Total cropland measurements from 1978 (Bureau of the Census 1980) showed a change in the distribution of the demand for cropland space: the Laguna Madre basin still had the most cropland (2996 sq km); but it was followed by the Matagorda (1876 sq km), Aransas-Copano (1619 sq km), and Galveston (1599 sq km) basins. Requirements for urban space were greatest in Galveston (710 sq km), Laguna Madre (314 sq km), Corpus Christi (118 sq km), and Aransas-Copano (100 sq km) basins, and lowest in the Colorado basin (17 sq km).

Comparing upland land uses as percent of total upland removes the bias of different basin sizes (Table 39). On this basis the greatest demand for cropland in the 1950's and 1960's was in the Nueces basin (65 percent), followed by the Rio Grande (54 percent), Galveston (46 percent), and Brazos (44 percent) basins. Percentages for 1978 show that the greatest demand occurred in the Corpus Christi (73 percent), Colorado (51 percent), Rio Grande (43 percent), Aransas-Copano (43 percent), and Matagorda (40 percent) basins.

In the interval between these measurements, cropland area increased in the Colorado (20 percent), Aransas-Copano (19 percent), Matagorda (9 percent), Corpus Christi (8 percent), and San Antonio (8 percent) basins. Cropland declined in the Galveston (20 percent), Brazos (11 percent), and Rio Grande (11 percent) basins. The greatest demand for urban space was in the Galveston

Table 39. Comparative resource demand measurements for basins.

Resource demand	Rio Grande	Laguna Madre	Corpus Christi	Aransas-Copano	San Antonio
% Upland that is cropland in 1956-1957 *	54	28	65	22	24
% Upland that is cropland in 1978 **	43	30	73	43 ***	32
% Change in cropland area	- 11	+ 2	+ 8	+ 19	+ 8
% Upland that is range in 1956-1957 *	26	63	20	66	61
% Upland that is range in 1978 **	18	59	25	61 ***	59
% Change in range area	- 8	- 4	+ 5	- 5	- 2
% Upland that is urban in 1956-1957 *	5	3	8	2	1
Liters of crude oil per sq km basin	177	57319	182765	1042866	363364
Thousand cu m of gas per sq km basin	43	923	1121	810	429
Cumulative million liters crude per sq km basin	1	9	52	36	34
Kiloliters of grain per sq km of cropland	448	276	255	205	234
Bales of cotton per sq km of cropland	105	81	55	35	2
Metric tons of rice per sq km of cropland	0	0	0	0	30
Cattle and calves sold per sq km of range	87	18	48	21	20
Kg bay shrimp per sq km estuary	0	0	1570	1723	1559
Kg bay crab per sq km estuary	0	194	134	1601	2136
Kg total commer. shellfish per sq km estuary + gulf	0	64	10619	(combined with Corpus Christi)	6418

Table 39 (continued). Comparative resource demand measurements for basins.

Resource demand	Matagorda	Colorado	Brazos-Colorado	Brazos	Galveston
% Upland that is cropland 1956-1957 *	31	31	32	44	46
% Upland that is cropland 1978 **	40	51	37	33	26
% Change in cropland area	+ 9	+ 20	+ 5	- 11	- 20
% Upland that is range 1956-1957 *	51	48	44	30	23
% Upland that is range 1978 **	45	35	37	35	31
% Change in range area	- 6	- 13	- 7	+ 5	+ 8
% Upland that is urban in 1956-1957 *	1	1	1	2	11
Liters of crude oil per sq km basin	294262	115096	340415	765336	603155
Thousand cu m of gas per sq km basin	533	634	787	871	1132
Cumulative million liters crude per sq km basin	20	7	13	36	56
Kiloliters of grain per sq km of cropland	209	164	105	113	64
Bales of cotton per sq km of cropland	7	15	14	34	4
Metric tons of rice per sq km of cropland	101	120	121	95	131
Cattle and calves sold per sq km of range	27	31	29	31	29
Kg bay shrimp per sq km estuary	1741	0	0	0	939
Kg bay crab per sq km estuary	208	0	0	0	432
Kg total commer. shellfish per sq km estuary + gulf	3836	0	0	0	4132

Table 39 (continued). Comparative resource demand measurements for basins.

Resource demand	Rio Grande	Laguna Madre	Corpus Christi	Aransas-Copano	San Antonio
% fishable and swimmable freshwater streams	80	0	100	100	91
Number of municipal discharges per 100 km of freshwater stream	2	19	2	8	2
Metric tons airborne partic. per sq km upland	5	5	16	2	2
Metric tons hydrocarbons per sq km upland	4	5	58	3	13
Kg 5-day BOD per sq km upland	231	71	1094	25	162
Cumulative metric tons of industrial solid waste per sq km upland	0	107	885	13	73
1000 cu m total water used per sq km upland	926	133	502	10	98
% surface water of total water used	73	97	24	50	50
% total water used for agriculture	80	93	78	19	26
% total agricultural water returned	11	0	2	12	5
Km of road and railroad per 100 sq km upland	156	84	196	81	84
Km of ditches and canals per 100 sq km upland	18	16	25	< 1	13
Cu m spoil per sq km estuary	8456	918	2235	424	1887
Km channel per 100 sq km estuary	21	18	31	15	16

Table 39 (continued). Comparative resource demand measurements for basins.

Resource demand	Matagorda	Colorado	Brazos-Colorado	Brazos	Galveston
% fishable and swimmable freshwater streams	100	100	100	95	75
Number of municipal discharges per 100 km of freshwater stream	2	4	4	20	131
Metric tons airborne partic. per sq km upland	2	1	2	2	12
Metric tons hydrocarbons per sq km upland	13	1	3	11	94
Kg 5-day BOD per sq km upland	43	6	679	786	1613
Cumulative metric tons of industrial solid waste per sq km upland	115	136	308	305	5203
1000 cu m total water used per sq km upland	169	262	142	193	270
% surface water of total water used	38	69	68	83	47
% total water used for agriculture	92	43	87	18	37
% total agricultural water returned	36	21	38	37	41
Km of road and railroad per 100 sq km upland	86	93	95	118	190
Km of ditches and canals per 100 sq km upland	4	8	11	10	27
Cu m spoil per sq km estuary	2264	2692	1349	6364	3812
Km channel per 100 sq km estuary	12	17	23	62	16

* From Fisher et al. (1972; 1973), McGowen et al. (1976a, 1976b), Brown et al. (1976, 1977, 1980).

** From Bureau of the Census 1980.

basin (11 percent), followed by Corpus Christi (8 percent) and Rio Grande (5 percent). Certainly the recent rapid population growth in the latter three basins is partially responsible for the decrease in cropland areas. Table 39, shows that large increases in cropland are often accompanied by decreases in range; undoubtedly some range is now being cultivated. The reasons for this shift in land uses are not clear, however.

Demand for petroleum. The Galveston basin led all others in total crude oil production in 1978 (6.6 million kiloliters). Production in the Aransas-Copano basin was also high (5.2 million kiloliters). In natural and casinghead gas production the Laguna Madre basin was the leader (15,667 million cu m) with Galveston (12,263 million cu m) not far behind. Galveston (614 million kiloliters) led all basins in the cumulative production of crude oil since exploration began. The Rio Grande basin was the lowest producer in all categories.

Adjusting oil and gas production figures by the total basin area provides a production rate statistic for comparing basins (Table 39). The highest production rate occurred in the Aransas-Copano basin (1 million liters per sq km), followed by the Brazos basin (765 thousand liters per sq km), the Galveston basin (603 thousand liters per sq km), the San Antonio basin (363 thousand liters per sq km), and the Brazos-Colorado basin (340 thousand liters per sq km). For casinghead and natural gas, the Galveston basin had the highest production rate (1132 thousand cu m per sq km), followed by the Corpus Christi (1121 thousand cu m per sq km), Laguna Madre (923 thousand cu m per sq km), Brazos (871 thousand cu m per sq km), and Brazos-Colorado (787 thousand cu m per sq km) basins. The Galveston basin also had the highest cumulative crude

oil production (56 million liters per sq km) with Corpus Christi (52 million liters per sq km), Aransas-Copano and Brazos (36 million liters per sq km), and San Antonio (34 million liters per sq km) following. Rio Grande had the lowest production rate for all indicators.

In terms of short- and long-term demand for oil and gas, the Galveston, Aransas-Copano, and Brazos basins are currently high producers of crude oil and gas, and have been high producers of crude oil for a long period. The Corpus Christi basin is currently a high natural gas producer and has produced a high volume of crude oil in the past. The San Antonio and Brazos-Colorado basins have moderate production of crude oil. The San Antonio basin has produced a high cumulative volume of crude oil, and the Brazos-Colorado basin is presently a moderately high gas producer.

Demand for biomass. The Laguna Madre basin had the highest grain production (826,000 kiloliters) in 1978; the Rio Grande basin had the lowest (49,000 kiloliters). Cotton production was also dominated by the Laguna Madre basin (241,926 bales), while the lowest production was in the San Antonio basin (1024 bales).

Rice is produced only as far south as the San Antonio basin; in 1978 the leading rice producers were the Galveston basin (209 thousand metric tons) and the Matagorda basin (190 thousand metric tons) basins. The Laguna Madre basin had the largest number of livestock sales (107,196) while the Rio Grande basin had the smallest (6521).

Production rates for agricultural biomass are calculated by dividing production by cropland area. Basins with high production rates for grain are the Rio Grande (448 kiloliters per sq km), Laguna Madre (276 kiloliters per sq km), and Corpus Christi (255 kiloliters per sq km) basins. Basins with high

cotton production rates include the Rio Grande (105 bales per sq km), the Laguna Madre (81 bales per sq km), and the Corpus Christi (55 bales per sq km) basins.

The highest rice production rate is found in the Galveston basin (131 metric tons per sq km), followed by the Colorado basin (121 metric tons per sq km), and the Brazos-Colorado basin (120 metric tons per sq km). The cattle production rate is highest in the Rio Grande basin (87 cattle and calves sold per sq km) and the Corpus Christi basin (48 cattle and calves sold per sq km); this is probably related to feedlot operations in these basins. The five northernmost basins all have similar but lower production rates (27 to 31 cattle and calves sold per sq km).

As measured by the production of grain, cotton, rice, and livestock, the demand placed upon cropland and range in the Texas Barrier Island Region is highest in the Rio Grande and Corpus Christi basins which produce the greatest amounts of agricultural biomass per unit area; agricultural demand on Colorado basin lands is slightly less. Basins with moderate production rates include Laguna Madre, Brazos-Colorado, Brazos, and Matagorda. The Galveston, Aransas-Copano, and San Antonio basins have lower production rates.

Fishery biomass is harvested in most but not all basins. In 1977, the greatest catches for bay shrimp were from the Matagorda (2 million kg), Galveston (1.7 million kg), and Aransas-Copano (1 million kg) basins. Bay crab catch was highest in the San Antonio basin (1 million kg), followed by the Aransas-Copano (975 thousand kg) and Galveston (792 thousand kg) basins. Total commercial shellfish catch (bay and gulf) was highest in the Galveston basin

(18.5 million kg); the Matagorda basin (7.2 million kg) had the second highest yield.

Comparative harvest rates or demand are derived by adjusting catch statistics for estuarine and gulf areas (Table 39). The highest harvest rate for bay shrimp occurred in the Matagorda basin (1741 kg per sq km), followed by the Aransas-Copano (1723 kg per sq km), Corpus Christi (1570 kg per sq km), San Antonio (1559 kg per sq km), and Galveston (939 kg per sq km) basins. The highest bay crab harvest rates were in the San Antonio (2136 kg per sq km) and Aransas-Copano (1601 kg per sq km) basins. Bay shrimp harvest is surprisingly constant except for the Galveston basin; perhaps the large proportion of Galveston Bay that is restricted to shellfishing biases these harvest figures.

Total shellfish harvest rates from gulf and bay waters did not vary greatly except in the Laguna Madre. Basin figures were: San Antonio, 8748 kg per sq km; Aransas-Copano and Corpus Christi, 10,619 kg per sq km (catch statistics combined); Galveston, 4757 kg per sq km; Matagorda, 4148 kg per sq km; and Laguna Madre, 386 kg per sq km. Exploitable shrimp populations in the Laguna Madre basin are restricted to the lower portion of the lagoon; shrimp are largely absent from Baffin Bay (Breuer 1957) and their presence in the upper Laguna Madre is variable (Simmons 1957).

These comparative measures indicate that the intensity of fishery harvest is highest in the San Antonio basin and only slightly lower in the Corpus Christi and Aransas-Copano basins. The harvest rate for the Galveston basin is a lower yet but slightly ahead of the Matagorda basin. The Laguna Madre basin has a much lower harvest rate for fishery biomass.

Since airborne particulates and hydrocarbons are largely produced by land use practices and other activities on the uplands, waste loads were adjusted for the upland areas of each basin (Table 39). On this basis the Galveston and Corpus Christi basins have the highest rates of production of airborne particulates and hydrocarbons. High levels of hydrocarbons are certainly related to the high density of refineries, petrochemical plants, petroleum storage facilities, and the transportation network in these two basins. The cause of high particulate levels is less obvious, although the high proportion of cropland in the Corpus Christi basin may result in high airborne particulate concentrations from wind-blown sediment.

On an annual basis the BOD load for the entire region (as measured by the 5-day BOD test) requires nearly 16 million kg of oxygen to oxidize the organic matter which is added to the region's waters. The Galveston basin contributes 69 percent of this total load, the largest proportion. Other basins with relatively high annual BOD loads are Corpus Christi (10 percent), Brazos-Colorado (9 percent), and Brazos (9 percent).

The Galveston and Corpus Christi basins have the highest rate of production of BOD adjusted for upland area. There is a statistically significant correlation ($R = 0.88$, $P < 0.01$) between the population density of a basin and the BOD production rate--the oxygen needed to oxidize the organic waste load. Since the population density of the Galveston basin is expected to increase by 39 percent over the period 1980 to 2000, a waste load increase of about the same magnitude should be expected.

Nearly 37 million metric tons of industrial solid wastes have been disposed of in the region's uplands. About 88 percent of this total has been

disposed in the Galveston basin; less than 4 percent has been disposed in the Corpus Christi basin, which has the second highest solid waste amount. On an areal basis, 5203 metric tons of industrial solid waste per sq km have been disposed on Galveston basin lands; this is a much higher disposal volume than for any other basin.

Demand for fresh water. The Galveston basin consumes the greatest quantity of freshwater, 1681 million cu m per year. The Laguna Madre basin consumes the second highest amount, 1354 million cu m per year; freshwater requirements for other basins range as low as 43 million cu m per year (Aransas-Copano basin). Basins that contained or were adjacent to major river systems used more surface water than basins with only small rivers flowing through them or basins with high water demands because of large urban areas. Rio Grande and Laguna Madre basin surface water use in 1974 was 73 and 93 percent respectively, almost entirely from the Rio Grande River (Table 39). Colorado, Brazos-Colorado, and Brazos basin surface water use was 69, 68, and 83 percent respectively, from the Colorado and Brazos rivers.

The amount of water used per square km in 1974 correlates highly with the degree of agricultural demand from basin croplands. The Rio Grande and Corpus Christi basins had the greatest cropland demand; they also had the highest demand for water, 926 and 502 thousand cu m per square mile. The Colorado, Laguna Madre, Brazos-Colorado, Brazos, and Matagorda basins had lower demands for production as well as water use, 133 to 262 thousand cu m per sq km. The basins with the lowest overall agricultural demand--Aransas-Copano and San Antonio--had the lowest water demand per square km. The Galveston basin was the only exception; its water demand was 270 thousand cu m per year, with about equal requirements for agriculture, manufacturing, and municipalities.

Return flows from agriculture varied, ranging from 253 million cu m for the Galveston basin to none for the Laguna Madre. In general, basins further to the north tended to return more of their agricultural water than basins to the south.

Hydrologic alterations. Basins with the highest population densities--Galveston, Corpus Christi, and Rio Grande--have the highest road and railroad densities as well as the highest ditch and canal densities (Table 39) and consequently the greatest modification to upland water flow. The Aransas-Copano, San Antonio, Matagorda, and Colorado basins all have low population densities as well as low road, railroad, ditch, and canal densities.

Hydrologic alteration in the estuaries is the result of channel dredging and spoil placement, especially for continuing maintenance. Table 39 shows the density of channels in each basin. The Brazos basin has the highest channel density. It has a very small estuarine area; the high density is due to the intracoastal waterway and Freeport harbor. The Corpus Christi basin also has a relatively high channel density but is an open bay of moderate size with a relatively large amount of channel. The Matagorda basin has the lowest channel density. The Rio Grande basin produces the largest maintenance spoil volume per sq km of estuary; the Brazos basin also has a high volume of spoil per unit of estuary area. The Aransas-Copano basin has the lowest maintenance volume.

When both channel density and spoil volume are taken into account, the Brazos and Rio Grande basins have had the greatest estuarine hydrologic change, followed by the Corpus Christi basin. The Aransas-Copano basin has had the least. Channel length and spoil volume are only rough indicators of estuarine hydrologic change; proximity to gulf tidal influence, estuarine bathymetry, and channel alignment are just a few of the factors that need to be considered. Both estuarine and upland hydrologic change are difficult to evaluate without

involved analytical methods such as hydrologic models that integrate many factors.

HABITATS OF THE TEXAS BARRIER ISLAND REGION

INTRODUCTION

The chapter about the regional level of organization focused upon broad gradients parallel and perpendicular to the Texas coastline that have influenced the physical development, environmental conditions, and land uses in each basin. The chapter about the basin level of organization concentrated on the processes--largely hydrologic--that govern the operation of each basin and the arrangement of habitats within each basin. The purpose of this chapter is to describe the habitats in some detail: to discuss their chemical, physical, and biological characteristics and to briefly explain how they function.

Time Scale for Habitat Processes

The habitats of the Texas Barrier Island Region have attained their current composition and distribution since about 4500 yr BP, when the region's climate and shoreline location stabilized.

Climate is an important influence on habitat development. Worldwide temperature patterns stabilized around 10,000 yr BP; the yearly average since that time has remained within 2 deg C of the present average (Anthes et al. 1978). But temperature is not the only determinant of coastal climate. The climate of the Texas Barrier Island Region is governed by the interaction of gulf-influenced air from the southeast, and the passage of frontal systems primarily from the north and northwest (Bomar 1983). Because proximity to the gulf also affects climate--and consequently the biotic and hydrologic features distinguishing habitats--present habitat patterns must have taken shape after

the gulf shoreline reached its present position with the stabilization of sea level.

The time periods within which individual habitats have developed during the past 4500 years have varied. For example, Matagorda Peninsula, a barrier habitat, began to form 1800 years ago as the Brazos and Colorado rivers filled their common estuary (McGowen et al. 1976a); the buried portions of some oyster reefs may be as old. Other habitat types develop rapidly. Spoil habitat may reach its climax state, with vegetation typical of range or barrier habitat, in 2 to 30 years. Salt marshes have developed on spoil outwash in comparable time periods. Highly stressed habitats such as wind-tidal flat may develop within a year or less.

Thus an appropriate time scale for the consideration of processes giving rise to most natural habitats is decades to centuries. The forces that shape natural habitats and that allow them to develop and flourish act within these time spans. The time scale appropriate for consideration of some man-made habitats (urban and cropland for example) or of impacts that occur from human activities is much shorter.

Sources for Ecosystem and Habitat Definition

The 18 habitat units described in this chapter and the 26 ecosystem units selected for modeling were derived from several preceding studies that present varying concepts about the definition of distinct natural areas. After these studies were examined, three criteria were established for the selection of units to be used in this report. First, it was decided that both natural units and land-use units should be recognizable by an on-site observer; they should not be so numerous or so narrowly defined that only an expert could distinguish among them. Second, the units should be based upon system

operation; their functional identity should be emphasized. Finally, they should be units for which accurate linear and areal measurements are available.

Resource capability units. Brown et al. (1971) presented the concept of resource capability units, mappable land or water units with definite chemical, physical, and biological characteristics or processes that are defined in terms of the nature and degree of activity or use they can sustain without losing an acceptable degree of environmental quality.

They defined 34 resource capability units; most were easily recognizable, but a few were geologically defined and not immediately obvious. Some maps and general diagrams of resource capability units for the entire coast had been made, but coastwide area measurements were not provided.

Biotopes. Biotopes--habitat units defined as regions uniform in environmental conditions and plant and animal populations--were described by Oppenheimer and Gordon (1972) to augment land-use maps of the Texas coastal region.

Eighteen biotopes were described in all. They included some, but not all, upland types found in the coastal counties. Biotope units were readily identifiable, were of a manageable number, and generally included land uses. The definition of biotopes emphasized homogeneous conditions rather than system function, however; and neither maps nor measurements were available for the entire region.

Units defined by the Bureau of Economic Geology. The most useful source for this report was the series of environmental geologic atlases prepared by the Bureau of Economic Geology (BEG). The environmental geologic maps span

the entire Texas coastal region. Areas were mapped at a large scale (1:24,000) from aerial photography and published at a smaller scale (1:125,000). Eight derivative maps (1:250,000) depict related themes: physical properties; environments and biologic assemblages; current land use; mineral and energy resources; active processes; man-made features and water systems; rainfall, stream discharge, and surface salinity; and topography and bathymetry. Environmental geologic atlases containing maps and descriptive reports were published over an 8-year period (Fisher et al. 1972; Brown et al. 1976; McGowen et al. 1976a, 1976b; Brown et al. 1977, 1980).

This series presents the most detailed and comprehensive sets of land and water units available for the Texas coast. The units defined for some map themes, however, are difficult to recognize or interpret without considerable knowledge, however; this is especially true for the geologic maps. Other drawbacks to use of the BEG units for this report were that the environments and biologic assemblages maps contain 61 units, too many for this study; upland environments and biologic assemblages display potential natural vegetation rather than actual land-use units; and major land uses in the coastal environment such as urban areas and cropland are distinguished only on the current land use maps. But the BEG atlases provided information that helped meet the criteria established for habitat selection. The map units are based upon geologic processes, and this orientation is consistent with the goal of explaining how the systems operate. In addition, detailed length and area measurements are available for most of the BEG's map themes.

Coastal ecological systems. Odum and Copeland (1974) presented a functional classification of the coastal ecological systems of all states with

marine shorelines. Their classification scheme was largely based upon each ecosystem's characteristic energy source or stress.

Odum and Copeland defined 20 different units for the Texas coast, but confined their classification system to estuarine and nearshore marine environments; upland systems were not included. Most of the units are easy to recognize, although a few require hydrologic information or specific knowledge of the sources of effluents. The principal value of this classification to the development of units for this report was the emphasis on characteristic energy sources and system operation.

Composite resource areas. The Texas Coastal Management Program prepared a series of maps and descriptions of ecosystems as part of the coastal zone management program (Texas Coastal Management Program 1976). Conceptual ecosystem models were later constructed for some of the composite resource areas and were used as the basis for an environmental impact assessment procedure (Snyder et al. 1978; Brogden 1978; Snyder et al. 1978; Longley and Stubbs 1980).

The 18 composite resource areas include only water and intertidal areas. The units are generally recognizable, but a few cannot be distinguished without specific hydrologic information. They were useful to this report because they demonstrated how the BEG environments and biological assemblage units could be combined to produce a convenient number of units for conceptual models emphasizing system operation. Since the composite resource areas are based upon BEG mapped units, mapped areas and measurements can be derived.

Selection of Habitat Units

The ecosystem units selected for conceptual modeling in Appendix C evolved from these earlier works. In all, 26 ecosystems were defined and

modeled (Table 40). The BEG mapped units were most influential: the upland land-use categories in the BEG current land-use maps were useful in defining the upland ecosystems; the geologic process orientation was helpful in designing the models; and the maps and measurements proved to be the only detailed source of that type of information available. Resource capability units, coastal ecological systems, and composite resource areas all offered useful information about how systems functioned.

When maps were planned for this study, 26 units proved too many to be easily distinguished. In addition, some groups of ecosystems were always adjacent or were so similar that it was desirable to combine them. The biotope units defined by Oppenheimer and Gordon suggested ways to simplify the mapped areas so that easily recognizable units could be defined. The 26 ecosystems were ultimately grouped into 18 mapped habitats. Table 40 shows the relationships between the habitat units described in this section and the 26 ecosystems modeled in appendix C.

Habitat Locations and Area Measurements

Because the habitat units defined in this study did not exactly correspond to units in the BEG geologic atlas, mapped areas and areal or length measurements were taken from more than one map theme. Table 41 shows the correspondence between the BEG geologic atlas map themes and the habitats described here. In most instances mapping from these three sources produced no inconsistencies; in a few cases units overlapped and it was necessary to map one unit and subtract its area from an overlapping unit of another theme. The habitat maps are presented in Plates 1 through 10.

Table 40. Correspondence between habitats described in chapter 4 and ecosystems described in the appendices.

Habitats	Ecosystems
Barrier	Active Dune Beach Dune and Barrier Flat
Bay	Bay Bay Margin
Bulkhead and Jetty	Bulkhead and Jetty
Channel and Tidal Stream	Channel Tidal Stream Reach
Cropland	Cropland
Forest	Floodplain Forest Forest
Freshwater Marsh	Freshwater Marsh
Gulf	Nearshore Gulf Upper Shoreface
Lake and Reservoir	Lake and Reservoir
Range	Brush Coastal Prairie
Reef and Reef Flank	Reef and Reef Flank
River and Canal	River and Canal
Salt and Brackish Marsh	Brackish Marsh Salt Marsh
Seagrass	Seagrass
Spoil	Spoil
Swamp	Swamp
Urban	Urban
Wind-Tidal Flat	Wind-Tidal Flat

Table 41. Correspondence between habitat units in chapter 4 and map units and areas from the BEG geologic atlas (Fisher et al. 1972; Brown et al. 1976; McGowen et al. 1976a, 1976b; Brown et al. 1977, 1980).

Habitat unit	BEG geologic atlas map and unit name
Barrier	Vegetated barrier flat : E&BA map
	Beach: : E&BA map
	Barren land (partial) : E&BA map
Bay	Bay : CLU map
Bulkhead and Jetty	Jetty or pier : MMF&WS map
	Seawall : MMF&WS map
	Texas City Dike : CLU map
Channel and Tidal Stream	Dredged channels in bays, gulf, and mouths of tidal streams : CLU map
Cropland	Agriculture, cultivated land: CLU map
	Prison farms in Brazoria and Fort Bend counties : CLU map
Forest	Woodland-timber : CLU map
	Includes oak mottes from Corpus Christi Bay north; oak mottes south of Corpus Christi Bay are range : E&BA map
Freshwater Marsh	Freshwater marsh : CLU map
Grassflat	Grassflats : E&BA map
Gulf	All gulf waters to 3 leagues except channels : CLU map
Lake and Reservoir	Lake or pond, natural, with minimum modification : MMF&WS map
	Lake or pond, natural, some areas artificially drained, ephemeral : MMF&WS map
	Artificial reservoir, etc. : MMF&WS map
	Slough or abandoned course : MMF&WS map

Table 41 (continued). Correspondence between habitat units in chapter 4 and map units and areas from the BEG geologic atlas (Fisher et al. 1972; Brown et al. 1976; McGowen et al. 1976a, 1976b; Brown et al. 1977, 1980).

Habitat unit	BEG geologic atlas map and unit name	
Range	Range-pasture	: CLU map
	• Exclude area at edge of Laguna Madre that is wind-tidal flat on MMF&WS map	
	Wildlife refuge land divided between marsh and range	: E&BA map
	Government land (blimp hanger) west of I-35 near Texas City	: CLU map
	One-mile-square land parcel north of the Blue Ridge State Prison Farm	: CLU map
	Live-oak mottes south of Corpus Christi Bay	: E&BA map
Reef and Reef Flank	Reef	: E&BA map
	Reef flank	: E&BA map
River and Canal	River or stream, natural drainage	: MMF&WS map
	Drainage or irrigation ditch or canal	: MMF&WS map
	Principal rivers and streams	: MMF&WS map
Salt and Brackish Marsh	Saline and brackish-water marsh	: CLU map
Spoil	Subaerial spoil	: CLU map
Swamp	Swamp-timber	: CLU map
Urban	Residential-urban	: CLU map
	Industrial-heavy industrial	: CLU map
	Undifferentiated urban land	: CLU map
	Park and recreational land	: CLU map
	Made land	: CLU map
	Government land other than range	: CLU map

Table 41 (continued). Correspondence between habitat units in chapter 4 and map units and areas from the BEG geologic atlas (Fisher et al. 1972; Brown et al. 1976; McGowen et al. 1976a, 1976b; Brown et al. 1977, 1980).

Habitat unit	BEG geologic atlas map and unit name	
Wind-Tidal Flat	Wind-tidal flats Delineated first since some range on CLU map overlaps	: MMF&WS map

CLU : Current Land Use maps from BEG geologic atlas

E&BA : Environments and Biologic Assemblages from BEG geologic atlas

MMF&WS : Man-made Features and Water Systems from BEG geologic atlas

Areal and length measurements of the habitat units for the descriptions in this chapter were cimpiled by county. In a few instances it was necessary to estimate or take measurements from the BEG geologic maps themselves to correct the areal or length totals in the BEG geologic atlas.

Since the areas and lengths of habitats were needed in the preceding chapter on basins, measurements were compiled by basin. Basin boundaries were defined and proportional areas measured for counties through which basin boundaries passed. Areas were measured separately for land, estuarine, and marine waters for each county. For example, after the boundary separating the San Antonio and Copano-Aransas basins was defined, 12 percent of the area of Refugio County (covered by the BEG geologic atlas maps and measurements) was land in the San Antonio Basin; 84 percent of the county area was land in the Copano-Aransas Basin; and 4 percent of the county area was estuarine water in the Copano-Aransas Basin. In compiling the basin total for the Copano-Aransas basin, the area of each upland unit in Refugio County was multiplied by 0.84 to give its proportionate amount to the total. Upland habitats in Goliad, Refugio, Bee, Aransas, and San Patricio counties contributed to the Copano-Aransas Basin upland total. The same calculations were made for estuarine and marine water areas. Habitat totals were determined by summing the basin totals.

Habitat Distribution in Basins

With a few exceptions, each basin contains some area of every natural habitat described. The exceptions--the absence of forest and swamp in the most southern basins--are the result of a broad environmental gradient of climate, especially rainfall. Forests and swamps require high rainfall or occasional inundation by fresh water from river flooding. The southern coast

has a hotter, drier climate and less river flow than the more northern basins. These climatic conditions, which have existed for at least the past several hundred years, have prevented the development of forest and swamp habitats in the southern basins.

Section Organization

Each habitat description is divided into seven sections: areal or linear extent, physical description, system operation, flora and fauna, adjacent systems and flows, economic uses, and impact of man's activities.

Areal or linear extent. The total area of habitat in the entire region is given and a comparison of the relative extent of the habitat in each basin is discussed. For the river and canal habitat and the channel and tidal stream habitats, only linear measurements were available.

Physical description. The physical description covers such topics as habitat shape, orientation and distribution, and levels of environmental parameters typical of the habitat.

System operation. The driving forces that control the habitat are identified and discussed. Important system components such as biota, sediment characteristics, and energy processes are identified, and relationships among the components that cause the system to operate in a characteristic fashion are described.

Flora and fauna. Producers and consumers that are typically found in the habitat are listed.

Adjacent systems and flows. Statistics on the frequency with which other habitat units are found adjacent to any given habitat unit were derived by randomly placing a straightedge ruler across basin maps of habitats and

recording adjacency for all habitats along the ruler edge within the basin boundary. Twenty samples for each basin proved enough to provide a reliable trend. Sample sizes were not large enough to give estimates of the percent of contact between habitats, but were sufficient to indicate what habitat units were adjacent most frequently. Material, energy, and biota imports and exports for each habitat are discussed in relation to the most commonly adjacent habitats. Some habitats are adjacent to others very infrequently. Rather than speculate, only the most frequently adjacent habitats are discussed. Consequently, adding the adjacent habitat proportions sometimes produces a total less than 100 percent.

Economic uses. Economic uses of the habitat are discussed if they occur. Where available, economic values of the uses are presented.

Impacts of man's activities. The impacts of direct and indirect use of the habitat by man are outlined. In some instances, methods used to mitigate adverse impacts are discussed.

HABITAT DESCRIPTIONS

Barrier Habitat

Areal extent. The barrier habitat comprises three distinct ecosystems: the gulf beach, an area of active dunes, and a wide region of stabilized dunes and barrier flat. These systems have been modeled separately (see appendix) but can be considered as one habitat unit because they always occur together. The barrier habitat includes most of the area of the barrier islands, the peninsulas (Bolivar and Matagorda), and a small portion of gulf beach near Freeport (the Brazos basin) where there are no true barrier islands or peninsulas. Barrier habitat occupies 449.2 sq mi, or 2.2 percent, of the

region. The Laguna Madre basin contains the largest amount of barrier habitat, 187.6 sq mi; the Brazos basin has the smallest area of barrier habitat, 3.0 sq mi (Figure 74). The relative proportion of this habitat is highest in the Rio Grande basin, which is the smallest of all the basins.

Physical description. On the gulf side, the barrier habitat has a wide, flat beach that slopes gradually to the berm, slightly above the mean high water elevation. The backbeach slope behind the berm is even gentler than the forebeach slope; the backbeach may be 50 to 400 ft wide. Sediment making up the beach is mainly fine sand.

Small dunes appear in the most inland portion of the beach. They form in the wind shadow of debris or where hardy vegetation has taken root. Small coppice mounds topped with vegetation are sites of deposition and dune growth. Behind these low dunes are hummocky, discontinuous foredunes that lead into higher foredune ridges and mark the edge of the area of stabilized dunes.

Stabilized dune areas have been reported to range in width from 50 to 2000 ft; a width of several hundred feet is more typical (White et al. 1978). Stable dunes are well vegetated, particularly along the foredune ridge, and range from 5 to 35 ft in height. There may be several rows of dune ridges separated by depressions and swales. Small ephemeral ponds and marshes may be present in the swales. Mainland areas that border on the gulf have low, narrow foredunes.

Behind the foredunes are lower backdunes that grade into the barrier flat. The barrier flat may be level or hummocky and is usually well vegetated with grasses. It slopes gently toward the bay, lagoon, or salt marsh landward of the barrier habitat. Where mainland borders the gulf the barrier flat is very narrow. On barrier islands and peninsulas, however, the vegetated flat

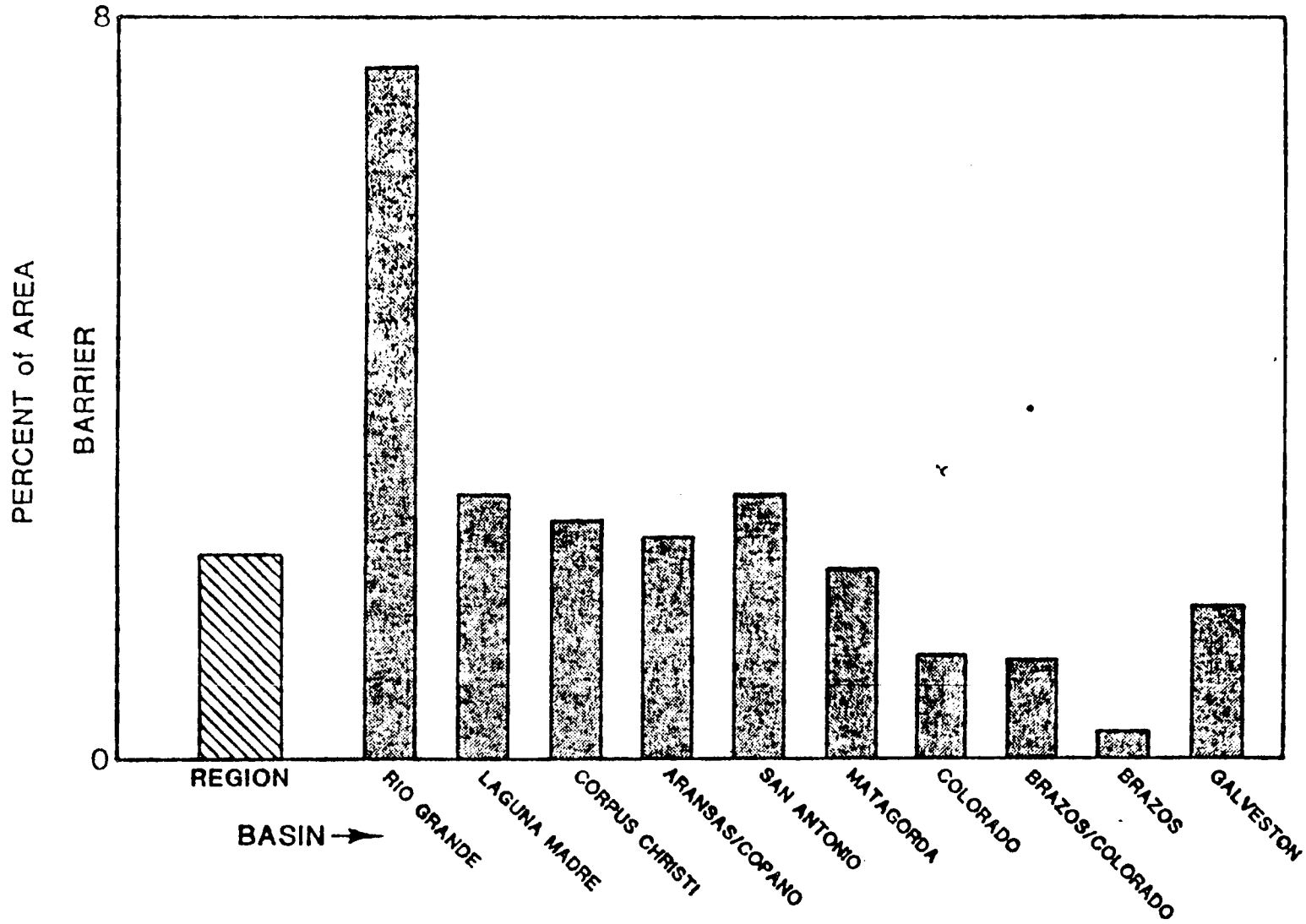


Figure 74. Percent of the region and basin area that is barrier habitat.

is usually the widest part of the barrier habitat, ranging from several hundred feet to a mile or more.

The foredune ridge is occasionally breached by blowout dune fields and washover channels. A blowout dune field is an area of active dunes that is formed and sustained by wind erosion. A washover channel is a pathway between the gulf and a bay formed by tidal surge and high waves during storms. Washovers that develop near passes may be relatively permanent features; others are short-lived, healed by natural dune-building processes.

System operation. In normal weather, waves carry sand from the upper shoreface in the gulf to the forebeach. As surface sand in the forebeach dries, predominant south and southeast winds transport it to the backbeach and foredune areas. Deposition in these areas is encouraged by the presence of sand-trapping pioneer vegetation and debris. Some sediment is transported to the barrier flat, but most is deposited in the foredune growth area. In dune-building experiments on the Texas coast, Dahl et al. (1975) measured sand accumulation at nearly 5 cu yd per linear foot of beach per year.

Dampness of the backbeach soil and soil organic content aid in stabilizing transported material. In the foredunes, vegetation is essential for dune growth. It traps sand and provides a matrix and organic binder that discourages eolian transport. The organic matter holds moisture and supplies nutrients as it decomposes. Salt spray provides some nutrients to the foredunes but also limits growth of vegetation (van der Valk 1974).

Under normal conditions the barrier system builds most of the year. Storms can reverse sediment flow, however. High water and storm wave energy carry sand from the forebeach to the gulf, from the backbeach to the gulf and

the forebeach, and from foredune areas to the backbeach, forebeach, gulf, or barrier flat (Davis 1972). Growth of barriers occurs at a slow pace over a period of months between storms. Reversal of the growth through storm action occurs very quickly; the rate and degree of storm erosion are related to both storm intensity and duration (Davis 1972).

Both natural events, such as fire or prolonged drought, and man's activities may cause localized disruption of foredune ridge vegetation. Devegetated areas are more susceptible to becoming blowout dune fields or washover channels. Strong steady winds promote sediment transport from the foredune ridge, causing dunes to migrate leeward. Active dunes often inundate stable dunes, smothering the vegetation. Without the stabilizing effects of vegetation, active dunes may completely cross the barrier habitat and deposit sand directly in the wetlands or bay further inland.

Less stable foredune ridges may succumb to hydraulic forces from the gulf during high tides and storms. Weakened dunes may be washed away completely to form washover areas where gulf waters directly enter the bay.

During wet years vegetation spreads and stabilizes the blowing sand of the active dunes. White et al. (1978) compared barrier habitat units on Mustang Island during a wet period (1974) and a dry period (1938). They noted 41 less beach area, 91 percent less active dune area, and 88 percent more vegetated dune and barrier flat area in the wet period than in the dry period.

The single most important factor in maintaining the barrier habitat is the supply of sand from the upper shoreface in the gulf. If sediment does not accumulate during good weather, erosion will predominate and eventually will affect the dune and barrier flat areas. In the backbeach, pioneer plants are essential to inhibit the movement of sediment. On the dunes and in the

barrier flats, rainfall and evaporation are the most critical factors. With sufficient moisture, these areas can recover from fire and other disturbances, such as overgrazing.

Over the long term, the net erosion or accumulation of dunes reflects the net erosion or accumulation of the adjacent beach shoreline. From historical data Seelig and Sorensen (1973) and Morton (1977) note that most of the region shows net shoreline retreat on the order of several feet per year over the period from the late 19th to the mid-20th century. In areas of greatest erosion, such as Sargent, south of the Brazos River, beaches are extremely narrow and there are no dunes.

Flora and fauna. The beach portion of the barrier habitat has a surprisingly diverse community living in and upon it. Blue-green algae and diatoms are autotrophs found in the upper layers of beach sand, particularly in the forebeach region. In the backbeach region sea oats (*Uniola paniculata*), goatfoot morning glory (*Ipomoea pes-caprae*), fiddle-leaf morning glory (*Ipomoea stolonifera*), bitter panicum (*Panicum amarum*), beach tea (*Croton punctatus*), and sea purslane (*Sesuvium portulacastrum*) are found (Judd et al. 1977; White et al. 1978). Larger consumers that live on the sand include the ghost crab (*Ocypode quadrata*), tiger beetle (*Cicindela sp.*), and various birds such as the laughing gull (*Larus atricilla*). Species such as the mole crab (*Emerita talpoidea*), the sand flea (*Orchestia grillus*), and the coquina (*Donax variabilis*) live in the portion of the beach swept by the waves, and a rich microfauna with representatives of many invertebrate groups lives in the interstitial spaces between sand grains (Riedl and McMahan 1974).

Vegetated dune areas contain many of the same plant species found on the back beach as well as gulfdune paspalum (Paspalum nonostachyum) and seacoast bluestem (Schizachyrium scoparium) (Judd et al. 1977). In swales and ephemeral marshes in the dunes the cattail (Typha domingensis) and common threesquare (Scirpus americanus) are found (White et al. 1978). Consumers in the dune areas include many kinds of insects and vertebrates. Baccus (1974) found the spotted ground squirrel (Spermophilus spilosoma) and the kangaroo rat (Dipodomys ordii). Dahl et al. (1975) noted rabbit and insect damage to plantings of grasses in the dunes. Large carnivores in the dunes include the coyote (Canis latrans), coachwhip (Masticophis testaceus), and rattlesnake (Crotalus adamanteus) (Oppenheimer and Gordon 1972).

While the barrier flat has many of the same plant and animal species as the dune region, seacoast bluestem (Schizachyrium scoparium) is usually dominant (Judd et al. 1977). There may be occasional stands of the silverleaf sunflower (Helinathus argophyllus). Marsh fimbristylis (Fimbristylis castanea), spike rush (Eleocharis obtusa), and saltmeadow cordgrass (Spartina patens) are often found in wet areas of the barrier flat (Judd et al. 1977). Rodents such as the Texas pocket gopher (Geomys personatus), and carnivores including the raccoon (Procyon lotor) and coyote (Canis latrans) are also found on the flat (Davis 1974).

Adjacent systems and flows. The gulf makes up more than 40 percent of the habitat units adjacent to the barrier habitat. Wind-tidal flat, salt marsh, bay, and grassflat are also adjacent to the barrier habitat. Materials that are imported into the barrier habitat include water, sediment, salt, organic debris, and on occasion oil and tar; the predominant direction of movement of these materials is from the gulf. The direction of movement of

the major export, sediment, is to the gulf, although some may be carried from the beach or washovers to the wind-tidal flat. The four habitats adjacent to the barrier habitat on the bay side are relatively isolated from it except for the movement of mobile terrestrial species such as birds and mammals.

Economic uses. Chapter 61 of the Texas Natural Resources Code defines the extent of public beaches in Texas. Except for San Jose Island, Matagorda Island, and Matagorda Peninsula west of the Colorado River, the statute substantially limits private or commercial gulf beach development. This prohibition together with the destructive force of tropical cyclones has discouraged most beach development. Most Texas gulf beaches are used for recreation, which is an important aspect of the coastal economy.

Counties north of the Mansfield Channel have the authority to establish a dune protection line landward of the line of mean high water of the Gulf of Mexico. Within this zone the commissioners court of a county may regulate most development activities in the dunes by permit. Petroleum exploration, grazing, and recreation are exempt from this regulation. Nueces and Galveston counties currently regulate activities under this statute.

Most of the economic use of the barrier habitat has occurred on the vegetated barrier flat. Uses have included oil and gas development; grazing; residential, municipal, and commercial development; airport and marina placement; navigational improvements; and recreational and educational facility placement. Residential, commercial, municipal, and recreational development occur on South Padre Island, North Padre Island, Mustang Island, the barrier flat on the mainland adjacent to the gulf between East Matagorda Bay and San Luis Pass, Galveston Island, and Bolivar Peninsula.

Impacts of man's activities. Development on the barrier flat introduces effects typical of urbanization: removal of vegetation or replacement of native vegetation with imported species; alteration of drainage patterns; reduction in the amount of permeable surface; introduction of toxics and nutrients; and general loss of natural habitat.

While direct use of the beach and dunes is limited primarily to recreation, its relative effect on the barrier habitat can be greater than that of activities of similar magnitude occurring on the barrier flat. Trampling and crushing of vegetation by pedestrian and vehicular traffic can result in direct plant losses. Motorized vehicle activity in the dunes can quickly initiate effects that spread across wide areas.

The net ecological effects of fire can be positive or negative depending upon circumstances (Baccus and Horton 1979). During dry periods campers' bonfires, fireworks, cigarettes, and deliberate ignition cause fires in the dunes and barrier flats which promote active dune field development. Conversely, fire can be beneficial, for it recycles living plants and litter to inorganic nutrients and may stimulate the following season's plant growth.

Most barrier islands in the study area were grazed by cattle until commercial development began in the 1970's; San Jose and parts of Matagorda Island continue to be used for grazing. Grazirg results in removal of stabilizing vegetation and the loosening of packed sand. The conversion of vegetated areas to active dunes has been partly attributed to grazing (Price and Gunter 1943; Sheire 1971).

Jetties, groins, and bulkheads placed within or along the surf zone to disrupt longshore current transport or protect private property against erosion are limited in the area of their direct effect. Their placement may

achieve the initial objective, but they may reduce the sediment supply to adjacent shoreline segments and to more inland portions of the habitat. Erosion of forebeach materials on the downdrift side of a jetty is an example. In some places the beach must be replenished with materials dredged from channels; dune development in these areas is limited.

Oil spills such as from Ixtoc II in 1979, torpedoed vessels in the Second World War, or natural oil seeps (Geyer 1978) have resulted in tar and heavy crude fractions washing onto the beach. The material is unpleasant for beach users and threatening to bird populations, but is quickly buried by sand. Sand adheres to tar balls, increasing their size. When they are washed off the beach, tar balls collect in the shallow nearshore areas. They may be repeatedly buried and exposed (Rabalais and Flint 1983) and have been shown to have negative effects on upper shoreface species (Rabalais et al. 1981; Kalke et al. 1982; Amos et al. 1983; Rabalais and Flint 1983).

While the areal extent of the barrier habitat is small, it serves as a storm buffer between the gulf and other habitats. Its location makes it subject to the most change of all habitats.

Bay

Areal extent. The bay habitat comprises the bay and bay margin systems modeled in Appendix C. Bay habitat occupies 4232 sq km (1634 sq mi) of the Texas Barrier Island Region, slightly more than eight percent of the region's total area. The Brazos basin, a long, thin river valley consisting mostly of upland, has the smallest quantity of bay habitat. The San Antonio basin contains the largest proportion of bay habitat, 15.9 percent (Figure 75). The Galveston basin alone contains slightly more than 25 percent of all the bay

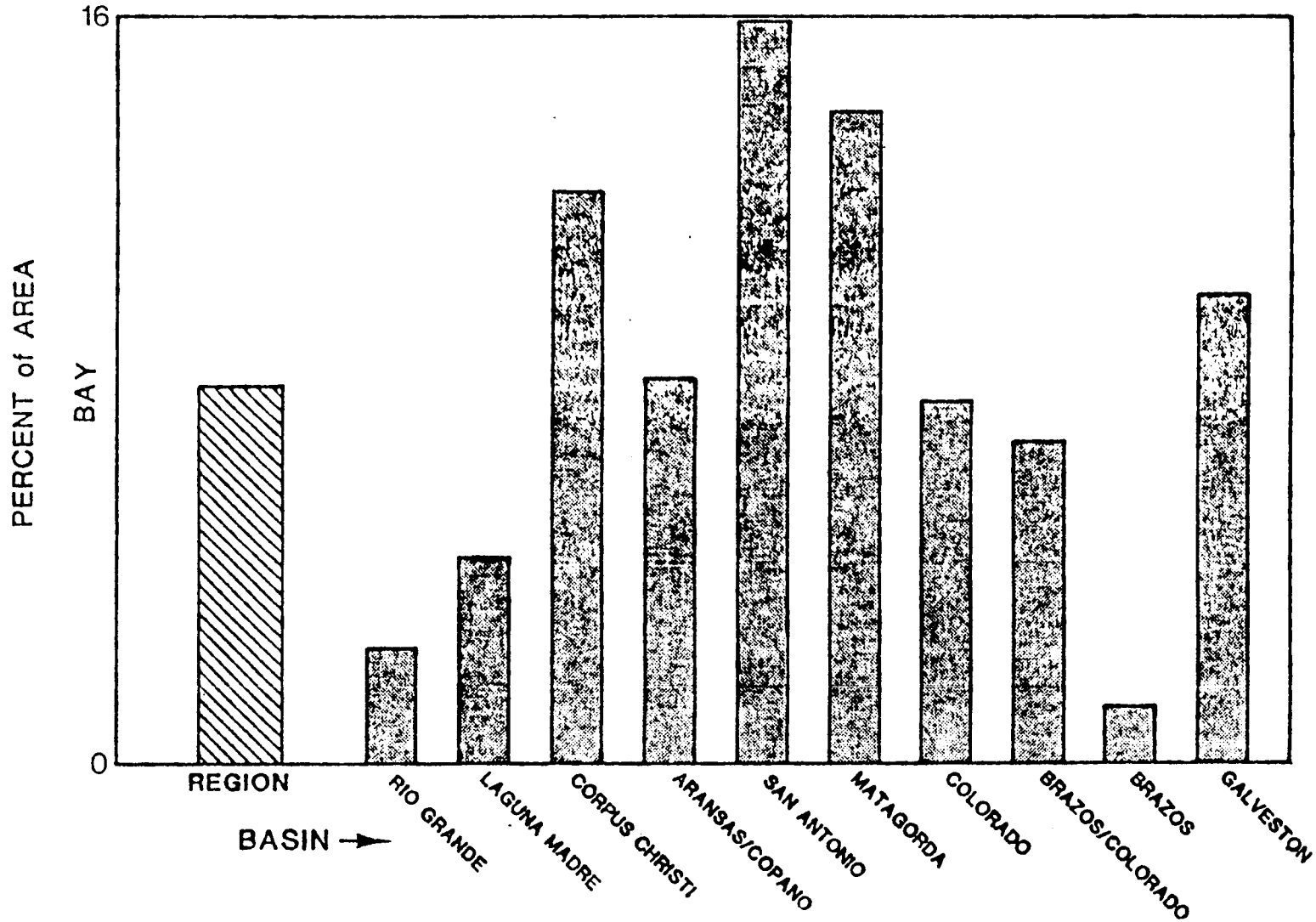


Figure 75. Percent of region and basin area that is bay habitat.

habitat in the region. The proportion of bay habitat in the Laguna Madre basin, 4.3 percent, is only about half that of the Barrier Island Region as a whole, even though the Laguna Madre basin makes up more than 32 percent of the study area.

Physical description. Bay is an aquatic habitat, separated from the gulf by barrier islands or peninsulas. There are basically two bay forms: lagoons, and classic bays formed from drowned river mouths. Lagoons are narrow bodies of water separating the mainland from the barrier habitat. The Laguna Madre and East Matagorda Bay represent this form. They are very shallow, generally less than 1.5 m (5 ft) deep, with large areas 0.3 to 0.9 m (1 to 3 ft) deep, and have only small streams draining into them.

The classic bay is located at the mouth of a major river system. This bay configuration shows the remnants of eroded river valleys since the heads of the bays jut inland, perpendicular to the coastline. River mouths are usually the most inland feature of these bays, but in San Antonio and Nueces bays the rivers have built sizable deltas. Classic bays are deeper than lagoons. The deeper portions of Galveston Bay are 3 m (10 ft); Matagorda and Aransas Bays have areas as deep as 4 m (13 ft). San Antonio Bay, the shallowest of the classic bays, is generally less than 1.8 m (6 ft) deep.

The classic bay form usually has a long fetch, a wide stretch of open water over which waves are generated by southeast winds during the spring and summer, and by north winds during the winter. Wind-induced wave movement causes these bays to be well mixed and to have a high suspended sediment content. The long fetch allows wind energy to be transformed into hydraulic energy which is expended on beaches, bluffs, and tidal flats on the mainland

sides of the bays, and on tidal flats and wetlands on the backsides of barriers.

All classic bays have a permanent or temporary outlet to the gulf at their southern end. Temporary passes such as Cedar Bayou, south of San Antonio Bay, open only as the result of extremely high water flows from tropical cyclone-induced rainfall or wind-driven tides from strong northers. The openings of unstabilized natural passes may move north or south several hundred feet along the barrier islands and peninsulas from year to year. The permanence of a pass is related to the effective hydrostatic head of the bay system during periods of extreme river flow and northers. The more regularly this flow occurs, the more likely it is that the pass will remain open and in the same place. Tidal influences within bays are small, decreasing from an average daily fluctuation at the passes of 0.4 m (1.4 ft) to less than 0.15 m (0.5 ft) near the mainland or river mouth (U.S. Department of Commerce 1982).

Circulation patterns in Texas bays are influenced by tidal currents, freshwater inflows, and wind. Tidal currents are strongest near deep channels and passes. Further away from the marine influence, large wind-induced circulation patterns dominate. These patterns are highly variable from one bay to another. Gyres occur in large bays; their presence and rotation varies seasonally and is closely related to wind direction and velocity.

Salinity patterns vary among the bays. A comparison of average salinities (Figure 76, four-year averages from Texas Department of Water Resources 1983a) shows that bays become progressively more saline to the south. The average salinity in Galveston Bay is 15 ppt; the average salinity in the Laguna Madre is 27 ppt. This may be a low average for Laguna Madre since Behrens (1966) concluded that a range of 30 to 40 ppt was normal.

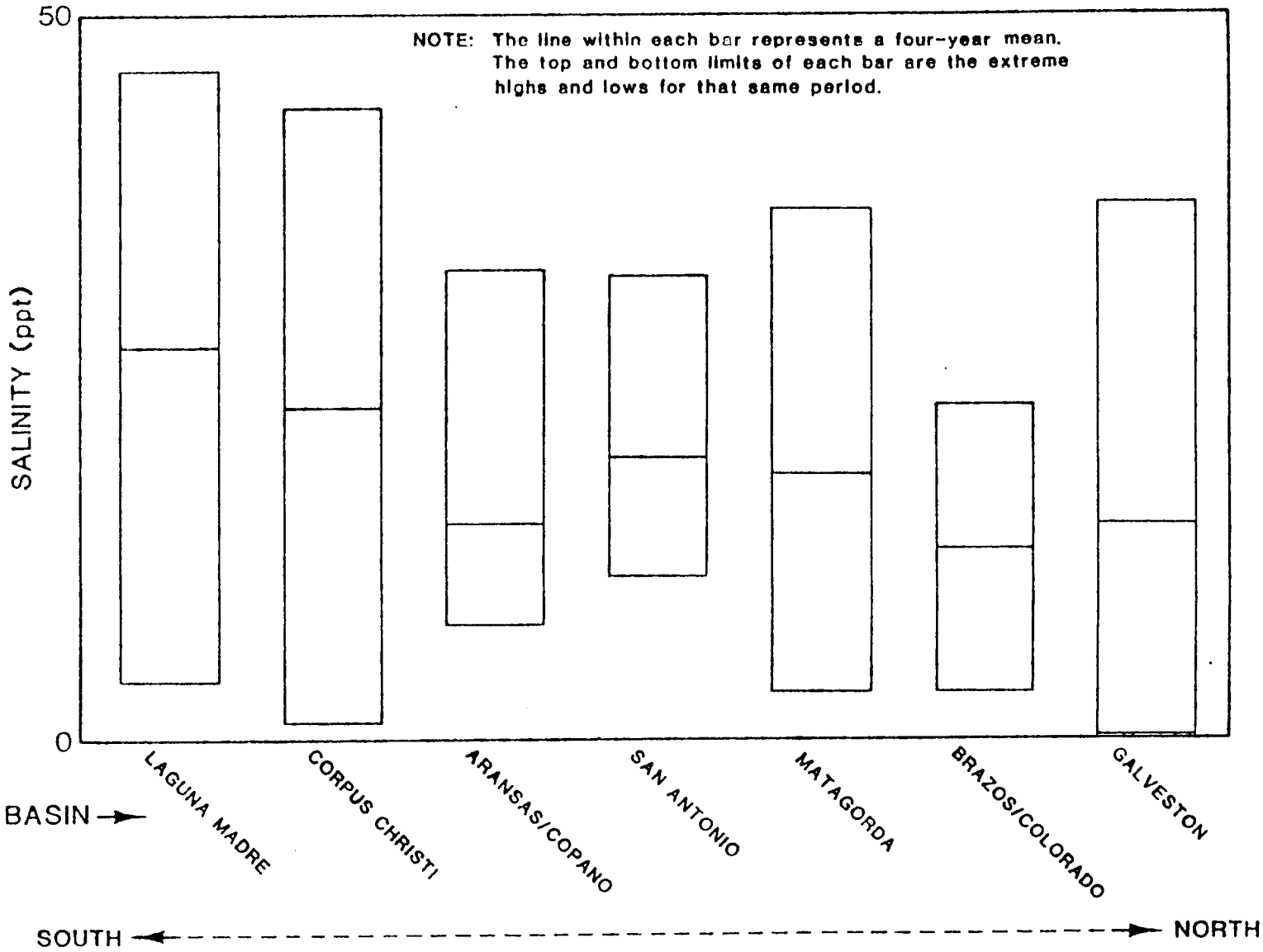


Figure 76. Four-year mean and extreme salinities of major bay habitats.

Hedgpeth (1953) noted a high of 113.9 ppt in the Laguna Madre before the Gulf Intracoastal Canal was completed.

Short-term salinity variation can be rapid and extreme. Behrens (1966) reported that rainfall in the Laguna Madre can cause the normally saline surface waters to become brackish; others (Holland et al. 1974, for example) have measured salinities of 0.0 ppt in bays after tropical cyclones.

Monthly average temperatures in Texas bays vary between 10 and 30 deg C. In shallower areas, temperature variation can be extreme. Simmons reported temperatures as high as 44 deg C in the shallow flats of Laguna Madre. Moore (1976) measured temperatures of 0.5 deg C in shallow margins of Redfish Bay in the Corpus Christi Bay system, and Gunter (1967) noted that the temperature of hypersaline waters could be even lower due to the freezing point depression of saline solutions.

System operation. Phytoplankton production and to a lesser degree the import of organic matter from adjacent systems are the components that control the biota in the bay habitat. Water movement is the major factor influencing conditions for phytoplankton production. Water movement, through wind, tide, and freshwater inflow, circulates and spreads nutrients, organic matter, phytoplankton, and zooplankton. Freshwater inflow carries nutrients and sediment to the bay; tidal forces assist in transporting biota, sediment, and saline water throughout the system.

The biotic community of the bay habitat contains a large number of species. Phytoplankton, zooplankton, consumers, omnivores, and predators constitute a complicated food web in the bay. Texas bay systems that do not have large adjacent seagrass areas are phytoplankton-based; for example,

Armstrong and Hinson (1973) reported that 94 percent of the net production in Galveston Bay is from phytoplankton. Texas bay phytoplankton production is nutrient-limited. Nitrogen seems to be the limiting factor more often than phosphate. Davis (1973) noted that the Lavaca, San Antonio, Copano-Aransas, and Corpus Christi-Nueces bay systems were all deficient in nitrogen when compared to optimal nutrient combinations for algal growth.

Texas bays receive nutrient input from precipitation, in situ fixation (Texas Department of Water Resources 1983b), regeneration from the sediments, rivers, marsh inundation (Texas Department of Water Resources 1980a; 1980b; 1981a; 1981b), and loading from wastes introduced by man (Oppenheimer et al. 1975). Nutrients from the latter three sources are imported into the bay from adjacent habitats. The supply of nutrients from river input and marsh inundation is highly dependent upon river flow into the bay system.

Bay systems are mixed by horizontal and vertical currents. Wind-driven circulation prevails over the entire bay system. Near passes and channels, tidal forces assume some importance in mixing. Texas bays tend to be very well mixed with little stratification from top to bottom except in very deep or restricted areas. The mixing minimizes low oxygen conditions and thoroughly disperses nutrients that have been regenerated from the sediments by the abundant infaunal groups.

The biotic communities in the bay habitat are influenced by seasonal fluctuations in freshwater inflow, nutrients, salinity, temperature, and light. Seasonal light and temperature variation not only influences the level of primary productivity (Odum and Wilson 1962), but causes different species groups of phytoplankton to predominate. Salinity and temperature patterns strongly affect the detritivore, consumer, and predator groups in bay systems,

influencing population distribution and life cycle sequence, and providing cues for migration.

Bay habitats with adjacent seagrass beds receive influxes of detrital plant material produced when stems and leaves of benthic plants die in the fall. Based upon carbon isotope labeling, Fry et al. (1977) have shown that seagrasses have a significant influence on sediment organic carbon in open bay areas of Laguna Madre adjacent to seagrass beds. They also showed that Corpus Christi Bay, more distant from seagrass sources than the bay areas of Laguna Madre, had carbon isotope ratios suggesting some seagrass carbon input.

Flora and fauna. Holland et al. (1975) identified more than 247 phytoplankton taxa in the Nueces-Corpus Christi, Copano, and Aransas Bay areas. Diatoms such as *Thallasiothrix* spp., *Nitzschia* spp., *Navicula* spp., *Chaetoceros* spp., and *Thalassionema* spp. were most prevalent. Blue-green algae *Oscillatoria* sp. and *Anabaena* sp. were common at some times of the year. Benthic algae grow in shallow areas and on hard surfaces. Conover (1964), Edwards and Caprun (1973), and Lowe and Cox (1978) have reported that the algal species *Cladophera dalmatica*, *Enteromorpha clathrata*, *Ulva lactuca*, and *Laurencia poitei* are common in bays at various times of the year.

Common zooplankton in Texas bays include *Acartia tonsa*, *Diaptomus* sp., *Cyclops* sp., and *Paracalanus crassirostris* (Cooper 1968; Holland et al. 1973). Holland et al. noted that some life stage of almost every major group of estuarine animals was represented in the zooplankton.

Benthic macroinvertebrates include many polychaetes such as *Mediomastus californiensis*, and pelecypods including *Mulinea lateralis* (Holland et al. 1973; Flint and Younk 1983). Consumer species in the bays are well known.

They include the striped mullet (Mugil cephalus), spot (Leistomus xanthurus), croaker (Micropogon undulatus), bay anchovy (Anchoa mitchelli), menhaden (Brevortia patronus), pinfish (Lagodon rhomboides), and blue crab (Callinectes sapidus). The brown, white, and pink shrimp, (Panaeus aztecus, P. setiferus, and P. duorarum) are present in bays as post-larvae and juveniles.

Higher consumers include the sand seatrout (Cynoscion arenarius), spotted trout (C. nebulosus), black drum (Pogonius cromis), red drum (Sciaenops ocellata), and southern flounder (Paralichthys lethostigma). The bottlenose dolphin (Tursiops truncatus) is common in deeper bays, especially near passes, and occasionally the American alligator (Alligator mississippiensis) is seen swimming in the bays.

Adjacent systems and flows. Over 47 percent of the habitats adjacent to bays are aquatic. These habitats are channel and tidal stream (18.7 percent), reef (19.3 percent), and grassflatbeds (9.2 percent). Adjacent aquatic habitats exchange most materials and biota freely with bay systems, although bays probably receive more organic material than they export to grassflats, and send more organic matter to reef and to channel and tidal stream than they receive from these habitats.

About 18 percent of the adjacent habitats are intertidal. These include salt and brackish marsh (12.1 percent) and wind-tidal flat (5.9 percent). During periods of high water, many organisms move freely between bay and adjacent intertidal habitats. Water, sediment, nutrients, and organic matter are exchanged, but the patterns of movement are difficult to establish.

Upland systems constitute more than 34 percent of the adjacent habitats. They include range (16.1 percent), urban (6.7 percent), spoil (6.4 percent), cropland (2.5 percent), barrier (1.3 percent), and forest (1.2 percent).

Other than during periods of storms, bay systems do not contribute material or biota to these habitats. Bays receive runoff, effluents, and cooling water, nutrients, sediment, some organic matter, waste and toxic materials, and organisms associated with animal and human wastes from upland systems.

Except for the biota, most of the materials imported into the bay are metabolized by microorganisms or phytoplankton trapped in accumulating sediments or exported through passes to the gulf.

Economic uses of system. Bay habitats are used directly or indirectly by all sectors of the coastal zone economy. The commercial fishing, recreation, and transportation sectors make direct use of the habitat. Most of the value of commercial fisheries comes from shrimp. The majority of the shrimp harvested are caught in the gulf, but because shrimp spend part of their life cycle in bays, the habitat indirectly contributes to commercial fisheries yield. Oysters, blue crabs, bait shrimp, and several finfish species are harvested from the bays. Their combined value is about one-tenth that of the gulf shrimp harvest (Liebow et al. 1980).

Recreational use of bays includes boating, fishing, and hunting. Much capital is expended for products that are used in bay recreation.

Transportation is one of the most important activities in the bay habitat. Hundreds of miles of channels have been dredged through Texas bays to accommodate commercial shipping and barge traffic. Three-quarters of all goods shipped to other states from Texas travel by water. In 1977 the volume of waterborne transportation was 417 metric tons (460 million short tons), approximately double the 1972 quantity (Texas Coastal Management Program 1975; Liebow et al. 1980). Offshore production of natural gas and crude oil is

transported across bays by pipeline. More than 11.4 billion cu m (400 billion cu ft) of natural gas and 715 million liters (4.5 million barrels) of crude were pumped ashore from gulf tracts in 1978.

Other sectors of the economy having effects upon bay habitat include mineral production in the bays, residential and industrial development, and agriculture. Minerals produced include oil and gas from wells under the bays, and oyster shell harvested from dead reefs to provide lime for cement. Shell dredging recently ceased, however, because of depletion of the resource.

Several municipal power plants located adjacent to bays use bay water for coolant. In addition, municipal and (to a lesser extent) industrial developments use bay water to receive and process waste effluents. More than half of the nearly 1600 permitted discharges in the barrier island region are from sanitary services. While there are a few point-source discharges from agriculture, its contribution to the bays is mainly non-point flows of sediment and agricultural chemicals.

Impacts of man's activities. Bait shrimp are harvested from bays with nets dragged across the bottom. Schubel et al. (1979) quantified the effects of this activity. They found that bait shrimping disturbed 10 to 100 times as much sediment as was disturbed by dredging for channel maintenance. In addition, the effects of trawling are spread over a much wider area and occur over a greater time period than dredging impacts.

Recreational vessels introduce hydrocarbons and debris into the bays. Until prohibited by recent federal regulations (33 CFR 159), inadequately treated sewage from pleasure boats and commercial vessels was dumped directly into bay waters, adding to existing water quality problems in high-density recreation areas. Marinas and residential and industrial developments convert

shallow bay margin areas to bulkhead and piling habitats with deepened aquatic areas to accommodate vessels. To provide calm waters for anchorage, marinas are designed to restrict the natural water flow. Toxic substances from antifouling paints and biocides that discourage boring species may collect in bottom sediments in marinas (Nixon et al. 1973).

The transportation sector affects the bay system by dredging deep channels. When bay habitat is converted to channel, spoil may be disposed near the channel. The effects of dredging and spoil placement include smothering of benthic organisms and introduction of suspended materials and nutrients into the water column. In addition, deep channels affect bay hydrology by allowing the inward flow of marine water and altering circulation patterns. Some changes in bay hydrology can be predicted with hydrologic models.

Municipalities and industries use bay waters to assimilate chemical, biochemical, and thermal wastes. Upper Galveston Bay, Trinity Bay, several tertiary bays along the Houston Ship Channel, and part of lower Galveston Bay have localized problems of oxygen depletion and excess nutrients from municipal and industrial discharges (Texas Department of Water Resources 1983a). Some of these areas also have minor pH, oil and grease, heavy metal accumulation, and bacterial level problems associated with municipal and industrial discharges. Portions of Matagorda Bay have localized water quality problems from heavy metals and high bacteria concentrations associated with industrial wastes (Texas Department of Water Resources 1983a).

At least four electric generating plants in the coastal region use bay water for cooling. French (1973) measured a temperature difference of 8.0 to

10.3 deg C between intake and discharge waters from the P.H. Robinson plant at Galveston Bay. In winter the heated effluent is attractive to estuarine species, but in summer heated effluent is an added thermal stress to estuarine species. Thermal additions as great as those reported by French may elevate summer temperatures near the effluent outfall above the tolerance levels for some species.

Runoff from agricultural land carries inorganic nutrients as well as agricultural chemicals to rivers entering the bays, or directly into the bay. Ahr et al. (1973) traced chlorinated hydrocarbons in Matagorda Bay to agricultural runoff. Measurable levels of chlorinated hydrocarbons have also been found in San Antonio Bay and Laguna Madre, although concentrations have not been high enough to cause health concerns (Texas Department of Water Resources 1983a). Oil spills from mineral exploration, production, and rransportation is a problem in the region. Liebow et al. (1980) reported an average of 28 spills per month for a total of 880 barrels (139,893 l) per month.

Bulkhead

Areal extent. The bulkhead habitat includes jetties, groins, navigation markers, wrecks, piers extending into the gulf, and oil and gas platforms offshore. In estuaries this habitat also includes boat ramps, docks, and bulkheads erected to prevent the sides of canals and waterways from eroding.

The bulkhead habitat is small in area, occupying less than 0.1 percent of the Texas Barrier Island Region. This areal estimate, however, does not convey the importance of this habitat. Since the bulkhead habitat is often the partition between upland and water, a linear measurement would be more meaningful. No such measurement is available, but it is likely that the

region contains several hundred linear miles of jetties, seawalls, and other submerged man-made structures. The greatest quantity of bulkhead habitat in the region is in the Galveston basin, where the most development has occurred (Figure 77).

Physical description. Estuarine and marine environments in the region have no natural rocky or hard surfaces except for natural accretions such as oyster and serpulid reefs in estuaries, and a few hard banks in offshore areas. Biotic communities that would inhabit natural hard surfaces form on the surface of man-made structures in the water.

Bulkhead habitat often consists of a vertical hard surface of concrete, steel, or treated wood. In some instances the hard surface is not vertical. Jetties typically are built so that the side slope of the rocky material is between 1:2 and 1:3. Since jetties at passes protect channels dredged as deep as 45 ft, the sloping rock sides may extend 200 to 300 ft from the center of the jetty to the channel bottom. This provides a very wide expanse of rocky habitat.

System operation. The biotic community of this habitat has an observable pattern. Many species that live on the outside of a structure--attached algae and sessile or only slightly mobile species--live in narrow zones that are vertically distinct. The abundance of producers, filter feeders, grazers, borers, and certain carnivores in the habitat is the result of a dynamic balance maintained by available space, predation, competition, and environmental parameters.

The environmental parameters that seem to have the most control over organism distribution and that qualify as driving forces are available

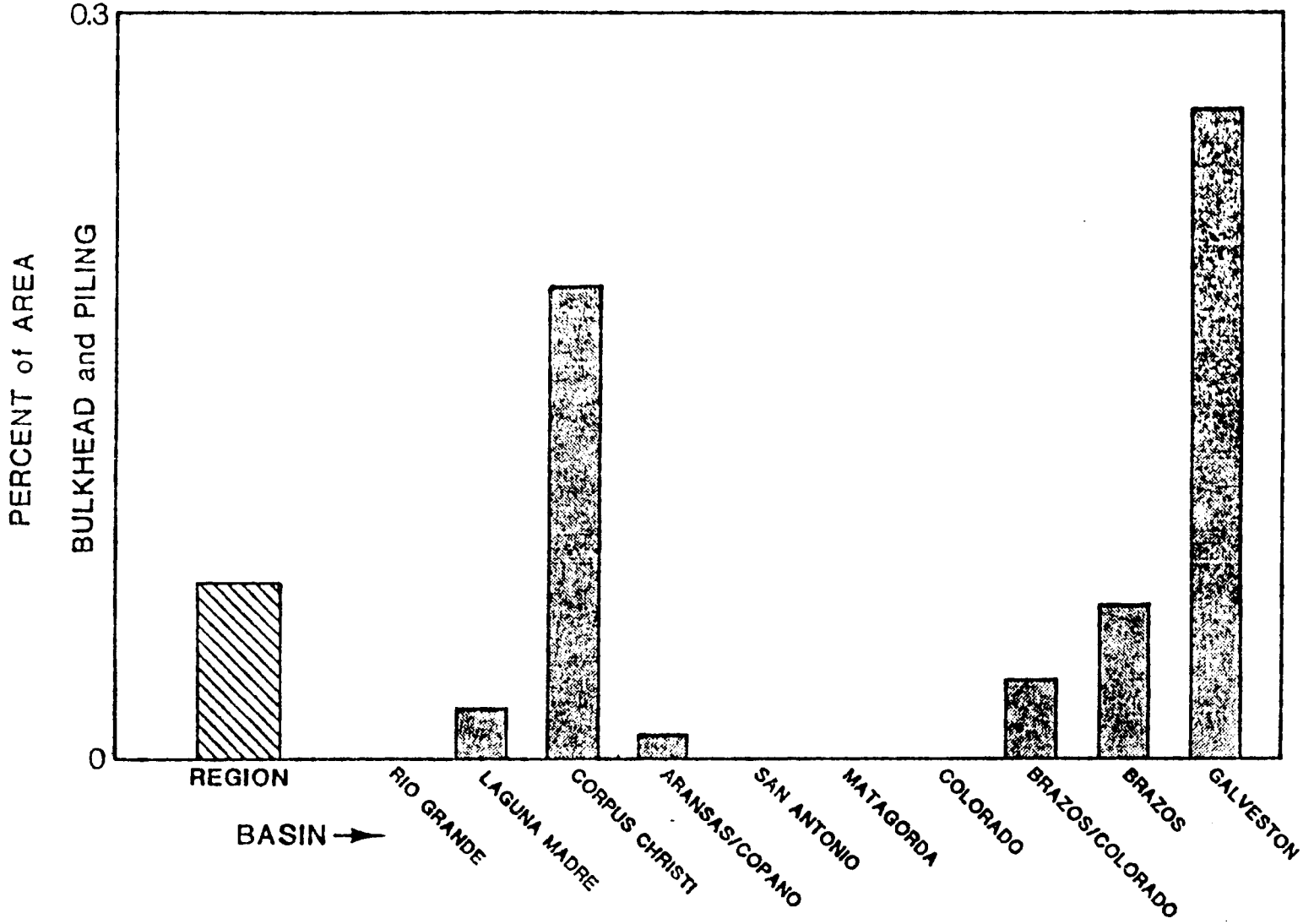


Figure 77. Percent of region and basin area that is bulkhead habitat.

sunlight, current energy, wave energy, and the duration and frequency of exposure to the air. Kapraun (1980) has graphically shown that the distribution of algae on jetties is a function of exposure to wave action and elevation with respect to tide level. Zonation of other species has been reported by Whitten et al. (1950), Hedgpeth (1953), and Gunter and Geyer (1955).

Algae are the dominant primary producers in this habitat. Algal production provides an energy source for grazing and mobile herbivore species. Most of the materials used by filter-feeding organisms are carried to the habitat by moving water. Grazing species, mobile herbivores, and carnivores consume the algae and filter feeders and thus exert a measure of control on their populations.

Wooden piles and timbers are often treated with creosote, a petroleum derivative of coal tar that is rich in aromatic hydrocarbons (Hochman 1967). They may also be treated with a variety of organochlorine additives, copper, or mercury compounds to combat boring species. These toxic materials gradually leach into the water column. Bulkhead habitats in marinas and docking areas are often close to boats and vessels whose hulls are painted with antifouling paints containing copper or mercury. In these areas water, sediment, and fouling species themselves have been shown to contain higher levels of the antifouling compounds than are found naturally in other estuarine areas (Nixon et al. 1973).

The hard surfaces on which the biotic community develops are often subject to fast water currents and high wave energy impacts. Many organisms found in this habitat are adapted to withstand these physical stresses. For example, anemones on jetties are typically shorter and fatter than those

inhabitating lower energy environments. Gastropods that live on jetties may create small depressions in the granite blocks that fit the edges of their shells and aid in stabilizing them against wave action.

Flora and fauna. Many algal taxa can be found attached to hard surfaces. Some common algae include Enteromorpha spp., Ulva fasciata, Cladophora spp., and Gracilaria spp. (Edwards and Kapraun 1973). Filter-feeding species include hydroids (Bougainvillia inaequalis and Obelia dichotoma), acorn barnacles (Balanus improvisus, B. eburneus, B. amphrite, and Chthamalus fragilis), the porcelain crab (Petrolisthes armatus), the warty sea anemone (Bunodosoma cavernata), and the eastern oyster (Crassostrea virginica) (Fotheringham 1980).

Grazing and scavenging species include the zebra periwinkle (Littorina lineolata), false limpet (Siphonaria pectinata), isopod (Ligia exotica), Antillean nerite (Nerite fulgurans), and striped hermit crab (Clibanarius vittatus). Predators that feed on mollusks and other consumers include the oyster drill (Thais haemastoma) and stone crab (Menippe mercenaria). Species that bore into wooden structures include the boring clams (Bankia gouldi and Teredo bartschia) and the boring isopod (Limnoria tripunctata).

Larger mobile herbivores include the striped mullet (Mugil cephalus) and blue crab (Callinectes sapidus). The pinfish (Lagodon rhomboides), Atlantic spadefish (Chaetodipterus faber), and sheepshead (Archosargus probatocephalus) are some of the larger mobile carnivores that frequent this habitat.

Adjacent systems and flows. The bulkhead habitat is usually adjacent to the bay, channel and tidal stream, or gulf aquatic system. Where bulkheads

are erected to prevent wave erosion, urban and barrier habitats are the most frequent upland units.

The bulkhead habitat exchanges materials only with aquatic habitats. Water movement transports organic matter, plankton, and oxygen to the community and removes toxic materials and waste products. The larvae of sessile species are dispersed to other habitats by currents.

Structures making up bulkead habitat may have hydrological effects on adjacent habitats. Frequently the rationale for placement of bulkheads is to control wave action in order to reduce bank erosion or create calm waters for boat mooring. Bulkheads accomplish this by presenting sloping or vertical obstructions to waves. For sloping surfaces the horizontal component of wave force is reduced by a function of the slope angle (Jachowski 1975) since some of the kinetic energy is redirected vertically while other energy is dissipated in friction. Vertical walls may be designed to create standing waves which minimize horizontal forces; however, vertical walls often reflect most of the wave energy, which can increase hydrologic forces in adjacent habitats.

Economic uses. The submerged or partially submerged structures forming bulkhead habitat are associated with a variety of coastal economic activities: navigation, oil and gas production, recreation, port development, and residential development. Their purposes include protecting land against erosion, calming wave action, supporting petroleum equipment, and marking navigation lanes. The biotic communities that develop on the hard surface are incidental to the structure's function to man.

The habitat attracts fish and crabs, and adjacent aquatic areas are often used for recreational fishing. Some abandoned structures are deliberately

left in place to enhance recreational fishing, and artificial reefs have been made by sinking old ship hulls and automobile tires.

Impacts of man's activities. Organisms in the bulkhead habitat are affected by whatever water transports past the system. Pesticides, fertilizers, spilled hydrocarbons, municipal waste, and suspended sediments produced by human activities in adjacent systems may be carried into the bulkhead habitat. These conditions may cause environmental stress or death to some inhabitants. Human activities may also lower the oxygen level in waters passing through the habitat and alter flow patterns or velocity. Maintenance actions such as replacement of weakened pilings may offer new settlement opportunities for colonizing species, but may also introduce antifouling materials toxic to biota in or near the habitat.

The major physical effect bulkhead development has upon adjacent communities is hydrologic. The hard surface of the habitat diverts, redirects, reflects, or absorbs kinetic energy from wave or current flow and increases or decreases the transfer of this energy to adjacent systems, depending upon the structure design.

Channel and Tidal Stream

Channel and tidal stream are discussed as a single habitat type though they have been modelled as separate ecosystems (Channel and Tidal Stream Reach, Appendix C). While there are some differences between these two systems, they share a major similarity: bidirectional water flow at different depths. The systems are often connected to each other, and it is sometimes difficult to discern the boundary between them.

Measurements of the length of channels and tidal streams in the Texas Barrier Island Region are available, but area has not been measured. There are an estimated 801 km (498 mi) of tidal stream and more than 1323 km (822 mi) of channel in the region. The channel figure is probably an underestimate since many small channels cannot be detected in the aerial photographs from which these estimates were made, and since development in the last few years may have doubled the channel mileage.

Tidal streams vary in width; 15 to 31 m (50 to 100 ft) may be typical. Channel widths vary from 15 to more than 305 m (50 to 1000 ft). Bolivar Roads, between Galveston Island and Bolivar Peninsula, is nearly 2438 m (8000 ft) wide between the jetties, but the dredged portion is much narrower, about 244 m (800 ft) (Espey, Huston and Associates 1978). The Gulf Intracoastal Waterway is 38 m (125 ft) wide and dredged to a controlling depth of 3.7 m (12 ft). Depths of other channels and tidal streams range from just a few feet to more than 13.7 m (45 ft).

The Galveston basin contains 689 km (428 mi) of this habitat, more than any other basin in the region. The Rio Grande basin contains the least, 19.8 km (12.3 mi). Figure 78 shows lengths of this habitat for all of the basins. Figure 79 illustrates the relationship between the channel and tidal stream length and the area of urban habitat in each basin. The correlation coefficient between the measures of these two habitats is 0.96 and is highly significant ($P<0.001$, using the test for critical values for correlation coefficients from Rohlf and Sokal 1969). This high level of correlation suggests that the length of channel and tidal stream habitat, largely a measure of dredged navigation channels, is directly related to the amount of developed or urban area within a basin.

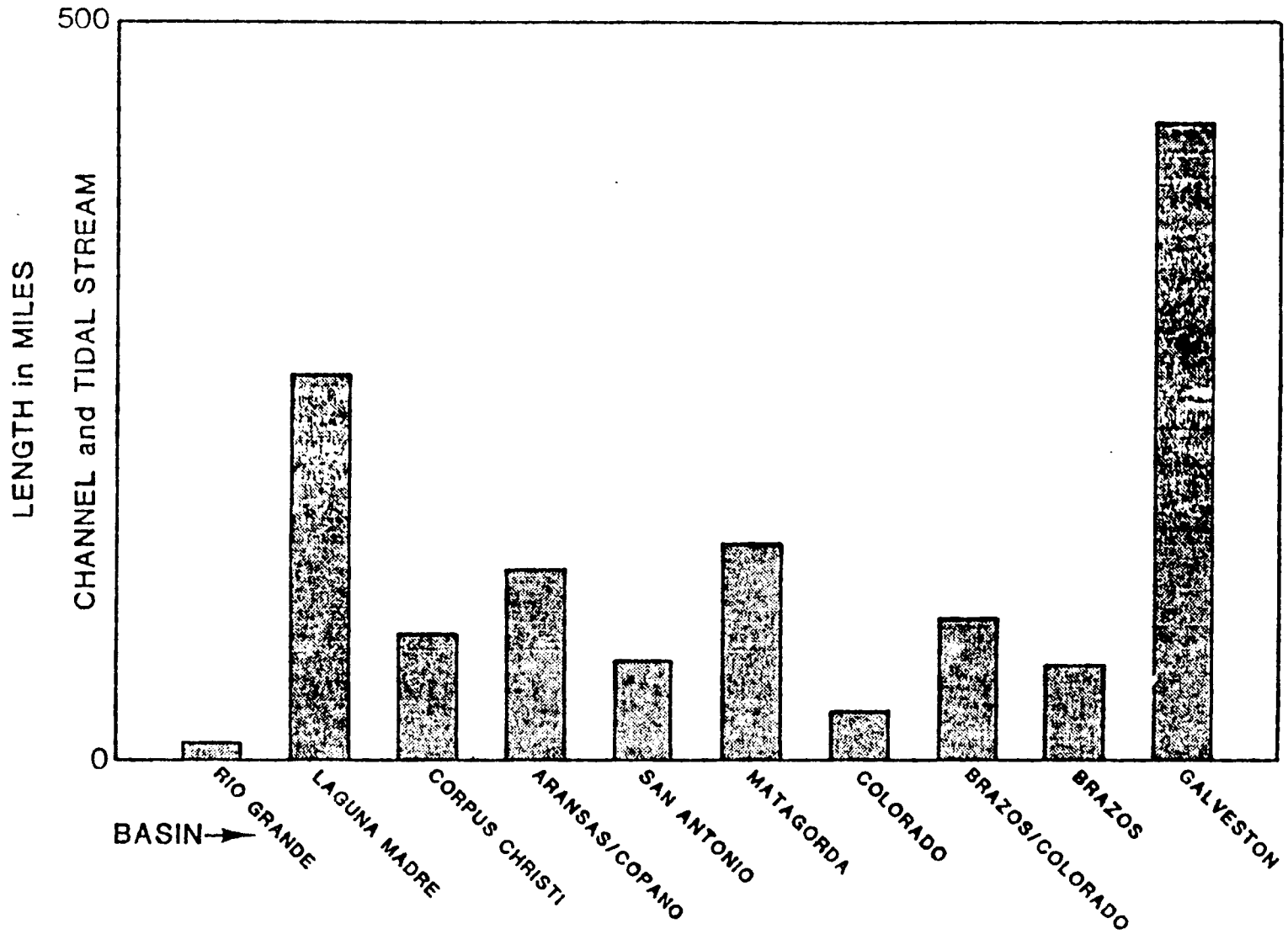


Figure 78. Length of channel and tidal stream habitat in basins.

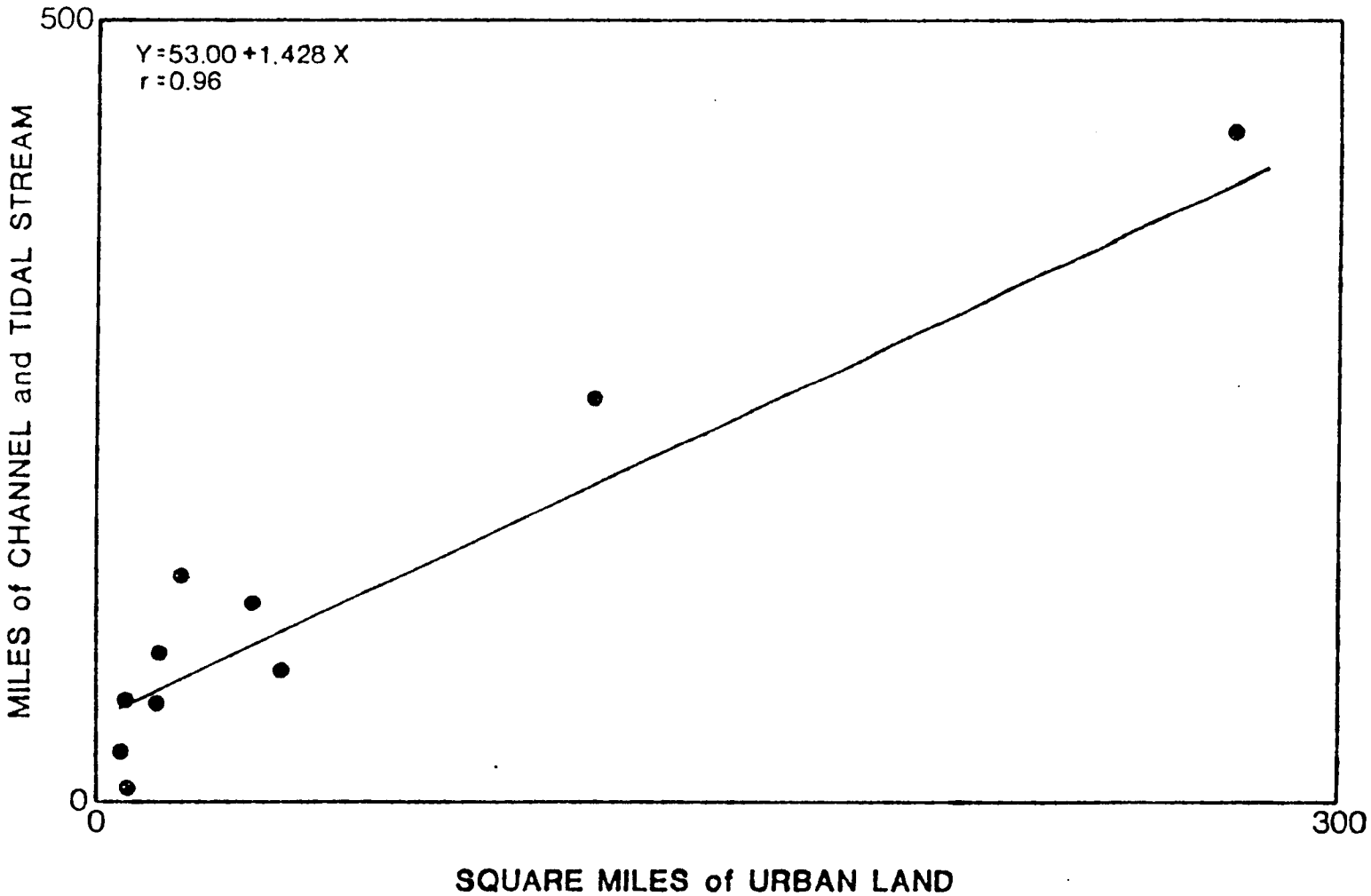


Figure 79. Length of channels and tidal streams versus the area of urban land in each basin.

Physical description. Tidal streams are connected at their upper ends to rivers and canals and at their lower ends to channels or bay. The upper boundary of tidal streams is the point where tidal influence ceases. The lower boundary is the area where turbulent energy from wave action may replace stream current as the dominant hydrologic force (Snyder et al. 1978). Many tidal streams have been dredged to form navigation channels across bays to the gulf; however, many channels run parallel to the shoreline.

The water flow pattern in this habitat distinguishes it from other aquatic habitats. Typically there are two levels of water flow; at times this can be observed by salinity differences at different depths. In tidal streams, the upper level is relatively fresh water (0 to 10 ppt, Snyder et al. 1978). This level of flow constantly moves seaward. The lower stratum is of higher density water (in this case more saline). Because the density difference between the layers produces a horizontal pressure gradient acceleration, the lower stratum is pushed upstream opposite to the upper stratum flow (Belaire 1976). Some mixing occurs at the boundary zone between the two layers. The upper limit of penetration of the lower stratum inland fluctuates depending upon the strength of the tidal force and the flow velocity of the upper stratum. Salinity stratification has been shown by Bryan (1971) and Hall et al. (1976).

Channels to the gulf usually have the same sort of flow pattern as tidal streams, although the upper levels of channels have measurable salinities. There is usually a salinity gradient between levels. At times the direction of flow of the upper and lower strata may reverse. Upper level water in channels in passes may flow seaward on ebb tides and landward on flood tides.

Likewise, the lower stratum may flow seaward with the upper level when there is a large hydrostatic head such as results from high runoff following major storms.

Bottom layer water in channels crossing bays (such as the Gulf Intracoastal Waterway) may move in the direction dictated by density currents, while surface water flows in a direction determined by wind-driven surface currents. Belaire (1976) notes that the intensity of density currents varies as the cube of the water depth of the channel, and that saline intrusion occurs preferentially up narrow, confined channels.

Turbidity and suspended sediment load may vary in this habitat; high flow usually means high levels of suspended solids. Large, deep channels such as the Houston Ship Channel may have very strong density currents that push saline water toward the head of the bay. All but a very thin surface layer of the channel waters may flow upstream. These currents often carry sediment upstream, but in general channels are less turbid than shallower adjacent bay areas that are more susceptible to wind-driven turbulence (Belaire 1976).

System operation. The driving forces that control system operation in this habitat are largely hydrologic. Stream flow or gulfward currents control the operation of the upper water layer. In channels and tidal streams that are wide or are adjacent to open stretches of bay, wave energy driven by the wind may create turbulent (vertical) circulation that is important to mixing of the layers (Hann et al. 1972). Turbulence caused by the movement of large vessels--ships in major channels, barges in the Gulf Intracoastal Waterway--is a significant contributor to mixing between layers (Liou and Herbich 1976, Brogden and Oppenheimer 1977).

Tidal energy is transmitted directly by channels and tidal streams. It is strongest near tidal passes and is attenuated with distance from the pass. While tidal energy exists throughout the water column, it is most important in the lower water layer, where tidal currents resuspend sediment and transport materials and organisms. Smith (1974, 1977) and James et al. (1977) have demonstrated the transmission of current energy through ship channels and the Gulf Intracoastal Waterway.

The effect of tidal forces on the habitat depends to some degree on the form of the basin. Tidal river mouths such as the Brazos River mouth are subject to strong tidal and density current forces. Other tidal streams, such as the Trinity River at the head of the Galveston Bay system, are less affected by tidal forces; however, even in these streams tidal influence extends as far as 48 km (30 mi) upstream (U.S. Army Corps of Engineers 1975).

The strength of density currents is less than that of tidal currents, but density currents contribute to the transport of materials and organisms over a wide area (Belaire 1976). Hydrologic forces, therefore, are the main factors supplying materials and energy to the the biota in the upper and lower water levels and in the sediments.

Snyder et al. (1978) noted that in flowing streams 40 to 99 percent of the organic matter available to consumers is imported material. Phytoplankton and macrophyte production within the habitat account for a minority of the production. The consumer populations in channels are often greater than can be supported by phytoplankton production alone. Since imported organic matter is necessary to support these populations, it must also be considered a driving force to the channel and stream habitat.

Because of the stratification of water flows, many important attributes of this habitat cannot be considered homogenous throughout the water column. Significant differences in the measured values of chemical characteristics may exist at different levels. System components at different levels with important effects upon the biota in this habitat include salinity, water temperature, direction of flow (Withers 1973, Belaire 1976), turbidity affecting light penetration, and toxic materials (Holmes et al. 1974). In addition, the overall flow pattern may be of importance to all components. Withers et al. (1974) found that nutrient levels in channels with good communication with adjacent bay systems were similar to nutrient levels in the adjacent bays. However, in channels with low flushing rates, municipal and industrial inputs caused nutrients to accumulate at levels higher than those of bays.

Oxygen can be a critical component in the channel and tidal stream habitat. Oxygen is consumed by species at all levels. Benthic species and microorganisms that decompose organic matter in the sediments can produce significant benthic oxygen demands (120 to 220 mg of oxygen per sq m per hour in Houston Ship Channel sediments, Reynolds et al. 1973). In most aquatic systems oxygen is replenished by photosynthesis and by turbulent mixing of surface waters with deeper waters. Stratification may limit the amount of oxygen transfer from the upper to the lower strata. In channels or tidal streams distant from the gulf, water in the lower strata may not have contacted oxygen-rich surface layers since before it entered the estuary through a pass and began to move up the channel. Consequently low dissolved oxygen concentrations may occur in the lower strata of deep, long channels (Bryan 1971, Bowman and Jensen 1978).

Sediment is another component that must be considered at all levels. In some channels there may be a net movement of sediment upstream as the result of density currents; Belaire (1976) noted this in analyzing the pattern of accumulation of sediments in navigation channels over the entire Texas coastal region.

At the same time sediment may be carried downstream with river flow. When the channel width is narrow, flow velocity and sediment load are high. Narrow channels and tidal streams may carry a large sediment load in the upper level. When narrow channels and tidal streams open into wide bay areas some of the suspended materials settle, both because the surface waters slow and because the physical behavior of clay particles carried in fresh water changes when they contact estuarine waters. Surface charges on clay particles tend to keep them separated in fresh water. When the clay particles contact the dissolved salts in estuarine waters, the surface charge is reduced. This allows the particles to form aggregates that may settle to the bottom (Ariathurai et al. 1977).

The amount of sediment flowing down tidal streams can vary substantially from year to year. Dougherty (1979) reported on water and sediment volumes flowing down Texas streams to the region for periods of record averaging 31 yr and ranging from 14 to 50 yr. Sediment volume extremes varied from a low of 1 percent of the average sediment volume per year to a high of 400 percent of the average per year.

The biotic communities of the channel and tidal stream habitat differ according to flow level. Phytoplankton occur throughout the water column. In turbid waters the compensation point--the depth at which the photosynthetic

production of oxygen just balances phytoplankton respiration--may be as shallow as 0.3 m (1 ft) because of light attenuation (Armstrong and Hinson 1973).

Suspended allochthonous organic matter is transported in the upper and lower levels. In the upper level, phytoplankton and macrophytes may contribute significantly to the organic input. Material transported in the lower level is deposited and resuspended from the bottom sediments, depending upon turbulence and water flow velocity at the bottom boundary layer. There may be some transfer from the upper to the lower level as the current forces in the bottom level decrease far from the source of gulf tidal and density current influence.

Most herbivores and detritivores, intermediate consumers, and top carnivores are mobile and move from one level to the other. They may have level preferences depending upon presence of food items or environmental conditions such as temperature or salinity. Hughes (1969) postulated a salinity-related mechanism controlling transport of postlarval pink shrimp by flood tides. Postlarvae swimming against a current can detect a salinity decrease of 1 to 3 ppt and react to the change by sinking to the bottom and gripping the substrate. They reenter the water column upon detecting increased salinities. This behavior gradually moves postlarvae toward low-salinity areas. Hughes also described a salinity-based mechanism orienting the swimming direction of juvenile pink shrimp toward more saline gulf waters. King (1971) reported on the vertical distribution of nine commercial and sports species passing through Cedar Bayou between Mesquite Bay and the Gulf of Mexico. Postlarval and juvenile species were not distributed homogeneously

throughout the water column. Their vertical distribution might be related to transport mechanisms of life stages into and out of the gulf.

Mobile species often congregate in channels and tidal streams for food, migration, or other reasons. Many require a larger organic base for their food web than is available from phytoplankton production alone. Most of the mobile species enter or leave this habitat if adjacent acceptable habitats exist.

Flora and fauna. Abundant producer species in the habitat include the phytoplankton *Nitzschia* sp., *Skeletonema* sp., *Leptocylindricus* sp., *Thallasionema* sp., *Chaetoceras* sp., *Thallasiothrix* sp., and *Navicula* sp. The blue-green algae *Nostoc* sp., *Oscillatoria* sp., and *Anabaena* sp. are also common (Copeland and Fruh 1970, Holland et al. 1975). In the fresher portions of tidal streams *Potamogeton* sp. may be found, and widgeongrass (*Ruppia maritima*) may grow in shallow, less turbid water (Snyder et al. 1978).

Benthic species are largely polychaetes and mollusks. Some of the most frequently encountered polychaetes are *Mediomastus californiensis*, *Streplospio benedicti*, *Prionospio pinnata*, *Lumbrineresis tenuis*, *Cossura delta*, and *Clymenella lacteus*. The mollusks include *Mulinea lateralis*, *Lyonsia hyalina floridana*, *Abra aequalis*, and *Sigambra tentaculata* (Holland et al. 1975, Woodward-Clyde 1977, Flint and Younk 1983).

Common zooplankton in the herbivore group of consumers include polychaete larvae, bivalve veligers, and barnacle larvae (*Balanus* sp.) during their reproductive periods. The copepod *Acartia tonsa* is abundant throughout this habitat and other estuarine and marine areas. Other common species are *Oithona* sp., *Diaptomus* sp., *Pseudodiaptomus* sp., *Labidocera aestiva*, and the

dinoflagellate Noctiluca scintillans (Copeland and Fruh 1970, Holland et al. 1975.

Common herbivores found in the habitat include the menhaden (Brevoortia patronus), striped mullet (Mugil cephalus), and shad (Dorosoma sp.). In a study of emigration through a tidal pass, Copeland (1965) found that the cabbagehead jellyfish (Stomolophus meleagris) was the most prominent animal encountered in terms of biomass.

Intermediate consumers common to channels and tidal streams include shrimp (Penaeus sp.), sheepshead (Archosargus probatocephalus), spot (Leiostomus xanthurus), pinfish (Lagodon rhomboides), anchovy (Anchoa sp.), Atlantic croaker (Micropogon undulatus), sea catfish (Arius felis), freshwater shrimp (Macrobrachium ohione), and the blue crab (Callinectes sapidus) (Reid 1957, Chambers and Sparks 1959, Pullen 1962, Parker 1965, Henley and Rauschuber 1981).

Top consumers in the channel and tidal stream habitat include spotted seatrout (Cynoscion nebulosus), sand seatrout (Cynoscion arenarius), red drum (Sciaenops ocellata), black drum (Pogonias cromis), southern flounder (Paralichthys lethostigma), alligator gar (Lepisosteus spatula), and bottlenose dolphin (Tursiops truncatus).

Adjacent systems and flows. The channel and tidal stream habitat is adjacent to a diversity of upland and estuarine habitats. Bay, which makes up 28 percent of adjacent habitats, and spoil whcih makes up 27 percent, occur in the greatest proportion. Forest constitutes 17 percent of the adjacent habitats; range, 11 percent; and salt and brackish marsh, 7 percent. Other habitats occasionally found adjacent to the channel and tidal stream are urban, freshwater marsh, cropland, and grassflat.

Of these systems, the estuarine and spoil habitats regularly exchange materials, energy, and biota with the channel and tidal stream system. The upland systems and fresh marsh may contribute to the channel system regularly, but are they receive little exported material this habitat except during floods or or storms.

Materials imported and exported by the upper layer include fresh water, nutrients, organic matter, toxic material, oxygen, and organisms. The upper layer transfers materials both to and from adjacent habitats and to the lower level. The lower level transports salt, sediment, organic matter, and organisms from sources further down the bay. In the mixing zone between the two levels all materials may be transported back and forth. Salt from the lower level and organic matter and toxic material from the upper level are probably the most important materials transferred.

Economic uses. The primary use of channels and tidal streams is for navigation. Tidal streams such as the Trinity River, Chocolate Bayou, Brazos River, San Bernard River, Colorado River, Arroyo Colorado are navigable some distance from their mouths. Eight stabilized passes or river mouths in the region are wide and deep enough for navigation; five of these passes can accommodate deep-draft ships. Many channels are dredged for shallower vessels, particularly barges. In 1977, 420 million metric tons (460 million short tons) of goods traveled waterways in the region (Liebow et al. 1980). About 30 percent of the tonnage was transported on the Gulf Intracoastal Waterway (Texas General Land Office 1975).

Channels are also used by commercial fishing vessels and recreational boats. Fishing vessels constitute 18 percent of the traffic on the Gulf

Intracoastal Waterway, and pleasure boats make up 19 percent of the traffic (Liebow et al. 1980). Recreational fishing is a common activity in channels.

Channels have been intentionally dredged through the barrier habitat to alter circulation patterns in the bays. Rollover Pass (Reid 1957), Yarborough Pass (Simmons 1957), and Corpus Christi Pass (Watson and Behrens 1976) were all dredged to increase circulation and provide migration pathways to the gulf for estuarine species. The goal for Rollover pass was to raise the salinity in East Bay to improve fishery production; the goal for Yarborough Pass was to lower the salinity of the Northern Laguna Madre to improve fishery production. The goals for Corpus Christi Pass were to increase bay circulation, and provide recreational opportunities. In addition, there was a vague possibility (later prohibited) that the pass would be navigable, affording a shortened route for sport-fishing vessals based in the southern portion of the Corpus Christi Bay. These attempts met with varying degrees of success. Sedimentation closed Yarborough Pass almost immediately after its construction. Corpus Christi Pass has been shown to have only a minor effect on bay circulation. Rollover Pass came closest to its objective of altering bay salinity patterns, but it experienced unexpected rapid erosion that was halted at great expense.

Impact of man's activities. The main activities that occur in the channel and tidal stream habitat are navigation and dredging to create or maintain navigation channels. The immediate effects of dredging are turbidity and direct removal of organisms and habitat. There is a potential for release of nutrients, a few heavy metals (Delahoussaye 1981), and oxygen-demanding materials (Belaire 1976) from disturbed sediment. Benthic organisms do recolonize the dredged area; in some instances recolonization has been rapid,

but in others complete restoration of the preexisting community appears to occur slowly (Rogers 1976).

The major long-term impacts of dredging are alteration of the habitat type (such as conversion of shallow water to deep channel) and hydrologic effects including changes in flow volume, flow direction, quantity and timing of peak flows, and salinity patterns. Hydrologic changes are usually the largest in scope and the least easily predicted. In addition to these changes, ship traffic causes large hydraulic displacements and waves that stir up bottom sediments and aggravate bank erosion. Reviews of the impacts of dredging in Texas are found in Belaire (1976), Bouma (1976), and Delahoussaye (1981).

While hydrologic changes in channels often increase flow out of estuaries into the gulf, they also encourage flow into the estuary from the gulf. Bayward flow through large passes increases the bay's vulnerability to gulf oil spills. The recent spill from the tanker Burma Agate off Galveston and the IXTOC I well blowout in Mexico (both in 1979) resulted in entry of crude into Galveston Bay and Laguna Madre from the gulf. Mansfield Pass and small natural passes with low tidal exchange were closed relatively easily, but attempts to block entry of material into the bays through major passes were only partially successful since not all of the oil floated at the surface.

Banks of channels and tidal streams are used by industry for manufacturing plants and docking facilities. Because of the proximity of channels to highly urbanized areas, industrial effluents, municipal wastes, and urban runoff are sometimes funneled directly into the habitat where they can easily flow to the estuary. Industrial effluents are more stringently

regulated than in the past; however, municipal wastes and runoff have not been controlled to the same degree.

Cropland

Areal extent. Cropland occupies 11,351 sq km (4399.7 sq mi) in the Texas Barrier Island Region and is the second largest habitat unit, accounting for 21.7 percent of the region's area. The cropland in the region is 8.3 percent of the cropland in the state (calculated from Texas Soil and Water Conservation Board 1981).

The Nueces basin has the largest proportion of cropland (Figure 80); cropland occupies 43.7 percent of the basin's area (957.5 sq km or 369.7 sq mi). The Brazos basin has the second largest relative amount, 31.2 percent (775.7 sq km or 299.5 sq mi). The San Antonio basin has the smallest proportion of cropland, 14.2 percent (320.6 sq km or 123.8 sq mi).

Physical description. In the Texas Barrier Island Region cropland exists in large tracts rather than scattered small parcels. Its seaward edge of usually lies no closer to the gulf shoreline than 11 to 16 km (7 to 10 mi). Cropland in the upper and midcoast areas is nearly level and consists of weakly dissected prairie. The soils in these areas are clays and clay loams. Rainfall is high, averaging 71 to 142 cm (28 to 56 in) per year. Rice is an important crop in the upper and midcoast areas. Dikes and canal systems are constructed for rice irrigation, and the rice fields are leveled for uniform inundation.

In Kenedy and Kleberg counties and in the upper portion of Hidalgo County, cropland is gently rolling dissected plain, and the soils are loamy sands and sandy loams. Rainfall averages 86 to 99 cm (34 to 39 in) per year. In the Rio Grande Valley the land is nearly level plain, and soils are deep

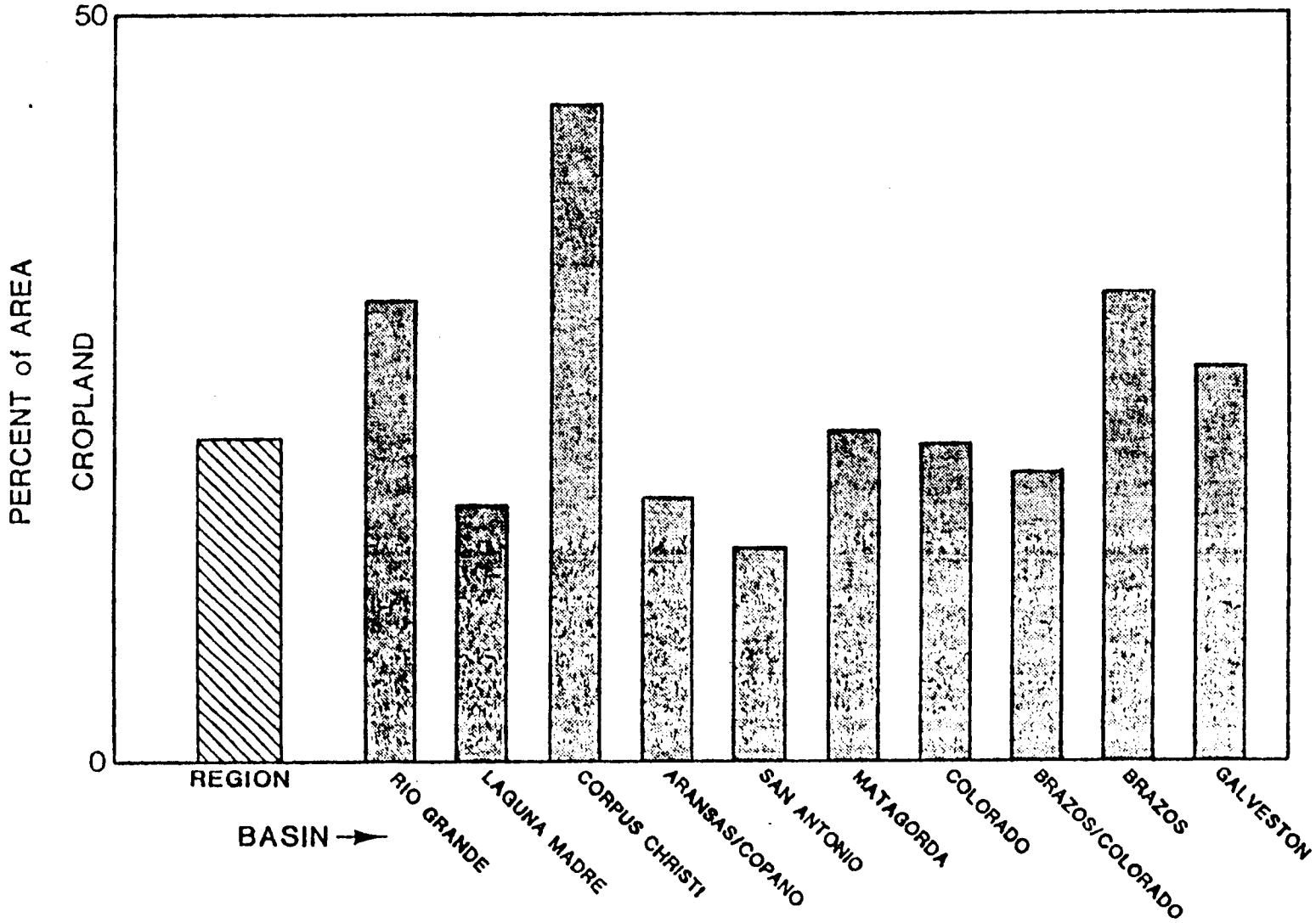


Figure 80. Percent of region and basin area that is cropland.

clay loams, clays, and sandy loams. Rainfall is low, averaging 43 to 71 cm (17 to 28 in) per year. Here crops must be irrigated; more than one-third of the irrigation canals in the region are found in the Lower Rio Grande Valley.

Most cropland has been developed on natural prairie or brushy savannah. In the upper and midcoast areas, however, areas of oak forest, oak-pine forest, and floodplain forest have been converted to cropland. Floodplain forest along the Lavaca, Colorado, and Brazos rivers has been particularly affected.

System operation. Cropland is used to grow food and fiber through the intense management and enhancement of natural plant growth. The objectives of agriculture are to achieve maximum yield, operate with maximum profit, minimize year-to-year instability, and prevent long-term degradation of the agricultural system (Altieri et al. 1983). In the past century agriculture in the region has changed from an intensive system emphasizing high inputs of labor to an extensive system minimizing labor costs. Farmers have found that selective addition of water, fertilizer, and agricultural chemicals (herbicides and pesticides), combined with new management actions (often requiring use of fossil fuels), increases crop yields and profits. These material additions and management actions along with solar radiation are the driving forces that direct the operation of cropland habitats.

In the Texas Barrier Island Region 3.97 billion cu m (3.22 million ac-ft) of water per year are used for irrigation to supplement natural rainfall. Most of that water is consumed; about 722 million cu m (585,000 ac-ft), or 18.2 percent returns directly to rivers, streams, and estuaries. About 64 percent of the water used for irrigation in the region comes from surface

sources; the remainder is groundwater (calculated from Texas Water Development Board 1977). The quantity of irrigation water supplied is roughly equivalent to enough water to cover all of the region's croplands to a depth of 0.5 m (1.6 ft) each year.

Because of the variety of fertilizers, agricultural chemicals, fossil fuels, and management techniques used on cropland, cost figures are one of the few measures indicating intensity of use. For the 827,000 ha (22.04 million ac) of cropland harvested in the region in 1978, $38.2 million was spent on fertilizers, $25.4 million on chemicals, $27 million on fossil fuels, and $47.2 million on hired labor. These expenses constituted 34.6 percent of the market value of the crops in 1978 (calculated from Bureau of the Census 1978).

Cropland habitats are ecosystems manipulated so that they remain in immature, early stages of succession (Odum 1969). As such they have characteristics different from those of natural ecosystems that are in mature or climax stages. Trophic chains are simple and short in croplands, while complex, long, or both in natural ecosystems; species diversity and genetic diversity are low in croplands, high in natural systems; mineral cycles are open in croplands, closed in natural ecosystems; and stability and permanence are low in croplands, high in natural systems (Altieri et al. 1983).

Changes that occur in natural systems during succession decrease net productivity by diverting organic matter to maintain the more complex, but stable, structure of a mature system. Since net production is the yield farmers seek, much effort is spent in resisting the successional trend. To maximize net production, farmers must combat growth of competing weeds, consumption of crops by herbivore pests, and infection by disease-producing organisms--all part of the natural succession process.

The essential components of cropland habitat include soil nutrients, soil structure, the microorganism-organic matter complex, and the plants themselves. Soil nutrients supply vital elements for plant growth and partially control the production of plant material. In most natural terrestrial systems, decaying organic matter releases bound nutrients that become available for use by plants; this allows a closed nutrient cycle with few losses to or gains from outside systems. Cropland nutrients are removed as part of the harvest and are not replaced through natural processes unless the rate of soil formation on the land is greater than the loss from harvest. In addition, soil erosion may result in large losses of soil nutrients as well as soil material itself. Moderate to severe erosional losses from water and wind have been reported in many coastal counties. Severe erosion rates may range from 3.4 to 13.4 metric tons (3.8 to 14.8 short tons) per acre, and in a few counties may affect as much as half the cropland (Texas State Soil and Water Conservation Board 1981).

Soil structure and texture--physical properties of the soil that determine characteristics such as permeability, water capacity, and cohesiveness--can strongly influence plant production. Consequently, farmers often alter soil structure by adding organic and inorganic matter and by tilling.

The microorganism-organic matter complex is a complicated component of cropland habitats. Microorganisms are intimately bound to soil organic matter. They improve the soil by degrading organic detritus, releasing inorganic nutrients to the soil, fixing atmospheric nitrogen into nitrates, and producing materials that stimulate plant growth. Microorganism

populations in the soil that perform these functions are actively developed by farm management actions.

Materials added to the soil and management actions taken by farmers directly influence soil components. Chemical fertilizers replace lost nutrients, provide extra nutrients at critical growth periods, and may stimulate microorganism populations. Fields are often planted with cover crops or nitrogen-fixing plants that are later plowed under to improve organic and nutrient content of the soil. Other materials may be plowed into the soil to alter its structure. Nearly all of these actions require the use of energy to fuel vehicles for application and spreading of material, and for mechanical soil manipulation.

The plants in croplands are usually monotypic stands raised on soil recently disrupted by tilling. Competing plant species such as weeds that thrive in these conditions must be controlled to maximize crop yield. This is usually accomplished by applying herbicides and by tilling. Likewise, monotypic stands of plants in croplands are particularly subject to rapid consumption by pest species (especially insects) and infection by plant disease organisms and nematodes (Altieri et al. 1983). Pests and disease organisms are usually controlled through application of pesticides and other agricultural chemicals. Thus the main management actions controlling these competitors and consumers involve the use of agricultural chemicals and energy to fuel vehicles that apply chemicals or plow the land.

Significant changes in U.S. agricultural practices over the period 1945 to 1970 have been documented by Pimentel et al. (1973). For example, significant increases in energy input per unit area were shown for maize production as follows: a 42 percent increase in fuel energy; a 1300 percent

increase in energy for fertilizer; an 82 percent increase in energy for irrigation; a 330 percent increase in energy for herbicides and insecticides; and a 2900 percent increase in energy for crop drying. Crop yield increased by 150 percent, while labor energy input dropped to 40 percent of the 1945 figure. Pimentel's data showed that although crop yields increased dramatically, the costly inputs to croplands increased at an even greater rate.

Increased use of chemicals, pesticides, and mechanization have had major economic consequences for the agriculture industry. Unforeseen ecological effects have further complicated the industrialization of cropland, as can be seen from the recent history of cotton production in Texas. Nearly 50 percent of all the insecticide used on crops in the U.S. is applied to cotton (Adkisson et al. 1982). In the 1930's the boll weevil (Anthonomus grandis) was the key cotton pest. The pink bollworm (Pectinophora gossypiella) and tobacco budworm (Heliothis virecens) were secondary pests. Calcium arsenate was used to control the boll weevil, and though the pesticide was not totally effective, it permitted profitable production. Calcium arsenate had one advantage: many natural insect enemies of cotton pests were only minimally affected.

In the mid 1940's DDT was used on cotton with great initial success; the boll weevil was controlled and farmers were able to increase yields with fertilizer and irrigation. At the same time, insect enemies of the bollworm were also decimated. As a result the bollworm, less affected by low DDT concentrations, became more common in cotton fields. By the 1950's the boll weevil had become resistant to DDT, and methyl parathion was used to control

it. Methyl parathion, however, killed insect enemies of the bollworm, so DDT was added to help control this pest. By the 1960's the bollworm and the tobacco budworm had become resistant to DDT, toxaphene, and endrin. To control them, more frequent, increased doses of methyl parathion were required. Control was not as complete for these pests, but was effective for boll weevils. By the late 1960's bollworm and tobacco budworms had become the key pest species, and by 1968 the tobacco budworm had become resistant to methyl parathion.

New strategies were required to control pest species and keep cotton crops in early successional stages. A new system involving the principles of integrated pest management was instituted in Texas. This system used a large number of strategies to control pests: special strains of plants were developed that were resistant to disease, cold-tolerant, and rapid-fruiting; plants were planted early, and fertilizer and irrigation were used to induce early plant maturation; insecticides were used infrequently to avoid killing insect predators and to attack pest species at critical points in their life cycles; desiccants and defoliants were used to terminate crop growth; cotton was harvested rapidly; and stalks and residues were ground up and plowed into the ground quickly.

For cotton grown in the coastal region the new strategy has been very successful. Compared to methods used before 1975 this strategy has doubled the yield to 209 kg (459 lb) per acre, more than doubled the profit to $170 per acre, and decreased the quantity of pesticides applied from 5.6 to 0.7 kg (12.3 to 1.5 lb) per acre (Adkisson et al. 1982).

The example of cotton production illustrates that cropland must be managed with careful attention to subtle details about the system to extract

the greatest yield and to keep from contributing to new problems in the future. Agricultural managers have learned that maintaining high production in early successional systems over a long period is very difficult and that many techniques must be used in combination to provide sustainable yields. Some of these techniques include: integrated pest management (Batra 1981); stringent soil conservation measures (Altieri 1983); reduced and no-tillage practices (Oldenstadt et al. 1982); breeding special varieties highly adapted to local conditions (Boyer 1982); and providing plant diversity in the field (Altieri 1982). Because of increases in energy and chemical costs, some strategies thought to be less profitable, such as organic farming, are being reevaluated (Lockeretz et al. 1981).

Flora and fauna. The main crops grown in the Texas Barrier Island Region include rice, sorghum, cotton, sugarcane, and soybeans; beets, broccoli, cabbage, spinach, lettuce, and other vegetables; cantaloupe, melons, grapefruits, peaches, and avocados; and pecans. Crops in the nation are affected by 160 species of bacteria, 250 kinds of viruses, 8000 species of fungi, 8000 insect species, and 2000 weed species. Species of rabbits, mice, rats, and birds are transient inhabitants of croplands.

Adjacent systems and flows. More than 62 percent of the habitats adjacent to cropland are rangeland; 19 percent are forest, and about 8 percent are urban land.

Cropland exports a number of materials to adjacent habitats. The materials are all associated with sediment, and they are exported with it in runoff water from cropland. Sediment solids, nutrients, and organic matter

are lost from croplands as part of the erosion process. Toxic materials--herbicides and pesticides applied to croplands--are also exported by runoff.

Salt is imported into croplands from irrigation water, rainwater, and dry fallout of particles carried through the air from the gulf (Fanning and Lyles 1964). High concentrations of salt can have a negative effect on plant productivity. Salt is removed from sediments only through runoff or flushing of salts to deeper groundwater. Because of the low permeability of most cropland soils in the region, salt removal generally occurs through runoff.

Economic uses. The harvest from cropland in the region was valued at nearly $400 million in 1978. This was 2.6 times the market value of crops in the region in 1969. A substantial portion of the increase in market value was due to inflation and an increase in harvested acreage (19.8 percent). Table 42 compares market values and some production expenses adjusted for inflation and converted to a per-acre basis. The dollar amounts for 1974 and 1978 are stated in terms of constant 1969 dollars (calculated from Bureau of the Census 1974, 1978).

Over the nine-year span, the market value of crops has varied widely--between $88.48 and $140.06 per acre. Production expenses have not fluctuated nearly as much. Energy and labor expenses have remained nearly constant. Expenditures for chemicals rose sharply in 1974 but have remained fairly constant since then. The expenditure for fertilizer jumped by 50 percent between 1969 and 1974 but decreased by 25 percent in 1978. This may indicate a trend of decreased use of fertilizer, as in the case of the recently revised cotton management techniques.

Cropland makes up about one-third of the habitats that lie immediately adjacent to urban land. In places with rapidly growing urban areas, cropland

Table 42. Market value and production costs for crops in the Texas Barrier Island Region.

Cost or value estimate	Year 1969	1974	1978
Acres harvested	1,705,235	1,728,572	2,042,712
Market value per acre	$88.48	$140.06	$104.12
Fertilizer cost per acre	$8.72	$13.11	$9.98
Chemical cost per acre	$4.80	$6.33	$6.63
Energy cost per acre	$6.29	$6.68	$7.08
Labor cost per acre	$13.34	$11.64	$12.33
Market value per unit cost for production (i.e., market value divided by the sum of fertilizer + chemical + energy + labor cost)	$2.67	$3.71	$2.89

is converted to urban land at a high rate. In Harris County (part of the Galveston basin), cropland declined from 71 percent to 44 percent of the county area between 1960 and 1974 (Houston-Galveston Area Council 1970). Other declines due to conversion to urban land have been reported for the Nueces basin and the Rio Grande Valley (Liebow et al. 1980).

Impacts of man's activities. When natural habitats are converted to cropland, the natural plant and wildlife populations are lost and hydrologic relations are altered. Removal of cover vegetation increases the soil temperature during the daytime, allows increased wind speeds at the soil surface, and results in lowered relative humidity. These combined influences may slightly increase the overall rate of evaporation of the soil, necessitating irrigation. Removal of cover also results in less anchoring of soil and increases wind erosion.

Croplands receive a larger quantity of water than the original natural system, both because of irrigation and because removal of the overstory and interfering vegetation allows more rain to reach the soil than in natural systems. Tiry (1976) notes that interception of rainfall and evapotranspiration are lower on croplands than on natural systems. However, because rainfall reaches the soil quickly, upper portions of the soil may be rapidly saturated or may be subject to soil capping--blocking of the soil pores by fine sediment grains, pulverized by the direct force of raindrops. As a consequence the infiltration rate into crop soils may be less than in fields with more ground cover (Tiry 1976).

A lower infiltration rate and less interception of rainfall mean that more surface water is available for surface runoff. The runoff transports

sediment and nutrients, organic matter, and toxic chemicals that adhere to it. These materials may be carried to adjacent systems, especially aquatic systems. The effects on adjacent systems can range from stimulation of production to interference with system function, depending upon the quantity and nature of the transported materials. The effect on the cropland system may range from removal of undesirable accumulated surface salts to an increase in soil erosion above the natural replacement rate.

Toxic materials used on crops may have planned and unplanned effects. While helping to control pest species and increase yield, some pesticides are harmful to other species. Natural predators of some pest species may be poisoned, allowing the prey species to flourish unchecked. Pollinators such as honeybees may be killed by pesticides; this can have a direct effect upon crop yield. Other species peripheral to the cropland habitat may be affected because toxic residues are transported to aquatic systems. To minimize these undesirable effects the emerging philosophy is to use pesticides sparingly and only at critical times in the crop growth cycle and pest life cycle.

The average yearly input of major streams into the region is approximately 17.9 billion cu m (14.5 million ac-ft) (Texas Water Development Board 1967; Texas Water Development Board 1970; Texas Water Development Board 1977; Texas Department of Water Resources 1979). About 2.5 billion cu m (2.1 million ac-ft), or 14 percent of the river flow, is diverted to agricultural use (Texas Department of Water Resources 1977). Subsidence and declining aquifer levels have been the impetus for preferential development of surface water resources to meet the region's water needs. While agricultural use of cropland results in increased runoff compared to the flow from the land in its natural state, the runoff increment does not make up for the quantity consumed

in agriculture. Since agricultural water use and surface water use are both increasing in the region, diversion of water from rivers and streams is certain to increase further. As it does, water diversion for agricultural use will gain in importance as the as the single most critical water use affecting freshwater inflows to Texas bays.

Freshwater Marsh

Areal extent. There are 264.4 sq km (102.1 sq mi) of freshwater marsh in the Texas Barrier Island Region. This constitutes 0.5 percent of the region's area. Freshwater marsh is found in all basins. Figure 81 shows the distribution of this habitat as a percentage of the basin area. The Matagorda basin has the largest amount of freshwater marsh, 72.5 sq km (28 sq mi), occupying 1.1 percent of the basin area. The Laguna Madre basin has 45.1 sq km (17.4 sq mi) or 0.27 percent of the basin area; the Galveston basin has 43.0 sq km (16.6 sq mi), or 0.4 percent of the basin area; and the Aransas-Copano basin has 42.2 sq km (16.3 sq mi), or 0.9 percent of the basin area. The Rio Grande basin has the smallest amount of freshwater marsh, 0.26 sq km (0.1 sq mi), which is less than 0.05 percent of the basin area.

Physical description. Large freshwater marshes occur along the lower portions of major rivers and streams that provide significant freshwater inflow into bay systems. The Trinity, Lavaca, Guadalupe, Mission, Aransas, and Nueces rivers all have large areas of freshwater marsh adjacent to them.

A second group of smaller freshwater marshes, not associated with river mouths, are found near inland streams, around small inland lakes, or in depressions that receive and trap rainwater but receive no stream flow. Blackjack Peninsula (site of the Aransas National Wildlife Refuge) and the mainland between San Antonio and Matagorda bays have many small inland

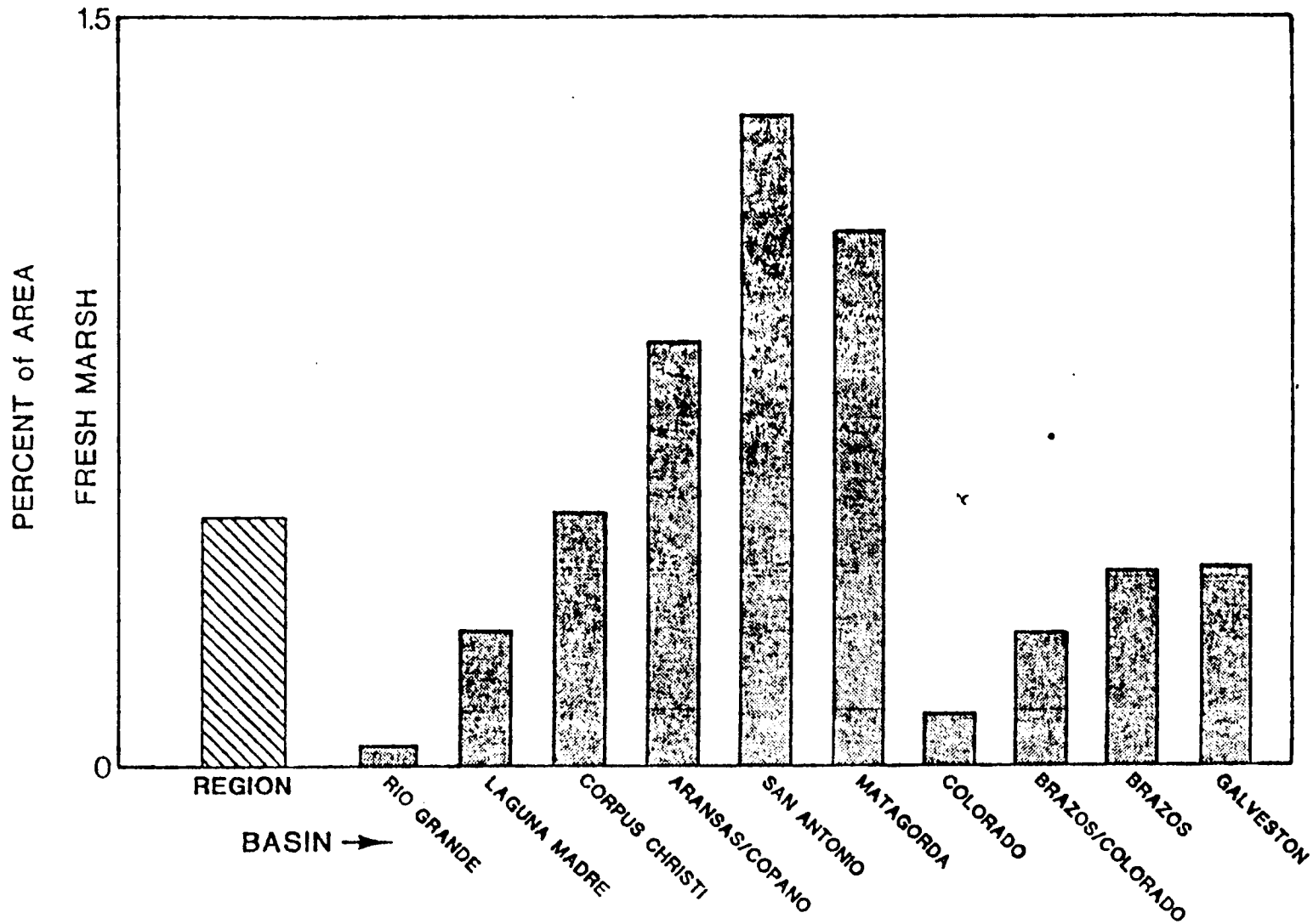


Figure 81. Percent of region and basin area that is freshwater habitat.

freshwater marshes supplied with water from rainfall and land runoff. These marshes are located in remnant swales and relict drainage systems that developed between Pleistocene strandplain beach ridges (McGowen et al. 1976). Many of them lie in long narrow bands parallel to the curve of the present shoreline. The substrate in these areas is mud, so drainage is poor and standing water remains in the marshes most of the time. During dry years they may dry up completely; in wet years they may form ponds.

In the Laguna Madre basin, ephemeral freshwater marshes form in numerous small depressions in swales on the barrier islands, among the clay dunes landward of the wind-tidal flats, and in blowout areas within the eolian sand sheet. An area of freshwater marsh has also developed on a thin Holocene mud covering Pleistocene marine deltaic sands at the edge of Laguna Larga, an inland lake on the Encinal Peninsula between Corpus Christi and Baffin bays (Brown et al. 1976, 1977).

A third type of freshwater marsh is the highest marsh unit in a gently sloping gradient of marsh types running from freshwater marsh to brackish marsh. This series of wetland units is typical of the chenier plain in the eastern portion of the barrier island region. Freshwater marshes in the extreme eastern edge of Galveston Bay are of this type (Gosselink et al. 1979).

Freshwater marshes vary greatly in form. Some are ponds or waterways that are partially or completely vegetated with floating or rooted plants. Others are located on solid ground where the water table is near or at the land surface; here freshwater marsh is difficult to distinguish from rangeland and may be grazed by cattle.

The elevation range for freshwater marsh is greater than for other wetland types. Scifres et al. (1980) studied an area of freshwater marsh in the Welder Wildlife Refuge. Wetland plants were found over a 2.6-meter (8.5-foot) elevation span, but definitely below the upland vegetation boundary. Freshwater marshes surrounding ponds may have even greater elevation ranges. Salt and brackish marsh vegetation occurs within a range of less than 1.5 m (4.9 ft) (McGowen and Brewton 1975; Henley and Rauschuber 1981).

System operation. Hydrology is the most critical driving force for this habitat. In shallow marshes, the presence of a thin layer of water or a high water table is the condition that excludes upland plants or allows emergent wetland plants to successfully compete with them. In deeper marshes, standing water provides the proper environment for floating plants or emergent species. Water enters the freshwater marsh from three sources: direct precipitation, runoff from the adjacent uplands, or floodwaters from nearby rivers and streams. For small, isolated inland freshwater marshes the former two water sources are critical; for marshes near river deltas, river flooding is the critical input. The latter have a more dependable water source since freshwater from an entire river basin passes nearby.

Water level fluctuation is of little importance for ponded freshwater marshes. Unlike swamp vegetation, floating and benthic freshwater plants do not need fluctuating water levels for seed germination. In shallow marsh areas, however, occasional water level fluctuation may be the main factor controlling vegetation success. For example, short-term accumulations of standing water appeared to be the only environmental parameter that could be related to gulf cordgrass (*Spartina spartinae*) distribution in a study by

Scifres et al. (1980). The presence of this plant was not correlated with any chemical or physical soil properties that usually govern plant distribution.

Freshwater marshes located near river mouths export some of their organic production. The gulf cordgrass component of the Nueces River deltaic marsh system produces and loses 16.9 Kg per sq m per year (Wiersma 1977). Annual primary production of freshwater marsh vegetation along the Trinity River ranges from 0.22 to 2.98 Kg per sq m per year (Adams 1977). Most of this production accumulates until episodic flooding transports some of it to the estuary downstream (Texas Department of Water Resources 1981). Isolated freshwater marshes tend to accumulate their organic production and form peat unless the accumulated matter is swept out by floods. Freshwater marsh in the eastern extreme of the region is periodically burned to release nutrients and encourage growth of particular species for cattle feeding.

Freshwater marshes that are occasionally flooded receive nutrient inputs from the floodwaters. Isolated freshwater marshes may receive some nutrients from rainwater and land runoff, but they recycle most nutrients since they are relatively closed systems. Many freshwater marsh plants remove dissolved nutrients from water so efficiently that they are used in tertiary treatment facilities as biologic filters to reduce nitrogen and phosphorus in sewage effluent (Kadlec 1979).

Flora and fauna. The water hyacinth (*Eichornia crassipes*) and alligator weed (*Alternanthera philoxeroides*) are floating plants found in many freshwater marshes. Southern wildrice (*Zizaniopsis miliacea*), cattail (*Typha* sp.), and arrowhead (*Sagittaria* sp.) are emergent species that grow in shallow standing water and spread into deeper water areas. Shallow-water plants include knotweed (*Polygonum* sp.), sawgrass (*Cladium jamaicense*), big cordgrass

(Spartina cynosuroides), leafy threesquare (Scirpus robustus), soft rush (Juncus effusus), and rattlebush (Sesbania drummondii). The common reed (Phragmites australis) and spikerush (Eleocharis sp.) grow at the water's edge and extend to higher elevations that are intermittently or rarely flooded. Longtom (Paspalum lividum) and gulf cordgrass (Spartina spartinae) inhabit the highest areas where standing water occurs infrequently (Box and Chamrad 1966; Rowe 1974; Adams 1977; Espey, Huston and Associates 1978; U.S. Army Corps of Engineers 1981; Lazarine 1982).

Common invertebrates include the conchostracan Caenestheriella belbelfragei, the anostracan Streptocephalus texanus, dragonflies (Libellulidae), water boatmen (Corixidae), backswimmers (Notonectidae), diving beetles (Dytiscidae), mosquitoes (Culicidae), midges (Chironomidae), and the crayfish (Procambarus clarkii) (Rowe 1974; Espey, Huston and Associates 1978).

Fish commonly found in freshwater marshes include the green sunfish (Lepomis cyanellus), bluegill (L. macrochirus), golden shiner (Notropis fumeus), catfish (Ictalurus spp.), mosquito fish (Gambusia affinis), and crappie (Pomoxis spp.) (U.S. Army Corps of Engineers 1981).

Freshwater marshes are attractive habitats for many amphibians and reptiles. Among them are the green treefrog (Hyla cinerea), cricket frog (Acris crepitans), leopard frog (Rana ultricularia), bullfrog (Rana catesbeiana), snapping turtle (Chelydra serpentia), red-eared turtle (Pseudemys scripta elegans), green watersnake (Natrix cyclopion cyclopion), ribbon snake (Thamnophis sauritus proximus), western cottonmouth (Agkistrodon piscivorus leucostoma), and the American alligator (Alligator

mississippiensis) (Rowe 1974; Espey, Huston and Associates 1978; U.S. Army Corps of Engineers 1981).

A variety of birds live in freshwater marshes; some are year-round residents and others are seasonal. Some of the common birds are the white-fronted goose (Anser albifrons), blue-winged teal (Anas discors), green-winged teal (A. crecca), northern shoveler (A. clypeata), American coot (Fulica americana), red-winged blackbird (Agelaius phoeniceus), cattle egret (Bubulcus ibis), great egret (Casmerodius albus), and snowy egret (Egretta thula) (Espey, Huston and Associates 1978; U.S. Army Corps of Engineers 1981).

Mammals that are commonly found in and around freshwater marshes include nutria (Myocastor coypus), muskrat (Ondatra zibethicus), raccoon (Procyon lotor), marsh rice rat (Oryzomys palustris), and swamp rabbit (Sylvilagus).

Adjacent systems and flows. Nearly 58 percent of the habitats adjacent to freshwater marsh are range. Both small, isolated freshwater marshes and those located near river deltas are adjacent to rangeland. Since water is the main material input to freshwater marshes, the importance of upland runoff to these systems is clear. The lake and reservoir habitat constitutes 15 percent of the adjacent habitats, and channel is adjacent 7 percent of the time. These systems are also important in supplying water and nutrients to freshwater marshes. Cropland makes up 5 percent of the adjacent habitats, forest 10 percent, and salt and brackish marsh about 3 percent.

Animal movement into and out of the freshwater marsh is a significant tie to adjacent systems. Except for the fish, most of the vertebrates and many of the invertebrates are not permanent residents of the freshwater marsh. Many come to the freshwater marsh only for food, water, or building materials for

nests. Others--insects, for example--require the marsh habitat for part of their life cycle.

Economic uses. Freshwater marshes adjacent to range and cropland are attractive areas for expansion of agricultural uses. Rowe (1974) notes that freshwater marshes in Chambers County have been reclaimed for riceland. In other areas cattle graze on plants at higher elevations. Freshwater marshes have been dammed to provide water storage and created to attract waterfowl for hunting.

Impacts of man's use. Some uses of freshwater marsh require extreme alterations that convert the wetland to a different habitat. Draining a fresh marsh to create cropland, or deepening and stabilizing it to create an open water body are two types of permanent habitat changes.

While rice farming alters the natural vegetation and hydrology, the operation of this cropland system is similar to the natural marsh function, and some consumer groups continue to be supported by the altered system. If abandoned, some riceland areas may revert to their natural state.

Freshwater marshes that are intensively managed for waterfowl may be enhanced by man's management actions. Diked areas with water control structures allow careful control of water levels to promote particular freshwater marsh plants attractive to waterfowl.

Forest

Areal extent. Forest habitat comprises two distinct ecosystems, floodplain forest and upland forest. These ecosystems have been modeled separately (see appendix) but can be considered a single habitat since they share many of the same species, look very similar, and generally function in the same manner.

Forest in the Texas Barrier Island Region covers more than 2823 sq km (1090 sq mi), 5.4 percent of the region's area. The proportion of forest habitat in each basin increases to the north (Figure 82). The Rio Grande basin contains no forest, and the Laguna Madre basin has very little. In the Galveston basin, forest occupies 940 sq km (363 sq mi), or 8.7 percent of the basin area; in the Matagorda basin 608 sq km (235 sq mi), or 9.0 percent of the basin area, is forested; and the Brazos-Colorado basin contains 404 sq km (156 sq mi) of forest, 11.2 percent of the basin area. Forest in the Brazos basin comprises the greatest proportion of basin area; the habitat occupies 383 sq km (148 sq mi), or 15.5 percent of the basin.

Forest habitat has been greatly altered by man in the past two centuries. Areal estimates of biologic assemblages and environments, a measure of the potential natural vegetation before the land was altered, show that more than 4053 sq km (1565 sq mi) of forest habitat existed in the region (Fisher et al. 1972; Fisher et al. 1973; Brown et al. 1976; McGowen et al. 1976a; McGowen et al. 1976b; Brown et al. 1979; Brown et al. 1980). Today more than 30 percent of the forest habitat has been transformed to other habitat types.

Physical description. Floodplain forest is the predominant forest habitat in the region. Floodplain forest plants are adapted to wet conditions ranging from year-round saturation to annual flooding with subsequent drying. Most floodplain forest areas are narrow and closely follow stream or river boundaries.

In the Colorado, Brazos-Colorado, and Brazos basins the span of floodplain forest is wide--in some places more than 40 km (25 mi). These three basins have been very active in recent geologic history. The Brazos

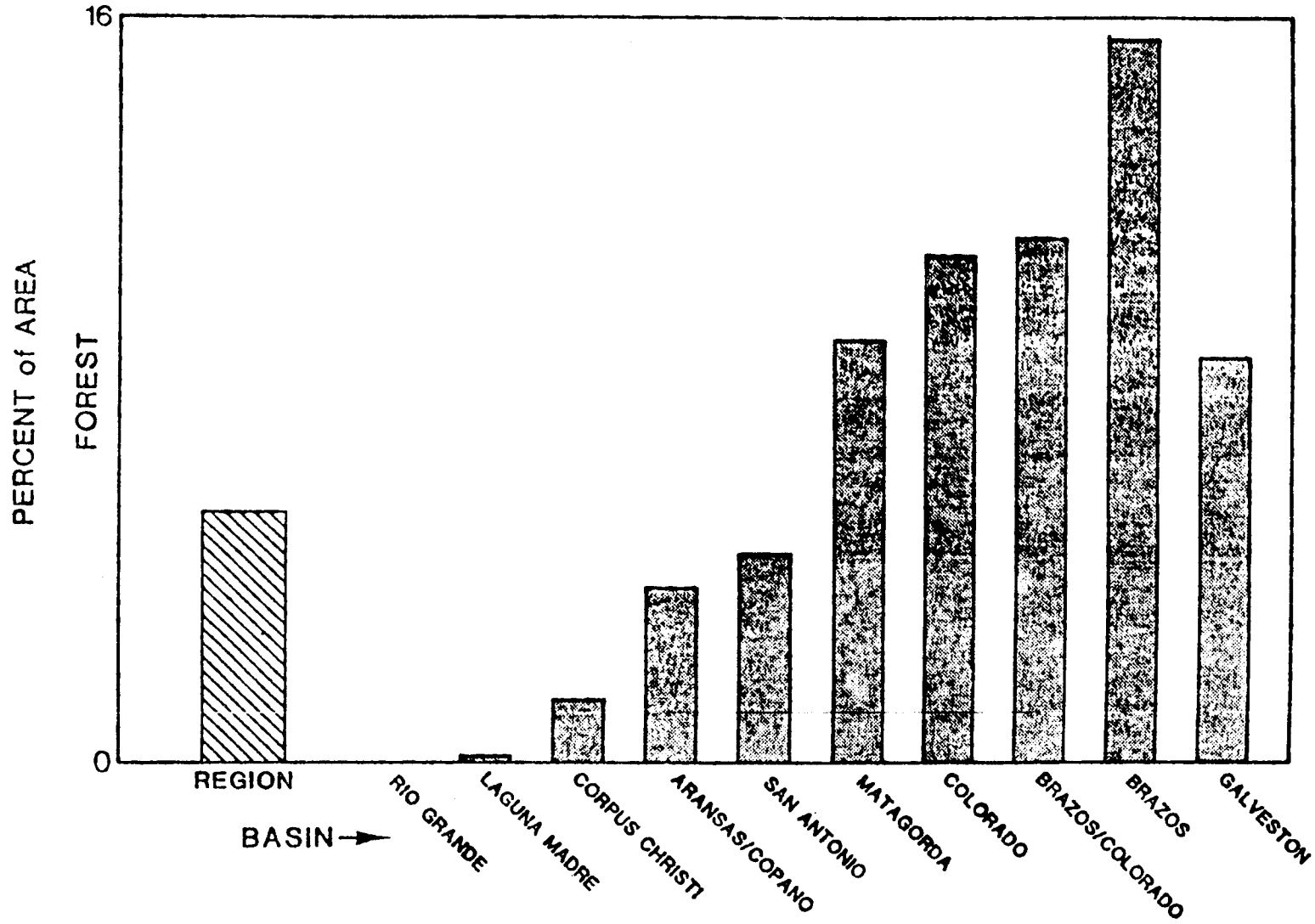


Figure 82. Percent of region and basin area that is forest habitat.

River completely filled its estuary about 1800 years ago. Since then the Brazos has built at least four different deltas between its present stabilized location and San Luis Pass more than 32 km (20 mi) to the northeast (McGowen et al. 1976a). The Colorado River changed its course about 1000 years ago and ceased flowing down the stream now called Caney Creek. It quickly filled its small estuary and built a small delta into the eastern arm of Matagorda Bay. During the past 2000 years these rivers and associated smaller streams have meandered back and forth across the basins, depositing fluvial sand and flood-basin mud. The sediment deposited by the streams, physiographic features such as depressions and oxbows, and ample rainfall have provided conditions that support a wide expanse of floodplain forest. Today, many parts of the original floodplain forest are located some distance from rivers and streams.

There are two distinct types of upland forest: mixed pine-hardwood and coastal maritime forest. Chambers, Harris, and Liberty counties are the southern and western boundaries of southeastern mixed pine-hardwood forest (Bailey 1978). This is an extension of the forest zone that stretches from New Jersey to Texas on the broad coastal plain, except for an area interrupted by the Mississippi Valley. Soils in this upland forest group are neutral to acid and may be sand, sandy loam, or clayey sand and silt.

The second type of upland forest, maritime forest, consists mainly of live oak trees and brush. Maritime forest grows on sandy soils located along a barrier-strandplain deposit that was the Pleistocene counterpart of today's barrier islands and peninsulas (McGowen et al. 1976b). The forest grows on strandplain sand, stabilized dune sand, and beach ridges that have been in place for the past 50,000 to 70,000 years. The trees occur in groves known as oak mottes.

The barrier-strandplain deposits are high; dune crests are commonly 7.6 to 10.6 m (25 to 35 ft) above mean sea level and can be as high as 13.7 to 15.2 m (45 to 50 ft) in elevation (McGowen et al. 1976b). The maritime forest is located on the first high point inland of the bays. Strong prevailing southeast winds carry both moisture and salt from the gulf to the forest plants. Their combined effect sculpts the windward line of trees and produces unusual bending and twisting of trunks and limbs.

System operation. Other than sunlight for photosynthesis, water input is the main driving force for forest habitats. Precipitation is the chief source of water for upland forests. Floodplain forests receive water and nutrients from floodwaters of overbanking streams and rivers as well (Wharton et al. 1982).

Subsidence in floodplain forests and adjacent areas causes a relative rise in the water table and wetter soil conditions. This may result in an increase in forested wetland areas, as noted in the swamp habitat description. Landform also assists in regulating water input to forest systems. For equivalent rainfalls, upland forests with steep slopes absorb less water in their soil than shallower-sloped areas because of rapid runoff.

Infiltration rates to forest soils in the region range from 0.15 to 51 cm (0.06 to 20 in) of water per hour (Crout 1976; Wheeler 1976; Guckian 1979; Miller 1982); area rainfall rates are also within this range. Organic litter consisting of leaves and pieces of woody vegetation that accumulate on the forest floor offers resistance to overland flow and reduces the velocity of the water (Blackburn et al. 1978). Consequently, by prolonging the presence

of water on the forest floor until it can be absorbed, litter hastens the infiltration of water into the soil.

Salt spray is a significant input to maritime forest close to the shoreline (Bourdeau and Oosting 1959). Soil salt concentration from airborne salt may limit the extent of maritime forest by retarding tree growth and may alter plant growth through the direct toxic effect of salt buildup on leaves and new growth. But salt spray may also stimulate plant growth since a variety of nutrients (potassium and magnesium, for example) are transported along with sodium chloride.

Fire can control the structure of forest habitats and mediate nutrient availability. It destroys old growth and opens the forest canopy to let in sunlight so understory vegetation can flourish. It also releases nutrients that are bound up in the standing wood; nutrients are returned to the soil where they become available for use by other plants. Fire is less important in floodplain forest, particularly near rivers and streams, than in upland forests since the former receive regular inputs of nutrients from river flooding.

Because fire retards the successional phase of a forest and returns it to an earlier seral stage where vigorous growth of many forms occurs, over-control of fire may decrease the diversity of a forest system. All earlier successional community species may be eliminated in favor of the climax community alone (Taylor 1973).

Nutrients enter forest soil through decomposition of parent rock, chemical reaction with the atmosphere, freshwater transport (in the floodplain forest), and biological processes such as nitrogen fixation, decomposition of organic matter, and excretion. Nutrients are lost from forest soil through

natural erosion, leaching of dissolved materials, volatilization by fire, harvest and removal of residual wood byproducts, and uptake by plants. Chemical and physical processes tend to move nutrients in one direction, from solid material in rock or gases in the atmosphere to dissolved nutrients in creeks and streams of the watershed. Biologic processes retard this unidirectional flow by cycling the nutrients back and forth between soil and plant through plant uptake and organic decomposition by soil consumers and microorganisms. For example, nutrients in litter is incorporated into the upper levels of soil through the action of decomposing organisms such as earthworms.

Soil oxygen is a controlling factor in floodplain forests. The lack of soil oxygen under saturated soil conditions inhibits seedling germination (deBell and Naylor 1972) and alters the physiology of trees by impeding water and nutrient uptake through the root system (Wharton et al. 1982; Kozlowski 1984). Tolerance to saturated soil conditions varies among species; consequently, high moisture levels and long periods of soil saturation along stream banks and in depressions give water-tolerant species an advantage in the competition for space in floodplain forests.

Forests include several types of plants that may be roughly grouped by the vertical zone they inhabit. Mature trees fill all strata from roots to crown. Shrubs, vines, and seedlings of tree species are initially shorter but may eventually reach crown level. Grasses and forbs are low and occupy the floor. All plants compete for space and nutrients; in addition, understory plants must compete for sunlight and are therefore strongly influenced by the density of crown vegetation.

Vegetation in forests is diverse in spite of the competition for resources. Marks and Harcombe (1975) evaluated mixed pine-hardwood forest to the north of the region. They found that forests had high within-habitat diversity because of the high shrub diversity. They also found a high diversity between different forest locations in their study area because of a long topographic-moisture gradient.

Flora and fauna. Vegetation in the floodplain forest includes pecan (*Carya illinoinensis*), Texas sugarberry (*Celtis laevigata*), bald cypress (*Taxodium distichum*), cedar elm (*Ulmus crassifolia*), oak (*Quercus* spp.), sweetgum (*Liquidamber styraciflua*), sycamore (*Platanus occidentalis*), and cottonwood (*Populus deltoides*). Lower story and shrub vegetation includes the buttonbush (*Cephalanthus occidentalis*), American holly (*Ilex opaca*), yaupon (*I. vomitora*), hornbeam (*Carpinus* sp.), and sebastiana (*Sebastiana fruticosa*). Some common vines are grape (*Vitis* spp.), greenbriars (*Smilax* spp.), Virginia creeper (*Parthenosissus quinquefolia*), peppervine (*Ampelopsis arborea*), and supplejack (*Berchemia scadens*). Forbs frequently seen are verbenas (*Verbena* sp.), Carolina elephantfoot (*Elephantopus carolinianus*), and pennywort (*Hydrocotyle* sp.). Switch grass (*Panicum virgatum*) and basket grass (*Oplismenus setaria*) grow on the forest floor. With a dense overstory layer, shrubs, forbs, and grasses may be sparse or absent (McCloud 1975; Ford and Van Auken 1982).

Mixed pine-hardwood forest includes loblolly pine (*Pinus taeda*), shortleaf pine (*P. echinata*), oaks (*Quercus* spp.), sweetgum (*Liquidamber styraciflua*), hickories (*Carya* spp.), elms (*Ulmus* spp.), and sycamore (*Platanus occidentalis*) in the overstory vegetation. Understory vegetation and shrubs include dogwood (*Cornus floridana*), American beautyberry

(Callicarpa americana), yaupon (Ilex vomitora), hornbeam (Carpinus sp.), and St. John's wort (Hypericum drummondii). Grape (Vitis spp.), greenbriar (Smilax spp.), southern dewberry (Rubus trivialis), and blackberry are abundant vines in this forest type. Spike grass (Jniola sessiflora), panic grasses (Panicum spp.), dallis grass (Paspalum dilitatum), and carpet grass (Axonopus affinis) grow where the canopy is thin. Carolina elephant's foot (Elephantopus carolinianus) and wooly elephant's foot (E. tomentosus) are abundant forbs (McCloud 1975).

Maritime forest is dominated by live oak (Quercus virginiana), although laurel oak (Q. laurifolia) and blackjack oak (Q. marilandica) are interspersed. Other woody species include red bay (Persea borbonia), waxmurtle (Myrica cerifera), and American beautyberry (Callicarpa americana) (White 1973).

Fauna does not differ among floodplain forest, mixed pine-hardwood forest, and maritime forest. Few waterfowl and game birds inhabit the forest, although bobwhite quail (Colinus virginianus), mourning dove (Zenaidura macroura), and wild turkey (Meleagris gallopavo silvestris) are found in maritime forest. Songbirds include the bluejay (Cyanocitta cristata), red-bellied woodpecker (Centurus carolinus), common crow (Corvus brachyrhynchos), robin (Turdus migratorius), mockingbird (Mimus polyglottos), cardinal (Cardinalis cardinalis), and yellow-shafted flicker (Colaptes auratus). The red-tailed hawk (Buteo jamaicensis) and red-shouldered hawk (B. lineatus) are frequently found. Black vultures (Coragyps atratus) and turkey vultures (Cathartes aura) are often seen circling above carrion in the forest.

Herbivores and consumers found in the forest include raccoon (Procyon lotor), fox squirrel (Sciurus niger), grey squirrel (S. caroliensis), white-tailed deer (Odocoileus virginianus), swamp rabbit (Sylvilagus aquaticus), cottontail rabbit (S. floridans), opossum (Diadelphis marsupialis), and nine-banded armadillo (Dasypus novemcinctus). Common predators are the coyote (Canis latrans) and grey fox (Urocyon cinereoargenteus). The bobcat (Lynx rufus) has also been reported (White 1973; Maestro 1975).

Adjacent systems and flows. Of the habitats adjacent to forest, 45.7 percent are range, 20.7 percent are river, 19.2 percent are cropland, 4.8 percent are channel, and 2.3 percent are urban. A large fraction of adjacent habitats are river or channel (25.5 percent); this is to be expected since most forest in the region is floodplain forest, which develops through the influence of rivers, streams, and channels. Only a small fraction of the habitats adjacent to forest are urban, which implies that the transformation of forest land into urban land has been relatively small. Nearly two-thirds of the habitats adjacent to forest are range or cropland. Since about 30 percent of the natural forest land in the region has been transformed to other land uses, it is clear that most of the change has been to agricultural use.

Materials imported from adjacent upland systems include runoff and sediment. Floodwaters, sediment, and nutrients may be imported from aquatic habitats. Exported materials include water, nutrients, organic matter (litter and harvested wood), and sediment. Other than harvested products, almost all of this export goes to aquatic systems. Nearly all of the faunal species listed move into and out of the forest habitat freely. Because the forest habitat provides cover, it is the home territory for many animal species that venture to and from other upland habitats.

Economic uses. Commercial timber harvest for lumber, pulp, and other wood products in the region comes entirely from Chambers, Harris, and Liberty counties (Liebow et al. 1980). In 1976 only 109,462 cu m (30,200 cords) of produced wood could be attributed to forestry production in the region (calculated from Blackburn et al. 1978). Because of this low production rate timber harvest is of only minor importance in the region. Wood gathering for firewood is an expanding use, but no statistics are available.

The main economic use of the region's forests is for conversion to range, cropland, or urban land. Areas not undergoing this conversion are in a relatively natural state and provide habitat for wildlife and recreational opportunities for society.

Impacts of man's activities. The effects of silvaculture harvest include erosion, increased sediment load in rivers and streams, and the release of organic and inorganic materials into rivers and streams. Minor timber cutting and wood gathering of the scale that occurs in the Texas Barrier Island Region may produce some of these effects, but they are likely to be short-lived and confined to small areas. The effects of clear-cutting and other large-scale forest control methods employed to convert forest land to other uses are far more dramatic. Severe erosion is usually the most conspicuous. A comprehensive methodology to predict nitrogen, phosphorus, organic, and pesticide loads in streams as a result of timber harvest or clearing was prepared by Espey, Huston and Associates (1976), and its utility has been assessed by Blackburn et al. (1978).

The use of herbicides may produce additional environmental stresses. Houston Lighting and Power Company (no date) noted that bottomlands

(floodplain forests) along the Colorado River had been cut and sprayed with 2,4-D to kill woody vegetation and promote range grasses for cattle. The spraying had occurred annually for more than eight years. The long-term impacts of herbicide use are not well established although unintentional physiological ecological effects of 2,4-D on plants, insects, and aquatic species have been documented (Hazardous Materials Advisory Committee 1974).

In addition to the impacts on adjacent aquatic systems, the major effect of forest transformation to other upland types is the loss of habitat for wildlife. Forest species such as songbirds and squirrels adapt well to range or urban habitats (Maestro 1975), but species such as wild turkey and coyote are adversely affected by the loss of forest habitat since they prefer natural cover and large land tracts away from human influence.

Grassflat

Areal extent. Grassflat covers 681.4 sq km (263.1 sq mi), or 1.3 percent of the Texas Barrier Island Region. More than 77 percent of this habitat (517.7 sq km or 203.8 sq mi) is located in the Laguna Madre basin, where it occupies 3.1 percent of the basin area. In the Nueces basin, grassflat covers 40.9 sq km (16.1 sq mi), 1.9 percent of the basin area. The Rio Grande basin has the highest proportion of the grassflat habitat, 5.3 percent, and the third largest amount, 38.4 sq km (15.1 sq mi). Figure 83 shows the distribution of grassflat in the region. The proportion and acreage of grassflat decrease to the north, but the habitat does not completely disappear; the basins north of the Nueces basin contain slightly more than 10 percent of the habitat in the region.

Physical description. Grassflats are shallow estuarine areas with thick growths of marine seagrasses. While algae are present in this habitat, the

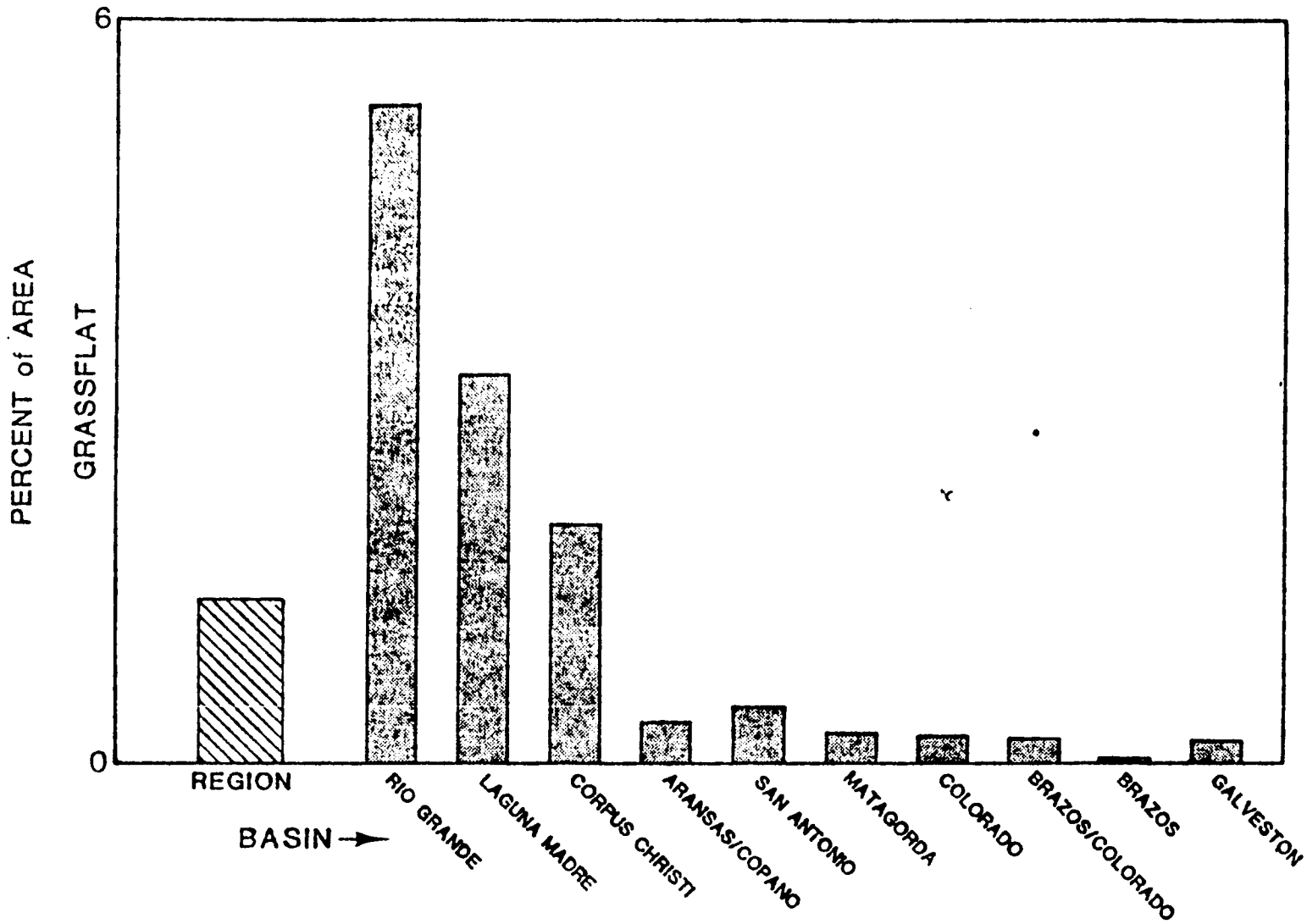


Figure 83. Percent of the region and basin area that is grassflat habitat.

predominant plants are five species of seagrasses: manateegrass, shoalgrass, gulf halophila, widgeongrass, and turtlegrass. Seagrasses are marine angiosperms that may produce flowers and seeds under the proper conditions. On the Texas coast flowering is rare except for widgeongrass, which does not have the thick rhizomes the other species use for propagation (McMillan and Moseley 1967). Grassflats have high natural productivities from seagrasses and other producers and support a diverse community of consumers and predators.

The five major seagrass species are unevenly distributed among areas where seagrasses are present. Conover (1964) reported that manateegrass (Syringodium filiforme) was found only at the extreme southern tip of Laguna Madre, near Port Isabel. Pulich (1980a) reported that manateegrass had spread north as far as Port Mansfield. Shoalgrass (Halodule wrightii), usually considered to be a pioneer species with a wide tolerance range, has been reported from Port Isabel (Conover 1964) to West Bay in the Galveston basin (Pullen 1962; Belaire 1979). Gulf halophila (Halophila englemanii) has been found from Port Isabel to Port Mansfield and from Baffin Bay to Redfish Bay (Conover 1964); unpublished reports claim that this species ranges as far north as Pass Cavallo. Widgeongrass (Ruppia maritima) is found from Baffin Bay north to West Bay (Pullen 1962; Conover 1964; Belaire 1979). Conover (1964) reported turtlegrass (Thalassia testudinum) in Laguna Madre from Port Isabel to Mansfield Pass and from Baffin Bay to Corpus Christi Bay. A large area of turtlegrass is located in Redfish Bay between Corpus Christi and Aransas bays.

Seagrass beds are large and dense south of Redfish Bay. North of Redfish Bay, seagrass beds are narrow bands of plants that often parallel the mainland or back side of the barrier island. North of Pass Cavallo, most seagrasses are restricted to a narrow area behind the barrier islands and peninsulas, between the deeper portions of the bay and the marshes or wind-tidal flats.

Conover (1964) observed that the areas with the greatest number of seagrass species had near-marine salinities, while fewer seagrass species occurred where the salinity often varied or was consistently above or below marine conditions. McMillan and Moseley (1967) grew the five major species under different salinity regimes. They found differences in tolerance to high salinities in the following order: shoalgrass > turtlegrass > widgeongrass > manateegrass. The salinity tolerance of gulf halophila was between that of shoalgrass and manateegrass. High salinity tolerance allows shoalgrass to grow in the upper Laguna Madre, where salinities sometimes range from 80 to 100 ppt; it can also grow in San Antonio Bay and West Bay where salinities of only a few parts per thousand may continue for several weeks after major storms. More stenohaline seagrasses, such as manateegrass, are restricted to areas with more constant salinity levels, such as near passes to the gulf (McMahan 1968).

The temperature in seagrass beds ranges from freezing to over 40 deg C (Smith 1978). Smith (1977) reported that the average daily temperature in seagrass beds fluctuated 2.4 deg C in a cycle of 8 hours of rapid warming and 16 hours of slower cooling in winter. From late fall to early spring, major cold fronts pass through the region about every 11 to 13 days and drop water temperatures by 8 to 14 deg C; rapid warming generally begins two days later.

Temperature tolerance varies among seagrass species; in a transplant experiment Phillips (1980b) found that turtlegrass was much less tolerant of low temperatures than shoalgrass. Phillips (1980a) reported that the tolerance range for turtlegrass varied with the location of the grass bed; northern gulf turtlegrass tolerated temperatures from 7 to 32 deg C, but Caribbean samples had a narrower tolerance range of 23 to 30 deg C. McMillan (1978) suggested that populations of seagrasses were adapted to a suite of local conditions; in some places tolerances were wide, while in others they were narrow.

Seagrasses grow on a variety of substrates, from soft mud to firm sand. Once established, the plants modify the sediment. They grow a web of rhizomes and roots which stabilizes the substrate (Phillips 1980a). They also slow water currents, which causes silt and fine organic particles to collect (Fonseca et al. 1982, 1983). The network of underground rhizomes and roots combined with the damping of water movement by seagrass stems and blades allows the habitat to withstand hurricanes with only minor effects upon the plant life (Thomas et al. 1961; Oppenheimer 1963).

Many mollusks inhabit seagrass beds; consequently the substrate contains more shell than bay and channel substrate. McMillan and Moseley (1967) reported that gulf halophila was usually found in areas containing large amounts of shell.

The depth of Texas seagrass beds varies over a narrow range. Turtlegrass has been reported from 0.15 to 1.5 m (0.5 to 5 ft) (Odum and Hoskin 1958; Conover 1964). Conover described manateegrass beds 2 m (6.5 ft) deep. Odum and Hoskin (1958) measured production in shoalgrass beds 1 m (3.3 ft) deep.

System operation. Mechanisms that influence the level of illumination determine the productivity of this habitat and are the most important driving forces. Light penetration is the most important factor affecting depth of the beds. Seagrasses in Texas grow no deeper than 2 meters because of low light penetration in turbid water. In clearer waters seagrasses are able to grow at greater depths; Phillips (1980a) reported turtlegrass growing at 12 m (39 ft) in Florida and at 30 m (98 ft) in the Bahamas.

Pulich (1980a) reported that 45 percent of the surface light was available at 0.5 m (1.7 ft) in the Laguna Madre, but only 27 percent was available at the same depth in Redfish Bay. The difference is due to the sediment types of the systems. Redfish Bay and most other Texas bay systems contain a high level of silts and clays. The Laguna Madre has a higher percent of quartz sand, which is less easily suspended than silt and permits deeper light penetration. Reimer et al. (1973) measured light penetration in seagrass beds in Redfish Bay; at two stations the average lengths of the light path to extinction were 0.42 and 0.69 m (1.4 and 2.3 ft).

Conover (1964) noted that light penetration was closely related to wind velocity. During high winds when sediment was stirred up, as much as 90 percent of the light was absorbed or scattered in the first 10 cm (4 in) of the water column; under calm conditions 10 to 30 percent was absorbed or scattered. Conover measured diurnal illumination and found that the highest levels of light, up to 50 Langleys (50 gm-calories per sq cm) per hour, were received during the morning hours. After noon, when the onshore sea breeze developed and stirred up the sediment, the illumination dropped to 15 Langleys. Summertime illumination was 80 to 120 Langleys per day, while the winter average was 90 Langleys per day. Although summer illumination was more

intense at the water's surface, the turbidity resulting from wind action resulted in similar illumination levels in both seasons.

The presence of clay particles selectively filters out shorter wavelengths of light in the water column (Conover 1964). The absence of short wavelengths may inhibit reproductive capabilities of seagrasses. Pulich (1980a) noted that blue light predominated in turbid waters; this may present an advantage to manateegrass, which is more effective in the use of blue light than is turtlegrass. The growth response to different intensities of light is not a linear function of intensity. Seagrasses do not grow at light intensities less than 100 foot-candles or greater than 450 foot-candles; maximum growth occurs at 225 to 300 foot-candles (Koch et al. 1974).

The relative depth of seagrass beds influences production since it determines the light path length and the amount of light energy absorbed by the water. Smith (1978) noted that the largest fluctuations in water level in the upper Laguna Madre occurred semiannually, with water level differences of about 0.5 m (1.7 ft); spring and fall were the periods of high water. Suggested causes of these cycles include spring runoff, seasonal warming and cooling of shelf waters that produce expansion and contraction and change the surface water level, and temporary storage of water in anticyclonic gyres in the Gulf of Mexico maintained by wind stress (Smith 1978). The latter two processes, which occur far from the habitat site, exert indirect control over grassflat productivity.

Circulation and currents in seagrass beds have only recently been studied in detail. Within the seagrass bed, below the level of the tips of the grass, grass blades slow the water velocity. Fonseca et al. (1982) considered flow

velocities of 5 to 40 cm per sec to be typical of natural eelgrass (Zostera marina) beds. Fonseca et al. (1983) reported that turtlegrass and eelgrass beds in Virginia could withstand flow velocities as great as 1.5 m per sec before sediment scouring occurred. Flow velocities of 3 to 18 cm per sec have been measured in seagrass beds in Florida (O'Gower and Wacasey 1967). No current volocity measurements for Texas grassflats have been reported, however.

Salinity is also a controlling force for seagrass systems. Long-term salinity patterns control the distribution of seagrasses; short-term salinity conditions may be important in regulating animal species in the seagrass community. Zimmerman and Chaney (1969) reported that heavy rains accompanying hurricane Beulah lowered salinities to 9 ppt in Redfish Bay and caused heavy kills of mollusks. Some species recovered rapidly, but others disappeared entirely.

Adequate sources of phosphate and nitrogen are needed to sustain high seagrass productivity. Armstrong and Gordon (1979) reported that Texas seagrasses can use nutrients from either the sediment or the water column. While there is a large reservoir of phosphate in the sediment, Armstrong and Gordon could not conclusively identify the nitrogen source. Patriquin and Knowles (1972) identified nitrogen-fixing bacteria in the rhizospheres of turtlegrass, shoalgrass, manateegrass, and eelgrass. Goering and Parker (1972) showed that epiphytic blue-green algae on turtlegrass and shoalgrass fix nitrogen which may be used by the seagrasses and other producers; they could not find other evidence of nitrogen fixation in seagrass beds, however. Eelgrass has been shown to operate as a nutrient pump, bringing phosphate and nitrogen from the sediments and releasing it through the leaves to the water

column (Phillips 1980a). No similar function for Texas seagrasses has been demonstrated (Armstrong and Gordon 1979), and McRoy and McMillan (1977) concluded that the sources of nitrogen for seagrasses were still open to question.

Uptake of other inorganic materials by seagrasses, epiphytes, sediment, and associated microflora has been studied by Parker (1966). He found that radioisotopes of cobalt, iron, manganese, and zinc were rapidly removed from the water by the plant leaves or the epiphytes on the leaves; roots absorbed only a small portion of the tracers. Isotopes were released to the water during the day, but were taken up again at night. The top few centimeters and organisms in the sediment apparently accumulated the tracers. The rapid uptake and release mechanisms for these materials reveal a dynamic biological system that rapidly interacts with materials in the water.

Seagrasses, like marsh plants, lose much of their aboveground biomass during November and December. Most of their biomass, 66 to 85 percent, is below ground (Zieman 1975; Pulich 1980a). Conover (1964) reported that the plants remained dormant through the winter until spring; growth occurred from April until the end of October, with peak growth periods from May through September. Peak growth was correlated with illumination rather than with thermal maximums.

Biomass has been measured for grassflats in Redfish Bay and the Laguna Madre. Turtlegrass biomass is quite variable from year to year; biomass measurements ranged from 81 to 4956 gm dry wt per sq m (Odum 1963; Parker et al. 1963; Armstrong and Gordon 1979; Pulich 1980a). Shoalgrass biomass is not

as variable; biomass ranged from 22 to 600 gm dry wt per sq m (Parker et al. 1963; McMahan 1968; Armstrong and Gordon 1979; Pulich 1980a).

Zieman (1975) reported that turtlegrass in Florida produced 6.8 crops of leaves per year; consequently standing crop measurements cannot easily be used to estimate productivity. Older productivity estimates for Texas seagrasses range from 225 to 2250 gm dry wt per sq m per year; Phillips (1980a) notes that these figures may be high. Armstrong and Gordon (1979) estimated daily net productivity (gross productivity minus respiration) at 4.5 gm dry wt per sq m, while Oppenheimer et al. (1975) calculated daily gross productivity of 10 gm dry wt per sq m.

The epiphytes that grow on the surface of seagrass stems and blades are mainly algae. Harlin (1975) reported that more than 100 species of algae are known to use seagrasses as hosts. Advantages of this commensal relationship to the epiphytic algae include distribution through part of the water column rather than restriction to the bottom, exposure to light and water movement, and access to nutrients that leak from the seagrasses. Phillips (1980a) reported that epiphyte production may constitute 20 percent of the net production of turtlegrass beds in Florida. In addition to these producers, grassflats also contain phytoplankton, benthic algae, and drift algae that contribute to habitat productivity.

Organic material produced in seagrass habitats may be directly ingested or may become part of the detritus cycle (Burrell and Schubel 1977). Fenchel (1977) noted that unconsumed organic material may directly release leachates and fall to the bottom as particulate detritus.

Leachates are taken up by bacteria and other microflora that live on the plant surfaces or on detritus particles. In fact, microorganisms are the most

important consumers in the seagrass habitat (Brazier 1975; Phillips 1980a). They are ingested by a variety of grazers and form the base of a food web for zooplankton; infaunal and epibenthic deposit feeders; infaunal, epibenthic, and epizoan suspension feeders; and carnivores (Brasier 1975). Many species that ingest detritus obtain nutrients by stripping and digesting microorganisms from detritus particles (Adams and Angelovic 1970; Hargrave 1970; Welsh 1975; Heinle et al. 1977).

Larger pieces of detritus are broken into smaller portions by mechanical action in the water column and through ingestion and maceration by consumers; Welsh (1975) demonstrated how grass shrimp (Palaemonetes pugio) mill Spartina detritus into fine particles and innoculate it with bacteria from their digestive tract.

There is evidence that microorganisms absorb nutrients and enrich detrital particles with phosphorus and nitrogen while they use the particles as energy sources or substrates (de la Cruz 1975; Welsh 1975; Fenchel 1977). Detritus is cycled through the digestive systems of many organisms, undergoing mechanical and chemical breakdown and biochemical enrichment until the particles finally come to rest in the organically rich sediments of the seagrass bed.

A thin aerobic sediment layer overlies a thick anaerobic layer in grassflats. Deposit feeders in the aerobic layer may further process the detritus, but once it enters the anaerobic layer a variety of fermentation and reduction processes involving anaerobic bacteria occur. Anaerobic decomposition favors the release of assimilable organic compounds and mineralized nitrogen and phosphorus (Phillips 1980a). Howarth and Teal (1979,

1980) investigated the sulfate reduction cycle in marsh sediments. They concluded that reduced inorganic sulfur compounds from anaerobic decomposition, which could be used by chemoautotrophic bacteria, may provide as much energy to adjacent ecosystems as is available from exportable aboveground production.

Fry et al. (1977) and Fry and Parker (1979) employed stable carbon isotopes as tracers to elucidate the movement of organic matter from seagrass beds to biota and sediments. They found that seagrass carbon could be detected in bay sediments and bay organisms and that some carbon is exported from grassflats to adjacent habitats. Brylinski (reported in Odum et al. 1974) prepared an energy budget for a turtlegrass community in Redfish Bay showing that about half of the net production was processed by detritivores and a small amount was exported.

Flora and fauna. Producers in grassflats include the seagrasses, phytoplankton, drift algae, and epiphytes. Seagrass species found in the region are manateegrass (*Syringodium filiforme*), shoalgrass (*Halodule wrightii*), gulf halophila (*Halophila englemanii*), widgeongrass (*Ruppia maritima*), and turtlegrass (*Thalassia testudinum*). Epiphytes come from four different plant divisions: *Chaetomorpha linium* is a green alga; *Myriotrichia subcorymbosa*, *Streblonema* sp., and *Stictyosiphon* sp. are brown algae; *Spyridia aculeata*, *Erythrotrichia carnea*, *Erythrocladia subintegra*, and *Chondria* sp. are red algae; and *Surirella fastuosa*, *Grammataphora marina*, and *Rhabdonema adriaticum* are diatoms (Estep et al. 1974).

Drift algae in seagrass beds include the green alga *Acetabularia crenulata*; brown alga *Dictyota dichotoma*; and red algae *Jania capillacea*, *Graciliaria* spp., *Hypnea* spp., *Laurencia poitei*, *Chondria* sp., and *Soliera*

tenera (Hoese and Jones 1963; Cowper 1978; Pulich 1980a). Phytoplankton in the seagrass habitat are the same species found in the bay habitat.

Fungi are present in the seagrass habitat (Armstrong and Gordon 1979). Bacteria are also abundant in the sediment, in the water column, and on plant surfaces (Oppenheimer and Jannasch 1962). It is likely that bacteria in the sediments include Nitrosomas sp., Nitrobacter sp., Thiobacillus sp., Thiothrix sp., and Desulfovibrio sp.

Zooplankton in the water column include zooplankton species common to the bay habitat such as the copepod Acartia tonsa, crab zoea, and amphipods. Sergestid shrimp (Acetes americanus louisianensis and Lucifer faxoni) and chaetognath Sagitta tenuis have also been identified (Reimer et al. 1973, Fotheringham and Brunenmeister 1975).

Many small invertebrates live as epibiota on seagrass leaves and stems, feeding on detritus and bacteria or suspension-feeding. Common forms include the amphipods Elasmopus sp., Cymadusa compta, Melita nitida, Leptchelia sp., and Hyale sp. The polychaetes Nereis succinis and Spirorbis sp., the gastropods Bittium varium and Anachis avara semplicata, and the ostracods Loxoconcha guttata and Cytherura sp. also live as epibiota.

Invertebrates that live in the sediment include the tube-building worm (Diopatrea cuprea), polychaete (Capitella capitata floridana), and serpulid (Eupomatus dianthus). The sea cucumber (Thyone mexicana) is occasionally found in seagrass beds. Some representative mollusks are the thick lucine (Phacoides pectinatus), cross-barred venus (Chione cancellata), moon snail (Polinices duplicatus), whelk (Busycon spp.), bay scallop (Aequipecten amplicostatus), virgin nerite (Neritina virginea), Willcox's sea hare (Aplysia

willcoxi), and dwarf cerith (Cerithium variabile) (Hoese and Jones 1963; Andrews 1971; Reimer et al. 1973; Fotheringham and Brunenmeister 1975).

Both adult and juvenile brown shrimp (Penaeus aztecus) and white shrimp (Penaeus duorarum) are found in seagrass habitats. Some other common decapods are grass shrimp (Paleomonetes pugio), blue crab (Callinectes sapidus), mud crab (Neopanope texana), snapping shrimp (Alpheus heterochaelis), arrow shrimp (Tozeuma carolinense), striped hermit crab (Clibanarius vittatus), caridean shrimp (Hippolyte pleuracantha), and spider crab (Libinia dubia) (Hoese and Jones 1963; Reimer et al. 1973; Fotheringham and Brunenmeister 1975).

Fish species are numerous in the seagrass habitat. Representatives include pinfish (Lagodon rhomboides), rainwater killifish (Lucania parva), silversides (Menidia beryllina), mojarra (Gerres cinereus), darter goby (Gobionellus bolesoma), code goby (Gobiosoma robustum), pipefish (Syngnathus scovelli and S. floridae), juvenile sand trout (Cynoscion arenarius), croaker (Micropogon undulatus), southern flounder (Paralichthys lethostigma), sheepshead minnow (Cyprinodon variegatus), dwarf seahorse (Hippocampus zosterae), pigfish (Orthopristes chrysoptera), spotted trout (Cynoscion nebulosus), crested blenny (Hypleurochilus germinatus), gulf toadfish (Opsanus beta), and striped mullet (Mugil cephalus) (Hoese and Jones 1963; Reimer et al. 1973).

Birds that frequent the habitat include the laughing gull (Larus atricilla), egret (Casmerodius albus), little blue heron (Florida caerulea), long-billed curlew (Numenius americanus), Hudsonian curlew (N. phaeopus), black skimmer (Rynchops nigra), lesser yellowlegs (Totanus flavipes), pintail (Anas acuta), redhead duck (Aythya americana), and lesser scaup (A. affinis) (McMahan 1970; Reimer et al. 1973).

Adjacent systems and flows. Upland systems account for 58.6 percent of the habitats adjacent to the seagrass habitat. The adjacent upland habitats are range (41.3 percent), spoil (9.5 percent), barrier (3.9 percent), cropland (2.2 percent), and urban (1.7 percent). Upland systems receive no materials or energy from seagrass habitats except as the result of storms. They may receive biota since birds can move freely from one system to the other. Grassflat systems may receive water, sediment, organic matter, and waste materials from upland systems, however.

Estuarine systems constitute 36.3 percent of the adjacent habitats (bay, 30.7 percent, and channel and tidal stream, 5.6 percent). These aquatic systems exchange nutrients, sediment, organic matter, and biota freely with the seagrass habitat.

Intertidal systems comprise 5.1 percent of the adjacent habitats (wind-tidal flat, 4.5 percent, and salt and brackish marsh, 0.6 percent). Seagrass systems probably exchange most of the same materials and biota with these habitats as they do with aquatic systems, but the transfer may be intermittent.

Economic uses. Sportfishing is a direct use of this habitat; commercial fishing benefits from it indirectly since species of commercial value use seagrass beds for nursery habitat.

The transportation sector has used portions of grassflat for channels and spoil placement. Most of the dredging of this habitat took place during the construction of the Gulf Intracoastal Waterway; however, occasional new dredging or maintenance dredging must be undertaken to reach oil and gas well sites. Pipelines from offshore cross the entire range of habitats in the

region. An effort is made to avoid grassflats, but it is sometimes impossible to route the pipelines around them. This is particularly true in the Laguna Madre.

Impacts of man's activities. Dredging removes plants from the habitat and stirs the sediment. Because seagrasses help clarify the water and stabilize the sediments, their removal increases turbidity. Added turbidity can have secondary effects on adjacent seagrass habitats. Odum (1963) reported that large decreases in productivity followed the dredging of the channel to Aransas Pass across Redfish Bay. He attributed the diminished production to shading from the suspended solids; he also noted that production the following year was well above normal levels, probably because the dredging released nutrients. In a transplant experiment, Phillips (1980b) found that tolerance of seagrasses to sediment deposition from dredging varied according to species; turtlegrass transplants, for example, declined and were invaded by shoalgrass. Thus dredging may have major effects on the type of seagrass community nearby.

The dredging of seagrass eliminates the protective cover many juvenile and small species require to escape predation. The high production of the habitat and detritus export to adjacent areas are also lost. When the channel and tidal stream habitat replaces the seagrass habitat, phytoplankton production is lower and is consumed by a different community. The types and number of organisms that can be supported by the food web change.

Drainage from upland areas brings water and materials that may enhance or degrade the seagrass habitat. Phillips (1980a) reported instances of both damage and heightened production from sewage effluents. Thayer et al. (1975) reported that sediment from agricultural land clearing, diversion of

freshwater input from rivers and streams, and waste materials from upland sources (including petroleum and pesticides) were also major problems. Heavy metals in urban and industrial wastes may be carried to seagrass systems. Parker (1963) showed that seagrasses could rapidly take up radioisotopes of several heavy metals. Pulich (1980b) found that shoalgrass accumulated high levels of cadmium and zinc that could be passed on to other levels in the food chain.

Most Texas seagrass habitats are not located near urban or industrialized areas. As a result dredging impacts are probably greater in magnitude than the effects of urban and industrial development.

Gulf

Areal extent. The gulf habitat occupies 10,479 sq km (4046 sq mi), or 20 percent, of the area of the Texas Barrier Island Region. It extends from the gulf beach shoreline eastward to the line of state-federal demarcation, three marine leagues (16.7 km or 10.35 mi) seaward of the shoreline. The Laguna Madre basin has the largest area of gulf habitat, 3837 sq km (1481 sq mi); the Rio Grande basin has the smallest, 145 sq km (55.9 sq mi) (Figure 84).

Physical description. The gulf habitat is entirely aquatic. The slope of the continental shelf differs according to latitude; slope in the southern portion is greater than in the northern portion. Depth of the water column ranges from zero at the shoreline to 95 ft at the three-league line off the lower coast. The maximum depth off of Galveston is only 45 ft.

The salinity of gulf waters varies with location. Offshore salinities are marine, 35 to 37 ppt, with relatively little variation. Inshore, particularly close to passes, salinity may range from 20 to 35 ppt depending

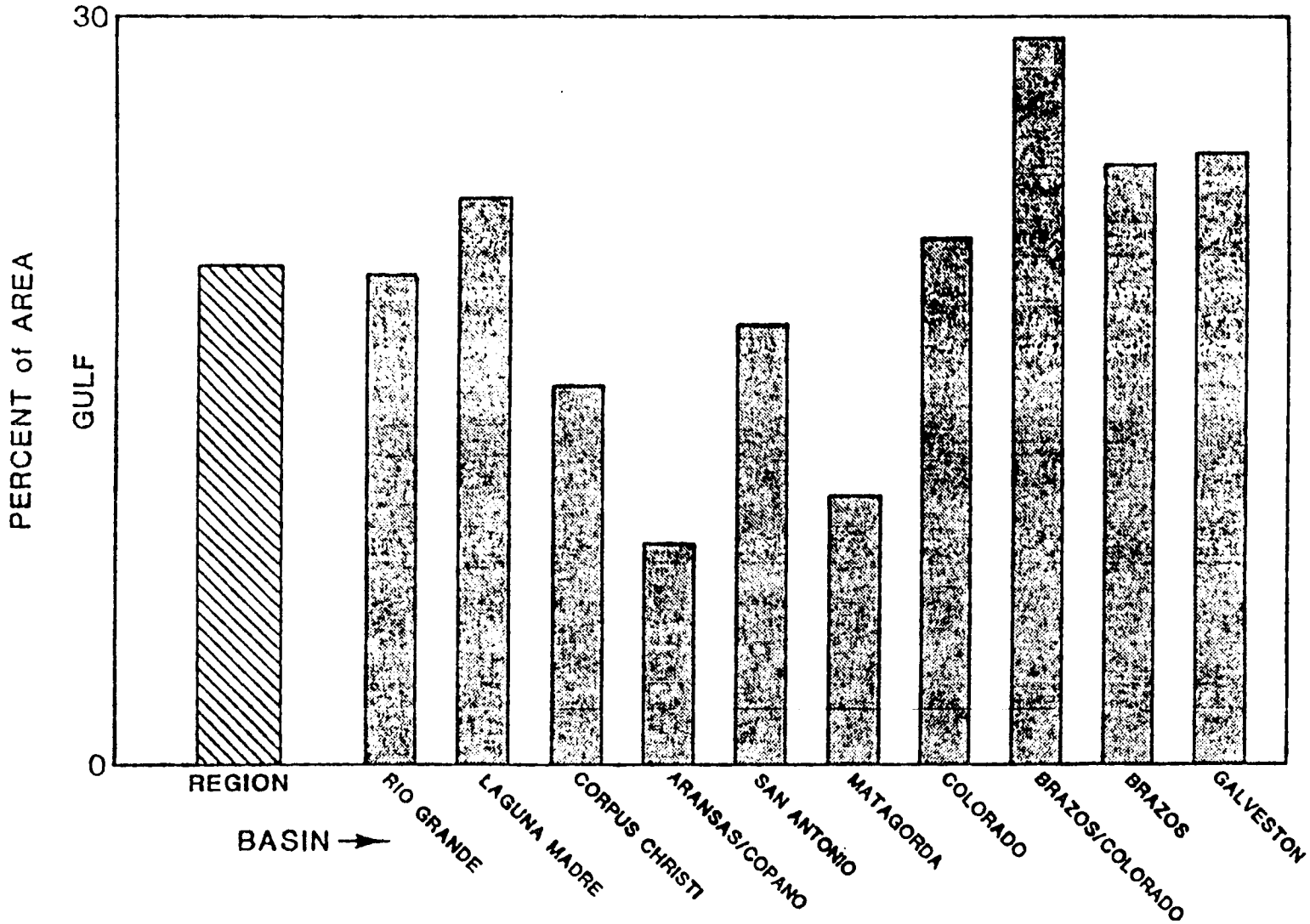


Figure 84. Percent of region and basin area that is gulf habitat.

upon rainfall and river flow (McFarland 1963b). Small but definite salinity gradients exist in the habitat (Jones et al. 1965).

The temperature of gulf water varies seasonally and with distance from the shoreline. Offshore near the line of state-federal demarcation, the temperature range is 12 to 32 deg C. In shallow nearshore areas, such as the surf zone, temperature variation is somewhat wider with a range of 9 to 35 deg C (Texas Coastal Management Program 1976).

Near the beach the dominant circulation pattern is the wind-driven longshore current parallel to the shoreline. This current is important to the balance of sediment between the gulf and barrier habitats (Watson 1975). Offshore currents vary seasonally and with depth. While wind is the primary determinant of offshore water circulation patterns in the gulf (Smith 1978), bottom currents may display different directions and velocities than the surface circulation patterns (Smith 1980).

The gulf water mass is subject to strong tidal influence. The pattern of tidal fluctuation is mixed about 75 percent of the time, with two distinct but unequal high and low waters in each 24-hour period (U.S. Department of Commerce 1982). During the remaining 25 percent of the time the tide is diurnal, with only one high and low water per day. The average fluctuation between high and low water is 0.4 m (1.4 ft).

Nearshore gulf water is very turbid because water movement keeps silt and clay particles in suspension. Near the barrier habitat, surface sediment is sandy because turbulence does not allow settling of the finer fractions. Further offshore, turbulent energy decreases and finer fractions of suspended sediment settle out. Offshore surface sediment tends to be fine material, although large deposits of sand and shell can be found.

System operation. Biota in the gulf are part of a phytoplankton-based food web. Detritus and Sargassum (Shelby 1963) are imported from estuarine systems and the open ocean, but their importance as energy sources in the gulf is not well demonstrated. For example, Fry and Parker (1979) showed that carbon isotope ratios of offshore consumers were consistent with the hypothesis that the consumers had a mixed diet of offshore plankton and estuarine seagrass organic carbon. However, other plausible hypotheses explaining the measurements could not be ruled out. There was no clear evidence that offshore species used detritus exported from the estuary.

Solar radiation and current energy are the inputs to the gulf habitat that control operation of the system. Solar radiation provides the energy for primary production, which affects all levels of the marine food chain. Current energy mediates movement of nutrients, sediment, and planktonic organisms.

Within the gulf habitat the microorganism-organic matter component is crucial since this association determines the rate at which nutrient materials are regenerated. Benthic infauna, in addition to providing food materials for other species, also contribute to regeneration by bioturbation (mixing of the upper sediments by burrowing and animal movement in the upper layers). Distribution of nutrients and other materials such as vitamin B-12 is the result of turbulent circulation in the habitat (Maurer and Parker 1968).

The biotic components in the gulf habitat form a complex food web with many species. Species diversity in benthic organisms tends to increase from the landward parts of estuaries to the offshore limits of state waters (Calnan et al. 1979). The diversity increase in the gulf appears to be inversely

related to bottom water conditions, especially temperature, the degree of temperature variability, and depth (Flint and Holland 1980). Nekton and planktonic species display the same trend. Gulf waters provide a habitat for a number of estuarine species that spend only part of their life cycle in the gulf. Some of these migrating species are: penaeid shrimp (Penaeus spp.), black drum (Pogonias cromis), blue crab (Callinectes sapidus), grey mullet (Mugil cephalus), sand seatrout (Cynoscion arenarius), red drum (Sciaenops ocellatus), and southern flounder (Paralichthys lethostigma).

Sediment solids are an important component of the gulf habitat. Nearshore sediments--fine to medium-grained sands--provide an environment for benthic species and are supplied to the adjacent barrier habitat. The barrier habitat is a net importer of sediment over the long term, and storms transport gulf sediments to flood-tidal deltas and washover fans. Because of the long-term movement of sediment landward, the gulf habitat is an exporter of material to the barrier habitat.

In the short term the nearshore portion of the gulf habitat is a major contributor to the dynamic equilibrium governing the beach erosion and accretion cycle. Davis (1972) graphically documented the sand movement between the beach and littoral zone accompanying hurricane passage. Measurements taken immediately before and after a hurricane and for a month thereafter showed nearly instantaneous erosion of the beach and gradual recovery during the following month. The sediment component equilibrium is of direct interest to man because changes in the balance may have direct and rapid effects upon land and structures of economic value.

Flora and fauna. Phytoplankton are the dominant flora in the gulf habitat, although Sargassum and attached algae (especially around jetties and

drilling platforms) are frequently seen. A few of the more common phytoplankton are Chaetoceros spp., Cyclotella spp., Nitzschia spp., Rhizosolenia spp., Skeletonema spp., Thalassionema spp., and Thallasiothrix spp. (Texas Coastal Management Program 1976). Zooplankton include Penilia avirostris, Temora turbinata, Acartia tonsa, and Paracalanus spp. (Texas Coastal Management Program 1976). Many larval forms of estuarine species are found in the gulf zooplankton.

Benthic forms include the sea pansy (Renilla mulleri), anemone (Calliactis tricolor), calico crab (Hepatus epheliticus), yellow box crab (Callapa sulcata), giant eastern murex (Murex fulvescens), giant cockle (Dinocardium robustum), incongruous ark (Anadara brasiliana), ponderous ark (Noetica ponderosa), and pen shell (Atrina serrata). A variety of benthic species live in the surf zone; these include the lettered olive (Olivia sayana), moon snail (Polinices duplicatus), surf clam (Donax spp.), tube worm (Diopatrea cuprea), sand dollar (Mellita quinquiesperforata), Scotch bonnet (Phalium granulata), and sundial (Architectonia nobilis) (Andrews 1971; Fotheringham and Brunenmeister 1975; Texas Coastal Management Program 1976).

In addition to the consumer species previously mentioned, the silver seatrout (Cynoscion nothus), Atlantic croaker (Micropogan undulatus), anchovy (Anchoa spp.), and Atlantic threadfin (Polydactylus octonemus) are common in the gulf (Miller 1965). In the surf zone the Atlantic stingray (Dasyatis sabina), Florida pompano (Trachinotus carolinus), gulf kingfish (Menticirrhus littoralis), and spot (Leiostomus xanthurus) are common (McFarland 1963).

Top consumers in the gulf habitat include the king mackerel (Scomberomorus cavalla), red snapper (Lutjanus campechanus), bonnethead shark

(Sphyrna tiburo), and tiger shark (Galeocerdo cuvieri) (Hoese and Moore 1977).

Adjacent systems and flows. More than 90 percent of the habitat units adjacent to the gulf are barrier habitat. Bulkhead habitat is adjacent in the form of the seawall along Galveston Island and as jetties at the stabilized passes. Urban habitat is adjacent to gulf only at Galveston.

Significant imports to the gulf habitat are nutrients and water from the estuary, and wave energy from the waters beyond the three-league line. Morton (1977) has noted that the import of sediment into the gulf from areas further offshore has been a major source of sediment in the past. However, not enough information is available to make a comprehensive sediment budget between the shelf and gulf.

Another major exchange is the import and export of biota that travel between the estuary and the gulf. Penaeid shrimp, for example, enter bays through passes from the gulf as post-larvae and juveniles. They grow and mature in the estuarine environment and return to the gulf habitat to spawn. The number of migration pathways through the passes is limited, and in some instances species migrating from the upper ends of bays must travel 30 to 40 miles to reach the gulf.

Economic uses. Channels have been dredged through the gulf to the mouths of the passes maintained for navigation. Areas on the downdrift side of channels are used for placement of spoil from channel and pass dredging. Near some ports there are anchorage areas in the gulf for large vessels to anchor to await open berths.

The nearshore portion of the gulf habitat is used for recreation--fishing, swimming, and surfing. The area further offshore is used for recreational and commercial fishing.

More than 80 oil and natural gas fields are located on state-owned lands beneath gulf waters. Exploration for these minerals began in the 1920's, and in the late 1940's offshore exploration and production platforms were built. Several hundred wells are currently productive, and in 1978 nearly 2.5 million barrels of crude and 230 trillion cu ft of natural gas were produced and carried ashore through pipelines. A few other pipelines cross the gulf habitat into the barrier island region from oil and gas fields in the Texas outer continental shelf, but federal development off the Texas coast is not nearly as well developed as off the Louisiana coast.

Impacts of man's activities. Channel dredging and jetty construction have interrupted longshore transport processes and may have trapped as much as 50 percent of the sand supply for Texas beaches (Morton et al. 1983). This has probably exacerbated the existing beach erosion problem. Morton et al. (1983) rated the Texas gulf shoreline for danger to development and housing. About 68 percent of the more than 200 miles of gulf shoreline in the region received a "caution" or "danger" rating, largely because of high erosion rates.

The primary impacts of dredging and spoil placement in the gulf are direct physical displacement or burial of biota and alterations in hydrology (Delahoussaye 1981). Benthic species are removed during dredging, and at the site of spoil placement other benthic biota are buried and may smother. Recolonization of spoil material is rapid, however. Dredging of deep channels increases flow velocity.

Impacts from oil and gas development include effects of structure and pipeline placement, direct effects of drilling, immediate impacts of spills,

and possible long term effects. Well platforms provide hard substrates in the gulf and thus lend diversity to the gulf habitat. They attract biota, which develop reef-like communities around the platforms (Gallaway and Lewbel 1982). The impacts caused by pipeline placement are the same as the short-term effects caused by dredging and spoil placement.

The disposal of drill cuttings, mud, and other wastes such as brine may have some adverse environmental effects. Cuttings may smother biota, but the effects are very localized. Gallaway and Lewbel (1982) observed only minimal effects from cuttings and drilling muds, although it is known that some components of muds may be detrimental to biologic communities (Environmental Protection Agency 1975). Tagatz and Tobia (1978) showed that barite (barium sulfate), one of the main components of drilling muds, can affect communities by impeding colonization of substrates by some species. Bactericides in muds can have lethal effects on gulf biota (Cantelmo and Rao 1978); and chromate salts, added to some muds, are definitely hazardous (Dresser Industries 1977).

Oil spills produce materials harmful to gulf species; the volatile fractions are particularly toxic. Massive spills such as the IXTOC I blowout in 1979 left large concentrations of weathered petroleum in the gulf. Kalke et al. (1982) observed that colonization by benthic species during exposure to the weathered material generally decreased, and oxygen penetration into the sediments was reduced. This could inhibit benthic processes such as nutrient regeneration. Spill volumes (including bay spills) in the region in 1977 and 1978 were 1.89 million l (500 thousand gal) and 1.51 million l (400 thousand gal) respectively (Liebow et al. (1980). IXTOC I raised the spill volume to more than 102 million l (27 million gal).

The long-term effects of oil and gas development on gulf habitat are unknown. One study (Sharp and Appan 1978) reported on the cumulative effects of development in the gulf off Louisiana. Its conclusion, based upon comparative biological, chemical, physical, and geologic investigation, was that there was no demonstrable degradation and that the area appeared ecologically healthy. Others (Bender et al. 1979) have criticized this study because control sites, chosen because there was no baseline data available for comparison, might themselves have been affected by oil and gas evelopment. Within the state-owned portion of the gulf habitat in Texas there is little baseline data that could be used as a basis for assessing long-term impacts of oil and gas development.

Lake and Reservoir

Areal extent. The Texas Barrier Island Region contains 1376 sq km (531 sq mi) of lake and reservoir habitat, 2.6 percent of the region's area. The Laguna Madre basin has the largest area of this habitat, 600 sq km (232 sq mi). While lake and reservoir in this basin comprises only 3.5 percent of the basin area, it amounts to nearly 44 percent of this habitat in the region.

Lake and reservoir habitat occupies 237.8 sq km (91.8 sq mi), or 2.2 percent, of the Galveston basin area. The Rio Grande basin has the highest proportion of this habitat, 11.3 percent, or 83.7 sq km (32.3 sq mi) (Figure 85).

Physical description. This habitat consists of large, shallow, land-locked open water bodies, both natural and man-made. Natural lakes in the region are rarely more than a few meters deep. Artificial reservoirs may be somewhat deeper, but the low, flat coastal landform limits the depth and capacity of lakes and reservoirs in the region. On the mainland most natural

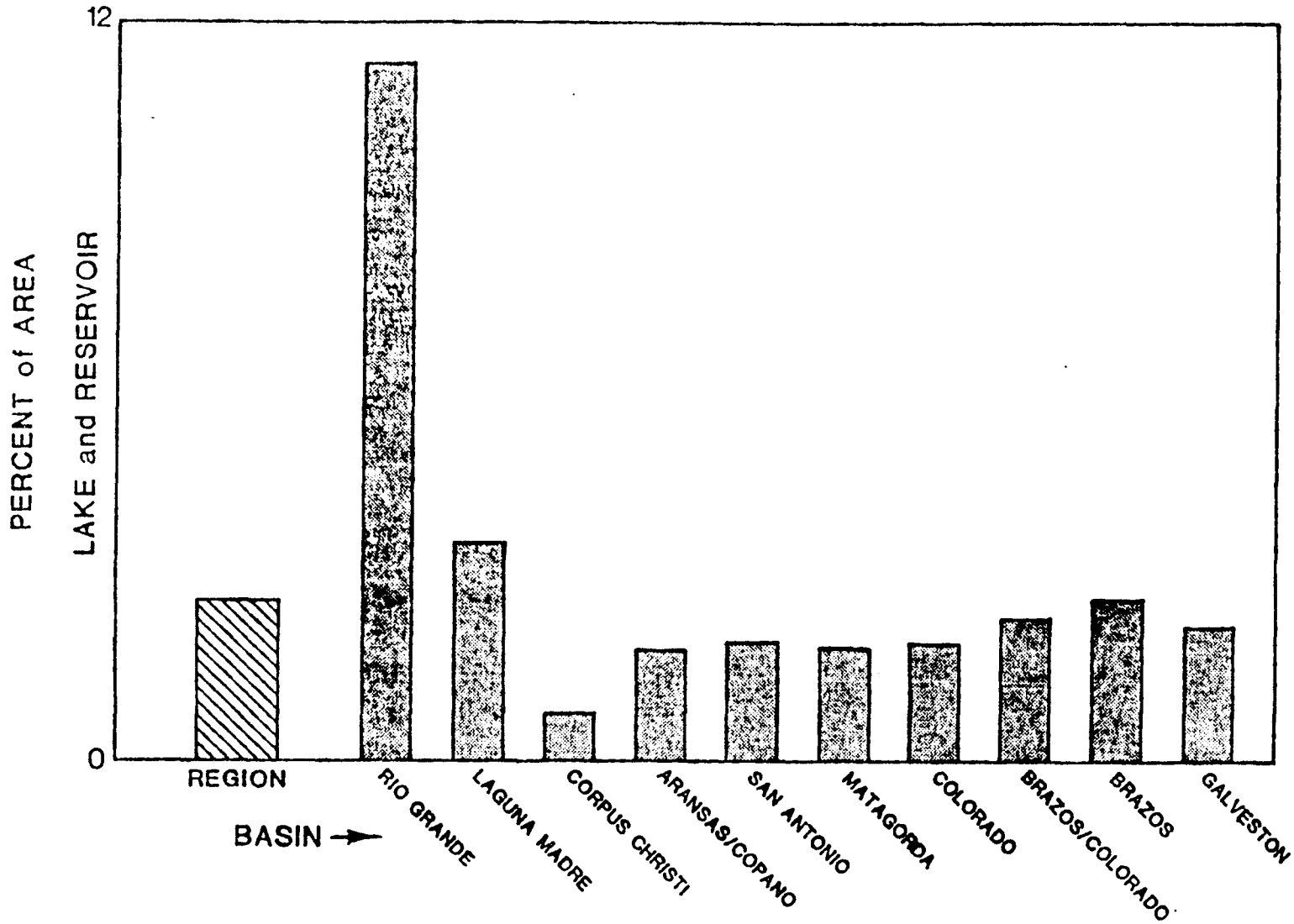


Figure 85. Percent of region and basin area that is lake and reservoir habitat.

lakes and ponds are circular to elliptical in shape. They are located on Pleistocene deltaic, fluvial-deltaic, or interdistributary deposits. Sediments range from mud to sand, and water sources include rainfall, land runoff, and stream flow (Fisher et al. 1972). Water in these lakes and ponds is generally fresh.

On the mainland of the Laguna Madre basin, small permanent and ephemeral ponds exist in wind-deflation depressions. The substrate is usually mud, but in a few places wind has eroded the sediment down to sandy substrates. If a high water table is present, the pond may be charged with groundwater in addition to receiving direct rainfall and runoff (Brown et al. 1977). Water salinity may range from fresh to brackish; in the latter case salt comes from airborne sources or from floodwaters during major storms.

The lower portions of some river floodplains contain abandoned river channels and oxbows. The Trinity River floodplain and the Brazos and Colorado basins exhibit many of these abandoned river features. Most are mud-filled and receive fresh water from rainfall, runoff, small streams, and occasional flooding of large rivers (Fisher et al. 1972; McGowen et al. 1976b).

Some smaller natural lakes and ponds are found in elongated swales on barrier islands. They are also present in mud-bottomed swales on Pleistocene barrier-strandplain systems such as Live Oak Peninsula, which parallels the coastline along the mainland of Aransas and Redfish bays. Water for these ponds comes from direct rainfall, land runoff, and occasional inundation by storms (Brown 1976; McGowen 1976a). It is fresh to brackish but can be highly variable depending upon rainfall, storms, and drought.

Many man-made lakes and reservoirs are located throughout the region. Most have been constructed by the placement of small earthen dams for impoundment in areas that collect water naturally. Water for these reservoirs comes from direct rainfall, land runoff, and river flow, or is pumped from wells or canals. Reservoirs supply water for agricultural, municipal or industrial purposes. To be suitable for these uses water must be within the range of fresh to only faintly brackish, usually with a salinity of less than 0.5 ppt. Water in some artificial reservoirs such as cooling ponds for power plants is not used for human or animal consumption. The salinity of this water is less critical to its use and may be fresh to brackish.

Because these water bodies are usually shallow, oxygen levels generally remain above 5 mg per l; the pH range is neutral, 6.5 to 8.5. At times lake and reservoir habitats may have high nutrient levels, especially if they receive sewage effluent or are near urban areas or fertilized croplands.

System operation. The flows of water entering lake and reservoir habitats in the coastal region transport sediment, nutrients, organic matter, and microorganisms from human and animal waste. Shallow lakes and reservoirs lose water through evaporation; through drawdown for agricultural, municipal, and industrial use; through the directing of flow to downstream segments; and through seepage into shallow aquifers in sandy substrates.

Little information is available about coastal lakes and reservoirs. A few monitoring studies have been made of Lake Corpus Christi in the Corpus Christi Basin, and Lake Houston, Lake Charlotte and Lost Lake, all located in the Galveston Basin. The studies indicate that these water bodies have an excess supply of phosphate and that phytoplankton production is sometimes limited by nitrogen availability (Kirkpatrick 1976; Twidwell 1976; U.S.

Environmental Protection Agency 1977a, b; Bedient 1980). Bedient (1980) constructed mass balances for Lake Houston, located just outside the inland boundary of the region. The lake was a sink for total sediment, nitrate nitrogen, and total phosphorus in wet, dry, and medium rainfall years. The proportion of materials retained ranged from 1.2 to 93.3 percent of the input; average retention was nearly 60 percent. Retained materials reside in the sediments, and Bedient noted that storms were probably important in releasing some materials back into the water column.

Phytoplankton are the dominant producers in lakes and reservoirs, although some macrophyte production occurs. There is evidence that water hyacinth (Eichornia crasspies), a floating macrophyte, is rapidly spreading in Texas's lakes; Benton (1978) has predicted that it may eventually cover 20 percent of the surface of many East Texas reservoirs. Some floating macrophytes take up nutrients rapidly and do not return them as quickly to the water as phytoplankton do (McCulloch 1978). In addition, floating macrophytes shade out phytoplankton and reduce wind-induced circulation.

While the lake and reservoir habitats may have large reserves of nutrients, water inputs and wind action are vital to the maintenance of adequate nutrient supplies for phytoplankton. Consequently water inputs and wind energy are the driving forces for the habitat. They also may control the upper limit of primary production. Normal Secchi disk readings in these water bodies is less than 0.5 m (1.6 ft). Primary production from phytoplankton is limited to a very thin zone near the surface since the turbidity caused by wind-induced mixing and high inflows can reduce light penetration to practically zero.

The fauna of lakes and reservoirs consist of zooplankton, benthic species, fish, and birds. Zooplankton utilize phytoplankton as a food source and form a level of the food web for filter-feeding benthic species and small fish. Benthic species such as worms and larval insect forms are an important food source for bottom-feeding fish. Carnivorous fish, birds, large reptiles, and a few mammals constitute the highest level of the food web in lakes and reservoirs.

Flora and fauna. Phytoplankton found in reservoirs include green algae, diatoms, and blue-green algae. Some common genera are *Chroomonas* sp., *Chroococcus* sp., *Merismopedia* sp., *Cryptomonas* sp., *Ankistrodesmus convolutus*, *Stephanodiscus* sp., *Oscillatoria* sp., *Oocystis parva*, *Scenedesmus* sp., and *Diploneis* sp. (Harrel 1973; Kirkpatrick 1976; Twidwell 1976; U.S. Environmental Protection Agency 1977a, b; McCullough et al. 1981). Floating macrophytes include the hyacinth (*Eichornia crasspies*), alligator weed (*Alternanthera philoxeroides*), and duck weed (*Lemna minor*). Hydrilla (*Hydrilla verticillata*) has been reported in East Texas reservoirs and is expected to invade Lake Wallisville (U.S. Army Corps of Engineers 1981). In brackish lakes and ponds, the same algal producer species that found in salt and brackish marshes may be present.

Zooplankton in freshwater lakes and reservoirs include the crustaceans *Daphnia pulex*, *D. parva*, *Diaptomus* sp., *Cyclops* sp., and the rotifers *Filinia* sp. and *Asplanchna* sp. Some abundant bottom-dwelling and burrowing species are the oligochaetes *Limnodrilus udekemianus*, *L. hoffmeisteri*, *Tubifex tubifex*, and *Dero digitata*; the leech *Helobdella stagnalis*; the snails *Amnicola* sp., *Ferrissia tarda*, and *Physa halei*; and the dipteran larvae

Chironomus sp., Pseudochironomus sp., Chaoborus punctipennis, and Glyptotendipes sp. (Harrel 1973; McCullough et al. 1981; Barra et al. 1982). The agasicles flea beetle (Agasicles hygrophila) and phycitid moth (Vogtia mallei), insects that use alligator weed, were reported in the Wallisville area on the Trinity River (U.S. Army Corps of Engineers 1981).

Estuarine fish that inhabit creeks in salt marshes may be found in brackish ponds and lakes. In strictly fresh waters some of the well-known species are the spotted gar (Lepisosteus oculatus), alligator gar (L. spatula), gizzard shad (Dorosoma cepedianum), threadfin shad (D. petenense), carp (Cyprinus carpio), golden shiner (Notemigonus crysoleucas), smallmouth buffalo (Ictiobus bubalus), blue catfish (Ictalurus furcatus), channel catfish (I. punctatus), mosquitofish (Gambusia affinis), bluegill (Lepomis macrochirus), largemouth bass (Micropterus salmoides), black crappie (Pomoxis nigromaculatus), and freshwater drum (Aplodinotus grunniens) (Harrel 1973; U.S. Army Corps of Engineers 1981).

Many birds frequent this habitat. Abundant species reported by Rowe and Williams (1976) include the greater yellowlegs (Totanus melanoleucas), lesser yellowlegs (T. flavipes), pied-billed grebe (Podilymbus podiceps), purple gallinule (Porphyra martinica), common gallinule (Gallinula chloropus), and the coot (Fulica americana).

The American alligator (Alligator mississippiensis) is frequently found in brackish and fresh natural ponds and lakes.

Adjacent systems and flows. More than 45 percent of the habitats adjacent to lake and reservoir are range. Other frequently adjacent habitats are forest (13.5 percent) and cropland (10.3 percent). Only 2.1 percent of the adjacent habitats are urban land. All of these habitats are commonly

adjacent to man-made reservoirs. They export materials to lake and reservoir, mostly through direct runoff from the land. Urban and cropland habitats may export nutrients (fertilizer or sewage) or toxins (pesticides or toxic chemicals) to the lake or reservoir habitat. It is unusual for an adjacent habitat to receive materials from the lake and reservoir habitat directly unless exceptional storms cause local flooding. Mobile consumers such as birds inhabit the lake and reservoir habitat as well as adjacent habitats.

Salt and brackish marsh (11.4 percent of adjacent habitats) is frequently adjacent to natural lakes and ponds. Salt and brackish marsh may border coastal lakes and ponds at a slightly higher elevation. Normal rainfall results in a one-way flow of water and materials into the ponds from the marsh areas (Borey et al. 1983). During storms floodwaters carried by creeks may inundate the area, and water and materials may be transported from the ponds and lakes to the marshes. Lakes and ponds may also be located at elevations slightly above salt and brackish marsh, especially on deltas. The ponds are filled by rainfall and river flooding and may occasionally supply materials and water to adjacent salt and brackish marsh.

Freshwater marsh frequently borders lake and reservoir, constituting 9.6 percent of the adjacent habitats. Materials and organisms are imported and exported between these habitats.

River and canal constitutes 1.8 percent of the adjacent habitats. If the connection is upstream, the lake and reservoir habitat imports water, sediment, nutrients, and organisms from river and canal. If the connection is downstream, lake and reservoir exports water but relatively less sediment, nutrients, and organisms than it imports.

Economic uses. Man-made reservoirs are primarily used for municipal, industrial, and irrigation water supplies. They are also used as cooling water ponds for electric generating plants, to retard water flow for local flood control, and for recreation. Natural ponds, dammed to create larger and more easily controlled impoundments, are used as watering sites for livestock. In some places natural ponds have been dammed to create larger open-water sites attractive to waterfowl.

Impacts of man's activities. Some natural ponds and lakes have been eliminated by filling or draining to create upland for urban or agricultural uses. Others have been dammed or have had wiers placed across them to hold water for longer periods. The main effects of damming shallow ponds are to make them more permanent, to deepen them, and to make them more dependent upon phytoplankton and less dependent upon benthic algal production.

Man-made reservoirs that are used for water supply may fluctuate in depth depending upon quantity of use and short-term water flow from rainfall, river inflow, and local runoff. During drought years lake levels and surface area may decline greatly.

Urban, cropland, and harvested forest areas near this habitat may be the sources of significant nutrient and organic loading as well as fecal coliform bacteria. Larger reservoirs like Lake Houston are already eutrophic. Massive control of non-point sources of nutrients would be necessary to change the trophic structure (Bedient 1980).

Range

Areal extent. Range habitat consists of two ecosystems, brush and coastal prairie. Though separate models have been made for these systems (see

Appendix C), they are fundamentally alike, differing in the relative proportion of plant types and levels of some environmental parameters.

Range is the largest single habitat unit in the Texas Barrier Island Region, occupying 16,023 sq km (6187 sq mi), or 30.6 percent of the region's area. The largest quantity of range is in the Laguna Madre basin: 6433 sq km (2483 sq mi), or 37 percent of the basin area. The Aransas-Copano basin has 2524 sq km (974 sq mi) of range, which is 50.6 percent of the basin area.

Figure 86 shows the relative distribution of range in the region. The mid-coastal region has the highest proportion of range. The Rio Grande, Nueces, and Galveston basins have the lowest proportions of range; of these, the Rio Grande and Nueces basins have particularly large areas of cropland that might be range area.

Physical description. The range habitat is a combination of grassland and brush. Most of the range habitat is in two natural vegetational areas in the region: the gulf coast prairie and the Rio Grande plain. Much of the area was perennial tallgrass prairie or post-oak savannah before man's activities became prevalent (Gould 1975).

Brush is not prominent in range habitat of the middle and upper coast. To the south, the relative proportion of brush increases. Smith and Rechenthin (1964) estimated that range with heavy brush (covering more than 20 percent of the land surface) constituted 73 percent of the habitat in the Rio Grande plain and that only 17 percent of the habitat in the gulf coast prairie contained heavy brush. Davis and Spicer (1965) also evaluated the brush invasion problem and concluded that more than 70 percent of the uncontrolled brush in the Rio Grande plain had a density exceeding 45 percent of the ground cover, with heights exceeding 2.3 m (7.5 ft).

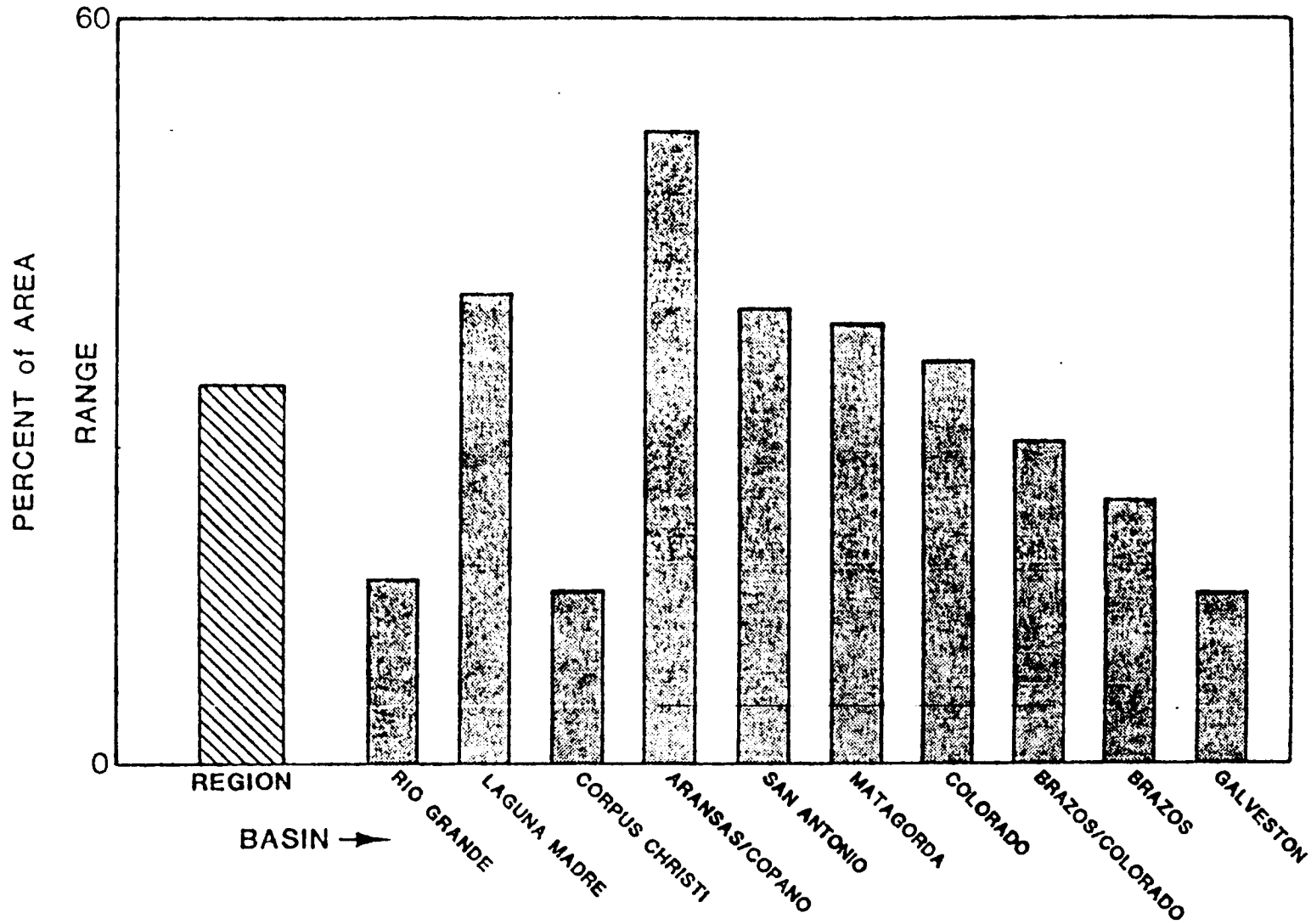


Figure 86. Percent of region and basin area that is range habitat.

Land elevation in the range habitat varies from about 1.6 m (5 ft) above mea high water (MHW) at the boundary of salt and brackish marsh to 46 m (150 ft) at the inland boundary of the region. Soils on which range vegetation grows are acid clays or clay loams with some sandy loam; permeability ranges from low on clays to high on sandy soils. Rainfall varies from 50 inches per year in the north to about 20 inches per year in the south.

System operation. Solar radiation, rainfall, and salt input are the main forces from outside the system that govern its operation. Precipitation is the only water source for most rangeland, but some low areas near the coast may be inundated infrequently during major storms. Both quantity and pattern of rainfall throughout the year are important to range plants. The northern parts of range habitat receive proportionally more of their annual moisture in the spring than the southern areas. The southern range areas receive a greater proportion of their precipitation during summer and fall.

The amount of rainfall that can be absorbed into the soil depends upon the soil type, rainfall rate, slope of the land, and amount of organic litter on the land surface. Very fine-grained soils cannot absorb surface water quickly; less water will be absorbed from short, hard rainfalls than from longer moderate rainfalls. Land slope determines the runoff rate from the land surface; flatter slopes allow standing water to slowly soak into the soil. Litter impedes the flow of runoff so that more is absorbed into the soil (Passey and Smith 1966); litter also insulates the soil surface, keeping it cooler and retarding evaporation (Weaver and Fitzpatrick 1934).

Soil characteristics influence plant survival under drought conditions. Herbel et al. (1972) noted that deep-rooted grasses on deep sandy soil dried

out more quickly under drought conditions than plants with shorter root systems. Plants on shallow sandy soil underlair with caliche were more successful in droughts since the caliche held some moisture.

Competition for water is an important aspect in the balance between grass and brush. Brush is particularly well adapted to dry conditions; Rechenthin and Smith (1967) reported that mesquite roots have been found as deep as 125. But while they are able to out-compete grasses for water, brush species are less efficient water users. Passey and Smith (1966) observed that mesquite needs more than twice as much water to produce a pound of biomass as grama grass. Brush species also provide less obstruction to runoff than grasses. A consequence of invasion of grasslands by brush is increased erosion and sediment transport.

Nutrient relations in the range habitat are essential to high production. Risser and Parton (1982), who modeled the nitrogen relations of a tallgrass prairie, noted more than a dozen pathways of nitrogen flow. Some major inputs into nutrient cycles include rainfall, dry deposition (from salt in the air), nitrogen fixation, substrate weathering, and remineralization from organic matter. The latter two inputs are particularly affected by pH, moisture content of the soil, temperature, and soil aeration. Nutrient losses result from runoff, volatilization of ammonia, and removal by large herbivores (Woodmansee 1978).

Fire, grazing, and drought have long-term effects on range habitat. Fire consumes dead organic matter on the range and releases inorganic nutrients--some to the soil, some to the atmosphere. The reduction of litter on the soil surface may promote or hinder grass growth depending upon the circumstances. If a thick layer of litter has built up, burning releases nutrients without

completely denuding the soil surface, and productivity may be improved. If only a thin litter layer is present, all the litter is consumed; nutrients may be released, but runoff or erosion may result. Everitt (1983) reported that the burning of South Texas rangeland under rainy conditions improved the forage quality of grasses and browse; nutrient and crude protein content was generally improved. However, he noted that areas burned under dry conditions might not show improvement because of limited regrowth.

The most important effect fire has on range is burning of woody brush (Bragg and Hulbert 1976). This balances the competitive edge that brush has in its ability to obtain water and shade out grasses, because grasses can regrow quickly after fire while small brushy vegetation cannot. The ability of fire to control brush is limited, however. Beyond a critical size and density, hardwood vegetation resists fire (Blakey 1947; Box et al. 1967). Consequently fire must occur frequently to control brush, or its effects may be more detrimental to grasses than to woody vegetation.

Antelope, buffalo, and deer were common grazers on grasslands before cattle were introduced. Smith and Rechenthin (1964) reported grazing densities of 0.9 to 2 animals per ha (2 to 5 animals per ac) year-round, much higher than grazing densities of natural populations. At high grazing densities, cattle eat nearly all of the leafy vegetation of grasses, leaving no photosynthetic machinery for the plant to use to replenish its energy reserves. Once all of the plant's energy reserves are used up it dies.

Cattle selectively eat the most palatable plants first. As grazing intensity increased on the natural prairies, this action served as a selective pressure on vegetation and led to the decline of the tallgrass prairie. By

eating the tall grasses nearly down to ground level and keeping them clipped low, cattle gave a competitive advantage to short grasses which were less palatable and less productive. This selection process eventually eliminated the preferred species and rplaced them with short grasses.

By eating all of the material that would become litter and opening nearly bare spots on the range soil, cattle produced advantageous conditions for brush invasion. Brush was less palatable than short grasses, so that brush species were given an additional competitive boost. These circumstances combined with occasional droughts and more control of fires produced the brush invasion seen today.

Flora and fauna. A wide variety of grasses on the range habitat provide most of the primary production that supports a diverse community. Some of the most common grasses are big bluestem (*Andropogon gerardii*), big sandbur (*Cenchrus myosuroides*), buffalograss (*Buchloe dactyloides*), bufflegrass (*Cenchrus ciliaris*), bushy bluestem (*Andropogon glomeratus*), California cottontop (*Digitaria californica*), common curlymesquite (*Hilaria belangeri*), eastern gammagrass (*Tripsacum dactyloides*), gulf cordgrass (*Spartina spartinae*), indiangrass (*Sorghastrum nutans*), longspike silver bluestem (*Bothriochloa saccharoides*), seacoast bluestem (*Schizachyrium scoparium*), switchgrass (*Panicum virgatum*), and tanglehead (*Heteropogon contortus*) (Beaty and Jameson 1973; Gould 1975; El Paso Eastern Company, El Paso LNG Terminal Company, El Paso Natural Gas Company 1977).

Brush and trees that have increased in density on rangeland include acacia (*Acacia* spp.), blackbrush (*Acacia rigidula*), groundsel tree (*Baccharis halimifolia*), huisache (*Acacia farnesiana*), live oak (*Quercus virginiana*), blackjack oak (*Q. marilandica*), post oak (*Q. stellata*), mescal bean (*Sophora*

secundiflora), mesquite (Prosopis glandulosa), prickly pear (Opuntia spp.), and retama (Parkinsonia aculeata) (Bogusch 1952; Gould 1975; Scifres 1980). Chinese tallow tree (Sapium sebiferum) is an imported species that has invaded range in the upper portion of the region (Beaty and Jameson 1973).

Many herbivorous, saprophytic, and predatory insects live in the range habitat; Beaty and Jameson (1973) report that more than 1000 species have been cataloged on a 372-hectare coastal prairie laboratory site near Houston.

Amphibians that live in the range habitat include the cricket frog (Acris crepitans), eastern spadefoot (Scaphiopus holbrooki), gulf coast toad (Bufo valliceps), lesser siren (Siren intermedia), and western chorus frog (Pseudacris triseriata). Many of these species are insectivores and may be prey for a wide variety of reptiles and birds. Common reptiles found in the habitat include the chicken turtle (Deirochelys reticularia), red-eared turtle (Chrysemys scripta), western box turtle (Terrapene ornata), eastern fence lizard (Sceloporus undulatus), green anole (Anolis carolinensis), Texas horned lizard (Phrynosoma cornutum), checkered garter snake (Thamnophis marcianus), coachwhip (Masticophus flagellum), common kingsnake (Lampropeltis getulus), common rat snake (Elaphe obsoleta), prairie kingsnake (Lampropeltis calligaster, western cottonmouth (Agkistrodon piscivorous leucostoma), and western diamondback rattlesnake (Crotalus atrox) (Beaty and Jameson 1973; El Paso Eastern Company, El Paso LNG Terminal Company, El Paso Natural Gas Company 1977).

Numerous birds--granivores, insectivores, and predators--inhabit the range. Common birds that have been reported include the blue jay (Cyanocitta cristata), bobwhite (Colinus virginianus), eastern meadowlark (Sturnella

magna), eastern phoebe (Sayornis phoebe), English sparrow (Passer domesticus), great horned owl (Bubo virginianus), Harris' hawk (Parabuteo unicinctus), indigo bunting (Passerina cyanea), loggerhead shrike (Lanius ludovicianus), mockingbird (Mimus polyglottos), mourning dove (Zenaidura macroura), prairie chicken (Tympanuchus sp.), red-tailed hawk (Buteo jamaicensis), red-winged blackbird (Agelaius phoeniceus), roadrunner (Geococcyx californianus), scissor-tail flycatcher (Muscivora forficata), screech owl (Otus asio), turkey vulture (Cathartes aura), warbler (Dendroica spp.), white-winged dove (Zenaida asiatica), and wild turkey (Meleagris gallopavo). The cattle egret (Bubulcus ibis) is a recent arrival to the western hemisphere from Africa; it favors range areas and a close association with cattle (Beaty and Jameson 1973; Rowe 1974; 1975; El Paso Eastern Company, El Paso LNG Terminal Company, El Paso Natural Gas Company 1977).

Among the small omnivorous mammals that live in the range habitat are the cotton rat (Sigmodon hispidus), eastern cottontail (Sylvilagus floridans), eastern mole (Scalopus aquaticus), fulvous harvest mouse (Reithrodontomys fulvescens), least shrew (Cryptotis parva), northern pygmy mouse (Baiomys taylori), rice rat (Oryzomys palustris), and Texas pocket gopher (Geomys personatus). Larger species include the opossum (Didelphis marsupialia), nine-banded armadillo (Dasypus novemcinctus), collared peccary (Dicotyles tajacu), and whitetail deer (Odocoileus virginianus). The coyote (Canis latrans), striped skunk (Mephitis mephitis), raccoon (Procyon lotor), and occasionally the bobcat (Felis rufus) are representative carnivores (White 1973; Beaty and Jameson 1973; Snyder et al. 1978; El Paso Eastern Company, El Paso LNG Terminal Company, El Paso Natural Gas Company 1977). Cattle are, of course, the most conspicuous large consumer on range land.

Adjacent systems and flows. Thirty-seven percent of the habitats adjacent to range are cropland. This high percentage indicates that there may be some conversion of one habitat to the other. Cropland acreage in the region increased from 1969 to 1974, while the amount of pasture land in 1974 was smaller than in 1962 and 1969 (Liebow et al. 1980). In addition there was a general decline in cattle population throughout the region between 1954 and 1974 (Liebow et al. 1980). Consequently it is likely that any land use conversion was from range to cropland.

Forest constitutes 27 percent of the habitats adjacent to range. Habitat maps of the Colorado, Brazos-Colorado, and Brazos basins (Plates 7, 8, and 9) show that much range habitat has been reclaimed from forest. Other adjacent habitats include lake and reservoir (5 percent), salt and brackish marsh (5 percent), river and canal (4 percent), urban (4 percent), and bay (4 percent).

The range exchanges relatively few materials with other habitats. Other than salt and nitrogen imported from other systems, most material exchanges are probably exports of water, sediment, and nutrients. Climax communities export only small quantities of nutrients. Odum (1969) and others have suggested that maturing ecosystems gradually reduce nutrient losses so there is a net accumulation at the climax condition. Woodmansee (1978) proposed a different viewpoint: that all seral stages conserved nutrients except during perturbations such as heavy grazing or fire. He noted that conservation of nutrients through accumulating litter, soil colloids, and plant biomass involved abiotic as well as biotic processes. He pointed out that removal of nutrients from grasslands by large ungulates and volatilization of their waste products may account for the majority of nutrient losses.

Economic uses. The main economic use of range is for cattle grazing. The number of cattle and calves on commercial farms in the region has steadily declined from 1,048,316 in 1954 to 974,929 in 1974. During the same period the market value of livestock increased from $49,167,000 to $124,883,000. Only about 5 percent of the cattle were held in feedlots (Liebow et al. 1980).

An important secondary use of range is for recreation, especially for hunting. In some areas where the range is marginal for grazing, hunting leases generate more revenue than cattle production.

Impacts of man's activities. Experts disagree about the relative amount of brush that existed naturally before overgrazing began. Smith and Rechenthin (1964) cite reports by early settlers of vast grasslands with scattered trees, mottes, and woody growth along water courses. Lehmann (1969) claims that much of the Rio Grande plain was vegetated with native brush.

All authorities agree that brush vegetation has probably spread because of heavy grazing since the mid-1800's. The major impacts of overgrazing have been known for 30 years. Where brush has invaded grasslands, the value of the range for cattle has declined. In some places the brush invasion has increased erosion and topsoil loss. Soil conservation publications note that the increased use of water by phreatophytes such as mesquite decreases the amount available for other uses (Rechenthin and Smith 1967; Texas Department of Water Resources 1977).

Brush control measures include mechanical removal or cutting, and chemical treatment with oil; 2,4,5-T; 2,4-D; dicamba; and picloram (Texas State Soil and Water Conservation Board 1981). Mechanical methods such as chaining, chopping, and root plowing cause major land surface disruptions and may increase erosion unless they are immediately followed by replanting.

Brush regrowth is problematic. Root plowing combined with reseeding seems to give the least regrowth (Davis and Spicer 1965).

While brush control is beneficial to agriculture, it has had mixed effects on wildlife populations. Lay and Culbertson (1978) noted that it is often detrimental to wildlife because cover, breeding and nesting areas, and forage plants are destroyed. In other areas the increased habitat diversity resulting from brushy invasion has improved the wildlife habitat. Some brush control practices are beneficial to both interests, however. Retention of some native brush species, selective removal of second or third-growth types that follow unsuccessful brush control, removal of brush unpalatable to wildlife, and prevention of overgrazing improve the habitat for both wildlife and cattle.

Reef Habitat

Areal extent. Reef habitat in the Texas Barrier Island Region consists of 331.8 sq km (128.1 sq mi) of dense oyster reef and reef flank. This constitutes 0.6 percent of the region's area. About two-thirds of the reef habitat, 221 sq km (85.3 sq mi), is in the Galveston basin. The Lavaca-Matagorda, Aransas, and San Antonio basins have 37.3, 32.1, and 22.3 sq km (14.4, 12.4, and 8.6 sq mi) of reef respectively. Basins in which the river runs directly into the gulf contain almost no reef habitat. Figure 87 shows the distribution of relative amounts of reef for the basins in the region.

The reef habitat includes both live and dead surface reefs. In some bays dead reef deposits extend below the surface sediments for some distance. In many places these deposits have been dredged as a source of shell and carbonate for building materials and the chemical industry.

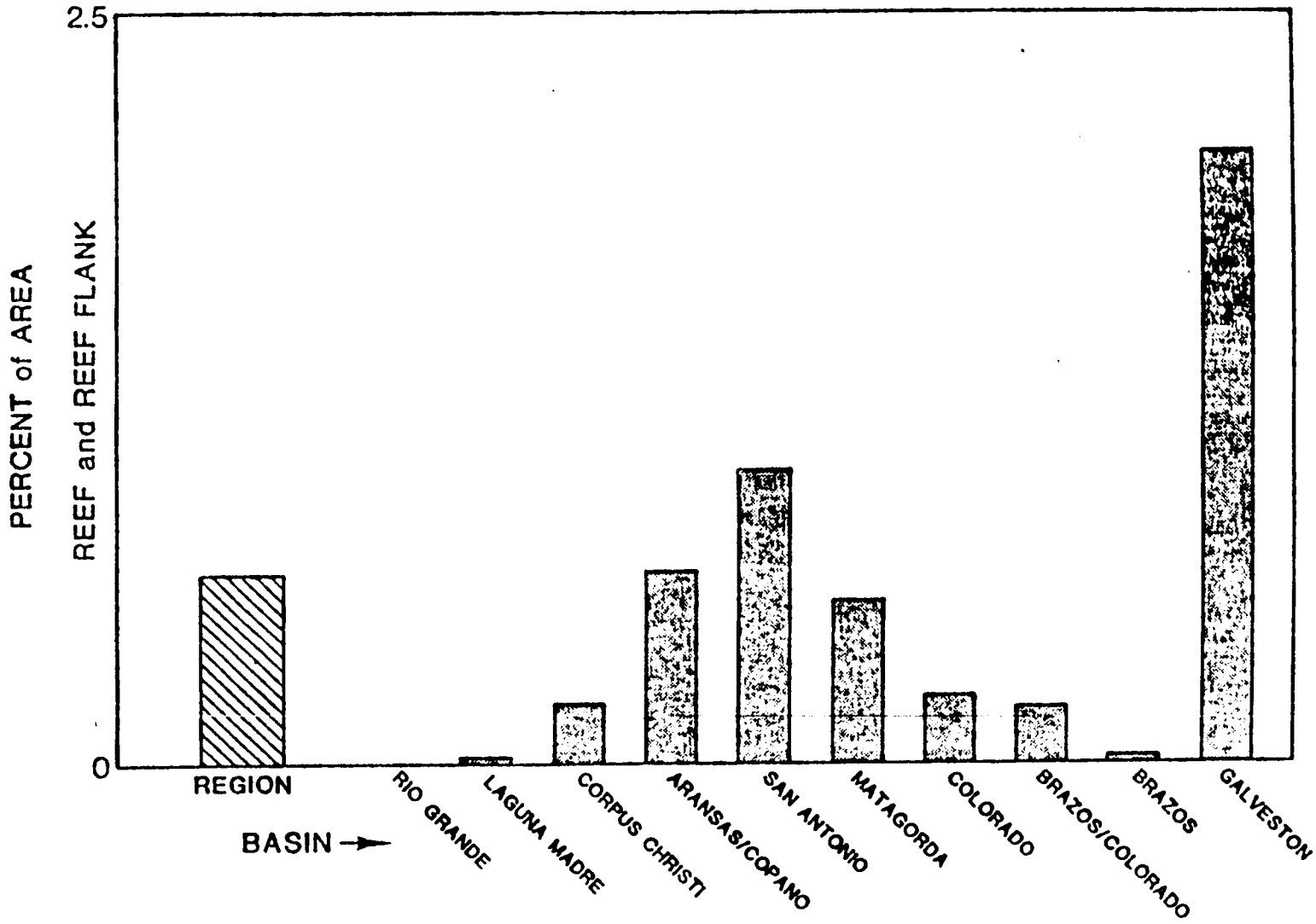


Figure 87. Percent of region and basin that is reef habitat.

Physical description. Texas reefs are rarely subaerial, and most are undetectable from the surface. Because of the small tidal fluctuation in Texas bays, large intertidal reefs like those described by Bahr and Lanier (1981) for the south Atlantic Coast are not seen. Some small areas of reef are located near marshes and seagrass beds where detrital material is plentiful. These may be intertidal like the oyster reefs studied by Copeland and Hoese (1966); however, most Texas oyster habitat is in large reefs in deep water.

Reefs vary in shape from circular to long and narrow (Fisher et al. 1972). Small reefs are often circular, but large reefs are almost always elongate with their axes perpendicular to the major direction of water flow. Live oysters are found at or near the surface of the reef or in locations within the reef where water circulation is adequate. Shell from previous generations of oysters makes up the interior of the reef. Spat that float in the plankton settle on the hard shell surfaces of the outer layers and grow there. Thus, unless they are buried by sediment or are killed by disease or temperature or salinity extremes, reefs continuously grow and change in shape.

System operation. The oysters themselves are the principal component of the reef habitat since their shells form its physical structure. The major driving force of the reef habitat is the current energy that moves material through the reef. Adult oysters cannot move about; therefore, while the reef as a whole may pump a large volume of water in a short time (Galtsoff 1964 reported that average adult oysters can filter at the rate of 15 liters per hour), individuals are dependent upon water circulation to bring phytoplankton, detritus, and oxygen to them, and to remove waste materials (Lund 1957a). During periods of low flow, when current energy is reduced,

oysters on the outer portions of the reef that are exposed to the incoming currents from the bay may filter almost all of the particulate matter out of the slow-moving water, leaving little for the remaining oysters.

The circulation pattern in the reef area changes as the reef form changes. Small reefs are circular since the reef area does not obstruct current flow. As the reef enlarges, some areas receive less current flow; consequently growth of oysters and the reef in these areas is low. The sides of the reef, perpendicular to the major direction of current flow, appear to be the most favorable for spat settling and rapid growth. As a result, the reef grows perpendicular to the direction of flow and becomes long and narrow.

Water level fluctuation and water salinity are also driving forces since in their extremes they can exert control over reef organisms. Extreme low tides that expose reefs to high temperatures and dessication cause high mortality in oysters and associated animals (Copeland and Jones 1966). This may affect the peaks of some large reefs, but most reefs remain entirely subaqueous even during low tides.

Brief salinity extremes and long-term salinity trends have important effects on the reef habitat. Davis and Calabrese (1964) showed that the optimum temperature and salinity combination for larvae was a temperature range of 30 to 32.5 deg C with salinities of 10 to 27 ppt. Lower salinities reduced the range of temperatures tolerated and impeded growth. Adult oysters can inhabit waters with a salinity range of 5 to 30 ppt (Galtsoff 1964), but prolonged exposure to salinities below 5 ppt may cause abnormal development and cessation of growth (Loosanoff 1953; Galtsoff 1964). Prolonged exposure to salinities above 30 ppt may slow growth and reproduction, but more

significantly it increases predation and parasite infestation (Gunter 1955). The flushing of the bays by periodic inflows of fresh water is beneficial to oysters because low salinities kill predators and parasites and restore bed productivity (Galtsoff 1964).

Important elements of the reef habitat include sediment solids, phytoplankton and organic matter, current energy, and the community of species that live on or around the reef. Suspended sediment is always present in Texas bays. High levels of suspended solids--carried by floodwaters or associated with dredging or other human activities--can smother reefs altogether; at lower concentrations sediment solids can decrease feeding efficiency.

The phytoplankton and organic matter in the water are the energy source for oysters and other reef dwellers. Since oysters filter-feed, they ingest and can accumulate any toxic materials or pollutants in the water as well. This includes petroleum hydrocarbons (Ehrhardt 1972), heavy metals (Kopfler 1974), and insecticides (Petrocelli et al. 1974).

The oyster reef community includes other sessile species, some of which are direct competitors with the oysters for food and attachment sites. The reef attracts predators that prey specificially upon oysters, and oysters are host to numerous parasites and disease organisms. Large mobile consumers, attracted to all the other species living in association with the reef, are transient inhabitants.

Flora and fauna. Producers in the vicinity of the reef community are the same as the producers in the bay habitat. The eastern oyster (*Crassostrea virginica*) is the primary oyster in Texas reefs; however, the horse oyster

(Ostrea equestris) also occurs, and under conditions of high salinity it may replace the eastern oyster (Menzel 1955).

Competing species include the anemone (Aiptasiomorpha texaensis), Atlantic slipper shell (Crepidula fornicata), serpulid worm (Hydroides dianthus), and barnacles (Balanus spp.). Some competitors--including the blister worm (Polydora websteri), boring sponges (Cliona spp.), and oyster piddock (Diplothyra smythii)--bore into the oyster's shell and then compete with the oyster for food (Fotheringham and Brunenmeister 1975).

Predators of oysters include a flatworm (Stylochus spp.), black drum (Pogonias cromis), sheepshead (Archosargus probatocephalus), blue crab (Callinectes sapidus), stone crab (Menippe mercenaria), and several xanthid crabs (Eurypanopeus depressus, Panopeus herbstii, Rhithropanopeus harrissi, and Neopanope texana) (Hofstetter 1977). The southern oyster drill (Thais haemastoma) is probably the most important predator (Mackin 1961). Its aversion to sustained periods of salinities lower than 15 ppt is the controlling factor in its predation.

Labyrinthomyxa marina (Mackin and Ray 1966) is a fungal parasite causing periodic mortality in oysters. It is controlled by extreme winter temperatures. Other parasites include Halosporidium spp. (Mackin 1960), a flagellate protozoan (Hexamita inflata), a trematode (Bucephalus sp.), and a gregarine (Nematopsis spp.) (Hoffstetter 1977). Mobile consumers attracted to the reef habitat include all those found in the bay habitat. White and Chittenden (1976) noted the particular affinity of older Atlantic croaker (Micropogon undulatus) to reef areas.

Adjacent systems and flows. Almost 90 percent of the habitat units adjacent to the reef habitat are bay habitats. Channel, salt and brackish

marsh, and spoil are sometimes found adjacent to reef habitat. Whatever materials are transported by currents through the bay waters are also transported through reef habitats. Thus, fresh water, suspended sediment, inorganic nutrients, organic detritus, toxics, and planktonic forms are transported to the reef. Oyster larvae and larval forms of other reef inhabitants are the major exports from the reef habitat to other systems.

Economic uses. Over the period 1965 to 1977 the annual oyster harvest in Texas ranged from 0.87 to 4.7 million lb, and the value of the harvest has ranged from $1.3 to $2.9 million per year (Liebow et al. 1980). Oyster harvest is restricted at times due to problems of water quality, especially in Galveston Bay. To encourage oyster production the Texas Parks and Wildlife Department and the Texas Department of Health have leased areas in unpolluted bays to oyster fisherman. Operators may transplant oysters to the leased areas from reefs closed because of poor water quality and harvest them after a prescribed holding period.

Shell dredging companies removed 88.4 million cu yd of oyster shell from Texas bays during the period 1962 to 1970. The uses of shell have been detailed by Arndt (1976). Dead reefs have been dredged in Galveston, Matagorda, San Antonio, and Nueces bays. By 1983 most of the exploitable dead reefs were gone and shell dredging had virtually ceased. Crushed limestone, supplied by rail from central Texas, is now used for construction material in place of oyster shell.

Impacts of man's activities. Very productive oystering areas such as Redfish Reef in Galveston Bay have been able to yield good harvests for more than 25 years despite frequent removal of large adult oysters. The greatest

adverse impact of man's activities on oyster populations is the degradation of water quality, particularly by high concentrations of coliform bacteria. Maps from Hofstetter (1977) and the Texas Department of Health (1979, 1983) show that areas closed to oystering have shifted only slightly over the period 1951 to 1979. About 45 percent of the area of Galveston Bay was closed to oyster harvest in 1979 (Texas Department of Health 1979); the closed area increased slightly in 1983 (Texas Department of Health 1983).

Mackin and Hopkins (1961) and Bouma (1976) reviewed the impacts from dredging dead reefs or near live reefs. Direct dredging of reef material removes the habitat and leaves a substrate less conducive to settlement by spat. Dredging near reefs produces high turbidity, loosening sediment that may settle directly upon live reef organisms and smother them. Reef contour, sediment composition, current direction, and intensity and distance from dredging are all important variables that determine whether dredged sediment will damage a reef (Benefield 1976).

Concern has been voiced that potential pollutants held in sediments may be resuspended by dredging and taken up by filter-feeding reef species. Experiments have shown, however, that dredging releases very few heavy metals, hydrocarbons, or pesticides and little oil and grease (Delahoussaye 1981).

Changes in hydrology, flow patterns, and freshwater inflows into bays have potential long-term impacts upon reef communities. For example, peak flows into the Matagorda Bay system are critical to the control of oyster predators; the moderation of peak flows associated with inflow reductions into Matagorda Bay is an important management consideration for the long-term fishery potential of the bay system (Armstong and Ward 1981). In recognition of the importance of hydrologic change to fisheries, the Texas Department of

Water Resources (1980) has presented the enhancement of shellfish harvest--including shrimp, blue crab, and oyster--as one of its three alternate estuarine objectives in Matagorda and other bay systems.

The effects of oil and gas activities on oyster reefs have been debated thoroughly. Mackin and Hopkins (1961) and Mackin (1971) have presented data showing that direct effects of brine, hydrocarbons, and other materials used in oil and gas exploration are minor. Benefield (1976) has noted that the shell pads (for temporary placement of floating drilling rigs), newly exposed shell, and alterations in currents in some oil exploration areas of Galveston Bay may have expanded oystering areas. It appears that the major adverse effects of oil and gas development have been the direct impacts of dredging through reefs and the smothering of live reef areas with spoil.

River and Canal

Extent. More than 5868 km (3646 mi) of river and canal habitat is found in the Texas Barrier Island Region. This measurement includes only principal rivers and major drainage ditches or irrigation canals; the region contains countless small creeks, streams, and minor canals that have not been measured. The density of the measured river and canal habitat within the region averages 0.11 km of habitat per sq km (0.18 mi per sq mi).

The Laguna Madre basin contains 1891.6 km (1175.4 mi) of river and canal habitat, more than any other basin. The Galveston basin has the second highest total, 1438.8 km (894 mi). The habitat density for the Laguna Madre basin is the same as for the region; the density in the Galveston basin is slightly higher, 0.13 km per sq km (0.21 mi per sq mi). The Rio Grande basin contains 257.5 km (160 mi) of river and canal with a habitat density of 0.35

km per sq km (0.56 mi per sq mi), higher than that of the larger basins. Figure 88 shows the relative lengths of the river and canal habitat for the basins in the region.

The length of irrigation canals and drainage ditches in the region is about ten times that of the rivers. The association between amount of river and canal habitat and cropland area is shown in Figure 89, which illustrates a linear regression of river and canal length on cropland area for each of the 10 basins. The regression accounts for 90.1 percent of the variance; the statistical significance of this association is very high ($P < 0.001$).

Physical description. Rivers and canals are narrow, flowing waterways containing fresh water. Major rivers are perpendicular to the coastline and flow toward it. Canals and drainage ditches have been built to take advantage of local topography and flow in whatever direction water transport requirements dictate. The orientation and direction of stream flow also depends upon local topography.

Rivers vary in width from less than a meter (3.3 ft) to as much as 100 m (328 ft); depth may range from 0.3 m (1 ft) to more than 4 m (13 ft). During years of normal rainfall, flow volume may range from practically nothing to more than 200 cu m per sec (7060 cu ft per sec) (Dougherty 1980). During droughts, small streams may dry up completely, and flow in rivers may fall to 10 or 20 percent of normal. In wet years, river flow may double or triple normal volumes. Stream velocity depends upon the flow volume and cross-sectional dimensions of the waterway, but is typically 0.1 to 0.4 m per sec (0.3 to 1.3 ft per sec).

River flow varies seasonally as well as from year-to-year; it is governed by upon rainfall within the drainage basin, which often extends much further

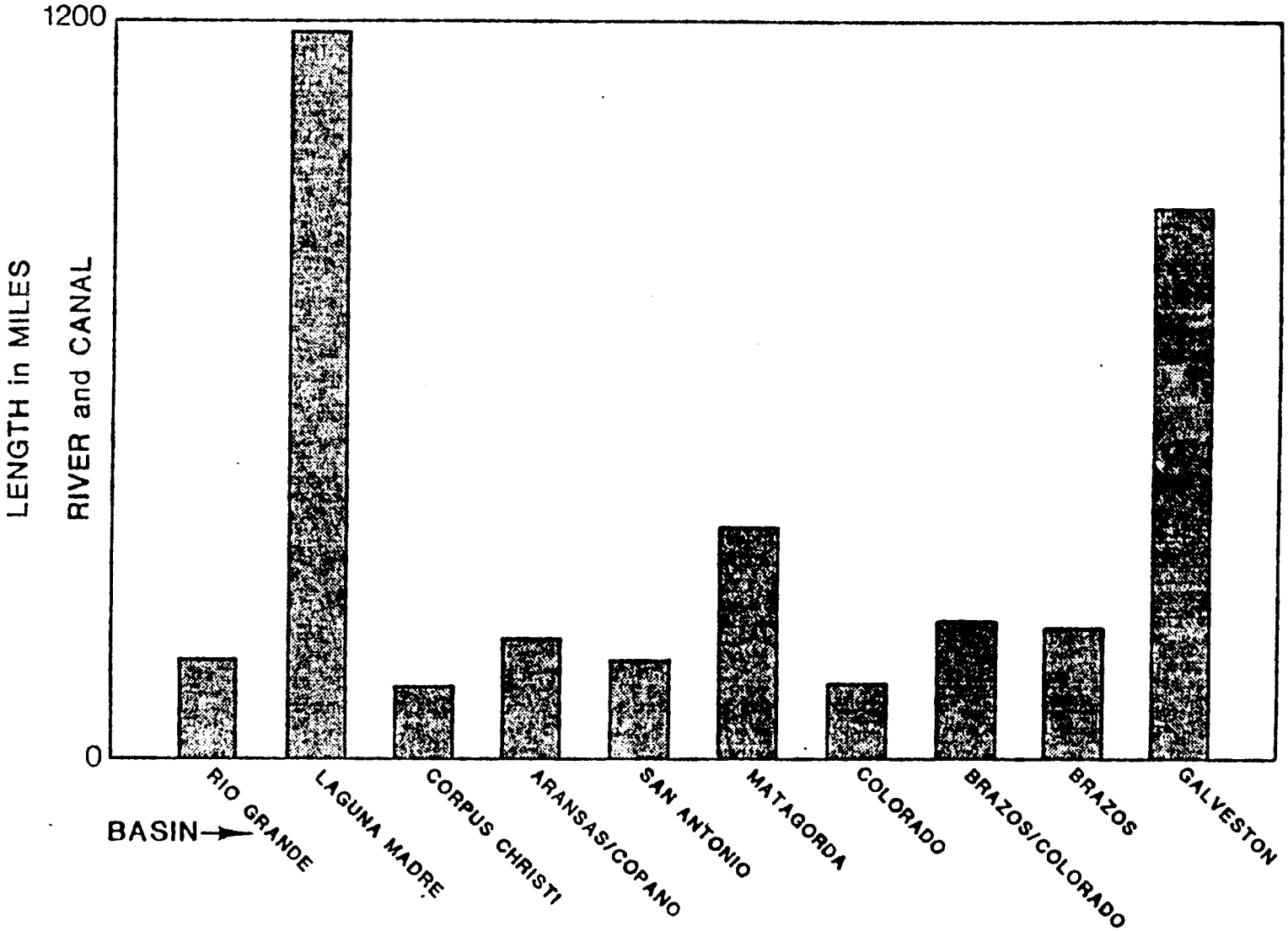


Figure 88. Length of river and canal habitat in basins.

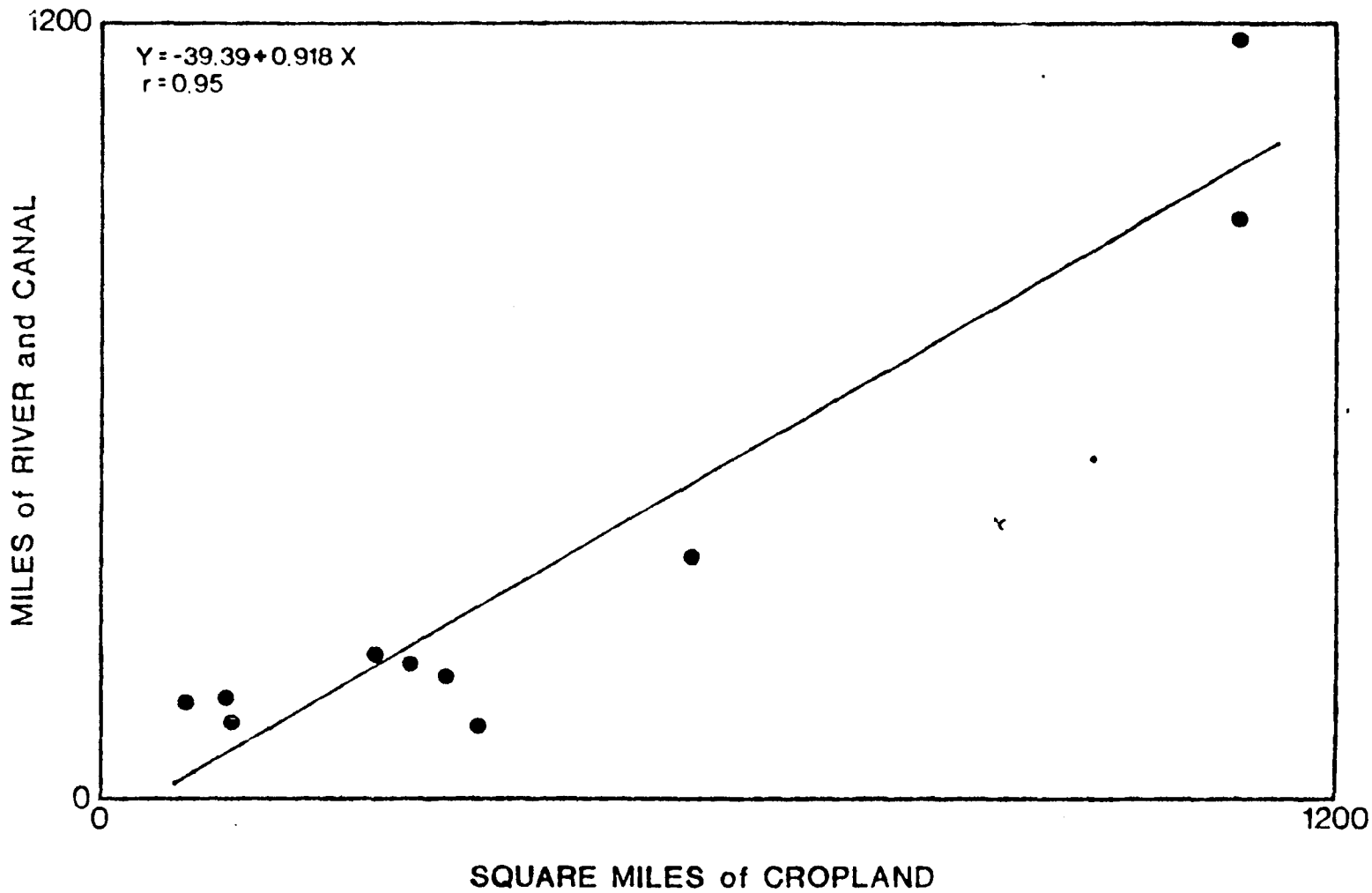


Figure 89. Length of rivers and canals versus the area of cropland in each basin.

inland than the Texas Barrier Island Region. On the upper coast, river flow is moderate during winter and early spring. It peaks during spring, especially in April and May, and remains low during summer and fall. On the lower coast river flow is low most of the year and peaks during September and October, the late part of the hurricane season. River flow maximums in mid-coast areas occur in the spring and fall, showing a combination of upper and lower coast patterns (see Woodruff 1975 for hydrographs of region rivers).

Irrigation and drainage canals vary in width from 1 m (3.3 ft) to more than 10 m (33 ft). Depth varies from 0.5 m (1.6 ft) to more than 4 m (17 ft). Flow velocity is slow in irrigation canals and depends upon the demand for water. More than 1.2 billion cu m (1 million ac-ft) of surface water was transferred to 368,000 ha (909,000 ac) of cropland in the region in 1979 through the irrigation canal network (Phluger et al. 1981). Some canals are reinforced or lined to limit meanders and infiltration losses to the sediment.

Drainage canals vary widely in size and flow characteristics. Some are natural streams with low to moderate continuous flows. Only during floods stimulated by local runoff does water flow rapidly. Other drainage canals are man-made or improved. Some are small ditches with reinforcement at critical points; others are large channels completely lined with concrete. A recent proposal for flood prevention on Sims Bayou in Houston contained plans for drainage canals with main channel bottom widths up to 137 m (450 ft), and overall widths around 200 m (656 ft) (U.S. Army Engineers 1982). The purpose of urban drainage channels is to allow rapid flow of accumulated water away from inhabited areas. Other than during flood periods, drainage flow occurs

in these channels only intermittently or through return flows of municipal and industrial waste discharges (U.S. Army Engineers 1982).

Rivers and canals pass through the coastal plain, which consists of Pleistocene deltaic and fluvial-deltaic sediments and Holocene-Modern fluvial deposits. The sediments are predominantly clayey sand and silt, or clay and mud. Because of the high proportion of silt and clay in the substrate, river and canal water is almost always turbid; Secchi disk readings of less than 0.3 m (1 ft) are normal. The sediment load carried by rivers and canals depends upon the source of the sediment and the stream flow. Average volumes of sediment range from practically nothing in some small streams to 24 million metric tons (26.7 million short tons) per year for the Brazos River (Cook 1967; 1970).

Rivers cut their way through the substrate, picking up sediment in one place and dropping it in another. They rarely flow in straight lines but usually meander as a result of the equilibrium between flow volume, stream gradient, land physiography, and sediment type. The course of a river or stream continually adjusts to the kinetic energy of the flowing water; adjustments in one part of the river may affect other parts both upstream and downstream.

The banks of rivers and small streams that have not been channelized or stabilized are cut or deposited by the river flow. If a river or stream occasionally floods its banks, a low, natural levee will form inland of the bank and parallel to the shoreline.

The pH of river and canal water varies from 6.9 to 8.5, depending upon location. The more acidic waters are found in the upper coastal region; more alkaline conditions are common to the south. Carbonate concentrations in the

more alkaline waters reflect the chemical composition of the substrate through which they pass. The alkalinity of most river and canal water in the region is high enough for the water to be considered "hard."

Oxygen concentration in unpolluted streams is greater than 5 mg per l; the water is often saturated or supersaturated with oxygen. Total phosphate concentrations range from 0 to 1 mg per l, nitrate concentrations, from 0 to 0.5 mg per l, and ammonia, from 0 to 0.1 mg per l. Phytoplankton photosynthesis may be limited by nutrients or by the availability of light, which is often low because of high turbidity.

Effluents from sewage treatment facilities and non-point runoff from urban and cropland habitats reach the river and canal habitat. High levels of dissolved organic matter, phosphate concentrations of 6 to 10 mg per l, nitrate from 5 to 12 mg per l, and ammonia from 4 to 20 mg per l are often associated with sources of pollution. Lead, mercury, zinc, and manganese are sometimes found in high levels in sediments near outfalls. Chlordane, dieldrin, arsenic, DDT, DDD, and DDE are also present in a few locations. Eighteen of 27 major stream segments above tidal influence in the region show high fecal coliform counts that cause at least localized water quality problems (Texas Department of Water Resources 1983a).

Relatively little information is available about the river and stream habitat in the region. Intensive monitoring surveys from the Texas Department of Water Resources contain the most chemical, physical, and biological information (Kirkpatrick 1977a, 1977b; Twidwell 1976, 1981, 1983).

System operation. From the region and basin perspective, the importance of the river and canal habitat is its role in transporting materials to the

basins from outside the region, and from one place to another within each basin. Over geologic time, the main material of interest is sediment. All of the uplands in the Texas Barrier Island Region, except for the barrier islands, peninsulas, and Pleistocene barrier-strandplain deposits, were formed by river deposition of sediment from inland areas. More recently, the conditions which created fertile bottomland and floodplain forest resulted from river transport of sediment and nutrients. Canals are an extension of the river system and supply water to areas beyond the natural floodplain; they do not supply significant quantities of nutrients or sediment.

Water flowing into a river or canal may come from the upstream section of the river and canal habitat, or from the adjacent upland habitats. Water from upstream segments and tributaries carries nutrients, sediment, organic matter, and organisms. Water from adjacent uplands may contain the same materials as well as organisms from upland environments and an additional fraction of sediment from bank erosion. Since transport of materials to, through, and within basins is the dominant function of rivers and canals, water flow is the main driving force for this habitat.

Some phytoplankton and macrophyte production occurs in the habitat, but it is limited by the turbidity of the region's rivers and streams (Wetzel 1975). River and canal habitats contain diverse consumer communities which are larger than the autochthonous production can support. Fisher and Likens (1973), Hynes (1975), and others have noted that continuous flow sections of rivers, those downstream portions with low gradients, have detritus-based communities. McCullough et al. (1979) have presented energy budgets for two insect genera (Simulium and Hydropsyche), common to Texas river and canal habitat, which show that these filter feeders play an important role in

processing suspended organic material and passing it on to higher trophic levels.

No direct measurements for Texas river and canal habitat production or organic use are available. However, estimates of the relative contribution of allochthonous organic material for a variety of streams outside Texas range as high as 99 percent of the energy sources for consumer species (Teal 1957; King and Ball 1967; Minshall 1967; Fisher and Likens 1972; Hynes 1972). River flow is crucial to the transport of imported organic matter that supports these communities.

River and canal habitat has a high surface area per unit volume compared to lakes and reservoirs or bays. The kinetic energy of the flowing water and the shape and roughness of the river bed create mixing currents that facilitate reaeration. Because oxygen levels are normally high, river consumer species are not adapted to low oxygen conditions and are relatively intolerant of them. In addition to reaeration of the water, the currents in this habitat influence the amounts of sediment and organic matter carried and kept in suspension.

Consumer species are adapted to the flowing water regime; their feeding methods, burrowing capability, and means of attachment to the substrate are designed for specific flow regimes (Fraser 1972). Hawkins and Sedell (1981) divided macroinvertebrates into the functional groups reflecting the flow regime of particular stream sections: shredder, collector, scraper, filterer, and predator.

Wallace et al. (1982) presented some evidence that microorganisms inhabiting the surface of organic particles are themselves important nutrition

sources for some consumers. Since this habitat is a detritus-based system, microorganisms are to be expected; their metabolism is an important aspect of the transformation of allochthonous organic material.

Fauna and flora. Some primary producers present in river and canal waters are the green algae Scenedesmus acuminatus, S. quadricauda, Pandorina sp., Haematococcus sp., Palmella sp., Chlorococcum sp., Chlorella sp., and Selenastrum sp.; the diatoms Chrysophyta Melosira varians, Navicula exigua, N. ingenua, N. laterostrata, N. luzonensis, N. viridula, Nitzschia palea, Surirella spp., and Cosinodiscus sp.; the blue-green algae Anabaena sp. and Oscillatoria sp.; and the euglenophyta Euglena sp., Trachelomonas sp., and Phacus sp. Some zooplankton are found in the habitat; these include the rotifer Brachionus sp., cladocerans, and the copepods Diaptomus pallidus and Eurytemora affinis.

Invertebrate benthic species form the major part of the habitat consumer community. Many benthic organisms are larval forms of insects. Some common types are the oligochaetes Dero obtusa and Limnodrilus hoffmeisteri, Nais sp.; the turbellaria Dugesia tigrina; larval coleopterans Stenelmis bicarinata, S. crenata, and Dineutus sp.; dipteran larvae Chironomus stigmaterus, Cricotopus sp., Cryptochironomus fulvus, Polypedilum convictum, P. halterale, Simulium sp., Thienemanniella sp., Orthocladius sp., Baetis sp., Thraulodes sp., and Tendipes sp.; mayfly larvae Stenonema tripunctatum and Tricorythodes sp.; trichopterans Hydropsyche sp., Cheumatopsyche analis, Hydroptila consimilis, Ochrotrichia sp., Hydropsyche sp., and Smicridea fasciatella; and dragonfly larvae Erpetogomphus sp.

Larger invertebrates in the habitat include the crawfish Procambarus clarkii and river shrimp Macrobrachium sp.; the gastropods Physa sp. and Heliosoma sp.; and the pelecypods Corbicula manilensis, C. fluminea, Unio sp.

The fish fauna in rivers and streams is very diverse with more than 70 species. Some common fish are the gizzard shad (Dorosoma cepedianum), threadfin shad (D. petenense), golden shiner (Notemigonus crysoleucas), silverband shiner (Notropis shumardi), spotted shiner (N. venustus), redhorse shiner (N. lutrensis), bullhead minnow (Pimephales vigilax), mosquitofish (Gambusia affinis), largemouth bass (Micropterus salmoides), bluegill (Lepomis macrochirus), and longear sunfish (M. megalotis) (Fisher 1972).

Aquatic mammals reported in the river systems include the beaver (Castor canadensis), nutria (Myocastor coypus), and a few isolated sightings of river otter (Lutra canadensis). (Flora and fauna from Fisher et al. 1972; Young et al. 1972; Ezell 1976; Kirkpatrick 1977; Twidwell 1981, 1983).

Adjacent systems and flows. The river portion of the river and canal habitat is almost entirely surrounded by floodplain forest (63.9 percent of the adjacent habitats). Other upland adjacent habitats are range (22.2 percent) and cropland (11.2 percent). These upland systems receive exports of water, sediment, and nutrients from the river during floods. During the rest of the time, the river imports runoff, sediment, and organic matter from these systems. Nutrients are imported from upland units undergoing land use changes, such as forests under harvest. Nutrients and toxics are imported from cropland.

Rivers contact two other systems: lake and reservoir, and channel and tidal stream. Because points of contact are few and small, no percentage figures are given for adjacent habitats. Rivers flowing into lakes and

reservoirs pass along all of their materials and some of their biota; mobile species move to and from the river. Rivers downstream of lakes and reservoirs receive water, but sediment, organic matter, and nutrients are trapped by the lake and reservoir habitat. Downstream rivers receive these materials from the upstream lake and reservoir system only as the result of large storm flows (Bedient 1980).

Habitats most commonly adjacent to irrigation canals are cropland and range. The canals mainly export water. They may import runoff, sediment, organic matter, nutrients, and toxic materials. The amount of material they import is influenced by management practices in adjacent croplands.

Habitats adjacent to drainage canals are urban land and cropland. The purpose of drainage canals is to receive materials from the adjacent systems, not to export them. Drainage canals import water, nutrients, organic matter, organisms (especially bacteria associated with urban systems), sediment, toxic materials, and various kinds of waste products. Overflow of drainage canals may transport all of the above materials to adjacent systems.

Economic uses. The three main economic uses of the river and canal habitat are to provide water--a material vital to society--at a low cost, to transport materials away from a given location, and to process societal wastes. Rivers and streams provide all of the surface water used in the region. Surface water supplies 60 percent of the water used in the region (Texas Department of Water Resources 1977). Nearly 70 percent of the surface water goes to irrigation, 18 percent to manufacturing, and 9 percent to municipal use. Water carried by canals has allowed distant range and marginal agricultural land areas to be converted into cropland.

The material-transport uses of rivers and canals include drainage of low relief urban and agricultural areas, removal of waste materials, and dispersal of pollutants so they are at lower concentrations.

The biotic community in rivers and canals processes waste by metabolizing organic and inorganic materials, and the sediment traps and holds harmful elements or compounds away from most human exposure. The physical mixing and temperature equilibrium processes of flowing water reaerate or lower the temperature of effluents.

Impacts of man's activities. Impoundment changes the characteristics of a river. Water flow at the impounded area slows dramatically; sediment and organic matter settle out, and the communities change to lake and reservoir biota. Since rivers are equilibrium systems throughout their length, upstream and downstream changes occur, although they are difficult to predict. One impoundment, Palmetto Bend dam, is currently under construction on the Lavaca River. Several others are in various stages of planning or discussion.

The river and canal habitat can process low to moderate levels of wastes added to it without destroying the biotic portion of the system. Beyond a point, however, river reaeration, mixing, and transport cannot compensate for high biochemical oxygen demands, toxicity, and algal respiration. The result can be an overloaded system with diminished natural benefits as well as potential nuisance and human health problems. Overloading has occurred on a number of stream segments in the region.

Diversion of water from rivers with little or no return to the system slows the flow rate. Because organisms are adapted to particular flow regimes, long-term decreases will ultimately cause changes in the communities. Processing of added wastes is somewhat flow-dependent: lower flow rates result

in less processing. Lower flows also reduce the export of materials from the river and canal to adjacent systems. Consequently, less water, sediment, and nutrients may be transported to systems whose operation has adapted those inputs.

Channelization involves the straightening of waterways, the construction of smooth concrete surfaces to promote rapid flow, and the building of high banks to prevent flooding. Impermeable surface linings may result in lowered water tables beneath the channel and under adjacent habitats (Darnell et al. 1976), and the extreme flow rates during storms cause erosion of exposed waterway sediments. The diversity of communities in channelized waterways is lower than in natural systems (Darnell et al. 1976). In urban areas, populations in highly channelized bayous and streams may be limited to algae and a few insect species.

Salt and Brackish Marsh

Areal extent. Salt and brackish marsh habitat comprises the salt marsh ecosystem and the brackish marsh ecosystem modeled in the appendix. These two systems are distinguished by differences in vegetation and hydrologic characteristics. They are combined here since they are often adjacent, have many operational similarities, and contain many species in common.

Salt and brackish marsh occupies 632.2 sq km (244.1 sq mi), or 1.2 percent, of the Texas Barrier Island Region. The habitat is present throughout the region, but there is relatively little in the southern basins. In general, salt and brackish marsh increases to the north (Figure 90). The Galveston basin has the largest area of this habitat, 247.1 sq km (95.4 sq mi), or 2.3 percent of the basin's area. Salt and brackish marsh in the Galveston basin accounts for 39 percent of this habitat in the region.

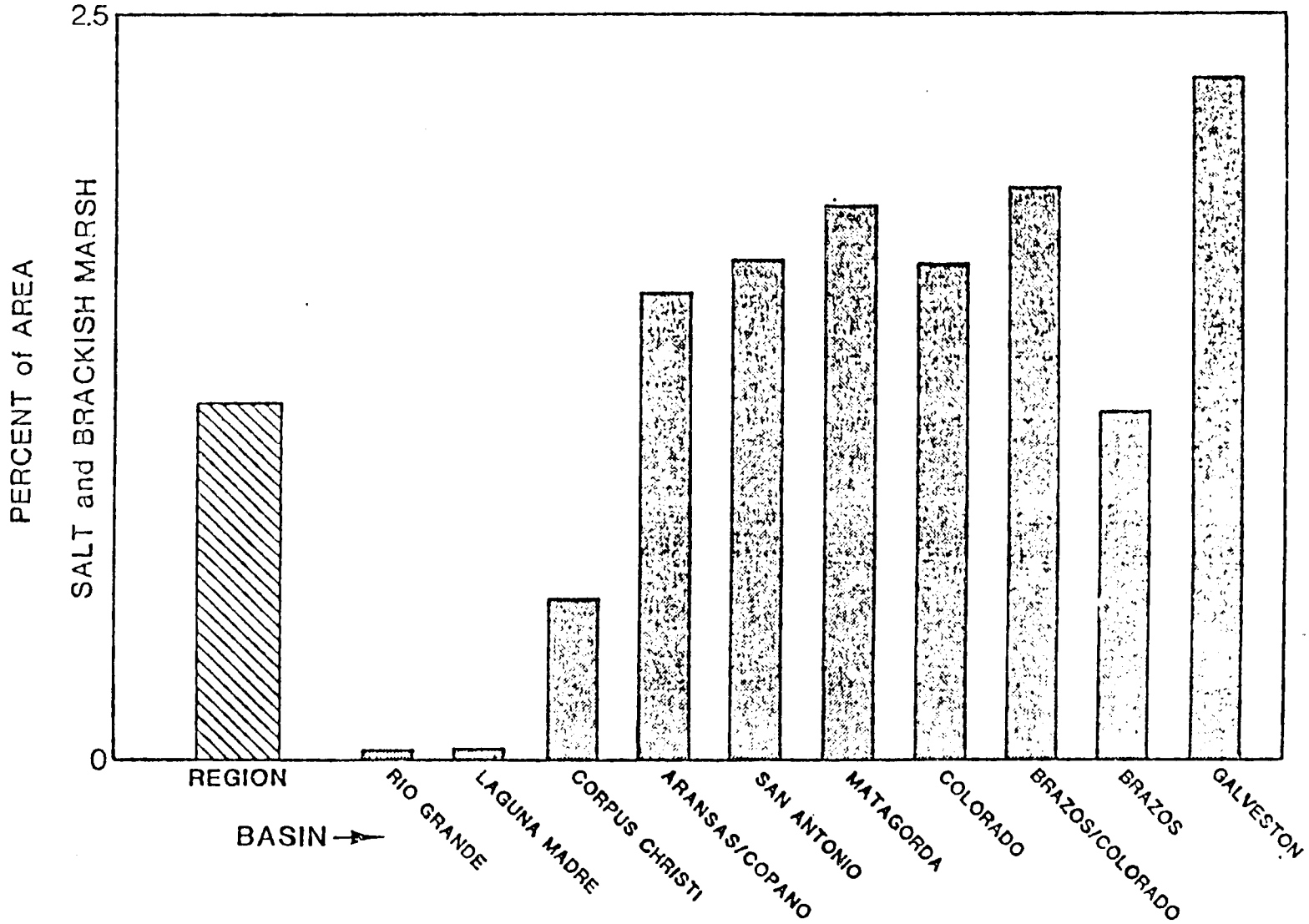


Figure 90. Percent of region and basin that is salt and brackish marsh habitat.

The Lavaca basin contains 125.4 sq km (48.4 sq mi) of salt and brackish marsh; the Aransas-Copano basin, 78.0 sq km (30.1 sq mi); and the Brazos-Colorado basin, 69.4 sq km (26.8 sq mi). The Rio Grande and Laguna Madre basins have very little salt and brackish marsh (0.3 sq km or 0.1 sq mi, and 7.5 sq km or 2.9 sq mi respectively). The measurement given here for the Laguna Madre basin is an underestimate since small, ephemeral fresh and brackish marshes exist in swales and depressions on both the barrier islands and mainland. These areas were too small to be depicted at the scale used for the original mapping of the region. In addition, they were difficult to distinguish because of limitations of the original photography from which the mapping was done. If the ephemeral marshes could be mapped, measured, and included in the Laguna Madre total, the area of salt and brackish marsh in the basin might be double or triple the present figure, but it would still be small compared to other habitats.

Physical description. Salt and brackish marshes are distinguished from freshwater marshes by saline soils and emergent, salt-tolerant vegetation. They usually lie within an elevation range from slightly below mean sea level to +1.5 m (+5 ft) MSL (McGowen and Brewton 1975; Henley and Rauschuber 1981), and contain standing water sometime during the year. Salinity, frequency of flooding, and duration of flooding in this habitat depend upon marsh location, land elevation, and the sources of the floodwaters.

Salt marshes are inundated by tide or wind-tide frequently, usually daily. Inundation frequency for brackish marshes ranges from daily to only once every few years, during major storms. Regularly flooded marshes contain tidal creeks and small ponds that channel water flow in and out of the marsh.

The morphology of the creeks and ponds is strongly related to the hydrologic forces affecting the habitat, vegetation type and substrate (Garofalo 1980). Channels with regular, strong tidal fluxes are more sinuous than channels with less tidal influence. The greater sinuosity is caused by stronger erosive forces, heterogeneous soil conditions, and the denser root systems of the salt marsh plants.

Salt and brackish marshes are found in four environments in the region: on the lower end of major river deltas where the river empties into a bay; at the edges of creeks and secondary or tertiary bays that open into larger bay systems; on the bay side of barrier islands; and on low areas along the mainland shoreline which parallel the gulf shoreline.

The major rivers with deltas containing salt and brackish marsh habitat are the Trinity, San Jacinto, Colorado (across East Matagorda Bay), Lavaca, Guadalupe, Mission, Aransas, and Nueces rivers. The more northern river deltas display a regular habitat progression of salt and brackish marsh, fresh marsh, swamp, and floodplain forest (moving inland from the bay). In the northern part of the region, these habitats tend to be wider than they are deep so that the most inland habitat, floodplain forest, is relatively close to the bay. To the south, salt and brackish marshes and fresh marshes decrease in width and depth. Small areas of wind-tidal flat become interspersed throughout the delta, swamp disappears, floodplain forest is located further inland from the delta, and an area of range becomes prominent between the marsh-tidal flat area and floodplain forest.

The emergence of tidal flat, the decrease in salt and brackish marsh, and the decrease in fresh marsh area are the most noticeable changes in river deltas from north to south. It is likely that river input, through seasonal

flooding, provides the conditions that allow salt and brackish marsh habitat to exist on deltas throughout the region.

Salt and brackish marshes occur on the edges of creeks and secondary bays over the breadth of the region. Salt marsh predominates in these habitat locations to the south, although some brackish marshes are present. In the Laguna Madre a small area of salt and brackish marsh is located near the mouth of the Arroyo Colorado. Local freshwater input probably provides the proper conditions for continued salt and brackish marsh existence in these small drainages throughout the region.

Land physiography is a major factor determining whether salt and brackish marshes are present on the mainland shoreline. Where the land slope is steep, only a very narrow salt and brackish marsh area can exist. As the land slope decreases and becomes more gentle to the north there is more opportunity for wetland plants to grow. The increase in average rainfall to the north must also be considered as a factor controlling the inland extent of salt and brackish marsh.

The mainland shoreline parallels the gulf shoreline 8 to 12 km (5 to 8 mi) inland throughout the entire region. From the Rio Grande River to Matagorda Bay, the mainland shoreline is approximately at the location of the gulf shoreline that existed during the previous interglacial period. Encinal Peninsula, Live Oak Ridge and Live Oak Peninsula, Lamar Peninsula, Blackjack Peninsula, and the mainland between San Antonio and Matagorda bays were strandplains, barrier islands, or peninsulas 45,000 yr BP (Brown et al. 1976; McGowen et al. 1976b; Brown et al. 1977; Brown et al. 1980). Today they are still high and relatively narrow land areas with only a thin strip of land

adjacent to the bay at an elevation less than +1.5 m (+5 ft) MSL. Because of this topography, only a narrow strip of salt and brackish marsh can exist along the bay side of these mainland areas.

North of Matagorda Bay, the mainland shoreline is seaward of the gulf shoreline that existed in the previous interglacial period. The present shoreline was formed by large quantities of sediment deposited by the Colorado, Brazos, Trinity, Neches, and Sabine rivers in the past 15,000 yr and is low with very gentle slopes. Between the Colorado River and northern boundary of the region, mainland elevation is no greater than +1.5 m (+5 ft) MSL for a distance of 1.6 km inland from the mainland shoreline. In a few locations the low mainland elevation extends inland as far as 11 km (7 mi). The gentle slope has allowed a progression of wetland units to develop from the bay to the upland. A strip of salt marsh is usually located adjacent to the bay with an area of brackish marsh behind it. Brackish marsh is often at a slightly higher elevation than salt marsh and, at its upland limit, grades into the range habitat. The boundary between range and brackish marsh may vary from year to year, depending upon rainfall and ground moisture. The width of the mainland salt and brackish marsh habitat may be as great as 3 km (1.9 mi).

Large salt marshes are located on the bay side of Bolivar Peninsula, between the bay and barrier habitats. From Galveston Island south to San Jose Island, salt marshes are almost always present on the bay side of barrier islands and peninsulas. They are usually separated from the barrier habitat by an area of wind-tidal flat and bounded on the bay side by a small area of seagrass. At Cedar Bayou, separating San Jose and Matagorda Islands, salt marshes suddenly become very sparse and the bay side of the barrier islands

becomes wind-tidal flats. This landscape continues all the way to the southern tip of Padre Island.

The disappearance of salt marsh on the bay side of barrier islands to the south is probably related to a combination of factors as suggested by Lindhurst and Seneca (1981). High soil salinity is the principal reason for the absence of smooth cordgrass (Spartina alterniflora), a typical salt marsh plant, on the bay sides of barriers. Salinities above 45 to 50 ppt have been shown to cause diebacks or death of smooth cordgrass (Shiflet 1963; Woodhouse et al. 1972). Webb (1983) measured soil salinities on Bolivar Peninsula and Galveston Island at a depth of 36 cm (14 in) around the mean high water elevation. He found low moisture levels and high soil salinities, ranging from 51.4 to 98.6 ppt. Webb found that smooth cordgrass was stunted or absent in these areas. He attributed the high salinities to salt deposition by alternate wetting and drying of the soil. At lower elevations which were more frequently inundated, soil salinities were lower and smooth cordgrass was present.

System operation. The supply of fresh water, estuarine water, or a mixture and its movement in the habitat are the main driving forces behind this system's operation. Salt and brackish marsh vegetation depends upon water inputs to keep soil conditions suitable for continued growth. Nutrient input, organism migration, and organic matter export are controlled by regular to occasional water entry and exit from the habitat. Water enters by tidal or wind-tidal flow, river flooding, upland drainage, or direct rainfall (Borey et al. 1983).

Salt marsh and brackish marsh species often grow well in fresh or low salinity conditions (Phleger 1971). It is their tolerance of saline conditions that gives them a competitive advantage over fresh marsh plants. Thus continued maintenance of soil salinity is necessary to keep salt and brackish marsh habitats operating.

Primary productivity in the salt and brackish marsh habitat is high. Turner (1976) reported end-of-season total aboveground production from smooth cordgrass of 735 to 1551 g dry wt per sq m for sample sites in Corpus Christi, Copano, and San Antonio bays. Estimates of mainland shoreline brackish marsh productivity varied from 1100 to 1800 g dry wt per sq m (Harcombe and Henderson 1976; Borey et al. 1983). Other estimates of net aboveground primary production for salt and brackish marsh have been restricted to river deltas. Annual aboveground net primary production between 254 g dry wt per sq m for smooth cordgrass and 1969 g dry wt per sq m for gulf cordgrass (Spartina spartinae) was reported for the Lavaca delta (Espey, Huston and Associates 1977b). Productivities within this range were measured on the San Antonio, Nueces, and Trinity deltas (Espey, Huston and Associates 1977; Adams 1977).

Emergent marsh grasses are the most visible producers in salt and brackish marshes; however, benthic algae (Lowe and Cox 1978) and phytoplankton also contribute to the primary production. Periphyton production ranging from 0.116 to 0.860 g ash-free dry wt per sq m per day was reported by Espey, Huston and Associates (1977a, 1977f).

While much U.S. wetland research has focused on the influx and export of dissolved and particulate organic and inorganic materials, no completely consistent pattern has emerged. De la Cruz (1979) and Nixon (1980) consider export of organic matter to be the predominate pattern. However, a few

studies have shown little export of carbon or a net import of it (Woodwell et al. 1977). A potentially important sulfate reduction cycle, elucidated by Howarth and Teal (1979), may account for a large portion of unexported carbon from salt marshes, and may produce chemical conditions in the soil that influence marsh plant productivity (Giblin and Howarth 1984). Smith et al. (1983) measured carbon release to the atmosphere (as carbon dioxide or methane) in a Louisiana marsh. The loss accounted for the difference between net production and accumulation through marsh accretion; from simple material balance considerations, exports of large quantities of organic matter seemed unlikely.

Borey et al. (1983) measured export of dissolved and particulate carbon from a brackish mainland shoreline marsh in Texas. Carbon export amounted to 2 to 6 percent of the net annual primary productivity and was largely mediated by local rainfall. There was no significant peat formation in this marsh area even though export was low; marsh burning might account for this, however. Most exported organic carbon was dissolved, and exported particulate organic carbon was highly decomposed. This study suggested that much of the marsh's net production was decomposed and consumed in the marsh, although no decomposer food web information was presented.

Studies by the Texas Department of Water Resources (TDWR) have focused on organic production and nutrient cycling in delta marshes--salt, brackish, and fresh. These studies include Dawson and Armstrong (1975), Armstrong et al. (1975, 1977), Armstrong and Brown (1977), Armstrong and Gordon (1977a, 1977b), and Espey, Huston and Associates (1977a-1977g; 1978a, 1978b). Results of these studies have been presented in Texas Department of Water Resources

reports (1980a, 1980b, 1981a, 1981b, 1983) on the influence of freshwater inflows to Texas bays. Generally, they describe a pattern where inorganic nitrogen is taken up by the coastal wetlands while dissolved and particulate organic material is exported to the estuaries (TDWR 1980a, 1980b; 1981). Studies have also shown instances of phosphate uptake and release (TDWR 1980a, b; 1981). These are considered to be long-term trends, and seasonal fluxes may deviate from the above patterns.

Espey, Huston and Associates (1977a) noted net imports of organic and inorganic materials to San Antonio, Lavaca, and Nueces bay wetlands. The TDWR (1981a, p.VI-15) considered this condition exceptional since the Espey, Huston and Associates study was undertaken at a time of low flows and minimum marsh inundation. An independent study of Nueces Bay conducted for the U.S. Fish and Wildlife Service (USFWS), however, reported the same net import pattern (Henley and Rauschuber 1979, p. 49).

Organic export has been causally linked to inundation. Dawson and Armstrong (1975) and Armstrong and Hinson (1978) noted a strong relationship between the frequency of inundation and the export of organic material. For modeling, the TDWR has assumed that export of materials is a direct result of inundation events in coastal wetlands (Espey, Huston and Associates 1978b, p.35; TDWR 1980, p. VI-14). Gosselink et al. (1979, p.159) have also noted this relationship.

Intermittent extremes such as flooding are probably essential elements in the cycle of marsh production and organic export (Taylor 1934). Due to sampling difficulties during floods, export has not been directly measured. Dawson and Armstrong (1975) noted that after a period of drying, the marsh surface released unusually large amounts of nutrients and sloughed-off dried

organic matter. Armstrong and Hinson (1977) concluded that floods following a dry period would be expected to dislodge and transport large quantities of the material from the marsh. This export has been measured indirectly by Hackney and Bishop (1981), who concluded that 16.7 percent of the annual net primary production of a Mississippi marsh was exported by storm surge during a small hurricane. This was many times greater than the usual low annual export from this marsh. Wolaver et al. (1983), in a study of tidal exchange of nutrients in Chesapeake Bay, also noted that the amount of detritus transported from marshes during storms would have to be known before nutrient cycling could be understood.

A few studies have attempted to put the contributions of marshes to Texas estuaries into perspective. Oppenheimer et al. (1974) indirectly estimated carbon and nutrient balances for the Corpus Christi Bay system. They concluded that wetland plants accounted for 7.5 percent of the gross productivity of aquatic and wetland habitats. Wetland export could not be estimated from their figures.

Henley and Rauschuber (1980) prepared a model of carbon flows into Nueces and Corpus Christi bays from outside the system. Their figures indicate that one-third of the carbon imported into the bays may come from the Nueces marshes. The production of carbon from phytoplankton and seagrasses in the bays was not considered in this budget. The researchers noted that there will be a substantial decrease in carbon import as upstream impoundments are completed.

Armstrong and Hinson (1973) calculated that wetlands contribute 3.6 percent of the total organic material influx on a daily basis in Galveston

Bay; the rest comes from phytoplankton production, freshwater inflow, and wastewater discharge. This amount may seem small when considered over the entire Galveston Bay complex; however, Armstrong and Hinson noted in their review of Copeland and Fruh (1969) and Copeland and Bechtel (1971) that there is a substantial import of organic material from marshes to Trinity Bay. The importance of this finding should be considered in relation to the detritus-based food chains in that bay system. Armstrong and Hinson concluded that marshes contribute 58 percent of the organic matter that drives these food chains in Galveston Bay.

Ward et al. (1982) estimated organic export from the marshes on Matagorda Bay and concluded that direct export of detrital material may be only 5 to 10 percent of annual net primary production. They pointed out that there is probably an additional, unmeasured export of migrating biomass. Tidal creeks have been recognized as important habitats and pathways for movement of invertebrates and fish between bay and marsh systems (Shenker and Dean 1979; Bozeman and Dean 1980; Horlick and Subrahmanyam 1983). Recent studies by Minello and Zimmerman (1983) and Zimmerman et al. (in press) suggest that Texas salt and brackish marshes may harbor large populations of larval and juvenile vertebrate and invertebrate species, and that some species benefit from the reduced predation the cover affords as well as from the organic material produced in the system. The use of marsh vegetation directly or indirectly by these species has not been well characterized and may have a bearing on the importance of organic export.

Experts disagree on the use of exported detrital material from salt and brackish marshes. On the basis of carbon isotope ratios, Haines (1977) concluded that Spartina did not contribute substantially to the organic carbon

in Georgia coastal waters. Reviewing Hayne's data, Nixon (1980) noted that the carbon might be a mixture of 30 to 40 percent Spartina carbon mixed with phytoplankton and terrestrial carbon. Ward et al. (1982) used isotope ratios to attempt identification of carbon sources for some detrital-feeding species in Matagorda Bay. Their data could be interpreted as showing some use of exported marsh detritus at various locations in the bay.

Elevation changes resulting from natural processes account for increases and decreases in the amount of salt and brackish marsh habitat in the region. Salt marsh vegetation traps particulate matter (Gleason et al. 1979). Organic and inorganic soil input constantly raises the elevation of the habitat. Countering this growth are soil compaction, local subsidence, and storm erosion. Changes in elevation within the marsh system alter the plant communities and habitat by changing drainage patterns, the level of the water table in the soil, frequency of tidal input, and ultimately, salinity levels in the soil. McGowen and Brewton (1975) and Benton and Snell (1983) studied historical changes in wetlands in Aransas and Matagorda bays over periods of about 120 yr. Both found marsh areas that remained stable over the period, and areas of losses and gains in marsh area that appeared unrelated to human activities. Only about 25 percent of the overall reduction in marsh area in Matagorda Bay was attributable to man's activities (McGowen and Brewton 1975).

Since Texas marsh studies have focused almost exclusively on delta marsh nutrient dynamics and production, practically no information is available about salt and brackish marsh systems in other areas. The work of Webb et al. (1978) on techniques and guidelines for development of salt marsh vegetation on the bay side of Bolivar Peninsula, and the studies of Harcombe and

Henderson (1976) and Borey et al. (1983) on mainland shoreline brackish marshes, are the only studies that describe the operation of other types of Texas salt and brackish marsh systems. Many questions that might bear on wetland operation--for example, whether nutrient coupling exists between Texas marshes and mudflats as suggested by Welsh (1981) and Wolaver et al. (1983)--have not been pursued because of the focus on delta marshes.

Flora and fauna. Emergent vegetation is the most recognizable aspect of the salt and brackish marsh habitat. Prominent species include smooth cordgrass (*Spartina alterniflora*), marshhay cordgrass (*S. patens*), gulf cordgrass (*S. spartinae*), saltwort (*Batis maritima*), sea ox-eye daisy (*Borrichia frutescens*), groundsel bush (*Baccharis halimifolia*), black mangrove (*Avicennia germinans*), seashore saltgrass (*Distichlis spicata*), saltworts (*Salicornia bigelovii* and *S. virginica*), shoregrass (*Monanthochloe littoralis*), black rush (*Juncus roemerianus*), and bullrushes (*Scirpus olynei* and *S. californicus*) (Rowe and Williams 1976; Ward and Armstrong 1980; Henley and Rauschuber 1980).

Other producers include the benthic algae *Enteromorpha clathrata*, *E. flexuosa*, *Ulva lactuca*, *Ectocarpus siliculosus*, and *Acrochaetium* spp. (Parker et al. 1971; Lowe and Cox 1978). Phytoplankton including pennate and centric diatom, dinoflagellate (Pyrrophyta), and euglenophyte species, and zooplankton such as copepods, ostracods, foraminiferans, and rotifers have been netted in the marsh habitat (Espey, Huston and Associates 1977b).

Many invertebrates live in the marsh sediments. These include the polychaete worms *Laeonereis culveri*, *Capitella capitata*, *Streblospio benedicti*, *Mediomastus californicus*, *Parandalia fauveli*, and *Eteone heteropoda*. *Limnodrilius maumeensis* is an abundant oligochaete in many

marshes (Espey, Huston and Associates 1977b; Webb et al. 1978). The amphipods Corophium louisianum and Gammarus mucronatus, and the isopod Xenanthura brevitelson are also marsh dwellers (Fotheringham 1975; Espey, Huston and Associates 1977a; Webb et al. 1978). The bivalve mollusk Macoma constricta, and snails Melampus bidentatus, marsh periwinkle (Littorina irrorata), and horn shell (Cerithidea pliculosa) are found in abundance (Fotheringham 1975; Webb et al. 1978).

Some crustaceans are permanent residents of the habitat; among them are the stone crab (Menippe mercenaria), fiddler crab (Uca spp.), striped hermit crab (Clibanarius vittatus), marsh crabs (Sesarma reticularia and S. conereum), and grass shrimp (Palaemonetes pugio, P. intermedius, and P. vulgaris) (Parker et al. 1971; Fotheringham 1975; Espey, Huston and Associates 1977b). Species that use the marsh for at least part of their life cycle include the blue crab (Callinectes sapidus), brown shrimp (Penaeus aztecus), and white shrimp (P. setiferus).

Thompson (1973) reported a variety of flies inhabiting coastal marshes including Tabanus nigrovittatus, horse fly (T. sulcifrons), and deer fly (Chrysops flavidus). The salt marsh grasshopper (Orchelium fidicinium) and salt marsh hopper (Prokelisia marginata) were reported by Oppenheimer and Gordon (1972).

Fish that have been collected in tidal creeks, ponds, and deeper areas of salt marshes include menhaden (Brevoortia patronis), spotted trout (Cynoscion nebulosus), croaker (Micropogon undulatus), striped mullet (Mugil cephalus), spot (Leiostomus xanthurus), naked goby (Gobiosoma bosci), pinfish (Lagodon rhomboides), tidewater silversides (Menidia beryllina), sheepshead minnow

(Cyprinodon variegatus), longnose killifish (Fundulus similis), and bayou killifish (F. pulvereus) (Parker et al. 1971; Espey, Huston and Associates 1977b).

A great variety of birds frequent salt and brackish marsh. Webb et al. (1978) reported 135 bird species that used a newly constructed marsh on Bolivar Peninsula. Some of the abundant species include the long-billed curlew (Numenius americanus), clapper rail (Rallus longirostris), coot (Fulica americana), great blue heron (Ardea herodias), cattle egret (Bubulcus ibis), common egret (Casmerodius albus), snowy egret (Leucophoyx thula), Louisiana heron (Hydranassa tricolor), red-winged blackbird (Agelaius phoeniceus), laughing gull (Larus atricilla), killdeer (Charadrius vociferus), semipalmated plover (C. semipalmatus), western sandpiper (Calidris maura), and least sandpiper (C. minutilla). Birds of prey that hunt in the marsh habitat include the red-tailed hawk (Buteo jamaicensis), red-shouldered hawk (B. lineatus), and marsh hawk (Circus cyaneus) (Rowe and Williams 1976; Webb et al. 1978).

A few reptiles and mammals use salt and brackish marsh habitat. The American alligator (Alligator mississippiensis) lives in brackish marshes throughout the region. Other reptiles include the Texas diamondback terrapin (Malaclemys terrapin littoralis), gulf salt marsh snake (Natrix sipedon clarki), and green anole (Anolis carolinensis carolinensis) (Rowe and Williams 1976). Raccoon (Procyon lotor), opossum (Didelphis virginiana), eastern cottontail (Sylvilagus floridanus), nutria (Myocastor coypus), cotton rat (Sigmodon hispidus), and nine-banded armadillo (Dasypus novemcinctus) have been captured or observed in the habitat (Webb et al. 1978).

Adjacent systems and flows. Upland systems constitute more than half of the habitats adjacent to salt and brackish marsh. Adjacent upland habitats include range (33.9 percent), spoil (7.9 percent), and cropland (6 percent). The habitat receives runoff water and possibly some sediment from these upland habitats. Organisms both enter the salt and brackish marsh system from upland habitats and enter uplands from the salt and brackish marsh system. Only 1.1 percent of the adjacent habitats are urban.

More than a third of the adjacent habitats are aquatic systems. Adjacent aquatic systems include bay (19.5 percent), lake (8.7 percent), and channel, (7.3 percent). Inputs to the marsh from these aquatic systems include water, sediment, nutrients, organisms, salt, and the hydrostatic head from tidal or wind-tidal forces. Outputs from salt and brackish marsh to aquatic habitats are water, organisms, nutrients, and organic matter.

Wind-tidal flat makes up 7 percent of the habitats adjacent to salt and brackish marsh. It is not consistently higher or lower in elevation than salt and brackish marsh; consequently it may exchange all of the materials of both upland and aquatic systems with the marsh.

Economic uses. More than 75 percent of the upland units adjacent to salt and brackish marsh are intensively used by man as range, cropland, or urban land. Cattle graze on marshlands in the upper coastal area; farmers have converted brackish marsh land to rice fields; and salt and brackish marshes have been filled or bulkheaded to extend dry land into the estuarine area for commercial, manufacturing, and residential uses.

Marshes adjacent to upland areas and in depressions or on natural waterways have been dredged to provide navigation channels for shipping. The dredged spoil is often disposed cheaply by placing it on adjacent marshes, or

by using it as fill for later land development. Marshes are also used by oil and gas developers who dredge channels for access to well sites by floating drilling rigs and for pipeline implacement.

Salt and brackish marshes in the Texas Barrier Island Region are used for recreation and conservation. Seven state parks, six national wildlife refuges, and one state park and wildlife management area jointly managed by the state and the federal government are located in the region. Their combined marsh acreage makes up about 25 percent of the region's salt and brackish marshes.

Impacts of man's activities. Man alters salt and brackish marshes in two ways. The most obvious is by filling the marsh to create upland. This is a permanent change that completely alters the system function.

The second type of change, alteration of hydrology, is more subtle. Water inflow and outflow are the most critical organizing forces for marshes. Nutrients, sediment, organic matter, tidal or wind-tidal force to stir the marsh's contents, and organism migration pathways are all tied to water movement. Any alteration of the marsh or adjacent systems that changes the pattern, quantity, or timing of water flows causes a change in the marsh system. The changes can enhance or disrupt the system's operation.

Since water exchange with uplands is mostly in one direction, from the uplands, changes in salt and brackish marsh systems as a result of hydrologic modifications at the marsh-upland boundary are less severe than equivalent modifications at the marsh-aquatic system boundary. The blocking of ebb and flood tidal forces in regularly inundated marshes causes the most drastic changes in these systems since tidal or wind-tidal action is the power source

for their hydraulic transport mechanisms. Transport of materials and organisms by this route can be reduced or eliminated. Blocking of intermittent flooding of brackish marshes from the aquatic side can reduce the saline input into soils that is essential for brackish marsh plants to successfully compete with freshwater species.

Water flow from the aquatic side of the marsh is sometimes blocked by the building of levees for rice farming, by mounds of spoil dredged from channels paralleling the edges of marshlands, and by roads or pipeline canals built across the major axis of flow to and from marshes in conjunction with oil and gas development. Marsh systems can recover and adapt to these activities if passages are provided for tidal or drainage flux through levees and other obstructions to flow.

Wide brackish marshes drain slowly through a network of shallow, convoluted natural drainage channels. Changes that increase the size or number of drainage pathways in brackish marshes hasten the drainage process. Because accelerated drainage shortens the time low-salinity water may stand on the brackish marsh surface and permits more frequent tidal flooding than these systems usually experience, salinity within the habitat will increase.

Cattle use the same pathways into and out of marshes, creating ditches parallel to the main direction of flow. Navigation canals, oil and gas well access canals, or pipeline canals dredged parallel to the drainage axis increase flows within the marsh dramatically, not only because they carry large volumes of water, but because they are usually straight channels.

Board roads placed directly on the marsh surface are sometimes used to reach well sites in brackish marshes from the upland side. This type of road avoids the kinds of changes a navigation channel to the well site would

create. Roads are often placed on low levees built with sediment from adjacent borrow ditches to avoid the problems navigation channels cause. Even if these ditches are staggered to avoid disruption of the natural drainage systems, however, natural flow or small channels created by animals such as alligators may connect them, in effect creating a channel into the brackish marsh. Channels inland through brackish marsh that are in continuous use will eventually accelerate drainage and permit enough saltwater intrusion to convert the area to salt marsh. Abandoned channels should be plugged if the integrity of brackish marshes is desired.

The Texas Coastal Management Program (1976) estimated that 214 sq km (82.8 sq mi), or 14 percent of the salt and brackish marsh area of the entire Texas coast had been altered by man's activities. This was measured over a larger area than the Texas Barrier Island Region, which includes only 38 percent of the salt and brackish marsh habitat in the state. They also estimated that 101 sq km (39 sq mi) of this change had occurred in the Galveston Bay area. At present no more refined estimates of wetland alteration are available.

Spoil

Aerial extent. Spoil habitat is the terrestrial portion of dredged material deposits; subaqueous spoil deposits tend to become bay bottom or transitional area and are not considered here. The Texas Barrier Island Region contains approximately 238 sq km (92 sq mi) of subaerial spoil habitat; this constitutes about 0.5 percent of the region's area.

The distribution of spoil as percent of each basin is shown in Figure 91. The Nueces, Rio Grande, and Laguna Madre basins have the greatest proportion

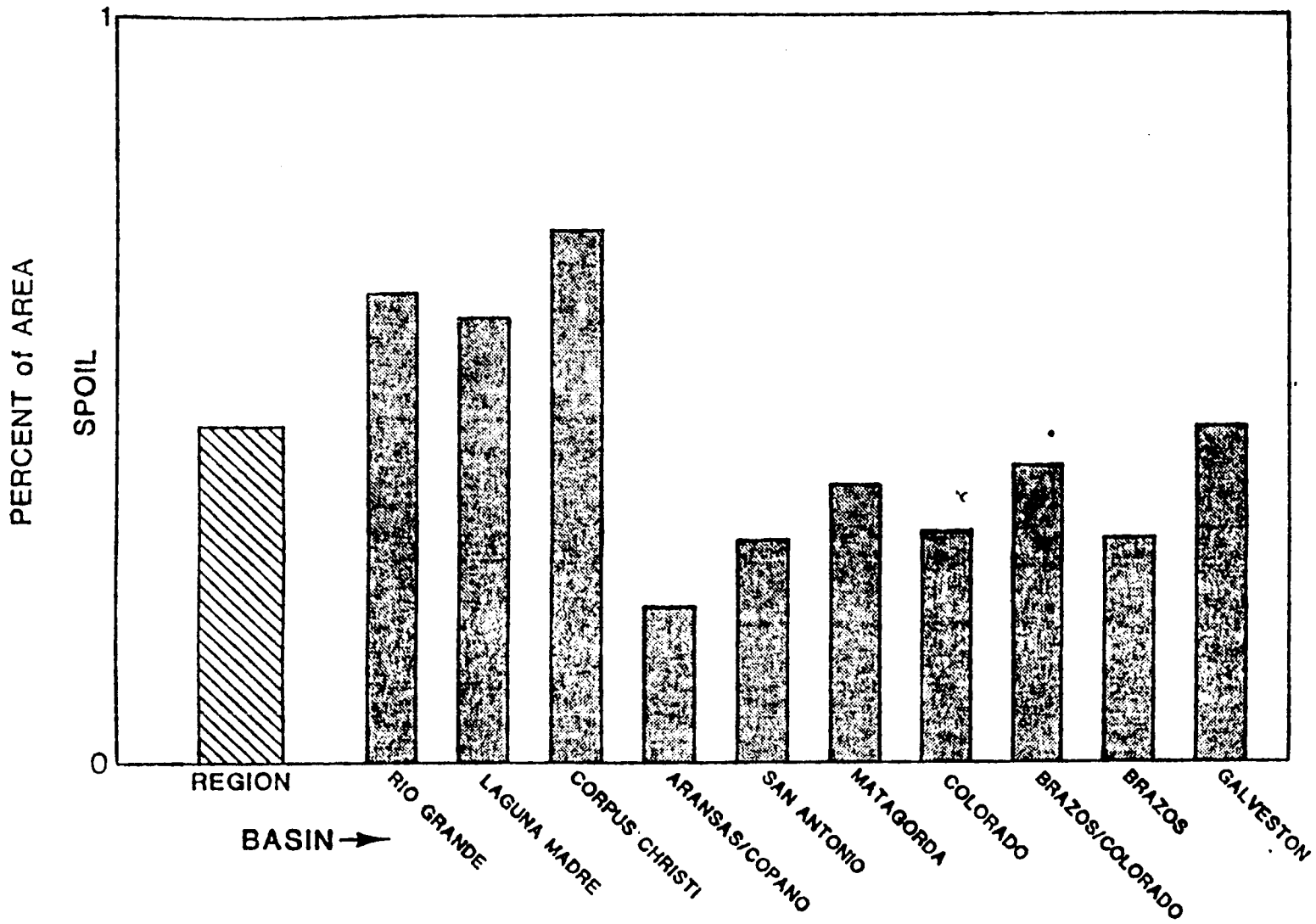


Figure 91. Percent of region and basin that is spoil habitat.

of spoil. Slightly more than 50 percent of the spoil habitat in the region occurs in these three basins; about 42 percent is located in the Laguna Madre. Much of the spoil habitat is located in the lower coastal region because bays in this area are shallow, and tidal forces and freshwater inflows are insufficient to keep navigation channels swept clean. Bays further north are deeper so less original dredging is necessary, and stronger tides and inflows reduce the frequency of maintenance dredging.

Liebow et al. (1980) reported that 51.6 million cu m (67.9 million cu yd) of material is dredged annually on the Texas coast. Authorized new dredging and its subsequent maintenance will require nearly 494 million cu m (650 million cu yd) of disposal space.

Physical description. Terrestrial spoil deposits are usually long, narrow areas that parallel channels. Spoil is placed in undiked piles or within diked areas, usually encircled by earthen levees. Some dikes are made from virgin material taken from within the diked area. This sediment may be fairly cohesive. Other dikes are simply rings of material dredged hydraulically and allowed to dry. Spoil is later pumped into the leveed area.

Spoil from hydraulic dredges contains about 1200 gm of solids per liter of water (Delahoussaye 1981). When the spoil is pumped into diked sites, the sediment settles and the water runs out over a wier. The settling process can reduce the sediment content of the effluent to less than 1 gm per liter of solids. Removing much of the remaining water is desirable to promote plant growth and to consolidate the dredged material so it is less plastic and prone to slump or flow. Parnell et al. (1978) showed water content to be higher in diked than in undiked spoil, suggesting that dewatering occurs more rapidly in undiked than in diked spoil. One reason for this is that dike walls are

usually higher than the interior sediment and rainwater may collect. To reduce water content in the spoil in diked areas, mechanical and biological dewatering processes have been developed.

Undiked subareal disposal areas are often cone-shaped with the peak where the discharge pipe opening was located. The direction of discharge may be controlled, but the slope of the spoil pile is dictated by the physical characteristics of the material.

Sediment characteristics of spoil deposits vary, depending upon the source of the dredged sediment. Bay sediment is generally fine-grained. Maintenance material dredged by the Galveston District of the Corps of Engineers is 14 percent mud, clay, and silt; 85 percent mixed silt and sand; and 1 percent sand, gravel, and shell (Boyd et al. 1972). Barko et al. (1977) and Parnell et al. (1978) noted that undiked sediment tended to be coarser grained than diked spoil. Dikes collect and contain fine material that is transported from undiked piles with surface water flow.

The appearance of the spoil habitat depends upon the interval since the area was last filled with maintenance material. Newly spoiled areas are bare, wet sediment supporting no vegetation. As plant succession occurs on the spoil, the habitat may range in appearance from sand dune, to grassland, to woody rangeland habitat.

System operation. The spoil habitat is periodically disturbed or destroyed and then left to recolonize. It proceeds through successional phases between disturbances. Periods between disturbances are short, usually less than a decade.

The initial placement or addition of spoil to this habitat is a massive driving force that influences every aspect of the system. The energy from the dredge moves sediment and creates mounds and slopes; this energy plus the material give the habitat its initial shape and its sediment, chemical, and physical structure. The sediment is reshapes by wind and waves. Wind erosion predominates on elevated portions of the habitat. Wind-generated waves combined with waves from barge and ship traffic erode and reshape the lower portions of unconfined spoil and spoil dikes (Chaney et al. 1978).

Water content of dredge spoil ranges from 70 to more than 90 percent by volume (Boyd et al. 1972). Salinity of the water varies with location, but a great deal of water with dissolved salts remains within the sediment as it is pumped or lifted onto the spoil pile. Salinity and moisture content of the soil are initially determined by and periodically supplemented by the addition of new spoil.

Other driving forces are not as extreme as the addition of new spoil to the spoil pile. Wind and wave energy are continuous influences. Their most important effect is probably the establishment of slope. Both wind and waves transport seeds and viable plant parts to spoil areas, and wind transports the seeds onto the spoil surface (Parnell et al. 1978). Organic debris that provides a wind shelter for seedlings, and organic matter that supports soil microorganisms are also carried to the habitat by wind and wave action. Airborne salt is continually transported to the habitat although in smaller quantities than salt supplied by the direct addition of salt water.

Sunlight is the energy source for autotrophs, and heat from radiant energy combines with wind to aid in drying upper soil levels to provide a hospitable environment for upland plants. Compaction of sediments and

subsidence in some coastal areas results in a relative rise in sea level which raises the groundwater level in the spoil habitat. This may increase soil moisture and salinity.

While many outside driving forces determine the shape and initial physical and chemical properties of the spoil habitat, processes within the habitat are largely responsible for its change over time and acceptability to plant communities. Plant assemblages respond to a combination of factors including soil moisture, salinity, aeration, and nutrient content. These are not independent components, but interact.

Soil moisture strongly influences plant communities. Vaughn and Kimber (1977) suggest that in some Texas coastal spoil habitats soil water is the major limiting factor to plant growth. Soil moisture is determined by soil texture, drainage, and the height of the water table.

Soil salinity is a function of salt and moisture content of the soil. Plant growth and survival is closely related to soil salinity as has been demonstrated by Woodhouse et al. (1974), Falco and Cali (1977), and others. Higher salinities result in poorer growth and survival.

Measurable differences develop in spoil over a period of time. Sediment in dikes, slopes, and domes that make up the higher elevations becomes coarser as silt, clay, and soil salts are carried by surface flow to swales at lower elevations (Parnell et al. 1978). As organic matter is added to the soil by wind and wave transport and plant production, soil begins to develop texture. This encourages soil aeration and enhances the soil's ability to hold nutrients for plant use.

Nutrients are largely derived from the spoil material. They are tightly bound to silt and clay particles. When soil texture improves with increased organic matter and microbial degradation, nutrients are released by chemical changes taking place in the soil (Mang et al. 1978). Nutrient concentration can be critical to plant growth in the spoil habitat. Eleuterius (1974) attributed poor survival and growth of transplanted vegetation to nutrient-poor old spoil deposits; Barko et al. (1977) noted that growth of coastal plants was limited on sandy dredged material.

Succession of plants on Texas spoil islands has been characterized by Chaney et al. (1978). Pioneer plants (halophytes) are transported by waves and wind and establish themselves in tidal drift lines; colonization is fairly rapid in this zone, occurring within six months.

In two to five years the lower portions of the spoil piles are invaded by perennial grasses and forbs, from the high tide line to the bases of the spoil domes. The slopes and then the tops of the domes are eventually invaded by annual, biennial, and perennial grasses and forbs. The length of time it takes fpr a spoil pile to become completely vegetated is related to rainfall and the leaching of salt and nutrients from the sediments. Invading vegetation which is less salt-tolerant than the halophytes covers spoil domes within two to four years on the upper coast, but 20 to 30 years on the lower coast (Chaney et al. 1978).

Climax vegetation in the southern region is grasses and herbs unless mesquite shrubs invade and then dominate the highest elevations. In the northern region, in bays with limited freshwater inflow, a dense shrub community has developed with a dense herbaceous understory. In areas with

large freshwater inflows the climax community consists of tree species typical of mesic eastern Texas forests (Chaney et al. 1978).

A similar climax vegetation pattern was reported by Coastal Zone Resources Corporation (1977), which noted that many spoil areas were subject to frequent spoil additions, cattle grazing, and fire that maintained communities at earlier seral stages. Vaughn and Kimber (1977) studied low-relief spoil islands along the central coast. While they could identify some plant associations, they could distinguish neither patterns of succession nor clear relationships of communities to environmental parameters.

With the development of separate plant zones, plant communities become more diverse and the animal populations become more varied. Herbivorous species including insects and small mammals live in the grasses. Colonial seabirds and wading birds frequent the spoil habitat. They are important components of the system because they transport seeds for marsh and upland plants to the spoil system, allowing rapid pioneer vegetation development. They also import inorganic nutrients to nutrient-poor spoil material; they use food materials from nearby habitats, but leave their droppings in the spoil habitat (Chaney et al. 1978).

Some spoil areas are built upon or adjacent to uplands; migration by colonizing animals is rapid because of the easy access from their upland habitats. Some spoil areas are located on isolated islands away from the upland shore. While birds and flying insects can easily migrate, many consumer and carnivore species may not be present on these insular spoil areas.

Flora and fauna. Three general plant zones develop on the spoil habitat: halophytes close to the water's edge, a lower slope community above mean high

water, and an upland community of grassland or woody species on the upper part of the spoil pile. Common plants in the halophytic community include glassworts (Salicornia sp.), saltwort (Batis maritima), sea purselane (Sesuvium portulacastrum), and sea blite (Suaeda linearis).

Common lower slope community plants include wiregrass (Spartina patens), saltgrass (Distichlis spicata), gulf cordgrass (Spartina spartinae), sea ox-eye daisy (Borrichia frutescens), Carolina wolfberry (Lycium carolinianum), camphor daisy (Machaeranthera phyllocephala), and salt-flat grass (Monanthochloe littoralis).

Common plants in the southern climax community are dropseed (Sporobolus sp.), bushy bluestem (Andropogon glomeratus), fingergrass (Chloris petraea), and Texas prickly pear (Opuntia Lindheimeri). Northern climax plants are dominated by marsh-elder (Iva frutescens) and sea-myrtle (Baccharis halimifolia). Clumps of sea-oxeye (Borrichia frutescens) and Carolina wolfberry (Lycium carolinianum) are found interspersed among the marsh-elder and sea-myrtle. A common plant in the dense herbaceous understory is the nettle (Urtica chamaedryoides). In Trinity Bay, salt cedar (Tamarisk sp.) dominates the high ground, while on old spoil islands along the Houston Ship Channel toothache tree (Zanthoxylum clavi-herculis) and hackberry (Celtis Lindheimeri) are common (plant information from Coastal Zone Resources Corporation 1977; Vaughn and Kimber 1977; Chaney et al. 1978).

Common herbivores on spoil habitats include the cotton rat (Sigmodon hispidus), marsh rice rat (Oryzomys palustris), eastern cottontail (Sylvilagus floridans), swamp rabbit (S. aquaticus), nutria (Myocastor coypus), and muskrat (Ondatra zibethica). The fire ant (Solenopsis invicta) is found in

spoil habitats adjacent to uplands. The ants make large mounds and burrow well below the surface. Construction of their mounds has been reported to alter the physical and chemical characteristics of the soil, probably through improved aeration and mechanical stirring of the soil particles (Coastal Zone Resources Corporation 1977). Fire ants are prey for the nine-banded armadillo (Dasypus novemcinctus).

Other consumers include the gulf coast toad (Bufo valiceps), horned toad (Phrynosoma cornutum), killdeer (Charadrius vociferus), laughing gull (Larus atricilla), gull-billed tern (Sterna albifrons), great blue heron (Ardea herodias), cattle egret (Bulbulcus ibis), snowy egret (Egretta thula), and red-winged blackbird (Agelaius phoeniceus).

Some representative top consumers are the western cottonmouth (Agkistrodon piscivorus leucostoma), barn owl (Tyto alba), marsh hawk (Circus cyaneus), coyote (Canis lupus), and American alligator (Alligator mississippiensis) (species from Coastal Zone Resources Corporation 1977; Chaney et al. 1978).

Adjacent systems and flows. The majority of habitats adjacent to spoil are channel (42 percent) and bay (18 percent). About 14 percent of the adjacent habitats are salt and brackish marsh, and 4 percent are grassflats. In many places spoil has been directly placed on salt and brackish marsh and grassflat habitats. In Matagorda Bay spoil outwash is occupied by marsh plants in some places (McGowen and Brewton 1975); in the Laguna Madre seagrasses are sometimes found in shallow subaqueous areas around spoil piles. While development of small areas of these two habitats is sometimes promoted by conditions near spoil piles, the newly developed marsh or seagrass beds are

at least an order of magnitude smaller than areas of the same habitats that have been replaced or altered by spoil placement.

About 7 percent of the habitats adjacent to spoil are range, the most prevalent upland unit adjacent to bays, lagoons, and tidal rivers. About 6 percent of the spoil habitat is adjacent to wind-tidal flat. This occurs almost entirely in the Laguna Madre basin where the Gulf Intracoastal Waterway is dredged across the Land Cut, a large area of wind-tidal flat.

The most significant imports to the spoil habitat are seeds, plant propagules, consumers, and nutrients from birds. In time salt and sediment is exported as materials leach out of the sediment and are transported by wind, runoff, and percolation water. Nearly 45 percent of the maintenance material disposed in the spoil habitat during federal dredging has levels of some chemical parameter higher than the EPA Region VI 1974 guideline screening levels (Belaire 1976). There has been concern that these materials might be remobilized and cause toxicity problems in adjacent waters. A study of long-term release of contaminants by Brannon et al. (1978), however, concluded that although there were some releases of materials from aquatic disposed spoil, they were not expected to cause significant long-term water quality degradation.

In a review of the effects of dredging on the Texas coast, Delahoussaye (1981) found only one published study that showed significant problems resulting from the release of heavy metals. The study reported an instance in Galveston Bay where manganese concentrations exceeded EPA levels for critical, chronic (lifetime) exposure for a period of a few minutes to a few hours (Lee et al. 1976). Ammonia was occasionally released during dredging, but it dispersed quickly. It is unlikely that ammonia would be released from spoil

habitats in significant quantities. Chlorinated hydrocarbon pesticides (CHPs) and polychlorinated biphenyls (PCBs) were not released from the sediments.

Economic uses. The most important economic use of spoil habitats is for the recurring disposal of spoil, dredged from channels and waterways to keep them clear for navigation. There were 41,312 ha (102,040 ac) of available disposal area in the region 1976. It has been projected that 33,000 acre-feet of spoil per year will be dredged by federal and private interests over the 10-year period from 1976 to 1986 (Espey, Huston and Associates 1976). Spoil areas near the Galveston Harbor, Texas City Channel, and Freeport Harbor are expected to be the most heavily used, with an average increase in sediment depth of 4.6 m (15 ft) over the period. Liebow et al. (1980) report that the annual volume of dredge spoil is even higher, 51.8 million cu m (42,000 ac-ft) per year. Finding disposal sites for that much spoil is a continuing problem.

Because spoil is a fine mixture of silt and sand, is largely very unsuited for most purposes other than fill (Delahoussaye 1981). Spoil habitats in Texas have been used experimentally for shrimp mariculture ponds (Quick 1978) and new marsh and upland habitats (Allen et al. 1978; Webb et al. 1978).

Spoil islands have proved to be recreational assets in some areas. The state currently leases more than 500 recreational cabins to individuals; most of these cabins are located on spoil islands. Spoil islands are used as nesting and roosting grounds by colonial seabirds and wading birds (Chaney et al. 1978; Mullins et al. 1982). Many persons visit spoil habitats to view and photograph birds and other wildlife. Several businesses in the Aransas-Copano

basin and the San Antonio basin cater to these visitors and thus profit indirectly from the presence of the spoil areas.

Impacts of man's activities. The major impact on the spoil habitat from man's actions occurs when new maintenance material is placed in the habitat. This usually results in a catastrophic change in the habitat, smothering existing vegetation and reinitiating the successional cycle. Small amounts of new material may not be quite as catastrophic, although additions of sediment and salt water usually result in the loss of some plants and burrowing animals, as well as changes in the plant community. Cattle may move into vegetated spoil on mainland areas to feed. Their feeding alters plant succession since they consume grasses but leave woody species alone. Fire has the opposite effect, retarding the success of woody species while only briefly interrupting the growth of grasses.

Use of spoil islands for recreation has created a few problems. Spoil habitats have increased bird habitat, and some spoil islands have become nesting areas for colonial waterbirds. Human presence on these islands can be disruptive. Cabins on rookery islands usually have no sanitary facilities, and short-term water quality problems are possible.

The major impact of spoil habitats on other habitats is hydrologic. Spoil piles built in bays or along the lower edges of mainland wetlands alter the circulation patterns of bays or drainage of land runoff. Sometimes this hydrologic change can be used to advantage; for example, to improve tidal flow through channels. In many instances, however, concerns about hydrologic alterations have been given secondary, if any, consideration in decisions about spoil placement.

Swamp

Areal extent. Swamp habitat occupies 111.5 sq km (43.2 sq mi) in the Texas Barrier Island Region; this constitutes approximately 0.2 percent of the region's area. Figure 92 shows the distribution of swamp habitat in the basins along the coast. Swamp habitat is not present below the Aransas-Copano basin. The relative proportion of swamp increases to the north, and nearly 75 percent of this habitat in the region is located along the floodplains of the Trinity and San Jacinto rivers, just above their modern deltas. Small isolated swamp areas are located in both ancient and recent floodplains of the Brazos and Colorado rivers.

Physical description. Swamps are low areas within a floodplain where the soil is waterlogged or is covered by shallow standing water for a substantial portion of the year, and where bushes and trees grow. The vegetation that grows in swamps is specially adapted to those conditions and generally does not grow on uplands. Upstream from the swamp there may be areas of fluvial woodlands with water-tolerant hardwoods. Downstream the swamps grade into lakes and freshwater marsh.

Most swamps along the Trinity and San Jacinto rivers are located behind low natural levees or point bars. Fresh water enters the swamps from adjacent rivers during floods and does not completely drain when the water level falls (Fisher 1972). Ground elevation is low, but numerous hummocks and relict bars remain from previous river courses.

The modern floodplain for the Trinity and San Jacinto Rivers is narrow. Above the floodplain level is a terrace built upon Pleistocene meanderbelt sands and muds. Mixed pine and hardwood forest grows on the terrace

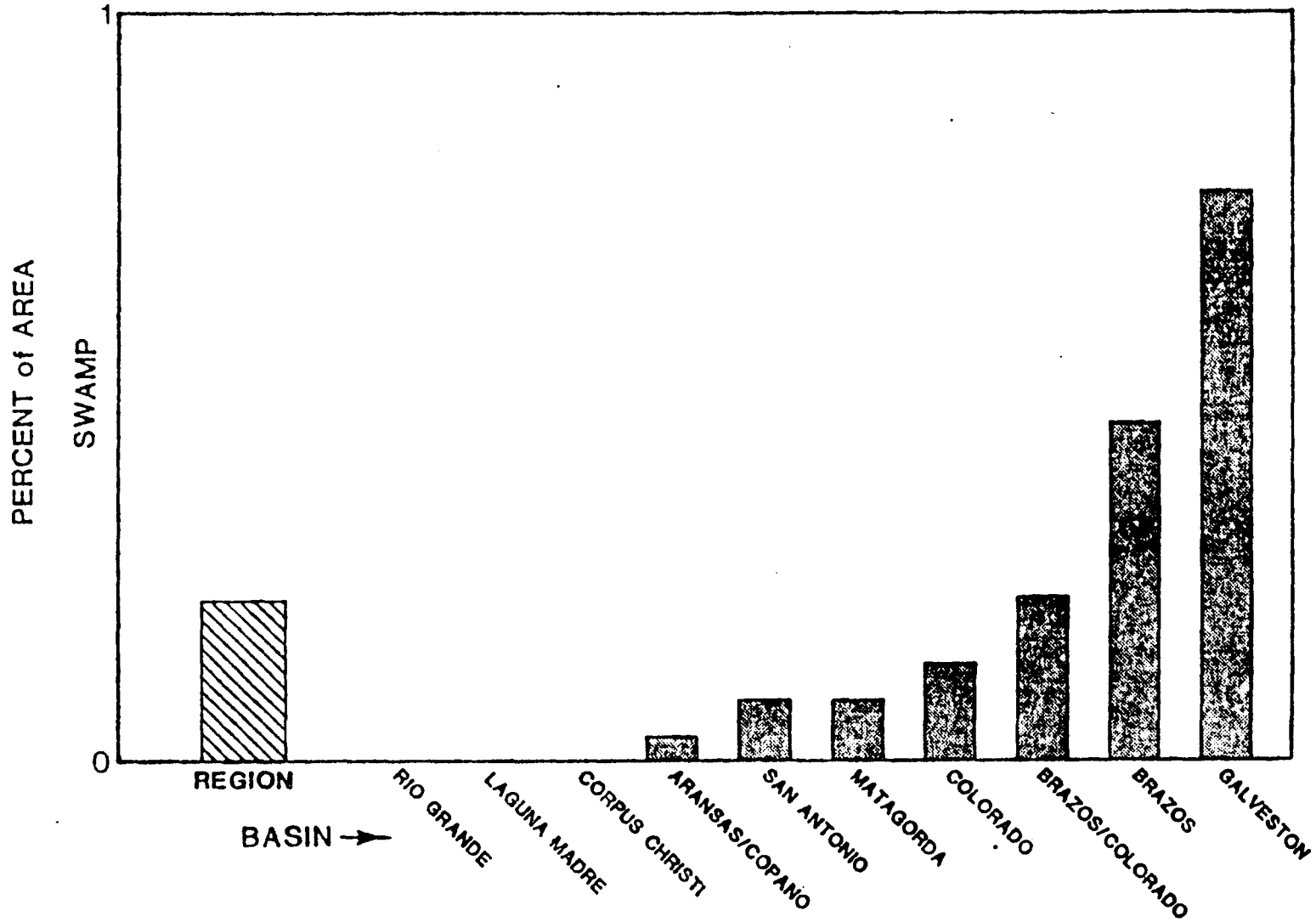


Figure 92. Percent of region and basin that is swamp habitat.

immediately adjacent to swamp, but the two habitats do not grade into each other because of the abrupt elevation change.

Swamp soils are generally clays (Fisher et al. 1972; Crout 1976; Wheeler 1976). The soils have a high water table, low permeability, and a pH ranging from slightly acid to barely alkaline (5.6 to 7.8). During periods of flooding or standing water the swamp sediments are often anoxic; this condition discourages germination of seedlings of major swamp trees (DeBell and Naylor 1972) and leads to a variety of stresses on flood-intolerant species that ultimately can result in plant dehydration and death (Wharton et al. 1982; Kozlowski 1984). Swamp plants have physical or metabolic adaptations that allow oxygen to be transported to the roots or allow a shift to glycolytic metabolism without accumulation of toxic metabolic by-products.

Inundation frequency and yearly pattern of flooding are important variables governing the supply and export of materials, and the life cycle of plants. Areas of swamp, brackish marsh, and fresh marsh along the Trinity River begin to receive floodwaters when the river discharge is between 198 cu m per sec (7000 cu ft per sec) and 566 cu m per sec (20,000 cu ft per sec) (U.S. Army Corps of Engineers; Texas Department of Water Resources 1981). Thus the swamp receives floodwater 11 to 25 percent of the time (U.S. Corps of Engineers 1981). While floods may occur in the Trinity basin at any time of year following heavy rainfall, high water flows are most prevalent in the upper coast during the spring. Flooding frequency of swamps on the San Jacinto River follows a similar pattern.

Small swamps in the basins to the south of the Galveston basin are located on streams or in small depressions surrounded by higher land. Swamps on small streams probably receive most of their water from periodic stream

flooding. Those in small depressions receive their water from direct rainfall and runoff from adjacent higher land. In a few places these swamps are associated with small lakes.

System operation. Swamps in the region receive water from floods, direct precipitation, land runoff, and seepage from sand deposits that underlie the swamp (Fisher et al. 1972). The major force that regulates the swamp habitat is periodic flooding. Floodwaters carry clay and inorganic nutrients into the swamp.

Day et al. (1979) noted that the nutrient chemistry of swamps is intimately tied to hydrology. Water flow determines the degree of aeration of overlying water, which in turn strongly affects soil chemistry. When the water and soil are oxygenated during a flood, most inorganic forms in the swamp are taken up and tightly bound by clay sediments. At this time nutrients can enter the swamp and become bound to the sediments. Reduced conditions in the soil that occur with standing water cause inorganic materials to be mobilized from the sediments and to become available for plant uptake. This assures a continual resupply of inorganic nutrients for the system.

Periodic flooding flushes standing water from swamps and sends it downstream. Dissolved organic matter, detritus, and nutrients are swept out of the swamp and carried to the estuary, where they become inputs to the bay system (Day et al. 1977). Since the major flooding of the Trinity and San Jacinto river swamps usually occurs in the spring, the pulse of materials sent to estuarine systems comes at an opportune time for bay productivity.

Subsidence has a strong effect on the swamp habitat. Some low upland areas may become swamp habitat, and the lowest swamp areas may become too deep for survival of swamp trees. Subsidence in the Trinity River swamp habitat has ranged from 0.06 to 0.3 m (0.2 to 1 ft); subsidence in the San Jacinto River swamp habitat has ranged from 0.3 to 1.5 m (1 to 5 ft)(Brown et al. 1974). Areal estimates of forested wetland along the lower portion of the Trinity River show that the amount of forested wetland (areas of woody plants including swamp vegetation that tolerate wetland conditions) has doubled from 1956 to 1979 (Anahuac and Cove 7.5 minute U.S.G.S. quadrangles, U.S. Fish and Wildlife Service, unpublished). Maps of the area (U.S. Fish and Wildlife Service, unpublished) show that the amount of forested wetland around the Trinity River swamp has declined; the increase in forested wetlands has occurred in tidally influenced areas and in depressions on the uplands. Comparative areal information for the San Jacinto River is not currently available. Since subsidence has been greater and more rapid in the San Jacinto swamp habitat than in the Trinity, however, it is likely that swamp area along the San Jacinto has decreased to an even greater extent.

Water depth and water flow within the swamp are important system components. While swamp vegetation can withstand periods of high water, prolonged periods (years) of constant high water result in mortality of even the best adapted swamp trees (Harms et al. 1980). The best hydrologic regime for swamps appears to involve fluctuating water depths and moving water during high water periods (Day et al. 1980). Low water allows new plants to germinate and establish themselves; moving water appears to enhance production, possibly by minimizing the buildup of toxic metabolic by-products and favoring Krebs cycle metabolism over gylcolysis.

Flora and fauna. Woody species in the swamp include bald cypress (*Taxodium distichum*), swamp privet (*Forestiera acuminata*), water locust (*Gleditsia aquatica*), water tupelo (*Nyssa aquatica*), and buttonbush (*Cephalanthus occidentalis*). Black willow (*Salix nigra*), water hickory (*Carya aquatica*), and water elm (*Planera aquatica*) occur at the periphery of the swamp and grade into the floodplain forest. Understory vegetation includes lizard tail (*Saururus cernuus*), climbing hempweed (*Mikania scandens*), dwarf palmetto (*Sabal minor*), dye bedstraw (*Galium tinctorium*), and ryegrass (*Lolium perenne*) (U.S. Army Corps of Engineers 1981).

Swamp provides a diverse habitat for many species. Mosquitoes, mayflies, damsel flies, and dragon flies are insects found in the swamp. Some of the aquatic invertebrates include river shrimp (*Macrobrachium* sp.), grass shrimp (*Palaemonetes* sp.), mysid shrimp (*Mysis* sp.), and blue crabs (*Callinectes sapidus*). Fish that use the swamp habitat include gizzard shad (*Dorosoma cepedianum*), threadfin shad (*D. petenense*), blue catfish (*Ictalurus furcatus*), gar (*Lepisosteus* spp.), golden shiner (*Notemigonus crysoleucas*), mosquito fish (*Gambusia affinis*), bluegill (*Lepomis macrochirus*), and crappie (*Pomoxis* spp.) (U.S. Army Corps of Engineers 1981).

Reptiles and amphibians that are commonly found in Texas swamps include the green treefrog (*Hyla cinerea*), southern leopard frog (*Rana ultricularia*), bullfrog (*R. catesbeiana*), gulf coast ribbon snake (*Thamnophis proximus ovarius*), and western cottonmouth (*Agkistrodon piscivorous leucostoma*). Avifauna is very diverse in swamps; more than 120 species have been recorded (U.S. Army Corps of Engineers 1971). Birds that commonly spend at least part of the year in the swamp habitat include the double-crested cormorant

(Phalacrocorax auritus), great blue heron (Ardea herodias), cattle egret (Bulbulcus ibis), common crow (Corvus brachyrhynchos), American robin (Turdus migratorius), and cardinal (Cardinalis cardinalis).

Mammals found in swamps include the raccoon (Procyon lotor), eastern grey squirrel (Sciurus carolinensis), American beaver (Castor canadensis), nine-banded armadillo (Dasypus novemcinctus), various canids (Canis spp.), and swamp rabbit (Sylvilagus aquaticus) (U.S. Army Corps of Engineers 1971).

Adjacent systems and flows. Nearly 57 percent of the habitats adjacent to swamp are forest, 13 percent are lake, 7 percent are river, and 3 percent are freshwater marsh. Range is the only major (13 percent) man-managed habitat adjacent to swamps. Since swamps are a part of an association of woodland habitats it is not surprising that forest predominates among the adjacent habitats.

Import and export with the river is the most important material transfer for swamps. Imported materials include fine clay sediments, inorganic nutrients, and oxygen in floodwaters; exported materials include sediment, nutrients, and organic matter. The transfer of the materials occurs simultaneously during floods, with river materials swept in and swamp materials swept out to eventually arrive at estuarine systems downstream (Day et al. 1977). Normal exchanges with lake and fresh marsh habitats occur continuously but with less intensity than with the river.

During periods of normal river flow materials are imported from floodplain forests. Generally only water and small quantities of nutrients are received by swamps. Only during periods of flooding is there a flow of water and other materials to the floodplain forest.

Locations where swamp is adjacent to range are not near major rivers. Range is topographically higher and swamps import materials from range as they do from floodplain forests during normal river flow. It would be unusual for materials to flow from swamps to range lands.

Economic uses. Swamps in the Galveston basin contain tall hardwood trees, but because of the available wood in the adjacent pine-hardwood forest, little effort has been made to harvest the swamp hardwoods. The abundance of excellent agricultural land on the adjacent uplands and the problems associated with flooding have discouraged reclamation of the lower Trinity swamps.

A few of the small swamps below the Galveston basin are adjacent to range habitat, and it is likely that some swamp land was reclaimed for use as range by cutting, draining, and filling in the past.

The Trinity River, which meanders through the swamp, has been used as a navigation route for more than 80 years. A navigable channel has been maintained in the river to Liberty, Texas, and at various times plans have been made to extend the channel to Dallas, Texas. In 1966 construction began on a 7976-hectare (19,700 acre) lake that supporters claimed would provide salinity control, water supply, navigation, fish and wildlife enhancement, and recreation. The lake would have permanently flooded almost all of the swamp, freshwater marsh, and brackish marsh on the lower Trinity, but construction was halted before completion. A revised proposal was offered that would decrease the area permanently flooded to 2266 hectares (5600 acres) (U.S. Army Corps of Engineers 1981). Under the revised plan 1256 hectares (3103 acres) of swamp (11 percent of the swamp habitat area in the region) would be

permanently inundated. The project is awaiting federal court approval of the revised plan.

Impacts of man's activities. Activities that change the flooding pattern alter swamp habitats. Impoundment of rivers upstream and channelization of rivers through swamps decrease the frequency and duration of flooding. This allows less tolerant floodplain forest species to successfully compete with swamp vegetation and eventually convert the swamp to floodplain forest.

Impoundments downstream of the swamps create large areas of standing water that does not fluctuate in depth. Harms et al. (1980) and the U.S. Army Corps of Engineers (1981) described the changes in swamp vegetation in Rodman Reservoir after it was permanently flooded. Less tolerant trees died rapidly. Cypress trees that were flooded two to three feet above normal died within seven years, and most remaining trees were in poor condition. In shallower parts of the impoundment--such as the edge--small fluctuations in water depth appeared to be adequate to allow survival of mature trees and germination and growth of saplings. In deeper areas of permanent standing water, however, no new saplings could root to replace old trees, and it was apparent that these areas would eventually become open water.

Urban Habitat

Areal extent. Concentrated development dense and populous enough to be called urban habitat is relatively new to the Texas Barrier Island Region, having been in existence for only about a century. Urban habitat currently occupies about 3 percent of the region's area (1424 sq km or 550 sq mi) but is growing fast and rapidly overtaking natural habitats. Land use projections made by the Houston-Galveston Area Council (1970) estimate that by 1990, space used for residential, commercial, and industrial development will increase 324

percent over the 1970 area; by 2020 the increase will be 550 percent. At this rate, urban habitat will constitute 9.7 percent of the region's area by 1990 and 16.5 percent by 2020.

Half of the urban habitat in the region (712 sq km or 275 sq mi) is located in the Galveston basin, where it occupies 6.5 percent of the basin area. The Laguna Madre basin has the second largest amount of urban habitat (313 sq km or 121 sq mi), but the habitat's proportion of the basin area is less than 2 percent. Urban habitat constitutes only about 0.8 percent of the area in both the San Antonio and Lavaca basins (Figure 93).

Physical description. The urban habitat consists of numerous components: a transportation network, surface drainage facilities, utility corridors, commercial buildings, industrial areas, municipal facilities for power generation and water management, parks, and residential areas. From the air, roads, freeways, and railroads are the most extensive feature.

The transportation network is the main organizing influence on urban habitat. In urban areas developed before the twentieth century, waterways were very influential, providing transport as well as access to freshwater supply. In this century the automobile has become the main organizing influence, although railroad lines also influence the location of commercial and industrial facilities. Physiography may be the critical determinant of transportation patterns in urban areas. Because the Barrier Island Region has low relief, transportation pathways have relatively few topographic restrictions other than natural drainage channels.

The urban habitat has a central area in which most commercial structures are located and where most commercial activities occur. This is usually the

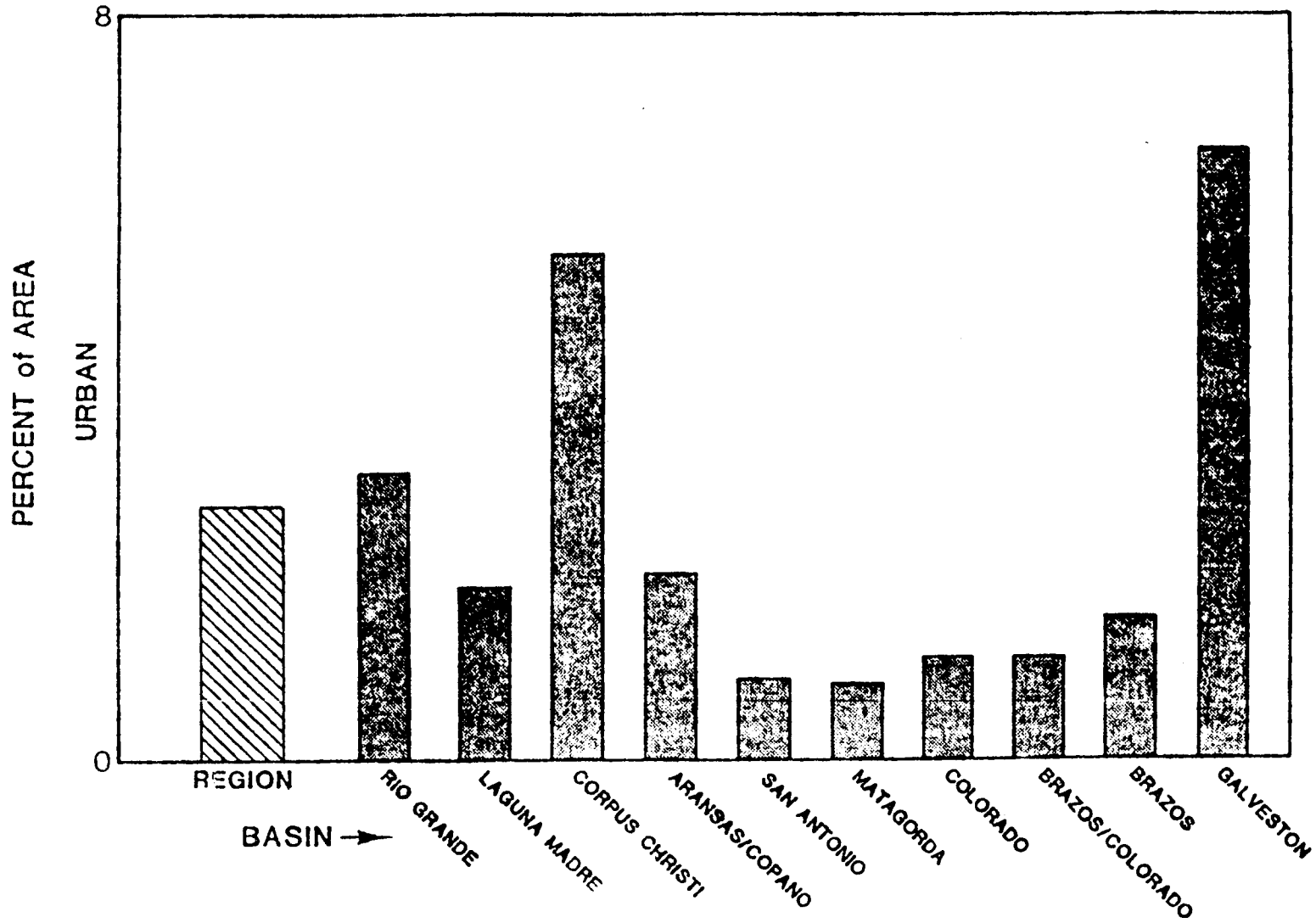


Figure 93. Percent of region and basin that is urban land.

oldest part of the urban habitat and has the highest density of structures and of components of the transportation and utility networks. Leading out from the central hub are transportation corridors. The farther away an urban area is from the center, the more recent its transformation to urban habitat.

The man-made drainage network generally follows the pattern of the transportation routes. Most of the smaller utility lines--electricity, gas, water, and sewage--also follow the transportation routes. High voltage power lines from electric generating plants to substations may take the shortest path connecting points rather than following the transportation corridor.

Some residential areas are located on the periphery of the central commercial area, but there is usually a steady conversion of low-density residences to commercial developments or high-density residences in the central city. Most large-scale residential development occurs near the outer fringe of the urban habitat because of lower land prices. These residential areas are subsumed into the urban habitat as the boundary of the habitat expands outward, and small commercial pockets develop adjacent to them. Average population density declines from the central city outward, although the decrease for Texas urban areas is much less dramatic than for older, East Coast urban centers (Holder et al. 1973). Many east Coast cities were established before the automobile came into use, and development was concentrated along public transportation routes. The automobile reduced dependence on communal transportation and permitted more diffuse development.

Greenbelts and parklands are interspersed throughout the urban area. In the outermost parts, parks are often located adjacent to recent residential developments as part of integrated residential, commercial, and recreational planning. In the older, central parts, random blocks exist as parks,

especially around municipal buildings or historical landmarks. New parks may be established in the center of urban areas as part of redevelopment efforts. Many urban areas have preserved one or more large tracts of parkland that are partially managed or are relatively unmanaged. Golf courses and airports are also major greenbelts in urban areas, although access to them may be restricted.

Residential areas typically constitute about 39 percent of the urban land area. Freeways, streets, alleys, and railroad lines occupy 36 percent of the urban land. Parks and greenbelts comprise 11 percent of the urban habitat. Industrial areas use about 10 percent of the land, and commercial facilities occupy 4 percent (figures from Holder et al. 1973).

In a growing urban habitat, population size and transportation modes impose practical limits upon the maximum size of the central business district. When automobiles on freeways and arterial roads are the primary transportation mode and most traffic in the central district is pedestrian, the maximum population that can be served by a single central business district is about 2,000,000 persons (Holder et al. 1973). To support more persons other types of primary and secondary transportation such as commuter trains and subways must be added, or additional central business focal points must be developed. Urban areas in the barrier island region favor the latter method of urban growth.

Large industrial portions of the urban habitat tend to be clustered in places where waterborne transportation is easily accessible. In the Texas Barrier Island Region, deep-draft port facilities are located along the Houston Ship Channel, at Bayport, Texas City, Galveston, Freeport Harbor,

Point Comfort, Port Lavaca, Harbor Island, Port Ingleside, along the La Quinta Channel, at Corpus Christi Harbor, and along the Brownsville Ship Channel. Eleven public shallow draft ports and many private shallow docks are located along the Texas coast between the Louisiana and Mexican borders (Warren et al. 1980). All have adjacent industrial facilities. Industrial developments next to the Houston Ship Channel, Bayport Channel, Texas City Channel, and Galveston Channel--all in Galveston Bay--comprise a large proportion of the industrial area in the urban habitat for the entire region.

System operation. The urban habitat is driven by inputs of fuel, water, agricultural products, minerals, and manufactured products from other habitats both within in the region and outside it. Most urban areas in the region are expanding; consequently the land converted from natural habitats to urban use can be considered an input to the urban habitat.

The urban habitat has two major consumers: the residential portion of the habitat, and the commercial-manufacturing portion. Both require the inputs listed above, but in varying degrees. For example, the residential portion of the habitat uses about one-third of the fresh water consumed in the habitat, and the commercial-industrial sector uses the other two-thirds (Liebow et al. 1980).

The commercial-industrial component produces outputs (food and goods) that are exported from the region or are consumed within it. The residential component acts like a top consumer since it uses and controls the production and movement of materials from other producing levels, but does not contribute consumable products for further use.

Because the population of the region is increasing at a rate of about 2.2 percent per year, almost all in the urban habitat, the population of the

residential component is increasing. About half of the increase is due to immigration; the other half is due to natural population increase (Liebow et al. 1980).

Both consumer groups produce wastes--solid, liquid, and gas. Gaseous wastes are processed by wind dispersal and photooxication. Liquid wastes may be partially processed in the urban habitat through mechanical and biological treatment. Municipal sewage plants treat liquid wastes and export the treated effluent to adjacent natural systems. There are nearly 1600 permitted waste discharges in the region (Liebow et al. 1980). Nearly 52 percent are from sanitary processing plants; 45 percent are from commercial-industrial sources.

From 100 to 150 solid waste disposal sites are located in the region. About 90 percent of the region's solid waste comes from urban areas in Harris and Galveston counties, which produce more than 63 million tons of solid waste per year (Liebow et al. 1980). Liquid wastes are heavily treated, but final processing of solid, gaseous, and permitted liquid waste effluents is left to the metabolism of primary producers and degrading organisms in adjacent habitats.

Exports from the urban habitat include food, goods (manufactured and processed products), waste materials, and pathogens. There is a continual flux of human population into and out of the habitat. Immigration exceeds emigration, and this trend is projected to continue through the end of the century.

The internal structure of the urban habitat is different from that of all other habitats. Urban habitats have very high energy flows, largely from fossil fuels. Power density, the energy flow per unit time per unit area, is

hundreds of times higher for urban habitats than for natural land or agricultural land (Odum 1983, figure 25-4). While there are primary producers in yards, parks, and undeveloped land, the main consumers in the urban habitat do not depend upon their production for energy input. Food materials are almost entirely imported from agricultural or other urban habitats. Energy, minerals, and manufactured goods largely come from other habitats. Primary producers do assist in processing wastes and producing oxygen. They also participate in the hydrologic cycle by retarding surface flow and transpiring water to the atmosphere. A large proportion of urban plants, however, are ornamental, intended more to enhance the image and esthetic aspect of the urban habitat than to contribute to its functioning.

Water needed for municipal, manufacturing, and steam electric generation purposes accounts for more than 31 percent of the water used in the region (Texas Department of Water Resources 1977). These water uses are closely related to the urban habitat. While agriculture accounts for more than twice this amount of water, cropland constitutes more than seven times the area. Consequently the intensity of water use in urban habitat is near 3.5 times the intensity of use for agriculture.

Flora and fauna. Although the urban habitat replaces other natural habitats, vestiges of the previous natural systems remain in undeveloped tracts and partially managed areas. On the upper coast, urban areas have developed upon grassland and forested areas. Native grasses and understory vegetation include little bluestem (*Schizachyrium scoparium*) and beaked panicum (*Panicum anceps*). The rest of the region was largely grassland or savannah; little bluestem is common to urban areas over the entire coast while switchgrass (*Panicum virgatum*) and Indian grass (*Sorghastrum avenaceum*) are

found in central coast area. Twoflower trichloris (Trichloris crinita) and fourflower trichloris (T. pluriflora) are common in the central and lower coast. Yards and parks contain introduced grasses including St. Augustine (Stenotaphrum secundatum), carpetgrass (Axonopus affinis), and manilagrass (Zoysia matrella).

The native woodland vegetation on the upper coast includes loblolly pine (Pinus taeda), southern red oak (Quercus falcata), water oak (Quercus nigra), shortleaf pine (Pinus echinata), and sweetgum (Liquidamber styraciflua). Many of these species remain in residential and park areas; other species, both native and introduced, have been planted in the urban habitat. On the upper coast, redbud (Cercis canadensis) and American elm (Ulmus americana) are common. Mimosa (Mimosa sp.) and live oak (Quercus virginiana) have been planted in the upper and mid-coast areas. On the middle coast, huisache (Acacia farnesiana), pecan (Carya illinoiensis), and chinaberry (Melia azedarach) are commonly planted. Eastern cottonwood (Populus deltoides) is grown on both the central and lower coast. Ash (Fraxinus sp.), salt cedar (Tamarix sp.), and palm (Sabal texana) are grown in southern urban areas.

The common oleander (Nerium oleander) is used as an ornamental shrub in all urban areas in the region. The pyracantha (Crataegus pyracanthoides) is planted in upper and middle coast areas. Evergreen sumac (Rhus sempervirens) is a shrub commonly used in the upper coast; common crape myrtle (Lagerstroemia indica) is often planted in mid-coast areas; bougainvillea (Bougainvillea sp.) and duranta (Duranta repens) are grown on lower coast.

English ivy (Hedera helix), a vine or ground cover, is grown in urban areas over the entire coast. Virginia creeper (Parthenocissus quinquefolia)

and Chinese wisteria (Wisteria sinesis) are more common in upper coast areas, while trumpet creeper (Campsis radicans) and peppervine (Ampelopsis arborea) grow well in mid-coast areas. (Floral information comes from Wheeler 1976, Guckian and Garcia 1979, Jacobs 1981, and Miller 1981).

Man, of course, dominates in the urban habitat. Domestic and wild mammals include dogs (Canis familiaris), cats (Felis catus), raccoons (Procyon lotor), opossum (Didelphis virginiana), and grey squirrels (Sciurus carolinensis). Birds are common in urban areas as residents or transients. Some common residents are pigeons (Columba livia), great-tailed grackle (Cassidix mexicanus), house sparrow (Passer domesticus), mockingbird (Mimus polyglottus), and robins (Turdus migratorius). Shorebirds such as the laughing gull (Larus atricilla) and herring gull (L. argentatus) are common in coastal urban areas.

Insects are always found in urban habitats. Houseflies (Musca domesticus), American cockroaches (Periplaneta americana), and German cockroaches (Blattella germanica) are particularly associated with man's living areas. Bees, wasps, grasshoppers, crickets, mosquitos, and many types of beetles are also common.

Adjacent systems and flows. More than 33 percent of the habitats adjacent to urban land are cropland habitats. Range makes up about 31 percent of the adjacent habitats, and forest constitutes about 10 percent. Since the urban habitat is expanding, these are the habitats that are most often converted to urban land. Nearly 12 percent of the adjacent habitats are bay. While bay areas have been filled to create urban land in the past, high costs and regulatory prohibitions generally make expansion onto adjacent upland habitats more attractive.

Adjacent upland habitats directly contribute relatively little material, energy or biota to urban habitat. Instead, they are subsumed and converted into urban habitat, providing a location for its development rather than inputs to support its operation. Materials that are imported into urban areas come from other areas over the transportation system, which is really an extension of the urban habitat over the entire region. Materials, energy, and biota are imported from other urban habitats, cropland, range, forest, or the gulf via the transportation network.

Food, goods, and population are exported over the same pathway. However, waste materials and microorganisms associated with human and animal wastes are exported directly from urban systems to adjacent natural habitats.

Economic uses. The urban habitat is the hub of human population, commerce, and manufacturing in the region. Houston-Galveston Area Council (1970) estimates suggest that the urban habitat will grow at a rate of 3.5 to 6 percent per year until 2020. Personal income statistics show that economic growth in the region has been the greatest for construction, wholesale and retail trade, and manufacturing (Liebow et al. 1980). These sectors of the economy are closely associated with growth and development of the urban habitat.

Impacts of man's activities. The development of the urban habitat has resulted in changes in biota, habitat organization, climatic conditions, and hydrology. As adjacent habitats such as cropland, range, and forest are converted to urban habitat, many primary producing species are eliminated and are replaced by buildings, pavement, and ornamental plants. The effect of the

change and loss of primary producers drastically alters natural consumer and carnivore species in the habitat.

The urban system depends mostly upon imported materials, biota, and energy. Man, represented as the residential and commercial-manufacturing consumer, is the predominant biotic group; producers and the natural consumer groups they usually support are largely peripheral to system operation. Development of urban habitat reduces the natural primary production of the area, causes major changes in species groups, alters the relative proportion and kinds of producers and consumers, and produces substantial changes in the organization and energy flow pathways.

Urban habitats alter climatic conditions. Since urban areas are heat islands due to the concentrated use of energy and the introduction of high levels of carbon dioxide and dust to the atmosphere, air temperatures are higher than in surrounding lands. Airborne particulate matter associated with urban areas provides nuclei for condensation and increased cloud and fog formation. Precipitation increases of 5 to 8 percent have been measured over urban areas in the U.S. (Chandler 1978). Attenuation of solar radiation because of the airborne pollutants, fog, and clouds associated with urban habitats has been measured in cities worldwide.

Tall buildings generally increase surface friction to air flow in urban areas; wind speed may decrease by as much as 30 percent (Elfers and Hufschmidt 1975). This effect may be reversed, however, when winds are very light, possibly because of rising air currents over built-up areas (Chandler 1978).

Urban habitats introduce increased quantities of carbon monoxide, sulfur dioxide, nitrogen dioxide, ozone, and hydrocarbons into the atmosphere. In the Texas Barrier Island Region 49 percent of the nitrates in the air

originate from industrial fuels and 28 percent come from electric power generation. The petroleum and chemical industries contribute 44 percent of the sulfates, with industrial fuels contributing 22 percent. The petroleum and chemical industries contribute 54 percent of the excess hydrocarbon emissions; transportation accounts for 20 percent; and storage and loading facilities produce 19 percent. The chemical and petroleum industries account for 55 percent of the carbon monoxide emissions, and transportation contributes 42 percent (data calculated from Texas Air Control Board 1976).

Urban habitats substantially alter preexisting surface water hydrology. Impervious surfaces are the norm for urban areas. Coverage of soil by pavement and buildings may be as high as 50 percent. The result is reduced infiltration of surface water into the sediment, greater volumes of runoff, increased flow velocities, and larger peak flows that occur earlier in drainage areas after storms. Stream flows become more variable, and there is a general decrease in base flows from small streams and creeks. Low areas flood more frequently and rapidly because of the increased flow volumes and lower surface resistance to water flow. Impervious surfaces may lessen the infiltration and recharge of shallow aquifers. Because nearly 45 percent of the water for municipal and manufacturing use comes from groundwater (Texas Department of Water Resources 1977), decreased recharge may ultimately contribute to localized subsidence.

The continued use of groundwater has caused subsidence in the Houston and Galveston urban habitats as great as 8.5 ft, although 1- to 5-foot changes are more representative of the large urbanized area. Land losses as great as 31 sq mi have been projected for this urban area (Brown et al. 1974). Reducing

the amount of groundwater supplied to urban components necessitates increases in surface water inputs; the increased demand may have effects on other habitats outside of the urban area.

Poor water quality is frequently associated with urban habitats because waste materials are produced in abundance and soil substrates containing decomposing microorganisms are less available. Nutrients from waste materials, lawns, and gardens are transported by water flows. Toxic substances and fecal microorganisms are also transported rather than degraded in situ. Increased water velocities and volumes associated with impervious surfaces can suspend and transport more sediment than undeveloped lands; this results in increased erosion in slopes and drainage areas.

Wind-Tidal Flat

Areal extent. Wind-tidal flat covers 1140 sq km (463.7 sq mi), or 2.4 percent, of the Texas Barrier Island Region. The greatest amount of this habitat, 948 sq km (383.8 sq mi), is located in the Laguna Madre basin. Flats in this basin constitute 5.9 percent of the basin's area and 83 percent of the wind-tidal flat habitat in the region. The Rio Grande basin also contains a relatively large proportion of wind-tidal flat; the habitat occupies 31.9 sq km (12.9 sq mi), or 4.5 percent of the basin's area. In the Aransas-Copano basin wind-tidal flats cover contains 69.2 sq km (28.0 sq mi), which is 1.5 percent of the basin's area. Wind-tidal flat decreases in extent to the north and is almost absent above the Brazos-Colorado basin (Figure 94).

Physical description. Wind-tidal flats are of two major types: sand flats and mud flats. The two types may grade into one another. Wind-tidal flats are often found on the bay side of barrier islands and peninsulas. In the Laguna Madre, large expanses of wind-tidal flat are located between the lagoon

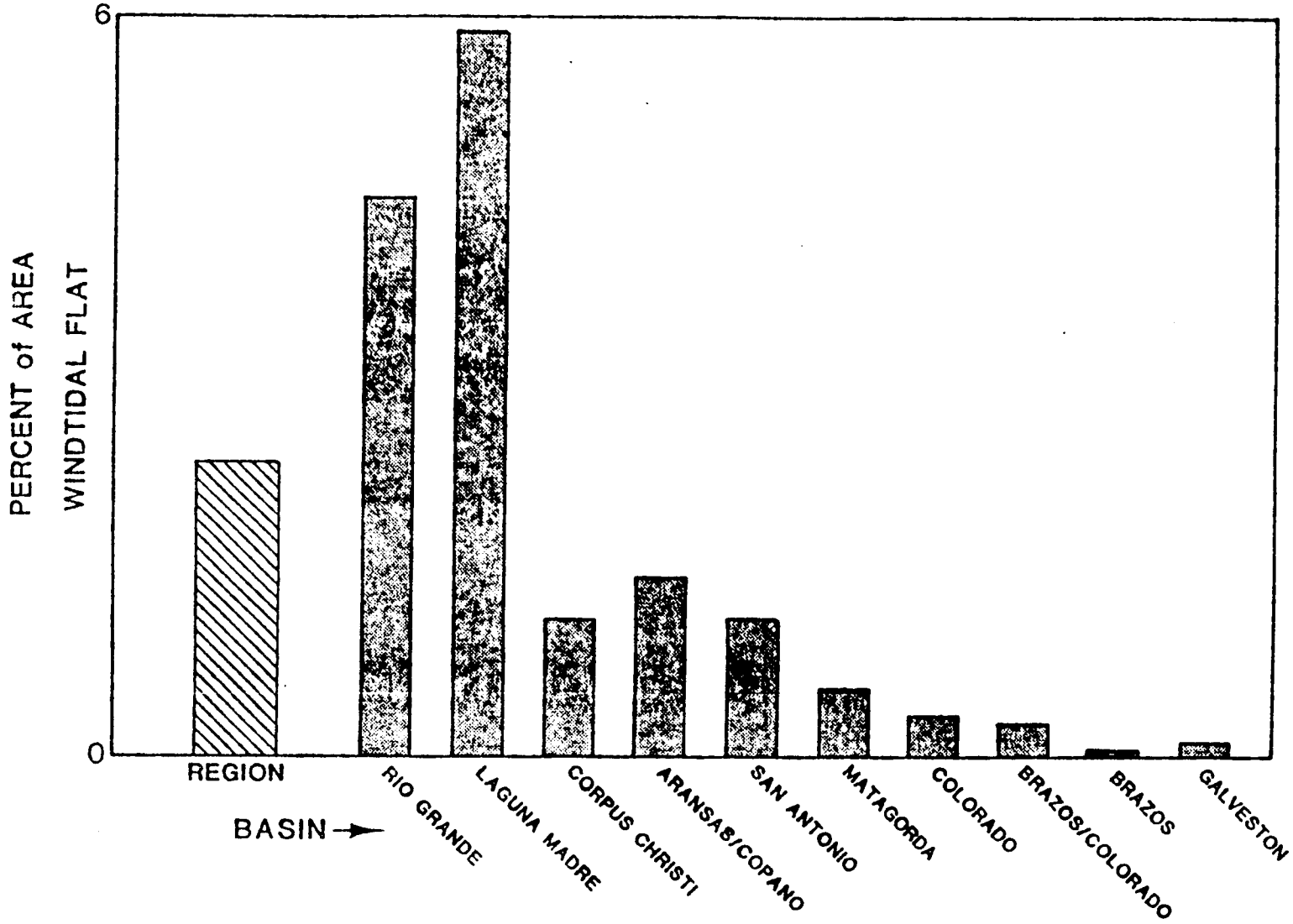


Figure 94. Percent of region and basin that is wind-tidal flat.

and the upland systems in the area known as the Land Cut just south of Baffin Bay.

Wind-tidal flats flood and drain under the combined influence of tide and wind. In sheltered areas, especially near tidal passes, they are subject to tidal forces. They may be flooded once or twice a day, depending upon the stage of the tidal cycle. Their elevation ranges from mean low water to mean high water, a difference of 0.5 m (1.5 ft). Away from tidal forces and in areas where the fetch across a bay is a kilometer or more, wind forces determine the frequency, duration, and depth of flooding (Smith 1977). In the Laguna Madre, the elevation of wind-tidal flats ranges from mean low water to 1.6 m (5 ft) above mean sea level. Duration of flooding varies widely. Higher elevations may be flooded only a few days each year; mid elevations may be flooded a few times a month to several times a week; and the lowest portions may be flooded daily. The rate of water rise (or fall) can be rapid on the flat; Collier and Hedgpeth (1950) reported changes as great as 0.5 m (1.5 ft) less than two hours following frontal passage. Because land slope in wind-tidal flats is very low, a rise of just a few centimeters may result in the inundation of areas hundreds of meters wide.

Sand flats and mud flats differ in sediment type and composition. The differences result from tidal-flat hydrology and the sources of the sediment that is carried into the habitat. Mud flats are located in low-energy environments--away from strong, regular tidal influence and wave action. Sediments transported to them are silts and clays. In many places they are located at slightly higher elevations than sand flats. Mud flats are often

associated with intertidal marshes and lie seaward of the marsh boundary. Larger marsh areas may have small mud flats within them.

Sand flats are located in higher energy environments than mud flats and are common near tidal passes, near channels, and at low elevations where they are subject to frequent wind-tidal flooding. The higher current energy allows more sand to be transported to sand flats than to mud flats.

Wind-tidal flats receive most of their seciment through hydraulic transport, but those on the bay side of barrier islands may receive sediment directly from washovers by eolian transport (Shepard and Rusnak 1957). The wind-tidal flats on the mainland side of the Laguna Madre receive part of their sand through direct eolian transport from the barrier habitat.

When submerged, the wind-tidal flat habitat looks like shallow bay and contains many of the same nekton species. When it has drained, the flat looks like a large expanse of bare sand or mud with few signs of life other than wading birds and shorebirds. Many invertebrates live in the sediments, however, and larger invertebrates such as fiddler crabs may be present on the surface.

The environments within the sediment of mud flats differ markedly from those within sand flat sediment. Because they consist of coarser sediments, sand flats have more interstitial water space and circulation than mud flats. Mud flat sediments usually contain a higher proportion of organic matter and decomposer microorganisms than sand flats. As a result all but the top centimeter is anoxic in mud flat sediments; the anoxic layer is at a deeper level in sand flat sediments. Harsh anoxic conditions limit the species that inhabit the deeper portions of the mud flat (Peterson and Peterson 1979).

Mud flats often develop layers of blue-green algae on their surface. The mats look much like the surrounding sediment, but thin layers can be peeled off. Algal mats have very high primary productivities and harbor an entire system of producers and consumers.

Wind-tidal flats are areas of environmental extremes and rapid change. In the Laguna Madre, hypersaline water in small depressions on the flats may evaporate and cause carbonates and sulfates to precipitate on the sediment surface (Pulich 1980). Hypersaline water, with a decreased specific heat, may reach temperatures above 40 degrees C. A severe cold front may trigger rainfall, reducing water salinity to nearly zero; air temperature may drop 20 degrees C with frontal passage, and water temperature in shallow areas may be near freezing in a few hours.

System operation. Primary production in wind-tidal flats is converted into benthic organism biomass which supports shorebirds, bottom-feeding fish, and invertebrates that periodically inhabit the area. Peterson and Peterson (1979) showed that intertidal flat benthic production in North Carolina was based upon organic matter imported from other estuarine systems. Not all wind-tidal flats are dependent on imported organic matter, however. Joint (1978) offered an example of a frequently flooded mud flat in the United Kingdom that depended upon autochthonous production. The ratio of imported organic matter to autochthonous production in Texas wind-tidal flats is unknown. Nevertheless, water flow governs the import of inorganic nutrients, the import of organic material (probably used by consumer species), and the ability of large aquatic consumers to enter the area to feed. Therefore tidal energy and wind energy are the driving forces for this habitat.

Benthic infauna inhabit the more regularly inundated parts of wind-tidal flats, where there is a large supply of organic matter from nearby marshes and seagrass beds and from producers within the habitat (Brogden 1977). Carbon levels in wind-tidal flats are variable, but the organic carbon content of algal flats has been found to be high: 1.5 percent carbon by dry weight (Volkman and Oppenheimer 1962). It is likely that the degree to which a wind-tidal flat serves as a benthic biomass production site depends on its frequency of inundation and possibly on the supply of importable organic material.

Primary production in the wind-tidal flat is provided by algae in the water column and on the sediment surface. Pulich (1980) noted the presence of drift algae in the Laguna Madre; these forms occur on the more frequently flooded portions of the flats. Phytoplankton are present in the floodwaters of the habitat. Joint (1978) measured annual phytoplankton productivity in a mud flat in the United Kingdom at 82 g of carbon per sq m per year. Clear waters for good light penetration and the exchange of nutrients between wind-tidal flat sediments and the water column probably result in comparable phytoplankton productivity in Texas. Algal flats are also important wind-tidal flat producers. Sorensen and Conover (1962) measured productivities of 5.0 gm of oxygen per sq m per day in algal mats near Port Aransas, Texas; Brogden (1977) estimated sand flat productivity at 1.0 g carbon per sq m per day for sand flats on the edge of Mustang Island and North Padre Island.

Nutrient dynamics on Texas wind-tidal flats have received little study. It is likely that the nutrient cycle is as complicated as that postulated by Ramm and Bella (1974), with many kinds of microorganisms oxidizing and reducing organic and inorganic compounds. Arenas and de la Lanza (1981) found

that the drying of sediment on exposed flats in Mexico accelerated the release of phosphorus and probably the recycling of other nutrients to producers.

Nitrogen is usually considered to be the limiting nutrient in Texas estuarine systems (Davis 1973); however, Gotto et al. (1981) measured high levels of nitrogen fixation (41 kg nitrogen per hectare per year) in wind-tidal flat algal mats. Because of the nitrogen availability and large store of phosphorus in the sediments it is unlikely that nutrients limit productivity on wind-tidal flats.

Environmental stresses on the wind-tidal flat probably limit its productivity more than any other factor. Sediment moisture, salinity, temperature, and oxygen levels are all interrelated, especially in areas of infrequent inundation. As water evaporates in upper sediment layers under the summer sun, temperature rises, salinity increases, and oxygen concentration decreases because of decreased exchange with the atmosphere. Sorenson and Conover (1962) reported temperature ranges of 0 to 70 deg C and salinity ranges of 0 to 200 ppt for algal mats in the Laguna Madre. Oppenheimer and Ward (1963) noted that in periods of drying, inorganic materials including salts traveled up from deeper strata by capillary action; when the flat was reinundated, salinities were further increased.

When they are submerged, shallow tidal flats are still subjected to extremes of temperature, salinity, and oxygen. High salinities require major osmoregulatory energy expenditure by producers and consumers. At very high salinities chemical ion imbalances may occur because of differential precipitation (Copeland 1967). Large algal mats may supersaturate the water with oxygen during the day; at night algal mat respiration may be so high that

nearly all oxygen is removed from the water column over the mat (Odum and Wilson 1962).

Welsh (1980) observed a coupling of marshes and mud flats on Long Island Sound. The mud flats trapped nutrients lost by the marsh and returned them to the marsh; they also trapped nutrients from the channel and sent them to the marsh. Little information is available to determine whether this is an operational mechanism for the Texas Barrier Island Region's wind-tidal flats, but Pulich (1980) noted that nutrient cycling in the Laguna Madre was a more closed process than in other bays.

Peterson and Peterson (1979) divided the wind-tidal flat consumer groups into benthic epifauna, benthic infauna, and mobile epibenthos. The benthic infauna could be further divided into deposit feeders, suspension feeders, scavengers, grazers, herbivores, and combinations of these groups (Broom 1982). Pulich et al. (1984) observed that the most prevalent consumers on drained Laguna Madre wind-tidal flats were insects, particularly beetles. During flooding, fish and larger invertebrates such as blue crabs move onto the flats to feed on the benthic species.

Flora and fauna. Benthic algal mats are predominantly *Lyngbya confervoides*, a filamentous blue-green alga (Pulich 1980). Other blue-green algae include *Oscillatoria* sp., *Microcoleus* sp., *Schizothrix* sp., *Phormidium* sp., and *Anacystis* sp. (Oppenheimer and Gordon 1972). Drift algae include the green alga *Acetabularia crenulata* and the red algae *Jania capillacea*, *Gracilaria* sp., *Laurencia poieta*, and *Chondria* sp. (Pulich 1980). Diatoms found in sand flat sediment include *Nitzschia* sp., *Mastogloia* sp., *Navicula* sp., and *Diplonesis* (Oppenheimer and Gordon 1972).

Large numbers of bacteria, nematodes, copepods, amphipods, and ciliates live within the mud flat sediment. Larger consumer species on both mud flats and sand flats include the razor clam (Tagelus plebeius and Ensis minor), dwarf surf clam (Mulinia lateralis), southern quahog (Mercenaria campechiensis), and ribbon worm (Cerebratulus lacteus). Predatory mollusks that feed on some of these species include the whelk (Busycon contrarium), oyster drill (Thais haemastoma); and moon snail (Polinices duplicatus). Many benthic worms live in the sediment of mud flats; these include the parchment worm (Chaetopterus variopedatus), lugworm (Arenicola cristata), and polychaetes (Clymennella torquata, Neanthes succinea, Capitella capitata, and Diopatra cuprea). Larger intertidal species include the fiddler crabs (Uca sp.), hermit crabs (Clibanarius vittatus and Pagurus pollicaris), mud crabs (Rithropanopeus harrisii and Panopeus herbstii), and mud shrimp (Callianassa jamaicense louisianensis) (Oppenheimer and Gordon 1972; Fotheringham and Brunenmeister 1975).

Large aquatic consumers on the wind-tidal flat include the striped mullet (Mugil cephalus), shrimp (Penaeus spp.), sheepshead minnow (Cyprinodon variegatus), killifish (Fundulus similis), silversides (Menidia beryllina), blue crab (Callinectes sapidus), and pinfish (Lagodon rhomboides) (Jones 1965; Moore 1974; Case and Wimer 1977).

Top consumers include spotted trout (Cynoscion nebulosus), redfish (Sciaenops ocellata), and black drum (Pogonias cromis) (Hoese 1965). Wading and shorebirds are frequent predators; the great blue heron (Ardea herodias) and reddish egret (Dichromanassa rufescens) were abundant in a survey in the Corpus Christi Bay area (Kier and Fruh 1977).

Adjacent systems and flows. Nearly 38 percent of the habitats adjacent to wind-tidal flat are range; 15.2 percent are barrier habitats, 6.4 percent are subaerial spoil, and 4.4 percent are cropland. Sediment and terrestrial species are the main system components exchanged by these habitats. Materials exchanged with spoil habitats depend upon the age of the spoil deposits and the frequency of inundation by wind-tide.

Bay constitutes 17 percent of the adjacent habitats; 12.7 percent are salt and brackish marsh, and 3.9 percent are grassflat. These habitats exchange water, inorganic nutrients, organic material, and aquatic species with wind-tidal flats.

Economic uses. Use of wind-tidal flats is restricted. A large portion of the wind-tidal flats in Texas are owned by the state. In the Laguna Madre basin many of the areas not claimed by the state are owned by a few private landowners with large holdings.

Significant oil and gas deposits are found at depth under some wind-tidal flats. The major use of the flats is for access to well sites for drilling rigs and service equipment. Most access is by dredged channel. Spoil is usually placed on the wind-tidal flat adjacent to the channel.

Impacts of man's activities. Dredging and spoil placement are the main activities on wind-tidal flats. Peterson and Peterson (1979) concluded that recolonization after perturbation in wind-tidal flats is rapid, although at first it is restricted to opportunistic species that prepare the upper sediment layers for later residents. Deeper layers are anoxic and require bioturbation before large-scale recolonization commences. Peterson and Peterson (1979) recommended that dredging on wind-tidal flats be conducted in winter to minimize impacts on the biota. Since winter conditions in Texas

Barrier Island Region wind-tidal flats are milder than in the East Coast area studied by Peterson and Peterson, this recommendation may not be applicable.

Channel dredging and spoil placement may produce changes in wind-tidal flat hydrology. The direction from which floodwaters ebb and flow may be altered, areas may be blocked from receiving frequent wind-tidal flow, or infrequently inundated areas may become more regularly flooded. Without site-specific information, changes in hydrologic patterns cannot be generalized.

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