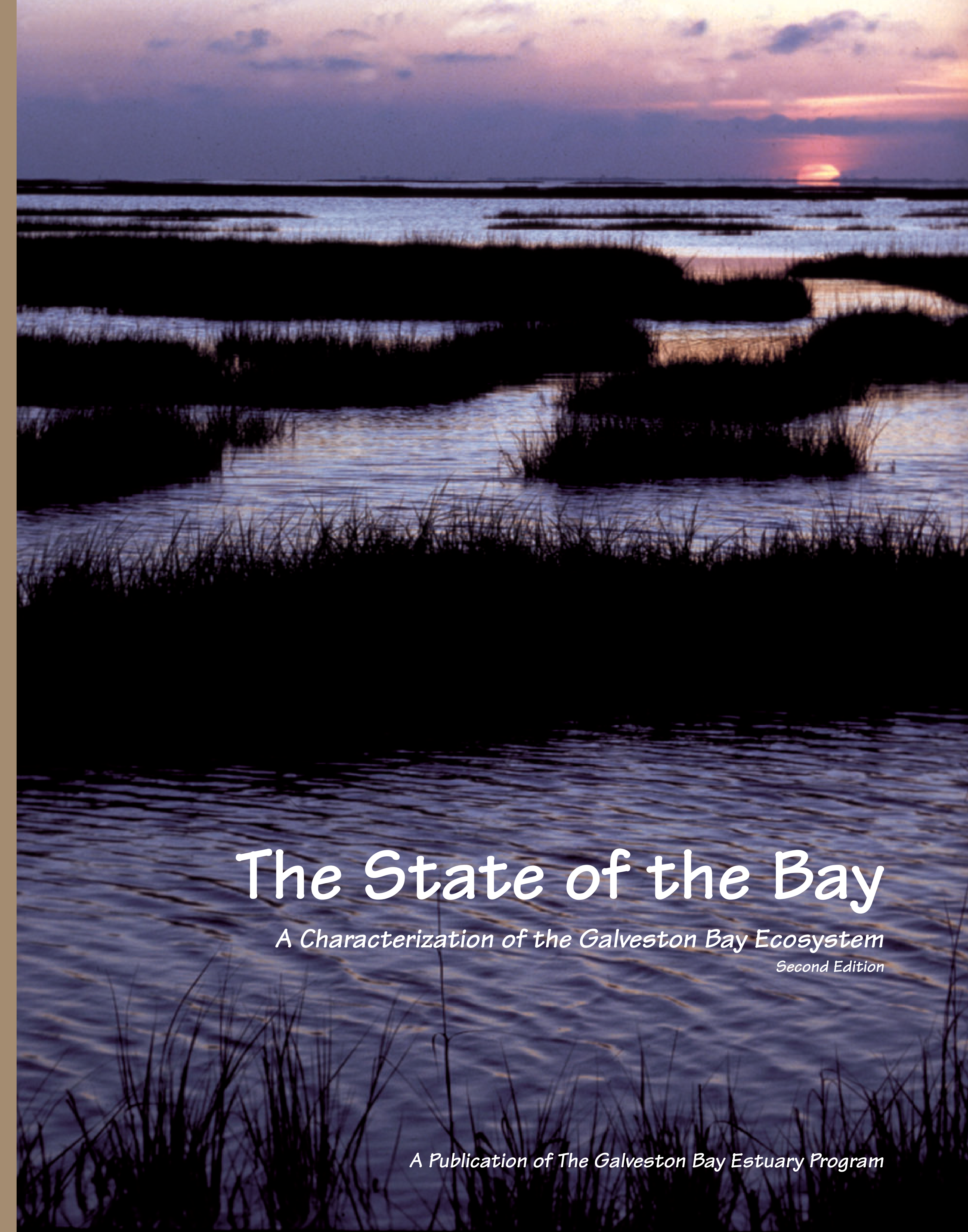
Preserving Galveston Bay for generations to come ....

CTF-012

GBEP T-7

The State of the Bay • A Characterization of the Galveston Bay Ecosystem • Second Edition

Lester and Gonzalez



The State of the Bay

A Characterization of the Galveston Bay Ecosystem

Second Edition

A Publication of The Galveston Bay Estuary Program

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The Galveston Bay Estuary Program (GBEP) Publication Series

The GBEP publication series was established in 1990 under the Galveston Bay National Estuary Program (GBNEP). The first set of publications, related during the planning phase of the Program, ran through 1995. These publicatio0ns, labeled GBNEP 1 through GBNEP 50, were characterization reports used for development of *The Galveston Bay Plan.*

The GBEP is continuing the publication series during implementation of *The Plan*. The purpose of the series is to relay information gathered during implementation. This set of the series is ongoing and is being labeled GBEP T. The first GBEP Technical publication was published in June 1997: *Proceedings, State of the Bay Symposium, III, January 10-11, 1997*; TCEQ document number CTF-07.

The State of the Bay: A Charactertization of the Galveston Bay Ecosystem, Second Edition document is the seventh in the new set. It is labeled GBEP T-7 with a TCEQ publication number of AS-186/02.

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Foreword

The Galveston Bay Estuary Program

The Galveston Bay Estuary Program, a program of the Texas Commission on Environmental Quality (TCEQ), is part of a network of twenty-eight National Estuary Programs (NEP) in the United States working with local stakeholders to restore and protect estuaries. The NEP was established under Section 320 of the Water Quality Act of 1987, and has become a model program for involving stakeholders in consensus-based resource management. In the Act, the administrator of the U. S. Environmental Protection Agency (EPA) is authorized to convene Management Conferences to develop Comprehensive Conservation and Management Plans (CCMPs) for estuaries of national significance that are threatened by pollution, development or overuse.

Initiated by local citizens, nominated by the Governor of Texas, and approved by Congress, the Galveston Bay *National* Estuary Program was established in 1989. Federal and state funding was provided by the U. S. Environmental Protection Agency at 75 percent and the Texas Commission on Environmental Quality at 25 percent. Over a five-year period, the GBNEP worked with the Management Conference, a set of committees composed of stakeholders representing state and federal agencies, local governments, business and industry, academia, environmental organizations, commercial and recreational users, as well as the general public. This group identified the Bay's priority problems, conducted scientific studies to characterize the problems; and drafted Galveston Bay's Comprehensive Conservation and Management Plan (CCMP) - *The Galveston Bay Plan (The Plan)*. *The Plan* identifies Galveston Bay's resource management needs and sets out a mechanism to identify priorities and develop partnerships to meet these needs over 20 years. The commitment of those who drafted *The Plan* was substantial.

> "No environmental program in the history of the state has involved citizens and stakeholders more directly in environmental problem solving. Working in a collaborative fashion, over 220 individuals helped to create *The Galveston Bay Plan*. It took three phases over a five year period."
>
> — The Galveston Bay Plan, *Executive Summary*

The Galveston Bay Plan was approved in 1995 and the program shifted from planning (a majority federally funded effort) to implementation (a primarily state and local funded effort). The word *National* was dropped from the program name and it became the Galveston Bay Estuary Program (GBEP). The GBEP functions to track, coordinate, and facilitate implementation. Program activities are advised by a 41-member body called the Galveston Bay Council, its subcommittees, and a variety of ad-hoc project-oriented task forces. The subcommittee structure parallels the organization of *The Plan*: natural resource uses, water and sediment quality, public participation and education, research, monitoring, and consistency review. Building on the momentum of *Plan* development, consensus among a variety of stakeholders continues to be the key to successful implementation.

Some of the material presented in this doument was developed by sources unrelated to the TCEQ, and therefore such material contained herein may not reflect the views and policies of the TCEQ.

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Texas Natural Resource Conservation Commission

Texas Commission on Environmental Quality

Same Agency, New Name! (on Sept. 1, 2002)

www.tnrcc.state.tx.us/name_change.html

Galveston Bay Council Representation

The Council is composed of 41 members representing the following:

Type of Organization	Interest Represented
Federal Agencies:	Environmental Protection Agency
	National Marine Fisheries Service
	U.S. Coast Guard
	U.S. Army Corps of Engineers
	U.S. Fish and Wildlife Service
	U.S. Geological Survey
	USDA – Natural Resources Conservation Service
State Agencies:	Texas Department of Agriculture
	Texas General Land Office
	Texas Department of Health
	Texas Department of Transportation
	Texas Commission on Environmental Quality
	Texas Parks & Wildlife Department
	Texas Railroad Commission
	Texas Soil & Water Conservation Board
	Texas Water Development Board
Regional/Local Governments:	Gulf Coast Waste Disposal Authority
	Houston-Galveston Area Council
	Port of Houston Authority
	City of Houston
	Large Local Governments (populations >500,000)
	Medium Local Governments (populations 25,000 — 500,000)
	Small Local Governments (populations <25,000)
	Trinity River Authority
	San Jacinto River Authority
Environmental/Citizen's Groups:	Galveston Bay Foundation
	Gulf Coast Conservation Association
	Citizens-at-Large
	League of Women Voters
	Low-income Community Representatives
	Minority Representatives
	Other Conservation Organizations
Private Sector:	Greater Houston Partnership
	Utilities
	Galveston County Chambers of Commerce
	Industry
	East Harris County Manufacturer's Association
	Marinas
	Commercial Fisheries
Research/Academia:	Major Universities
	Texas Sea Grant College Program

Galveston Bay Council

Jim Kachtick, Chair (1995-1997)
Greater Houston Partnership

Glenda Calloway, Chair (1997-1999)
Galveston Bay Foundation

Kerry Whelan, Chair (1999-2001)
Reliant Energy

DeGraff Adams, Vice Chair (2001-present)
Coastal Conservation Association

***Natural Resource Uses Subcommittee**

Bill Jackson, Chair
National Marine Fisheries Service

Will Roach, Vice Chair
United States Fish and Wildlife Service

***Water and Sediment Quality Subcommittee**

Carl Masterson, Chair
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Chuck Wemple, Vice Chair
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***Research Subcommitee**

Ron Morehead, Chair
Texas Chemical Council

Jim Lester, Vice Chair
Environmental Institute of Houston

* Subcommittee chair and vice chair during development of this report

Program Director

Helen Drummond

Contents

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In two areas, history and physical processes, the editors acknowledged their shortcomings and solicited help on revision from close associates expert in those areas. Alecya Gallaway wrote and edited Chapter 3 and provided historical photos and timelines. Dr. Theron Sage wrote and edited Chapter 5 and reviewed and contributed to Chapter 6.

On many issues of content and accuracy, we sought the knowledge and opinions of experts in other organizations. Jim Rivers, Texas Parks and Wildlife Department (TPWD), provided data on fishing and hunting license sales for Chapter 4. Freshwater inflow data and analyses for Chapter 5 were provided by Gary Powell, Ruben Solis and Zhenwen Jia, Texas Water Development Board. Charlie Berger of the U.S. Army Corps of Engineers Galveston District supplied Galveston Bay current models used in Chapter 5. Steve Smith, Linda Broach, Raphael Calvino and Meredith Worthen of the Texas Natural Resources Conservation Commission (TNRCC) provided photos of and clarification on water and sediment monitoring data and methodologies for Chapter 6. George Ward, University of Texas at Austin, graciously shared his knowledge about the information acquired on water and sediment quality for the first State of the Bay volume. Guy Grossman, Texas Railroad Commission, answered questions about produced water from oil wells. Geoffrey Matthews of the National Marine Fisheries Service and Jarrett Woodrow of TPWD provided data on marsh restoration projects. Lance Robinson, Kurtis Schlict and other staff members with the TPWD Seabrook Lab provided information, reviewed, and contributed to Chapter 8. Additionally, Larry McEachron and Barbara Gregg, TPWD, provided data for Chapter 8. Phil Glass of the U.S. Fish and Wildlife Service provided data from nesting surveys of coastal colonial water birds. Bob McFarlane provided information and analytical results on bird species abundance. Tom Minello, Jim Nance and Pete Sheridan of National Marine Fisheries Service shared their information on sources of data about coastal wetlands habitat and associated species. Dr. Andre Landy, Texas A&M University at Galveston provided information on the abundance of sea turtles. Gary Heideman, Kate Hendricks, Lisa Marengo, Michael Ordner, Norman Rice, Jerry Ward and Kirk Wiles of the Texas Department of Health provided data, current information and analyses on public health aspects of seafood harvesting and contact recreation.

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Preface

As a nation, our focus of concern for conservation of nature is shifting to include the oceans. The coastal zone where the land meets the ocean is an area of critical importance to both terrestrial and marine environments. The Houston-Galveston region illustrates well the nature of society's relationship with coastal systems.

Coastlines have developed the highest densities of people and industry in this country. Houston grew into a global hub for the petrochemical and energy businesses because of its status as a port with transportation links to the world. Shipping encouraged the growth of population and industry around Galveston Bay. During this development, the bay provided utilitarian services, such as seafood, and non-utilitarian value, such as recreational opportunities. Some types of development make it difficult to maintain the services and opportunities that the Bay has historically provided.

The past and current modifications of Galveston Bay and its tributaries according to the needs of the businesses and people who reside near them generate great challenges. People still depend on the bay for their livelihood and quality of life. Some of the ways the bay has been used in the past are incompatible with some of the features many currently value. Conflicts over uses of the bay and its watershed provide justification for study and management of this important resource. The Galveston Bay Estuary Program is a leader in the efforts to understand and manage well the array of resources and uses represented in Galveston Bay.

This document is about the nature and history of the Galveston Bay system, the findings of studies on Galveston Bay and its watershed, and the management actions based on those findings. We have written about the whole bay and the diverse information that is required to understand it as a system. Of course, boundaries had to be established and limits set or the volume would have expanded to infinity. You may disagree with what was included and what was omitted. Please make your suggestions known to the Galveston Bay Estuary Program. The story of Galveston Bay is a continuing one and this document is certainly not the last one to be written on the status and trends of its properties.

As in the first volume, the scientific information is placed in the context of historical resource use and modern social and economic features of the Galveston Bay watershed. While most of our scientific information covers only a brief snapshot of time extending back about 30 years, man has been modifying Galveston Bay for much longer. The bay as a geological feature of the Texas coast and an ecosystem extends back far beyond the presence of humans in southeast Texas.

No plan guided the historical use of the bay and its watershed, but now we have the Galveston Bay Plan based on the accumulated knowledge of the studies represented here and the wisdom of all of the people who participated in the crafting of that plan. Part of this document is about the validity of that plan and the progress achieved under it. We hope you agree that protection of this resource has been enhanced and progress has been made toward restoring the vitality of the ecosystem through the efforts of the Galveston Bay Estuary Program.

Clearly our knowledge is incomplete and our management approaches could be improved. Hopefully this volume will spark new studies and actions for the betterment of the bay. Perhaps it will also generate new commitments to the work required to preserve Galveston Bay amidst conflicting uses.

Everyone who reads this work is in some way connected to the bay and benefits from its resources. We hope after reading this volume you have a better appreciation of the intricacies and value of Galveston Bay.

Jim Lester
Lisa Gonzalez

Chapter One

Assessing the State of Galveston Bay

Solutions to environmental problems involving relationships between human society and its ambient environment are seldom "strictly scientific" –human culture, and all it implies, influences the way in which the problem is defined and science is used.

— Lynton K. Caldwell, Science Assumptions and Misplaced Certainty in Natural Resources and Environmental Problem Solving, 1996

The Galveston Bay system is a complex ecosystem and a valuable resource for the state and the nation because it provides natural resources, ecological services, recreational opportunities, transportation links, economic benefits and aesthetic rewards. The bay is valued by many people for attributes that cannot be replicated or replaced by human creations. However, the growing number of users and uses and the intended and unintended impacts on the system strain the ability of Galveston Bay to meet historical needs and provide traditional rewards.

The goal of protection and management of the bay is to provide for the sustainable use of its resources while maintaining the quality of its assets. The information summarized in this volume was gathered for a single purpose: to improve our management of Galveston Bay. Establishing this foundation for management relies on defining the status of bay resources and indicators of quality, identifying their trend over time, and determining probable causes for any trends emerging as concerns. Interpreting monitoring information depends on knowledge of the processes and connections that tie all of the components of the bay system together.

The Galveston Bay Plan (GBNEP, 1994a) was formulated to set objectives for management efforts and to recommend approaches that would reduce the potential for future problems and user conflicts. The management challenges for Galveston Bay were identified in the assessment of status and trends of Galveston Bay parameters. This chapter addresses the significance of the estuary program process and the resulting findings. First, a brief overview is presented concerning the participatory process. Second, seventeen priority problems that form the backbone of *The Galveston Bay Plan* are explained and progress on them is described. The assessment is based on the first five-year review of Plan implementation conducted by the Galveston Bay Estuary Program (GBEP, 2001).

Management Expectations

Expert opinion alone would have failed to serve managers well in solving bay problems. As *The Galveston Bay Plan* was developed over a five-year period, prevailing scientific opinions of estuarine problems were re-cast in light of new studies and input from bay stakeholders. State and federal agencies, local governments, business and industry, academia, environmental organizations, commercial and recreational users, as well as the general public joined to: identify the Bay's priority problems; conduct scientific studies to characterize the problems; and draft Galveston Bay's Comprehensive Conservation and Management Plan (CCMP) - *The Galveston Bay Plan (The Plan)*. *The Plan* identifies Galveston Bay's resource management needs and sets out a mechanism to identify priorities and develop partnerships to meet these needs over 20 years. The commitment of those who drafted *The Plan* was substantial. Recognizing the important role of bay users in addition to scientists, the GBEP continues this participatory process in implementation. An advisory board, the Galveston Bay Council, consists of representatives similar to those involved in the initial planning process, and meets quarterly to guide the implementation efforts that are designed to address the bay's management needs.

What are Galveston Bay's management needs? Seventeen issues needing attention emerged from the bay characterization process. As characteristics of any ecosystem, these management concerns can never be completely separated from one another. For example, non-point sources of pollution contribute to both habitat degradation and toxic contamination of sediments. These interconnections suggest that actions to solve the bay's problems also be undertaken in the context of an integrated, watershed-level management program.

Seventeen Priorities

The following issues were distilled and ranked by the Galveston Bay National Estuary Program as it deliberated on both results of the technical work, and the historical and current management efforts of public agencies. These issues constitute the Galveston Bay *Priority Problems List.* The following discussion summarizes the problem and progress that has been made since the implementation of *The Galveston Bay Plan* began.

1. *Vital Galveston Bay habitats including wetlands have been lost or reduced in value by a range of human activities, threatening the bay's future sustained productivity (Chapter 7).*

White et al. (1993) described wetland losses in the Galveston Bay estuarine system from the 1950s to 1989. Pulich and Hinson (1996) classified the region's vegetation types and documented a continuing decline in wetland acreage. The leading causes of wetland loss have been subsidence from groundwater withdrawal and conversion to upland range. In comparison to wetlands, a far greater proportion of the bay's historical submerged aquatic vegetation beds has been lost since the 1950s, due to a complex and interactive group of causes, which includes dredging, subsidence, hurricane effects, shoreline development, and boat traffic (Pulich and White, 1991; TPWD, 1999).

Encouragingly, the rate of loss has decreased over time. Groundwater withdrawal is regulated and subsidence has slowed greatly. Shell dredging for use in construction and industrial raw materials was banned in 1969 and navigational dredging began to avoid open water disposal of dredged materials in the 1990's. Wetland conversion requires a permit and a mitigation plan to compensate for wetlands lost.

Habitat restoration and rehabilitation programs have been implemented to increase the acreage of wetlands and submerged aquatic vegetation in the Galveston Bay system. Over 1,000 acres of shoreline on the bay and in tributaries have been subject to marsh rehabilitation efforts. Efforts to rehabilitate seagrass habitat have achieved some success in West Bay. Dredged material is being used for creation of marsh and colonial nesting bird habitat. The current widening and deepening of the Houston Ship Channel will yield 4,500 acres of new land in and around the bay. While only a small percentage of the habitat lost has been restored or fully rehabilitated, these efforts are steps in the right direction.

Many acres of watershed habitat have been preserved through land acquisition by agencies and conservation easements on private land. Protection of valuable remnant habitats has exhibited increasing activity. Some of the most important examples of land conservation around Galveston Bay include the:

- designation of the Christmas Bay and Armand Bayou Coastal Preserves,
- acquisition of land parcels such as Pierce Marsh obtained by the Galveston Bay Foundation, bird-nesting areas acquired by the Audubon Society, marsh corridor obtained by Scenic Galveston and the Texas Nature Conservancy's prairie preserve at Moses Lake.

Several inventories of potential conservation sites have been compiled, including the Habitat Conservation Blueprint by the Galveston Bay Foundation. Acquisition of wetlands habitat is facilitated by the Coastal Wetlands Acquisition Plan for Texas (Calnan, 1995), which identifies and ranks coastal wetlands by region for acquisition. Management strategies for sustaining the habitat value of these parcels are being developed.

2. *Contaminated runoff from non-point sources degrades the water and sediments of some bay tributaries and near-shore areas (Chapter 6).*

For many pollutants of concern, loadings to Galveston Bay are dominated by nonpoint sources of pollutants, transported by runoff from the surface of the land to the bay and its tributaries (Newell et al., 1992). Nonpoint source (NPS) pollution remains the top water quality problem in Galveston Bay, as well as nation-wide. The pattern and impact of NPS pollution is not the same as that of point source pollution. NPS pollution is a highly variable loading because it is driven by intermittent rainfall. The greatest loading occurs during the first flush of stormwater when the surface flow picks up all the pollutants deposited on the ground since the last rainfall. The impact is acute and at times severe where the highest loadings enter the system, but it is usually short term. Indications are that non-point sources of pollutants have steadily increased to the present day.

Non-point loading to the estuary for total suspended solids, fecal coliform bacteria, total phosphorus, and oil and grease is greater than point source loadings. Some 90 percent of the oil and grease loading originate in sub-watersheds with high-density urban land uses. Much of this type of pollutant flows from the surfaces of roadways.

The Texas Department of Transportation is incorporating NPS minimization in roadway design and promoting demonstration projects in the Galveston Bay region. The diffuse sources of these pollutants, the need for widespread social and cultural changes by residents of the watershed, and the intractability and cost of retrofitting urban stormwater infrastructures pose challenges.

Although the diffuse nature of NPS makes it very difficult to manage, the Texas Pollutant Discharge Elimination System (TPDES) Stormwater Program administered at the state level by the Texas Natural Resource Conservation Commission (TNRCC), is beginning to address it. Phase I of the program is being implemented, requiring cities with a population of over 100,000 to develop and implement storm water management plans. These plans must address six minimum control measures, including: public education and outreach, public participation/involvement, illicit discharge detection and elimination, construction site runoff control, post-construction runoff control, and pollution prevention/good housekeeping.

The federal rules for Phase II, requiring similar programs for cities with populations below 100,000, but greater that 10,000, were finalized in 1999. The TNRCC will be developing state rules to implement Phase II of the program. In the Galveston Bay region, a Stormwater Management Joint Task Force has been working on the issues and has produced a Construction Handbook and Stormwater Quality Management Guidance Manual. GBEP is developing a model stormwater management plan, which will be implemented first in Pearland, Texas.

3. *Raw or partially treated sewage and industrial waste enters Galveston Bay due to design and operational problems, especially during rainfall runoff (Chapters 6 and 9).*

As cities in the Galveston Bay watershed have grown, their aging sewage collection systems have suffered from subsidence, corrosion, and larger-than-design flows. As a result, leaks occur and allow entry of stormwater during wet periods, exceeding the capacity of lines, lift stations, and treatment plants. The result is sewage bypasses to the bay's tributary waters. Conversely, sewage can also leak out of broken lines and flow to groundwater or the storm sewer system (Jensen et al., 1991).

In response to a U.S. Environmental Protection Agency (EPA) initiative, the City of Houston undertook a major construction project to improve and expand the city's underground wastewater collection system. It has now completed a 1.2 billion dollar collection system rehabilitation. Other cities throughout the Galveston Bay watershed have initiated evaluations of their collection systems and have completed rehabilitation plans.

The discharges of small utility districts have substantial effects on several urban bayous with flows dominated by wastewater during dry periods. These districts cannot afford the same operation and maintenance cost for their treatment plants as larger utilities. Implementation studies conducted by the GBEP, Harris County Pollution Control, and the Gulf Coast Waste Disposal Authority found that technical assistance provided to these facilities made a difference in reducing waste discharges. A major component in addressing the problems of small utility districts will be the provision of technical assistance.

4. *Future demands for freshwater and alterations to circulation may seriously affect productivity and overall ecosystem health (Chapter 5).*

Continued high productivity of Galveston Bay depends to a great degree on the maintenance of adequate, high-quality fresh water inflow. Fresh water inflows affect circulation and water quality within the estuary. Many species of fish, wildlife, aquatic plants, and shellfish depend on adequate fresh water inflows for survival or reproduction. The partners of the GBEP have increased their efforts to educate the public on these relationships because future water management will demand civic participation in difficult decisions.

A comparison of monthly mean flows prior to

(1941-1969) and after (1972-1987) Lake Livingston Dam construction indicates that peak flows have been cropped and low flows have been increased, and that the timing of peak flows have been delayed slightly. Increasing return flows to the Trinity River and other watersheds have elevated base flow during critical low flow periods. These return flows, in conjunction with inter-basin transfers of water, will likely continue to significantly dampen seasonal flow variations in the future (Solis and Longley, 1993). An analysis of fresh water inflow trends did not identify statistically significant trends indicative of a reduction of fresh water inflow volume from the Trinity River, or to the estuary as a whole (see Chapter 5).

The Texas Water Development Board and the Texas Parks and Wildlife Department (TPWD) have worked together to establish estimates of quantitative freshwater inflow needs to the bay. They found that maximum harvest of six representative aquatic species was achieved at 5.2 million-acre feet of inflow per year. However, due to the complexity and dynamics of an estuarine system, further evaluation of the temporal and spatial distribution of these flows is needed. Based on the results of the detailed evaluation, management strategies are being discussed by members of the Galveston Bay Freshwater Inflows Group, working in cooperation with the GBEP and the Region H Water Planning Group. The Region H water management plan, developed under a new statewide watershed management design, includes consideration of the freshwater needs of the Galveston Bay ecosystems.

5. *Certain toxic substances have contaminated water and sediment and may have a negative effect on aquatic life in contaminated areas (Chapter 6).*

Human activity in the bay's watershed produces a complicated array of toxic compounds, many of which are routinely discharged, spilled, or washed into the estuary. Once in the bay, toxicants can cycle back and forth among the water, sediment, and tissues of living organisms.

In water, most of the metals are declining in areas of maximal concentrations, possibly because the concentrations of suspended solids have shown declines. Typically, levels of toxic contaminants in open bay waters are below detection limits.

In sediments, there are elevated contaminant concentrations in regions of runoff, inflow and waste discharges. Overall, metals are declining in navigation channels, however, there are low, relatively stable concentrations of some metals in the open bay segments of the Houston Ship Channel. Although, no criteria have been set by the EPA or TNRCC for sediment quality, the TNRCC is using National Oceanic and Atmospheric Administration (NOAA) guidelines for screening sediment for benthic ecosystem health. Often the array of benthic species is the best indicator of sediment contamination.

In tissues, various studies have measured contaminants in a number of species. In oysters, Wade et al. (1991) reports polynuclear aromatic hydrocarbons (PAHs) in a form suggesting contamination by combustion products (from heavier fuels like diesel). Ultimately, toxic contaminants have effects on the bottom-dwelling community (Carr, 1993; Roach et al., 1993a, 1993b) and on estuarine-dependent species like colonial-nesting birds (Rice and Custer, 1991). Conditions appear to be improving, but problems remain near urban areas, points of surface runoff, waste discharges, and shipping facilities.

Metals and other toxicants remain a problem only in select areas, e.g. the Houston Ship Channel. Levels of polychlorinated biphenyl (PCB), a class of chemicals once used mostly in electrical transformer oil, has declined due to an EPA ban on their manufacture in 1979. Dioxin has since replaced PCB as the bioaccumulant of concern in localized areas around Galveston Bay.

Those regulated segments of water that have not achieved their target criteria for water quality are now or will in the future be subjects of the TNRCC Total Maximum Daily Load (TMDL) Program. A TMDL project studies the pollution problems and allocates loadings of the subject pollutant to stakeholders in the watershed. Summaries of TMDL projects undertaken in the lower Galveston Bay watershed are briefly described below.

Although water quality in the Houston Ship Channel system has improved dramatically since the 1970's, a TMDL project addressing dissolved nickel concentrations in water was conducted. Analyses indicate that nickel criteria are being met in the Houston Ship Channel system. There is some amount of potentially useable loading capacity that remains unallocated at this time (with the exception of Tucker Bayou). The final TMDL report was forwarded to EPA Region 6 for approval in August 2000.

Clear Creek is on the Texas 2000 Clean Water

Act Section 303(d) List for impairments due to pathogens; the legacy pollutant, chlordane; and the volatile organic compounds, dichloroethane, trichloroethane, and carbon disulfide (TNRCC, 2000a). The TMDLs for dichloroethane, trichloroethane, and carbon disulfide were adopted by the TNRCC in February 2001 and forwarded to the EPA for approval. Additionally, the TMDLs addressing chlordane in fish tissue were adopted by the TNRCC in January 2001 and submitted to the EPA for approval. Legacy pollutants are substances that have been banned or severely restricted by the EPA. Therefore, gradual declines in environmental legacy pollutant concentrations are expected to occur as a result of natural attenuation processes.

The upper portion of Galveston Bay and the Houston Ship Channel are on the Texas 2000 Clean Water Act Section 303(d) List for impairments due to elevated levels of dioxin in catfish and blue crab tissue. This TMDL project, initiated in fall 1999, is assessing current conditions to determine the appropriate direction and methods to be used to establish a pollutant load allocation to address the dioxin impairment in these water bodies. The University of Houston is conducting the technical assessment and the Houston-Galveston Area Council (H-GAC) is coordinating the public participation component of this project.

Patrick Bayou is on the Texas 2000 Clean Water Act Section 303(d) List for impairments due to elevated levels of dissolved copper, elevated water temperature, and water and sediment toxicity. This project will address all of the parameters of concern. Unlike other TMDL projects, a consortium of permitted dischargers in the Patrick Bayou area initiated this project. Data analysis and modeling will be completed by the summer 2002.

A statewide project will assess the presence and causes of in-situ toxicity in several Texas waterbodies including sediment toxicity in Vince Bayou located in Harris County. A TNRCC contractor is: 1) compiling and reviewing existing data and information pertaining to toxicity and potential toxicants in the water bodies and watersheds of concern, 2) conducting water quality monitoring and investigations of toxicity to assess the presence and causes of in-situ toxicity, and 3) coordinating and reporting project activities with other state and federal agencies and stakeholders.

The TNRCC is making use of studies done for permit renewal to obtain more information on the discharge, concentration and effects of toxics and nutrients. In one case, permits have been eliminated for an entire category of dischargers. In another, the EPA banned the discharge of produced water from coastal oil wells.

6. *Certain species of marine organisms and birds have shown a declining population trend (Chapter 8).*

Intensive harvest of seafood, combined with habitat losses and contamination of the ecosystem, has resulted in widespread concern over possible species reductions in the Galveston Bay watershed. Analyses of recent data outlined in Chapter 8 confirm that most monitored species exhibit no trend or an upward trend in density, indicating a generally healthy estuarine community. Apparent decline in a few species, particularly blue crab, is a concern. TPWD has addressed concerns about living resources by implementation of strict management regimes, including license buy backs in the inshore shrimp fishery.

Review of old maps of the Texas coast (Quast et al., 1988) indicated an extensive loss of intertidal oyster reefs along the bay's shoreline. Past shell dredging reduced the amount of shell substrate on the bay bottom and may have decreased oyster reefs in some areas. A successful methodology for the restoration of oyster reef using fly ash (a byproduct of coal combustion) pellets has been tested at six locations in Galveston Bay. However, the oyster reef reserve program recommended in The Plan has not yet been implemented.

Estuarine-dependent species analyzed included birds (see Chapter 8). A decreasing population trend was noted for black skimmers and least terns (McFarlane, 2000). These are colonial nesting species, which generally nest on exposed beaches. Two species of tern, royal and sandwich, are apparently increasing, as is the brown pelican. The bird data were particularly difficult to interpret due to the variability of the abundances and the limitations of observations based only on sightings at nesting locations.

Oysters continue to play a significant role in monitoring the health of the bay's living resources. Dr. Sammy Ray, Professor Emeritus at Texas A&M University at Galveston, is using the incidence of a parasitic infection, "dermo," to assess the stress levels of oyster populations. One effect of the recent drought conditions in 1999 and 2000 was to contribute to a higher level of dermo in the populations, especially in lower Galveston Bay.

Populations of some species are impacted by incidental harvest during shrimp trawling and recreational fishing. The installation of Bycatch Reduction Devices (BRD) on trawls could contribute to a greater recovery of these organisms. Both demonstration projects and educational outreach programs on bycatch reduction are supported by the TPWD. One example of the impact of educational programs is the increased popularity of catch and release fishing. The use of Turtle Excluder Devices (TEDs) has begun to impact turtle populations in a positive way, although strandings are still observed.

7. *Shoreline management practices frequently do not address negative environmental consequences to the bay, or the need for environmentally compatible public access to bay resources (Chapter 5 and 7).*

The environmental impact of bulkheads, docks, and revetments may be larger than the actual physical modifications would suggest. Ward (1993) estimated that about 70 miles (10 percent) of the bay shoreline has been either bulkheaded or converted to docks or revetments. Continued development of the shoreline contributes to erosion, increased turbidity, loss of wetlands, increased point and non-point source pollution, and reduced public access to beaches and the shore.

Local governments are working with GBEP and the H-GAC to provide assistance on developing model municipal ordinances to protect valuable shoreline areas and provide guidelines for residential and industrial development. Integrated planning and management efforts are needed to reconcile the activities of improving public access and expanding recreational opportunities with maintaining shoreline integrity. The Coastal Coordination Council is compiling data on public shoreline access along the Texas coast. This will be used to coordinate efforts to provide more public access to public resources like Galveston Bay.

8. *Bay habitats and living resources are impacted by spills of toxic and hazardous materials during storage, handling, and transport (Chapter 6).*

Accidental spills or deliberate dumping of oil and toxic materials affect both aesthetics and ecological functions of Galveston Bay. The concentration of industry, shipping operations and urban development in the watershed puts the bay at risk of spills. Prevention is the key in protecting the bay from these types of impacts with public education and enforcement being integral components.

When these incidents inevitably occur, improved response and cleanup become important. Most spills that occur in the Galveston Bay area are relatively small and involve chemicals that decompose over time. Efforts by the Coast Guard, Texas General Land Office (GLO) and resource agencies to better plan and coordinate spill responses have produced cleanup improvements. These improvements are often based on proactive study and planning. For example, the GLO has characterized the shoreline as it relates to cleanup methodology and relevant agencies have also been proactive in establishing recommended compensation levels based on the volume spilled and ecosystem impacted.

Solid waste disposal is still a problem, but several partnership efforts at solid waste reduction have been implemented. Solid waste reduction is the target of Trash Bash and litter abatement programs by Keep Texas Beautiful and affiliated organizations. Reduction of waste from boaters is the focus of the Boater Waste Discussion Group and Clean Marina Program. At the municipal and community level, NPDES Storm Water programs have reduced debris flowing through the stormwater system to the bay.

9. *Seafood from some areas in Galveston Bay may pose a public health risk to subsistence or recreational catch seafood consumers as a result of the potential presence of toxic chemicals (Chapter 9).*

Maintenance of adequate public health standards for estuarine seafood is important for protection of the general public, and is also critical for the long-term viability of the fishing industry. Fish and shellfish from Galveston Bay are sampled for toxic contaminants, and consumer risks on a non-routine basis. The Texas Department of Health (TDH) in cooperation with the GBEP has recently performed several studies of seafood safety. These provide a comprehensive updated risk assessment of local seafood and will be used to communicate the information to the public.

Contamination of estuarine organisms is most prevalent in areas of elevated pollution levels, such as the upper Houston Ship Channel. An advisory for dioxin has been issued by the TDH to restrict harvest of fish and shellfish for human consumption from the Houston Ship Channel. The TDH also issued a fish consumption advisory for Clear Creek in 2001 due to the presence of three toxic compounds: dichloroethane, trichloroethane and carbon disulfide. This advisory has since been lifted. A study by Brooks et al. (1992) involved analysis of contaminants in five species of seafood from four sites in Galveston Bay. Oysters were generally the most contaminated species. Contaminant levels were generally high at Morgan's Point and decreased to the south. Compounds of concern included PAHs and PCBs. Based on the contaminant values from Galveston Bay, most average consumers would experience no increase in risk. However, risk levels for recreational or subsistence fishermen who eat large quantities of seafood (about ten pounds per month) would exceed the EPA benchmark risk level.

The GBEP and TDH partnered to develop a Seafood Safety Consumption Program. Through this joint effort, standard sampling methodologies have been established for Galveston Bay. In 2001 the TDH completed a comprehensive risk assessment of seafood through the Galveston Bay Complex. Highlights of their findings are presented in Chapter 9.

10. *Illegal connections to storm sewers introduce untreated wastes directly into bay tributaries. (Chapter 6)*

Several bay tributaries, including Buffalo Bayou and White Oak Bayou, have been listed on the Texas 2000 Clean Water Act Section 303(d) List for bacterial contamination. Most of the urbanized streams in the Galveston Bay area are most likely subjected to water quality degradation from sewage sources. The City of Houston conducted a survey that found accidental and intentional connections of sanitary sewage lines to the storm sewers that were responsible for elevated concentrations of fecal coliform bacteria in Buffalo Bayou. A program to identify and eliminate dry-weather illegal connections has also been initiated by the Galveston County Health District. By eliminating these discharges, there was a marked improvement in dry-weather water quality in the bayou, but elevated levels of fecal coliforms remain.

Illegal connections, noted in previous GBEP studies as a source of bacterial contamination in urban bayous, are recognized as a national issue. The significance of this issue is further emphasized by inclusion of requirements to develop illicit connection detection programs in both Phase I and Phase II NPDES Storm Water Programs.

11. *Dissolved oxygen is reduced in certain tributaries and side bays, harming marine life (Chapter 6).*

Dissolved oxygen (DO) is generally satisfactory throughout the bay. However, poorly flushed tributaries are subjected to runoff inflow and waste discharges. The trend since the early 1970s is an increase in DO concentration. Even in the Houston Ship Channel, the DO has been improving, although, the bay's western, urbanized tributaries remain problem areas. These waters receive the bulk of the bay's NPS pollutants in runoff, and have the greatest frequency of fish kills related to oxygen depletion, particularly in areas with poor circulation. Interpretation of DO variation and identification of potential causes of low DO concentration is challenging because the natural system has daily and seasonal variation patterns.

Sensitive areas and areas impacted by nutrients or oxygen-demanding substances are being identified through the 303(d) listing process. The Texas 2000 Clean Water Act Section 303(d) List identifies four waterbodies in the Galveston Bay area impacted by reduced dissolved oxygen levels: Armand Bayou, Dickinson Bayou, Taylor Bayou, and the Texas City Ship Channel. These waterbodies will be the subjects of TMDL projects to characterize the problems, identify causes and allocate loadings to ensure that they meet water quality standards and maintain their designated uses.

12. *About half of the bay is permanently or provisionally closed to the taking of shellfish because of high fecal coliform bacteria levels that may indicate risk to shellfish consumers (Chapter 9).*

The TDH conducts monitoring of oysters for the National Shellfish Sanitation Program on a routine basis. Based on their monitoring, TDH classifies areas of the bay for oyster harvesting. Approximately 300 square miles (200,000 acres) of Galveston Bay are classified by the TDH in one of three categories: conditionally approved, restricted and prohibited. The remainder is approved for public harvest. The prohibited category is the smallest in extent, but is deemed by the TDH to pose a significant risk of disease to shellfish consumers. The risk of disease is not determined directly, but is addressed by measuring concentrations of fecal coliform bacteria as an indicator organism. These bacteria indicate the contamination of waters by wastes from birds or mammals (including humans) that could also contain much more dangerous pathogens, for example those causing typhoid fever. Wet weather runoff is the most significant source of bacteria (Jensen et al., 1991). Based on measurements of fecal coliform bacteria in water and oysters, and by establishing relationships between rainfall runoff and elevated fecal coliforms, classification maps are produced by the TDH and utilized by commercial fishermen and the public to determine where oyster harvest can legally occur.

Changes in classification of harvest areas from 1996 to 2000, based on fecal coliform concentrations in Galveston Bay, indicate some areas of improvement and some areas of degradation (See Chapter 9). Large areas of the bay have changed from restricted to approved and conditionally approved, but some areas have been downgraded from approved to conditionally approved. Resource managers believe that additional monitoring could result in better evaluation of conditions that may open more reefs for harvest.

Some human pathogens are not coliforms, but normal constituents of estuarine ecosystems, e.g. *Vibrio* species.

Vibrio vulnificus is responsible for a small number of deaths and illnesses arising from consumption of raw or partially cooked seafood by people with compromised immune systems or malfunctioning livers. A major outbreak of gastrointestinal illness in 1998 from *Vibrio parahaemolyticus* in Galveston Bay oysters resulted in allocation of additional funds to study the bacteria. A routine monitoring program has been established by TDH for *V. vulnificus* and *V. parahaemolyticus* in oysters.

The TNRCC has incorporated into the Texas Surface Water Quality Standards (30 TAC 307) a recommendation for replacement of the traditional bacterial indicator, fecal coliform, with *Escherichia coli* for freshwater and *Enterococcus sp.* for saltwater for use in contact recreation designations. However, TDH is restricted by federal requirements to the use of fecal

Plant 'til You Drop

The Success of Marsh Restoration in Galveston Bay

State and federal agencies, environmental organizations, local industry, and citizens working together in the fight to restore vital lost habitat in Galveston Bay certainly have the right to brag! An amazing 4,500 acres of marsh habitat have been restored, protected, or created in just the last five years (TPWD, 2001). Since 1980, there have been over 70 separate marsh restorations projects in the Galveston Bay system (Matthews, 1999).

In 1999, the Galveston Bay Foundation and its partners began Marsh Bash (now called Marsh Mania), an event so successful it is now held annually. With the help of over 1,500 volunteers, more than 15 acres of marsh habitat were restored in eight locations around the Bay in the first year alone. Over the past three years, Marsh Mania has restored over 60 acres of marsh in 12 locations around the Bay and has recruited more than 2,600 volunteers to accomplish this effort.

Linda Shead, Executive Director of the Galveston Bay Foundation from 1989 until 2002, emphasizes the importance of restoration, "Marsh restoration is critical for the future health of Galveston Bay ... habitat loss has been identified as the #1 priority problem for the Bay. Without restoration, declines in species that depend on marshes can be expected to continue or even accelerate."

The partnerships created by government agencies and private organization are, in a large part, responsible for the success of marsh restoration around the Bay. The Texas Parks and Wildlife Department, the US Fish and Wildlife Service,Texas General Land Office, the National Marine Fisheries Service and many other organizations have taken part in some of the largest restoration projects in this region. Their restoration efforts on Galveston Island have been outstanding. Projects at Delehide Cove, Jumbile Cove and Galveston Island State Park have contributed significantly to the overall acreage restored and protected in Galveston Bay.

Will Roach is the Texas Coastal Program Coordinator for the US Fish and Wildlife coliform for shellfish consumption designations.

13. *Water and sediments are degraded in and around marinas from boat sewage and introduction of dockside wastes from non-point sources (Chapter 6).*

Raw or partially treated sewage has been discharged directly from boats to estuarine waters due to lack of pump-out facilities and lax enforcement. Boat maintenance activities often result in wastes that wash into the bay with runoff and deliberate dumping of debris like batteries. This may result in high bacterial levels, low dissolved oxygen, and toxic contamination of water and sediment. Contaminant concentrations can be exacerbated by marina construction designs, which limit circulation in boat slip and maintenance areas.

The Clear Lake area has been designated a "zero discharge zone" by the EPA and TNRCC. This designation, which bans the discharge of waste from boaters, was a significant step, but enforcement remains a challenge. This same area is a demonstration site for a Clean Marina Guidebook produced by GBEP and Sea Grant. TPWD, Sea Grant and the GBEP have formed a boater waste discussion group composed of agencies, educators, boaters, and marina operators to coordinate and address education, training and enforcement needs for the Galveston Bay area.

14. *Some bay shorelines are subject to high rates of erosion and loss of stabilizing vegetation due to past subsidence/sea level rise and current human impacts (Chapter 5 and 7).*

Sixty-one percent of Galveston Bay's 232 miles of shoreline is composed of highly productive fringing wetlands. This shoreline is eroding at an average annual rate of 2.4 feet (Paine and Morton, 1991). The erosion is exacerbated by hurricanes, global sea level rise, historical land subsidence, shoreline development

Service. He feels very strongly about the importance of partnerships in the success of marsh restoration. "We believe partnerships are essential to the implementation and completion of a successful restoration project, which best meets the mission and goals of the various federal, state, and non-governmental agencies. Our goal is to complete restoration projects throughout the Bay, which are acceptable to the federal, state, and non-governmental agencies, as well as the citizens of Texas."

Restoration efforts at Atkinson Island, near the Houston Ship Channel, are another contributor to marsh habitat in Galveston Bay. Work on this island, constructed mainly of dredge disposal material, has added over 220 acres of vital habitat. There are plans to add another 1,200 acres of marsh on dredge material in the near future (TPWD, 2000).

New methodologies and technologies enhance marsh restoration success. Marsh terracing, beneficial uses of dredge disposal material, geotubes and advances in smooth cord grass propagation have dramatically increased the amount of habitat restoration possible in Galveston Bay. Understanding of the effects of wave energy, land elevations and soils has also improved.

Volunteers plant widgeongrass on Armand Bayou. (Photo courtesy Armand Bayou Nature Center)

In the last decade, marsh restoration in Galveston Bay has proven to be successful and feasible.†With increased knowledge and funding, dedicated partners and many wonderful volunteers, the marsh habitat of Galveston Bay will flourish.

and shipping activity (White et al., 1993). The increasing importance of coastal erosion is evidenced by passage of the Coastal Erosion Planning and Response Act. This act, established under Senate Bill (SB) 1690 in 1999, represents significant progress for organizations responding to erosion problems. As noted in the Act, "Public beaches and bays are the economic backbone of the cities and counties on the Texas Gulf Coast. Natural and man-made forces are eroding those beaches and bay shores, threatening the coastal tourism industry, parks and other public lands and facilities, hotels, restaurants, businesses and other commercial property, highways and other transportation infrastructure, and fish and wildlife habitat, and destroying the public's right to enjoy free public beaches guaranteed under the Texas open beaches law." Chapter 61, Natural Resources Code (SB 1690, 1999).

Erosion problems are correlated to some human activities (e.g. shipping traffic, subsidence and bulkheading), which could be subject to management. For example, the Harris-Galveston Coastal Subsidence District (HGCSD) was created in 1975 to regulate groundwater withdrawal. The subsidence issue is considered largely resolved in the Harris and Galveston county area; however, new information indicates it may still be a problem in other areas. Christmas Bay continues to subside from groundwater withdrawals in the Pearland-Brazoria area.

Efforts have been made to reduce erosion in sensitive areas of the bay. The US Fish and Wildlife Service (USFWS) installed articulated stainless steel matting in Christmas Bay to stabilize vulnerable areas of shoreline. Geotubes filled with dredged material are being used on many projects involving creation of land with dredged material, e.g. Atkinson Island, and creation of marsh through terracing, e.g. Galveston Island State Park. In other areas of the Bay, USFWS, TPWD, GLO and GBEP have worked cooperatively with conservation groups to create oyster reefs and fringing wetlands, which have the effect of reducing erosion.

15. *Illegal dumping and water-borne and shoreline debris degrade water quality and aesthetics of Galveston Bay (Chapter 6).*

Estuarine debris represents a serious aesthetic and ecological concern in Galveston Bay. Debris is concentrated along the shoreline, where it accumulates due to the actions of winds, currents, and waves. Floating debris, particularly plastic, can harm wildlife, entangle propellers and clog the intakes of marine engines and industrial facilities. Plastic products are a major component of debris in Galveston Bay. In samples of the Houston Ship Channel, most items appear to be stormwater-related, rather than sewage-related (Radde et al., 1991).

Some efforts to reduce trash are being made by local governments through implementation of storm water management plans. These have provisions for removing trash and debris from storm water discharges. The Gulf Coast Waste Disposal Authority's Annual Trash Bash event, involving citizens in shoreline and nearshore trash cleanup at select sites in the bay watershed, has been successful both in the amount of trash removed and the number of people involved. However, cost to recover trash can be very high. The most effective means of addressing debris is prevention, which requires public education and involvement. Some of this will occur through implementation of the Storm Water Management Program.

16. *Some tributaries and near-shore areas of Galveston Bay are not safe for contact recreational activities such as swimming, wade fishing, and sailboarding due to risk of infection (Chapter 9).*

Overall, potential risks from pathogens associated with contact recreation in the bay system are considered to be relatively low. The current Texas water quality criterion for contact recreation is 200 fecal coliform bacteria colonies per 100 ml of water. All open bay areas of the estuarine system generally conform to this standard. Fecal coliform concentrations within western bay tributaries declined dramatically during the 1970s and 1980s, reflecting the improvement of wastewater treatment. A number of bay tributaries have been listed on the Texas 2000 Clean Water Act Section 303(d) List for bacterial contamination, likely resulting from storm water run-off and other human activities. Better screening procedures and more appropriate indicator species are recommended in The Plan.

A Beach Monitoring Program was initiated under the Coastal Management Program for six counties on the Texas coast. It consists of a water sampling program and notification process for potential beach users. This program began in the fall of 2000 in coordination with the TNRCC and the TDH. The Coastal Management Program provided initial funding for the program.

17. *Some exotic/opportunistic species (e.g. nutria*

and grass carp) threaten desirable native species, habitats, and ecological relationships.

Within the Galveston Bay estuary, the introduction and proliferation of exotic species has contributed to the degradation of some portions of the estuarine habitat. Significant populations of nutria, a large beaver-like rodent that migrated from Louisiana where they were imported for their fur during the 1930's, strip vegetation within freshwater and brackish water wetlands. Grass carp, which were introduced to control aquatic vegetation, have established a reproducing population in the Trinity River and have dispersed to many tributaries of the estuary and may be feeding on emergent marsh vegetation. The encroachment of fire ants into the estuarine ecosystem poses an increasing threat to nesting bird populations. Giant salvinia, an aquatic plant capable of completely filling waterbodies, is present in the lower Galveston Bay watershed. A large-scale control effort is currently underway for giant salvinia, but not the other species described. Some conservation efforts include removal of exotic species such as the Chinese tallow and water hyacinth.

The impacts and threats to the region from exotic species are being addressed, both locally and regionally. The TPWD and USFWS coordinate efforts on a statewide and regional level. Federal law prohibits introduction of non-indigenous aquatic nuisance species to United States territory, and Texas attempts to prohibit introduction of similar species to Texas. Unfortunately, prohibition is limited to species that are known to be problems or have characteristics that will cause problems. It is usually very difficult to predict how an exotic species will respond in a new environment. Effective enforcement remains a challenge because exotic species are "presumed innocent until proven guilty".

Enforcement officials are being trained to improve enforcement of exotic species regulations. The potential introduction of invasive species through ballast water has become a growing nation-wide concern. Federal regulations have been established to regulate the discharge of ballast water in the nearshore environment. Currently only the Great Lakes is protected by mandatory rules against ballast water exchange in the waterbody. A voluntary program for ballast water exchange outside the estuary has been implemented for Galveston Bay.

Summary

The management of Galveston Bay under *The Galveston Bay Plan* is dependent on availability to and interpretation of scientific information about the bay and impacts of human activities. This information is used for assessment of risk from the identified impacts. A wide variety of actors must participate in a complex set of actions to safeguard the Bay. The Galveston Bay Estuary Program has compiled most of the available information on the Bay and coordinates many of the participants in protection and conservation of this important resource.

Seventeen priority problems were identified and have been addressed over the five years of plan implementation. The problems range from too much pollution to too few pelican nesting sites and too much erosion to too little environmental education. The priority problems and highlights of the information currently available on them are presented in Chapters 5 through 9.

The actions proposed as solutions are quite disparate. Some actions proposed in *The Plan* are based on governmental regulation and some on voluntary measures. Most actions have a local component, but some need watershed level commitment to be effective. Progress or change in the status of problems identified in *The Galveston Bay Plan* will be highlighted in the following chapters. Assessments of the action plans in *The Galveston Bay Plan* and prospects for the future of Galveston Bay are presented in the Epilogue.

Fig. 2.1. As seen from space photography, the bayous flowing into Galveston Bay apear to have been channels separated from the Brazos and Trinity Rivers as the rivers' courses meandered. (Courtesy of NASA Johnson Space Center)

Chapter Two

Galveston Bay: An Overview of the Ecosystem

> *Ecosystems are open systems, that is, things are constantly entering and leaving, even though the general appearance and basic functions may remain constant for long periods of time.*
>
> —*E. P. Odum, Ecology and Our Endangered Life Support Systems, 1989*

Galveston Bay is a tremendous recreational, economic, and environmental asset to Texas and the Nation. To properly manage human activities that affect this ecosystem it is necessary to understand the system's composition, the processes that link its components and how it interacts with its environs.

Conceptual models of complex systems can be useful management tools if they identify the critical components and processes of the ecosystem. Over recent decades scientists have come to recognize a hierarchy of structure in ecological systems. Each successively higher level of organization constrains activity within the next lower level (O'Neill et al., 1986). This chapter describes several scales of organization, biological components of the Galveston Bay system, hydrological components of the larger system and conceptual models of some of the components (McFarlane, 1994).

The Estuary as an Ecosystem

Estuaries are defined as semi-enclosed, transitional zones where freshwater flowing from rivers and streams mixes with salt water from the sea. Estuarine habitats include marshes, mud and sand flats, seagrass beds, oyster reefs, open bay bottoms and open bay water, all of which occur in the Galveston Bay system. The abundance of nutrients and the diversity of available habitats within the estuary provide for very high levels of biological productivity. Many of the commercially harvested seafood species in the Gulf of Mexico and its bay systems require estuarine environments like Galveston Bay for one or more of their life stages.

Galveston Bay is a bar-built estuary formed in a drowned river delta. From space photography the bayous appear to have been channels of the deltas separated from the Brazos and Trinity Rivers as their courses meandered (see Figure 2.1). Galveston Island is a sand bar about 5,000 years old that impedes the flow of freshwater from the Trinity River and San Jacinto Rivers into the Gulf of Mexico. Sediments from the river watersheds and the immediate surroundings blanket the bay bottom. Weather, e.g. rainfall and wind, strongly affects the composition and circulation of bay waters. Only those plants and animals that can tolerate fluctuating salinities and temperatures are found in this environment.

Estuaries, such as Galveston Bay, are ecosystems that exhibit high variability because they respond to many temporal and episodic perturbations. Estuaries change in response to daily cycles, tidal cycles, seasonal cycles, hurricanes, droughts and other episodic influences. Knowledge of the components of the ecosystem, the diverse plants and animals that build and inhabit its distinct habitats, does not automatically lead to an understanding of ecosystem functions. The function of an estuary -that is, how it acquires, processes and stores its materials and energy, releases and assimilates its waste products, and interacts with adjacent waters and the surrounding landscape- is a much more subtle and challenging problem.

Of course, man often dramatically influences the bay, either by influencing the natural pattern of bay inputs, or by disrupting its habitats. Changes in inputs include discharging pollutants into the bay or altering the natural patterns in freshwater inflow. Conversion of marshland to other land uses is an example of how human activities can alter some of the bay's most critical habitats.

Characterization of the Ecosystem

Ecosystems are difficult to define because they have "fuzzy" edges, come in all sizes, and overlap and interact with one another. Galveston Bay is influenced significantly by the interchange between river and bayou watersheds and the Gulf of Mexico ecosystems. The gulf ecosystems are major contributors of larvae and juveniles of many marine species that enter the estuary and seek food and shelter within the system. Due to its smaller size and variability, the estuary exhibits less biodiversity than Gulf ecosystems. The distribution of organisms varies greatly in time and space. Species seen on the bay-shore of Galveston Island will differ somewhat from species frequenting the shoreline of Trinity Bay. For example, smallmouth buffalo, a predominantly freshwater species, can be found on occasion in Trinity Bay, but would rarely be found in the higher salinity waters of lower Galveston Bay and West Bay. Seasonal changes occur as well. Species commonly observed at a site during the summer may be replaced with other species in winter.

The aquatic ecosystems of the watershed provide both "goods" and "services" to society (Odum, 1997). Ecosystem "goods" include food, cooling water and shell. Ecosystem "services" include storing and cycling essential nutrients, absorbing and detoxifying pollutants, maintaining the hydrologic cycle, and moderating the local climate. In human terms, services also include providing sites for recreation, tourism, research and inspiration. When human activities disrupt the essential functions of an ecosystem, the assimilative capacity of the natural system is exceeded and the normal flow of "goods" and "services" provided by healthy ecosystems is impaired.

Estuaries are among the most naturally fertile waters in the world (Odum, 1997). Their high productivity results from their unique juxtaposition at the edge of the continent. Nutrients from four sources contribute to the productivity of estuaries: 1) fresh water flowing off the land; 2) tidal exchange with the ocean; 3) the atmosphere; and 4) the recycling of material from the estuarine bottom sediments. The most important nutrient is nitrogen, a component found in all proteins. Phosphorus, carbon and other compounds in lesser amounts also serve as nutrients to living things in the estuary.

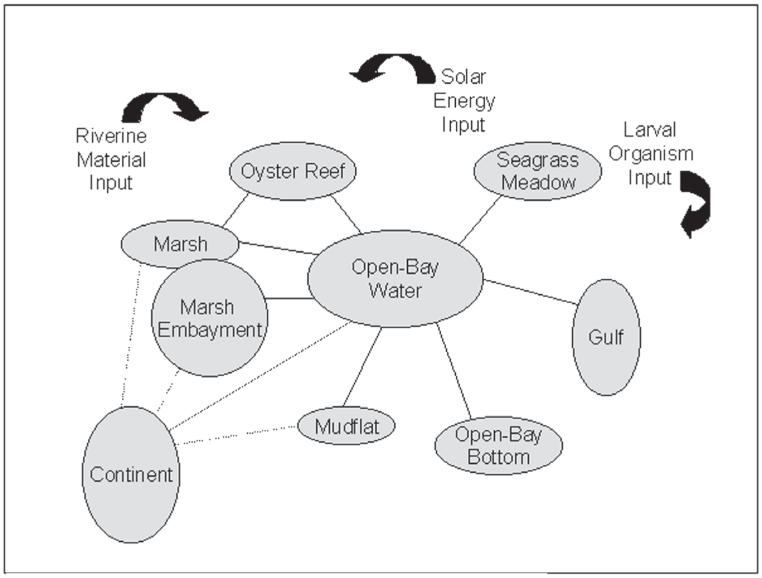


Fig. 2.2. Conceptual model of Galveston Bay showing the major habitats and their connections to the continent and the Gulf of Mexico. (Source: McFarlane, 1994)

Galveston Bay Food Webs

From the simplest microscopic plants to the largest animals, organisms are connected to each other in pathways of consumption known as a food web. In a food web, plants and animals are connected by paths of energy flow from plants to herbivores to predators and from all three to decomposers.

Estuarine foodwebs (Monroe and Kelly, 1992) are organized by energy flow from green plants (such as planktonic algae) to higher consumers (such as bay anchovies, red drum, and humans) and to consumers of dead organisms (such as bacteria and seagulls). The same organization can be analyzed by describing the cycling of compounds like carbon and phosphorus, which are essential nutrients for life.

Food webs in Galveston Bay are essentially of two types (Armstrong, 1987). One web is based on production and consumption of living plant tissue in the form of free floating phytoplankton. The second web is based on detritus, dead plant and animal tissue, produced both within and outside the bay system. Detritus is received from the watershed in river and bayou inflow and from the fringing marshes. Detritus-based food chains are complex and poorly understood.

Occasionally the balance of the ecosystem is upset and some of the species that are part of the food web exhibit dramatic increases or decreases in abundance. One example of such episodes is the phenomenon of algal blooms. Phytoplankton species can become so abundant that their nocturnal metabolism uses most of the available oxygen in the water and larger organisms either leave the area or die. Some species of dinoflagellates produce harmful toxins and cause the phenomenon known as red tide. Red tide toxins can kill or harm organisms in or near the water. Lethal exposures to fish and shellfish are typical when organisms encounter high concentrations of toxins in the water. Humans can be impacted when red tide toxins become aerosols in the surf zone (see Chapter 9). Toxins have serious impacts on sessile benthic animals, such as oysters, which have no ability to avoid them.

Galveston Bay Habitats

Habitats are a standard way to ecologically subdivide an estuary. As seen in Figure 2.2., the major habitats are quite distinctive and easily recognized. The largest habitat is the three-dimensional open-bay water itself, to which all other habitats are linked. Equally large in area, but virtually two-dimensional, is the underlying open-bay bottom. The bottom functions as a matrix upon which several different types of habitat can be found. Patches of oyster reef rise up on bottoms where stable sediment and ample current flow occurr. On softer sediments in shallow water, patches of submerged aquatic vegetation - the subtidal seagrass meadows - can be found near the periphery of the bay. Much of the bay bottom is soft, rippling mud and silt, uncovered by oysters or plants. As the bay bottom slopes upward at the edge of the bay, emergent intertidal marsh vegetation lines the shore. Some low-sloping shore zones do not support emergent vegetation, and remain as intertidal mud flats. Patches of very soft, unconsolidated subtidal bottom are scattered within various shoreline wetlands to create the peripheral marsh embayments.

The conceptual models presented in this chapter are based upon the identification of ecosystem structure inherent in the major habitat type. The relationships of these ecosystems to the surrounding upstream and marine systems, and to one another are noted. Each habitat is connected (directly or indirectly) to the upstream freshwater riverine-floodplain ecosystem, to the downstream marine waters of the nearshore-gulf ecosystem, and to the terrestrial ecosystems. Six key habitats are highlighted for ecosystem descriptions in this chapter. McFarlane (1994) has modeled each of these ecosystems. Three of the ecosystem models are shown here. The organisms living within these habitats have been aggregated into functional groups based upon their distribution within the habitat and their primary feeding or energy/nutrient gathering technique. These functional groups have been arranged to reflect the general flow of energy through the food web (see Figures 2.3, 2.4 and 2.5).

Open-Bay Water

The open-bay water habitat has the simplest structure of all the habitats considered. It is a large volume of water consisting of many water masses. The bay's pelagic inhabitants include all of the active swimmers and passive drifters found in the water column. The open bay water is essentially featureless except for an invisible horizontal and vertical salinity gradient, and at times, gradients of temperature and dissolved oxygen. It varies spatially in the load of suspended solids, the concentration of nutrients and contaminants, and the abundance of organisms.

The open-bay water covers nearly 600 square miles and has an average depth of seven feet. Subsidence has increased the volume of the bay through flooding and inundation. As seen in Figure 5.2, the land surface in and around Galveston Bay has sunk by as much as 10 feet in some places since 1906 (HGCSD, 1998).

The primary producers of the open-bay water are composed of various groups of phytoplankton, especially diatoms and dinoflagellates (Buskey and

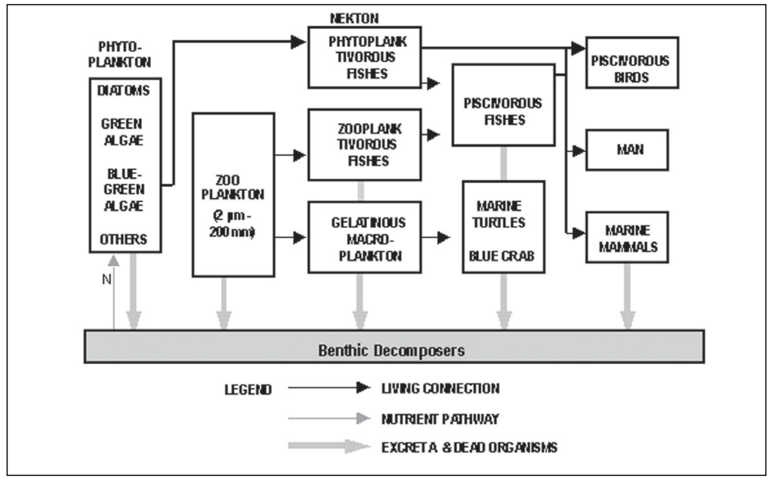


Fig. 2.3. Schematic model of open bay water habitat in Galveston Bay. (Source: Modified from McFarlane, 1994)

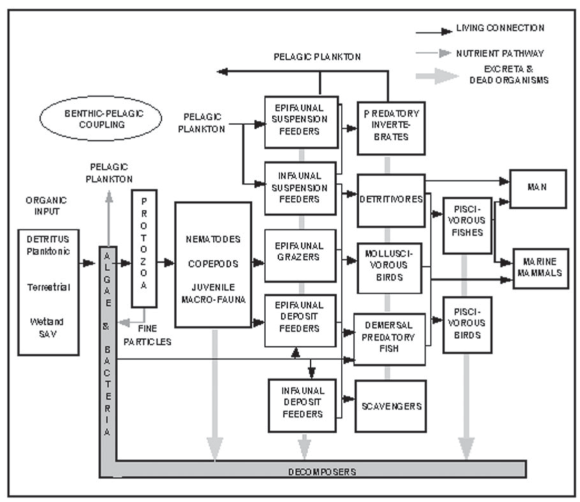


Fig. 2.4. Schematic model of the open bay bottom habitat in Galveston Bay. (Source: Modified from McFarlane, 1994)

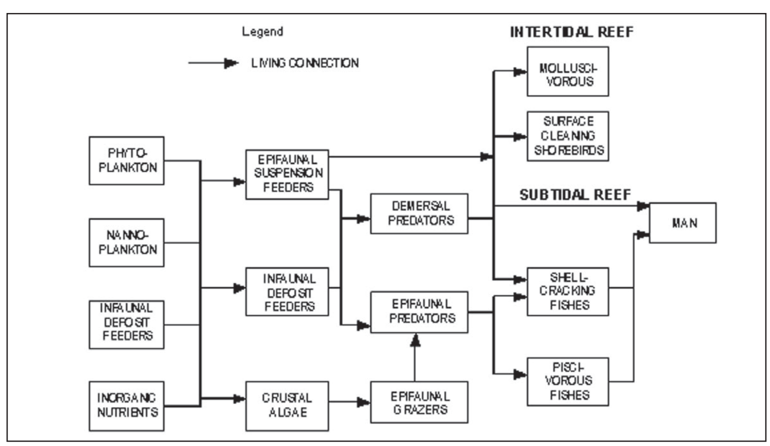


Fig. 2.5. Schematic model of the oyster reef habitat in Galveston Bay. (Source: Modified from McFarlane, 1994)

Schmidt, in Green et al., 1992). The primary consumers that feed upon these phytoplankton are the numerous and diverse zooplankton, e.g. copepods (animals which are suspended in and transported by water) and phytoplanktivorous, or plant-eating, fishes, e.g. menhaden.

The secondary consumers are principally larger organisms capable of self-directed swimming and feeding activity. Food chains in this habitat can be quite long, extending to six or seven levels, and permitting high concentrations of some pollutants at the top trophic levels through bioamplification. Dead organisms and egested material sink to the bottom to be recycled by the benthic decomposers (see Figure 2.3). Only a limited amount of nutrient recycling occurs in the water column. The predators of the open bay waters are fish species of varying size, e.g. pinfish and spotted seatrout; birds, e.g. terns and cormorants; marine mammals, e.g. bottle-nosed dolphin; and humans.

Emergent wetlands provide ecological and economic benefits including habitat for valuable estuarine species, flood control and improved water quality. (Courtesy Galveston Bay Estuary Program)

Energy leaves the open bay water ecosystem through a variety of pathways. Death of plankton and nekton results in the sinking of biomass to the bottom for processing by decomposers. Suspension feeders on the bottom can capture plankton from the water column in Galveston Bay because the bay is shallow and well mixed. Successful fishing by birds and humans results in biomass leaving the bay and being consumed by components of the terrestrial ecosystem.

Open-Bay Bottom

The open-bay bottom is the second largest habitat of the bay, consisting of those areas of the bay bottom not covered with oyster reef or seagrass meadow. This habitat is nearly two-dimensional; its depth is measured in inches. For the most part, the sediment surface seems featureless except for sculpted waveforms, trawl marks and evidence of burrowing animals. To a benthic organism, however, the features of this environment can be patchy, caused by the specific distribution of sediments of different particle size and the clumped distribution of life forms themselves. The interface between sediment and water is the location of chemical and physical exchanges essential to species living in and above the sediment. The size of this habitat has increased over the last 100 years, primarily by the removal of shell from large areas of the bay bottom and by the open bay disposal of dredged material.

The food web of the bottom habitat (Figure 2.4) is based upon biological decomposition of detritus and the capture of phytoplankton circulated from the surface. Although depths within Galveston Bay are generally shallow enough for light to penetrate to the bottom, turbidty of the water typically precludes significant light penetration and photosynthetic activitiy on the bottom. Except for some shoreline areas, primary productivity on the bay bottom is limited or nonexistent. Detritus reaches this zone in the form of dead organisms, "planktonic rain" (dead planktonic organisms), egested material, dissolved organic matter, and particulate organic matter transported from the riverine and peripheral wetlands or submerged aquatic vegetation (Day et al., 1989).

Many of the primary consumers in the bay system consume detritus as well as the bacterial and fungal decomposers associated with it. These detritivores include many benthic organisms including marine worms, bivalves, gastropods, crustaceans, bottom feeding fishes and macro-invertebrates (Sheridan et al., 1989; Gosselink et al., 1979). Fungi, bacteria, and protozoans play a key role as benthic decomposers. They manufacture digestive enzymes capable of breaking down cellulose, the structural component of higher plants. Their action releases nutrients from decomposing plant and animal tissue to the water column.

Protozoans and other organisms consume bacteria directly, egesting fine particles of organic material. In this manner organic molecules (originally bound in plant tissue) become bundled into bite-sized packages; first as fungi and bacteria, then as larger protozoans.

Preying upon the micro-fauna is a diverse meiofauna. Nematodes are most numerous but copepods and juvenile stages of the larger invertebrates are also abundant. These organisms find protozoans and bacteria to be conveniently sized prey. The meiofauna are most abundant in sediment with high silt fractions.

Larger organisms subdivide the habitat into two components (Harper, in Green et al., 1992; LaSalle et al., 1991; Ray et al., 1993). The epifauna live on the surface of the bottom sediment. The infauna burrow into the bottom sediment. Some feed by straining suspended particles from the water column (e.g. most bivalve mollusks). Others feed by ingesting sediment and extracting nutrients in the digestive tract (i.e. deposit feeders, including many worms). Snails and brittle stars graze along the sediment surface. Crabs and shrimp scavenge on the surface and prey on smaller animals.

The open-bay bottom habitat is closely coupled with the open-bay water habitat. Plankton are consumed by epifaunal and infaunal suspension feeders. In turn, many benthic organisms contribute their larvae to the water column. Numerous fishes (e.g. croaker, spot, mullet and drum) forage on benthic organisms. Diving birds (particularly ducks) reach the benthos to consume small mollusks and other organisms. Reproduction of planktonic larvae and predation by birds and pelagic fishes transfer energy from the open-bay bottom ecosystem to other ecosystems.

Oyster Reef (see Chapter 7)

Clusters of oyster shell, live oysters and other commensal organisms form a distinct oyster reef habitat (Figure 2.5).

Oyster reefs tend to form where a hard bottom and sufficient current exist to transport planktonic food to the filter-feeding oysters and to carry away sediment, feces, and pseudofeces (material which has been filtered from the water by bivalve mollusks, such as oysters, but not processed through the digestive tract).

The reefs form in the open bay, along the periphery of marshes, and near passes and cuts, and can be either subtidal or intertidal (Powell, 1993). Reefs are typically elongated in form and run perpendicular to the direction of the current. They are particularly abundant along the side slopes of navigation channels where tidal exchange currents are dependable. The reef itself is three-dimensional because oyster larvae settle on the top of old shells to permit growth into the water column above the established oysters. The shells cemented together create an irregular surface that establishes a myriad of microhabitats for smaller species.

Oysters, a commercially important seafood species in Galveston Bay, create reef habitat utilized by many other species. Encrusting organisms such as Rangia *clams, bryozoans and barnacles take advantage of the hard substrate created by oysters. (Courtesy Texas Parks and Wildlife Department)*

The oyster reef community is very diverse. While oysters are dominant, other bivalve mollusks, gastropods, barnacles, crabs, amphipods, isopods, and polychaete worms are normally abundant. Although shallow reefs often have some primary production from algae growing on the shells, they are dependent on the importation of food resources from open bay water and peripheral marshes. Plankton is filtered from the water moving over the reef by oysters and other suspension feeders. Dissolved and particulate organic matter, particularly the feces and pseudofeces emanating from the suspension feeders, support various deposit feeders living in the interior of the reef.

Secondary consumers of the reef include predators, parasites and pathogens, some of which are important oyster population control agents. Demersal fish with crushing teeth (e.g., black drum), blue crabs and stone crabs prey on small oysters with thin shells. Another group of predators are the oyster drills. They have the unique capability of being able to drill through the shells of larger bivalves. A separate food web encompasses small fishes (e.g. gobies) and crustaceans (numerous crabs), which do not consume oysters but exploit the three-dimensional microhabitat provided by the aggregated oyster shells.

Oysters have a valuable ecological role as filter-feeders in the estuary. The volume of water filtered per hour is approximately 1,500 times the volume of their body (Powell, et al., 1992). A large, healthy oyster population is able to filter large volumes of bay water, and may therefore influence conditions such as water clarity and phytoplankton abundance. At the same

Underwater seagrass meadows support a diverse and productive community, including such organisms as pipefish and seahorses, as well as important commercial and recreational species. Most of the seagrass beds once present in the Galveston Bay system have been lost since the 1950s. (Courtesy Texas Parks and Wildlife Department)

time, their propensity to bioaccumulate some pollutants, combined with their lack of mobility, make them important indicator organisms for determining the health of the estuary.

Oyster reefs are connected to the open bay water ecosystem through the consumption of plankton by reef suspension feeders and the predation of reef dwellers by demersal fishes. Some oyster predators, such as the blue crab and oyster drill, move between the oyster reef and open bay bottom habitats and other ecosystems. At low tide, avian predators can obtain prey from an oyster reef and transfer it to terrestrial systems. Also, tons of oyster biomass are transferred from Galveston Bay to human dominated ecosystems every year by the oyster fishery.

Seagrass Meadow (see Chapter 7)

Patches of submerged aquatic vegetation (SAV) and associated consumers compose the seagrass meadow community in soft sediments along the shorelines. In the low-salinity northern parts of the estuary, wigeongrass (*Ruppia maritima*) is the dominant species of SAV. Shoalgrass (*Halodule wrightii*) is the dominant species forming seagrass meadows in the higher salinity waters of West and Christmas Bays. Shoalgrass beds often contain clovergrass (*Halophila engelmannii*) and turtlegrass (*Thalassia testudinum*). The sunlight requirement of these plants limits their distribution to low turbidity, shallow waters. They are also sensitive to high nutrient conditions because they can be overgrown by epiphytic algae.

This habitat provides food resources and protective cover for a number of associated species and contributes substantial quantities of detritus to the open bay bottom food web. The fauna associated with patches of SAV is quite diverse (i.e. 20 fish and 15 crustacean species; Zieman and Zieman, 1989; Czapla, 1991).

Many juvenile and small organisms are resident in the seagrass. Juveniles of shrimp, crab and fish species leave the seagrass ecosystem as they mature. Some predators, such as spotted seatrout and blue crab, are transients to the ecosystem and are present for the capture of prey. Some herbivores, such as ducks, are transient because they migrate to the Galveston Bay system for overwintering.

Seagrass meadows were once extensive in Upper Galveston Bay and West Bay. Over the last 50 years this habitat has almost disappeared from West Bay. The rapid decline in seagrass acreage from the 1950's to 1990's is cause for concern because seagrass meadows are important nurseries and are indicators of water quality.

Marsh (see Chapter 7)

Emergent wetlands (better known as marshes) provide valuable ecological and economic benefits including habitat for valuable estuarine species, flood control and improved water quality (TPWD, 1997). *Spartina alterniflora* (smooth cordgrass) is the dominant species of shoreline vegetation found in the fringing marshes of Galveston Bay (Minello and Webb, 1997). This and other species of wetland plants found in the bay's estuarine marshes are ecologically adapted to a special set of environmental parameters associated with a tidal coastline.

Intertidal marshes are structurally resilient. Where subsidence, dredging, filling and shoreline development have not disturbed them, marshes appear little affected by human agriculture or industry. The grasses adapted to high-salinity marshes are particularly tough, mineralized and therefore resistant to herbivory. In addition, the osmotically-stressed intertidal system is not an easy target for the invasion of exotic plants and animals. Estuarine wetland acreage in the Galveston Bay system decreased overall by approximately eight percent between 1950 and 1989 (TPWD, 1997). Losses in estuarine wetlands in one area are often offset by gains in another due to marsh establishment in inundated upland areas.

Emergent marshes produce an enormous biomass, about 10 percent of which supports terrestrial herbivores. The remainder flows to a large detritivorous

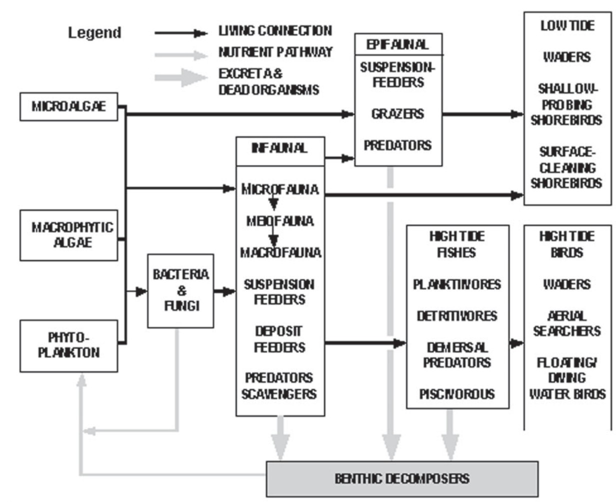


Fig. 2.6. Schematic model of the intertidal mud flat habitat in Galveston Bay. (Source: Modified from McFarlane, 1994)

estuarine food chain (Wiegert and Freeman, 1990). The enormous productivity of marshes and the significance of their detrital pathways to the estuary at large have long been recognized (Wiegert and Freeman, 1990). Even so, much of the detritus deposited in the marsh is not decomposed and forms an anaerobic peat in the sediment.

One of the most significant ecological roles of tidal wetlands is their function as habitat for key estuarine species, particularly for those requiring food and cover as juveniles. The closely ranked stems of the emergent plants create an environment at their base that supports epiphytic algae and shelters phytoplankton and epibenthic algal assemblages (Zimmerman, in Green et al., 1992). These, in turn, support additional grazer and planktivore food webs, which include important fishes and crustaceans. Wading birds are common at the marsh-water interface where they prey on buried invertebrates or fish. Large quantities of biomass are transported out of the marsh by the tidal movement of detritus, emigration of juveniles, and predation by transient predators.

Intertidal Mud Flat

Mud flats develop on shorelines of very low wave energy where small particles of mud or silt are deposited. The intertidal mud flat habitat is an exceptionally open ecosystem both physically and biologically (Peterson and Peterson, 1979). It lacks the emergent grasses and other plants of the peripheral marshes, or the submerged grasses of the seagrass meadows. The intertidal mud flat habitat is "vegetated" by microalgae, macroalgae and phytoplankton (see Figure 2.6). The importation of organic and inorganic material and detritus is important to the food web. Most of the benthic biomass is supported by primary production from outside of the habitat and imported via water currents and tidal action (Peterson and Peterson, 1979). The only animals relatively fixed in position and restricted to a single habitat are the infauna, such as worms and bivalves. Most of these are supported by detritus imported by water currents and tidal action.

Bacteria and fungi play important ecological roles converting organic matter into inorganic nutrients and serving as a trophic intermediate between relatively indigestible plants and consumers of detritus (Peterson and Peterson, 1979). This process of microbial growth on detritus may determine the abundance of deposit-feeding species, such as snails. The majority of the organisms in mud flat ecosystems are invertebrate deposit feeders, mollusks and polychaetes.

On mud flats, members of the higher trophic levels appear as transients with the tides. At high tide, fishes move onto the flats to feed, followed by piscivorous predators, both birds and fishes. At low tide, gleaning and probing shorebirds feed on and in the exposed surface while waders seek prey stranded in tidal pools. Overall, nutrients, organic particles and living organisms readily move in and out of the habitat.

On mud flats, members of the higher trophic levels appear as transients with the tidal phase. At high tide, small fishes move onto the flats to feed, followed by predatory wading birds and fishes. At low tide, gleaning and probing shorebirds feed on and in the exposed surface while waders seek prey stranded in tidal pools. (Courtesy Randy Green/Texas Department of Transportation)

Characterization of the Watershed

A watershed can be defined as a drainage basin - that area of land from which water drains into a river, bayou, stream, lake or bay. Watersheds come in many shapes and sizes ranging from just a few acres to millions of square miles with smaller watersheds often nested within larger ones. They know no geopolitical boundaries and as a result cut across county, state and international borders. Residential, industrial and agricultural lands all reside within watersheds. A land-based activity can have an impact on the quality of water within the watershed. Fertilizers and pesticides from lawns, herbicides from fields, oil and grease from roads and parking lots can progress from the land into the water when transported via surface runoff. In recent years, water management strategies have begun to follow a watershed approach

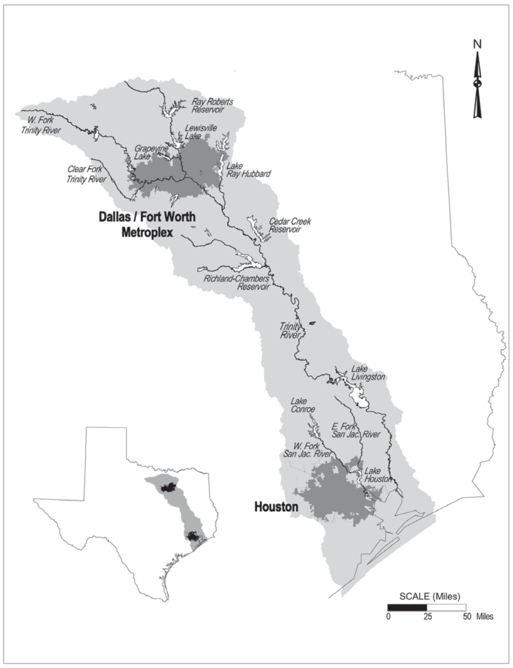


Fig. 2.7. The Galveston Bay watershed covers approximately 33,000 square miles. (Source: Houston-Galveston Area Council)

Streams and rivers are longitudinal systems surrounded by watersheds. There are watersheds surrounding the major rivers flowing into Galveston Bay, i.e. the Trinity, a large river system with a watershed that extends north to encompass the Dallas-Fort Worth region, and the San Jacinto, confined to Southeast Texas. The bay is also fed by small watersheds surrounding minor bayous, e.g. Cedar Bayou, Chocolate Bayou, Armand Bayou, etc. Processes that take place upstream have impacts on downstream components. Processes that occur in the watershed impact the river or stream, and all of these watershed processes affect the connected estuary.

Without the inflow of freshwater, nutrients and sediments transported by rivers and streams, the estuary would not exist. It would be a lagoon, a salty extension of the gulf.

In-stream biological communities change from upstream to downstream. Much of the organic matter carried by rivers and streams is degraded into nutrients prior to reaching the estuary (National Research Council, 1992). Watersheds play a critical role as contributors of pulses of nutrients, organic matter and contaminants. Our current understanding indicates that freshwater inflows transport 96 percent of the imported carbon and nitrogen and 95 percent of the phosphorus to Galveston Bay, with the remainder contributed by peripheral marshes (Armstrong, 1982; Borey et al., 1983).

The entire Galveston Bay watershed consists of 33,000 square miles of land and water, which dwarfs the 600 square miles covered by the bay (see Figure 2.7). Within this large system, bayous, streams and rivers carry surface flow to the bay. These bayous, streams and rivers are quite different in character. The Trinity and San Jacinto Rivers are gauged and monitored for quantity and quality of water carried to the bay. Much less is known about the hydrology of bayous, the most common form of tributary to Galveston Bay. They operate primarily as extensions of the tidal bay system and change their nature from source to mouth. As water volume increases, the load of sediment carried by the bayous, streams and rivers increases and the aquatic communities change as well.

As seen in Figure 2.8, Galveston Bay is commonly divided into four major sub-bays.Upper *Galveston Bay* receives the outflow of the San Jacinto River and much of the local drainage from the City of Houston via the Houston Ship Channel. *Trinity Bay* receives the outflow from the Trinity River. *East Bay* lies landward of Bolivar Peninsula and receives inflow from Oyster Bayou and other runoff from Chambers County. *West Bay* is situated landward of Galveston Island, and receives runoff from Chocolate Bayou, Mustang Bayou and other local bayous. Christmas Bay and Bastrop Bay are two relatively undisturbed, somewhat isolated, secondary bays in the far southwestern part of the estuary.

There are three tidal inlets to the bay, but only two are of major importance with regard to flow. Bolivar Roads, between Galveston Island and Bolivar Peninsula, accounts for the majority of the tidal exchange between the bay and the Gulf of Mexico. San Luis Pass, between the western end of Galveston Island and Follets Island, is a natural inlet that provides a lesser amount of the bay's tidal

Fig. 2.8. Galveston Bay is subdivided into four major sub-bays. (Source: Modified from Houston-Galveston Area Council)

exchange. Rollover Pass is a man-made cut through Bolivar Peninsula that provides minor tidal exchange between the Gulf of Mexico and East Bay. Areas with greater tidal flushing and less urban and industrial development generally exhibit higher water quality.

Water quality in the estuary is a key attribute affected by watershed events. Figure 2.9 illustrates the determinants of water quality in sequential order as they occur from watershed to estuary. Dissolved and suspended materials are incorporated wherever water moves, even by raindrops moving through the atmosphere. Freshwater inflow is essential, but may contain contaminants. Point and nonpoint source discharges add various contaminants to the bay and its tributaries, particularly in urban-industrial areas and intensely cultivated sub-watersheds. Aquatic microorganisms and in-stream chemical events alter or reduce contaminant levels. Particles and compounds may settle in reservoirs upstream from the estuary. Flooding periodically introduces pulses of organic material from the surrounding floodplain and resuspends contaminants in the stream bed. These materials are carried to the estuary by the high water flows.

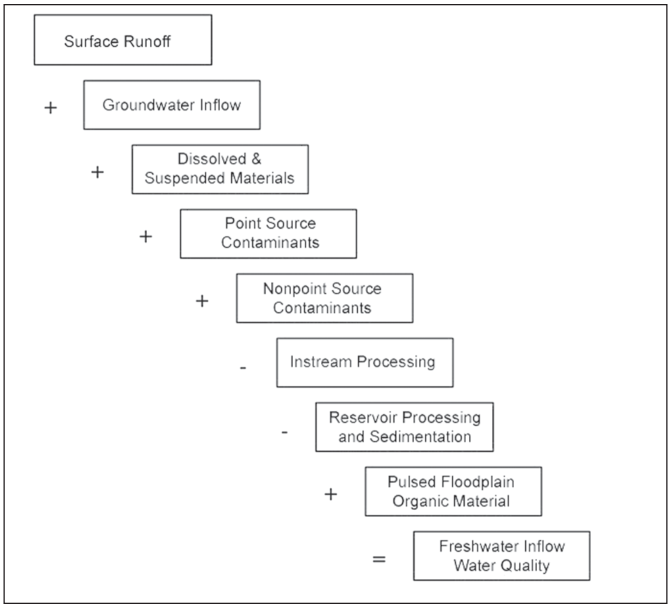


Fig. 2.9. The quality of freshwater feeding an estuary is greatly influenced by the events in the watershed. The determinants of water quality are shown in sequential order as they occur from watershed to estuary. (Source: McFarlane, 1994)

The Lower Watershed

The lower watershed is defined as the 4,238 square mile area draining to the bay downstream of two major impoundments: Lake Houston on the San Jacinto River, and Lake Livingston on the Trinity River. These two reservoirs provide some attenuation of runoff and pollutant loads. Therefore, the lower watershed more directly contributes runoff and runoff-borne detritus and pollutants to the bay than does the upper watershed.

The metropolis of Houston and its associated suburban communities occupies the western side of the bay, while the eastern side remains largely agricultural and undeveloped. Urban and suburban development is very significant to the bay through their contribution of polluted stormwater runoff from parking lots, streets, highways, roofs, and yards (Newell et al., 1992). Agricultural development on the eastern shore contributes non-point sources of nutrients, fecal coliforms, herbicides and pesticides.

The Upper Watershed

Galveston Bay has two large "upper watersheds," consisting of 2,828 square miles upstream of Lake Houston on the San Jacinto River and 26,000 square miles upstream of Lake Livingston on the Trinity River. The Trinity extends past the Dallas-Fort Worth metroplex with numerous man-made reservoirs on tributaries in addition to Lake Livingston on the main stem. Land uses within the watershed include forest and wetland along the river floodplain; agriculture in many parts of the watershed; urban areas and range-land in the far northwestern part of the drainage area. The San Jacinto River is mostly forested upstream of Lake Houston, with some urbanization in its lower drainage area.

Summary

The Galveston Bay ecosystem is composed of a complex set of overlapping habitats that function with inter-linking energy and materials processes. Energy is constantly transferred among open bay water, open bay bottom, seagrass meadow, oyster reef, marsh and mud flat. The integrity of these distinct but interacting habitats is vital to the continued natural function and life-support capability of the estuary.

Models of the various habitats show that the well-being of these habitats is partially dependent on distant events, such as the spawning of shrimp and finfish in the gulf or stormwater runoff from a remote watershed. Hence the estuary as a whole can be greatly influenced by actions occurring far from the bay. This implies the need for a watershed-level approach to future management of the system.

Remnants of the Past

A Tale of Two Coastal Preserves

The Houston-Galveston area is fortunate to be home to two of four state-designated coastal preserves. The Christmas Bay and Armand Bayou Coastal Preserves are remnant habitats, our best examples of the bay and its tributaries as they existed prior to man's influence. The coastal preserves, designated by the State of Texas in 1990, are leased and managed through the Texas Coastal Preserves Program, a partnership between the Texas Parks and Wildlife Department (TPWD) and the Texas General Land Office.

The 319-acre Armand Bayou Coastal Preserve is located in southeast Harris County along a stretch of Armand Bayou. The preserve is home to the American alligator, osprey, river otter and a diversity of fish and other wildlife. Mark Kramer is the Stewardship Coordinator for the 2,500-acre Armand Bayou Nature Center, which surrounds the preserve. He believes that Armand Bayou was a logical choice to receive a coastal preserve designation due to its proximity to such a large urban area, its near-pristine nature and the potential for educational and restoration activities through the involvement of the Nature Center.

> *For me it is a living museum. It is a relic, an example of remnants that are growing more and more rare as each year passes in the Houston area.*
>
> *—Mark Kramer*

The 5,660-acre Christmas Bay Coastal Preserve is located in the extreme southwestern portion of Galveston Bay in Brazoria County. The preserve is a near-pristine secondary bay composed of seagrass meadows, oyster reefs and coastal marshes. These habitats serve as vital breeding, nursery and foraging areas for a rich diversity of finfish, shellfish, colonial

Visitors on Armand Bayou. (Jack Lewis for Texas Department of Transportation)

nesting birds and migratory waterfowl. Dr. Larry McKinney is the Senior Director of Aquatic Resources for the TPWD, the agency responsible for the management of the coastal preserves.

> *I always think of Christmas Bay as a microcosm of what Galveston Bay once was and should be. It is that last refuge where the ecosystem still overrides our ability to overwhelm it.*
>
> *—Larry McKinney*

The Coastal Preserve program is an excellent first step toward protecting coastal Texas' unique biological communities. However, urban and industrial development and channelization projects continue to threaten water quality and habitat diversity. The effort to protect these and other unique habitats must continue if we hope to preserve these untamed areas for future generations.

> *The two preserves are very different in nature, but common in purpose - assuring a healthy bay for the future and building the constituency to keep it that way.*
>
> *—Larry McKinney*

Chapter Three

The Human Role: Past

By Alecya Gallaway

At sundown we reached Redfish Bar, composed almost entirely of shells which extend from bank to bank the distance of several miles and appear to be formed by the confluence of the tide and the waters of the San Jacinto and Trinity, which unite a short distance above. This point is undoubtedly the head of navigation for vessels of heavy burden and has occurred to some as a more suitable site for a city than Galveston itself.

—Anonymous, Texas in 1837*, edited by Andrew Forest Muir, 1958*

This chapter will provide insight to the history of resource use in Galveston Bay and its adjacent land area. The chapter begins with a look back to the Pleistocene Ice Age and the impact of the earliest humans. It continues with the use of resources by Native Americans and changes engendered by the transition to European-American settlement. The chapter then focuses on the alterations that occurred to the bay as the regional focus shifted from agriculture to municipal and industrial development. This chapter describes resource use and human impact from pre-history to 1950. More recent development and impacts are covered in Chapter 4.

Resource Use: Prehistory to 1800

Galveston Bay is a recent feature of the Earth by geological reckoning. Thousands of years before the bay formed, water was held in continental ice sheets causing the sea level to be considerably lower than it is today. The shoreline was located fifty to one hundred miles farther south into the area now covered by the Gulf of Mexico. The great mammals of the Pleistocene moved southward as the ice sheets spread, pushing many species to lower latitudes. Many of these species inhabited the land where Galveston Bay would later form. This land was crossed by rivers and streams running in deeply entrenched valleys (LeBlanc and Hodgson, 1959).

After the last glacial maximum, 18,000 B.P. (years before present), the Earth began to warm and sea level rose. Many of the great mammals went extinct. The shoreline moved north and the rising water drowned the mouths of the Trinity and San Jacinto Rivers. The long shore currents deposited sediments across the new mouth of the rivers and an island was created. Behind the island, an estuary developed, known as Galveston Bay.

Archeological evidence uncovered by erosion and dredging in Galveston Bay tells the story of the great Pleistocene mammals and the men who hunted them. Fossils and artifacts were uncovered by erosion along the high banks of the western shore of the bay and the dredging of the Texas City Channel. In 1916, the fossil remains of the first of three mammoth skeletons were discovered on the eastern shoreline of San Leon (Blume, 1992; Saunders, 1992; Saunders and Blume, 1980). Near the sites of these discoveries local residents found many stone artifacts washing out of the bank. Similar artifacts have been dated to the Paleo-Indian Stage, circa 12,000 – 8,000 B.P. (Ricklis, 1994; Meltzer, 1986).

From 1895 to the early 1960's, the Texas City Dike was constructed using local dredged material that contained an abundance of fossils. When the clays used to build the first three miles of the dike started eroding, the remains of thousands of Pleistocene animals began to emerge. The fossil material came from mammoths, mastodons, bison, camels, horses, armadillos, saber-toothed cats, wolves, sloth and more. Some of these fossilized bones showed butcher marks or had been worked into tools and decorative items (Johnstone, 1975; Wolf, 1991; Few, 1991). Other documented sites where Paleo-Indian stone artifacts have been discovered and documented near Galveston Bay are: McFaddin Beach Site, Addicks Reservoir, Smith Point, and Bolivar peninsula. Except for the flint points and a few bone artifacts, little is known about these first residents (Hester, 1980; Patterson et al., 1999; Ricklis, 1994).

The next archeological evidence of human residents comes from the shell middens that were laid down during the period from circa 8,000 until shortly before the European Americans began to settle around Galveston Bay in 1810. The shell middens were mounds or high ridges of *Rangia* clams and (or) oyster shells deposited near the shore of the bay or on tributaries. For thousands of years the hunter-gatherer tribes camped on the shores of Galveston Bay at these midden sites. They came to eat these mollusks, a staple food that was always accessible. Each year the middens grew, fed by the empty shells and other materials left near the camps. Some of these middens gained religious significance and were used as cemeteries (Aten, 1983; Campbell, 1957).

Early indigenous people of Galveston Bay moved with the rhythms of nature that controlled their food supply. Primarily fishermen, they traveled along the shores of the bay and gulf, fishing with nets, traps and flint armored projectiles. Punched oyster shells used as weights on fishing nets are found at eroding midden sites on East Bay and West Bay mingled with the shells that were discarded from meals.

Another lasting change made to the environment by these early inhabitants is the introduction of non-native plants. On and near midden sites, plants with long histories of use as food, medicine and dyes can be found. Many of the plants are native to east, central and west Texas, not the upper Gulf Coast.

During the late 1700s, the Karankawa and the Coco, natives of the mid and lower coastal regions, moved to Galveston Bay. By 1800, these groups had set up permanent camps on old midden sites at Redfish Bar, Red Bluff, and the mouth of the San Jacinto River. These two tribes had been traveling to Galveston Island seasonally to fish and hunt for centuries (Aten, 1983; Dyer, 1916)

The Karankawa, Coco, and Tonkawa tribes also became regulars at Lafitte's town, bringing hides and other things to trade (Dyer, 1916). Unfortunately these tribes did not experience the same relationship with Stephen F. Austin's settlers. By the time Texas won independence from Mexico, the people of these hunter-gatherer tribes not killed by the settlers were pushed off their tribal lands into Mexico.

Galveston Bay, a Cornucopia of Resources: Early Settlement to 1850

The Islands: A Changing Landscape

Midden burial site eroding into the ship channel at the town of San Jacinto. (Courtesy John Ward)

Galveston Island

Galveston Island until 1816 was a low flat uninhabited barrier island except at the seasonal campsites of Native Americans. The whole length of the island was protected by sand dunes of varying heights and widths. The interior was tall grass prairie with several small brackish ponds and one "sweetwater" lake. The bay side of Galveston Island was made up of marsh and bayous. These areas were constantly accreting with sediments and shell deposited by the currents flowing into West Bay. On the bay side of Galveston Island, directly across from Virginia Point, was a group of oaks named Eagle Grove for the bald eagle that nested there yearly. This grove was destroyed when the first railroad bridge was built in the 1850s to connect the island to Virginia Point (Hayes, 1879 reprint 1974; WPA, 1936).

Pelican Island

Colonel Warren D.C. Hall, a long time resident of west Galveston Island, was one of the early visitors to Galveston Bay in 1815. Colonel Hall gave the historian, Charles Hayes, a comparison of the smaller islands in the bay between his earliest viewing and 1850 when the first surveys of the bay were made.

> *"In 1815, Pelican Island was merely a narrow slip of a marsh, on which it was impossible to walk dry-footed, except on a spot that was a hundred feet over, which was all that was dry. The marsh was covered with seaweed growing in the mud, and covered with water at all ordinary tides, and was not visible at any distance off. I saw the island again in 1820, when it had increased to a kind of shell-bank, twenty or thirty yards over, and one hundred and fifty to two hundred yards*

in length on the east side, and had a few small bushes growing on it. The rest was still a marsh, but had increased in extent greatly since 1815."

By 1820 Pelican Island was a noted nesting site for the brown pelican, and by 1850 it had accreted to be the largest of the islands located entirely within the bay. The island was described as being four miles from the city and island of Galveston, and being four miles in length and about one-half mile wide (Glass, 1986; Hayes, 1879 reprint 1974).

Deer Islands

Colonel Hall visited the Deer Islands in 1820. He states that,

"there was not then an acre of dry land on the largest of them, and they were all entirely covered with water at ordinary high tides. They were known as 'Egg Islands,' and there was not then a bush or shrub upon them."

The name Deer Islands was given by the early settlers for the large numbers of deer that waded the reef and swam across the channels from the mainland to feed on the rich, luxuriant grasses growing on Galveston Island. In 1850, these islands were surveyed and North Deer Island was found to contain eighty acres of good land. South Deer Island had an area of about two hundred acres. When Charles Hayes wrote his book *Galveston in the 1870s*, he noted that the accretion was still occurring (Dyer, 1911; Hayes, 1879 reprint 1974).

Vingt-et-une Islands

At the beginning of immigration into Texas, Elias R. Wrightman surveyed Galveston Bay for Stephen F. Austin. One of the landmarks he listed to mark navigation between the entrance into the bay at Bolivar and the Trinity River was an island he called "Bird Key". This island was described as a colonial waterbird nesting island and rookery in 1831, and later referred to by the French name, Vingt-et-une, for the 21st island of Redfish Bar. This French name was later shortened by the English-speaking settlers to 'Vantoon Island' (Helm, 1884, Glass, 1986).

Redfish Bar

Wrightman described Galveston Bay from Point Bolivar to the San Jacinto River as being three distinct bays: East Bay, Galveston Bay (included West Bay) and Trinity Bay. Trinity Bay was all of the bay system lying north of Redfish Bar. Wrightman had this to say about navigation through the bay.

"The Trinity Bay is about nine feet deep, the entire bay is intercepted by a shoal reaching clear across from Davis Point [Eagle Point] on the west, to Persimmon Point [Smith Point] on the east, a distance of eleven miles, called Redfish Bar, with only a pass near the middle admitting vessels to pass which have draught of about seven feet, when they may ascend to the San Jacinto and Buffalo bayous. But at the harbor of Galveston ... vessels drawing sixteen feet may enter by passing around Campeachy and entering the harbor directly south of Point Bolivar."

(Helm, 1884 reprint 1987)

Redfish Bar, the great barrier across the bay received its name from the Spanish and Mexican fishermen who came regularly to harvest the abundant redfish, which fed along the miles of oyster reefs. They called it Barra de las Pescador Encarnador (Glass, 1986).

From a book published in England in the 1840s we are given a view of Redfish Bar from the high bank of Eagle Point.

"...a vast expanse of bay, studded with numberless little islands or banks of nothing but shells, entirely destitute of verdure, but rendered beautiful by fanciful forms their lines composed...it is called Redfish Bar..." (Hooten, 1847)

The shell gravel of the reef was constantly being moved by the currents causing the topography of the bar to change with strong tidal current. The depth of the natural channel through the bar could vary by as much as two feet as it filled with loose shell and sand or was scoured by floodwaters.

Land Use

Land formations have always influenced how land is developed. The land around Galveston Bay was flat coastal prairie with ribbons of riparian forests snaking across the landscape to end at the bay. Higher elevation middens developed at the campsites used for thousands of years by early native tribes. The middens that accumulated at some sites on the fringes of Galveston Bay became topographic land features. Some had elevations of over twenty feet above sea level. Many of the early European-American settlers used them as home-sites, and the shell from the middens was used as construction material for wagon paths.

The riparian corridors of the rivers, creeks and bayous were the first places around the bay to be settled. The soils there were sandier and drained faster. Wild game abounded in these greenbelts and there was always fuel for a fire. Early settlers depended on the waterways for transportation routes inland from Galveston Bay.

In the 1820s, two towns, Lynchburg and San Jacinto, were established directly across from each other on the lower San Jacinto River at the juncture of the river and Buffalo Bayou by Nathaniel Lynch. Several more towns were platted on the San Jacinto, Buffalo Bayou and other tributaries flowing into the bay, including the town of Anahuac platted in 1831 (Foster et al., 1993). The two cities that would grow to most influence the future of Galveston Bay would be Houston platted in 1836 and Galveston in 1838.

Water Use

For the early settlers, water for household use and drinking came mostly from creeks, rivers and the upper reaches of the bayous. Cisterns to catch rainwater were common, and wells had to be hand dug, so they were at times shallow and their quality poor. Waterways provided water for household and industrial use. Also they aided in the removal of trash and the dilution of sewage waste.

Fisheries

Shrimp were harvested by seine as they migrated out of the bay at the inlets at each end of Galveston Island. A young Irishman named Sheridan documented this fishery in 1839-1840. He was familiar with the European prawn fishery and was impressed by the size of the Galveston Bay shrimp, describing the average length of the Texas prawns to be approximately six or seven inches. He described the quantity of one seine haul to be seventy pails of shrimp plus many pails of fish. The other seafood he describes as being sold at the Galveston dock are oysters, flounder, mullet, redfish, skate, turtle, crabs, and many fish he had only European names for (Sheridan, 1954).

The Redfish Bar fishing industry was well described by Charles Hooten, an English visitor to Galveston in the early 1840s. His book, *San Luis Isle* (1847) tells of his visit to Edwards Point at San Leon to stay at the headquarters of a fishing business owned by a doctor. He first accompanied the fishermen to hunt terrapin.

> *"The terrapin, - a small kind of sea-tortoise, is used in Texas for the manufacture of soups. They had engaged to supply one of the hotels with, I think, two thousand...Anxious to see the sport, I set out with them at about noon, - the hottest part of the day being precisely that during which the terrapins come to the surface of the water. A net fifty or sixty yards long was provided for the taking of them, - a smaller one to cover the boat with and prevent their escape when caught, and an axe to kill a dangerous kind of fish called "alligator gar" with, in case any should get into the net. The sky was wholly-cloudless, the sun burning hot, and the water beautifully calm, as we rowed amongst the little shell islands...the noses of many terrapins were seen sticking out of the water,." (Hooten 1847)*

By five o'clock that afternoon they had a boat loaded with three hundred terrapin, a great quantity of redfish, flounder and other unnamed fish. As they made their last haul of the net two hawksbill turtles were taken. The author describes them as "being the only pair ever known to have been caught in Galveston Bay."

Shipping

The natural harbor at the eastern end of Galveston Island attracted mercenaries and privateers in the 1800s before settlement began. These men used the island as a base as they conducted a war on Spanish trade ships in the name of helping the Mexicans gain independence. This short-lived piratical shipping industry lasted from about 1815 to 1821. Jean Lafitte was in charge of the last settlement.

The privateers had plenty of silver, but lacked food supplies and wood for cooking and heating. This need brought a new type of settler to some of the riparian areas around the Galveston Bay, called leatherstockings. They hunted wildlife for food and hides, grew a few vegetables and cut firewood. These necessities were loaded on to small boats and transported to Galveston to sell to the privateers (Epperson, 1995; Holley, 1836, 1990).

In this period, the principal function of shipping was to bring new settlers and needed supplies to Texas. On October 17, 1825 Galveston was made a port of entry although no town, customhouse or wharves had been built to accommodate shipping. In 1830 a small customs house was erected on the eastern end of the island. A few years later Colonel Juan Davis Bradburn closed all maritime ports of Texas except Galveston, and designated Anahuac the only place of entry and collection of customs. Galveston Island remained undeveloped until after the revolution

Tannery slaughterhouses were built at San Leon and on Dickinson Bayou after the railroad was constructed in the 1850s. Chambers County cattlemen drove herds of longhorn cattle across Redfish Bar at low tide when they only had to swim across the narrow natural cut. (Courtesy Wallisville Hertigage Park)

was won in 1836 and the Republic of Texas had formed.

Galveston was incorporated as a city in 1839. That same year the steamboat tonnage doubled and Galveston became an active cotton market (Hayes, 1879 reprint 1974). During the days of the Republic of Texas, maritime shipping increased greatly. During the first quarter of 1843, the following domestic exports were shipped from Galveston to Great Britain: 3,663 bales of cotton, 1,810 bundles of cattle hides, 46 casks and 149 bags of pecans, 3 bundles of deer skins, 1 box of beeswax, 3 barrels and 1 box of beef tallow, 1 box of dressed deer skins, 1,273 white oak staves, 364 sacks of bones, 4,000 pounds of bones, 1 barrel of leaf tobacco, 1 buffalo robe, and 258 cedar logs (Hayes, 1879 reprint 1974). The plantations on the Brazos River had cotton, sugar, timber and stock to export, but shipping by water from the Brazos was difficult. Most cargoes were taken to Galveston by small boats and lightered onto deep-water ships.

To the north, the new city of Houston was chosen as the capital of the Republic of Texas in 1836. In January 1837, the city had few real structures, tents were the main housing. By summer the quickly growing city of Houston was incorporated. Steamboats plied up and down Buffalo Bayou from Galveston, and by 1841, Houston City Council had established the Port of Houston with authority over the wharves, landings, slips and roads on the banks of Buffalo and White Oak bayous within the city limits.

The Trinity River had navigation to Liberty. In 1848 city leaders in Dallas began discussing the possibility of having a navigable Trinity River channel from Dallas to Galveston Bay (Alperin, 1977; Johnston, 1991; Sibley, 1968).

Resources and Industry

Cattle

Cattle have been documented in Texas since 1714 when Louis de St. Denis came to "Tejas" and "found cattle in great abundance." By 1775, Texas had thousands of unbranded wild cattle and horses (Jackson, 1997; Love, 1916). The wild cattle and horses descended from stock that escaped from Spanish herds, and would become one of the first major resources to be managed around Galveston Bay. These herds of wild Spanish cattle were the ancestors of the tough, resilient longhorns that would become a symbol of the Texas west.

The saltgrass prairies with their nutritious grasses would become the key element in the open range cattle industry around the bay. The cattle industry was begun on the eastern side of the bay after 1819 by immigrants who came from Louisiana and were second or third generation saltgrass stockmen. They were masters of the Spanish methods of managing stock from horseback and using the saltgrass marshes to fatten cattle during the winter. They came in extended family groups with their slaves to settle near creeks and bayous, and immediately began gathering the wild cattle.

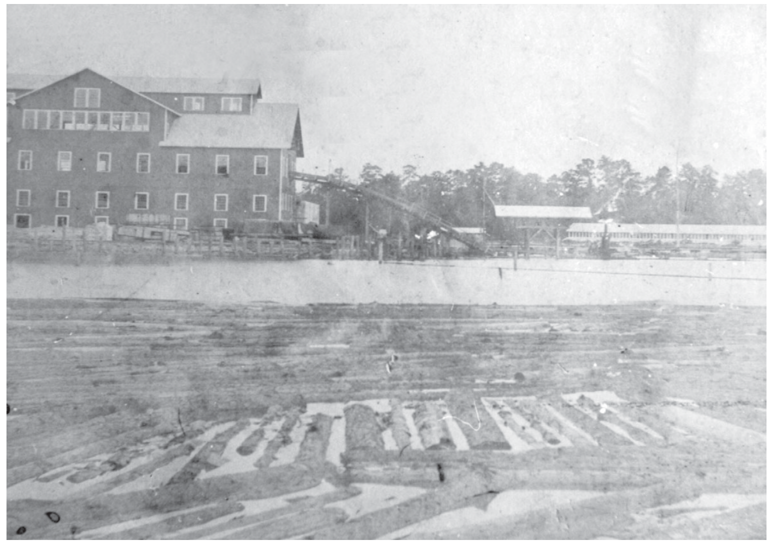
By 1831 one of these cattlemen, James Taylor White who settled on Turtle Bayou, had established a herd of over 3,000 head of branded free-ranging cattle (Anonymous, 1834, 1952). By 1840, his herd had increased to over 8,000 head (Byford, 1983). It was James Taylor White who is credited for being the first to bring the range management practice of burning to the coastal prairies of Galveston Bay (Erramouspe, 1996).

Lumber

From the early 1800s until the early 1900s, lumber production depended on water transportation. This caused the riparian corridors to be exploited before other forests. The bottomland forests were not only the easiest to access, they also contained the most prized woods of that era including cypress, cedar, water-woods and tall straight pines. These trees were felled as near as possible to the body of water. The logs were hauled to the water's edge by oxen and rolled into the waterway to be rafted down the rivers to the sawmills that were also established near or on the bay. The milled lumber was loaded onto ships anchored in Galveston Harbor and transported to places as near as New Orleans or as far away as Europe (Henson and Ladd, 1988; Johnston, 1991; Smith, 1934).

Clay

The heavy clay found along the banks of bayous and creeks around the bay was first dug by the Native Americans to manufacture their pottery. The first settlers used this same clay for making bricks. Brick making was a very profitable business during the late 1830s. Bricks imported from Boston were reported by a man of the British diplomatic service to be going for forty dollars per thousand at Galveston, and skilled brick makers newly emigrated from England were making up to forty dollars a week (Sheridan, 1954). Several brick factories were established at Cedar Bayou and on other bayous and creeks around the bay. The heavy alluvial clay was mined on the banks of many bayous, which changed their natural shores. Galveston Bay bricks were transported on barges



Cummings Sawmill and log trap at Wallisville circa 1900. (Courtesy Wallisville Heritage Park)

pulled by shallow draft schooners to Galveston, Houston and Harrisburg to be used in the construction of buildings, homes and roads (Sheridan, 1954).

The Years of Change: 1850 – 1900

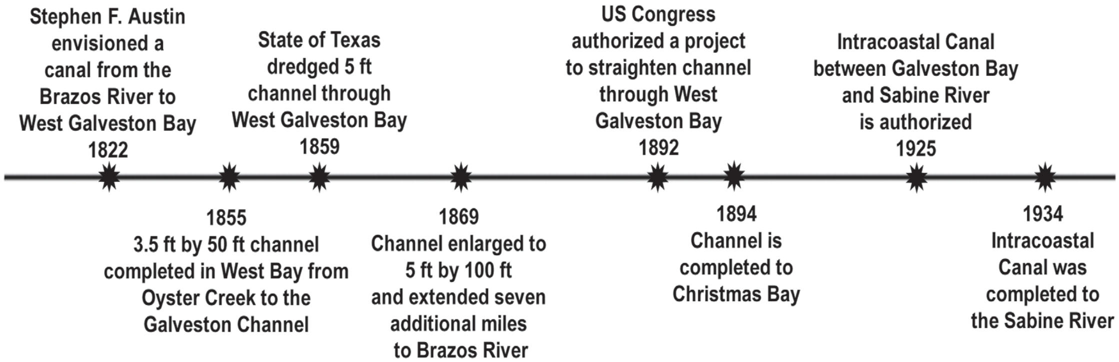
In 1850, the U.S. Coast and Geodetic Survey began a detailed mapping of the entire Galveston Bay system, and produced the first accurate navigational charts of the bay. Lighthouses were proposed to mark the treacherous channels through the most dangerous obstructions: Clopper's Bar, Redfish Bar, Shoal Point and Half-moon Shoal.

Navigational Projects

Intracoastal Waterway

Years after his death Stephen F. Austin's 1822 dream of a channel from the Brazos River to Galveston Bay would become a reality. The plantations along the Brazos River needed a safe dependable way to ship their cotton crop. On February 8, 1850 the Galveston and Brazos Navigation Company was chartered and contracted to build a canal from the Brazos River through West Galveston Bay. This 50-foot-wide channel from Oyster Creek to San Luis Pass and through West Bay to the Galveston Channel was finished in 1855. In 1869 this channel was extended the seven miles from Oyster Creek to the Brazos River and enlarged to a depth of five feet and a width of 100-feet.

Congress authorized a survey for inland cuts and channels along the margin of the Gulf of Mexico in 1873. During the 1880's hurricanes damaged the



Construction of the Gulf Intracoastal Waterway was initiated to provide a protected inland route for the waterborne transportation of goods and troops in the event of war. The waterway has been modified numerous times since its inception in the 1800s. (Modified from Alecya Gallaway)

Dredging the Texas City Channel. (Courtesy Moore Memorial Public Library)

existing east-west channels that could contribute to an inter-estuary shipping route. Little would be done to make the interstate channel a reality until 1892 when Congress authorized further dredging. In West Bay, the channel was dredged to a depth of 3 1/2 feet and a width of 100 to 200 feet up to Christmas Bay and the route was straightened (Alperin, 1977; Sibley, 1968).

Houston Ship Channel

A flood in 1850 filled in Buffalo Bayou with mud from the unpaved streets of the city and from erosion of the banks that were cleared for easier navigation. Steamship traffic to the city of Houston was almost entirely stopped until the city had the mud dredged from the bayou in 1852. That same year the Houston Navigation Company was organized.

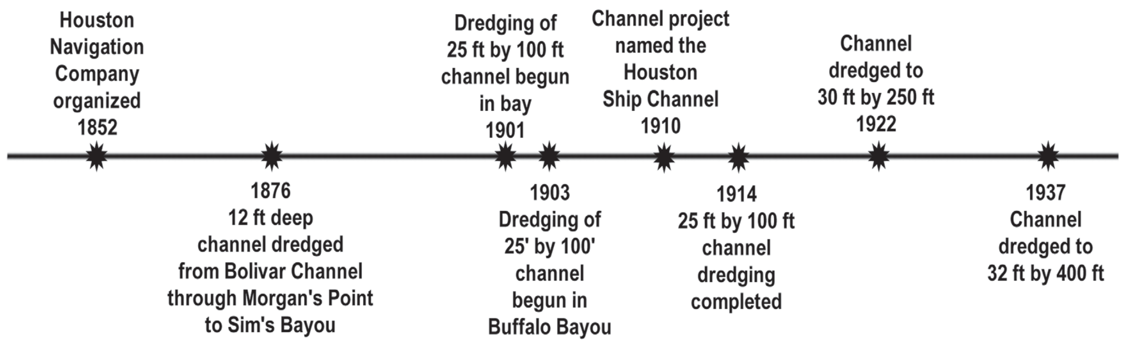
Clopper's Bar and Redfish Bar had been the natural barriers hindering shipping from Galveston to Houston. Schooners attempting to bring settlers through Galveston Bay ran aground and passengers were shipwrecked on these reefs. Only shallow draft steamboats were able to navigate in the shallow bay waters. In 1857, a contract was let for dredging through Clopper's Bar and Redfish Bar.

During the Civil War, the Union Blockade stopped regular shipping and all channel improvements. Lighthouses in the bay were burned, and only local navigators familiar with the channels were able to maneuver through the shallow, reef-filled bay.

After the war was over, the lighthouses were rebuilt and dredging projects for larger channels were undertaken. In 1871 a 9-foot-deep channel from Bolivar Roads to Main Street in Houston was finished. Congress appropriated money in 1872 to improve the channel through Redfish Bar. Commodore Charles Morgan signed a contract in 1874 to dredge a 9-foot-deep channel 120-feet-wide from Galveston Bay to Houston. The U.S. Army Corps of Engineers started dredging a 12-foot deep channel from Galveston in 1877 (Alperin, 1977; Johnston, 1991; Sibley, 1968). Work began in 1899 on a project, which would keep the upper reaches of the ship channel from shoaling. A pile and brush dike would be placed along the channel from Morgan's Point to Redfish Bar (Alperin, 1977; Sibley, 1968).

The Jetties

In the twenty years following the Civil War, the U.S. Army Corps of Engineers worked on projects to keep a deep-water channel open in Galveston Bay from Galveston Island to Houston. A proposal was made in 1872 to remove the bar between Fort Point and Pelican Spit and to deepen the Galveston Channel over the outer bar to 18 feet. Stone quarries



Much of the Houston region's growth has been attributed to the development of the Houston Ship Channel. Periodically, the channel has been enlarged to accommodate increasing size and number of ships. (Modified from Alecya Gallaway)

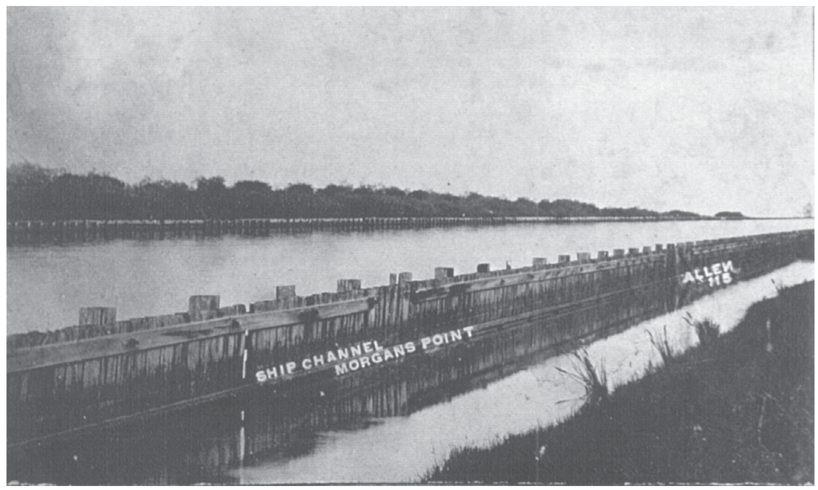
had not been established in Texas so gabions, 6-foot by 6-foot cages of wire and wicker covered with cement and filled with sand, were used as submerged jetties. These were placed 5 to 6-feet below mean tide to extend the Fort Point breakwater. This gabionade was completed in 1876.

Both Congress and the Texas Legislature supported the construction of jetties and other harbor improvements. The federal Rivers and Harbors Act of 1880 appropriated $175,000 for Galveston Harbor improvement and a new jetty project. In 1883, the Texas Legislature authorized coastal cities to issue bonds for harbor improvements. The foundation layer of the north jetty was completed and the second layer was near completion by 1883. When finally complete the north jetty extended out 25,907 feet.

Congress appropriated $300,000 in 1886 for work on the south jetty. The north and south jetties would be separated by 7,000-feet at the Gulf and built with rubble stone capped with concrete. The slopes would be covered with huge granite boulders and the outer section built as a solid concrete pier. It would take until 1897 before the south jetty was considered complete at a length of 35,603 feet.

Texas City Channel

On March 23, 1893 the U.S. Government granted permission to the Meyer Brothers of Duluth Minnesota to dredge an 8-foot-deep channel for a deep-water railroad terminal. The Texas City Terminal Company dredged a seven-mile long, 16-foot deep channel from the Galveston Harbor in 1895. In 1899, the army engineers took over the channel project and deepened it to 25 feet (City Commission, 1963; Holbrook, 1971).



Morgan's Point Timber Pile Dike circa 1904-1908. Construction of the 60,000-foot dike of timber pilings and brush began in 1901. The dike was completed in 1902 using 500,000 linear feet of timber and 6,000 cords of brush. Dredged material was then placed on the eastern side of the structure. This dredged material added to the tip of Morgan's Point began what today is called Atkinson Island. (Courtesy Gallaway Collection)

Land Use

Shell

Settlers in the developing towns around the bay used the shell from the Native American middens as a source of gravel. With the coming of the railroads, the midden shell became a major resource. Rocks and gravel for paving materials were absent from the coastal prairies. When railroads proposed to cross the wet prairies on the western shore of Galveston Bay, a ballast material had to be found for the base of the tracks. From the mid 1800s until the late 1890s, shell middens on the western shore of Galveston Bay were heavily mined for this purpose.

One of the largest of the Galveston Bay middens was located at the entrance to Clear Lake. It was a high ridge of *Rangia* shell that was formed by the currents and thousands of years of midden use by

Farmers shocking rice. (Courtesy Wallisville Heritage Park)

Native Americans. Its huge size protected the snaking channel into Clear Lake, keeping the low salinity bay waters from entering into the upper reaches of the lake except during storm tides. This barrier that once joined land where the Kemah waterfront is today was heavily mined before the 1900s.This midden was reported to be nearly thirty feet high in places and contained numerous burial sites according to the daughter of the man who sold the shell to the railroad. This ancient *Rangia* shell midden deposited by Native Americans for thousands of years was sold for seventy-five cents a rail car load (Benson, 1935; Kenyon, 1976).

The shell of the middens was insufficient to meet demand for construction material and shell mining expanded to the oyster reefs and islands in the bay. To mine the shell, small schooners and barges were brought in close to a shell island during high tide and anchored off. During low tide the loose shell would be shoveled into the boat's hold, and at the next high tide the boat would shove off the bar and sail to Galveston or up Buffalo Bayou where the shell was loaded onto mule drawn wagons (Galveston Daily News, 1940).

Agriculture

Along the railroads that ran from Galveston to Houston farming communities sprang up where the shipping docks were built. The railroad companies promoted this growth by platting towns and bringing excursion trains full of mid-western farmers to see the rich, productive, rock-free prairies that were plow ready and cheaply priced.

The saltgrass prairies that fringed the edges of Galveston Bay provided rich, nutritious grasses for cattle production. These wet prairies were never productive for growing cotton, but were well suited for rice farming. The low heavy clay soil of the marshland was ideal for holding water during rice cultivation. Near the turn of the century, all around the bay, canals were dug from fresh water sources to flood the new rice fields. The first canals were dug with oxen in 1888 by the Jackson family on Double Bayou in Chambers County. The Hankamer-Stowell Canal Co. began pumping water for rice irrigation out of Turtle Bay in 1899.

Brick Manufacture

In the years from early settlement until the Civil War, brick making was done locally by slave and immigrant labor. After the Civil War a building boom in Houston and Galveston made brick manufacture a major industry around the bay. Some of the larger factories located near the bay removed tons of clay from the tributaries.

Brick factories were established on both the Harris and Chambers County sides of Cedar Bayou causing it to be one of the waterways most altered by clay extraction. The area where the bayou was located contained all of the right ingredients for successful brick-making: heavy clay for hard bricks, riparian hardwoods for fuel, and water deep enough for barges and shallow-draft schooners to be loaded with bricks and sailed to Galveston (Henson, 1986). Other brick factories built before the turn of the century were near League City on Clear Creek, and at Factory Bayou in San Leon (Gallaway, 1999a; Warco, 1982).

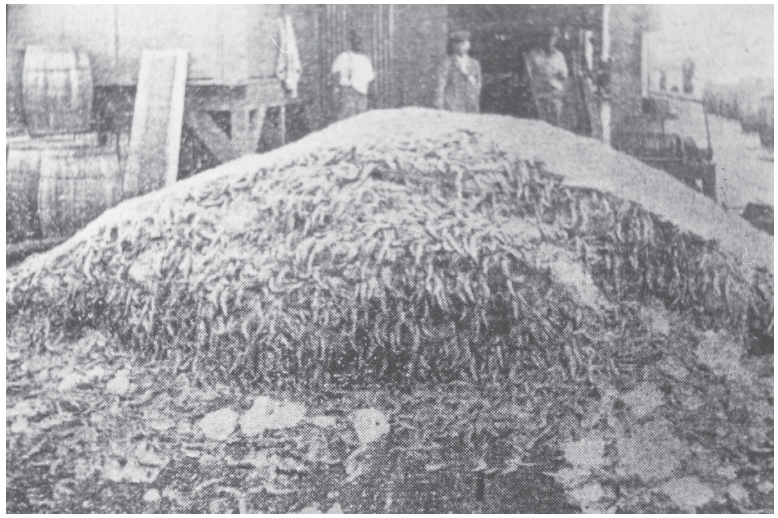
Lumber

Lumber continued to be a resource that made many of the first fortunes in Texas, but the prized cypress and large oaks were gone from the old-growth bottomland forests near Galveston Bay. Woodcutters had to fell trees further and further inland and struggle with oxen to get them out.

Water Use

Until railroads were built across the coastal prairies, the immigrants settled along the rivers, bayous and creeks to provide themselves and their stock with a constant supply of good water. From the 1850s to the late 1800s, the railroads brought settlers to areas of the

Artesian well at San Leon 1982. (Courtesy of Gallaway Collection)



Shrimp on Galveston dock waiting to be packed in barrels for shipping to Japan in 1920. (Courtesy Gallaway Collection)

prairies located far from sources of flowing water. Subsequently, ground water use increased. Artesian wells were drilled all around the perimeter of the bay and along the railways. The wells flowed constantly, water not captured for use spilled onto the prairies and into the bay. This prolific waste of groundwater contributed to land subsidence around Galveston Bay (see Chapter 5).

Fisheries

The oyster industry was limited to local trade until after the 1870's when cold shipping and processing industries were developed. In 1885, the oyster industry was reported to employ approximately five hundred men and have fifty boats working the bay. Galveston reportedly shipped about 25,000 oysters daily; most of them to markets within the state. The city of Galveston alone was said to consume 25,000 to 30,000 oysters daily in season (Galveston Daily News, 1885).

Natural oyster reefs of Galveston Bay were so heavily harvested after cold shipping was developed that the state intervened. In 1895 the state Oyster and Fish Commission was established. Oystermen were encouraged to lease portions of the bay bottom from the state and taught how to raise oysters. Private oyster reefs in Galveston Bay took in 3,861 acres by 1912 (Galveston Daily News, 1910, 1912; Tucker, 1929).

Shrimping was done by hand until after 1900. Cast nets and haul seines were used in the marshes to harvest small shrimp, which were then sun-dried or pickled in salt for export. At the inlets of Galveston Island, large migrating shrimp were seined for local sales (Iversen et al., 1993).

Terrapins were always a popular item at the Galveston harbor, but were so common in the bay that the only market for them was at the hotel restaurants in Houston and Galveston and the inland fish markets. Sea turtles were not harvested in the bay, but were shipped to Galveston from the sea turtle canneries located in the coastal bend area (Doughty, 1984).

The fishing industry for the whole state of Texas was small, with only 291 fishermen listed as fulltime in 1880. Most fishing was done in Galveston Bay out of Houston and Galveston or out of Indianola at Matagorda Bay. Methods most commonly used for fishing included bay and beach seines, hook and line and the pole gig method used for flounder fishing at night. The most popular market fish were redfish, sea trout, mullet, croakers and sheepshead (Doughty, 1984).

Transportation and Shipping

Maritime shipping before the Civil War was limited to sailing vessels. Domestic exports shipped by sea from Galveston in 1860 were 193,963 bales of cotton, 235 barrels of salted beef, 96,017 cattle hides, 11,245 horned cattle, 9,003 barrels of molasses, 1,792 bags of pecans, 278 bales of pelts, 3,462 hogsheads of sugar 227 sacks of wheat, 4,382 bales of wool. After the Civil War steamships began to replace the sailing ships, and they soon became the major shipping vessels (Hayes, 1879 reprint 1974).

There were only eight railroads in various stages of construction in the state of Texas before the Civil War. One of these was the Galveston, Houston & Henderson Railroad chartered in 1848. Construction began in 1853 and it was completed from Houston to Virginia Point in 1859. A bridge to be constructed from Virginia Point to Galveston was authorized in 1857, and the first train crossed from the mainland to Galveston in January of 1860. This railroad connected to the Buffalo Bayou and Brazoria Railroad at Harrisburg.

The railroad to Galveston now connected with the other railroads from Houston including the Houston & Brazoria, the Houston & Central Texas, and the Houston & New Orleans. Railroad building was halted by the Civil War until 1867 when the great railroad expansion across America began (Hayes, 1879 reprint 1974). Before 1900, three railroad bridges and a wagon bridge would join Galveston Island to the mainland at Virginia Point (McComb, 1986).

Resources and Industry

Topsoil

Topsoil was a local resource first dug from the pimple mounds by the families who settled on the prairies. They called the mounds sand knolls. The rich sandy loam soil was loaded onto wagons and transported to their kitchen gardens. Later this became a prairie industry for many hard-working entrepreneurs who made their livings selling the topsoil to settlers around the bay. As technology advanced, digging and hauling became more efficient, the mounds were completely removed from most prairie lands on the western side of the bay (Deats, 2000).

Natural Gas

There were many clues in this period of the abundant fossil fuel resources of the region that would soon produce fame and fortune. Mr. Smith, who owned the property at High Island that today is the Houston Audubon sanctuary known as "Smith Oaks," had a water well that produced natural gas. The surface of the water at the top of the well boiled with such a force that the sound was described "like a bunch of geese cackling." Smith ran a pipe from the well to his house, and had gas jets arranged like a stove to cook on. He amazed visitors by cooking eggs on one and bacon on another while at the same time boiling coffee (Anderson, 1907).

Industrialization: 1900 – 1950

Human Alterations of the Bay and Surroundings

Houston Ship Channel

The 1900 Storm caused great destruction to the city of Galveston and the towns around the bay. It also gave Houston the advantage in the political struggle over whether a deep-water channel would be dredged to its inland port. In 1901, construction began on a 25-foot-deep by 100-foot-wide improved channel through the length of the bay. At the same time, work began on a 60,000-foot dike of timber pilings and brush that would extend from the dredged cut in Morgan's Point to the new channel cut through Redfish Bar.

The new channel at Redfish Bar was nearer to the western shore of the bay than the original one. The dike extending along the eastern side of the channel from Morgan's Point was completed in 1902, and the dredged material from the new channel was placed on the eastern side of the timber-pile structure. Over the years more dredged material was deposited on the eastern side of the channel creating a long spoil island later named Atkinson Island.

In 1910, the name of the channel was officially changed from the "Galveston Ship Channel and Buffalo Bayou Project" to the "Houston Ship Channel". In 1934 work began on a project to enlarge the channel to a depth of 32-feet and a width of 400-feet. It was completed in 1937. World War II interrupted shipping operations at the ports of Galveston and Houston, but after the war shipping increased and intense industrial and municipal development began an era of rapid alteration of Galveston Bay.

Raising the City of Galveston

Any settlement on Galveston Bay is vulnerable to storm surges from hurricanes and tropical storms. This was especially true of Galveston in the late 1800's. The city had removed the natural 12 to 15-foot high sand dunes from the east beach area in the 1800s to allow easier carriage access and give better visibility of the beachfront. The 1875 hurricane caused severe damage. City officials began looking for a way to make a barrier to help protect them from future storm tides. Salt cedars were planted on the old dune line in the hopes that they would catch sand and re-establish the removed dunes.

The hurricane in 1886 that destroyed Indianola, ravaged Galveston and convinced some city leaders that a sea wall was the only solution to protect Galveston from inundation by gulf waters. Residents of Galveston protested the issuance of bonds for this project so strongly that it was never put to a vote. The 1900 hurricane battered Galveston Island, destroying most of the city and killing an estimated six thousand people throughout the Galveston Bay region. The beachfront lost over 300-feet to erosion. Immediately after the storm businessmen joined in an effort with the city to protect Galveston from future storm waters. In 1902 a plan was accepted and funds appropriated for the building of a sea wall and raising the city grade to 17-feet above mean low tide.

Raising the city of Galveston was a tremendous dredge and fill operation. New technology allowed huge deposits of sand to be removed from the east beach area, Offatts Bayou and other sites on the West Bay side of Galveston Island. This dredged material was pumped in to fill the area behind the new seawall. As the seawall was extended west, more sand was removed from Offatts Bayou to build-up the Fort Crockett site. Later when the seawall was extended to the extreme eastern end of the island more sand was removed from the "Atlantic Hole" pit that later was named the East Lagoon. Westward extensions continued on the seawall through the 1950s.

Intracoastal Waterway

In 1902 the purchase of the Galveston and Brazos Navigational Company by the U.S. Government was completed. The final leg of the Intracoastal Waterway, the channel between Galveston Bay and the Sabine River was authorized in 1925. Nine years later in 1934, the long planned channel through the inland coastal waters of Texas was opened.

Texas City Channel

On July 28, 1900, dredging on the 25-foot-deep by 100-foot-wide channel began, only to be halted by the 1900 hurricane when the dredge washed ashore. The deeper channel opened five years later. By 1909 the channel had shoaled again. A 27-foot by 200-foot channel was authorized in 1910 and completed one year later. In 1913, Congress approved a 30-foot by 300-foot channel.

When the first clamshell dredge dug the deep-water rail terminal off Shoal Point in Texas City in 1893, the dredged material was deposited on the bottom of the bay north of the channel. The process continued creating a spit of land over the years from the shore that paralleled the channel. Currents continually washed material into the channel. In 1913, Congress appropriated $1,400,000 for a timber-pile dike to be constructed on the north side of the channel to keep the dredged material and river sediment from migrating into the channel. The dike was finished in 1915 using 950,000 linear feet of timber pilings.

In 1916 the channel was enlarged to a depth of 30-feet and a width of 300-feet. The new dredged material was continually added to the existing dike greatly increasing its width and length. Granite boulders were placed on the edge of the channel in 1931 to reinforce the deteriorating timber piles. That same year a strip of land down the middle of the dike 1,000-feet wide was patented to the city of Texas City by the Texas Legislature, and the channel was increased to 30-feet by 800-feet. In 1934, the rubble-mound Texas City Dike was finished and the Texas City Harbor was enlarged.

Dredging irrigation canal from Turtle Bay in 1902. (Courtesy Wallisville Heritage Park)

Turtle Bay/Lake Anahuac

Turtle Bay was a brackish to fresh water estuary fed by storm water run-off from Turtle Bayou and low salinity water from Trinity Bay. Prior to 1900, logging was the major industry for boatmen on Turtle Bay, and the channel through the bay was important to their industry. After a century of logging, the lumber industry had exhausted the old growth riparian forests above Turtle Bay, and rice production was quickly replacing logging as an important industry. An irrigation canal had been dug from the lake in 1902, but salt-water intrusion ruined the crops.

Congress passed an Act in 1902 that declared Turtle Bay non-navigable and authorized a 4-foot-wide by 50-foot-deep channel from the entrance of Turtle Bay to Turtle Bayou. In 1911 the Trinity River Irrigation District No.1 was established. Bonds were issued in 1912 to build a bulkhead across the mouth of Turtle Bay. The 1915 hurricane destroyed the bulkhead. Cycles of salt-water intrusion and maintenance dredging continued until 1931 when the Trinity River Irrigation District began construction of a new bulkhead at the entrance to Turtle Bay.

Oil was discovered at Turtle Bayou in 1935, increasing opposition to the barrier. The problem was turned over to the War Department, which resolved the conflict by giving the district 60 days to finish all their work on the barrier, locks, and dam. The time limit was met and Turtle Bay was isolated from Galveston Bay, and later renamed Lake Anahuac.(Alperin 1977; Henson and Ladd 1988; Ward 1993)

Redfish Bar

Redfish Bar, the prominent land bridge between Eagle Point and Smith Point that was used to drive herds of cattle across it until the 1890s, was completed dredged away before 1950. Tons of shell gravel and reef shell were removed by the early clam shell dredges, loaded onto barges, and transported to land where it was used to build roads and railroads. Later the shell would be used as a source of calcium carbonate for the chemical industries that established around the bay. Still later, hydraulic dredges would remove even deeper shell. As World War II approached, reef shell from the bay supplied Galveston Bay based industries with about 4,500,000 cubic yards per year. After the war the amount of shell being removed from the bay doubled. This shell went into chemical manufacturing and construction (Galveston Daily News, 1941; Ward, 1993).

Demand for more shell was the cause of a 1954-58 geological survey to locate the ancient shell reefs buried under the bottom sediments of the bay. The survey maps gave the shell dredgers access to reef shell laid down as long ago as the Pleistocene. The removal of this shell and the live oysters building on top of it was a very controversial issue. Jurisdiction over permits for dredging that might affect wildlife was given to the office of the Texas Game, Fish and Oyster Commission in 1911. This same agency regulated the oyster fishery in the bay. The oystermen protested the damage of shell dredging to the live oyster reefs and the destruction of the habitat by the constant release of sediment into the bay waters. The protests continued for years, as more and more of the bay was affected by the turbid water. It was 1969, before mudshell dredging was banned in Galveston Bay (GBNEP, 1994; Ward, 1993).

Land Use

Agriculture production was a major use of the coastal prairies from the late 1800s. After 1900, a group of Japanese came to farm rice in Harris, Galveston and Brazoria counties. They brought cultivation methods that would revolutionize farming practices. The Japanese methods of budding and grafting plants were soon used to establish large citrus farms in many areas on western side of the bay. After World War II, men coming home from the war left the farms and went to work for the industries around Galveston Bay.

Construction of buildings and roads used increasing quantities of shell, soil and sand resources after 1900. The hydraulic dredge made river sand from the San Jacinto and Trinity rivers available. Bank sand from ancient river tributaries was the next soil resource mined from the coastal prairies. These "sand pits" created new pond habitats and wetlands on the coastal prairies.

Water Use

The demand for fuel for internal-combustion engines brought about a fundamental change in ground water usage from the aquifers under Galveston Bay. The growth of refinery operations on or near the new Houston Ship Channel and at Texas City was dependent on water resources. The refining process uses extremely large quantities of water, up to 1,851 gallons of water to refine one barrel of petroleum. During the late 1930s and early 1940s the artesian wells drilled in the late 1800s stopped flowing (Sibley, 1968).

Industry was not the only user of ground water in the region. Ground water irrigation was used for rice farming around Galveston Bay. The city of Galveston and the entire island depended on ground water from the mainland. The city of Galveston drilled wells at Alta Loma into the same water sand tapped by the early wells of the industries at Texas City.

As water demand rose, surface water sources were developed to meet the demand. During the

1940's the Houston region began to see some surface water use from Lake Sheldon and the San Jacinto River. In the 1950's, Lake Houston began supplying some of the city's water. Slowly the use of ground water was shifted to surface water as fresh water tributaries flowing into Galveston Bay were dammed and reservoirs built to meet the constantly increasing demand. The brackish water of Turtle Bay (Lake Anahuac) was converted to fresh water to meet the demands of the growing rice fields in Chambers County. Today water from the Brazos River is diverted to a reservoir at Texas City to supply industry (Gabrysch et al., 1974; Paulsen et al., 1941).

Fisheries

By 1910, the Galveston Bay oyster industry had grown to such an extent that articles filled the newspapers saying that the public oyster beds could no longer supply the demand. Problems, from slow growth to disease, plagued oyster production in Galveston Bay by 1913. A state biologist decided the cause was overproduction and recommended dredging to thin out the reefs. State law was changed and the dredging of live oysters was permitted. By 1929, this law had been misused and dredging was labeled "the source of all evils" to the loss of oyster production in the bay (Tucker, 1929; Galveston Daily News 1910, 1912).

The fishing industry still depended on bay and gulf seines to harvest fish. A marked decline in the fish population of Galveston Bay was noted before 1900. Breeding season closures were instituted in most of Galveston Bay to protect fish in nursery grounds. In 1907, the total catch of fish from Galveston Bay was 185,119 pounds. The state reported that the catch was not enough to supply local markets. Salt-water fish hatcheries were proposed as a solution to the shortage. Controversy between fishermen and the commissioner's over the closures to seining and netting kept restrictive netting laws from being passed until 1929 when all littoral waters were closed permanently to drag seines. Gill nets would replace the fishermen's drag seines for several decades (Tucker, 1929).

After 1920 the shrimp fishing industry became a vital fishing industry in Galveston Bay. Gasoline motors were used to power boats and canning factories were built throughout the bay. By 1932 the United States Bureau of Commercial Fisheries and the Texas Game, Fish and Oyster Commission began the first shrimp studies. After World War II, shrimping in Galveston Bay waters increased even more and it quickly became the leading fishery of Galveston Bay and the state of Texas (Gallaway, 1999b).

Goose Creek Oil Well, 1922. (Courtesy Houston Metropolitan Research Center)

Transportation and Shipping

The discovery of oil in the region and the increase in refining caused a shipping boom at Houston. In 1930 exports from Houston were 2,069,792 bales of cotton and 3,920,100 tons of petroleum products. Grain exports reached a total of 4,947,515 bushels that same year. Barely thirty years into the new century, Houston had taken the lead over Galveston in shipping by sea (Sibley, 1968).

Resources and Industry

Oil production came to Galveston Bay soon after the turn of the century, and by 1915 there were at least 25 wooden rigs at Tabbs Bay. By 1917, World War I had produced a demand for petroleum. Lumber barons were investing their fortunes in drilling for oil. Cattlemen who owned large acreage of rangeland began leasing to the oil companies. In 1908 oil was discovered at Goose Creek and the small community became an oil boomtown, but the closest refineries were at Beaumont and Port Arthur (Henson, 1993). Construction of the first refinery along the Houston Ship Channel on Buffalo Bayou began in 1918. Humble, now Exxon Mobil, built its Baytown refinery in 1919. By 1927 eight oil refineries were in operation on the channels in Galveston Bay. After 1930, new oil refineries were built on the upper reaches of the Houston ship channel, and on the southwestern shore of the bay at Texas City (GBNEP, 1994; Sibley, 1968). This early development was the beginning of a trend that resulted in the highest concentration of refineries and petrochemical plants in the world and a very high concentration of oil and gas wells in and around the bay.

Summary

Archaeological evidence shows that humans have been using the resources of Galveston Bay for at least 5,000 years. Early hunter-gatherers modified the bay environment by harvesting shellfish and other wildlife, producing shell middens and introducing plants from other ecoregions. After 1800, settlers exploited the fish, shellfish, prairies and forests in and around the bay to develop the early fishing, cattle and lumber industries. Commercial fishing for shrimp, oysters and fish continues today with modern technology, but the composition of the catch has changed.

In addition to its biological resources, the bay's physical resources were utilized as well. The bay and its tributaries yielded construction materials in the form of shell, sand and clay. Ranch land composed of upper prairies and lower saltgrass marsh areas were used over time for other purposes including farming, oil extraction and industrial and urban development. Riparian resources became scarce and the lumber industry disappeared from the vicinity of Galveston Bay.

Alterations of the bay for navigation include channels to three major ports and many smaller harbors. Dredged material from the Gulf Intracoastal Waterway, the

Texas City Channel, the Galveston Channel and the Houston Ship Channel have been deposited on the open bay floor or into designated containment areas creating planned and unplanned islands which alter bay currents. Heavy exploitation of buried shell and groundwater produced detrimental effects. Growth of the petroleum industry led to changes of land use in and around Galveston Bay. Industrial and residential growth increased the use of groundwater that attributed to subsidence and taxed the limits of aquifers.

Chapter Four

The Human Role, Present

The segment of the planet Earth called the coastal zone is especially important in the context of diversity and human interactions. This is by far the most populated and urbanized portion of our planet, as well as the richest and among the most perturbed. It is a bit surprising that it is also not the most familiar in concept and dimension, in view of the fact that so many people live within it or near it.

-G. Carlton Ray, Sustainable Use of the Global Ocean, 1989

Human activities in and around Galveston Bay have shaped the watershed for thousands of years. The categories of resource use are wide-ranging. From man's creation of the first shell middens to the present dredging of the Houston and Galveston Ship Channels, human inhabitants have had an impact on the bay and its surrounding landscape. Our influence on the physical and ecological components of the bay system has become more pronounced as our populations grow.

As the population surrounding Galveston Bay increases, additional stresses are placed upon the bay's resources. These stresses impact the health of the bay and the quality of life of the human residents. The health of Galveston Bay is a general indicator of the health of the regional environment. Most people realize that the bay is an important regional ecosystem, and they have a keen interest in protecting and maintaining its productivity and splendor for future generations.

This chapter will focus on the region's economic activity, resource use and associated impacts. Information is presented regarding the major current uses of the Galveston Bay system, including surface water use, extraction of groundwater and minerals, urban and agricultural land use, commercial fishing, shipping and water-related recreation.

Attributes of the Regional Economy

Economic Activity

The economy of the Houston Primary Metropolitan Statistical Area (PMSA), which consists of Chambers, Fort Bend, Harris, Liberty, Montgomery, and Waller counties, has diversified since the crash of the oil industry in the 1980s. While the petroleum industry still plays a large role in maintaining the region's economic health, many firms in the computing, biotechnology and aerospace industries now play major roles in the region as well. The Houston PMSA's central U.S. location and proximity to Latin America make it a convenient location for industry and trade. The region also possesses an established infrastructure, relatively low cost of living and reasonable property costs (Texas Comptroller of Public Accounts, 1999).

The Houston metropolitan area has a large population and is composed of many adjacent communities and counties. The social and economic fabric of these communities is highly integrated. Because of this integration, the consequences of an event in one community (e.g. the dissolution of a large business) can often be felt in the adjacent communities. Agencies often group these counties and communities in ways to better analyze certain factors (e.g. economic, social, environmental, etc.) for statistical purposes. The Federal Office of Management and Budget's definition of the Houston PMSA is used by state and local agencies and organizations to analyze economic and social data. A different commonly used county grouping is the Houston-Galveston Area Council's 13-county region (Austin, Brazoria, Chambers, Colorado, Fort Bend, Galveston, Harris, Liberty, Matagorda, Montgomery, Waller, Walker and Wharton). This book deals primarily with the concerns of the Galveston Bay Estuary Program (GBEP) which has a five-county project area (Brazoria, Chambers, Galveston, Harris and Liberty counties). This grouping is based on counties that surround the Bay and have tidal waters.

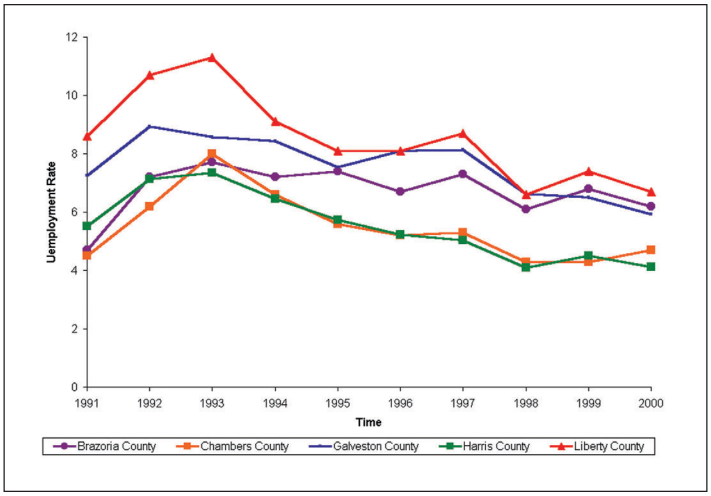


Fig. 4.1. Unemployment rates for the five counties surrounding Galveston Bay (Brazoria, Chambers, Galvesotn, Harris and Liberty Counties), 1990-2000.

County	2000 Population (number of people)
Brazoria	241,767
Chambers	26,031
Galveston	250,158
Harris	3,400,578
Liberty	70,154
Five-county Total	**3,988,688**

Table 4.1. Current human populations in the five counties surrounding Galveston Bay (Brazoria, Chambers, Galveston, Harris and Liberty Counties.) Source: U.S. Census Bureau (2001)

According to the Texas Comptroller of Public Accounts (1999), main sectors of the Houston metropolitan economy include the mining (oil and gas extraction), government (including Johnson Space Center), services (business services and healthcare), manufacturing (petrochemical and high tech), construction, trade and transportation, public utilities, real estate, tourism, and agriculture industries. These industries directly and indirectly depend upon and impact bay resources.

As seen in Figure 4.1, of the five counties surrounding Galveston Bay, Chambers and Harris Counties have experienced the lowest unemployment rates in the region over the last ten years. Comparatively, it is typical for Brazoria, Galveston and Liberty Counties to have a higher unemployment rate than its neighbors. In Galveston County, Texas City has an economy based primarily on its petrochemical refining industry while the City of Galveston centers its economy on tourism, trade and its medical center.

In contrast to the urban and industrial development located on the western flank of Galveston Bay, the eastern side of the bay is primarily rural. This area relies on the promotion of its natural resources, which include salt domes, industrial sand, pine and hardwood timber, oil, gas, and sulfur (Texas State Historical Association, 1999). Lowland marshes support the production of rice, the major agricultural crop. The economy is also supported, in part, by a growing tourism industry. As seen in Figure 4.1, Liberty County experiences some of the highest unemployment rates in the Galveston Bay area, while the Chambers County unemployment rate is very similar to that experienced by Harris County (U.S. Bureau of Labor Statistics, 2000).

Large and small businesses rely upon the resources or the use of Galveston Bay for their operations. Based on a telephone survey of households in a four-county area (Chambers, Harris, Galveston and Brazoria), Allison et al. (1991) estimated that nine percent of the households in the area derived their income from activities *directly* associated with the bay.

The Human Population

The Galveston Bay system is adjacent to one of the most urbanized and industrialized areas in Texas and the nation. According to U.S. Census Bureau redistricting data for the year 2000, approximately four million people reside in the five counties surrounding Galveston Bay (Brazoria, Chambers, Galveston, Harris, and Liberty Counties). The Houston metropolitan area ranks fourth largest nationally behind New York, Los Angeles and Chicago. Harris County remains the most populous in the state with 3.4 million people (see Table 4.1) (U.S. Census Bureau, 2001). Population growth in the region is expected to continue.

Over the years, the bay area has become increasingly urbanized. The larger central cities, such as Galveston and Houston, experienced relatively low growth rates compared to suburban communities (e.g., Friendswood, Humble, and League City). Average population density in the five-county area is 546.5 persons per square mile (U.S. Census Bureau, 2001). Harris County is the most densely populated county with 1,967 persons per square mile and Chambers County remains the most sparsely populated county in the bay area with 44 persons per square mile (U.S. Census Bureau, 2001).

The Houston-Galveston Area Council calculated the number of people living within a two-mile buffer zone around the bay and its tidally influenced tributaries. This analysis was completed in order to examine the potential pressures of population and urban land uses immediately surrounding the bay. The buffer area contains 25 percent of the total area of the five counties and 21 percent of the land surface area (major water bodies excluded). More than 70 percent of the Galveston County population and almost 45 percent of Chambers County population reside in this two-mile zone. About 20 percent of the four million people in the five-county area live within two miles of the bay and its tidally influenced tributaries.

The region has exhibited continuous immigration and economic expansion over most of the past 50 years. Much of the region's growth has been attributed to the construction of the Houston Ship Channel and the discovery of oil in the early part of the twentieth century. The ascent of the Houston metropolitan area to the major population and industrial center it is today, however, has taken place largely since World War II. Houston's population gains during the 1970s and early 1980s were remarkable. Immigration from national and international sources traditionally has accounted for a large part of the population growth in the Houston area (Kingston, 1988). The strength of the region's economy and its ability to provide jobs has continually attracted new residents.

Shipping and Ports

The bay is an important transportation artery. Many of the area's petrochemical and other industries rely on the Houston Ship Channel, Gulf Intracoastal Waterway, and other navigation channels for transportation. While the region has other forms of transportation, shipping is still a major attraction to commercial and industrial interests. Shipping by the major ports (Houston, Galveston, and Texas City) in the region grew dramatically since 1955, while the tonnage associated with several smaller ports (Double Bayou, Anahuac Channel, Cedar Bayou, Trinity River Channel) declined to almost nothing (Allison et al., 1991).

There are growing concerns and policy discussions regarding the potential impacts of shipping on the ecosystems of Galveston Bay. Issues include the alteration of salinity from the saltwater wedge in the channels, introduction of exotic organisms via ballast water discharge in the Houston Ship Channel, and accelerated erosion of shorelines from the wakes of large vessels. Additionally, government agencies have increased their regulatory oversight of commercial shipping activity to reduce oil and chemical spills.

The Houston-Galveston Navigation Channels

Of all the human influences on Galveston Bay, the Houston Ship Channel has perhaps caused the most pervasive changes to bay circulation and salinity. Changes in the size and number of ships visiting the port have justified periodic expansions of the navigation channel since it was first completed. The most recently proposed expansion was contentious because there were concerns about whether the benefits from the project justified the impacts on the bay.

After almost 30 years of planning and debate, the Houston-Galveston Navigation Channel Project has been congressionally authorized and dredging has begun. This project will enlarge the Houston Ship Channel from its previous dimensions of 400 feet wide by 40 feet deep to a width of 530 feet and a depth of 45 feet. The Galveston Channel will also be deepened from 40 to 45 feet. The Galveston Channel was last deepened in 1976 from a depth of 36 feet to its current depth of 40 feet (U.S. Army Corps of Engineers, 2000a).

For many years debate has centered on environmental concerns connected to the Houston-Galveston Navigation Channel Project. In 1989, an Interagency Coordination Team (ICT) was created to bring about consensus regarding these issues. In 1990, the ICT created a subcommittee known as the Beneficial Uses Group (BUG) (see Chapter 5). The group was created to evaluate the possible beneficial uses of dredged material and to incorporate those uses into a dredged material placement plan.

The ICT and BUG transformed a contentious issue into an acceptable solution. While some debates remain, the outcome of the ICT and the BUG has received broad support. Dredged material excavated from the Houston Ship Channel, rather than being spread in unconfined disposal areas over hundreds of acres of bay bottom, will be beneficially used for the restoration and creation of intertidal marshes, bird nesting habitat, oyster reefs and boater access channels over the fifty-year life of the project.

The Texas City Channel and Dike

Aside from the Houston Ship Channel, there are many more miles of additional channels in Galveston Bay. One of the earliest channels completed was a 16-

Aerial view of the Fred Harman Bridge on Highway 146 and the Houston Ship Channel. This cable-stayed bridge extends 1,250 feet across the Houston Ship Channel and replaces the old tunnel from Baytown to LaPorte. (Courtesy Stan A. Williams, Texas Department of Transportation)

	Port of Houston Authority Tonnage	Port of Texas City Tonnage	Port of Galveston Tonnage
1996	148,182,876	61,240,390	8,100,000
1997	165,456,278	60,275,287	6,100,000
1998	169,070,334	63,254,526	6,200,000
1999	158,828,203	64,761,538	8,200,000
2000	175,000,000	67,335,291	6,900,000
Average Yearly Tonnage	**163,307,538**	**63,373,406**	**7,100,000**

Table 4.2. Comparison of tonnage statistics for the Ports of Houston, Texas City and Galveston for the years 1996-2000. Tonnage is expressed in terms of short tons (2,000 pounds per ton). Source: Port of Galveston (2001); Port of Houston Authority (2001); Port of Texas city (2001)

foot deep channel from the Houston Ship Channel to the port of Texas City. This channel required extensive maintenance dredging because it was laid out perpendicular to a natural scour area called Half Moon Channel. The channel was protected from sedimentation by building a 5.3-mile timber-pile dike along the north side of the channel in 1914 (see Chapter 3). Since its annexation by the city of Texas City in 1961, the dike has been used as a recreational area popular for picnicking and fishing. A segment of the Texas City Dike has been proposed as a marsh restoration area by the Galveston Bay Foundation (GBF) in its *Habitat Conservation Blueprint* (1998).

The Texas City Dike has fundamentally altered the currents in the lower bay and has reduced circulation to West Bay (Ward, 1991; Paine and Morton, 1986). A large part of the ebb tide was probably directed into West Bay prior to construction of the dike; now practically none of the tidal current enters West Bay north of Pelican Island (see Figure 5.7a and Figure 5.7b. In addition, northers probably do not push as much water through West Bay now that the dike is in place, affecting the flow through San Luis Pass.

The Texas City Channel is currently 40 feet deep and 400 feet wide. A plan to deepen the channel to 45 feet has been introduced by the city of Texas City in conjunction with its plans to build a new container terminal at Shoal Point, a dredged material site formerly called Snake Island. An intent to prepare a Draft Environmental Impact Statement for the container terminal was issued by the US Army Corps of Engineers (COE, 2000b) in August 2000. The new container terminal would include 400 acres of container yard, six berths, a 1000-foot wharf and a landside access corridor (COE, 2000b).

Gulf Intracoastal Waterway

Construction of the Gulf Intracoastal Waterway was initiated to provide a protected inland route for the waterborne shipping and transportation of goods and troops in the event of war (TXDOT, 2000). Its current functions include its use for trade, national defense, and as a passage for recreational vessels. In 1998, $25.2 billion worth of goods were transported along the Texas stretch of the waterway (TXDOT, 2000).

Since creation, some routes of the Waterway have changed. Although the segment through Drum Bay has not been dredged since the early 1900s, it is still an apparent landmark in the physiographics of the area. In 1934 the connection of East Bay to Sabine Lake was completed. The Gulf Intracoastal Waterway's reach across the Galveston Bay estuary has been deepened to 12 feet and widened to 125 feet

The waterway must be annually dredged by the COE to maintain the depth and width necessary for navigation activities. Over the years objections have been raised regarding the locations where dredged material is placed. The COE's Section 216 study process and the Texas Coastal Management Program are working to address this problem.

Port of Houston

The Port of Houston is the largest port in the Galveston Bay area. It is the eighth largest port in the world and ranks second in the nation in total tonnage

(Port of Houston Authority, 1998). It is estimated that in the year 2000 the Port of Houston handled 175 million tons of cargo. In the year 2000 more than one million containers were handled and 6,801 vessels entered and exited the port (Port of Houston, 2001). This shipping volume is distributed among berths along the Houston Ship Channel, Barbour's Cut and the Bayport Channel.

The Port of Houston Authority, a public agency that operates in Harris County, has proposed a container and cruise terminal to be located at the Bayport Channel in southeast Harris county. At completion, this facility would have 7,000 feet of wharves and berths for container vessels on a 752-acre terminal complex and 5,000 feet of wharves and berths for cruise ships on a 192-acre terminal complex. In November 1999, voters approved bonds to finance $387 million of the total $1.2 billion that will be needed to complete the project. Residents living near the proposed terminal site and many environmentalists oppose the project because of concerns regarding increased traffic, degraded air and water quality, property devaluation and habitat loss issues. Supporters of the proposed project contend that the new terminal will bring jobs, economic benefits, road improvements and environmental enhancements to the region. The Port of Houston, the COE and a third-party contractor are in the process of preparing an Environmental Impact Statement (EIS) and released a draft EIS on November 12, 2001.

Port of Texas City

Compared to the Port of Houston, the Port of Texas City operates on a smaller scale (see Table 4.2). It is privately owned by the industries it serves. The Port of Texas City ranks as the eighth largest port in the United States and the third largest in Texas (Port of Texas City, 2001). In the year 2000 net tonnage handled at the Port of Texas City totaled more than 67 millions tons. More than 9,600 ships and barges entered the port located at the edge of Texas City's industrial complex.

Port of Galveston

The Port of Galveston, currently operated by the Galveston Wharves Board and owned by the City of Galveston, is the smallest of the three main ports in Galveston Bay ranking 27th among the nation's largest ports (Hacker and Nissan, 2001). During 2000, the Port of Galveston handled approximately 6.9 million tons of cargo carried by 927 vessels (Port of Galveston, 2001). In addition to handling vessels with dry and liquid cargoes, the Port of Galveston also serves as a cruise ship terminal. In February 2001 the Galveston Cruise Ship Terminal saw the 50,000th passenger sail on the cruise line that utilizes the port. While the Port of Galveston has a prime location, its proximity to the Port of Houston has posed major challenges. The proposed merger between the Ports of Houston and Galveston would establish some regional port management for the area.

Dredging Projects

Dredge and Fill Operations

In addition to the large federal navigation projects described above, many dredge-and-fill operations are conducted by private interests and public agencies and are regulated through Clean Water Act Section 404 permits issued by the COE. These permits are a part of a federal regulatory program, under which the sponsors of dredge-and-fill projects submit applications to the COE, followed by evaluation and approval or denial by the COE.

A survey of recent Section 10 (of the Rivers and Harbors Act of 1899) and Section 404 (of the Clean Water Act) dredging activity looked at 31 permits submitted to the COE during the years 1995 to 2000 (Table 4.3). 17 of the 31 permits submitted were for maintenance dredging. The amount of sediment permitted to be dredged totaled more than 180 million cubic yards. It should be noted that this is not an inclusive list and the amount of material permitted for dredging is actually higher.

Year	Permitted Dredging Location	Permitted Dredge Amount (cubic yards)
2000	Offatts Bayou	0[1]
2000	Houston Ship Channel	10,000,000
2000	Galveston Bay	0[1]
2000	Buffalo Bayou	15,000
2000	Bayport	170,000,000
2000	Tike Island	125
1999	Houston Ship Channel	50,000
1999	Cedar Bayou	360
1999	Texas City Ship Channel	30,000
1998	Trinity Bay	0[1]
1997	Houston Ship Channel	120,000
1997	Gulf Intracoastal Waterway	0[1]
1997	Harbor Side Drive	0[1]
1997	Robinson Lake	7,500
1996	Galveston Bay / Bolivar Ferry	76,455
1996	Gulf Intracoastal Waterway	200,000
1996	Offatts Bayou	0[1]
1996	San Jacinto River	437,400
1995	Old River	13,200
1995	Houston Ship Channel	125,000
1995	Port Bolivar	30,000
Total		180,215,485

[1]Extension of time; no dredging took place between 1995 and 2000.

Table 4.3. A survey of recent Section 10 (of the Rivers and Harbors Act of 1899) and Section 404 (of the Clean Water Act) dredging activity based on a sample of 31 permits submitted to the COE during the years 1995-2000. Source: U.S. Army Corps of Engineers Galveston District (2001)

Dredge and fill activities have impacted sensitive areas of the bay. Ward (1993) estimated that over 2,800 acres of marsh have been replaced by private inland fill activities since World War II.

Dredging Controversy: Clear Creek

Clear Creek is located on the western edge of Galveston Bay at the southern boundary of Harris County and is one of only four bayous remaining in the Houston area with an unmodified channel. Vestiges of riparian hardwood forests and tidal marshes flank its banks as it meanders through the urbanized landscape. Over time homes and businesses have been built along the shores of Clear Creek in the bayou's floodplain.

The tendency of Clear Creek to flow out of its banks prompted Congress to authorize a channelization project in 1968. The project remained inactive until floodwaters associated with Tropical Storm Claudette inundated homes and businesses in 1979. The Clear Creek channelization project has since been the center of a debate among those seeking to protect the bayou's beauty and ecological integrity, those concerned about flooding of downstream communities, and those favoring channelized flood control. If channelized, the winding bayou would be deepened and straightened with the modified channel cleared of woody vegetation.

The debate prompted the local sponsors, the Harris County Flood Control District, to review the channelization plan and submit several enhancements to the COE in 1997. The COE decided that the suggested changes would exceed its authorization. The parties agreed in 1999 to a general reevaluation study, which is in progress. Opposition to channel modification still exists. Many would like to see a non-structural approach to flood reduction. Non-structural alternatives might include voluntary property buyouts and stormwater detention ponds.

The issue of flooding on Clear Creek regained public attention in June 2001 when Tropical Storm Allison produced rainfall amounts in excess of 20 inches in the Clear Creek watershed. Some homes in the area were inundated by floodwaters. Far more serious flooding damage occurred along other tributaries of Galveston Bay. Damage estimates for Harris County alone total nearly $5 billion. This event dramatically illustrates the effects of flat topography and high rainfall on drainage in this region.

Shoreline Modification

Shoreline Access

Shoreline access around the bay is a concern of

Preserving the Fabric of Life

The Seabrook Wetland Conservation Plan

The Houston-Galveston metropolitan area is comprised of a diverse assemblage of communities each with its own identity, heritage and values, making life around Galveston Bay as varied as the pattern of a patchwork quilt. The City of Seabrook, along the western edge of Galveston Bay, is a quiet bayside community with a rich history. The city is experiencing unprecedented growth, as are many other communities in this region. No stranger to land use planning and citizen involvement, Seabrook is looking to the future to balance economic growth and conservation of their unique natural resources.

Seabrook is home to an extensive park system, recreational facilities and a diverse array of wildlife and wetland habitats. Issues of concern for the city include public access to shoreline, land subsidence and shoreline preservation (H-GAC, 2000). While residents and city leaders recognize the valuable roles that wetlands play in providing habitat for wildlife, they also recognize the value of wetlands as solutions for flood and erosion control.

The Houston-Galveston Area Council (H-GAC) recently partnered with the City of Seabrook to undertake an innovative plan for wetland conservation and land use planning, the first such plan undertaken by a municipality in the Houston-Galveston area. Christy recreational users. Public shoreline access to the bay is generally limited to a few parks and boat ramps. As population in the area around the bay grows, there is likely to be demand for additional public facilities in these areas. The Galveston Bay Plan (GBNEP, 1994) proposes improving public access to the shoreline in a manner that is consistent with the protection of the bay's resources.

According to the GBEP, there have been various efforts to gradually acquire land and public recreational facilities along bay shorelines. However, funding constraints have prevented the development of an overall plan to acquire land for public facilities. Additionally, no plan exists to encourage voluntary land dedication for use as public access points in major shoreline developments.

There have been some projects to develop passive recreational opportunities around the bay. The Texas Parks and Wildlife Department recently completed the Great Texas Coastal Birding Trail, which provides access and observation sites to birders along the Texas coast. The Cities of Webster, League City, La Porte, Baytown and Seabrook are developing trails and shoreline access for low-impact recreation along the bayous in their jurisdictions. The GBF has identified a list of sites for a "Galveston Bay Drive and Discover Project." The Texas Department of Transportation has endorsed the project, and GBF will place signs marking the identified sites.

The Coastal Coordination Council (CCC) is in the process of conducting a coastwide inventory of shoreline access points. The inventory will be used in developing a beach and bay access guide. The guide is part of a CCC effort to determine which coastal areas are most in need of enhanced access.

Shoreline Development and Bulkheads

While bulkheads, docks, and revetments usually generate lower volumes of dredge and fill material compared to channel construction, their environmental impact may be disproportionately greater than the actual physical modifications would suggest (Ward, 1993). Most shoreline modifications involve a direct conversion of shoreline and near shore habitat from a sloping, vegetated, natural state to an abrupt vertical land-water barrier.

Using COE permit data and assumptions about standard bulkhead configurations, Ward (1993) developed estimates for the amount of shoreline converted from natural habitats to man-made shoreline since World War II. He concluded that 42 miles of the bay shoreline had been bulkheaded and 28 miles had been converted to docks or

Durham, an Environmental Planner with the H-GAC involved in the project says, "The City of Seabrook has a sense of what is important to them and what makes them unique. They care about issues such as quality of life and want to preserve their wetland resources for the benefit of the community".

The Seabrook Wetland Conservation Plan was funded by the U.S. Environmental Protection Agency and was coordinated by the Texas Natural Resource Conservation Commission through the Galveston Bay Estuary Program. Major objectives of the wetland conservation plan include the identification of areas for wetland conservation projects, development and implementation of strategies to guide land development, and public education on the value of wetland conservation and the wetland conservation plan (H-GAC, 2000).

The wetland conservation plan has the potential to be used as a model for other coastal communities. Chris Kuhlman is a longtime Seabrook resident and has been involved the development of the wetland plan. He believes that, "The City [of Seabrook] is in a position to set a new standard for conservation and preservation which other coastal community's can follow."

Though each community is different, Seabrook is proof that economic growth need not come at the expense of quality of life and habitat preservation. As Chris Kuhlman says, "A great deal of time has already been spent in Seabrook developing a Master Plan and zoning ordinances. The Wetland Conservation Plan adds another dimension to this and helps with our road map to the future."

Many of the Houston area's industries rely on the Houston Ship Channel for transportation. There are growing concerns and policy discussions regarding the potential impacts of the shipping industry on the ecosystems of Galveston Bay. (Courtesy Greg White/Texas Department of Transportation)

revetments. By using an estimate prepared by Orlando et al. (1988) of a 743-mile shoreline around Galveston Bay, about ten percent (74 miles) of the bay shoreline has been modified: six percent (45 miles) by bulkheading and four percent (30 miles) by dock and revetment construction.

Other Shoreline Modifications

One of the greatest engineering achievements in the early 20th century is attributed to Galveston's response to the devastating Great Storm of 1900. Vast quantities of sand were mined and transported by pipeline to "raise the grade" of the entire City of Galveston by up to 11 feet above the previous land surface. Fill material was taken from several borrow areas including Offatts Bayou. By the time the project was completed in 1911, over 9,900 acre-feet of material had been moved to help protect the city from future hurricanes.

In 1931, despite the protests of oil, towing, and timber interests, the Trinity River Irrigation District No. 1 closed the entrance to Lake Anahuac (then called Turtle Bay) to protect rice irrigation systems. The district had authority because of a 1902 provision by Congress that declared Lake Anahuac to be non-navigable. This 6,000-acre area was isolated from the bay system and converted to a shallow, freshwater lake. Other isolations include the privately owned Delhomme hunting area and the impoundment utilized as part of the Reliant Energy Cedar Bayou Generating Station's cooling system.

Petroleum Discovery and Petrochemical Industries

Platforms for producing oil, condensate, and natural gas and the pipelines for their transport are present in all parts of Galveston Bay. Oil and gas wells also are found on land in Brazoria, Chambers, Galveston, Harris and Liberty counties. There are a total of 5,354 oil wells and 1,571 gas wells in the five counties around Galveston Bay (Texas Railroad Commission, 2000a; 2000b). The greatest number of regularly producing oil wells in the Galveston Bay area can be found in Liberty, Harris and Brazoria counties respectively. Brazoria, Harris and Chambers counties lead the bay area in the number of regularly producing gas wells.

This activity has the potential to affect Galveston Bay through subsidence resulting from removal of subsurface fluids (see Chapter 5) and the unintentional discharge of petroleum or produced water, which can be toxic to estuarine organisms. In the past, normal discharge of produced water had the potential to impact water quality in the bay. However, in 1998 the USEPA passed regulations prohibiting this practice.

Ditton et al. (1989) pointed out that petroleum exploration and refining is frequently thought to be Houston's largest and most valuable industry. However, the chemical and allied products industry ranks first in the Houston area in terms of value added by manufacturing. Nearly one-half of the total chemical production in the United States takes place in the Galveston Bay area. The vast majority of the plants are located in Galveston and Harris Counties.

Most of the industrial development around Galveston Bay is concentrated in two areas, one along the upper Houston Ship Channel and the other in Texas City along the southwestern shore of the bay. Ditton et al. (1989) pointed out that the level of infrastructure in the region is an indicator of the extent to which the petroleum industry along the Texas coast is focused on Galveston Bay. Obviously, the petroleum industry is an important presence in the Galveston Bay region. Much of the water and sediment quality monitoring reported in Chapter Six focuses on the potential impacts of industrial wastewater discharges.

Water Resources

Surface Water

The location and timing of freshwater inflows affect salinity, circulation and the supply of sediments and nutrients to the bay (see Chapter 5). These changes in physical characteristics could impact the biological communities in the bay. Also, the growth of population and industry in an area is affected by the availability of suitable freshwater supplies.

Surface water in Texas is owned by the State, which issues permits for diversion and use of the water in the State's streams. In 1997, the State of Texas passed legislation creating 16 water-planning regions throughout the state. Region H encompasses 15 counties in Southeast Texas and includes the San Jacinto and lower Trinity River basins, which feed into Galveston Bay (Taylor et al., 2000). Current water supplies available to Region H are estimated to be approximately 3.7 million acre-feet per year. This amount is expected to decline over the coming decades due to the decreasing availability of groundwater (Taylor et al., 2000). Approximately two thirds (or 2.6 million acre-feet per year) of the Region H water supply is surface water.

Surface water uses are divided into several categories including: municipal water uses, manufacturing uses, irrigation, electric power production, mining and livestock uses. Much of the surface water appropriated for human use is returned to the bay system. Return flows from groundwater usage and diversions from other watersheds, such as the Brazos River, are also discharged to the bay's waters. Increases in water usage have obvious implications for wastewater collection and treatment systems as well as freshwater inflow to the bay.

To secure water for population and industry in the metropolitan area, several reservoirs have been created on major tributaries of the Galveston Bay system. On the San Jacinto River, Lake Conroe and Lake Houston were built for the San Jacinto River Authority and the City of Houston. On the lower Trinity River, Lake Livingston was built principally for the Trinity River Authority and the City of Houston. Turtle Bay, a small brackish side bay off Trinity Bay in the upper bay system, which is fed by Turtle Bayou, was converted into Lake Anahuac to provide a freshwater supply for the city of Anahuac and for agriculture in Chambers County.

There have been major shifts in recent years in the source of the water used in some parts of the study area. For example, in the City of Houston household use has shifted more toward surface water in an effort to control subsidence in the region. However, there are still some problems with integrating surface water supplies into the current distribution system. Adequate capacity to transport surface water to some locations in the watershed does not exist and will require investment in infrastructure improvements.

Groundwater and Subsidence

Approximately one third or 1.1 million acre-feet per year of the 3.7 million acre-feet per year of current water supplies available to Region H is comprised of groundwater. The majority of the groundwater available to Region H is supplied by the Gulf Coast Aquifer system (Taylor et al., 2000). This system is comprised of four aquifers that include the Catahoula, Jasper, Evangeline, and Chicot. The available groundwater supply is expected to decrease in coming decades as regulations limiting groundwater withdrawal take effect. Uses of groundwater are categorized as municipal water uses, manufacturing uses, irrigation, electric power production, mining and livestock uses. As a general rule, groundwater in Texas is subject only to the "rule of capture" and is not regulated. Groundwater conservation districts are an exception to this general rule.

Since its creation by the Texas Legislature in 1975, the Harris-Galveston Coastal Subsidence District (HGCSD) has been working to reduce groundwater withdrawal and subsidence in Harris and Galveston counties. Groundwater withdrawal management practices formulated by the HGCSD have almost eliminated excessive pumping in the near-bay areas. Because of these efforts, the rate of subsidence has slowed in and around Galveston Bay over the past fifteen years.

However, tremendous groundwater withdrawal is still occurring in northern and western Harris county. This is significantly increasing local subsidence and is adversely affecting subsidence rates in the coastal portions of Harris county (HGCSD, 1998).

In 1999, the North Harris County Regional Water

Canoeing past drowned trees along scenic Armand Bayou. (Courtesy Jack Lewis/Texas Department of Transportation)

Authority (NHCRWA) was created to assist water utilities and independent well owners with the conversion from groundwater to surface water or other alternative water sources. Water utilities and well owners that fail to have a Groundwater Reduction Plan approved by the Harris-Galveston Coastal Subsidence District by 2003 may be assessed a disincentive fee of at least $3 per one thousand gallons of groundwater pumped (NHCRWA, 2000).

Reservoir Controversy: Trinity River

The Trinity River flows south from the Dallas-Fort Worth metroplex to its endpoint at Trinity Bay, the northeastern arm of Galveston Bay. The Trinity is the major source of freshwater inflow for the Galveston Bay system (see Chapter 5). Along the river's path exist several reservoirs utilized for municipal and industrial water supply, flood control and crop irrigation.

Following World War II, many water management projects were implemented across Texas. Four dams and reservoirs on the Trinity River were authorized by 1950. In 1950 the COE established a second civil works district in Texas at Fort Worth, in addition to the first located in Galveston. The projects on the upstream Trinity River were controlled by the Fort Worth District and responsibility for navigation and drainage projects in coastal water bodies was retained by the Galveston District (Gallaway, 2001).

The Wallisville Reservoir Project began in 1962. It grew out of an almost century old navigation project providing a channel from Trinity Bay up to Liberty, Texas and originally proposed to extend to the Dallas area. During the 1950s saltwater-intrusion had damaged the rice crops irrigated by water from the Trinity River. One purpose of the new 19,000+ acre, multipurpose project was to prevent saltwater-intrusion. Another was to provide more freshwater for the Houston region.

The project was halted in 1973 by a federal district court injunction due to deficiencies in the project's Environmental Impact Statement. Plans for a 5,000-acre lake were developed between 1973 and 1990, but were rejected. In the early 1990's a revised plan for a pool-less saltwater barrier was finally accepted. The COE began operation of the Wallisville Saltwater Barrier in 1999. The barrier now functions to prevent the intrusion of saltwater into the Trinity River.

Municipal and Industrial Discharges

Water quality in Galveston Bay has historically been impaired by the discharge of wastewater. In the late 1800s, street drains and sewers in Houston emptied separately but directly into Buffalo Bayou (Henson, 1993). The city built the first sewer system in 1899 with a central pumping station on the northeast side of Buffalo Bayou and siphon pumps to bring the sewage across the bayou (Henson, 1993). Within six years, the capacity of the system was exceeded and the quality of its performance was suspect.

The State Water Pollution Control Act of 1961 authorized Texas to issue permits to municipal and industrial wastewater sources. In 1967, the Texas Water Quality Board (TWQB) was established. It evolved into what is today the TNRCC. In 1969, the TWQB instructed Houston to provide chlorination to disinfect effluent at the North Side and Sims Bayou wastewater treatment plants (WWTP). The City of Houston plants were already disinfecting effluent, but there was a long-standing policy not to chlorinate the effluent from plants that discharged near the channel area. The Sewer Division was concerned with possibility of an accidental release of a large volume of chlorine gas. An alternative technology using bleach was considered and tested. This started a program in the City of Houston to convert the WWTPs from chlorine gas to bleach solution for disinfection. By the end of the decade, the City of Houston was disinfecting flow from all the WWTPs (Espey, Huston & Associates, Inc. 1997).

Galveston and the other smaller communities around the bay improved their wastewater disposal systems by changing from outhouses and cesspools or septic tanks to city sewers. In a 1950 study conducted by Galveston County, officials found that most of the municipalities were still dumping raw sewage into the bay. Two decades later, a federal study dealing with water pollution determined that of seven million gallons of sewage discharged by the city of Galveston in 1970, only 40 percent was adequately treated (Henson, 1993). Today Galveston treats its wastewater effluent prior to discharging it into the bay. There are still small communities around the bay dependent on septic tanks for sewage treatment. The progression to centralized sewage treatment service is underway but it is costly and thus progressing slowly (Glanton, 2001).

A large volume of effluent from industrial and municipal sources is still received by the bay. In 1987, Ditton et al. (1989) estimated that about 3,756 wastewater permittees were located in the Galveston Bay watershed. About one third were in the immediate vicinity of the bay, with 484 active domestic permittees and 235 active industrial permittees. Pacheco et al. (1990) estimated a total of 224 billion gallons of process water (non-cooling water industrial discharges) was discharged into the bay in 1990. The majority of that flow was from municipal sources (174 billion gallons per year), and the remaining 49 billion gallons were discharged from non-municipal sources.

Two large power generating stations are currently drawing water directly from Galveston Bay for cooling purposes, with important effects on the bay's internal circulation. The intake for the P.H. Robinson station is located south of Eagle Point and discharges north of Eagle Point near Bacliff. The Cedar Bayou Generating Station has a longer diversion, with the intake in the Cedar Bayou and the outlet in the Trinity River Delta in the northwestern part of Trinity Bay. The general flow pattern caused by the P. H. Robinson plant is clockwise around Eagle Point. The most notable effect of the Cedar Bayou plant is occasional flow reversal upstream to the intake.

Land Use

There is extensive residential and commercial use of coastal land. While data are not available to distinguish the value of real estate for recreational, aesthetic or commercial purposes, it is obvious that vacation residences built on the bay shore represent recreational and aesthetic values over and above the value of the structures. Similarly, the many industries and shipping concerns located on the Houston Ship Channel are concentrated in the channel area. The access to water transportation and wastewater discharge sites are valuable commercial features.

Urban and Industrial Development

Urban development is most pronounced along the western edge of the Bay. Land use categories include developed upland (industrial and municipal), cultivated upland and undeveloped land (uplands, wetlands and transitional lands) (Pulich and Hinson, 1996).

A strong relationship exists between land uses and pollution from rainfall runoff. Conversion of undeveloped land to impervious surfaces such as roads and parking lots increases the amount of surface runoff flowing into the bayous and bay. This increased amount of surface runoff carries with it pollutants such as oil and grease, herbicides and fertilizers. The existence and effects of non-point source loadings resulting from runoff have been noted for some time, but the problem is generating more concern recently.

Land use also impacts the quantity and quality of habitat. Filling wetlands and converting bottomland forests and prairies to residential, commercial and industrial development reduces the quantity and quality of wildlife habitat. Continuous stretches of native vegetation become divided into separate, isolated fragments leaving the wildlife that inhabits them more vulnerable to human activity.

Industrial activities, especially refining and petrochemical industries, are most prominent in the eastern portion of Harris County around the Houston Ship Channel. Highly industrialized areas are contained in the boundaries of several municipalities, including Houston, Pasadena, Baytown, Deer Park and La Porte.

Galveston County includes the urbanized eastern portion of Galveston Island; the industrialized Texas City-La Marque area and suburban Dickinson, League City and Friendswood. Land available for development in Galveston County is limited due to existing

	Number of Farms	Total Cropland (acres)	Total Irrigated Land (acres)
Brazoria	1,783	203,341	29,596
Chambers	421	118,316	24,894
Galveston	519	30,285	1,449
Harris	1,727	118,827	10,454
Liberty	1,138	159,841	14,092
Total	5,588	630,610	80,485

Table 4.4. Number of farms, total cropland and total irrigated land in the five counties surrounding Galveston Bay during the year 1997. Source: U.S. Department of Agriculture (1997)

development and natural barriers, and much of its open land does not have good transportation access.

Chambers County remains largely agricultural producing primarily rice and soybeans, but has some petrochemical plants near the border with Harris County. Large areas of land in this county are set aside for conservation and recreation, including ten county parks, the state Candy Abshire Wildlife Management Area and the Anahuac National Wildlife Refuge.

The majority of Brazoria County is rural with a few medium sized communities. Two suburban areas provide residences for commuters to Houston and for employees of the major petrochemical complexes in the county: the Pearland-Manvel-Alvin area in the northern part of the county and the Brazosport area in the southern portion (not in the Galveston Bay watershed). Brazoria also has large areas set aside for conservation and recreation, including two high priority wetlands, Freshwater Lake and Hoskins Mound, Brazoria and San Bernard National Wildlife Refuges and Peach Point Wildlife Management Area.

Liberty County is the fastest growing county in the Galveston Bay Estuary Program five-county area. Land use is primarily devoted to ranching and agricultural uses. As the city of Houston's population increases, development has moved beyond Harris County and this county is now experiencing suburban development.

Agriculture

Agricultural activities are also present in each of the counties surrounding the bay. While the western side of Galveston Bay is heavily urbanized, the lands east of Trinity and north of West Bay have more rural uses. Even along the western shore of the bay, suburban and industrial development is interspersed with grazing and agricultural operations. Agricultural land use is most pronounced in Liberty and Brazoria counties with livestock grazing and crop production being the primary activities.

According to the U.S Department of Agriculture (1997), more than 5,500 farms are located within the five counties surrounding Galveston Bay (Brazoria, Chambers, Galveston, Harris and Liberty). This results in more than 630,000 total acres of cropland with more than 80,000 acres of this being irrigated land (see Table 4.4).

Crops harvested in the counties surrounding the bay include soybeans, rice, sorghum and cotton. Of these, soybeans represent the largest crop, harvested from more than 60,000 acres in 1997. While a variety of crops are cultivated in the counties surrounding the bay, each county has one main crop. More than 21,000 acres of rice were harvested in Chambers County in 1997. In the same year, Liberty County had more than 37,000 acres of soybeans harvested, and Brazoria County had more than 14,000 acres of sorghum harvested (USDA, 1997).

Livestock grazing operations (primarily cattle) are evident in every county surrounding the bay. In 1997, Brazoria County led all others with nearly 80,000 head of cattle. Harris County reported approximately 50,000 head of cattle.

Agricultural use of the land surrounding the bay has been declining for many years. Nevertheless, agriculture, and particularly irrigated agriculture such as rice farming, can be an important factor affecting the bay system. Irrigation, erosion control and pest control practices can affect the amount, timing, and quality of freshwater inflows. Impacts on the bay include water quality degradation through the introduction of fecal coliform bacteria from livestock waste and the introduction of nutrients, herbicides and pesticides from crop management. On the other hand, conversion of agricultural land to more urban uses can result in even greater impact on water supply and quality of runoff to the bay system.

Roads and Highways

There are more than 3.2 million vehicles registered in the five counties surrounding Galveston Bay (TXDOT, 2001a,b). Houston ranks second behind Dallas-Fort Worth in the number of registered vehicles. These and vehicles from outside the area travel on roads and highways that cover the land with impervious surfaces preventing water penetration and plant growth. Some of these roads cross-sections of Galveston Bay or its tributaries with bridges that impede water flow and create turbulence.

Accommodating growth in number of vehicles has meant continued growth in the land area covered by roads and highways. In 2001 more than $409 million

	Finfish *		Shrimp		Eastern Oysters		Blue Crab		Total	
	Weight (lbs)	Ex-vessel Value	Weight (lbs)	Ex-vessel Value	Weight (lbs)	Ex-vessel Value	Weight (lbs)	Ex-vessel Value	Weight (lbs)	Ex-vessel Value
1994	169,575	$117,212	6,323,315	$9,943,152	4,230,787	$7,247,432	1,762,088	$1,009,174	12,501,794	$18,326,746
1995	219,549	$156,720	6,655,181	$8,224,700	4,096,195	$7,948,372	1,538,151	$977,319	12,519,773	$17,313,824
1996	226,417	$160,914	7,322,821	$11,155,139	4,892,240	$11,010,000	2,126,126	$1,351,359	14,545,555	$23,718,759
1997	202,109	$143,029	7,487,255	$13,119,858	3,409,242	$8,787,110	1,918,585	$1,231,965	13,041,473	$23,300,610
1998	239,347	$179,698	6,954,572	$7,407,095	2,969,106	$7,071,136	2,615,085	$1,631,016	12,816,822	$16,318,809
Yearly Average	**211,399**	**$151,515**	**6,948,629**	**$9,969,989**	**3,919,514**	**$8,412,810**	**1,992,007**	**$1,240,167**	**13,085,083**	**$19,795,750**
Total	**1,056,997**	**$757,573**	**34,743,144**	**$49,849,944**	**19,597,570**	**$42,064,050**	**9,960,035**	**$6,200,833**	**65,425,417**	**$98,978,748**

Table 4.5. Weight in pounds and ex-vessel value of finfish, shrimp, oysters and blue crab landed commercially in Galveston Bay, 1994-1998. Finfish include flounder, black drum, sheepshead and mullet; shrimp include brown, white and pink shrimp. Shrimp does not include bait shrimp. Source: Texas Parks and Wildlife Department (Robinson et al., 2000)

was spent on combined construction and maintenance of roads and highways in the five-county GBEP region. As the metropolitan area has grown, the number of roads and the number of lanes on the highways have increased. As of 2001, there were 8,453-lane miles in the five counties (TXDOT, 2001a,b).

One result of increased growth of the metropolitan area and the number of lane miles is an increase in vehicle miles traveled. In 2001, more than 61.5 million daily vehicle miles were traveled on the roads in this region (TXDOT, 2001a,b).

Shipping by Rail

Chapter 3 describes the role of railroads in the settlement and development of the area around Galveston Bay. This mode of transportation no longer moves many people, but it is a very important avenue for the movement of materials and products for the region's industry. In 1998, 45 freight railroads operated 10,713 miles of track in the State of Texas (American Association of Railroads, 1999). Of the more than 97.4 million tons of rail freight originated in Texas in 1998, 62 million tons, or 64 percent, consisted of chemical, nonmetallic minerals and petroleum products (American Association of Railroads, 1999).

Fisheries

Commercial Fishing Industry

Galveston Bay historically has been the leading fishery resource base in Texas. Approximately one third of the state's commercial fishing income comes from the bay.

Finfish

The annual finfish catch is a relatively small part of the total Galveston Bay harvest (see Table 4.5). Between 1994 and 1998, the annual commercial bay harvest of finfish averaged approximately 211,400 pounds. For the same period, the annual, ex-vessel value of finfish caught in Galveston Bay averaged $151,500 (Robinson, et al., 2000). Currently four species account for the majority of the total finfish harvest: southern flounder, black drum, mullet, and sheepshead.

Sorting shrimp at the wharf in Galveston. White and brown shrimp are the dominant shellfish species in the Galveston Bay commercial catch. Shrimp account for nearly half the total Galveston Bay seafood harvest. (Courtesy Randy Green/Texas Department of Transportation)

Shrimp

White and brown shrimp are the dominant shellfish species in the Galveston Bay commercial catch. Shrimp account for nearly half the total Galveston Bay seafood harvest. Between 1994 and 1998, the annual commercial bay harvest of shrimp averaged near seven million pounds. The annual, average, ex-vessel value of shrimp caught in Galveston Bay between 1994 and 1998 approached ten million dollars (Robinson, et al., 2000).

Blue Crab

Blue crab is a popular seafood species found along the Gulf and Atlantic coasts. More blue crabs are commercially harvested in Galveston Bay than in

Blue crab is a popular seafood species found along the Gulf and Atlantic coasts. More blue crabs are commercialy harvested in Galveston Bay than in any other Texas estuary. (Courtesy Texas Parks and Wildlife Department)

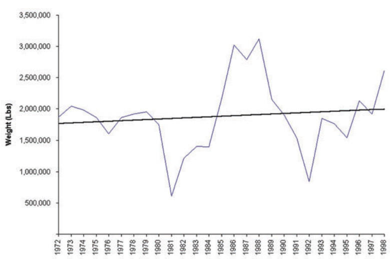


Fig. 4.2. Weight in pounds of blue crab landed commercially in Galveston Bay, 1972-1998. Source: Texas Parks and Wildlife Department (Robinson et al., 2000)

any other Texas estuary. The Texas Parks and Wildlife Department has calculated that 33 percent of the Texas commercial blue crab harvest came from Galveston Bay during the years 1994 to 1998 (Robinson, et al., 2000). More than 2.6 million pounds in of blue crab were commercially harvested in Galveston Bay in 1998 with an ex-vessel value of more than $1.6 million (Robinson, et al., 2000).

Since 1972, the amount of blue crab harvested in Galveston Bay has exhibited a slightly increasing trend with a robust increase seen for the period 1992 to 1998 (see Figure 4.2). While the amount of blue crab harvested has increased over the past three decades, blue crab populations exhibit a declining trend over the same period (see Chapter 8).

As a popular commercial species eaten by many people, it is important to look at the safety of consuming blue crab taken from Galveston Bay. Blue crab is a species included in recent Texas Department of Health analyses of organic and inorganic contaminant concentrations in fish and crab tissue and their associated risk to human health (See Chapter 9).

Oysters

The Galveston Bay oyster fishery has been an important commercial species for over one hundred years (See Chapter 3). Oysters are harvested from both public reefs and private oyster leases in the bay. Between 1994 and 1998, the annual commercial harvest of oysters from Galveston Bay averaged close to four million pounds. For the same period, the annual, ex-vessel value of oysters caught in Galveston Bay averaged more than eight million dollars (Robinson, et al., 2000).

It should be noted that there are health concerns associated with the commercial harvesting of oysters. The Texas Department of Health has a program to restrict the harvesting of oysters to protect the public from health risks associated with pathogens in the bay resulting primarily from human wastes. These public health issues are discussed in more detail in Chapter Nine.

Sport Fishing

In addition to the important commercial finfish fishery in the bay, there is also a significant sport fishery. Sport fishing expenditures associated with the estuary account for approximately 50 percent of all sport fishing expenditures in Texas. Gross direct contribution to the local economy amounted to $171.5 million in 1986. These figures are much higher than those reported by the Texas Department of Water Resources for 1976. In 1976, sport fishing expenditures in the estuary were reported by Texas Department of Water Resources to be slightly less than $8 million.

According to the Texas Parks and Wildlife Department (2000a), more than 262,000 recreational fishing licenses, including resident, non-resident and combination fishing/hunting licenses, were sold in the five counties surrounding Galveston Bay (Brazoria, Chambers, Galveston, Harris and Liberty) in fiscal year 1998/1999.

Atlantic croaker, sand sea trout, and spotted seatrout are the sport fishes taken most frequently.

Other Recreational Uses

Residents of the Gulf Coast use Galveston Bay for many of the more popular outdoor activities identified in the Texas Outdoor Recreation Plan. These recreational activities include duck hunting, saltwater fishing, swimming, nature viewing, pleasure boating, camping, picnicking, and sightseeing.

The percentage of area residents expected to annually participate in walking, saltwater swimming, and/or picnicking is well over 40 percent (Houston-Galveston Area Council, 1993a; 1993b). More than 20 percent of the region's population is expected to participate in saltwater fishing and the use of open space and about 15 percent will enjoy saltwater boating.

In May 1993, Whittington et al. (1993) surveyed bay area households in four counties bordering the bay about their use of the bay for recreational and other purposes. Results of the survey indicated that approximately 20 percent of the population of the five-county area use the bay for recreational boating and fishing at least once a year. In addition to those households that fish or boat on the bay, 13 percent reported that they used the bay for other recreational activities (hiking, picnicking. camping, hunting, swimming, bird-watching, etc.). Thus, about 34 percent of bay area households use the bay at least once a year for recreational purposes (Whittington et al., 1993).

Boating

Recreational boating is popular along the Texas Gulf Coast in general and around Galveston Bay in particular. Practically every type of watercraft, from kayaks to million-dollar pleasure cruisers, can be found along the bay and its tributaries. The Clear Lake-Galveston Bay area has been referred to by many as the "boating capital of Texas". With more than 98,000 pleasure boats registered in the five counties surrounding the bay, this accolade is easily defended (TPWD, 2000b). Boater impacts on the bay include disposal of raw or poorly treated sewage, resuspension of sediment and damage to seagrass beds.

For many years, the disposal of untreated sewage was one of the pressures placed on bay resources by boaters. In 1993, the first marina pump-out station was placed on the bay. As of October 2000 there are 12 pump-out stations located around Galveston Bay (see Figure 9.4). Nine of these are public, while the remaining three are for private use. These pump-out stations along with boater education programs provided by the Texas A&M Sea Grant Program, have resulted in a dramatic decrease in the amount of raw or poorly treated sewage placed into bay waters by boaters.

Boating accidents are also a risk for some users of the bay. Various organizations including Texas Parks and Wildlife Department and the Coast Guard Auxiliary offer courses on boating safety. Both organizations also conduct inspections of pleasure boats on Galveston Bay to insure compliance with safety regulations.

Nature Viewing and Ecotourism

Tourism that is based on nature rather than man-made attractions is the tourist industry's most rapidly expanding sector (Eubanks, 1993). Birding has become a very popular outdoor activity along the Texas Coast. The City of Rockport, for example, now enjoys over $4.5 million in economic benefits annually from ecotourists who come to enjoy the whooping cranes at Aransas National Wildlife Refuge. Chambers County is visited by tourists primarily for natural attractions such as bird watching at High Island or wildlife viewing at the Anahuac National Wildlife Refuge. This county has experienced significant growth in the tourist industry between 1975 and 1988, with total expenditures increasing from $600,000 to over $9 million (Allison et al., 1991). There are many stops around Galveston Bay on the Great Texas Coastal Birding Trail, which links 500 miles of coastal bird viewing sites from Brownsville to Beaumont.

This woman is fishing from a dock in the Kemah/Seabook area of Galveston Bay. Recreational fishing is an important contributor to the local economy. (Courtesy Bob Parvin/Texas Department of Transportation)

Galveston Bay has several ecologically valuable sites that serve as ecotourist attractions. For example, bird watching at locations around the bay attracts visitors from all over the United States and many foreign countries. Eubanks (1993) listed over 21 potential birder attractions around Galveston Bay, which include Bolivar Flats, High Island, Anahuac National Wild Refuge, Candy Abshire Wildlife Management Area, Trinity River Delta, Atkinson Island Wildlife Management Area, San Jacinto Battleground, Armand Bayou Nature Center, Challenger Park, Texas City Dike/Moses Lake, Brazoria National Wildlife Refuge, San Luis Pass, Galveston Island State Park, North Deer Island, and Kempner Park.

Allison et al. (1991) examined the contribution of tourism to the economic infrastructure of counties adjacent to the bay. They found substantial growth between 1975 and 1988. Expenditures for tourism in 1992 in Harris, Chambers, Brazoria and Galveston counties totaled $3.5 billion; $307 million, $91 million, and $10 million, respectively.

Birding has become a very popular outdoor activity along the Texas Coast. There are many stops around Galveston Bay on the Great Texas Coastal Birding Trail, which links 500 miles of coastal bird viewing sites from Brownsville to Beaumont. (Courtesy Randy Green/Texas Department of Transportation)

The number of tourism-related jobs in 1992 for Harris, Galveston, Brazoria. and Chambers counties totaled 73,000; 5,600; 1,500; and 130; respectively. The authors pointed out that the proportion of the tourism expenditures that is directly or indirectly related to the bay is not known. Allison et al. (1991) also noted that growth in travel expenditures for the bay area tended to mirror the growth in tourism expenditures for the state as a whole.

There are other important recreational activities in the Galveston Bay area, which have little or no information available on them. These include swimming and other forms of "contact recreation" such as water skiing, and nature study. Although there are no data collected on contact recreation in Galveston Bay, there are major areas known to attract contact recreation in bay waters. These areas include Mud Lake, Offatts Bayou, the Texas City Dike, Clear Lake and Clear Creek. In terms of nature study, the Armand Bayou Nature Center has the largest interpretive program in the bay area.

Other programs focused on the bay's resources are offered by the Galveston Bay Foundation, the City of Baytown, Sea Camp at Texas A&M Galveston, and some smaller outdoor programs. An assortment of Galveston Bay wildlife and habitats can be viewed at locations around the bay. Major public park facilities include San Jacinto State Park, Sylvan Beach Park, Texas City Dike, Seawolf Park, and Galveston Island State Park.

A few facilities also provide interpretive services to educate visitors about the organisms and processes associated with the bay. The public is educated about fish and fishing at the Texas Parks and Wildlife Department's Sea Center Texas marine hatchery and visitor center in Lake Jackson. Endangered sea turtles are on display at the National Marine Fisheries Service's Sea Turtle Facility located on Galveston Island. Remnants of coastal prairies and wetlands can be viewed and explained at the Armand Bayou Nature Center in Houston and the Eddie V. Gray Education and Recreation Center in Baytown. These facilities serve a valuable role in educating children and adults on the importance of preservation, restoration and stewardship.

Hunting

Waterfowl hunting has a rich tradition in Texas and along the Gulf Coast. For the years 1998-1999, the TPWD has calculated that 58,177 hunting licenses (resident and non-resident) were sold in the five counties surrounding Galveston Bay (Brazoria, Chambers, Galveston, Harris and Liberty) (TPWD, 2000a). Hunters utilize private wetland areas through lease arrangements and public lands through access programs of Texas Parks and Wildlife Department and U.S. Fish and Wildlife Service. Anahuac National Wildlife Refuge and Peach Point Wildlife Management Area support large concentrations of migratory waterfowl, as do nearby private leases. While not everyone appreciates the role that hunters play in managing wildlife populations, it is hard to ignore their economic impact in Texas and their contributions to wildlife conservation.

Summary

Galveston Bay has supported economic growth in the region and is surrounded by intensive urban and industrial development. Resources in the Galveston Bay watershed have been utilized for construction, transportation, oil, gas and petrochemical production, water supply, fisheries, agriculture and recreational uses.

Projected growth in population and economic activity will result in increasing use of the bay resources. Major expansions and management changes are in progress or proposed for the ports and navigation channels in the Galveston Bay system. More people will place more demands on water supply, roads and highways and land for development. Controversies have arisen over changes to bay tributaries through channelization and impoundments. Residents want more access to the bay and its associated recreational resources. In cases absent of controversy, governments are responding with programs to meet those demands. Increases in future resource demand must be addressed via planning, funding, monitoring and research to avoid user conflicts and resource degradation in the future.

Chapter Five

Physical Form and Processes

By Theron Sage

(Texas Bays) are a magnificent resource, shallow and brackish and marshy-bordered and rich with life.... The flat land runs to the flat bays, and beyond the flat sand islands is the blue flat Gulf but it is dramatic enough for all that, because of the life that is thereÖ. Nearly any memory of that coast has in it a sense of teeming life....
—John Graves, in The Water Hustlers, 1971

This chapter will examine the formation of Galveston Bay, the natural physical processes operating in the Bay, how humans have modified the natural processes and what the results of these modifications have been.

The Formation of Galveston Bay

Galveston Bay is a large, shallow estuary composed of four major sub-bays: Galveston, Trinity, East and West Bays. The two upper bays, Galveston and Trinity, comprise most of the area of the Bay. The combined area of the four sub-bays, 384,000 acres (600 square miles) makes Galveston Bay the largest estuary along the Texas Gulf Coast.

The entire bay complex, outside of channels, is relatively shallow with maximum depths no greater than 12 feet. Average bay depth is considerably less then 12 feet. Trinity Bay averages about 8 feet deep, East Bay ranges from 4 to 8 feet deep, and most of West Bay is 4 to 6 feet deep. More shallow areas are common where oyster reefs, such as Carancahua Reef, Redfish Bar and Hanna Reef, are built up to near surface level. Large scale deepening of the bay bottom occurred during the removal of bivalve shells through dredging. In some areas, the Bay was deepened as much as 8 to 10 feet. Subsequent sedimentation has produced the bathymetry evident today. The shallow depth combined with the large areal extent (600 square miles) yields an average volume of 2.2 million acre-feet (National Ocean Service, 1985).

Natural processes operating over geologic time created Galveston Bay and continue to slowly modify the Bay today. The two upper bays, Galveston and Trinity, were formed as many modern estuaries are, through the drowning of river valleys. During the last ice advance when sea level was about 400 feet below present levels, rivers cut relatively deep valleys on their way to the ocean. Both the Trinity and San Jacinto Rivers incised their valleys in response to this lowered sea level. Rehkemper (1969) estimated that at the present site of the Trinity River delta, the Trinity River valley was 60 feet below present sea level; at Bolivar Roads the valley was incised to a depth of 160 feet. As sea level began rising toward modern levels, the rivers slowed their down cutting and sediment accumulated in the submerged portions of the river valleys. Rising marine waters filled the valleys and formed Trinity and Galveston Bays. The arcuate shape of the Galveston Bay shoreline between Red Bluff and the San Jacinto River and between Red Bluff and Eagle Point may be the result of ancient meander scars. Aerial views of Galveston Bay clearly illustrate the relationship between the rivers and the bays formed by their valleys (Figure 2.1). Today, widespread shoreline erosion, exacerbated by relative sea level rise, along with localized accretion modifies the shape of the bay.

The two lower bays, East and West Bay, are coastwise lagoons that were segregated from gulf waters by the linear barrier system, which developed around 4,000 years ago as sea level reached near present levels. East Bay formed as a result of Bolivar Peninsula; West Bay formed landward of Galveston Island.

Although natural processes are at work modifying the bay, the most visible changes have come at the hands of humans. The greatest alteration to the shoreline occurred when portions of the Bay were enclosed to create Lake Anahuac and Moses Lake. The segregation of these lakes from the Bay proper reduced the surface area of the Bay by approximately eight percent (Ward, 1993).

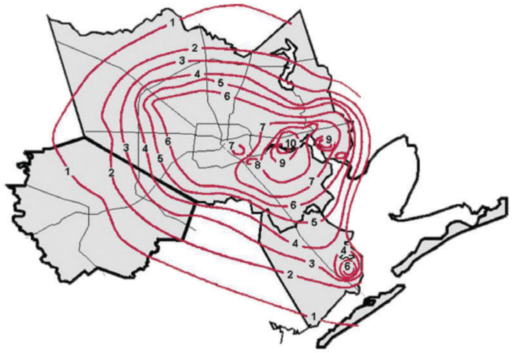


Fig. 5.1. Subsidence around Galveston Bay from 1906 to 1995. Map is contoured in 1-foot intervals. (Source: Harris-Galveston Coastal Subsidence District)

Relative Sea Level Rise

The combination of sinking land and rising sea levels can significantly alter the physical parameters of a bay over time. Sea level change affects estuaries in two notable ways. In cases where sea level is constant or falling, estuaries tend, over time, to fill with the sediment carried by their rivers. When sea level is rising relative to the land, estuaries tend to enlarge due to the deepening floor and permanent inundation of land adjacent to the estuary. In the case of modern Galveston Bay, relative sea level rise (a combination of a rising sea and subsiding land) is occurring at a greater rate than sediment accumulation, thus the volume of the Bay is increasing as marine waters move inland. According to Ward (1993) the volume of Galveston Bay has increased over 8,000 acre-feet, due to the gradual lowering of the bay bottom.

Relative sea level rise in Galveston Bay is caused by: 1) global increases in sea level; 2) natural, regional compaction of Gulf Coast sediments; and 3) accelerated local compaction due to withdrawal of groundwater and the hydrocarbons, oil and gas.

Sea Level Rise

Global sea level is controlled to a large extent by the global ice budget, which in turn, is controlled by global temperatures. Sea level has been on the rise since the end of the last glacial period 10,000 years ago. Since 1850, the rate of global temperature rise has accelerated; an acceleration often attributed to human-induced global warming. However, this date, 1850, coincides closely with the ending of the Little Ice Age, which had kept global temperatures well below normal for several hundred years (Crowley, 1996). While some of the temperature rise of the past 150 years may be due to human-induced global warming, it is likely that some of the rise is due to natural causes associated with a return to warmer global temperatures associated with interglacial periods.

Significant rises in sea level over several scales appear in geologic history. During the peak of the last ice advance, gulf water levels were so low that the shoreline of Texas was about 70 miles (42 km) offshore from the present location. Anderson et al, (1991) suggest that rather than a slow, incremental return to present levels, sea level rise during the past 12,000 years has been punctuated by rapid rises on the order of 10 to 15 feet per 100 years.

Much attention is currently being given to the effect that global warming may have on sea level rise. The Environmental Protection Agency (Titus and Narayanan, 1995) has indicated that global temperatures will most likely rise 2°C by the year 2100. This rise in global temperature will most likely cause a world-wide sea level rise of more than one foot during the next 100 years compared to the 6 to 8 inches recorded during the twentieth century (Titus and Narayanan, 1995). In addition to human induced climate change, natural compaction and subsidence due to natural sediment compaction and subsurface fluid withdrawals could contribute to an even greater increase in the relative sea level rise along much of the coastal U.S. The effects of such a sea level rise on the Bay would be very significant.

Measuring sea level changes is complex, particularly in areas that are actively subsiding. Since 1992, the Center for Space Research at the University of Texas at Austin has been using satellite imagery to measure sea level rise. This technology measures only sea level rise as opposed to tidal gages that also record the effects of vertical landmass movements in coastal areas. Over the past 8 years, they measured an average rate of rise of 0.12 inches/year (12 inches/100 years). (Nerem, 1995).

Subsidence

On a regional scale, natural subsidence often occurs along coasts located on a trailing continental plate edge. These regions accumulate huge troughs of sediment. In the Galveston Bay region, these sediments exceed 10 miles in depth. Over time, dewatering at depth causes clays to collapse and the sediments to compact, thus causing the surface to slowly subside.

Superimposed on regional subsidence are areas of accelerated subsidence, which result when subsurface fluids are withdrawn from unconsolidated sediment. Pumping groundwater and hydrocarbons accelerates the natural compaction process and concentrates it in the upper few thousand feet of the sediment trough. According to Titus and Narayanan (1995) subsidence associated with subsurface fluid withdrawals could contribute to an even greater relative rise in sea level rise than the predicted 13 inches/100 years of relative sea level rise along much of the U.S. coast. Clearly, the combination of a rising sea and a sinking land mass will produce a relative sea level rise that is much greater than sea level rise alone.

Evidence for this apparent accelerated sea level rise is evident in measurements of mean sea level taken in the bay. White and Calnan (1990) estimated that the local mean sea level rise at the Trinity River delta has been about 2.4 feet per 100 years. Stumpf and Haines (1996) analyzed monthly mean water level values and determined that from 1908 to 1994 sea level at Galveston had risen 1.8 feet (56 cm) compared to a sea level rise at Pensacola, Florida from 1923-1994 of less than 6 inches.

Galveston Bay and the surrounding area have already felt the impact of human accelerated subsidence. Initially, the subsidence was caused by high pumping rates in oil fields. Development of the Goose Creek Oil Field at the mouth of Goose Creek was well underway in 1917. By 1918 it was apparent that land around the oil field was being lost to subsidence (Pratt and Johnson, 1926).

Today, more than 3,640 square miles (9,428 km^2) of the Houston-Galveston area has subsided one foot or more. Most of this subsidence is due to groundwater withdrawal. Until the mid 1950s, industrial, metropolitan and agricultural growth was supported entirely by groundwater use. This high level of groundwater withdrawal contributed to subsidence that exceeded ten feet in the areas of high industrial activity centered along the ship channel (Holzschuh, 1991) (Figure 5.1). To combat the effects of subsidence, the Texas Legislature, in 1976, created the Harris-Galveston Coastal Subsidence District to regulate groundwater withdrawals in the region. Under District control groundwater pumping and human-induced subsidence in the near-bay areas has been greatly reduced (See Chapter 4).

In an area with very little elevation gradient, a relative sea level rise of as little as one foot will translate to loss of a large area of land through permanent marine inundation. The Bay has experienced an eight percent increase in surface area as a result of relative sea level rise (Ward, 1993) which has submerged low lying bay margins. Many local features have been lost in this manner including the Brownwood subdivision of Baytown (Figure 5.2), over 10 percent of the land in the San Jacinto Battleground State Park, the riparian forest along many bayous, many fringing wetlands of the Bay and some bay islands. Relative sea level rise along with erosion has kept shorelines in retreat since the first surveys of Galveston Bay were made in 1850-51 (Figure 5.3)

Fig. 5.2. Homes in the Brownwood subdivision in Baytown were permanently inundated by bay waters as a result of land subsidence. In 1994 work was begun to convert the drowned neighborhood into a nature sanctuary. The site is now the home of the Baytown Nature Center. (Courtesy Dr. Theron Sage)

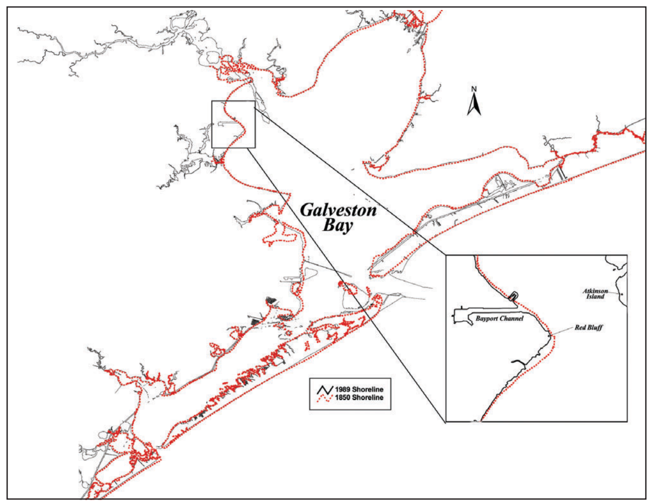


Fig. 5.3. A comparison of the Galveston Bay shoreline as surveyed in 1851 and delineated from aerial photography in 1989. (Source: Texas General Land Office, 1995; Wampler, J.M. 1851)

Recent Temperature Change in Galveston Bay

Temperature changes can also affect sea level. At Galveston and other stations on the Gulf, mean sea level rises about 25 cm from winter (typically January) to late summer (typically September). This rise is attributable to thermal expansion of Gulf waters (Stumpf and Haines, 1998). On a larger scale, rising global temperatures will contribute to a rising global sea level.

In Galveston Bay, average summer temperatures (collected for July and August of each year) ranged from approximately 28°C (82∫F) to greater than 31°C (87°F) in a few locations. Summer temperatures have exhibited a gradual rise over the 30 years of record shown in Figure 5.4. Average temperatures for the Bay during winter (December through February) ranged from approximately 9°C (48°F) to greater than 18°C (64°F) in a few locations (Criner and Johnican, 2001). Winter temperatures show a pattern of decline through the 1970s and early 1980s, followed by a rise from the late 1980s to the present (Figure 5.4). The increase in water temperatures over time in Bay waters is consistent with increases in mean temperatures nationally, which have risen sharply since the 1970s (Karl et al., 1995).

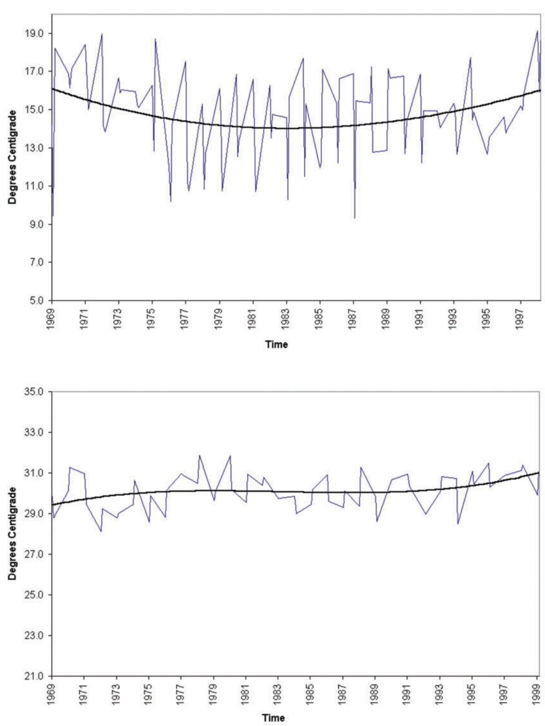


Fig. 5.4. Average summer and winter temperature in Galveston Bay for all reporting stations between 5 a.m. and 10 a.m. at 0.3-meter depth, 1969-1999. source: Criner and Johnican (2001)

Water temperature changes in an estuary are important to many of the bay's chemical, physical, and biological processes. It also affects the composition of the biological community through the thermal tolerances of different species of aquatic organisms. In Galveston Bay, shallow depths and mixing by wind produce water temperatures that are homogeneous with little vertical stratification. The principal source of variation in temperature is seasonal change

Processes Affecting Shorelines

Erosion

The 232 miles of Galveston Bay shoreline consists of three main shoreline types: steep, clay-rich bluffs which dominate in Galveston and Trinity Bays; marshes which are most common in East and West Bays; and sand and shell beaches that form on promontories or in other areas where wave energy is sufficient to remove smaller particles. An analysis of the different shoreline types revealed that sand beaches had the highest rate of retreat at 6.1 feet/year, marshes retreated 4.1 feet/year, and bluffs retreated at an average rate of 3.2 feet/year (Paine and Morton, 1991). Embayments generally had lower erosion rates while promontories experienced rates as high as 7 feet/year (Paine and Morton, 1986).

In areas of maximum subsidence near Baytown and Texas City, shoreline erosion rates from 1850 to 1982 were as much as 11 feet/year. Geographically, the highest rate of retreat was in northwestern Galveston Bay between Cedar Bayou and Virginia Point, an area of high human-caused subsidence.

Shoreline retreat almost universally affects the Galveston Bay system (Morton, 1974; Paine and Morton, 1986). Paine and Morton (1986) report that between 1850 and 1982, about 78 percent of the Bay shoreline was affected by erosion; about 12.5 square miles of land were lost. From 1850 to 1932 the average rate was 1.8 feet/year. However, since 1932 the average rate has been 2.4 feet/year; an increased rate that coincides with greater human alteration within the Galveston Bay system. Notable erosional changes during this time have been the loss of Redfish Island off Eagle Point; the loss of most of the Vingt-et-Unes Islands off Smith Point; the loss of bottomland along the upper Houston Ship Channel; and the loss of marshlands along Galveston and West Bays. According to the authors, the major contributors to shoreline erosion include local subsidence and circulation changes caused by the dredging of a network of navigation channels throughout the bay.

Erosion results in shoreline retreat in addition to that resulting when land is submerged due to relative sea level rise. Rate of erosion is influenced by sediment supply, type of shoreline protection (if any), wave fetch and orientation of the shoreline with respect to prevailing winds and storms. Prevailing southeasterly winds produce waves that subject the northwestern part of the Bay to persistent erosion (Fisher et al., 1972). Over time, the shoreline along the upper Bay has been shaped by these wind-driven waves.

Of all natural events, hurricanes can produce the most dramatic changes in shorelines (Wermund et al., 1989). Hurricane Carla in 1961, with winds of 140 mph, eroded one shoreline facing the gulf over 800 feet with a concomitant accretion of about 500 feet on the bay side of the barrier island. In addition to the erosion caused by wind driven waves, tropical storms also cause erosion through coastal flooding. When sea levels rise several feet in response to lowered atmospheric pressure, low lying coastal areas are inundated. Hurricane Carla raised water levels in upper Galveston Bay by 15 feet (U.S. Army Corps of Engineers, 1962). In 1983, Hurricane Alicia, with a slightly smaller storm surge, caused most shoreline bluffs in the Bay to retreat. Since 1850, 15 hurricanes with surge heights greater than six feet have struck Galveston Bay (Paine and Morton, 1991). While producing less acute erosion than tropical storms, wave energy generated by the wakes of ships and boats also takes a toll on the shoreline.

The best protection against shoreline erosion is the presence of fringing marshes, which absorb the wave energy. In many places, however, the protecting marshes have been drowned due to relative sea level rise or been destroyed through dredging or other near shore activities. Since World War II, private dredging activities have destroyed approximately 461 acres of tidal marsh through channel construction and filled in over 2,800 acres of marsh with dredged material (Ward, 1993).

In response to accelerated shoreline erosion, humans are seeking to armor the shoreline to prevent loss. Most of the efforts to "stabilize" shorelines have occurred in Galveston Bay and western Trinity Bay where erosion rates are high due to subsidence. These efforts, including bulkheads, riprap, wetland restoration or adding additional material to the shore, have met with mixed results. Some shoreline modifications involve a direct conversion of shoreline and near shore habitat from a gradually sloping, vegetated, natural state to an abrupt vertical barrier. Ward (1993) estimates that 42 miles of the Bay shoreline has been bulkheaded and 28 miles have been converted to docks or revetments.

Accretion

In a few areas, accretion and deposition have occurred. The only area of natural accretion was observed in the Trinity River delta, which advanced between 14 and 43 feet/year for the period since the 1850s (Paine and Morton, 1991). Artificial accretion has occurred and new land has appeared as a result of dredged material disposal.

Ward (1993) found that about 25,000 acres of designated disposal area currently exists, most of which (19,500 acres) is in open water. The open water sites are generally associated with a particular channel. Running parallel to the Houston Ship Channel is the large dredge disposal area, Atkinson Island. Shoal Point (formerly Snake Island) receives the material dredged from the Texas City channel. The Galveston Channel dredged material feeds Pelican Island. Dredge spoils also appear along the Trinity River Channel near Anahuac and along the intracoastal waterway in both East and West Bays (Paine and Morton, 1986).

In addition to the formation of dredge disposal islands, dredged material has also been used to remediate erosion along shorelines. Examples of successful marsh restoration projects using dredged material along the bay margins include Galveston Island State Park, San Jacinto State Park and Pierce Marsh. The size and number of marshes constructed of dredged material will increase as a result of the widening and deepening of the Houston Ship Channel, which began in 1999. The plan includes construction of dredged material marshes in three locations: Bolivar Peninsula marsh, Atkinson Island marsh and a mid-bay marsh/island east of Clear Lake (Beneficial Uses Group, 1995). Construction of the Bolivar Peninsula marsh began in 2000. This project will require the disposal of an estimated 252 million cubic yards (approximately 156,000 acre-feet) of bay sediment over the 50-year project life.

Dredging and Disposal of Dredged Material

Commercial shipping in a bay with a maximum depth of 12 feet clearly requires the dredging of navigational channels with sufficient depth to accommodate large vessels. Many navigation channels related to shipping have been cut through the Bay (see Chapter 3). Maintenance dredging is undertaken frequently to keep the channels navigable. On a smaller scale, canals have been constructed into bay side communities and small harbors.

Sediment

An analysis of dredging data by Ward (1993) indicates that a total of about 160,000 acre-feet of sediments were removed from the Bay for new navigation channels and another 400,000 acre-feet were removed during maintenance dredging between 1900 and 1990. From 1950 to 1990, nearly 100 permits per year, on average, were issued for the Galveston Bay system. The total volume of these permitted dredging operations was estimated to be about 40,000 acre-feet. According to the author, dredging should have increased the volume of the Bay from about 1.5 to about 2.2 million acre-feet. Due to the low sediment load of rivers and streams flowing into the Bay, it is likely that the majority of dredged sediment originates through resuspension of bay bottom sediments.

Oyster Shell

Dredging in the Bay has not always been confined to bay sediments. Dredging of oyster shell began in 1905 (See Chapter 3) and continued until 1969 when the practice was banned. As a result of increased demand following World War II, the rate of shell removal increased from about 2,500 acre-feet per year in 1945 to over 5,000 acre-feet per year in the mid 1960s. Shell dredging activity removed thousands of years of biological contribution to the bay sediment. It also opened completely the Redfish Bar that had previously restricted water circulation between the upper and lower bay. Ward (1993) estimates that approximately 135,000 acre-feet of shell were removed between 1910 and 1969.

Freshwater Inflow

An estuary is, by nature, a transitional environment between freshwater and the saline open ocean. Naturally, among the most important factors governing the health of an estuary will be the volume, timing, and quality of freshwater inflows (Solis and Longley, 1993). This inflow helps determine bay circulation patterns and the estuarine salinity regime. The salinity regime in any estuary influences important aspects of the ecology. Thus, changes in the volume, timing and spatial distribution of freshwater inflow is a key concern for those responsible for managing Galveston Bay resources.

Given the importance of freshwater inflow to an estuary, it is understandable that a variety of agencies and programs provide data necessary to evaluate and manage freshwater inflow. The Texas Water Development Board, Texas Parks and Wildlife Department and the Texas Natural Resources Conservation Commission cooperatively work to determine the freshwater inflow needs for the state's bays and estuaries through the use of fisheries harvest data and instream flow data and models. The U.S. Geological Survey maintains flow gage stations at many of the rivers, streams and bayous that flow into Galveston Bay. The stream gauge at the Lake Houston Dam provides information on San Jacinto flow. Trinity River flow is measured by the stream gage at Romayor, downstream from Lake Livingston. The gages on the Trinity and San Jacinto rivers monitor runoff from over 85 percent of the total watershed area. In addition, many local bayous have gages, including: Armand Bayou, Brays Bayou, Buffalo Bayou, Cedar Bayou, Chocolate Bayou, Clear Creek, Greens Bayou, Halls Bayou, Sims Bayou and White Oak Bayou. However, a good portion of the 4,238 square mile lower watershed is ungaged and flow must be estimated.

Sources of Freshwater Inflow

Freshwater enters Galveston Bay from a variety of sources. The Trinity and San Jacinto Rivers along with the bayou watersheds that flow directly into the Bay provide *virtually all* of the freshwater inflow.

The Trinity River basin is responsible for the majority of the average total inflow into Galveston Bay while the San Jacinto basin (including areas below Lake Houston) and runoff from coastal urban watersheds contributes the remainder. The inflow from all three sources is quite variable over time. Figure 5.5 shows the annual inflow volumes from the Trinity and San Jacinto Rivers from 1977 to 1998. Although the Trinity watershed is relatively small (17,500 square miles), it ranks first among other Texas rivers in average discharge (5-6 million acre feet per year) due to its location in the moist subhumid climactic zone (Rehkemper, 1969). The daily flow of the Trinity River can range from 100 to over 100,000 cubic feet per second. For the period 1941 to 1987 flow averaged 5.34 million acre-feet per year, which was 51 percent of the total inflow to Galveston Bay (Solis & Longley, 1993). Clearly, changes in the Trinity River watershed that affect the volume of water in the river will have a proportionally greater effect on Galveston Bay than changes in the other freshwater inflow sources.

Bayou watersheds in the Houston metropolitan area contribute approximately nine percent of the total inflow volume; a volume that is disproportionate relative to the land area involved. During extremely wet years, runoff from these watersheds may increase by 60 percent over runoff in average years. Several flow gages have measured increasing base flow to Galveston Bay from urbanized watersheds, primarily due to return flow from treated wastewater. Brays Bayou at Main Street, for example, shows a base flow component of over 6,000 acre-feet per year (approximately 6 to 10 cubic feet per second), compared to an absence of permanent base flow prior to 1955. A similar trend has been observed in several other urbanized bayous in the Houston area, most of which discharge into the upper Houston Ship Channel (Buffalo Bayou).

Overall, the effects of municipal and industrial return flows can be an important component of the typical four-month summer drought flow. In 1990, industrial process wastewater return alone was equivalent to approximately 20 percent of the average annual summer drought flow and roughly equivalent to some of the lowest summer drought flows on record (Pacheco et al., 1990). Most of this wastewater returns to the Bay via the upper Houston Ship Channel, making the ship channel a significant source of freshwater inflow to the Bay during extreme low-flow conditions. While much of this return flow originates as water supply from Lake Livingston and Lake Houston, some fraction is groundwater acquired for the drinking water supply and discharged as treated wastewater. This wastewater represents an external source of freshwater to Galveston Bay.

Several investigators have examined long-term trends in total annual freshwater inflows to Galveston Bay. Solis and Longley (1993) analyzed Trinity River inflow along with total freshwater inflow from 1941 to 1987 and found that over this 46-year period both total inflow and inflow on the Trinity River remained essentially unchanged. Total inflow volume during this period averaged 10.06 million acre-feet per year; a volume that is 4.6 times the volume of the bay. Solis and Brock (1991) analyzed data collected by the U.S. Geological Survey stream gage network, the National Weather Service meteorological stations and the Texas Water Commission. By reviewing monthly inflow records from 1968 to 1987 the investigators determined a statistically significant increase of 0.52 percent in total annual inflow. Since this trend was not identified in the Trinity River, the authors suggested that the increase in total inflow was most likely the result of water obtained from sources other than the surface watershed of Galveston Bay for increased urbanization and industrialization in the Houston area. Solis and Longley (1993) concluded that there has been no statistically significant alteration in total annual freshwater inflows to Galveston Bay in recent years compared to the historical record. No surface inflow trends, either decreasing or increasing, were observed for river inflow to Galveston Bay for the period 1977 to 1998 (Criner and Johnican, 2001).

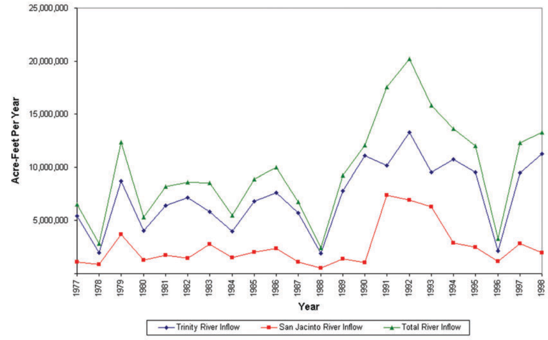


Fig. 5.5. Average annual inflow for the Trinity and San Jacinto Rivers, 1977-1998. (Source: Texas Water Development Board)

Natural Variability in Inflow Patterns

Although total inflow to Galveston Bay appears to be stable over decadal time scales, variability in inflow commonly occurs over shorter time scales. The greatest short-term influence on inflow is the amount of precipitation received in the watersheds. As figure 5.5 illustrates, the extreme drought years of 1978, 1988 and 1996 were periods of significantly lower freshwater inflow; wet years (1977 and 1991 through 1994) yielded higher than average inflow volumes.

During extreme flood events, the volume of freshwater inflow in one month can approach the entire volume of the bay. On average, the greatest inflows occurred in the winter and spring, while inflows are lowest during the summer and fall (Solis and Brock, 1991; Criner and Johnican, 2001).

Ward and Armstrong (1992) conducted a study of seasonal flow patterns, specifically the spring freshet (period of high stream flow) in April and May and the summer low flow season from July through October. Data from the freshet and low-flow summer periods at the Trinity River gage were analyzed for the years 1920 to 1990. The year-to-year variability was the most important feature of the data. Some years had a strong freshet, during others the freshet was nonexistent. The low flow season was sometimes interrupted by large freshwater inflows associated with tropical weather systems. In other years it extended for long periods of time and inflow dropped to nearly zero. Ward and Armstrong's study indicated that a three-month freshet during the first part of the year comprises over 50 percent of the average annual flow of the Trinity River. A statistical analysis of freshet data indicated some periodicity in the data. The size of flow from the freshet appeared to change on cycles of about four years and 14 years.

Human Modifications to Inflow Patterns

As the demand for water has increased in Southeast Texas, humans have begun altering surface water flow in an effort to increase the amount of water available for municipalities, agriculture and industry. The most visible form of human modification is the construction of dams in the major watersheds emptying into Galveston Bay. The dam on the Trinity River formed Lake Livingston while dams on the San Jacinto River formed Lake Houston and Lake Conroe. It appears, however, that these structures have not affected total inflow into Galveston Bay. Solis and Longley (1993) compared monthly flow rates before and after the construction of Lake Livingston and found no statistical differences. However, the flow data presented by Ward and Armstrong (1992) indicate there may have been some increase in the flow during summer low-flow periods for the Trinity River due to operation of Lake Livingston and wastewater from groundwater sources.

In a continuing effort to develop adequate surface water supplies, Senate Bill 1, passed in 1997, created regional watershed planning groups. Region H, which encompasses the lower

Oh Mud, Wonderful Mud

Successful Use of Dredge Material in Galveston Bay

Dredging navigation channels directly changes the physical properties of the bay and can have serious negative effects on the surrounding ecosystems. The BUG Plan is one example in which channel dredging was planned to maximize beneficial effects and minimize negative impacts.

The proposal to widen and deepen the Houston Ship Channel to 50 feet deep and 600 feet wide was first made in 1968. It eventually led to serious objections based on environmental concerns. Specifically, natural resource agencies, environmental groups and citizens worried about the impacts of greater salinity intrusion, burial of bottom fauna by dredge material and higher turbidity from open bay disposal. The widening and deepening project had significant, substantial and persistent opposition (Dick Gorini, pers comm).

In 1989 agency heads formed the Interagency Coordination Team (ICT) to address concerns, identify key studies, oversee them and make recommendations. The primary effort of the ICT was the Beneficial Uses Group (BUG), an ICT subcommittee which undertook a planning effort to reduce open bay disposal and maximize creative uses of the sediment removed by the dredging. Initially ICT members had to build mutual trust. After two to three meetings, a shared purpose was negotiated. Dick Gorini represented the Port of Houston Authority and Chaired the BUG. He recalls those first few meetings.

> *Agency heads probably did not expect the level of cooperation or consensus on outcomes, but they made a top down commitment to bottom up solutions ... The members left their allegiance at door and functioned as a group.*
>
> *—Dick Gorini*

The ICT authorized many environmental studies related to the channel expansion. One of them, a contaminant study, showed that the dredged material would be relatively clean. This opened the way for large marsh creation projects.

> *If it is clean, we will use it all.*
>
> *—Dick Gorini*

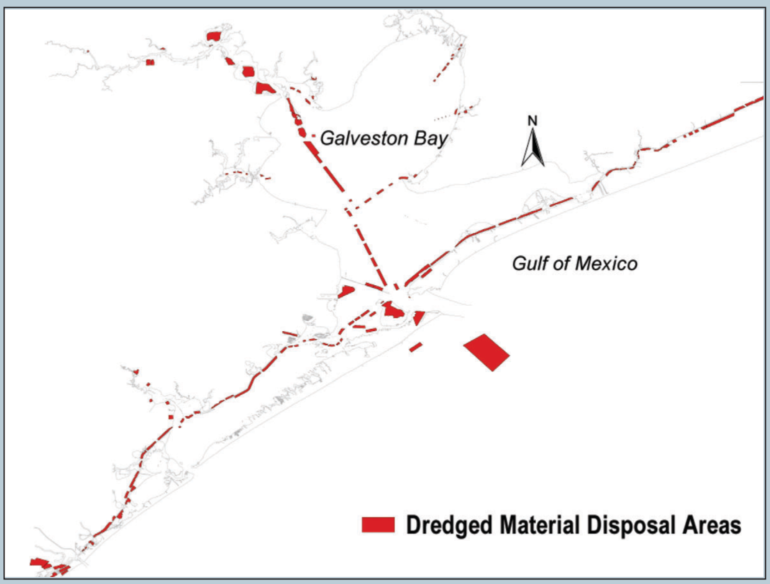
The original 600 foot by 50 foot widening and deepening project was removed from table and the Port offered a 530 foot by 45 foot project to voters. The new plan was called the "Local Sponsor Preferred Plan" by the Corps of Engineers. It was called the BUG

Galveston Bay watershed submitted a regional plan to the Texas Water Development Board in January 2001. Proposed strategies to ensure future supplies include the construction of three small reservoirs located within the Brazos River and Trinity River watersheds, increased municipal and irrigation water conservation and increased interbasin transfers (Taylor et al., 2000).

Expansion of interbasin transfers is also recommended in the upper Trinity watershed (Region C) regional plan. As the Dallas-Fort Worth metroplex acquires more water from sources outside the watershed and returns it by municipal and industrial treatment, upper Trinity River flow may increase. Whether interbasin transfers will result in more water entering the Bay will depend on management decisions of water users.

Processes Associated with Circulation

The circulation of water in Galveston Bay is influenced by many factors, including freshwater inflow, salinity changes, winds and tides, In turn, circulation is a major force affecting the distribution of sediments, oyster reefs, wetlands and other features of the bay habitat. Typical circulation patterns are shown in Figure 5.6a and Figure 5.6b. On an incoming tide, the water flows rapidly through the Bolivar Roads between Galveston Island and Bolivar Peninsula and shown in Figure 5.6a. The vectors of highest surface velocity clearly follow the path of the Houston Ship Channel. Water that takes a path diagonal from the HSC slows rapidly. Most of the Bay shows very low current velocities. The circulation is generally away from the inlet. When the tide turns and flows out the circulation reverses as shown in Figure 5.6b, but the



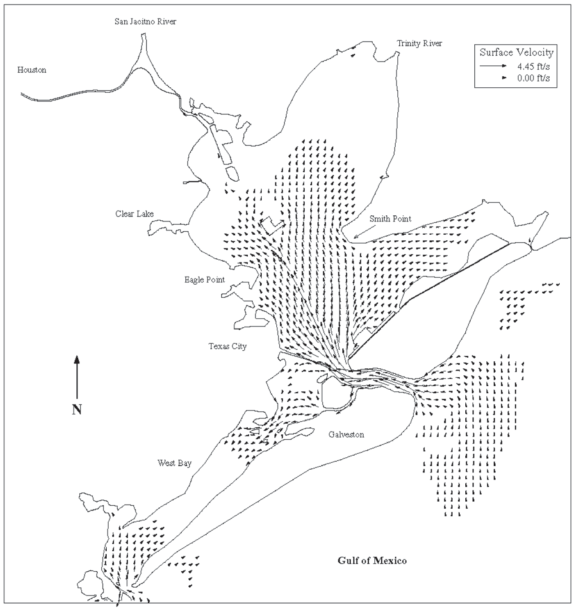
Areas in Galveston Bay designated by the U.S. Army Corps of Engineers for placement of materials dredged from ship channels and the Intracoastal Waterway. (Source: Texas General Land Office)

The ICT process and the BUG Plan are considered a success because they changed vocal opposition to quiet acquiescence of all interested parties. The BUG proactively solicited ideas from bay interest groups. They did not wait for complaints. Group members worked on a shared ethic of stewardship. They focused on objectives rather than methods and made a significant effort at communication.

The agencies maintained their top down commitment to bottom up problem solving. A creative tension existed in the group and is still present to spark ideas. Construction on the Houston-Galveston Navigation Channel is underway and should be completed in 2003 with marsh construction and other environmental projects being completed by 2005. The ICT still meets monthly and has agreed to continue for 50 years to monitor the dredging program and the constructed marshes.

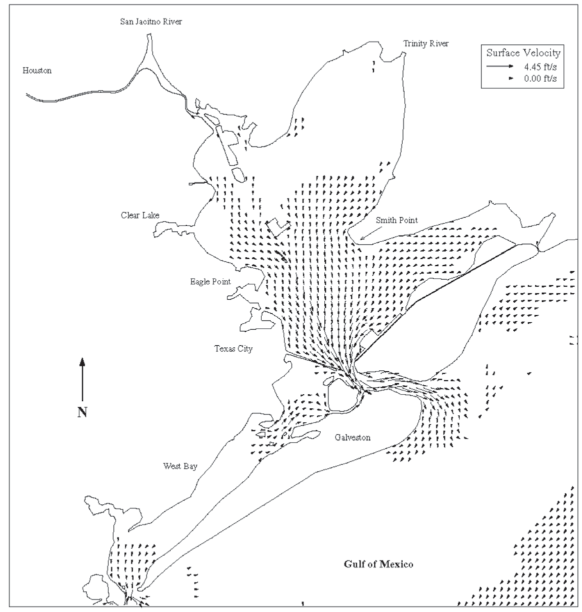
plan by everyone else. The new plan had better engineering, was more cost effective, and was environmentally balanced.

Components of the BUG Plan included construction of 4,250 acres of intertidal marsh; construction of a bird nesting island in the lower bay; restoration of Red Fish Island; restoration of Goat Island near the San Jacinto Monument; creation of 118 acres of oyster reef and construction of boater access channels.



Galveston Bay Water Surface Velocities – Hour 4636

Fig. 5.6a. Typical Galveston Bay circulation patterns during an incoming (high) tide. (Source: Carillo and Berger, 2001)



Galveston Bay Water Surface Velocities – Hour 4652

Fig. 5.6b. Typical Galveston Bay circulation patterns during an outgoing (low) tide. (Source: Carillo and Berger, 2001)

pattern of highest surface velocity are quite similar, the longest vectors are found in the lower HSC and in the Bolivar Roads (Carillo and Berger, 2001). The circulation patterns shown in this figure can be viewed as a baseline for the modifications described below.

Wind Forces

Water movement in Galveston Bay is determined mainly by winds that affect Galveston Bay circulation in a variety of ways including the development of waves, the internal mixing of the water column and changes in water level. The most dramatic effect of winds is the change in water level in the bay caused by the force of the wind.

Northern cold fronts cause the most important wind related depth changes in the bay. As a "norther" passes through the bay, water levels, which increased during the approach of the front, are lowered by the increased barometric pressure after frontal passage. As powerful north winds lower water levels in the upper bay, the water surface is elevated along the north-facing shore of the barrier beach. In the upper bay, water levels can drop over three feet in less than 24 hours. During one intense norther in November 1936, over 60 percent of the total water volume of the Bay was temporarily expelled to the Gulf of Mexico (Ward, 1991). Alternately, prevailing south and southeast winds drive water in the direction of the wind and raise water levels 2 to3 feet.

Influence of Freshwater Inflow and Salinity on Circulation

Salinity, one of the essential properties of estuarine waters, is determined by the intermixing of fresh and oceanic waters. It is an excellent indicator of circulation and flushing in an estuary. Salinity also affects the suitability of habitats because the osmoregulatory capability of a species determines whether it can survive in a particular salinity regime.

As would be expected, freshwater inflow is the best overall predictor of salinity even though it explains no more than half the variation in bay salinity. Salinity gradients from the upper to lower bay are a normal feature. Salinity measured near the principal points of inflow such as the Trinity River may be as low as 3 parts per thousand (ppt) while values as high as 30 ppt may occur at the Gulf inlet. Under most conditions, the upper half of the bay, above Smith and Eagle Points, exhibit salinities that are less than 10 ppt while higher salinities are common in the lower bays. Vertical salinity stratification of bay waters is slight, generally averaging less than 0.6 ppt/m.

Trinity Bay is particularly sensitive to the effects of freshwater inflow from the Trinity River. When Trinity River flows are relatively high, greater than 15,000 cfs, Trinity Bay is virtually fresh. In these conditions shrimpers even report catches of freshwater fish species.

Much of the Trinity River water entering the Bay follows the southern shore of Trinity Bay carrying low salinity water to Smith Point. Galveston Bay, which receives urban watershed runoff in addition to San Jacinto River inflow, also experiences lower average salinity. The higher salinities of East and West Bays are caused by high salinity gulf water, which enters the bays through the tidal passes. A prominent ridge of high salinity water occurs in East Bay between Hanna Reef and Bolivar Peninsula. West Bay experiences the highest average baywide salinity (15 ppt) due to the influence of both more saline gulf waters and the presence of the Texas City Dike.

Salinity variation was examined over the last 20 years for the upper 1.5 meters of the water column (Criner and Johnican, 2001). A baywide decline in salinity was observed in the monthly averages from 1980 to the mid 1990s. From 1997 through 1999, drought conditions appear to have reversed the trend and resulted in rising salinities. A stronger trend exists for Winter (December to February) monthly average salinity, which shows a linear decrease from about 15 ppt to about 5 ppt over the period from 1980 to 1998 (Figure 5.7)

Because of this wide spatial and temporal variability in salinity, the measurement of average salinity (17 ppt) has limited value. Some of the inflow received by Galveston Bay is lost to evaporation, which is estimated to be approximately 1.4 million acre-feet per year (Texas Department of Water Resources, 1981). During wet years, when surface inflow exceeds 10 million acre-feet, evaporative loss is a relatively small proportion of inflow received. During drought years, when surface inflow is closer to two million acre-feet, over half the annual inflow volume may be lost to evaporation.

Weather Related to Circulation

On a shorter time frame, weather events both in the upper watersheds and in the local area of Galveston Bay affect salinity. Heavy precipitation in the watersheds will translate to higher levels of freshwater being received by the Bay through stream flow. Local weather events including freshets, northers and tropical storms also lower salinity and affect circulation. Development of widespread high salinity in the upper bays generally requires months of low freshwater inflows and low southerly flows accompanied by high evaporation rates. Freshets, floods and tropical storms associated with high runoff rates can displace brackish water with freshwater much more rapidly and result in larger gulfward flows.

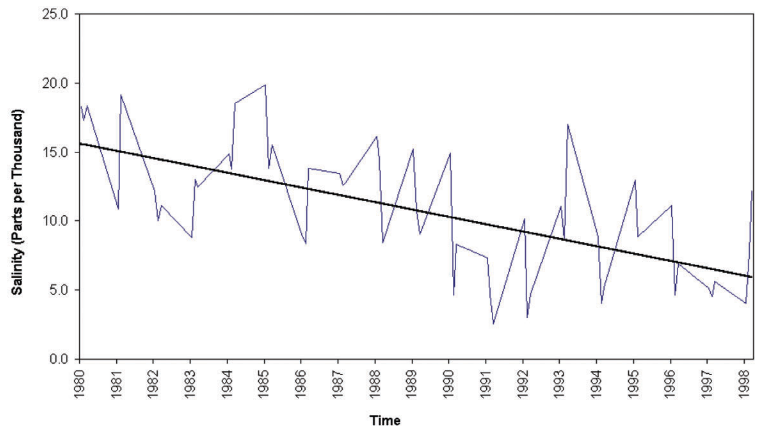


Fig. 5.7. Average monthly winter salinity in Galveston Bay, 1980-1998. (Source: Criner and Johnican, 2001)

Tidal Forces

The Gulf of Mexico is a microtidal marginal sea with tidal ranges of less than 3 feet (Stumpf and Haines, 1998). On the Texas coast tides are considerably weaker than along either the Atlantic or Pacific coasts. Therefore, tides influence circulation much less in Galveston Bay than in estuaries like Cheasapeake Bay, which is located on the Atlantic shoreline. According to Ward (1991) the mean annual tidal range is 2.1 feet at the Galveston Channel. The weak tides entering Galveston Bay dissipate rapidly, losing approximately 30-40 percent of their range across the Bolivar Roads inlet. At the Texas City Dike, the tide has lost approximately 60 percent of its Gulf range.

Within Galveston Bay, diurnal tides (one high and low tide per day) have a range of up to three feet at the Gulf but less than one foot in the upper bay. Semidiurnal tides (two cycles per day) raise water levels more than diurnal tides. At times, Redfish Reef (stretching across the Bay from Eagle Point to Smith Point) can eliminate the smaller of the semidiurnal tide so that the lower bay experiences two tides while the upper bay appears to have only one.

During maximum tidal conditions, approximately 250,000 acre-feet of tidal water moves into the bay. At minimum tidal conditions, about 75,000 acre-feet are set in motion. Eighty percent of the water entering or exiting Galveston Bay moves through Bolivar Roads. Twenty percent moves through San Luis Pass producing rip currents as the tidal water is constricted through the inlet. Very little water currently moves through Rollover Pass (an artificial inlet cut through the Bolivar Peninsula) due to the presence of a weir, which slows water movement.

Water levels in Galveston Bay are also subject to longer term sea level changes that occur in the Gulf of Mexico. From January to September, water levels in the Gulf increase due to thermal expansion (Patulla et al. 1955). The western Gulf, including Galveston, also experiences a peak in the Spring, which is attributed to seasonal variations in the wind field stress (Blaha and Sturges, 1981).

Human Influence on Circulation Patterns

Human alterations in the Bay have likely exerted more profound influence on bay circulation than natural processes. The Houston Ship Channel has caused the most pervasive change to circulation by greatly increasing the flow of Gulf water into the bay; a 50-foot scour hole in Bolivar Roads attests to the movement of gulf waters in and out of the bay. Unfortunately, there are no direct measurements of bay circulation prior to 1900 before large-scale navigation channel expansion began. However, it is likely that the channel has directly altered circulation by providing a larger cross section for north to south water movement on the main axis of the Bay and by breaching Redfish Bar, which limited water exchange between the upper and lower bay. The Houston Ship Channel exhibits an increase in salinity with depth since it tends to serve as a conduit for Gulf water to intrude into the upper bay system.

The disposal of dredged material in elongate sites parallel to the ship channel, i.e., Atkinson Island, create barriers to flow across the bay. dredged material islands have increased the salinity of the western part of the Bay (Espey, Huston and Associates, 1978).

The upper Houston Ship Channel is a major contributor of freshwater coming from industrial processing. This less-dense, freshwater moves into the Bay above the more-dense saltwater moving along the open bay reaches of the ship channel. A permanent density current exists in the base of the Houston Ship Channel set up by the intrusion of high salinity gulf waters into the fresher environment of the upper bays.

Preliminary modeling of a wider and deeper Houston Ship Channel indicates that an enlarged channel will increase salinity in the Bay and make the salinity "tongues" in the ship channel longer and sharper (Martin, 1993). A possible outcome is further intrusion of higher salinity water into Trinity Bay and less flow of low salinity water to the west side of upper Galveston Bay. The mid-bay structures of geotubes and dredged material for marsh and anchorage along with several boater cuts will most likely modify circulation in upper Galveston Bay.

Additional human activities that have altered circulation patterns in the Bay are the Texas City Dike and the interbasin transfer of water from the Trinity River to the upper ship channel. Construction of the Texas City Dike has had a profound influence on the circulation in the lower bay by essentially preventing fresher upper bay waters from entering West Bay.

Sedimentation Processes

The waters of the Galveston Bay System are nearly always turbid. The relatively low energy system of the Bay is reflected in the fine-grained nature of the bay sediments (Lankford & Rehkemper, 1969). High levels of turbidity affect the Bay in a variety of ways including 1) a negative effect on the biological community (see Chapters 7 and 8), 2) transport of pollutants (see Chapter 6) and 3) increased dredging requirements. Therefore, the origin, transport and deposition of sediments are important processes in Galveston Bay.

According to White et al., (1985), the dominant sediment types present on the bay bottom are mud (clay and silt), muddy-sand and sandy mud. Much of the sand size fraction consists of shell hash rather than silicate sands. The central areas of the two upper bays, which are relatively low energy environments, contain large areas covered by mud as does the northern and southwestern regions of East Bay. Muddy sands and sandy muds are found offshore from sandy shorelines while the coarsest particles are found in the high-energy environments of the Trinity River delta front area, Bolivar Roads and San Luis Pass. The distribution of sediment types in the southern part of Galveston Bay is complex due to the hydrodynamic conditions, oyster reefs, barrier islands, Pelican Island, strandplain sands and spoil mounds.

Transportation and depositional patterns in Galveston Bay are affected by a variety of natural processes and man made alterations. In the absence of the human factor, sediment in the water column would most likely be the result of waves that drag bottom in the shallow estuary combined with wave erosion along the shoreline. This process of vertical mixing assures that the water column will be well mixed under most conditions.

The human factor also plays an important part in resuspension, erosion and deposition in Galveston Bay. Trawling and dredging activities are main contributors to resuspension of bottom sediments. The use of bulkheads to protect the shoreline against erosion increases wave energy and contributes to the movement of sediment away from shorelines. The wave energy created by boat and ship wakes resuspend and transport sediment. Deep channels across the bay bottom capture sediment that would be transported to more shallow bay bottoms. The Texas City Dike traps sediment moving toward West Bay or Bolivar Roads.

Total Suspended Solids

Analysis of the Total Suspended Solids (TSS) found in Bay water shows that they consist of both organic and inorganic particles. The inorganic particles originate from a variety of sources. Rivers acquire sediments through erosion and transport the sediments to the bay where deposition occurs, often forming deltas such as the Trinity River Delta. Most riverine sediment reaches the bay under flood conditions. Sediment derived from the clearing of land prior to urbanization is delivered to Galveston Bay through various tributaries. Wind driven currents and waves produce sediment through erosion along the shoreline, particularly where the shoreline protrudes into the bay. These currents and waves also resuspend bottom sediments and set them in motion. As would be expected, more sediment erosion, resuspension and transportation occurs during infrequent but intense storm events than under normal conditions.

The NASA images in Figures 5.8a and 5.8b illustrate the conditions associated with sediment transport by flood and wind driven erosion and resuspension. Another source of sediment is the sediment plume from the Mississippi that is carried westward by longshore currents. This sediment enters the Bay through the tidal passes.

The very smallest particles of sediment, the clays, are easily put into motion and kept in suspension. The small fraction sediment in Galveston Bay is dominated by montmorillonite clays (Garcia & McVay, 1995). These clays are known for their strong ability to exchange cations with their environment. Cation exchange in clays regularly involves heavy metal along with other positively charged pollutants. Thus, suspended sediments transport pollutants and, upon

Fig. 5.8a. Shuttle image showing flood-driven sedimentation in Galveston Bay. (Source: NASA Johnson Space Center)

Fig. 5.8b. Shuttle image showing wind-driven sedimentation in Galveston Bay. (Source: NASA Johnson Space Center)

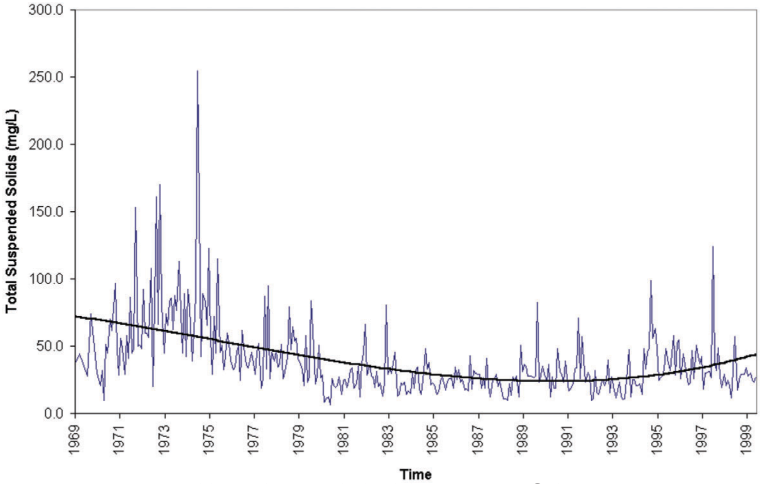


Fig. 5.9. Average monthly total suspended solids in water in Galveston Bay, 1969-1999. (Source: Criner and Johnican, 2001)

deposition, become sinks for many pollutants.

In addition to being important in the fate and transport of various pollutants, the suspended inorganic material can have a deleterious effect on biological communities. Photosynthesizing organisms are negatively affected by large quantities of TSS that block sunlight. Filter feeding organisms can be overwhelmed by high TSS loads.

The organic particles in TSS consist of detritus and plankton. (See chapter 2 for further discussion). Analysis of TSS since 1969 (Figure 5.9) indicates that, on the whole, TSS has remained stable throughout the period of record. A slightly elevated period occurred from 1972 –1975. Several of the highest readings during this period were recorded at sample points receiving runoff from the Houston Metropolitan area and thus, may reflect high sedimentation rates commonly associated with urbanization.

Summary

Galveston Bay is a shallow, wind-dominated system of relatively recent geologic origin. Its 33,000 square mile watershed has three main drainages: the Trinity River watershed, the San Jacinto River watershed, and the coastal bayou watershed. The Trinity River provides the majority of freshwater inflow to the bay. There have been no increasing or decreasing trends in total freshwater inflow since 1941. Reservoir construction and elevated base flows resulting from urban return flows may have dampened the historically high temporal variation of inflow.

The shape of the Bay has been altered by relative sea level rise and shoreline erosion along with human modification. Erosion rates remain high while shoreline accretion is primarily the result of marsh construction projects using dredged material. Hurricanes are particularly important natural events that can drastically change the shoreline and sediment distribution

High rates of relative sea level rise have increased both the surface area and the volume of the Bay. It is likely that this trend will continue since global sea level is projected to rise significantly more in the 21st century than in the past century due to global warming. This increase in sea level coupled with ongoing subsidence will continue to affect the shoreline, drowning the fringing wetlands and submerging low-lying areas. Efforts to control subsidence may slow the effect.

The bay's circulation is controlled primarily by winds. Salinity currents, tides, and freshwater inflow exert lesser effects. Sustained strong winds associated with northers can dramatically change water levels in the Bay over a short period of time. Tidal exchange is relatively weak, with 80 percent of the tidal exchange occurring through Bolivar inlet. Dredging the Houston Ship Channel through Redfish Bar has produced the greatest impact on circulation by providing a conduit for saltwater intrusion into the upper bay.

Bay circulation has been modified by construction of dredge disposal islands, the Texas City Dike, interbasin transfers and navigation channels. The Houston Ship Channel provides a conduit for saline gulf waters to intrude much further into the Bay than would be possible without the channel. The ship channel has undoubtedly resulted in considerable change in the salinity regime of the bay. The current widening and deepening of the Houston Ship Channel will accentuate the effect of the channel on bay salinity regimes.

The dominate sediments of the bay bottom are fine grained clays and silts. Other sediments include muddy sands and sandy muds, which occur offshore from sandy shorelines. The clay portion is composed primarily of montmorillonite, a reactive clay with the ability to exchange cations with the environment.

The turbidity of the bay waters results from suspended organic and inorganic particles. The clay portion of the sediment is easily resuspended by sustained winds and is instrumental in the fate and transport of pollutants in the Bay. Trawling and dredging activities also resuspend bottom sediments. It appears that there has been little change over the past three decades in the total amount of suspended particles (TSS).

Chapter Six

Water and Sediment Quality

"The wondrous nature of water, that it is at once the 'universal solvent' and the global transport system for molecules and masses of debris alike, also makes it particularly vulnerable to debilitating, sometimes lethal, contamination."

—Sylvia A. Earle in Sea Change: A Message of the Oceans, 1995

Prior to the mid-1970s, the portion of the Houston Ship Channel above Morgan's Point was listed as being among the ten most polluted water bodies in the United States by the U.S. Environmental Protection Agency (EPA). The Texas Water Quality Board (now the Texas Natural Resource Conservation Commission) initiated several corrective measures to improve the water quality of the Houston Ship Channel and Galveston Bay even prior to the passage of the Clean Water Act and the establishment of the EPA.

Stringent discharge goals were established in 1971 for industrial and municipal point sources along Buffalo Bayou and the Houston Ship Channel. All industries discharging to the Houston Ship Channel were required to upgrade their wastewater treatment facilities. Municipal waste treatment facilities discharging to the tributaries of Galveston Bay were upgraded and expanded. Eventually, the EPA recognized that several Texas waterways were getting cleaner and singled out the Houston Ship Channel as "the most notable improvement, a truly remarkable feat" (EPA, 1980).

For the most part Galveston Bay has historically maintained good water quality. The water quality problems have been concentrated in the western urban tributaries to the bay. The bay's good water quality can be attributed to its characteristics. It is shallow, well mixed, well aerated and undergoes a total water exchange more than four times a year due to fresh water inflow and tidal action.

This chapter deals with the present status and historical trends of water and sediment quality in the bay. Point and non-point source contributions are discussed as well as localized problem areas. Biological monitoring of contaminants is included since some chemicals can only be detected after they accumulate in organisms living in the water or sediment.

The analyses described below characterize the large-scale temporal and spatial patterns of water and sediment quality in Galveston Bay. Spatial variation throughout the Galveston Bay system is addressed by aggregating the data into sub-regions of the bay, using segmentation developed by Ward and Armstrong (1992) (see Figure 6.1). Statistical trends of the parameters were analyzed using linear or multinomial regression by segment or for the entire bay. In most cases, the parameters are over-sampled in the tributaries and around the shoreline and under-sampled in the open waters of the bay. The temporal distribution of sampling is also uneven. Many parameters were sampled extensively in the 1970's and early 1980's, but have been sampled less frequently in more recent years. Some parameters were collected in special studies and show spatial and temporal clusters of data. The problems with temporal and spatial distributions of the data make the interpretation of patterns more difficult.

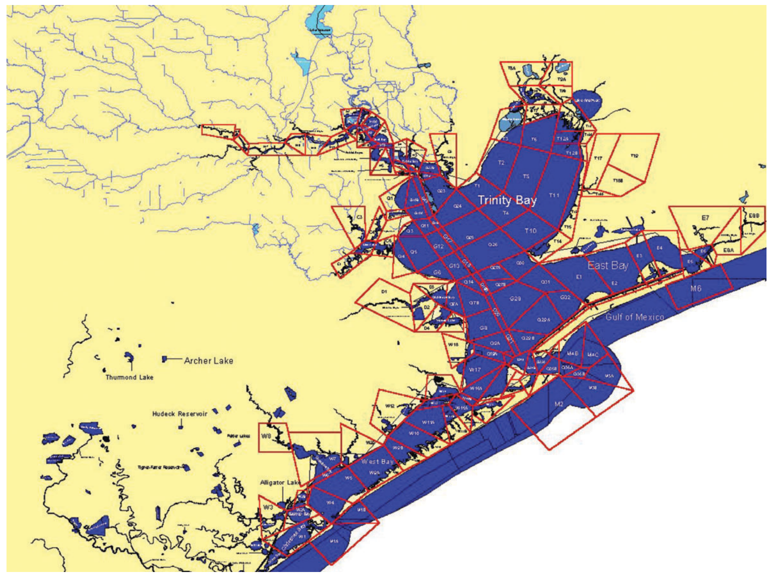


Fig. 6.1. Spatial variation throughout the Galveston Bay system was addressed by aggregating the data into sub-regions of the Bay. (Source: Ward and Armstrong, 1992; Criner and Johnican, 2001)

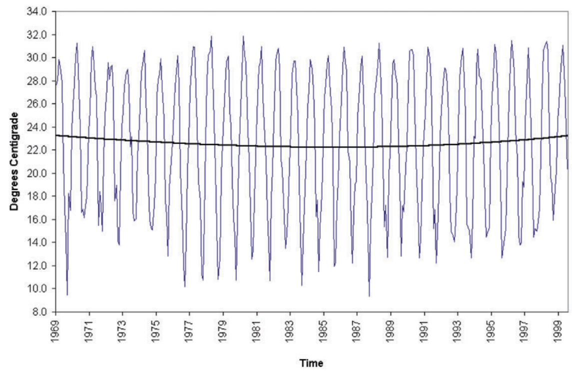


Fig. 6.2. Average temperature in the Galveston Bay estuary with all stations reporting between 5 a.m. and 10 a.m. at 0.3m depth, 1969-1999. (Source: Criner and Johnican, 2001)

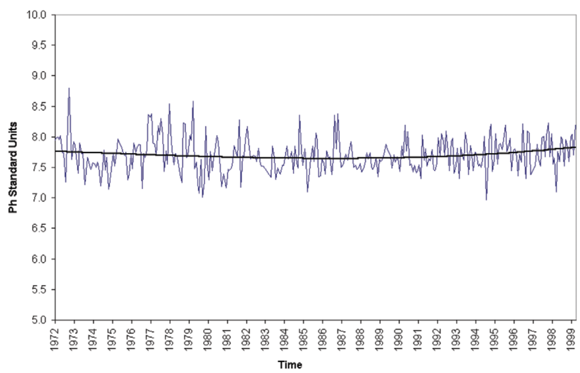


Fig. 6.3. Average pH in Galveston Bay estuary, 1972-1999. (Source: Criner and Johnican, 2001)

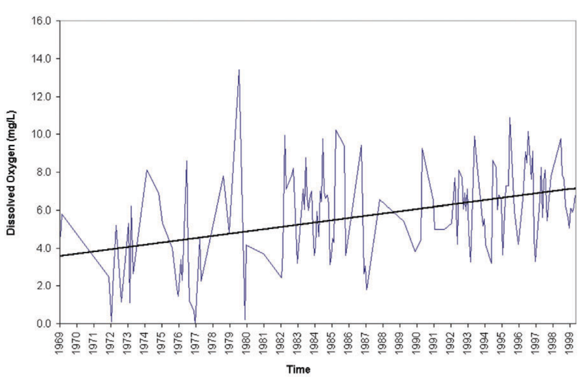


Fig. 6.4. Average monthly dissolved oxygen in Galveston Bay estuary with all stations reporting between 5 a.m. and 10 a.m. at 0.3m depth, 1969-1'999. (Source: Criner and Johnican, 2001)

Water Quality

Parameters reported here are chosen from 73 water quality and 50 sediment quality parameters. For most water quality parameters, the data record extends back at least 25 years, and for a few conventional parameters, back to the 1950s. The current report is based on data compiled by the Texas Natural Resource Conservation Commission (TNRCC) and analyzed by Criner and Johnican (2001). Positive and negative trends of parameters indicative of the health of the bay are highlighted in this report. Parameters that exhibit no trend are largely omitted. Some water quality parameters, such as salinity and total suspended solids are discussed in Chapter 5.

Temperature

Temperature is discussed in Chapter 5 as a parameter of the physical characteristics of the bay. In the context of water quality, temperature is an important determinant of the rates of many chemical reactions and physical processes. The degradation of organic pollutants occurs faster at higher temperatures, if all other reaction conditions are constant. The solubility of oxygen in water increases as temperature decreases. Another important effect is related to the maximum and minimum temperatures tolerated by different species of aquatic organisms.

Shallow depths and mixing by wind produce water temperatures that are homogeneous with little vertical stratification. The principal source of variation in temperature is seasonal change as shown in Figure 6.2. The trend in bay water temperatures over the 30-year time period is consistent with increases in mean temperatures nationally, which have risen sharply since the 1970s (Karl et al., 1995). The pattern seems to be driven primarily by winter temperatures.

Water temperatures in localized areas of the bay can be altered by human actions as well. Effluents with elevated temperatures are discharged from many industrial facilities that use pass-through cooling water. Elevated temperature at discharge sites has been shown to change the composition of the ecosystem in the vicinity of the discharge, but the effect is localized. Thermal pollution is regulated through a state permitting process administered by the TNRCC.

pH

pH is a measure of the concentration of ions [H^+] and [OH^-] related to the acidity or alkalinity of a substance. In water, various dissolved compounds, including salts and gases, affect pH. It determines, in part, the reactivity of water with various pollutants and therefore the toxicity of those pollutants. Seawater has a higher pH (is more alkaline) than freshwater due to the concentration of bicarbonate ions in seawater. Therefore, pollutants will react differently in seawater as compared to freshwater. It is also interesting to note that photosynthetic organisms can affect pH during respiration, i.e. carbon dioxide expelled during hours of darkness can lower pH at night and in the early morning.

Generally, pH exhibits low variability in coastal environments due to the high buffering capacity of seawater. The average pH is approximately 7.7. However, rather extreme pH values have been recorded in the Galveston Bay system as can be seen in Figure 6.3. Values greater than pH 9 have been recorded in the Houston Ship Channel, Trinity Bay, Clear Lake, Armand Bayou and Taylor Bayou. All but one of the high values occurred between 1973 and 1982, but a pH 10 was recorded from Clear Lake in December 1992. pH values less than 6 have been recorded from deep water in the Houston Ship Channel in winter 1986 and 1996 and from Dickinson Bayou in March 1995. The baywide record of average monthly pH shows no historical trend, but the trend line falls and then rises over the 29-year record.

Dissolved Oxygen

Dissolved oxygen (DO) is a traditional indicator of aquatic health. It determines the ability of aerobic organisms to survive. In most cases, higher dissolved oxygen is better. The relationship between temperature and DO is inverse, meaning that as temperature rises, DO levels fall. Other important factors controlling DO include salinity, wind and water turbulence, atmospheric pressure, the presence of oxygen-demanding compounds and organisms, and photosynthesis. Of these, DO is introduced into the water column principally through simple mechanical agitation by wind and from plants, algae and bacteria as a byproduct of photosynthesis.

It is not simple to analyze the record of DO collected from the bay and its tributaries. Concentrations of oxygen vary over a daily cycle as a result of a complex interaction of the factors that produce it, use it and affect its concentration. The photosynthetic organisms in water are dependent on light for the energy to drive photosynthesis. Thus during daylight of suitable intensity these organisms release oxygen to the water and raise the DO, sometimes above chemical saturation levels. During nighttime these organisms require oxygen for respiration and remove it from the water. In high nutrient water, photosynthetic organisms can be present at densities high enough to reduce DO to levels too low to support fish and other aquatic animals. Under other conditions, bacterial populations can be responsible for depleting the oxygen in the water and causing the death of other aquatic life. Low DO is the most common cause of fish kills in the Galveston Bay system. This is particularly true in some of the coastal communities where a boat channel may have a bloom in a small segment and the fish population becomes trapped. As the fish die the carcasses provide more food for the bacteria and the bloom expands killing a larger population further up in the channels.

A low level of DO was a common symptom of high levels of pollution in the Houston Ship Channel prior to discharge permits. The Ship Channel and other portions of the bay exhibited impaired water quality and depressed DO levels that decreased the abundance of aquatic life. DO measurements over the last 27 years indicate a gradual increase in DO levels. Figure 6.4 shows the plot of average monthly DO for all segments over the entire sampling period in the TNRCC database. The positive trend clearly shows improvement in this water quality parameter.

Nutrients

Nutrients are chemical elements or compounds essential for plant and animal growth. Water quality monitoring parameters that measure nutrients include total phosphorus, ammonia-nitrogen, nitrate-nitrogen and total Kjeldahl nitrogen. High amounts of nutrients have been associated with over-fertilization, i.e. eutrophication, of a water body. Low levels of nutrients can reduce growth and survival of photosynthetic organisms, thereby limiting the biomass of animals that consume phytoplankton. In Galveston Bay, nitrogen is generally considered to be the "limiting nutrient," i.e., adding more nitrogen would result in more plant growth. However, it is possible that under some conditions phosphorus is a limiting nutrient in Galveston Bay's ecosystems. No research has been done to determine the details of nutrient fluxes in the bay system.

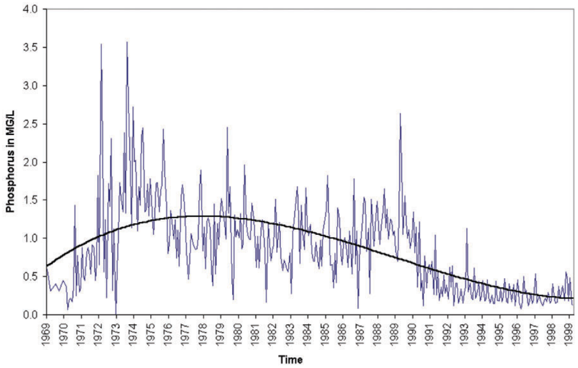


Fig. 6.5. Monthly average total phosphorus in Galveston Bay, 1969-1999. (Source: Criner and Johnican, 2001)

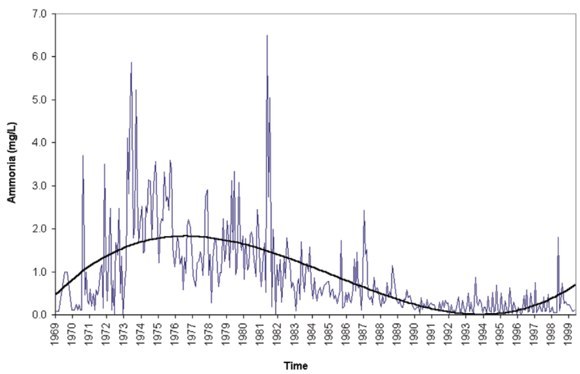


Fig. 6.6. Average monthly total ammonia-nitrogen in Galveston Bay, 1969-1999. (Source: Criner and Johnican, 2001)

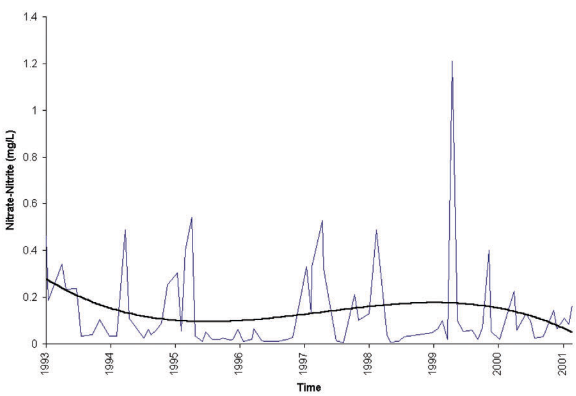


Fig. 6.7. Average monthly total nitrate-nitrite in Galveston Bay, 1993-2001. (Source: Texas Natural Resource Conservation Commission.)

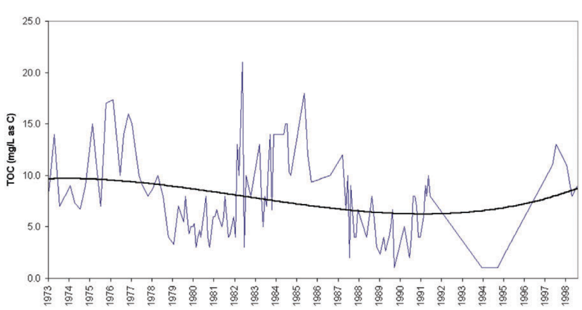


Fig. 6.8. Monthly average total organic carbon in the open waters of Galveston Bay near Eagle Point, 1973-1998. (Source: Criner and Johnican, 2001)

Phosphorus

Phosphorus is an important nutrient because it is required for synthesis of genetic material. Total phosphorus concentrations recorded from Galveston Bay range from less than 0.1 mg/L to greater than 12.9 mg/L. The highest values in excess of 6 mg/L were collected from Trinity Bay, the Houston Ship Channel, Buffalo Bayou, Armand Bayou and Moses Bayou. Collection dates of these high value samples ranged from 1972 to 1990 and they were obtained in all seasons (Criner and Johnican, 2001).

The trend in monthly averages of total phosphorus from samples of the bay and its tributaries is one of decline (Figure 6.5). A polynomial trend line exhibits a sharp increase in the early 1970s followed by a 15-year period of high, but variable concentrations followed by a sharp drop in 1990. This pattern of rise and fall is duplicated in the graph below (Figure 6.6) for ammonia, but the timing of the fall is not the same. The possible correlation of these variables is discussed below.

Nitrogen

Ammonia is a nitrogen compound that typically results from the breakdown of organic material. It is toxic at high concentrations and contributes to higher pH. Its recorded concentrations in the Galveston Bay system ranged from less than 0.1 mg/L to 39 mg/L. Very high values greater than 10 mg/L were recorded in HSC, Buffalo Bayou, Cedar Bayou and Vince Bayou. The high values occurred in the Houston Ship Channel and Buffalo Bayou between 1972 and 1983. Extreme values were recorded from Cedar Bayou in July 1987 and from Vince Bayou in 1986 and 1998.

Some segments of the bay show an uncertain time trend for this parameter. The baywide trend shown in Figure 6.6 is based on monthly averages of all values recorded for the bay and its tidal tributaries during that period. It is similar to the graph of total phosphorous values (Figure 6.5) and shows a temporal decline in ammonia concentrations. The pattern is one of increasing concentrations in the early 1970s, followed by a high and fluctuating period that ends around 1983. The concentration of ammonia then drops significantly and remains low to the present.

Note that the decline in phosphorus occurred in 1990, not the mid 1980s. The time lag between the decline in ammonia concentrations and the decline in phosphorus concentrations suggests that the changes are not coupled or that the causal factors are not completely shared by the two parameters. If the concentrations were changing as a result of nutrient release from non-point source input of detritus, the concentrations of the two nutrients would change synchronously. It is likely that ammonia declines are related to changes in the secondary and tertiary phases in wastewater treatment facilities.

Nitrate is a nutrient that can be readily used by plants in the production of protein. It is commonly the largest nutrient component of commercial fertilizers. Nitrate is an important nutrient for phytoplankton production.

The TNRCC monitored nitrate in water until 1993/1994 when the data collection shifts from nitrate only to nitrate plus nitrite. This change makes assessment of a trend difficult. Monthly average nitrate concentrations prior to 1994 ranged from 0.01 mg/L to greater than 2.8 mg/L with the average value falling in the middle range for U.S. estuaries. Individual measurements ranged as high as 9.92 mg/L.

The general trend of nitrate concentration from 1969 to 1994 was an increase throughout most of the bay with the exception of West Bay. No data are available for East Bay. Segments in the Houston Ship Channel recorded increasing nitrate concentration. This increase may have occurred due to the move by most point sources to nitrify the ammonia they previously discharged, thus discharging this oxidized form of nitrogen. Nitrate concentrations begin to decline after peaking in 1989-1990. Figure 6.7 graphs the concentration of nitrate-nitrite found at sample stations in the open bay. The graph shows a typical pattern of high spring concentrations captured by the monitoring program. Examining the record of nitrate-nitrite concentrations in the bay yields no explanation for a trend in phytoplankton described below.

Water quality management has succeeded in reducing nutrients in most of the Galveston Bay system, but each nutrient has a different historical pattern. Over the last 30 years, ammonia is the first to decline, then phosphorus, then nitrate-nitrite.

Total Organic Carbon

Carbon is found in all organic compounds, such as the proteins in our body. It is monitored as a measure of the loadings the bay is receiving from sources of organic material, such as sewage treatment facilities or runoff from marshes and forests. Total Organic Carbon (TOC) samples have been analyzed since 1973. Figure 6.8 shows a graph of TOC concentrations in the open bay off Eagle Point. The same pattern is exhibited in the records from the Houston Ship Channel. The graph of TOC concentrations shows a complex pattern in which it is possible to see two cycles. The average concentration remains high from 1973 to 1978 and falls to a lower level in 1979. Between 1979 and 1982 the concentration remains low and rises in 1983. After remaining high for four years, the concentration drops and remains low until 1997. The most likely explanation for such a pattern is that TOC is entering the bay primarily from runoff and the pattern is induced by the relationship between productivity and rainfall in the terrestrial and wetland ecosystems around the bay.

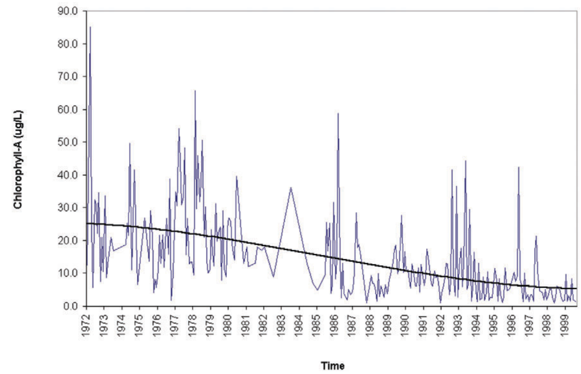


Fig. 6.9. Monthly average chlorophyll-a concentrations in Galveston Bay, with all stations reporting, 1972-1999. (Source: Criner and Johnican, 2001)

Chlorophyll-a

Chlorophyll-a reflects the concentration of the principal photosynthetic pigment in green plants. As such, this parameter is a surrogate indicator of phytoplankton standing crop, the amount of single-celled algae that is present in the water. Chlorophyll-a concentrations occasionally reach very high levels in the waters of the bayous and the bay. The TNRCC database contains a record of 455.8 ug/L of chlorophyll-a in Chocolate Bayou in 1978. Values of 255 and 268 ug/L were recorded in Taylor Bayou in 1977 and 1976 respectively. Chlorophyll-a concentrations greater than 100 ug/L have been observed in Buffalo, Dickinson, Armand, and Moses Bayous as well. Similarly high concentrations occasionally occur in Upper Galveston, Lower Galveston and Trinity Bays. Most of these high values were recorded between 1972 and 1980. The exception to this temporal pattern is Armand Bayou, which has exhibited very high chlorophyll-a concentrations as recently as 1996.

The graph in Figure 6.9 indicates a 28-year declining trend in the monthly average concentrations of chlorophyll-a. Thus, despite increasing concentrations of nitrate, a major nutrient for plant growth, chlorophyll-a measurements in Galveston Bay are not

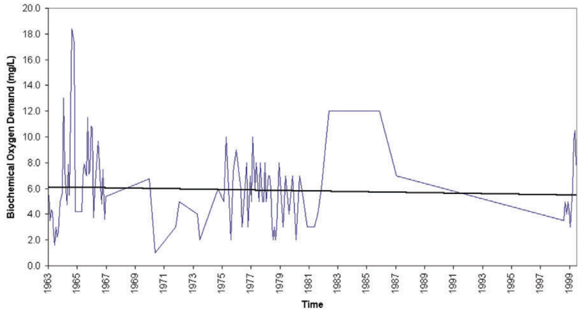


Fig. 6.10. Monthly average biochemical oxygen demand in Clear Creek, 1963-1999. (Source: Cruiner and Johnican, 2001)

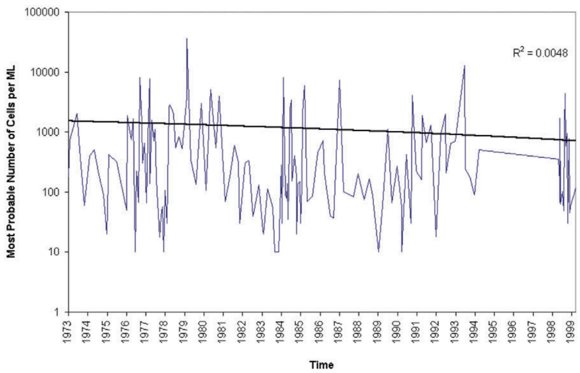


Fig. 6.11. Monthly average fecal coliform concentrations in Clear Lake 1963-1999. (Source: Criner and Johnican, 2001)

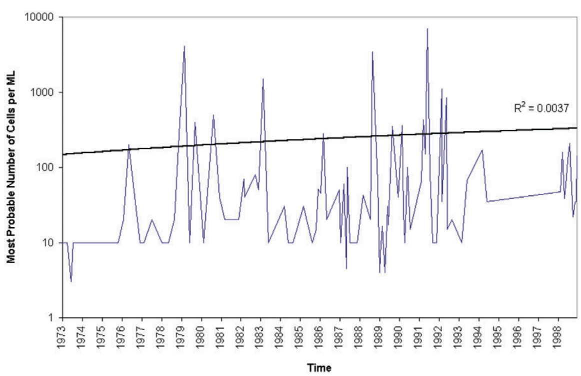


Fig. 6.12. Monthly average fecal coliform concentration in Galveston Bay or sub-bays, 1973-1998. (Source: Criner and Johnican, 2001)

rising. This trend in phytoplankton may be a result of less primary production or faster cropping of phytoplankton by herbivores. See Chapter 8 for a discussion of trends in animal populations relevant to the concentration of phytoplankton.

Biological Oxygen Demand

Biological oxygen demand (BOD) measures the metabolic requirements of all of the organisms in the water mass. This parameter is of concern when high levels of nutrients support large standing crops of bacteria or algae. High BOD can produce low oxygen concentrations that are detrimental or lethal to less tolerant organisms in the water mass. BOD has been monitored for many years in the Galveston Bay system. As seen in figure 6.10, BOD concentrations in Clear Creek from 1963 to 1999 show no apparent trend.

Contaminants

Fecal Coliform Bacteria

Fecal coliforms are used as the primary indicator for determining whether water is contaminated by animal or human waste. Presence of coliforms suggests that potentially dangerous pathogens could also be present. A fecal coliform standard of less than 2000 colonies/ 100 mL geometric mean concentration has been established for non-contact recreation sports such as sailing. A standard of less than 200 colonies/100 mL (ln 200 = 5.3) was established for contact recreation such as swimming. Fecal coliform counts below 14 colonies/ 100 mL (ln 14= 2.6) are within the water quality standard for shellfish harvesting. Chapter 9 presents a detailed discussion of fecal coliform bacteria as indicator organisms and the public health implications raised by coliform bacteria related to Galveston Bay.

Many of the sampling stations are in tributaries of the bay. High coliform counts are associated with these slow flowing bayous in summer months when high temperatures contribute to the growth of the bacteria. The most probable number of cells of fecal coliforms per ml of water samples taken from the Clear Lake watershed between 1973 and 1999 are shown in Figure 6.11. The trend line shows no significant trend over the period.

Water samples taken from the open bay waters show consistently lower values for colony counts of fecal coliforms (Figure 6.12). Fecal coliforms exhibit an intolerance for saltwater. This intolerance is exhibited by a faster mortality rate. There is no significant temporal trend in the concentration of fecal coliforms in bay water. Long-term average fecal coliform concentrations were low in most locations within the Galveston Bay system when compared to water quality standards, but exceedance of state criteria for contact and non-contact recreation by individual measurements was common.

Metals

Under normal conditions, the concentration of metals in the water is quite low and often below the detection limits of standard instrumental methods. Monitoring of metals dissolved in water has decreased over time. Fewer metals were analyzed at fewer sampling stations in 1999 than in the 1980s. The majority of data on dissolved metal concentrations is collected from sampling stations in the upper Houston Ship Channel.

In recent years, the trend of dissolved metal concentrations is declining. For example, Figures 6.13a and 6.13b show the concentrations of mercury and zinc from 1989 to 1998 in the Houston Ship Channel (GBEP Segments H11 to H19- See Chapter 2 for an explanation of GBEP segmentation). Mercury shows a dramatic drop in concentration after 1994. None of the concentrations shown on the graph are close to the criterion level for chronic toxicity to marine aquatic life (30 TAC 307). Zinc shows a decline after 1994, but the pattern is less extreme. The criterion set for aquatic life protection from dissolved zinc is 89 °g/L, which is not reached in the graph.

Organics

No organic compounds have been analyzed consistently from water samples over the time period since passage of the Clean Water Act. The concentration of dissolved organics shows the same relationship between water and sediment as metals. It is more efficient to sample the concentration in sediment because the compounds tend to accumulate there. In the case of toxic organics, even better information may be obtained by analyzing the concentration in tissue of organisms living in the water. Considerable recent data is provided below on the detection of organic contaminants in tissue samples.

Organic contamination of water can have many sources. One source for which new data is available is spillage of petroleum products into bay waters. Petroleum is highly toxic to some estuarine organisms,

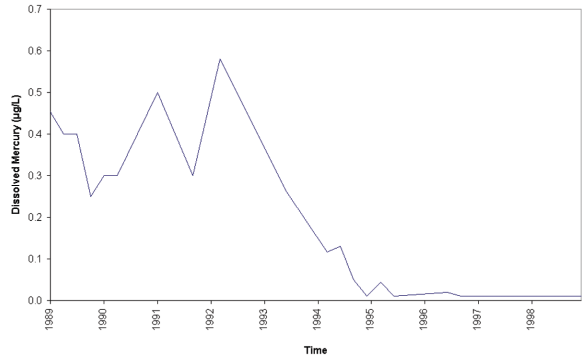


Fig. 6.13a. Monthly average mercury concentrations in water in the upper Houston Ship Channel, 1989-1999. (Source: Criner and Johnican, 2001)

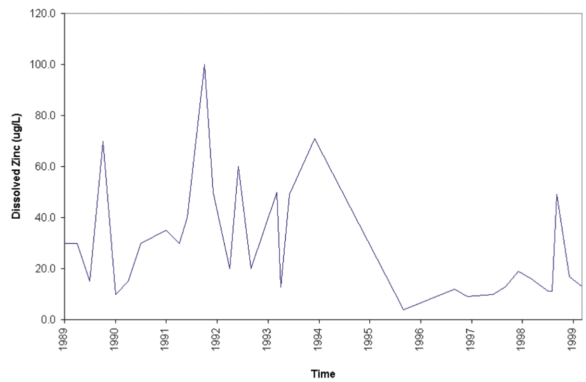


Fig. 6.13b. Monthly average zinc concentrations in water in the upper Houston Ship Channel 1989-1999. (Source: Criner and Johnican, 2001)

Location	1998		1999		2000	
	Number of Spills	Quantity Spilled (Gallons)	Number of Spills	Quantity Spilled (Gallons)	Number of Spills	Quantity Spilled (Gallons)
Galveston Bay	25	153	11	3,571	26	12,384
Houston Ship Channel	106	11,797	182	22,238	146	79,707
Clear Lake	16	27	19	68	44	68

Table 6.1. Summary of the number of petroleum product spills and the quantity spilled in specific areas of the Galveston Bay system, Upper and Lower Galveston Bay, Houston Ship Channel and Clear Lake during 1998, 1999 and 2000. (Source: Texas General Land Office)

particularly the larval stages. When spilled in water the lightest components evaporate and become air contamination. Heavier components may float and combine into tar balls. The heaviest components sink to the sediment where they may damage benthic organisms, like oysters. Petroleum compounds from a spill can be degraded by microbes present in the environment, but may remain at harmful levels for many years before complete degradation.

The Texas General Land Office made available the information on reported or detected spills in the segments of the Galveston Bay system since 1998. Table 6.1 illustrates this data with summaries of the number and quantity of spills in Galveston Bay, the Houston Ship Channel and Clear Lake in the years 1998, 1999 and 2000. The trend of increasing quantity may be explained in part by improvements in detecting and describing spills. However, in spite of the efforts to reduce the number and volume of spills, this reduction does not appear to be occurring. Clearly more work is needed to reduce this form of contamination in Galveston Bay.

Tributyltin contamination of water is hazardous to a wide variety of marine life, but the sensitivity differs among species and location. Aquatic communities in Galveston Bay are less sensitive than those in Puget Sound and Narragansett Bay (Cardwell et al., 1999). Marinas maintain the highest level of tributyltin contamination in U.S. estuaries and in the Galveston Bay system. The expected total risk to aquatic life around Galveston Bay marinas is 3 percent (Cardwell et al., 1999). Expected total risk is calculated by summing the product of the percentage of species expected to be at risk at a given concentration and the probability that a concentration level will be encountered over all of the concentration ranges used. According to the study by Cardwell et al. (1999), the risk to aquatic life from tributyltin in Galveston Bay's water has declined in all locations to levels below the EPA criteria.

Water Quality Trends

- Declines in ammonia-nitrogen and total phosphorus concentrations baywide have occurred over the past three decades.
- Nitrate-nitrogen exhibited an upward trend from 1969 until 1994. There is no trend for nitrate-nitrite for the period 1993-2001,however, the data does indicate seasonal peaks in nitrate-nitrite concentrations.
- Dissolved oxygen is generally higher throughout Galveston Bay and in major tidal tributaries.
- Total Organic Carbon has an unusual pattern of multiyear cycles.
- Chlorophyll-a has declined over the last 25 years to less than 25 percent of its 1975 value.
- Dissolved metals have declined in the Houston Ship Channel over the last ten years.
- Organic contamination from spillage of petroleum products is substantial in the Houston Ship Channel, but limited in other segments.

Sediment Quality Monitoring

Sediments store many contaminants. Materials discharged in water may adsorb onto sediment particles. Frequently, contaminants can be detected in analytical or toxicity testing of sediments, when neither type of test detects these contaminants or their effects in overlying water from the same location. Whether adsorption or desorption of pollutants occurs is a function of several factors including pH, type of sediment and the type and concentration of pollutant. Over time, an equilibrium is established between the water and sediment concentrations of various compounds. However, both natural and human disturbances of the system can alter the equilibrium. Sediments are also a biological habitat. Sediment concentrations of contaminants can influence food web uptake of toxic pollutants, but not all contaminants in sediment are in a biologically available form.

Reaching conclusions about sediment quality is constrained by the shortage of data for most parameters. There are fewer data available on concentrations of pollutants in sediment samples than in water samples. Large areas of the bay bottom remain unsampled and frequency of sediment sampling has decreased. Processing sediment for chemical analysis is often laborious, difficult and costly.

In Galveston Bay sediments, metals and commonly measured organic compounds appear to follow the same general spatial distribution as do most of the other water quality parameters. Elevated concentrations occur in regions of runoff, inflow and waste discharges, and lower, relatively uniform concentrations occur in the open bay. The upper Houston Ship Channel is generally the locus of maximal concentration in the system (Ward and Armstrong, 1992).

	Arsenic		Cadmium		Chromium		Copper		Mercury		Lead		Zinc	
GBEP Segment	Most Recent Year sampled	Value	Most Recent Year sampled	Value	Most Recent Year sampled	Value	Most Recent Year sampled	Value	Most Recent Year sampled	Value	Most Recent Year sampled	Value	Most Recent Year sampled	Value
H19	1999	7.94	1998	0.96	1999	49.00	1999	42.50	1999	10.42	1999	72.30	1999	286.0
H18	1981	9.83	1987	0.70	1987	17.43	1998	8.16	Not Sampled	--	1987	48.48	1987	106.4
H17	1998	1.59	1999	0.21	1998	17.00	1998	20.10	Not Sampled	--	1998	54.00	1998	72.5
H16	1992	11.50	1980	14.50	1980	71.50	1980	38.00	Not Sampled	--	1980	155.00	1980	235.0
H15	1992	7.94	1985	1.50	1988	48.00	1988	33.00	Not Sampled	--	1988	46.00	1988	134.0
H14	1994	2.72	1994	0.33	1994	50.80	1994	54.70	Not Sampled	--	1994	45.40	Not Sampled	--
H13	1999	10.90	1998	0.34	1999	58.00	1999	25.40	Not Sampled	--	1988	16.00	1999	157.0
H12	1985	1.60	Not Sampled	--	Not Sampled	--	Not Sampled	--	Not Sampled	--	1984	7.00	1984	15.7
H11	1999	8.08	Not Sampled	--	1999	59.80	1999	19.30	Not Sampled	--	1999	33.90	1999	92.0
Probable Effect Level		41.60		4.21		160.40		108.20		0.70		112.18		271.0

Table 6.2. Most recent sampling years and values for metal contaminants in sediment from all segments in the upper Houston Ship Channel. (Source: Criner and Johnican, 2001)

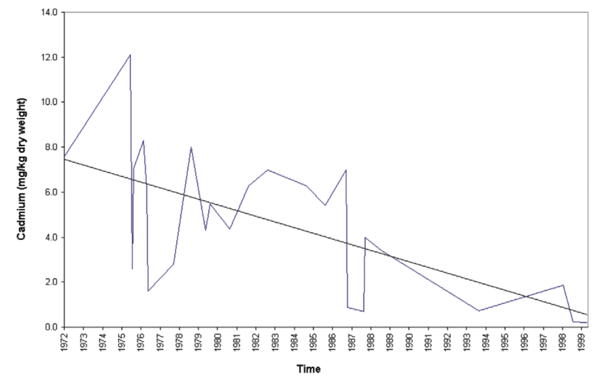


Fig. 6.14. Monthly average cadmium concentrations in sediment in the Houton Ship Channel, 1989-1999. (Source: Criner and Johnican, 2001)

Contaminants

Metals

Since metals do not degrade into other substances, they cause the most permanent contamination of sediments. However, they can be incorporated into tissue by deposit feeders and they can be resuspended in the water column and transported elsewhere.

Data on sediment levels of metals are very limited for open bay locations and most abundant for locations in the Houston Ship Channel, Texas City Ship Channel, Clear Creek, Dickinson Bayou and Chocolate Bayou. Arsenic, cadmium, chromium, copper, lead, mercury, and zinc are typically assayed. The time covered by the TNRCC database is from 1974 to 2000.

Table 6.2 shows a matrix of the best most recent metals data available on which to assess the status of the GBEP segments on the Houston Ship Channel. These segments extend from the Turning Basin to Morgan's Point. From this summary it is clear that very little information is collected on mercury. Fewer metals are monitored in the segments near Morgan's Point and GBEP segments H12, H14, H15 and H16 have not been tested for metals since 1994 or earlier. Only in segment H19 (the Turning Basin) have all of the metals been monitored in recent years.

The Houston Ship Channel will be used to illustrate the trends of sediment metal contamination in the bay because it has historically been a focus of metal contamination. Historical trends in sediment metal contamination of specific segments of the Houston Ship Channel will be compared to an open bay segment. G18 is along the Ship Channel where it passes Eagle Point in the open bay. This segment is sampled on a much more regular basis than other open bay segments.

In the upper Houston Ship Channel, cadmium, chromium, copper, lead and zinc exhibit downward trends over the recorded period. High values for cadmium in sediment are common in the Houston Ship Channel, but are declining. Figure 6.14 shows the cadmium concentrations in segment H17 since 1989. This declining trend is typical of the declines exhibited by all of the metal species in the Houston Ship Channel, except mercury. Cadmium values range from 12 mg/kg to 0.22 mg/kg. Chromium also has a downward trend with values between 219 mg/kg in 1975 and 17 mg/kg in 1998.

Copper concentrations in the sediment database ranged from below 10mg/kg to greater than 100 mg/kg across all bay segments. The higher concentrations (greater than 30 mg/kg) were associated with the upper Houston Ship Channel, Trinity Bay, Clear Lake, and the Texas City Ship Channel. Figures 6.15a and 6.15b contrast the trends in copper concentrations in

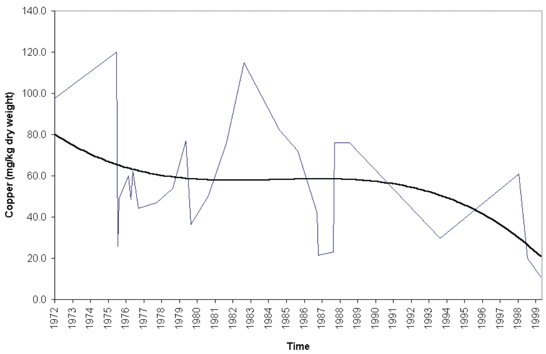


Fig. 6.15a. Monthly average copper concentrations in the Houston Ship Channel, 1972-1999. (Source: Criner and Johnican, 2001)

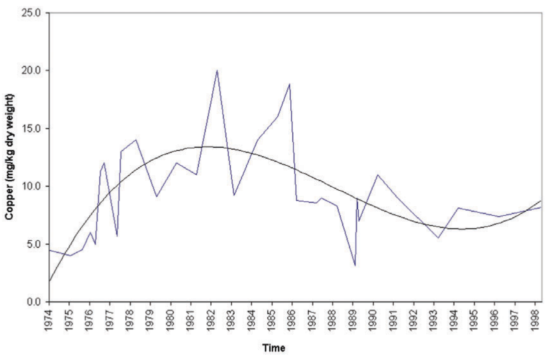


Fig. 6.15b. Monthly average copper concentrations in sediment in the open waters of Galveston Bay, 1974-1998. (Source: Criner and Johnican, 2001)

the Houston Ship Channel and the open bay. Copper concentrations in the sediments of segment H17 in the upper Houston Ship Channel are high until the mid 1980s and then decline to 60 mg/kg in the 1990s (Figure 6.15a). In two instances during the first half of the record, the values exceed the probable effects level of 108 mg/kg dry weight of sediment. In the open bay, the concentrations of copper never approach the probable effects level and have been below 15 mg/kg for the last 15 years (Figure 6.15b).

Sediment concentrations of arsenic are well below the probable effects level for aquatic life (41.6 mg/kg dry wt) in the Houston Ship Channel and the open bay. The concentration in segment H19 shows a single spike of arsenic to approximately 25 mg/kg in 1993, but has otherwise been below 10 mg/kg for the last 20 years. Arsenic concentrations of the sediments in segment G18 have been below 7 mg/kg for the last 20 years.

Concentrations of lead in sediments from segment H17 range from nearly 290 mg/kg of sediment to less than 30 mg/kg. Lead concentrations exhibit a declining trend since 1972 in sediments of all segments around the bay that have some data to analyze.

Zinc concentrations ranged from less than 50 mg/kg to, greater than 250 mg/kg, with highest concentrations in the upper Houston Ship Channel and Trinity Bay. Zinc had a downward trend in segment H17. This downward trend appears unstable because a concentration greater than the probable effects level was recorded for segment H19 in 1999. Zinc concentrations in the open bay segment, G18, rose from 1974 to 1984 and then fell to a stable level around 55 mg/kg. The highest recorded concentration in the open bay segments was 73 mg/kg.

Chromium and zinc show similar patterns in the open bay segment G18. The concentrations of these metals rise during the first ten years of the record and decline since the mid-1980s. Chromium has recorded concentrations ranging from 64 mg/kg in 1982 to 3.3 mg/kg in 1989, but the concentration appears relatively stable around 16 mg/kg in 1998.

Mercury is different from the other metals in the open bay segment. Mercury shows a simple decline from 1974 to 1998. The high value was 0.25 mg/kg recorded in 1975. In 1998 a measurement of 0.03 mg/kg was made. It was one of the two lowest values on record.

Organics

Data collected by Carr (1993) from 24 sites around the bay yielded additional information about the sediment quality in Galveston Bay. The concentration of chlorinated hydrocarbons, for example, was below the detection limit (0.01 ng/g) for most of the samples except a few stations with detectable concentrations of polychlorinated biphenyls (PCBs). Polynuclear aromatic hydrocarbons (PAHs) were elevated at a number of sites; specifically at three sites adjacent to produced water separator platforms.

Sericano et al. (1994) found the highest concentrations of PCBs in oysters near Morgan's Point, 1,100 ppb total PCBs. Concentrations in their study decreased seaward. All of the Galveston Bay sample sites with high PCB concentrations in oysters are associated with population centers on the nearest shore.

Willett et al. (1997) studied biomarkers in hardhead catfish and croaker for evidence of exposure to PAHs and PCBs. The study provides evidence of bioaccumulation of these toxins in the species studied and found a correlation of toxicant concentration in fish to collection location.

Toxicity

Analytical findings of the sort presented above provide good information about the presence and concentrations of contaminants in sediments, but shed little light on their effects in the ecosystem. Important questions relate to the toxicity of contaminants to organisms utilizing sediments, and the resulting implications for biological community structure. Crocker (1991) found that Houston Ship Channel bottom sediments were relatively nontoxic to test amphipods and sheepshead minnows.

Carr (1993) conducted a sediment quality triad study of Galveston Bay. Sediments were analyzed for trace metals, PAHs, chlorinated hydrocarbons, total organic carbon (TOC), and acid volatile sulfides. Two different toxicity tests were employed and yielded contradictory results.

Sediment Trends

- Chromium and lead were generally elevated in sediments throughout Galveston Bay, relative to data compiled on natural aquatic systems in Moore and Ramamoorthy (1984).
- Cadmium, mercury, copper, and zinc were generally low in the open bay.
- Cadmium, chromium, copper, lead and zinc have declined in the upper Houston Ship Channel.
- Trends of chromium, copper, lead and zinc in the midbay potions of the Houston Ship Channel show a rise from the 1970s to mid 1980s followed by a decline to a moderate level.
- Mercury concentrations have declined in the midbay potions of the Houston Ship Channel, but have remained relatively unchanged for the last 15 years in the upper Houston Ship Channel.

Biological Monitoring of Contaminants

The presence of contaminants in water and sediment may be episodic, but it is persistent in the tissues of organisms living in or ingesting the water or sediment. Studies of the concentration of contaminants in the tissues of finfish and shellfish have been conducted to assess the potential for health effects from consumption of seafood (See Chapter 9) or the level of ecological effects from the pollution.

The difficulty of measuring the concentration of contaminants in the water can be overcome if there is a method for concentrating them and collecting them over time. Nature has provided a collection and concentration device in the form of sessile benthic filter-feeding organisms. The most common in Galveston Bay is the oyster. Although it is not evenly distributed over the bay bottom, it is sufficiently common to use the concentration of pollutants in the tissue of oysters as an indicator of the prevalence of pollutant concentrations of concern. In addition to studies of oysters, reports of contaminant concentrations in finfish and blue crabs compiled for human health studies will be provided.

	Silver	Arsenic	Cadmium	Copper	Iron	Lead	Zinc
Galveston Bay	3.0	4.9	3.5	150.0	424.0	0.7	2082.0
Gulf of Mexico	2.2	9.7	4.2	156.0	320.0	0.7	2417.0

Table 6.3. Comparison of the average metal concentrations in oysters collected from Galveston Bay (Jiann and Presley, 1997) and from estuary systems around the entire Gulf of Mexico (Morse et. al. 1993). Concentrations are given as ng/kg of dry weight.

Metals

Several studies of the concentration of metals in the tissue of Galveston Bay oysters have been published. Jiann and Presley (1997) reported on the concentrations of seven metals in oysters collected from 15 sites during 1992-1993. They concluded that problems from metal pollution in Galveston Bay were not serious when compared to some other estuarine systems, such as Chesapeake Bay and Hong Kong harbor. Arsenic averaged 4.92 ppm dry weight in Galveston Bay collections, while the average for all Gulf of Mexico samples was 9.69 (Jiann and Presley, 1997; Morse et al., 1993). Most of the metals had similar average concentrations in Galveston Bay and across Gulf of Mexico samples.

Table 6.3 gives a comparison of the average metal concentrations for oysters collected from Galveston Bay and the average for the entire Gulf of Mexico. Six of the metals exhibited strong correlations in their concentrations. The authors suggest that this results from changes in response to the same environmental conditions. Bioaccumulation of silver, copper and zinc in oysters seemed to be largely determined by salinity (Jiann and Presley 1997). Only one site, Swan Lake near Texas City, greatly exceeded the bay averages for concentrations of silver, copper, lead and zinc most likely from the nearby Tex-Tin Superfund site.

An EPA study (1987) measured concentrations of selected trace metals in the Wah Chang Ditch, a tributary that flows from the Tex-tin superfund site into Swan Lake. As seen in Table 6.4, trace metal concentrations far exceeded surface water quality criteria established for the protection of aquatic life. Perhaps the most startling are the concentrations of copper and lead. Concentrations of these metals

Trace Metal	Concentrations found in Wah Chang Ditch (ug/L)	Acute Aquatic Life Saltwater Criteria	Chronic Aquatic Life Saltwater Criteria (ug/L)
Cadmium	283.0	45.6	10.0
Chromium	274.0	1100.0	50.0
Copper	15000.0	16.3	4.4
Lead	16000.0	140.0	5.6
Mercury	3.0	2.1	1.1
Silver	245.0	2.3	N/D

*N/D=Criteria not determined

Table 6.4. Comparison of concentrations of trace metals sampled in the Wah Chang Ditch near the Tex-Tin superfund site and Swan Lake and Surface Water Quality Standards for Aquatic Life Protection (EPA, 1987).

	Cadmium	Lead	Chlordane	DDE	PCB
Trinity Bay	0.014	0.003	0.030	0.008	0.017
Upper Galveston Bay	0.016	0.002	0.370	0.007	0.006
Lower Galveston Bay	0.030	0.011	Brl[2]	0.006	0.005
East Bay	0.020	0.023	0.008	0.001	Brl[2]
West Bay	0.015	0.014	0.004	Brl[2]	Brl[2]
Christmas Bay	0.070	0.006	0.001	0.001	Brl[2]
Houston Ship Channel[1]	0.001	0.009	0.763	0.044	0.016
Clear Lake	0.010	0.021	0.053	0.003	0.011

[1]HSC = Houston Ship Channel above Morgan's Point
[2]Brl = Below reporting limits

Table 6.5. Average concentrations of common contaminants detected in the tissue of finfish and blue crab collected in different areas of the Galveston Bay system (TDH, 1999; 2000a; 2000b; 2000c; 2001a; 2001b; 2001c; 2001d). Concentrations are given in mg/kg of wet weight for each of the reporting areas.

measured 15,000 and 16,000 ug/L, respectively (EPA, 1987). Such elevated concentrations must surely contribute in some way to elevated metal concentrations in the waters of Swan Lake.

Jiann and Presley (1997) also showed a seasonal difference in the tissue concentrations of copper, lead and zinc in Galveston Bay oysters. Concentrations were higher in Summer and Fall than in Winter and Spring. Oysters are apparently able to purge the metals from their tissue during periods when they are less metabolically active.

The recent seafood safety assessment by the Texas Department of Health sheds light on the prevalence of metal contaminants in species other than oysters. They sampled finfish and blue crabs from sites throughout the bay system. Six metals, cadmium, copper, lead, mercury, selenium and zinc, were detected in organisms from all of the collection areas. The highest average concentrations of the potentially toxic metals occurred in different areas. For example, samples from the lower San Jacinto River and the Houston Ship Channel near the river mouth had the highest average concentration of mercury, but samples from Christmas Bay had the highest cadmium concentration. The metal concentrations observed in finfish are based on mg/kg wet weight, which makes comparison with the oyster data difficult. However, the values shown in Table 6.5 are orders of magnitude lower than the values in Table 6.3 indicating less bioaccumulation for mobile species. Chapter 9 explains the relationship between the observed concentrations and health effects criteria.

Organics

Table 6.5 shows that organic contaminants, particularly pesticides are common in the tissue of finfish and shellfish in Galveston Bay (Texas Department of Health (TDH) 1999a, 2000a,b,c; 2001a,b,c,d). The TDH study assayed for 27 pesticides and found at least one present in the tissue of samples from all parts of the bay system. Eight pesticides were detected in tissue from animals collected in the upper bay. Seven different pesticides were detected in samples from Trinity Bay and the Houston Ship Channel. Chlordane and DDE were the most common pesticides found. Their average concentrations are given in Table 6.5. PCBs are still a cause for concern in the Houston Ship Channel and adjacent waters. PCBs were not detected in samples from East Bay, West Bay or Christmas Bay. This study also examined samples from Lower Galveston Bay, Christmas Bay and Clear Lake for dioxin. Multiple forms of dioxin were detected in fish from each area, but the concentrations were low when compared to criteria for health effects.

Jackson et al. (1998) investigated the temporal trends from 1986 to 1994 in the concentrations of selected organic pollutants in the tissue of oysters from certain Galveston Bay sites. The study examined the tissue concentrations of chlordane, DDT and derivatives, dieldrin, PAHs, PCBs, and tributyltin. All of these compounds are toxic to aquatic life at certain concentrations and they have the potential to bioaccumulate in oysters. The contaminant concentrations found in oysters from the Houston Ship Channel, the Houston Yacht Club and Offats Bayou cause these sites to rank within the most contaminated areas in the Gulf of Mexico. Alternatively, the contaminant concentrations in oysters from Hanna Reef, which supports the commercial oyster fishery, was consistent with a rank among the cleanest sites in the Gulf.

Concentrations of PAHs in oysters collected from different regions of the bay show no particular spatial pattern, except that the Houston Ship Channel has the highest concentration. Compared to the mean for Gulf of Mexico sites, 30 percent of Galveston Bay sites were high (16 percent are expected to be high). At specific sites, the concentrations rise and fall between years over the period from 1986 to 1994. The most likely explanation is periodic localized input of the compounds (Jackson et al., 1998). The prevalence of two particular PAHs (pyrene and fluoranthene) suggested that the major source of PAHs in the Galveston Bay area was combustion products.

Forty percent of oyster samples from Galveston Bay had high levels of the legacy pollutant, chlordane. High concentrations were those that exceeded the median of the Gulf of Mexico data by more than one standard deviation. If Galveston Bay matched the Gulf-wide samples, 16 percent of samples would be high. In 1991 oysters from the Houston Ship Channel had a median concentration of 0.169 mg/kg dry weight of chlordane. This is lower than the wet weight value of 0.763 mg/kg observed in finfish from the Houston Ship Channel in the TDH (2001d) study. In the same year, dieldrin had a median concentration of 0.064 mg/kg dry weight. Over the course of the study, 49 percent of samples were high for dieldrin, which means more than 9.1 ng/g dry weight (Jackson et al., 1998).

The concentrations of DDT and its derivatives in Galveston Bay oysters were similar to the distribution of concentrations across the Gulf Coast. The highest concentrations were in the Ship Channel. DDT concentrations show a decreasing trend over the sample period (Jackson et al., 1998).

While 38 percent of Galveston Bay oyster samples were high for PCB concentration, 1 percent exceeded the National Academy of Sciences criterion of 2500 ng/g dry weight for the protection of predatory wildlife. Galveston Bay oysters show a decreasing concentration of PCBs from 1986 to 1994. By the end of the study period, all the sample sites had median concentrations of less than 600 ng/g dry weight (Jackson et al., 1998). The values obtained from finfish and crabs sampled in 1998-1999 for the TDH study were even lower.

Tributyltin has been used as an anti-fouling paint on marine vessels. Its use is restricted on large vessels because it has adverse effects on nontarget organisms. Forty-five percent of the oyster sample sites in Galveston Bay were high compared to the Gulf of Mexico samples. At four of six sites there was a significant decline in tributyltin concentrations over time (Jackson et al., 1998).

Comparisons of sites within Galveston Bay and among Galveston Bay and other estuaries in the Gulf of Mexico indicate that the levels of contamination found in oysters is reason for concern. The average Galveston Bay oyster has higher concentrations of most organic contaminants, including chlordane, dieldrin, PCBs, PAHs and tributyltin, than the average oysters from other Gulf estuaries (Jackson et al., 1998).

Future Concerns

Dry and wet (through precipitation) atmospheric deposition of such pollutants as PCBs, mercury, and PAHs to Galveston Bay requires further study. The contribution of atmospheric deposition is increasingly being recognized as significant. Studies in other parts of the country are being undertaken to identify the role of atmospheric deposition in the contamination of water, sediment and tissues. Similar studies would be of great use for improving the water and sediment quality of the Galveston Bay system. Inadequate monitoring information to assess the status and trends of some water and sediment quality parameters, especially metals and toxics, is a cause for concern.

Summary

In summary, the geographical areas of Galveston Bay with contamination problems are in regions of intense human activity, including urban areas, points of surface runoff, waste discharges, and shipping. The quality of the bay is generally good, and there is a general trend of improvement. In many cases, substantial improvements are evident.

Water quality parameters of concern are chlorophyll-a and fecal coliforms. Chlorophyll-a needs attention because it has declined steadily for 25 years and the cause of its decline is unknown. Fecal coliform concentrations in Galveston Bay tributaries are of concern because, unlike many of the water quality measures, they have not shown improvement.

Sediment quality is improving in the areas of greatest contamination, e.g. the Houston Ship Channel. Cadmium, chromium, copper, lead and zinc have declined in the upper Houston Ship Channel sediments. Some metals still exhibit spikes in concentration. Sampling of sediment contamination is temporally and spatially sparse, making careful assessment of progress difficult.

Monitoring of water and sediment contamination by assaying the concentration in tissues of organisms provides a less optimistic view of Galveston Bay contamination. More pesticides and other organic contaminants are detectable in tissue samples. Metals appear to be in concentrations similar to other Gulf of Mexico estuaries, but pesticides, PCBs, PAHs and tributyltin appear elevated in Galveston Bay samples compared to other Gulf sites.

Return from the Noxious

The Story of Water Quality in the Houston Ship Channel

In 1959 when I was in sixth grade, my class took a field trip to the Port of Houston and went for a cruise on the Houston Ship Channel. My most vivid memory is how noxious the air was. It was difficult to breathe on deck. I would take a breath in the air-conditioned cabin and run outside to look around. My outside excursions lasted just as long as a lungful of air. Some of the smell was coming from the water, which was dark and lifeless. Back then the adults often said that it smelled like money, but it just smelled bad to my classmates and me.

—Jim Lester

In 1967, the Texas Water Quality Board was created by the Legislature. The first order of business was to initiate a statewide effluent reduction program. Because of the heavy industrial discharge load to the Houston Ship Channel (HSC), far more than half of the available regulatory resources were brought to bear on the Greater Houston Area.

Joe Teller was the first Deputy Executive Director of the Texas Water Quality Board and served in that capacity from 1967 until 1972. He reports that there was really no significant resistance to tightening permit requirements, primarily because all like industries were being given the same limitations. That is, all refineries, regardless of physical location, would have essentially the same effluent requirements, as would all paper mills, all chemical companies, etc.

One needs to remember that in those early days we had no guide; we were plowing new ground. There was no permit system anywhere in the country. EPA had not even been thought of then, and the federal agencies involved expressed concern that we were about to legalize pollution. But when the federal program came out, it looked remarkably like the Texas Plan.

—Joe Teller

I vividly recall hearing, some ten years later, the manager of utilities for one of the industries complaining bitterly that the ship channel water had improved to such an extent that his cooling water intake screens were being clogged by shrimp. That was as good a test of water quality improvement as one could hope for considering where we started.

—Joe Teller

The HSC is still a major focus of water quality monitoring. There is simply too much potential for problems to arise to let it go unwatched. Discharges from sewage treatment plants continue to grow simply by virtue of population growth. The non-point source load from one storm event alone can easily overwhelm the HSC's assimilative capacity. The same is true of the occasional accidental discharge from industrial treatment failures. There is simply not enough assimilative capacity in that slow moving, stagnant body of water. There has been a great deal of improvement in the water quality of the Houston Ship Channel, but further progress will require continued effort.

Chapter Seven

Key Habitats: Marsh, Seagrass and Oyster Reefs

The plants, predominantly grasses, that flourish in this environment (East Bay Wetlands) serve two biological functions: productivity and protection. From the amount of reduced carbon fixed by these plants during photosynthesis, this ecotone must be considered one of the most productive areas in the world and truly the pantry of the oceans. The dense stand of grass also represents a jungle of roots, stems, and leaves in which the organisms of the marsh, the "peelers", larvae, fry, "bobs", and fingerlings seek refuge from predators.

—Frank Fisher, Jr., The Wetlands, Rice University Review, 1972

The Galveston Bay system is composed of a variety of habitat types, ranging from open water areas to wetlands and upland grasslands. These habitats support specific plant, fish, and wildlife species and contribute to the tremendous diversity and overall abundance of bay life. The continued productivity and biological diversity of the estuarine system is dependent upon the maintenance of varied and abundant high-quality habitat. The major habitat types have been identified and described in Chapter 2. The importance of these habitats, their community composition, and their interconnectedness were presented there.

Three of the bay's habitats are emphasized in this chapter because they have been identified in the Galveston Bay Plan for special conservation and restoration efforts. First, wetlands, primarily marshes, serve important biological, hydrological, and ecological functions in the bay ecosystem, but have experienced significant rates of loss. Second, seagrass meadows are a valuable but endangered habitat in the Galveston Bay system outside Christmas and Bastrop Bays. Third, oyster reefs are important as indicators of the overall condition of the ecosystem and are the basis for an important commercial fishery. Oysters and their shells have been exploited, sometimes with attendant ecological detriment, for many decades.

Wetlands

"Wetlands are lands transitional between terrestrial and aquatic systems where the water table is usually at or near the surface, or the land is covered by shallow water" (Cowardin et al., 1979). Wetlands in Galveston Bay play several key ecological roles in protecting and maintaining the health and productivity of the estuary.

The Origin and Importance of Wetlands

Wetlands were formed in Galveston Bay from the long-term interaction of the ecosystem's physical processes. These processes have occurred throughout geologic time and most still occur today. They include glacial changes, rainfall and runoff, water table fluctuations, streamflow, evapotranspiration, waves and longshore currents, lunar and wind-driven tides, storms and hurricanes, deposition and erosion, subsidence, faulting, and sea-level rise (White and Paine, 1992). These processes have formed an array of physical environments that range from being infrequently to permanently inundated with water. The resulting elevations of these environments range from submerged bay bottom, through the intertidal zone, to the zone above high tide that is infrequently flooded by wind and storm. The continuing action of physical processes and the proximity to salt and fresh water sources determine the location and composition of wetland plant communities. Based on the work of Pulich and Hinson (1996), vegetated and unvegetated wetlands in the Galveston Bay coastal region total 260,680 acres.

In addition to being formed by physical processes, wetlands are important elements of many biological processes that support the bay ecosystem. Hydrologically, fringing wetlands are valuable filtering zones for polluted runoff, protecting the bay from excessive organic and sediment loadings from the land. Particularly in river bottomlands, they serve as good flood-control areas that release runoff water slowly to the bay compared to the rapid discharge from man-made drainage systems. Finally, well-developed vegetated wetlands also provide a buffer between high-energy water and land, preventing or reducing shoreline erosion.

Wetlands are among the most productive biological systems on the planet. They may be more important to the Galveston Bay system than is true for many other bays (Sheridan et al., 1989). Among the most important of wetland functions is their role in providing habitat for many species of plants, fish, birds, and other wildlife. All of Galveston Bay's principal commercial and recreational fishery species rely on wetlands during at least some part of their life cycle. These species include brown shrimp, blue crab, red drum, spotted seatrout, southern flounder and Gulf menhaden. In the same way, wetlands are important nurseries to hundreds of non-commercial species that comprise a large part of the food web. Several bird species, such as snowy egrets, roseate spoonbills, tri-colored herons, black skimmers and great egrets use the marsh as feeding habitat.

Trends in Wetland Distribution

Understanding where wetlands are located and how their area has changed over time is critical if they are to be effectively protected, managed and restored. Studies to classify and assess wetlands are a priority nationally and in the Galveston Bay system. Nationally, three-fourths of the remaining estuarine wetlands classified by Dahl and Johnson (1991) were "intertidal emergent", typified by cordgrass (*Spartina sp.*) salt marshes. These authors estimated a relatively small 1.5 percent loss nationwide from the mid 1970s to the mid 1980s for this important habitat type. In 1997 the coterminous United States had five million acres of saltwater wetlands and 100.5 million acres of freshwater wetlands (Dahl, 2000). The rate of wetland loss has slowed to 58,500 acres annually. Coastal areas lost 14,450 acres of estuarine emergent wetlands between 1986 and 1997 primarily to urban and commercial development (Dahl, 2000).

The area of estuarine marshes in the Galveston Bay system as determined by aerial photo interpretation has decreased since the 1950's. White et al. (1993) reported a decrease from 165,500 acres in the 1950s to 130,400 acres in 1989. Pulich and Hinson (1996) reported a total of 120,132 acres of marshes in the Galveston Bay region based on 1995 aerial photography. Despite the precision of these estimates, showing a decline of 35,100 acres from 1953 to 1989 and a further loss of 10,268 acres from 1989 to 1995, the actual loss of marsh area may not be 45,368 acres.

Wetland distribution is difficult to determine. The factors influencing wetland distribution are complex, making it difficult to get an annual "snapshot" of wetland status. Land cover mapping from aerial photographs is difficult to compare because variation is introduced by differences in photographic methods, seasonal vegetation, weather, climate changes (e.g. the El Niño Southern oscillation) and classification algorithms. These estimates are sufficient to establish a trend of wetland loss, but insufficient to compare precise rates of loss and the levels of classification error.

Even within the limitations of the methodology, these estimates document a substantial loss of Galveston Bay wetlands. The proportional loss in Galveston Bay is higher than the national loss of estuarine wetlands. National wetland loss was estimated to be 59,400 acres or about 0.5 percent annually in the decade before 1986 (Dahl and Johnson, 1991). The rate of loss based on the data of White et al. (1993) was 975 acres or about 0.7 percent per year in the decade prior to 1989. The rate of loss estimated from the classification of Pulich and Hinson (1996) was 1080 acres or about 0.9 percent annually based on the acreage in 1995. These estimates are similar and confirm the chronic nature of wetland loss around Galveston Bay.

Status of Different Types of Wetlands

Several different wetland communities can be found in the Galveston Bay system. These include salt marshes, brackish marshes, intermediate marshes, freshwater marshes and forested swamps. The land cover classifications performed by White et al. (1993) and Pulich and Hinson (1996) indicated gains and losses in these different classes of wetlands. Losses in emergent wetlands in some areas were partly offset by gains in emergent wetlands in other areas. Relative sea level rise was responsible for converting previously upland areas to wetland areas. Around the Galveston Bay system, increases in marsh were most pronounced on the north shore of East Bay, on the bay side of Galveston Island, and on the north shores of West Bay and Christmas Bay (White et al., 1993).

The following discussions on the status of wetland communities in Galveston Bay are based primarily upon the work of Pulich and Hinson (1996). They summarized wetland mapping and monitoring efforts of the Texas Parks and Wildlife Department Coastal Studies Program in several coastal areas including Galveston Bay.

Salt Marsh

Salt marsh communities (Figure 7.1) are found in high salinity areas along protected estuarine shorelines. Prevalent species in the salt marsh community include smooth cordgrass, saltwort, saltgrass and glasswort. Smooth cordgrass, which lives in the intertidal zone, dominates the low salt marsh community. At higher elevations, marsh hay (or saltmeadow cordgrass) and Gulf cordgrass occur, although they are more common in brackish marshes (White and Paine, 1992). Pulich and Hinson (1996) reported that there are approximately 33,775 acres of salt marshes in the Galveston Bay coastal region.

Fig. 7.1. Wetlands provide habitat for many species of plants, fish, birds and other wildlife. Many of Galveston Bay's principal fishery species rely on wetlands during some part of their life cycle. (Courtesy Galveston Bay Estuary Program)

Brackish Marsh

This community inhabits the transitional zone between salt marsh and fresh marsh and is affected by a widely varying range of water levels and salinities. As would be expected, a number of species utilize this habitat, ranging from near-fresh water to saltmarsh species. In general, the brackish marsh is dominated by marsh hay cordgrass and saltgrass. Other species include needlegrass rush, common reed and big cordgrass (on levees), seashore paspalum and longtom (in fresher areas) and isolated clumps of saltmarsh bulrush and Olney bulrush (White and Paine, 1992). According to Pulich and Hinson (1996), approximately 64,158 acres of brackish and intermediate marsh exist in the Galveston Bay coastal region.

Fresh Marsh

Fresh marshes (Figure 7.2) are primarily found in areas that are affected by saltwater flooding only during large tropical storms or hurricanes. The fresh water in these marshes is sufficient to maintain a low salinity suitable for such species as marsh millet (or giant cutgrass), coastal arrowhead and squarestem spikesedge (*Eleocharis sp.*). In low, wet areas, the exotic water hyacinth can be found, while panic grasses and spiny aster can be found in higher areas. Shrubs become established around the margins of the marsh (White and Paine, 1992). A large portion of the overall losses in wetlands can be attributed to the loss of fresh-water marshes (White et al., 1993). The apparent increase in "estuarine bay marshes, salt and brackish water" areas are in large part due to reclassification of fresh-water marshes and other marsh types to this category. Permanent fresh or inland marshes covered approximately 22,199 acres in the Galveston Bay coastal region in 1995 (Pulich and Hinson, 1996).

Fig. 7.2. Freshwater marshes are primarily found in areas that are affected by saltwater inundation only during large tropical storms or hurricanes. A large portion of the overall losses of wetlands in the local Galveston Bay watershed can be attributed to the loss of freshwater marshes (White et al., 1993). (Courtesy Bob Parvin/ Texas Department of Transportation)

Fig. 7.3. Cypress swamps, bottomland hardwoods and associated riparian forests contribute important nutrients as well as dissolved oxygen to the estuarine system. (Courtesy Bob Parvin/Texas Department of Transportation)

Swamps

Forested wetlands include woodlands or forested areas with saturated soils, which are inundated by water much of the year (Figure 7.3). In the Galveston Bay system, this community is located almost exclusively in the Trinity River valley. The dominant plant species in this swamp community is bald cypress. The plant community also includes buttonbush, water elm, and water hickory (White and Paine, 1992). Forested wetlands increased by 3,600 acres between the 1950s and 1989. Almost all of this gain was in the Trinity River valley. Most of the forested wetland gain since the 1950s was due to the invasion of Chinese tallow, an exotic species with rapid growth potential and low wildlife value. Some losses were due to changes in hydrology. According to Pulich and Hinson (1996), swamp habitat amounts to 9,731 acres while freshwater shrubland covers approximately 5,778 acres.

Causes of Wetlands Loss

The U.S. Fish and Wildlife Service reports that wetlands losses at the national level between 1986 and 1997 were caused by urban development (30 percent), agriculture (26 percent), silviculture (23 percent) and rural development (21 percent) (Dahl, 2000). Causes of wetland losses in the Galveston Bay system from the 1950s include relative sea-level rise; land use conversion for agricultural, urban, industrial, and transportation purposes; dredge-and-fill activities; and isolation projects.

Relative Sea Level Rise

Relative sea level rise (See Chapter 5), the combination of land subsidence (due to subsurface fluid withdrawal) and rising ocean levels, has resulted in the drowning of numerous wetland areas throughout the bay system, and in creation of new wetlands by inundation of uplands. Overall, losses exceed gains. About 26,400 acres of 1950s marsh were converted to open water/barren flat habitats by 1989. Most of this conversion was due to subsidence caused by pumping of groundwater and petroleum over the last 100 years. Subsidence is discussed in detail in Chapter 5. Wetland areas affected by subsidence include the north, west, and south margins of Galveston Bay and the northeast part of West Bay (White et al., 1993).

In certain parts of the bay system, the effects of relative sea-level rise have been particularly severe. For example, more than 3,600 acres of marshland in the Virginia Point area around Jones Bay and Swan Lake were replaced by open water and barren mud flat between the 1950s and 1989 (White et al., 1993). In San Jacinto State Park, subsidence has exceeded 9 feet since 1900 and several thousand acres of marsh were replaced by open water until restoration efforts began in 1998. The Clear Lake and Baytown areas offer other examples of the effect of land surface subsidence and the subsequent intrusion of open water into vegetated wetlands. Since the 1950s, there has been a significant loss of fresh water wetlands along Armand Bayou (McFarlane, 1991).

Losses in emergent wetlands in some areas were partly offset by gains in emergent wetlands in other areas. Bay-wide subsidence and sea level rise were probably responsible for converting part of approximately 21,000 acres of previously upland areas to wetland areas. Some conversion of uplands to wetlands were the result of water management programs implemented in national wildlife refuges. Regionally, these increases in marsh were most pronounced inland from East Bay, on Galveston Island and inland from West Bay. The conversion of uplands to wetlands generally took place in transitional areas peripheral to existing wetlands. Additional increases in emergent wetlands resulted after emergent vegetation spread over areas previously mapped as intertidal flats. This type of change was common in intertidal mud flats on the barrier islands (White et al., 1993).

Conversion to Upland Land Uses

Draining of wetlands has also caused a significant loss since 1950. Much of this loss has occurred in fresh water marshes rather than the saltwater or brackish marshes. The lost area is about 35,600 acres, which accounts for most of the total loss in estuarine and fresh water emergent wetlands. Much of the change can be attributed to drainage ditches constructed to reduce flooding and increase the area available for livestock grazing (White et al., 1993).

Conversion to cropland and pastureland claimed 3,600 acres mostly in the Hitchcock, Oyster Bayou and Chocolate Bay areas. Most of the new cropland area was for rice cultivation. Although some of these wetland conversions to uplands were related to natural conditions, such as annual (and seasonal) changes in moisture levels, most of the loss may be due to direct conversion to upland range and cropland (White et al., 1993).

Conversion of wetlands to urban upland areas totaled 5,700 acres. This was concentrated in the south and west side of the bay, particularly around the Virginia Point area. Urban development of wetlands occurred also in the municipalities of Galveston, League City and Sea Isle (on West Galveston Island) (White et. al., 1993).

Other upland conversion since the 1950s included conversion to oil and gas production, resulting in a net loss of 800 acres. Much of the oil and gas production losses were concentrated in the Virginia Point, Texas City, and High Island areas (White et. al., 1993).

Dredge and Fill Impacts

The relative impact of dredging and filling on marshes is difficult to quantify due to the lack of a good baseline. The 1851 map shown in Figure 5.4 recorded the shoreline position, but the type of vegetation in an area is not noted. Also, there was little regulation of wetland conversion until 1972. The Rivers and Harbors Act of 1938 charges the U.S. Army Corps of Engineers (COE) to provide due regard to wildlife conservation in planning Federal water projects, but this did not result in collection of data on acres of wetlands converted to other uses. The implementation of Section 404 of the Clean Water Act of 1972 put in place a permitting system to protect wetlands or mitigate wetland loss, which has produced a record of requests for wetland conversion and agreements for mitigation. Unfortunately the data on permits is not complimented by data from assessment of wetland protection or wetland mitigation results.

Ward (1993) estimated the total loss of marsh due to dredge and fill activities by analyzing available records from federal dredging projects, available maps of the bay over time, and COE Section 404 dredge-and-fill permits since the 1970s. (See Chapters 4 and 5 for more discussion of dredging projects and their impacts.) Based on this information, he estimated that a total of 7,070 acres of marsh had been lost to dredging, filling, and disposal activities from 1900 to 1990. Of this loss, 2,920 acres were lost due to creation of designated disposal areas, 860 acres to navigation channels, and 3,290 acres to private dredge and fill operations under the COE Section 404 Permit program. The total area of wetlands lost to dredge and fill was up to five percent of the total wetland area and up to 20 percent of the net losses estimated for Galveston Bay (Ward 1993). The area affected by permitted dredging activities between 1995 and 2000 is discussed in Chapter 4.

Isolations

As described in Chapter 3, several large-scale modifications to the bay's shoreline have resulted in large areas of open bay and marshland being isolated from the bay itself. The most significant of these was the closure of Turtle Bay (now called Lake Anahuac) in 1936. Ward (1993) estimated that the closure of this area near the mouth of the Trinity River eliminated about 6,000 acres of shallow bay bottom and 10,000 acres of marshland from the estuarine system. Other estuarine marshlands that have been isolated from the bay include:

- 1,100 acres in the Trinity River delta for the Delhomme hunting area;
- 2,500 acres on the west side of Trinity Bay and Trinity River delta for the Reliant/HL&P Cedar Bayou Generating Station's cooling pond;
- Approximately 2,000 acres on the north shore of East Bay for salt water barriers; and
- About 700 acres in the Moses Lake and Dollar Bay area for the Texas City flood control project.

While these isolation projects have not resulted in a total conversion of these marshes to upland land uses, they have reduced the estuarine marshland in the Galveston Bay system by 16,000 acres (Ward, 1993).

Marsh Restoration and Creation

The Galveston Bay Plan identifies Priority Problem 1 as lost or degraded aquatic habitats (See Chapter 1) and sets a goal of expanding areas and restoring quality of wetland habitats. Specifically this goal calls for the

Year	Bay or Tributary	Number of Projects	Sum of Acreage (acres)	Sum of Assessment
1973	East Bay	1	1.00	NA
1974	East Bay	1	Unknown	NA
1977	East Bay	1	3.00	50%
1978	East Bay	1	0.01	NA
1980	West Bay	1	0.04	NA
1983	West Bay	1	15.00	NA
1983	Chocolate Bayou	1	15.00	NA
1983	Lower Galveston Bay	1	7.00	NA
1984	Lower Galveston Bay	1	0.50	50%
1984	West Bay	1	0.80	50%
1985	Lower Galveston Bay	1	0.30	50%
1986	East Bay	2	0.04	80% to 90%
1987	East Bay	2	0.92	5% to 70 %
1987	Lower Galveston Bay	1	6.47	75%
1988	East Bay	1	0.80	85%
1989	East Bay	1	1.48	80%
1989	Trinity Bay	1	0.16	70%
1990	San Jacinto River	1	0.10	32%
1990	Trinity River	1	0.14	0%
1991	San Jacinto River	1	0.10	95%
1991	Trinity Bay	4	0.63	0% to 100%
1991	Upper Galveston Bay	1	0.10	55%
1992	Lower Galveston Bay	1	3.00	NA
1992	West Bay	1	0.10	80%
1992	San Jacinto River	2	0.20	32% to 65%
1992	Upper Galveston Bay	1	0.10	0%
1992	Clear Lake	1	0.01	0%
1993	West Bay	1	25.70	42%
1993	Lower Galveston Bay	1	1.00	NA
1994	Clear Lake	13	2.1	25% to 95%[1,2]
1994	Upper Galveston Bay	2	0.49	100%[2]
1994	West Bay	1	0.17	NA
1994	Clear Lake	2	Unknown	67% to 85%[1]
1994	East Bay	1	5.14	32%
1995	Upper Galveston Bay	2	227.00	85% to 95%
1995	Clear Lake	1	5.73	67%
1996	Upper Galveston Bay	1	10.87	69%
1997	Upper Galveston Bay	1	0.00	NA
1998	Trinity River	1	0.75	30%
1999	Trinity River	1	100.00	80%
1999	West Bay	3	149.00	10%2
1999	Upper Galveston Bay	1	0.00	NA
1999	Lower Galveston Bay	1	1.80	NA
2000	West Bay	4	100.00	NA[1,2]
2000	East Bay	1	750.00	In Progress
Total		**71**	**1436.75**	

[1] Total acreage of some projects unknown

[2] Total assessment of some projects undetermined

creation or restoration of 5,000 acres of freshwater marsh and 8,600 acres of estuarine emergent marsh.

Table 7.1 provides a partial list of marsh restoration and mitigation projects conducted between 1973 and 2000. The number of projects and the size of some projects are quite impressive. There is no repository for data on all of the mitigation projects required by Section 404 permits. This list does not contain projects performed as mitigation by private companies. The projects listed are those undertaken by public organizations that participate in the Galveston Bay Estuary Program.

Emergent marsh restoration methodology has evolved in recent years. Early restoration efforts involved the transplantation of *Spartina alterniflora* (smooth cordgrass) propagules from a healthy marsh to the restoration site. The development of nurseries for wetland plants has made transplantation unnecessary. Propagation currently involves two types of smooth cordgrass: a cultivar developed by the U.S. Department of Agriculture in Louisiana and the indigenous variety. Seed collection at nurseries has made it possible to propagate smooth cordgrass at restoration sites by sowing seed. In brackish and freshwater sites additional species of wetland plants can be obtained and are regularly planted to enhance habitat value. As the table shows, some projects include the planting of *Spartina patens* (saltmeadow cordgrass) or *Zizaniopsis miliacea* (giant cutgrass).

Many of the marsh restoration projects involve planting propagules along shoreline that appears to be a suitable site. In larger projects with substantial funding, site preparation may include the use of heavy equipment or dredging to shape the substrate and enhance the surface topography for marsh establishment. Some of these projects in recent years have created extensive fields of terraces, e.g. Galveston Island State Park (Figure 7.4). Other types of projects include the formation of new substrate with dredged material. Dredged material is now commonly used for marsh restoration activities, e.g. at San Jacinto State Park. Some projects do not require such site preparation, but merely need protection from wave erosion and predation (e.g. along Armand Bayou).

A compilation of marsh restoration projects implemented by public organizations around the Galveston Bay system from 1973 to 2000 is provided (Table 7.1). No substrate modification is listed if propagules were planted in the existing shoreline

Fig. 7.4. As seen in this aerial view of the marsh restoration project at Galveston Island State Park, extensive fields of terraces were used to re-establish emergent marsh vegetation. (Courtesy U.S. Fish and Wildlife Service Texas Coastal Program)

environment. Only species planted in addition to smooth cordgrass are listed. Values for percent cover are listed for all projects that were assessed for survival. The year after planting in which the assessment was conducted is shown in parentheses. Other projects may be successful, but quantitative assessments were not available. This does not purport to be a complete list of marsh restoration projects during this period.

Table 7.1 makes it very clear that marsh restoration and creation occur on several scales. Many of the projects cover only a fraction of an acre. The significance of this may be misleading. Projects that cover a small area may actually be quite large in terms of the amount of linear feet of newly created shoreline.

Many restoration projects are often the result of volunteer action by organizations with a conservation mission, e.g. Galveston Bay Foundation and Armand Bayou Nature Center. More ambitious projects may cover from 1 to 15 acres. They are labor and cost intensive, but may be accomplished by a single organization. Then there are the very large projects of 20 to 200 acres that involve participation by multiple organizations, e.g. Atkinson Island and Galveston Island State Park. These large projects will be essential if the goal of the Galveston Bay Plan, restoration of 8,600 acres of estuarine marsh, is to be achieved. Despite the large number of projects, only about 500 acres of marsh have been restored.

It is significant that the technology applied to marsh creation has proven successful. Placement of wave breaks around the large projects appears to improve the ability of created marshes to hold and capture sediment. Terracing provides variation in elevation, which is an important characteristic of marshes and offers habitat to many different types of species. Placement of dredged material along a shoreline increases the amount of shallow water and intertidal environment essential to establishment of smooth cordgrass, the dominant plant species in marshes. These technical methods are expensive, but allow managers to reclaim former marshes that have been largely degraded.

Seagrass Meadows

The Importance of Seagrass Communities

Seagrass meadows (Figure 7.5) are highly productive communities that support a diversity of life. They provide food, shelter and nursery habitat for many commercially and recreationally important species of finfish, shellfish and migratory waterfowl. Seagrasses are very valuable for sustaining the yield of commercial and recreational species from the bay system. This ecosystem also provides food resources and protective cover for a number of other species and contributes substantial quantities of detritus to the open bay bottom food web. In addition to their ecological importance, submerged aquatic vegetation (SAV) play an important role in the physical processes of shorelines. They stabilize coastal erosion, reduce wave energy and trap sediments and nutrients.

Trends in Seagrass Distribution

The majority of Texas seagrass meadows occur along the middle to lower Texas coast, e.g. the Laguna Madre. Seagrasses typically thrive in warm, clear waters with higher salinities.Some seagrasses, like *Ruppia maritima* (widgeongrass), can be found in fresh water. The more halophytic varieties include *Halodulewrightii*

Fig. 7.5. *Underwater seagrass meadows support a rich and diverse community. They provide food, shelter and nursery habitat for many commercially and recreationally important species of finfish, shellfish and migratory waterfowl. (Courtesy Jamey Tidwell/Texas Sea Grant College Program)*

(shoalgrass) and *Thalassia testudinum* (turtlegrass).

Salinity, turbidity and rainfall/inflow patterns seem to be the controlling factors for natural seagrass growth in Galveston Bay (TPWD, 1999). Tidal current and circulation also have an important effect on seagrass beds. This water movement cleanses the leaves of epiphytic algae and allows for greater light attenuation.

In the bay system, SAV historically flourished in four locations: 1) around Trinity River Delta (widgeongrass and tape grass); 2) along the western shoreline of Galveston Bay from Seabrook to San Leon (widgeongrass); 3) along the southern shoreline of West Bay (shoalgrass mixed with widgeongrass); and 4) in Christmas Bay (shoalgrass mixed with turtlegrass and clovergrass) (Renfro, 1959; Pullen, 1960).

Most of the seagrass beds once present in the Galveston Bay system have been lost since the late 1950s (Pulich and White, 1991; Pulich, 1996). The probable distribution in the 1950's and the location of beds extant in 1987 and 1996 are shown in Figure 7.6. While restored populations of shoalgrass and clovergrass were observed in West Bay in 2000 and 2001, a remnant population of approximately 280 acres of true perennial seagrass beds (excluding widgeongrass) has survived in Christmas Bay (TPWD, 1999).

Widgeongrass is ephemeral and more tolerant of lower salinities and can still be found scattered in upper Trinity Bay near the mouth of the Trinity River, in Galveston Bay tributaries and in isolated ponds (TPWD, 1999). The widgeongrass beds along the western shore of upper Galveston Bay have disappeared without remnant populations. Mysteriously, populations of this species are observed to appear, disappear and reappear elsewhere quickly for reasons unknown (Roach, 2001). Submerged aquatic vegetation habitat decreased from 2,500 acres in the 1950s to approximately 700 acres in 1987. In 1995 there were 280 acres in Christmas Bay (TPWD, 1999), plus some amount of widgeon grass in tributaries and upper portions of Trinity Bay. The decline in this habitat type between 1950 and 1995 was about 2,000 acres, or 80 percent of the 1950s habitat (White et al., 1993; TPWD 1999). Since 1995, seagrass beds of shoalgrass and clovergrass have developed in West Bay following planting and restoration efforts (see below).

Causes of Seagrass Loss

The exact reasons for the decline in submerged aquatic vegetation are not known. Plausible reasons include: 1) subsidence; 2) effects of hurricane Carla on western Galveston Bay; 3)decrease in light attenuation and 4) human activities including development, wastewater discharges, chemical spills, and dredging activities in West Bay.

Czapla (1993) indicated that light attenuation (the reduction in light penetration) was presumably the major limiting factor to SAV growth in Galveston Bay, as in other estuaries. In addition, submerged aquatic vegetation requires a low-energy environment with limited water current or turbulence. High wave energy and turbidity in locales where submerged aquatic vegetation formerly existed may reduce the potential for re-establishment. Placement of geotubes for protection of shorelines at Galveston Island State Park has certainly encouraged the growth of seagrass meadows in that location (see Figure 7.7) (Roach, 2001).

Dunton (1999) categorizes the causes of seagrass loss into natural and anthropogenic disturbances. Natural disturbances are produced by storms, e.g. hurricanes, floods and droughts. These directly impact seagrass growth and survival through changes in turbidity and sedimentation. Anthropogenic disturbances are of three basic types: dredging, boating and pollution. Dredging increases the suspended solids in the water and may impact seagrass through light attenuation or direct burial of plants. Powerboats, while not a significant threat in Galveston Bay, can directly excavate plants and roots, leaving prop scars that take years to revegetate. Nutrient enrichment from agricultural runoff, aquaculture effluents, improperly functioning sewage treatment systems or groundwater discharged from septic system drainage fields can lead to excessive algal growth that shades the grass or leads to stressful low oxygen conditions.

Seagrass Bed Restoration and Creation

In recognition of the value being lost with declining seagrass resources, state agencies approved a Seagrass Conservation Plan for Texas (TPWD, 1999). The plan recommends management actions to reverse the decline in this resource. Water quality criteria that promote optimum seagrass health should be established for estuaries. The Clean Water Act section 401 and 404 permitting processes emphasize avoidance of damage to seagrass beds rather than readily accept compensation.

Seagrass restoration is much more challenging and expensive than cordgrass restoration (Roach, 2001). Historically, restoration and creation of seagrass meadows has been quite difficult and not very successful. This seems to be changing in the Galveston Bay system and more seagrass restoration activity is occurring.

Biologists and managers working on Galveston Bay are optimistic about the prospects for restoring seagrass habitat in the bay system. As discussed in Chapter 6, water quality has improved and light penetration should have increased. Development along the bay shore on West Galveston Island has slowed and sewage treatment systems have expanded. Open bay disposal of dredged material is no longer a threat to seagrass populations since the use of this disposal method is now only accepted as beneficial use for marsh creation (Roach, 2001) (see Chapter 4).

Studies have shown that planting shoalgrass can lead to restoration of a seagrass ecosystem (Sheridan et al., 1998). Recently a seagrass ecosystem colonized the terraces created for the Galveston Island State Park marsh restoration project. Three seagrass planting techniques were utilized: 1) broadcast of live and dead plant material, 2) planting of seagrass in peat pots and 3) bare-root planting via pontoon/tractor boat. Of the three, the broadcast method was found to be the most successful technique (Roach, 2001). Widgeongrass is currently being planted under experimental protocols in tidal sections of Armand Bayou. More restoration projects are proposed in support of the objective of the Galveston Bay Plan that calls for creation of 1400 acres of seagrass beds.

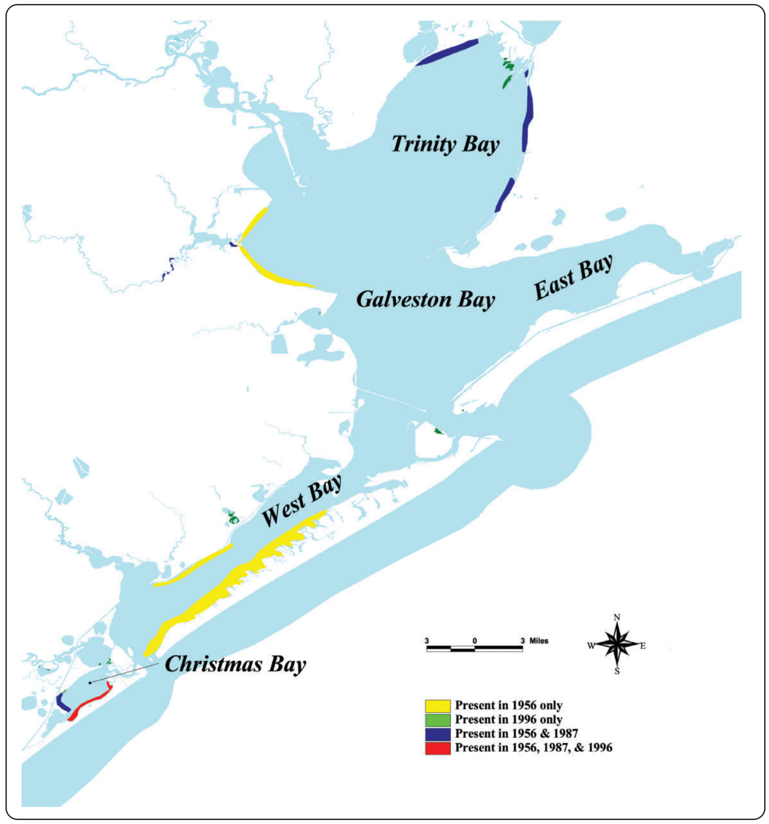


Fig. 7.6. Distribution of submerged aquatic vegetation in the Galveston Bay System as surveyed in 1956, 1987 and 1996. (Source: Pulich and White, 1991; Pulich, 1996)

Fig. 7.7. As seen in the foreground of this photo, geotube levees are constructed to protect wetland restoration areas and shorelines from wave energy and erosion. (Courtesy Cherie O'Brien/Texas Parks and Wildlife Department)

Fig. 7.8. Oyster reefs are important as indicators of the overall condition of the ecosystem and are the basis for an important commercial fishery in Galveston Bay. Oysters in the Galveston Bay system create a reef ecosystem based on the formation of a three-dimensional structure from the growth of the shells of a single species, Crassostrea virginica. *(©Stephan Myers)*

Oyster Reefs

The Importance of Oyster Reef Communities

In addition to being commercially important, oysters serve an important ecological role in the bay system. Locations of reef and unconsolidated shell sediments have been identified by three studies over a period of 40 years: in the1950's (Turney, 1958), in 1976 (Benefield and Hofstetter, 1976), and in 1991 (Powell et al., 1994). There have been no baywide estimates of the areal extent of oyster reefs since 1991.

The oyster reefs of Galveston Bay can be divided into naturally occurring reefs that have existed over historic time and reefs that have been created as a result of human influences. Natural reefs are primarily of four types: 1) longshore reefs oriented parallel to shore and located near or attached to the shoreline; 2) reefs extending perpendicular from the shoreline or a point near shore out into the bay; 3) patch reefs composed of one or more relatively circular bodies; and 4) barrier reefs extending across or nearly across the bay. Reefs created through human influences include those associated with: 1) placement of dredged material; 2) oil and gas development; 3) oyster leases and 4) modifications in current flow. The reef types resulting from human activity account for a substantial fraction of all of the present reefs in Galveston Bay. In many areas of the bay, they account for 80 to 100 percent of the entire reef area.

As described in Chapter 2, oysters create a reef ecosystem based on the formation of a three dimensional structure from the growth of the shells of a single species, *Crassostrea virginica* (Eastern oyster) (Figure 7.8). Oysters start life as a floating egg that upon fertilization develops into a planktonic larva that feeds on phytoplankton. The last larval stage settles to the bottom, seeks an appropriate substrate and if successful, metamorphoses into a miniature oyster called a spat. The environmental cues used by larval oysters involve the presence of a hard substrate (preferably the shell of an adult oyster) water movement, salinity and food supply. Once metamorphosis occurs an oyster is anchored to the substrate and has no locomotory ability. However, humans move oysters around the bay as part of the commercial lease program. In the past, reefs were undisturbed and generations upon generations of oysters settled on previous reef occupants. Historically, the height and areal extent of the reefs in the bay were considerably greater. Oyster reefs were a major hydrological feature of Galveston Bay during settlement. They are still important from economic (see Chapter 4), ecological and hydrologic points of view.

Trends in Oyster Reef Distribution

This discussion emphasizes the trends in distribution of oyster reefs; Chapter 8 includes a discussion of the status and trends of the oyster as a fishery species. Oyster reefs, shell-dominated bay bottom and buried "mud shell" were mapped in a survey conducted by Turney (1958). The purpose of the survey was to provide location and abundance information for companies engaged in dredging oyster shell. Mining oyster shell from the bay bottom for construction and industrial purposes continued until 1969. Benefield and Hofstetter 1977 and Powell et al. (1994) surveyed the oyster reefs as a fishery resource. The maps produced by these three studies are shown in Figure 7.9. Shading indicates locations of reefs and unconsolidated shell sediments in the bay. Comparing the maps serves to illustrate some of the changes that have occurred in Galveston Bay over recent history.

The area of oyster reef and oyster shell bottom identified by Powell et al. (1994) was substantially greater than depicted on earlier Texas Parks and

Wildlife Department charts from the 1970s prepared by Benefield and Hofstetter (1977). This may have been due to differences in survey methods used to map the reefs. Comparing all but the West Bay area, the 1994 survey identified 14,210 acres of oyster reef and shell compared to the 7,424 acres of reef measured by the 1976 study. Reef accretion was most noticeable in three areas: 1) along open-bay reaches of the Houston Ship Channel; 2) at the southern edge of Redfish Bar and the Bull Hill extension of the Hanna Reef tract; and 3) in the Dickinson Embayment. Reef loss, although minor overall, was concentrated in three areas: 1) along the southern shore of Trinity Bay; 2) in the Mattie B./Tom Tom Reef area at the northern end of the Hanna Reef tract; and 3) in the inner portion of the Clear Lake Embayment.

The greater extent of reef identified by Powell et al. (1994) can be ascribed to several factors. Some new reef formation has probably occurred in the ensuing 20 years since the Texas Parks and Wildlife Department study was completed. Technology used by Powell et al. generated a new definition of an oyster reef and resulted in more positive classifications, particularly in deeper water. A comparison of the 1976 and 1994 maps indicates that little loss of oyster reef has occurred over the last 20 years. Those few areas where reef decline has occurred can be ascribed mainly to regional subsidence and burial by sedimentation. The disagreement is in the areas that were not previously classified as oyster reef.

There are large differences between the mapping done in the 1950's and the study done in the 1970's. Although the records are not available for quantification of the differences, examination of the maps provided in Figure 7.9 support the conclusion that the location and areal extent of Galveston Bay oyster reefs changed considerably over the period in which shell dredging was permitted. For example, one of the reefs shown south of the Texas City Dike in the 1950's appears to be located where a spoil island currently exists. The 1950's map shows two large reefs east of the mouth of Clear Lake where no reefs appear on the Benefield and Hofstetter (1977) map. The extent of the reef complex in East Bay appears to have been much larger in the 1950's than in the 1970's or the 1990's. The area between Eagle Point and Smith Point has a dense complex of oyster reefs in all three maps, but the largest reef area appears to have shifted from west to east across the HSC.

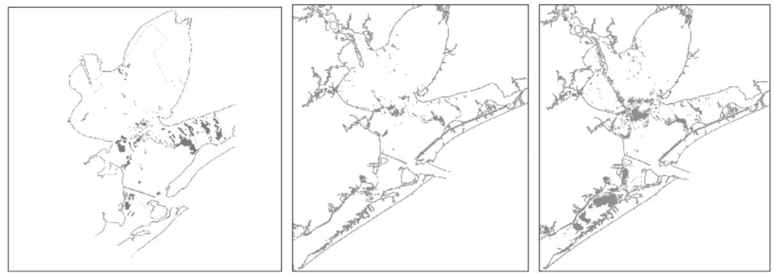


Fig. 7.9. The probable distribution and the location of oyster beds extant in the 1950s, 1970s and 1990s. [a]Exposed oyster reefs in Galveston Bay. Based on shell surveys from 1954-1958 by J.G. Turney. Modified from Horton and Horton (1958). [b] Major public oyster reefs in the Galveston Bay System in 1977. Modified from Hofstetter (1977). [c]Oyster reefs and shell-dominated bottom in Galveston Bay in 1994, based on a survey, which used state-of-the-art sonar, global positioning and geographic information system technologies. (Modified from Powell et al., 1994).

Causes of Reef Distribution Changes

A few of Galveston Bay's oyster reefs have persisted throughout recorded time; others have exhibited substantial malleability, changing position and shape over time spans of a half century or so in response to natural and man-made changes in the bay system. Oysters respond to changes in circulation and current, standing crop of phytoplankton, salinity, disease and predation.

The largest impact on the reef system in the bay has been removal of shell for construction and the chemical industry. When industry and development were booming after World War II, the production of shell from fossil deposits or "mud shell" was permitted. Chapter Three describes the historical utilization of this resource. This dredging removed shell from the substrate to depths of more than ten feet. The mud from which the shell was obtained was disposed in the open bay waters. In some areas, the dredging removed the substrate needed for spat settlement and reef continuance.

There is no record of the total volume of oyster shell, either living or fossil, that has been removed from the bay. Dredging of oysters and shell from living reefs began more than a century ago and continues today. Chapter 3 discusses the early dredging of shell for construction purposes. Prior to 1969, oyster shell was the principal reason for shell dredging. Ward (1993) estimated that 135,000 acre-feet of shell was removed by shell dredgers, not oyster fishermen, between 1910 and 1969 (see Chapter 5). The dredging of oysters for

Efforts have been made to create oyster reefs in new places to increase the benefits provided by this ecosystem. An artificial substrate was developed based on flyash from the combustion of coal at a Reliant Energy power plant. This large experiment consisted of the deposition of more than 12,000 cubic yards of pellets composed of flyash cement in Lower Galveston Bay and at five other sites around the bay. (Courtesy Reliant Energy HL&P)

seafood removes shell from the bay, but not in the volume removed for industrial and construction purposes, and the fishery does not remove reefs.

No evidence exists for a substantial impact by the commercial oyster fishery on the number and size of oyster reefs in the bay. Some of the most heavily fished reefs have not varied much in size and shape since the original surveys of Galveston Bay in the 1850s. Most heavily fished reefs have accreted more area in the past 20 years than reefs not fished. Reefs that are open or closed to harvest for public health reasons did not differ uniformly in their structure. The most significant areas of estimated reef loss were in areas of the bay closed to oyster harvesting due to public health regulations (Powell et al., 1994). Chapter 9 contains a discussion of management of oyster harvesting for protection of public health.

There are several likely impacts on reef area by the oyster fishery. Many reefs in naturally favorable areas are accreting at their margins. An unknown amount of this marginal accretion was due to shell movement by the fishery. Most private leases today contain reef or semi-consolidated shelly areas based on shell transplanting by the lease holders. The accretion of these reef areas was dependent on siting in relation to natural factors affecting oysters. Movement of shell off of reef edges, in many cases, has appeared to aid reef growth (Powell et al., 1994).

Some reefs have declined because they are no longer optimally located for productivity as a result of circulatory changes in the estuary (e.g. Carancahua Reef in West Bay). Conversely, some areas formerly with few oysters now support productive reef if satisfactory substrate was available for spat settlement. Observations suggest that reefs build only slowly out onto muddy bottom, due to several inhibitory processes (Powell et al., 1989). This slow process of shell consolidation may make reefs susceptible to damage from commercial dredging during the early stages of their development.

According to Powell et al. (1994), most reefs are now detached from the shoreline, a likely result of subsidence and shoreline retreat. Additionally, the increase in water depth (particularly for barrier reefs) has reduced the extent to which reefs are exposed while at the same time drowning the natural alongshore berms that can develop into reefs. Areas of high subsidence, such as upper bay near Clear Lake, have suffered reef attrition due to siltation.

Channelization, dike construction, and loss of Redfish Bar have substantially altered bay circulation patterns. The pre-1900 circulation pattern in Galveston and Trinity Bays is unknown, but the salinity regime must have been drastically different from today. Prior to 1900, Redfish Bar was crossed by three channels, only one of which (West Pass) permitted significant water interchange between the upper and lower bay systems. In all likelihood, a salinity gradient existed such that the upper bay system was substantially fresher than today. The breaching of Redfish Bar by the Houston Ship Channel produced major circulatory changes influencing oysters. Other changes have probably also been important. For example, the Texas City Dike has reduced circulation from Galveston Bay to West Bay.

Bay-wide changes in circulation have resulted from the major dredge and fill projects. The Houston Ship Channel has increased the penetration of more saline water into the upper estuary and has increased current velocities, extending the area of oyster productivity northward. Over 2,500 acres of reef have developed along this channel, a substantial fraction of which occurs between the shoulder of the channel itself and the crest of the parallel disposal banks (Powell et al., 1994).

Today, the bulk of the Trinity River flow exits Trinity Bay along the southern shore, not through the historical delta channels, and Turtle Bay has been changed into Lake Anahuac. The river flow wraps around Smith Point, and flows across Mattie B. Reef and Tom Tom Reef, reaching nearly to Bolivar Peninsula before becoming entrained in the seaward flowing water at Bolivar Roads. This circulation pattern has likely existed for many decades (Reid, 1955: Diener, 1975), but its intensity must have dramatically increased as the Houston Ship Channel became deeper and Redfish Bar ceased to function as a circulation barrier.

Artificial Reef Creation

Oyster reefs are valued for their production of seafood, provision of resources and habitat for sport fish and stabilization of sediment for erosion prevention and turbidity reduction. The Galveston Bay Plan calls for protection of oyster reef habitat. Efforts have been made to create oyster reefs in new places to increase the benefits provided by this ecosystem.

In the first effort, an artificial substrate was developed that could substitute for oyster shell as a cultch material, an attachment location for the metamorphosis of oyster larvae. The substrate was based on flyash from the combustion of coal at a Reliant Energy power plant. This large experiment consisted of the deposition of more than 12,000 cubic yards of pellets composed of flyash cement in Lower Galveston Bay and at five other sites around the bay. The Lower Galveston Bay site was east of Eagle Point and covered five acres of bay bottom. Pellets were deposited in May and August of 1993. Spat set in 1994 was heavy and survival good (Baker, 2001).

At least one other reef creation project has been initiated in the Galveston Bay system. It is located in Dickinson Bay and was undertaken by the Natural Resources Conservation Service through a grant from the Galveston Bay Estuary Program. In this case, oyster reef was constructed to protect a newly created wetland. Intertidal oyster reefs trap sediment and actually enhance sedimentation. Additionally, intertidal reefs protect the shoreline from wave action and they lessen erosion.

Summary

Wetlands, seagrass meadows and oyster reefs are three important habitat types in Galveston Bay. Wetlands and seagrass meadows have declined substantially over the past five decades while the trend for oyster reefs appears to be a decline followed by an increase.

Most of the loss of salt and brackish marsh has been caused by relative sea level rise and subsequent conversion to open bay and barren flats. Loss of freshwater marshes is primarily associated with conversion to upland for agricultural purposes. Other major changes in these habitats have resulted from projects that have isolated about 16,000 acres of formerly estuarine marshland and shallow water from the bay. Marsh restoration and creation projects have added a significant amount of freshwater, brackish and salt marshes.

Continuous beds of submerged aquatic vegetation flourished, around the Trinity River Delta, along the west shoreline from Red Bluff to San Leon, and in West Bay prior to the post-WW II period of intense dredging and poor water quality. Only a remnant of the historical habitat has been preserved in Christmas and Bastrop Bays and Trinity Bay. Suspected reasons for the decline include subsidence, effects of Hurricane Carla, decreased light attenuation and human activities. Recent successful establishment of seagrass beds in West Bay suggests that water quality is once again suitable for these species.

The distribution and areal extent of oyster reefs in Galveston Bay have changed since the 1950s. One study reports a significant increase in extent of oyster reefs over the last 20 years. This has not yet replaced the large amounts of shell that were removed by shell dredging. Changes in circulation and salinity appear to be largely responsible for the changes in size and shape of some reefs between the 1970s and the 1990s. For example, the Houston Ship Channel has increased the penetration of the salinity wedge into the estuary and supports an area of about 2,500 acres of oyster reef and unconsolidated shell bottom along its fringes. New potential for creation and restoration of oyster reefs was demonstrated when a new oyster reef was successfully created in Galveston Bay by addition of artificial substrate.

Partnership and Habitat:
That's Where It's At

Many restoration projects around Galveston Bay are the result of volunteer action. Volunteers plant Spartina alterniflora *(smooth cordgrass) propagules at the annual Marsh Mania restoration event. (Courtesy Galveston Bay Foundation)*

The number of marsh restoration activities around Galveston Bay has been on the increase during the past ten years. Local organizations, state and federal agencies are finding support and funding for public and private projects. As the number and scale of wetland restoration projects increases around the bay, so does the demand for coastal marsh plants. It is only natural to wonder where all these plants come from- are they transplanted from existing wetlands or are they grown from seed and cuttings? The answer may surprise you.

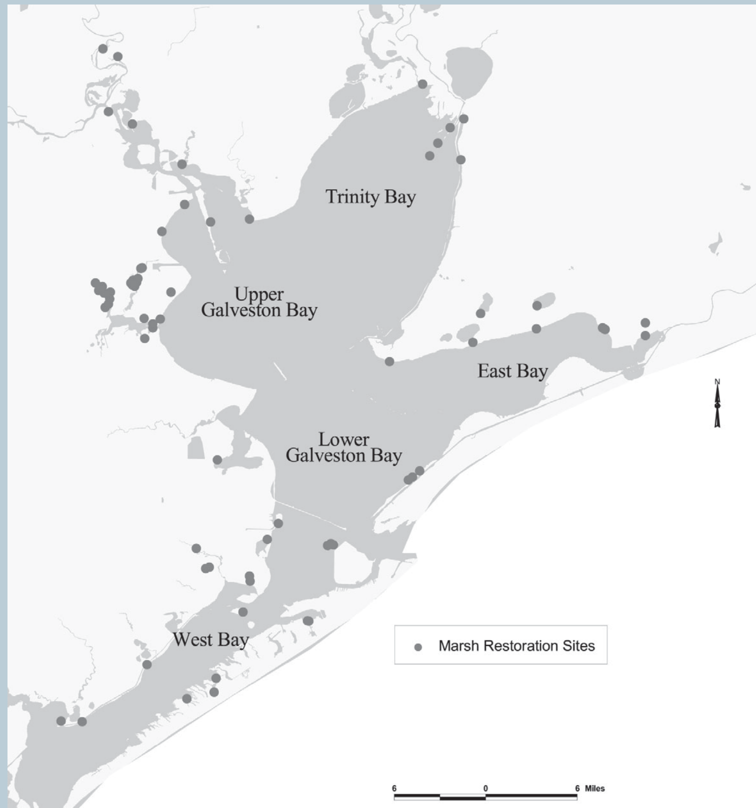
Until recently, marsh restoration projects had no alternative but to use plants taken from established habitat. However, that is changing. A partnership between Reliant Energy and the US Department of Agriculture's Natural Resource Conservation Service (NRCS) has resulted in the development of new propagation techniques to cultivate wetland plants from seed and cuttings. Eddie Seidensticker, a Soil Conservationist with the NRCS, believes that these new techniques are drastically changing the way in which marsh restoration projects are conducted, "*Spartina* propagation keeps us from robbing Peter to pay Paul. We no longer have to take plants from established wetlands to plant new habitat."

The Reliant Energy Natural Resource Center located at Reliant's Cedar Bayou Plant, is now the largest supplier of coastal marsh plants along the Texas coast. The nursery produces 350,000 to 500,000 plants a year (primarily *Spartina alterniflora,* smooth cordgrass) and is instrumental in the success of many public and private restoration projects in the area.

What began in the 1970s as a research facility to study the impacts of thermal loading on the marine environment became a wetland plant nursery in the 1990s and is now a newly renovated plant nursery and education facility. Bill Baker, Reliant Energy's expert on marsh restoration, devotes much of his time to researching and cultivating marsh vegetation. He believes firmly in the value of wetland restoration and in the importance of the Natural Resource Center's work and says, "The Reliant Energy Natural Resource Center offers the opportunity for schools, families, and a host of organizations and agencies to learn about the functions of wetlands and become involved in the restoration of these vital natural resources."

Baker and Seidensticker both acknowledge that without the help of the many partners that are involved, the wetland plant nursery and marsh restoration efforts around the bay would not be nearly as successful. The efforts of Reliant Energy and its many partners have received many local and national awards. Most recently, the Galveston Bay Estuary Program awarded them the *2001 Stewardship Award*. In 1999 Reliant Energy and its Environmental Partners Program at the Natural Resource Center received a *Coastal America Award* for *Partnership Efforts to Restore and Protect the Coastal Environment*.

The future for marsh restoration and wetland plant propagation looks bright. As the partnerships to promote marsh restoration efforts continue to flourish, so too will Galveston Bay's wetland habitat.



Restored, enhanced and created Spartina alterniflora *marshes in the Galveston Bay System, 1973 to 2000. Source: Modified from National Marine Fisheries Service (1994)*

The Bay's Living Resources

Early European colonists had an abundance of wildlife to serve subsistence needs. Seemingly endless flocks of ducks, geese and swans and a bounty of fish and shellfish. This abundance quickly established a viewpoint that the New World's wildlife resources were inexhaustible.

—Milton Friend in LaRoe et al., 1995

Galveston Bay is home to a myriad of organisms. Fish and wildlife resources provide some of the Bay's greatest economic, recreational and aesthetic assets. These organisms can also serve as useful indicators of the overall condition of the ecosystem. Therefore, considerable scientific and regulatory resources are devoted to studying these populations.

Long term commercial and recreational fishing harvest records show no dramatic examples of collapsing fisheries, but large population fluctuations of commercial species have occurred over time. Historical accounts indicate that several Galveston Bay fish and wildlife species, including striped bass and the diamondback terrapin, have either disappeared or declined dramatically in the last 150 years. Striped bass declines are most likely due to habitat alteration in the form of dams, bay closures and shell dredging.

The population size of a given species is determined by many relevant factors; among them are habitat (both quantity and quality), degree of environmental contamination, and a host of natural forces such as predation, competition and diseases. The causal mechanisms affecting the population dynamics of a given species are seldom obvious. Therefore, resource managers must work with the scientific knowledge and tools available while awaiting more research.

This chapter summarizes recent findings on the bay's living resources. Major taxonomic categories in the food web are considered in separate sections, beginning with the base of the food chain and progressing to higher levels.

Monitoring the Bay's Food Chain

Food web theory provides a context for selecting particular species at different trophic levels to indicate the overall condition of the ecosystem. These "indicator species" can be chosen to help evaluate particular environmental conditions (for example, degraded water quality), or they can be chosen as representative of a class of species with similar trophic roles. This chapter considers a spectrum of indicator categories with an eye to a generalized evaluation of the bay ecosystem. These categories are:

- Primary producers: These include phytoplankton (free-floating algae), benthic microflora (microscopic bottom-dwelling plants), and higher plants which comprise the habitats discussed in Chapter Seven: seagrass meadows and marshes.
- Primary consumers (including detritivores): These graze on the phytoplankton, bottom dwelling microflora, and detritus; they include microscopic floating zooplankton and benthic invertebrates. Some benthic invertebrates are good environmental indicators of contaminated sediments.
- Economically important groups generally utilize middle trophic levels. These include finfish and most shellfish. Example species include spotted seatrout, Atlantic croaker, southern flounder, white shrimp, brown shrimp, and blue crab.
- Species of special interest including carnivores such as water birds and dolphins; abundant prey species, such as Gulf menhaden; and endangered species, such as sea turtles.

Species within each of these categories are marked by variability occurring on different time scales, especially fluctuations over the seasonal cycle. Many species are migratory or time their reproduction based upon seasonal water temperatures or food supply. Investigations focusing upon population dynamics must account for this source of natural variability before long-term trends relating to anthropogenic changes can be deciphered. One key challenge to biologists is to obtain a sufficiently lengthy data record to partition the sources of variability affecting species population dynamics.

Primary Production

As discussed in Chapter 2, primary producers form the base of the food chain. A healthy community of primary producers is necessary to maintain the populations of organisms that exist at higher trophic levels. In Galveston Bay, there are six main primary producer communities ranging from phytoplankton (algae) in open bay water to trees and perennials in the riparian woodlands and swamps bordering the estuary. Each of these communities is partly responsible for the photosynthetic production of organic matter that sustains the estuary's primary consumers and their predators.

Sheridan et al. (1989) used literature values to estimate primary production for six main classes of flora. The study concluded that phytoplankton, benthic microflora, plants in salt and brackish marshes, and trees in woodlands and swamps all contribute roughly the same quantity of organic food to the estuary. It is interesting to note that submerged vegetation had the highest productivity per square kilometer, however, their small areal extent in the bay made them less significant in terms of the amount of energy contributed.

Although the overall level of primary production contributed by marshes and phytoplankton is similar, there is conflicting evidence about which is more important as an energy base. Sheridan et al. (1989) presented three reasons why marshes may be more important: 1) zooplankton in the bay generally occur in low densities, indicating a relatively low level of direct grazing on phytoplankton (Texas Department of Water Resources, 1981); 2) Texas salt marshes are high producers of herbaceous matter when compared to marshes in other Atlantic and Gulf Coast states (Turner, 1976); and 3) many bay species grow up to be omnivores or carnivores, relying upon phytoplankton only in their larval stages (Gosselink et al., 1979). On the other hand, Armstrong (1987) concludes that only five percent of the carbon and primary nutrients in Galveston Bay originate from peripheral marshes. More research is needed to resolve this conflicting data.

Much of the primary production identified by Sheridan et al. (1989) is separated in time and space from the estuary's primary consumers. For example, woodlands, swamps, and fresh water marshes export less than ten percent of their primary productivity to consumers in the bay because of their relative isolation from bay waters, whereas saltwater marshes may export 35-40 percent (Texas Department of Water Resources, 1981; Gosselink et al., 1979).

Phytoplankton

Phytoplankton are microscopic algae and bacteria that drift with the motion of the currents and produce organic matter by photosynthesis. A shortage of phytoplankton depletes the food supply of primary and higher consumers such as oysters, shrimp, fish, and birds. Excessive production of phytoplankton, usually caused by enhanced levels of nutrients, can exert high oxygen demand on the water through nocturnal respiration and decomposition following death (see the section on dissolved oxygen in Chapter 6).

Over 132 species of phytoplankton have been documented in upper Galveston and Trinity Bays, with diatoms (54 taxa), green algae (45 taxa) and blue-green algae (14 taxa) being dominant (Texas Department of Water Resources, 1981). Armstrong and Hinson (1973) identified the dominant genera in 1969 for Trinity Bay, Upper Galveston Bay, Lower Galveston Bay, East Bay, and West Bay. Other studies revealed that diatoms and green algae were dominant during cold months, whereas several other species were dominant during other times of the year (Zotter, 1979). Occasionally certain species of planktonic algae exhibit exponential growth in density and create algal blooms. Some blooms are of concern to resource managers or public safety personnel because they produce toxins.

Phytoplankton are commonly subdivided based on their size. In Texas estuaries, small nanoplankton (less than 20 microns) dominate both numerically and in total biomass when compared to larger phytoplankton (Stockwell, 1989). In general, phytoplankton densities in Galveston Bay are lower than in many other Texas estuaries (Texas Department of Water Resources, 1981), which are on the low end of estuary production in general (Sheridan et al., 1989). Overall productivity of the phytoplankton populations in the bay is similar to other estuaries.

Trends in Space and Time

Phytoplankton productivity in the bay is monitored by sampling the water column for chlorophyll-a, the green pigment used by plants during photosynthesis. Ward and Armstrong (1992) indicated some possible areas of high chlorophyll-a abundance, such as Clear Lake, Black Duck Bay, and Trinity Bay near the Cedar

Bayou Generating Station outfall. Work performed by the Texas Department of Water Resources (1981) and Sheridan et al. (1989) suggested that in low salinity regimes, blue-green and green algae dominate, whereas higher salinity sites are dominated by diatoms.

There is some evidence of an increase in chlorophyll-a from the late 1950s to the 1970s (Buskey and Schmidt in Green, 1992). Since the 1970s, routine monitoring data for chlorophyll-a indicate a clear declining trend in the measured concentration (Ward and Armstrong, 1992; Criner and Johnican, 2001).

Mean chlorophyll-a concentrations fell by more than 75 percent throughout much of the Galveston Bay watershed from 1972 to 1998 (see Figure 6.9). In 1972, the monthly chlorophyll-a concentration averaged over all samples taken in the bay and tidal tributaries was 28.5 mg/L. This calculation for 1998 yields an average concentration of 3.6 mg/L. This trend in chlorophyll-a monitoring measurements indicates that phytoplankton biomass levels are lower than levels typical of Galveston Bay in the 1950s. Mean chlorophyll-a concentration from Zein-Eldin (1961) sampling an embayment of Galveston Bay in the late 1950s was 16 mg/L, which compares closely to an overall mean of 13 mg/L and 17 mg/L for stations in Trinity Bay measured by Mullins (1979) and Strong (1977), respectively.

It should be noted that the methodologies of these studies are not comparable and that the long term Texas Natural Resource Conservation Commission database is limited by the spatial distribution of the samples. Most of the water samples came from tributaries and not from open bay waters. The value of chlorophyll-a in tributaries is not highly correlated to the value in the open bay.

Possible Causes of Trends

There are three potential hypotheses to explain the observed decline in chlorophyll-a concentration in Galveston Bay waters. First, improvements in effluent discharges after 1970 have allowed for a resurgence in zooplankton populations, which may have subsequently reduced phytoplankton populations. Not enough data are available to confirm such a temporal change in zooplankton populations, but populations of planktivorous fishes have an increasing trend.

Second, declining concentration of a limiting nutrient could be causing a decline in primary production and phytoplankton concentration (Ward and Armstrong 1992). A decline in nutrients could be inferred from curtailed point source loadings from permitted discharges, trapping of Trinity River nutrients by the dam on Lake Livingston, and reduced fertilizer use in the upper watershed due to changes in land use. Chapter 6 documents declines in phosphorus and ammonia concentrations.

Finally, the decline in phytoplankton might be the result of an increased population of filter-feeders, such as oysters, clams or menhaden. In selected areas of San Francisco Bay, the unintentional introduction of the Asian marine clam (*Potamocorbula amurensis*) resulted in a phenomenal ten-fold reduction in phytoplankton levels in two years (Monroe and Kelly, 1992). While this clam is not found in Galveston Bay, Powell et al. (1994) identified substantially higher oyster reef area in 1992 than was documented for the late 1960s and early 1970s. Whether the oyster population expanded between the studies in the 1970s and 1990s or the methodology used in the recent study was more sensitive and better able to detect the presence of oyster shell is unknown.

Toxic Blooms and Red Tides

When present in large enough concentrations, some species of phytoplankton can harm the health of marine life and humans. Some toxic algae cause shellfish-associated illnesses in humans (see Chapter 9) while others have an effect on finfish populations.

Red tides are blooms, or high concentrations of toxic phytoplankton often resulting in fish kills and water discoloration. These red tides are occasionally observed inside Galveston Bay, but are typically uncommon. The usual bloom organism is a species of dinoflagellate (*Karenia brevis* syn. *Gymnodinium breve*) commonly found in offshore waters, but in small concentrations. When conditions favor its growth (high salinity, calm waters and warm temperatures), the phytoplankton "bloom" to concentrations that are large enough to affect the health of marine life and humans.

The Texas red tide organism produces brevetoxin, a neurotoxin that can paralyze the muscles and nerves of fish causing them to suffocate. At a concentration of 100 to 200 cells per milliliter of water there is enough toxin produced to affect fish populations (Denton, 2001). Shellfish can also accumulate the toxin causing neurotoxic shellfish poisoning (NSP) in humans who ingest the contaminated tissue. Additionally, wave action can send the neurotoxin airborne allowing it to irritate the eyes and upper respiratory tract of humans (see Chapter 9).

A major outbreak of red tide occurred off much of the Texas coast in 1986. Since that time, the frequency of red tide events has increased with blooms occurring along the Texas coast in four of the last five years (Denton, 2001). During the summer and fall of 2000, a large occurrence of red tide was observed along the coast from Sabine Pass to Mexico. Fish kills related to the 2000 bloom were reported in lower Galveston Bay. Shellfish beds must be closed to harvesting when cell concentrations exceed 5 cells per ml. Galveston Bay oyster beds were closed in the summer of 2000. It was the first time they had been closed due to a toxic algal bloom (Evans and Hiney, 2001).

Macrophytes

As mentioned above, ecosystems with vascular plants as the dominant primary producers contribute as much or more fixed carbon to the Galveston Bay system as phytoplankton. The dominant form of primary producers in swamps, marshes and seagrass meadows are the trees and grasses familiar to humans. They reproduce by flowers and seeds and provide a three dimensional structure to habitats.

As described in Chapter 7, marshes and seagrass beds have been lost over historical time in the bay. It is estimated that over 30,000 acres of marsh have disappeared in the last 50 years. From a species perspective, this means that the population of *Spartina alterniflora* (saltmarsh cord grass) has declined. Other plant species that are marsh specialists, such as *Salicornia virginica* (glasswort) will have experienced the same loss of abundance. Marsh restoration projects usually revegetate areas with *S. alterniflora* only. The diversity of macrophyte communities in these restored marshes has been lower than natural marshes for some time.

Submerged aquatic vegetation, the seagrasses discussed in Chapter 7, has also exhibited a decline in abundance over historical time in Galveston Bay. This decline in habitat translates into a decline in abundance of the species that create that habitat. *Ruppia maritima* (widgeongrass) is much less abundant in Trinity and Upper Galveston Bays than in the 1950's. *Halodule wrightii* (shoalgrass), *Halophila engelmanii,* (clovergrass) and *Thallasia testudinum* (turtlegrass), must all have lower abundances than in the 1950's because the areal extent of seagrass meadows is much less. The decline in abundance of seagrasses impacts other species through loss of habitat. Seagrass meadows are a preferred habitat for the juveniles of many macroinvertebrates and fish species. Several species are important food items for over-wintering waterfowl and sea turtles.

There are other macrophytes that exhibit changes in abundance in the Galveston Bay system. During periods with warm winters, some individuals of the black mangrove, *Avicennia germinans,* can become established and grow near the Galveston Bay passes, only to be killed by low winter temperatures. Other species are influenced by the salinity regime of the bay system. Sedges, rushes and cattails can grow among the cord grass in low salinity areas, but may be killed by salinity rise during drought periods. The introduced species water hyacinth can become a problem in some of the tidal reaches of bay tributaries, but their distribution is limited by their salinity tolerance.

Zooplankton

Zooplankton are microscopic drifting animals that feed on phytoplankton or smaller zooplankton. Factors controlling zooplankton abundance are not well understood in Texas estuaries. Large increases in zooplankton populations are often observed after extensive flushing of estuaries from high river runoff (Buskey, 1989). Galveston Bay may have lower zooplankton abundance than many other Texas estuaries (Buskey and Schmidt in Green et al., 1992), with a typical range for Trinity Bay of 1,200 to 16,000 zooplankters per m^3 of water. The status and trends of zooplankton in Galveston Bay are more difficult to determine than for phytoplankton because of the lack of long-term studies and use of variable sampling techniques by different researchers.

Benthic Organisms

Benthos refers to organisms that live in, on, or near the bottom, including plants, invertebrates, and fish of all sizes. The epifauna and infauna of the bay bottom ecosystem are discussed in Chapter 2. Benthic organisms are an important component of the estuarine food web. Fish including Atlantic croaker, spot, mullet and drum; and birds including ducks and other marsh birds feed upon benthic organisms. Recent research has determined that marsh benthos have a larger effect on estuarine fish populations than previously thought, i.e., juveniles of many fish species consume benthic organisms in tidally-flooded marshes (Zimmerman in Green et al., 1992).

Sampling of benthic invertebrates is performed by dredging or coring to collect sediment samples, which are then sieved to separate organisms from the sediment. Because there is considerable variation in sampling techniques, it is difficult to compare abundances reported in different studies.

Benthic organisms are good environmental indicators of contaminant impacts because their relative immobility results in their continual exposure to any pollutants bound to sediments (see Chapter 6 for a discussion of the concentration of contaminants in sediments). Since anoxia is generally most severe near the bottom (e.g. in the Houston Ship Channel), they are first to experience the effect of oxygen depletion. Environmental stressors often cause a normally high benthic community diversity to decline to a suite of fewer, more tolerant species.

Open Bay Benthos

During 1976 and 1977, White et al. (1985) collected core samples on one-mile centers in Galveston Bay to define benthic assemblages and to measure the physical and chemical characteristics of the sediment. Typically, one or two species dominated a community composed primarily of polychaetes (marine worms), mollusks, and crustaceans. Muddy bottoms supported a richer polychaete community, while sandy bottoms were found to support more crustaceans. Ray et al. (1993) concluded that observed patterns in benthic assemblages were primarily attributable to the prevailing salinity regime and secondarily influenced by substrate type.

White et al. (1985) reported that Galveston Bay exhibited low to moderate benthic diversity, with the highest diversity in areas with stable salinity regimes (e.g., near inlets such as Bolivar Roads and Rollover Pass). Clear Lake, the San Jacinto River, and the Houston Ship Channel had much lower species diversity than any of the open bay stations. Open bay benthos generally increased in abundance from the Trinity Bay-Upper Bay region to the Lower Galveston-West Bay region (Harper in Green et al., 1992).

A seasonal trend occurs, with peak abundance in the Spring, between February and May, and decline in October and November (Harper in Green et al., 1992). As open bay benthos are very good indicators of salinity stress, fresh water flood events can alter this cycle.

Marsh Benthos

Marsh areas are vital ecological components in nutrient cycling, and serve as habitat for many types of plants and animals (see Chapters 2 and 7). Zimmerman (in Green et al., 1992) performed a study of six marshes in the Galveston Bay complex near Christmas Bay, Galveston Island State Park, Smith Point, Moses Lake, Inner Trinity Delta, and Outer Trinity Delta. He concluded that marsh-dwelling benthos in the bay are comprised of generally the same species found in other Gulf Coast estuaries, with over 90 percent of the infauna consisting of marine worms and small crustaceans. Densities of marsh infauna and epifauna were generally higher on the marsh surface than in bare subtidal habitat adjacent to the marsh. In the marsh itself, infauna were usually more numerous when associated with plants, than in the bare substrate of marsh embayments and channels (Zimmerman in Green et al., 1992).

Spatially, the highest densities and greatest species richness occur in the mid-salinity marshes near Moses Lake and Smith Point. Temporally, marsh infauna display a seasonal periodicity, peaking in abundance in the late winter and early spring (Zimmerman in Green et al., 1992). The abundance of benthic predators is strongly correlated with this seasonal pattern; shrimp, crab and fish predators are more abundant in warm weather. Zimmerman et al. (1991) indicated that when marshes are drowned as a result of subsidence, they have a period of higher secondary productivity. Increased water coverage leads to a more rapid decomposition of organic matter than in stable marshes. This increase in the release of organic matter from the plants and the sediment continues until the marsh is succeeded by open-bay habitat. This creates a temporary benefit for fish, invertebrates, birds, reptiles, and mammals that use the marsh.

Oysters (See also Chapters 4 and 7)

Physical and Biological Factors

Salinity is a critical factor influencing oyster production. The quantity and timing of suitable freshwater inflows is paramount to the health of the bay's oyster communities. Only those Texas bays with high rates of freshwater inflow support a productive shellfish industry (Montagna and Kalke, 1995).

Specific water flow requirements for Texas oysters are not known (Quast et al., 1988). However, Wilson-Ormand et al. (1997) determined that food concentrations and water flow speeds vary spatially and temporally within the water column. They further discovered that water flow rate is most likely a greater limiting factor than food concentration in determining oyster population densities.

While oysters are typically found in areas where long-term salinity ranges between 10 and 30 parts per thousand (ppt), salinity effects on the population depend largely on the range of fluctuation and rate of change (Quast et al., 1988). Data from 23 years of reef sampling indicated the best spat sets (corresponding, in commercial terms, to an oyster "crop") occurred when spring salinity ranged between 17 and 24 ppt. The poorest sets occurred when salinity dropped below 8 ppt (Hofstetter, 1983). A short term lowering of salinity (5-10 ppt for two to six weeks) is beneficial to oysters because it reduces predation and disease.

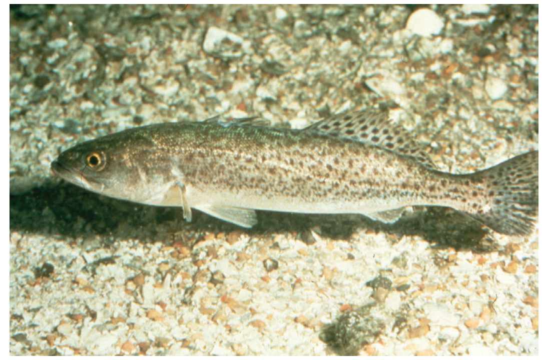
Factors that stress oyster populations include competition, parasites, diseases, and predation from other organisms. The most important of these biological stresses in Galveston Bay is infection by "Dermo" (*Perkinsus marinus*) (Powell et al., 1994), a protozoan parasite that thrives in warm waters of relatively high salinity. Mortality of market oysters in Galveston Bay resulting from this parasite can range from 10 percent to 50 percent annually.

A new development in the struggle to manage Dermo is an internet-based tool known as "DermoWatch", which can calculate the time until critical levels of *Perkinsus marinus* will be reached. The web tool also provides recent Dermo data for nine oyster reefs around Galveston Bay (Ray et al., 2001; Ray, 2001).

Trends in Space and Time

Old maps of the Texas coast show more extensive shoreline oyster reefs than are seen today in Galveston Bay. As discussed in Chapters 3 and 5, commercial shell dredging that operated until the late 1960s greatly diminished oyster reefs.

More recently, research by Powell et al. (1994) indicated an increase in overall oyster reef area since the 1970s. It should be noted, however, that this reported increase might be due to more sensitive surveying techniques rather than an actual increase in reef area. One practice that does result in increased oyster reefs is oyster transplantation, whereby, oysters are transplanted from productive leases to previously non-producing bay bottoms (Robinson, 2000). Chapter 7 includes a discussion of the change in oyster reef habitat since the 1950s and shows the location of reefs in Galveston Bay as mapped in the late 1950's, the mid-1970's and the mid-1990's (Figure 7.9).



Spotted seatrout are a premier recreational game species in Galveston Bay. Collections with shrimp trawl and with gill nets exhibit upward trends. (Courtesy Texas Parks and Wildlife Department)

Finfish, Shrimp and Crab Populations

The Galveston Bay system maintains important recreational and commercial fisheries for shrimp, crabs, and fishes. During the last 100 years, the total landings from the estuary have doubled, mostly due to the increased harvest of shrimp and crabs. How have the various bay species fared under this increased fishing intensity?

Scientific monitoring of indicator species conducted by Texas Parks and Wildlife Department (TPWD) will be used to assess trends in fishery organisms because the data provide better information than landings to estimate actual population sizes (Green et al., 1992; Green et al., 1993). TPWD utilizes several techniques for monitoring, including: 1) bag seines for collecting smaller organisms in near-shore environments; 2) trawls for collecting organisms found on or near the open bay bottoms; and 3) gill nets for catching larger fish near shore. Data are compiled as catch per unit effort (CPUE), defined as the number of individual fish or shellfish caught for a given area seined or time trawled.

The temporal trends for several selected species are presented in this section based on Green et al. (1992) and the Texas Parks and Wildlife Department (2001). White and brown shrimp and blue crab were selected because of their commercial importance and association with sediment. Four finfish species were selected for detailed presentation. The spotted sea trout is a top carnivore of the open bay and an important recreational species. Gulf menhaden are important herbivores in the open bay and useful as indicators of plankton biomass. Atlantic croaker and southern flounder are benthic predators and are useful as indicators of benthic community health.

Trawling studies by the TPWD have identified about 13 species of shrimp, 17 species of crab, and over 150 finfish species in Galveston Bay (McEachron

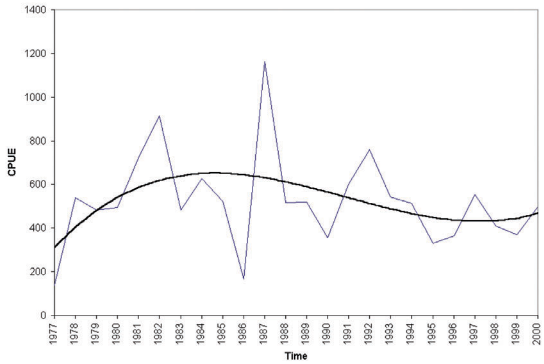


Fig. 8.1a. Brown shrimp sampled with bag seine in Galveston Bay, 1977-2000. (Source: Texas Parks and Wildlife Department.)

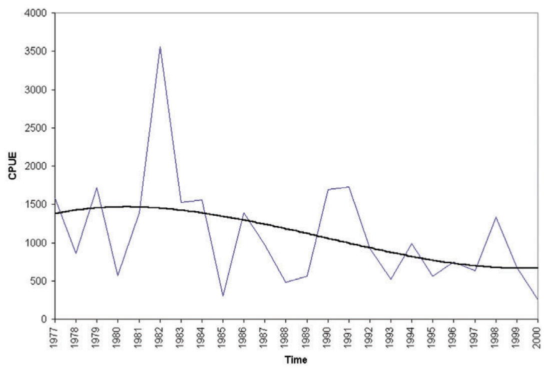


Fig. 8.1b. White shrimp sampled with bag seine in Galveston Bay, 1977-2000. (Source: Texas Parks and Wildlife Department)

Fig. 8.2a. White shrimp sampled with shrimp trawl in Galveston Bay, 1982-2000. (Source: Texas Parks and Wildlife Department)

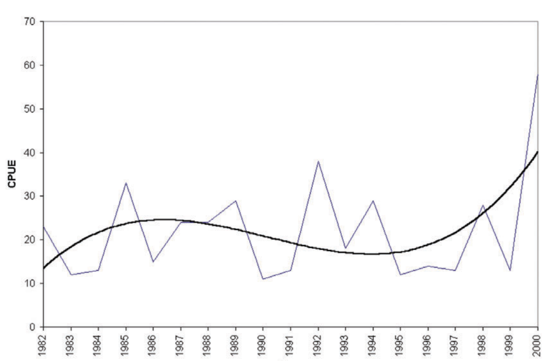


Fig. 8.2b. Brown shrimp sampled with shrimp trawl in Galveston Bay, 1982-2000. (Source: Texas Parks and Wildlife Department)

et al., 1977; Parker, 1965; Loeffler in Green et al., 1992). The TPWD monitoring data indicate that the overall health of the Galveston Estuary appears to be fair to good. However, there is concern about white shrimp and large blue crab, which have shown periods of decline and are subject to significant fishing pressure.

Selected Species Summaries

White and Brown Shrimp

TPWD's bag seine collections capture small shrimp (3-7 cm in length) along vegetated and non-vegetated shorelines. Shrimp trawl collections capture the larger shrimp (7-10 cm in length) as they occupy the open bay bottom and make their way to the Gulf. Sampling for the bag seine collections of white shrimp (*Litopenaeus setiferus)* and brown shrimp (*Farfantepenaeus aztecus)* show large fluctuations among years in the abundance of both species in the nursery habitats. Figure 8.1a shows that 1986 had a density of less than 200 small brown shrimp per hectare in near shore habitats, but in 1987 the abundance rebounded to almost 1,200 per hectare. Shrimp species abundances are naturally variable. No trend is apparent over the historical record for catch per unit effort (CPUE) of small brown shrimp sampled with bag seines. White shrimp populations, however, show a declining trend with a peak of more than 3,500 per hectare in 1982 and a low of approximately 250 shrimp per hectare for the year 2000 (see Figure 8.1b).

A strong decline in white shrimp was observed in trawl samples from 1982 through 1990 (Walton and Green, 1993; Green et al., 1993). The sharp decline of white shrimp CPUE for trawl samples was followed by a period from 1991 to 2000 of highly variable years (TPWD, 2001). The period of 1996-1998 saw an increase in trawl sample CPUE for white shrimp. However, the year 2000 saw a marked decrease to 26 white shrimp captured per hour as compared to a CPUE of 64 in 1999. Figure 8.2a shows the annual averages and a polynomial trend line that emphasizes the declines and rebounds of white shrimp abundance as seen in trawl samples. Brown shrimp abundance shows a slightly increasing trend in CPUE for shrimp trawl collections over the same time period with almost 60 brown shrimp caught per hour in 2000 compared to a CPUE of 13 in 1999 (Figure 8.2b).

Blue Crab

More blue crabs *(Callinectes sapidus)* are commercially harvested in Galveston Bay than in any other Texas estuary (TPWD, 2000). Commercial landings of this popular seafood species totaled more than 2.6 million pounds in Galveston Bay in 1998 (TPWD, 2000).

Blue crabs had different temporal trends for different size classes. Recruitment did not appear to be a problem, as a linear trend line of CPUE for bag seine samples is nearly flat from 1977 until 2000 (TPWD, 2001). The trend for larger crabs captured in shrimp trawl sampling is negative. The CPUE declines of blue crabs in trawl samples appear consistent from 1982 until 1995 when the trend turns upward. The trend then plunged downward in 1999 with CPUE reaching six individuals captured per hour. The year 2000 again saw a slight increase. Figure 8.3 shows the annual average CPUE plotted over sampling years.

The blue crab's life cycle is fairly complex and may be impacted by a variety of natural processes and human alterations to the estuarine environment. Factors possibly affecting the blue crab population may include pollutant contamination, habitat alteration, freshwater inflows, eutrophication and fishing pressure. Engel and Thayer (1998) measured the amount of hemocyanin (the blue pigment responsible for oxygen transport in many arthropods) in blue crabs collected from the Houston Ship Channel. They found that hemocyanin concentrations varied inversely to the degree of organic contamination. The Texas Department of Health has issued a consumption advisory for blue crab and catfish in the upper Houston Ship Channel (see Chapter 9). While contaminant stress may play a role, fishing pressure is more likely to provide an explanation of the decline in blue crab.

Senate Bill 1410, recently signed into law by Governor Rick Perry, requires the TPWD to close the crab season for a period of time during the months of February and March each year. This closure will allow for the removal of thousands of lost and abandoned crab traps lying in Texas waters. These traps continue to attract and capture crabs and other organisms, long after they have been abandoned. Additionally, they pose a safety hazard to recreational boaters and commercial and recreational fishermen.

Gulf Menhaden

Gulf menhaden (*Brevoortia patronus*) feed on phytoplankton, zooplankton and organic detritus. This species provides an important link in the food chain as prey for larger fish species. As evidenced by bag seine and trawl samples, this species shows an overall

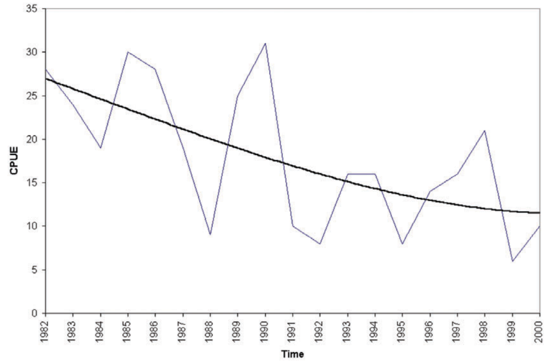


Fig. 8.3. Blue crab sampled with shrimp trawl in Galveston Bay, 1982-2000. Source: Texas Parks and Wildlife Department.

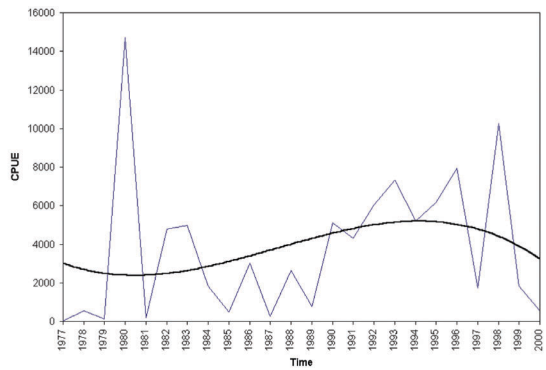


Fig. 8.4. Gulf menhaden sampled with bag seine in Galveston Bay, 1977-2000. Source: Texas Parks and Wildlife Department

increasing trend for the period 1977-2000 (TPWD, 2001). However the years 1998-2000 saw a decrease in abundance of small individuals.

As seen in Figure 8.4, CPUE for juvenile menhaden captured in bag seines decreased from more than 10,000 menhaden per hectare in 1998 to 555 individuals per hectare in 2000 (TPWD, 2001). Abundance of this species relies in part on the concentration of chlorophyll-a in the bay. Concentrations of chlorophyll-a have consistently decreased over the past 30 years (see Figure 6.9).

Atlantic Croaker

This species (*Micropogonias undulatus*) is a common target of recreational fishermen using bottom gear. It is an abundant demersal predator feeding primarily on invertebrate prey. Monitoring data for young-of-the-year croaker captured by bag seine show a decrease in abundance from 1977-2000 (TPWD, 2001). The average values prior to 1984 are higher than the average values after spatially randomized sampling begins. The decrease, therefore, may be a result of the change in sampling methodology rather than real decrease in the population.

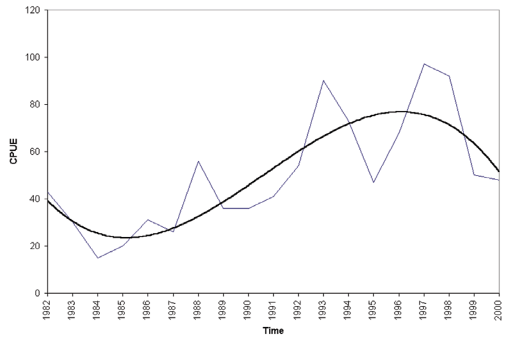


Fig. 8.5. Atlantic croaker sampled with shrimp trawl in Galveston Bay, 1982-2000. Source: Texas Parks and Wildlife Department

Shrimp trawl samples were also spatially randomized, but appeared less sensitive to site selection, showing a strong increasing trend in CPUE. The linear trend line for these samples rises from around 20 fish per hour in 1982 to near 100 fish per hour in 1997 (see Figure 8.5). CPUE's then decline to near 70 in the year 2000.

Southern Flounder

The southern flounder (*Paralichthys lethostigma*) is a prized food and recreational game fish. Like croaker, flounder are demersal predators. They often move into shallow waters at night to feed. They lie partially hidden along the bottom in wait for their prey. This feeding habit has historically made flounder an easy prey for fishermen who use pole gigs to capture the fish.

CPUE for flounder captured by bag seine shows a nearly stable, slightly increasing trend for young-of-the-year for the period of 1977-2000 (TPWD, 2001). 1977 and 1979 saw densities of 0 and 1 fish per hectare respectively. Alternately, flounder abundance peaked in 1987 and 1990 at a CPUE of 21 and 22 individuals per hectare respectively (see Figure 8.6). The early 1990s saw another decline followed by an increase during the years 1995-1998.

Spotted Seatrout

The spotted seatrout (*Cynoscion nebulosus)*, also referred to as speckled trout, are a premier recreational game species in Galveston Bay. CPUE for spotted seatrout captured in bag seines decreased during the study period from 1976 to 2000 (TPWD, 2001). The values seem to have two ranges, high values before 1984 when a randomized spatial sampling scheme was implemented and lower values after implementation (Robinson, 2000). During the last 16 years, older age classes have shown notable increases in abundance.

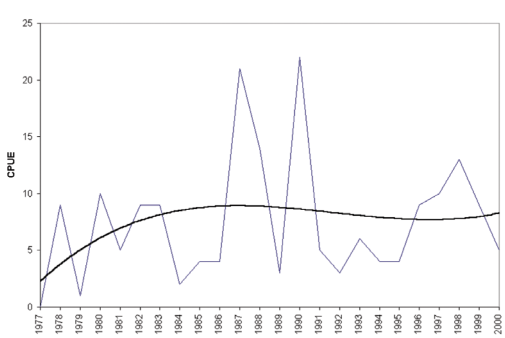


Fig. 8.6. Southern flounder sampled with bag seine in Galveston Bay, 1982-2000. Source: Texas Parks and Wildlife Department

Spotted seatrout collections with gill nets exhibit upward trends. Larger fish sampled by gill net exhibit an increasing trend in CPUE (Figure 8.7). The first three years of the record, 1975-1977, have an average CPUE of 0.29 while the last three years, 1998-2000, of the record have an average CPUE of 0.69. Spotted seatrout capture is subject to minimum size regulations. The effect of the regulation appears to have increased survival of larger size classes.

Probable Causes of Fish and Shellfish Declines

The declines noted above, particularly for blue crab populations, raise some concerns for the species and for potential bay conditions, which may have influenced the declines (Walton and Green, 1993). In addition, anecdotal information exists for several other species (such as tarpon, snook, and striped bass), indicating long-term declines compared to 19th century levels. Some reasons for declines were discussed above, such as over-fishing, loss of marsh habitat, changes in fresh water inflow, and changes in riverine organic loads to the bay.

Shrimp Trawl Bycatch

Bycatch is a broad term to describe unwanted incidental harvesting of organisms during pursuit of a different species. A study to assess shrimp trawl bycatch in Galveston Bay was conducted by the National Marine Fisheries Service (NMFS) Galveston Laboratory during the 1992 shrimp season (Martinez et al., 1993). One fish was captured as incidental bycatch for every 1.9 shrimp landed during the March to November shrimping season. Dominant bycatch species captured included Atlantic croaker, Gulf menhaden, sand seatrout, bay anchovy, sea catfish, spot, squid, and blue crab.

The TPWD conducted bycatch characterization studies in Galveston Bay during 1995 and had results similar to the NMFS study. Though bycatch ratios for Galveston Bay were the smallest seen on the coast, the numbers of individuals caught were still significant (i.e. total finfish bycatch per hour of trawling in the Spring = 4,256; total finfish bycatch per hour of trawling in the Fall = 1,844) (Robinson, 2000).

A local bycatch study, funded by the GBEP, is currently being performed by the TPWD. Through the use of comparative trawl studies, TPWD is evaluating the effectiveness of different bycatch reduction devices to increase the escapement of bycatch organisms while minimizing the loss of shrimp.

Recreational Bycatch

Recreational bycatch occurs when recreational anglers capture and release unwanted species or game fish of non-legal size or condition, e.g. incubating female crabs. When handled and released properly, these bycatch organisms often survive. However, mortalities can result from stress or physical damage. Public education is key in reducing recreational bycatch mortalities.

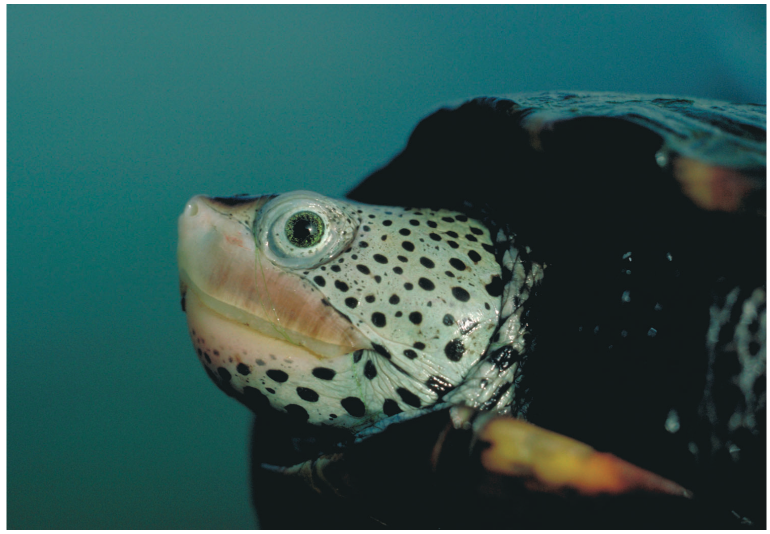
Based on federal and state fisheries data, Saul et al. (1992) concluded that recreational sport-boat fishermen caught and released about two fish for every fish retained. When applied to the entire Galveston Bay system, about 1.2 to 3.5 million fish are caught and released each year. Approximately five percent of the released fishes were reported as being released dead. Available literature on hooking and handling mortality suggests that 10-15 percent of red drum released alive and up to 30 percent of spotted seatrout released alive, die from injuries or stresses related to capture within approximately seven days.

Industrial Incidental Capture

Industrial cooling water intake systems can cause incidental mortality of bay organisms through impingement and entrainment. Impingement occurs when a screen at a water intake structure incidentally collects organisms. Entrainment occurs when organisms too small to be intercepted at the intake screens pass through the cooling water system.

The impact of cooling water use on fishery resources was studied using historical data (Palafox and Wolford, 1993). Using 1978-1979 data from five Houston Lighting and Power (HL&P) generating plants located on Galveston Bay, they concluded that about 84 million organisms representing a total biomass of 477,000 kg were impinged each year at the five HL&P plants located on Galveston Bay.

None of the historical data used to develop these conclusions focused on the overall scope of cooling water impingement and entrainment. In particular, there may be considerable environmental impact on marine eggs, larva, and other juvenile organisms entrained by the cooling systems. On one day in October 2000, a



The terrapin supported one of the earliest capture fisheries to disappear due to overfishing. It was vulnerable because it depends on exposed nesting sites. (Courtesy Texas Parks and Wildlife Department)

sudden drop in water temperature contributed to the impingement of 14 green sea turtles at a power plant on the west side of Galveston Bay (Rivera, 2000). All 14 turtles were successfully captured with the help of power plant employees, medically evaluated and released at another location.

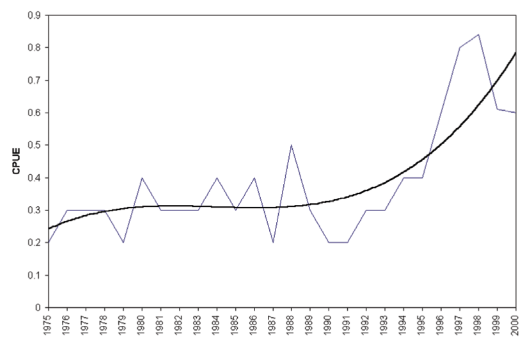


Fig. 8.7. Spotted seatrout sampled with gill net in Galveston Bay, 1975-2000. Source: Texas Parks and Wildlife Department

Both industry and government recognize entrainment and impingement as an important issue. Texas Coastal Coordination Council rules (31TACß501.14) now address impingement and entrainment of estuarine organisms as it relates to electrical power generation facilities utilizing once-through cooling systems. The rules require that these facilities "shall be located and designed to have the least adverse effects practicable." The power generators themselves wish to lessen the effects of impingement and entrainment by developing new cooling water intake technologies.

Fish Kills

The Texas Gulf Coast has some of the nation's largest and most frequent fish kill events, partially because of the hot climate and physical features such as low circulation. Fish kills often occur as a result of low dissolved oxygen levels in the water column

Waders	
Black-crowned Night	Stable
Great Blue Heron	Decrease
Great Egret	Stable
Little Blue Heron	Stable
Reddish Egret	Stable
Roseate Spoonbill	Decrease
Snowy Egret	Stable
Tricolored Heron	Stable
White-faced Ibis	Stable
White Ibis	Increase

Open Water Feeders	
Black Skimmer	Decrease
Brown Pelican	Increase
Caspian Tern	Stable
Forster's Tern	Stable
Gull-billed Tern	Increase
Laughing Gull	Stable
Least Tern	Decrease/Stable
Neotropic Cormorant	Increase
Royal Tern	Increase
Sandwich Tern	Increase

Fig. 8.8. Population trends of colonial waterbird species in Galveston Bay, 1972-1998. Source: McFarlane (2001)

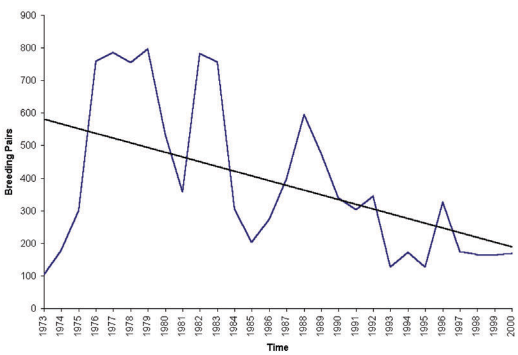


Fig. 8.9. Population of great blue heron in Galveston Bay, 1973-2000. Source: U.S. Fish and Wildlife Service

caused by human activity or naturally occurring events. Human activities include point source and nonpoint source loadings of nutrients and pollutants to estuarine waters.

In September 1998, Tropical Storm Frances produced a large amount of rainfall along the Southeast Texas coast. Stagnant waters were pushed into Galveston Bay resulting in major fish kills in East and West Bays (TPWD, 1998). In late summer 2000, an extensive toxic algal bloom impacted the coast of Texas. In Galveston Bay, fish kills were observed in West Bay, East Bay, Dickinson Bay, and Chocolate Bayou and along the Texas City Dike (Contreras, 2001).

Habitat Loss

It is difficult to document a causal relationship between species abundance and habitat size, and no studies of the Galveston Bay system have purported to do so. The loss of acreage of two important habitats, marsh and seagrass meadows, could impact the abundance of fish and shellfish that utilize these habitats. However, many of the fish and shellfish species that use marshes as nursery areas can survive and grow over open bay bottom. Their populations may maintain lower densities in unvegetated areas versus densities in optimal habitat, but the available data cannot document a quantitative relationship between acres of marsh and abundance or size of harvest. Evidence of correlated changes in abundance of species that use seagrass habitat is anecdotal since much of the loss of seagrass in Galveston Bay and West Bay occurred prior to the beginning of scientific monitoring of species abundances by the TPWD.

The question of how the habitat value of created marshes compares to preserved natural marshes is relevant to an understanding of how habitat quality affects species abundance. Minello and Webb (1997) found that created marsh, three to fifteen years after planting, had significantly lower densities of decapod crustaceans than natural marshes. This suggests that the productivity of the estuary is reduced by loss of marsh habitat and the function of that habitat is not completely or rapidly restored simply by planting the appropriate vegetation.

Birds

Bird populations in Galveston Bay have significant commercial, recreational, ecological, and aesthetic values. Many bird species observed on the bay are predators on fish, shellfish, or benthic organisms, and therefore are important indicators of the health of the food webs. Observers have noted 139 bird species associated with Galveston Bay wetlands and open-bay habitats (Arnold, 1984).

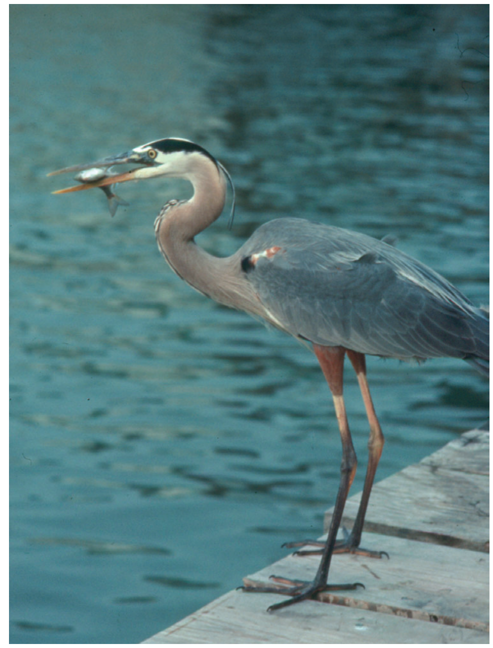
Colonial Waterbirds

Data from the U.S. Fish and Wildlife Service Texas Colonial Waterbird Surveys from 1973 to 2000 were used to evaluate trends for bird species that utilize Galveston Bay to feed and nest nearby in colonies (USFWS, 2001). This survey is done annually and attempts to count all of the nesting pairs in all of the colonies along the Texas coast. This excludes waterfowl and solitary nesters, such as osprey and kingfishers, but includes the herons, egrets, gulls, terns, ibises, etc. It may not include all nesting sites because new ones may take some time to be discovered. Also, some species are so numerous in some colonies that numbers of nesting pairs can only be approximated. The three most commonly sited species in the 2000 survey were the laughing gull, cattle egret and royal tern (USFWS, 2001).

Factors that affect populations of colonial waterbirds can include predation by coyotes, fire ants, human disturbance of nesting areas, freshwater inflows, chemical contamination and habitat loss. According to McFarlane (2001), six colonial waterbird species exhibited increasing trends, while four species exhibited decreasing population trends for the period 1973-1998. Ten bird species exhibited stable populations (Figure 8.8).

To enhance recognition of patterns in the abundance of bird species over time, bird species will be grouped into guilds dependent on similar feeding

The roseate spoonbill, a large wading bird, is among the most visually striking and valued species inhabiting Galveston Bay. The unique, flattened bill is specialized to capture small fish and invertebrates. (Courtesy Texas Parks and Wildlife Department)



Herons are common predatory wading birds that utilize the shoreline and provide people with ecological awareness of the bay's resources. (Courtesy Jack Lewis/Texas Department of Transportation)

or nesting resources. The first guild to be considered consists of wading birds feeding in marshes, i.e. great blue heron, great egret, snowy egret, tricolor heron, little blue heron, ibises and roseate spoonbills.

Two species exhibiting significant trends are the great blue heron and the white ibis. The great blue heron is the largest member of this guild. It shows a significantly negative trend in abundance from 1973 to 2000 (USFWS, 2001) (see Figure 8.9). Alternately, the white ibis exhibited a significantly positive trend. A record number of white ibis chicks were fledged in 1999 from colonies in the bay, but the numbers fall very low in drought years, such as 1988. This bird is negatively affected by conditions that decrease availability of freshwater crustaceans.

Other waders that feed on small fish and benthic invertebrates along shoreline marsh edges include the snowy egret, roseate spoonbill, tricolored heron, and great egret. For these species, the number of colonies increased in the 1970s and 1980s, but numbers of individuals per colony decreased. Great and snowy egrets saw slightly increasing trends, while tricolored herons and roseate spoonbills (see Figure 8.10) saw decreasing trends.

An open-water feeding group includes royal terns, Caspian terns, least terns, sandwich terns and neotropic cormorants among others. These species depend primarily upon fish caught from open-bay habitats. As seen in Figure 8.11, the data from 1973 to 2000 show that the abundance of Caspian, sandwich

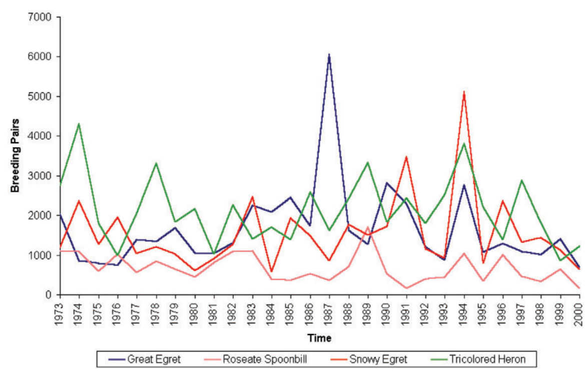


Fig. 8-10. Population of marsh wading birds by species in Galveston Bay, 1973-2000. Source: U.S. Fish and Wildlife Service

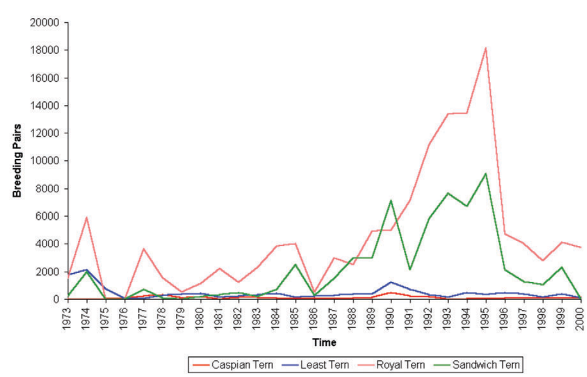


Fig. 8-11. Population of terns by species in Galveston Bay, 1973-2000. Source: U.S. Fish and Wildlife Service

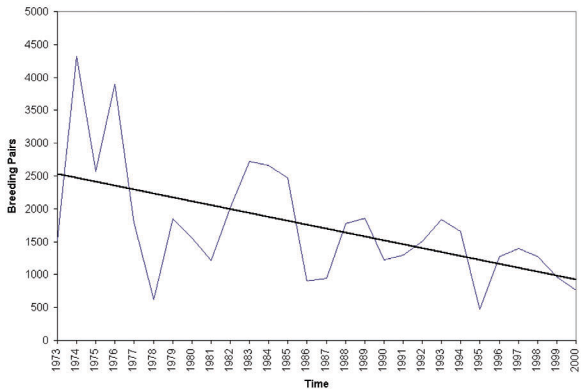


Fig. 8.12. Population of black skimmers in Galveston Bay, 1973-2000. Source: U.S. Fish and Wildlife Service

Skimmers amaze observers with their skill at flying with their beak in the water and catching fish on the wing. Their population is declining. (Courtesy Texas Parks and Wildlife Department)

and royal terns has a wave-like pattern of abundance. They declined in the late 1970s, increased from 1980 to 1995 and declined in 1996-2000 (USFWS, 2001). Over the entire period, royal and sandwich tern numbers show a significant positive trend. Least terns show a significant decline. As seen in Figure 8.12, the black skimmers show a steady and significant decline in numbers as well (McFarlane, 2001).

Waterfowl

The marshes, coastal prairies and rice fields of the upper Texas coast constitute a vital winter foraging area for waterfowl as they migrate along the Central and Mississippi flyways each year. Species observed in the Galveston Bay system include the blue-winged teal, green-winged teal, mallard, Northern pintail, American widgeon, gadwall, Northern shoveler, ring-necked duck, lesser scaup, red-breasted merganser, ruddy duck, Canada goose, snow goose and specklebelly.

Because of the nature of these and other migratory species, population regulation is impossible to evaluate by studying populations at any one location. Reduction in numbers utilizing a wintering area, while not necessarily reflecting population reductions, could reflect decreased habitat utilization in response to habitat loss or deterioration. Breeding and wintering populations of waterfowl are monitored by state and federal surveys. The resulting population estimates form the basis for annual harvest regulations.

Duck breeding population estimates compiled by the U.S. Fish and Wildlife Service for the years 1955-2001 show that several species of ducks exhibit declining trends, while trends for other species have increased (Wilkins et al., 2001). Breeding populations of mallard, American widgeon, Northern pintail and scaup appear to be in decline over the 46-year period. Increasing trends are seen for gadwall, blue-winged teal, green-winged teal, Northern shoveler, redhead and canvasback.

While some species of ducks have declined, geese populations have increased. Geese are more efficient at using winter rice fields and other uplands for their food supply and they are adaptable to a variety of breeding habitats (Bateman et al., 1988).

Shorebirds

The Galveston Bay system has been identified as a regionally significant reserve site for migrating shorebirds, and supports more than five percent of all mid-continental shorebird populations during their annual migrations. The most common shorebirds are the American avocet, willet, sanderling, western sandpiper, dunlin, dowitchers and black-bellied plover. The Christmas Bird Counts and the Bolivar Flats Shorebird Survey indicate a possible increase in shorebirds, although the data are difficult to interpret due to lack of standardization.

Threats to shorebird populations include human disturbance of nesting areas, oil spills and habitat alteration. For these reasons a number of areas along the upper Texas coast are designated as bird sanctuaries. This system of bird sanctuaries protects nesting and foraging areas utilized by shorebird species along their annual migratory route. Galveston Bay is home to several Houston Audubon Society bird sanctuaries including the Jerry R. Smith Nature Sanctuary in West Bay, the North Deer Island Sanctuary and the newly expanded Bolivar Flats Shorebird Sanctuary located on Bolivar Peninsula adjacent to the North Jetty.

Threatened or Endangered Bird Species

A number of federal and state designated endangered and threatened bird species can be found during at least some part of the year in and around Galveston Bay. Brown pelicans were listed as an endangered species after they declined to low levels as a result of bioconcentration of pesticides, many of which have now been eliminated. Brown pelicans have shown dramatic increases in Galveston Bay during the past eight years due to the successful establishment of nesting colonies (see Figure 8.13). More than 800 breeding pairs were sited in 2000 (USFWS, 2001). Other colonial waterbirds listed as threatened by the State of Texas include the reddish egret and white-faced ibis. As seen in Figure 8.8, both of these threatened species have exhibited stable population trends.

The bald eagle, a Texas threatened species and federally listed endangered species (pending a federal proposal to de-list the species), has nesting sites in Chambers, Galveston, and Harris counties. The piping plover is a federal and state designated threatened species that has overwintering habitat along Bolivar and Galveston beaches.

Reptiles

Many species of amphibians and reptiles have been observed in the counties adjacent to Galveston Bay. Of particular interest is the American alligator (*Alligator mississippiensis*), a once endangered species that has made a remarkable recovery. The alligator has increased throughout much of its range due to regulated hunting of alligators and regulated trade of alligator products. The American alligator inhabits fresh and brackish waters and wetlands and can be found in the bayous that flow into the bay. While the harvest and trade of alligators is regulated, the greatest threat to alligator populations around Galveston Bay is that posed by encroaching development.

Three sea turtle species, the endangered Kemp's ridley sea turtle (*Lepidochelys kempii*), the threatened green sea turtle (*Chelonia mydas*) and the threatened loggerhead sea turtle (*Caretta caretta*) can be found

The American alligator is common in many of the tributaries of Galveston Bay. It has rebounded from a threatened status due to regulation of human exploitation and protection of wetlands. (Courtesy Texas Natural Resource Conservation Commission Region 12)

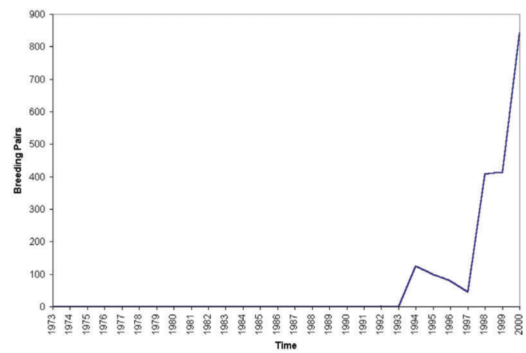


Fig. 8.13. Population of brown pelicans in Galveston Bay, 1973-2000. Source: U.S. Fish and Wildlife Service

along the Texas coast. They are not known to permanently inhabit Galveston Bay waters, but use the bay as a seasonal foraging area as they make their way along the coast.

Green sea turtles prefer the seagrass-laden areas of the Laguna Madre but are sporadically captured in research netting efforts as are young loggerheads. Loggerhead sea turtles, found in Texas nearshore waters, prefer deeper, more offshore areas such as those around petroleum platforms and are known to forage on shrimp grounds. Loggerheads are a mainstay of the turtles that strand along Texas beaches (Landry, 2001).

Kemp's ridley are by far the dominant species that occur in nearshore waters of the upper Texas coast (Landry, 2001). Manzella and Williams (1992) developed an atlas of Kemp's ridley distribution along the Texas coast based on data collected from the late 1940s through 1990. The Galveston Bay region ranked third in Kemp's ridley frequency distribution behind the Sabine Pass/High Island and Corpus Christi/North Padre Island regions.

Sea turtles tend to show fidelity towards passes. Netting studies undertaken by researchers at Texas A&M University at Galveston have seen a decline in the numbers of sea turtles captured at Sabine Pass over the past several years. The cause of this decline is unknown, but researchers believe it may be linked to the decline in blue crab populations, a primary prey species of the Kemp's ridley and green sea turtles (Landry, 2001). Management activities of interest include special precautions taken prior to marine seismic blasting and the required use of turtle excluder devices (TEDS) by shrimp trawlers.

Populations of another species of turtle, the diamondback terrapin (*Malaclemys terrapin*), an inhabitant of brackish water marshes, have declined over the last 150 years. According to Hogan (2001), turtle abundance and diversity largely depend on habitat and food availability and land-use of the surrounding area. The terrapin was once valued as a delicacy and exploited heavily in the 1800's (Lovich in LaRoe et al., 1995). Terrapin populations then recovered somewhat, but are now threatened by habitat loss and degradation.

Mammals

Land mammals that inhabit wetlands around Galveston Bay include the swamp rabbit, gray squirrel, beaver, muskrat, roof rat, northern rice rat, nutria, raccoon, mink, and river otter. Nutria, a species introduced from South America via Louisiana, has been identified as a particular management problem for some of the bay's wetlands. Nutria can consume large amounts of the emergent vegetation in wetlands, contribute to wetland loss, and can hinder wetland creation efforts in the area.

The most commonly occurring marine mammal in Galveston Bay is the bottlenose dolphin. Maze and Würsig (1999) examined the occurrence, site fidelity, habitat use and movement of bottlenose dolphins at San Luis Pass at the western end of Galveston Bay. In a 12-month period, they identified 71 individuals, which included 37 bay residents and 34 transients. They concluded that some individuals exhibit long-term fidelity for a given site while others tend to move between sites along the coast. They also found that dolphins frequent the bay's shallow waters during the summer, but prefer the deeper waters of the Gulf in the winter. The navigation channels in Galveston Bay provide a year round deepwater habitat for this popular species.

Bottlenose dolphins and other marine mammals are sometimes found stranded along the beach shoreline or in very shallow waters. While this phenomenon is not fully understood, strandings can occur as a result of injury, illness or disease. As top predators of the food chain, marine mammals can serve as indicators of overall ecosystem health.

Summary

A wide variety of fish, wildlife, plant, and invertebrate populations either reside in or periodically utilize Galveston Bay and its associated habitats. Most of the Bay's living resources appear to be in good health, with some exceptions posing management concerns.

Phytoplankton abundance, as measured through chlorophyll-a concentrations, has changed significantly through the years, possibly in response to increases in nutrients peaking in the late 1960s, followed by nutrient reductions. Over wide expanses of the bay, the benthic community remains abundant and diverse, following a natural gradient of increasing diversity from the upper bay system seaward.

Although oyster reefs appear to have expanded in recent years and commercial fish and shellfish populations are generally stable, the oyster population is nowhere near the levels found in Galveston bay prior to shell dredging. This was a major habitat alteration from which the bay has yet to recover. While most finfish populations appear to be in good health, monitoring data for large blue crabs exhibit a declining trend. Their complex life cycle makes the cause of this decline difficult to determine.

The total number of colonial waterbirds has remained relatively stable since the early 1980s. However, the composition of the colonial waterbird community is thought to be changing with increasing numbers of royal terns, sandwich terns and brown pelicans. Shorebirds also utilize Galveston Bay as a foraging and nesting area. A system of bird sanctuaries located around the bay protects some of these areas and creates a great opportunity for nature viewing. Bottlenose dolphin, two species of sea turtles and several endangered and threatened bird species can be found in and around the bay as well.

When compared to other estuaries of the eastern United States, Galveston Bay's living resources appear to be relatively well preserved and managed. As stewards of the bay's living resources, it is important to promote continued monitoring of populations, to support habitat protection and restoration activities and to encourage improvements in water quality.

Return of the Brown Pelican

This majestic bird has become more abundant after being decimated by pollution and slaughter. (Courtesy Richard Reynolds/Texas Department of Transportation)

One of the most dramatic recent developments for wildlife conservation in Galveston Bay is the return of the brown pelican. This large waterbird is an odd mixture of majesty and comedy. Watching a formation of pelicans slowly beating upwind along the shore can be a majestic site, and observing a flock herding mullet around an inlet as they feed on them can be comedic. The species is symbolic of estuarine dependent birds, but it is listed as endangered in Texas.

According to Phil Glass of the US Fish and Wildlife Service, in 1918 an estimated 5,000 brown pelicans nested on the Texas coast, but fishermen killed them and pesticide pollution reduced their nesting success. Between 1967 and 1974, fewer than 10 pairs bred each year along the Texas coast.

Today recovery efforts have been very successful and more than 800 brown pelicans nest in the five counties around Galveston Bay. Pelicans prefer to nest on small isolated islands uninhabited by coyotes or raccoons, predators that like to feast on eggs and small birds. Local Audubon Society chapters and state and federal resource agencies have worked to protect and enhance the nesting habitat of brown pelicans and other colonial nesting waterbirds. Protection involves signage to reduce human disturbance, predator removal from nesting islands, and erosion control projects for nesting islands.

Colonial nesting waterbirds are also benefiting from new concepts in beneficial uses of dredge material. A new nesting island was constructed in Lower Galveston Bay from the dredging of the Houston Ship Channel in 2000. Phil Glass observed that waterbirds colonized it quickly and nesting success resulted in “a tremendous fledgling rate” in 2001. Houston Audubon Society sanctuary manager Winifred Burkett looked to the future and stated, “The first nesting season has already been a tremendous success and we anticipate that future nesting seasons will be even more successful and the new vegetation will attract an even greater variety of birds.”

The future appears bright for pelicans and most colonial nesting waterbirds in the Galveston Bay system as a result of efforts to protect and create nesting sites and to manage the biological productivity of the bay. One type of reward for bay users from these management efforts will be the sight of sailing pelicans, hovering terns and stalking herons around the bay for years to come.

Chapter Nine

Impact on Public Health

> *"Public-minded citizens came to believe that, since disease always accompanied want, dirt, and pollution, the best and perhaps the only way to improve health was to bring back to the multitudes pure air, pure water, pure food, and pleasant surroundings. .... this point of view relates directly to the problems of disease being created in the modern world by the second Industrial Revolution, and to their control by social improvements."*
>
> *—Rene Dubos in Man, Medicine, and Environment, 1968*

Could swimming in Galveston Bay make me sick? Is it risky to eat the seafood from the bay? To citizens of Texas and the Galveston Bay region, these are compelling questions. News accounts of bay-related health threats get lots of attention from the media and the public. For example, contamination in Upper Galveston Bay and its tributaries has led to an advisory from the Texas Department of Health (TDH) to avoid certain seafood taken from that area. Similarly, large areas of the bay are closed to shellfish harvesting due to potential risk to consumers from pathogenic bacteria.

This chapter summarizes the various types of risk to human health that may be associated with using the bay. Public health risks are placed in three categories: pathogens, such as the bacteria that cause cholera; toxicants, such as dioxins or mercury; and other risks, such as drowning. The discussion of risk factors is followed by a description of the ways in which the responsible agencies address these risks through management strategies, such as the classification of shellfish harvest areas and the issuance of seafood advisories. The management strategy implemented is based upon the type of human use being managed. First, human health is threatened when human pathogens or toxic compounds are present in the water used for recreation. This can be addressed through warning against contact recreation in an area of the bay. Also, certain types of recreation may be inherently dangerous, such as boating, and justify the implementation of safety regulations. Second, concentrations of pathogens and toxic chemicals in fish and shellfish from the bay may be dangerous to consumers of the seafood. This risk can be addressed through seafood risk assessments and seafood advisories.

Human Health Risk Factors

Pathogens in Water and Seafood

The potential presence of human pathogens in bay waters is an important health concern related to human use of Galveston Bay. Exposure to these pathogens could occur through contact and non-contact recreation or through the consumption of seafood. Molluscan shellfish, primarily oysters, are especially associated with the risk of infection because they are often consumed raw. However, all types of seafood can serve as vectors for some form of disease agent. History provides valid reasons for concern about such diseases as infectious hepatitis, dysentery, and cholera. Thanks to scientific understanding and effective regulation by public health agencies, outbreaks related to environmental conditions are now rare. However, occasional instances still occur, reminding us that the sources for contamination still exist and that some pathogens occur naturally in the bay ecosystem.

Indicator Tests for Pathogens

Ideally, the concentrations of pathogens should be measured directly in water or seafood organisms. However, this is often not practical owing to the difficulty and expense of routinely identifying and enumerating the many different kinds of pathogenic microbes. Instead, indicator organisms have been adopted for regulatory purposes, especially for recreational and shellfish-growing waters. Indicator organisms suggest but do not confirm the presence of actual pathogens.

Fecal coliform bacteria are used in the TDH Shellfish Sanitation Program as an indicator of human health risk. Since 1983, fecal coliform most probable number (MPN) data have been used by TDH. The

Texas Natural Resource Conservation Commission (TNRCC) does not regulate oyster harvest, but the Texas Surface Water Quality Standards maintain an "oyster waters" designation for water quality protection of oyster reefs. The TNRCC uses the membrane filtration test method. The differences between the membrane filter and MPN tests used by these two agencies have prevented their data from being strictly comparable.

Under the TNRCC program, portions of the bay system designated as "oyster waters" include Upper Galveston Bay, Lower Galveston Bay, Trinity Bay, East Bay, West Bay, Chocolate Bay, Bastrop Bay, Christmas Bay and Drum Bay. Bay segments not meeting water quality standards for the "oyster waters" designation are placed on the Texas 2000 Clean Water Act Section 303(d) List for future assessment by the TNRCC's Total Maximum Daily Load (TMDL) Program.

Overall, the fecal coliform test used by the TDH has been successful in assuring the high quality of shellfish from Galveston Bay sold for human consumption. However, the indicator approach has limitations for regulation of oyster harvest. Fecal coliform testing produces many false positive results, and fails to indicate risk from naturally occurring non-intestinal pathogens such as *Vibrio vulnificus*.

Fecal Coliform Bacteria as Indicator Organisms

A number of possible metrics indicative of human pathogens in water are available, including: fecal coliform bacteria, total coliform bacteria, *E. coli*, fecal S*treptococcus sp.*, and *Enterococcus sp*. The TDH Shellfish Sanitation Program currently uses fecal coliform bacteria as the indicator, but has used total coliform in the past. Based on a recent study, the TNRCC has incorporated into the Texas Surface Water Quality Standards recommendations regarding appropriate bacterial indicator measures for estuarine and marine waters. Research indicated that the relationship between gastroenteritis and *E. coli* or *Enterococci* concentrations were signifcantly better than that of the traditional fecal coliform bacteria indictor. Therefore, the traditional bacterial indicator, fecal coliform, was replaced with *E. coli* for freshwater and *Enterococci* for saltwater. These criteria revisions for contact recreation use have been adopted by the TNRCC.

Fecal coliform bacteria naturally occur in the intestines of mammals and birds. Their fecal material contains some one million organisms per gram. Each human produces from 100 to 400 billion coliform organisms per day. The primary public health concern in the past has been diseases caused by improper treatment and disposal of human wastes. The absence of coliform organisms indicates that a sample is likely free of disease-producing organisms originating in human waste. Conversely, the presence of fecal coliforms indicates contamination that could (but may not) involve human pathogens.

The use of fecal coliform bacteria as an indicator in drinking and recreational waters dates back to the almost half a century. Prior to that total coliform data was used. The certification of oysters did not begin until 1925 following the typhoid fever epidemic affecting New York, Chicago, Washington D.C. and other cities on the east coast.

The use of fecal coliforms as an indicator has its limitations. There are some bacterial pathogens, which are unrelated to human wastes. Therefore, they are not detected in the routine tests. For example, *Vibrio vulnificus* is a human pathogen occurring naturally in the waters and biota of Galveston Bay. Conversely, many non-fecal coliforms common in soil and on the surface of plants cannot be distinguished from fecal coliforms by the tests commonly used. Thus, elevated concentrations of organic materials from a wide range of sources can support bacterial populations that are interpreted as indicative of human health risks. The total and fecal coliform tests need to be interpreted with caution.

Studies suggest that the principal source of fecal coliform bacteria to Galveston Bay is runoff from upland areas, with urbanized areas being one of the major components (see Chapter 6). Part of the reason fecal coliform levels are high in urbanized areas is the contribution from sewer leaks and overflows. However, even when the collection systems are not leaking, urban area runoff generally has high fecal coliform levels, and runoff occurs in much greater volumes than sewage leaks or overflows.

Neither septic systems along the bay's shoreline nor permitted point source discharges are major contributors of fecal coliform bacteria to the bay as a whole (Jensen, 1992). Locally, however, septic systems and permitted discharges can both be important contributors of bacteria. This is especially true for enclosed tributaries, as pointed out below in the discussion of water conditions in the bay, which affect human activities. Runoff from totally undeveloped land also tends to be high in fecal coliform bacteria (TDH et al., 1990), with low incidence of pathogenic organisms.

Common Bacterial Pathogens

Species of the bacterial genus *Vibrio* have been identified as pathogenic for humans, with the potential to cause extreme illness and sometimes death. Several *Vibrio* species pose a concern in coastal waters, the most common being *Vibrio vulnificus,* which can cause rapid and devastating disease symptoms in humans. *Vibrio cholerae* and *Vibrio parahaemolyticus* also occur in estuarine waters and can occur in Galveston Bay. *Vibrio* infection is usually associated with eating raw or undercooked shellfish, particularly oysters. The bacteria occur naturally in coastal waters and are most common in warm waters with a temperature range of 10° to 30°C and a salinity range of 5 to 30 parts per thousand (ppt) — conditions representative of Galveston Bay. Fecal coliform testing will not detect these estuarine bacteria and their occurrence cannot be correlated to concentration of sewage or abundance of coliform bacteria. Therefore, they present a problem for current methods of certifying seafood and regulating harvest areas.

One of the largest outbreaks of *Vibrio parahaemolyticus* ever reported occurred in the summer of 1998 and was caused by oysters harvested from Galveston Bay waters. Between the end of May and early July 1998, 416 persons in 13 states reported cases of gastroenteritis after eating raw oysters harvested from the bay (Daniels et al., 2000). At the time, oyster beds met bacteriological standards and fecal coliform levels were in acceptable regulatory limits. This suggests that current policies regarding water quality testing associated with oyster harvests may need to be reevaluated.

Consumption of seafood is not the only mode of infection by pathogens in bay waters or biota. On rare occasions, *Vibrio vulnificus* can infect fishermen via puncture wounds from the fins of fish. Similarly anglers and swimmers can be infected through any open wound exposed to pathogens in water or on the surface of organisms. Cholera and other *Vibrio* infections can also be acquired through ingestion of contaminated water, but this mode of infection appears much less likely in the Galveston Bay region than in less developed areas of the world.

Other types of bacteria are of course present in the waters of Galveston Bay. The density of human settlements around the bay and the intensity of human use ensure the entry of human pathogens into the system. Research has shown that pathogenic bacteria, such as fecal *Streptococci, Salmonella* and *Clostridium botulinum* are able to survive for some time in estuarine waters (Colwell and Kaper, 1978). Studies of the bacterial and viral contamination of the canals into bayside communities from Galveston Bay show that the pathogens survive longer in the sediment than in the water column (Gerba and McLeod, 1976; Smith et al., 1978). This suggests that the sediments of Galveston Bay hold a reservoir of an assortment of human pathogens at all times.

The abundance of most pathogenic species can be estimated by the concentration of fecal coliforms detected by water quality testing. The number of fecal coliform cells per milliliter of water using the membrane filter test ranges from 10^2 in open bay waters to 10^{11} in Buffalo Bayou and the Houston Ship Channel (See chapter 6).

Viruses

Bacteria are not the only pathogens to be included in a discussion of human health. Hepatitis A is caused by a virus that comes from the same family of viruses as the polioviruses and rhinoviruses (common cold). The hepatitis virus is excreted in the feces of infected persons and can contaminate water or food products, including shellfish. There is great concern that hepatitis may be contracted by consumption of raw or improperly cooked seafood. Incubation of the virus varies from 10 to 50 days with the actual disease lasting one to two weeks. Once infected, a person will experience symptoms including fever, malaise, nausea, anorexia and jaundice. Because of the long incubation period, the suspected food is often no longer available for analysis. No satisfactory method is presently available for routine analysis of seafood for hepatitis virus (USFDA, 2000a).

Other viruses that can be traced to raw or partially cooked shellfish include rotaviruses, Norwalk viruses and parvo-like viruses. These can cause viral gastroenteritis resulting in symptoms such as nausea, vomiting, diarrhea, malaise, abdominal pain, headache, and fever (USFDA, 2000b).

As in the case of bacteria, consumption of seafood is not the only potential route of viral infection for users of Galveston Bay. Transmission of poliovirus by water ingestion in the context of contact recreation was a public health concern before the polio vaccine became available. Many swimming pools were closed during polio outbreaks. Many viruses can attach to other particles and remain viable in the water or sediment of the bay for days (Sage, 2000). This reservoir of viruses has an unknown impact on human health.

Toxicants in Seafood Organisms

Data on concentrations of toxic chemicals in estuarine organisms are important indicators of ecosystem health and provide critical information on human health risks related to seafood consumption and contact recreation. Thousands of compounds, which could affect living organisms in an estuarine environment, occur in runoff and effluents. Those described below belong to categories known to be associated with human health risks. Studies of toxicants in Galveston Bay, that used concentrations of the compounds in seafood as a monitoring tool, but did not address the relationship of the tissue concentrations to the health of humans, are described in Chapter 6. Studies that relate their findings to public health are included in the discussion below.

A very extensive series of health consultations by the TDH (1999a, 2000a, 2000b, 2000c, 2001a, 2001b, 2001c, and 2001d) surveyed finfish and crabs from all regions of the Galveston Bay system for seven metals, 27 pesticides, seven polychlorinated biphenyls, 92 semivolatile organic compounds, and 72 volatile organic compounds. In three areas, dioxins and furans were assayed. Organotin compounds were assayed in fish and crabs from Clear Lake and nearby bay waters. Most of the discussion below will be based on these studies because they are the most current and the most extensive completed on the safety of seafood from Galveston Bay.

Reactive Hydrocarbons

Phthalates are used as plasticizers to make plastics pliable. They are contained in many products, but are not bonded to the carrier material. Thus, phthalates migrate into the environment from many sources and are now ubiquitous in the air, water and food of developed countries. In the aquatic environment, they are very toxic to some species. Exposure of humans to phthalates over long time periods can result in damage to liver and testicles (Crosby, 1998).

Samples of fish tissue from Upper and Lower Galveston Bay tested positive for three phthalate compounds (TDH 1999a, 2001b). These were detected in a low percentage of the samples tested and were found at low concentrations.

Polynuclear Aromatic Hydrocarbons (PAHs)

PAHs are toxic compounds, some of which are carcinogens. They are absorbed by fatty tissues in living organisms and therefore have the potential to bioaccumulate. Aquatic animals with gills are very sensitive to membrane damage from PAH molecules activated by ultraviolet energy in light. Mammals are capable of rapidly oxidizing PAH molecules, but degradation may produce DNA damage and cancer (Crosby, 1998).

PAHs are related to fossil fuel use. As environmental contaminants, they arise primarily from the discharge or combustion of petroleum products and other organic compounds. Major sources in the coastal environment include drilling operations and petroleum production, transportation activities, riverine inputs, and atmospheric deposition of fossil fuel combustion products. PAHs are also introduced into the environment from some organic chemical reactions and from fires. Fires can emit PAHs whether the fuel is biomass, as in forest fires, or synthetic materials, as in waste incinerators. Because of the persistent and "fat-binding" nature of PAHs, it is not surprising that they have been frequently detected as a widespread contaminant in estuarine organisms.

Brooks et al. (1992) conducted a survey of five species of seafood organisms from four locations in the bay. The study analyzed for 24 individual PAHs and revealed total PAHs ranging from nondetectable to 1253 ng/g. Oysters had higher total PAH concentrations than fish and crabs, except at Hannah's Reef in Lower Galveston Bay. Concentrations found in the study were within the range of concentrations reported for oysters for Galveston Bay as part of the National Status and Trends Program, which found PAHs in Galveston Bay oysters to be among the highest 25 percent of sample sites throughout the Gulf of Mexico.

The only evidence of PAHs in Galveston Bay seafood in the most recent study by TDH is a single instance of naphthalene detected in a smallmouth buffalo collected in the Turning Basin of the Houston Ship Channel (TDH, 2001d). Based on this evidence, PAHs do not occur in high enough frequency or concentration in Galveston Bay seafood to represent a public health concern.

Contaminant	Sample Area	Average Concentration in Finfish Tissue (mg/kg)
Chlordane	Houston Ship Channel / Turning Basin	0.763
p,p' –DDE	Houston Ship Channel / Turning Basin	0.044
p,p'-DDD	Houston Ship Channel / San Jacinto River	0.01
p,p'-DDT	Houston Ship Channel / Turning Basin	0.0045
Dieldrin	Houston Ship Channel / Turning Basin	0.025
Heptachlor Epoxide	Houston Ship Channel / Turning Basin	0.016
Hexachlorobenzene	Houston Ship Channel / Turning Basin	0.005
Aroclor 1260 (PCB)	Houston Ship Channel / San Jacinto River	0.068

Table 9.1. Results of the health consultation completed in 2001 for the Houston Ship Channel and lower San Jacinto River. Only those contaminants detected at levels sufficiently above reportable limits to justify health concern are shown. The sample area from which the highest concentration was recorded and the average concentration in that area are given. (Source: Modified from Texas Department of Health (2001a, 2001b, 2001c and 2001d)

Sampling Area	Chlordane Concentration (mg/kg)	DDT, DDE and DDD Total Concentration (mg/kg)
Houston Ship Channel Turning Basin (fish only)	0.763	0.0505
San Jacinto River (fish only)	0.161	0.042
Trinity Bay	0.03	0.0136
Upper Galveston Bay	0.037	0.009
Clear Lake	0.053	0.0035
Lower Galveston Bay	brl	0.0063
East Bay	0.0076	0.001
West Bay	0.0036	brl
Christmas Bay	0.0012	0.0021

brl = below reporting limits

Table 9.2. Concentrations of the pesticides chlordane and a combination of DDT + DDE + DDD in fish and crab tissue from the areas of the bay system sampled by Texas Department of Health in the latest set of Health Consultations. Concentrations for the turning basin of the Houston Ship Channel and the lower San Jacinto River are from fish tissue only. (Source: Modified from Texas Department of Health, 1999, 2000a, 2000b, 2000c, 2001a, 2001b, 2001c and 2001d)

Chlorinated Hydrocarbons

Most attention to this class of toxic compounds has been focused on pesticides and polychlorinated biphenyls (PCBs). Pesticides studied by TDH included DDT and related degradation compounds DDD and DDE; chlordane; aldrin, which degrades to dieldrin; and heptachlor, which degrades to heptachlor epoxide; endrin; and lindane. The use of some of these toxic and persistent compounds has been banned or severely restricted in most developed countries because of their tendency to bioconcentrate in food chains.

Health effects of pesticides can include such short-term effects as: tremors, convulsions, mental confusion, depression, anemia and even certain types of leukemia (USEPA, 2001). Long-term effects of human exposure to some forms of synthetic pesticides can include liver and kidney damage, damage to the central nervous system, and cancer (USEPA, 2001). PCBs are classified as suspected human carcinogens and known animal carcinogens.

Studies reveal that, in spite of the current bans, a variety of organochlorine residues exist in Galveston Bay organisms and sediment. Compounds most commonly found included PCBs, DDT metabolites, and occasionally, dieldrin and chlordane.

Jackson et al. (1998) examined the concentration of PCBs in oysters collected from six sites in the bay over the period from 1986 to 1994. PCB concentrations are trending down in Galveston Bay oysters. Most collection sites show PCB levels above the median for Gulf of Mexico collection sites. In the same study, DDTs showed a general decreasing trend, except at the most polluted site, the Houston Ship Channel, and the least polluted site, Hannah's Reef, which exhibit no trend (Jackson et al., 1998).

Portions of Clear Creek appear on the Texas 2000 Clean Water Act Section 303(d) List for elevated levels of chlordane and the volatile organic chemicals; dichloroethane, trichloroethane and carbon disulfide (TNRCC, 2000b). Four TMDLs for Clear Creek will assess current conditions to determine the appropriate direction and methods to be used to bring the stream back into compliance with the Texas Surface Water Quality Standards (see Chapter 6).

The recent TDH health consultations assayed Galveston Bay seafood for chlorinated hydrocarbons. Concentrations of chlorinated hydrocarbons in tissue of finfish and blue crabs were analyzed from all parts of the bay system. Finfish from the Houston Ship Channel and the lower San Jacinto River had high concentrations of these chemicals. Table 9.1 shows the compounds detected, the sample site with the highest average value and the average concentration in the organisms collected from this site. Only those contaminants detected at levels sufficiently above reportable limits to justify health concern are shown.

One cause for concern regarding chlorinated hydrocarbons is the wide distribution of these compounds in the bay system. Table 9.2 shows the reported concentrations of the two most common pesticides (chlordane and DDT) detected in fish and crab tissues from the regions of the bay sampled by TDH (1999a, 2000a, 2000b, 2000c, 2001a, 2001b, 2001c, and 2001d). Concentrations for the turning basin of the Houston Ship Channel and the lower San Jacinto River are from fish tissue only.

Dioxin and Furans

Polychlorinated dibenzo-p-dioxins (referred to herein as dioxins) and polychlorinated dibenzofurans (referred to herein as furans) are toxic, highly stable substances that bind strongly to soil and sediments. This makes them extremely persistent in the environment. These compounds can occur naturally, but the most significant sources today are incinerators of chlorinated wastes. Dioxins are also byproducts of bleached paper manufacture.

Dioxins and furans are capable of affecting health at low concentrations. The toxicity response in experimental animals is unusual. After exposure to a lethal dose, the animals stop eating and can die from starvation or toxic effects. Other responses include immunotoxicity and carcinogenicity. Several compounds in this group are probable human carcinogens (Malachowski 1995).

Elevated levels of these compounds in the Houston Ship Channel and nearby waters have resulted in the issuance of a TDH seafood advisory and the development of a TMDL. In the recently completed TDH health consultation studies, dioxins and furans were assayed from finfish and blue crab tissue in Lower Galveston Bay, Christmas and Bastrop Bays, and Clear Lake. Dioxins were detected in all three areas. The most commonly detected dioxin congeners were 2,3,7,8-Tetrachlorodibenzofuran (TCDF), 2,3,7,8-Tetrachlorodibenzo-p-dioxin (TCDD), and Octachlorodibenzodioxin (OCDD) (TDH, 1999a, 2000a, 2000b, 2000c, 2001a, 2001b, 2001c, and 2001d). The concentrations of all of the detected dioxins and furans were combined in a formula that weighted the compounds by their toxicity with TCDD as the standard. Table 9.3 shows toxicity weighted concentrations in ng/kg of the dioxins and furans detected in seafood tissue collected in different areas of the bay system.

Sample Area	Sample Organism	Number affected / Number sampled	Toxicity-weighted concentration
Clear Lake	Blue crabs	6/12	0.547
	Fish	20/36	0.346
Lower Galveston Bay	Fish	29/65	0.185
Christmas Bay	Blue crabs	6/6	0.058
	Fish	1/11	0.009

Table 9.3. Toxicity weighted concentrations in ng/kg of the dioxins and furans detected in seafood tissue collected in different aras of the bay system. (Source: Modified from Texas Department of Health, 1999, 2000a, 2000b, 2000c, 2001a, 2001b, 2001c and 2001d)

Trace Metals

Bivalves are often assayed for concentration of metals in their tissues as a component of water quality studies (see Chapter 6). Adult bivalves are fixed in place and pass large volumes of water through their shell and over their tissue as they feed. Metal atoms and compounds are ingested with food particles or absorbed. The metals can be deposited in soft tissue or in shell and their concentrations in tissue or shell serve as short-term or long-term indicators of past water quality. Other organisms, principally finfish and crustaceans, are also used to assess the potential health effects of seafood consumption, but their mobility introduces uncertainty into the relationship between contaminant concentration and sample location.

Those metals found in the tissue of seafood and of greatest health concern for consumers of seafood are mercury, cadmium, chromium, arsenic and lead. Each of the metals has different effects on human development and physiology. Physiological and developmental effects on humans can vary depending upon the person's age and health condition. Children, pregnant women, the elderly and those with certain preexisting health conditions are among the most susceptible to this type of contamination.

Mercury is known to cause neurological dysfunction and can bind sulfhydryl groups to inhibit respiratory enzymes (Crosby, 1998). Chronic exposure to cadmium results in liver and kidney damage (Malachowski, 1995). Poisoning by chromium and chromates is destructive to all cells in the body. Chronic exposure leads to serious dermatitis. Hexavalent chromium is considered a carcinogen (Malachowski, 1995). Arsenic exposure increases the chance of skin and lung cancer. Symptoms of chronic arsenic exposure include gastrointestinal distress, hyperpigmentation, thickening of the skin of the palms and soles, and several neuropathies (Malachowski, 1995). Lead contamination is a common environmental problem, especially for children. Humans respond to high doses of lead in a variety of ways. Some studies have documented behavioral changes involving antisocial behavior. Physiologically lead can replace calcium in bone tissue and compete with it in nerve function. It is also able to block the synthesis of heme,

Bay Region	Organism	Cd	Cu	Pb	Hg	Se	Zn
Christmas Bay	Fish & Crabs	0.07	4.32	0.006	0.075	0.5	15.8
Clear Lake	Fish & Crabs	0.01	2.12	0.021	0.02	0.538	11.2
East Bay	Fish & Crabs	0.02	1.06	0.023	0.016	0.55	9.4
Houston Ship Channel & San Jacinto River	Fish	0.001	0.267	0.004	0.126	0.539	3.52
Houston Ship Channel & San Jacinto River	Crabs	0.132	16.3	0.015	0.055	0.71	44.4
Lower Galveston Bay	Fish	0.03	2.15	0.011	0.031	0.584	12.4
Trinity Bay	Fish & Crabs	0.014	1.3	0.003	0.03	0.5	9.3
Upper Galveston Bay	Fish & Crabs	0.016	1.7	0.002	0.057	0.92	10.2
West Bay	Fish	0.015	1.53	0.014	0.078	0.58	10.7

Table 9.4. Average concentrations of metals measured in the tissue of fish and crabs collected in the sub-bays and tributaries of the Galveston Bay system in 1998 and 1999 by the Texas Department of Health. Concentrations are given as mg/kg of wet weight. (Source: TDH, 1999, 2000a, 2000b, 2000c, 2001a, 2001b, 2001c and 2001d)

Fig. 9.1. Microscopic photo of the red tide organism, K. brevis. (Courtesy Texas Sea Grant College Program)

which is required to synthesize hemoglobin (Crosby, 1998).

Brooks et al. (1992) analyzed fish, crabs, and oysters for a suite of trace metals. They found concentrations similar to the National Status and Trends findings, excepting zinc. Values for zinc were lower in the study by Brooks et al. (1992) than in the EPA report, and did not correlate with urban and industrial areas, as determined in the National Status and Trends work. In general, Brooks et al. (1992) found no strong relationship between metals in fish tissue and proximity to industrial discharges. The metal concentrations appeared to have no geographical pattern in their distribution.

Crocker et al. (1991) reported limited analyses for metals in fish and crabs from nine stations in the Houston Ship Channel during two time periods. Fish analyzed included sea catfish, spot, white bass, striped mullet, red drum, and spotted seatrout. Crabs were also analyzed. Tissue concentrations were measured for eight metals. Antimony, arsenic and selenium concentrations exceeded EPA fish tissue criteria, while chromium, copper, cyanide, silver, and zinc concentrations were below the EPA criteria.

Toxic metals were included in the recent series of TDH health consultations (1999a, 2000a, 2000b, 2000c, 2001a, 2001b, 2001c, and 2001d). The distributions of metal concentrations detected in that study are shown in Table 9.4. Toxic metals were observed in the tissue of seafood from all areas of the bay system. The distribution of concentrations is approximately what would be expected based on a correlation with industrial and urban inflow. However, the concentrations of six metals in Christmas Bay are surprisingly higher than those in Upper Galveston Bay and in five cases higher than the same metals in the Houston Ship Channel.

Organotin

Tri-n-butyltin oxide (TBTO) is used to retard the attachment of invertebrates to the bottoms of boats. It is banned for use on large commercial ships because it is highly toxic to aquatic organisms, but is still used in the recreational boating industry. TDH (2001a) assayed the fish and crabs collected from Clear Lake and Galveston Bay near the entrance to Clear Lake for the presence of organotin compounds. This was the only region of the bay in which these chemicals were analyzed. Clear Lake has the highest concentration of marinas and recreational boats on the Texas coast. Recreational boaters use the waters of the lake for contact and non-contact recreation and could be exposed to toxic compounds in the water and seafood. TBTO is a suspected immune suppressant in humans and may be more toxic in children (USEPA, 2000).

Tributyltin, dibutyltin and monobutyltin were all more concentrated in Clear Lake than in nearby Galveston Bay. The total organotin concentration in Clear Lake was 0.00390 mg/kg in fish and crabs. In Galveston Bay near the lake, the concentration of organotin dropped to 0.00081 mg/kg. However, the compounds were found in more than 85% of the samples tested in both areas (TDH, 2001a).

Algal Toxins

As discussed in Chapter 8, some species of phytoplankton produce toxins that accumulate in the tissues of shellfish and can, when ingested by humans, cause illness. Several of the most notorious phytoplankton-related pathologies include Amnesic Shellfish Poisoning (ASP), Paralytic Shellfish Poisoning (PSP), Ciguatera Fish Poisoning (CFP) and Neurotoxic Shellfish Poisoning (NSP). Unfortunately, it is difficult to measure the true occurrence of these illnesses as they are frequently misdiagnosed or are not reported at all.

The organism responsible for red tide algal blooms (*Karenia brevis* syn. *Gymnodinium breve*) (Figure 9.1) produces a substance known as brevetoxin. When this toxin is ingested by humans, NSP can result. Symptoms may include dizziness and nausea and, although not life-threatening, can be debilitating. *K. brevis* can also cause respiratory irritation when the neurotoxin becomes airborne through wave action. During the summer of 2000, a large occurrence of red tide was observed along the Texas coast from Galveston to Padre Island. High concentrations of toxic algae were detected in Lower and Upper Galveston Bay. The Galveston Bay oyster fishery was closed as a result of high brevetoxin concentrations.

The reported frequency of toxic algal blooms is increasing globally. While no causal factor has been documented, coastal water pollution probably plays a role. It seems contradictory that standard water quality parameters indicate that the quality of Texas' coastal water is improving, but the frequency, size and duration of toxic or noxious algal blooms is increasing.

Drowning

Pathogens and toxic contaminants are not the only sources of human health risk associated with Galveston Bay. The most acute and lethal impact of Galveston Bay occurs when someone drowns in its waters. However, drowning is more common in the surf along the Gulf beaches of the Texas coast and in swimming pools than in the bay. In 1999, there were 55 drownings in Harris County, 12 in Galveston County, 3 in Brazoria and none in Chambers (TDH, 1999b). To the best of our knowledge, none of these occurred in Galveston Bay.

Drownings in bay waters are usually related to boating accidents, storms and sometimes to dangerous currents. There have been catastrophes that resulted in many drownings in Galveston Bay. Nine of ten deaths associated with hurricanes are due to drowning in tidal waters (National Hurricane Center, 2001). The 1900 hurricane swept many people off Bolivar Peninsula and Galveston Island. They subsequently drowned in the waters of the bay. The storm surge of hurricanes is a great threat to human health associated with the bay.

Bay waters are a vital source of recreation but can also prove deadly. Drownings in bay waters are usually related to boating accidents, storms or dangerous currents. (Courtesy Texas Sea Grant College Program)

Human Health Risk Management

Records indicate that Galveston Bay seafood landings account for more than 30 percent of the statewide inshore total (Brooks et al., 1992), and more than 85 percent of oyster landings (Robinson, et al., 2000). Seafood from Galveston Bay is distributed in a national commercial market. Recreational catch is also consumed by a wide array of people. The number of consumers and the potential for harmful contaminants in seafood are cause for concern about the risk to consumers of Galveston Bay seafood.

What is the health risk associated with eating our seafood? Generally, but not always, the health risk is negligible. This is especially true for commercially caught fish and shellfish, which tend not to come from the most contaminated portions of the upper estuary and which are subject to regulation for health protection. Seafood from some areas of the bay contains generally low but variable concentrations of toxic chemicals that can represent health risks of some concern under certain conditions.

The responsibility for protecting the health of citizens from the various risk factors identified is distributed among several Texas state agencies. The Texas Department of Health is responsible for assessing and managing the risks associated with seafood consumption. The TDH classifies shellfish harvest areas and issues seafood advisories. The TNRCC is responsible for classifying water bodies including sections of the bay and its tributaries according to their ability to support the traditional uses of contact recreation and fishing. The Texas Parks and Wildlife

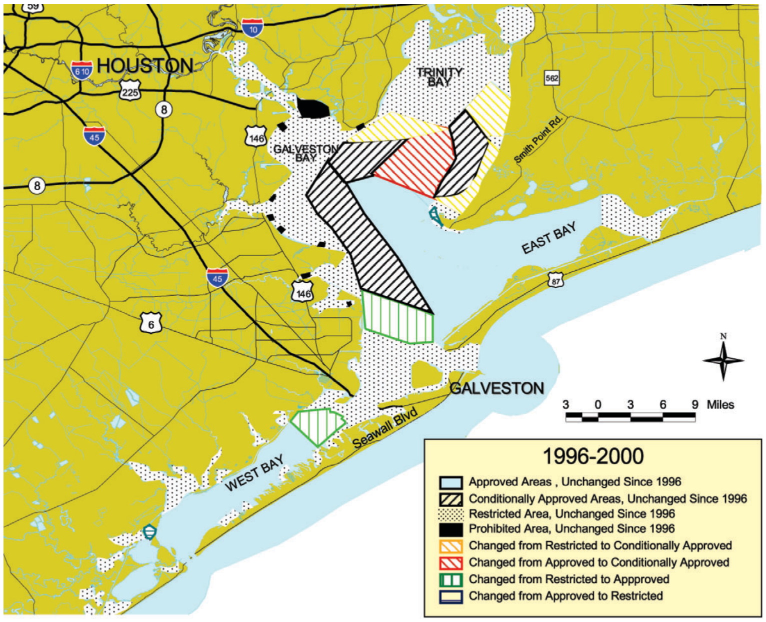


Fig. 9.2. Classification of shellfish harvesting areas in Galveston Bay, 1996 versus 2000. (Source: Modified from Texas Department of Health)

The consumption of raw oysters can be a risk for certain people. Cooking or irradiation destroys most of the harmful bacteria. (Courtesy Jamey Tidwell/Texas Sea Grant College Program)

Department enforces boater safety regulations.

These state agencies are supported in their roles by federal agencies. In 1995, the US Food and Drug Administration passed new seafood safety regulations based on the Hazard Analysis Critical Control Point (HACCP) system. These regulations must be followed by all seafood processors engaged in interstate seafood commerce. Rather than focusing on the end-product, HACCP controls are implemented in all stages of processing and shipping. The EPA supports water quality monitoring projects and the establishment of criteria for quantifying risk from exposure to specific compounds. The Coast Guard cooperates to enforce boater safety regulations.

Seafood Consumption

Classification of Shellfish Beds

The consumption of oysters, especially raw, can pose a significant health risk because oysters can concentrate bacterial and viral pathogens in their tissues. The TDH Seafood Safety Division is responsible for regulating the harvest of oysters to protect the public from this health risk. Alternately, the TNRCC is responsible for regulating water quality in areas designated for shellfish harvest via the Texas Surface Water Quality Standards. Harvest areas are classified based on the observed concentrations of fecal coliforms in the water around the oyster reef. Oyster reefs can be closed on an emergency basis when pathogens or other harmful agents are detected in the water or in the oyster tissue. This type of closure occurred in summer 2000 due to red tide toxins in the oysters and in summer 1998 due to *Vibrio parahaemolyticus* infections in consumers.

Shellfish Harvest Area Trends

Maps are periodically produced by the TDH as a regulatory tool to designate shellfish harvest area classification in Texas bays. Harvest areas are classified as approved, conditionally approved, restricted or prohibited. All shellfish harvested in Texas waters must come from approved or conditionally approved areas. Conditionally approved areas remain subject to classification changes based upon meteorological conditions that influence runoff. Oysters may be transplanted to private leases from restricted areas and harvested after a specified depuration period.

Maps published by the TDH in November 2000 (TDH, 2000d) indicate that classifications of some harvest areas remain the same. Changes between the 1996 and 2000 maps of oyster harvest area classifications are summarized in Figure 9.2. The upper Houston Ship Channel remains prohibited to oyster harvests while the northern portion of Trinity Bay, the western shoreline of Galveston Bay, the eastern end of East Bay and portions of West Bay remain restricted to harvests. Two notable changes have been made in the oyster harvest areas indicating improved water quality. First, two areas, one north of the Texas City Dike and one west of the Deer Islands, have changed from restricted to approved. Second, several areas along the eastern fringe of Trinity Bay have been changed from restricted to conditionally approved, as has an area in the upper bay east of the Houston Ship Channel. These areas were reclassified after a period of drought. Runoff is a major contributor to fecal coliform concentrations in bay waters so the improvement in oyster waters may not be the result of better management.

Changes indicative of declining water quality can also be found. First, two small areas, one near Smith Point and the other near Bastrop Bay, have been changed from approved to restricted. Second, an area in the middle portion of Galveston Bay has changed from approved to conditionally approved.

Seafood Risk Assessments

Seafood risk assessments are conducted by sampling a variety of organisms at multiple collection sites. The analytical methods follow standard procedures for the compounds to be screened. Brooks et al. (1992) called for the analysis of contaminants in five species of seafood organisms from four sites. Heavy metals, hydrocarbons, pesticides, and PCBs were measured in oysters, blue crabs, spotted seatrout, black drum and southern flounder. In the recent TDH health consultations several finfish species and blue crab were collected from 35 sample sites in eight areas of the bay system. These tissue samples were tested in the laboratory for metals, pesticides, semivolatile organic compounds, and volatile organic compounds. Samples from some of the locations were also tested for dioxins and furans, as well as organotin compounds (TDH, 1999b, 2000a, 2000b, 2000c, 2001a, 2001b, 2001c, and 2001d).

Once the concentrations of the various contaminants are known, they can be used to estimate risk from human exposure. This requires assumptions about the number of meals per week or month that would contain Galveston Bay seafood and how much of that seafood would be consumed per meal.

For cancer risk, consumers eating average amounts of seafood from some locations in Galveston Bay are at risk above a benchmark level used by the EPA according to Brooks et al. (1992). The risk from consuming oysters taken from Morgan's Point and fish from Morgan's and Eagle Points was estimated to be higher than the risk of consuming oysters or fish from other locations. A person who consumes *large quantities* of seafood would exceed the EPA benchmark risk at all sites examined in that study.

Most of the cancer risk was associated with PCB and PAH concentrations, with PCBs usually providing a larger portion of the overall risk. Analysis of the specific PAH compounds indicated that most of the PAHs originated from combustion and were not directly associated with release of oil to the bay (Brooks et al., 1992). For non-cancer risk, Brooks et al. indicated no exceedances of health-based standards at average seafood consumption rates, but some exceedances were predicted for high seafood consumption rates, primarily related to oysters.

The TDH has evaluated potential health risks associated with the consumption of fish and crabs from all parts of Galveston Bay. Estimated contaminant exposures from Galveston Bay seafood were compared to health-based assessment comparison values obtained from the EPA and the Agency for Toxic Substances and Disease Registry (ATSDR). The criterion level is the contaminant concentration yielding the highest estimated exposure that is unlikely to cause adverse health effects. All exposure estimations assumed that a person weighing 70 kg was exposed to Galveston Bay seafood at a rate of eight ounces per meal usually once per week. Lower Galveston Bay risks were estimated based on consumption of one, three and four meals per week. Carcinogenic and non-carcinogenic health effects were assessed. Cancer risks assumed an exposure period of 30 years.

The TDH health consultations concluded that contaminant concentrations detected in organisms sampled from most portions of Galveston Bay did not exceed comparison values, thus non-carcinogenic health effects are not likely to result from an average person consuming one eight-ounce meal of seafood per week. The studies also found that there is a less than 1 in 10,000 chance of an additional cancer case from consumption of seafood harvested from most areas of Galveston Bay, with the exception of the HSC-San Jacinto River area. The results of the study are described below.

Risk by Toxicant Type

Pesticide—The concentrations of chlordane, DDE, DDD, dieldrin, heptachlor epoxide and hexachlorobenzene in the Houston Ship Channel and elsewhere detected by TDH are cause for concern regarding chronic low exposure level effects. The EPA chronic oral reference dose for chlordane is 0.0005 mg/kg/day and for dieldrin 0.00005 mg/kg/day. This is the value used to assess non-cancer health effects from intake of the compound. Only the chlordane concentration of fish in the Turning Basin could yield an exceedance of the reference dose from weekly consumption of one meal. The estimated risks of non-cancer effects from the other detected pesticides at all other sites were less than the comparison criteria calculated by TDH.

Using assumptions about the relationship between chronic intake dose and development of cancer, the TDH estimated thoretical cancer risks for the consumption of seafood from the Turning Basin of the Houston Ship Channel (HSC), the area around the confluence of the HSC and San Jacinto River, Tabbs Bay and Lower Galveston Bay.The DDE found in the tissue of fish and crabs from Lower Galveston Bay will raise the lifetime cancer risk 1.2×10^{-6} when eating three meals per week. The concentration of chlordane in seafood from the HSC could increase lifetime cancer risk by 4.9×10^{-5}, at the same consumption level. The threat of a carcinogen is considered negligible by TDH and EPA if the increased cancer risk is less than 1×10^{-4}.

PCB—In the recent studies by TDH, the concentration of PCB in finfish from the region around the confluence of the HSC and San Jacinto River exceeded the comparison value based on the EPA chronic oral reference dose for non-carcinogenic health effects. TDH concluded that regular consumption of one-half meal per week of finfish from this region could cause someone to exceed the reference dose for immunological effects.

The comparison value for cancer risk was not exceeded by the observed concentration of Aroclor 1260, a PCB. This value was based on the assumptions described above for amount, frequency and length of consumption. Lifetime cancer risk was estimated to increase by 2.5×10^{-5} from one meal per week of seafood from the HSC and Lower San Jacinto River and did not exceed the criterion of 1 excess cancer in 10,000 people used by TDH for public health action (TDH, 2001d).

Dioxins—The concentrations of all the dioxin congeners detected in tissue from a sampling area were combined based on their equivalent toxicities into a toxicity-weighted concentration. These calculated concentrations were compared to criterion levels for cancer and non-cancer risks. The dioxin levels in seafood tissue from the sampled areas of Galveston Bay were well below the comparison values from EPA for cancer and from ATSDR for chronic non-cancer pathologies (TDH, 1999a, 2000b, 2000c, 2001a). Dioxin and furans were not analyzed for tissue samples from the Houston Ship Channel and San Jacinto River where a seafood advisory based on dioxin levels is already in effect.

Metals—The average concentrations of cadmium, mercury, selenium and zinc observed in the recent TDH health consultations did not exceed the comparison values for non-cancer risks in any area of the bay (TDH, 1999a, 2000a, 2000b, 2000c, 2001a, 2001b, 2001c, and 2001d). No comparison values were available for copper and lead. However, the values in Table 9.4 show that the observed concentrations of lead in seafood were less than or approximately equal to those of mercury, which is a more toxic compound. This implies that lead is not a significant health risk for consumers of Galveston Bay seafood. Copper is even less likely to represent a threat to public health at the concentrations observed; although some marine oganisms could be affected because they are much more sensitive than humans.

Organotin—The measured level of butyltin compounds in seafood from Clear Lake was more than two orders of magnitude below the comparison level for non-cancer effects based on the chronic oral reference dose. The comparison level is based on assumptions about how much seafood is consumed as described above. This result suggests that there is a negligible public health risk associated with the consumption of seafood from Clear Lake containing organotin compounds (TDH, 2001a).

Brevetoxin—The National Shellfish Sanitation Program requires that shellfish harvest areas be closed when the concentration of *K. brevis* in the water reaches five cells per milliliter. All shellfish harvest areas in Galveston Bay were closed during and for at least six weeks after the red tide event in summer 2000. Harvesting was permitted when brevetoxin was no longer detected in the tissue of oysters. This was the first time that oyster harvest areas have been closed due to a toxic algal bloom. There were no cases of NSP reported to the TDH in association with the toxic algal bloom (Evans and Hiney, 2001).

Cumulative Risks

While individual contaminants are not present in concentrations representing significant risks to seafood consumers, the consumption of these contaminants together may result in an additive or multiplicative combination of risks. Cumulative estimates of risk were made by the TDH in the Health Consultations for the area from the Houston Ship Channel (HSC) to Tabbs Bay (TDH, 2001d) and Lower Galveston Bay (TDH, 1999a). In both cases, the cancer and noncancer risks were assumed to be additive.

Cumulative noncancer risks were only addressed for the Turning Basin, HSC-San Jacinto River confluence and Tabbs Bay. The method of assessment employed a hazard index (HI), which is "the sum of the ratios of the estimated exposure doses for each contaminant divided by its respective reference dose or minimal risk level." If the hazard index is greater than one, there is a possibility of adverse noncancer health effects and the responsible agency should act to manage those risks. The HI for finfish and blue crab was calculated using the concentrations of seven pesticides and one PCB found in the tissue samples from the three areas associated with the HSC. None of the HI for blue crab exceeded or were even close to one. The HI for finfish exceeded one for samples from the Turning Basin and the area around the confluence of HSC and the river. For the latter area, the HI was 1.82 primarily because the HI for PCB was 1.46. This figure certainly justifies a new seafood advisory in this area. For the Turning Basin, there was no PCB involved, but the combined HIs for the pesticides detected was 1.45. Again this is justification for a warning to the public about the risks associated with consumption of seafood from this area.

The cumulative risk of cancer was estimated for consumption of seafood from Lower Galveston Bay based on four contaminants: DDE, 2-(diethylhexyl) phthalate, methylene chloride and dioxins. If an average adult consumed one meal per week of this tissue for 30 years, the estimated excess lifetime cancer risk is 5.7×10^{-6}. If this is viewed from a population perspective, it estimates an additional 5.7 cases of cancer per million people who consume the subject seafood at the assumed rate. Consuming three meals per week of this seafood raises the risk to 1.8×10^{-5}. The biggest contributor to this cumulative risk is the concentration of dioxins found in these samples (TDH, 1999a).

A similar estimate of excess cancer risk was performed for the seven pesticides and one PCB found in the HSC area. The concentrations of chlordane and DDE found in seafood from Tabbs Bay resulted in estimated cumulative risks of 1.1×10^{-6} for the consumption of finfish and 3.6×10^{-6} for consumption of crabs. The risk rises considerably for seafood collected in the Turning Basin of the HSC. The excess lifetime cancer risk from weekly consumption of finfish from this area is estimated to be 1.6×10^{-4} or 1.6 additional cases of cancer for every 10,000 people at risk from consumption of this seafood (TDH, 2001d).

Seafood Advisories

Seafood consumption advisories are issued by the TDH under the Aquatic Life Law. When indications of a risk to human health are brought to the agency's attention, a risk assessment is conducted. If a risk assessment indicates an imminent health hazard, the affected area is declared "Prohibited" for affected species, and taking those species from the area becomes a violation of law. An imminent hazard would exist if just one or a few meals would result in an acute health problem. If a less immediate hazard exists, one created by longer-term consumption habits, a "Consumption Advisory" would be issued with consumption recommendations for affected populations.

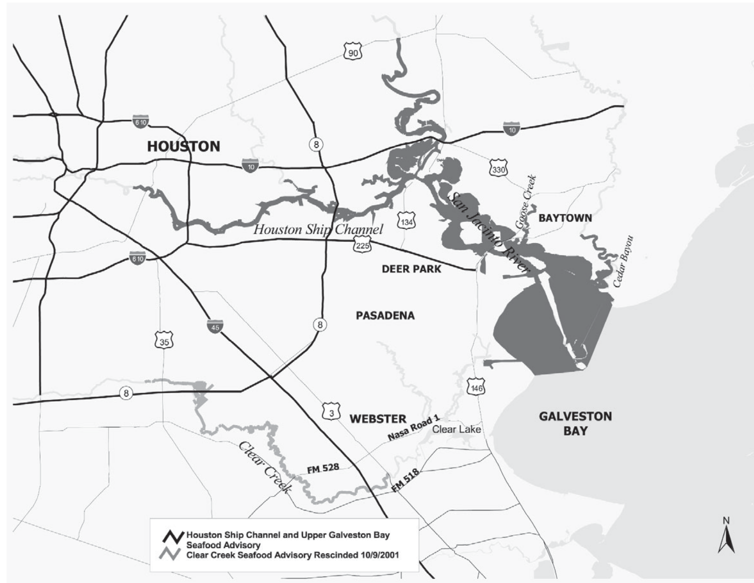


Fig. 9.3. Map of the seafood consumption advisories issued by the Texas Department of Health for Galveston Bay. Source: Modified from Texas Department of Health

Four seafood advisories have been issued for the Galveston Bay system since 1990. The locations of the designated areas are shown in Figure 9.3. The two most recent advisories modified past seafood advisories and were recommended by the TDH staff as a result of the recent health consultations discussed above.

A seafood consumption advisory was issued by the TDH in September 1990 for the upper portion of Galveston Bay and segments of the HSC due to elevated levels of dioxin found in catfish and blue crab tissues. The TDH advised that no one should consume more than one seafood meal (not to exceed eight ounces) each month from this area; and that women of child-bearing age and children should not consume any sea catfish or blue crabs from this area. These areas of the bay are now listed on the Texas 2000 Clean Water Act Section 303(d) List due to the elevated levels of dioxin. In 1999, the TNRCC initiated a TMDL project to deal with these elevated dioxin levels.

Galveston Bay's commercial fisheries supply seafood for distribution throughout Texas and the nation. The Texas Department of Health is responsible for assessing and managing the risks associated with seafood consumption in the State of Texas. (Courtesy Bob Parvin/Texas Department of Transportation)

The second advisory, issued in 1993, was based on three toxic compounds discovered in fish from Clear Creek, one of the principal tributaries on the bay's western shoreline. The three chemicals, all of which are industrial solvents, are dichloroethane and trichloroethane — both of which are believed to cause cancers of the liver and kidneys- and carbon disulfide, which can cause nervous disorders (TDH, 1993). The contaminated fish were found in the vicinity of the former Brio Refining Company, an EPA Superfund site where a cleanup of toxic industrial compounds is underway.

More recent samples of fish and blue crabs from Clear Creek for the contaminants that gave rise to the consumption advisory in 1993 have documented decreased concentrations. This prompted the Texas Commissioner of Health to issue an advisory in October 2001 rescinding the consumption advisory on seafood from Clear Creek (TDH, 2001e).

The most recent risk assessment for the seafood from the HSC found levels of PCBs in finfish from the area around the confluence of the HSC and San Jacinto River and levels of organochlorine contaminants in finfish from the Turning Basin that represent potential threats to public health. The estimated risks from consumption of this seafood were sufficient to merit an advisory from the Texas Commissioner of Health in October 2001. This most recent advisory extended the previous seafood advisory on the HSC and contiguous waters to include all finfish.

Consumption advisories serve to protect seafood consumers. However, there is no enforcement associated with the advisory to ensure that seafood is not taken from the impacted areas. It is common to see fishermen and crab traps in the areas of Upper Galveston Bay that are included in the consumption advisory on the HSC area. Another shortcoming in the current regulatory system is the lack of a program of routine tissue monitoring to determine changes in risks associated with Galveston Bay seafood.

Contact Recreation

Although swimming beaches are not widespread along the Bay's shoreline, considerable contact recreation occurs in various portions of the Galveston Bay system. Clear Lake is known for jet skiing and water skiing; Mud Lake for sail boarding; Taylor Lake for water skiing, and much of the lower bay shoreline offers good wade fishing. The TDH does not have a program for regulating contact recreation, nor does it have a public education program regarding contact recreation.

The TNRCC indirectly addresses contact recreation by establishing "designated uses" and related water quality standards. This program is aimed at water quality management rather than determining any risks to the public engaged in contact recreation. These standards and the TNRCC water quality monitoring data can be used to determine whether water quality generally supports the use of bay waters for contact recreation. The criterion for this designation is the fecal coliform test. Water bodies that fail to meet the standards for this use become the focus of Total Maximum Daily Load (TMDL) efforts, an intensive water quality management program of the TNRCC.

In general, the open waters of Galveston Bay appear to be safe for contact recreation. In bay tributaries with poor circulation and numerous sources of contamination, the picture is somewhat different (see Chapter 6 for a discussion of fecal coliform monitoring).

Several urbanized bayous on the western side of the bay had a TNRCC contact recreation designation, but were found to exceed the contact recreation water quality criterion. They are therefore, listed on the Texas 2000 Clean Water Act Section 303(d) List as impaired for this use. These include Spring Creek, Cypress Creek, Cedar Bayou Tidal, Buffalo Bayou Tidal and Above Tidal, White Oak Bayou Above Tidal, Greens Bayou Above Tidal, San Jacinto River

Tidal, Tabbs Bay and Scott Bay, Clear Creek Tidal and Above Tidal, and Armand Bayou Tidal and Above Tidal (TNRCC, 2000a). TMDLs dealing with contact recreation are currently underway for White Oak Bayou, Buffalo Bayou and Armand Bayou.

Potential contact recreation risks also exist in the non-urban, western tributaries of the bay system, Dickinson Bayou Tidal and Above Tidal, Chocolate Bayou Above Tidal, and Oyster Creek Tidal and Above Tidal. These also have a moderate potential to infect humans engaged in water-related activities.

Some of the more popular areas for contact recreation in the bay, for example the shallow water around the Texas City Dike and Pelican Island, are not currently sampled for fecal coliform bacteria. The open bay waters, by contrast, generally have low bacterial concentrations. Improvements in sewage treatment over the last several decades have likely helped to reduce overall bacterial contamination. Localized contamination from commercial shipping and pleasure boats can still present problems. Programs have been initiated to reduce the discharge of sewage from ships, boats and marinas (see Chapter 6 and Figure 9.4).

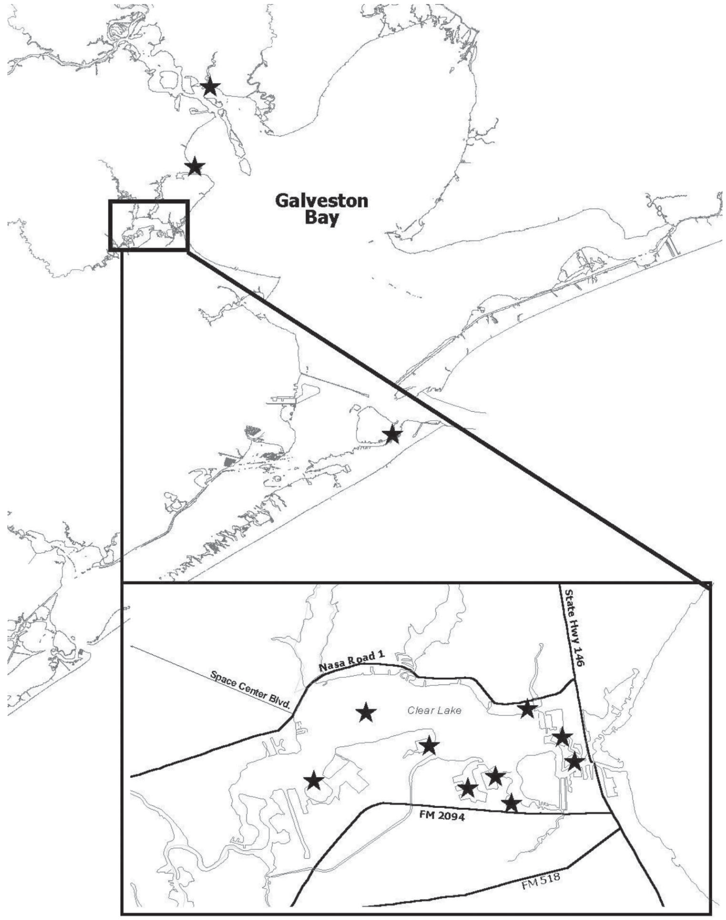


Fig. 9.4. Map of the marina pumpout stations located in Galveston Bay. Source: Texas Sea Grant College Program

Summary

Maintaining good water quality is not only important to the ecological health of the bay, but also to the public health of bay users. Bay users can come into contact with pathogens and toxics through various activities including contact recreation and seafood consumption. Fecal coliform indicators have been used to detect pathogens, but with some uncertainty. Some viruses and bacteria can escape detection as experienced in the *Vibrio parahaemolyticus* outbreak of 1998.

There have been changes, both in the classification of shellfish harvesting areas and the regulation of seafood processing. Improved water quality has resulted in the reclassification of some areas near the Texas City Dike and Deer Islands from restricted to approved status. Declining water quality has resulted in the reclassification of two areas, one near Smith Point and the other near Bastrop Bay, from approved to restricted status. In addition to these state actions, the federal government passed the HACCP regulations to further ensure seafood safety.

Health consultations, or risk assessments, conducted by the TDH concluded that contaminant concentrations detected in oragnisms sampled from most portions of Galveston Bay did not exceed comparison values, thus non-cancer health effects are not likely to result from an average person consuming one eight-ounce meal of seafood per week. The studies also found that there is a less than 1 in 10,000 chance of an additional cancer occurrence from consumption of seafood harvested from most areas of Galveston Bay.

Open-water portions of Galveston Bay generally conform to Texas water quality criteria for contact recreation. Areas where fecal coliform bacteria levels exceed the state standard are located in the western, developed tributaries of the bay.

In reality, science cannot currently determine the true risk to bay users or seafood consumers resulting from contamination by bacteria, viruses or toxic materials. Risk varies among different segments of the population. Some risk estimates are available as guidelines, but decisions about tolerable risk are a matter for the individual.

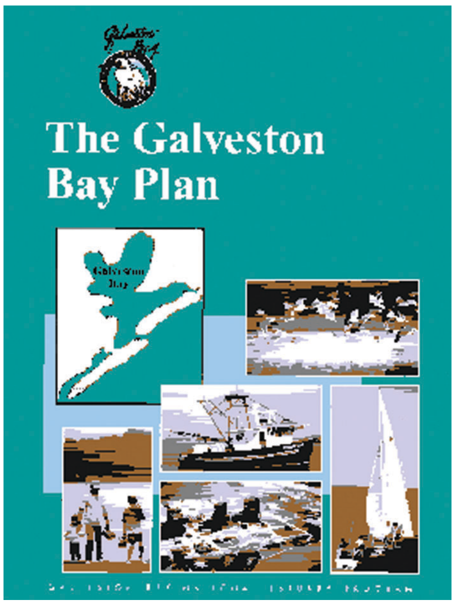
Epilogue

Sustaining Galveston Bay for Future Generations

BY HELEN DRUMMOND

"The challenge is to convert humanness from being the destroyer of nature and productivity to being the supporter of nature, the sensitive gardener, the caring mother or husbandman."

—Frank B. Golley in A Primer for Environmental Literacy, 1998



Long lasting solutions emerging from natural resource management recognize the need for a balance between economic development and a healthy environment. The Galveston Bay Estuary Program is using a consensus-based holistic approach to manage the complexity of Galveston Bay in a balanced manner. Movement from traditional mechanistic approaches to stewardship-based management is a trademark of the National Estuary Program. The development and implementation of *The Galveston Bay Plan (The Plan)*, a Comprehensive Conservation and Management Plan for the Galveston Bay Ecosystem, embodied the latter strategy. Historical top-down, command and control, piece-meal processes have evolved into bottom-up, consensus-based, ecosystem level, adaptive management systems. Clearly, this approach is necessary due to the interconnectedness and complexity of the bay and its processes, the overlapping mandates of agencies with responsibility, and the political nature of user interactions.

Implementation of the Galveston Bay Plan

The Galveston Bay Plan is implemented with the understanding that the bay's health is dependent on its surroundings. It is impacted by the tributaries that feed it as well as by activities on neighboring lands, which drain to those tributaries. *The Plan* provides the focus necessary to integrate diverse programs and jurisdictions for improved stewardship of the bay. We have made significant progress through implementation of *The Plan*, as described below.

The end of the millennium also marks the end of the first phase of *The Galveston Bay Plan*. Five years of implementation have been reviewed by a set of Task Forces and priority areas for the next five years proposed. *The Plan* contains 82 recommended actions. The reviewers determined that 67 percent of those recommended actions had been initiated and 5% had been completed. Each of the seventeen priority problems listed in Chapter One is a component of an action plan. Implemented progress on these action plans was assessed and summarized in a plan review document submitted to the Texas Natural Resource Conservation Commission (TNRCC).

While implementing *The Plan* over the past five years, we have discovered that comprehensive management which will successfully sustain the economic and ecological viability of Galveston Bay requires us to consider two additional factors: "development of a common vision" and "encouragement of active partnerships."

Assessment of the Galveston Bay Plan

Some of the action plans have shown very significant progress. Our thanks to new programs developed by partners of GBEP. For example, on the Public Health Action Plan, GBEP has worked closely with Texas Department of Health (TDH) on increased monitoring of seafood for fecal coliforms, *Vibrio* bacteria, and toxic contaminants. GBEP provided funding for a comprehensive risk assessment of Galveston Bay seafood regarding chemical contaminants. TDH has performed fecal coliform testing in excess of monitoring requirements to reclassify oyster harvest areas, an objective of *The Plan*. There has also been progress by the Texas General Land Office (GLO) under the Coastal Management Program on monitoring beach water for contaminants that could impact contact recreation. The health of Galveston Bay's users is better protected since GBEP encouraged collaboration among management agencies.

The Habitat Protection Action Plan has progressed through many projects of different sizes, planned and initiated by organizations sharing a vision of reversing the loss of habitat around the bay. In sum, more than 500 acres of brackish water marsh have been created or restored. Nesting sites for birds are receiving additional protection. Seagrass meadows were established in new areas of West Bay. A significant plan was developed under the auspices of the Galveston Bay Foundation for habitat conservation around the bay. The Texas Parks and Wildlife Department (TPWD) and GLO developed a cooperative plan to acquire coastal wetlands for conservation. Partnerships involving the Audubon Society and the Texas Nature Conservancy have provided significant benefits to the biodiversity of the bay. Now partners from private industry have stepped in and provided resources. For example, Reliant Energy has provided nursery space for plant propagation and leadership in nationally recognized wetland restoration efforts. The partners of *The Plan* have shown a strong and continuing commitment to habitat conservation and restoration.

The Freshwater Inflow and Bay Circulation Action Plan has been advanced through a regional collaborative effort. The TPWD and the Texas Water Development Board (TWDB) were already at work on estimates of the freshwater needs of Texas' estuaries when legislation was passed to initiate regional watershed planning. Their study of the needs of this estuary provided critical information for consideration of this issue to the Galveston Bay Freshwater Inflow Group (GBFIG) supported in part by GBEP. GBFIG discussed the study results and made recommendations to the Region H watershed planning group on essential flow levels. Region H incorporated the needs of the bay into our regional water plan. This is the only region in Texas to specifically address the needs of an estuary during its planning process. Water conservation education has also made large strides to reduce our vulnerability to future drought conditions. A vision of sustainable water supplies for people and nature is growing.

The Natural Resources Damage Assessment program (NRDA) made very important contributions to progress on the Spills/Dumping Action Plan. NRDA partners greatly facilitated the process of turning environmental damage into habitat conservation opportunities. The Texas Sea Grant Marine Advisory Service developed a Clean Marina Program for Texas and is working cooperatively with the GBEP to address boater waste issues. The implementation of Phase I of the NPDES Stormwater program under the Clean Water Act will have major positive impacts on spills and solid waste associated with runoff. Public attention has been focused on this source of pollution through the successful Trash Bash activity coordinated by Gulf Coast Waste Disposal Authority. Public recognition of the pollution problems associated with runoff could change our vision of what it means to be environmentally responsible. This new focus could lead to increased partnerships with local governments, thus increasing our effectiveness.

Action plans addressing water and sediment quality have progressed through the implementation of Total Maximum Daily Load (TMDL) and other projects on the bay and its tributaries. A total of 8 TMDLs were initiated by the TNRCC in the lower Galveston Bay watershed. Voluntary programs for municipalities (Clean Cities) and businesses (Clean Industries) demonstrate the value of non-regulatory initiatives to improvement of water quality. These participatory programs address the problems of every impaired water body in the region, build partnerships, and contribute to a shared vision of the environmental future of the Galveston Bay watershed.

GBEP is contributing to the reduction of runoff pollution through a technical assistance program for local governments and stakeholders. Non-point source pollution prevention is also addressed through cooperative programs on septic systems. Monitoring of small wastewater treatment plants is increasing and technical assistance is improving through cooperation of national, state and local governments.

The Public Participation and Education Action Plan recognizes the value of an educated citizenry for the protection and monitoring of Galveston Bay. The Galveston Bay Council has representatives from many partners of GBEP and sets the standard for participatory guidance of a state agency program. The public's attitude toward the environment and the bay are monitored by the *Texas Environmental Survey*. Results of this research provide the GBEP subcommittees with useful information on the public views of environmental issues. Trend analysis provides a picture of how effective outreach efforts have been in the past. Planning for the biennial State of the Bay Symposium is another stakeholder driven activity, which provides a forum for sharing results of *Plan* implementation demonstration projects, results of monitoring and protection programs, and current update on the state of the bay. Some of the most successful citizen involvement projects have included: Bay Day, Marsh Mania, Trash Bash, Citizen Water Quality Monitoring, and the Galveston Bay Yards and Neighborhoods. Actions in the volunteer arena make important contributions to a widely held stewardship-based vision of the bay, which is captured in *The Galveston Bay Plan*.

Recently, in an effort to increase local government and user group partnerships, the GBEP initiated a new grant program. The Galveston Bay Grant Program is one of the newest tools available for protecting and improving Galveston Bay's water quality and natural resources. Grant dollars help communities, non-profit organizations, local governments, school districts, and state agencies to implement *The Galveston Bay Plan.* The program supports programs to create solutions to local water pollution problems; protect, preserve and restore habitat; and encourage people of all ages to be environmental stewards.

The Future: Vision and Partnerships

> *As we move forward in restoring Galveston Bay's habitat and water quality, and in the midst of the bay's multiple uses, one very large question looms ... What do we in the Galveston Bay community want the bay to look like in the next 20-50 years?*
>
> *—Linda Shead,*
> *Galveston Bay Foundation, 2000*

GBEP must ensure that *The Plan* is designed to implement a realistic vision based on thorough understanding of the processes and organisms that compose the system we call Galveston Bay. Research is a continuing need because our understanding of the complex bay system is so limited. Research partnerships are growing as a result of the GBEP coordination efforts. It will take time, resources and commitment to obtain the knowledge we need to chart the path to the vision embodied in *The Plan*.

We live in a global economy with competing forces that create pressure to build, expand, and mass-produce, and to do so expeditiously. Meeting these demands without consideration of the long-term impact on our resources or without consideration of the impact of actions on others, might be appropriate if we lived in a world of infinite natural resources, or if we lived in isolation. But neither is the case. Our resources are finite and we are connected. We breathe the same air and our local waterbodies are connected to those around the world.

What does all this mean? It means that in order to have sustainable communities and provide a bright future for generations to come, we must have a vision of what we want our surroundings to look like in 10, 20 or 50 years. We then must evaluate the impact of our decisions on that vision.

Galveston Bay is part of our "Community", whether we live in Harris, Galveston, Chambers, Liberty, or Brazoria County. Everyone living in this area should make the bay a part of his or her vision for the future. Galveston Bay's resources are the property of no one group, agency, or person. Preserving and sustaining it is everyone's responsibility. An expression of this broad responsibility is reflected in the breadth of organizations that collaborate with GBEP on preserving and restoring the Bay. Government agencies, corporations, citizen groups, educational institutions, and individuals contribute resources, time, and expertise to the effort. Yet, to be effective, a common vision is needed. It is said that without a vision, the people perish.

What is our common vision for Galveston Bay and our neighboring communities? Is it economic prosperity, clean air and water, environmentally safe places for our children to play? That is a start, but the true question is... what part will you play in preserving and protecting the bay to realize your vision?

Glossary

A

Abiotic—The non-living, or physical part of an environment.

Accretion—Accumulation of sediments by deposition, e.g. the gradual buildup of land along a river delta or shoreline.

Aerobic—Occurring in the presence of, or utilizing oxygen; also refers to metabolic function in the presence of oxygen.

Algal Bloom—Population explosion of phytoplankton in response to optimal growth conditions, including nutrient over-enrichment from wastewater and nonpoint sources. Blooms can result in oxygen depletion and biological impacts; see also eutrophication.

Alluvium—Stream deposited sediment.

Ambient—Prevailing environmental conditions, as opposed to measurement in a laboratory or waste stream.

Amphipod—A member of the crustacean order, Amphipoda, these flea-like organisms are numerous and small. The body is generally flattened from side to side. They are abundant in marine and estuarine environments.

Amnesic Shellfish Poisoning (ASP)—Caused by exposure to Pseudo-nitzchia sp. Characterized by both gastrointestinal and neurological disorders. Gastroenteritis usually develops within 24 hours of the consumption of toxic shellfish; symptoms include nausea, vomiting, abdominal cramps, and diarrhea. In severe cases, neurological symptoms also appear, usually within 48 hours of toxic shellfish consumption.

Anaerobic—Occurring in the absence of oxygen; also refers to metabolic function in the absence of oxygen, an ability of some species of microbes.

Annelid—Segmented worms of the invertebrate phylum, Annelida. Annelids are subdivided into three classes: Polychaeta (marine worms), Oligochaeta (earthworms) and Hirudinea (leeches).

Anoxia—Absence of oxygen, e.g. sediments and the water column can become anoxic when depleted of oxygen; see also anaerobic and hypoxia.

Aquifer—A subsurface water-bearing layer of rock or sediment that can yield water.

Artesian—A perpendicular well bored into the ground through which water rises to the surface, due to underground pressure.

Anthropogenic—Human caused; related to the origin and development of humans.

Assimilative Capacity—The amount of pollution a water body can receive without degradation as a result of the natural ability of the water and its associated chemical and biological systems to dilute or transform contaminants.

Atmospheric Deposition—The contribution of atmospheric pollutants or chemical constituents to land or water ecosystems. Deposition can occur as a result of human activities (e.g. fossil fuel combustion, industrial processes and transportation) or natural processes (e.g. volcanic activity).

Autotrophic—An organism sustained entirely by food created within; contrasts with heterotrophic.

B

Ballast Water—Water used to stabilize a ship; sometimes in place of cargo.

Base Flow—The volume of flow in a stream or river during dry conditions (as opposed to conditions influenced by storm runoff).

Bathymetry—The science of measuring depths; underwater topography defined by patterns in depth.

Berm—An elongated mound of sediment elevated above the surrounding area; can be natural (e.g. an underwater longshore bar created by currents) or man-made (e.g. a ridge of sediment disposed along a navigation channel.

Benthic Organism—An organism living primarily in or on bottom sediments.

Benthos—Term for the organisms living in or on the bottom of a body of water.

Bioaccumulate—The accumulation of a contaminant in the tissues of a living organism due to uptake from the environment.

Bioamplification—The process of increasing the magnitude of a contaminant in the tissues of a living organism due to uptake from the environment.

Biochemical Oxygen Demand (BOD)—A measure of the amount of oxygen consumed by natural, biological and chemical processes that break down organic matter. High levels of oxygen-demanding wastes in waters deplete *dissolved oxygen (DO)* thereby endangering aquatic life.

Bioconcentrate—The magnification of contaminant concentrations in organisms' tissues at each successive level in a food chain; generally occurs due to a contaminant being soluble in fatty tissues and not in water.

Biogenic—Created by biological processes.

Biomass—The amount of living tissue (e.g. the unit area or volume of habitat).

Bioturbation—The disturbance of sediments due to the physical and biological activities that occur at or near the sediment surface.

Bivalve—A mollusc with two hinged shells belonging to the class, Bivalvia (e.g. oysters, clams and scallops).

Blue-Green Algae—Bacteria–like, primitive algae which manufactures photosynthetic pigments but lack chloroplasts; an increase in blue-green algae can indicate an environmental stress such as pollution.

Brackish—Water with a salinity lower than that of seawater; seawater and freshwater mixed; typical of estuarine environments.

Bulkhead—A man-made vertical wall constructed to stabilize shorelines and prevent wave damage to upland property.

Bycatch—The incidental catch of one species during pursuit of another, the term is often applied to species of fish and shellfish captured incidentally by commercial fishing and shrimping operations.

C

Carbon Flux—The transformation and transport of organic compounds in an ecosystem via trophic dynamics, chemical conversion and physical movements.

Catch Per Unit Effort (CPUE)—The number or weight of organisms caught per unit of fishery effort; often used as a measure of abundance.

Channelization—The conversion of a naturally flowing river or stream to a dredged drainage or navigation channel, often lined with concrete; channelization increases flow velocity, but negatively impacts stream ecology.

Ciguatera Fish Poisoning—Caused by exposure to *Gambierdiscus toxicus* sp., *Prorocentrum* sp., *Ostreopsis sp.*, *Coolia monotis*, and *Thecadinium sp.* and *Amphidiuim carterae*; produces gastrointestinal, neurological, and cardiovascular symptoms. Generally, diarrhea, vomiting, and abdominal pain occur initially, followed by neurological dysfunction including reversal of temperature sensation, muscular aches, dizziness, anxiety, sweating, and a numbness and tingling of the mouth and digits.

Coarse Particulate Organic Matter (CPOM)—Carbon compounds in an aquatic system greater than 1mm in size; sources may include leaf litter, dying aquatic plants and animal feces.

Colonial Nesting—The propensity for some bird species, e.g. most egrets and herons, to nest in dense colonies.

Colony Forming Units (CFU)—A unit of measure used to determine the concentration of bacterial colonies on laboratory media.

Commensal—A symbiotic relationship in which one individual benefits while the other neither harmed nor benefited.

Community—An assemblage of various plant and animal species that share a given habitat at the same time.

Competition—Rivalry by multiple individuals or populations in pursuit of a limited resource (e.g. food or space).

Contact Recreation—Human activity involving bodily contact with water, e.g. wade fishing and swimming; increases the risk to health when contaminants or pathogens are present in the water.

Copepod—A member of the class, Copepoda, the largest group of small crustaceans; comprises a major portion of the zooplankton and is used as a food source by some species of birds and commercially important fish.

Cordgrass—Any member of the genus, *Spartina*; a partially submerged wetland plant common to brackish and salt marshes of the Gulf Coast.

Coriolis Force—A force resulting from the earth's rotation which affects the path of winds and ocean currents; causes hurricanes and whirlpools to rotate counter-clockwise in the northern hemisphere and clock-wise in the southern hemisphere.

Crustacean—Any member of the Arthropod class, Crustacea, which includes shrimp, crabs, barnacles, and lobsters.

Ctenophore—A member of the marine phylum, Ctenophora, also known as "comb jellies"; closely related to jellyfish, but lack the stinging cells.

Cubic Feet Per Second (cfs)—Standard unit for measurement of stream flow or wastewater discharge.

Cultivar—A variety of a plant developed from a natural species and maintained under cultivation.

D

Decomposer—An organism which consumes and breaks down organic matter.

Delta—An exposed or submerged deposit of stream-born sediments found at the mouth of rivers.

Demersal—Animals living on or near the bottom of a body of water; e.g. bottom-feeding fish such as the croaker.

Denitrification—A function of the nitrogen cycle, it is the bacterial conversion of nitrates, nitrites and ammonia to elemental nitrogen.

Denivellation—Wind forcing of water resulting in water depth changes; denivellation in Texas estuaries can produce more extreme water level fluctuations than tides.

Density Current—Water currents resulting from water of differing densities; dependent upon varying salinity, temperature or pressure, e.g. seawater from the Gulf intrudes landward along the bottom of the Houston Ship Channel, displacing lighter, low salinity waters; a salinity wedge.

Deposit Feeder—An organism that ingests bottom sediments and digests the microorganisms and organic matter present.

Dermo—A disease of oysters caused by the parasitic protozoan *Perkinsus marinus*; outbreaks are most severe during drought periods in high salinity estuarine waters.

Detritivore—An organism that derives nutrients and energy by consuming decaying organic matter.

Detritus—Decaying organic material.

Diatom—A group of photosynthetic, unicellular or colonial algae; they use silica as a structural component of the cell wall; they are a dominant component of the plankton in Galveston Bay.

Dinoflagellate—Unicellular algae with two flagellae arranged in a characteristic pattern; have characteristics of both plants and animals; this group includes some common plankton species and also red tide organisms such as *Gonyaulax monilata* and *Karenia brevis* (syn.*Ptychodiscus brevis).*

Dissolved Organic Matter (DOM)—Carbon compounds in water solution, generally from decomposition of plant and animal tissues in natural settings, but including also some contaminants.

Diurnal Tide—Tide occurring on a cycle of once daily; one low and one high tide occurring within one lunar day.

Diversity—A measure of the variety of living things in a community, based upon one of several mathematical formulae which account for both numbers of species and numbers of individuals within species. High diversity results from high numbers of species and an even distribution of numbers within species. Stressed environments generally have low diversity.

DO Deficit—The difference between the oxygen saturation value in water (calculated under the conditions measured at sampling) and actual oxygen concentration. The measure is useful because it corrects for temperature, salinity, and atmospheric pressure-conditions that influence the saturation level. A high deficit can be indicate a water quality problem.

E

Ecological Niche—Encompasses the habits of a species; the way a species relates to, or fits in with, its environment; where it lives, what it consumes, and how it avoids predators or displacement by other species.

Ecosystem—A natural system that includes the sum total of all living things, their physical environment and the interrelationships among them.

Ecotourism—Tourism involving travel to areas of natural or ecological interest for the purpose of observing wildlife and learning about the environment, e.g. bird watching.

Effluent—Wastewater discharged to a receiving body of water.

El Niño Southern Oscillation—Result of the cyclic warming and cooling of the ocean surface of the central and eastern Pacific. This phenomenon can have dramatic effects upon weather patterns and the movement of marine populations.

Embayment—A bay or body of water enclosed in such a way as to resemble a bay.

Emergent Wetlands—Marshes in which vegetation is rooted underwater and the tops exposed (as contrasted with submerged vegetation or upland habitats).

Enterococcus—Bacteria species, some of which are pathogens, that are enteric to humans or animals;

considered a possible replacement for fecal coliform bacteria as an indicator of water contamination

Entrainment—Transport of sediment or living organisms in a water current, as occurs when organisms enter a cooling water intake structure.

Epibenthic—Located on the bay bottom.

Epifauna—Organisms living on the bay bottom.

Epiphytic—Any plant growing on another plant; e.g. epiphytic algae growing on the surface of submerged aquatic vascular plants.

Estuary—A coastal, semi-enclosed body of water within which saltwater from the sea mixes with freshwater from land drainage.

Estuarine Debris—Trash in a bay or along its shoreline; debris consists of tires, construction wastes, household trash, and plastic; debris degrades aesthetic values and represents a hazard to wildlife (e.g. entanglement or mistaken consumption as food).

Eutrophication—Nutrient over-enrichment of a water body resulting in overgrowth of algae, frequently followed by algae die-offs and oxygen depletion.

Evapotranspiration—Loss of water from the soil through uptake by living plants, transport to leaf surfaces, and evaporation to the atmosphere.

Exotic Species—Nonindigenous species of plants and animals (e.g. grass carp, chinese tallow tree) often established purposefully or inadvertently by human activity; some exotic species have fewer natural population controls in their new environment, becoming a pest or nuisance species.

F

Fecal Coliform Bacteria—Microorganisms that usually occur in the intestinal tract of "warm blooded" animals (including humans), e.g. *Escherichia coli*; commonly used as an indicator of contamination, (see also *Most Probable Number.)*

Feedback Loop—A self-regulatory process in a biological or physical system whereby extremes trigger forces to moderate that condition and maintain a steady state, for example population size (environmental) or body temperature (physiological).

Filter Feeder—An organism (e.g. oyster) which feeds by pumping and filtering large volumes of water to consume material in suspension, such as phytoplankton.

Fine Particulate Organic Matter (FPOM)—Organic matter (for example plant tissue) which has undergone the first stages of decomposition to the fine particle stage.

Finfish—Fish, as opposed to shellfish.

Flocculent—Fine-grained material in suspension in water, which can settle to form a coating on the bottom.

Flushing—The natural process of water replacement in an estuary; for example Galveston Bay is flushed four to five times per year by river water and other runoff.

Food Chain—A series of interconnected feeding relationships; the process of energy capture (by green plants) and successive transfer to grazers (primary consumers) and predators (secondary consumers and above).

Food Web—The network of trophic relationships in an ecosystem; a complex network of food chain interactions.

Foraminifera—A group of mostly marine, amoebae-like protozoans characterized by an internal calcareous shell.

Freshet—A large influx of fresh water inflow, for example following seasonally high precipitation.

G

Gastropod—A member of the class Gastropoda of the phylum Mollusca; examples include shelled snails, limpets, abalones and shell-less nudibranchs.

Geographic Information System (GIS)—Computer hardware and software systems that relate and display collected data in terms of geographic or spatial location; GIS tools are increasingly being applied to ecosystem, watershed, and landscape studies, both in ecological research and for the environmental management planning.

Green Algae—Algae that belong to the division Chlorophyta; contain chlorophyll and accessory pigments called carotenoids.

Groundwater—Subsurface water, in the zone of saturation (below the water table); occurs in aquifers at one or more depth levels.

Guild—A group of species with similar ecological niches; the planktivorous fishes would constitute an estuarine species guild.

Gyre—Circular, rotational current pattern established by winds or other physical forces.

H

Habitat—The place in the environment where an organism lives or can be found.

Hazard Analysis Criteria Control Point (HACCP)—Management system in which food safety is addressed through the analysis and control of biological, chemical and physical hazards from raw materials production, procurement and handling, to manufacturing, distribution, and consumption of the finished product.

Herbivore—An animal that eats only plants or algae.

Herbaceous Matter—Refers to a non-woody perennial plant in which the aboveground biomass dies back each year.

Heterotrophic—A species which acquires its energy through the consumption of other organisms rather than by producing it's own food within; contrasts with autotrophic.

Homogeneous—Of uniform nature, similar in kind.

Hydrologic Cycle—The continuous cycling of water in the biosphere as solid, liquid, and gas; water evaporates from oceans to the atmosphere and is returned to the ocean via precipitation and river flow.

Hypoxia—Depletion of dissolved oxygen to low levels in water, i.e. less than 2 mg/L; can result from natural or human introduction of oxygen-demanding compounds or from nutrient over-enrichment.

I

Impervious Cover—Land surfaces with a low capacity for soil infiltration, e.g. parking lots and roadways; degrades water quality by increasing surface runoff and the quantity of nonpoint source pollution.

Impingement—The accumulation of organisms on a water intake screen, e.g. at a power plant cooling-water intake.

Indicator Species—A species which, through its population size or condition, mirrors environmental conditions within an ecosystem.

Infauna—Animals living within sediments.

Inflow—The water feeding an estuary, generally referring to river sources.

Intertidal—The portion of shoreline exposed at low tide and inundated by high tide.

Isopod—A member of the crustacean order Isopoda; the body is covered by a series of armor-like plates (the pillbug is a terrestrial isopod).

L

Lacustrine—Relating to a lake environment.

LANDSAT—An unmanned satellite system, which acquires images of the earth's surface features and digitally transmits them to earth for use in a variety of applications.

Loading —The rate of introduction of a constituent (e.g. contaminant) to a receiving water, for example in pounds per day. Loading is significant in relation to the volume and circulation of the receiving water; problems occur when high loadings occur into receiving waters with limited assimilative capacity.

Longshore Drift—The movement of water and suspended and dissolved materials along and parallel to a shoreline as a result of tidal, wind-driven, or other currents.

M

Macroalgae—Algae large enough to be visible.

Macrobenthos—Bottom-dwelling organisms larger than 1 mm (0.04 inch); dominated by polychaete worms, anthozoans, echinoderms, sponges, ascidians, and crustaceans.

Macroflora—Plants large enough to be visible.

Macroinvertebrates—Invertebrates large enough to be retained on a 0.5 mm mesh screen.

Macrophyte—A higher green plant for example rooted aquatic vegetation.

Macrozooplankton—Planktonic animals that range in size from 200 to 2,000 mm.

Meander—One of a series of curves in the course of a stream.

Meiofauna—Intermediate-sized animals in the 0.002 to 0.02-inch size range; in part composed of nematodes, copepods, and juvenile forms of larger invertebrates.

Meroplankton—Temporary planktonic life stages of non-planktonic species

Mesozooplankton—Planktonic animals 200 μm to 2 centimeters in size.

Microalgae—Planktonic, epiphytic, or epibenthic algae smaller than visible size range.

Microfauna—Benthic animals smaller than 0.1 mm.

Microflora—Microscopic plants.

Microzooplankton—Microscopic planktonic animals.

Mollusc—Soft-bodied invertebrates of the phylum Mollusca, usually possessing a calcium carbonate shell; examples include chitons, oysters, clams, nautiluses, squids and octopuses.

Most Probable Number (MPN)—A method of measuring the concentration of fecal coliform bacteria in a water sample.

Mysid—A family of small shrimp common in marine environments and utilized for standardized laboratory toxicity testing.

N

Nanoplankton—Members of the plankton assemblage 2 to 20 µm in size.

Nanozooplankton—Planktonic animals 2 to 20 µm in size.

National Pollution Discharge Elimination System (NPDES)—A federal regulatory program to control discharges of pollutants to surface waters of the United States; see also TPDES.

Nekton—Free-swimming animals of the water column (contrasted with most plankton, which are at the mercy of currents.

Neurotoxic Shellfish Poisoning (NSP)—Caused by exposure to brevetoxin (a toxin produced by some species of dinoflagellates). Symptoms may include dizziness and nausea and, can also cause respiratory irritation when the neurotoxin becomes airborne through wave action.

Non-contact Recreation—Human activity on water but not involving bodily contact with water, e.g. boating.

Non-point Source (NPS)—Constituents in water (including pollutants) originating from diffuse, land-based sources, and generally transported in runoff from precipitation. This contrasts with point sources, or "end of the pipe" constituents generally transported in wastewater from a discrete source. The regulatory definition of non-point source is "anything not a point source."

Nursery Habitat—Portions of the estuary utilized by early life stages of marine species, fulfilling life requirements for adequate food and protection from predators. e.g. emergent marshes and seagrass beds.

Nutrient Cycle—Chemical transformation of nitrogen, phosphorus and silica compounds in continuous cycles of organic and inorganic phases in an ecosystem.

O

Omnivores—An animal that feeds on both consumers and producers.

Opportunistic Species—Species which take advantage of an ephemeral condition of great resource availability, especially soon after a disturbance.

Osmoregulation—The physiological ability of organisms to regulate cellular ion concentrations, thus maintaining biochemical balance in the face of variability in environmental conditions such as salinity.

Ostracod—A member of the crustacean subclass Ostracoda; small marine organisms resembling a clam with appendages.

Outfall—A site where there is a large point loading of domestic, industrial or heat wastes to an aquatic system; a discharge point for a wastewater stream, e.g. a sewage treatment plant or refinery.

P

Paralytic Shellfish Poisoning (PSP)—Caused by exposure to *Alexandrium sp.* Symptoms are purely neurological and their onset is rapid. Duration of effects is a few days in non-lethal cases. Symptoms include tingling, numbness, and burning of the perioral region, ataxia, giddiness, drowsiness, fever, rash, and staggering.

Palustrine—Relating to a freshwater environment, for example a fresh marsh.

Pathogen—A disease-causing microbe.

Pelagic—Organisms living in open waters; not associated with the bottom or other structures, e. g. sharks of the open ocean.

Penaeid shrimp—Members of the shrimp family Penaeidae, including the well-known commercial species (brown, pink, and white shrimp).

Percolation Rate—A property of sediments measured by the volume of water that can infiltrate per unit time. Fine clays have extremely slow percolation, while percolation into coarse sand is essentially instantaneous.

Photic zone—The upper portion of the water column admitting sufficient light for photosynthesis. The photic zone is reduced with increased turbidity, and in Texas estuaries, rarely reaches the bottom in open bays.

Photosynthesis—The incorporation of solar energy into carbon compounds by green plants, chemically combining atmospheric carbon dioxide and water. The chemical opposite of respiration (the "burning" of carbon compounds to power metabolism), ultimately powering the vast majority of life on earth.

Physiography—The physical structure of an environment.

Phytoplankton—Green plants (for example algae) inhabiting waters, unattached and drifting with the currents.

Piscivorous—Fish-eating.

Planktivore—Plankton-eater.

Planktonic—Drifting unattached in water, the plankton include both plants and animals ranging from microscopic to those weighing several pounds or more (e.g. jellyfish).

Polychaete—Marine worms of the class Polychaeta of the invertebrate worm order Annelida; polychaete species dominate the marine benthos, with dozens of species present in natural marine environments. These worms are highly diversified, ranging from detritivores to predators, with some species serving as good indicators of environmental stress.

Polychlorinated Biphenyls (PCBs)—A family of organic compounds; mixtures of up to 209 individual chlorinated compounds. They have been used as coolants and lubricants in transformers, capacitors, and other electrical equipment because they don't burn easily and are good insulators. Many commercial PCB mixtures are known in the US by the trade name Aroclor.

Polynuclear Aromatic Hydrocarbons (PAHs)—A family of organic compounds deriving from fossil fuels and their combustion. The higher the molecular weight, the more environmental concern due to their bioaccumulation in organisms and their toxic, carcinogenic metabolic activity.

Population—An aggregation of organisms of a given species, capable of interbreeding.

Pore Water—The water found in the interstices of submerged sediments. Pore water is the basis of some types of toxicity testing, since it is pore water to which benthic organisms are exposed.

Predation—Capture and consumption of one organism by another.

Primary Consumer—An organism deriving its energy directly from green plants.

Primary Producer—Green plants capable of photosynthesis; the base of the food chain.

Protozoan—Single-celled, nucleated organisms lacking cell walls, smaller than one millimeter; some protozoa are photosynthetic.

Pseudofeces—Material that has been filtered from the mantle cavity of bivalve molluscs such as oysters, but not processed through the digestive tract.

R

Reaeration—Elevation of the dissolved oxygen concentration in water resulting from mechanical agitation, for example by wave action.

Red Tide—Algae bloom involving dinoflagellate phytoplankton species which naturally manufacture biotoxins. Depending upon species, red tides can cause fish kills, irritation of the human respiratory tract and several types of shellfish poisoning in human consumers.

Residence Time—The period of time water is retained in a reservoir, bay, or other system, based upon flow rates into and out of the system. See also *flushing.*

Resuspension—Incorporation of non-soluble matter into water by physical forces, e.g. sediments resuspended by currents or dredging activity.

Return Flow—Wastewater discharged to an aquatic or marine environment. Return flows can alter hydrology and fresh water inflow when the original source of the water is not the ultimate receiving water. For example groundwater discharge (as wastewater) to an estuary i.e. surface water.

Riparian—Associated with the bank of a watercourse, for example the riparian woodlands bordering a river.

Riprap—Rock, concrete, or other material used as a hard, artificial shoreline facing to reduce erosion.

Risk Analysis—The estimation of hazards associated with containments or other environmental conditions, as they affect exposed humans or selected elements of the ecosystem. Seafood consumption risk analysis procedures normally follow a standardized EPA protocol.

S

Salinity—A measure of salt concentration in marine waters, ranging from zero to about 33 parts per thousand (ppt) in estuaries.

Salinity Gradient—A spatial salinity transition, e.g. from a fresh river mouth to saline ocean inlet.

Seafood Advisory—Warning issued by a public health authority recommending avoidance or reduced intake of certain species of seafood that may pose health risks to consumers.

Seagrass—Rooted, submerged marine or estuarine macrophytes of several species. Habitats created by seagrass meadows are among the most diverse and productive estuarine environments. Loss of seagrass has become a marine conservation issue Gulf-wide.

Secchi disc—An opaque, black and white disk lowered into water until its black-white demarcation is no longer visible. The resulting "secchi depth" is a practical, traditional measurement of water clarity, and is well-correlated with turbidity and the depth of the biological photic zone.

Secondary Consumer—Predator which derives its energy from eating plant-eaters (primary consumers).

Segmentation—Demarcation of a water body into subsections, for purposes of monitoring or management.

Semi-diurnal Tide—Tide occurring on a cycle of twice daily.

Sentinel Species—A species which, through its numbers or condition, can provide advanced warning of more generalized environmental degradation. (See also *indicator species).*

Sergestid Shrimp—Several species of non-commercial shrimp of the decapod crustacean family Sergestidae.

Sessile—Attached at a given location; non-mobile (for example an oyster).

Shoaling—Decrease in water depth due to sediments deposited by currents.

Siltation—The accumulation of sediments transported by water. Siltation is an ongoing process of one to three feet accumulation per century in Galveston Bay.

Silviculture—Use and management of forest resources.

Spat—An oyster life cycle term; oysters during early growth on a hard substrate. The spat set is the process of settling and attachment of planktonic larvae and onset of shell growth, establishing new recruitment on a reef.

Stakeholder—An individual or organization with a "stake" in a natural resource or other issue by virtue of livelihood or simple personal interest.

Standing Crop—The biomass of a trophic level, species, or community at a given time and location; contrasts with *produc*tivity-the rate of biomass creation.

Storm Surge—The increase in water depth caused by a Hurricane, due to a combination of low atmospheric pressure (which creates a "bulge" in surface waters) and wind-piling of water. Serious damage can result after a storm surge moves onshore as waters rush back to their source.

Stratification—Vertical separation of water masses into layers with different characteristics. For example, dense salt water intruding under fresher water in a navigation channel can establish salinity stratification.

Stress Proteins—Proteins synthesized by aquatic organisms as a physiological response to environmental stress. Tissue analysis for stress proteins can be combined with other more traditional measurements to indicate the presence of environmental contamination.

Subaerial—Surrounded by air, for example terrestrial plants and animals.

Submerged Aquatic Vegetation (SAV)—Rooted, submerged macrophytes, including seagrasses and freshwater rooted macrophytes; contrasts with *emergent* species such as smooth cordgrass.

Subsidence—The loss of land elevation due to groundwater or petroleum withdrawal and natural settling. Groundwater withdrawal has been the most important contributor to subsidence for up to nine feet in the Galveston Bay region.

Subtidal—Below the low tide line, submerged virtually continuously; contrasts with *intertidal,* which is the area intermittently submerged.

Subwatershed—A subdivision of a watershed based on hydrology, generally corresponding to the area drained by a small tributary or bayou, as opposed to a major river.

Supersaturation—A concentration of a gas in water (e.g. oxygen) above the equilibrium concentration. This occurs when the gas enters the solution more quickly than releases it from the liquid to a gas phase, for example under extremely high rates of plankton photosynthesis.

Surface Microlayer—The immediate surface of the water, important as the interface for atmosphere/ water equilibrium processes; the location of highest concentrations of hydrophobic pollutants like oil, and the location of floating marine eggs and other biological forms.

Suspension Feeder—An organism that feeds on materials in water suspension, for example oysters which filter plankton.

T

Terrestrial—Refers to land, as opposed to the aquatic or marine environment.

Tidal Prism—The volume of water transported in a defined area as a result of tide currents

Total Dissolved Solids (TDS)—Sum of all dissolved materials e.g. salts, which are non-filterable and remain following evaporation of the water.

Total Maximum Daily Load (TMDL)—The total amount of a pollutant a water body can accumulate and still meet state water quality standards.

Total Organic Carbon (TOC)—Sum of all organic carbon compounds in water.

Total Suspended Solids (TSS)—Solids in water, filterable with a 0.45-micrometer mesh.

Toxicant—An element or compound with a negative effect on physiology or behavior of an organism.

Toxicity Test—Laboratory procedure in which living organisms are subjected to varying dilutions of sampled water or sediment, measuring mortality, declines in reproductive rates, or behavioral changes indicating a toxic response. Toxicity tests with mysid shrimp or juvenile sheepshead minnows, can be used to establish toxicity both for effluent and for ambient waters and sediments.

Texas Pollutant Discharge Elimination System (TPDES)—Texas' state water quality program administered by the TNRCC; authorized by the USEPA in September 1998; it has federal regulatory authority over discharges of pollutants to Texas surface waters.

Trophic Level—The position in the food chain relative to eating and being eaten; including primary producers, primary consumers, and higher consumers.

Turbidity—The relative lack of clarity (cloudiness) of water, caused by suspended material (e.g. sediments), colored materials in solution, and plankton. Turbidity correlates (inversely) with available light for photosynthesis; can be measured with a transmissometer.

Turtle Excluder Device (TED)—One of several devices attached to trawls, used to deflect sea turtles from the catch. TEDs are in wide use in offshore shrimping operations to prevent incidental capture of sea turtles.

V

Vibrio—Genus of bacteria containing 11 naturally-occurring species, some of which have the potential to cause rapid and sometimes life-threatening infections in humans. *Vibrio vulnificus*, an estuarine species, favors warm saline conditions in Texas bays.

W

Washover Fan—The fan-shaped deposits of sediment resulting from deposition by water currents, e.g. when a storm surge breaches a barrier island.

Water Column—The portion of an aquatic or marine environment extending from the water surface to the bottom.

Watershed—The land area drained by a river or stream. The watershed is the natural hydrologic unit associated with numerous ecological and physical processes involving water. Increasingly, the watershed is being accepted as the most appropriate geographic unit for management of water quality.

Wetland—An area where saturation with water is the dominant influence on characteristics of the soil and on composition of the plant community.

Z

Zooplankton—Animals that are suspended in and move within the water column.

References

Allison, R.C., R. Durand, R. Hill, K. Coppenbarger, N. Hameed, and B. Willey. 1991. A socioeconomic characterization of the Galveston Bay system. Galveston Bay National Estuary Program unpublished report. Webster, Texas.

Alperin, L.M. 1977. Custodians of the coast. Galveston District, U.S. Army Corps of Engineers. Galveston, Texas.

American Association of Railroads. 1999. Railroad Service in Texas. Policy and Communications Department, American Association of Railroads. Washington, D.C.

Anderson, J., F. Siringan, and W. Smyth. 1991. Long-term impact of rising sea level and major hurricanes on Galveston Bay. Shipley, F. S. And R. W. Kiesling, editors. Proceedings of the Galveston Bay characterization workshop; 1991 Feb 21-23; Galveston Bay National Estuary Program Publication GBNEP-6. Webster, Texas. p. 163-164.

Anderson, J.W. 1907. From the plains to the pulpit. Anderson and Sons. Goose Creek, Texas.

[Anonymous]. 1834, 1952. Visit to Texas being the journal of a traveler. The Steck Company. New York, New York; Austin, Texas.

Armstrong, N.E., and M. Hinson. 1973. Galveston Bay ecosystem freshwater requirements and phytoplankton productivity. Galveston Bay project toxicity studies, a report to the Texas Water Quality Board by the University of Texas Marine Science Institute, IAC (72-73) Part II. Austin, Texas. p 1-98.

Armstrong, N.E. 1982. Responses of Texas estuaries to freshwater inflows. Estuarine Comparisons. V.S. Kennedy, Academic Press. New York, New York. p 163-164.

Armstrong, N.E. 1987. The Ecology of open-bay bottoms of Texas: a communityprofile. United States Fish and Wildlife Service Biological Report 85(7.12). Washington, D.C.

Arnold, K.A. 1984. Checklist of birds of Texas. Texas Ornithological Society. Austin, Texas.

Aten, L. 1983. Indians of the upper Texas coast. Academic Press. New York, New York.

Baker, W. 2001. Personal communication. Reliant Energy, HL&P. Houston, Texas.

Bateman, H.A., T. Joanen, and C. K. Stutzenbaker. 1988. History and status of midcontinent snow geese on their Gulf coast winter range. Waterfowl in winter Weller, M. W., editor. University of Minnesota Press. Minneapolis, Minnesota. p. 495-515.

Beneficial Uses Group. 1995. The recommended beneficial uses plan for placement of dredged materials. Prepared for the Port of Houston Authority. Houston, Texas.

Benefield, R.L., and R.P. Hofstetter. 1976. Mapping of productive oyster reefs in Galveston Bay, Texas. Texas Parks and Wildlife Department, Coastal Fisheries Branch Publication PL88-309 2-218R. Austin, Texas.

Benson, K.B. 1935. Exploring Spaniards cruised along coast four centuries ago. Galveston Daily News, December 16.

Blaha, J.P. and Sturges. 1981. Evidence for wind forced circulation in the Gulf of Mexico. J. Mar. Res. 39(4), 711-734.

Blume, J. 1992. Interview Topic: The history of San Leon. In taped interview, February 3, 1992 by Alecya Gallaway. San Leon, Texas.

Borey, R.B., P.A. Harcombe, and F.M. Fisher 1983. Water and organic carbon fluxes from an irregularly flooded brackish marsh on the Upper Texas Coast, U.S.A. Estuarine, Coastal and Shelf Science 16:379-402.

Boyle, R.H., R.H. Graves, and T.H. Watkins, editors. 1971. The Water Hustlers. Sierra Club. San Fransisco, California.

Brooks, J.M., T.L. Wade, M.C. Dennicuff II, D.A. Wiesenburg, D. Wilkinson, T.J. McDonald, and S.J. McDonald. 1992. Toxic contaminant characterization of aquatic organisms in Galveston Bay: a pilot study. Galveston Bay National Estuary Program Publication GBNEP-20. Webster, Texas.

Buskey, E.J. 1989. Effects of freshwater inflow on the zooplankton of Texas coastal bays. Texas Water Development Board Report. Austin, Texas.

Byford, D. 1983. State's cattle industry had its start on Southeast Texas' white spread. The Baytown Sun, 27th March, 1983.

Caldwell, L.K. 1996. Science assumptions and misplaced certainty in natural resources and environmental problem solving. Scientific uncertainty and environmental problem solving. Lemons, J., editor. Blackwell Science. Cambridge, Massachusetts. p 394-421.

Calnan, T.R. 1995. A coastal wetlands acquisition plan for Texas project report. Texas General Land Office. Austin, Texas.

Campbell, T.N. 1957. Archeological investigations at the Caplen site, Galveston County, Texas. Texas Journal of Science Vol. 9, no. No. 4: 451-57.

Cardwell, R.D., M.S. Brancato, J. Toll, D. DeForest, and L. Tear. 1999. Aquatic ecological risks posed by tributyltin in United States surface waters: pre-1989 to 1996 data. Environmental Toxicology and Chemistry 18(3):567-577.

Carillo, T. and C. Berger. 2001. Galveston Bay current velocities maps. Coastal and Hydraulics Laboratory, USAE Research and Development Center. Vicksburg, Mississippi.

Carr, R.S. 1993. Sediment quality assessment survey of the Galveston Bay System. Galveston Bay National Estuary Program Publication GBNEP-30. Webster, Texas.

City Commission, Texas City. 1963. Historical background of the Dike. City Commission. Texas City, Texas.

Colwell R.R. and J. Kaper. 1978. Distribution, survival, and significance of pathogenic bacteria and viruses in estuaries. Estuarine Interactions. Wiley, M.L., editor. Academic Press, New York. p 443-457.

Cowardin, L.M., V. Carter, F.C. Golet, and E.T. LaRoo. 1979. Classification of wetlands and deep-water habitats of the United States: U.S. Department of the Interior, Fish and Wildlife Service Publication FWS/OBS-79/31. Office of Biological Services. Washington, D. C.

Contreras, C. 2001. Chronology of the 2000 red tide bloom. http://www.tpwd.state.tx.us/fish/recreat/rt_chron_2000.htm . Texas Parks & Wildlife Department. Austin, Texas. Accessed 2001 Jul 16.

Criner, O. and M.D. Johnican. 2001. Update 2000: Current status and historical trends of the environmental health of Galveston Bay. Galveston Bay Estuary Program. Webster, Texas. Forthcoming.

Crocker, P.A. 1991. Water quality and ambient toxicity investigation of the Houston Ship Channel and tidal San Jacinto River. Shipley, F. S. and R. W. Kiesling, editors. Proceedings of Galveston Bay Characterization Workshop; 1991 Feb 21-23; Galveston Bay National Estuary Program Publication GBNEP-6. Webster, Texas. p 46-48.

Crocker, P. A., G. J. Guillen, R. D. Seiler, E. Petrocelli, M. Redmond, W Lane, T. A. Hollister, D. W. Neleigh, and G. Moffson. 1991. Water quality, ambient toxicity, and biological investigations in the Houston Ship Channel and tidal San Jacinto River. U.S. Environmental Protection Agency Region 6 Report. Dallas, Texas.

Crosby, D.G. 1998. Environmental toxicology and chemistry. Oxford University Press. New York; Oxford. p. 336.

Crowley, T.J. 1996. Remembrance of things past: greenhouse lessons from the geologic record in consequences, (John A. Eddy, ed.), Vol. 2, No.1, Saginaw Valley State University.

Czapla, T.E. 1991. Diets and prey selection of pinfish and southern flounder in a *Halodule wrightii* seagrass meadow. Ph.D. Dissertation. Texas A&M University. College Station, Texas.

Czapla, T.E. 1993. Potential restoration for submerged aquatic vegetation. Jensen, R., R. W. Kiesling, and F. S. Shipley, editors. Proceedings of the second State of the Bay symposium; 1993 Feb. 4-6; Galveston Bay National Estuary Program Publication GBNEP-23. Webster, Texas. p 239-243.

Dahl, T.E., and C.E. Johnson. 1991. Status and trends of wetlands in the conterminous United States, mid-1970s to mid-1980s. U.S. Department of Interior, Fish and Wildlife Service Publication. Washington, D.C.

Dahl, T.E. 2000. Status and trends of wetlands in the conterminous United States 1986 to 1997. U.S. Department of Interior, Fish and Wildlife Service, Washington, D.C. p 82.

Daniels, N. A., B. Ray, A. Easton, N. Marano, E. Kahn, A. L. McShan, L. Del Rosario, T. Baldwin, M. A. Kingsley, N. D. Puhr, J. G. Wells, F. J. Angulo. 2000. Emergence of a new *Vibrio parahaemolyticus* serotype in raw oysters. Journal of the American Medical Association, 284(12): 1541-1545.

Day, J.W, Jr., C.A.S. Hall, W.M. Kemp, and A. Yez-Arancibia. 1989. Estuarine Ecology. John Wiley and Sons. New York, New York.

Deats, Ernest E. 2000. Interview topic: Saltgrass, Cattlemen, Texas City, Hitchcock, Last trail drive from saltgrass, rreezes, tannery on Dickinson Bayou, and prairies. In taped interview, 2000 by Alecya Gallaway. Dickinson, Texas.

Denton, W. 2001. Red tide in Texas: frequency and distribution. Proceedings of the fifth Galveston Bay Estuary Program State of the Bay symposium; 2001 Jan 31- Feb 2; Galveston Bay Estuary Program Publication GBEP T-5 (CTF 09/01). Webster, Texas.

Ditton, R.B., D.K. Loomis, D.R. Fesenmaier, M.O. Osborn, D. Hollin, and J.W Kolb. 1989. Galveston Bay and the surrounding area: human uses, production and economic values. Galveston Bay: issues, resources, status and management. NOAA Estuary-of-the-Month seminar series No. 13, National Oceanic and Atmospheric Administration. Washington, D. C. p 53-66.

Diener, R.A. 1975. Cooperative Gulf of Mexico estuarine inventory and study Texas; area description. National Oceanic and Atmospheric Administration, National Marine Fisheries Service Circular 393. Rockville, Maryland.

Doughty, R.W. 1984. Sea turtles in Texas: a forgotten commerce. Southwestern Historical Quarterly 88: 43-70.

Dunton, K. 1999. Research issues for Texas. Texas Parks and Wildlife. Seagrass Conservation Plan for Texas. Resource Protection Division, Texas Parks and Wildlife Department, Austin, Texas. p 30-43.

Dyer, J.O. 1911. Galveston's historic ridge. Galveston Daily News. Galveston, Texas.

Dyer, J.O. 1916. Comparison of wild tribes near Galveston a century ago with ancient semitic customs. Dyer. Galveston, Texas.

Engel, D.W. and G.W. Thayer. 1998. Effects of habitat alteration on blue crabs. Journal of Shellfish Research. 17(2):579-586.

Erramouspe, R. 1996. Whites Ranch: carved from land founded in 1819, Whites Ranch along the Gulf coast has been owned and operated by the same family for almost 200 years. The Cattleman, 10 - 13, 20.

Epperson, J.L. 1995. Historical viginettes of Galveston Bay. Dogwood Press. Woodville, Texas.

Espey, Huston, and Associates. 1978. Proposed multipurpose deepwater port and crude oil distribution system for Galveston Bay, Texas. Environmental Assessment Report prepared for the Board of Trustees, Galveston Wharves, by Northville Industries Corporation. Galveston, Texas.

Espey, Huston & Associates. 1997. A brief history of wastewater treatment in the City of Houston. Espey, Huston & Associates, Inc. Austin, Texas.

Eubanks, T.L. 1993. Ecotourism in Galveston Bay: an economic opportunity. Jensen, R., R. W. Kiesling, and F. S. Shipley, editors. Proceedings of the second State of the Bay symposium; 1993 Feb 4-6; Galveston Bay National Estuary Program Publication GBNEP-23. Webster, Texas. p 367-369.

Evans, M. and J. Hiney. 2001. Tide and tide again. Texas shores. Texas Sea Grant College Program. 34(2):2-16, 2-17.

Fisher, F., Jr. 1972. The wetlands. Rice University Review 7:16.

Fisher, W.L., J.H. McGowan, F. Brown, Jr., and C.G. Groat. 1972. Environmental geologic atlas of the Texas Coastal Zone-Beaumont Port Arthur area. University of Texas at Austin. Bureau of Economic Geology, Austin, Texas.

Few, J. 1991. Texas City Dike fossil collection. Pasadena, Texas.

Foster, E.R., J. Gilvar, and S.D. Hoyt. 1993. Archival research, Houston-Galveston navigation channels, Texas project, Galveston, Harris, Liberty and Chambers Counties, Texas. U.S. Army Corps of Engineers. Austin, Texas.

Gabrysch, R.K., W.L. Naftel, G.D. McAdoo, and C.W. Bonnet. 1974. Groundwater data for Harris County, Texas, 1892-1972. Texas Water Development Board. Austin, Texas.

Gallaway, A. 1999a. The history of San Leon. Scalare publications. Bacliff, Texas.

Gallaway, A. 1999b. A history of the scientific management of shrimp in the Galveston Bay System. The Environmental Institute of Houston, University of Houston-Clear Lake. Houston, Texas.

Gallaway, A. 2001. Historical timeline for Trinity River and Wallisville, 1884-1962. Environmental Institute of Houston. Unpublished.

[GBEP] Galveston Bay Estuary Program. 2001. Plan review summary (1996-2000). Galveston Bay Estuary Program Publication. Webster, Texas.

[GBF] Galveston Bay Foundation. 1998. Habitat conservation blueprint: a plan to save the habitats and heritage of Galveston Bay; sites strategies and resources. Galveston Bay Foundation. Webster, Texas.

[GBNEP] Galveston Bay National Estuary Program. 1994a. The Galveston Bay plan: The comprehensive conservation and management plan for the Galveston Bay ecosystem publication GBNEP-49. Galveston Bay National Estuary Program Publication. Webster, Texas.

[GBNEP] Galveston Bay National Estuary Program. 1994b. The State of the Bay: a characterization of the Galveston Bay ecosystem. F.S. Shipley and R.W. Kiesling (Eds.). Galveston Bay National Estuary Program Publication. Webster, Texas.

[GBNEP] Galveston Bay National Estuary Program. 1994c. The Galveston Bay plan: the comprehensive conservation and management plan for the Galveston Bay ecosystem. Webster, Texas. p 457.

Galveston Daily News. 1885. Advent of the oyster. Galveston Daily News. Galveston, Texas.

Galveston Daily News. 1910. Demand for oysters exceeds the supply. Galveston Daily News, Nov 18. Galveston, Texas.

Galveston Daily News. 1912. 3,361,48 acres are planted in oysters. Galveston Daily News, Sunday, March 3. Galveston, Texas.

Galveston Daily News. 1940. Oyster shell industry, founded here, many articles manufactured from overcoats of bivalves. Galveston Daily News. Galveston, Texas.

Galveston Daily News. 1941. Oyster shell industry, founded here. Galveston Daily News. Galveston, Texas.

Garcia, T.D. and McVay, K.R. 1996. Clay mineralogy of the Trinity Bay Estuary in.

Proceedings, Clay Mineralogy Society, Gatlinburg, TN, June 15-20.

Gerba, C.P. and J.S. McLeod. 1976. Effect of sediments on the survival of *Escherichia coli* in marine waters. Applied and Environmental Microbiology. 32:114-120.

Glass, J.L. 1986. The history of the Houston-Bay Country region from the foot of Main Street to the Galveston Bay. Kelvin Press. Houston, Texas.

Glanton, T. 2001. Personal Communication. City of Houston Department of Public Works and Engineering. Houston, Texas.

Gosselink, J.G., C.L. Cordes, and J.W. Parsons. 1979. An ecological characterization study of the Chenier Plain coastal ecosystem of Louisiana and Texas. Vols.1-111. U.S. Fish and Wildlife Service, Office of Biological Services Report FWS/OBS-78/9-1 1. Washington, D.C.

Green, A., M. Osborn, P. Chai, J. Lin, C. Loeffler, A. Morgan, P. Rubec, S. Spanyers, A. Walton, R. D. Slack, D. Gawlik, D. Harpole, J. Thomas, E. Buskey, K. Schmidt, R. Zimmerman, D. Harper, D. Hinkley, T. Sager, and A. Walton. 1992. Status and trends of selected living resources in the Galveston Bay system. Galveston Bay National Estuary Program Publication GBNEP-19. Webster, Texas.

Green. A., A. Walton, M. Osborn, P. Chai, J. Lin, C. Loeffler, A. Morgan, P. Rubec, S. Spanyers, R. D. Slack, D. Gawlik, D. Harpoole, J. Thomas, E. Buskey, K. Schmidt, R. Zimmerman, and D. Harper. 1993. Status, trends, and probable causes for changes in living resources in the Galveston Bay system. Jensen, R., R. W. Kiesling, and F. S. Shipley, editors. Proceedings or the second State of the Bay symposium; 1993 Feb 4-6; Galveston Bay National Estuary Program Publication GBNEP-23. Webster, Texas.

Haby, M., D. Hollin, and M. C. Russell. 1989. Texas commercial fisheries profile. Technical fact sheet. TAMU-SG-90-501, Texas Grant College Program. College Station, Texas.

Hacker, K. and S. Nissan. 2001. Grain transportation report. United States Department of Agriculture, Agricultural Marketing Service. Washington, D.C. p 8. <http://www.ams.usda.gov/tmd/7_17_01.pdf>. Accessed 2001 Sep 20.

[HGCSD] Harris-Galveston Coastal Subsidence District. 1998. Groundwater management plan. Harris-Galveston Coastal Subsidence District. Friendswood, Texas.

Hayes, C.W. 1879 reprint 1974. Galveston, history of the island and the City. Jenkins Garrett Press. Austin, Texas.

Helm, M.S. 1884 reprint 1987. Scraps of early Texas history. Lorraine Jeter, editor. Eakin Press. Austin, Texas.

Henson, M. and K. Ladd. 1988. Chambers County. A pictorial history. The Donning Company. Norfolk, Virginia.

Henson, M.S. 1986. History of Baytown. Baytown Historical Society. Baytown, Texas.

Henson, M.S. 1993. The history of Galveston Bay resource utilization. Galveston Bay National

Estuary Program Publication GBNEP-39. Webster, Texas.

Hester, T.R. 1980. A survey of Paleo-Indian archaeological remains along the Texas coast. Proceedings of the Archeology of the Texas Coast for Archeological Research. Lynn Highley and Thomas R. Hester, editor, 11:1-12. The University of Texas. San Antonio, Texas.

Hofstetter, R.P. 1983. Oyster population trends in Galveston Bay 1973-1978. Texas Parks and Wildlife Department Management Data Series Number 51. Coastal Fisheries Branch. Austin, Texas.

Hogan, J. 2001. Diamondback terrapin (*Malaclemys terrapin*) distribution and nesting in Armand Bayou, Texas: a developed urban estuary. U.S. Geological Survey Report. Austin, Texas.

Holbrook, R. 1971. History of the Texas City Dike. Galveston County Commissioners Court. Galveston, Texas.

Holley, M.A. 1836, 1990. Texas. Texas Historical Association. Lexington,Kentucky; Austin, Texas.

Holzschuh, J.D, editor. 1991 Land subsidence in Houston, Texas USA. Field trip guidebook, Fourth International Symposium on Land Subsidence. Houston, Texas.

Hooten, C. 1847. St. Louis Isle, TEXIANA. Simmonds and Ward Company. London.

[HGAC] Houston-Galveston Area Council. 1993a. Galveston Bay area socioeconomic planning data. Houston-Galveston Area Council. Houston, Texas.

[HGAC] Houston-Galveston Area Council. 1993b. Interim long range plan forecasts, Access 2010: Revised. Transportation Department. Houston-Galveston Area Council. Houston, Texas.

Iversen, E.S., A. Higman, and J.B. Higman. 1993. Shrimp capture and culture fisheries of the United States. John Wiley & Sons, Inc. New York, New York.

Jackson, J. 1997. Los Mestenos, Spanish ranching in Texas 1721-1821. Texas A&M Press. College Station, Texas.

Jackson, T.J., T.L. Wade, J.L. Sericano, J.M. Brooks, J.M. Wong, B. Garcia-Romero, T.J. McDonald. 1998. Galveston Bay: temporal changes in the concentrations of trace organic contaminants in national status and trends oysters (1986-1994). Estuaries 21(4B):718-730.

Jenson, P. 1992. Characterization of selected public health issues in Galveston Bay. Galveston Bay National Estuary Program Publication GBNEP-21. Webster, Texas.

Jensen, P., S. Valentine, M.T. Garrett, and Z. Ahmed. 1991. Nitrogen loads to Galveston Bay. Shipley, F. S. and R. W. Kiesling, editors. Proceedings of the Galveston Bay Characterization workshop; 1991 Feb 21-23; Galveston Bay National Estuary Program Publication GBNEP-6. Webster, Texas. p 99-104.

Jiann, K. and B.J. Presley. 1997. Variations in trace metal concentrations in American oysters (*Crassostrea virginica*) collected from Galveston Bay, Texas. Estuaries 20(4): 710-724.

Johnston, M. 1991. Houston, the unknown city 1836-1946. Texas A&M Press. College Station, Texas.

Johnstone, M. 1975. The Texas City Dike vertebrate fauna. Unpublished paper. College of the Mainland, Texas City.

Jones & Neuse, Inc. 1992. Segmentation development for Galveston Bay. Galveston Bay National Estuary Program Publication GBNEP-18. Webster, Texas. 125pp.

Karl, T. R., R. W. Knight, D. R. Easterling and R. G. Quayle. 1995. Tends in U.S. climate during the Twentieth Century. Consequences. John A. Eddy, editor. 1(1): 3-12.

Kenyon, D. 1976. From arrows to astronauts, a short history of the communities surrounding Clear Creek. National Association of Conservation Districts. League City, Texas.

Kingston, M., ed. 1988. The Texas Almanac, 1988. The Dallas Morning News. Dallas, Texas.

Landry, A.M. 2001. Personal communication. Texas A&M University at Galveston. Galveston, Texas.

Lankford, R.R. and Rehkemper, L.J. 1969. The Galveston Bay complex: a summary of characteristics in Galveston Bay geology. Lankford, R.R. and L.J. Rehkemper, editors. Houston Geological Society. Houston, Texas.

LaRoe, E. T, G. S. Farris, C. E. Puckett, P. D. Doran, and M. J. Mac, editors. 1995. Our living resources: a report to the nation on the distribution, abundance and health of U.S. plants and animals, and ecosystems. U.S. Department of the Interior, National Biological Service, Washington, DC.

LaSalle, M., R.J. Bass, and G. Ray. 1991. Preliminary characterization of benthic assemblages of

Galveston Bay, Texas: results from benthic infaunal sampling. Shipley, F. S. and R. W. Kiesling, editors. Proceedings of the Galveston Bay Characterization workshop; 1991 Feb 21-23; Galveston Bay National Estuary Program Publication GBNEP-6. Webster, Texas. p 148-149.

LeBlanc, R.J. and W.D. Hodgson. 1959. Origin and development of the Texas Shoreline. Gulf Coast Association of Geological Societies Transactions IX: 197-220. Austin, Texas.

Love, C.M. 1916. History of the cattle industry in the southwest. The Texas State Historical Association 4, no. April 1916: 370 - 399. Austin, Texas.

Malachowski, M.J. 1995. Health effects of toxic substances. Government Institutes, Inc. Rockville, Maryland. 254pp.

Manzella, S.A. and J.A. Williams. 1992. The distribution of Kemp's Ridley sea turtles (*Lepidochelys kempi*) along the Texas Coast: an Atlas. NOAA Technical Reports NMFS 110. National Marine Fisheries Service. Galveston, Texas. p 52.

Martin, W.D. 1993. 3-D Hydrodynamic model of Galveston Bay. Jensen, R., R. W. Kiesling, and F. S. Shipley, editors. Proceedings of the second State of the Bay symposium; 1993 Feb. 4-6; Galveston Bay National Estuary Program Publication GBNEP-23. Webster, Texas. p 327-330.

Martinez, E.X., J.M. Nance, Z.P. Zein - Eldin, J. Davis, L. Rathmell, and D. Emilian. 1993. Trawling bycatch in the Galveston Bay system. Galveston Bay National Estuary Program Publication GBNEP - 34. Webster, Texas.

Maze, K.S. and B. Würsig. 1999. Bottlenose dolphins of San Luis Pass, Texas: occurrence patterns, site-fidelity, and habitat use. Aquatic Mammals 25(2): 91-103.

McComb, D. 1986. Galveston: a history. University of Texas Press. Austin, Texas.

McEachron, L.W, C.R. Shaw, and A.W. Moffat. 1977. A fishery survey of Christmas, Drum, and Bastrop Bays, Brazoria County, Texas. Texas Parks and Wildlife Department, Technical Series No. 20. Austin, Texas.

McFarlane, R.W. 1991. An environmental inventory of the Armand Bayou Coastal Preserve. Galveston Bay National Estuary Program Publication GBNEP-8. Webster, Texas. p 66.

McFarlane, R.W 1994. A conceptual model of Galveston Bay. Galveston Bay National Estuary Program Publication GBNEP-42. Webster, Texas.

McFarlane, R.W. 2000. Unpublished data. Mcfarlane and Associates, Houston, Texas.

McFarlane, R. W. 2001. Population trends of colonial waterbirds in Galveston Bay, Texas. Proceedings of the fifth Galveston Bay Estuary Program State of the Bay symposium; 2001 Jan 31- Feb 2; Galveston Bay Estuary Program Publication GBEP T-5 (CTF 09/01). Webster, Texas.

Meltzer, D.J. 1986. The Clovis Paleo-Indian occupation of Texas: results of the Texas Clovis Fluted Point Survey. Bulletin of the Texas Archeological Society 57:27-68.

Minello, T.J., and J.W. Webb, Jr. 1997. Use of natural and created *Spartina alterniflora* salt marshes by fishery species and other aquatic fauna in Galveston Bay, Texas, USA. Marine Ecology Progress Series 151:165-179.

Monroe, M.W and J. Kelly. 1992. State of the estuary. A report on conditions and problems in the San Francisco Bay/Sacramento-San Jaoquin estuary. San Francisco Estuary Project, Association of Bay Governments. Oakland, California.

Montagna, P.A. and R.D. Kalke. 1995. Ecology of infaunal mollusca in South Texas estuaries. *American Malacological Bulletin* 11:163-175.

Moore, J. W, and S. Ramamoorthy. 1984. Heavy metals in natural waters. Springer-Verlag. New York, New York.

Morse, J., B. Presley, R. Taylor, G. Benoit, and P. Santschi. 1993. Trace metal chemistry of Galveston Bay: water, sediments and biota. Marine Environmental Research 36:1-37.

Morton, R.A. 1974. Shoreline changes on Galveston Island (Bolivar Roads to San Luis Pass), an analysis of historical changes of the Texas Gulf shoreline. Bureau of Economic Geology. Austin, Texas.

Mullins, H.L. 1979. The effects of power plant effluents on the growth of phytoplankton in adjacent areas of Trinity Bay. Master's Thesis. Texas A&M University. College Station, Texas.

National Hurricane Center. 2001. National Hurricane Center Hurricane Awareness. http://www.nhc.noaa.gov/HAW/ Accessed August 29, 2001.

National Ocean Service. 1985. National estuarine inventory data atlas. Physical and hydrologic characteristics. National Oceanic and Atmospheric Administration, National Ocean Service, Strategic Assessment Branch, Rockville, Maryland, V.1.

National Research Council. 1992. Restoration of aquatic ecosystems: science, technology, and public policy. National Academy Press. Washington D.C.

Nerem, R.S. 1995. Global mean sea level variations from TOPEX/POSEIDON altimeter data. Science, 268.

Newell, C.J., H.S. Rifai, P.B. Bedient. 1992. Characterization of nonpoint sources and loadings to Galveston Bay. Volume I, Technical Report Galveston bay National Estuary Program Publication GBNEP-15. Webster, Texas.

[NHCRWA] North Harris County Regional Water Authority. 2000. Answering your questions about the North Harris County Regional Water Authority. http://www.regionalwaterauthority.com/about/pdf/brochure.pdf. Accessed 2000 Dec 12.

Odum, E. P. 1989. Ecology and our endangered life-support systems. Sinauer Associates. Sunderland, Massachusetts.

Odum, E.P. 1997. Ecology: a bridge between science and society. Sinauer Associates. Sunderland, Massachusetts.

O'Neill, R.V., D.L. DeAngelis, J.B. Waide, and T.F.H. Allen. 1986. A hierarchical concept of ecosystems. Princeton University Press. Princeton, New Jersey.

Orlando, P., F. Shirzad, J. Schuerolz, P. Mathieux and S. Strassner. 1988. Shoreline modification, dredged materials, and dredged material disposal areas in the nation's estuaries. Draft report, National Oceanic and Atmospheric Administration, National Ocean Science Strategic Assessment Branch. Rockville, Maryland.

Pacheco, P., D. Farrow, T Manuelides, S. Rohmann, M. Katz, and J. McLeod 1990. Point source discharges in coastal areas of Texas. Draft report. National Oceanic and Atmospheric Administration, National Ocean Survey. Washington, D. C.

Paine, J.G., and R. A. Morton. 1986. Historical shoreline changes in Trinity, Galveston, West and East Bays, Texas Gulf Coast. The University of Texas at Austin, Bureau of Economic Geology, Geology Circular 86-3. Austin, Texas.

Paine, J.G., and R.A. Morton. 1991. Historical shoreline changes in the Galveston Bay. Shipley, F. S. and R. W. Kiesling, editors. Proceedings of the Galveston Bay Characterization workshop; 1991 Feb 21-23; Galveston Bay National Estuary Program Publication GBNEP-6. Webster, Texas. p165-170.

Palafox, S.D., and E.D. Wolford 1993. Non-fishing/human induced mortality of fisheries. Galveston Bay National Estuary Program Publication GBNEP-29. Webster, Texas.

Parker, J.C. 1965. An annotated checklist of the fishes of the Galveston Bay system, Texas. Publications of the University of Texas Institute for Marine Science 10:201-220.

Patterson, L., R.L. Gregg, S.M. Kindall, and G. Marubio. 1999. The Whitehead Collection, Chambers County Texas. Houston Archeological Society Report 15. Houston, Texas.

Patullo, J., W. Munk, R. Revelle and E. Strong. 1955. The seasonal oscillations in sea Level. Journal of Marine Research, v.14.

Paulsen, G.C., D. H. Barber, C.E. Ellsworth, R. Follansbee, and B. Johnson. 1941. Surface water supply of the United States, part 8, western Gulf of Mexico basins. United States Department of the Interior. Washington, D.C.

Peterson, C.H., and N.M. Peterson. 1979. The ecology of intertidal flats of North Carolina: a community profile. U.S. Fish and Wildlife Service publication FWS/OBS-79/39. Office of Biological Services. Washington, D.C.

Port of Galveston. 2001. Port report, a special report to the Galveston community. Vol.3, No. 1. Galveston, Texas. <http://www.portofgalveston.com/news/publications/portreport/Vol.%203%20No.%201.pdf>. Accessed 2001 Sep 20.

Port of Houston Authority. 1998. The Port of Houston Authority. <http://www.portofhouston.com/>. Accessed 2000 Sep 21.

Port of Houston Authority. 2001. Port of Houston / PHA History. Port of Houston Authority Market Development. Houston, Texas. <http://www.portofhouston.com/bulletin/stat00p2.pdf>. Accessed 2001 Sep 20.

Port of Texas City. 2001. Distribution of net tonnage handled at Port of Texas City, Texas. Facsimile from Port of Texas City. Texas City, Texas.

Powell, E.N., E.E. Hoffmann, J.M. Klinck, and S.M.

Ray. 1992. Modeling oyster populations I. A commentary on filtration rate. Is faster always better? Journal of Shellfish Research V.11, No.2. p. 387-398.

Powell, E.N. 1993. Status and trends analysis of oyster reef habitat in Galveston Bay. Jensen, R., R. W. Kiesling, and F. S. Shipley, editors. Proceedings of the second State of the Bay symposium; 1993 Feb. 4-6; Galveston Bay National Estuary Program Publication GBNEP-23. Webster, Texas. p 207-209.

Powell, E.N., J. Song, and M. Ellis. 1994. The status of oyster reefs in Galveston Bay, Texas. Galveston Bay National Estuary Program Publication GBNEP-37. Webster, Texas.

Pratt, W.E. and Johnson, D.W. 1926. Local subsidence of the Goose Creek Oil Field. Journal of Geology, V.34, No.7

Pullen, E .J. 1960. A checklist of marsh and marine flora in area M-2. Texas Game and Fish Commission, Marine Fisheries Division Project Reports, 1959-1960, Project No. M-2-R-2, Job No. C-2. Austin, Texas.

Pulich, W.M., Jr. 1996. Map of Galveston Bay submerged aquatic vegetation. Refer to: Compilation of a digital data layer composed of wetland habitats and coastal land cover data: final report to Natural Resources Inventory Program, Section B. Seagrass and submerged habitats for Corpus Christi Bay system.1995 Aug 31. Texas Parks and Wildlife Department. Austin, Texas.

Pulich, W.M., Jr. and Hinson, J. 1996. Coastal studies technical report No. 1: development of geographic information system data sets on coastal wetlands and land cover. Texas Parks and Wildlife Department. Austin, Texas.

Pulich, W.M., Jr., and W.A. White. 1991. Decline of submerged vegetation in the Galveston Bay system: chronology and relationship to physical processes. Journal of Coastal Research 7:1125-1138.

Quast, W.D., M.A. Johns, D.E. Pitts, G.C. Matlock, and J.E. Clark. 1988. Texas oyster fishery management plan. Texas Parks and Wildlife Department. Austin, Texas.

Radde, L.J., D. Redford, and W. Trulli 1991. Survey of floatable debris in the Houston Ship Channel. Shipley, F.S and R. W. Kiesling, editors. Proceedings of the Galveston Bay Characterization Workshop; 1991 Feb 21-23; Galveston Bay National Estuary Program Publication GBNEP-6. Webster, Texas. p 75-82.

Ray, G. L., D. G. Clarke, and R.J. Bass. 1993. Characterization of benthic assemblages of Galveston Bay: 1990-1992. Jensen, R., R. W. Kiesling, and F. S. Shipley, editors. Proceedings of the second State of the Bay symposium; 1993 Feb. 4-6; Galveston Bay National Estuary Program Publication GBNEP-23. Webster, Texas.

Ray, O.L., D. G. Clarke, and R. J. Bass. 1993. Characterization of Benthic Assemblages of Galveston Bay 1990-1992. Jensen, R., R. W. Kiesling, and F. S. Shipley, editors. Proceedings of the second State of the Bay symposium; 1993 Feb 4-6; Galveston Bay National Estuary Program Publication GBNEP-23. Webster, Texas. p 185-190.

Ray, S.M. 2001. DermoWatch: A Web-Based Approach for Managing *Perkinsus marinus* Disease of Oysters. Proceedings of the fifth State of the Bay symposium; 2001 Jan 31- Feb 2; Galveston Bay Estuary Program Publication GBEP T-5 (CTF 09/01). Webster, Texas.

Ray, S.M., T.M. Soniat, L. Robinson, and E. Kortright. 2001. DermoWatch Home. http://blueblee.com/cgi-blueblee/dermo/dermo.pl?all. Accessed 2001 Jul 1.

Rehkemper, J.L. 1969. Sedimentology of holocene estuarine deposits, Galveston Bay in Galveston Bay geology (Lankford, R.R. and Rogers, J.J.W., eds.), Houston Geological Society. Houston, Texas.

Reid, G. K., Jr. 1955. A summer study of the biology and ecology of East Bay, Texas. Part 1. Introduction, description of area, methods, some aspects of the fish community, the invertebrate fauna. Texas Journal of Science 7:316-343.

Renfro, W.C. 1959. Checklist of the flora of area M-2. Texas Game and Fish Commission, Marine Laboratory Reports, 1959, Project No. M-2-R-1, Job No. C-2. Austin, Texas.

Rice, C.P. and T.W. Custer. 1991. The occurrence of chlorostyrenes in egrets and herons collected in Galveston Bay. Shipley, F. S. and R. W. Kiesling, editors. Proceedings of the Galveston Bay Characterization workshop; 1991 Feb 21-23; 1991; Galveston Bay National Estuary Program Publication GBNEP-6. Webster, Texas.

Ricklis, R.A. 1994. Aboriginal life and culture on the Upper Texas Coast: archaeology at the Mitchell Ridge Site, 41GV66, Galveston Island. Coastal

Archaeological Research, Inc. Corpus Christi, Texas.

Rivera, D. 2000. Personal Communication. National Marine Fisheries Service, Galveston Laboratory. Galveston, Texas.

Roach, R.W. 2001 Personal Communication. US Fish and Wildlife Service. Houston, Texas.

Roach, R.W, R.S. Carr, C.L. Howard, and B.W. Cain. 1993a. An assessment of produced water impacts at two sites in the Galveston Bay system. Shipley, F.S. and R. W. Kiesling, editors. Proceedings of the Galveston Bay Characterization Workshop; 1991 Feb 21-23; Galveston Bay National Estuary Program Publication GBNEP-6. Webster, Texas. p 135-147.

Roach, R.W., R.S. Carr, C.L. Howard, and B.W. Cain. 1993b. An assessment of produced water impacts at two sites in the Galveston Bay system. United States Fish and Wildlife Service, Clear Lake Field Office unpublished report. Houston, Texas.

Robinson, L. 2000. Personal Communication. Texas Parks and Wildlife Department. Seabrook, Texas.

Robinson, L., P. Campbell, and L. Butler. 2000. Trends in commercial fishery landings, 1972-1998. Texas Parks and Widlife Department, Coastal Fisheries Division. Austin, Texas. p 176.

Sage, T. 2000. Personal communication. University of Houston - Clear Lake. Houston, Texas.

Saul, G.E., R.K Reichers, and H.R. Osburn. 1992. Recreational fishery bycatch in the Galveston Bay system. Galveston Bay National Estuary Program Publication GBNEP-25. Webster, Texas.

Saunders, S. 1992. Topic of interview: history of San Leon. In taped interview; 1992 Feb 25 Alecya Gallaway. Dickinson, Texas.

Saunders, S. and J. Blume. 1980. Interview topic: growing up on the prairie at San Leon. In taped interview; 1980 Mar 4; Betty Fisher. San Leon, Texas.

Sheridan, F. 1954. Galveston Island or a few months off the Coast of Texas.; The Journal of Francis Sheridan 1839-1840. Willis W. Pratt, editor. University of Texas Press. Austin, Texas.

Sheridan, P.F., R.D. Slack, S.M. Ray, L.W McKinney, E.F. Klima, and T.R. Calnan. 1989. Biological components of Galveston Bay. Galveston Bay: issues, resources, status and management. National Oceanic and Atmospheric Administration Estuary-of-the-Month Seminar Series No. 13. Washington, D. C. p 23-51.

Sheridan, P., G. McMahon, K. Hammerstrom, W. Pulich, Jr. 1998. Factors affecting restoration of *Halodule wrightii* to Galveston Bay, Texas. Restoration Ecology 6:144-158.

Sibley, M.M. 1968. The Port of Houston, a history. University of Texas Press. London; Austin, Texas.

Smith, D.L. 1934. The history of Harrisburg, Texas 1822-1927:63. Department of History, George Peabody College for Teachers. Nashville, Tennessee.

Smith, E.M., C.P. Gerba, and J.L. Melnick. 1978. Role of sediment in the persistence of enteroviruses in the estuarine environment. Applied environmental microbiology 35:685-689. Texas Department of Health. 2001a. Health Consultation for Clear Lake, Texas and Galveston Bay. Texas Department of Health Seafood Safety Division and Environmental Epidemiology and Toxicology Division. Austin, Texas.

Solis, R.S. and D.A. Brock. 1991. Freshwater inflows to Galveston Bay. Shipley, F. S. and R.W. Kiesling, editors. Jensen, R., R. W. Kiesling, and F. S. Shipley, editors. Proceedings of the Galveston Bay Characterization workshop; 1991 Feb 21-23; Galveston Bay National Estuary Program Publication GBNEP-6. Webster, Texas. p 171-173.

Solis, R.S., and W.L. Longley. 1993. Trends in freshwater inflows to Galveston Bay. Proceedings of the second State of the Bay symposium; 1993 Feb 4-6; Galveston Bay National Estuary Program Publication GBNEP-23. Webster, Texas. p 289-298.

Stockwell, D.A. 1989. Effects of freshwater inflow on the primary production of a Texas Coastal Bay System. Report to Texas Water Development Board. Austin, Texas.

Strong, C.B. 1977 Discharge waters from a power plant as an influent of phytoplankton in adjacent estuarine waters. Master's Thesis, Texas A&M University. College Station, Texas.

Stumpf, R.P. and J.W. Haines. 1998. Variations in tidal level in the Gulf of Mexico and implications for tidal wetlands. Estuarine, Coastal and Shelf Science V.46.

Sericano, J.L., S.H. Safe, T.L. Wade, and J.M. Brooks. 1994. Toxicological significance of non-, mono- and diortho-substituted polychlorinated biphenyls in oysters from Galveston and Tampa Bays. Environmental Toxicology and Chemistry 31: 1797-1803.

Taylor, J., G. Callaway, M.V. Lowry, R.G. Olive. 2000. Region H Regional Water Planning Group, Regional Water Plan Executive Summary. Joint Venture: Brown & Root, Turner Collie & Braden, Ekistics Corporation, LBG-Guyton Associates. Houston, Texas.

Texas Comptroller of Public Accounts. 1999. Gulf Coast Regional Outlook <http://www.window.state.tx.us/ecodata/regional/gulf/gulfhmsa.html>. Accessed 2000 Aug 29.

[TDH] Texas Department of Health, United States Food and Drug Administration, and United States Fish and Wildlife Service. 1990. Cow Trap Lake-a study of pathogens, indicators, and classification of a Texas shellfish. Growing area, unpublished report. Austin, Texas.

[TDH] Texas Department of Health. 1993. Health Commissioner advises "zero consumption" of fish from Clear Creek. Texas Department of Health Seafood Advisory News Release. Austin, Texas.

[TDH] Texas Department of Health. 1999a. Health consultation for Lower Galveston Bay, Galveston, Galveston County, Texas. Texas Department of Health Seafood Safety Division and Environmental Epidemiology and Toxicology Division. Austin, Texas.

[TDH] Texas Department of Health. 1999b. Deaths from selected causes - Texas, 1999 by public health region and county of residence. Texas Department of Health Bureau of Vital Satistics. http://www.tdh.state.tx.us/bvs/stats99/annr_htm/99t23a1.htm#C. Accessed 2001 Aug 29.

[TDH] Texas Department of Health. 2000a. Health consultation for East Galveston Bay, Galveston County, Texas. Texas Department of Health Seafood Safety Division and Environmental Epidemiology and Toxicology Division. Austin, Texas.

[TDH] Texas Department of Health. 2000b. Health consultation for Trinity Bay, Chambers County, Texas. Texas Department of Health Seafood Safety Division and Environmental Epidemiology and Toxicology Division. Austin, Texas.

[TDH] Texas Department of Health. 2000c. Health consultation for Christmas Bay, Drum Bay, Bastrop Bay, Galveston County, Texas. Texas Department of Health Seafood Safety Division and Environmental Epidemiology and Toxicology Division. Austin, Texas.

[TDH] Texas Department of Health. 2000d. Classification of shellfish harvesting areas of Galveston Bay. Texas Department of Health Seafood Safety Division, Order No. MR-795. http://www.tdh.state.tx.us/bfds/ssd/images/gal2000.jpg Accessed 2001 Aug 29.

[TDH] Texas Department of Health. 2001a. Health consultation for Clear Lake, Texas and Galveston Bay. Texas Department of Health Seafood Safety Division and Environmental Epidemiology and Toxicology Division. Austin, Texas.

[TDH] Texas Department of Health. 2001b. Health consultation for Upper Galveston Bay, Galveston, Galveston County, Texas. Texas Department of Health Seafood Safety Division and Environmental Epidemiology and Toxicology Division. Austin, Texas.

[TDH] Texas Department of Health. 2001c. Health consultation for West Galveston Bay, Galveston, Galveston County, Texas. Texas Department of Health Seafood Safety Division and Environmental Epidemiology and Toxicology Division. Austin, Texas.

[TDH] Texas Department of Health. 2001d. Health consultation for Houston Ship Channel and Tabbs Bay, Harris County, Texas. Texas Department of Health Seafood Safety Division and Environmental Epidemiology and Toxicology Division. Austin, Texas.

[TDH] Texas Department of Health. 2001e. TDH study shows fish, crabs from most of Galveston Bay safe to eat. TDH News Release: October 25, 2001. Austin, Texas.

[TXDOT] Texas Department of Transportation. 2000. The Gulf Intracoastal Waterway in Texas. Texas Department of Transportation, Transportation Planning and Programming Division. Austin, Texas.

Texas Department of Water Resources. 1981. Trinity-San Jacinto estuary: a study of the influence of freshwater inflows. Texas Department of Water Resources Report LP-1 13. Austin, Texas.

Texas General Land Office. 1995. Gulf and bay shoreline of Texas classified by shoreline types coded for environmental sensitivity to oil/hazardous material spills and cleanup operations. Texas General Land Office/University of Texas Bureau of Economic Geology. Austin, Texas.

[TNRCC] Texas Natural Resource Conservation

Commission. 2000a. Draft Texas 2000 Clean Water Act Section 303(d) List (August 31, 2000). http://www.tnrcc.state.tx.us/water/quality/00_303dlist.pdf. Accessed 2000 Nov 7.

[TNRCC] Texas Natural Resource Conservation Commission. 2000b. Four TMDLs for VOCs in Clear Creek. http://www.tnrcc.state.tx.us/water/quality/tmdl/clearcreek_voc.html. Accessed 2000 Dec 4.

[TPWD] Texas Parks & Wildlife Department. 1998. Frances' Rains Leave Deadly Legacy: Fish Kills. Sept. 28, 1998. http://www.tpwd.state.tx.us/news/news/980928a.htm. Accessed 2001 May 7. Texas Parks & Wildlife Department. Austin, Texas.

[TPWD] Texas Parks and Wildlife Department. 1997. Texas Wetlands Conservation Plan. Austin, Texas.

[TPWD] Texas Parks and Wildlife Department. 1999. Seagrass conservation plan for Texas. Resource Protection Division, Texas Parks and Wildlife Department, Austin, Texas. p 79.

[TPWD] Texas Parks and Wildlife Department. 2000a. FY1998-1999 recreational hunting and fishing license sales by county. Unpublished data. Austin, Texas.

[TPWD] Texas Parks and Wildlife Department. 2000b. Boat registration for the five counties surrounding Galveston Bay. Austin Boat Registration Office. Unpublished data. Austin, Texas.

[TPWD] Texas Parks & Wildlife Department. 2001. Unpublished data. Texas Parks and Wildlife Department. Seabrook, Texas.

Texas Railroad Commission. 2000a. Oil well counts by county as of September 2000. <http://www.rrc.state.tx.us/divisions/og/information-data/stats/ogowlct.html>. Accessed 2000 Nov 20.

Texas Railroad Commission. 2000b. Gas well counts by county as of September 2000. <http://www.rrc.state.tx.us/divisions/og/information-data/stats/oggwlct.html>. Accessed 2000 Nov 20

Texas State Historical Association. 1999. Handbook of Texas online. <http://www.tsha.utexas.edu/handbook/online/articles/view/CC/hcc9.html>. Accessed 2000 Oct 11.

Titus, J.G. and V.K. Narayanan. 1995. The probability of sea level rise. Environmental Protection Agency No. 230-R-95-008. Washington, D.C.

Tucker, W. J. 1929. Review of Texas wildlife and conservation. Game, Fish and Oyster Commission. Austin, Texas.

Turner, R.E. 1976. Geographic variations in salt marsh macrophyte production: a review. Contributions in Marine Science 20:47-68.

Turner, R.E. 1976. Intertidal vegetation and commercial yields of penaeid shrimp. Transactions of the American Fishery Society 106:411-416.

Turney, J.G. 1958. Shell surveys of Galveston Bay. Horton and Horton. Houston, Texas.

United State Army Corps of Engineers. 1962. Report on Hurricane Carla, 9-12 September 1961. U.S. Army Engineer District, Corps of Engineers, Galveston, Texas.

United States Army Corps of Engineers. August, 2000a. Houston-Galveston Navigation Channel Project Online Resource Center. †http://www.swg.usace.army.mil/hgnc/> Accessed 2000 Sep 21.

United States Army Corps of Engineers. 2000b. Public open house and scoping meeting, Shoal Point Container Terminal Environmental Impact Statement, October 3, 2000. U.S. Army Corps of Engineers Galveston District. Galveston, Texas.

United States Army Corps of Engineers. 2001. Section 10 and Section 404 permits; 1995-2000. U.S. Army Corps of Engineers Galveston District. Galveston, Texas.

United States Bureau of Labor Statistics. 2000. Local area unemployment statistics. †http://data.bls.gov/labjava/outside.jsp?survey=la <http://146.142.4.24/cgi-bin/SeriesHist?lausm 33600003>. Accessed 2001 Oct 1.

United States Census Bureau. 2001. U.S. Census Bureau state and county quick facts, Texas. <http://quickfacts.census.gov/qfd/states/48000.html>. Accessed 2001 Apr 20.

[USDA] United States Department of Agriculture. 1997. Census of Agriculture: state and county highlights. United States Department of Agriculture, National Agricultural Statistics Service. <http://www.nass.usda.gov/census/census97/highlights/tx/tx.htm>. Accessed 2001 Aug 10.

United States Environmental Protection Agency. 1980. A water quality success story, Lower Houston Ship Channel and Galveston Bay. U.S. Environmental Protection Agency Report. Washington D.C.

United States Environmental Protection Agency. 1987. Hazard ranking system package, Tex-Tin Corporation, Texas City, Texas. USEPA 6, Dallas, Texas.

United States Environmental Protection Agency. 2000. Integrated risk information system. Environmental Protection Agency, Office of Research and Development, National Center for Environmental Assessment. http://www.epa.gov/iriswebp/iris/index.html. Accessed 20 September 2001.

United States Environmental Protection Agency. 2001. National Primary Drinking Water Regulations — EPA's Drinking water Standards Environmental Protection Agency, Office of Water. http://www.epa.gov/safewater/mcl.html. Accessed 20 September 2001.

United States Fish and Wildlife Service. 2001. Texas colonial waterbird database. 2001 Aug 8. http://www.quickbase.com/db/7awreh65. Accessed 2001 Jul 12. U.S. Fish and Wildlife Service.

[USFDA] U.S. Food and Drug Administration. 2000a. Foodborne pathogenic microorganisms and natural toxins handbook: hepatitis A virus. http://vm.cfsan.fda.gov/~mow/chap31.html. Accessed 2000 Nov 16.

[USFDA] U.S. Food and Drug Administration. 2000b. Foodborne pathogenic microorganisms and natural toxins handbook: other gastroenteritis viruses. http://vm.cfsan.fda.gov/~mow/chap35.html. Accessed 2000 Nov 16.

Warco, J. (Ed.). 1982. League City: A history from its Beginning to 1912. League City Historical Committees. League City, Texas.

Wade, T., J.M. Brooks, J.L. Sericano, T.J. McDonald, B. Garcia-Romero, R.R. Fay, and D.L. Wilkinson. 1991. Trace organic contamination in Galveston Bay: results from the NOAA National Status and Trends Mussel Watch Program. Shipley, F. S. and R. W Kiesling, editors Proceedings of the Galveston Bay Characterization workshop; 1991 Feb 21-23; Galveston Bay National Estuary Program Publication GBNEP-6. Webster, Texas. p 68-70.

Walton, A.H., and A.W. Green. 1993. Probable causes of trends in selected living resources in the Galveston Bay system. Galveston Bay National Estuary Program Publication GBNEP-33. Webster, Texas.

Wampler, J.M. 1851. Galveston Bay topographical survey. United States Coast Survey.

Ward, G. H. 1991. Galveston Bay hydrography and transport model validation. National Oceanic and Atmospheric Administration, Strategic Assessment Branch, National Ocean Service Report. Rockville, Maryland.

Ward, G.H. 1993. Dredge and fill activities in Galveston Bay. Galveston Bay National Estuary Program Publication GBNEP-28. Webster, Texas. Galveston Bay National Estuary Program Publication GBNEP-31. Webster, Texas.

Ward, G.H. and N.E. Armstrong. 1992. Ambient water and sediment quality of Galveston Bay: present status and historical trends. Galveston Bay National Estuary Program Publication GBNEP-22. Webster, Texas.

Wermund, E.G., R.A. Morton, and G. Powell. 1989. Geology, climate, and water circulation of the Galveston Bay System. Galveston Bay: issues, resources, status and management. National Oceanic and Atmospheric Administration Estuary-of-the-Month seminar series No. 13. Washington, D. C. p 3-22.

White, W.A. and T.R. Calnan. 1990. Sedimentation and historical changes in fluvial-deltaic wetlands along the Texas Gulf Coast: Literature synthesis. Interagency contracts (88-89) 0820 and 1423. Sponsored by the Texas Parks and Wildlife Department, Resource Protection Division. Austin, Texas.

White, W A., and J. G. Paine. 1992. Wetland plant communities, Galveston Bay System. Galveston Bay National Estuary Program Publication GBNEP-16. Webster, Texas.

White, W.A., T.A. Tremblay, E.G. Wermund, Jr., and L.R. Handley. 1993. Trends and status of wetland and aquatic habitats in the Galveston Bay system, Texas. Galveston Bay National Estuary Program Publication GBNEP-31. Webster, Texas.

White, W.A., T.R. Calnan, R.A. Morton, R.S. Kimble, T.G. Littleton, J.H. McGowan, H.S. Nance, and K.E. Schmedes. 1985. Submerged lands of Texas, Galveston-Houston area: sediments, geochemistry, benthic macroinvertebrates, and associated wetlands. Bureau of Economic Geology, The University of Texas at Austin. Austin, Texas.

Whittington, D., D. Amaral, and G. Cassidy. 1993. Research on economic resource valuation studies in Galveston Bay. Jensen, R., R. W. Kiesling, and F. S. Shipley, editors. Proceedings of the second State of the Bay symposium; 1993 Feb 4-6; Galveston Bay National Estuary Program Publication GBNEP-23. Webster, Texas. p 361-362.

Wiegert, R.G. and B.J. Freeman. 1990. Tidal salt marshes of the southeast Atlantic coast: a community profile. U. S. Fish and Wildlife Service Biol. Rep. 85(7.29).

Wilkins, K.A., M.C. Otto and P.R. Garrettson. 2001. Trends in duck breeding populations, 1955-2001. U.S. Fish and Wildlife Service Administrative Report. Laurel, MD.

Willett, K.L., S.J. McDonald, M.A. Steinberg, K.B. Beatty, M.C. Kennicutt and S.H. Safe. 1997. Biomarker sensitivity for polynuclear aromatic hydrocarbon contamination in two marine fish species collected in Galveston Bay, Texas. Environmental Toxicology and Chemistry 16:1472-1479.

Wilson-Ormand, E.A., E.N. Powell and S.M. Ray. 1997. Short-term and small-scale variation in food availability to natural oyster populations: food, flow and flux. Marine Ecology 18(1): 1-34.

Wolf, G.E., Jr. 1991. Amateurs guide to the pleistocene fossils of the Texas City Dike. Deepwater Museum. Pasadena, Texas.

WPA. 1936. 1853 Causeway bridge contract. The Center for American History, University of Texas at Austin. Galveston, Texas.

Zein-Eldin, Z.P. 1961. Plankton pigments in East Lagoon, Galveston, Texas. Transactions of the American Fisheries Society 90:32-41.

Zieman, J.C. and R.T. Zieman. 1989. The ecology of the seagrass meadows of the west coast of Florida: a community profile. U.S. Fish and Wildlife Service Biol. Rep. 85(7.25).

Zimmerman, R.J., T.J. Minello, T. Baumer, and M. Pattillo. 1991. Can Galveston Bay fisheries benefit from marsh creation? Jensen, R., R. W. Kiesling, and F. S. Shipley, editors. Proceedings of the second State of the Bay symposium; 1993 Feb 4-6; Galveston Bay National Estuary Program Publication GBNEP-23. Webster, Texas. p. 223-230.

Zotter, J. 1979. Species composition and seasonal occurrence of nanoplankton in the Galveston Bay estuary. Master's Thesis, Texas A&M University. College Station, Texas.

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