The State of the Bay

A CHARACTERIZATION OF THE GALVESTON BAY ECOSYSTEM

A Publication of

The Galveston Bay National Estuary Program

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Preface

Galveston Bay is a resource of immense value to Texas and the nation. It is also an exceedingly interesting coastal ecosystem. In this volume, produced by the Galveston Bay National Estuary Program, these two features highlight a comprehensive review of the State of the Bay—an overview of the ecosystem from an environmental management perspective.

Our purpose in undertaking this ambitious task was clear: we sought to establish a factual basis for improving the way we govern Galveston Bay. This book is about stewardship, providing information that is one step removed from the hands-on management of bay resources, but which nevertheless is absolutely vital for effective conservation in the long run. Specifically, we sought to understand the State of the Bay in order to draft *The Galveston Bay Plan*, a comprehensive blueprint for bay governance. In this role, this book may well help determine the State of the Bay twenty, or even fifty years hence.

The work leading to completion of this book has a significant history. In 1987, the United States Congress designated Galveston Bay as an Estuary of National Significance in its passage of the Water Quality Act of 1987. Along with other nationally significant bay systems on all three coasts, Galveston Bay was recognized for its premier values to man—economic, biological, and cultural. Through this legislation, Galveston Bay entered the National Estuary Program (NEP), a focused attempt to remedy the pressing problems affecting bays besieged by human pollution, development, and overuse.

Based on lessons learned from Chesapeake Bay in the mid-1980s, the National Estuary Program prescribed reliable science as the basis for comprehensive bay management. For Galveston Bay, this process began with the support of an ad hoc consortium of university, agency, and private sector scientists interested in Galveston Bay. Leaders of this consortium presented a seminar in Washington, D.C. on March 14, 1988, to key federal agencies and legislators. They described the physical, biological, and economic significance of the bay and produced a seminal report which identified critical bay issues and associated information needs (*Galveston Bay: Issues, Resources, Status, and Management,* number 13 in the National Oceanic and Atmospheric Administration Estuary-of-the-Month series, 1989).

Shortly thereafter, a Scientific/Technical Advisory Committee (STAC) was appointed by the Governor and Environmental Protection Agency Regional Administrator as part of the Galveston Bay NEP Management Conference, a consortium that would develop *The Galveston Bay Plan.* The STAC would provide scientific and technical guidance to the Management Conference by identifying estuarine problems and by overseeing studies to establish the trends and probable causes necessary for management action (a list of these projects is given on page 23). The STAC began their work in March, 1989 and convened symposia in 1991 and 1993 (both of which resulted in published proceedings). The culmination of the Committee's work is this volume.

The work undertaken by the STAC from 1989 through 1994 has been the most ambitious yet attempted for Galveston Bay on an ecosystem scale. In commencing this work, some guiding principles were agreed upon, establishing a clear focus for projects, and preventing the distraction of research proposals on peripheral issues. These principles were:

> Projects would address an understanding of estuarine problems agreed upon by the entire Management Conference (reflecting a consensus among all the varied participants with interests in the bay);

The focus would be on analysis of existing data, with new data collected only to fill identified data gaps; and

Projects would be completed in time for use in creating *The Galveston Bay Plan*. Pure research questions and long-term investigations, while recognized as important, would not be funded.

When this work began in earnest, the high level of commitment to Galveston Bay on the part of the scientists involved produced a level of effort far out of proportion to the available time and money. The efforts of STAC members and many of the project principal investigators and reviewers frequently exceeded the call of duty. Additional zeal was sparked by the synergism of simultaneously addressing different research questions in a collaborative ecosystem context.

Much work was accomplished by university scientists, and some projects were contracted to private consultants. But throughout the process, state and federal natural resource agencies played a key role. These agencies employ numerous highly committed scientists and resource managers engaged in projects with a bearing on Galveston Bay. For example, the existing two-dimensional (length and breadth) hydrodynamic models were believed inadequate to address the potential impacts which might result from deepening and widening of navigation channels. A three-dimensional (length, breadth, and depth) model has been developed by the U.S. Army Corps of Engineers and their Waterways Experiment Station, with a budget that exceeds the total Galveston Bay National Estuary Program program budget. Similarly, the determination of fresh water inflow needs of the bay relied on the development and implementation of a Texas Water Development Board model.

Some questions were necessarily addressed with use of cursory surveys rather than full-scale studies. For example, the Texas Department of Health has been hampered for years by inadequate funding to determine the accumulation of toxic substances by seafood organisms. Although the public identified this issue as a priority problem, high analytical costs have placed constraints on this type of work. A full-scale detailed survey, while perhaps justified, would have consumed the entire Galveston Bay National Estuary Program scientific budget.

In describing the State of the Bay, we have attempted to simplify and summarize this wealth of new understanding. You will find conclusions which differ from "conventional wisdom" and prior opinions. The effects of early human interventions, some more than a century old, clearly emerge. Such projects as the Texas City Dike, the navigation channels, and petroleum and groundwater extraction, have fundamentally altered the ecosystem. Throughout the presentation, we have sought to guide the interested reader to publications that can amplify what is presented here.

Above all, the difficulty of managing Galveston Bay as a self-sustaining ecosystem clearly emerges. We have discovered that the most compelling problems afflicting Galveston Bay are truly ecosystem problems, not limited to individual natural resources, nor circumscribed by political boundaries. In solving these problems, decades of traditional, narrowly focused management practices will be difficult to overcome—the governance of the bay remains a tangled mosaic of narrow and fragmented jurisdictions and public policies. Now, however, our appreciation of the myriad connections between human activities and bay components is greatly enhanced. Each action, however great or small, has produced an effect elsewhere. It is truly impossible to do merely one thing in an ecosystem; our challenge is to establish stewardship that mirrors this fundamental truth.

—Robert W. McFarlane
Frank S. Shipley

January, 1994

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ENDORSEMENT OF THE SCIENTIFIC/TECHNICAL ADVISORY COMMITTEE

This volume is the culmination of five years' effort by the Scientific/Technical Advisory Committee of the Galveston Bay National Estuary Program. Its purpose is to improve future management of Galveston Bay by acquiring the most complete scientific and technical understanding possible. On November 4, 1993 the Scientific/Technical Advisory Committee approved the contents of this document by unanimous consent, forwarding their findings to the Management Committee. On November 17, 1993, the Management Committee ratified the work of the Scientific/Technical Advisory Committee, also by unanimous consent. Finally, in January, 1994, the Policy Committee granted final approval for publication and approved the distribution of this work to the citizens of the Galveston Bay region, Texas and the Nation.

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Many individuals also helped us complete this project. The overwhelming complexity of the Galveston Bay ecosystem required that we adopt a multi-disciplinary approach to draw from such diverse fields as engineering, biology, physics, economics, ecology, and chemistry. When we sought to involve some of the foremost practitioners in these disciplines in the work of advancing our knowledge of the State of the Bay, we received an exceedingly positive response. Only a collaborative approach could possibly have produced this work, and it is with a great sense of accomplishment that we thank our many contributors.

Our help came in phases as the work progressed. First, more than two dozen specific studies of the estuary were commissioned, most of which were major collaborative projects in themselves. The authors of these special studies drafted reports published in the Galveston Bay National Estuary Program publication series (these reports are cited throughout the work). Their efforts frequently (but not always) exceeded the expectations of reviewers and the level of funding provided. In many instances, wording from these authors has been directly adopted by the contributing authors of this work. Principal project investigators, and others who contributed substantially to our efforts to characterize Galveston Bay, include:

Neal Armstrong, Richard Allison, Phil Bedient, Clyde Bohmfalk, James Brooks, Scott Carr, Roger Durand, Bill Evans, Robert McFarlane, Roger Fay, Al Green, Tom Greib, Galveston Bay Foundation, George Guillen, Dick Gorini, Larry Handly, Margaret Henson, Cindy Howard, Paul Jensen, Robert Nailon, James Nance, Charles Newell, Eduardo Martinez, Anita Morgan, Dennis Palafox, Victor Palma, Cathy Palmer, James Pateck, Eric Powell, Hanadi Rifai, R. Will Roach, Gary Saul, Edward Seidensticker, Priscilla Seymour, Mark Shibata, Annie Walton, George Ward, E. G. Wermund, Natalie Wiest, Dale Whittington, Nancy Worst.

Initial drafts by the contributing authors of this volume were assembled with ongoing help from the staffs of Groundwater Services, Incorporated (particularly for creation of the figures), the Rice University Department of Environmental Science and Engineering, and the Galveston Bay National Estuary Program. Most chapters were then submitted to a team consisting of several to numerous reviewers, led by a "Designated Reviewer" conscripted by the Scientific/Technical Advisory Committee. Designated Reviewers were responsible for the complex task of compiling review comments and determining the acceptability of revisions. The expertise of the Designated Reviewers in the estuarine disciplines, and the sheer time and effort devoted to the review process provided valuable improvements to the developing work. The Designated Reviewers were:

Chapter Four	Glenda Callaway;
Chapter Five	E. G. Wermund;
Chapter Six	George Guillen;
Chapter Seven	Will Roach;
Chapter Eight	Al Green;
Chapter Nine	Kirk Wiles.

The peer-reviewed chapters were then reassembled and the compiled draft work was distributed to members of the Scientific/Technical Advisory Committee and other committees of the Galveston Bay National Estuary Program, and to staff members of several state and federal resource agencies involved in the work. At this point, the draft document was fair game to approximately one hundred and twenty individuals, many of whom took up the torch to suggest substantial additional improvements. In alphabetical order (and with varying levels of torch-bearing), these were:

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Finally, the entire text was edited, re-drafting many sections to incorporate review suggestions and additional information. At this point, photographs were obtained from various sources and archived at Imáge Realize, Inc. (noted throughout the text) to illustrate various points. Design and layout were accomplished by Anne Darrah and Calzone and Associates to yield a seamless and appealing final product. Pre-press and printing were done in Houston, Texas by Imáge Realize, Inc. and Lee Printing.

These, then, are the individuals who have helped define the State of the Bay, circa 1994. We thank this spirited group of contributors, one and all.

—Frank S. Shipley
Russell W. Kiesling

A Note to the Reader

This book is organized in three sections: an overall summary of findings and their implications (Chapter One); an introduction to Galveston Bay, its watershed, and its uses (Chapters Two, Three, and Four); and specific discussions of key aspects of the ecosystem (Chapters Five through Nine).

Chapter One encapsulates bay management issues in the form of seventeen key conclusions. These conclusions are of central importance to *The Galveston Bay Plan*, a comprehensive conservation and management plan drafted by the Galveston Bay National Estuary Program to guide future stewardship of this estuary. Chapter One, in this sense, can stand alone as a summary for managers and policy makers.

Chapters Two, Three and Four introduce the reader to Galveston Bay itself, providing a context for presentation of specific technical findings in the remainder of the book. Chapter Two provides a generalized overview of the estuary and its watershed, and an introduction to the effects of human activities. Chapter Three describes the "interconnectedness" of the various components of the estuary: a conceptual model is used to show how various bay habitats compose the functioning estuarine ecosystem. Chapter Four provides a brief history of the bay from pre-settlement to the present, emphasizing contemporary diverse uses and values associated with its resources.

The remainder of the book is a more detailed and technical presentation of specific subject areas. Chapter Five describes the physical form and processes of the bay and its watershed. Here the emphasis is on fresh water inflow and physical factors like wind and tides, which influence hydrology and circulation. Human alterations, particularly to enhance navigation, have profoundly affected some of these physical processes, which underlie many biological functions and affect the fate and effects of pollutants.

Water and sediment quality issues are presented in Chapter Six. A review of water quality parameter definitions is followed by a summary of water and sediment quality status and trends. The role of point sources of pollution ("end of the pipe") and nonpoint sources (transported as rainfall runoff) in determining overall environmental quality are addressed. A synthesis of this information highlights the relative importance of different sources of pollution–as they affect the bay as a whole, and for the upper Houston Ship Channel where the impacts are greatest.

Chapter Seven is devoted to wetlands and oyster reefs–key habitats which give rise to much of the abundant life in the bay, and which support important commercial seafood fisheries in both the bay and (in the case of wetlands) the larger Gulf of Mexico. Wetlands and oyster reefs also serve important natural roles in maintaining water quality. The changes in these critical habitats since the 1950s are identified with reference to the probable causes of trends, where causes are sufficiently known.

Chapter Eight describes status and trends for particular species of plankton, benthos (bottom-dwellers), shrimp, crabs, fish, birds, alligators, turtles, and dolphins. Galveston Bay teems with life, but declines in the populations of certain species pose management concerns. Living species not only support the economy and aesthetic values, they also serve as indicators of overall environmental health and life-support capability of the ecosystem.

Chapter Nine addresses the safety of eating Galveston Bay seafood and engaging in contact recreation in its waters. To the general public, these issues are frequently among the most important and controversial of all. Information is presented on bacterial contamination affecting oyster reef harvest closures, the concentrations of toxic compounds in seafood organisms, and the resulting levels of potential risk to consumers.

Finally, the Epilogue points toward the future of Galveston Bay. How can knowing "The State of the Bay" today help us determine its fate tomorrow and decades hence? Public policy makers and the larger

community of individuals, organizations, enterprises, and agencies which depend upon or interact with this remarkable section of Texas coast are called upon to take up the challenge for stewardship.

Throughout, this book uses several conventions aimed at augmenting its value to those interested in learning more about Galveston Bay. Selected technical terms are printed in boldface where they first appear and are defined in the glossary. At the conclusion of each chapter, additional reading is recommended under the heading "For More Information." Citations are given throughout the text, listed in the "References" section. However this book is not primary scientific literature, and does not use the same rigor for citations as technical journals. One of the values of this volume is its compilation of previously unpublished, sometimes obscure information. Reports which were either unpublished or published with limited distribution were frequently consulted.

CHAPTER ONE

On Knowing the State of the Bay

If we don't change direction we are apt to end up where we are headed.

–Old Chinese Proverb, appropriated for estuaries by J. R. Schubel

The information summarized in this volume was gathered for a single unifying purpose: to improve our management of the valued resources of Galveston Bay. Establishing this factual foundation for management relied on defining the status of key bay resources, identifying their trend over time, and determining probable causes for any trends emerging as concerns.

In three sections, this chapter addresses the significance of this process and the resulting findings. First, a brief overview is presented concerning the relationship between scientists and resource managers, whose fundamentally different world views influence the effectiveness of bay problem-solving. Second, some significant and unexpected findings regarding the **estuary** are described, prompting a re-definition of how we manage the bay. Finally, in the bulk of the chapter, seventeen key conclusions are stated in the form of management issues. These are the problems that need to be addressed in future comprehensive management of the estuary. In total, this chapter encapsulates the management implications of the information presented in this book.

BOUNDARIES TO GUIDE SCIENTISTS AND RESOURCE MANAGERS

To manage the important and varied resources in this bay system, managers agreed they needed the right kind of information. But how can the infinite scope of possible research projects be narrowed to those which are relevant and meaningful? As Tuohy (1993) has noted:

> *There is more potential information about the world (or even a large estuary) than our intellects can grasp, so much so that the universe for all practical purposes can be described as infinite... And if the mere number of phenomena and relationships at any given time were not enough, there is constant change, adding to the complexity of the universe we are trying to understand.*

Generally speaking, scientists are interested in all of the infinite information that can be gathered about an estuary, so long as it contributes to new knowledge. Managers, by contrast, expect concise answers to certain short-term questions that help solve bay problems. Clearly, some sort of agreed-upon guidance is necessary for these diverging views about information to be reconciled. Certain conceptual boundaries therefore, apply to scientific activity aimed at providing information to managers, summarized by Shipley (1991):

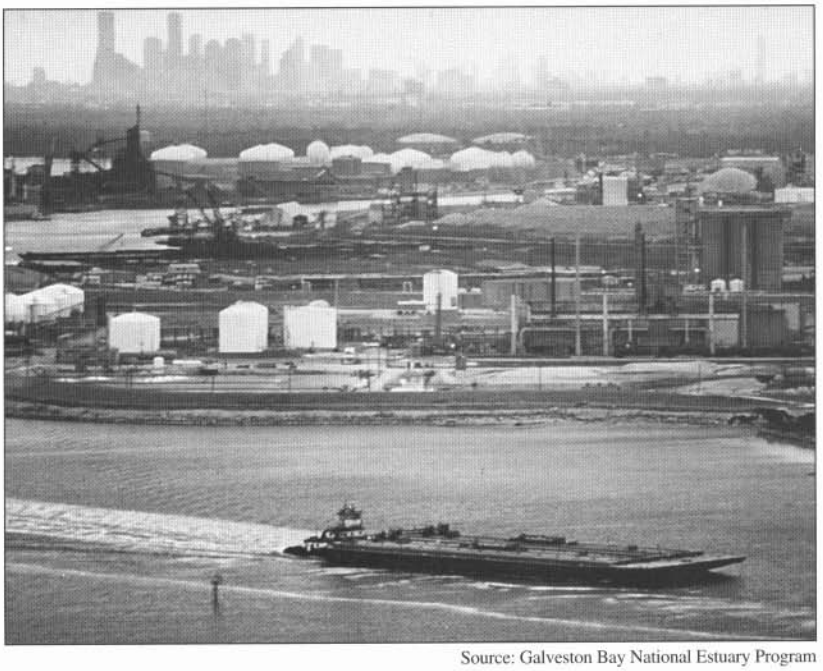
> Projects must address the right questions, requiring that managers have a role in identifying and ranking project topics;
>
> Work must be undertaken in the context of a perturbed ecosystem, requiring that projects focus on impact dynamics rather than traditional ecology alone;
>
> Research must provide data at a scale of resolution

applicable to management, requiring generalized geographic ordering of projects and sampling within projects;

Results must be available to managers in an accessible, useful format, requiring that data be converted to synoptic information; and

Ongoing work must fulfill a sensory feedback function to managers, requiring a monitoring program with a direct link to management objectives.

Within these conceptual boundaries, a practical mechanism must then be agreed upon to tailor research to the particular ecosystem issues of concern. The first step for such a process was established by the National Estuary Program guidance itself, from lessons learned mainly in Chesapeake Bay. A *Priority Problems List* identifies and ranks estuarine management issues, serving as a focal point for consensus about where to begin. Generally, issues are advanced in this process if they have system-wide impact, impair designated uses, or (more practically) if they can be quickly or cheaply fixed. The key feature of the *Priority Problems List* is that it be adopted by the consensus of managers, scientists, and bay **stakeholders** represented on the Management Conference. In the event of disagreement, managers carry the day, in observance of the first conceptual boundary listed above.



Source: Galveston Bay National Estuary Program

Galveston Bay: how can we identify and solve its problems? Shown here is the upper Houston Ship Channel, surrounded by petrochemical industries (center), shipping activities (foreground) and the skyline of Houston (background).

For Galveston Bay, the preliminary *Priority Problems List* was drafted by scientists based upon joint expert opinion. The list was then adopted by consensus of the Management Committee, but not before concerns about estuarine living resources were elevated above public health issues, reversing their original order. Notwithstanding controversy engendered by managers second-guessing scientists, the list survived to guide the expenditure of more than two million dollars in research funding.

To managers, the best use of the *Priority Problems List* was to prevent distractions from scientists seeking to fund projects which (although they addressed issues intensely interesting to the proposers) did not help managers. To scientists, the list became a set of broadly-stated hypotheses to be strengthened or refuted.

Hypotheses must by falsifiable to be scientifically valid, and some of the most interesting work conducted during the research program resulted in the falsifying of some long-held conventional wisdom about Galveston Bay. This process led to a productive redefinition of estuarine problems, summarized in the bulk of this chapter. First, however, consider several of the most significant novel findings which shape future specific management efforts.

UNEXPECTED FINDINGS

Good science frequently yields unexpected truths which turn out to be more interesting than the speculations which naturally begin the scientific process. For Galveston Bay, our understanding of even the most fundamental estuarine processes is being reshaped. Summarized below are four issues at the heart of managers' needs to understand the estuary.

Salinity

Conventional wisdom suggests the bay is threatened by a harmful increase in **salinity** resulting from human diversion of river **inflow** and intrusions of Gulf sea water landward through dredged channels. However, Ward and Armstrong (1992) revealed a three-decade general *decline* in bay salinity totaling more than four parts per thousand (specific trends vary throughout the bay). Supporting evidence was provided by Solis and Longley (1993) who indicated no significant decreases in inflow for both the Trinity River (the principal source of fresh water) and for the **watershed** as a whole. In their findings, four of the most urbanized bayous showed *increasing* flow since the 1960s, perhaps related to increases in **impervious cover** (development) and increased **return flows** of wastewater, including **groundwater**. Low flows along the main stem of the Trinity and in some tributaries (e.g. during droughts) are today apparently several times greater than historically. Overall, salinity dynamics in Galveston Bay have proven more obscure, complex and intractable (even to hydrodynamic modelers) than we previously knew.

Nutrients

Sixty percent of the wastewater in Texas flows to Galveston Bay, and much of the upper watershed consists of cultivated and urban lands with high nutrient runoff potential. These observations engender a concern for nutrient over-enrichment, a concern en-

Source: Frank S. Shipley

Several species of herons have shown population declines in Galveston Bay. These egrets nest in colonies (below) and disperse each day to feed along shallow marshy shorelines (above). In the Galveston Bay system, some 30,000 ac of wetland habitats have been lost since the 1950s.

Source: Frank S. Shipley

couraged by well-documented **algae blooms** and dissolved oxygen depletion in the literature for east coast estuaries. However, Ward and Armstrong (1992) revealed a substantial general *decline* in the **loading** of nutrients to Galveston Bay, with localized exceptions. We now know that lakes Houston and Livingston serve as efficient nutrient traps which alter bay nutrient dynamics.

Improved wastewater treatment by cities and industries has established a trend of reduced point source loadings. A future **phytoplankton** population crash and the demise of some of Galveston Bay's oyster reefs within the next decade have even been suggested and vigorously debated. At the least, findings have shifted management interest away from bay-wide point source and river loadings to more specific urbanized tributaries where fish kills and dissolved oxygen problems suggest **nonpoint source** problems.

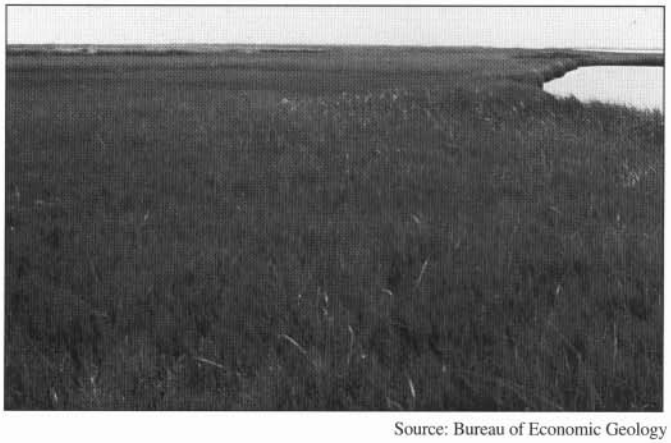
Wildlife, Fish and Shellfish

White et al., (1993) have reported a 17-19 percent loss in **emergent wetlands** since the 1950s. The leading single cause of **habitat** loss (greater than 26,000 ac) was conversion to open water/barren flats (e.g. from land **subsidence** due to groundwater withdrawal). Urban development unexpectedly accounted for less

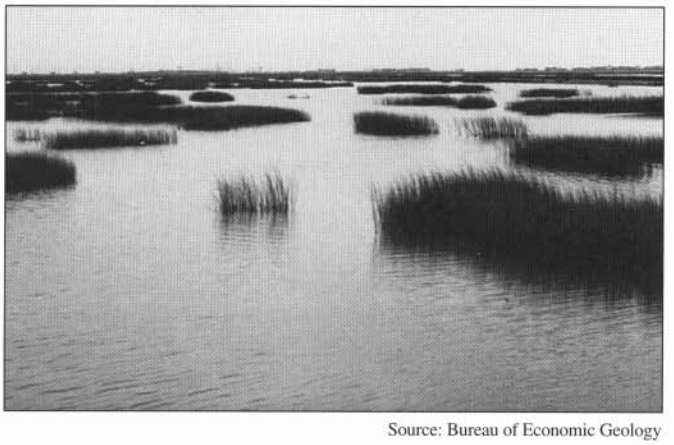
than ten percent of the **wetland** loss. In spite of the substantial habitat losses, the living resources trend studies of Green et al. (1992) revealed chronic declines for just two of fourteen **finfish** and shellfish species analyzed: blue crabs and white shrimp. Perhaps the most troubling findings concerned bird species which feed at the marsh-bay interface (tricolored herons, snowy egrets, black skimmers, roseate spoon bills, and great egrets). A decline for this **guild** of estuarine-dependent species could be the direct result of habitat losses, or the indirect result of declines in habitat-dependent species preyed upon by the birds. Overall, findings lend hope that habitat losses can be stemmed before major marine species crashes occur of the sort seen in Chesapeake Bay.

Toxicants

Toxic contamination has emerged as a complex and difficult issue for Galveston Bay. Brooks et al. (1992) indicated potentially elevated risk to individual recreational or subsistence seafood consumers, based on tests of seafood organisms from four locations not associated with known potential contaminant sources. Highest concentrations of **toxicants** generally occurred in the upper bay.



Source: Bureau of Economic Geology



Source: Bureau of Economic Geology

A major cause of wetland losses in the estuary has been land subsidence, primarily due to the removal of groundwater for human use. Healthy fringing salt marsh (left) is drowned by increasing water depth (right), leading to eventual losses of vegetation and conversion to open water. These wetlands are nursery areas for numerous commercial and recreational species.

These findings contrasted with commercially-taken seafood (generally from the lower bay, and eaten in smaller quantities) found to be within accepted risk levels. In a separate study, Carr (1993) reported on some sites more specifically associated with contamination. Half of these locations resulted in toxicity to developing sea urchin (*Arbacia punctulata*) embryos exposed to extracted **pore water** from bay-bottom sediments. In contrast, no sites were indicated toxic with parallel tests using a different standardized exposure of **amphipods** to bay sediments. Findings highlight the need for development of sediment standards, the improvement of analytical techniques, and (perhaps most importantly) improved **risk analysis** and communication of risks to the seafood-consuming public.

A REVISION OF MANAGEMENT EXPECTATIONS

One conclusion, at least, is clear: expert opinion alone would have failed to serve managers well in solving bay problems. The thrust of the *Galveston Bay Plan* relies upon findings summarized in this volume, validating the role of scientists in the management process. Estuarine problems were re-cast in light of the new knowledge, resulting also in a subsequent re-ordering in their emphasis.

What are Galveston Bay's management needs? Seventeen issues have emerged from the bay characterization process as worthy of our attention over the next several decades. Characteristic of any ecosystem, these management concerns can never be completely separated from one another. For example, nonpoint sources of pollution contribute to both habitat degradation and toxic contamination of sediments; declining populations of certain estuarine and estuarine-dependent species could relate to both habitat loss and/or water quality problems. These interconnections suggest that actions to solve the bay's problems also be undertaken in the context of an integrated, ecosystem-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.*

> ***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 Seven).***

Wetland losses in the entire estuarine system were described by White et al. (1993). From the 1950s to 1989, there was a net 17 to 19 percent loss of vegetated wetlands totaling some 32,400 ac. Encouragingly, the rate of loss has decreased over time from about 1,000 ac per year between 1953 and 1979, to about 700 ac per year between 1979 and 1989. The leading causes of wetland loss were conversion to open water or mud flats (principally a result of subsidence from groundwater withdrawal and conversion to upland range (in which intentional draining of wetlands played a major

role). Wetland conversion of some 25,000 ac to upland range dominated the conversion to other kinds of upland land uses consisting of urban, oil and gas, agricultural, and dredge disposal land uses totaling 11,000 ac.

In comparison to wetlands, a far greater proportion of the bay's historical submerged aquatic vegetation beds (primarily **seagrasses**) have been lost. Seventy to 86 percent of this significant habitat type has been lost since the 1950s, due to a complex and interactive group of causes which includes subsidence, Hurricane Carla, shoreline development, wastewater discharges, chemical spills, boat traffic, and dredging (Pulich and White, 1991).

Taken together, these declines in biologically productive habitat directly threaten future seafood productivity and the capacity for Galveston Bay to function as a healthy ecosystem. Major species declines noted in other bay systems with more advanced problems have not yet occurred in this estuary, making management intervention all the more feasible.

2. Contaminated runoff from nonpoint sources degrades the water and sediments of some bay tributaries and near-shore areas (Chapter Six).

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., 1992a). For example, nonpoint loading to the estuary for many pollutants exceeds the combined total loading from all other sources: the San Jacinto and Trinity Rivers, municipal discharges from treatment plants, and industrial sources. This is true for **total suspended solids** (particularly sediment), oxygen-demanding pollutants, **fecal coliform bacteria**, total phosphorus, and oil and grease. For example, oil and grease washing into the bay in an average one-year period is approximately equivalent to 40 percent of the historic *Exxon Valdez* spill.

The geographic sources of these pollutants within the watershed were reported in an atlas of high-resolution maps (Newell et al., 1992b) which clearly associates the most severe nonpoint source problems with urban/industrial land uses. For example, some 90 percent of the oil and grease loading originates in sub-watersheds with high-density urban land uses. Within sub-watersheds, the origins of pollutants are transportation activity, **atmospheric deposition** of air pollutants, residential yards and households, purposeful and inadvertent dumping on land and to storm drains, and a host of other diffuse human sources.

The impact on the bay from all these sources, while clearly present, is incompletely defined. Runoff mingles with wastewater from point sources and river flow to produce water quality problems to which individual causes cannot easily be ascribed. We know, however, that nonpoint sources have become our greatest water quality challenge. The imposing analysis by Ward and Armstrong (1992) of 26 Galveston Bay data sets indicates the influx of conventional pollutants from both point sources and river flow (summarized in Chapter Six) peaked in the 1960s and has declined since. In contrast, all indications are that nonpoint sources of pollutants have steadily increased to the present day. Principal effects of the nonpoint source pollutants include:

Low levels of dissolved oxygen in urban bayous and other poorly flushed tributaries;

Possible toxic contamination of sediment and living tissue from metals or trace organics like **Polycyclic Aromatic Hydrocarbons (PAHs)** washed off streets with runoff (PAHs are a family of toxic compounds from petroleum and its combustion in engines and industrial processes); and

Closure of half of the bay to oyster harvest, due to elevated bacteria levels.

The upper Houston Ship Channel remains the most significant region of concern, due in large part to runoff from the greater Houston area.

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 a challenge. But on the positive side, national legislative mandates for stormwater cleanup under the National Pollution Discharge Elimination System (NPDES) and special mandates for coastal zones will contribute much of the momentum and some of the dollars necessary to address the issue.

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

As cities in the Galveston Bay watershed have grown, their aging sewage collection systems have suffered from soil settlement, corrosion, and larger-than-design flows. As a result, leaks allow entry of stormwater during wet periods, exceeding the capacity of lines, lift stations, and treatment plants. The ultimate 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).

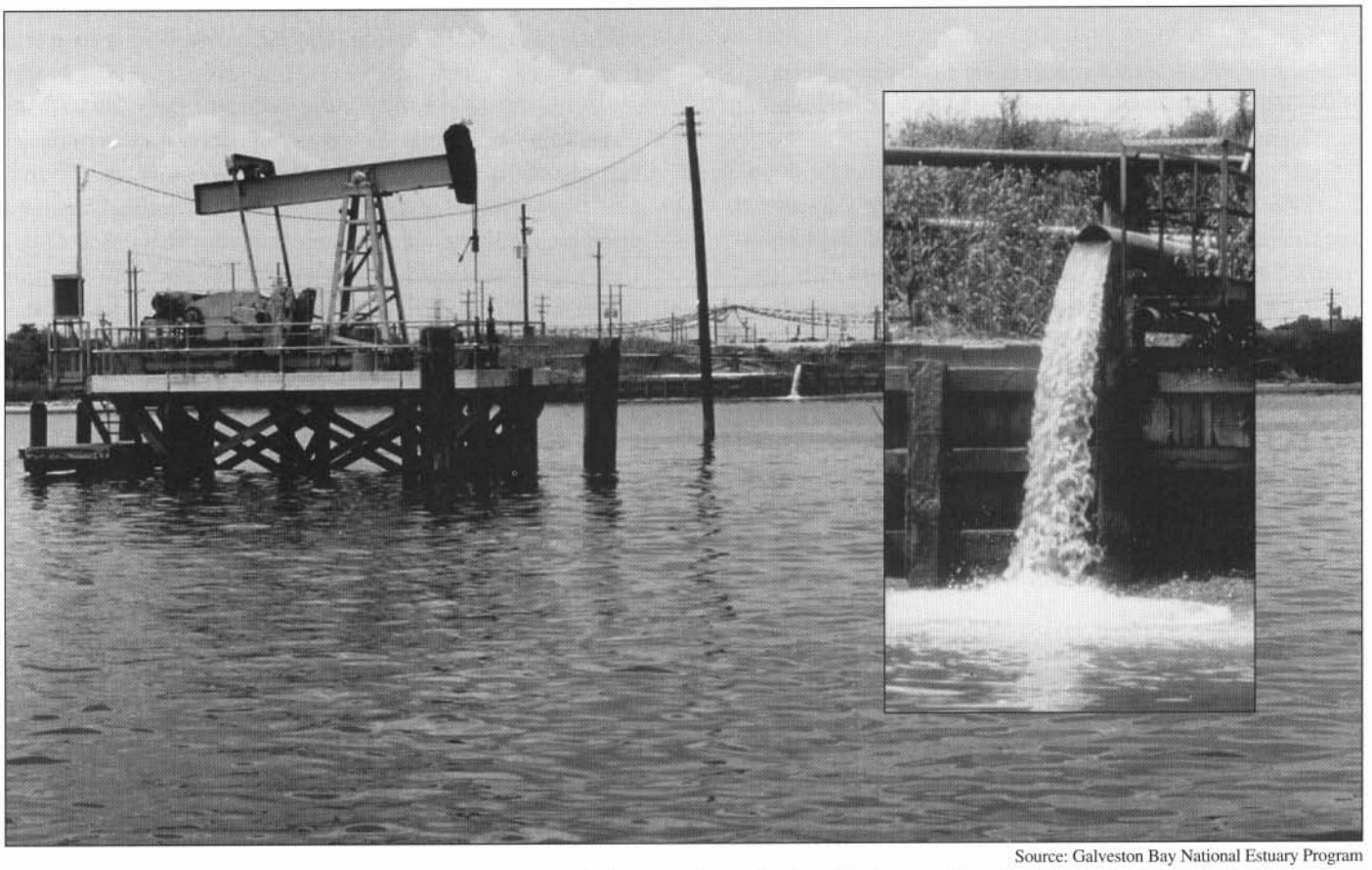
One study (Winslow and Associates, 1986) indicated that the total loading of Biochemical Oxygen Demand (BOD) from bypasses and overflows to the Houston Ship Channel was 3.1 million kilograms per year (equivalent to an average value of 18,900 pounds per day) or about 11 percent of the annual BOD load to the Houston Ship Channel from all sources. In response to an Environmental Protection Agency initiative, the City of Houston undertook a major construction project to improve and expand the city's underground wastewater collection system. A series of deep tunnels are being constructed to eliminate bypasses and overflows for all but the largest rainfall events (greater than two to five year frequency storms).

More recent information (Guillen et al., 1994) provided a total of 789 and 578 reported instances of sewage bypasses in the Galveston Bay watershed during 1991 and 1992 respectively. An estimated 237.3 and 451.0 million gallons of partially treated sewage were discharged from these bypasses during 1991 and 1992 respectively. The majority (85 to 93 percent) of these occurred in the immediate Galveston Bay Watershed.

This issue involves more than the City of Houston. Surrounding Houston, but still in the Galveston Bay watershed, are numerous small independent utility districts. These small operations are not subject to state and federal regulatory requirements as stringent as larger metro treatment works, and individually, the districts cannot afford the same level of operation and maintenance attention. Collectively their discharges have substantial effects on several urban bayous which are dominated by wastewater during dry periods.

ary, and many species of fish, wildlife, aquatic plants, and shellfish depend on adequate fresh water inflows for survival. The continued high productivity of Galveston Bay is due to a great degree on the maintenance of adequate, high-quality fresh water inflow.

The increased demands for fresh water by a growing population along with the construction of surface impoundments and diversions are widely perceived as having reduced fresh water inflow to the bay over time. (Of course, natural variability in rainfall explains far more of the variability in inflow to Galveston Bay than does human activity.) However, an analysis of fresh water inflow trends for the period from 1968 to 1987 did not identify statistically significant trends which would indicate a reduction of fresh water inflow volume from the Trinity River, or within the estuary as a whole. Four of the most urbanized streams which discharge into the bay (White Oak Bayou, Brays Bayou, Sims Bayou, and Greens Bayou) all exhibit increasing flow since the 1960s (one



Source: Galveston Bay National Estuary Program

Toxic contamination of sediments and the bottom-dwelling biological community results from discharges of "produced water," a by-product of oil and gas production. Here, wells in the Goose Creek oil field collect produced water for ultimate discharge at a shoreline outfall (background and inset).

4. Future demands for fresh water and alterations to circulation may seriously affect productivity and overall ecosystem health (Chapter Five).

The biological communities living in and around Galveston Bay are largely defined by the volume, timing, and quality of fresh water inflows into the bay from surrounding drainage basins. Fresh water inflows affect **circulation** and water quality within the estu-

to three percent per year on average), likely due to increases in impervious cover (such as parking lots, buildings, and roads) and increased return flows of wastewater.

On a seasonal basis, fresh water inflow to the estuary is normally characterized by peak springtime inflows in May followed by minimum inflows in August. Comparison of monthly mean flows before dam construction (1941-1969) and after dam construction (1972-1987) 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.

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

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 in a water solution or suspension. Once in the bay, toxicants can remain in the water, or (more commonly) are incorporated in bottom sediments. Water and sediment-dwelling species can accumulate toxic compounds, affecting the composition and health of living estuarine communities. Toxicants can cycle back and fourth among the water, sediment, and tissues of living organisms. These patterns are shaped by hundreds of influences: which chemical compounds are involved; bay water chemistry; sediment grain size; and overall patterns of water circulation and movements of life forms. Measurement technologies, which are complex and expensive, impose another layer of uncertainty on our state of understanding. In addition some water quality limits are set below analytical detection limits, further complicating the issues.

In *water*, Ward and Armstrong (1992) described elevated levels of oil and grease, metals, and trace organics in regions of waste discharge and runoff, with generally the highest values in the upper Houston Ship Channel. Encouragingly, most of the metals are declining in areas of maximal concentrations, possibly because suspended solids (to which metals bind) have shown a decline. Typically, levels of toxic contaminants in open bay waters are below detection limits.

In *sediments*, Ward and Armstrong also showed elevated contaminant concentrations in regions of runoff, inflow, and waste discharges. Carr (1993) measured elevated concentrations of PAHs of a composition that suggested both long-term chronic and short-term acute sources (depending upon sampling location). PCBs (Polychlorinated Biphenyls, once common in transformer and hydraulic oil) were detected at several stations.

In *tissue*, various studies have measured contaminants in a variety of species. Oysters, for example, are employed as a **sentinel species** (a biomonitor for contamination) in the National Oceanic and Atmospheric Administration's National Status and Trends "Mussel Watch" program. In reports by Wade et al. (1991), PAHs were measured in a form suggesting contamination by combustion products. Concentrations of contaminants in oysters from the upper estuary were generally above Gulf of Mexico averages. Sericano et al. (1991) transplanted oysters from an open bay reef to the Houston Ship Channel (above Morgans Point) and demonstrated dramatic concentration increases over a period of seven weeks for most organic compounds measured (including toxic PAHs and PCBs).

Ultimately, toxic contaminants have effects on both the bottom-dwelling bay **community** (Carr, 1993; Roach et al., 1993a, 1993b), on estuarine-dependent species like **colonial-nesting** birds (Rice and Custer, 1991), and upon the risk associated with human consumption of seafood (Brooks et al., 1992; see problem nine, below and Chapter Nine). Conditions appear to be improving, but problems remain near urban areas, points of surface runoff, waste discharges, and shipping facilities.

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

The total human harvest of animals that depend on Galveston Bay has increased by 2000 percent during the last century (Green et al., 1992). Intensive harvest of seafood, combined with habitat losses and contamination of the ecosystem, have resulted in widespread concern over possible species reductions. Population crashes have already occurred in other bay systems subject to similar human influences (for example oysters and striped bass in Chesapeake Bay).

The Galveston Bay National Estuary Program study led by Green et al. (1992, summarized in Chapter Eight) confirmed that a well-balanced number of species still remain in all **trophic levels**, indicating a generally healthy estuarine community. Resource managers have surmised that (at least for water quality) the estuary reached its "low point" in the 1960s, and therefore analysis of recent data would reveal either no trends or increasing populations. However, apparent declines in several species provide continuing reasons for concern.

Of the fourteen different marine species that were analyzed, blue crab and white shrimp showed distinct chronic problems since the early 1980s (white shrimp are apparently rebounding). For each of these species, the decline included older age classes (first-time spawners), implicating over-harvest as a possible cause. For white shrimp, juveniles also declined, indicating habitat loss or pollution could also be involved. Several much longer-term changes are evident in old commercial fishery records. The commercial striped bass fishery apparently collapsed in the early 1900s, and the disappearance of the green turtle and diamondback terrapin fisheries almost a century ago also indicate declines of a longer-term nature. Review of old maps of the Texas coast archived in the Texas General Land Office (Quast et al., 1988) indicated an extensive loss of **intertidal** oyster reefs along the bay's shoreline. In spite of these declines, it is surprising to find most species have done so well. The data testify to the resilience of estuarine species, which evolved to withstand drastic natural variability in their environment.

Estuarine-dependent species analyzed included shorebirds, waders, waterfowl, and the American alligator. A decreasing population trend was noted for snowy egrets, black skimmers, tricolored

Source: United States Fish and Wildlife Service

Rosaeate spoonbills are among the valued species which depend upon Galveston Bay. The flattened bill, unique among all North American species, is specialized to capture minute marine life.

herons, and roseate spoonbills. These are colonial nesting species which generally feed on shoreline marsh edges. It is currently unknown whether habitat (and therefore prey) reductions have caused this decline, or changing nesting conditions combined with bird movements. Other kinds of estuarine-dependent species showed variable results: 1) populations of American alligators and six shorebird species appear to be stable or increasing: 2) mottled ducks, northern pintails, and blue-winged teal are apparently declining; and 3) olivaceous cormorants, in contrast to other colonial-nesting waterbirds, appear to be increasing. The bird data were particularly difficult to interpret, due to the variety, limitations, and conflicting results from available surveys.

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 Five).

While **bulkheading**, docks, and revetments usually generate low volumes of dredge and fill material compared to channel construction, the environmental impact may be larger than the actual physical modifications would suggest. As estimated by Ward (1993), about 70 miles of the bay shoreline has been either bulkheaded or converted to docks or revetments. By one estimate, this corresponds to ten percent of the entire bay shoreline. Continued development of the shoreline contributes to shore erosion, loss of wetlands, increased point and nonpoint source pollution, and reduced public access to beaches and the shore.

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

Accidental spills or deliberate dumping affect both aesthetic and ecological aspects of Galveston Bay. Intensive petrochemical and refining industries, shipping operations, and the highly urbanized local watershed puts the bay at risk from these major sources of pollution. Clearly the most effective means to deal with spills and dumping is to prevent them. Secondarily, when these incidents inevitably occur, improved cleanup becomes important. Much progress has been made toward these goals as a result of federal and state legislation since the landmark *Exxon Valdez* spill.

Several factors must be considered to evaluate the effect of spills on the bay. In general, the more material released, the greater the repercussions on natural resources. However, even a small amount of a very toxic or concentrated substance has the capacity to affect large volumes of water. Most spills that occur in the Galveston Bay area on a regular basis are relatively small and involve constituents which degrade.

Although spills of all sizes cannot always be prevented, compensation for environmental damages can be provided by the responsible party. The award of compensation for damaged natural resources, however, has not been an effective process in Galveston Bay. Of the numerous spills, fewer than five have proceeded through the damage assessment process to final payment.

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 Nine).

The contaminants known to occur in the tissue of estuarine organisms from Galveston Bay are most prevalent in the upper Houston Ship Channel, where, for example, a dioxin advisory has been issued to restrict harvest for human consumption. A Galveston Bay National Estuary Program study by Brooks et al. (1992) involved analysis of contaminants (including heavy metals, hydrocarbons, pesticides, and PCBs) in five species of seafood organisms (oyster, blue crab, spotted seatrout, black drum and southern flounder) from four widely separated sites in Galveston

Bay. Collection sites included Morgans Point, Eagle Point, Carancahua Reef in West Bay, and Hanna Reef in East Bay.

The study determined that oysters were generally the most contaminated species, fish were intermediate, and crabs were the least. Although results varied among compounds and organisms, higher contaminant levels were generally confirmed at Morgans Point, near the Houston Ship Channel, and decreased down-bay. Compounds of concern included PAHs and PCBs. Specific concentrations of these contaminants provided few surprises; they fell within the expected range based on previous studies.

What do these findings imply about seafood safety? In general, risk is expressed as the probability for a 154-pound human to contract cancer as a result of eating the assumed amount of seafood (about one pound per month) over a 70-year lifetime. Based on the contaminant values from Galveston Bay, most average consumers would experience a risk roughly similar to that of eating other commonly consumed foods not associated with the estuary. However, risk levels for recreational or subsistence fishermen (resulting primarily from PCBs and PAHs) who eat large quantities of seafood (about ten pounds per month) would exceed the Environmental Protection Agency benchmark risk level at all sites examined in the study. Most people believe that seafood from Galveston Bay is routinely monitored for toxic contamination, or they are not sure

Source: Texas Parks and Wildlife Department

Loaded to the brim with oysters. About half the bay is closed to the taking of shellfish due to risk of disease to consumers. Oysters taken from the open areas provide high quality seafood that is marketed throughout the nation.

(Philips, 1993). In fact, fish and shellfish from Galveston Bay are not routinely sampled for toxic contaminants, nor are consumer risks routinely assessed and communicated to the public, nor are fishermen prohibited from fishing contaminated areas.

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

Despite improvements to point sources and reductions in bypass/overflows discharged into Buffalo Bayou, overall water quality in that urban tributary of Galveston Bay remains poor. To determine the reason for this unexpected result, the City of Houston conducted a special survey of illicit discharges of sewage to the storm drainage system for Buffalo Bayou. This survey found several 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. By eliminating these discharges, there was a marked improvement in dry-weather water quality in the bayou.

There is no reason to believe that illegal connections are confined to Buffalo Bayou, and therefore most of the urbanized streams in the Galveston Bay area are probably subjected to water quality degradation from these sources. Illegal connections are indicated when water remains degraded between runoff incidents. Additional work is required to determine the severity of this problem in other parts of the bay.

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

Dissolved oxygen (DO) is generally high throughout the bay, averaging near saturation through large areas of open water. Exceptions to this are in poorly flushed tributaries subjected to runoff inflow and waste discharges. A remaining problem area is the upper Houston Ship Channel, which has improved from essentially zero dissolved oxygen twenty-five years ago, to levels that support an improving living community of fish and other organisms. In the upper Houston Ship Channel, oxygen remains most depleted in bottom waters.

Ward and Armstrong (1992) have provided the most complete description of water quality status and trends characterizing dissolved oxygen conditions in Galveston Bay. In the Houston Ship Channel above Morgans Point, deficits in dissolved oxygen (the increment below saturation level) range to seven parts per million. The concentration has been improving over the last two decades at about 0.1 mg/L/yr in the worst areas near the turning basin, and at a higher rate downstream nearer the open bay. Oxygen-demanding pollutants (BOD) remain highest in the upper Houston Ship Channel, but are declining commensurate with the improvement noted in DO levels.

The bay's western, urbanized tributaries (e.g. Clear Lake, Buffalo Bayou) also remain problem areas. These waters receive the bulk of the bay's nonpoint source pollutants in runoff, and have the greatest frequency of fish kills related to oxygen depletion–particularly in areas with poor circulation. The **DO deficit** near the outlet of Clear Lake is increasing, in contrast to the improving trend in much of the estuary. On a smaller scale, marinas, particularly in Clear Lake, have clear localized problems associated with boat sewage and other wastes (see Problem 13).

12. About half of the bay is permanently or provisionally closed to the taking of shellfish because of

high fecal coliform bacterial levels that may indicate risk to shellfish consumers (Chapter Nine).

Approximately 300 sq mi (200,000 ac) of Galveston Bay are subject to some form of shellfish harvest restriction and are deemed by the Texas Department of Health to pose a 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.

Oysters, which filter bacteria from the water as they feed, are by far the most important species involved in Galveston Bay shellfish regulation. Based on measurements of fecal coliform bacteria in water and oysters, and by establishing relationships between rainfall runoff and elevated fecal coliforms, closure maps are produced by the Texas Department of Health and utilized by commercial fishermen and the public to determine where oyster harvest can legally occur.

Wet weather runoff is the most significant source of bacteria (Jensen et al., 1991), but no single land use dominates the contribution of bacteria to the bay. Furthermore, no trends in fecal coliforms levels since 1950 can be tied to human development of the watershed (Jensen, 1992), although some human activities like leaking septic systems and illicit sewage connections to storm sewers clearly affect localized receiving waters. While extensive areas violate the bacteria standard for legal oyster harvesting, near-shore areas and tributaries frequently have levels much higher than the standard. This has contributed to the lack of any substantial changes in closures over time.

In spite of difficulties in defining the specific sources of the problem, the closure of substantial oyster reefs to the commercial market represents a large loss to the local economy, and oysters taken from closed areas (intentionally or unintentionally) remain a public health concern. Therefore, actions that could result in opening of some currently restricted and conditionally approved reefs would be of great benefit. These actions could take the form of:

Increased frequency of measurement. Many restricted or conditionally approved reefs do not necessarily have high long-term indicator levels. In some cases, restriction results from either a small portion of the data exceeding higher values after rains, or a judgment made about the potential for upland facilities to introduce pathogens (Jensen et al., 1991).

Improved indicator measures. Although the fecal coliform approach has a long and successful history of preventing disease, its success results in part from conservative restrictions that are more extensive than true measures of the actual pathogens would dictate if they could be measured. Indicators that more accurately parallel pathogen risk have long been sought and are currently being researched under the "National Indicator Study," a multi-million dollar cooperative research program.

Source reductions. Source reduction actions could be tailored to target specific bacterial sources–for example, failing shoreline septic systems or wet weather bypasses and overflows of sewage collection systems (see Problem Three). This solution is limited by the possibility that natural sources of bacteria are a substantial source of the problem.

13. Water and sediments are degraded in and around marinas from boat sewage and introduction of dockside wastes from nonpoint sources (Chapter Six).

Marinas, particularly in Clear Lake, pose significant localized water quality problems. Raw or partially treated sewage has traditionally been discharged directly from boats to estuarine waters, due to lack of pump-out facilities and lax enforcement. Boat maintenance activities result in wastes which wash into the bay with runoff, and deliberate dumping of debris like batteries has been common. These activities result in high bacterial levels, low dissolved oxygen, and toxic contamination of water and particularly sediment–all of which are exacerbated by marina construction designs which limit circulation in boat slip and maintenance areas.

Guillen et al. (1993) described conditions at four marinas and one canal subdivision, all in the western portions of the estuary. Fecal coliform bacteria increased in concentration toward the inner part of each marina, and violations of the state water quality standard were common in "dead ends" and other areas with limited circulation. Dumping of untreated human waste–which contains approximately one million fecal coliform bacteria per gram-represents an aspect of the problem which is both well-defined and correctable.

Dissolved oxygen levels were depressed within the marinas studied by Guillen et al. (1993). Potential causes included the nutrients contained in dumped sewage, the oxygen demanding materials in both sewage and runoff from maintenance areas, parking lots, and other adjacent shoreline areas, and the lack of circulation. The more open the marina design (e.g. bulkheads that do not extend to the bottom), the less severe was the problem.

A definite trend of increasing copper, lead, and arsenic in sediments toward the inner portions of marinas was also present. The trend suggests a chronic source–for example, leaching from treated boat hulls, battery leakage, and use of toxic maintenance products.

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 Five).

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 of some three to five cm/year, and most importantly, historical land subsidence of up to ten feet elevation. These factors have combined to cause major losses of estuarine wetlands (White et al., 1993).

The erosion problem has significant elements related to human activity which could be subject to management. Wave energy and subsequent shoreline erosion have been increased as larger ships in greater numbers use deeper channels. Subsidence has been caused by both groundwater and petroleum withdrawal for human use. Structures like **riprap** and bulkheads have slowed erosion locally. Reductions in riverine sediments resulting from reservoir construction slow expansion of the Trinity delta (the only area of extensive shoreline **progradation** in the last century).

Some human activities that contribute to erosion are already being addressed. For example, the Harris-Galveston Coastal Subsidence District was created in 1975 to regulate groundwater withdrawal. Their periodically updated *District Plan* has reported that subsidence of Galveston Bay's shoreline has slowed to near zero. Other elements remain to be addressed with future management actions. For example, smooth **cordgrass** plantings have been accomplished by the Galveston Bay National Estuary Program on a demonstration scale to re-establish fringing wetlands. These erosion management activities could be expanded to an estimated 40 percent of the bay's shoreline (Seidensticker, 1993).

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

Estuarine debris represents a serious aesthetic concern in Galveston Bay, particularly to citizens who live along the shoreline or who use the bay for recreational activities such as fishing or sailing. Floating debris–particularly plastic–can also 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 a Galveston Bay National Estuary Program study conducted by citizen volunteers and the Texas Parks and Wildlife Department, Morgan and Lee (1993) reported plastic products to compose over 50 percent of the items collected overall, at 37 shoreline stations, in 88 near-shore bay seine samples, and 104 open-bay trawl samples. Debris was most concentrated along the shoreline itself, where it tends to accumulate with the actions of winds, currents, and waves.

A large source of floatable debris in the estuary is stormwater. In samples of the Houston Ship Channel, Radde et al. (1991) indicated most items to be stormwater-related, rather than sewage-related. Items included plastic pellets, bags, cups, fast food containers, toys, bottles, jugs, and general street litter. In comparison to other U.S. harbors, their study showed the Houston Ship Channel to have the highest incidence of plastic pellets, a debris type known to be ingested by more than 60 species of birds.

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

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 are generally in conformance with this standard. Fecal coliform concentrations within western bay tributaries declined dramatically during the 1970s and 1980s, reflecting the influence of improved wastewater treatment. However, fecal coliform levels above the standard have recently been reported from three tidal tributaries on the west side of the bay: Buffalo Bayou Tidal, Clear Creek Tidal, and Dickinson Bayou Tidal. Additional contact recreation violations have also been observed in many urbanized fresh water segments as well.

Potential risks from pathogens associated with contact recreation in the bay system are considered to be relatively low. Variation in recreational water quality due to rainfall and changes in circulation patterns make real-time information concerning water quality virtually impossible to attain. Currently, no routine sampling is conducted within the estuary to monitor fecal coliform or toxicant concentrations in contact recreation areas, nor are contact recreation warnings or advisories routinely issued.

17. Some exotic/opportunistic species (e.g. nutria and grass carp) threaten desirable native species, habitats, and ecological relationships (Chapter Eight).

In many locations worldwide, the introduction of **exotic species** has had a dramatic impact on the ecology of estuarine systems. For example, within San Francisco Bay, the unintentional introduction of the Asian marine clam *Potamocorbula amurensis* has resulted in a ten-fold reduction in the phytoplankton levels within a two year period and has caused a potentially catastrophic disturbance of the estuarine **food web**. The development of faster cargo ships and increased worldwide trade has heightened the potential for such unintentional introductions of harmful species.

Within the Galveston Bay Estuary, the introduction and proliferation of exotic **opportunistic species** has also contributed to the degradation of some portions of the estuarine habitat. Significant populations of nutria, a large beaver-like rodent which strips vegetation within fresh water and brackish water marshland, and grass carp, which consumes aquatic vegetation, have been reported in the Trinity River and San Jacinto River portions of the estuary. The encroachment of fire ants into the estuarine ecosystem may pose an increasing threat to nesting bird populations.

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CHAPTER TWO

Galveston Bay: An Overview

...the Bay exists at some remove from the daily lives of most Houstonians. Because it lacks the constant proximity and the visual splendor of a San Francisco Bay or a Puget Sound, it is easy to ignore. Its soil characteristics and land formation, combined with massive upstream erosion, produce water that bears a close resemblance to café au lait. Its flat and untimbered shorelines lack dramatic views and escarpments. Consequently, the casual visitor is not likely to leave his heart in Galveston Bay or even consider it, on visual evidence alone, a resource worth saving.

–James Noel Smith, *The Decline of Galveston Bay*, 1972

(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 there. Some of my own youngest outdoor memories are going out at dawn with one of my hunting and fishing uncles to anchor on an oyster reef in Aransas Bay and cast into the swarms of speckled trout.... that were slashing at shrimp and bait fish. Nearly any memory of that coast has in it a sense of teeming life....

–John Graves, in *The Water Hustlers*, 1971

Galveston Bay is full of surprises. While on the surface it may not look impressive, it is teeming with life despite steadily increasing pressures from human disturbances. It is large, complicated, productive, and a tremendous recreational, economic, and environmental asset to Texas and the nation.

WHAT IS AN ESTUARY?

Estuaries are unique waterbodies where fresh water from rivers, streams, and direct rainfall mixes with salt water from the sea. In Texas, estuaries are protected by barrier islands. Estuarine habitats include river deltas, emergent marshes, mud and sand flats, submerged seagrass beds, oyster reefs, and open bay bottoms–all of which occur in the Galveston Bay system. The abundance of nutrients and shelter provided in the estuary make the environment extremely productive biologically. Many finfish and shellfish species use the area as nursery habitat for their young. More than 90 percent 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 an ecosystem. An ecosystem is the total of all the living things and the non-living physical environment–and more importantly the relationships among these. The estuarine ecosystem includes the energy flow from green plants (such as planktonic algae) to higher consumers (such as bay anchovies, red drum, and humans). It includes the cycling of important compounds like the nutrients nitrogen and phosphorus (which are vital for life but can harm the system when over-abundant). Viewing the estuary as an ecosystem accounts for the fundamental connections of one component to another and reveals how inadvertent harm resulting from human activity affecting one component can inadvertently harm another.

THE VALUE OF GALVESTON BAY

Galveston Bay is valuable for many reasons (See Chapter Four). Any list of important uses of the bay would likely include the following:

The bay is a great place to fish. Approximately one third of the state's commercial fishing income comes from the bay. Over half of the state's expenditures for recreational fishing are related to Galveston Bay.

The bay is an important transportation artery. Measured by tons of materials transported, the Port of Houston is the third largest port in the country, sixth largest in the world. Many of the area's petrochemical and other industries rely on the Houston Ship Channel, Gulf Intracoastal Waterway, and other navigation channels for transportation.

Source: Galveston Bay National Estuary Program

Estuaries are among the most productive ecosystems in the world. The fertile mixture of fresh water from land runoff and salt water from the Gulf of Mexico supports an abundance of commercially and recreationally important fish and shellfish species. For example, the shrimp being harvested here spend their juvenile stages foraging in the productive marshes of the estuary.

The bay is the final recipient of treated wastewater from over 1400 industrial and municipal point source discharges. This amounts to about 60 percent of the wastewater discharged in Texas. It also receives nonpoint source pollutants in stormwater runoff from agricultural, urban, suburban, and rural lands in the watershed.

Galveston Bay provides important natural habitats for many species of particular environmental interest to Texans, such as colonial waterbirds, shorebirds, dolphins, sea turtles, alligators, and numerous other species.

Other uses of the bay include: cooling water, sailing, motorboat cruising, sightseeing, and oil and gas production.

Most important, perhaps, is the value of Galveston Bay as a general indicator of the health of the environment. Most people realize that the bay is an important regional ecosystem, and they have a keen interest in protecting and maintaining the productivity of the bay for future generations.

Even though the values and uses of the bay have long been recognized, fragmented management efforts in the past have been unable to address the system-wide problems that affect this complicated resource. Therefore, the Galveston Bay National Estuary Program was established in 1990 to establish management of Galveston Bay as an entire ecosystem. Although there was a general idea of what the problems were prior to the Galveston Bay National Estuary Program, there was still not enough information to develop a detailed management plan that would solve the problems. Neither was there any means to focus the attention of the various agencies, user groups and citizens on developing solutions to the bay's problems. To address these challenges, the Galveston Bay National Estuary Program adopted an ecosystem-based approach developed by the Environmental Protection Agency's National Estuary Program–an approach that has been applied to some other threatened estuaries across the country (TABLE 2.1).

The ecosystem-based approach relied on scientific *and* envi-

TABLE 2.1. Comparison of Estuaries in the National Estuary Program.

Project Location	Surface Area (sq mi)	Drainage Basin Area (sq mi)	Watershed Population	Priority Environmental Problems
Galveston Bay, TX	600	25,256	6,000,000	Habitat loss, urban runoff, sewage bypasses and overflows, potential inflow and circulatory modifications, toxic contamination of water and sediments, declining trends in certain species of birds and marine organisms.
Albemarle/Pamlico Sound, NC	2,900	30,880	1,898,000	Wetland losses, nutrient over-enrichment, fish disease, land use, fresh water flows, habitat loss.
Barataria-Terrebonne, LA	2,141	5,460	695,000	Hydrological modification, eutrophication, pathogen contamination of shellfish, changes in biological resources, habitat loss.
Buzzards Bay, MA	228	432	236,000	Pathogens, nitrogen loading, shoreline development, habitat loss, toxicants.
Casco Bay, ME	152	979	251,000	Toxicants, nutrient over-enrichment, pathogens, habitat loss.
Delaware Bay	768	475	6,000,000	Habitat loss, nonpoint source pollution, lack of public access, estuarine education, compliance.
Delaware Inland Bays	32	255	50,000	Habitat loss, eutrophication, land use, point/nonpoint pollutants.
Indian River Lagoon, FL	353	2,284	630,000	Nutrient over-enrichment, circulation, wetland loss, increased toxicants, pathogens and suspended sediments.
Long Island Sound CT/MA/NY/RI	1,281	16,000	8,400,000	Eutrophication, hypoxia, toxicants, pathogens, floatable debris, living resources.
Massachusetts Bays	2,000	2,900	4,000,000	Toxicants in water, sediments, fish and shellfish; pathogens; habitat loss and modification.
Narragansett Bay, RI/MA	146	1,677	1,800,000	Pollutants, pathogens, living resources management needs, habitat losses, sewer overflow.
New York / New Jersey Harbor	298	8,467	17,000,000	Urban runoff, contaminated sediments, shoreline development, pathogens.
Puget Sound, WA	931	16,000	3,000,000	Pollutants, loss of aquatic habitats, eutrophication, dredging.
San Francisco Bay/ Sacramento-San Joaquin Delta, CA	554	61,313	9,900,000	Decline of biological resources, altered fresh water flows, pollutants, dredging, land use.
Santa Monica Bay, CA	266	414	9,000,000	Contaminants in fish and sediments, marine habitat, swimmable waters, municipal effluent, urban runoff.
Sarasota Bay, FL	40	500	425,000	Nutrient over-enrichment, habitat loss, declines in living resources, population growth.
Tampa Bay, FL	398	2,300	2,100,000	Habitat loss and modification, altered fresh water inflow, natural flushing.

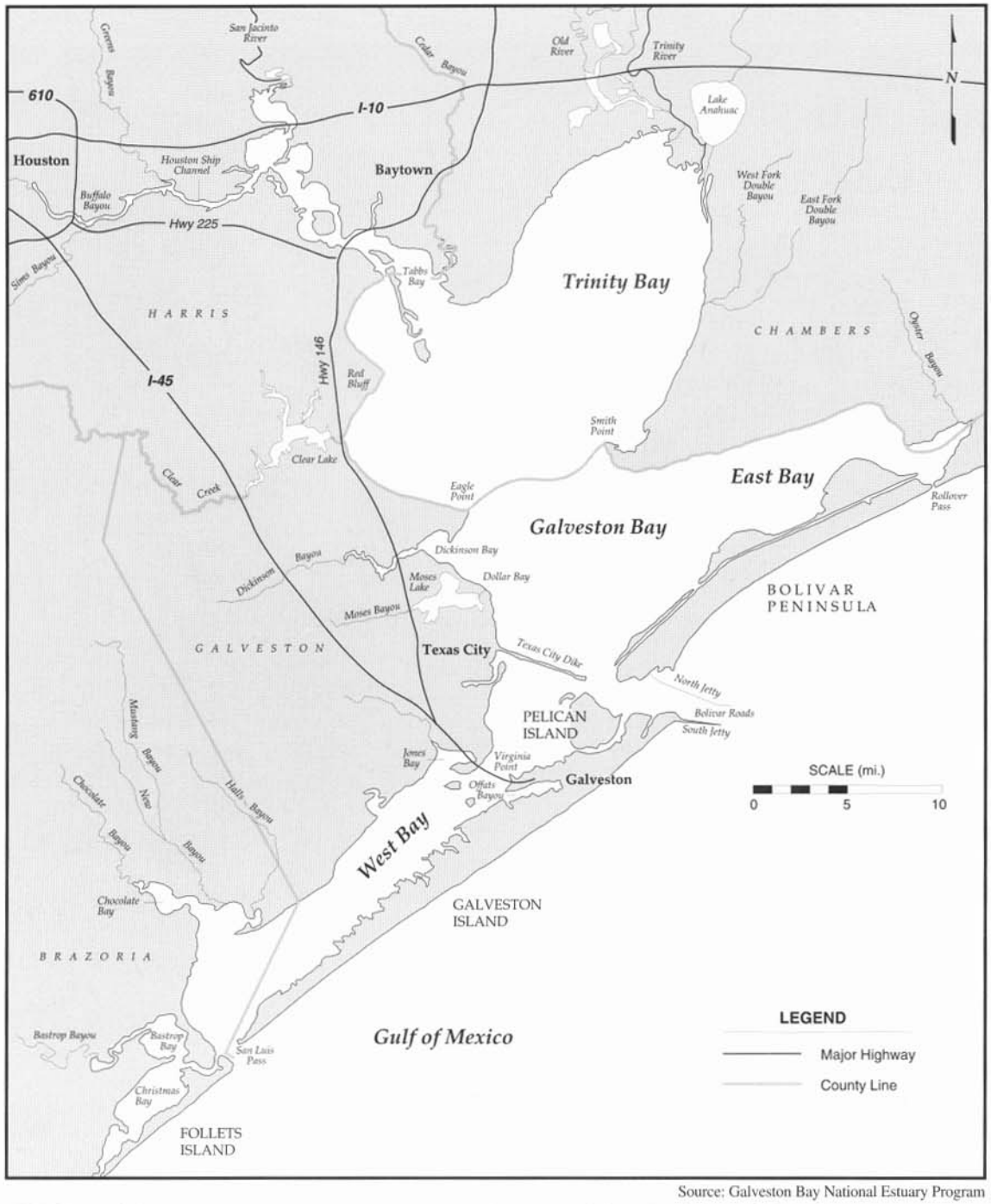
Source: National Estuary Program

Source: National Aeronautics and Space Administration

Galveston Bay as viewed from the Space Shuttle. The greater Houston area (upper left) dominates the regional population of more than three million people. In a closer view of the upper bay (inset) barge and ship traffic in the Houston Ship Channel and the worm-like trails of shrimp trawls are visible.

ronmental management information. On the scientific side, the Galveston Bay National Estuary Program embarked on a four-year program of scientific studies that covered the bay's water quality, living resources, habitats, public uses, and many other topics. This book combines these recently completed Galveston Bay National Estuary Program studies with historical and recent scientific studies by others to describe the current state of Galveston Bay. On the management side (and not addressed in this book), the governance of Galveston Bay was scrutinized for its effectiveness in addressing

Source: National Aeronautics and Space Administration



Source: Galveston Bay National Estuary Program

FIGURE 2.1. *Galveston Bay, encompassing some 600 sq mi of water area, is fed primarily by the Trinity River (upper right) and secondarily by the San Jacinto River (upper left).*

the emerging bay problems. Combining the scientific and management work, the Galveston Bay National Estuary Program undertook development of a comprehensive management plan for the bay, *The Galveston Bay Plan*.

GEOGRAPHY OF THE BAY AND WATERSHED

Galveston Bay

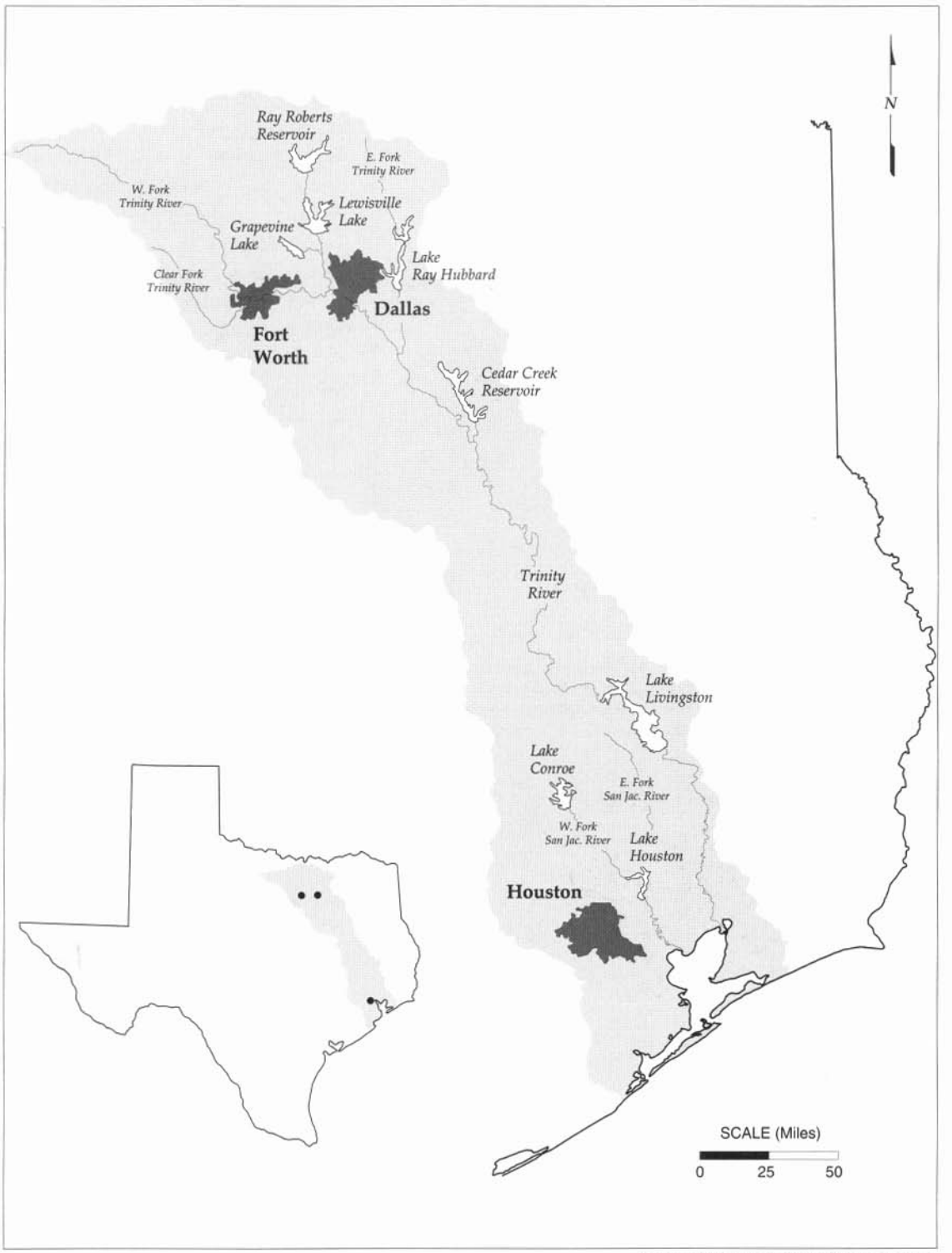
Galveston Bay is typically only six to 12 feet deep. The effects of wind dominate many physical processes, and biologically, extensive oyster reefs, marshes, and open water habitats predominate. The bay's 600 sq mi of surface area is commonly divided into four major sub-bays (FIGURE 2.1).

Galveston Bay receives the outflow of the San Jacinto River and much of the local drainage from the City of Houston via Buffalo Bayou and the Houston Ship Channel. *Trinity Bay* receives the outflow from the Trinity River, a large river system with a watershed that extends north to encompass the Dallas-Fort Worth region. The Trinity Basin contributes 54 percent of the inflow to Galveston Bay, compared to 28 percent for the San Jacinto Basin. *West Bay* is situated landward of Galveston Island,

FIGURE 2.2. *The lower Galveston Bay watershed. This portion of the watershed, below lakes Houston and Livingston, defines the study area for most findings in this book. The reservoirs mediate upper watershed influences on the bay by trapping nutrients, sediment and pollutants. While Dallas and Fort Worth are within the watershed (see FIGURE 2.3) the most important human influences on Galveston Bay occur within the area depicted. Nonpoint sources of pollution are among the most important lower watershed influences. With each rainfall, runoff from this area carries fertilizers, pesticides, oil from roadways, and numerous other pollutants to the bay. Water quality, particularly in the western urbanized tributaries, suffers.*

and receives runoff from Chocolate and Mustang Bayous and other local streams. *East Bay* lies landward of Bolivar Peninsula and receives inflow from Oyster Bayou and other runoff from Chambers County. Christmas Bay and Bastrop Bay are two relatively undisturbed secondary bays in the far southwestern part of the estuary that are somewhat isolated from the rest of the estuary.

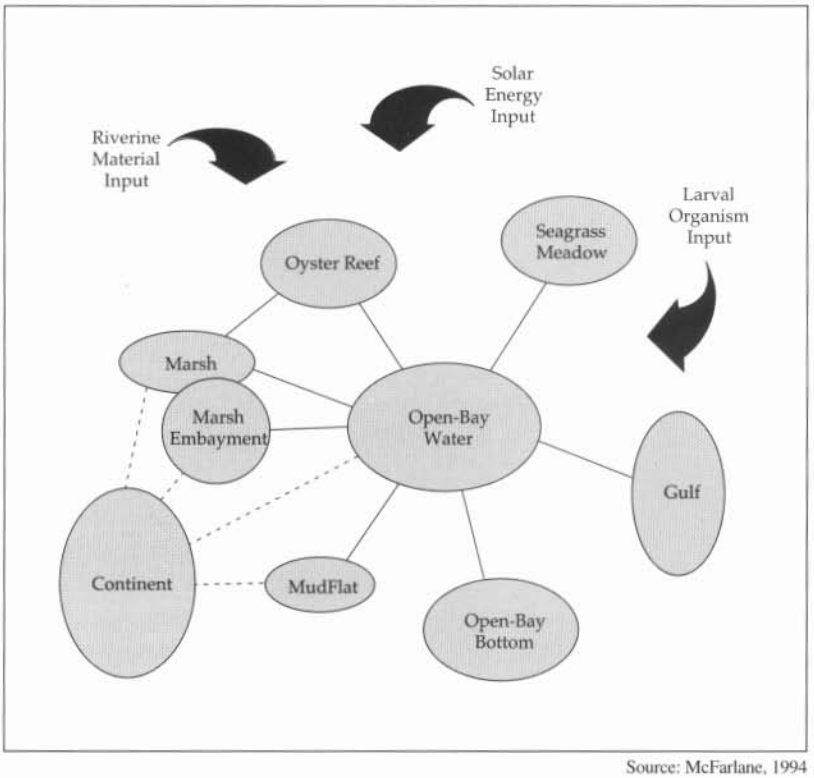
There are three tidal inlets to the bay, but only two are of major importance with regard to flow. Bolivar Roads (between Galveston Island and Bolivar Peninsula) accounts for over 80 percent of the tidal exchange between the bay and the Gulf of Mexico. As shown in FIGURE 2.1, both sides of Bolivar Roads have long jetties that were built to extend out into the Gulf and stabilize the inlet. San Luis Pass, between the western end of Galveston Island and Follets Island to the southwest, is a natural inlet that provides slightly less than 20 percent of the bay's tidal exchange but provides important access for commercial and recreational fishermen. Rollover Pass is a man-made cut through Bolivar Peninsula that provides minor tidal exchange between the Gulf and East Bay.



Source: Galveston Bay National Estuary Program

FIGURE 2.3. *The entire Galveston Bay watershed. At 33,066 sq mi, the watershed represents just 12.6 percent of Texas' surface area, but receives about 60 percent of the state's wastewater discharges.*

The total shoreline length of Galveston Bay is a difficult parameter to define. It is greatly dependent upon the scale of resolution employed; as the scale becomes finer, the measured shoreline length increases. For example, an estimate of 232 miles used by Paine and Morton (1991) to measure erodable shoreline along Galveston Bay varies significantly from the 743-mile figure used by Orlando et al. (1988). The latter measurement includes such features as small boat basins, service canals, and other forms of modified shoreline that substantially expand the measurable length of the Bay shoreline. While the measurements vary considerably, each is valid in the context of its intended use.



Source: McFarlane, 1994

FIGURE 2.4. *A conceptual model of Galveston Bay, indicating the major habitats and their connections to the continent and the Gulf of Mexico. The complexity of the interactions among the various components of this natural system make management a challenge. This model is the basis of a detailed discussion in Chapter Three.*

The Lower Watershed

For the purpose of this book, the lower watershed is defined as the 4,238 sq mi area draining to the bay, downstream of two major impoundments: Lake Houston on the San Jacinto River, and Lake Livingston on the Trinity River (FIGURE 2.2). These two reservoirs provide some attenuation of runoff and pollutant loads, and therefore the lower watershed acts as a more direct contributor of runoff and runoff-borne pollutants to the bay than does the upper watershed.

The sprawling city of Houston with its associated urban communities occupies the western side of the bay, while the eastern side remains largely agricultural and undeveloped. Urban development becomes most important in its contribution of polluted rainfall runoff from parking lots, streets, highways, roofs, and yards (Newell et al., 1992), while the eastern shore remains largely grassland, marshes and rice fields, with the potential to contribute nonpoint sources of herbicides and pesticides.

The Upper Watersheds

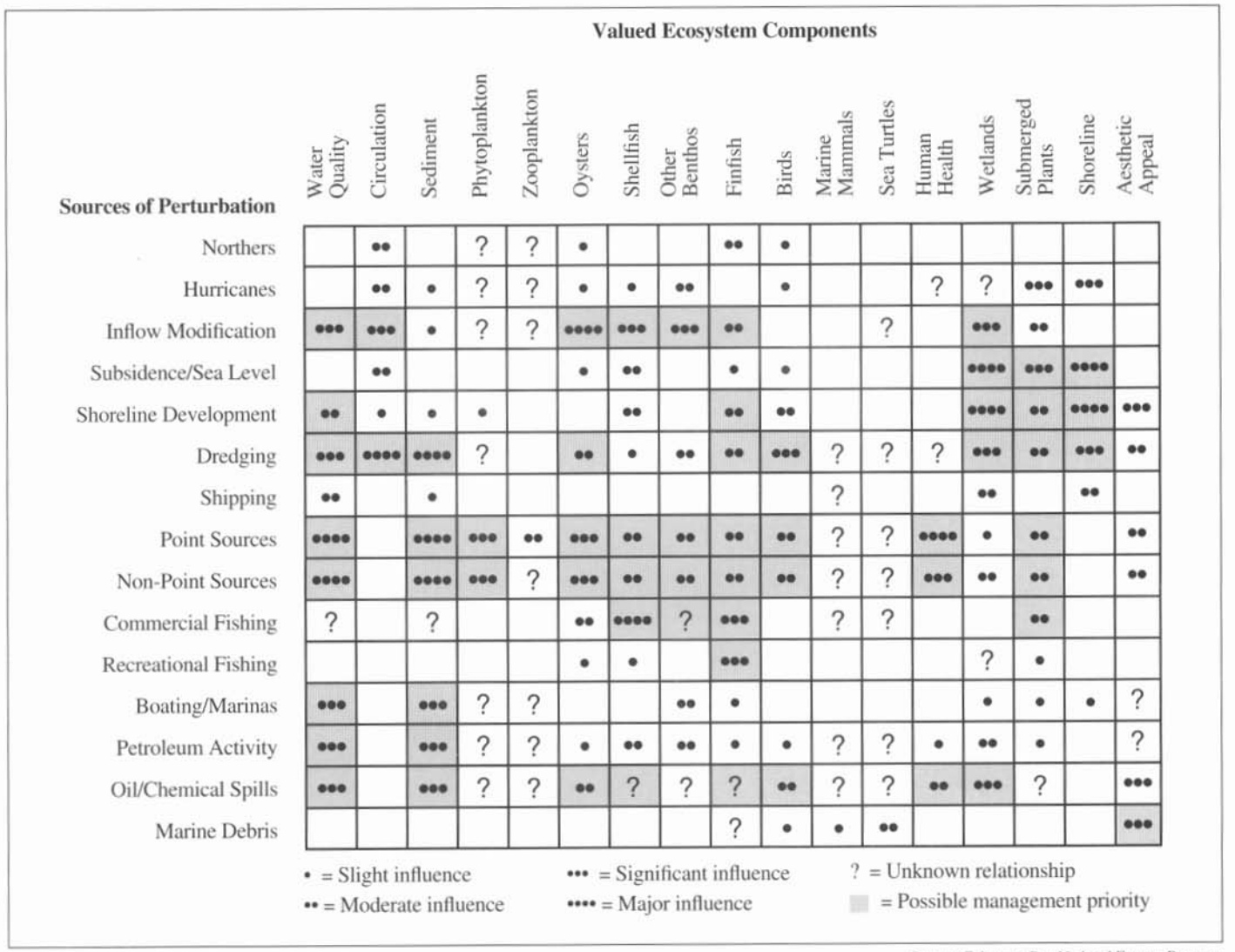
Galveston Bay has two large "upper watersheds," consisting of 2,828 sq mi upstream of Lake Houston and 26,000 sq mi upstream of Lake Livingston. The Trinity River extends north past the Dallas-Fort Worth metroplex (FIGURE 2.3) with tributaries that flow through numerous man-made reservoirs in the upper watershed in addition to Lake Livingston on the main stem to the south. Land uses within the watershed include forested and wetland areas along the Trinity River Bottom; intense agricultural in many parts of the watershed; urban areas; and dry rangeland 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. The entire watershed lies within Texas, a fact that simplifies management planning.

Source: Galveston Bay National Estuary Program

Humans have dramatically altered Galveston Bay. The Houston Ship Channel, shown here, is a 51-mile cut dredged to 40 feet deep. This feature has altered circulation and salinity patterns in this otherwise shallow (eight to ten foot deep) system. The vessels shown here have just engaged in a maneuver known as "Texas Chicken," in which the vessels approach head on, then veer apart at the last minute. The resulting hydrostatic forces provide a "cushion" of water between the two vessels and the side-slopes of the channel, allowing the vessels to pass without running aground. This maneuver has occurred an estimated 40,000 times in the last five years. Also visible on each side of the channel are wakes washing over the berms parallel to the channel, caused by open-water disposal of dredged material.

THE BAY AS AN INTERRELATED SYSTEM OF PROCESSES

The maps presented in this chapter show where different parts of the bay are located, but do not indicate how the bay functions. FIGURE 2.4 diagrams the different habitats that comprise the Galveston Bay estuary and various external influ-



Source: Galveston Bay National Estuary Program

Figure 2.5. *Matrix of environmental impacts to Galveston Bay. Valued elements of the estuary (across the top) are influenced by both natural and human perturbations (down the left side). Some of the influences highlight potential management needs. The matrix was constructed as a consensus of expert opinion among participants of the Galveston Bay National Estuary Program.*

ences on these habitats (McFarlane, 1994). Example habitats include open-bay water and marshland, while examples of the external inputs are solar energy and river inflow.

The bay system is in a constant state of change, responding to many short and long-term natural forces. For example, the bay responds to changes in tide and runoff (short-term), seasonal changes in light and temperature (medium-term), and other changes such as the slow, naturally-occurring rise in sea level (long-term).

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 fresh water 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.

Consequences of Human Activities in and Around the Bay

The major problems facing Galveston Bay have been defined using various approaches. By examining existing scientific data, involving experts, and talking with bay users, important cause-and-effect relationships were identified. Some of the cause-and-effects were similar to those found in other bays around the county. Others appeared to be unique to Gulf Coast situations or the Galveston Bay system.

One outcome of the problem-defining process was creation of the *Environmental Impact Matrix* shown in FIGURE 2.5. The matrix presents a consensus view of the effects of different perturbations (natural and man-made disturbances) on various ecosystem resources and processes (labeled "valued ecosystem components"). The circles indicate the degree of influence and the shaded areas denote possible management issues. For example, nonpoint source pollution was considered a major influence on water quality to an extent suggesting management actions. On the other hand, recreational fishing has only a slight influence on oysters, a relationship not suggesting that conservation efforts be undertaken.

The matrix points out that Galveston Bay is a complex sys-

Source: National Aeronautics and Space Administration

This high-altitude photograph of lower Galveston Bay during ebb tide reveals many human alterations affecting estuarine processes such as circulation. The Texas City Dike (extending from the west shore on the left) forces currents to converge and exit the bay via Bolivar Roads. Before dike construction on 1915, substantial water would have flowed through West Bay (lower left). The strong currents between the jetties has led to formation of "Big Reef" adjacent to the south (lower) jetty and a deep scour hole at the base of the north jetty. Extending up the center of the bay, the Houston Ship Channel is clearly visible as a line of dark water. Heavy salt water from the gulf of Mexico enters the bay via a "density current" up the 40 ft deep channel, as fresher bay water moves seaward in the shallow areas to the sides of the channel. The wavy pattern on the edge of the Ship Channel near the Texas City Dike (see inset), results from "Kelvin-Helmholtz billows" that indicate current shear resulting from the density current. The lighter areas adjacent the the Channel, from which plumes of turbid water are emanating, are open-bay disposal areas for dredged material. A discussion of these and other human modifications to Galveston Bay appears in Chapter Five, Physical Form and Processes.

TABLE 2.2. Technical Characterization Projects on Galveston Bay.

Project Title	Conducted By
Point Source Loading Study	*University of Texas at Austin*
Shoreline Survey for Unpermitted Point Sources	*Texas A&M University, GERG*
Nonpoint Source Loading Study	*Groundwater Services, Inc.*
Treated/Untreated Effluent Loadings	*Texas Natural Resource Conservation Commission*
Ambient Water/Sediment Quality	*University of Texas at Austin*
Dredge/Fill Impacts	*University of Texas at Austin*
Toxicants in Sediment and Benthos	*U. S. Fish and Wildlife Service*
Oyster Survey	*Texas A&M University*
Living Resources Status and Trends	*Texas Parks and Wildlife Department*
Trawling By-Catch	*National Marine Fisheries Service*
Recreational By-Catch	*FTN Associates, LTD*
Non-Fishing Incidental Mortality	*Jones and Neuse, Inc.*
Wetland Habitat Survey	*Bureau of Economic Geology*
Ecosystem Conceptual Model	*McFarlane & Associates*
Bay Debris Survey	*Texas Parks and Wildlife Department*
Toxicants in Seafood Organisms	*Texas A&M University, GERG*
Public Health Synopsis	*Espey, Huston & Associates*
Regional Monitoring/Data Management	*Tetra Tech, Inc.*
Regional Monitoring Methods Standardization	*Tetra Tech, Inc.*
Data Base Inventory	*University of Texas at Austin*
Galveston Bay Information Center	*Texas A&M University at Galveston, TIO*
Galveston Bay Bibliography	*Texas A&M University at Galveston, TIO*
Acquisition of 1930 Aerial Photo Set	*TOBIN Research, Inc.*
Natural Resource Economics	*University of North Carolina*
Segmentation of Galveston Bay	*Jones and Neuse, Inc.*
History of Resource Utilization	*Margaret Henson*
Socioeconomics of Bay Utilization	*University of Houston–Clear Lake*
Environmental Inventory of Armand Bayou	*Galveston Bay Foundation*
Environmental Inventory of Christmas Bay	*Galveston Bay Foundation*

Source: Galveston Bay National Estuary Program

tem affected by numerous human activities and natural processes. The process of developing the matrix focused attention on several key cause-and-effect relationships, such as:

> The impacts of sea level rise, shoreline modification, and dredging on important habitats such as wetlands and submerged aquatic vegetation;
>
> The effect of runoff (nonpoint sources), wastewater discharges (point sources), marinas, petroleum production, transportation, and refining on water and sediment quality;
>
> The response of aquatic organisms and birds living in and around the bay to a wide variety of man-made and natural perturbations.

The matrix stimulated and helped to guide efforts to learn more about these cause-and-effect relationships and determine the overall status and trends of the major components that make up the Galveston Bay ecosystem.

Galveston Bay National Estuary Program Characterization Studies

Guided by the early problems identification, the Galveston Bay National Estuary Program then commissioned a series of characterization studies. These projects were designed to fill knowledge gaps about key problems and management issues. During the period 1990 to 1993, over 25 different studies were undertaken, ranging from measuring unwanted by-catch from shrimping to investigating the effects of toxic contaminants on sediment and bottom-dwelling organisms (TABLE 2.2). These studies form the primary basis for findings presented in this book.

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CHAPTER THREE

An Ecosystem Conceptual Model

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**

The First Law of Ecology, "We can never do merely one thing," warns us that any human intervention in the order of things will likely have unforeseen consequences; and that many, perhaps most—perhaps all—will be contrary to our expectations and desires.

–Garrett Hardin, ***Filters Against Folly,*** **1985.**

Estuaries such as Galveston Bay are complex and constantly changing ecosystems. To best manage human activities which affect the ecosystem, and to be able to predict the potential impact of specific proposed human actions, it is necessary to understand how the system is constructed and how it interacts with its environs. Knowledge of the structure of the ecosystem or the diverse plants and animals which build and inhabit its distinct habitats does not automatically lead to an understanding of ecosystem function. The function of an estuary–that is, how it acquires its materials and energy, processes its waste products, and interacts with adjacent waters and the surrounding landscape–is a much more subtle and challenging problem.

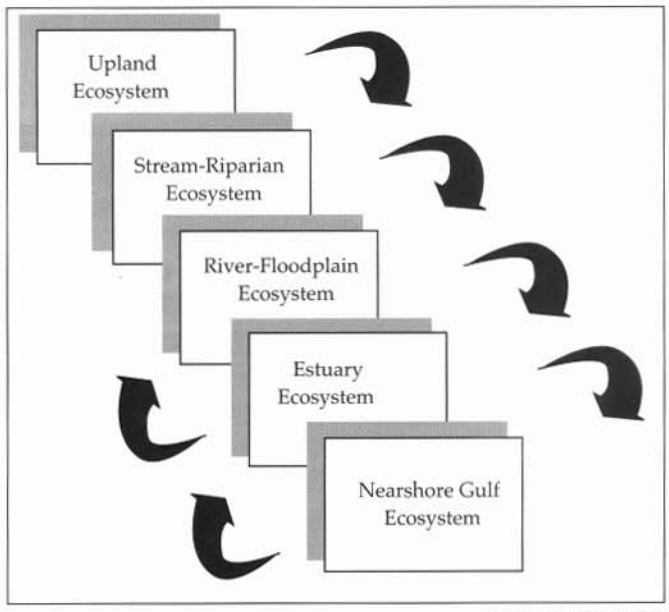
Conceptual models of complex systems can be useful management tools if they identify the critical components of the ecosystem and if they demonstrate important (or reveal hidden) linkages between these components. Over the past decade scientists have come to recognize a hierarchy of structure in ecosystems, with each successively higher level of organization operating at a slower speed than, and constraining activity within, the next lower level (O'Neill et al., 1986). The model described in this chapter is a set of habitat-based, problem-oriented, nested, hierarchical, box-and-arrow conceptual models (McFarlane, 1994).

OVERVIEW OF THE ECOSYSTEM

A human observer standing on the shore of Galveston Bay typically perceives two extreme ends of the ecological spectrum–individual organisms that inhabit the environment and the entire landscape that provides the overall setting. The individual organisms could be fish reeled in from the waters below, the crab scurrying across the beach, or the bird flying overhead. The landscape is the sum total of surrounding environs–the water, the beach, the nearby marsh and uplands. Unseen (and much more difficult to elucidate) are the intervening levels in the hierarchy, for example **populations**. However, it is in the intermediate levels where the bulk of ecological activities defining an ecosystem occur.

Populations are reproducing aggregations of individuals of a given species. Individuals have life histories–they are born in particular places, grow up in certain habitats, and reproduce to ensure continuity of the species. The aggregation of individuals composing a population may migrate to and from the bay, or perhaps go extinct. It is difficult to envision a population, because there are many individuals (frequently too many to count) spread over a large area, often out of sight.

When populations of different plants and animals intermingle they compete for scarce resources, establish a food web as they eat one another, and thus exhibit **competition** and **predation** as community characteristics. When the non-living components of the environment are added to these interacting communities, an ecosystem is created. At this level of complexity, new functions like energy flow and the cycling of matter arise and can be mea-



Source: McFarlane, 1994

FIGURE 3.1. *Diverse ecosystems from the upper watershed to the open sea all affect estuaries. Each link in the system is affected by all of the upstream links, but the effect of the nearshore Gulf of Mexico and estuary ecosystems only extends upstream to the lower reaches of the river-floodplain.*

sured. From the perspective of bacteria and parasites, individual humans are wonderful ecosystems. On a larger scale, Galveston Bay can be conveniently considered as a single 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 two-way interchange with both the river-floodplain and nearshore Gulf of Mexico ecosystems. The nearshore gulf ecosystem is a major contributor of organisms, as larvae and juveniles of many marine species enter the estuary seeking food and sheltering habitat. A few marine or estuarine species even reach the lower reaches of the river-floodplain ecosystem. Thus the distribution of organisms highly varies in time and space. The aggregate of species seen on the inland shore of Galveston Island will differ somewhat from species frequenting the shoreline at Kemah or the Trinity River delta. Species commonly observed at a single site during the summer may be replaced with other species in winter.

The entire Galveston Bay watershed could be considered the next higher level of the hierarchy. The 26,000 sq mi of watershed dwarf the 600 sq mi of bay (which is matched by 580 sq mi of urban-industrial development within the city limits of Houston alone). Within this larger system, streams and rivers are important features affecting the bay. The character of streams and rivers changes from source to mouth in a predictable fashion, in what is termed the river continuum (Vannote et al., 1980). Stream size and water volume increase, and both the kind of plants and animals and the overall number of species change as well.

Upland ecosystems contribute surface runoff and groundwater inflow to the stream-**riparian** ecosystems, often filtered by greenbelts of riparian corridor vegetation (National Research Council, 1992). Portions of stream-riparian ecosystems have flowing waters transparent enough to permit the growth of aquatic plants and algae and establish self-sustaining food webs. Headwater streams and larger streams with murky waters have food webs dependent on the input of plant products and animals from the surrounding upland ecosystems. In the downstream reaches, river-floodplain ecosystems contribute water, nutrients and sediments to floodplain forests, which return organic material of terrestrial origin to the river system.

The aquatic ecosystems of the watershed (FIGURE 3.1) provide both "goods" and "services" to society (Odum, 1989). Ecosystem "goods" include food, such as fresh water finfish and estuarine finfish and shellfish. Ecosystem "services" include maintaining the **hydrologic cycle**, regulating climate, cleansing water and air, maintaining the gaseous composition of the atmosphere, storing and cycling essential nutrients, and absorbing and detoxifying pollutants. 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. Highly managed ecosystems, such as agro-ecosystems and urban-industrial ecosystems, are embedded within, and highly dependent upon, unmanaged natural ecosystems which ultimately provide human life-support.

The Estuary as an Ecosystem

An estuary is a semi-enclosed body of water with variable salinity intermediate between salt and fresh water. Estuaries are among the most naturally fertile waters in the world (Odum, 1989). 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 of all protein. Phosphorus, silica, and other compounds in lesser amounts also serve as nutrients to living things in the estuary.

The estuary functions as an efficient nutrient trap that is partly physical and partly biological. Three major life forms of photosynthesizing organisms play key roles in maintaining high productivity by exploiting nutrient sources: 1) phytoplankton are suspended within the sunlit zone of the **water column**; 2) **benthic microflora** are microscopic plants living on the sediment surface wherever sufficient light reaches the bottom; and 3) **macroflora** or rooted plants and rootless algae grow in shallow water and along the shoreline. These plants are the foundation of complex food webs and provide structural habitats which create **nursery habitat** for most coastal shellfish and finfish. Physical processes contribute to the acquisition and transformation of nutrients by living things. For example, the importation of nutrients and exportation of waste products to and from the estuary are subsidized by gravitational energy in the form of streamflow and tidal exchange. As a result,

the estuary becomes a productive seafood factory.

Events occurring in the estuary's watershed (even hundreds of miles away) greatly influence processes in the estuary itself. Some watershed processes are vital. Without fresh water inflow and the nutrients and sediments transported by rivers and streams, the estuary would not exist; it would be a lagoon, a salty extension of the gulf. But the rivers do not discriminate. Any material reaching a river–including pollutants–will be transported, perhaps undergoing chemical transformation enroute.

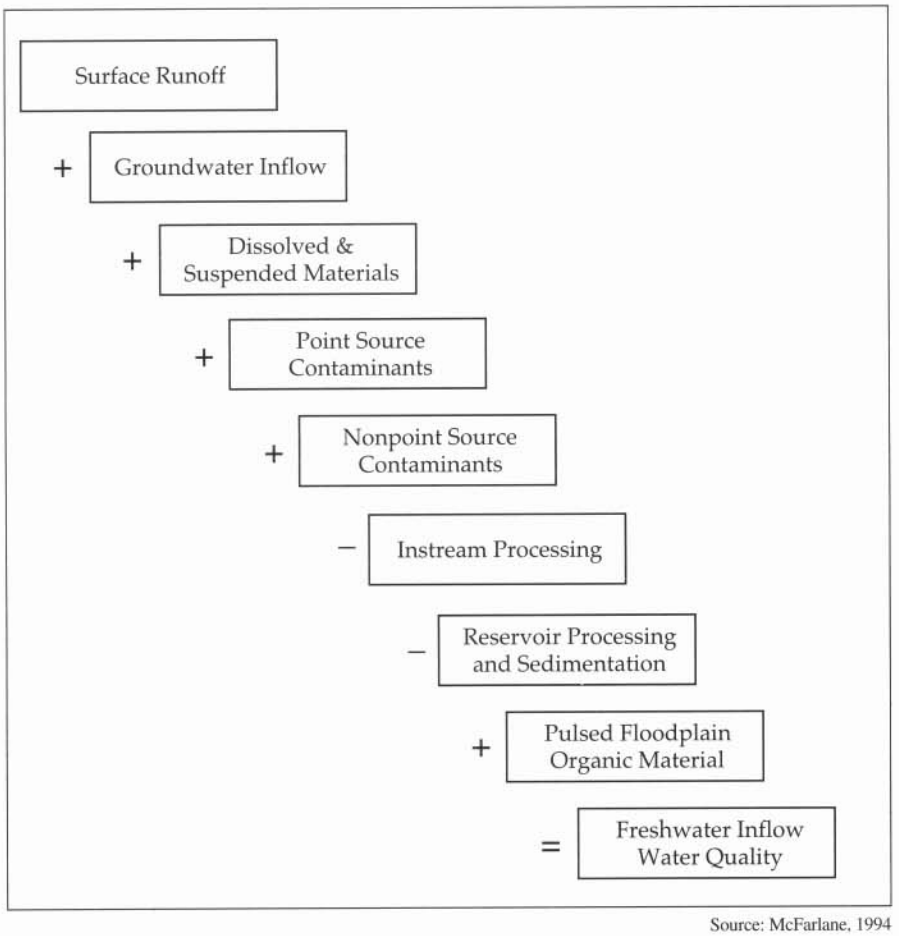
Water quality in the estuary is a key attribute affected by watershed events. FIGURE 3.2 illustrates the determinants of water quality in sequential order as they occur from watershed to estuary. Dissolved and suspended materials are incorporated wherever water moves, even by raindrops moving through the atmosphere. Precipitation results in surface runoff and groundwater inflow to streams. Point and nonpoint source discharges add various contaminants, particularly from urban-industrial areas and intensely cultivated sub-watersheds. Stream microorganisms and in-stream chemical events typically alter or reduce contaminant levels. Further processing and settling out occur in each reservoir upstream from the estuary. Flooding of the lower river floodplain periodically introduces pulses of organic material from the surrounding landscapes. Water quality may both degenerate and regenerate during passage through various river segments before entering the bay.

COMPONENTS OF THE ESTUARINE ECOSYSTEM

The bay itself shows marked variability. Even the apparently homogeneous open water is composed of subtly varying water masses. Recreational fishermen search for patches of clear "green water" where artificial lures can be seen by visual-feeding fishes, and "slicks", said to exude a "watermelon" odor associated with feeding predaceous fish (a phenomenon yet undescribed by scientists). These areas contrast with the turbid, river-influenced regions sought by commercial crabbers. Of course, bay habitats themselves are more readily distinguished. Patches of differing habitat are prominent along the shoreline and across the bottom of the estuary; corridors of forest or brush stretch as greenbelts along the shoreline and line small tidal streams. Edges, created where two habitats meet, are particularly significant in the estuary, sought by **planktonic** larvae and stalked by predators.

Habitats emerge as a compelling way to ecologically classify an estuary. The major habitats are quite distinctive and easily recognized (see FIGURE 2.4 on page 20). The largest habitat is the three-dimensional open-bay water itself, to which all other habitats are linked. Equally large in areal extent but virtually two-dimensional, is the underlying open-bay bottom. The bottom functions as a matrix upon which two different types of habitat patches can be found. On hard bottoms with strong currents, patches of oyster reef rise up to provide the only hard substrate and elevated surface above the bay bottom. On softer sediments in shallow water, patches of submerged aquatic vegetation–the **subtidal** seagrass meadows–can be found near the periphery of the bay. As the bay bottom slopes upward at the edge of the bay, meadows of emergent intertidal vegetation, the peripheral marshes, line the shore. Some low-sloping shore zones do not support emergent vegetation, remaining as intertidal mud flats. Patches of very soft, unconsolidated subtidal bottom are scattered within various shoreline wetlands to create the peripheral marsh embayments.

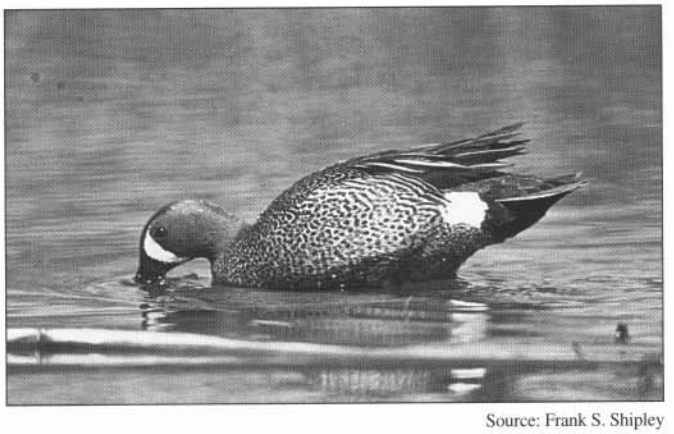
The conceptual model presented in this chapter is based upon the varying relationships of bay habitats to the surrounding upstream and marine systems, and to one another. Each habitat is connected (directly or indirectly) to the upstream fresh water riverine-floodplain ecosystem and downstream to the marine waters of the nearshore-gulf ecosystem, and via migratory birds, to the interior of the continent. Seven key habitats are singled out for the sake of the model (FIGURES 3.3–3.9) The structure and connectedness



Source: McFarlane, 1994

FIGURE 3.2. *The quality of fresh water feeding an estuary is greatly influenced by events in the watershed. Human and natural influences on runoff reaching streams–and alterations of the streams themselves–help shape water chemistry and physical processes in the downstream bay.*

of an eighth habitat type, the peripheral marsh **embayments**, are so poorly known that a model would be conjectural at this time. For each habitat, the living components 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 nutrients and energy through the food web, although they do not represent schematics of energy flow or nutrient cycling in the strictest sense. In some instances unique subsystems of the habitat emerge from the models and have been identified.

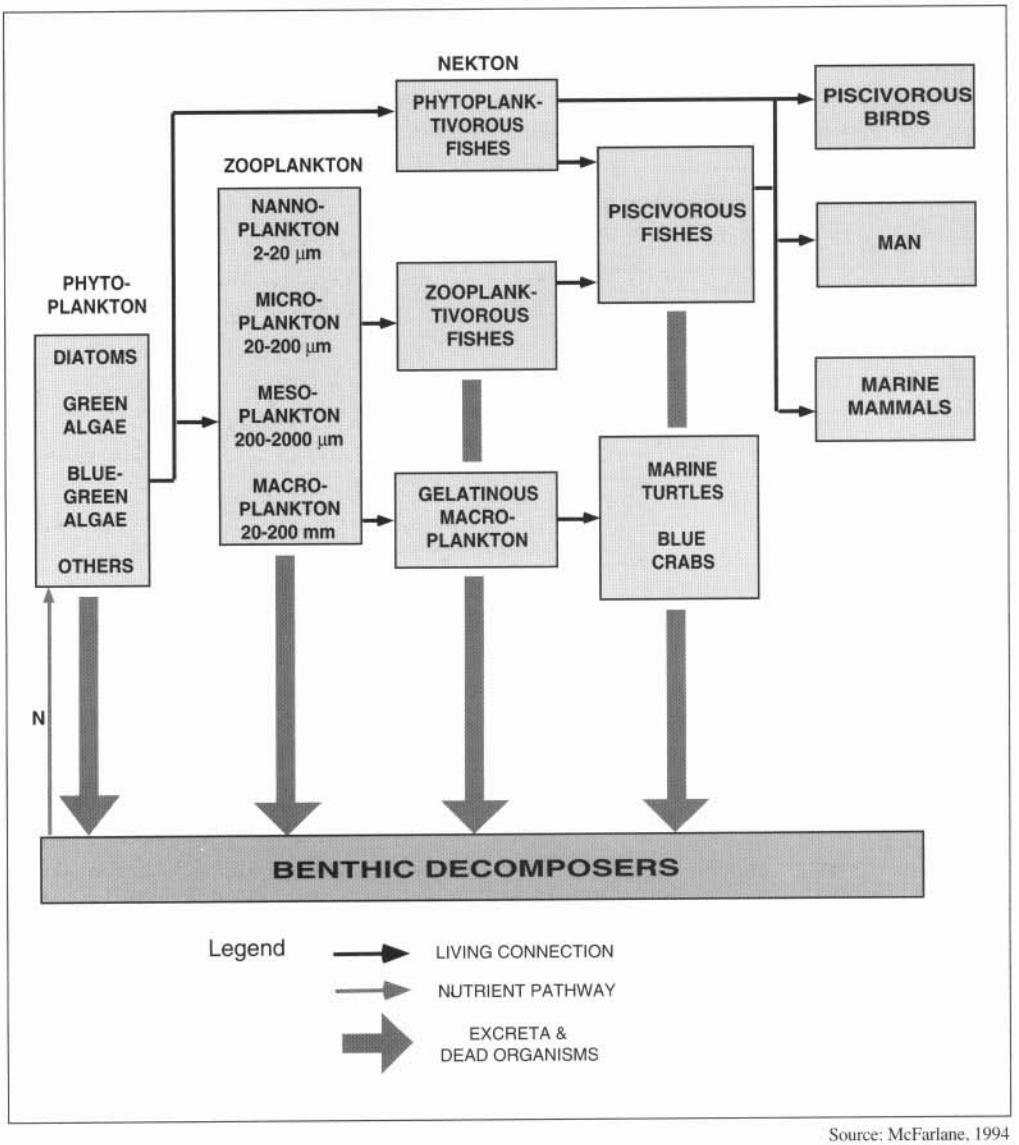


Source: Frank S. Shipley

The bay can be clasified by its habitats, areas that sustain the needs of particular living species. This blue-winged teal utilizes shallow, fresher marsh areas in the upper bay system.

Open-Bay Water

The open-bay water is the largest and most conspicuous habitat of the ecosystem (FIGURE 3.3). It has the greatest areal extent, 354,000 ac, and is three-dimensional, with an average depth of seven feet. Its **pelagic** inhabitants include all of the active swimmers and passive drifters found in the water column. This habitat has the simplest structure of all the habitats considered, and is essentially featureless except for an invisible horizontal and vertical salinity gradient, and at times, gradients of temperature and dissolved oxygen.



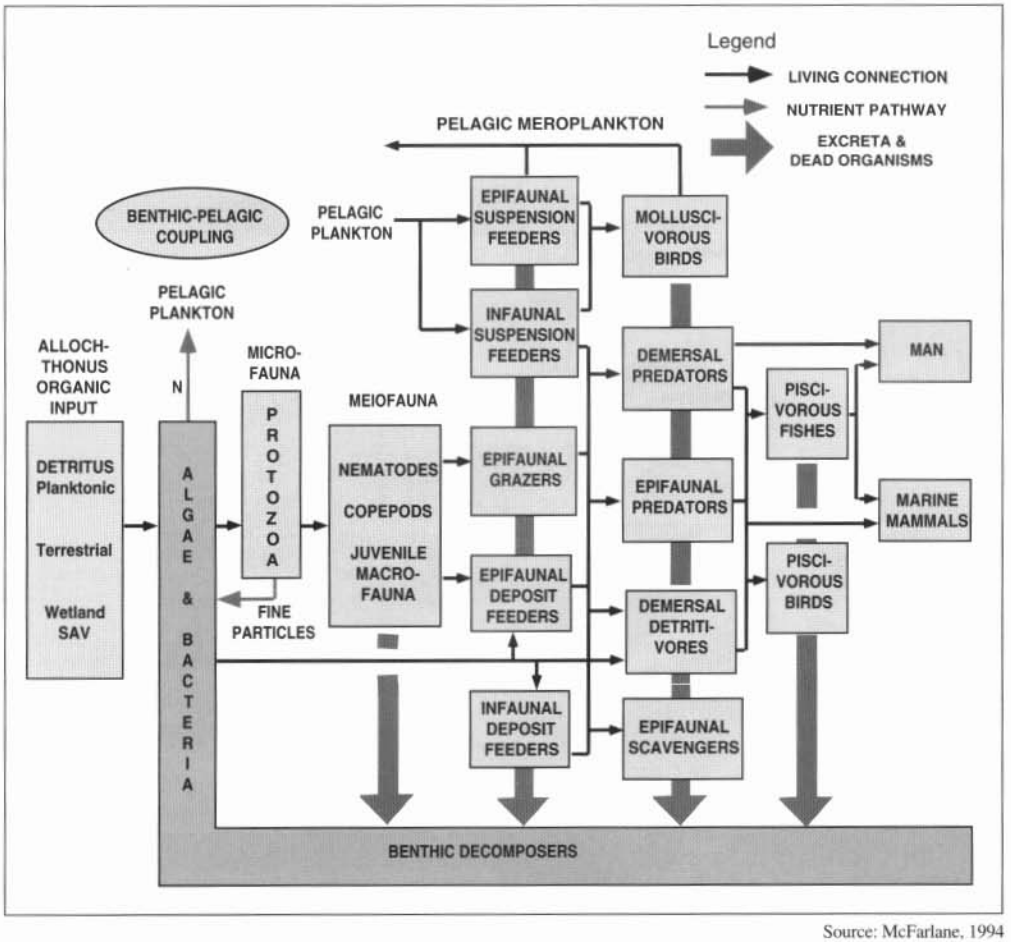
Source: McFarlane, 1994

FIGURE 3.3. *Schematic model of open bay water habitat in Galveston Bay.*

The **primary producers** of the open-bay water are composed of various groups of phytoplankton, which capture the physical energy of sunlight and package and store this energy in organic molecules constructed from carbon dioxide gas (Buskey and Schmidt, in Green et al., 1992). The **primary consumers** which feed upon these phytoplankton are the numerous and diverse **zooplankton** and phytoplanktivorous fishes. The **secondary consumers** are principally **nekton**, 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. Dead organisms and egested material sink to the bottom to be recycled by **decomposers** inhabiting the open-bay bottom.

Open-Bay Bottom

The open-bay bottom (FIGURE 3.4) is the second largest habitat of the ecosystem, being equivalent to the open-bay water habitat minus those areas of the bay bottom covered with oyster reef or seagrass meadow. This habitat is essentially two-dimensional; while its length and breadth are measured



Source: McFarlane, 1994

FIGURE 3.4. *Schematic model of open bay bottom habitat in Galveston Bay.*

in miles, its depth is measured in inches. For the most part, the surface seems featureless except for sculpted waveforms, trawl marks, and evidence of burrowing animals. To a burrowing benthic organism, however the features of this benthic environment can be patchy, caused by the specific distribution of sediments of different particle size and the clumped distribution of life forms themselves.

The food web of the bottom habitat is based upon biological decomposition of **detritus**. Except for shallow shoreline areas where light penetrates the turbid water to reach the bottom, photosynthetic algae and primary productivity are limited or nonexistent. Organic matter reaches this zone in the form of "planktonic rain" as dead organisms or egested material sink to the bottom, or is imported as **dissolved organic matter** (DOM) and **fine** or **coarse particulate organic matter** (FPOM, CPOM) transported from the riverine and peripheral wetlands or submerged aquatic vegetation (Day et al., 1989).

The most striking feature of the benthic food web is the key role of fungi, bacteria, and **protozoans** which comprise the benthic decomposer organisms at both the beginning and the end of the food chains. Vascular plant material has limited usefulness to most estuarine organisms in its raw state. It must first undergo "conditioning" or partial digestion by certain types of the fungi and bacteria. Few animals manufacture the digestive enzymes necessary to break down cellulose, the structural component of higher plants. Bacteria are capable of this but apparently their activity is limited to the surface of the plant material. More important are various fungi which are able to penetrate deep into cracks and crevices of plant material to extract nutrients. In doing so, the microbes release various nitrogen compounds to the water column. Various protozoans and other organisms which comprise the **microfauna** (small enough to pass through a 0.062 mm mesh screen; 2/1000ths of an inch) 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. The protein content of the food "packages" also increases with each successive step, creating higher quality food.

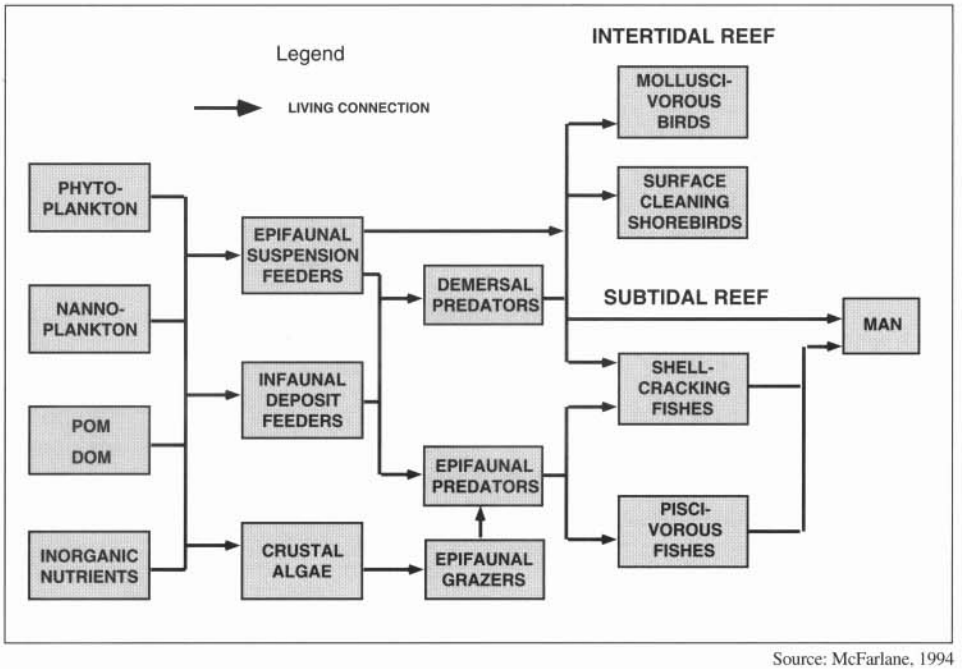
Dependent upon the microfauna for food is a diverse **meiofauna** comprised of organisms between 2/1000ths and 2/100ths of an inch (0.062-0.5 mm) in size. Nematodes are most numerous but **copepods** and juvenile stages of the larger **macrobenthos** are also abundant. These organisms find protozoans and bacteria to be conveniently-sized prey. The meiofauna are most abundant in sediment with high silt fractions.

As the food web organisms increase in size to macrobenthos (> 2/100ths of an inch) they also begin to subdivide the habitat into two components (Harper, in Green et al, 1992; LaSalle et al., 1991; Ray et al., 1993). One diverse assemblage of organisms, the **epifauna**, lives on the surface of the bottom sediment. Another assemblage burrows into the bottom sediment, either superficially under a dusting of **flocculant** sediment, or deeper in vertical tubes; these organisms form the **infauna**.

Epifaunal and infaunal organisms overlap in feeding strategies. Some feed by straining suspended particles from the water column (the **suspension feeders**, e.g. most **bivalve** mollusks). Others feed by ingesting sediment and extracting nutrients in the digestive tract (these are known as **deposit feeders** and include many worms). **Gastropod** mollusks graze along the sediment surface. Both mobile and **sessile** animals exist here. Many crabs forage on the surface but burrow beneath it to escape detection by larger predators between foraging excursions. Scavengers and several trophic links of predators are found on the bottom.

The open-bay bottom habitat is closely coupled with the open-bay water habitat. Pelagic plankton, which frequently under-

go diurnal vertical migrations, are consumed by epifaunal and infaunal suspension feeders. At the same time many **mollusks** and other benthic organisms contribute planktonic larvae to the **meroplankton** assemblage. **Mysids** and **ostracods** spend time on the bottom and in the water column. Denitrifying bacteria release nitrogen compounds to the sediment and thence to the overlying water column. At the larger end of the scale, numerous fishes (e.g. croakers, spot, mullet and drum) and shrimp forage on benthic organisms. These are considered as **demersal** predators and **detritivores** in this model to indicate their ability to move freely within the water column. Diving birds (particularly ducks) reach the benthos to consume small mollusks and other organisms.



Source: McFarlane, 1994

FIGURE 3.5. *Schematic model of oyster reef habitat in Galveston Bay.*

Oyster Reef

Clusters of oyster shell, live oysters, and other **commensal** organisms form a distinct oyster reef habitat (FIGURE 3.5). Oyster reefs tend to form wherever a hard bottom and sufficient current exist to transport planktonic food to the filter-feeding oysters and carry away sediment, feces, and **pseudofeces**. 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). They are particularly abundant along the side slopes of navigation channels where tidal exchange currents are dependable. The reef itself is three-dimensional to the extent that the shells cemented together create an irregular surface that establishes a myriad of microhabitats for smaller species.

Source: Texas Parks and Wildlife Department

Oysters, an economically important seafood species in Galveston Bay, create reef habitat utlilized by many other species. Encrusting organisms such as ribbed mussels, bryozoans, and barnacles take advantage of the hard substrate created by the oysters as they secrete calcium shell. These species in turn attract predators like oyster drills (a snail) and fish species adopted to crush shellfish with specialized teeth as they forage.

The oyster reef community is very diverse. While oysters contribute the dominant **biomass**, other bivalve mollusks, gastropods, barnacles, crabs, amphipods, **isopods**, and **polychaete** worms are normally abundant. In West Bay, for example, oyster reef communities were shown to be comprised of 18 fishes, 22 shrimps and crabs, 17 mollusks, and 34 **annelid** worms (Zimmerman et al., 1989). The reef community is **heterotrophic**, dependent on the importation of food resources from other habitats, principally the open-bay water and peripheral emergent marshes. **Nanoplankton** and phytoplankton are filtered by oysters and other epifaunal suspension feeders. Dissolved and particulate organic matter, particularly the feces and pseudofeces emanating from the suspension feeders, support various deposit feeders sequestered in the interstices of the aggregated shell. Oyster reefs are most successful where bottom currents sweep sediments away from the reef;

Source: Galveston Bay National Estuary Program

Underwater seagrass meadows, as shown here in Christmas Bay, support a diverse and productive community, including such organisms as pipefish and seahorses, as well as recreational species such as spotted seatrout. Of the 2,500 acres of seagrass habitat present during the 1950s, only about 700 acres remain today.

otherwise, the oysters can be inundated with their own feces and pseudofeces to the point where filter-feeding is inhibited. Crustal algae attach to shell substrate in some instances, particularly in shallow shoreline areas, supporting a small grazing food chain.

Secondary consumers of the reef include predators, parasites and pathogens, some of which are important oyster population control agents. Demersal fishes with crushing teeth (e.g. black drum) and epifaunal **crustaceans** (e.g. stone and blue crabs) prey on small oysters with thin and weaker shells. Oyster drills capable of drilling through the shells of larger, but immobile, prey reverse the usual large predator/small prey size ratio. 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 about 1500 times the volume of their body (but see Powell, et al., in press). A large, healthy oyster population is able to filter large volumes of bay water, and may therefore influence conditions such as water clarity bay-wide. At the same 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.

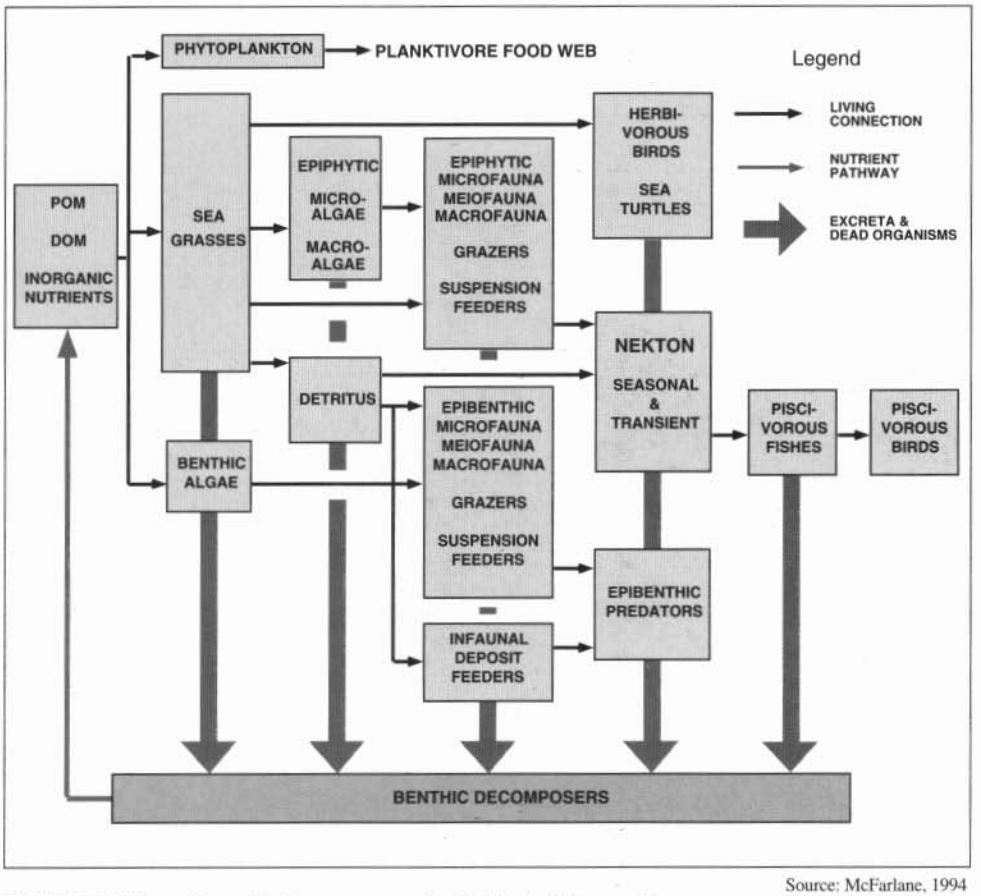
Seagrass Meadow

Patches of **submerged aquatic vegetation** (SAV), composed of fresh water and marine plants and their attached **epiphytic** algae, form the three-dimensional seagrass meadow habitat in soft sediments along the shorelines (FIGURE 3.6). Only 700 ac of this habitat remain in Galveston Bay, half within Christmas Bay alone (White et al., 1993; Pulich and White, 1989; Pulich et al., 1991). This habitat provides food resources and protective cover for a number of associated species and contributes substantial quantities of detritus to the food web. The fauna associated with these patches of SAV is quite diverse (e.g. 20 fish and 15 crustacean species; Zimmerman et al., 1989; Czapla, 1991).

Marsh

Approximately 61 percent (142 mi) of the Galveston Bay shoreline is vegetated by intertidal emergent plant communities (Paine and Morton, 1991), totaling 108,200 ac (White et al., 1993). These marshes (FIGURE 3.7) are subjected to periodic subsidies of tidal energy (highly modified by winds) as they are inundated by the ebb and flood of tides once or twice each day. Flow from the adjacent upland watershed is unidirectional, but subject to extreme pulses corresponding to rainfall episodes. Flow onto and off the marsh from both the watershed and the tides determines the nature of flow through the interstitial pore space of the marsh sediment (Wiegert and Freeman, 1990).

Intertidal marshes are structurally resilient. Where they have

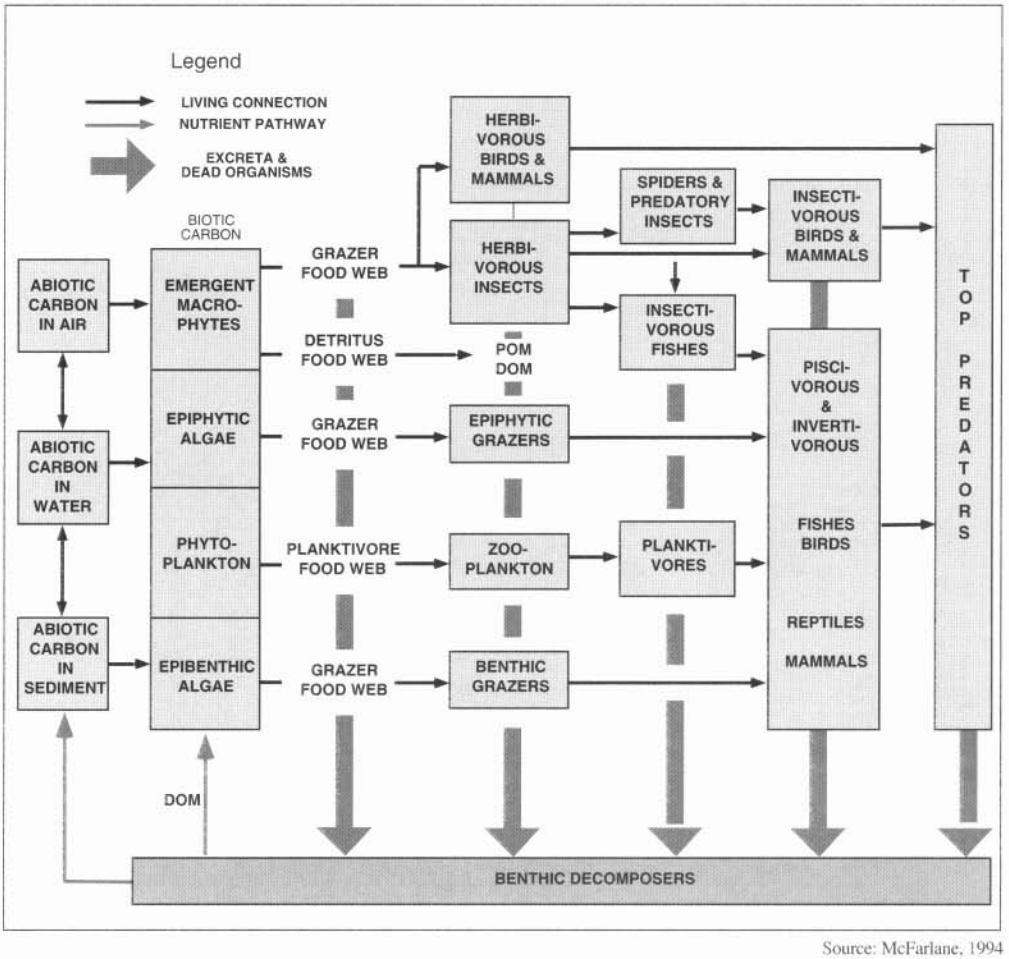


Source: McFarlane, 1994

FIGURE 3.6. *Schematic model of seagrass meadow habitat in Galveston Bay.*

Source: Galveston Bay National Estuary Program

Intertidal salt marshes dominated by smooth cordgrass (Spartina alterniflora) *form productive nursery areas for many invertebrate and fish species. More than 90 percent of the commercial and recreational harvest from the Gulf of Mexico is composed of species dependent on wetlands like this for some part of their life cycle.*



Source: McFarlane, 1994

FIGURE 3.7. *Schematic model of intertidal marsh habitat in Galveston Bay.*

not been disturbed by subsidence, construction, transportation, or energy-extraction activities, marshes appear little affected by human agriculture or industry. With their soft substrates and twice-daily tides, they are not very suitable habitats for large grazing **herbivores**, such as bison or cattle. The grasses evolved in high-salinity marshes are particularly tough, being mineralized and therefore resistant to herbivory. Unlike the continental grass, desert or forest ecosystems, the extinction of large herbivores did not alter the vegetational composition and productivity of intertidal marshes. In addition, the osmotically-stressed intertidal system is not an easy target for the invasion of exotic plants and animals.

Marshes, however, can be converted by extensive and expensive modification to uplands, and 35,600 ac of marshes surrounding Galveston Bay have been so converted since the 1950s (White et al., 1993; see Chapter Seven). Fresh marshes appear to be the most vulnerable, being composed of species with softer tissue, and sometimes occurring in smaller patches. Only in fresh water tidal lands have introduced species, such as water hyacinth, nutria, and grass carp caused physical obstruction and destruction. Thus the less-modified brackish and saltwater marshes represent a relict of the most nearly pristine wetland types, surrounded by greatly modified ecosystems (Wiegert and Freeman, 1990).

Marsh function is influenced by three distinct environmental conditions, with which each plant must cope. Their culms and leaves are continually exposed to direct sunlight, neither filtered nor attenuated, the basal stem is periodically bathed in water, while their roots are anchored in **anaerobic** sediments (see the left portion of FIGURE 3.7). From all three layers, emergent

plants are able to extract or interchange **abiotic** carbon; in addition the plants promote the production of biotic carbon in four different compartments shown in the model.

As photosynthesizers, the emergent **macrophytes** produce carbon molecules that support a grazing, herbivorous, terrestrial food chain. Typically, only about ten percent of this primary production is incorporated into the grazing food chain. The remainder is diverted to the estuarine detrital food web. The enormous productivity of marshes and the significance of their detrital pathways to the estuary at large have long been recognized. Frequently overlooked is the fact that secondary production by the primary consumers of this green plant material is one of the largest of any terrestrial system known (Wiegert and Freeman, 1990).

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 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, including forage fish, juvenile game fish, shrimp and crabs. The outpouring of bacteria and plankton on the falling tide support adjacent oyster beds and reefs, while seagrass meadows shelter small fishes returning from intertidal zone foraging.

Intertidal Mud Flat

The intertidal mud flat habitat is an exceptionally open ecosystem (FIGURE 3.8) 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 flat is "vegetated" only by **microalgae**, **macroalgae** and phytoplankton. Import of organic and inorganic material and detritus are important to its functioning. The only animals relatively fixed in position and restricted to a single habitat are the components of the benthic infauna and, to a lesser extent, the epifauna. The benthos is supported by primary production from outside of the habitat and imported via water currents and tidal action.

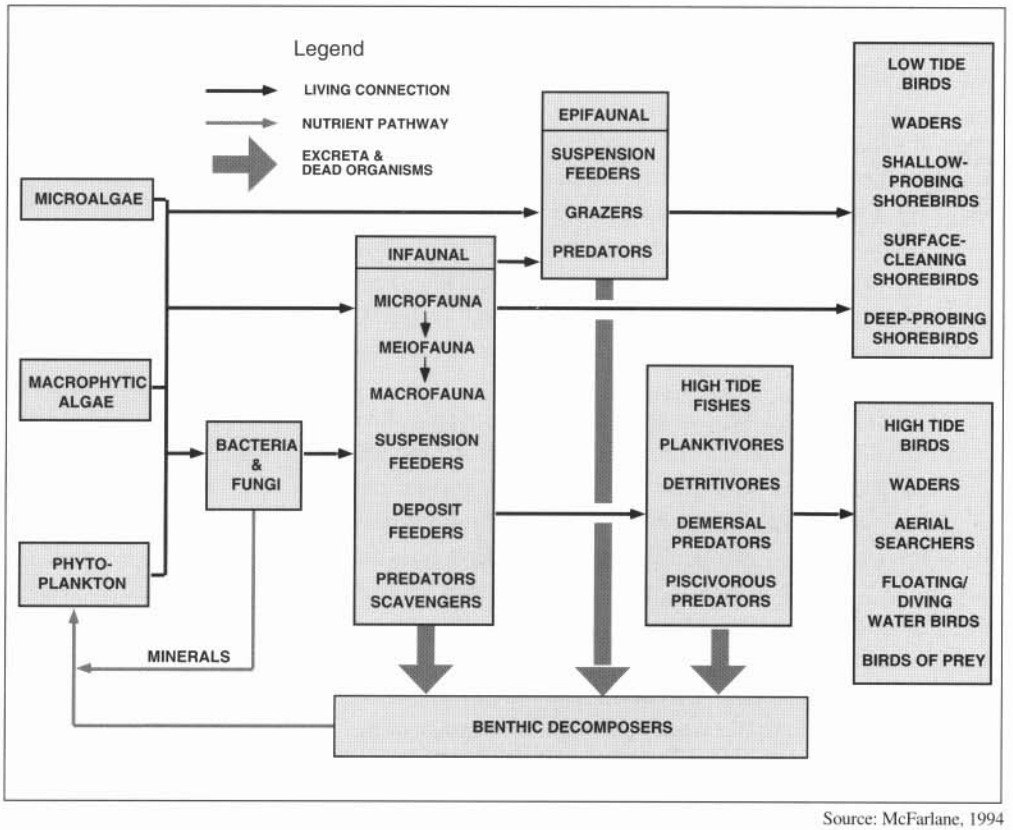
On mud flats, members of the higher trophic levels appear as transients with the tides. At high tide, planktivorous, detritivorous, and demersal fishes move onto the flats to feed, followed by **piscivorous** predators, both birds and fishes. At low tide, gleaning and probing shorebirds feed on and in 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.

Bacteria and fungi play an important ecological role in mineralization of dead organic matter to inorganic nutrients. They also serve as a trophic intermediate between relatively indigestible plants and consumers of plant detritus (Peterson and Peterson, 1979). These microbes consume indigestible cellulose and lignin, add protein, and transmit energy and nutrients to detritivores. Fecal pellets are colonized by decomposers and cycled through detritivores once more. This process of microbial renewal on detritus may be an important rate-limiting step which determines the abundances of deposit-feeding species, such as snails, in the community.

The sediments of mud flats serve as a nutrient sink. Nutrients and other compounds adsorb to sediment particles. In this shallow zone, the sediments are subject to **resuspension** by wave action and **bioturbation** from the many infaunal animals. Biodepositon by suspension feeders in the form of feces and pseudofeces adds to the nutrient bank. When nutrient concentrations in the water column decline, the sediments give up their adsorbed nutrients to establish chemical equilibrium.

Secondary and Tertiary "Lakes"

A conspicuous feature of bay topography is a number of shallow, soft-bottomed, "lakes" (actually small embayments) which



Source: McFarlane, 1994

FIGURE 3.8. *Schematic model of intertidal mud flat habitat in Galveston Bay.*

Source: Galveston Bay National Estuary Program

Source: Frank S. Shipley

Mudflats offer rich foraging grounds for many species of birds. Here, laughing gulls loaf at low tide (above) and a stilt sandpiper forages for such sediment-dwelling organisms as polycheate worms, clams, and burrowing crabs (right).

occur near the terminus of the drainage bayous. Examples are Salt Lake, Nick's Lake, Alligator Lake, Oyster Lake, Hall's Lake, Carancahua Lake, Greens Lake, and Swan Lake which are connected to West Bay and the Christmas Bay complex; Dollar Bay and Clear Lake on Galveston Bay; Robinson Lake on East Bay; and Cotton Lake, Lost Lake, and Old River in the Trinity River delta. Their deep, unconsolidated mud bottoms, (which poorly support the weight of humans) have inhibited scientific study of the systems. As a result, our incomplete knowledge of these systems precludes creation of a schematic model. Each of these water bodies is directly connected to the bay system, edged with emergent marsh habitat, and is subject to highly variable salinity depending upon recent precipitation and location in the estuary. High **turbidity**, perhaps wind-driven, hinders the growth of submerged aquatic vegetation.

These marsh embayments appear to be highly productive nursery areas (Conte, 1971; 1972a; 1972b). Alligator Lake and Oyster Lake harbor brown and white **penaeid shrimp**, grass shrimp, **sergistid shrimp**, and five species of mysid shrimp. Brown shrimp, grass shrimp, blue crabs, pinfish and bay anchovies have been collected in Hall's Lake (Minello et al., 1991). Bay anchovies, gulf killifish, diamond killifish, spotted seatrout, spotfin mojarra, brown shrimp, white shrimp, grass shrimp, blue crabs, and mud crabs were collected in Carancahua Lake (McFarlane, 1994). Shallow, turbid, soft-bottomed lakes and blind bayous of interior marshes of the Trinity River delta are the target habitats of many migratory marine animals seeking food and protective cover. Atlantic croaker, gulf menhaden, sand seatrout, bay anchovy, hogchoker, pinfish, ladyfish, bay whiff, southern flounder, brown shrimp, and white shrimp are particularly abundant in these habitats.

With a high ratio of surrounding marsh to open water area, these marsh embayments appear ideal to support a detrital-based food web. The benthos of the exceptionally soft, nearly flocculant, bottom sediment is unknown. Microbial decomposers undoubtedly fill a critical **ecological niche** in this benthic habitat. In the water, Phytoplankton and zooplankton are also yet to be described, but the abundance and **diversity** of secondary consumers attests to the efficacy and productivity of the primary consumers and green plant producers. The vertical structure of the surrounding marshes provides protective cover for the smallest species and life stages while the shallowness of these systems may limit large predators.

INTERCONNECTEDNESS OF THE ECOSYSTEM

Food webs in Galveston Bay are essentially of two types (Armstrong, 1987). One web is based on production of live plant tissue–carbon produced by photosynthetic plankton and which can be grazed upon by consumers as described for the open-bay water habitat. This web is relatively simple and involves few species. The second web is based on detritus produced both within and out-

Source: Texas Parks and Wildlife Department

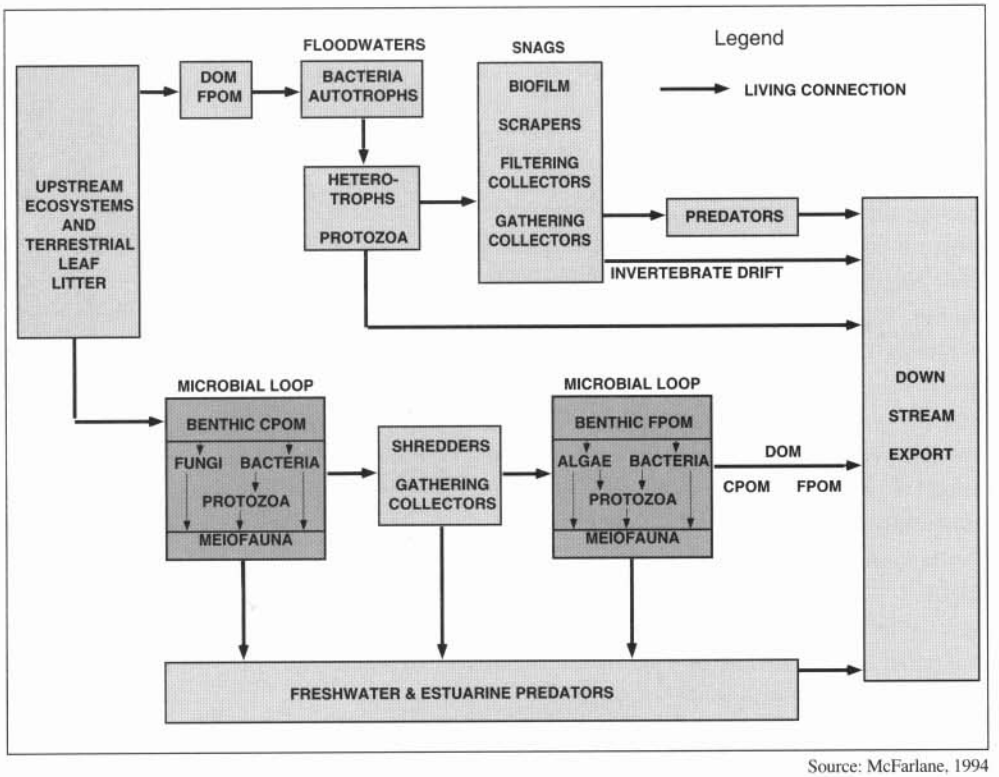
Tidal ponds ranging in size from small marsh openings to secondary and tertiary "lakes" covering many acres form an important but poorly understood habitat type within the bay. The salt marsh ponds shown occur along the north shore of West Bay.

side the bay system. From outside the bay itself, detritus is received from the watershed (transported to the bay with river and stream inflow) and from the fringing marshes (transported tidally). Within the bay, detritus arises from seagrass meadows and as planktonic "rain" as outlined above. Detritus-based food chains are more complex and poorly understood, with more links between consumers, and major roles for microbial populations.

Riverine/Floodplain Dynamics

Streams, rivers, and their floodplains are dynamic systems of great importance to estuarine trophic function (FIGURE 3.9). Stream and rivers are longitudinally linked systems: processes which take place upstream have impacts on downstream components. The in-stream biological community changes in a predictable manner in progressing downstream, responding to changes in channel geomorphology and available resources. Much of the degradation of organic matter occurs prior to reaching the estuary in moderate sized channels, and lateral linkages to the riparian zone (the source of much organic matter) are as vital as the longitudinal links of the river continuum itself (National Research Council, 1992). Floodplains play a critical role as sediment and nutrient filters, as contributors of pulses of nutrients and organic matter during floods, and as habitat for fishes at certain life stages (Wharton et al., 1982).

In the riverine/floodplain system (as in the bay itself), microbes are critical components in the sequential decomposition of leaf litter to coarse, then fine, particulate organic matter. Nutrient export from riverine floodplains is pulsed–leaves from terrestrial plants and trees are seasonally dropped to the forest floor where leaching and disintegrative processing begins. Periodic overbank flooding and drainage of the floodplain redistributes this organic material downstream, at times sweeping the forest floor clean of leaf litter. At least two microbial loops are involved in the decomposition process (Meyer, 1990). One process is fueled by dissolved and particulate detritus that is consumed by bacteria, which then becomes food for protozoa and other organisms. Another process begins when shredding insect larvae in the unstable stream and river sediments participate in reducing detrital particle size and har-



Source: McFarlane, 1994

FIGURE 3.9. *Schematic model of riverine/floodplain habitat in Galveston Bay.*

vesting attached microbes. Grazers and filtering or gathering collectors inhabit stable substrates, such as snags and logs. Dissolved organic matter (DOM), coarse particulate organic matter (CPOM), fine particulate organic matter (FPOM), and invertebrate drift organisms are exported to downstream habitats, including the estuary.

Our current understanding indicates that fresh water inflows transport 96 percent of the imported carbon and nitrogen, and 95 percent of the phosphorus, with the remainder contributed by peripheral marshes (Armstrong, 1982; Borey et al., 1983). Yet a large proportion of the annual **carbon flux** within the bay (that is carbon acquisition and transformation) is believed to come from phytoplankton within the estuary (Armstrong, 1987). The relative importance of plankton versus detritus as the base of secondary productivity in the bay deserves further study. Does the abundant seafood production in Galveston Bay ultimately depend more upon green plant tissue, or upon dead organic matter? Certainly detritivores are both prominent and dominant components of the ecosystem.

The Influence of Human Activities

Upon this complex and dynamic mosaic of natural functions are imposed the sometimes-disruptive activities of human society. Growth of the human population and increasing per capita use of resources mean human influences on the ecosystem are increasing, rather than decreasing. If not addressed, these activities will increasingly threaten the life-support system of the estuary. Agriculture, forestry, fisheries, water diversion, mineral extraction, fuel consumption, industrialization, urbanization and recreation, are intended to improve the quality of life by providing food and fiber production, shelter, water supply, consumer goods, and economic growth. These activities can also produce unintended results, such as habitat alteration and destruction, **eutrophication**, pollution, loss of biodiversity and extinction of species. Each of the seven estuary habitat types can be degraded, and some can be lost entirely. Ecological knowledge can be applied in the management of these activities to reduce the incidence of negative, unintended results.

A summary of human activities which potentially degrade or destroy habitats is provided in FIGURE 3.10. The vulnerability of the habitats varies. Open-bay waters, open-bay bottom, and intertidal mud flats are the least susceptible to degradation. The open-bay water habitat can be altered or degraded, but not destroyed, by changes in its physical gradients (depth, temperature, transparency, currents) or chemical constituents (salinity, dissolved oxygen, contaminants). Floating oil or chemicals can affect organisms inhabiting the **surface microlayer**. Likewise, the open-bay bottom habitat is very resilient. It can be temporarily destroyed by burial under dredged material or excess sedimentation, and degraded by brine discharge or **anoxia**. Subsidence can convert the intertidal mud flat habitat to subtidal bottom, shoreline development can displace the habitat, disposal of dredged material can bury it, and oil or chemical spills can coat the surface with toxic or smothering substances.

Three habitats are created and maintained by living organisms, and are therefore more vulnerable to degradation or destruction. Oyster reefs originate when oyster **spat** settle upon hard bottoms but, once the initial layer of oysters covers the bottom, subsequent reef growth occurs on existing oyster shell. This provides considerable resiliency to reefs because all of the oysters may be

	Open-Bay Water	Open-Bay Bottom	Oyster Reef	Seagrass Meadow	Marsh	Marsh Embay-ment	Mudflat
FW Inflow Modification	✔		✔		✔		
Subsidence			✔	✔	✔	✔	✔
Shoreline Development			✔	✔	✔	✔	✔
Dredge & Fill		✔	✔	✔	✔		✔
Point Source	✔			✔			
Nonpoint Source	✔			✔			
Commercial Fishing		✔	✔				
Recreational Fishing				✔			
Boating & Marinas		✔		✔			
Petroleum Activity		✔					
Oil/Chemical Spills	✔				✔		✔
Circulation		✔	✔				
Shoreline Erosion					✔		
Exotic Species					✔		
Storms & Hurricanes				✔			

Source: McFarlane, 1994

FIGURE 3.10. *Perturbation of Galveston Bay estuarine habitats. The seven habitats described in this chapter (across the top) are influenced by a variety of perturbations (in the left column), many of which result from human activities.*

killed during unfavorable conditions, only to be recolonized by spat from elsewhere when a favorable environment returns. The greatest vulnerability of this habitat is to changes that prevent long-term survival of oysters at that location in the bay. These include permanent changes in salinity and circulation (e.g. from navigation projects), alterations of currents over the reef, increased sedimentation that physically buries the reef, and overfishing that depletes the supply of oyster shell faster than it is replaced by oyster growth.

Seagrass meadows are known to be adversely affected by many kinds of environmental changes (Pulich and White, 1989). Subsidence can increase water depth, placing plants below the **photic zone** (rendering them incapable of **photosynthesis**). Point and nonpoint source discharge of excessive nutrients can overstimulate the growth of epiphytic algae. This reduces light penetration to the leaf surface and creates drag in water currents that can uproot the grasses during storms. Boat traffic can create propeller swaths through beds of seagrass, and wading fisherman trample the grass underfoot. Dredge and fill activity can bury the grasses beneath sediment. Shoreline development, particularly canal-access residential use, may result in all of the above.

Peripheral marshes are damaged or eliminated by subsidence and shoreline development, particularly dredge-and-fill projects (see Chapter Seven). Drainage and conversion to upland habitat is particularly destructive (White et al., 1993). Reduction of fresh water inflow can result in inadequate sediment transport and lead to erosion of delta marshes. Exotic species, particularly nutria and grass carp, can produce excessive cropping (eat-outs) of marsh plants and change the vegetative composition of these wetlands. Peripheral marsh embayments are poorly known but seemingly would be affected by subsidence and shoreline development.

The perturbations shown in FIGURE 3.10 could be improved by ranking the relative impact of each perturbation-habitat interaction. In reality, the severity of an impact will vary greatly by the type, site, and season of the impact. Each instance is unique.

Source: United States Fish and Wildlife Service

This sandwich tern forages in open-water habitats for such species as the bay anchovy. It nests in colonies, sometimes located on islands or banks created by disposal of dredged material.

SUMMARY

The Galveston Bay ecosystem is composed of a complex set of overlapping habitats that function with a myriad of natural and inter-linking energy and materials processes. This chapter has described seven distinct habitats which help define the larger estuary, and which link it to riverine and gulf ecosystems and more distant portions of the continent. The integrity of these highly connected, distinct but interacting habitats is vital to the continued natural function and life-support capability of the estuary.

The use of conceptual models of the various habitats has shown 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 precipitation runoff from a remote watershed. Therefore, these habitats, and hence the estuary as a whole, can be greatly influenced by actions occurring far from the bay. This implies the need for an ecosystem-level approach to future management of the system.

Other, more immediate perturbations have more obvious outcomes. Water and sediment quality reductions and direct habitat destruction are examples. Having developed in a physically variable and stressful environment, the habitats which comprise the estuary ecosystem can withstand considerable abuse and survive. Some habitats are clearly more vulnerable than others; however, constant chronic abuse or frequent episodic abuse at intervals too short to permit recovery between episodes can ultimately influence each type of environment. For example, seagrass meadows and marshes have suffered well-documented losses over the last several decades.

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CHAPTER FOUR

The Human Role, Past and Present

Galveston will be the seaport sir, for this province. Water plenty, good Harbour, also the anchorage are excellent by non . . .

–Edward Lovelace to S. F. Austin, June 26, 1882 *in* McComb, 1986

Houston, Texas, is Boom Town, U.S.A.

–James Noel Smith, *The Decline of Galveston Bay*, 1972

The Galveston Bay estuarine system is adjacent to one of the most populated areas in Texas. With a population over 3.3 million in 1990, the Houston metropolitan area ranks second in population only to the Dallas-Fort Worth area among metropolitan areas in Texas (Houston-Galveston Area Council, 1993a). Population growth in the region is expected to continue, with more than four million persons projected to live in the five counties surrounding Galveston Bay by the year 2000 (Houston-Galveston Area Council, 1993a).

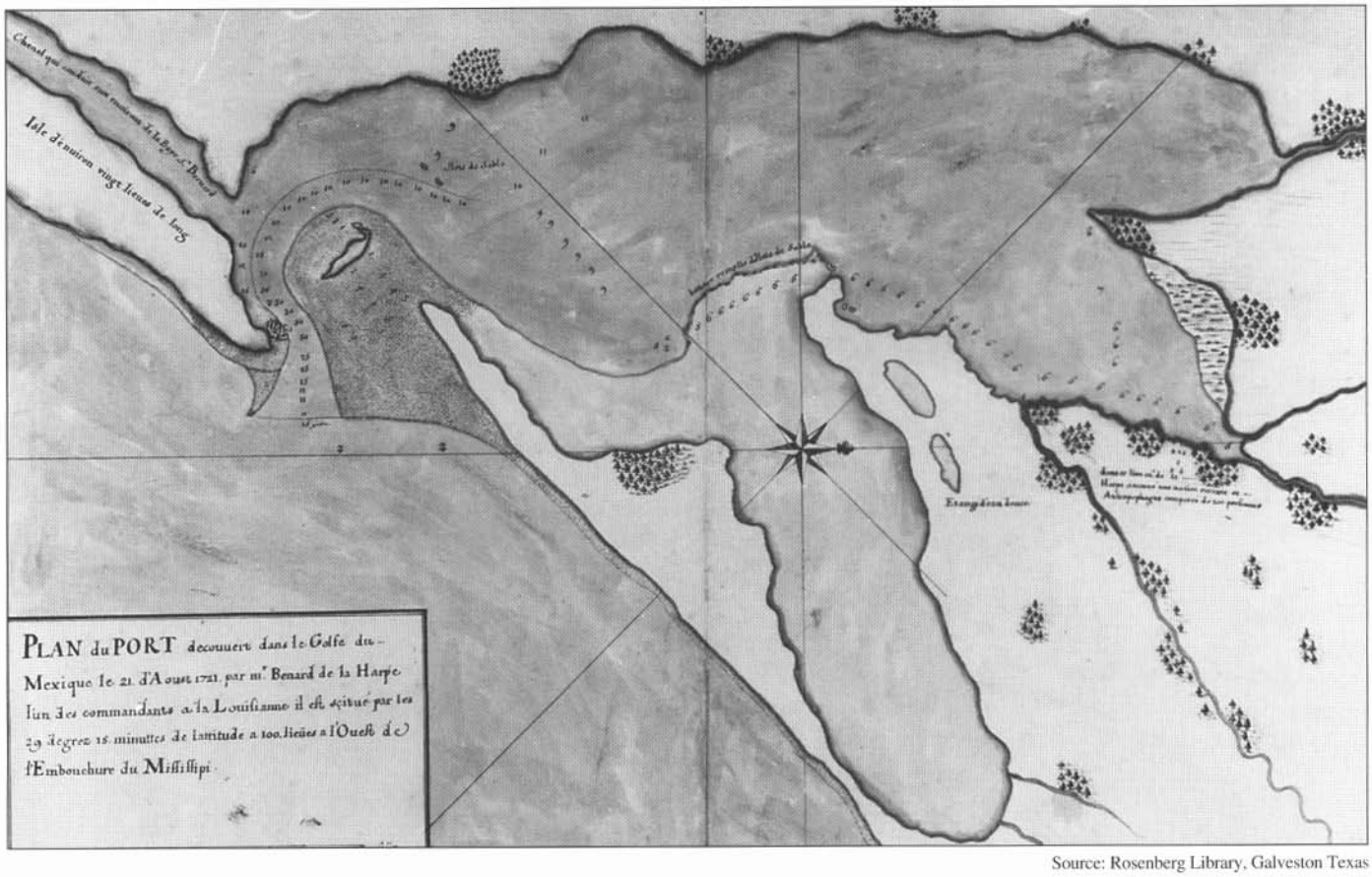
The purpose of this chapter is to provide information on the ways people use the resources of Galveston Bay and its adjacent land area. The chapter begins with a look back to the role the bay system played in the lives of native Americans and European explorers and settlers. The chapter then focuses on the changes in the area's economy prompted by the construction of the Houston Ship Channel and the discovery of oil in the area in the early 1900s. Information is then presented on the major current uses of the Galveston Bay system, including agriculture, commercial fishing and oystering, recreation, shipping, and industrial and municipal uses.

CHANGES IN BAY USE: AN HISTORICAL PERSPECTIVE

Henson (1993) described the first known human use of Galveston Bay as having occurred about 14,000 years ago when Paleo-Indians hunted woolly mammoths, mastodon, and large bison in the area. At that time, Galveston Bay had not yet taken its present shape, and the shoreline extended about fifty to one hundred miles farther out in the Gulf from where it is today. For over 13,000 years humans continued to use the bay and its surroundings as a source of food. The only changes these early residents made to their host environment, according to Henson (1993), "were the gradual accumulation of piles of discarded shells" from oysters and clams and "pottery shards scattered around the waterways."

Spanish and French explorers visited the bay area between 1528 and 1722. Upon finding no mineral riches, these explorers turned to trade with the local natives. The bay, in the meantime, was changing from being a food source for the native Indians to a conduit for colonization and settlement. By 1815, the harbor at Galveston Island attracted mercenaries, called filibusters, and privateersmen who claimed to be helping the Mexican republicans in gaining their independence from Spain. By 1822, Anglo Americans began arriving and settling in the area.

The settlers around the bay in the 1820s were primarily agrarians (Henson, 1993). Most were farmers, others were planters of cotton, and a few owned boats and became merchants taking wood and agricultural products to New Orleans or the Mexican ports. The newcomers, both American and European, cleared stands of trees, planted fields and built homes. These changes encouraged erosion and silting of the waterways because of, as stated by Henson (1993), "denuded forest and prairie lands that turned



Source: Rosenberg Library, Galveston Texas

A small party of French explorers surveyed Galveston Bay by canoe in 1721 in hopes of establishing a trading post with local Indians. Although the undertaking failed as a commercial venture, it produced the earliest known map of Galveston Bay.

to dust and mud before blowing or washing into streams and the bay." In further attempts to make their new homes resemble where they had come from, the immigrants imported trees, crops, and animals that were not previously found in the Galveston Bay system.

Henson (1993, based on Barker, 1924) recounts the following description of the first shipwreck on Redfish Bar:

> *The first of many vessels wrecked on Redfish Bar was the schooner* Mary *from New Orleans in March 1835 with 36 passengers and their goods. The ship drew seven feet and even though the captain sent a boat out to sound for a channel, the signal was too late and he went hard aground. The vessel beat on the bottom and the captain ordered barrels of flour and tobacco jettisoned. Nevertheless, the ship was a total loss and the passengers demanded that the captain pay for their property. This disaster inspired [Stephen F.] Austin to sound and map the bay and he spent over two weeks in 1826 with a crew of nine in three boats marking safe channels.*

The population of Texas and Galveston Bay increased during the 1830s and the bay became a major artery for goods and passengers going to the San Jacinto and Trinity Rivers. Communities around the bay underwent some change after the Battle of San Jacinto in April 1836 and declaration of the Republic of Texas. Anahuac and Lynchburg remained small transfer depots for goods and passengers heading inland. Two new towns, Houston and Galveston, were both private ventures founded in 1836 and 1837. Houston was established by A. C. and John K. Allen, New York natives who resided in Nacogdoches; Galveston was founded by Michael B. Menard, Thomas F. McKinney, and Samuel M. Williams.

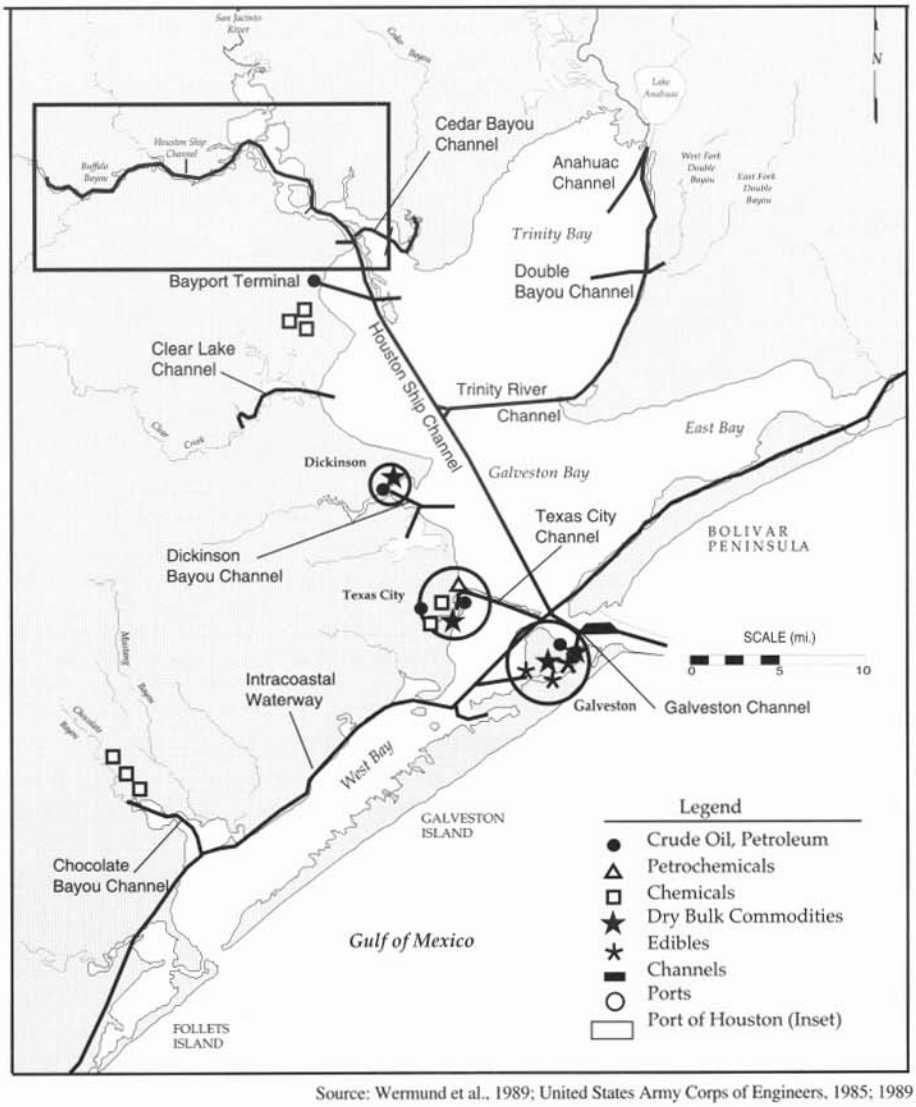
Texas was finally annexed to the United States in December 1845. This, however, initiated a two-year war with Mexico. The war according to Henson (1993) "stimulated business and commerce and brought new people to the bay area, some of whom stayed because of the economic promise." Galveston in 1850 was the largest town in Texas with 4,177 people (Henson et al., 1993, after Kingston, 1964). The data from the 1850 United States Census show that the bay functioned primarily as a transportation system with limited commercial fishing. However, given the rural nature of the bay shore at the time, Henson (1993) concluded that "one can assume that fishing, like hunting, was also a normal activity of many individuals living in the vicinity...," and that "the maritime activity, in turn, provided many area residents with the means of their livelihood beyond seamen and boat builders; supplying the vessels with wood, water, and food at the various stops was a way farmers could earn money."

In 1850, the U. S. Army Corps of Engineers began surveying

the bay and publishing updated charts detailing the depth of the bay and its channels, buoys and lights. The Corps also marked hazards such as shipwrecks and shoals and marked wharves and piers, towns and roads along the shore. Between the years 1850 and 1914, transport related to deep-water shipping was the principal use of the bay. A bitter rivalry developed between Houston and Galveston as each tried to dominate commerce. While most ships could enter Galveston's harbor through the natural channel, only the shallow-draft river steamers could go up the bay to Houston. This rivalry eventually led to the dredging of the Houston Ship Channel, one of the major events discussed in this chapter as shaping the history of the Galveston Bay system.

Toward the end of that period, about 1903, an inquisitive oil scout brought petroleum production to Galveston Bay. The first producing well was on the shore of Tabbs Bay in 1907. By 1915 there were at least 25 wooden rigs around Tabbs Bay producing about 130,000 barrels of oil per year (Henson, 1993). The discovery of oil in the region in the 1920s ushered in the petroleum/petrochemical and industrial era of use for Galveston Bay.

In summary, to the native Americans, Galveston Bay was a major source of food and raw materials for tools and utensils. During the subsequent years of settlement, Galveston Bay was used for exploration, transportation, and shipping purposes. During the late 1800s and the turn of the century, dredging and **channelization** projects gave rise to prosperous shipping and commerce activities, first in Galveston and subsequently in Houston. Prior to the discovery of oil, agriculture and fishing were the main activities of the region with cotton being the major export commodity (Texas Water Quality Board, 1975). The discovery of oil in the region, however, gave rise to one of the largest petroleum/petrochemical complexes in the world. The economic vitality of the region, in turn, led to the growth of one of the largest metropolitan areas in the nation.



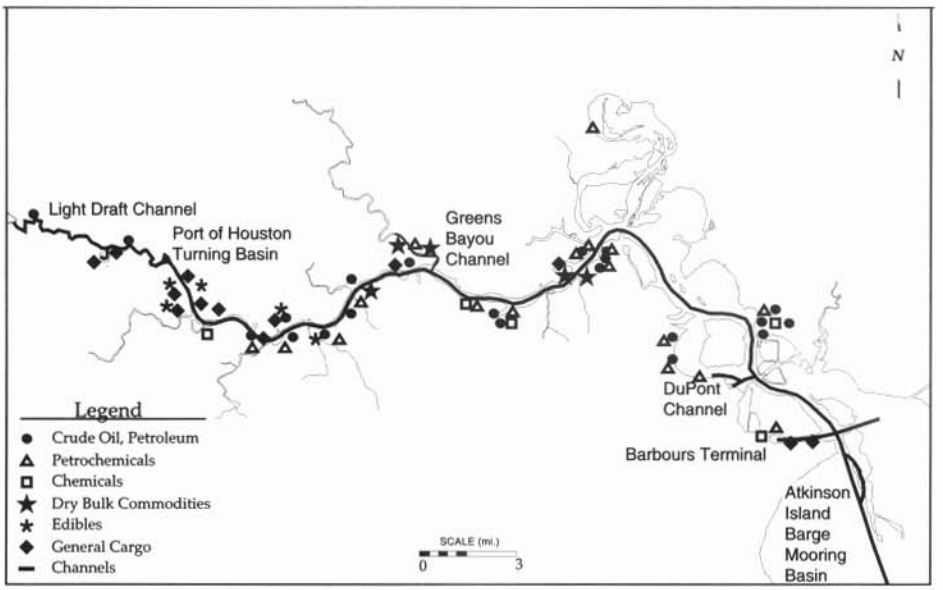
Source: Wermund et al., 1989; United States Army Corps of Engineers, 1985; 1989

FIGURE 4.1. *Channels, ports, and industries in the Galveston Bay system. Completion of the Houston Ship Channel in 1914 allowed large vessels from the Gulf of Mexico to reach the lower reaches of Buffalo Bayou, stimulating industrial development. The inset area (the highly industrialized upper Houston Ship Channel) is shown in FIGURE 4.2.*

The Houston Ship Channel and Other Navigation Channels

Much of the growth and development of the Houston area is attributable to the completion of the Houston Ship Channel in 1914 (FIGURE 4.1). The channel permitted ocean-going vessels to traverse the shallow Galveston Bay all the way to Houston, resulting in a tremendous upsurge in new industrial growth in Houston. Buffalo Bayou and the Houston Ship Channel boast an interesting history (see Sibley, 1968 and Alperin, 1977). As early as 1837 John James Audubon, on a visit to the Galveston Bay area, had described Buffalo Bayou, now the upper Houston Ship Channel, as being "usually sluggish, deep and bordered on both sides with a strip of woods not exceeding a mile in depth" (Farrar, 1926). Also in that same year, the steamboat *Laura* became the first to visit Houston in an attempt to prove that Buffalo Bayou was navigable (McComb, 1981). Steamboat service to Harrisburg began shortly after the Texas revolution. In 1839, city officials passed an ordinance establishing the Port of Houston.

The latter half of the nineteenth century saw the first attempts to significantly widen and deepen Buffalo Bayou to accommodate larger vessels. In 1856 the City of Houston began operating a 70-ft dredge to deepen a passage at Cloppers Bar (near Morgans Point) and to improve Buffalo Bayou. It was not until after the Civil War (1861-1865), however, that Houstonians obtained permission from



Source: Port of Houston Authority, 1992

FIGURE 4.2. *Channels, ports, and industries in the upper Houston Ship Channel. Development of this region as a major industrial complex was made possible by dredging Buffalo Bayou, the Lower San Jacinto River, and by cutting through Morgans Point.*

the State of Texas to dredge a 12-ft deep channel from the main entrance channel at the Gulf of Mexico to their town. Politics and a lack of money delayed the project until the 1870s, when local interests cut a five-mile 14-ft deep canal in upper Galveston Bay through Morgans Point to bypass Cloppers Bar at the tip of Morgans Point (the remnant of the tip of the Morgans Point peninsula is now known as Atkinson Island, see FIGURE 4.2). At that time, luxury steamboats began offering service between Galveston and Houston, and numerous barges, tugs, fishing vessels, and other boats plied the bay.

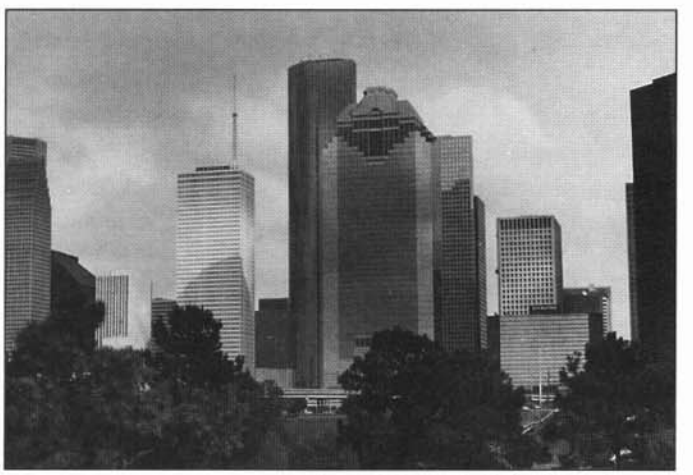
Meanwhile, federal participation in building the Houston Ship Channel had originated with the Rivers and Harbors Act of 1872. In 1877 Congress authorized the U. S. Army Corps of Engineers to dredge a 12-ft deep and 100-ft wide channel from Bolivar Peninsula to Redfish Bar. The project was accomplished in stages and was eventually extended northward.

The Corps of Engineers in 1880 began designing jetties into the Gulf to attain the long-range plan of a 25-ft deep channel through the inner and outer bars. After almost 20 years of planning and failed experiments with gabions (rock-filled wire baskets), the Corps completed the South jetty to a length of 6.5 miles and the North jetty to almost five miles. The water over the outer and inner bars reached just over 25 ft and 26 ft, respectively. The Corps' dredging project allowed Galveston to emerge as a major port. By 1907, Galveston ranked second among all U. S. ports in the value of foreign exports, with cotton being the predominant article of export (Alperin, 1977).

The rise and success of the port of Galveston prompted Houstonians to begin a deep-water movement of their own in the late 1890s. Their arguments in favor of a more protected port were strengthened when the 1900 hurricane destroyed much of Galveston and killed thousands of people in the worst natural disaster in United States history. In 1900, the Corps began dredging an 80-ft wide channel, 17.5 ft deep with a dike from Morgans Point to Redfish Bar. It was not until 1910, however, and as a result of a new federal Rivers and Harbors Act, that the dredge project was named the Houston Ship Channel. By 1912, financing was assured and work on the channel was underway. The Houston Ship Channel was officially opened on November ten, 1914. It was 51

Source: Galveston Bay National Estuary Program

Nearly half of the nation's petrochemical production occurs along Galveston Bay's shores, constituting the largest petrochemical complex in the world.



Source: Galveston Bay National Estuary Program

Explosive population growth in the early 1980s was fueled by the petroleum and petrochemical industries. Boomtown Houston required expanded sewage treatment capabilities, more highways, and greater areas of impervious cover—all of which placed greater stress on the natural assimilative capacities of Galveston Bay.

mi in length, with a maximum depth of 26 ft and a maximum width of 150 ft.

The Houston Ship Channel was enlarged to a depth of 32 ft and a width of 400 ft after the 1935 Rivers and Harbors Act authorization. The final expansion of the channel started in 1963 and had a project depth of 40 ft. A congressionally authorized study is in progress to consider a proposal to deepen and/or widen the Houston and Galveston channels.

Today, the Houston Ship Channel (FIGURES 4.1 and 4.2) extends approximately 50 mi from the Port of Houston to the Gulf of Mexico. It follows the course of what were formerly the lower portions of Buffalo Bayou and the San Jacinto River in Harris County. It then joins Galveston Bay at Morgans Point, and crosses the bay to the Gulf of Mexico. The narrow, confined, 25-mi long portion of the channel between Morgans Point and the Port of Houston's upper turning basin near downtown Houston is one of the most heavily industrialized water bodies in the world (FIGURE 4.2).

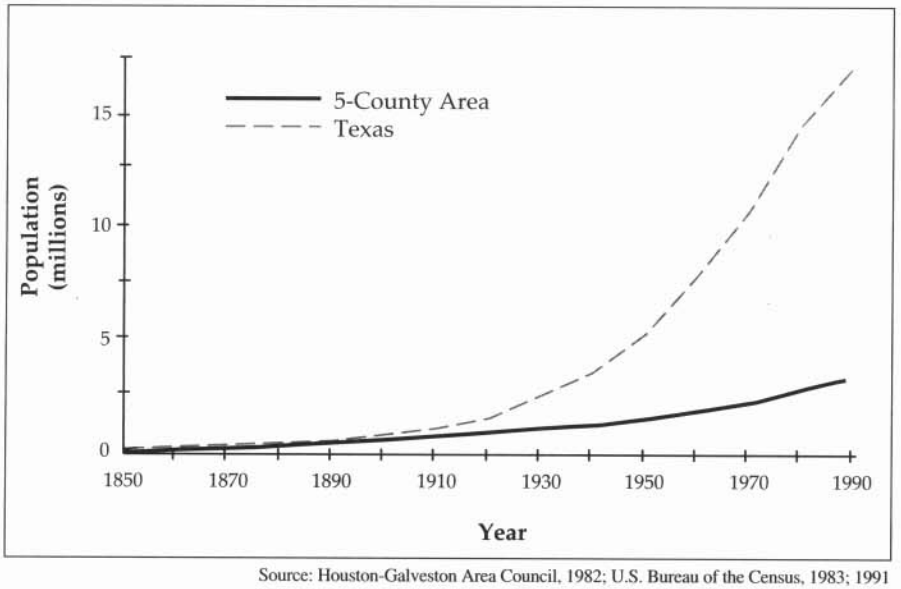
TABLE 4.1. Population 1850 - 1990 (Number of Persons).

Year	Brazoria	Chambers	Galveston	Harris	Liberty	All Five Counties	Entire State
1850	4,481	N/A	4,529	4,668	2,522	16,200	212,592
1860	7,143	1,508	8,229	9,070	3,189	29,139	604,215
1870	7,527	1,503	15,290	17,375	4,414	46,109	818,579
1880	9,774	2,187	24,121	27,985	4,999	69,066	1,591,749
1890	11,506	2,241	31,476	37,249	4,230	86,702	2,235,527
1900	14,861	3,046	44,116	63,786	8,102	133,911	3,048,710
1910	13,299	4,234	44,479	115,693	10,686	188,391	3,896,542
1920	20,614	4,162	53,150	186,667	14,637	279,230	4,663,228
1930	23,054	5,710	64,401	359,328	19,868	472,361	5,824,715
1940	27,069	7,511	81,173	528,961	24,541	669,255	6,414,824
1950	46,549	7,871	113,066	806,701	26,729	1,000,916	7,711,194
1960	76,204	10,379	140,364	1,243,158	31,595	1,501,700	9,579,677
1970	108,169	12,187	169,812	1,737,235	33,015	2,060,418	11,196,730
1980	169,587	18,538	195,940	2,409,547	47,088	2,793,612	14,229,191
1990	191,707	20,088	217,399	2,818,199	52,726	3,300,119	16,986,510

Source: Houston-Galveston Area Council, 1993a

Aside from the Houston Ship Channel, there currently are over 150 mi of other channels in Galveston Bay (FIGURE 4.1). One of the earliest channels completed was a 16-ft deep channel from the deep water near Galveston to a new port in Texas City. Because this channel was laid out perpendicular across a natural scour area called Half Moon Channel, it required extensive dredging to keep it open. Because of this maintenance problem, the channel was protected from currents by building a 5.3-mi timber pile dike along the north side of the channel that was later replaced by a rubble dike in 1934. Today, the Texas City Channel is 40 ft deep and 400 ft wide.

Segments of the Gulf Intracoastal Waterway (sometimes called the "intracoastal canal") that traverses the coastline of the Gulf of Mexico were constructed as early as 1909 by the federal government. The modern channel with a nine-ft depth by 100-ft width configuration was completed in 1942. The Gulf Intracoastal Waterway reach across the Galveston Bay estuary has been deepened and widened to 12 ft by 125 ft (FIGURE 4.1).



Source: Houston-Galveston Area Council, 1982; U.S. Bureau of the Census, 1983; 1991

FIGURE 4.3. *Population growth in the five-county region surrounding Galveston Bay, and in Texas as a whole. Between 1980 and 1982, Houston grew by 12 percent, followed by much slower growth to the present resulting from a recession.*

Other channels in the bay system (FIGURE 4.1) include the Trinity River Channel along the east side of Trinity Bay, as well as shorter channels dredged from the Trinity River Channel and leading to Anahuac and Double Bayou (in Chambers County). A short channel to the east of the Ship Channel leads to industrial facilities along Cedar Bayou. Channels also were dredged to the west of the Ship Channel into Bayport, Clear Lake, Dickinson Bayou, and Offatts Bayou (located in the mid-part of Galveston Island on the bay side).

Petroleum and Petrochemical Industries

Oil was first produced in the Galveston Bay area in 1907 on the shore of Tabbs Bay near modern day Baytown. The oil field camp on Goose Creek became a boomtown between 1917-1919 with production of seven to nine million barrels per year. Prior to 1919, the closest

TABLE 4.2. Population Growth: 1970 - 1990.

County	Number of Persons 1970	1980	1990	% Growth 1970 - 1980	% Growth 1980 -1990
Brazoria	108,169	169,587	191,707	57	13
Chambers	12,187	18,538	20,088	52	8
Galveston	169,812	195,940	217,399	15	11
Harris	1,737,235	2,409,547	2,818,199	39	17
Liberty	33,015	47,088	52,726	43	12
Total	**2,060,418**	**2,840,700**	**3,300,119**	**38**	**16**

Source: Houston-Galveston Area Council, 1993a

refineries were in Beaumont and Port Arthur, about 90 mi to the east. The Humble Oil Company (now Exxon) built a refinery in 1919 west of Goose Creek and named their landing Baytown. At that time, there were about 22 industries along the bayou below the turning basin and 16 above it. By the end of the 1920s, however, there were more than 50 businesses along the channel and eight refineries along the upper Ship Channel with a capacity of about 125,000 barrels of crude per day (Henson, 1993, after McComb, 1969).

By 1930, over 80 percent of the ocean-going tonnage from the Port of Houston was in the form of oil and related chemicals. Also by this time, many large oil companies had established their offices in the area, and refineries were well developed along the upper Houston Ship Channel (FIGURE 4.2). Other chemical and steel industries developed in the region during World War II, so that by 1948 Texas was sixth in the nation in chemical production (Stanley, 1992). It has since risen to first place (Texas Water Quality Board, 1975).

Ditton et al. (1989) pointed out that petroleum 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, making up about a third of the total value added by manufacturing for the region. Nearly one-half of the total chemical production in the United States takes place in the Galveston Bay area. Ditton et al. (1989) found that more than 500 chemicals are produced in 300 chemical plants in the area, providing a total of 36,100 jobs and a payroll of $1.1 billion. The vast majority of the plants are located in Harris County.

Thirty percent of the total U. S. petroleum industry is located adjacent to the bay (Ditton et al., 1989). Most of this industrial development is concentrated in two areas, one along the upper Houston Ship Channel and the other in the Texas City vicinity along the southwestern shore of the bay. Ditton et al. 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. Of 31 oil refineries along the Texas coast, 12 are located around Galveston Bay. Of the 74 gas processing plants on the Texas coast, 22 are located in the bay region. Of the 38 pipelines originating from either state or outer continental shelf waters along the Texas coast, 16 make landfall in counties around the bay. Obviously, the petroleum industry is an important presence in the Galveston Bay region.

TABLE 4.3. Population Changes for Cities and Places Over 10,000 Population: 1980 - 1990.

City or CDP[1]	County	Number of Persons 1980	1990	% Growth
Houston	Harris	1,611,382	1,630,553	1
Pasadena	Harris	112,560	119,363	6
Baytown	Harris/Chambers	57,339	63,850	11
Galveston	Galveston	61,902	59,070	-5
Texas City	Galveston	41,201	40,822	-1
Kingwood (CDP)	Harris	16,094	37,397	132
Spring (CDP)	Harris	14,692	33,111	125
League City	Galveston/Harris	16,578	30,159	82
La Porte	Harris	19,226	27,910	45
Deer Park	Harris	22,648	27,652	22
Channelview	Harris	17,471	25,564	46
Friendswood	Galveston	10,719	22,814	113
Lake Jackson	Brazoria	19,102	22,776	19
Alvin	Brazoria	17,877	19,220	8
Pearland	Harris/Brazoria	13,958	18,697	34
Cloverleaf (CDP)	Harris	1,533	18,230	1089
Angleton	Brazoria	13,929	17,140	23
South Houston	Harris	13,293	14,207	7
La Marque	Galveston	15,372	14,120	-8
Bellaire	Harris	14,950	13,842	-7
West University Place	Harris	12,010	12,920	8
Humble	Harris	6,729	12,060	79
Freeport	Brazoria	13,444	11,389	-15
Aldine (CDP)	Harris	12,623	11,133	-12
Mission Bend (CDP)	Harris	N/A	10,750	N/A
Galena Park	Harris	9,879	10,033	2

Source: United States Bureau of the Census, 1983; 1991

[1]CDP = Census Designated Place

The Growth of the Houston Metropolitan Region

Even though the City of Houston was established in 1836, it remained a smaller town than Galveston, San Antonio and Dallas until the turn of the century. In 1880, for example, the population was just 16,513, trailing Galveston and San Antonio. Population increased to 27,557 in 1890, but Houston still trailed Dallas, San Antonio and

TABLE 4.4. Population Density: 1980 and 1990 (Persons per sq mi).

County	1980	1990
Brazoria	120	136
Chambers	29	31
Galveston	492	546
Harris	1,407	1,645
Liberty	41	46
All Five Counties	**533**	**619**

Source: United States Bureau of the Census, 1983; 1991

Galveston. It was not until after the 1900 hurricane devastated Galveston that Houston was ranked second in the state with a population of 44,633. Finally, during the decade after the construction of the Houston Ship Channel, Houston led the state in population.

Much of the area's growth has been attributed to the completion of the Houston Ship Channel in 1914 in combination with the discovery of oil in the region in the 1920s. 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. TABLE 4.1 and FIGURE 4.3 provide data from 1850 through 1990 for the five counties around Galveston Bay and for Texas, compiled by the Houston-Galveston Area Council (the regional council of governments) from the U.S. Census of Population. The region has exhibited boomtown characteristics over most of the past 50 years.

Houston's population gains during the 1970s and early 1980s were remarkable. Growth between 1970 and 1980 averaged 3.7 percent annually, and between 1980 and 1982 Houston's population grew an incredible 12 percent. Since 1982, however, population growth has slowed considerably as the region's economy suffered a prolonged recession. Migration 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 attracted new residents in great numbers. Since the early 1980s, however, growth has been much slower.

CURRENT USES OF THE BAY

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. Oil production, transportation, and construction were most often cited as bay-related economic activities. The most common recreational uses mentioned by survey respondents included swimming, picnicking, shoreline walks, bird or wildlife watching, and fishing. Whittington et al. (1993) found that 34 percent of area households use the bay for recreational activities. The following sections discuss the major commercial and recreational activities in and around the bay.

TABLE 4.5. Population in a Two-Mile Buffer Area Surrounding Galveston Bay.

County	1990 Population in 2-mi Buffer	% of County Total
Brazoria	8,925	4.66
Chambers	8,979	44.70
Galveston	153,690	70.69
Harris	467,595	16.59
Liberty	9,570	18.15
All Five Counties	**648,759**	**19.66**

Source: United States Bureau of the Census, 1991

Current Population

Demographic characteristics for the bay area have been analyzed in detail by the Houston-Galveston Area Council (Houston-Galveston Area Council, 1993a; 1993b). The Galveston Bay system study area defined by the Houston-Galveston Area Council contains Brazoria, Chambers, Galveston, Harris, and Liberty counties.

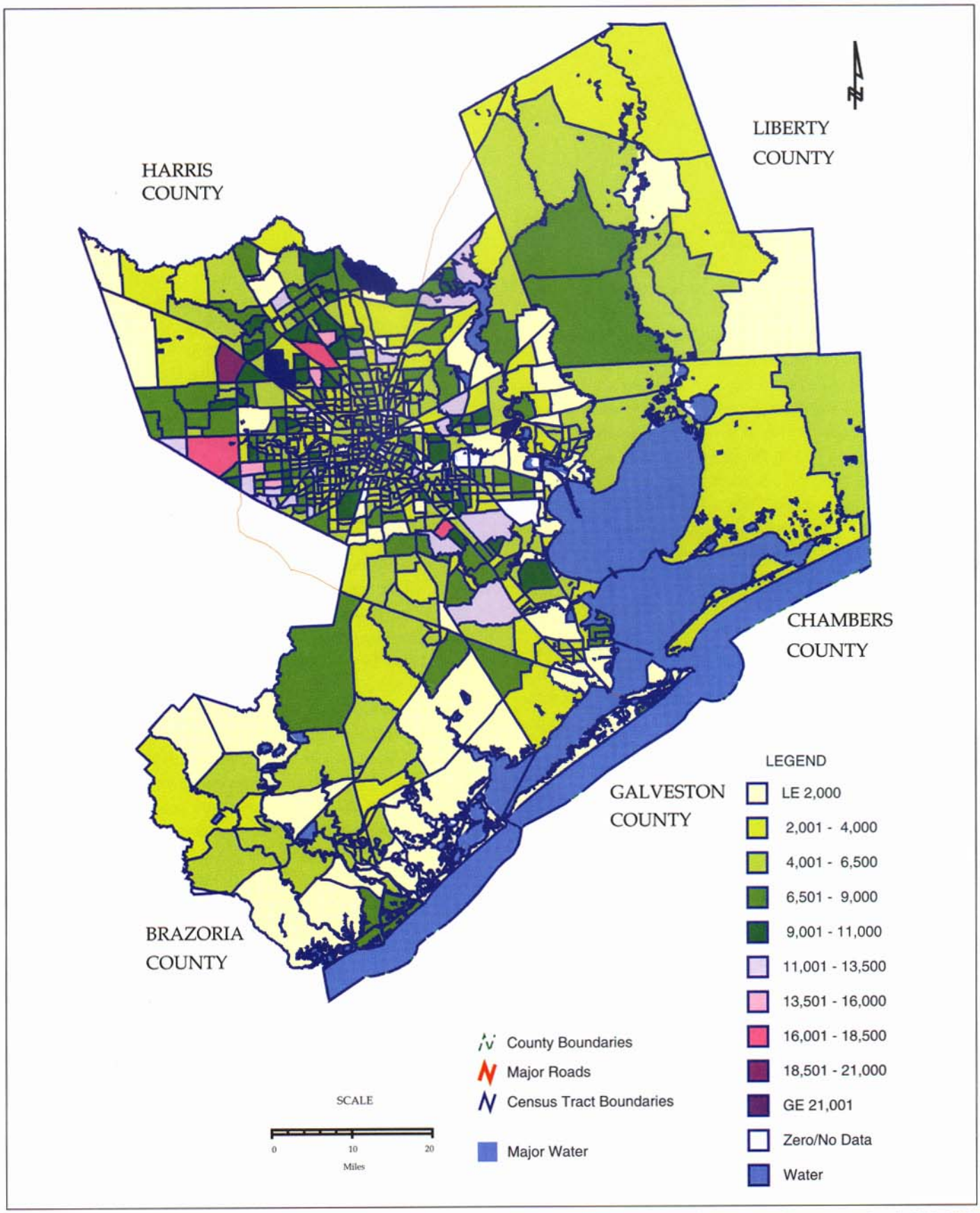
In 1990 the population of the five-county Galveston Bay study area was 3.3 million persons, or 19 percent of the population in the State of Texas. Population data for the years 1970 through 1990 are shown in TABLE 4.2. The data in TABLE 4.2 indicate that the population in the study area increased by 38 percent between 1970 and 1980, but by only 16 percent between 1980 and 1990. These ten-year snapshots of population cannot show that most of the growth between 1980 and 1990 occurred before 1983. The region experienced a high rate of growth in the 1970s and the early 1980s largely due to the expansion of the petrochemical industry. Since then, the population growth rate has declined.

Harris County remains the most populated county in the State of Texas, containing 17 percent of the state population and 85 percent of the population in the Galveston Bay region (see TABLE 4.1). While Harris County experienced the highest population growth rate in the area between 1980 and 1990; Brazoria and Chambers counties marked the most dramatic decrease in rate of growth from the previous decade (TABLE 4.2).

Over the years, the Galveston Bay area has become increasingly urbanized. TABLE 4.3 provides information on 1980 and 1990 populations of cities and places with over 10,000 people. The larger central cities, such as Galveston and Houston, experienced relatively low growth rates. Suburban communities (e.g., Friendswood, Humble, and League City), on the other hand, experienced the largest growth in population. FIGURE 4.4 illustrates the distribution of population by census tract for 1990 (census tracts are sub-county districts used for counting and reporting population for the decennial census).

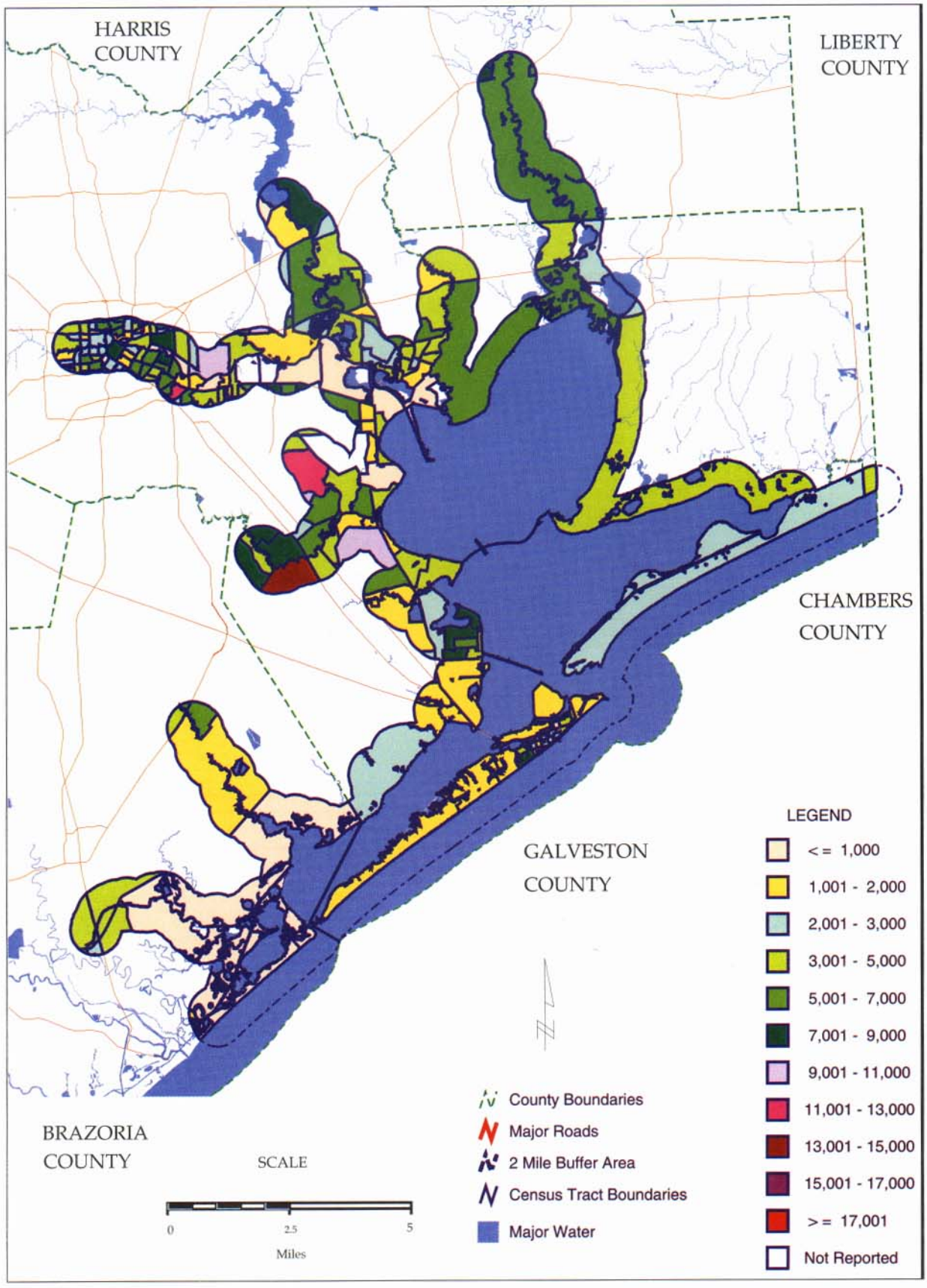
Population density in the five-county area has increased over the last decade from an average of 533 persons per sq mi to 619 persons per sq mi, a 17 percent increase in density (TABLE 4.4). Harris County is the most densely populated county with 1,645 persons per sq mi and Chambers County remains the most sparsely populated county in the study area with 31 persons per sq mi.

The Houston-Galveston Area Council additionally calculated



Source: Houston-Galveston Area Council, 1993a; 1993b

FIGURE 4.4. *Population of the Galveston Bay region by census tract. Note that the census tracts are in general much smaller in more highly populated areas.*



Source: Houston-Galveston Area Council, 1993a; 1993b

FIGURE 4.5. *Population residing within two miles of the Galveston Bay shoreline, including its tidally-influenced tributaries.*

TABLE 4.6. Land Use by Percentage of Total Acreage.

Year/ County[1]	Single Family	Multi-Family	Com-mercial	Indus-trial	Public Instit.	Open Space	Protec-ted[2]	Right of Way	Not Devel-oped[3]	Water[3]
1970										
Brazoria	1.28	.05	.24	.53	.11	2.69	.10	.05	86.71	.826
Chambers	.38	.00	.07	.19	.02	1.78	.11	.22	67.33	29.89
Galveston	3.58	.17	1.13	1.94	.26	.31	.21	.27	77.05	15.08
Harris	11.96	.70	2.67	3.49	.64	1.42	.50	1.30	73.83	3.49
Liberty	.76	.01	.15	.16	.03	.02	.24	.07	98.16	.41
1980										
Brazoria	2.28	.07	.29	.96	.16	2.55	.11	.12	86.42	7.04
Chambers	.75	.01	.08	.35	.07	2.43	.16	.32	92.46	3.36
Galveston	3.33	.22	.96	1.42	.27	.33	.07	.22	81.13	12.05
Harris	15.15	1.69	2.99	5.05	.85	3.71	.22	1.29	65.49	3.55
Liberty	1.47	.00	.17	.18	.06	.00	.16	.08	97.86	.00
1990										
Brazoria	2.80	.10	.37	.99	.13	2.53	.11	.25	86.15	6.57
Chambers	.64	.01	.08	.33	.05	1.78	.12	.23	67.20	29.57
Galveston	7.34	.67	4.73	2.59	.55	.38	.15	.43	82.54	.63
Harris	13.29	2.08	3.22	14.59	1.82	7.00	.20	13.73	41.61	2.45
Liberty	1.88	.01	.30	.18	.07	.00	.17	.08	97.63	.00

Source: Houston-Galveston Area Council

[1]Total acreage by County for 1990: Brazoria 1,022,425.6; Harris 1,137,849.6; Liberty 752,851.2; Chambers 555,897.6; Galveston 560,934.4
[2]Protected = Areas considered undevelopable due to resource constraints
[3]The assignment of acreage to undeveloped area or water used inconsistent methodology for 1970 and 1990

TABLE 4.7. Selected Economic Data for Counties Surrounding Galveston Bay, 1992.

Attribute	Brazoria	Chambers	Galveston	Harris	Liberty
Total Employment	67,100.0	5,400.0	80,400.0	1,467,600.0	13,900.0
Percent of Total Employment in:					
Manufacturing	26.3	22.9	10.9	10.8	13.7
Services	14.6	11.5	16.5	27.1	26.6
Government	18.2	22.6	31.3	13.0	21.8
Trade	19.1	19.8	21.1	24.2	22.3
Construction	13.1	5.6	6.5	6.9	4.0
Agriculture Receipts (1,000,000s)	82.0	43.3	7.7	11.2	39.2
Oil Production (1,000s BBL[1])	3,119.0	2,466.0	1,377.0	4,851.0	2,414.0
Oil Taxable Value (1,000s)	60,827.0	47,544.0	26,776.0	96,146.0	47,008.0
Natural Gas Production (1,000s MCF[2])	60,241.0	23,967.0	14,239.0	29,106.0	11,180.0
Natural Gas Taxable Value (1000s)	89,610.0	33,942.0	22,884.0	47,098.0	18,371.0
Retail Sales (1,000s)	1,288,775.0	141,396.0	1,436,684.0	28,596,036.0	364,379. 0
Unemployment Rate (percent)	7.6	6.6	8.7	7.3	10.6
1990 Per Capita Income (dollars/yr)	13,468.0	12,218.0	13,993.0	15,202.0	9,982.0

Source: State Comptroller of Public Accounts

[1]Barrels
[2]Million Cubic Feet

Source: Russell W. Kiesling

Source: Texas Sea Grant Grant College Program

This shrimp trawler (left) and oyster lugger (right) typify bay commercial fisheries. Galveston Bay provides the most valuable estuarine fishery on the Texas coast. While over 50 percent of the bay is closed to oyster harvest due to bacterial contamination, oysters can be transferred from closed waters to private leases in approved areas for later harvest.

the number of people living within a two-mile buffer zone around the bay and its tidally influenced stream segments (TABLE 4.5 and FIGURE 4.5). 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). As can be seen in TABLE 4.5, over 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 3.3 million people in the five county area live within two miles of the bay and its tidally influenced tributaries.

Land Use

Historical land use information for the Galveston Bay area was analyzed by the Houston-Galveston Area Council in a recent socioeconomic report (Houston-Galveston Area Council, 1993a). Most of the land use data presented by the Houston-Galveston Area Council were obtained from the Texas Department of Transportation and the City of Houston Planning Department. These land use data are presented at a highly aggregated level of categorization (TABLE 4.6).

The Houston metropolitan area boasts heavy industry, high-rise office and residential buildings, single-family subdivisions and apartment complexes. Industrial activities, especially petroleum and petrochemical industries, are most prominent in the vast industrial concentrations around the Houston Ship Channel in the eastern portions of Houston and Harris County, including Pasadena, Baytown, Deer Park and La Porte. Other heavy industry is located in the Texas City and Brazosport areas.

Galveston County includes the highly urbanized eastern portion of Galveston Island; the Texas City-La Marque area which is highly industrialized; and League City-Friendswood, a suburban area. Land available for development in Galveston County is limited due to existing development and natural barriers, and much of its open land does not have good transportation access.

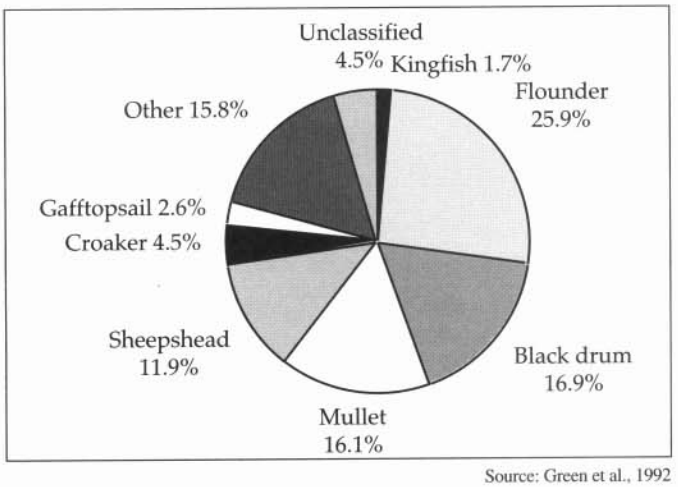
Chambers County remains largely agricultural–primarily rice and soybeans. There are ten county parks as well as the Candy Abshire Wildlife Management Area and the Anahuac National Wildlife Refuge. Additionally, the eastern portion of the county contains several large national priority wetlands designated by the U. S. Fish and Wildlife Service under the Emergency Wetlands Resources Act of 1986, for example: Middleton Marsh, Horseshoe

TABLE 4.8. Commercial Fish Landings[1] from Galveston Bay Comparing 1890 to 1989.

Species	Total Landings (1,000s of Pounds) 1890	1989
Fish:		
Red Drum	404.2	0.0
Black Drum	4.0	21.8
Flounder	46.0	14.6
Mullet	39.3	108.0
Sheepshead	17.0	16.2
Striped bass	5.0	0.0
Trout	427.4	0.0
Other fish	542.9	60.5
Total Fish	1485.8	221.1
Shellfish		
Oyster	1647.1	705.5
Crabs	162.5	2149.5
Shrimp	138.0	4056.1
Terrapins (Turtles)	2.4	0.0
Other shellfish	0.0	13.4
Total Shellfish	1950.0	6924.5
Total Fish and Shellfish	**3435.8**	**7145.6**

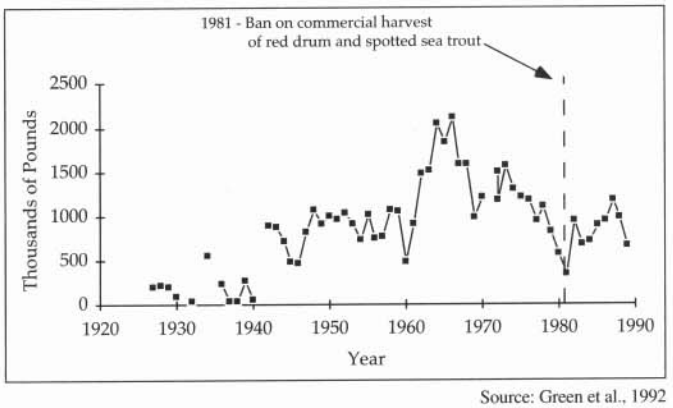
Source Green et al., 1992.

[1]Landings reflect changes in both biological and regulatory factors, and do not indicate more or fewer fish or shellfish present in the bay



Source: Green et al., 1992

FIGURE 4.6. *Finfish make up only about five percent of the commercial catch from Galveston Bay, which is dominated by oysters, crabs, and shrimp. Commercial harvest of spotted sea trout and red drum was prohibited in Texas bays beginning in 1981, followed by a prohibition on the netting of any sort of finfish.*



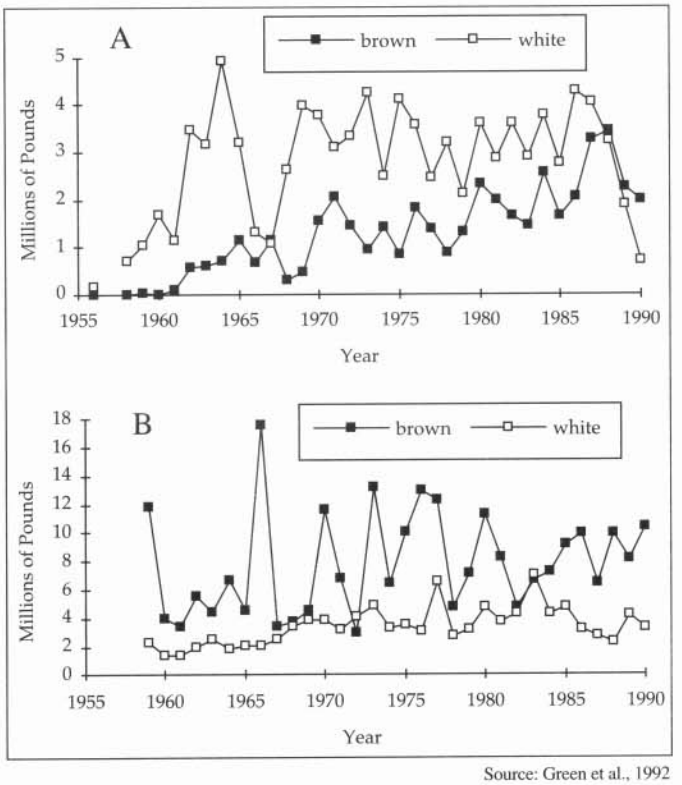
Source: Green et al., 1992

FIGURE 4.7. *Commercial harvest of finfish from the Galveston Bay system, 1920–1990. The commercial catch is only about 14 percent of the total finfish catch from the bay, the remainder being accounted for by recreational fishing.*

Marsh, Lower Marsh, Robinson Bay Marsh, and Delhomme Marsh.

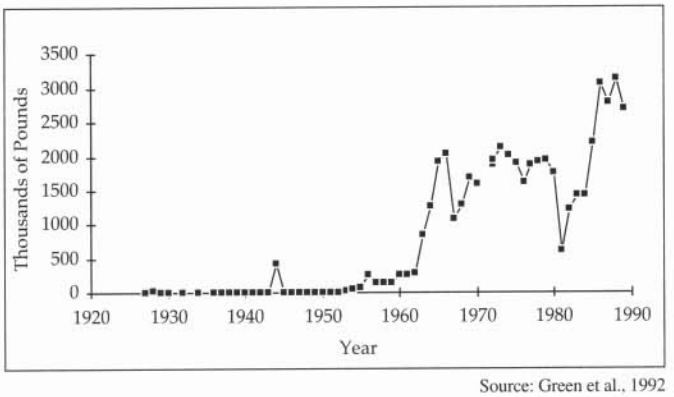
The majority of Brazoria county is rural with a few medium sized communities. Two suburban areas provide residences for commuters to Houston and for employees of the major petrochemical complexes in the county: the Pearland-Manvel-Alvin area in the northern part of the county and the Brazosport area in the southern portion (not in the Galveston Bay watershed). Two national priority wetlands are located in Brazoria County: Freshwater Lake and Hoskins Mound. Hoskins Mound has been incorporated into the Brazoria National Wildlife Refuge, which borders Bastrop, Christmas, and Drum Bays.

TABLE 4.6 presents percentage of land use by major development category by county for 1970, 1980 and 1990. In spite of the region's urban character, the majority of the five county area is undeveloped. Most of the counties have experienced an increase in single family residential area, typical of historical development patterns in this region. Harris County, however, showed a decline in acreage given to single family dwelling units between 1980 and



Source: Green et al., 1992

FIGURE 4.8. *Commercial shrimp landings 1955-1990 in Galveston Bay (a) and the Gulf of Mexico off Galveston (b). The shrimp fishery is characterized by wide natural variability among years, but is essentially at its maximum sustained yield. Shrimp grow up in estuaries like Galveston Bay, migrating to the Gulf of Mexico as they mature to adults.*



Source: Green et al., 1992

FIGURE 4.9. *Commercial blue crab catch in Galveston Bay 1920–1990. Recent declines in adult size classes have indicated possible over-harvest, a concern being addressed by the Texas Parks and Wildlife Department in new regulatory actions.*

1990, with an increase in multi-family dwellings, reflecting an increase in population density.

A current land use map (see FIGURE 5.2) was developed by Newell et al. (1992) using satellite imagery data from November 1991 (note that the land use map developed in their study considers only the contributing drainage areas of the lower watershed which are adjacent to the bay). The land use data presented by Newell et al. (1992) indicated that the majority of the watershed remains agricultural and open/pasture in nature. Urban areas occupied about 19 percent of the watershed (total area = 4,238 sq mi). The percentage

of watershed area for the major land use categories used in the study were:

High-Density Urban	10%
Residential	9%
Open/Pasture	23%
Agriculture	22%
Barren	1%
Wetlands	15%
Water	1%
Forest	18%

A strong relationship exists between land uses and pollution from rainfall runoff. Nonpoint source (NPS) loadings resulting from runoff due to rainfall have only recently received a great deal of attention, but their presence and effect on the bay has been noted for many years. As early as the 1820s, Henson (1993) documented the silting of the waterways due to urbanization: "as early as 1839 a visitor to Houston noted the amount of soil washing down Main Street into the bayou after every rain threatened to fill the steamboat landing."

More recently, NPS loads for a total of eight different water quality constituents in runoff were estimated for the bay area by Newell et al. (1992). A detailed discussion of nonpoint source pollution is found in Chapter Six.

TABLE 4.9. Licensed Fishermen by Fiscal Year.

License Type	Fiscal Year[1]	Brazoria	Chambers	Galveston	Harris	Liberty	All Five Counties
Commercial[2]	1992	754	261	1,287	1,193	123	3,618
	1991	898	326	1,336	1,631	155	4,346
	1990	954	394	1,498	1,461	197	4,504
	1989	1,050	589	1,910	1,635	282	5,466
	1988	1,220	622	2,327	1,917	276	6,362
	1987	1,284	711	2,258	2,100	309	6,662
	1986	1,457	638	2,261	2,283	280	6,919
	1985	1,271	619	2,353	2,522	292	7,057
	1984	1,657	576	2,518	2,787	268	7,806
	1983	1,905	616	2,960	3,275	312	9,008
	1982	1,873	576	2,875	3,459	327	9,110
Sport[3]	1992	32,256	2,755	51,600	199,882	9,073	295,566
	1991	32,537	2,957	51,468	210,420	10,822	308,204
	1990	35,624	3,043	53,398	206,448	11,396	309,909
	1989	33,964	3,229	53,767	231,502	10,076	332,608
	1988	35,369	3,732	52,184	209,997	10,507	311,789
	1987	37,184	3,678	52,529	204,445	10,997	308,833
	1986	40,684	4,105	60,834	206,508	10,424	332,555
	1985	35,228	3,445	46,709	1878,381	8,832	272,593
	1984	31,986	3,669	53,190	193,458	10,390	292,691
	1983	37,538	4,355	71,098	215,596	10,761	339,348
	1982	35,921	4,386	63,792	218,270	13,909	336,278

Source: Texas Parks and Wildlife Department, 1993

N/A = Data Not Available

[1]Fiscal Year from 9/1 through 8/31

[2]Commercial fishing licenses held by residents residing within county

[3]Sport fishing licenses sold within county

Economic Activity

The Texas Comptroller of Public Accounts (Sharp, 1993) has compiled recent economic data for counties in the Galveston Bay area and discussed the region's economy (TABLE 4.7). For the five counties around Galveston Bay, almost 90 percent of the employment in 1992 is located in Harris County. Retail sales is similarly concentrated in Harris County. Although oil and gas production is important in all five counties, Brazoria has a large share (about 43 percent) of the area's natural gas production. Not surprisingly, agricultural receipts are greatest in Brazoria, Chambers, and Liberty counties. Even in Harris and Galveston counties, however, agriculture accounted for 11.2 and 7.7 million dollars in receipts respectively in 1992.

TABLE 4.10. Direct and Total Economic Impact of Commercial Fishing in Galveston Bay in 1986 (in Millions of 1986 Dollars).

	Ex-Vessel Value of Landings		Total Impact[1]			
			Inshore		Inshore/ Offshore	
	Inshore	Inshore/ Offshore	Region	State	Region	State
Output	12.50	63.60	32.90	41.10	167.60	209.30
Employment	683.00	3,476.00	799.00	896.00	4,063.00	4,558.00
Income	3.50	18.00	7.30	10.40	37.20	52.70
State Tax Rev.	0.06	0.31	N/A	0.50	N/A	2.80
Local Tax Rev.	0.08	0.43	N/A	0.86	N/A	4.40

[1]Total Impact includes direct, indirect, and induced

Source: Fesenmaier et al., 1987

Sharp (1993) found that unemployment in 1992 ranged from 6.6 percent in Chambers County to 10.6 percent in Liberty County. Liberty County had the lowest per capita income ($9,928) and Harris County the highest ($15,202) for that year. The State Comptroller has forecast average annual growth rates for employment, retail sales, and personal income for the 13-county state planning region (which includes the five-county Galveston Bay area) that are slightly lower than similar rates for the State of Texas for

TABLE 4.11. Direct and Total Economic Impact of Commercial Fishing in Galveston Bay in 1976 (in Millions of 1986 Dollars).

	Fishing Sector	Total Impact[1] Regional	State
Output	115.0	244.2	358.0
Income	38.3	81.3	98.4
State Tax Rev.	0.4	2.3	3.2
Local Tax Rev.	0.5	4.0	4.5

Source: Texas Department of Water Resources, 1981a

[1]Total Impact includes direct, indirect, and induced

the period from 1990-2000 (Sharp, 1993).

Economic activities that are important within the five counties surrounding the bay can be characterized by looking to historical data compiled by various government agencies. The following sections describe these activities.

Commercial Fishing and Oystering

Galveston Bay historically has been the overall leading fisheries resource base in Texas. Between 1982 and 1986, the annual commercial bay harvest of finfish and shellfish has averaged 11.5 million pounds, approximately one-third of the state total (Osburn et al., 1987).

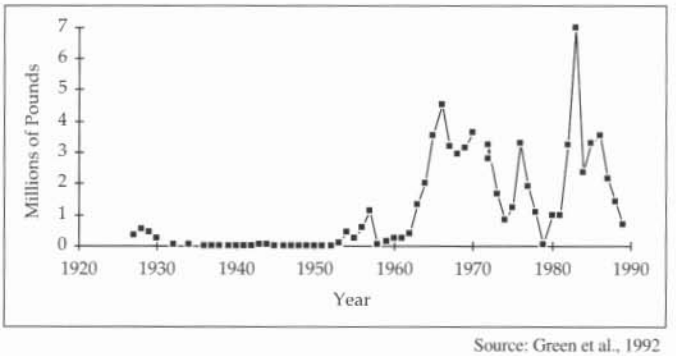
In 1890, the catch was evenly distributed between finfish and oysters with much less shrimping compared to present-day landings (TABLE 4.8). During this time the bay also supported small fisheries focusing on striped bass and sea turtles. Almost 100 years later, the totals landings have more than doubled but are now dominated by oysters, crabs, and shrimp. The annual finfish catch is a relatively small part (4.9 percent) of the total harvest, averaging about one-half million pounds per year (FIGURE 4.6; TABLE 4.8). Part of the reason for this decline is the ban on commercial harvesting of spotted seatrout and red drum imposed in September 1981 due to concerns about over-harvesting (FIGURE 4.7). Currently four species account for nearly 75 percent of the total finfish harvest: southern flounder, black drum, mullet, and sheepshead.

Shrimp, blue crabs, and oysters have been the dominant shellfish species in the commercial catch, making up nearly 95 percent of the total annual bay catch (FIGURES 4.8 through 4.10). Shrimp (white and brown) accounted for nearly half the total seafood harvest between 1982 and 1986. Over three million pounds of white shrimp along with 1.9 million of brown shrimp were caught in the bay in an average year (FIGURE 4.8). There were about 1.8 million pounds of blue crabs (FIGURE 4.9) in an average year's harvest (Osburn et al., 1987). Finally, by weight, the eastern oyster was the single most important species harvested in the bay during the period (3.9 million pounds per year, FIGURE 4.10).

The number of commercial fishing licenses issued between 1982 and 1992 are listed in TABLE 4.9. The data for 1992 indicate a total of 3,618 licenses for the five-county region. Overall, there has been a general ten-year decline of nearly 60 percent in the number of commercial fishing licenses issued in these counties.

Fesenmaier et al. (1987), in a report to the Texas Water Development Board, estimated the economic impact of commercial fishing. The authors used commercial finfish and shellfish volumes from both inshore (bay system) and offshore landings to estimate the direct and total economic impact of commercial fishing in the Galveston Bay estuary (called the Trinity-San Jacinto estuary in their report). These impacts, including personal income and employment are presented in TABLE 4.10 and TABLE 4.11.

These data suggest the importance of offshore landings supported by the estuary. Offshore seafood landings represent an indirect use of Galveston Bay because much of the seafood, particularly shrimp, spends at least part of its life cycle in the bay. The average annual inshore commercial fish landings (finfish and shellfish) for the estuary were reported to be 11.3 million pounds with an ex-



Source: Green et al., 1992

FIGURE 4.10. *Commercial oyster catch in Galveston Bay, 1920–1990. In recent decades, as the oyster production in some east coast estuaries like Chesapeake Bay has plummeted, Galveston Bay oysters have supplied many cities throughout the nation.*

vessel value of $12.5 million for 1984 through 1986. Of this, eastern oyster, shrimp and flounder made up almost 91 percent of the total value of landings. Adding the offshore ex-vessel value for this same time period results in more than $63 million generated, as can be seen in TABLES 4.10 and 4.11. Additionally, these data indicate that the inshore catch provided for 683 full-time jobs (direct employment) with personal income of about $3.5 million. Adding offshore landings supported by the estuary accounted for 3,476 jobs, and generated personal income of $18 million. Local and state taxes amounted to $81,000 and $61,000, respectively, attributable to inshore landings (Fesenmaier et al., 1987).

Other data published by the Texas Department of Water Resources (1981a) estimated the economic impact to the state from commercial fishing in Galveston Bay to be about $358 million (TABLE 4.10 and 4.11) in 1976. This dollar amount is higher than the $209.3 million estimated by Fesenmaier et al. (1987) for 1986.

Galveston Bay oysters are an important commercial species. Prior to 1870, oysters were not harvested commercially because there were no efficient methods for transporting the oysters inland (Stanley, 1992). The development of shipping and processing industries along the coast allowed the growth of the commercial oyster industry.

Most of the oyster reefs in the estuary are located in the cen-

Source: Galveston Bay National Estuary Program

Source: Galveston Bay National Estuary Program

Products ranging from automobiles to bulk products such as grain are handled at the Port of Houston, which now ranks sixth in the world in tonnage.

tral portion of East Bay and in mid-Galveston Bay where fresher waters of the major tributaries mix with saline waters of the gulf. The largest reef complex is around Redfish Bar, between Eagle Point and Smith Point, in central Galveston Bay. Oysters are harvested from both public reefs and private oyster leases in the bay. (Oysters and their reefs have a role in many aspects of the bay; additional information is found in Chapters Three, Five, Seven, Eight, and Nine).

Historical trends in the Galveston Bay oyster harvest are shown in FIGURE 4.10. Stanley (1992) estimated annual production rates ranging from 244,000 to 336,000 pounds of shucked oyster meats for the period between 1900 and 1910. After 1911, Stanley (1992) indicates that harvests dropped substantially from almost 100,000 pounds in 1914 down to slightly below 15,000 in 1920. Within two years, however, production jumped by about ten times to almost 150,000 pounds and varied between 100,000 to over 300,000 until 1930. Between 1930 and 1950, the oyster harvest plummeted to less than 1,000 pounds in some years and no harvest was reported in 1948. Oyster harvesting did not recover substantially until the 1960s when production skyrocketed to four million pounds. Another cycle of rising harvests was capped off in 1983 with a seven million pound harvest. The catch has been declining throughout the late 1980s and has dropped down to about one million pounds per year in the early 1990s.

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 due to pathogens in the bay resulting primarily from human wastes. These public health issues are discussed in more detail in Chapter Nine. Suffice it to say, however, that about 21 percent of the oyster reefs in Galveston Bay (about half the bay's total area) are classified as prohibited or polluted and the Texas Department of Health has declared them off-limits for harvesting. Periodically, additional areas are temporarily closed to harvesting for short durations following heavy rainfall or river floods (Benefield and Hofstetter, 1976; Texas Parks and Wildlife Department, 1988).

Shipping

While the region has other forms of transportation, shipping is still a major attraction to commercial and industrial interests

TABLE 4.12. Total Shipping Tonnage in the Galveston Bay System.

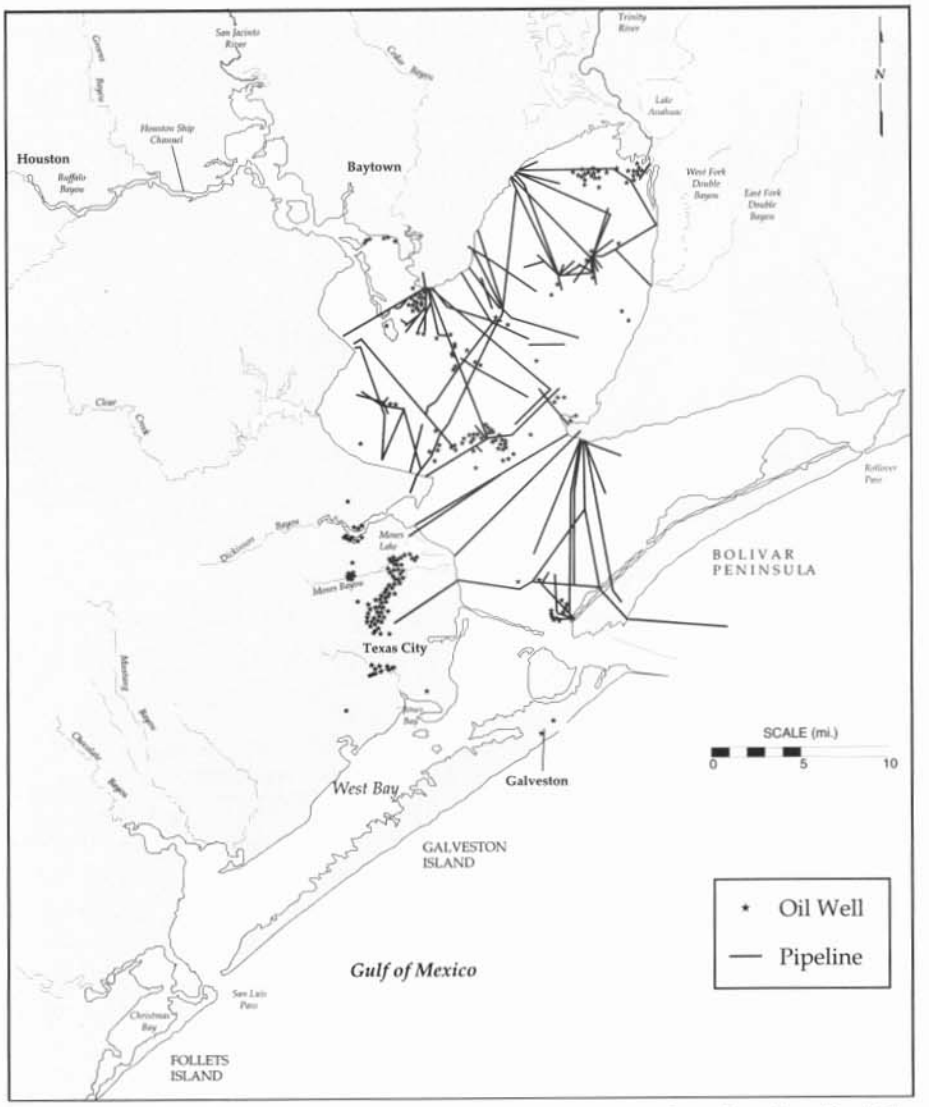
Year	Total Tonnage	Year	Total Tonnage
1970	84,417,200	1980	142,760,400
1971	89,125,700	1981	139,329,500
1972	94,670,900	1982	136,181,300
1973	114,244,100	1983	132,070,000
1974	115,511,700	1984	137,504,100
1975	112,731,500	1985	130,617,700
1976	124,794,700	1986	142,551,900
1977	145,452,300	1987	155,355,900
1978	153,009,400	1988	177,036,700
1979	172,324,600	1989	175,608,200

Source: U.S. Army Corps of Engineers, 1993

TABLE 4.13. Historical Shipping in Galveston Bay.

Ports	1955 (1000s Tons)	1970 (1000s Tons)	1988 (1000s Tons)
Major			
Houston Ship Channel	47,000	65,000	125,000
Texas City Channel	14,000	17,000	43,000
Galveston Channel	6,000	3,000	13,000
Chocolate Bayou	100	2,500	3,500
Minor			
Double Bayou	67	6	3
Anahuac Channel	512	480	3
Cedar Bayou	532	487	275
Clear Creek	44	397	N/A
Dickinson Bayou	425	457	722
Trinity River Channel	497	355	4

Source: U. S. Army Corps of Engineers



Source: Texas General Land Office

FIGURE 4.11. *Petroleum wells and pipelines in Galveston Bay. This infrastructure helps sustain the oil and gas production industry, which directly employs about 11,000 persons in the region.*

(Sharp, 1993). Shipping by the major ports (Houston, Galveston, and Texas City) in the region grew dramatically from 1955 to 1988, 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). TABLES 4.12 and 4.13 present data for waterborne commerce in the Galveston Bay system. Total tonnage transported in 1989 has grown to more than double the tonnage shipped in 1970 (U. S. Army Corps of Engineers, 1993).

The dominance of petroleum and related industries around the bay is reflected in the types of commerce on the Ship Channel. The major cargo types are refined petroleum products (37 percent), chemicals and plastics (21 percent), crude petroleum (13 percent) and wheat (13 percent). Wheat, petroleum products and chemicals and plastics are the primary exports, while crude petroleum, various mineral ores, steel products and motor vehicles are the main imports (Liebow et al., 1980).

Oil and Gas Production

Petroleum extraction, while still an important industry, has declined considerably since the 1970s. Platforms for producing oil, condensate, and natural gas and pipelines for its transport (FIGURE 4.11) are present in Galveston Bay in Chambers County (Trinity Bay and Upper Galveston Bay) and Galveston County (Lower Galveston Bay, East Bay, and West Bay) . Oil and gas wells on land also are found in Harris, Brazoria, Chambers and Galveston counties.

TABLES 4.14 (oil), 4.15 (gas), and 4.16 (total petroleum) list the petroleum production in four counties around the bay for the years 1979 through 1992. As of April 1993, there were a total of 1,096 producing oil wells and 550 gas wells in the four counties (Texas Railroad Commission, 1993). Total oil production exceeds 11 million barrels per year with a direct value of $231 million. The Texas Railroad Commission estimated that employment directly and indirectly attributable to the oil industry in the region was about 6,000 persons in 1992. Total gas production was approximately 128 million MCF (million cubic feet) in 1992 with a direct economic value of $193 million and an associated employment of nearly 5,000 persons.

The discharge of **produced water** into Galveston Bay waters during the extraction of oil and gas has raised environmental concerns regarding the impact of these brines on water quality in the estuary. In 1990 over 353,000 barrels per day of brines were produced in Harris County. In early 1993, the discharge of brine into the Galveston Bay system was estimated to be 137,000 barrels per day (Texas Railroad Commission, 1993). These brine production volumes have declined from their peak values in the early 1980s. Chapters Six and Nine address the resulting water quality problems, biological impacts, and public health issues associated with the discharge of brines into the estuary.

Shell Dredging

Beginning in 1905, large quantities of shell were removed from the Galveston Bay system for industrial and construction purposes. New industrial processes after World War II greatly increased the value of the shell as a raw material, and the volume of shell removed increased from about four million cubic yards per year in 1945 to over eight million cubic yards per year in the mid-1960s. Increasing environmental concerns resulted in more stringent regulation of the industry, and since 1969 shell dredging has

TABLE 4.14. Oil Production in the Four County Galveston Bay Region: Brazoria, Chambers, Harris and Galveston Counties.

Year	Producing Wells	Production (MillionBbl)	Direct Value[1] (Million $)	Total Value[2] (Million $)	Jobs Supported[3]
1979	2,848	52	655.7	1,914.6	16,655
1980	2,946	37	802.5	2,343.3	20,384
1981	2,953	32	1,106.2	3,230.1	28,097
1982	2,915	29	916.9	2,677.3	23,289
1983	2,851	26	789.8	2,306.1	20,060
1984	2,777	25	759.3	2,217.2	19,286
1985	2,760	25	691.7	2,019.9	17,570
1986	2,694	24	367.5	1,073.0	9,333
1987	2,460	21	388.2	1,133.5	9,860
1988	2,396	18	283.5	827.8	7,201
1989	2,170	16	289.6	845.5	7,355
1990	2,002	14	315.0	919.8	8,001
1991	1,995	12	246.9	720.9	6,271
1992	1,947	12	231.3	675.4	5,875

Source: Texas Railroad Commission, 1993

[1]The direct value of production reflects the total taxable value

[2]The total value of production includes the direct value plus the indirect value computed as $1.92 per $1.00 of production value

[3]The number of jobs is computed as 25.4 jobs per $1 million in production output. Includes 7.7 jobs in the production industry plus 17.7 jobs in supporting industries

The economic multipliers used are as quoted by the office of the Texas Comptroller of Public Accounts, Austin

TABLE 4.15. Gas Production in the Four County Galveston Bay Region: Brazoria, Chambers, Harris and Galveston Counties.

Year	Producing Wells	Production (Million MCF)	Direct Value[1] (Million $)	Total Value[2] (Million $)	Jobs Supported[3]
1979	1,120	592	704.5	2,057.1	17,894
1980	1,012	515	772.5	2,255.7	19,622
1981	1,007	408	730.3	2,132.5	18,550
1982	1,003	317	659.3	1,925.1	16,746
1983	898	330	559.0	1,632.4	14,199
1984	918	361	560.0	1,635.2	14,224
1985	898	279	523.9	1,529.8	13,307
1986	791	264	314.4	918.1	7,986
1987	746	253	265.7	775.8	6,748
1988	728	222	274.2	800.7	6,965
1989	697	190	235.1	686.4	5,971
1990	654	179	224.2	654.7	5,695
1991	635	155	184.9	540.0	4,697
1992	596	128	193.6	565.2	4,916

Source: Texas Railroad Commission, 1993

[1]The direct value of production reflects the total taxable value

[2]The total value of production includes the direct value plus the indirect value computed as $1.92 per $1.00 of production value

[3]The number of jobs is computed as 25.4 jobs per $1 Million in production output. Includes 7.7 jobs in the production industry plus 17.7 jobs in supporting industries

The economic multipliers used are as quoted by the office of the Texas Comptroller of Public Accounts, Austin

been banned from the bay. Ward (1993) estimates that approximately 220 million cubic yards of shell was removed between 1910 and 1969, a volume on the same order of magnitude as the cumulative new work excavation from navigation channel work.

Recreational Uses

The bay is used for numerous recreational activities including duck hunting, saltwater fishing, swimming, nature viewing, pleasure boating, camping, picnicking and sight-seeing (FIGURE 4.12). Not many direct quantitative measures of these activities are available, however, estimates of the amount of money generated from them is an indication of their importance. In 1986, for example, $122 million was spent in the Galveston Bay area on recreation and tourism; this amount was about one-third of the amount spent on the Texas coast for sport fishing and was 55 percent of the total expenditures for recreation and tourism on the Texas coast (Texas Water Commission, 1988). Gross Texas business resulting from tourism and recreational uses of the Galveston Bay complex amounted to $425.2 million in 1986 (Texas Water Commission, 1988).

Many of the more popular activities participated in by residents of the Gulf Coast Region as identified in the Texas Outdoor Recreation Plan (TORP), can be associated with the use of Galveston Bay. The percentage of residents expected to at least 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.

TABLE 4.16. Total Direct and Indirect Economic Impact from Oil and Gas in the Four County Galveston Bay Region: Brazoria, Chambers, Harris and Galveston Counties.

Year	Value (Million $)	Total Jobs
1979	3,971.7	34,549
1980	4,599.0	40,006
1981	5,362.6	46,647
1982	4,602.4	40,035
1983	3,938.5	34,259
1984	3,852.4	33,511
1985	3,549.7	30,878
1986	1,991.1	17,320
1987	1,909.3	16,608
1988	1,628.5	14,166
1989	1,531.9	13,326
1990	1,574.6	13,696
1991	1,260.9	10,968
1992	1,240.6	10,791

Source: Texas Railroad Commission, 1993

In 1986, the Texas Parks and Wildlife Department completed a survey of recreation participation (Texas Parks and Wildlife Department, 1986). TABLE 4.17 presents the total amount of recreation user occasions occurring in one year in the 13-county Gulf Coast Region in 1985 (the population in 1985 of the Gulf Coast Region was estimated at 3.7 million residents). The data in TABLE 4.17 indicate that recreational activities such as walking, bicycling, jogging, open space and playground use are extremely popular pastimes.

TABLE 4.17. Total Recreational User Occasions for 1985, For the 13-County Gulf Coast Region of Texas.

Activity	Number of Occasions[1]
Walking for Pleasure	57,951,297
Bicycling	46,296,097
Jogging	23,727,075
Playground Use	23,283,212
Open Space Activities[2]	14,142,232

Source: Texas Parks and Wildlife Department, 1986

[1]Based on a total population of 3.7 million

[2]Activities such as kite flying, sunbathing, frisbee throwing, exploring, etc., at an undeveloped place open to the public

TABLE 4.18. Total Recreational User Occasions with a Specific Destination (1985) For the 13-County Gulf Coast Region of Texas.

Activity	Destination	Number of User Occasions[1]
Hiking	Bolivar Peninsula	15,781[2]
	Houston Area	226,741
	Galveston Island	190,861
	All Destinations	417,602
Picnicking	Bolivar Peninsula	254,403
	Houston Area	2,387,686
	Galveston Bay Area	259,350
	Galveston Island	1,177,133
	All Destinations	4,078,572
Nature Viewing	Chambers County	17,947
	Houston Area	343,757
	Galveston Bay Area	499,349
	Galveston Island	448,548
	All Destinations	1,309,601
Saltwater Swimming	Bolivar Peninsula	597,462
	Galveston Bay Area	470,510
	Galveston Island	7,505,894
	All Destinations	8,573,866
Saltwater Fishing	Bolivar Peninsula	306,156
	Galveston Bay Area	2,393,338
	Galveston Island	2,021,712
	All Destinations	4,721,206
Saltwater Boating	Bolivar Peninsula	1,874[2]
	Galveston Bay Area	2,116,647
	Galveston Island	844,210
	All Destinations	2,960,857

Source: Texas Parks and Wildlife Department, 1986

[1]One user occasion results if any part of a day is devoted to a recreational activity by a single recreationist at a single site

[2]Only partial data available for use

TABLE 4.18 presents the total number of recreation user occasions occurring in one year, with the destination of the user identified. Picnicking, fishing and swimming top the list in terms of participation (most of the saltwater swimming shown for Galveston Island relates to the gulf beaches rather than the bay). Note that the data presented in this table are for Texas residents only; it is unknown how many out-of-state visitors are using the same resources every year.

In May 1993, Whittington et al. (1993) surveyed bay area households 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 (TABLE 4.19). 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, or 400,000 households, use the bay at least once a year for recreational purposes (Whittington et al., 1993). Whittington et al. (1993) noted that many people from outside the five-county area also use the bay for recreational purposes.

Sport Fishing

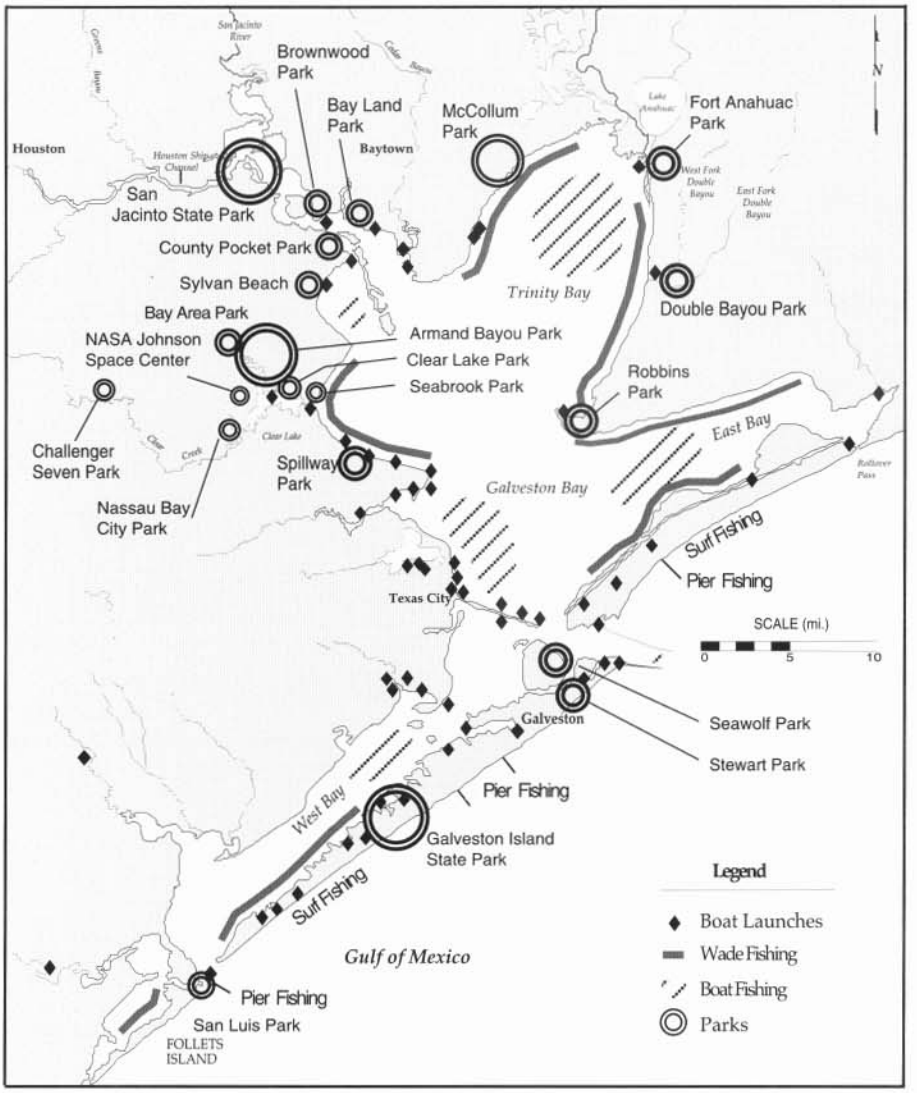
In addition to the important commercial finfish fishery in the bay, there is also a significant sport fishery (see FIGURE 4.12 for locations). In fact, commercial fishing on the average accounts for only about 14 percent of the total catch within the bay, with the remainder (86 percent or 498,960 kg in 1986) going to the sport catch (Texas Department of Water Resources, 1981b; Texas Water Commission, 1988). The bay supports approximately two million hours of sport fishing annually, (FIGURE 4.13) creating economic benefits estimated at $364 million in 1986 (Texas Water Commission, 1988).

TABLE 4.19. Estimated Number of Greater Houston/Galveston Area Households that Use Galveston Bay for Recreational Purposes at Least Once a Year.

	Households Using the Bay	
Recreational Use	Number	%
Fishing/Boating		
Boat/Shore Fishing	125,000	11
Boating (Without Fishing)	50,000	4
Households That Fish and Boat	75,000	6
Total (Fishing and Boating)	250,000	21
Other Recreational Activities[1]	150,000	13
Any Type of Recreation	400,000	34

Source: Whittington et al., 1993

[1]Includes hiking, bird watching, picnicking, camping, hunting, swimming, etc.



Source: Galveston Bay National Estuary Program, 1992

FIGURE 4.12. *Recreation is a key human use of the bay system. Some features related to boating, fishing, and parks are indicated. Currently, public access to the Galveston Bay shoreline is limited in comparison to beaches on the Gulf of Mexico.*

TABLE 4.9 lists the number of recreational fishing licenses issued in the five counties around the bay between 1982 and 1992. The number of recreational fishing licenses issued has declined during this period from 336,278 in 1982 to 295,566 in 1992.

Fishing pressure on the bay due to commercial and recreational catches has increased in recent years while the estimated success of the fishing by sports fishers has been decreasing (FIGURE 4.14). For example, Allison et al. (1991) reported that in the 1974-1976 period over 2.8 million hours of private fishing effort resulted in a total catch of 5.5 million fish, or about two fish caught per hour. In the 1986-1987 period, however, only 2.4 million fish were caught from 2.2 million hours of fishing, an average of about one fish caught per hour.

About three-quarters of the annual sport fishing effort, and catch, occurs between May 15 and November 20. Atlantic croaker, sand sea trout, and spotted seatrout are the sport fishes taken most frequently. Together they comprised 76 percent of the total catch (by numbers) between 1974 and 1985 (Osburn and Ferguson, 1986; FIGURE 4.15).

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 (TABLE 4.20). 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 (TABLE 4.20).

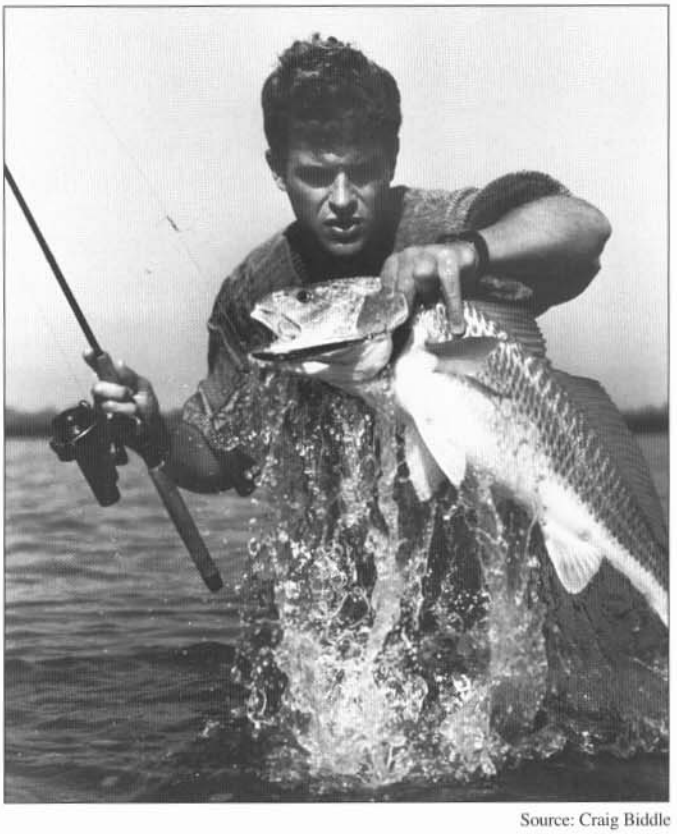
Boating

Boating, along with shipping, has been an integral use of the bay throughout history. TABLE 4.21 lists boating registration data for recreational and commercial boats from 1980 through 1992. Overall, there has been a slight decline in the number of annual commercial boating registrations in all the counties since 1980. Still, over a thousand commercial boating registrations were issued in the bay area in 1992.

Recreational boating is popular on the Texas coast in general and around Galveston Bay in particular. The Clear Lake-Galveston Bay area has been referred to as the "yacht capital of Texas." Residents in a four-county area around the bay in 1986 held approximately 102,000 pleasure boat licenses and were served by 38 marinas and 8,000 boat slips (Texas Water Commission, 1988). In 1992, the number of recreational boat registrations was about 98,000 (TABLE 4.21). The bay system accounts for 30 percent of the total number of marinas on the Texas coast and 63 percent of the total wet slips in commercial marinas (Texas Water Commission, 1988). This has grown from a 1976 figure of 27 percent of total marinas and 56 percent of coastal wet slips.

Tourism

Ecotourism, or tourism that is based on nature rather than man-made attractions is the tourist industry's most rapidly expanding sector (Eubanks, 1993). The City of Rockport on the Texas coast, 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, visited by tourists primarily for natural attractions such as bird-watching at High Island or wildlife viewing at the Anahuac National Wildlife Refuge, has experienced significant growth in the tourist



Source: Craig Biddle

Recreational fishing supports a multi-million dollar economy. Anglers pursue fish such as spotted seatrout, red drum, flounder, and croaker. Here, a wade-fisherman lands a red drum on light tackle.

TABLE 4.20. Direct and Total Economic Impact (Millions of 1986 dollars) from Sport Fishing Expenditures Related to Galveston Bay.

	Direct[1]		Total	
	Regional	State[2]	Regional	State[2]
1986				
Output	171.5	181.2	433.2	276.7
Income	53.6	66.1	104.0	154.5
State Tax Revenues	N/A	0.8	7.4	7.8
Local Tax Revenues	N/A	2.3	13.1	13.9
1976-1977				
Output	7.7	7.9	17.7	25.8
Income	2.8	3.0	5.2	7.3
State Tax Revenues	N/A	0.1	0.2	0.3
Local Tax Revenues	N/A	1.0	0.3	0.4

Source: For 1986: Fesenmaier et al., 1987; for 1976-1977: Texas Department of Water Resources, 1981a

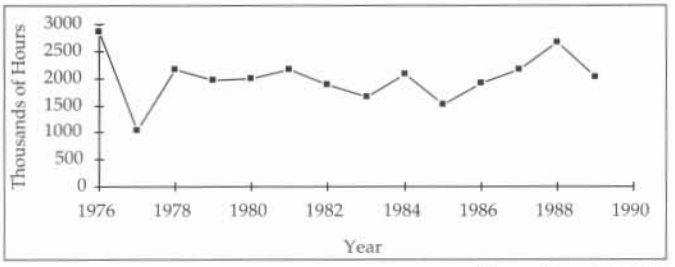
N/A = data not available

[1]Direct impacts for the region and the state differ due to the travel expenditure adjustment

[2]Total statewide expenditures include the regional impacts

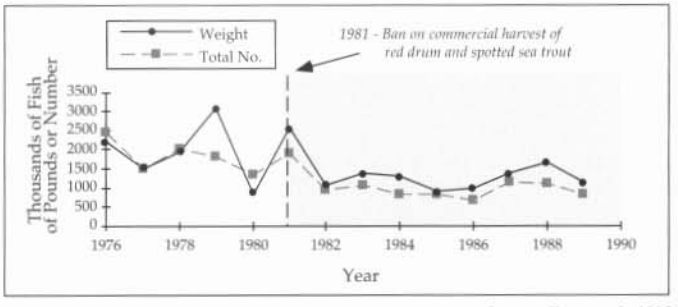
industry between 1975 and 1988, with total expenditures increasing from $600,000 to over $9 million (Allison et al., 1991).

Galveston Bay has several ecologically valuable sites that serve as ecotourist attractions. For example, bird-watching at High Island and other locations around the bay attracts visitors from all



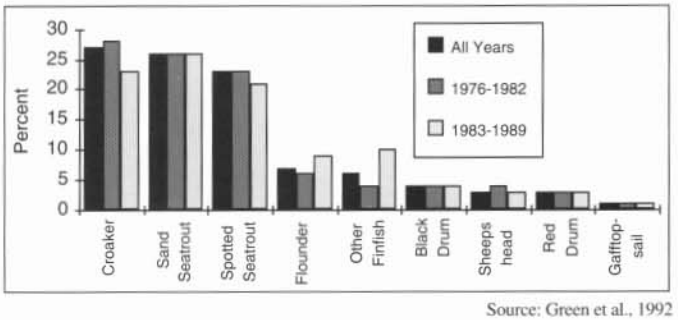
Source: Green et al., 1992

FIGURE 4.13. *Trends in total hours spent sportfishing in Galveston Bay, 1976–1990. Economic benefits from this activity are estimated to exceed $364 million annually.*



Source: Green et al., 1992

FIGURE 4.14. *The total recreational and commercial catch of finfish from Galveston Bay, 1976–1990. Fishing pressure has increased, while success per hour per individual has declined.*



Source: Green et al., 1992

FIGURE 4.15. *Composition of the sportfishing catch by species, comparing 1976–1982, 1983–1989, and all years.*

over the United States and many foreign countries. Eubanks (1993) listed over 21 potential ecotourist attractions around Galveston Bay: Bolivar Flats, Rollover Pass, High Island, Anahuac National Wild Refuge, Chambers County Ricefields, White Memorial Park, Candy Abshier 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, Follets Island, San Luis Pass, West Galveston Island, Galveston Island State Park, North Deer Island, Kempner Park, and Big Reef.

Allison et al. (1991) examined the contribution of tourism to the economic infrastructure of four counties around the bay (Harris, Chambers, Brazoria and Galveston). They found substantial growth between 1975 and 1988, with much smaller increases after 1988 (Allison et al., 1991). Economic data (travel expenditures, payroll, and number of jobs) compiled from the Texas Department of Commerce (Tourism Division) are presented in TABLE 4.22.

Expenditures for tourism in 1992 in Harris, Galveston, Brazoria, and Chambers counties totaled $3.5 billion; $307 million, $91 million, and $10 million, respectively. The number of jobs for 1992 in Harris, Galveston, Brazoria, and Chambers counties totaled 73,000; 5,600; 1,500; and 130; respectively. Allison et al. (1991) pointed out that the proportion of the expenditures shown in TABLE 4.22 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 not been discussed in detail because little or no information is available for them. These include swimming and other forms of "contact recreation" such as water skiing, as well as nature study, and hunting. Although there are no data on swimming in Galveston Bay, major areas known to attract contact recreation in bay waters 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 only fully developed interpretive program in the bay area. New programs centering on the bay's resources are being developed by the Galveston Bay Foundation at its Rich Sanctuary in Chambers County and by the City of Seabrook at its Nature Center.

One of the concerns generated by recreational use of the bay is that of shoreline access. Public shoreline access to the bay is generally limited to the parks and boat ramps shown on FIGURE 4.12. As population in the area around the bay grows, there is likely to be demand for additional public facilities in these areas.

In summary, the economic impact from recreational activities in Galveston Bay is quite substantial. Visitors participating in fishing, hunting, picnicking, camping, pleasure boating and sightseeing spent approximately $122.4 million in 1986 (TABLE 4.23). Gross personal income derived directly from this activity was on the order of $38.2 million for that year. There were no other data on economic benefits from these activities prior to 1986.

Source: Galveston Bay National Estuary Program

More than 5000 boat slips are available in the Galveston Bay system. Sixty-three percent of boat slips on the Texas coast can be found around Galveston Bay. Clear Lake (shown here) hosts many of these boats and has been dubbed the "Yacht Capitol" of Texas.

TABLE 4.21. Number of Boat Registrations for Counties Surrounding Galveston Bay, 1980 - 1992.

Type of Boat	Year	Brazoria	Chambers	Galveston	Harris	Liberty	All Five Counties
Commercial	1992	114	76	345	505	33	1073
	1991	112	83	364	506	44	1109
	1990	122	107	417	522	53	1221
	1989	131	132	433	514	63	1273
	1988	128	136	499	533	62	1358
	1987	126	135	514	554	52	1381
	1986	121	140	492	546	49	1348
	1985	130	107	523	585	44	1389
	1984	140	118	581	638	43	1520
	1983	147	114	576	613	51	1501
	1982	142	93	509	560	47	1351
	1981	135	86	495	562	51	1329
	1980	144	88	527	585	60	1404
Recreational							
	1992	9,967	1,334	10,308	76,307	2,740	100,656
	1991	10,069	1,384	10,124	77,335	2,890	101,802
	1990	10,206	1,444	10,160	78,603	2,873	103,286
	1989	10,097	1,493	9,956	78,591	2,822	102,959
	1988	9,909	1,484	9,718	78,592	2,815	102,518
	1987	9,822	1,472	9,608	79,714	2,886	103,502
	1986	9,736	1,479	9,539	81,098	2,938	104,790
	1985	9,668	1,442	9,447	82,519	2,940	106,016
	1984	9,664	1,385	9,503	84,190	2,987	107,729
	1983	9,633	1,385	9,547	85,604	3,103	109,272
	1982	9,605	1,329	9,348	86,127	3,105	109,514
	1981	9,267	1,282	8,982	84,947	3,034	107,512
	1980	9,156	1,222	8,838	84,261	2,858	106,335

Source: Texas Parks and Wildlife Department, 1993

Agriculture

Agricultural use of the land surrounding the bay has been declining for many years. Nevertheless, agriculture, and

TABLE 4.22. Jobs and Dollars Derived from Tourism in the Counties Surrounding Galveston Bay (Millions of Dollars Not Adjusted for Inflation).

Year	Category	Brazoria	Chambers	Galveston	Harris	Liberty	All Five Counties
1992	Travel	91.20	10.39	306.75	3,511.45	35.21	5947.00
	Payroll	18.60	1.78	6617	1,400.14	8.44	1493.13
	Jobs	1470	130	5580	72550	510	80240
1991	Travel	89.88	10.04	301.03	3,380.73	33.81	5806.49
	Payroll	18.71	1.74	65.91	1,380.45	8.20	1483.01
	Jobs	1520	140	5660	72250	510	80080
1990	Travel	81.57	10.55	284.25	3,136.90	35.10	5538.37
	Payroll	16.67	1.79	61.16	1,242.72	6.50	1328.84
	Jobs	1400	150	5540	69470	570	77130
1989	Travel	73.19	9.80	249.23	2,797.96	33.25	5152.43
	Payroll	15.01	1.64	53.04	1,037.74	6.07	1113.50
	Jobs	1310	140	4970	61670	540	68630
1988	Travel	70.46	81.50	260.10	3,218.79	13.72	5540.57
	Payroll	13.21	1.60	51.73	711.70	2.19	780.43
	Jobs	1264	148	4693	51470	189	577
1985	Travel	29.54	4.78	242.28	3924.56	12.79	8196.97
	Payroll	5.50	0.94	48.80	814.08	2.02	869.34
	Jobs	529	70	4698	69232	197	74726
1980	Travel	49.06	11.13	179.47	2,585.18	8.00	4812.84
	Payroll	9.73	1.70	35.89	548.97	1.46	595.75
	Jobs	1188	193	4623	58811	200	65015
1975	Travel	28.71	0.58	108.17	1,037.15	10.18	3159.80
	Payroll	4.97	0.18	22.41	221.85	1.27	250.88
	Jobs	894	30	4651	41802	141	47518

Source: Texas Department of Commerce (1985; 1990; 1992)

TABLE 4.23. 1986 Direct and Total Economic Impact from Other Recreation Expenditures Related to Galveston Bay (Millions of 1986 dollars).

	Direct[1]		Total	
	Regional	State[2]	Regional	State[2]
Output	122.4	131.8	311.0	425.2
Income	38.2	48.5	74.5	113.3
State Tax Revenues	N/A	0.6	5.3	5.7
Local Tax Revenues	N/A	1.6	9.5	10.1

Source: Fesenmaier et al., 1987

N/A = data not available

[1]Direct impacts for the region and the state differ due to the travel expenditure adjustment

[2]Total statewide expenditures include the regional impacts

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 fresh water inflows. Frequently, conversion of agricultural land to more urban uses results in even greater impact on water use and runoff to the bay system.

Between 1967 and 1982, there was a decrease of 21 percent or 297,374 ac in the acreage used for agriculture (Ditton et al., 1989). In 1982, there were over 1.4 million acres of farm land in the four counties surrounding the bay (Harris, Brazoria, Chambers, and Galveston). The market value of agricultural products sold from the four counties in 1982 was estimated by Ditton et al. (1989) at $113 million.

The number of farms in Brazoria county increased by 17 percent from 1959 to 1987 with a total of about 1,500 farms in the county in 1987. However, during the same period the size of the average farm decreased by about 28 percent; and the total farmed land in Brazoria county decreased by 15 percent over the period. The unadjusted value of all crops sold tripled during that 28-year period, while the value of livestock sold increased by about 185 percent (Allison et al., 1991).

In Chambers county, the number of farms in 1987 came to 337; a 30 percent decrease from 1959. The unadjusted value of crops sold increased by about 100 percent while the value of livestock sold increased by about 85 percent. The number of large farms (with more than 1000 ac) increased over the period (Allison et al., 1991).

Similar trends in the number and size of farms were experienced in Galveston County. The number of farms decreased by about ten percent between 1959 and 1978, however, a slight rebound occurred between 1978 and 1987. The unadjusted market value of crops increased by 124 percent from 1959 to 1987, but livestock declined in market value over the period. Most of the farms in Galveston County are in the ten to 500-ac size range (Allison et al., 1991).

The number and size of farms in Harris county also declined over the period between 1959 to 1987, by about 20 percent and 30 percent respectively. The result was a 44 percent reduction in agricultural land from 1959 to 1987. The unadjusted market value of products sold increased by 152 percent with the value of livestock increasing by 38 percent. As with Galveston County, the majority of the farms are in the ten to 500-ac range (Allison et al., 1991).

Water Use

The location and timing of fresh water inflows affect salinity, circulation and the supply of sediments and nutrients to the bay (see Chapter Five–Physical Form and Processes of the Bay). At the same time, the growth of population and industry in an area is controlled to a large extent by the availability of suitable fresh water supplies. Allison et al. (1991) point out that fresh water is particularly important to economic growth in a four-county region surrounding the bay, since much of the economic activity in the Galveston Bay region is associated with the petroleum and petro-

chemical industries. These industries traditionally have used a large amount of water in their processes. For example, 1,851 gallons of water are required to refine one barrel of petroleum and 55 gallons of water are required to produce one pound of synthetic rubber.

To secure water for population and industry of 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. A dam and associated shallow reservoir now under construction at Wallisville at the mouth of the Trinity is designed to serve as a saltwater barrier to protect fresh water supplies. 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 fresh water supply for the city of Anahuac and for agriculture in Chambers County. (For a discussion of the effects of these impoundments and alterations, see Chapter Five–Physical Form and Processes of the Bay.)

Source: Galveston Bay National Estuary Program

Tourism is a major industry in the bay area. In particular, ecotourism is a growing segment of the industry which utilizes the environment as an attraction. Here, tourists feed laughing gulls from the ferry crossing Bolivar Roads between Galveston Island and the Bolivar Peninsula.

TABLE 4.24 summarizes water use by purpose and source (groundwater or surface water) in 1990 for the five counties surrounding the bay (Texas Water Development Board, 1991). In the five-county area in 1990, over 1,400 million gallons per day (MGD) of fresh water were used. More than two-thirds of that amount was from surface water sources, principally the Trinity and the San Jacinto Rivers. Parts of Galveston County and Brazoria County receive surface water from the Brazos River, which in its ordinary course does not drain into the Galveston Bay system.

TABLE 4.25 provides information on historical water use in the Galveston Bay area compared to the entire State of Texas (Texas Water Development Board, 1991). Although the Galveston Bay area is highly urbanized, the continued importance of agriculture in the region is emphasized by the increase in fresh water used during 1988. Most of that increase was attributable to water used for irrigation (Texas Water Development Board, 1991).

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.

Industrial and agricultural uses of groundwater in Harris and Galveston counties have declined by 81 percent and 50 percent since 1976, respectively. To accomplish that reduction in groundwater use, the Trinity River has grown as a major water supply from 3.7 MGD in 1976 to 177 MGD in 1990 (Allison et al., 1991).

Much of the surface water appropriated for human use is returned to the bay system. A statewide water use inventory for 1980 by the Texas Water Development Board found a range of return flows between 27 and 68 percent, with an average of 45 percent, for basins around Galveston Bay. Return flows from

Source: Texas Sea Grant College Program

Agriculture remains an important economic and environmental influence in the Galveston Bay system. Rice farming predominates in the immediate watershed, while row crops such as sorghum, soybeans and cotton are more common in the upper watershed. These activities, including livestock production, can be nonpoint sources of pesticides, fertilizers, and other pollutants, but are overshadowed by even higher pollutant loadings from urban sources.

TABLE 4.24. 1990 Water Use (Millions of Gallons per Day) by Purpose and Source for Counties Surrounding Galveston Bay.

Water Purpose	Water Source	Brazoria	Chambers	Galveston	Harris	Liberty	All Five Counties
Public	Ground	17.0	1.7	6.2	313.1	6.7	344.7
	Surface	7.5	0.9	23.9	126.0	0.0	158.2
	Total	24.5	2.5	30.1	439.1	6.7	503.0
Industrial	Ground	3.3	2.7	0.4	38.4	0.2	45.0
	Surface	175.4	10.9	52.6	287.5	0.0	526.4
	Total	178.7	13.6	53.0	326.0	0.2	571.4
Agriculture	Ground	5.1	0.2	0.8	24.7	10.9	41.8
	Surface	121.7	104.1	17.9	4.0	79.9	327.5
	Total	126.8	104.3	18.7	28.7	90.8	369.2
Total	Ground	25.5	4.6	7.3	376.3	793.7	431.5
	Surface	304.5	115.8	94.4	417.5	17.9	1,012.1
	Total	330.0	120.4	101.7	793.7	97.7	1,443.6

Source: Texas Water Development Board, 1991

TABLE 4.25. Historical Water Use (Millions of Gallons per Day) for Counties Surrounding Galveston Bay, Compared to Water Use in the Entire State of Texas.

Year	Brazoria	Chambers	Galveston	Harris	Liberty	All Five Counties	Entire State
1974	353.2	116.3	102.5	695.1	100.9	1368.0	15,479.5
1977	333.8	111.2	106.4	798.5	102.7	1452.6	14,503.0
1980	477.9	194.7	123.0	781.5	134.7	1711.8	15,914.7
1984	336.4	156.0	97.4	752.8	102.5	1445.1	13,618.6
1985	364.4	109.8	95.0	763.8	95.3	1428.3	12,587.4
1986	325.9	100.6	95.3	769.2	83.6	1374.6	11,682.2
1987	297.1	95.3	98.6	749.2	78.9	1319.1	11,114.2
1988	368.2	145.7	99.9	835.6	165.9	1615.3	12,500.8
1989	323.4	104.7	97.5	753.3	90.3	1369.2	13,434.0
1990	330.0	120.4	101.7	793.7	97.7	1443.5	14,089.6

Source: Texas Water Development Board, 1991

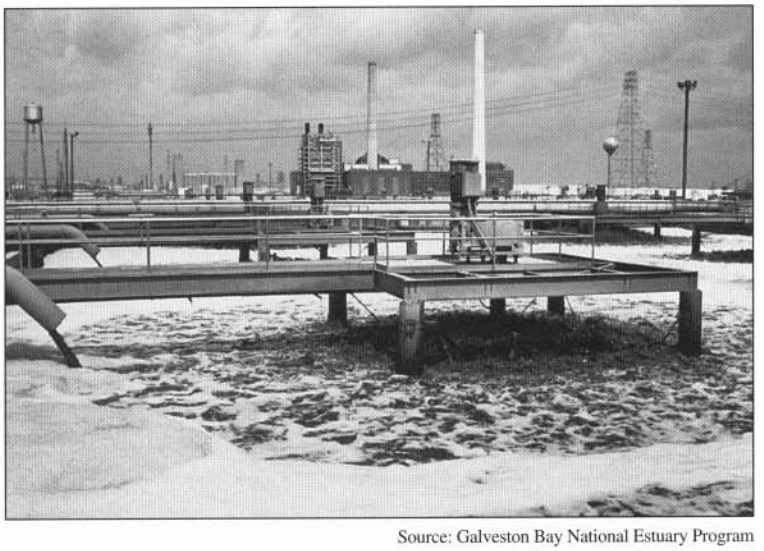
groundwater usage, and diversions from other basins such as the Brazos, are also discharged to the bay's waters. Increases in water usage have obvious implications for fresh water inflow to the bay as well as wastewater collection and treatment systems in the bay region.

Discharge of Treated Wastewater

Galveston Bay has historically suffered from the discharge of wastewater into its receiving waters. In the late 1800s street drains and sewers in Houston emptied separately but directly into Buffalo Bayou (Henson, 1993). Because of numerous accounts of resulting pollution, the city built the first sewer system in 1899 with a central pumping station on the northeast side where siphon pumps brought the sewage across the bayous (Henson, 1993). Within six years of that time, however, the capacity of the system was exceeded and the quality of its performance was suspect.

More disposal plants were built but in 1916 between 70 and 80 percent of the raw sewage still went directly to the bayou. Untreated disposal continued until the late 1960s when Dr. Joseph Melnick, an expert on virology and epidemiology, found a wide range of bacteria and viruses in the bayou water (Henson, 1993). By the early 1970s, the city began treating its raw sewage with chlorine. Today, much of the wastewater **effluent** is treated, however many communities around the bay still discharge raw sewage because of breakdowns in the systems and bypasses during flooding events.

In addition to the city of Houston, Galveston and the other smaller communities around the bay improved their wastewater disposal systems by changing from cesspools and outhouses (or septic tanks) to city sewers. In a 1950 study conducted by Galveston County, however, officials found that most of the municipalities were still dumping raw sewage into the bay. Much later, a federal study dealing with water pollution determined that of seven million gallons of sewage in 1970 from the city of Galveston, only 40 percent was adequately treated (Henson, 1993). Galveston eventually began treating its waste-



Source: Galveston Bay National Estuary Program

Galveston Bay receives municipal and industrial wastewater from more than half of all permitted discharges in the state. Shown is a regional industrial treatment facility which receives wastes from many of the ship channel industries.

TABLE 4.26. Number of Discharge Facilities in Estuarine Drainage Areas (1987).

Code[1]	SIC[2] Major Group Activity	Major[3] NCPDI[4]	Major[3] Total[5]	Minor[3] NCPDI[4]	Minor[3] Total[5]
13	Oil and Gas Extraction	-	-	41	224
15	General Building Contractors	-	-	0	25
20	Food and Kindred Products	-	-	5	6
26	Paper and Allied Products	2	2	1	1
28	Chemicals and Allied Products	50	50	35	61
29	Petroleum and Coal Products	10	10	6	8
30	Rubber and Misc. Plastics Products	-	-	4	5
32	Stone, Clay, and Glass Products	-	-	5	12
33	Primary Metals Industries	4	4	2	7
34	Fabricated Metals Products	1	1	11	21
35	Industrial Machinery and Equipment	-	-	10	21
37	Transportation Equipment	-	-	2	4
42	Trucking and Warehousing	1	1	10	27
44	Water Transportation	-	-	2	4
47	Transportation Services	-	-	2	7
49	Electrical, Gas, and Sanitary Services	102	102	478	511
50	Wholesale Trade - Durable Goods	-	-	5	13
51	Wholesale Trade - Nondurable Goods	1	1	6	16
58	Eating and Drinking Places	-	-	0	8
65	Real Estate	-	-	4	75
70	Hotels and Other Lodging Places	-	-	0	10
72	Personal Services	-	-	4	5
73	Business Services	1	1	0	6
79	Amusement and Recreation Services	-	-	2	6
82	Educational Services	-	-	0	7
86	Membership Organizations	-	-	0	3
99	Nonclassifiable Establishments	-	-	2	2
	Other[6]	-	-	6	26
	Total	**173**	**173**	**643**	**1122**

Source: Pacheco et al., 1990

[1]Code = Standard Industrial Classification major group code number
[2]SIC = Standard Industrial Classification
[3]Major and Minor are used to classify discharges according to their relative importance as pollutant sources
[4]NCPDI = National Coastal Pollution Discharge Inventory
[5]Facility counts under "Total" include all facilities with NPDES permits listed in the Permit Compliance System
[6]Other includes activities with codes 14,16,17,24,36,40,46,48,54,55,75,76,78,80,83,95,96,97

TABLE 4.27. Population Projections to the year 2010 for the Galveston Bay Region.

Year	Brazoria	Chambers	Galveston	Harris	Liberty	All Five Counties
1990	191,707	20,088	217,399	2,818,199	52,726	3,300,119
1995	205,398	22,531	232,443	3,008,008	55,915	3,524,295
2000	220,069	25,271	287,678	3,217,690	58,738	3,809,446
2010	252,627	31,793	310,129	3,707,869	66,053	4,368,471

Source: Houston-Galveston Area Council, 1993b

water effluent prior to discharging it into the bay.

Today, many improvements have been accomplished in terms of municipal wastewater treatment and discharges into the bay. However, 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 in the State of Texas were located in the Galveston Bay watershed. About 31 percent 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) were 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. Different types of permit holders are shown in TABLE 4.26.

Armstrong and Ward (1994) estimate an annual **biochemical oxygen demand** (BOD) loading of 4.7 million kg per year in 1990 resulting from waste discharges and 22.4 million kg per year (1969 - 1988 average) from the tributaries. A remarkable 95 percent reduction has been achieved since 1968 in BOD discharged to the upper Houston Ship Channel. This has resulted in water quality improvements and the return of some fish species to the area. More detailed information on the location and trends in wastewater discharge is provided in Chapter Six.

Other Uses: Real Estate Development

There is extensive residential/commercial real estate use of coastal land. For example, the four counties surrounding Galveston Bay contained 1.1 million or 77 percent of the housing units in the 16 Texas coastal counties in 1980 (Ditton et al., 1989). This pattern was much the same in 1960 and according to recent data from the U.S. Bureau of the Census the four counties accounted for 66 percent of the building permits issued for single and multi-unit housing on the Texas coast in 1987.

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 and fishing cabins in and around the smaller bays 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 there because of the commercial location values represented by water transportation and waste discharge sites.

Source: R. Will Roach

Cabins in Christmas Bay, viewed from the air (above) and the water (below), are built on oyster reefs. These cabins were built on public lands by private citizens and are leased from the Texas General Land Office. Recent controversial issues related to raw sewage discharges and proximity to publicly-held resources have prompted policy changes.

SUMMARY

Galveston Bay has been the focus of numerous uses by humans throughout history, including food supply, transportation, oil and gas production, and recreation. The surrounding watershed has been used for urban development, petroleum and petrochemical production, and agricultural uses. Currently, the estuary accounts for 20 to 70 percent, depending on the species, of the total fisheries production in Texas and one-half of the state's recreational fishing expenditures. Sixty to 70 percent of the Texas' oyster fishery is also concentrated in the estuary. About one-third of the households in the counties surrounding the bay use the bay at least once a year for recreational purposes. Galveston Bay is surrounded by the eighth largest metropolitan area in the United States. Its chief port, the Port of Houston, ranks third among United States ports in total tonnage. More than one-half of the state's wastewater discharge permittees are sited within the estuary's watershed.

Galveston Bay shares many problems with other estuaries of a similar stature chiefly in the rapidly escalating demands placed upon its resources because of an expanding population and associated development. It is estimated that by 1996, the Houston-Galveston area will have a population exceeding 3.6 million, an 11 percent increase from 1990. The year 2010 population is expected to reach nearly 4.4 million residents (TABLE 4.27; Houston-Galveston Area Council, 1993b). This projected growth in population and the associated increasing use of the bay resources pose a resource management challenge that must be addressed to avoid larger resource management problems in the future.

Source: Texas Sea Grant College Program

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CHAPTER FIVE

Physical Form and Processes

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 waters of the San Jacinto and Trinity, which unite a short distance above. The water upon the bar does not generally exceed three or four feet in depth but at some seasons of the year is often found at six. 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.

–Anonymous "Citizen of Ohio," 1837 in *Texas in 1837*, edited by Andrew Forest Muir, 1986

Physical form and processes determine the basic character of any estuary. Water circulation patterns, influenced by the wind and tides, determine the mixing of fresh and sea water, affecting fish, shellfish, and the locations of wetlands. Oyster reefs create natural barriers, in turn influencing the nature of the circulation patterns. The rivers that feed the bay influence salinity, water clarity, and a suite of chemical conditions that affect living things. Human activities–even those activities which take place within the watersheds miles from the bay–have the potential to greatly alter these natural processes.

Galveston Bay is a shallow, wind-driven estuary, shaped by natural and man-made forces over the past 150 years. For example, historical information indicates that oyster reefs had a significant effect on bay circulation and salinity prior to 1900, while after 1900 the Houston Ship Channel (which cut through these reefs) became a dominating influence. Withdrawal of groundwater has caused land in the bay region to sink as much as nine feet, drowning marshes and significantly increasing the volume of the bay. Other activities like shell dredging, isolation of side bays, and diversions of river water have also had important consequences.

This chapter summarizes the physical components and processes which most affect Galveston Bay. A description of the bay's origin begins this discussion. The climate of the region and the nature of the bay's watersheds (both locally and far upstream) are described as they affect bay conditions. Fresh water inflow and circulation (determined by winds, tides, and bay geometry) are described as critical elements linked to natural processes in the bay. Finally, human alterations to the basic structure and function of the bay are summarized. These include dredging and sediment disposal, shoreline modification, the historical removal of oyster shell for use in road bed construction, and land subsidence. Overall, the conditions and processes described in this chapter provide the setting for discussion of water quality issues (Chapter Six) and living resource concerns (Chapters Seven and Eight).

ORIGIN OF GALVESTON BAY

Geologic History

Galveston Bay was formed by the falling and rising of the sea. Beginning about 30,000 years ago, the oceans began to drop as the last major period of glaciation began in the northern hemisphere, incorporating more of the earth's water into the polar ice caps. Major rivers, including the San Jacinto and Trinity, responded by eroding deep, broad, scalloped-shaped valleys in the surrounding alluvial sediments (Wermund et al., 1989; Fisher et al., 1972). This process continued for the next 12,000 years as the sea level dropped more than 400 feet from its original level.

Then, as the glaciers began retreating, their melt water caused the sea to rise. While rivers continued to meander through the coastal plain, the ocean slowly began to inundate portions of the valleys. The sea stopped rising about 4,500 years ago, and the

drowned valleys of the San Jacinto and Trinity Rivers became what we now call Galveston Bay. Currently the bay has an area of about 384,000 ac (600 sq mi).

Several processes began shaping the bay when sea level stabilized about 4,500 years ago (Fisher et al., 1972):

> The deeper parts of the drowned valleys began to fill with sediment delivered from upstream;
>
> Bayhead **deltas** began to form in the upper part of the estuary near the new outlets of the San Jacinto and Trinity Rivers;
>
> Small streams around the bay continued to erode headward into the surrounding mud and silt landscape; Bolivar Peninsula developed through **longshore drift** of deltaic sands from near High Island;
>
> Galveston Island and Follets Island developed as exposed off-shore bars and migrated landward, forming West Bay and Christmas Bay;
>
> Marshes formed on the margins of drowned shorelines, including bayhead and tidal deltas and **washover fans**; and
>
> Sediments continued to be delivered to the bay from streams discharging into the bay.

The bay has been slowly filled with sediments, as is evidenced by buried oyster reefs. The long-term natural **siltation** rate for the open Galveston Bay bottom (not navigation channels) was estimated by Gilardi (1942) to be 1.5 feet per 100 years while Shepard (1953) estimated the total rate of average sedimentation (submergence vs. **shoaling**) to be about three feet per 100 years for Texas bays. As would be expected, most of these sediments come from streams and shoreline erosion.

Contemporary Natural Processes

In more recent geologic time, several natural processes are particularly significant in affecting the bay: sea level rise and shoreline erosion. While both of these processes are driven by natural forces, they are also influenced substantially by human activity.

Sea Level Rise

A relative sea level rise has occurred in the Galveston Bay area due to: 1) world-wide increases in sea level; 2) natural compactional subsidence of Gulf Coast sediments; and 3) land surface subsidence caused by excessive groundwater withdrawals. The first two natural processes are discussed in this section, while subsidence, caused mainly by human activity, is addressed later in this chapter under "Human Physical Alterations".

Gornitz et al. (1982) estimated that sea level in the Gulf of Mexico and Caribbean region has risen about 0.8 ft during the past century. White and Calnan (1990) estimated that the local mean sea level rise for the Trinity River delta was about 2.4 ft per 100 years, which accounts for both regional sea level rise and that portion of subsidence attributable to natural causes. Local tidal records also confirm a relative sea level rise of 1.5 feet between 1904 and 1980 at Galveston Island (Morton, 1974).

More dramatic increases in future sea level have been postulated by some researchers. Such rapid sea level rises appear to be a fact of geologic history. For example, available data suggests sea level rises of ten to 15 feet per 100 years have occurred during short intervals in the past 12,000 years (Anderson et al., 1991). The Environmental Protection Agency has indicated that world-wide, sea level could rise over five feet during the next 100 years if global warming effects are realized (Titus, 1986). Although there is considerable debate on the accuracy of global warming predictions (and whether sea level rise would result), effects on the bay if it occurs are less debatable–there would be significant impacts on wildlife and their habitats (see Chapter Eight).

Shoreline Erosion

Galveston Bay's natural shoreline consists of 61 percent marshes, 35 percent steep clay bluffs ranging from five to 35 feet in height, and four percent sand and shell beaches (excluding man-made shorelines, discussed below). Most of the marsh shoreline is located on East and West Bays, while the bluffs are located on Trinity and Galveston Bays.

Retreat of these shorelines due to erosion is a natural and almost universal process affecting the Galveston Bay system (Paine and Morton, 1986; Paine and Morton, 1991; Morton, 1974). The erosion of shorelines has occurred more or less constantly since sea level stabilized after the end of the last period of glacial melting. About 78 percent of the bay's shoreline has been affected by erosion during the period 1850 to 1982 (Paine and Morton, 1991). The only area of accretion (the opposite of erosion) was observed in the Trinity River delta, which advanced between 14 and 43 ft/year for the period since the 1850s (Paine and Morton, 1991).

The average shoreline retreat in Galveston Bay was 2.2 ft/year, for 1850-1982, corresponding to over 8,000 ac of lost land since the 1850s, or about two percent of the bay's surface area (Paine and Morton, 1991). An analysis of the different shoreline types showed that sand beaches had the highest rate of retreat at 6.1 ft/year, marshes retreated 4.1 ft/year, and bluffs retreated at an average rate of 3.2 ft/year (Paine and Morton, 1991). Geographically, the highest rate of retreat was in northwestern Galveston Bay between Cedar Bayou and Virginia Point (the area of highest human-caused subsidence). Throughout the bay system, erosion rates have increased recently, from an average rate of 1.8 ft/year during the 1850 to 1932 period to 2.4 ft/year after 1932.

The natural causes of shoreline erosion in Galveston Bay include: 1) wind-driven waves; 2) hurricanes, tropical storms, and northern cold fronts; and 3) sea level rise. Human activities have also contributed greatly to this natural process in recent decades.

Source: Galveston Bay National Estuary Program

Natural vegetation along the shoreline helps to stabilize sediments and reduce erosion rates. For some eroding shorelines, smooth cordgrass transplanting provides an economical alternative to bulkheading for shoreline stabilization. Here volunteers plant sprigs of smooth cordgrass to re-establish fringing vegetation (inset). Temporary wave barriers (above, left) reduce wave energy until the marsh becomes fully established.

Land surface subsidence has contributed to the drowning of shorelines and the loss of stabilizing marsh vegetation. The construction of upland reservoirs has probably contributed to the acceleration of marsh erosion since the 1930s by robbing the bay of sediments transported down the rivers. In addition, reduced erosion rates due to changing land uses in the upper watershed may also be responsible for reducing sediment loads to the bay (Ward and Armstrong, 1992).

Of all natural events, hurricanes can produce the most dramatic changes in shorelines (Wermund et al., 1989). During Hurricane Carla in 1961, one shoreline facing the gulf eroded over 800 feet and was accompanied by about 500 feet of accretion on the bay side of the barrier island. Hurricane Alicia in 1983 was responsible for an 80-foot retreat of the vegetation line on Galveston Island, and caused most shoreline bluffs in the bay to retreat between five and 20 feet.

THE NATURE OF THE WATERSHED

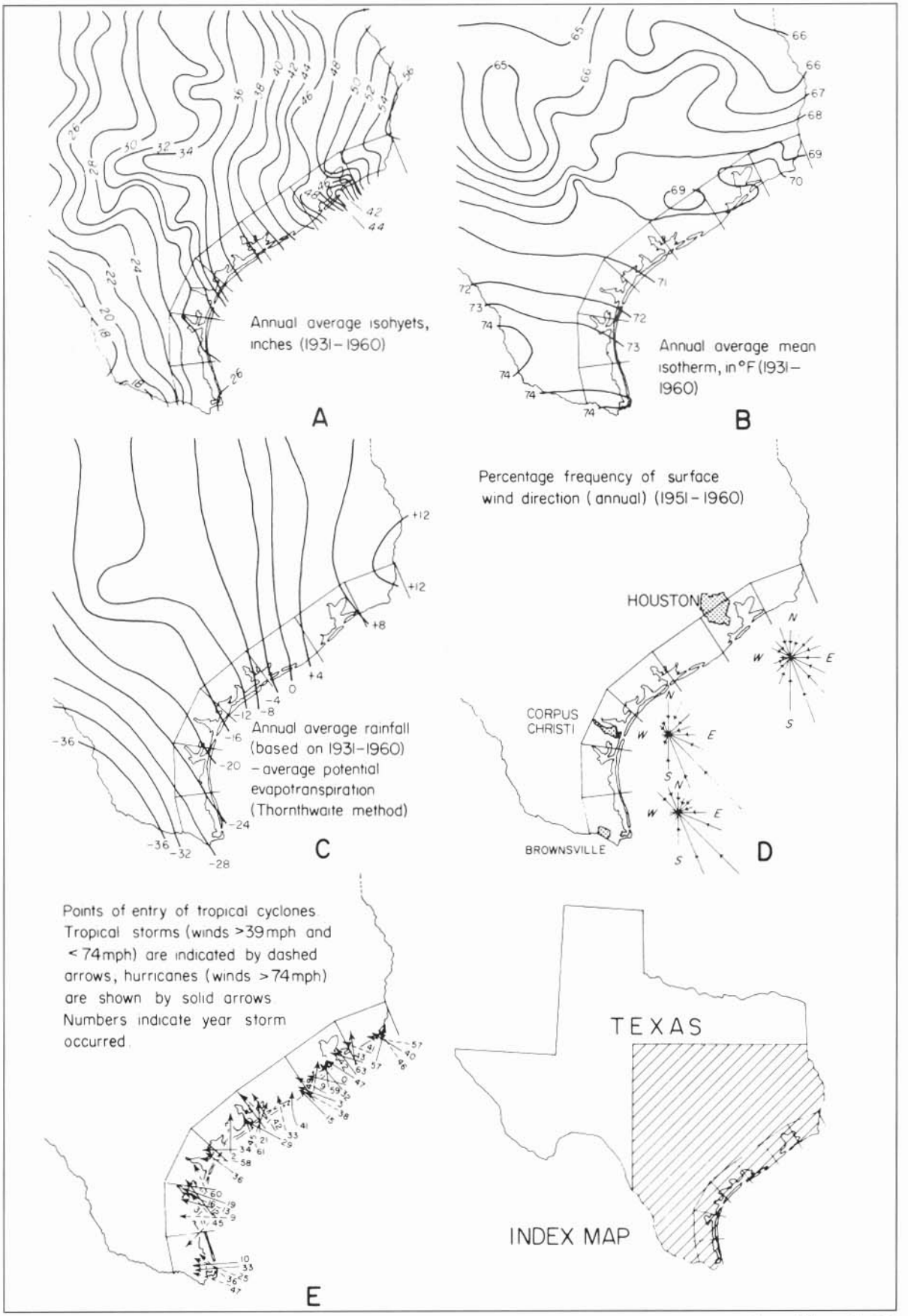
Regional Climate

The climate of the Galveston Bay region is classified as subtropical-subhumid, meaning warm and wet. The climate is controlled by: 1) latitude; 2) proximity to the Gulf of Mexico; 3) winds blowing gulfward from Pacific and arctic frontal systems; 4) decreasing elevation towards the Gulf of Mexico; and 5) a position west of the Bermuda high-pressure cell (Larkin and Bomar, 1983). In addition, hurricanes and droughts both have great effects. FIGURE 5.1 summarizes some significant aspects of climate for the upper Texas Coast.

Rainfall

Rainfall occurs as heavy thunderstorms during the spring, summer, and fall, gentler rain from passage of winter storm fronts, and deluges caused by tropical storms and hurricanes. The rainfall is almost evenly distributed throughout the year, with slightly higher rainfall in the late summer months. The average annual rainfall for the lower Galveston Bay watershed over the past twenty years was 51.8 inches (Newell et al., 1992). Once out of every eight years the Galveston Bay area will receive over 58 inches per year, and once every eight years there will be less than 33 inches per year. Over the entire period of record for the Houston weather station, the maximum annual rainfall was 72.9 inches of rain in 1900 and the minimum annual rainfall was 17.7 inches in 1917.

A statistical analysis of rainfall data indicates that during an "average" year there are approximately 80-85 storm events (rainfalls over 0.05 inches) with an average rainfall per storm between 0.4 and 0.6 inches (Winslow & Associates, Inc., 1986). Based on rainfall within a 24-hour period, the two-year storm (occurring on the average once every two years) is 5.2 inches of rain. The 100-year, 24-hour rain storm is about 13 inches of rain. The Houston area is also noted for one of the greatest 24-hour rainfalls ever



Source: Fisher et al., 1972

FIGURE 5.1. *Climate on the Texas coast.*

recorded anywhere: an estimated 43 inches of rain fell near Alvin as a result of tropical storm Claudette on July 25-26, 1979.

Temperature

The annual mean temperature in the region is about 70° F, with variability in the temperature increasing with distance inland. In Galveston, winter lows are usually in the mid-40s (°F) while average summer highs are in the low 90s. Although Galveston only experiences four days below freezing in an average year, parts of Galveston Bay have frozen upon occasion. Most notably, Jane Long, the "Mother of Texas," watched Galveston Bay freeze over from her ramshackle cabin on Bolivar Peninsula while waiting for her husband to return from an invasion of Mexico during the winter of 1820-1821. In 1888 the bay froze out to a distance of five miles with ice over two inches thick, trapping several schooners and causing the death of one captain (McComb, 1986).

Rapid temperature drops are often observed with the passage of "northers," fast-moving winter cold fronts from the north that can be "wet or dry, but always cold" (McComb, 1986). Northers are marked by strong north winds and can lower the temperature by 24° F in one hour.

Winds

Although the prevailing wind direction is from the southeast (FIGURE 5.1), wind patterns differ from summer to winter. Summer patterns are marked by relatively constant winds out of the south, while winter winds are dominated by brief, intense northers that can bring wind speeds of over 40 mph out of the north and northwest. These two wind regimes are important processes controlling the circulation in Galveston Bay (see below).

From March to November, about ten percent of the days are calm and almost half of the days have southerly, southeasterly, or easterly winds. From December through February, however, stronger winds from the north, northwest, or northeast occur about half the time and alternate with lighter southerly winds or calm periods.

Hurricanes

Tropical storms and hurricanes are extraordinary weather events that strike the Texas coast on the average of once every one to two years (see photo on next page). Some record extremes for Texas hurricanes were compiled by Wermund et al. (1989):

Wind speed:	140 mph, Hurricane Carla, 1961
Approach speed:	17 mph, Port O'Connor storm, 1929
Barometric pressure in eye:	27.49 inches, Hurricane Carla, 1961
Storm surge height:	22 feet, Hurricane Carla, 1961
Maximum wave height at sea:	40 feet, Hurricane Carla, 1961

The storm surge of a hurricane is caused by its extremely low barometric pressure, combined with winds that can drive water onto the land. Since 1850, 15 hurricanes with surge heights greater than six feet have struck Galveston Bay (Paine and Morton, 1991). As noted in Chapter Four, the 1900 storm striking Galveston was the worst natural disaster in the history of the United States, with over 6,000 deaths. Hurricane Alicia, a medium-sized hurricane, caused great damage to the bay area in 1983 and altered many of the bay's shorelines and habitats. Hurricanes affect sediments, circulation, fresh water inflow, and many other natural processes.

The Upper Watershed

As described in Chapter Two, this book divides the Galveston Bay drainage into the lower and upper watersheds. The upper watershed includes the drainages upstream of two main reservoirs. Lake Houston on the San Jacinto was constructed in early 1954, and Lake Livingston on the Trinity was begun in 1966, but did not reach normal pool capacity until late 1971 (Rawson, 1979). A short description of the upper watershed is presented below.

Lake Houston Watershed

Lake Houston's total drainage area is 2,828 sq mi (1.81 million ac), with the West Fork of the San Jacinto River contributing over half of this area. Most of the area is forested (73 percent) with significant pasture land (14 percent; Newell, 1980). Precipitation averages 50 inches per year. One major reservoir, Lake Conroe, is found in the watershed above Lake Houston and drains a 445 sq mi area. Since 1970, intense urbanization along Cypress Creek and Spring Creek in the southern part of this watershed has impacted water quality in these streams and in Lake Houston.

Lake Houston was created in 1954 by construction of an earth-filled dam on the San Jacinto River, producing an initial storage capacity of about 146,800 ac-ft and a surface area of 12,765 ac. The typical annual runoff discharged from Lake Houston was estimated to be about 1.4 million ac-ft per year (Newell et al., 1992). The City of Houston and the San Jacinto River Authority remove between 200,000 and 300,000 ac-ft of water from the reservoir each year.

The annual sediment load to Lake Houston was estimated to be 160 million kilograms per year in 1980, with over 70 percent settling out in the lake during an average year (Baca et al., 1982). Trapping of nitrogen and phosphorus is variable, but generally lower than for sediment. However, during high flow periods, **residence times** are sufficiently small so that a washout effect occurs, moving sediment, nutrients, and algae towards the bay.

Trinity River Watershed/Lake Livingston

The 26,000 sq mi Trinity River watershed varies dramatically from Lake Livingston to the headwaters of the Trinity near Throckmorton County, Texas (see FIGURE 2.3). The Trinity River drops 1,215 feet from its source near Oklahoma to its mouth in Trinity Bay. Although the average rainfall is 36 inches, some of the upper parts of the watershed receive less than 30 inches of rain per year compared to close to 50 inches per year for the Lake Livingston area. Average annual runoff ranges from greater than 16 inches in the southern part of basin to less than four inches per

Source: Texas Sea Grant College Program

Hurricanes are a major influence on Texas estuaries and their associated human development. Here, Hurricane Gilbert crosses the Yucatan Peninsula on its way to the Gulf of Mexico. The inset shows damage from Hurricane Carla, one of the worst storms since the hurricane of 1900. The un-named hurricane of 1900 leveled Galveston Island and killed 6,000 residents.

year in the far northwestern portion of the watershed.

Rural portions of the Trinity basin support agricultural, rangeland, and forestry-based economies. Most of the forested areas are found in the river bottoms and in the lower, wet portion of the watershed, while rangeland is located in the arid northwestern region.

The Trinity River drains the entire Dallas/Fort Worth metroplex, which contributes significant amounts of urban runoff and wastewater discharges to the river. During recent years, improved sewage treatment in the Dallas/Fort Worth area has reduced biological oxygen demand and ammonia discharged to the Trinity River, (see Chapter Six for a definition of water quality terms). The total loading of phosphorus and nitrogen from point sources has remained the same despite improved treatment. Overall, conditions in the upper Trinity River itself have greatly improved in the last decade. Numbers and diversity of fish have increased and the incidence of so-called "black rise" events that robbed oxygen and killed fish has greatly declined.

Due to flood control, water supply, and recreational needs, numerous reservoirs have been constructed in the upper watershed (see FIGURE 2.3). These include Lake Worth, Lewisville Lake, Lake Ray Hubbard, Cedar Creek Reservoir, Richland-Chambers Reservoir, Benbrook Lake, and Lake Livingston. Twenty-nine major reservoirs identified by Stanley (1992) had a cumulative dead pool storage capacity of about eight million ac-ft, with Lake Livingston being the largest at 1,750,000 ac-ft. These reservoirs were all constructed between 1910 and 1987, with over 80 percent of the storage capacity being added in the 1950s and 1960s. Lake Livingston, which began impounding water in October of 1968 (Rawson, 1979), has a significant effect on water quality in the Trinity: most of the suspended solids carried by the river settle out in the lake, and about two-thirds of the phosphorus and one third of the nitrogen is removed (see Chapter Six).

The Lower Watershed

The lower watershed includes 4,238 sq mi of land downstream of Lake Livingston and Lake Houston. Major urban drainages within this area include the Houston Ship Channel-Buffalo Bayou system and its associated tributaries: White Oak Bayou, Brays Bayou, Sims Bayou, Hunting Bayou, and Greens Bayou in the Houston area. Significant rural watersheds include the lower Trinity River, Chocolate Bayou, and Austin/Bastrop Bayous. The proximity of these drainages to the coast and their predominantly urban character result in major direct effects on Galveston Bay. Overall, the most pressing management issues for Galveston Bay are seen to result from activities within its lower watershed. Below are presented several key aspects of the lower watershed which affect Galveston Bay.

Soils

Dark, fine-grained clays, locally termed "gumbo" predominate in the lower watershed. Other soils are comprised of clay loams and fine sandy loams that are also poorly drained and have low permeability. These soils exhibit very low **percolation rates** when wetted and have a very high runoff potential. A small section of more permeable sandy loams are found along the Trinity below Lake Livingston in Polk County. More detailed soils data are available from county soil maps prepared by the U.S. Soil Conservation Service.

Land Cover/Land Use

Using **LANDSAT** imagery from 1991, a land use/land cover map of the lower Galveston Bay watershed was prepared (FIGURE 5.2 and TABLE 5.1; Newell et al., 1992). Commercial areas, heavy industry, light industry, multi-family residential areas, high density single family residential areas, and transportation were included in the category of "high density urban" areas, while "residential" was comprised primarily of low density single family residential areas. Open/pasture areas corresponded to any open areas with a good grass cover. Generally, intense urbanization was focused in and around the ship channel, downtown Houston and Buffalo Bayou. Residential patterns extended northward to Cypress Creek, westward and northward past Addicks and Barker Reservoirs, and southward into Brays and Sims Bayous. Other high-intensity urbanized areas are located near Clear Creek and Clear Lake on the bay's western shore, and further south in the Texas City area and on Galveston Island.

The land use analysis revealed that land cover in the non-urban portion of the lower watershed consisted of roughly equivalent fractions of open/pasture, agriculture and forest. The bulk of the lower Trinity River basin (1,099 sq mi below Lake Livingston Dam) was forested and had large areas of open/pasture, agriculture and wetlands, especially near Trinity Bay. Much of Chambers County to the east was composed of wetlands, agriculture and open/pasture. The West Bay drainage area also consisted largely of open/pasture, wetlands and agriculture. The far western area (west of Addicks-Barker) consisted of mostly agricultural and open/pasture areas. More detailed information on land use and habitat distribution is provided in Chapters Six and Seven.

Lower Watershed Runoff

Precipitation which falls on the watershed and does not evaporate or infiltrate the soil becomes runoff. Runoff is important in influencing many conditions in the bay; for example nonpoint source pollution (discussed in Chapter Six) has emerged as a major management issue. Runoff varies significantly across the lower watershed and is usually controlled by land use and land cover. In the Brays Bayou watershed, for example, a runoff rate of about 1.6 **cubic feet per second** (cfs) per sq mi was observed, compared to about 0.7 cubic feet per second per sq mi for the rural and forested lower Trinity River watershed (1992 land uses for average year, Newell et al., 1992). The higher runoff is produced by impervious cover, i.e., areas with concrete, asphalt, roofs or other materials that prevent water from infiltrating into the soil.

The Galveston Bay National Estuary Program nonpoint source project performed hydrologic modeling of the lower water-

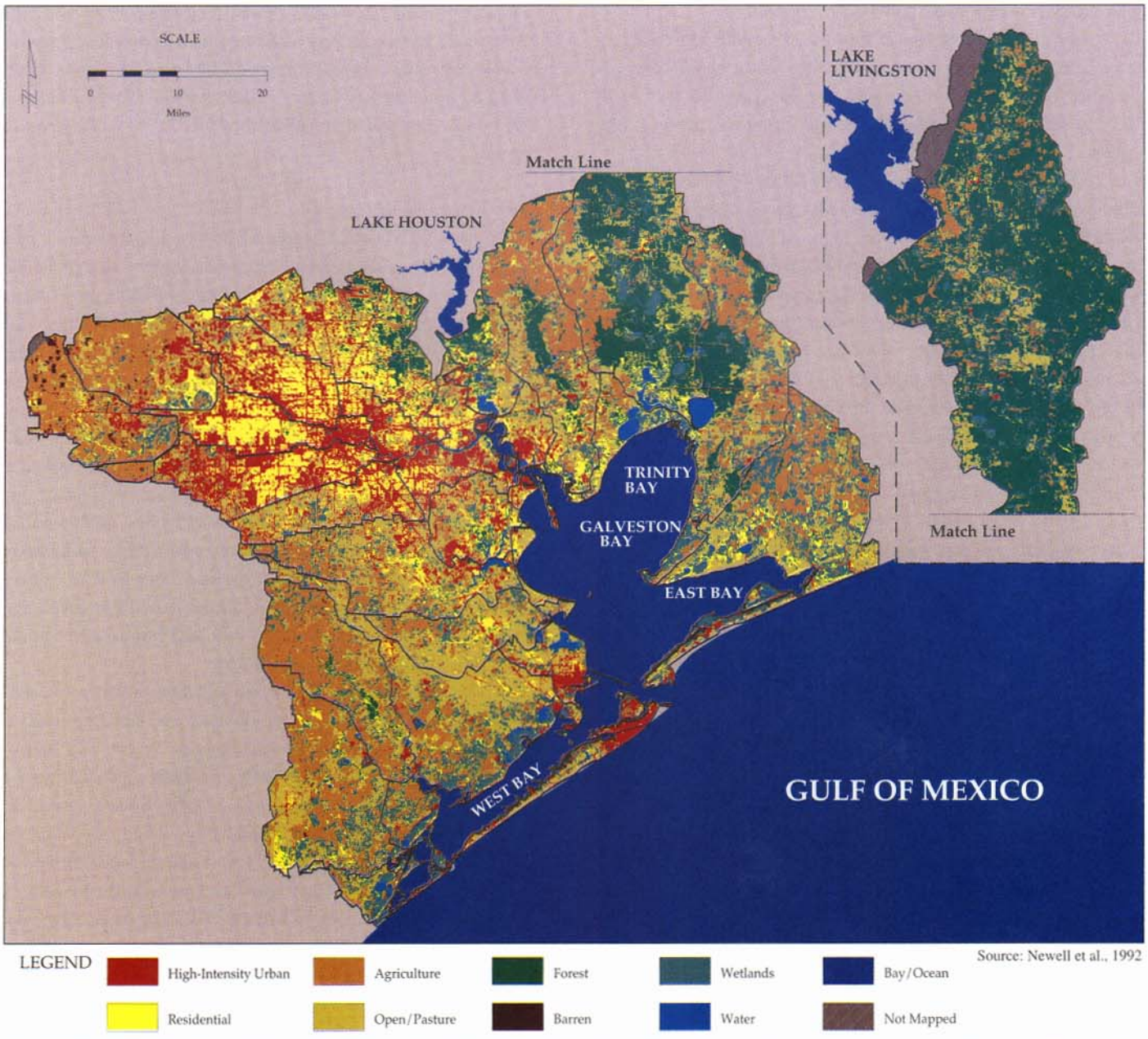


FIGURE 5.2. *Land use and watershed boundaries in the lower Galveston Bay watershed. Land use was classified by the digitizing of LANDSAT satellite imagery, achieving a resolution of 30 m by 30 m land areas. This map, one part of a larger geographic information system (GIS), serves as a tool for bay managers to address such issues as nonpoint source pollution (see Chapter Six).*

shed using a **geographic information system** and land use/cover data from satellite imagery (Newell et al., 1992). This model simulated the conversion of rainfall to runoff for 100 **subwatersheds** draining to the bay. Under average rainfall conditions, the model predicted that about three million ac-ft of runoff would be generated annually from the lower watershed. This corresponds to 13 inches of runoff and about one-quarter to one-third of the total average fresh water inflow to Galveston Bay. The runoff contribution from different land uses is shown in TABLE 5.2.

These runoff estimations revealed that urban land uses contributed a disproportionate volume of runoff compared to the relative amount of urbanized land in the area. The watersheds in the Houston metropolitan region accounted for 34 percent of the total runoff from the lower watershed but constituted only 25 percent of the area. This corresponds to about nine percent of the total fresh water inflow to the bay during an average year. These urban watersheds include Buffalo, Brays, White Oak, and Sims Bayous, Barker and Addicks Reservoirs, and the Houston Ship Channel. FIGURE 5.3 shows the distribution of runoff from different areas in the lower watershed.

During extremely wet years, much more local runoff flows into the bay than during an average year. For example, for a wet year that occurs on the average once every ten years (about 67 inches of rain), local runoff was predicted to increase to 4.8 million ac-ft, equivalent to a 60 percent increase in runoff over the average year.

THE BAY-WATERSHED LINK: FRESH WATER INFLOW

Among the most important factors governing the health of an estuary is the volume, timing, and quality of fresh water inflows (Solis and Longley, 1993). This inflow, as it interacts with (and helps determine) bay circulation patterns, ultimately defines the estuarine salinity regime. The salinity regime, in any estuary, influences important aspects of species biology, habitat structure, and overall productivity. Alteration of the natural volume and timing of fresh water inflow is a key concern for managers. Sources of data used in this chapter to determine inflow and evaluate management needs are described in the box above.

SOURCES OF INFLOW DATA: JOINT AGENCY STUDIES

A variety of agencies and programs provide data necessary to evaluate and manage fresh water inflow. Foremost among these is an ongoing evaluation of the fresh water inflow needs for Texas bays being conducted jointly by the Texas Water Development Board, Texas Parks and Wildlife Department, and Texas Natural Resource Conservation Commission.

This joint agency analysis utilizes a fresh water inflow model that identifies optimal salinities for several key estuarine species. The Texas Parks and Wildlife Department also utilizes results from the model to determine the effects of various salinity regimes on bay habitats like fringing marshes. The model utilizes flow data from three main basins (Solis and Longley, 1993): 1) the Trinity River Basin; 2) the San Jacinto River Basin; and 3) the coastal basins. Geographically, these watersheds are defined slightly differently than in this book.

Particular data sources are utilized in the joint agency process. The U. S. Geological Survey maintains flow gauging stations at several streams and rivers that flow into Galveston Bay. These stations consist of water level recorders that convert stage (water depth) into discharge information (flow rate), and are placed at stable channel locations upstream of tidal influences. Both of the large upper watersheds have stream gauges, providing flow information at the Lake Houston dam and at the Trinity River at Rayomar, downstream of Lake Livingston. (Measurements for flow over the Lake Houston dam are based on a 1965 stage-discharge relationship that has not been corrected for subsidence, therefore decreasing the accuracy of these flow measurements.)

The gauges on the Trinity and San Jacinto rivers represent over 85 percent of the total watershed area draining into Galveston Bay. In addition, several local streams have gauges, including: Brays Bayou near Main Street, Buffalo Bayou near Shepherd Drive, Cedar Bayou, Chocolate Bayou, Clear Creek, Greens Bayou, Halls Bayou, Sims Bayou, and White Oak Bayou. However, because of the need to place gauges upstream from the influence of tides, more than two thirds of the 4,238 sq mi lower watershed is ungauged. Therefore, ungauged runoff must be estimated utilizing an estimation procedure.

Fresh Water Inflow Patterns

For the period 1941 to 1987, the average fresh water inflow to the Galveston Bay system was 10.1 million ac-ft per year, or about 4.6 complete **flushes** of the bay. The Trinity River basin was responsible for 54 percent of the total inflow while the San Jacinto basin (including areas below Lake Houston) contributed 28 percent. The total inflow from all three sources vs. time was quite variable, as shown by a plot of monthly inflow vs. time (FIGURE 5.4a). The daily flow of the Trinity River can range from 100 to over 100,000 cubic feet per second.

One source of variability in flow volume is year-to-year changes in rainfall. The effects of droughts and wet periods can be seen in FIGURE 5.4a, where the severe drought in the 1950s and wet periods in the mid 1940s and early 1970s are apparent. For the period 1941 to 1976, the peak annual inflow was 24 million ac-ft in 1973 and the minimum was 2.9 million ac-ft in 1956 (Texas Department of Water Resources, 1981). When one accounts for evaporation losses, the inflow extremes diverge even further: the net inflow (inflow minus evaporation) was 23 million vs. 1.3 million ac-ft for a flood year (1973) vs. a drought year (1956), respectively. Annual average evaporation from the bay is estimated to be approximately 1.4 million ac-ft per year (Texas Department of Water Resources, 1981).

A second source of inflow variability is seasonal. As shown by monthly data from 1977 to 1987, there is a distinct seasonal trend with peak inflows in May-June and low-flow conditions in August, primarily a result of the Trinity River's influence (FIGURE 5.5). The average total bay inflow (indicated by an open circle in FIGURE 5.5b) for May is 1.5 million ac-ft, almost four times the average of 0.4 million ac-ft discharge during August. The peak monthly flow is over five million ac-ft, about two complete flushings of the Galveston Bay system, while some months have had almost no fresh water inflow at all.

Ward and Armstrong (1992) conducted a study of seasonal flow patterns, specifically the spring **freshet** (a large inflow of fresh water into the bay) 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 gauge were analyzed for the years 1920 to 1990. Again, the year-to-year variability was the most important feature of the data. Some years had a strong freshet, while during others the freshet was nonexistent. The low-flow season is sometimes interrupted by large fresh water inflows, while other years it extends for long periods of time and inflow drops 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 annual flow of the Trinity River. A statistical analysis of freshet data indicates some periodicity in the data on cycles of about four years and 14 years.

TABLE 5.1. Watershed Land Use.

Watershed	Land Use by Watershed (sq mi)									
	High Density	Residential	Open/ Pasture	Agricultural	Barren	Wetlands	Water	Forest	Total	% of Total
Addicks Reservoir	13	9	32	66	3	10		1	134	3
Armand/Taylor	15	10	28	10	0	9	1	3	77	2
Barker Reservoir	7	4	23	65	8	13			122	3
Bastrop/Austin	6	13	58	88	1	42	2	3	213	5
Brays Bayou	53	27	26	16	1	4			127	3
Buffalo Bayou	39	32	15	14	0	4		1	105	2
Cedar Bayou	8	18	50	80	1	31	1	24	211	5
Chocolate Bayou	4	6	32	95	1	26	1	5	170	4
Clear Creek	20	15	67	44	1	28	3	3	182	4
Dickinson Bayou	5	9	45	20	0	19	1	1	101	2
East Bay	10	28	72	73	0	89	6	8	288	7
Green's Bayou	37	52	54	18	1	14		31	208	5
North Bay	6	5	9	1	0	2		1	25	1
San Jacinto	5	11	17	8	0	8	4	15	68	2
Ship Channel	56	31	42	15	1	13	4	4	166	4
Sims Bayou	23	15	34	11	0	8		1	93	2
South Bay	25	6	22	7	0	12	6		78	2
Trinity Bay	6	19	69	79	0	67	14	62	317	7
Trinity River	11	34	135	145	2	151	7	613	1,099	26
West Bay	30	22	105	79	1	94	11	2	344	8
White Oak Bayou	39	32	25	10	1	3			110	3
Total (sq mi)	418	400	962	947	22	648	62	779	4,238	100
% of Total	10	9	23	22	1	15	1	18	100	

Source: Newell et al., 1992

Human Alterations

A significant preliminary conclusion from the ongoing joint agency inflow study is that there has been no statistically significant alteration in total annual fresh water inflows to Galveston Bay in recent years compared to previous years (Solis and Longley, 1993). No long term inflow trends, either decreasing or increasing, were observed for total inflow to Galveston Bay, nor for the Trinity River for the period 1941 to 1987.

Change in Seasonal Inflow from Reservoirs

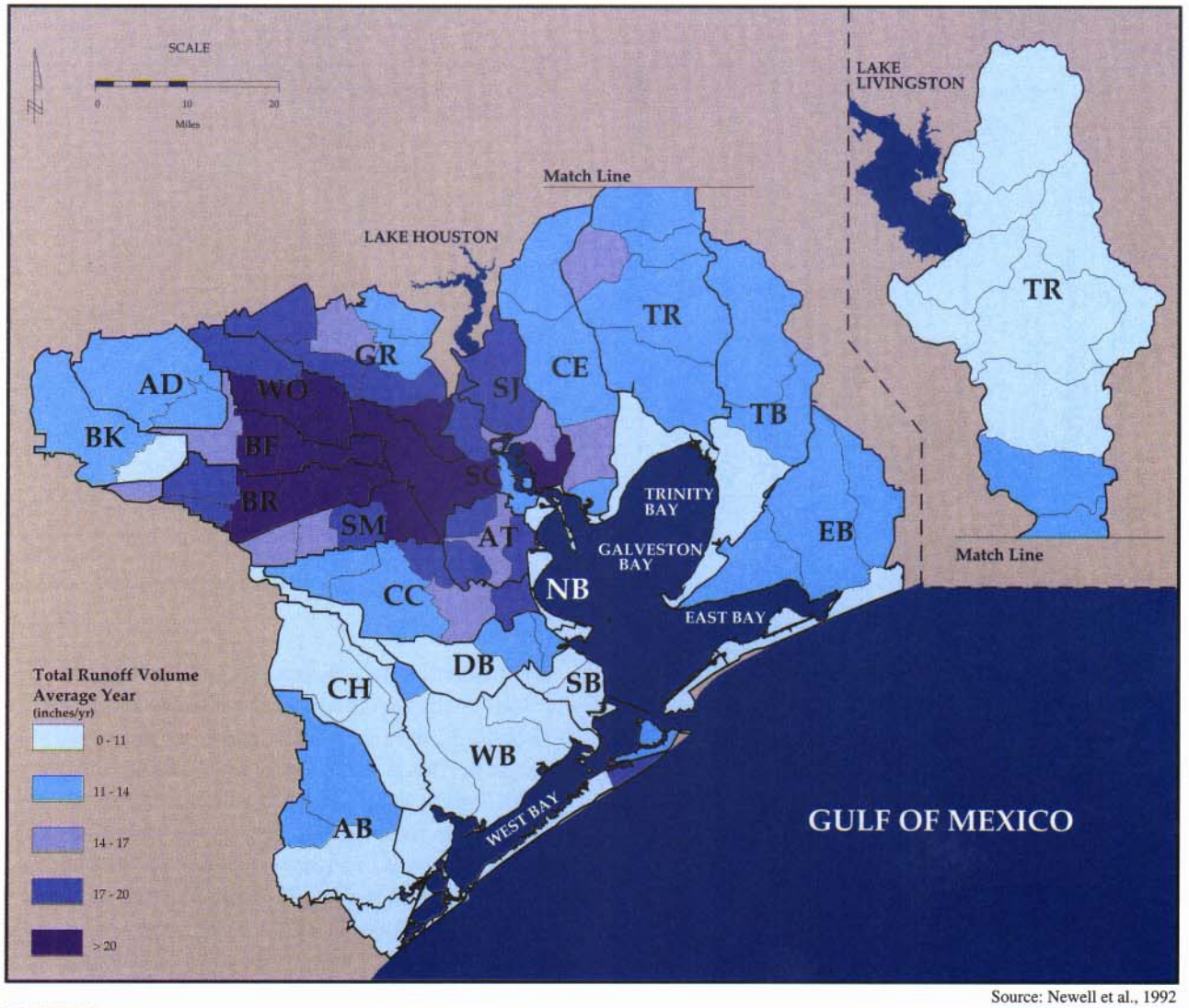
For Galveston Bay, changes in inflow timing have been postulated from the construction of Lake Houston, Lake Conroe, and Lake Livingston. FIGURE 5.6 indicates that any effects of reservoirs are likely to involve a reduction and time delay in the seasonal peak and an increase in the seasonal low flow, caused by the timing of reservoir releases and base flow alterations.

Estimates vary concerning the degree to which inflow alterations have occurred. Somewhat surprisingly, Solis and Longley (1993) report that the seasonal variation in fresh water inflows has "remained nearly constant." They compared monthly flows before and after the construction of Lake Livingston and showed 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. This would be a likely result of operation of the reservoir to capture water during floods and release it during subsequent lower flow periods. The highest summer low-flow volume occurred in 1940, 1957, and 1973, while the lowest summer low-flow period occurred in 1956. Additional work is

TABLE 5.2. Runoff Volume by Land UseType in the Lower Galveston Bay Watershed (Average Year).

Land Use Type	Runoff Volume (1000s ac-ft)	Runoff Volume (% of Total)
High Density Urban	766	25
Residential	371	12
Open	567	19
Agriculture	593	20
Barren	21	1
Wetlands	187	6
Water	164	5
Forest	345	11
Total	**3,014**	**100**

Source: Newell et al., 1992



Source: Newell et al., 1992

LEGEND

AB Austin/Bastrop Bayou	CC Clear Creek	GR Greens Bayou	SM Sims Bayou
AD Addicks Reservoir	CE Cedar Bayou	NB North Bay	TB Trinity Bay
AT Armand/Taylor Bayou	CH Chocolate Bayou	SB South Bay	TR Trinity River
BF Buffalo Bayou	DB Dickinson Bayou	SC Ship Channel	WB West Bay
BK Barker Reservoir	EB East Bay	SJ San Jacinto River	WO White Oak Bayou
BR Brays Bayou			

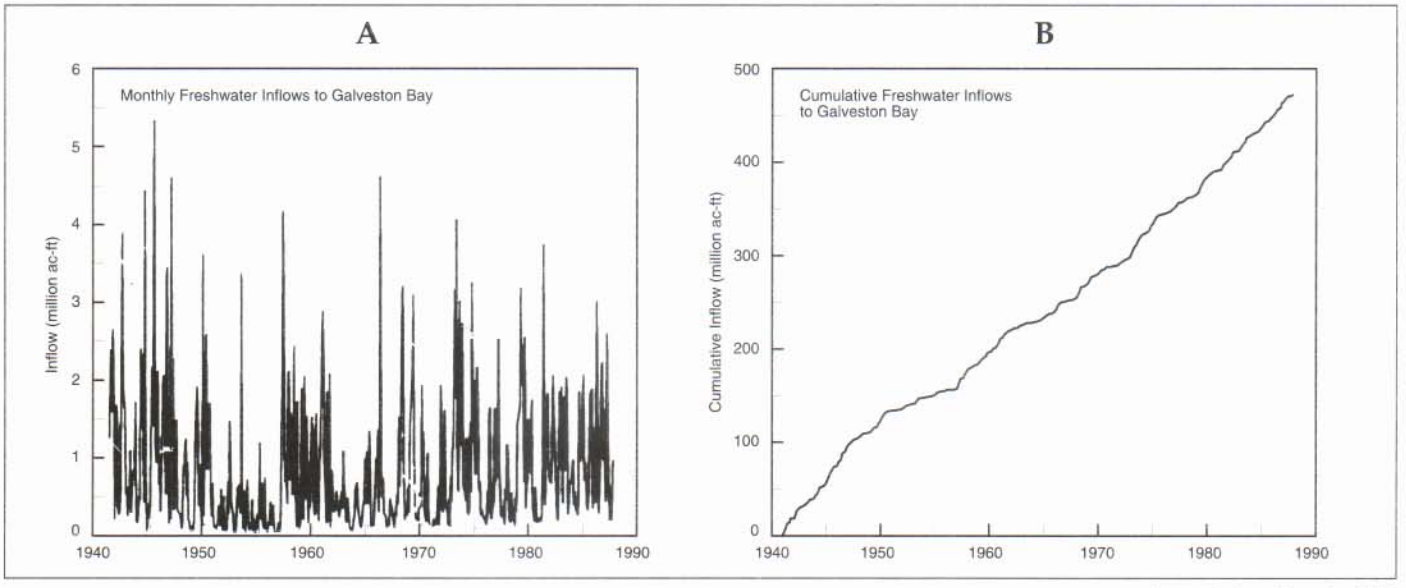
FIGURE 5.3. *Total runoff volume from the lower Galveston Bay watershed in an average year. Urbanized regions contribute the largest amounts of runoff reaching the bay as a result of their impervious concrete and asphalt surfaces and roofs. The runoff from urban areas greatly increases in wet years; a 30 percent increase in average annual rainfall results in about a 60 percent increase in runoff. The urban runoff is also much more polluted than rural runoff in this area, contributing to the bay's nonpoint source pollution problems.*

required to interpret the overall trend in summer drought flows to Galveston Bay.

Urban Base Flows

Several flow gauges have measured increasing **base flow** to Galveston Bay from urbanized subwatersheds, primarily due to return flow from treated wastewater. Brays Bayou at Main Street, for example, now shows a base flow component of over 6,000 ac-ft per year (approximately six to ten cfs), compared to no permanent baseflow prior to 1955 (FIGURE 5.7). This corresponds to a wastewater return flow produced by a population of around 25,000 people, mainly from the City of Houston Southwest Plant. A similar trend has been observed in several other urbanized bayous in the Houston area, most of which discharge into the Houston Ship Channel.

Overall, the effects of municipal and industrial return flows can be an important component of summer drought flows. For example, process wastewater return flows around the bay were approximately 690,000 ac-ft per year in 1990 (Pacheco et al., 1990). This corresponds to a 230,000 ac-ft flow during the four-month annual summer drought (assuming the wastewater volume is seasonally constant). This is about 20 percent of the average annual

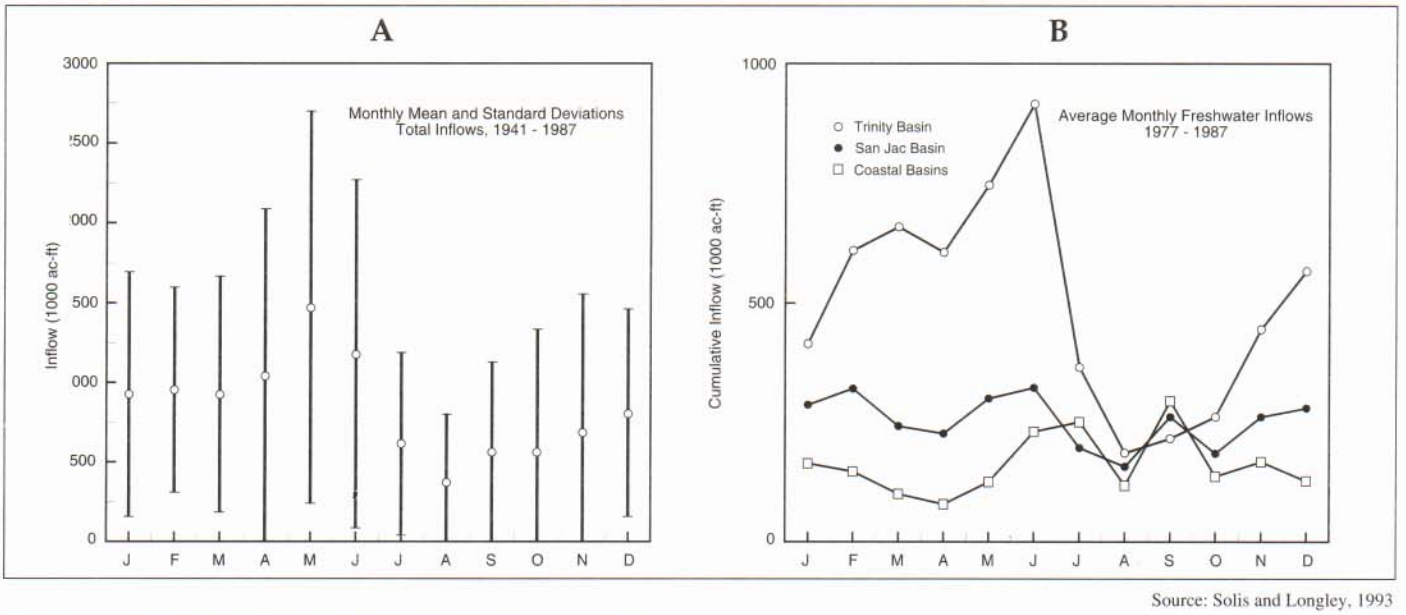


Source: Solis and Longley, 1993

FIGURE 5.4. *Long term fresh water inflow to Galveston Bay from all sources, monthly (a) and cumulative (b). Inflow is highly variable, both seasonally and in response to the effects of floods and droughts.*

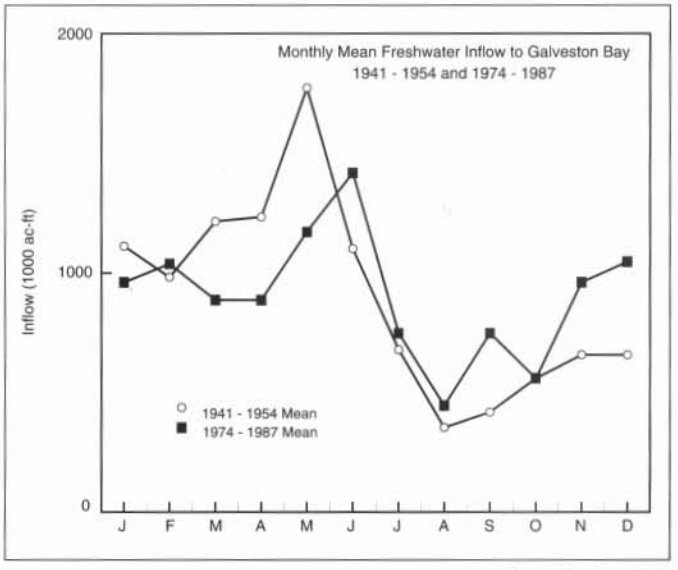
summer drought flow and roughly equivalent to some of the lowest-flow summer droughts on record. While much of this return flow originates as water supply from Lake Livingston and Lake Houston, some fraction is groundwater acquired for the drinking water supply and discharged as treated wastewater. This wastewater represents an external source of fresh water to Galveston Bay. Note that most of this wastewater returns to the bay via the Houston Ship Channel, making the Ship Channel a larger source of fresh water inflow to the bay during extreme low-flow conditions than historically occurred.

Two proposed water supply projects have the potential to alter fresh water inflow patterns to Galveston Bay. The Wallisville Project is a reservoir on the lower Trinity River near Interstate Highway 10, designed for water supply and as a barrier to saltwater intrusion. This project would divert Trinity River water westward to the Houston metropolitan region. Some diverted water would be lost through yard watering, process use, and distribution losses, while some would be returned to the bay via wastewater treatment plants. A second project (the Texas Water Development Board's "Trans-Texas Project") would divert water westward from the Sabine River basin. This would result in additional fresh water brought to Galveston Bay from outside the watershed, for a net



Source: Solis and Longley, 1993

FIGURE 5.5. *Seasonality of fresh water inflows to Galveston Bay. Monthly means and standard deviations are given in (a) for all inflow sources, while monthly means only are shown separately for the Trinity, San Jacinto, and Coastal Basin sources in (b). The Trinity River (supplying 54 percent of total inflow) drives the May-June peak and August low flow. (A) is a long-term analysis, while (b) corresponds to the period following construction of major reservoirs.*



Source: Solis and Longley, 1993

FIGURE 5.6. *Comparison of monthly fresh water inflow before (1941-1954) and after (1974-1987) construction of Lake Livingston on the Trinity River. Apparent is the seasonal variation in inflow corresponding to rainfall patterns. The effect of the reservoir has not been statistically verified, but may delay the spring inflow peak and increase the seasonal low flow, dampening the seasonal inflow signature.*

increase in inflow. Conceivably, the Trans-Texas Project could reduce the reliance of Houston on water from the Wallisville Project.

CIRCULATION

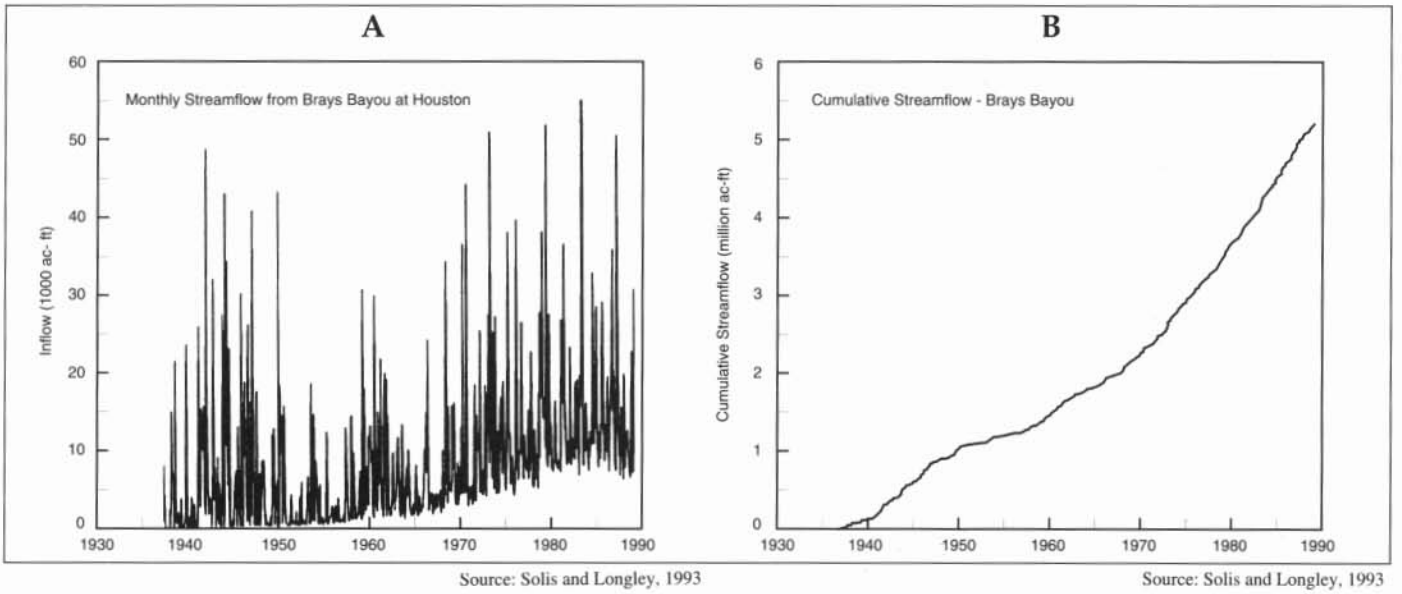
The circulation of water in Galveston Bay is influenced by many bay features, including depth patterns, winds, tides, and fresh water inflow. In turn, circulation is a major force affecting the distribution of sediments and the location of oyster reefs and other habitat elements. When compared to other estuaries, Galveston Bay is affected much more by winds and less by tides than east and west coast bays. Its overall shallow nature has resulted in channel dredging for navigation, with corresponding significant influences on circulation.

The Influence of Bathymetry

Bathymetry refers to patterns in water depth–an obvious concern to those who use the bay for marine transportation (FIGURE 5.8). The central areas of the bay system are typically less than 12 feet deep (excluding channels). Trinity Bay averages about eight feet deep, East Bay ranges from four to eight feet deep, and most of West Bay is four to six feet deep. Surrounding the main bay complex are even shallower secondary and tertiary bays such as Chocolate, Bastrop, Jones, Dickinson, Dollar, and Tabbs bays, and Clear Lake and Moses Lake (White et al., 1985; see FIGURE 2.1). Most of these shallow bays are less than four feet deep. Shallow reefs, such as Redfish Bar described in the quote at the beginning of the chapter, are produced by oysters and subsequent trapping of sand. The total bay volume is 2.2 million ac-ft or 3.6 billion cubic yards (National Ocean Service, 1985).

The deepest part of the bay system is in Bolivar Roads, which has a 50-ft scour hole caused by tidal currents between the bay and the gulf. Off the Gulf Coast, the continental shelf is relatively steep for the first mile, sloping 24 feet per mile. After the first mile the slope lessens to become one to two ft per mile at a point ten miles from shore. The edge of the continental shelf is found approximately 80 to 90 miles off of Galveston Island.

Several man-made navigation channels have been cut into the bay to provide deeper water for maritime traffic. In Galveston Bay, the 40-ft deep Houston Ship Channel cuts northward across the bay to the mouth of the San Jacinto River, then extends up Buffalo Bayou to the Turning Basin. The Gulf Intracoastal Waterway runs parallel to the coast, bypassing East Bay by travers-



Source: Solis and Longley, 1993

Source: Solis and Longley, 1993

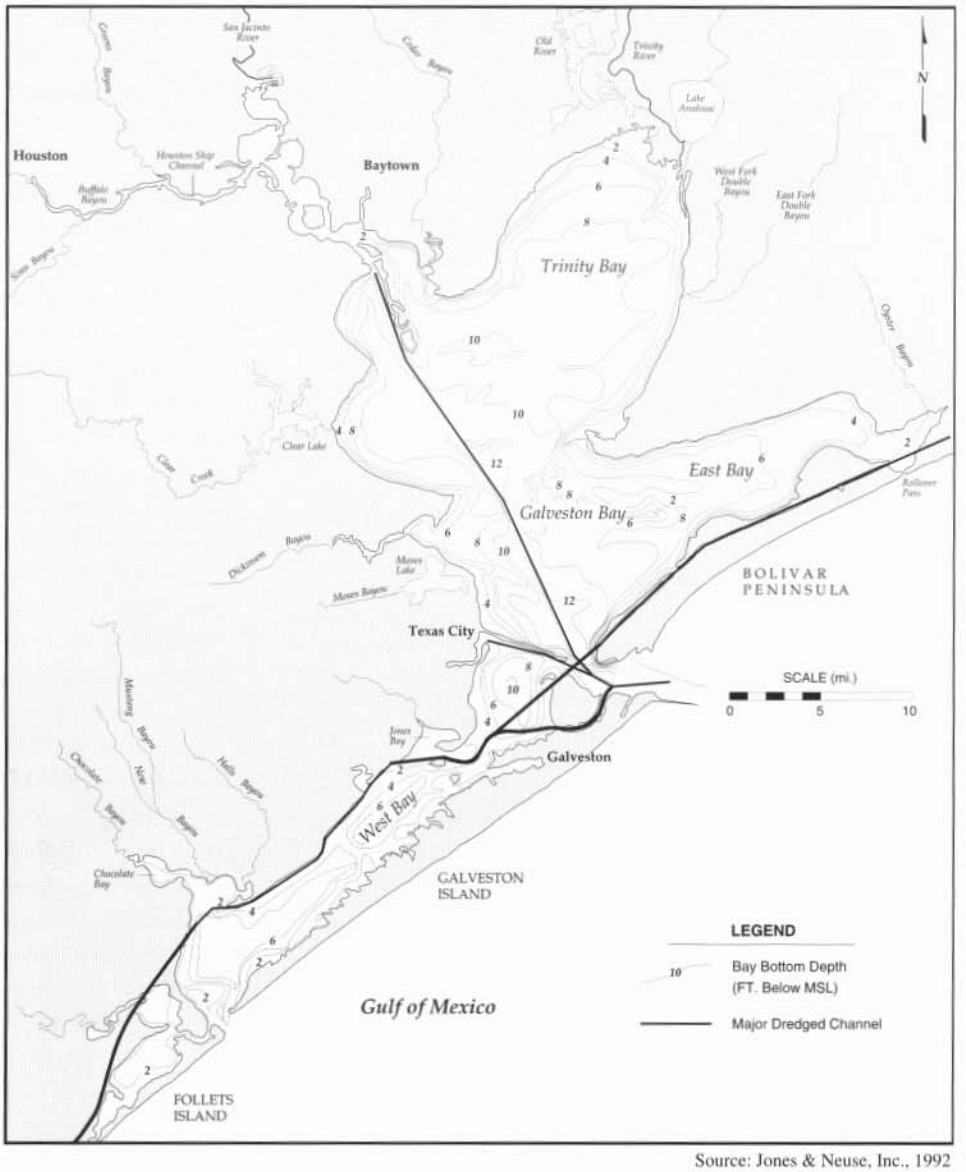
FIGURE 5.7. *Growth of base flow due to wastewater return flow to Brays Bayou. In this intensely urbanized watershed, increases in return flows from human uses contribute to an elevated seasonal low flow compared to historical levels.*

ing the entire length of Bolivar Peninsula inland, crossing lower Galveston Bay and western West Bay, continuing inland from Jones Bay to Chocolate Bay, and then inland to the southwest. The Waterway passes immediately to the north of Bastrop, Christmas, and Drum Bays. A number of smaller channels have also been dredged in other parts of the bay.

Bay Sediments

Sediments are delivered to the bay from several sources, including rivers, erosion of bay margins, gulf sediments transported through the passes, and sediments created by oysters and other hard-shelled organisms. The entrance to Galveston Bay is in the plume of the Mississippi River, transported to the southwest by longshore currents.

The bay bottom is formed from the interaction of the various sediment sources and physical processes, including currents and wave energy (FIGURE 5.9). Areas with high wave and current energy deposit mainly coarse-grained sediments (sand, gravel, and shell), since fine-grained material (mud and silt) are kept in suspension. The result is often a beach or bar composed of shell hash or sand. High energy areas include the Trinity River delta front (along the eastern shore of Trinity Bay) and lower Galveston Bay near Bolivar Roads. Low-energy areas with relatively quiet waters are marked by deposits of fine-grained materials such as muds, silts, and clays. Low-energy areas include the northwestern part of Galveston Bay, the center of Trinity Bay, and sections of East Bay. Overall, the predominant sediment types in the bay are fine-grained: mud, muddy sand, and sandy mud (White et al., 1985).



Source: Jones & Neuse, Inc., 1992

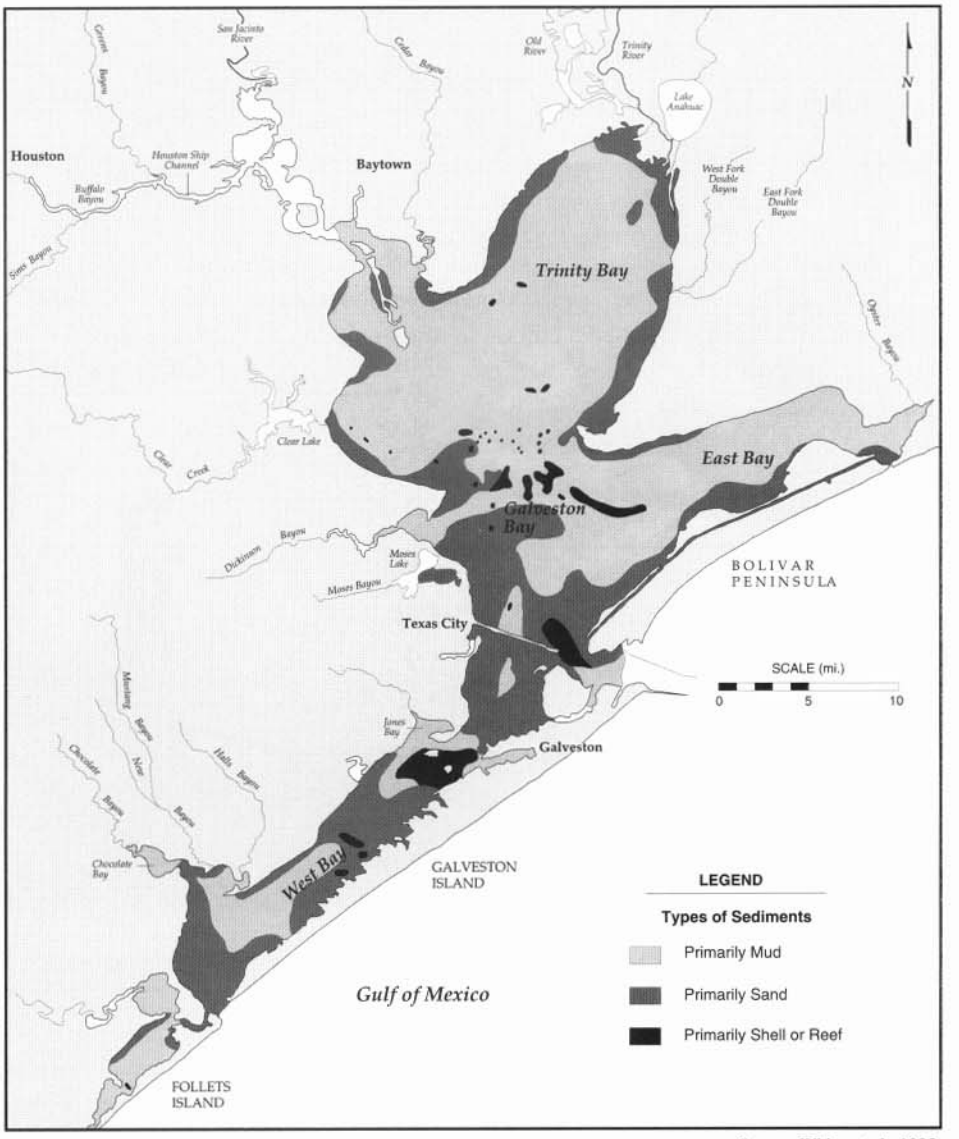
FIGURE 5.8. *Bathymetry–the depth patterns in Galveston Bay. Like other Gulf estuaries, Galveston Bay is quite shallow, affecting human navigation activity and natural patterns in circulation and water quality. Total bay volume is 2.2 million acre-ft or 3.6 billion cubic yards.*

Other factors affect circulation and sediment distribution patterns, locally forming a patchwork-like appearance of different sediments on the bay floor. Some major influences on sediments in particular parts of the bay are: 1) oyster reefs; 2) relict barrier islands and deltas established during the period before the sea level drop 30,000 years ago; 3) dredged material islands; and 4) the effect of sand sources from Bolivar Peninsula and Galveston Island on water flow. Extreme currents during large storms and hurricanes also transport sediments across the barriers into washover areas along Galveston Island, Follets Island, and Bolivar Peninsula. Far more sediment is transported during the infrequent but intense storm events than occurs under normally conditions.

Oyster Reefs

Oyster reefs are a primary geologic feature of Galveston Bay and are present on over 26,700 ac of the bay bottom (Powell et al., 1994; see FIGURE 7.8). These reefs are an important habitat, and significantly affect bay circulation. Oyster reef formation and distribution is very sensitive to long-term natural variations in salinity, and to man-made changes to the estuary which affect currents, the mixing of river and sea water, and the availability of hard substrates to which oysters can attach. The overall man-made changes to the bay's circulation have resulted in significant increases in the overall area of reef and their locations in recent decades. Specific actions in certain places have produced negative effects as well (for example the effect of Texas City Dike on West Bay oysters, described in Chapter Eight).

On a longer time scale of about a century, major changes have also occurred in the distribution of oyster reefs. The most noteworthy of the historical reefs was Redfish Bar, which extended from Eagle Point to Smith Point and appeared as a series of small islands across the narrow portion of the central bay system (see FIGURE 2.1). Work on breaching this navigation barrier began in 1872 and, subsequently, parts of the bar moved south or disappeared for reasons that cannot be verified. Anecdotes from early bay residents refer to cattle drives across the bar, and charts as late as 1927 show this bar with only three narrow, shallow passes (including the Houston Ship Channel). Early scientific descriptions indicate that this barrier reef was a significant impediment to water flow, dividing the bay into an upper, fresh region and a lower, more marine portion (Burr, 1929).



Source: White, et al., 1985

FIGURE 5.9. *Sediment texture in Galveston Bay. Compared to other U.S. estuaries, sediments tend to be fine-grained. The Mississippi River plume flows southward along the Texas coast, transporting fine clay, while landward coastal plain clays are eroded and transported seaward to the bay. Coarser sands and shell hash are deposited in areas of high wave and current energy.*

Wind Forces

Winds affect Galveston Bay circulation in three ways: the development of windwaves, the generation of internal wind-driven circulation, and large-scale excursions in water level (Ward, 1991). Windwaves from the prevailing southeasterly winds subject the northwestern part of the bay to persistent wave and current erosion (Fisher et al., 1972). The bluffs near La Porte, Seabrook, and the Trinity River delta have all been influenced by these waves. Windwaves are also responsible for the intense vertical mixing that characterizes Galveston Bay and in part for the usual absence of **stratification** (separation of layers of different salinity) in the shallow parts of the system.

The most dramatic effect of winds is **denivellation,** or changes in water level in the bay caused by the force of the wind (Ward, 1991). That is, water "piles up" on the windward shores as depth decreases in leeward areas. Part of this is due to wind effects on the Gulf of Mexico, where there is a general seasonal shift in the level of the gulf due largely to prevailing winds, with highs in spring and fall, and lows in winter and summer (Chew, 1964). The overall change from the Gulf of Mexico sea level variation is on the order of one foot.

The most important depth changes caused by wind are the effects of northern cold fronts on bay water levels. These fronts bring about an abrupt change in wind direction and barometric pressure and can reduce water levels in the bay, obliterating tidal effects (Ward, 1991). As a "norther" passes through the bay, water levels that increased during the approach of the front are lowered by the increased barometric pressures after frontal passage. Powerful north winds often lower the water surface in the upper bay and tilt the water surface upward against the north-facing shore of the barrier beach. In the upper bay, these changes in water level can exceed over three feet in a few hours. Field data collected by the Corps of Engineers in the 1930s and analyzed by Ward (1991) show the dramatic effect of northers on the bay. 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.

Tidal Forces

The tides in Galveston Bay are relatively weak, with the tide gauge in the Galveston Channel showing a mean annual tide range

Source: Galveston Bay National Estuary Program

San Luis Pass is one of only two remaining natural inlets along the Texas coast. The natural tidal gorge is visible as the dark area on the left side of the inlet with numerous sand waves and bars visible inside the inlet. The bar structures are the product of the interaction between natural currents and the sand they carry in suspention. All of these sedimentary features are eliminated when an inlet is "stabilized" for navigation.

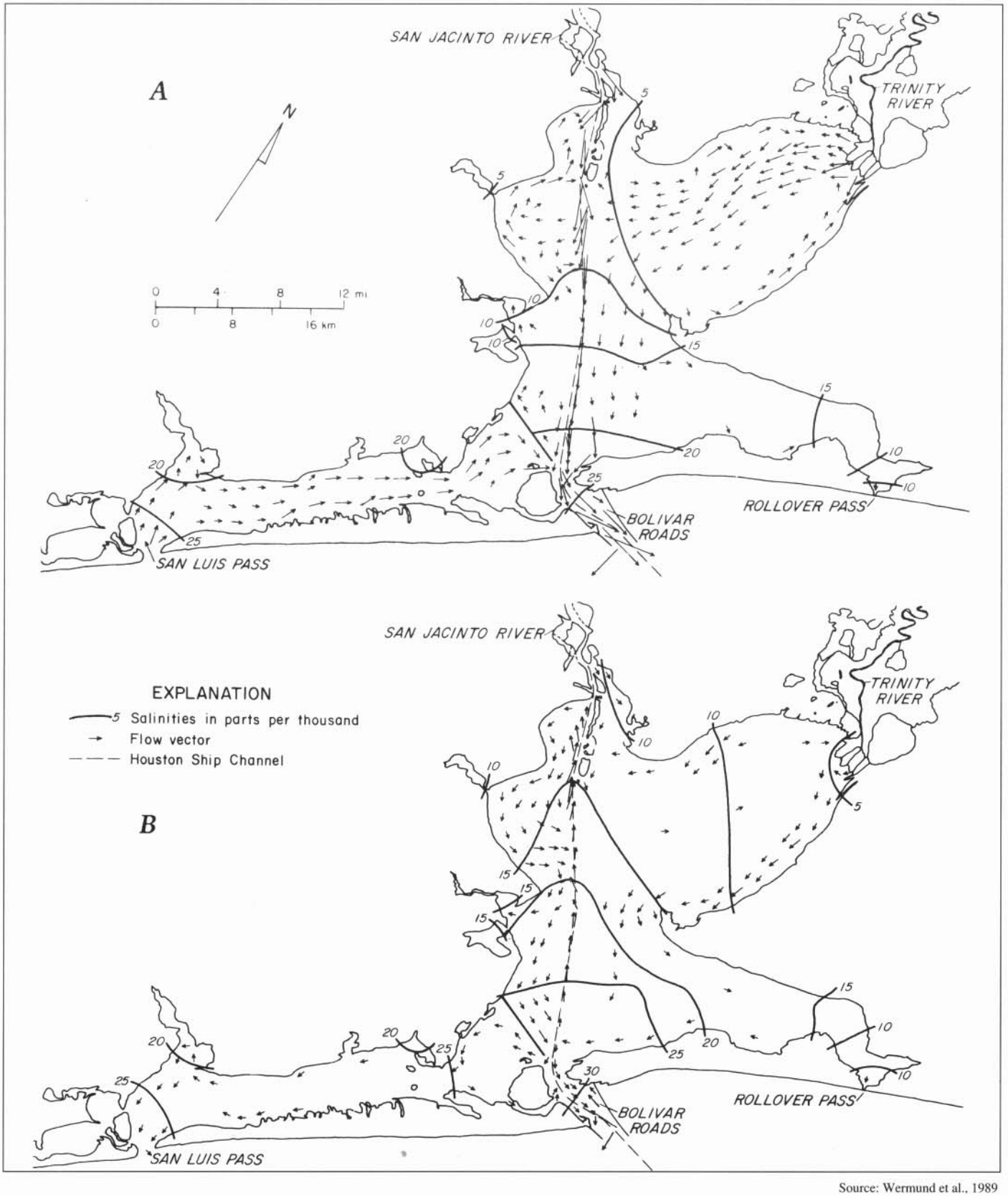
of 2.1 feet. In addition, the tide dissipates rapidly within Galveston Bay, losing approximately 30-40 percent of its range across the Bolivar Roads inlet (Ward, 1991). At the Texas City Dike, the tide has lost approximately 60 percent of its Gulf range. Tides do not dominate Galveston Bay; winds and atmospheric pressure frequently disrupt the astronomical tidal cycles.

The tide is composed of two "modes," a **diurnal** (one cycle per day) and a **semi-diurnal** (two cycles per day). Which mode dominates depends primarily upon the elevation of the moon above the horizon. The usual tide is a mixture of these two types, containing both diurnal and semi-diurnal components in varying proportions. The tidal sequence of diurnal plus semi-diurnal tides is approximately 14 days long. However, this theoretical pattern can be obscured by local variability in tidal dynamics. The interaction of numerous complex factors like land mass location, meteorology, and **coriolis force** (from the earth's rotation) all play a role.

Within Galveston Bay, diurnal-dominated tides have the greatest range between high and low tide, on the order of three feet at the Gulf but less than one-third of this in the upper bay. Semi-diurnal dominated tides, however, exhibit a higher mean tide level than diurnal-dominated tides. Thus, semi-diurnal tides hold more water in the bay. At times, Redfish Reef (stretching across the bay from Eagle Point to Smith Point) can eliminate the smaller semi-diurnal tide so that the lower bay experiences two tides while the upper bay has only one.

The tides are important forces in transporting water in and out through the inlets to the Gulf of Mexico. The inlets vary greatly in transport volume: in general about 80 percent of the tidal exchange in Galveston Bay occurs through Bolivar Roads, and less than 20 percent through San Luis Pass. The contribution of Rollover Pass (an artificial opening built in 1950) is relatively minor, as a submerged weir was installed to prevent excessive erosion.

The most detailed study of tides was conducted by the Corps of Engineers in 1936-1937. Although much valuable raw data were lost, Ward (1991) analyzed remaining information and estimated several **tidal prisms**. (A tidal prism is roughly the amount of water passed through a part of the bay during a tidal cycle). For a great declination tide (two strong tidal cycles per day) the tidal prism to the bay was about 250,000 ac-ft of water. At low declination tides (one weaker tidal cycle per day) the tidal prism was approximately 75,000 ac-ft. Selected tidal prisms for specific areas calculated by Ward, provided in TABLE 5.3, show roughly how much water is moved through different parts of the bay by tides.



Source: Wermund et al., 1989

FIGURE 5.10. *Net current flow in Galveston Bay under May high flow (a) and August low flow (b) conditions. Salinity, fresh water inflow, and current dynamics are all closely coupled in this system. Salt water intrudes up the Houston Ship Channel during low flow and reverses during greater river discharge, affecting current directions and magnitudes throughout the system. Note that the net flow shown does not illustrate the high variability that actually occurs under both low flow and high flow regimes.*

Note that East Bay receives considerably more tidal influence than the eastern portion of West Bay. This is probably caused by the influence of the Texas City Dike, as described later in this chapter.

Effects on Salinity

The average annual fresh water inflow to the bay of some 10.1 million ac-ft is equivalent to 4.6 total "flushes" of the bay during an average year. During the spring, the bay is flushed approximately twice, while an average summer low-flow period may flush less than 75 percent of the bay's volume. During extreme flood periods, the volume of fresh water inflow in one month can approach the entire volume of the bay. As would be expected, fresh water inflow is one of the most important factors controlling circulation and salinity in Galveston Bay.

In Galveston Bay, salinity averages around 17 ppt (parts per thousand), or about half the salinity of seawater. However, the salinity range is approximately six to 28 ppt and is highly variable both in time and space due to the effects of fresh water inflow, winds and tides. The dominant time scale over which salinity varies in the bay is seasonal. However, other events such as freshets, northers, and the salinity of the Gulf of Mexico greatly influence salinity in the bay on different time scales (Orlando et al., 1991). In addition, circulation and salinity patterns are also influenced by **density currents** (caused by heavier salt water displacing lighter fresh water), the Houston Ship Channel, two large power generating stations on the bay, and the Texas City Dike.

Salinity-induced density currents are an important process in Galveston Bay and, in total, have about the same magnitude as the average river flow in the mid-bay (Ward, 1991). The first type of density current is vertical, where salt water in the deeper channels intrudes along the bottom, displacing fresh water masses seaward at the surface. At slack tide, vertical density currents can sometimes be visually observed in the deeper part of the Ship Channel. Horizontal density currents are also observed in the bay, where salt water moves up the Ship Channel and fresher return flow in the opposite direction occurs in the shallow open bay on either side. Near the Texas City Dike and Bolivar Peninsula, the currents from each side of the channel converge and create a zone of high lateral shear on either side of the Channel that can be observed in aerial photos.

TABLE 5.3. Selected Tidal Prisms in Galveston Bay.

Location of Tidal Prism	Volume of Tidal Prism (ac-ft)	
	High Declination (2 Tides per Day)	Low Declination (1 Tide per Day)
Entire Galveston Bay system	250,000	75,000
East Bay	81,000	25,000
West Bay, east of Karankawa Reef	26,000	5,000
West Bay, west of Karankawa Reef	34,000	6,000
Trinity Bay	89,000	27,500

Source: Ward, 1991

Variability Related to Inflow and Intrusion

An analysis of net circulation patterns over an entire year provides some insight on the relative importance of different processes, but does not show the extreme variability in the system. In reality, variability occurs on time scales ranging from hours to seasonal. On a net circulation basis, one important feature is the Houston Ship Channel, which provides the primary mechanism for salt water intrusion. Dredged material areas on the margins of the Ship Channel form a barrier between the eastern and western portions of the bay, allowing for a steep salinity gradient between the two. The Ship Channel also provides a conduit for higher salinity water to intrude farther into the bay. Other circulation patterns include (Ward, 1991):

A prominent region of higher salinity between Bolivar Peninsula and Hanna Reef;

A zone of fresh water along the south shore of Trinity Bay, projecting past Smith Point to Hanna Reef; and

Relatively uniform salinity in West Bay

Intrusion of higher salinity water into the upper bay generally requires months of low fresh water inflows, while salinity extrusion from freshets and high runoff events can displace brackish water with fresh water much more rapidly. Although fresh water inflow only explains about 50 percent of the variation in bay salinity at most, it remains the best overall predictor of salinity.

Net flow regimes for two specific conditions were modeled in 1982 by the Texas Water Development Board (in Wermund et al., 1989). During the most saline periods, such as occur in August, a northwesterly current in the Ship Channel occurs along with a clockwise circulation pattern along the eastern shore of Trinity Bay (FIGURE 5.10b). Return flow from saltwater intrusion up the channel occurs primarily along the western shore of the bay, restricted largely by dredge disposal barriers. There is very little flow in West or East Bays. Resulting salinity is greater than ten ppt throughout most of the bay, excepting the eastern half of Trinity Bay.

Conditions contrast during the spring freshet in May. During the freshet, there is a strong southeasterly current in the ship channel, produced by a dominant current flowing along the northern part of Trinity Bay from the delta to the channel (FIGURE 5.10a). In addition, there is an easterly current from San Luis Pass towards the opening between Pelican Island and the Texas City Dike. Most of the upper half of the bay, above Smith and Eagle Points, exhibits salinities less than ten ppt.

By virtue of receiving flow from the Trinity River, Trinity Bay is particularly sensitive to the effects of fresh water inflow. When Trinity River flows are greater than 15,000 cfs, Trinity Bay is virtually fresh; shrimpers even report catches of fresh water fish species. When flows are less than 5,000 cfs, salinity is variable, but

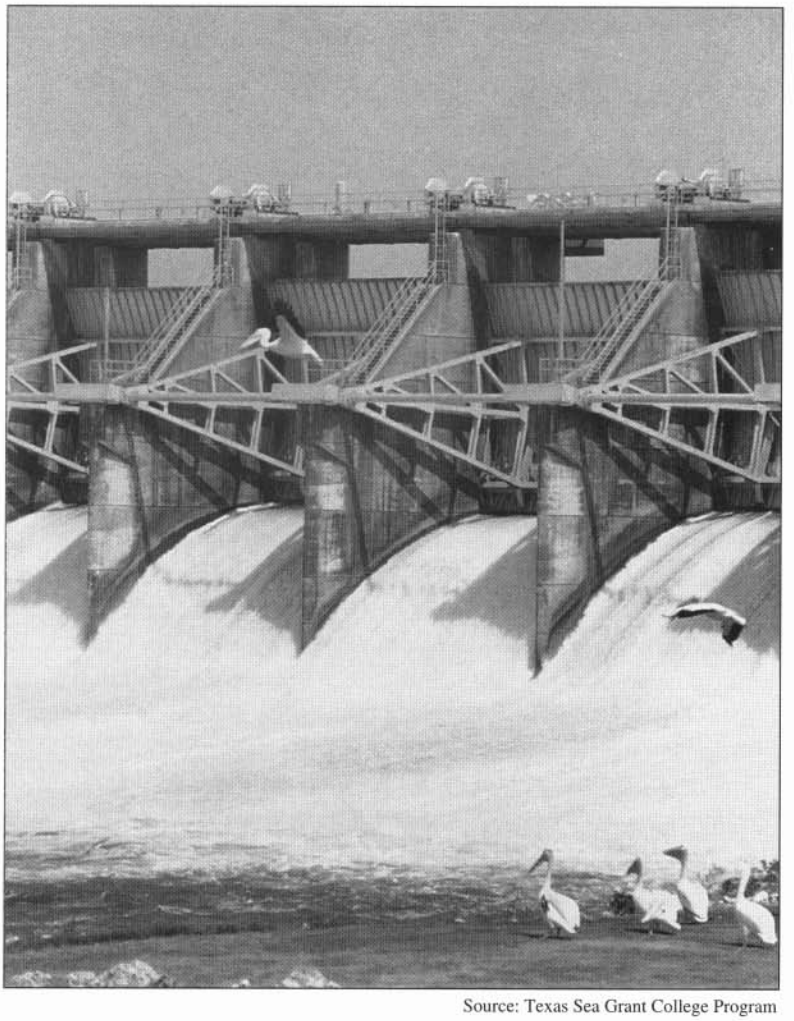
not directly correlated to the river flow. On a physical basis, flows above 14,000 cfs begin to saturate the marshes in the Trinity River delta, while flows exceeding 35,000 cfs completely inundate the delta marshes.

HUMAN ALTERATIONS

Human activities have resulted in extensive physical alteration of Galveston Bay over the past 150 years. These alterations have led to changes in related bay processes like circulation, which in turn affect the chemistry and biology of the system. Many alterations are related to the construction and maintenance of navigation channels, beginning in the nineteenth century. Other changes result from groundwater withdrawal (causing subsidence), isolation of side bays, and various shoreline modifications. Some of the principal human activities affecting the structure and processes of Galveston Bay are summarized in this section.

The cumulative effects of human activity have led to a net 30 percent increase in total volume of the bay (Ward, 1993). Subsidence was responsible for the largest overall volume change, an increase of 36 percent over the bay's former volume (siltation and dredge material disposal make the net increase less than the effect due to subsidence). Most of the effects of subsidence are concentrated in upper Galveston Bay where industrial and municipal consumption of groundwater was greatest. Shell dredging, which was banned in 1969, resulted in a six percent increase in bay volume since 1900.

Human activities have both increased and decreased surface area in different geographic locations. The increases (e.g. resulting from subsidence) have approximately equaled the decreases (e.g. from side bay isolations and dredged material disposal), yielding little net change in the 384,000 ac (600 sq mi) area of the bay (TABLE 5.4).



Source: Texas Sea Grant College Program

Slightly more than half of the freshwater inflow to Galveston Bay comes via the Trinity River. The volume of water released from Lake Livingston, shown here, influences the salinity of Galveston Bay downstream.

Nineteenth Century Navigation Projects

The Bolivar Inlet presented a significant challenge to navigation during the nineteenth century. Shoaling due to deposition of sediment was one problem affecting the sides of Bolivar Inlet. This problem, noted as early as 1866, may have been exacerbated by chain and piling obstructions placed there as a blockade during the Civil War. From 1875 through 1897 the Army Corps of Engineers built the south and north jetties using barge-mounted hoists to place large granite blocks. The resulting jetty system was successful in maintaining the navigation channel at a depth of over 25 feet through the Bolivar Inlet.

Besides the inlet work, a series of major and minor channelization projects was initiated prior to 1900. Several of the prominent projects are listed below, summarized by Ward (1993):

1852 Federal government provides aid to remove bar across Trinity River mouth.

1872 Corps of Engineers starts on six-ft deep by 100 ft wide channel through Redfish Bar.

1874 Commodore Charles Morgan enlarges Buffalo Bayou and builds cut through Morgans Point.

1877 Corps starts work on a 12-ft deep channel from Galveston to Houston.

1880 Corps begins work on 12-ft deep by 100-ft wide channel in Buffalo Bayou from Morgans Cut to White Oak Bayou.

1883 Bay channel project suspended for five years due to lack of use and "lack of permanence."

1895 Texas City Terminal Company dredges 16-ft deep by 100-ft wide channel from just north of Bolivar inlet to Texas City.

1894 Entrance and lower reach of Clear Creek dredged.

1897 Congress directs Corps to survey and plan for 58-mile, 25-ft deep by 100-ft wide channel from Bolivar Roads to the city of Houston.

Twentieth Century Projects

The Houston Ship Channel

Work on navigation projects intensified after the turn of the century. To reduce maintenance problems for the 25-ft deep channel to Houston, two sediment disposal strategies were proposed. First, dredged material was to be placed on the western side of the channel in lower Galveston Bay seaward of Redfish Bar. Second, a long dike was to be constructed on the eastern side of the channel in the upper part of the bay, disposing the dredged material on the east side of the dike. These activities were intended to help prevent resuspension of dredged material and subsequent re-siltation of the channel.

Work on the 11-mi pile-and-brush dike in the upper bay began after the great hurricane of 1900, and dredging of the channel began forming what is today called Atkinson Island. Deterioration and the storm of 1911 destroyed all but the upper 1.5 miles of this wooden structure, but Atkinson Island was by then firmly enough established to protect the upper section of the channel. Work continued on the 25-ft deep Houston Ship Channel project, and by 1914 the channel was completed. Despite the measures described above, annual maintenance dredging was required to maintain the channel.

Partially because of the expected increase in petroleum-related shipping, a further expansion to a 30-ft depth was authorized in 1919 and completed in 1926. The next forty years saw expansion to a 32 by 400 ft channel in 1937 and 36 by 400 ft in 1949. The current channel configuration of 40 by 400 ft was completed in 1963.

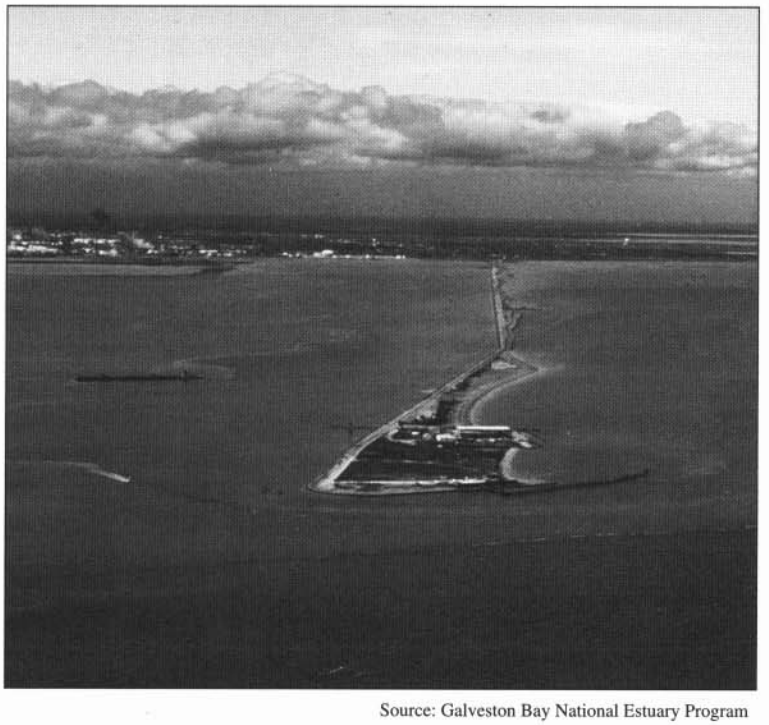
Additional enlargement for the Houston Ship Channel has been studied by the Corps of Engineers in the early 1990s. One proposed alignment described by Martin (1993), would consist of two phases: A Phase I project with a 45-ft deep by 530-ft wide channel, to be followed by a Phase II project consisting of a 50-ft deep channel 600 ft wide. Hydrodynamic simulations indicate that these channels would increase salinity in the estuary, with more change expected in the upper bay than lower bay.

An important change in the most recent proposals to enlarge the Houston Ship Channel involves disposal of the dredge material produced. Historically, the material has been disposed based only upon navigation and cost concerns. The most recent proposals, however, include identification of 18 sites where dredged material would be put to beneficial habitat and recreational uses. Creation of wetlands by establishing smooth cordgrass on disposal areas engineered to support a permanent wetland has already been initiated as a pilot test phase. Recreational uses proposed include creation of boater destination islands and beach nourishment.

Other Navigation Channels

The 5.3-mile Texas City Dike was constructed in 1915 to reduce maintenance problems on the Texas City Channel; subsequently the channel itself was enlarged in 1916. Originally the dike was constructed of timber piles, but this deteriorated rapidly and was replaced by a rubble-mound dike in 1934 that remains today. Other channels that were expanded included the Galveston Channel and several channels associated with Trinity River traffic. Several channels were completed to link the bay with tributaries. Lower Bastrop Bayou, for example, was dredged to a depth of four feet in 1907, but maintenance dredging was stopped in 1927.

An early step in creation of the Gulf Intracoastal Waterway was completed by the Corps in 1909 and included a cut through Karankawa Reef in West Bay as part of the route to the Brazos River. 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 apparent in the **physiography** of the area. In 1934 the Bolivar Peninsula connection to the Golden Triangle and Sabine Lake was completed. The Galveston Bay section of the waterway was completed in 1942.



Source: Galveston Bay National Estuary Program

The Texas City Dike, constructed in 1915, protects the Texas City Channel. Its construction has reduced the natural circulation into West Bay, redirecting most tidal exchange through Bolivar Roads.

Dredging and Disposal of Dredged Material

The navigation projects described above relied upon substantial dredging of bay sediments to reach depths adequate to support shipping. An analysis of dredging data by Ward (1993) indicates that a total of about 160,000 ac-ft of sediments have been removed from the bay for new navigation channels (new work, as opposed to maintenance dredging). As would be expected, most of the new

TABLE 5.4. Summary of Physical Modifications to Galveston Bay Since 1900.

Activity	Change in Volume [1] Of Bay Since 1900		Change in Area[2] of Bay Since 1900		
	1000s ac-ft	% of Bay Volume	Total (1000s Ac)	Net to Bay (1000s Ac)	Net to Bay (%)
Subsidence	+ 800	+36.0	26.5	+26.5	+ 8
Siltation	- 310	-14.0	unknown	0.0	0
Dredged Material Disposal & Fill	- 185	- 8.5	19.4	-19.4	- 6
Deepdraft (>36 ft) channels	+ 145	+ 6.0	3.5	0.0	0
Shell Dredging	+ 135	+ 6.0	unknown	0.0	0
Other Dredging & Shallow Channels	+ 55	+ 2.5	3.5	+ 0.5	0
Isolation	- 20	+ 1.0	7.5	- 7.5	- 2
Net	**+ 620**	**+30.0**	-	**+ 0.1**	**0**

[1]Current total bay volume: ~ 2.2 million ac-ft.
[2]Current total bay area: ~ 384,000 ac (600 sq mi).

Source: Ward, 1993

dredging has been for construction of the Houston Ship Channel, with approximately 62,000 ac-ft dredged for the upper inland reach, and 62,000 ac-ft for the bay reach. The Texas City Channel and the Gulf Intracoastal Waterway represent smaller volumes of new work, at 31,000 and 8,000 ac-ft, respectively.

Almost all of this new dredging work proceeded at a relatively constant pace from 1900 to 1965, corresponding closely to the channel enlargements of the Houston Ship Channel (FIGURE 5.11). Currently all channels combined occupy about 6,400 ac of bay bottom, of which 80 percent is deep draft.

Maintenance Dredging

The navigation channels in Galveston Bay require frequent maintenance dredging to keep them open. Since 1900, over 400,000 ac-ft of maintenance dredging (more than twice the volume of new work) has been undertaken in the bay. Ward (1993) estimated that since World War II, the average maintenance dredging for all channels in the bay was about 5,300 ac-ft per year, and that the total dredged area was about 9,000 ac. This corresponds to an average annual siltation rate for all bay channels of about 0.6 ft/year. Contributions of total suspended solids (TSS) into Galveston Bay from rivers and streams comprise only one to two percent of the annual volume from maintenance dredging, indicating that the majority of dredged sediment originates from other sources such as resuspension of sediments from the bay bottom (Ward, 1993).

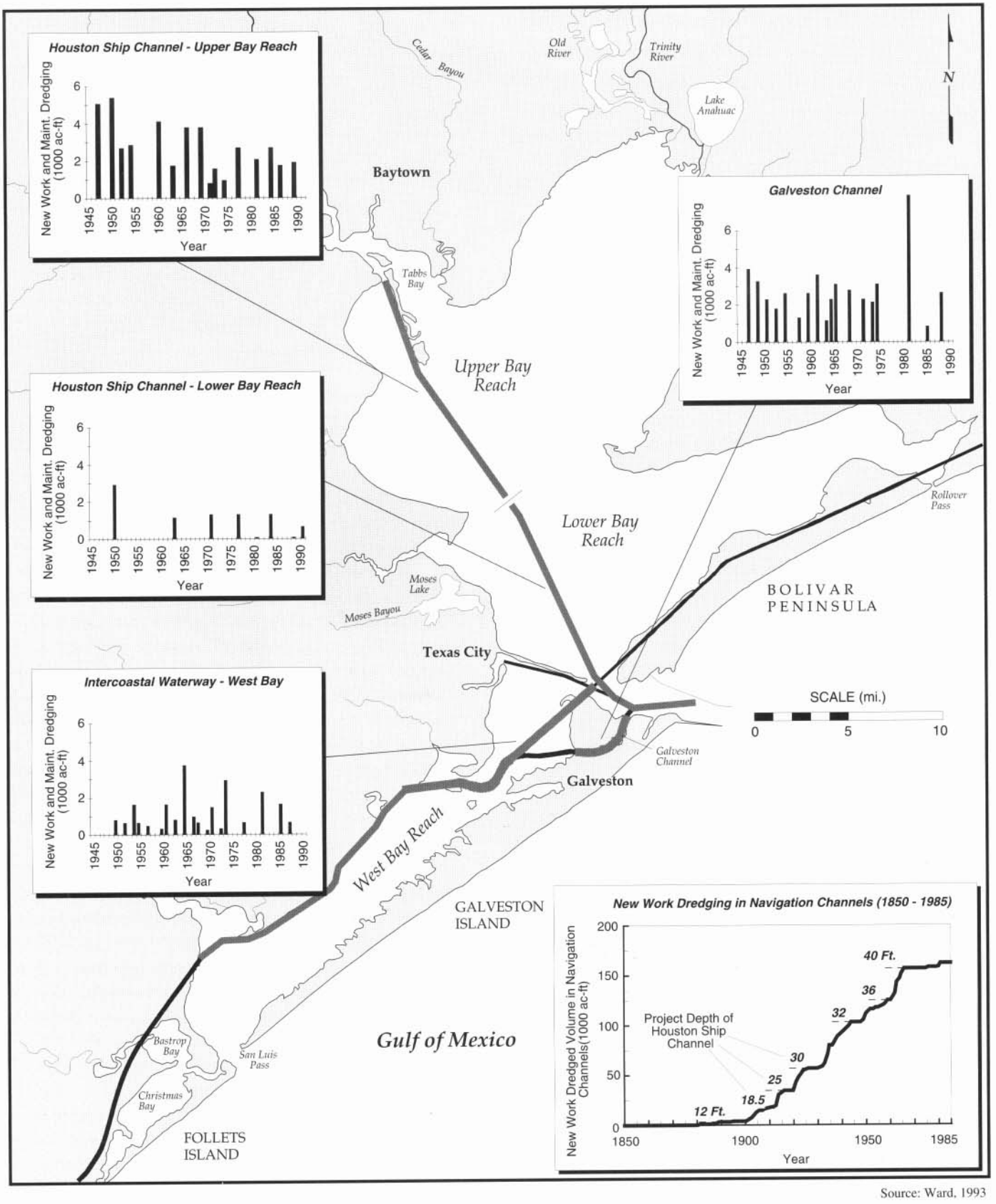
The siltation rate varies dramatically for different channels and different reaches, however. A detailed analysis of siltation by Ward (1993) indicated that siltation rates in most channel reaches ranged from zero to two ft per year. Galveston Channel (between Galveston Island and Pelican Island) requires considerably more maintenance dredging than most other channels in the region. A study performed by the Corps in the 1930s indicated that the Galveston Channel intercepts a large portion of the ebb flow from the bay, bringing large sediment loads to the channel. In general, the open bay channel landward from Redfish Bar requires greater maintenance than sections in the lower bays. A six-mile section of the lower channel, for example, has required almost no dredging the past 50 years because it runs through a scour zone caused by the natural convergence of flows in and out of the bay.

Maintenance dredging work has varied considerably over time, due in part to the scheduling of various projects (FIGURE 5.11). Interestingly, there is a weak relationship between maintenance dredging and total channel depth in the Houston Ship Channel. There has been a significant reduction in maintenance requirements in the bayou reach and the open-bay reach landward from Redfish Bar since 1960-1970, however. This is probably caused by the effects of subsidence in this area, and suggests that increased dredging may be required sometime in the near future, since subsidence has greatly slowed in the bay area in the past ten years (see below).

Dredged material is disposed of in specific locations by attachment of the cutter heads to pipelines temporarily linked to the disposal location. Currently there are about 25,000 ac of designated disposal area, of which 19,500 ac are open-water sites (about five percent of the total bay area). Many of these disposal areas have now become shoals or islands, such as Atkinson Island. About half of these disposal areas are associated with dredging for the Houston Ship Channel, both for original new work and maintenance.

Private Dredge-and-Fill Operations

In addition to the large federal projects described above, many dredge-and-fill operations are conducted by private interests and public agencies and are regulated through Clean Water Act Section 10/404 permits from the Corps of Engineers. These permits are a part of a federal regulatory program, under which the sponsors of dredge-and-fill projects submit designs in applications to the U.S. Army Corps of Engineers, followed by evaluation and approval or denial by the Corps. On the average, almost 100 per-



Source: Ward, 1993

FIGURE 5.11. *Summary of dredging activities in Galveston Bay. Since dredging began, dredge material sufficient to fill the Astrodome more than 100 times has been removed from channels in the creation of new projects. Maintenance dredging, an ongoing activity throughout the bay, generates substantial additional sediment which must be disposed somewhere in or near the estuary.*

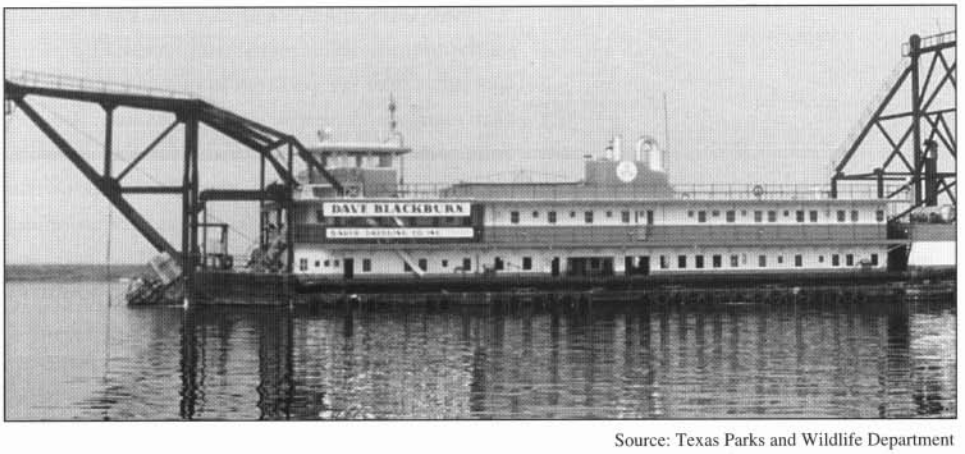
mits per year have been issued for the Galveston Bay system since 1950 (Ward, 1993). The total volume of these dredging operations was estimated to be about 40,000 ac-ft and involved nearly 3,000 ac of bay waters, an order of magnitude less than for the federal channel projects.

Based on an analysis of the Section 10/404 permits, the Houston Ship Channel, associated side bays, and San Jacinto River have the highest intensity of private dredging work (Ward, 1993). Over half of the permits were issued for the Houston Ship Channel, Galveston Channel, Texas City Channel, and Clear Lake.

These private dredge and fill activities have impacted sensitive areas of the bay. Ward (1993) estimated that approximately 461 ac of tidal marsh have been replaced by privately dredged channels and over 2,800 ac of marsh were replaced by private inland fill activities since World War II.

Influences on Circulation

Any activity which alters the bathymetry of the bay can be expected to potentially affect circulation. Other practices, for example cooling water discharges, also have an effect on circulation in some locations. Elements of circulation subject to alteration from these activities include salt water intrusion, fresh water inflow, and current regimes. Some of these human influences are discussed below.



Source: Texas Parks and Wildlife Department

To maintain depth in the bay's navigation channels, periodic maintenance dredging is required, carried out by vessels such as the one pictured. Increasingly, beneficial uses of the sediment produced from dredging are being pursued. Construction of bird islands and marsh restoration projects have both been successful beneficial uses of dredged material.

The Houston Ship Channel

Of all the Human influences on Galveston Bay, the Houston Ship Channel has perhaps caused the most pervasive changes to circulation and salinity. However, there are no direct measurements of bay circulation or salinity prior to 1900 when large-scale channel expansion began, preventing a direct measurement of the degree of the Ship Channel's impact. In general, three kinds of impacts could be expected: 1) making a larger cross section for flow to move up and down the entire length of the bay; 2) breaching Redfish Bar; and 3) creating barriers to flow in the form of dredge-disposal areas such as Atkinson Island. On average, the salinity in the channel is about two ppt higher than the surrounding shallow bay waters, due to denser, more saline waters intruding landward along the channel. In Matagorda Bay to the south, a similar channel constructed in 1963 was shown to have increased bay salinities by five ppt (Ward, 1983).

Indirect measurements indicate that the upper bay was once much fresher than it is today, suggesting a link to the continued expansion and deepening of the ship channel. Yuill (1991) reported a paleoecological shift in the **foraminifera** (small hard-shelled organisms) found in Galveston Bay sediment cores corresponding to the past 100 years. This shift from low-salinity foraminifera to higher-salinity organisms occurred in the late 1800s in lower and middle Galveston Bay, and as late as 1970 in one portion of the Trinity River. Yuill concluded the most likely mechanism for the apparent change in salinity regime was the dredging of the Houston Ship Channel.

Dredged material islands have had several effects on circulation patterns in the bay, including: 1) diverting the return flow of high-salinity water moving up the ship channel to the western side of the bay (FIGURE 5.10); and 2) serving as a barrier to fresh water flowing from the Trinity River delta to the channel. These effects have increased the salinity of the western part of the bay (Espey, Huston and Associates, 1978), and may have decreased turbidity (water cloudiness) to the point where the filtration rate of oysters may be affected (Powell et al., 1994). Overall, there has been significant realignment and accretion of oyster reef in response to the circulation changes in the bay (see Chapter Seven). These changes are relatively recent, however, and the comparison to oyster reef coverage prior to all channel dredging cannot be made.

A three-dimensional circulation model developed by the Corps of Engineers (Martin, 1993) is now being used to predict the change in bay circulation and salinity from a proposed project to enlarge the Houston Ship Channel. The proposed expansion may eventually lead to a 50-ft depth with a 600-ft width, compared to the 40-ft by 400-ft configuration today. Preliminary modeling results indicate that an enlarged channel will increase salinity in the bay and make the salinity "tongues" in the ship channel longer and sharper. Additional simulations are being conducted to further estimate the environmental effects of the proposed project.

Power Generating Stations

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 dis-

charges to a point north of Eagle Point near Bacliff. The Cedar Bayou Generating Station flow has a longer diversion, with the intake in Cedar Bayou and the outlet in the Trinity River Delta in the northwestern part of Trinity Bay. The annual volume of flow through both stations combined is equal to about half of the annual fresh water inflow to the bay. The generating plants recirculate bay water at a constant rate, while the rivers provide fresh water inflow at an extremely variable rate.

The general flow pattern caused by the P. H. Robinson plant is clockwise around Eagle Point, while the most notable effect of the Cedar Bayou plant is water being directed upstream to the intake on Cedar Bayou. Ward (1991) indicated that the influence of the Cedar Bayou plant may have also changed or neutralized the effect of wind-spun **gyres** caused by the wind in Trinity Bay. In addition, much of the effluent from municipal and industrial dischargers to Cedar Bayou, as well as nonpoint source runoff from the Cedar Bayou watershed, is effectively diverted to the Trinity River Delta, as water from Cedar Bayou is drawn into the cooling system.

Source: Galveston Bay National Estuary Program

Armand Bayou, north of Clear Lake, has subsided nearly seven feet due to the extraction of groundwater and subsequent compaction. Nearly all the wetlands in this area were drowned. The dead trees in the foreground were once along the shoreline and have since been flooded by open water.

Bolivar Roads Inlet and Texas City Dike

When the Galveston jetties were completed near the turn of the century, they eliminated the natural bar structure across the inlet and diverted the tidal flow away from its original path through the Galveston Channel (between Pelican and Galveston Islands). Estimates performed by Ward (1991) indicate that the new inlet structure may have also increased the overall tidal flow to the bay, perhaps by 20 percent. These tidal flow data are not well-documented, however, and should only be considered an estimate.

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 in 1915; now practically none of the tidal current enters West Bay north of Pelican Island. 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.

Subsidence

Over the long term, Galveston Bay has been filling with sediments. However, subsidence caused by excessive groundwater withdrawal has temporarily reversed this overall geological trend and has resulted in an increase in bay volume over the past century (Ward, 1993). This process has produced many secondary responses, including loss of fringing wetlands (see Chapter Seven).

Loss of land elevations from subsidence has created a bowl-shaped area 80 miles in diameter (FIGURE 5.12; Gabrysch and Bonnet, 1975; Ratzlaff, 1982). Local subsidence of up to ten feet has been observed in some locations since the turn of the century, and approximately one foot of average subsidence has occurred in the upper Galveston Bay area. As a result, many local land features have now been inundated, such as the Brownwood subdivision near Baytown, over 30 percent of San Jacinto Park, and the 100-year old jetties at the mouth of Cedar Bayou.

Groundwater withdrawal management practices formulated by the Harris-Galveston Coastal Subsidence District have almost eliminated excessive pumping in the near-bay areas. A permitting system was initiated in the mid 1970s along with a program to convert former groundwater users to surface water. Because of these efforts, subsidence has virtually stopped in and around Galveston Bay over the past ten years. In the Pasadena area, near the center of the "subsidence bowl," subsidence rates have decreased from 0.3 ft/yr for the period 1973–1978 to 0.03 ft/yr for the period 1978–1987 (Gabrysch and Coplin, 1990). Although subsidence is increasing is some areas, such as along U. S. Highway 59 in Fort Bend County, these areas are farther inland and do not affect the bay directly.

Because of subsidence, the volume of Galveston Bay has increased over 800,000 ac-ft, due to the gradual lowering of the bottom of the bay (Ward, 1993). This is over three times the entire volume of all federal, public, and private dredge and fill operations, including all dredging related to the Houston Ship Channel. Although the environmental effects of subsidence are much different than channel dredging, which deepens only very local areas of the bay and produces disposal material, subsidence has probably influenced circulation and sediment distribution.

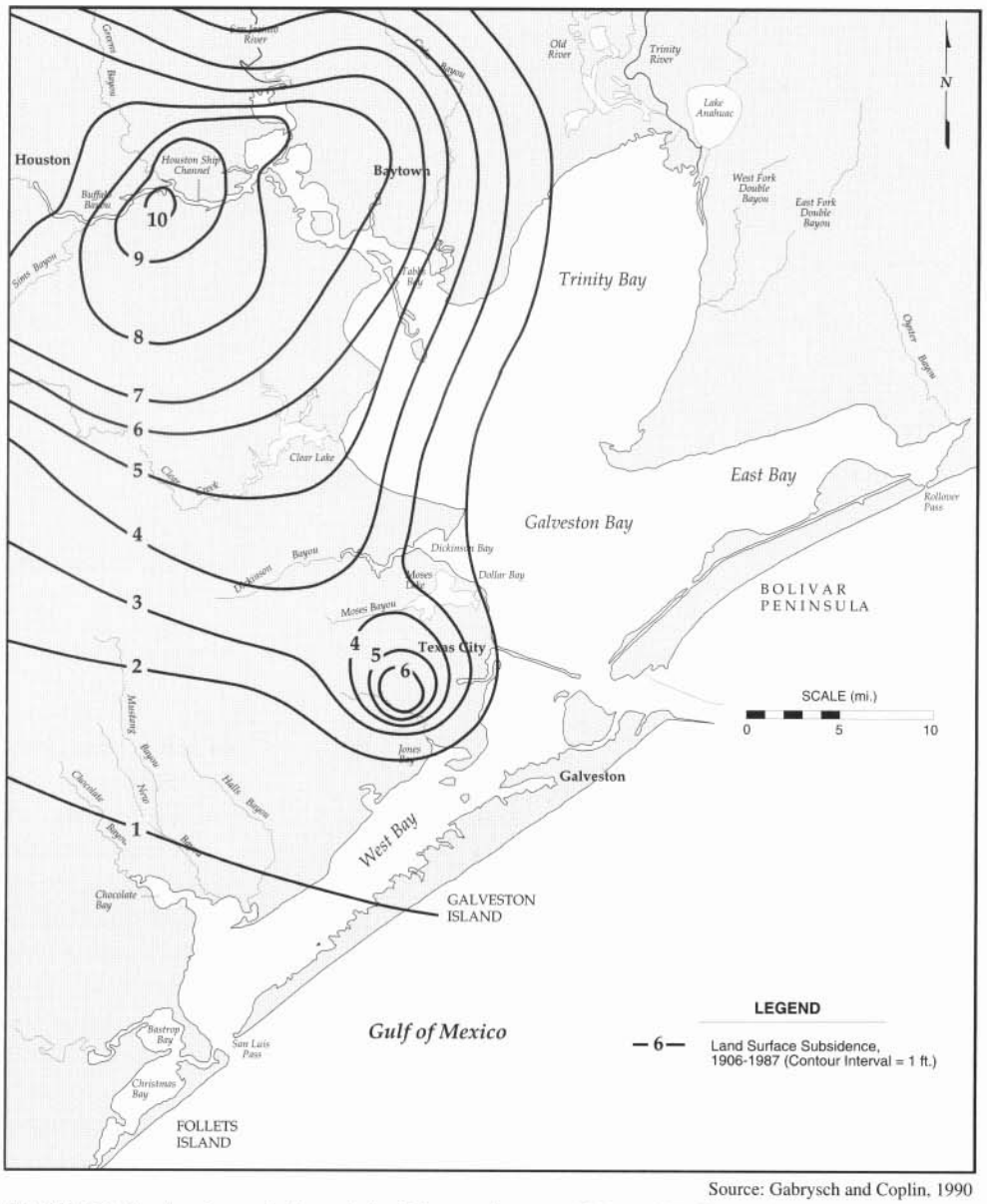
Other Modifications

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, an existing channel. By the time the project was completed in 1911, over 9,900 ac-ft 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 entrance to Lake Anahuac (then called Turtle Bay) was closed by the Trinity River Irrigation District No. 1 to protect rice irrigation systems. The district had proper authority because of a 1902 provision by Congress that declared Lake Anahuac to be non-navigable. Subsequently, this 6,000-ac area, once part of the Galveston Bay estuary, was removed from the bay system and converted to a shallow, fresh water lake.

Other "isolations" include the privately-owned 1,100-ac Delhomme hunting area and the 2,500 ac impoundments utilized as part of the Houston Lighting and Power Cedar Bayou Generating Station's cooling system. The total amount of isolated bay area (including Lake Anahuac) is 7,500 ac of bay bottom (about two percent of the bay's original area) and 16,000 ac of marsh.



Source: Gabrysch and Coplin, 1990

FIGURE 5.12. *Land-surface subsidence in the Galveston Bay area, 1906 to 1987. Unregulated groundwater withdrawal prior to the 1970s resulted in land subsidence that has important implications for the bay. Wetlands have been drowned and converted to open water, and shorelines have been eroded. Regulation of water well production has greatly slowed the subsidence process, but the historical effects remain a problem for bay management.*

Shoreline Modification

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 nearshore habitat from a sloping, vegetated, natural state to an abrupt rectangular land-water barrier.

Using the U. S. Army Corps permit data and assumptions about standard bulkhead configurations, Ward (1993) estimated the amount of shoreline converted from natural habitats to man-made shoreline since World War II. He concluded that 42 mi of the bay shoreline had been bulkheaded and 28 mi had been converted to docks or revetments. By using an estimate prepared by Orlando et al. (1988) of a 743-mi shoreline around Galveston Bay, about ten percent (74 mi) of the bay shoreline has been modified: six percent (45 mi) by bulkheading and four percent (30 mi) by dock and revetment construction.

Shell Dredging

Beginning in 1905, large quantities of shell were removed from the Galveston Bay system for industrial and construction purposes. New industrial processes after World War II greatly increased the value of the shell as a raw material, and the volume of shell removed increased from about 2,500 ac-ft per year in 1945 to over 5,000 ac-ft per year in the mid 1960s. Increasing environmental concerns resulted in more stringent regulation of the industry, and by 1969 shell dredging had been banned from the bay. Ward (1993) estimates that approximately 135,000 ac-ft of shell had been

Source: Galveston Bay National Estuary Program

Many of the shorelines in Galveston Bay have been significantly modified. The aerial photograph (above) shows a residential "canal community" being constructed adjacent to a salt marsh, replacing the natural gradual depth gradient with an abrupt bulkhead (below).

Source: Houston-Galveston Area Council

removed between 1910 and 1969, a volume on the same order of magnitude as the cumulative new work excavation from navigation channels.

SUMMARY

Galveston Bay is a relatively shallow, wind-dominated system of relatively recent geologic origin (4000 years). Its 33,000 sq mi watershed has three main drainages: the Trinity River watershed, San Jacinto River watershed, and the coastal basin. Both the Trinity and San Jacinto rivers flow through large reservoirs, located close to the bay, that have reduced sediment and nutrients entering the bay and may have altered some fresh water inflow patterns.

The 26,000 sq mi Trinity River watershed has a mixture of agricultural and forestry land uses, and includes the highly urbanized Dallas/Fort Worth metroplex. The San Jacinto watershed is only about a tenth this size and is about three-fourths forested land with minimal urban development. The 4,238 sq mi coastal basin is comprised of roughly equal portions of urban areas (Houston), agricultural lands, open/pasture lands, and forests. The local climate is warm and wet, with an average of 51.8 inches of rain per year.

The Trinity River provides slightly more than half the average 10.1 million ac-ft of fresh water inflow annually reaching the bay. There have been no increasing or decreasing trends in total fresh water inflow since 1941. Preliminary information suggests that the Lake Livingston dam on the Trinity River, combined with elevated urban base flows, may have dampened the historical seasonal inflow extremes.

The bay's circulation is controlled primarily by winds, tides, and fresh water inflow. Winds can have a dramatic effect on the bay–an intense norther can push over half of the bay's water out to the gulf in less than 24 hr and reduce water levels by more than three feet in some places. Tidal exchange is relatively weak, with 80 percent of the tidal exchange occurring through Bolivar Inlet.

Circulation patterns in part determine the distribution of bottom sediments. Mud predominates, interrupted by areas of sand, shell, and oyster reef, depending upon the currents and their energy. The shoreline of the bay consists primarily of marsh and clay bluffs that have eroded an average of 2.2 ft per year since the 1850s. Hurricanes are particularly important natural events that can drastically change the shoreline and sediment distribution.

Significant modifications to the physical structure of the bay have occurred since the 1850s. Most notable have been construction of navigation channels, subsidence, and isolation of secondary bays and marshes. The Houston Ship Channel, the Texas City Channel, the Gulf Intracoastal Waterway, and other channels have been excavated, and have created adjacent dredge disposal areas. Subsidence from groundwater pumping has lowered the bottom of the northwestern portion of the bay by several feet, contributing to an overall 30 percent increase in bay volume since 1900 to 2.2 million ac-ft. Isolation has removed some of the original bay area, such as when Turtle Bay was closed off in 1931 to form a fresh water system now called Lake Anahuac. Overall, however, the 600 sq mi area of the bay has remained about constant due to inundation of low-lying areas by subsidence.

These human activities have also affected circulation. At the turn of the century, Redfish Bar ran across the middle bay, limiting circulation and salt water intrusion into the upper estuary. Now the Houston Ship Channel is the dominant feature and is the main factor bringing salt water further up into the bay. This has probably resulted in considerable change in the bay over time, for example changes in oyster reef distribution.

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CHAPTER SIX

Water and Sediment Quality: Status and Trends

...in order to continue improvements in the bay's water quality, the next phase of the campaign must be bolder, with deeper societal commitment. We have achieved what in many ways is the easiest part of the cleanup, regulating point source discharges. We must now look at changing the way we think and act.

–Donald R. Baugh, the Chesapeake Bay Foundation

Galveston Bay is arguably the most important estuary on the Texas coast. It harbors the State's largest seaport, houses the world's largest industrial complex, and produces the largest shellfish catch on the Texas coast at 38 percent of the state's total. Thousands of weekend fishermen and boaters use the bay. However, Galveston Bay also receives more industrial and municipal effluent than all the other Texas estuaries and their watersheds combined. Contributions of wastewater from the Houston region, combined with Dallas/Fort Worth wastewater discharged to the Trinity River amount to some 60 percent of the total wastewater generated in the state.

Prior to the mid-1970s, the land-locked portion of the Houston Ship Channel above Morgans Point was listed by the U.S. Environmental Protection Agency (EPA) as one of the ten most polluted bodies of water in the United States. The dissolved oxygen necessary for marine life rarely measured above zero in some areas, rendering them essentially sterile. In 1969, state water quality specialists determined that this water quality degradation caused frequent and massive fish kills downstream in the upper portion of Galveston Bay (U.S. Environmental Protection Agency, 1980).

In response to increasing public concern and pressure from the fledgling Environmental Protection Agency, 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. Most notable were Operation Clean Sweep, which included detailed monitoring of Ship Channel discharges, and the Galveston Bay Project, the first comprehensive scientific study of the bay. Both of these programs were implemented in the 1968-1972 time period, the era of the Nation's first Water Quality Act.

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 ordered to upgrade their wastewater treatment facilities to secondary treatment or better. Between 1973 and 1980, millions of dollars were spent by the Environmental Protection Agency to upgrade and expand municipal waste treatment facilities discharging to the Houston Ship Channel and Galveston Bay. Eventually, the Environmental Protection Agency recognized that several Texas waterways were getting cleaner and singled out the Houston Ship Channel as "the most notable improvement, a truly remarkable feat" (U.S. Environmental Protection Agency, 1980). Additional investments in wastewater treatment since 1980 have continued to improve water quality in the Houston Ship Channel.

Galveston Bay itself has never experienced the serious water quality problems observed in the Houston Ship Channel, even during the 1960s and 1970s. The open bay is shallow, well-mixed, well-aerated by prevailing winds, and flushed more than four times

a year by fresh water inflow and the tides. Therefore, one of the main features of Galveston Bay is that the open bay historically maintained good water quality, while serious water quality problems have been concentrated in the western urban tributaries to the bay, particularly the ship channel.

This chapter deals with the present status and historical trends of water and sediment quality in the bay as well as quantification of the main sources of pollutants to the bay. Point and nonpoint source contributions are discussed as well as localized specific problem areas such as marinas and brine discharges resulting from petroleum production. An analysis of the major pollutant sources and observed cause-and-effect mechanisms over the past 20 years is also presented. A significant conclusion is the identification of nonpoint sources as the greatest contributor of some pollutants to the bay system.

REVIEW OF WATER AND SEDIMENT QUALITY PARAMETERS

Quantifying water and sediment quality in an estuary requires measurement of a suite of physical and chemical properties, termed "parameters." Some parameters serve as indicators, (indirect measures of pollutants that could not be measured directly, such as fecal coliform bacteria and biochemical oxygen demand or BOD). Other parameters play major roles in biochemical processes, for example nitrogen and phosphorus compounds, or toxic contaminants such as polycyclic aromatic hydrocarbons (PAHs) and pesticides. Finally, some of the parameters, such as salinity, serve as both indicators and take on important roles in biological processes.

Source: Texas Natural Resource Conservation Commission

Water quality in the upper Houston Ship Channel has improved over the past 25 years. During the early 1970s when this photograph of the turning basin was taken, dissolved oxygen and living organisms were non-existent over wide areas. Now, thanks to pollution abatement programs, some species have returned, and the most serious dissolved oxygen problems are near the bottom, rather than throughout the entire water column.

For the purposes of this discussion, water and sediment quality parameters have been divided into two categories: pollutants and water/sediment quality indicators. This division is arbitrary and was used to simplify the discussion.

Types of Pollutants

Biochemical Oxygen Demand

Biochemical Oxygen Demand (BOD or BOD_5) is an indirect measure of biodegradable organic compounds in water, and is determined by measuring the dissolved oxygen decrease in a controlled water sample over a five-day period. During this five-day period, **aerobic** (oxygen-consuming) bacteria decompose organic matter in the sample and consume dissolved oxygen in proportion to the amount of organic material that is present. In general, a high BOD reflects high concentrations of substances that can be biologically degraded, thereby consuming oxygen and potentially resulting in low dissolved oxygen in the receiving water. The BOD test was developed for samples dominated by oxygen-demanding pollutants like sewage. While its merit as a pollution parameter continues to be debated, BOD has the advantage of a long period of record.

Nutrients

Nutrients are chemical elements or compounds essential for plant and animal growth. Nutrient parameters include ammonia, organic nitrogen, Kjeldahl nitrogen, nitrate nitrogen (for water only) and total phosphorus. High amounts of nutrients have been associated with eutrophication, or overfertilization of a water body, while low levels of nutrients can reduce plant growth and (for example) starve higher level organisms that consume phytoplankton. In Galveston Bay, nitrogen is generally considered to be the "limiting nutrient," i.e., the most important nutrient that actually controls plant growth in the system, because of its low and limiting concentrations compared to other nutrients (see the Chapter Eight discussion of phytoplankton).

Organic Carbon

Most organic carbon in water occurs as partly degraded plant and animal materials, some of which are resistant to microbial degradation. Organic carbon is important in the estuarine food web and is incorporated into the ecosystem by photosynthesis of green plants, then consumed as carbohydrates and other organic compounds by higher animals. In another process, formerly living tissue containing carbon is decomposed as detritus by bacteria and other microbes. **Total organic carbon** (TOC) bears a direct relationship with biological and chemical oxygen demand; high levels of TOC can result from human sources, the high oxygen demand being the main concern. Carbon processes involving both organic

and inorganic forms are vital in bay biology and chemical cycling.

Oil & Grease

Oil and Grease constitutes one of the most common parameters for quantifying organics from human sources and, to a lesser extent, **biogenic** sources (e.g., algae and fish). Some examples of oil and grease loadings to Galveston Bay are leaks from automobile crankcases, illegal dumping into storm sewers, motorboats, oil spills, and discharge from oil production platforms in the bay. Oil and grease is a generic term for material which actually contains numerous and variable chemical compounds, some of which are typically toxic.

Priority Pollutants

Priority Pollutants refer to a list of 126 specific pollutants that includes heavy metals and specific organic chemicals. The priority pollutants are a subset of "toxic pollutants" as defined in the Clean Water Act. These 126 pollutants were assigned a high priority for development of water quality criteria and effluent limitation guidelines because they are frequently found in wastewater. Many of the heavy metals, pesticides, and other chemicals listed below are on the priority pollutant list.

Heavy Metals (Total and Dissolved)

Heavy metals are elements from a variety of natural and human sources. Some key metals of concern and their primary sources are listed below (Cole et al., 1984):

Arsenic (from fossil fuel combustion and industrial discharges);

Cadmium (from corrosion of alloys and plated surfaces, electroplating wastes, and industrial discharges);

Chromium (from corrosion of alloys and plated surfaces, electroplating wastes, exterior paints and stains, and industrial discharges);

Copper (from corrosion of copper plumbing, anti-fouling paints, and electroplating wastes);

Lead (from leaded gasoline, batteries, and exterior paints and stains);

Mercury (from natural erosion and industrial discharges); and

Zinc (from tires, galvanized metal, and exterior paints and stains).

High levels of mercury, copper, and cadmium have been proven to cause serious environmental and human health problems in some bays around the world. Some of the sources listed above, such as lead in gasoline and heavy metals in some paints, are now being phased out by environmental regulations issued in the past ten years.

Pesticides

Pesticides comprise a large class of compounds of concern in Galveston Bay. Typical pesticides and herbicides include DDT, Aldrin, Chlordane, Endosulfan, Endrin, Heptachlor, and Diazinon. Surprisingly, concentrations of pesticides in urban runoff may be equal or greater than the pesticides in agricultural runoff in the bay area (Newell et al., 1992). Besides toxicity, persistence in the environment is a key concern. Some of the more persistent compounds including DDT and dioxin (not a pesticide) are subject to stringent regulation including outright bans.

Polycyclic Aromatic Hydrocarbons (PAHs)

Polycyclic Aromatic Hydrocarbons include a family of semi-volatile organic pollutants such as naphthalene, anthracene, pyrene, and benzo(a)pyrene. There are two main sources of PAHs to Galveston Bay: spilled or released petroleum products (from oil spills or discharge of oil production brines) and combustion products that are found in urban runoff. Specifically, phenanthrene, pyrene, and fluoranthene are products of the incomplete combustion of fossil fuels. Naphthalene is found in asphalt and creosote. PAHs from combustion products have been identified as a source of some carcinogenic risk for eating seafood caught in Galveston Bay (see Chapter Nine).

Polychlorinated biphenyls (PCBs)

Polychlorinated biphenyls are organic chemicals that formerly had widespread use in electrical transformers and hydraulic equipment. This class of chemicals is extremely persistent in the environment and has been proven to **bioconcentrate** in the food chain, thereby leading to environmental and human health concerns in areas such as the Great Lakes. Because of the potential to accumulate in the food chain, PCBs were intensely regulated and subsequently prohibited from manufacture by the Toxic Substances Control Act (TSCA) of 1976. Disposal of PCBs is tightly restricted by TSCA. As with PAHs, PCBs have been identified as a source of some carcinogenic risk through ingestion of seafood from Galveston Bay (see Chapter Nine).

Key Water Quality Indicators

Temperature

Temperature of water in an estuary is important to many of the bay's chemical, physical, and biological processes. One of the important effects of temperature is on the rate of chemical and biological reactions, for example the solubility of oxygen in water increases as temperature decreases. Of course, aquatic organisms die when the water temperature falls below a certain level (e.g., 0°C for most species) or when it exceeds a maximum value (about 35°C for many finfish).

pH

pH is a measure of the state of equilibrium between water (H_2O) and its ions (H^+) and (OH^-) and is determined by various dissolved compounds in water, including salts and gasses. When compounds having ionizable H^+ or OH^- groups dissolve in water, the equilibrium between H_2O, H^+, and OH^- shifts and the pH value increases (becomes more basic) or decreases (becomes more acidic). pH reflects the reactivity of water with various pollutants, and therefore the toxicity of those pollutants. Generally, pH exhibits low variability in coastal situations due to the high buffering capacity of seawater. Departures from the normal range of seven to nine are therefore especially significant.

Salinity and Related Parameters

Salinity is one of the quintessential properties of estuarine waters, being fundamentally determined by the intermixing of fresh and oceanic waters. As a conservative parameter, it is an excellent indicator of circulation in an estuary (see Chapter Five). It is also a key ecological indicator, since it affects the suitability of habitats due to varying **osmoregulation** capabilities of organisms. One of the most common methods of estimating salinity of a water sample is measurement of its electrical conductivity. For a given temperature, conductivity of water varies linearly with ion concentration, making measurement of electrical current between two submerged electrodes a convenient measurement. An additional indicator of salinity is the refractive index of water, which is measured with a portable refractometer. The refractometer is calibrated for a direct read-out of salinity. Salinity is generally expressed in parts per thousand (ppt).

Turbidity and Related Parameters

Turbidity is the converse of water clarity–referring to interference with the passage of light by suspended matter, soluble colored organic compounds, or plankton in the water. The measurement of turbidity is used as an indirect indicator of the concentration of suspended matter, and also is important for evaluating the available light for photosynthetic use by aquatic plants and algae. One method of measuring turbidity is with an electronic transmissiometer, which measures light attenuation in water optically, yielding a percent transmittance. A much simpler, traditional method is use of a Secchi disc (a Secchi disc is a black and white disc which is lowered in water to the point where it is just barely visible in order to measure the depth of light penetration). The long-term average Secchi depth for Galveston Bay is about half a meter, extremely turbid in comparison to east and west coast situations.

Total Suspended Solids (TSS)

Total suspended solids refers to the concentration of suspended solid matter in water. TSS is measured by weighing the undissolved material trapped on a 0.45 micrometer filter after filtration. The constituents that pass through the filter are designated **total dissolved solids** (TDS) and are comprised mainly of ions such as iron, chloride, sodium, sulfate, etc. It should be noted that there is a direct proportional relationship between suspended solids and turbidity. The solids in suspension may include sediment or detrital particles and plankton.

Dissolved Oxygen and Related Parameters

Dissolved oxygen (DO) is the traditional and ubiquitous indicator of aquatic health. It determines the ability of aerobic organisms to survive, and in most cases higher dissolved oxygen is better. The concentration of dissolved oxygen depends upon temperature (an inverse relationship), 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 **reaeration**, (simple mechanical agitation by wind) and through photosynthesis.

Dissolved oxygen *deficit* is the difference between the capacity of the water to hold oxygen and the actual amount of DO in the water (the converse of percent saturation). A large deficit is an indicator of some oxygen demanding stress on natural waters, while a low deficit is an indicator of generally unstressed conditions (DO gives no indication of possible toxic contamination). A DO saturation greater than 100 percent can occur when the water is supersaturated with oxygen, a temporary condition that typically results from rapid photosynthesis. This is not uncommon during colder winter months when water temperatures are low.

Chlorophyll-a

Chlorophyll-*a* reflects the concentration of the principal pigment in green plants responsible for photosynthesis. As such, this parameter is a surrogate indicator of phytoplankton biomass, the amount of unattached single-celled algae that is present in the water (see Chapter Eight).

Fecal Coliform Bacteria

Fecal coliforms are present in the intestines or feces of warm blooded animals in normal numbers of about a million per gram of feces. Fecal coliforms are used as the primary indicator for determining if the water is contaminated by animal or human waste. Although fecal coliforms do not normally cause illness in humans, their presence suggests that other potentially dangerous pathogens could also be present. A fecal coliform standard of less than 2000 colonies per 100 mL has been established for non-contact recreation sports such as sailing. A standard of less than 200 colonies per 100 mL was established for contact recreation such as swimming. Fecal coliform counts below 14 colonies per 100 mL comprise the standard for shellfish harvesting. Chapter Nine presents a detailed discussion of fecal coliform bacteria, their limitations as an indicator organism, and public health implications related to Galveston Bay.

Relationships Among Parameters

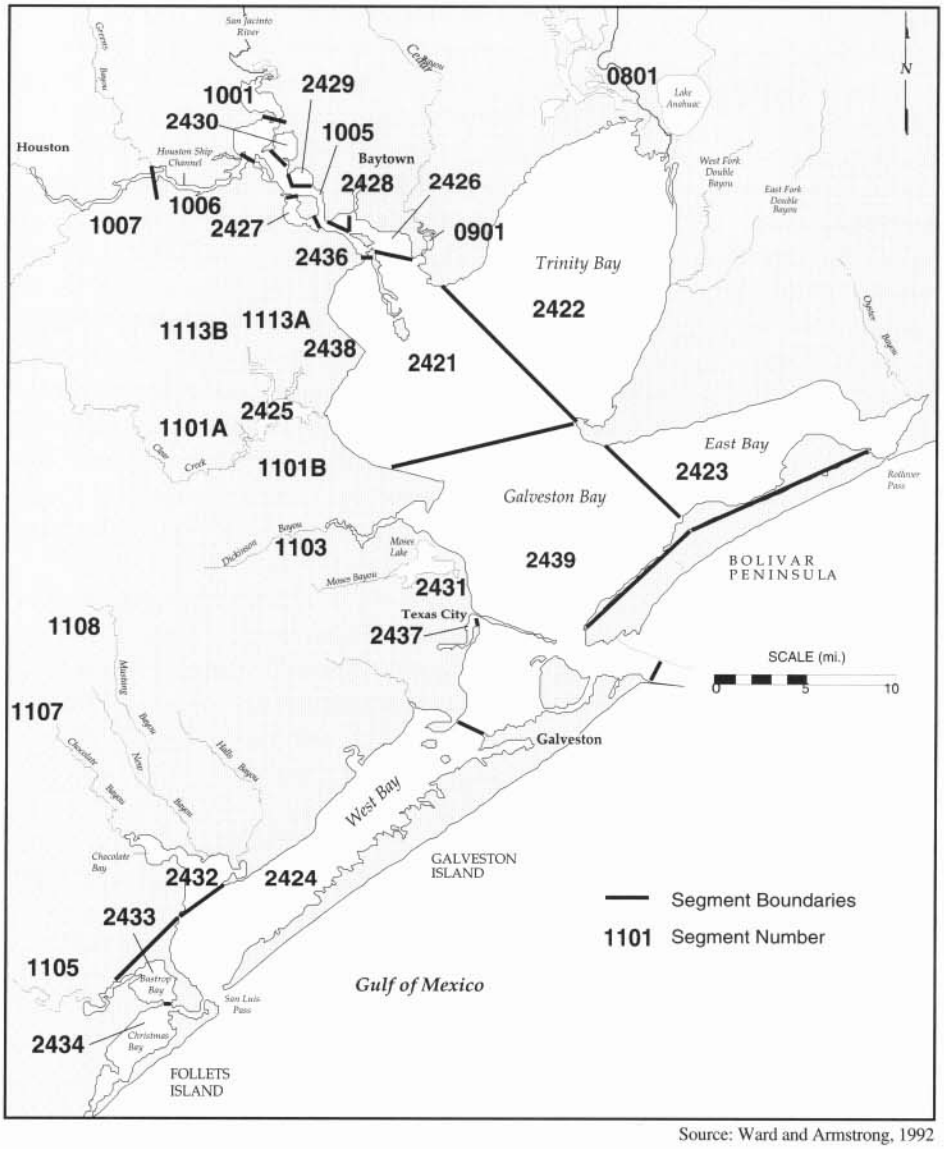
In determining estuarine water quality, several different parameters can sometimes be interpreted to measure the same essential property. For example, salinity (an essential property) can be estimated from measurements of chlorides concentration, total dis-

solved solids, density, conductivity, or light refraction. Different data collection programs in the bay may employ different measures, depending upon objective, convenience and tradition (Ward and Armstrong, 1992).

Relationships among parameters are important for two reasons. First, one parameter may have conceptual advantages over another, e.g., DO deficit may be more indicative of the effects of pollutant loading and biological activity than the concentration of dissolved oxygen itself (because the deficit normalizes the effects of temperature and salinity on the solubility of DO in water). Second, measurements of one parameter can frequently be used to estimate another, providing a means to establish a denser, longer-term data set by converting various parameters to a common measurement. Since no two parameters are completely interchangeable, this process requires caution. To establish whether such relations are justified for a given class of parameters is a central step in a long-term trend analysis. In this chapter, for example, these "proxy" relationships were utilized by Ward and Armstrong (1992) to improve the density of long-term data sets for salinity, BOD, DO, DDT, turbidity, nitrogen, phosphorus, and coliforms.

WATER QUALITY SEGMENTS AND BAY MONITORING PROGRAMS

Segmentation refers to the subdivision of the estuary into regions. The Galveston Bay system, including the tributaries, is presently subdivided into about 40 different geographic segments by the Texas Natural Resource Conservation Commission (FIGURE 6.1). The agency's Water Quality Segments (also referred to as Classified Segments or Designated Segments) are the basis for evaluating waste load capacity and for setting water quality standards (TABLE 6.1), hence they underlie discharge permitting, compliance enforcement, and administrative actions. In the monitoring realm, the Water Quality Segments are the basis for establishing the geographic location of monitoring stations and for determining the **ambient** water and sediment quality of particular areas.



Source: Ward and Armstrong, 1992

FIGURE 6.1. *Texas Natural Resource Conservation Commission Water Quality Segments for Galveston Bay. Future regional monitoring of the bay system may require further subdivision of some segments in order to increase the resolution of the information available to resource managers.*

Existing monitoring programs are of central importance to Galveston Bay, since these are the means for continued, routine acquisition of data to determine water quality and its trends. Currently, four major monitoring programs contribute information on water and sediment quality of the bay. These programs are operated and maintained independently by the following agencies:

Texas Natural Resource Conservation Commission ;

Texas Parks and Wildlife Department;

Texas Department of Health; and

U. S. Geological Survey.

The Texas Natural Resource Conservation Commission maintains the Surface Water Quality Monitoring database, a principal source of continuous broad-spectrum environmental data on the state's surface waters. This program includes water, sediment, and biological measurements acquired at fixed stations at regular intervals. Generally, field parameters are obtained *in situ*, by means of instrument probes or portable analytical kits. Once collected,

shipped to the laboratories of the Texas Natural Resource Conservation Commission and/or Texas Department of Health for analysis. Parameters have been expanded from a few conventional variables in the early 1970s to include trace constituents, pesticides and priority pollutants (toxicants) in recent years.

Surface water quality monitoring data are accessible through the Texas Natural Resource Conservation Commission Regulatory Activities & Compliance System (TRACS), a data management system operated by the agency and also accessible through the Texas Natural Resources Information System of the Texas Water Development Board. In addition to a compilation of all sampling data from the Surface Water Quality Monitoring Program, TRACS also contains data from special studies and intensive surveys (most of the data in the TRACS database is also in Environmental Protection Agency's STORET database). TRACS also includes data from other agencies, notably the Texas Water Development Board and U. S. Geological Survey.

The Texas Parks and Wildlife Department and its predecessor agencies (the Texas Game and Fish Commission and the Texas Game, Fish and Oyster Commission), have monitored the fishery resources of the system for many years (see Ward and Armstrong, 1992). In association with biological sampling, the program has obtained a limited suite of water quality measurements as well. These tend to focus on estuarine habitat characteristics, e.g., salinity, dissolved oxygen, turbidity and temperature. While the range of water quality variables is obviously much more limited than that of the Texas Natural Resource Conservation Commission, the frequency of sampling is much greater. The Texas Parks and Wildlife Department obtains data virtually on a daily basis, however the sample stations are randomized for statistical reasons so that there is no sampling continuity at any fixed point in the bay. The data is entered into a digital data base at agency headquarters for detailed statistical analyses.

The Shellfish Sanitation Division of the Texas Department of Health samples the bay at regular stations with varying frequency, depending upon season and recent rains that could affect bacterial concentrations. Texas Department of Health sampling is now limited to fecal coliform bacteria and a few associated hydrographic variables, salinity, temperature and pH. Like the Texas Parks and Wildlife Department, this program samples more intensely in space and time than the Surface Water Quality Monitoring program of the Texas Natural Resource Conservation Commission, and has accumulated data over many years from Galveston Bay. The collected data is maintained in a digital database at Texas Department of Health headquarters in Austin.

The activities of the U. S. Geological Survey emphasize the quantity and quality of inflow to the bay, though the Houston office also performs sampling within the estuary itself to help meet the needs of other federal and state agencies. This data is published annually and is maintained in a digital database. Data collected in support of other agencies may be managed differently, depending upon the nature of the data and the needs of the sponsoring agency.

There are other important data collection programs in Galveston Bay that deserve mention even though they are not *monitoring* programs. These include: 1) the sediment quality sampling performed by the Galveston District Corps of Engineers in association with its Operations and Maintenance Program for navigation; 2) the first Galveston Bay Project–a comprehensive program conducted by the Texas Water Quality Control Board involving monthly sampling at a network of fixed stations; 3) the sampling conducted in the Submerged Lands Study of the University of Texas Bureau of Economic Geology, sponsored by the Texas General Land Office; 4) sampling by the Texas Department of Health; 5) sampling completed by the U. S. Bureau of Commercial Fisheries; and 6) the Datasonde data collection program sponsored by the Texas Water Development Board. Data from these programs has contributed to the findings summarized in the next section of this chapter.

WATER QUALITY

Ward and Armstrong (1992) conducted a detailed study of water and sediment quality in Galveston Bay. The project compiled data from 26 separate data collection programs, including the three major state monitoring programs described above. Work began with a Data Inventory (Ward and Armstrong, 1994), which resulted in recovery of significant "lost" data pertaining to the bay, including some data from the 1968-72 Galveston Bay Project.

For each of 73 water quality parameters and 50 sediment quality parameters, Ward and Armstrong created a master data file. Each record in these files included the date, sample depth, latitude and longitude of the station, the measurement itself, estimated uncertainty of measurement, and a code identifying the origin of the data. For most water quality parameters, the data record extends back at least two decades, and for a few conventional parameters, back to the 1950s. This compilation is easily the most extensive and detailed long-term record of water and sediment quality ever assembled for Galveston Bay.

The study characterized the magnitudes and large-scale distributions of major water and sediment quality parameters throughout Galveston Bay. Spatial variation throughout the Galveston Bay system was addressed by aggregating the data into subregions of the bay, using two independent segmentation systems: the traditional Texas Natural Resources Conservation Commission Water Quality Segments described above (see FIGURE 6.1), and a system of "Hydrographic Segments" based upon physical criteria such as regions of homogeneity and locations of key gradients. The maps presented in this chapter are based on the hydrographic segments, which show higher resolution than Texas Natural Resources Conservation Commission segments.

Statistical trends in each of the different segments were mapped (FIGURES 6.2–6.11) using the following rules: a *probable* increasing or decreasing trend corresponded to 95 percent confidence boundaries on the slope of the time regression; a *possible* increasing or decreasing trend corresponded to 80 percent confidence boundaries. Since each hydrographic segment contains its own data sets and is analyzed separately, a pattern of consistent

TABLE 6.1. Present Texas Natural Resource Conservation Commission Water Quality Segments, Designated Uses, and Standards in the Galveston Bay System.

Segment Number	Segment Name	Designated Uses[1]								Standards	
		cr	hqh	sfw	iws	ncr	iqh	pwds	nav	DO	FC
2421	Upper Galveston Bay	•	•	•						4.0	14
2422[2]	Trinity Bay	•	•	•						4.0	14
2423	East Bay	•	•	•						4.0	14
2424	West Bay	•	•	•						4.0	14
2425	Clear Lake	•	•							4.0	200
2426	Tabbs Bay	•	•							4.0	200
2427	San Jacinto Bay	•	•							4.0	200
2428	Black Duck Bay	•	•							4.0	200
2429	Scott Bay	•	•							4.0	200
2430	Burnett Bay	•	•							4.0	200
2431	Moses Lake	•	•							4.0	200
2432	Chocolate Bay	•	•	•						4.0	14
2433	Bastrop Bay/Oyster Lake	•	•	•						4.0	14
2434	Christmas Bay	•	•	•						4.0	14
2435	Drum Bay	•	•	•						4.0	14
2436	Barbours Cut	•	•							4.0	200
2437	Texas City Ship Channel		•			•				4.0	200
2438	Bayport Channel		•			•				4.0	200
2439	Lower Galveston Bay	•	•	•						4.0	14
Trinity River											
0801	Trinity River Tidal	•	•							4.0	200
0802	Trinity River below Lake Livingston	•	•					•		5.0	200
Trinity–San Jacinto Coastal											
0901	Cedar Bayou Tidal	•	•							4.0	200
0902	Cedar Bayou Above Tidal	•	•					•		5.0	200
Houston Ship Channel/San Jacinto River											
1001	San Jacinto River Tidal	•	•							4.0	200
1005	HSC/San Jacinto River		•			•				4.0	200
1006	HSC				•				•	2.0	2000
1007	HSC/Buffalo Bayou				•					1.0	2000
1013	Buffalo Bayou Tidal	•					•			3.0	200
1014	Buffalo Bayou Above Tidal	•					•			—	—
San Jacinto-Brazos Coastal											
1101[2]	Clear Creek Tidal	•	•							4.0	200
1102[2]	Clear Creek Above Tidal	•	•							5.0	200
1103	Dickinson Bayou Tidal	•	•							4.0	200
1104	Dickinson Above Tidal	•	•					•		4.0	200
1105	Bastrop Bayou Tidal	•	•							4.0	200
1107	Chocolate Bayou Tidal	•	•							4.0	200
1108	Chocolate Bayou Above Tidal	•	•							5.0	200
1113	Armand Bayou Tidal	•	•							4.0	200

Source: Galveston Bay National Estuary Program

[1]Note: cr = contact recreation, hqh = high quality habitat, sfw = shellfish waters, iws = industrial water supply, DO = dissolved oxygen, mg/L, ncr = non contact recreation, iqh = intermediate quality habitat, pdws = public domestic water supply, FC = fecal coliform, colonies/100mL, nav = navigation

[2]Segments 1101, 1113, and 2422 are subdivided, constituting a total of seven segments

trends from segment to segment in a region of the bay strengthens the statistical "reality" of the computed trend (Ward and Armstrong, 1992). For these analyses, measurements in the data set designated "below detection limit" were assigned a value of zero.

Water Quality Status and Trends

Temperature

Temperature in the bay was generally homogeneous with little systematic stratification (depth variation), due to shallow depths in the bay and the prominence of mixing due to wind. The principal source of variation in temperature was variation among seasons. Average summer temperatures for the bay (FIGURE 6.2a) ranged from approximately 29°C (84°F) to greater than 31°C in a few locations. Summer temperatures as low as ten °C and as high as 39°C were recorded in some segments of the bay. FIGURE 6.2a also shows the effect of power plants on bay temperature: the Cedar Bayou Generating Station appears to have increased water temperature near its northeast Trinity Bay **outfall** by 0.3°C, while the P.H. Robinson plant may have increased the temperature of middle Galveston Bay above Eagle Point by about 0.7°C. Statistical trends for summer temperatures are shown in FIGURE 6.2b, where a general reduction of about two °C over the past thirty years was observed. Because the average temperatures shown are based on 30 years worth of data, the average temperature today is probably as much as one to two °C lower than the average temperature shown in FIGURE 6.2a.

Although not shown in the figures, average temperatures for the bay during winter conditions (December through February) ranged from approximately ten °C to greater than 16°C in a few locations. Winter temperatures as low as zero °C and as high as 29°C were recorded in some segments of the bay .

Salinity

Salinity gradients from the upper to lower bay are a normal feature, with Gulf inlet values of about 30 ppt declining to about three ppt near principal points of inflow such as the Trinity River. Vertical salinity stratification of bay waters was slight compared to East and West Coast estuaries, generally averaging less than 0.6 ppt/m, with about half the bay less than 0.3 ppt/m. Salinity stratification did not correlate with depth in the bay as a whole, but the Houston Ship Channel tends to serve as a conduit for Gulf water to intrude into the upper bay system. Salinity data and trends for the upper 1.5 m of the bay are shown in FIGURES 6.3a and 6.3b. Increasing salinity was observed in parts of upper Trinity Bay, while a widespread decline in salinity was observed, particularly in the lower bay. An additional discussion on the relationship between circulation and salinity is provided in Chapter Five.

Total Suspended Solids (TSS)

Total suspended solids data for Galveston Bay are depicted in FIGURE 6.4a and the statistical trends over time are shown in FIGURE 6.4b. Generally, TSS concentrations in the bay varied from less than ten mg/L to greater than 60 mg/L in a few of the segments. The data in FIGURE 6.4b show that the general trend in TSS throughout the bay was an overall decrease over the past 20 years.

Dissolved Oxygen (DO)

Dissolved oxygen was generally high throughout Galveston Bay, averaging near-saturation across large areas (FIGURE 6.5a), with frequent occurrences of concentrations greater than the equilibrium concentration with air (**supersaturation**). Exceptions to this were in poorly flushed tributaries subjected to inflow and waste discharges, the most significant of which was the Houston Ship Channel.

Trends in the DO deficit are shown in FIGURE 6.5b; data indicated a strong decreasing trend in the upper Houston Ship Channel of about 0.1 mg/L per year over the past 20 years. There was no statistical trend over much of the middle bay, but an increase in oxygen deficit (a lowering of the oxygen concentration) occurred in the following areas: the outlet of the Trinity River, the outlet of Clear Lake, and East Bay-lower Galveston Bay.

Total Phosphorus

Total phosphorus concentrations ranged from less than 0.2 mg/L to greater than two mg/L (FIGURE 6.6a). The general trend in total phosphorus data was one of decline, shown in FIGURE 6.6b.

Nitrate (NO_3)

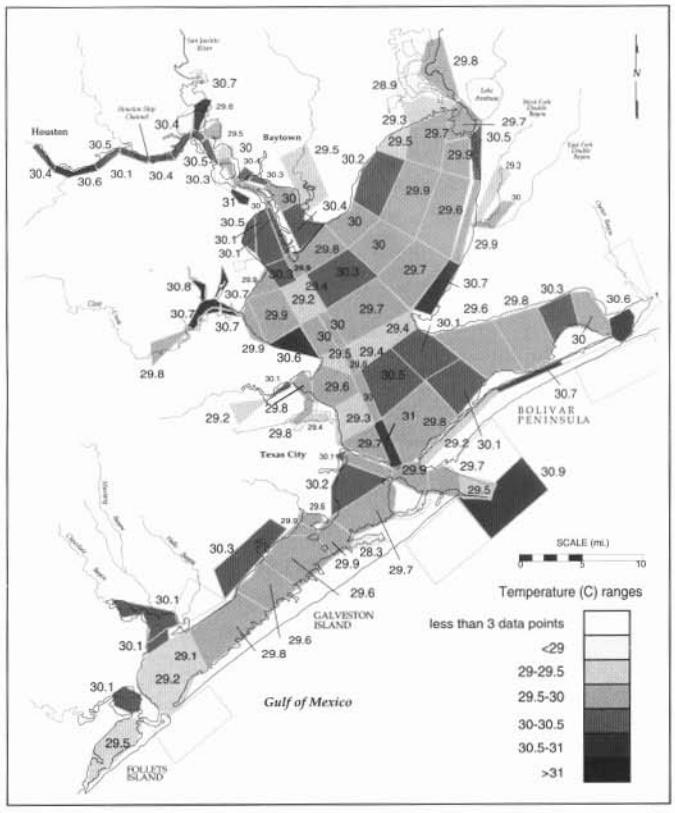
Nitrate concentrations ranged from 0.1 mg/L to greater than 0.5 mg/L (FIGURE 6.7a) with the average value falling in the middle range for U.S. estuaries. The general trend was a decline throughout most of the bay (FIGURE 6.7b). One area of increasing nitrate concentration was the Houston Ship Channel, which can be interpreted as an improvement: where most plants once discharged the majority of their non-organic nitrogen as ammonia, they now nitrify the ammonia and discharge the oxidized form of nitrogen as nitrate. This change corresponds to discharge permit requirements for secondary treatment and other process improvements. It should be noted, however that nitrate is an important source of nutrients for phytoplankton production. Too much nitrate can cause eutrophic conditions.

Ammonia

Ammonia concentrations ranged from 0.2 mg/L to greater than two mg/L. Many areas of the bay show an uncertain time trend for this parameter, but where trends occurred, they tended to reveal a decline in ammonia concentrations. A clear ammonia decline in the upper Houston Ship Channel due to wastewater treatment improvements is discussed later in this chapter.

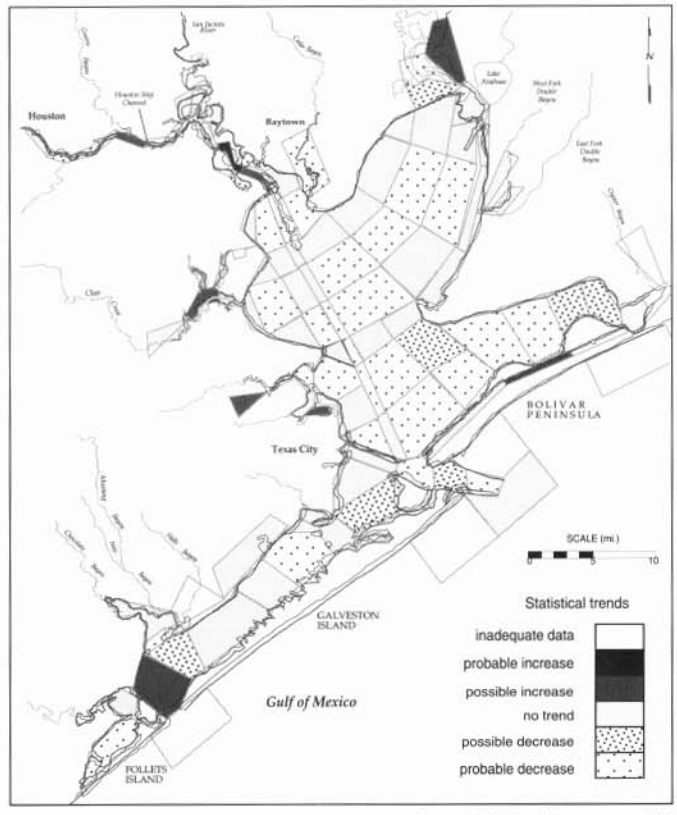
Chlorophyll-a

Concentrations ranged from less than ten µg/L to over 50 µg/L (FIGURE 6.8a) with the average value falling in the middle range for U.S. estuaries. Chlorophyll-*a* concentrations exhibited a clear declining trend throughout much of the bay (FIGURE 6.8b).



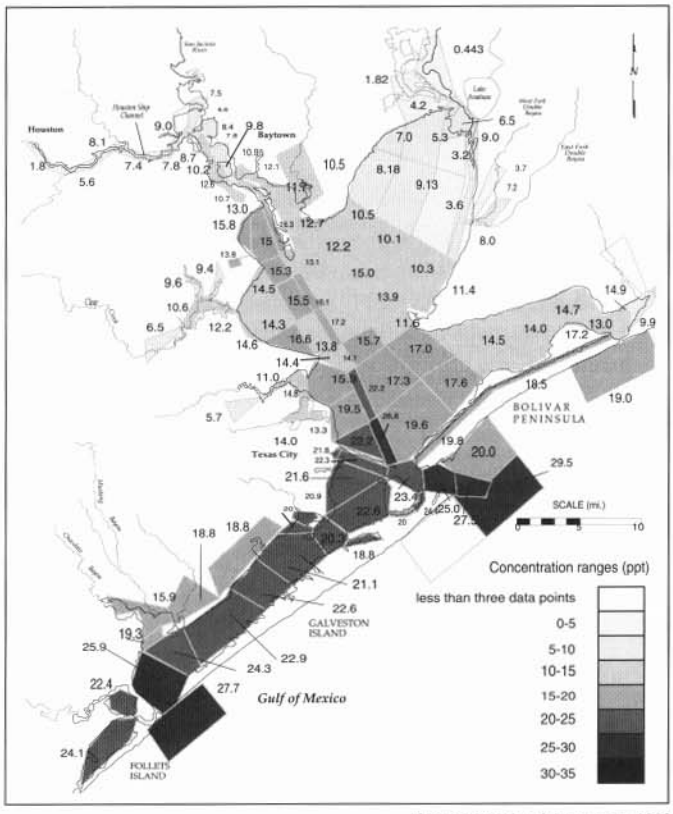
Source: Ward and Armstrong, 1992

FIGURE 6.2a. *Average summer water temperature in the upper 0.5 m of Galveston Bay, 1950-1991.*



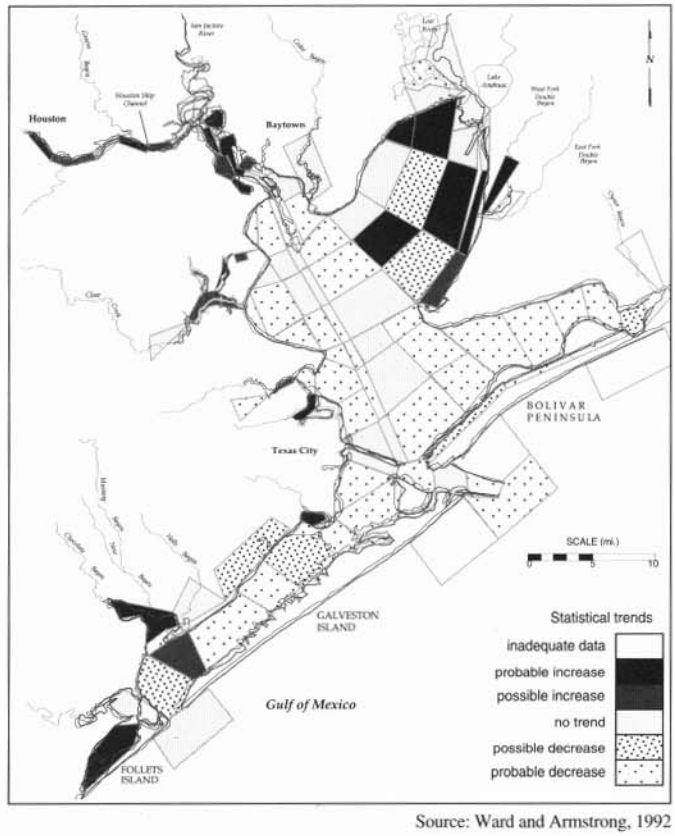
Source: Ward and Armstrong, 1992

FIGURE 6.2b. *Statistical trends for summer water temperature in the upper 0.5 m of Galveston Bay, 1950-1991.*



Source: Ward and Armstrong, 1992

FIGURE 6.3a. *Average salinity in the upper 1.5 m of Galveston Bay, 1950-1991.*



Source: Ward and Armstrong, 1992

FIGURE 6.3b. *Statistical trends for salinity in the upper 1.5 m of Galveston Bay 1950-1991.*

A discussion of the significance of this decline is presented in the Chapter Eight discussion on phytoplankton.

Fecal Coliform Bacteria

Fecal coliform bacteria concentrations ranged from less than ten organisms per 100 mL to greater than 100,000 organisms per 100 mL in the vicinity of the upper Houston Ship Channel (FIGURE 6.9a). Long-term average fecal coliform concentrations were low in most locations but exceedances of state criteria by individual measurements were not unusual (See Chapter Nine). The trend in concentrations over time varied across the bay, with a general decline in the Houston Ship Channel and some increases in West Bay (FIGURE 6.9b).

Oil and Grease

Oil and Grease concentrations ranged from less than two mg/L up to 20 mg/L (FIGURE 6.10a). Highest concentrations were centered around the Houston Ship Channel, Texas City, and the inlet to Galveston Bay. The database for oil and grease is so incomplete that Ward and Armstrong (1992) were unable to determine any definite trends over much of the bay (FIGURE 6.10b).

Total Copper

Concentrations ranged from less than 20 µg/L to over 100 µg/L (FIGURE 6.11a). The database for total copper measurements is not complete enough to determine trends (FIGURE 6.11b). Note that there is some controversy over the validity of copper and other metals data (see metals discussion on page 110).

Biological Oxygen Demand

BOD was elevated in regions of runoff and waste discharge, with generally the highest values in the upper Houston Ship Channel and lowest values in open bay waters. The influx of conventional pollutants from point sources peaked in the 1960s and has declined since, primarily due to implementation of advanced wastewater treatment. For example, a 20-fold reduction has occurred in BOD loading since about 1970 (see FIGURES 6.12 and 6.27 for upper Houston Ship Channel). Within the upper Houston Ship Channel, the average DO deficit was reduced about four mg/L in the past 20 years, mainly due to the reduction in oxygen-demanding materials discharged in wastewater. In addition, there was a decrease in mass loading of BOD from river and stream inflows due to a combination of improved waste treatment, altered land use, and impoundments on the principal rivers.

PCBs, PAHs, and Pesticides

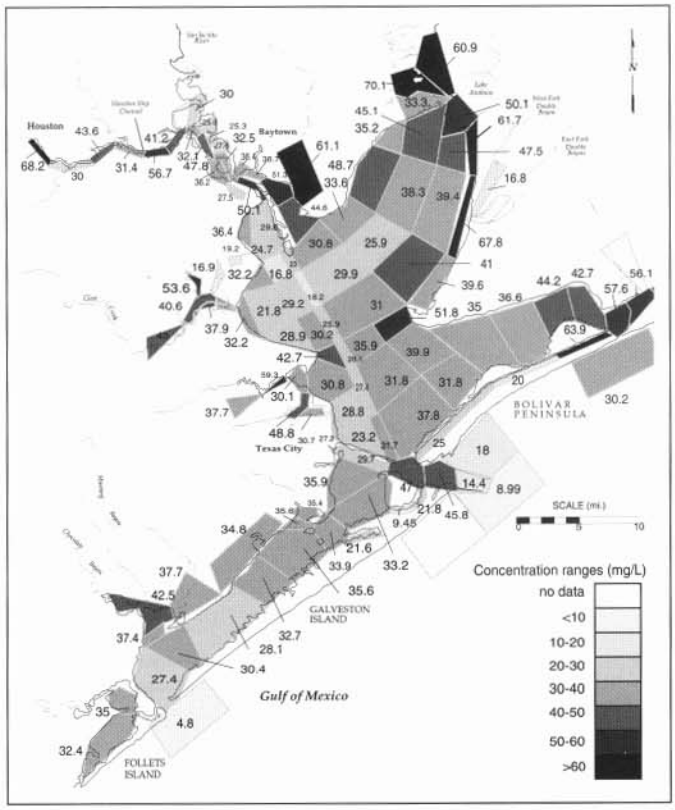
The data for these toxic organic constituents were very sparse, but indicated higher concentrations near urban and industrial areas. The best-monitored database was for DDT but most areas of the bay lacked data or were below detection limits. Detectable values generally occured in areas affected by inflow and waste discharges like the Houston Ship Channel, Clear Creek, and Texas City Turning Basin. Concentrations below detection limits were recorded in the San Jacinto River, Chocolate Bay and Cedar Bayou. No time trends were computed due to the sparse data.

Summary of Water Quality Trends

Ward and Armstrong (1992) summarized major alterations in water quality in the Galveston Bay system over the last several decades:

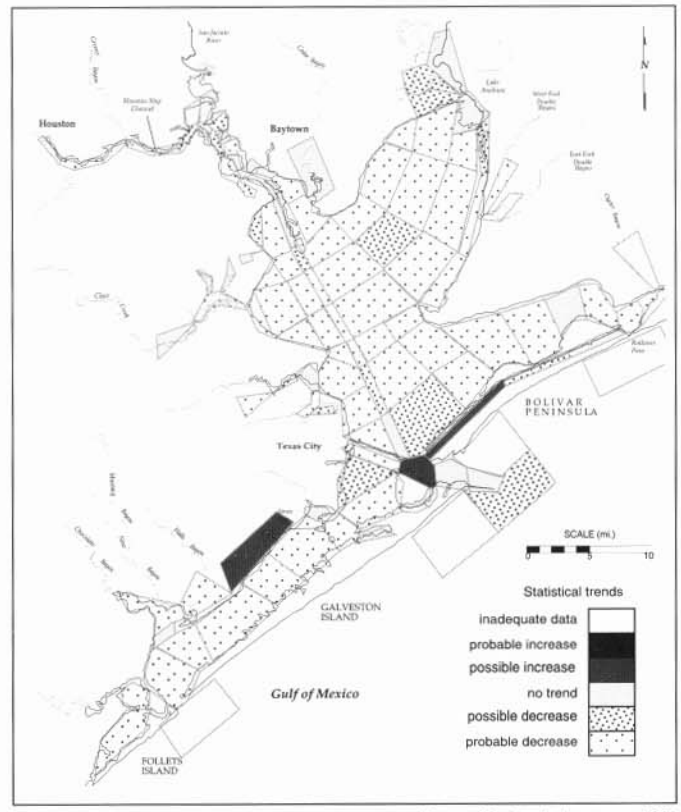
> Salinity has declined about 0.1-0.2 ppt per year over the three-decade period of record.
>
> Water temperature, especially in the summer, has declined at a nominal rate of 0.05°C/yr.
>
> Dissolved oxygen is generally high throughout Galveston Bay, averaging near saturation over extensive areas. Exceptions to this are in poorly flushed tributaries that receive runoff and waste discharges.
>
> Total suspended solids have declined throughout the system to levels roughly one-third of those 25 years ago.
>
> Declines in nitrogen and phosphorus concentrations throughout the bay have occurred over the past two decades, total ammonia nitrogen on the order of 0.1 mg/L/yr; total nitrate on the order of 0.01 mg/L/yr; and total phosphorus on the order of 0.05 mg/L/yr.
>
> Total organic carbon has declined to about one-third of its concentration in the mid-1970s, and chlorophyll-*a* to about one-half the level of a decade ago.
>
> Most metals in water and sediment have declined, particularly in areas of maximal concentrations, (the upper Houston Ship Channel), where the rates of decline per decade for sediment concentrations of chromium, mercury and zinc are a factor of two, copper and nickel a factor of three, and arsenic, cadmium and lead a factor of ten.
>
> Fecal coliform bacteria levels have generally declined over much of the bay due to improved/increased sewage treatment. Exceptions to this trend occur in a few isolated areas in West Bay, and the western urbanized tributaries of the bay system retain high bacterial levels.

In summary, the geographical problem areas of Galveston Bay 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 where it is degraded there is a general trend of improvement, in many cases substantial (see FIGURE 6.12 for summary of trends in the upper Houston Ship Channel).



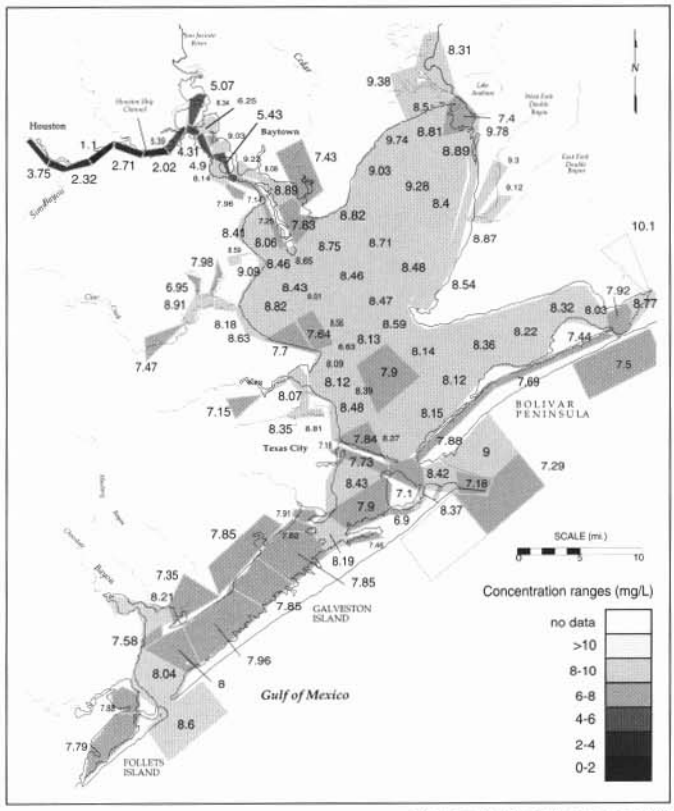
Source: Ward and Armstrong, 1992

FIGURE 6.4a. *Average concentration of total suspended solids in Galveston Bay, 1950-1990.*



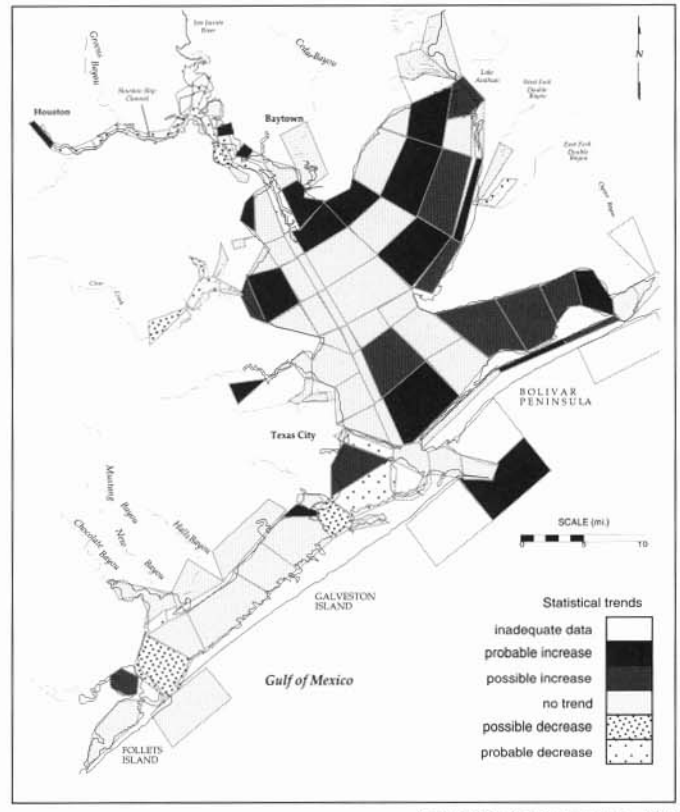
Source: Ward and Armstrong, 1992

FIGURE 6.4b. *Statistical trends for total suspended solids in Galveston Bay, 1950-1990.*



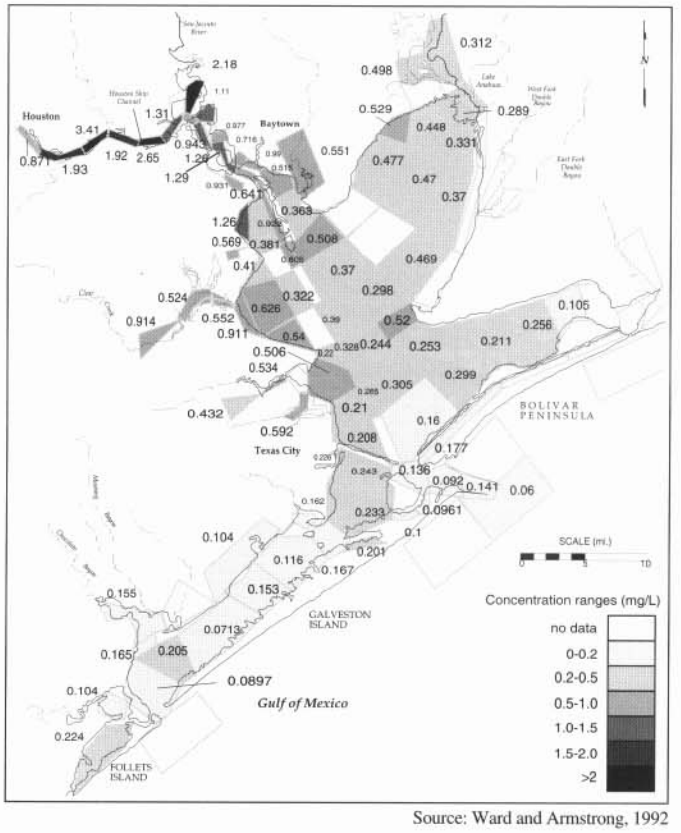
Source: Ward and Armstrong, 1992

FIGURE 6.5a. *Average concentrations of dissolved oxygen in the upper 0.5 m of Galveston Bay, 1950-1990.*



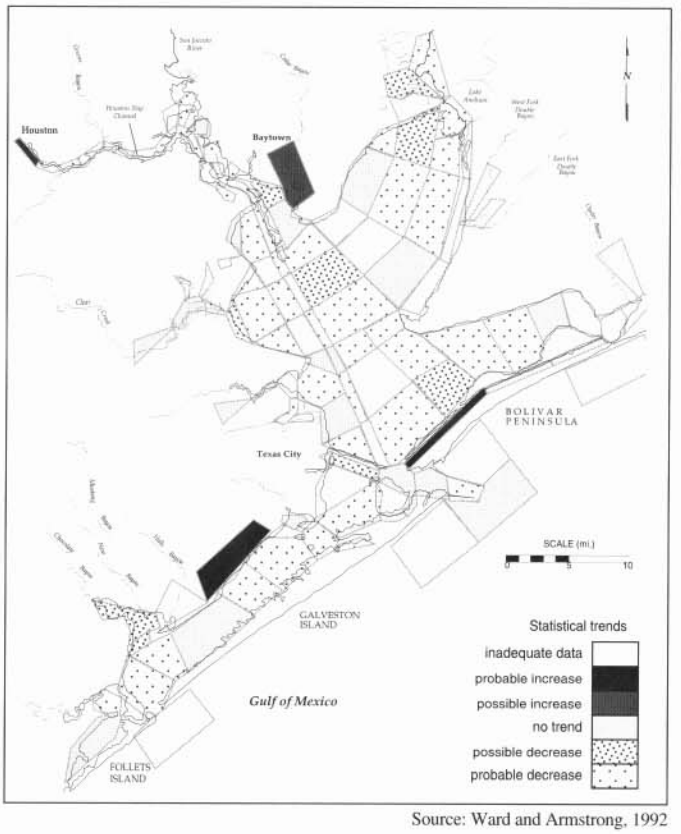
Source: Ward and Armstrong, 1992

FIGURE 6.5b. *Statistical trends for dissolved oxygen deficit in the upper 0.5 m of Galveston Bay, 1950-1990. Dissolved oxygen deficit is the difference between saturation level and the observed level.*



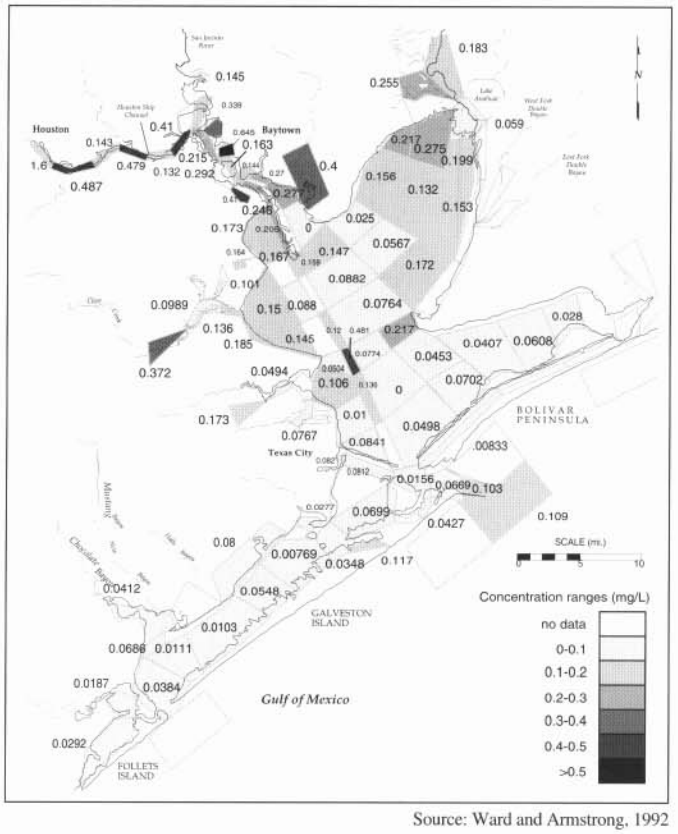
Source: Ward and Armstrong, 1992

FIGURE 6.6a. *Average concentrations of total phosphorous in water for Galveston Bay, 1967-1990.*



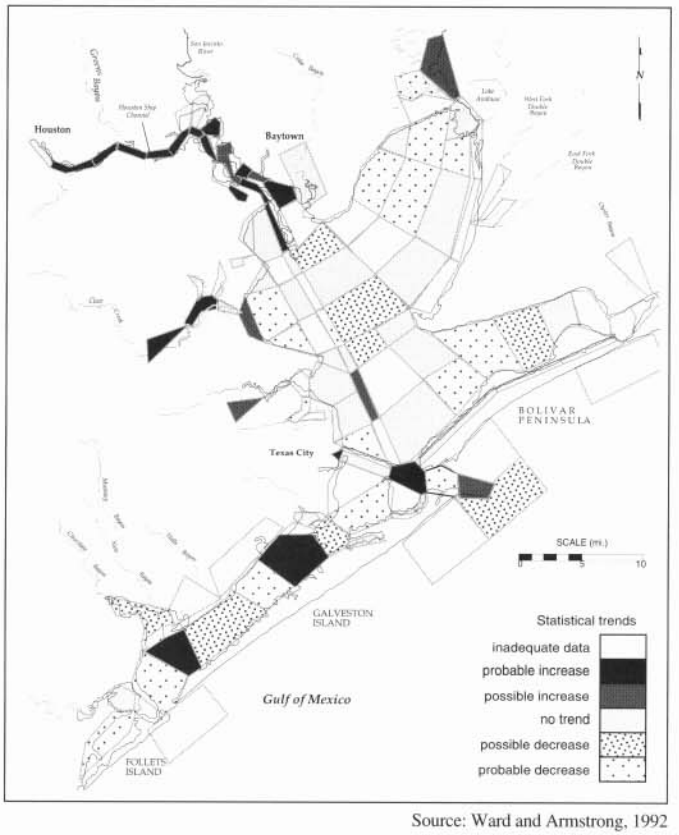
Source: Ward and Armstrong, 1992

FIGURE 6.6b. *Statistical trends for total phosphorus in water for Galveston Bay, 1967-1990.*



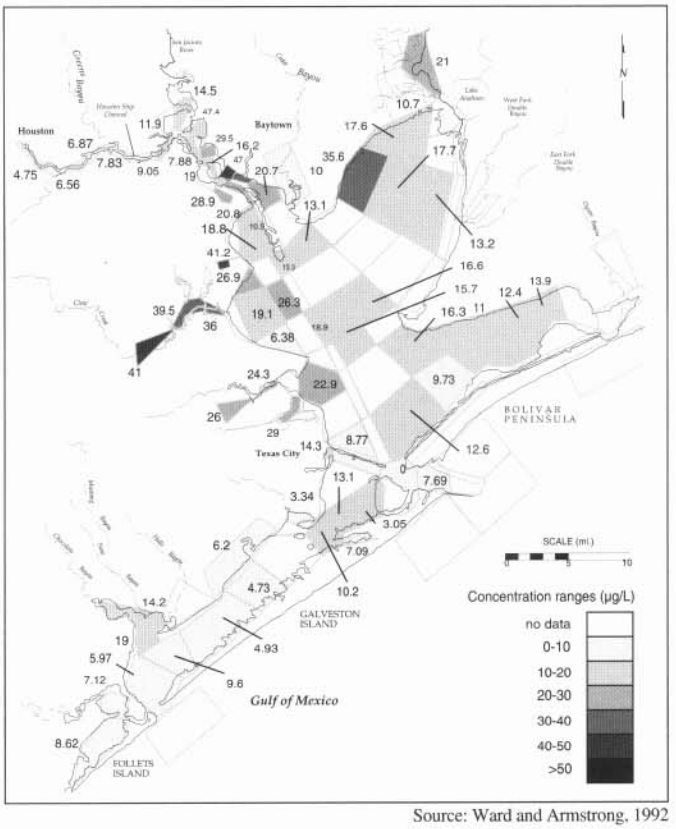
Source: Ward and Armstrong, 1992

FIGURE 6.7a. *Average concentrations of nitrate (NO_3) in water for Galveston Bay, 1967-1990.*



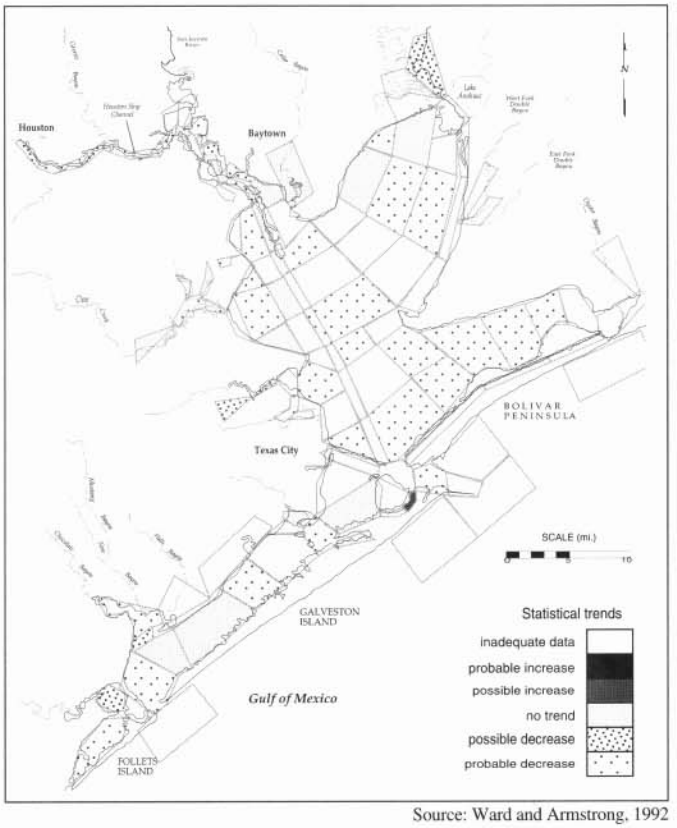
Source: Ward and Armstrong, 1992

FIGURE 6.7b. *Statistical trends for nitrate (NO_3) in water for Galveston Bay, 1967-1990.*



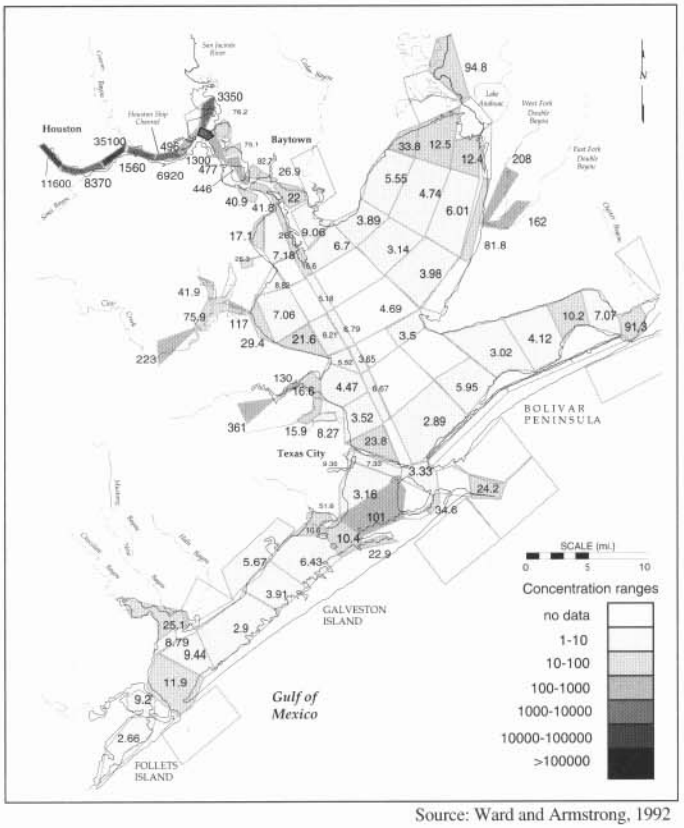
Source: Ward and Armstrong, 1992

FIGURE 6.8a. *Average concentrations of chlorophyll-a in water for Galveston Bay, 1967-1990.*



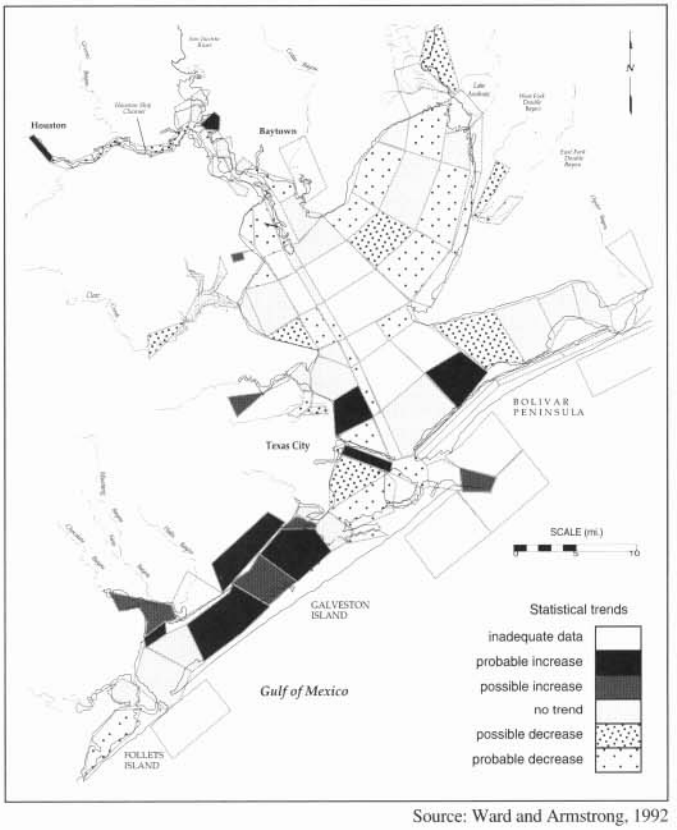
Source: Ward and Armstrong, 1992

FIGURE 6.8b. *Statistical trends for chlorophyll-a in water for Galveston Bay, 1967-1990.*



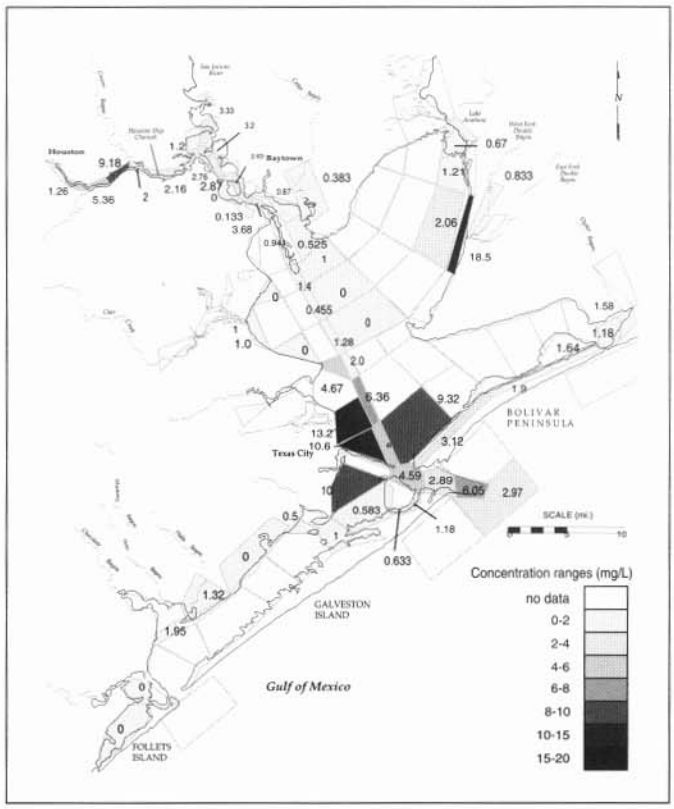
Source: Ward and Armstrong, 1992

FIGURE 6.9a. *Geometric mean concentrations of fecal coliform bacteria in water for Galveston Bay, 1968-1991.*



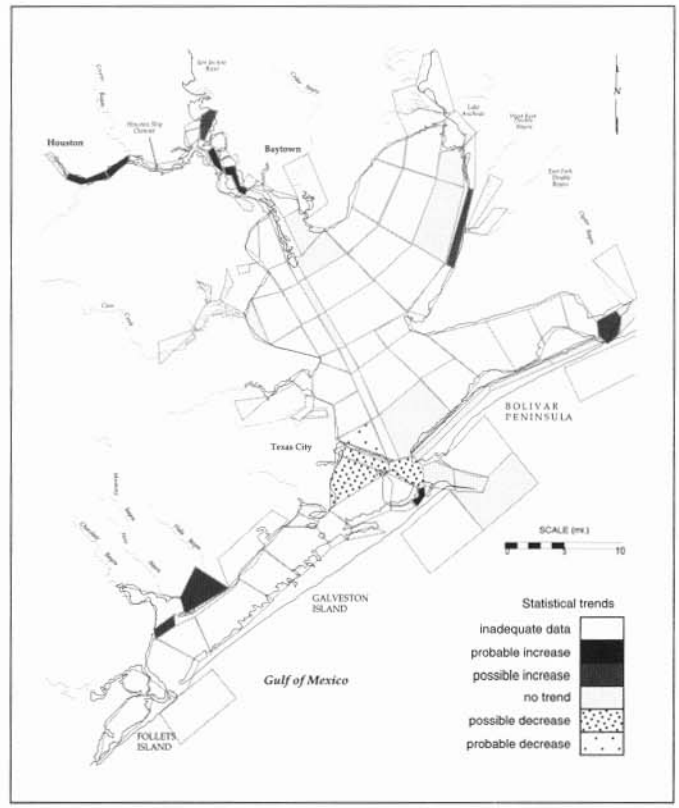
Source: Ward and Armstrong, 1992

FIGURE 6.9b. *Statistical trends for fecal coliform bacteria concentrations in water for Galveston Bay, 1968-1991.*



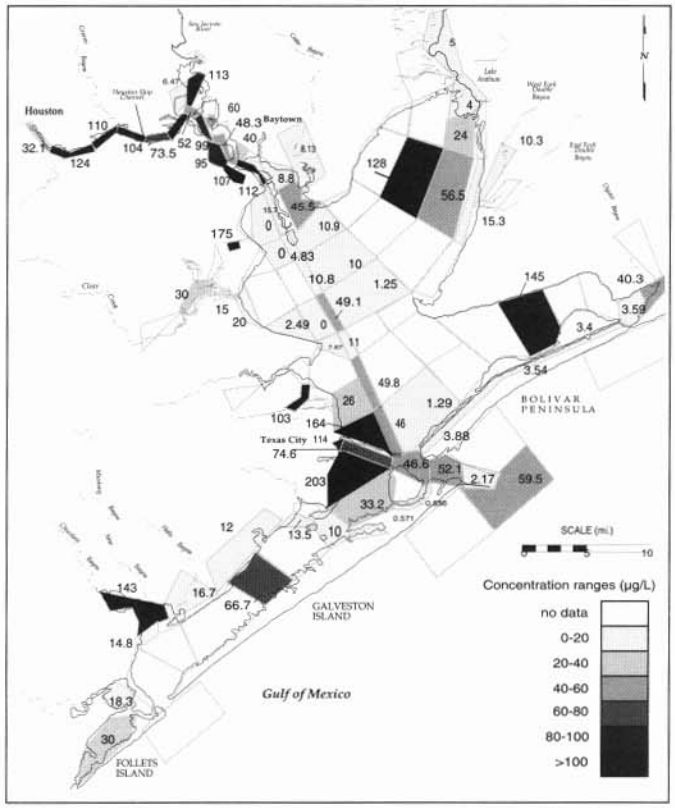
Source: Ward and Armstrong, 1992

FIGURE 6.10a. *Average concentrations of oil and grease in water for Galveston Bay, 1974-1988.*



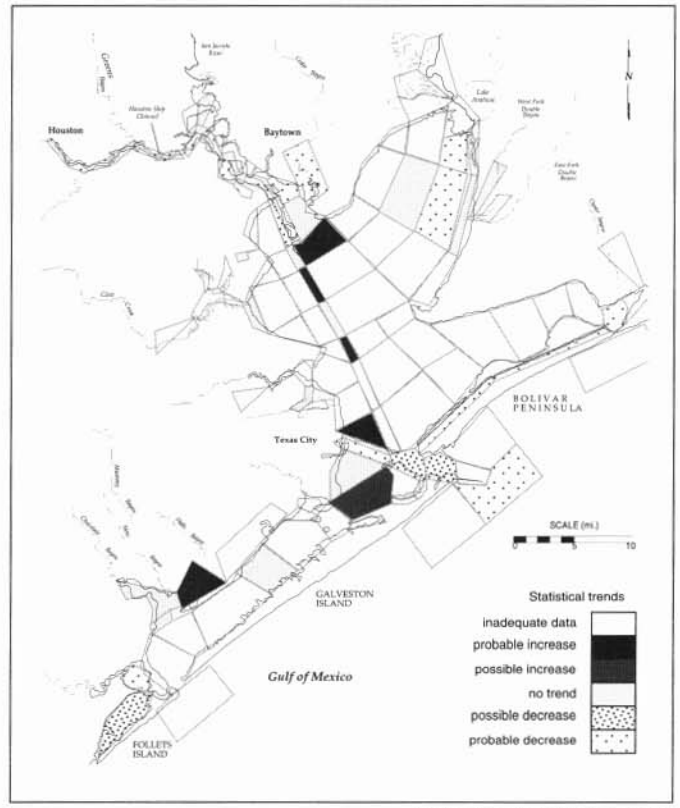
Source: Ward and Armstrong, 1992

FIGURE 6.10b. *Statistical trends for oil and grease in water for Galveston Bay, 1974-1988.*



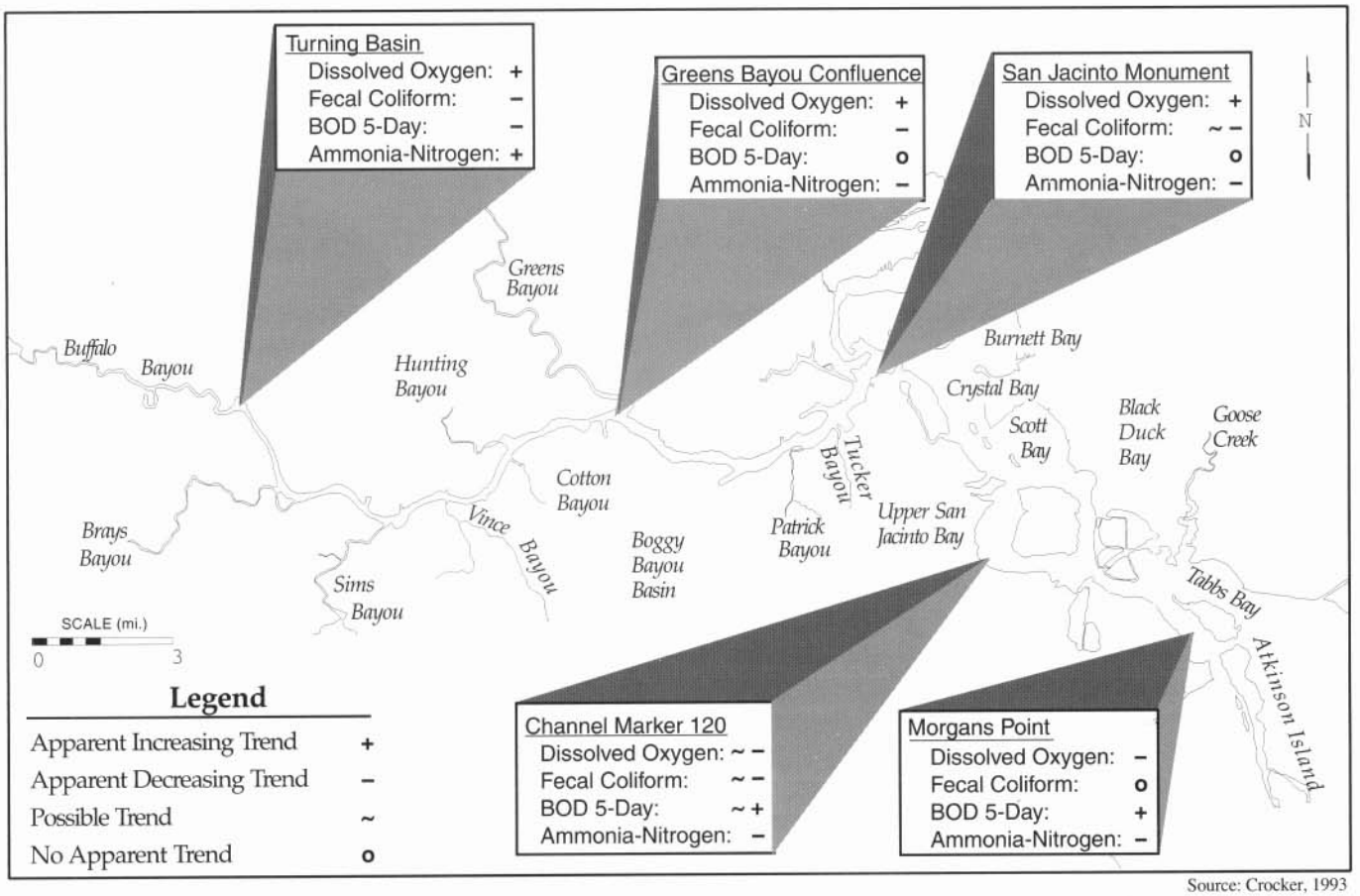
Source: Ward and Armstrong, 1992

FIGURE 6.11a. *Average concentrations of total copper in water for Galveston Bay, 1967-1990.*



Source: Ward and Armstrong, 1992

FIGURE 6.11b. *Statistical trends for total copper in water for Galveston Bay, 1967-1990.*



Source: Crocker, 1993

FIGURE 6.12. *Water quality trends at several locations in the upper Houston Ship Channel. Period of record for the listed parameters varied, but in general corresponds to a ten to 20 year history.*

Violations of State Standards and Federal Criteria

Ward and Armstrong (1992) compared the compiled bay data set to current Texas Natural Resource Conservation Commission *Surface Water Quality Standards* (which are segment-specific and legally enforceable; see TABLE 6.1) and Environmental Protection Agency water quality criteria (which are more general in nature). They tabulated the violations of these standards, and indicated that these exceedances "may be indicative of degraded water quality." The *Standards* require certain measurement protocols and frequencies to establish violations. While the historical data do not necessarily meet these requirements, standards exceedances can nevertheless indicate possible problems.

Temperature

Since 1985, there have been violations of the 95°F (35°C) standard in two segments, both in the upper Houston Ship Channel. The frequency of violation is on the order of five percent for these two segments.

Dissolved Oxygen

In the open bay and other segments with a four or five mg/L DO standard, there were scattered violations representing some two percent of the data. These violations were concentrated in areas near outflows and wastewater treatment discharges, such as Chocolate Bay and the upper Houston Ship Channel downstream of the San Jacinto Monument. The three upper Houston Ship Channel segments that experienced severe DO depletion in the past have improved significantly in violation frequency. In Segment 1005, all violations of the past 2.0 mg/L standard have been eliminated (the standard is now 4.0 mg/L). Segment 1006 experiences about a ten percent violation rate in the upper reaches now, compared to over 50 percent prior to 1985. In the Turning Basin area (Segment 1007) most locations had less than a five percent frequency of violation of the current 1.0 mg/L standard. The standards set for dissolved oxygen on the upper Houston Ship Channel are the lowest for any waters of the state.

Fecal Coliform Bacteria

For tributary segments where the 200 colonies/100 mL standard applies, the frequency of violations was on the order of 30 percent of the data pre-1985. There was no systematic change between the pre-1985 and post-1985 data. Recent coliform measurements, however, may be biased to higher values as a sampling artifact, since in recent years (for regulatory purposes) the sampling was directed more to events which would be expected to cause increases in coliforms.

Among the bay segments, the most frequent violations for

Clear Lake, the upper Houston Ship Channel, the Trinity River, Chocolate Bayou and Galveston Channel. In the upper Houston Ship Channel, where the standard is 2000 colonies per 100 mL, there was a substantive reduction in the violation rate since 1985, though recent frequencies were still on the order of 35 percent. Violation of the 14 colonies per 100 mL criterion for oyster growing waters is discussed in Chapter Nine.

Metals

Metals data are difficult to interpret because: 1) most of the data is reported as total metals while the Texas Natural Resource Conservation Commission water quality criteria are for dissolved metals (Ward and Armstrong, 1992); 2) the data are sparse; and 3) traditional sampling methods and analytical techniques for heavy metals may have greatly overestimated the actual concentrations in estuaries (Benoit and Santschi, 1991; Santschi et al., 1993). When the existing total metals data were used to compare against the dissolved metals criterion, it appears that Galveston Bay is "at the threshold of what would be satisfactory for an estuarine regime" (Ward and Armstrong, 1992). However, if dissolved metals data from ultraclean analytical programs are examined, the ambient metal concentrations in Galveston Bay appear to be lower by a factor of ten than the state's chronic aquatic life criteria for zinc and lead and one-forth of the chronic criterion for copper (Benoit and Santschi, 1991).

Pesticides and Organics

Two of 18 measurements in two Houston Ship Channel segments exceeded the Environmental Protection Agency's criterion for chronic DDT concentration, 0.001 µg/L (one part per trillion). In three of the Ship Channel segments the PCB criteria for marine and fresh water environments were violated in eight of 16 measurements. Both these compounds are now highly regulated, but their high persistence is evident in the data.

Discussion

Ward and Armstrong (1992) noted that the above-stated trends in hydrographic parameters such as salinity and temperature are unexplained. They found no clear association between the decline in salinity and the volume of fresh water inflow. Hypotheses to account for the observations involve variations in the timing of inflow events and the associated salinity response, reduced salinities in the adjacent Gulf of Mexico, or reduced intensity of interaction between estuarine and Gulf waters. Hypothetical causes for the decline in temperature include alteration in climate (e.g., air temperature, wind, cloud cover) and altered interaction with the Gulf of Mexico.

Toxic contaminants are present in the waters of Galveston Bay, but their significance is difficult to assess. One tool utilized to assess toxicity is **toxicity testing**, in which live laboratory organisms are exposed to samples of bay water using standardized methodologies. Crocker (1991) conducted a water quality and ambient toxicity investigation of the upper Houston Ship Channel and San Jacinto River (Segments 1001, 1005, 1006 and 1007) and three tidal tributaries (Brays, Greens, and Sims Bayous). Results showed no significant chronic toxicity effects to sea urchins or sheepshead minnows. However, some toxicity was evident in algal and mysid shrimp tests. The recurring pattern of ambient toxicity indicated that water quality was variable and that the potential exists for impairment of the aquatic life use designated for segments 1001 (San Jacinto River Tidal) and 1005 (in the upper Ship Channel).

In the Environmental Protection Agency Ship Channel Study, water quality was observed to exceed standards and criteria for several parameters (Crocker, 1991). During warm weather, dissolved oxygen standards were not achieved in Segment 1005 and Segments 1006 and 1007 had pronounced **hypoxia** (low dissolved oxygen). Chemical-specific criteria exceedances were noted for ammonia, arsenic, copper, cyanide, lead, manganese, nickel, selenium, and total residual chlorine. However, these metals data are subject to the same limitations previously noted because they were not collected and analyzed using ultraclean techniques, and the analytical method used was subject to positive salinity interferences. Several organic priority pollutants were detected at low concentrations.

An overall trend of interest is the systematic decline in nutrients, suspended solids, and chlorophyll-*a* in the bay over the past several decades (Ward and Armstrong, 1992). The TSS decline may have resulted from a general pollutant load reduction due to a combination of advanced waste treatment, entrapment within reservoirs, and changing land use. There is some evidence that suspended solids from urban watersheds (such as Brays Bayou) have declined as construction activity has dwindled over the past 15 years in Houston. Nitrogen, and particularly phosphorus, have an affinity for fine-grain particulates (TSS), so their declines may be due to the same causes, although some of the decline in nitrogen concentrations could also be attributed to more stringent regulation of discharges.

Biologically, the nutrient declines appear to have led to associated declines in chlorophyll-*a* (Chapter Eight) and organic carbon due to reduced phytoplankton biomass. This may also be causing a slight increase in the dissolved oxygen deficit in parts of the bay (see FIGURE 6.5b). The optimal level of nutrients and primary productivity in Galveston Bay is a topic of ongoing debate. The trends may reflect desirable water quality improvements, or they may signal a warning that the base of the food chain, if trends continue, may be jeopardized. In either case, future monitoring of the involved parameters is crucial.

Several recommendations by Ward and Armstrong (1992) addressed data collection and management problems which have traditionally constrained bay managers. A need exists to recognize data collection as a collective enterprise among the various agencies, with improved altruism among scientists working in the estuary. Continuity of data in time and space, for a long period of record, are necessary for a basic understanding of the complex dynamics in the system; this need implies stable funding. The

diverse mandates of the agencies involved will always translate to differing data collection programs, but the potential for coordination of these programs is great. For example, the cost of putting a sampling crew on a specific station far outweighs the relatively small incremental cost of acquiring additional measurements for use by other agencies or investigators. Currently, the various data collection programs contribute to no overall bay monitoring goals or information syntheses; bay-wide studies currently require prodigious efforts to retrieve information sets individually from diverse agency sources.

SEDIMENT QUALITY

Estuarine sediments are a significant aspect of the overall environmental quality of Galveston Bay. Many materials introduced originally in a water phase have an affinity for sediment particles, for example phosphorus compounds and many organic toxicants. An equilibrium is established between the water and sediment concentrations of various compounds–an equilibrium that can be altered by both natural and human disturbances of the system. Sediments are an environmental sink (storage compartment) for many contaminants, and because sediments are also a biological habitat, food web uptake of toxicants can be influenced by sediment concentrations of these contaminants. Frequently, contaminants can be detected in analytical or toxicity testing of sediments, but neither type of test detects these contaminants or their effects in overlying water from the same location. Overall, the role of sediments in the fate and effects of environmental contaminants is complex, dynamic, and incompletely understood.

The analysis by Ward and Armstrong described above for water quality was also applied to existing sediment data. The sediment analyses, however, were hampered by sparse data and a predominance of measurements below analytical detection limits. The concentration ranges reported are representative only of the collected samples and may not be representative of the entire bay, due to the fact that large areas of the bay remain unsampled. Likewise, the data scarcity imposed statistical limitations on the trend analyses, making any trends (even if they actually exist) difficult to identify. Sediment findings are summarized in FIGURES 6.13–6.15, which follow the same rationale as for water quality parameters, and for which concentrations below the detection limit were assigned a value of zero.

Sediment Quality Status and Trends

In Galveston Bay sediments, metals and commonly measured organic compounds (such as total phosphorus, oil and grease, Kjeldahl nitrogen, and volatile solids) appear to follow the same general spatial distribution as most of the water quality parameters. Elevated concentrations occur in regions of runoff, inflow and waste discharges, and lower, more-or-less uniform concentrations in the open bay, with the Houston Ship Channel generally the focus of maximal concentrations in the system (Ward and Armstrong, 1992). Specific findings are given below.

Total Phosphorus

Total Phosphorus concentrations for the few segments that were sampled ranged from below 200 mg/kg to greater than 1000 mg/kg in the upper Houston Ship Channel. Sediment phosphorus content is not always meaningful for silts, clays, and muds, which tend to have generally high absorbed phosphorus. There were virtually no phosphorus data for sediments from open bay segments.

DDT

DDT concentrations in the bay ranged from less than one µg/kg to more than 30 µg/kg (FIGURE 6.13). The highest DDT levels were in the upper Houston Ship Channel and near other points of inflow (Cedar Bayou, Clear Creek and the Trinity River). Two segments in the upper Houston Ship Channel were noteworthy for their elevated DDT concentrations of 154 and 467 µg/kg. For this parameter, data were inadequate for a meaningful trends analysis.

Oil & Grease

Oil & Grease concentrations ranged from less than 1,000 mg/kg to greater than 5,000 mg/kg in the upper Houston Ship Channel. Only five segments within the bay itself had oil and grease concentrations which exceeded 2,000 mg/kg: one segment in Trinity Bay, two segments near Clear Lake, one segment near the Texas City Dike, and one segment near Chocolate Bayou (FIGURES 6.14a and 6.14b).

Metals

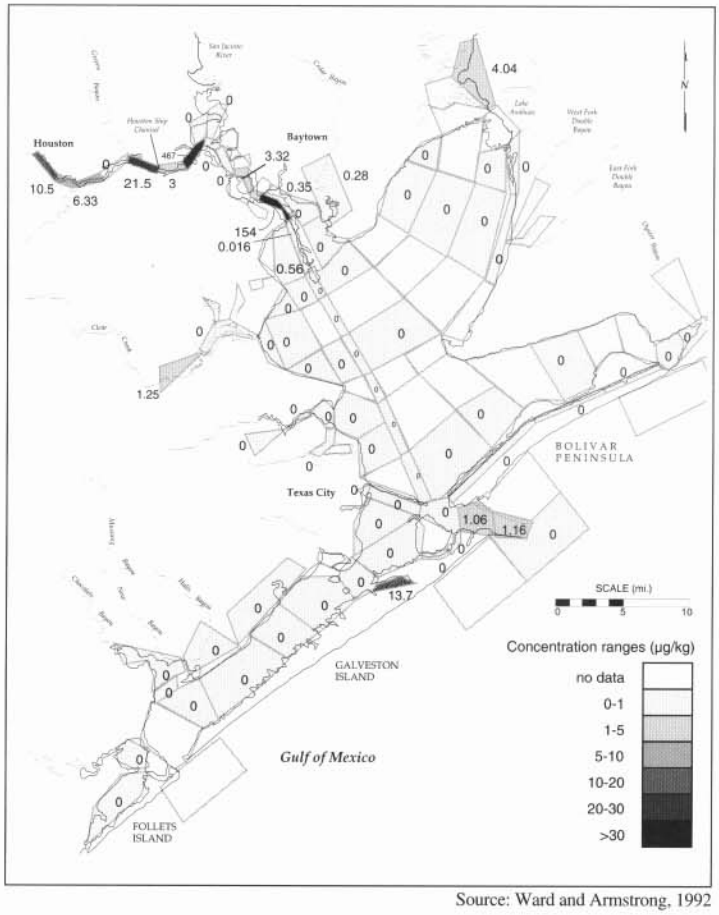
Copper concentrations ranged from below ten µg/kg to greater than 50 µg/kg. The higher concentrations (greater than 30 µg/kg) were associated with the upper Houston Ship Channel, Trinity Bay, Clear Lake, and the Texas City Dike (FIGURES 6.15a and 6.15b). Zinc concentrations ranged from less than 50 µg/kg to greater than 250 µg/kg, with highest concentrations in the upper Houston Ship Channel and Trinity Bay. Other mean concentrations included: mercury–0.005 to 0.5 µg/kg; lead–ten to 50 µg/kg; and chromium–20 to 100 µg/kg.

PCBs

Approximately ten percent of the bay has been sampled for PCBs, yielding an average sediment concentration of 76.8 µg/kg (282 samples, for which 233 samples below the analytical detection limit were assigned a concentration of 0). By using this average over an area equivalent to ten percent of the bay's area and applying a range equal to two orders of magnitude to account for uncertainty, a preliminary estimated range for the total weight of PCBs in bay sediments is between 830 and 83,000 kgs.

Summary of Sediment Status and Trends

Highest metals concentrations were found in upper Houston Ship Channel sediments. Clear Lake and, to a lesser extent, Dickinson Bayou sediments also contained elevated concentrations, especially arsenic, copper and mercury. Sediments in the vicinity



Source: Ward and Armstrong, 1992

FIGURE 6.13. *Average sediment concentrations of DDT in Galveston Bay, 1971-1990. Data were inadequate for a meaningful trend analysis.*

of the Trinity River in upper Trinity Bay contained relatively low concentrations of metals. Chromium and lead were generally elevated in sediments throughout Galveston Bay, relative to data compiled in Moore and Ramamoorthy (1984) typifying natural aquatic systems. Arsenic, cadmium, mercury, copper, zinc, and nickel were generally low in the open bay.

Excepting arsenic, trends for the metals are generally downward. This is especially true in the upper Houston Ship Channel where arsenic is also declining. In the channel, the rates of decline over a decade are sufficient to reduce sediment concentrations of chromium, mercury and zinc by a factor of two; copper and nickel by a factor of three; and arsenic, cadmium and lead by a factor of ten (Ward and Armstrong, 1992). One notable exception to this general improvement is the segment just north of the Texas City Dike, which shows increasing trends in arsenic, chromium, lead, nickel and zinc.

In a recent EPA study (Crocker, 1991), Houston Ship Channel bottom sediments were relatively nontoxic to test amphipods and sheepshead minnows, excepting three sampling stations. Environmental Protection Agency priority pollutants were not detected in sediments, but a variety of metals and organic priority pollutants were detected in edible fish and crab tissue at concentrations below levels of concern.

Sediments may constitute a long-term continuing source of PCBs and PAHs, even after sources are reduced or removed. Manufacture of PCBs in the U.S. was banned by the Toxic Substances Control Act of 1976, but certain existing uses of PCBs are currently allowed under controlled conditions. PAHs may largely be associated with combustion products and urban oil and grease (crankcase oil) and tend to be associated with sediments. Atmospheric deposition and precipitation of such pollutants as PCBs, mercury, and PAHs to Galveston Bay requires further study, but are increasingly being recognized as significant in other parts of the country.

Recent 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 µg/g) for most of the samples except a few stations with detectable concentrations of PCBs. The concentration of the pesticides Aldrin, Dieldrin, Endrin and Mirex were below detection limits for all stations. PAHs were elevated at a number of sites; specifically at three sites adjacent to produced water separator platforms. Additional results from the Carr study are presented below and in FIGURE 6.16.

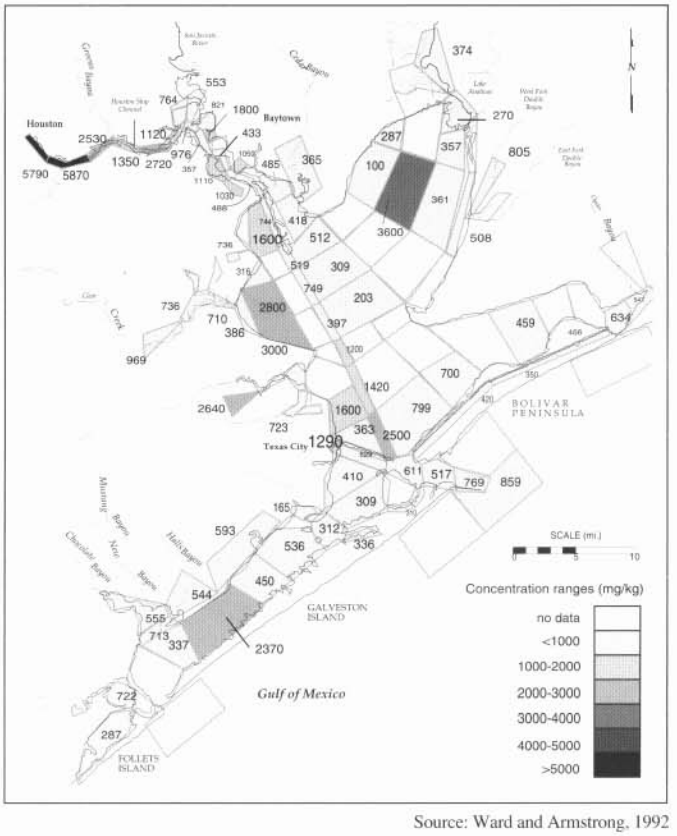
Sediment Toxicity

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. Ultimately, food chain concentration of sediment contaminants can affect humans through consumption of seafood taken from the estuary.

To address some aspects of sediment toxicity, Carr (1993) conducted a sediment quality triad study of Galveston Bay. The triad approach involves collection of three different sorts of data from each location, producing amore comprehensive description of toxic contamination than any measurement alone. The three types of measurements utilized were: 1) chemical analysis for specific contaminant concentrations in sediment; 2) toxicity testing of sediments and sediment pore water using standard living laboratory organisms; and 3) abundance and diversity of the natural bottom-dwelling community.

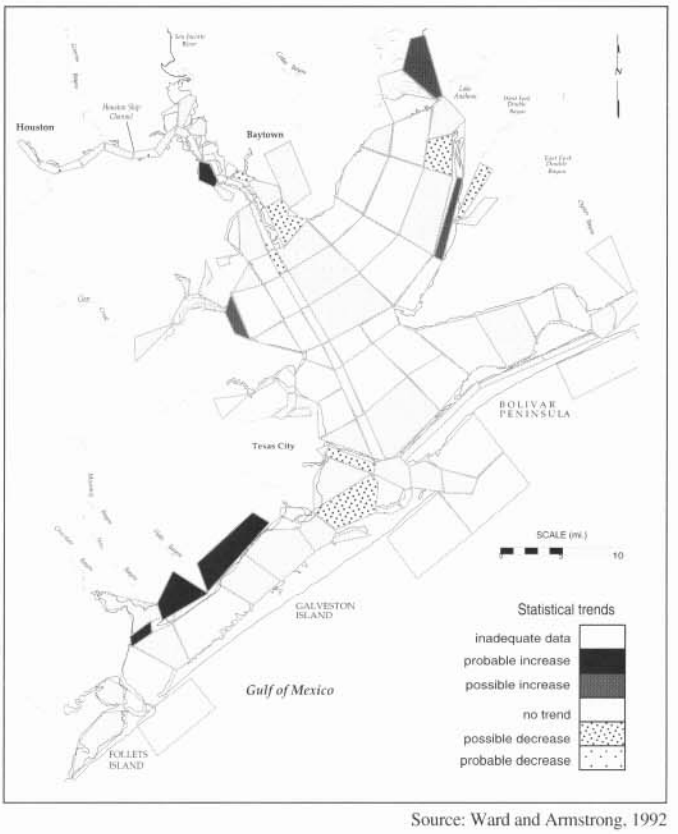
In the study, sediments were analyzed for trace metals, PAHs, chlorinated hydrocarbons, total organic carbon (TOC), and acid volatile sulfides. Two different toxicity tests were employed: 1) an American Society for Testing Materials (ASTM) method, in which a benthic amphipod was exposed to actual sediments (solid phase) to determine toxic effects; and 2) a method exposing sea urchin gametes to sediment porewater to determine toxic effects. To determine benthic community structure, organisms were identified and counted from core samples using standard benthic techniques.

The two types of sediment toxicity test yielded contradictory results. The ASTM method showed no toxicity at any station, while the porewater/sea urchin test showed significant toxicity for



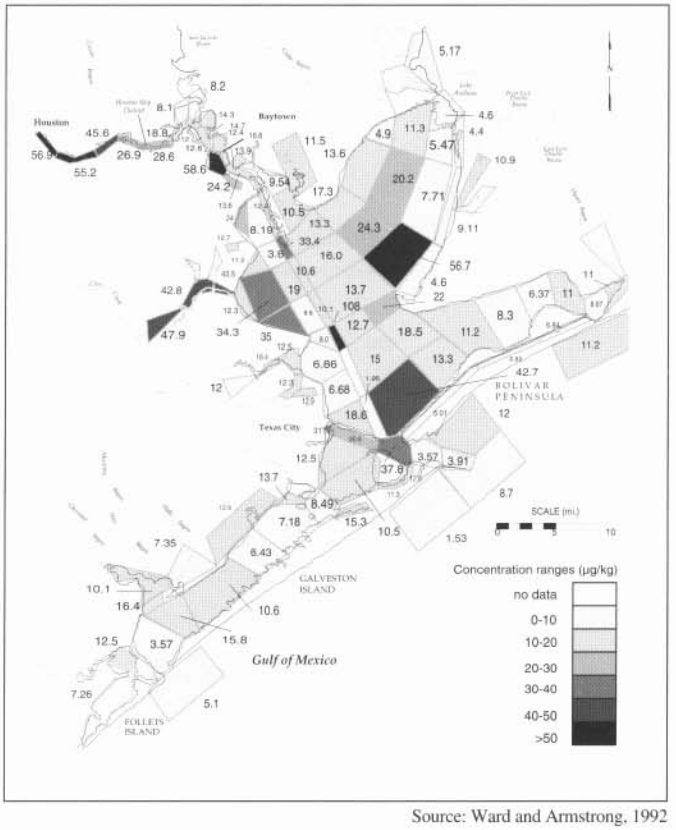
Source: Ward and Armstrong, 1992

FIGURE 6.14a. *Average sediment concentrations of oil and grease in Galveston Bay, 1972-1988.*



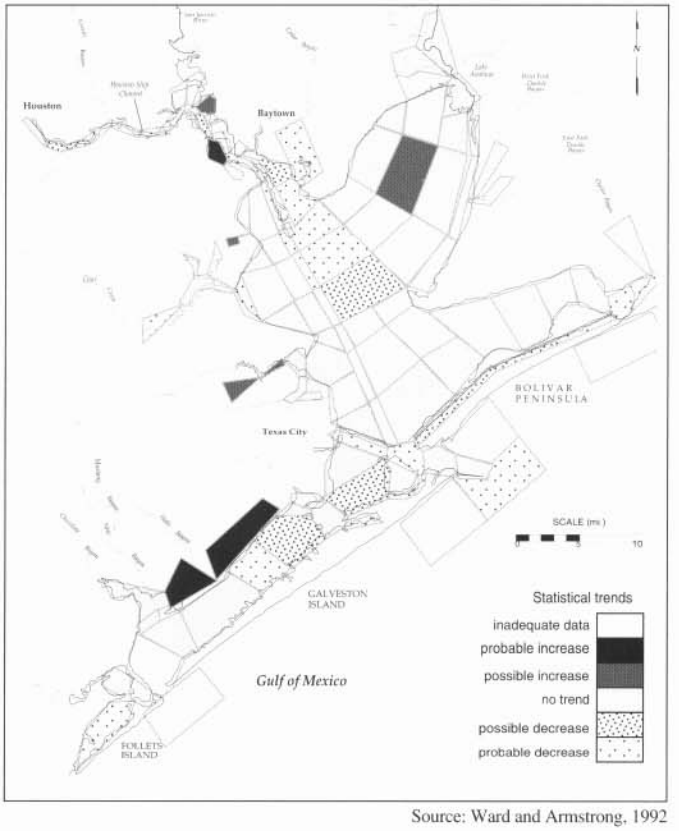
Source: Ward and Armstrong, 1992

FIGURE 6.14b. *Statistical trends for sediment concentrations of oil and grease in Galveston Bay, 1972-1988.*



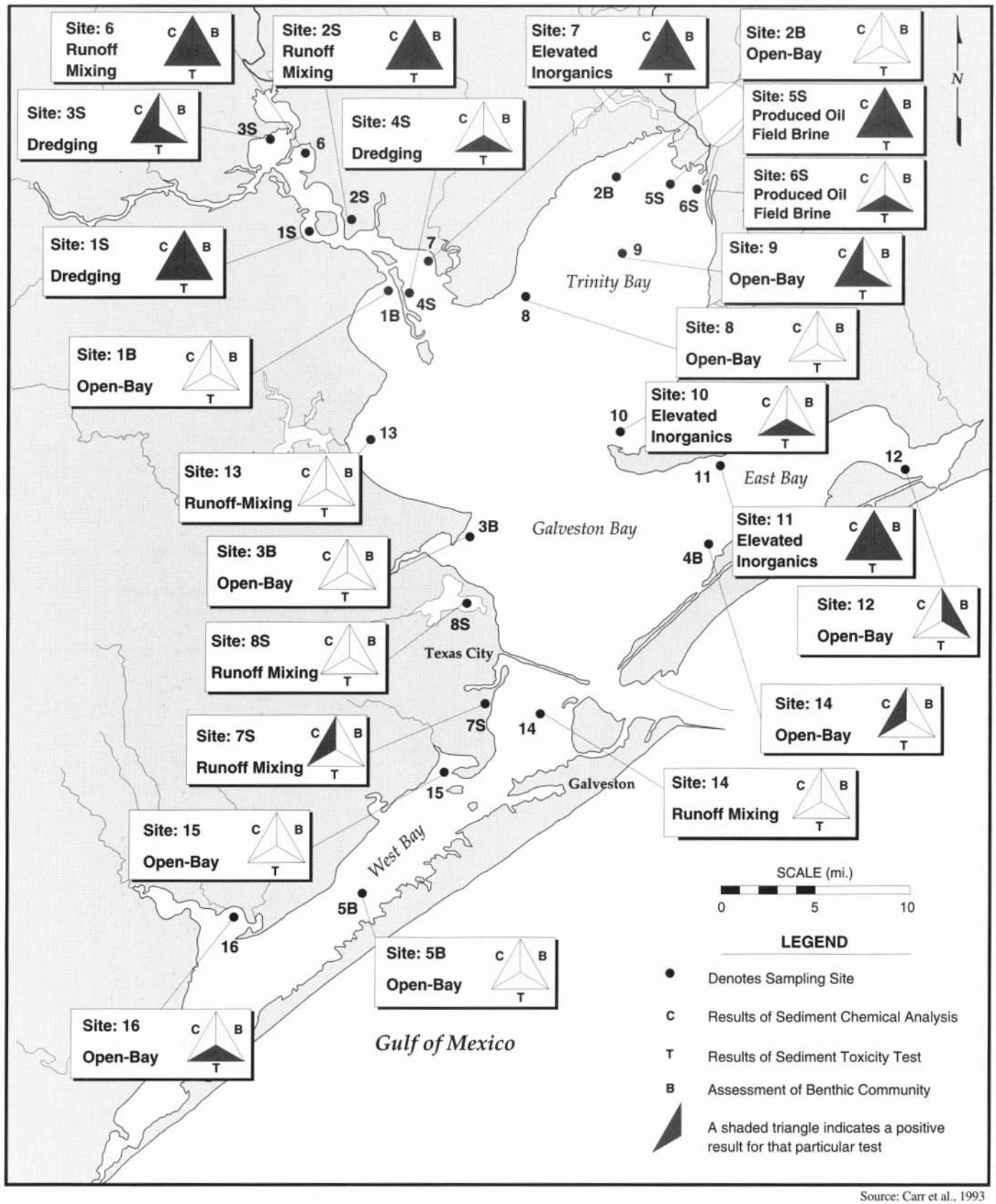
Source: Ward and Armstrong, 1992

FIGURE 6.15a. *Average sediment concentrations of total copper in Galveston Bay, 1967-1990.*



Source: Ward and Armstrong, 1992

FIGURE 6.15b. *Statistical trends for sediment concentrations of total copper in Galveston Bay, 1967-1990.*



Source: Carr et al., 1993

FIGURE 6.16. *Results of the Galveston Bay National Estuary Program Sediment Quality Triad Study. In the triad approach, chemical analysis of sediments, laboratory toxicity tests with live organisms, and the composition of the natural bottom-dwelling community give a comprehensive view of contamination. Most contamination was associated with known human activities, and was generally concentrated in the upper estuary.*

while the porewater/sea urchin test showed significant toxicity for 12 of the 24 sites. Using the more sensitive porewater/sea urchin testing method, all of five sites associated with dredge disposal of sediments showed toxicity, while only two of six sites associated with either urban or industrial runoff showed toxicity (FIGURE 6.16). Results also indicated sites sampled in the upper Houston Ship Channel were all highly degraded.

Sites adjacent to produced water separator discharges had high PAH concentrations and were highly toxic (see also the discussion of oilfield produced water in the point source section of this chapter). While the impact of these discharges decreased with distance from the outfall, the impact of chronic produced water discharges in shallow estuaries, such as Trinity Bay, was evident for some time after the discharge was discontinued, due to the accumulation and persistence of high molecular weight PAHs in sediments.

The study concluded that large expanses of bay bottom were in good condition. However, the presence of locations impacted from the specific industrial, petroleum, and dredging activities noted suggests the need for improved management of these activities.

Contaminant Potential of Dredged Material

Medina (1993) reported on the contaminant potential from the disposal of dredged maintenance material from the proposed project to widen and deepen the Houston Ship Channel. Samples were collected every 1000 feet along the entire 50-mi length of the channel, and were analyzed for chemical composition and grain size distribution. Every five stations were composited and analyzed for priority pollutants, while selected stations were analyzed for dioxin, a known contaminant north of Morgans Point. Toxicity tests and bioaccumulation analyses were also performed using Corps of Engineers/EPA guidance for testing dredged material.

Source: Pacheco et al., 1990

LEGEND

Point Source Discharge | Watershed Boundary | Stream | Water

FIGURE 6.17. *Major point source dischargers in the lower Galveston Bay watershed. Major dischargers are those which discharge more than one million gallons of wastewater per day; numerous other smaller point source discharges are not shown. Galveston Bay ultimately receives about 60 percent of the state's discharge wastewater.*

the range of historical data (which may include excessive concentrations), while organics were generally below detection levels. Dioxin was detected in one sample in very low concentrations. Water column toxicity tests from the open bay generally indicated little or no differences in organism survival between test and reference (control) sites.

An Interagency Coordinating Team (including representatives from the Corps of Engineers, Environmental Protection Agency, U.S. Fish and Wildlife, Texas Parks and Wildlife, and the Texas Natural Resource Conservation Commission) determined that "there are no contaminant concerns related to the dredging and disposal of maintenance material" from the proposed project (Medina, 1993). The group also concluded that there were no dioxin concerns with the dredged material.

HUMAN IMPACTS: POINT SOURCE DISCHARGES

The impacts of point source discharges on water and sediment quality in Galveston Bay have been studied for many years. Principal point sources include: permitted discharges (municipal and industrial), bypasses and overflows from municipal sewage systems, unpermitted or illegal discharges, and produced water discharges. This section describes each of these point sources and their respective impact on water quality in the bay. A brief discussion of fecal coliform bacteria is also included; bacterial concentrations in estuarine waters are affected by each point source identified (as well as by nonpoint sources).

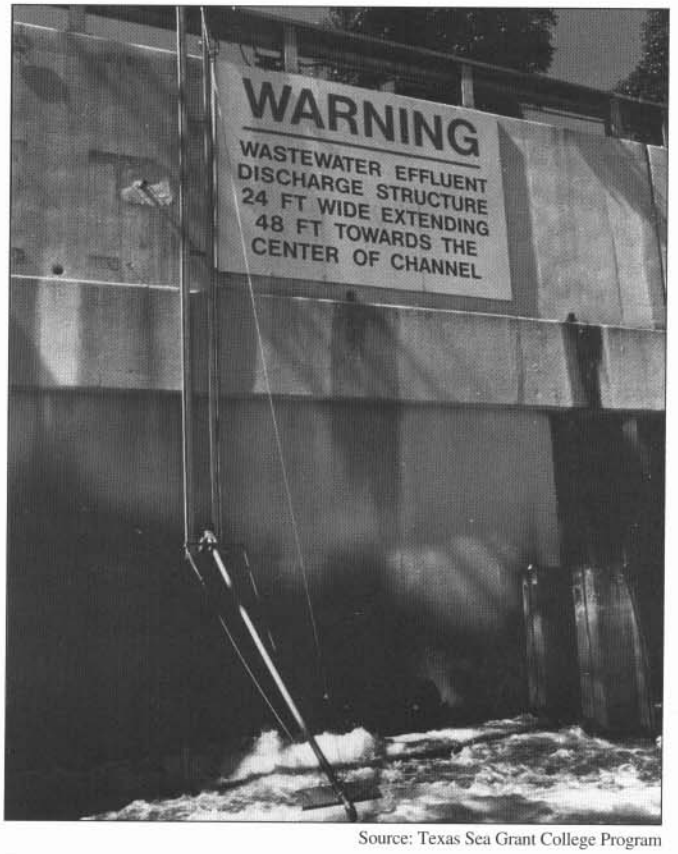
Permitted Discharges

Loadings to Galveston Bay from permitted point sources (FIGURE 6.17) were estimated by Armstrong and Ward (1994). Most discharge permits require the permittees to report their releases of some selected constituents (such as BOD and pH) in the effluent. This self-reporting data was the basis for most loading estimates calculated in the study. Because not all parameters are reported, particularly for smaller discharges, estimates for some constituents were made after the method of Pacheco et al. (1990), based on the expected effluent composition ("typical concentrations") for particular industries. This approach was used to estimate most of the loadings for the heavy metals and specific organic pollutants discussed below. In other cases (for example municipal wastes and rivers) estimates were based on correlations between reported constituent concentrations and flow.

Conventional Parameters

Annual loading estimates of each constituent reported in the 1990 self-reporting data are given in TABLE 6.2 (Armstrong and Ward, 1994). Over 1.356 trillion gallons (4,161,000 ac-ft) of wastewater were discharged to the Galveston Bay system per year, with 75 percent of this discharge from the cooling water from the Houston Lighting and Power plants located near Clear Lake, Trinity Bay, and mid-Galveston Bay. Pacheco et al., (1990) estimated that the overall "process" flow (total discharges with cooling water excluded) was 224 billion gallons per year, with the industrial and municipal components being 49 and 174 billion gallons per year, respectively. Armstrong and Ward (1994) estimated that the overall municipal wastewater discharge rate in 1990 was 135 billion gallons per year.

Biochemical and chemical oxygen demand loadings from permitted point sources amount to over 4.5 and 6.2 million kg/yr, respectively, with most of that going into the Houston Ship Channel/San Jacinto River. Total organic carbon, total suspended solids, and oil and grease follow similar patterns. Nitrogen and phosphorus are not all reported by these dischargers, making these nutrient loadings difficult to evaluate. From the limited data, ammonia appears to be the dominant form of nitrogen discharged. The reported quantities of phosphorus discharged are almost certain to underestimate the actual amounts discharged. No residual or free available chlorine or total dissolved solids loadings were reported.



Source: Texas Sea Grant College Program

The nation's third largest city produces a huge volume of treated wastewater. Here, the City of Houston's 69th Street Plant discharges to Buffalo Bayou in the upper bay system.

Priority Pollutants

Priority pollutants data were grouped by type of compound. Loadings for the phenols and substituted phenols are reported primarily as total phenols although several other forms are permitted. Some 2,800 kg/yr of total phenols (a derived estimate) were discharged to the bay, primarily into the Houston Ship Channel. Only two organonitrogen compounds had reported discharge data, and the amounts reported totaled 29 kg/yr into Segment 901. Minimal

TABLE 6.2. Constituent Loadings From Point Sources to the Galveston Bay System in 1990.

Segment[1]	Flow (Million Gallons/yr)	BOD5 (kg/yr)	Chemical Oxygen Demand (kg/yr)	Total Organic Carbon (kg/yr)	Total Kjeldahl Nitrogen (kg/yr)	Ammonia Nitrogen (kg/yr)	Phosphate Phosphorus (kg/yr)	Total Suspended Solids (kg/yr)
0801 - Trinity River Tidal	825	17,151				5,847		47,024
0802 - Trinity River below Lake Livingston	467	18,656						73,596
0901 - Cedar Bayou Tidal	3,845	58,579	272,412	14,991		37,290		108,968
0902 - Cedar Bayou Above Tidal	386	8,381	44,107					21,970
1001 - San Jacinto River Tidal	19,111	89,788	1,092,097		13,512	16,970		198,501
1005 - HSC/ San Jacinto River	7,778	631,097	214,303	1,018,939	401	264,089		862,787
1006[2] - HSC	67,993	911,155	3,152,204	249,009	198,058	155,791		2,080,112
1007 - HSC/ Buffalo Bayou	123,856	1,486,180	633,451	6,309,606	618,923	405,003	2,272	3,546,839
1013 - Buffalo Bayou Tidal	6,704	28,827	2,405	125	45,114	28,415		126,313
1014 - Buffalo Bayou Above Tidal	12,160	61,158	98	359	94,451	46,300	12	188,624
1101[3] - Clear Creek Tidal	3,003	12,278				10,866		28,915
1102 - Clear Creek Above Tidal	6,077	33,294				5,014	59	36,854
1103 - Dickinson Bayou Tidal	1,002	22,173		10,301		2,077		12,981
1104 - Dickinson Bayou Above Tidal	72	589				306		1,617
1105 - Bastrop Bayou Tidal	121	4,103						4,637
1107 - Chocolate Bayou Tidal	5,084	106,303	308,094	153,858				339,486
1108 - Chocolate Bayou Above Tidal	19	487						873
1113[3] - Armand Bayou Tidal	2,983	17,838				10,580		17,840
2421[2]- Upper Galveston Bay	436,928	34,173	7,913					43,607
2422[2,3] - Trinity Bay	417,649	2,714						5,145
2424 - West Bay	2,044	24,080						26,881
2425[2] - Clear Lake	117,648	927				65		1,989
2426 - Tabbs Bay	1,409	24,258	5,248		34,726	22,032		37,750
2427[2] - San Jacinto Bay	67,666	54,848	15,511	226,338	50,323	6,538	1,945	196,885
2429 - Scott Bay	106							
2430 - Burnett Bay	8	548	5,522					1,129
2431 - Moses Lake	2,758	75,788				85		97,906
2432 - Chocolate Bay	987	15,153						37,386
2436 - Barbours Cut	21				318	100		1,562
2437 - Texas City Ship Channel	7,490	454,881	484,347	333,443		61,239		848,364
2438 - Bayport Channel	5,172	164,470		696,482		23,072		400,661
2439 - Lower Galveston Bay	34,736	145,612	6,478	260,463		32,264		215,369
Discharge Totals	**1,356,108**	**4,505,489**	**6,244,190**	**9,273,915**	**1,055,825**	**1,133,941**	**4,288**	**9,612,571**

Source: Armstrong and Ward, 1994

[1]No data for East Bay, Black Duck Bay, Bastrop Bay/Oyster Lake, Christmas Bay, and Drum Bay

[2] Segments 1006, 2421, 2422, 2425, 2427 are influenced by cooling water discharges; HSC = Houston Ship Channel

[3]Segments 1101, 1113, and 2422 are subdivided, constituting a total of seven segments

amounts of the low and high molecular weight polycyclic aromatic hydrocarbons (PAHs) were reported. Of the chlorinated aromatic hydrocarbons, only chlorobenzene and 1,2-dichlorobenzene were reported to be discharged into Segment 901. No chlorinated aliphatic hydrocarbons, halogenated ethers, phthalates, or miscellaneous oxygenated compounds were reported discharged. One discharger of PCBs with an estimated discharge rate of 15.7 kg/yr of PCBs was identified in the Houston Ship Channel. It should be noted that the techniques for calculating the total loads for priority pollutants tended to overestimate discharges to the bay.

Over 1,800 kg/yr of chlorinated hydrocarbons were released by permitted point sources, mostly into the Houston Ship Channel and Cedar Bayou. Toluene was the major volatile aromatic hydrocarbon discharged, amounting to almost 37 kg/yr discharged into Segments 901 and 1107. Benzene was also released into Segment 1107. No volatile chlorinated aromatic hydrocarbons, volatile unsaturated carbonyl compounds, nor volatile ethers were reported as discharged. Metals discharges ranging from 0.19 kg/yr for silver to over 13,000 kg/yr for zinc were reported, with most of these discharges located in the Houston Ship Channel/San Jacinto River area.

Besides the study cited above, a second study of permitted point source discharges funded by the Galveston Bay Foundation presented additional data generated under the 1988 SARA Title III Section 313 Toxics Release Inventory program. McCormick (1991) estimated the loading of "toxic chemicals" (a legal definition) to the Houston Ship Channel using: 1) the list of specific chemicals provided in the Toxics Release Inventory regulations; and 2) self-reported data from 97 industrial dischargers collected under the Toxics Release Inventory program.

Twenty-nine of these industries self-reported discharges of 68 of 320 toxic substances listed under the Toxics Release Inventory program. Segment 1007, extending from Greens Bayou to the Turning Basin (14 miles long), received an estimated 380,000 kg/year of listed toxic chemicals. McCormick noted this estimate included parameters such as ammonia, ammonium sulfate, and several inorganic acids which are required by state and federal discharge permits to be neutralized prior to discharge. When these easily-neutralized inorganic chemicals are not considered, the annual discharge of listed toxic chemicals to Houston Ship Channel Segments 1005, 1006, and 1007 was estimated as about 123,000 kg/year (McCormick, 1991).

Bypasses and Overflows

Raw or partially treated sewage can be discharged into Galveston Bay waters through bypasses or overflows from municipal wastewater collection systems. Wastewater collection systems were not designed to convey stormwater (intended to be conveyed in storm drains or via surface drainage in the streets). During rains, water enters the collection system thorough cracks in pipes (public and private) and through manholes leaks that have developed over the years from soil settlement, corrosion of concrete pipe, and in some cases, poor construction practices. Sufficient rainwater can enter the collection system to cause an overload, resulting in overflows of diluted sewage from manholes or overflow structures specifically installed to provide system relief.

Loading Estimates

Estimation of the loadings to Galveston Bay from bypasses and overflows is a difficult task. Bypasses and overflows are notoriously under-reported, in part because they are worst during bad weather. Any methods used require assumptions which are not necessarily easy to verify.

From a historical perspective, a 1986 study (Winslow and Associates, 1986) estimated the relative contribution of different wet weather pollutant sources to the Houston Ship Channel by collecting over 500 samples of storm data from numerous streams, land use areas, wastewater treatment plants, and parts of the wastewater collection system. This effort indicated that the total BOD loading from bypasses and overflows to the Houston Ship Channel was 3.1 million kg/year. By comparing all the loading sources, the authors concluded that bypasses and overflows contributed approximately 11 percent of the annual BOD load, seven percent of the TSS load, and seven percent of the ammonia load to the Ship Channel in 1986. These loading estimates are no longer likely to be accurate, due to actions currently being undertaken by the City of Houston (described below).

Preliminary results from a more recent survey by Guillen et al. (1994) documented the occurrence and magnitude of partially-treated effluent loadings from the immediate bay watershed. In 1991, a total of 789 reported bypass incidents accounted for 237.3 million gallons of partially treated sewage discharge; in 1992, 578 reported instances resulted in an estimated 451.0 million gallons of discharge. The majority (85 percent to 93 percent) of these bypasses occurred in the San Jacinto Watershed (excluding the area above the Lake Houston dam). Assuming these discharges have a composition similar to others which have been analyzed, an estimated 131,000 and 69,000 pounds of BOD were discharged during 1991 and 1992 respectively. In both cases the final amount that eventually reached the waterways and the final chemical composition was unknown. Many of the problems with collection systems were associated with infiltration during heavy storms and the general deterioration of older system components.

City of Houston Actions

Collection system overflows in the City of Houston currently occur in some locations as often as 20 times per year. This system consists of over 30 million feet of sewer in the public right-of-way, plus an approximately equal length of small-diameter pipe connecting private homes and businesses to the public sewer. The City of Houston is addressing this problem with an ambitious construction program to control wet weather overflows. The program consists of the construction of new relief sewers, treatment plant expansions, and the addition of wet weather facilities. In some locations, wet weather facilities will be designed to retain most stormwater flows in detention basins until after the storms have passed, and capacity once again exists in downstream sewers and treatment plants.

When the City of Houston system is constructed, untreated overflows will occur only during the largest rainfall events (greater than two to five year frequency storms). In addition to these facilities, the City of Houston has undertaken the largest sewer rehabilitation program in Texas (and possibly in the U.S.). This program will provide structural integrity to the sewer system and eliminate some of the stormwater flows currently entering the system. New design and construction practices will be utilized to minimize stormwater entry into the sanitary sewer system in the future.

Fecal Coliform Bacteria

All of the above point sources of waste water can contribute to the overall bacterial loading to Galveston Bay, however nonpoint sources are likely to be an even greater contributor. An analysis by Jensen (1992) focused on indicator fecal coliform bacteria inputs to Galveston Bay from permitted wastewater discharges, wastewater collection system leaks, overflows and excursions, partially treated wastewater from failed septic systems, and runoff from watershed areas.

Based on Jensen's analysis, treatment plants operating normally were not a significant source of fecal coliform bacteria. The study suggested that bypasses do not occur with sufficient regularity or magnitude to warrant quantification. Overflows and other collection system releases will continue to be a significant wet weather source of bacteria, but the data available suggest that it will be considerably less in the future than the estimates presented in Newell et al. (1992), which relied primarily on 1980s data. The contribution of fecal coliforms from malfunctioning septic systems is typically detectable only in the immediate locale, and then only during wet weather conditions (when other runoff sources will likely dominate anyway).

Unpermitted or Illegal Discharges

Fay et al. (1991) surveyed unpermitted discharges along nine shoreline segments of the Galveston Bay system and compared the magnitude of these unpermitted discharges to permitted discharges. The nine selected segments include Cedar Bayou (0901), Galveston Bay (2421), Double Bayou (unclassified segment), East Bay (2423), Chocolate Bayou (1107), Armand Bayou (1113), Dickinson Bayou (1103 and 1104) and Carancahua Lake and Bayou (unclassified segment). These nine segments were chosen to represent shorelines typical of the estuarine environment.

Fay et al. enumerated a total of 69 permitted discharges in the nine segments versus a total of 117 unpermitted discharges. The main permitted discharge types included oilfield related discharges, chemical and sewage plants, power plants and unknown/miscellaneous. Unpermitted discharge types, on the other hand, related to storm drains, dredge material, petroleum activity, lawn drainage, sewage discharge, and unknown/miscellaneous. A follow-up enforcement study by the Texas Natural Resource Conservation Commission indicated that most of the unpermitted discharges were not discharging illegally and were probably not a major source of pollution to the bay.

Produced Water

Produced water is an unwanted by-product of petroleum production (see box). On average, approximately nine barrels of water are recovered for each barrel of oil, although the "water cut" varies from well to well (one barrel = 42 gallons). The water-oil mixture from producing wells is separated by flotation or gravity separation in tank batteries, heat separation, skimming pits, or some combination of these methods, then is either re-injected underground or discharged to surface waters under a permit from the Texas Railroad Commission. The only discharges to surface waters permitted in Texas are coastal; inland produced brines are routinely disposed by injection due to potentially severe impacts to fresh receiving waters.

PRODUCED WATER IN GULF ESTUARIES

Oil field brines produced on the Texas coast range from slightly brackish to a salinity of five or six times seawater, with an ion composition skewed from both fresh and sea water. Brine typically contains soluble polynuclear aromatic hydrocarbons (PAHs) known to be toxic and carcinogenic, elevated metals, and radium-226 (in Texas, typically exhibiting less radioactivity than the minimum threshold for regulation as a Naturally Occurring Radioactive Material by the Texas Department of Health).

Typically, the coastal discharge of brine results in receiving water impacts that are more severe in enclosed areas with little circulation, and less severe in open water situations such as open bay waters or Gulf of Mexico. Typical impacts in estuaries include (Shipley, 1991; St. Pé, 1990; Roach et al., 1993a; 1993b; Caudle, 1993):

Hydrocarbons and salts contaminate sediments near discharges. Brines can be extremely dense, concentrating near the bottom and infiltrating the sediments. Sediment contamination is persistent for a period of years after discharges cease.

In sediments, toxicity severely depresses or eliminates benthic organisms to a substantial distance from discharges.

Fish populations and movements can be severely impacted, particularly in enclosed situations like bayous.

Hydrocarbons, including PAHs, are ingested and incorporated into the tissues of various aquatic organisms. Shorebirds feeding in the vicinity of brine discharges can accumulate significant body burdens of metals and hydrocarbons.

Marsh and other shoreline vegetation is killed or severely degraded by contact with brine.

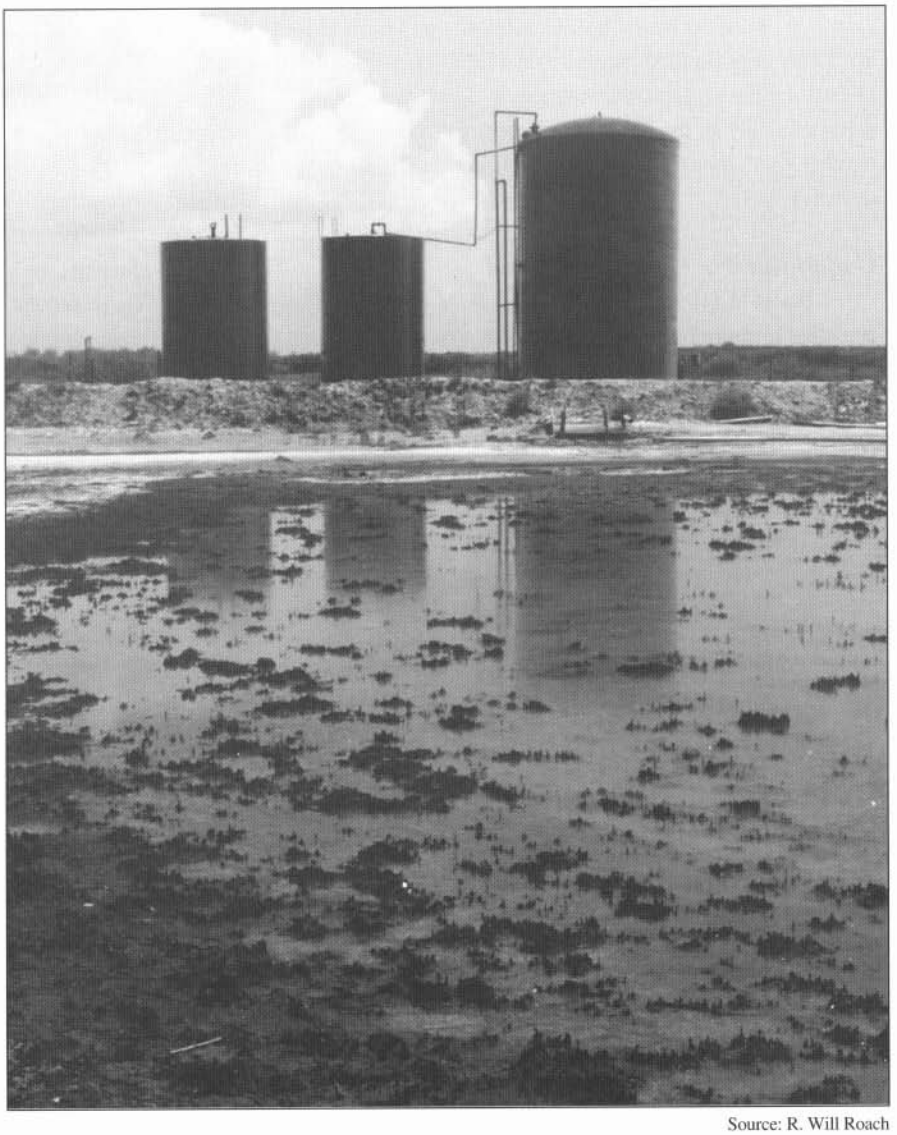
The Oil and Gas Division of the Texas Railroad Commission handles all permitting and enforcement for the discharge of produced water from oil and gas operations. Dischargers of produced brine in Texas are issued tidal disposal permits that allow up to 25 parts per million oil and grease, provided the discharge will not cause a violation of applicable Texas Surface Water Quality Standards, and which require permittees to report discharged volume and other information. Statewide Rule Eight, which includes a provision expressly forbidding pollution of offshore waters and adjacent estuarine zones, is the basis for actions concerning water pollution.

Texas Railroad Commission data indicates that some 93 discharges were permitted in 1991 to release up to 15.2 million gallons of produced brine per day to Galveston Bay and its tributaries. Of these, some 62 discharges were thought to be active, for an estimate of 5.8 million gallons per day actual discharge. Of this amount, however, approximately 3.4 million gallons per day were from one source, which voluntarily began deep-well injection in early 1993. Actual discharges into the bay vary greatly, depending upon the economic feasibility of oil production and the length of reservoir production (i.e., older fields yield proportionally more water).

Roach et al. (1993a; 1993b) evaluated some effects from produced water discharges to Galveston Bay. The study focused on impacts to sediments at Cow Bayou (a brackish urbanized bayou receiving a large volume of brine via ditch) and Tabbs Bay (an open-bay shoreline discharge location affected by wave action and tidal currents). Each location was sampled using a series of stations extending to several hundred meters from the discharge point, combined with reference stations for comparison, away from the discharges.

Data collected included: 1) number and kinds of benthic organisms; 2) analysis of sediments for petroleum hydrocarbons, metals, radium, and some other compounds; 3) toxicity tests on live laboratory organisms using both sediments (solid phase) and pore water extracted from sediments; 4) toxicity tests using sediment and water surface microlayer samples; 5) analysis of grass shrimp exposed to the samples for **stress proteins** (compounds that indicate sublethal environmental stress); and 6) analysis for PAH metabolites in bile of striped mullet collected at discharge locations (indicators of possible exposure to PAHs in the water column or via the food chain).

Findings reported by Roach, et al. (1993a; 1993b) included the following:



Source: R. Will Roach

Impacts resulting from produced brines from petroleum extraction include destruction of marsh vegetation due to excess salinity, shown here. Inland from the coast, produced waters are disposed by re-injection to the oil formation.

High concentrations of petroleum hydrocarbons, brine salts, and ammonia occurred in sediments near the discharges and generally decreased with distance from the discharge at both locations.

Benthic communities were non-existent or depressed near the discharge at both locations. The density of organisms, number of species, and community diversity (a mathematical index) all showed significant reductions extending to several hundred meters from the discharge.

Toxicity test results for two species of burrowing amphipods (sediments) and for sea urchin embryos/sperm (pore water) confirmed the toxicity of samples. Survival of both amphipods at the two stations nearest the Tabbs Bay discharge ranged from zero to about 20 percent, compared to some 90 percent for reference station samples.

Grass shrimp which survived exposure to re-suspended and whole sediments significantly accumulated two stress proteins for stations nearest the discharges.

Mullet from near both discharges had substantially higher concentrations of two PAH metabolites in bile than did comparison mullet from reference stations.

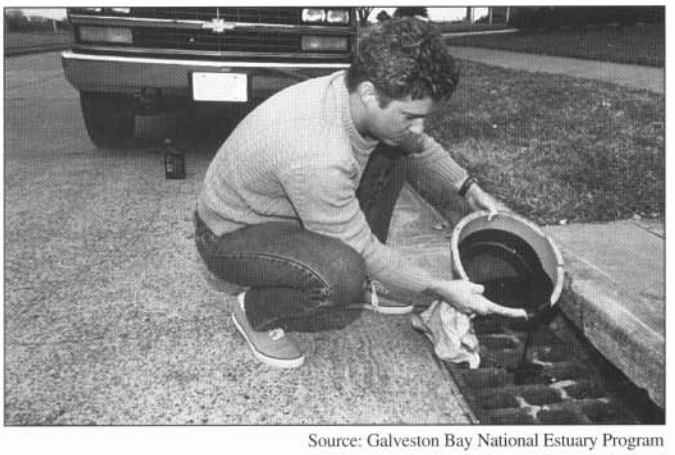
Although the Environmental Protection Agency does not currently regulate these discharges under its National Pollution Discharge Elimination System (NPDES), general NPDES permits for each of five discharge subcategories are currently being drafted. The subcategory of concern for the Galveston Bay system, the Coastal Subcategory, was issued on December 22, 1992 as a proposed rule, open for public comment. As currently drafted, this proposed rule would require "no discharge" to marshes, wetlands, swamps, bayous or coastal bays from all wells, including stripper wells.

HUMAN IMPACTS: NONPOINT SOURCES AND LOADINGS

Overview of Nonpoint Sources

We now know that the influx of conventional pollutants from point sources of wastewater peaked in the 1960s and has declined since. This is due in large part to the creation of the first federal Water Quality Act, and the subsequent permitting, compliance, and enforcement activities which began nearly three decades ago.

In contrast, all indications are that nonpoint sources of pollutants have steadily increased to the present day, and significantly influence the water and sediment quality in various portions of Galveston Bay. Effects of these pollutants are seen in low dissolved oxygen in urban bayous and other poorly flushed tributaries, possible toxic contamination from metals or trace organic compounds, and closure of about half of the bay to oyster harvest, due to elevated bacteria levels. The upper Houston Ship Channel remains a significant region of concern, due in large part to runoff from the greater Houston area. Nonpoint sources, because of their diffuse nature and association with runoff over extensive land areas, present a major management challenge (see box).



Source: Galveston Bay National Estuary Program

One of the bay's nonpoint sources of pollution. From stormwater runoff each year, the bay receives oil equivalent to a 130,000 barrel spill—an amount equating to 40 percent of the historic Exxon Valdez *spill. Much of this oil originates from parking lots and city streets, including what has been dumped down storm sewers since the last rainfall.*

For Galveston Bay, urban land uses in the lower watershed pose the greatest challenge in the NPS arena. In general, the net effect of urbanization is to increase pollutant export by at least an order of magnitude over pre-development levels (Schueler, 1987). A variety of urban sources have been generally identified as NPS contributors: bird and pet populations, street litter accumulation, tire wear of vehicles, oil from car crankcases, fertilizer and pesticide application, eroded areas, abrasion of road surfaces by traffic, and construction activities. Water quality constituents of concern

SOME GENERAL CHARACTERISTICS OF NONPOINT SOURCE POLLUTION

Nonpoint source pollution (NPS) has become the largest single factor in preventing attainment of water quality standards nationwide. Novotny and Chesters (1981) described some general characteristics of nonpoint source pollution:

Nonpoint source discharges enter surface waters in a diffuse manner and at intermittent intervals that are related mostly to the occurrence of rainfall.

Pollution arises over an extensive area of land and is in transit overland before it reaches surface waters.

Nonpoint sources generally cannot be monitored at their point of origin, and their exact source is difficult or impossible to trace.

Elimination or control of pollutants must be directed at specific sites.

In general, the most effective and economical controls are land management techniques and conservation practices in rural zones and architectural control in urban zones.

Compliance monitoring for nonpoint sources is carried out on land rather than in water.

Nonpoint source pollutants cannot be measured in terms of effluent limitations.

The extent of nonpoint source pollution is related, at least in part, to certain uncontrollable climatic events, as well as geographic and geologic conditions, and may differ greatly from place to place and year to year.

Nonpoint sources are derived from operations on extensive units of land, as opposed to industrial activities that typically use repetitive operations on intensive (small) units of land.

in urban runoff include sediments, nutrients, oxygen-demanding compounds, oil and grease, bacteria, heavy metals, and synthetic organic chemicals.

Nonpoint pollutant loading is closely tied to land use. Of all the urban land uses, low-density residential zones and open areas yield the lowest NPS loads, while highest pollution loads are associated with high-density commercial areas, industrial centers and, above all, construction sites. During construction activities considerable areas are stripped of vegetative cover, exposing open soil. The NPS loadings from construction areas can be an order of magnitude higher than other land uses, and can dominate the total NPS loadings in some watersheds.

In general, rural nonpoint sources are related to agricultural and silvicultural activities, such as fertilizer and pesticide application, tillage and logging. Since these operations do not occur continuously, nonpoint source loads from rural areas can fluctuate significantly from storm to storm. For many agricultural areas, high sediment and nutrient loads are observed in the spring, when plowing and agricultural chemicals are added to the soil. Much lower loads are observed after harvesting, when cultivated fields lie fallow or are grazed by livestock. Because major reservoirs on both the Trinity and San Jacinto are downstream of most agricultural activities in the watershed, these activities have limited influence on Galveston Bay.

Pollutant Loadings from Runoff

Until recently, no comprehensive estimates of nonpoint pollutant loadings to the Galveston Bay system were available. Recently, Newell et al. (1992) have provided such a study. NPS loads for a total of eight different water quality constituents in

Source: Newell et al., 1992

FIGURE 6.18. *Boundaries for watersheds (bold lines) and subwatersheds (fine lines) of the lower Galveston Bay watershed. These land units contribute variable types and amounts of pollutants to Galveston Bay during runoff. Land use generally determines the kind and severity of pollution, with the urban subwatersheds of greater Houston posing the greatest concern.*

TABLE 6.3. Nonpoint Source Loads to Galveston Bay by Land Use for a Year With Average Rainfall.

Constituent	Land Use Type								
	High Density Urban	Residential	Open	Agricultural	Barren	Wetlands	Water	Forest	Total
Runoff Volume									
1,000 ac-ft	766	371	567	593	21	187	164	345	3,014
(% of Total)	(25)	(12)	(19)	(20)	(1)	(6)	(5)	(11)	(100)
TSS									
Million kg	157	46	49	147	57	9	0	17	481
(% of Total)	(33)	(10)	(10)	(31)	(12)	(2)	(0)	(3)	(100)
Total Nitrogen									
1,000 kg	1,985	1,561	1,056	1,142	134	192	0	353	6,422
(% of Total)	(31)	(24)	(16)	(18)	(2)	(3)	(0)	(5)	(100)
Total Phosphorus									
1,000 kg	350	362	84	264	15	14	0	26	1,113
(% of Total)	(31)	(32)	(8)	(24)	(1)	(1)	(0)	(2)	(100)
BOD									
Million kg	8	7	4	3	0	1	0	3	26
(% of Total)	(31)	(26)	(16)	(11)	(1)	(5)	(0)	(10)	(100)
Oil and Grease									
Million kg	12	2	0	0	0	0	0	0	14
(% of Total)	(87)	(13)	(0)	(0)	(0)	(0)	(0)	(0)	(100)
Fecal Coliform									
$x10^{15}$ col	208	101	17	18	0	4	0	7	355
(% of Total)	(59)	(28)	(5)	(5)	(0)	(1)	(0)	(2)	(100)
Dissolved Cu									
kg	2,930	1,419	2,167	2,269	80	716	0	1,318	10,900
(% of Total)	(27)	(13)	(20)	(21)	(1)	(7)	(0)	(12)	(100)
Pesticides									
kg	378	183	70	73	3	0	0	43	749
(% of Total)	(50)	(24)	(9)	(10)	(0)	(0)	(0)	(6)	(100)

Source: Newell et al., 1992

runoff were calculated: sediment, nutrients (total phosphorous and total nitrogen), biochemical oxygen demand, oil and grease, fecal coliform bacteria, heavy metals, and synthetic organic constituents. Typical pollutant concentrations were estimated from available NPS data, in particular, data collected from previous Houston-area NPS studies. Total NPS loads were then calculated by multiplying runoff volumes estimated by a Soil Conservation Service hydrologic model (U.S. Soil Conservation Service, 1986) with the appropriate NPS concentration for each land use.

This study took a geographic approach to identify regions contributing the greatest NPS loadings to the bay system. For the study, the Galveston Bay watershed was divided into 21 watersheds and 100 subwatersheds (FIGURE 6.18). Three rainfall scenarios were formulated from rain gauge data in the basin: an average year, a wet year with a ten-year probability, and an individual storm. The rainfall amounts were transformed into runoff volume using the U.S. Soil Conservation Service curve number method.

Within the study area, land use was mapped using LANDSAT satellite image interpretation. (LANDSAT is an unmanned satellite system which acquires images of the earth's surface features.) A more detailed summary of land use in the local watershed is provided in Chapter Five, including a land use map (see FIGURE 5.2). The technology utilized produced a 30 m by 30 m resolution, allowing geographic information system calculation of subwatershed loadings for each constituent.

Geographic and Land Use Targeting of Nonpoint Sources

Within the study area, type of land use was the main factor determining loadings. For example, "high density urban" land uses across the watershed contributed approximately 87 percent of the annual oil and grease loading, 59 percent of the annual fecal coliform bacteria loading (estimate does not include overflow, the study was strictly a wash-off analysis), 31 percent of total nitrogen and total phosphorus loading, and 50 percent of the annual pesticide loadings from the study. Urban areas were also shown to be

TABLE 6.4. Nonpoint Source Loads to Galveston Bay for an Average Year by Watershed.

Watershed	Area (sq mi)	Runoff Volume (1,000 ac-ft)	Total Susp. Solids (Million kg)	Total Nitrogen (1,000 kg)	Total Phos-phorus (1,000 kg)	Bio-chemical Oxygen Demand (Million kg)	Oil and Grease (Million kg)	Fecal Coli-form ($x10^{15}$ Col)	Diss. Copper (kg)	Pesti-cides (kg)
Addicks Reservoir	134	82	22	195	36	0.7	0.4	9	312	20
Armand/ Taylor Bayou	77	70	12	167	29	0.7	0.5	11	255	22
Austin/ Bastrop Bayou	213	121	21	245	44	0.9	0.2	9	442	21
Barker Reservoir	122	71	32	181	31	0.6	0.2	6	271	14
Brays Bayou	127	147	29	406	75	1.7	1.7	34	561	63
Buffalo Bayou	105	116	22	337	65	1.4	1.3	27	445	51
Cedar Bayou	211	153	26	321	58	1.2	0.3	13	576	30
Chocolate Bayou	170	95	19	188	36	0.6	0.1	5	354	15
Clear Creek	182	138	22	301	51	1.2	0.7	16	503	34
Dickinson Bayou	101	60	8	130	21	0.5	0.2	6	223	13
East Bay	288	193	26	388	68	1.6	0.5	17	679	36
Greens Bayou	209	184	30	497	92	2.1	1.4	34	702	66
North Bay	25	25	4	65	11	0.3	0.2	5	94	9
San Jacinto River	68	65	8	126	22	0.5	0.2	7	202	14
Houston Ship Channel	166	198	34	498	90	2.0	1.9	39	713	74
Sims Bayou	93	91	16	235	41	1.0	0.8	17	346	33
South Bay	78	68	10	138	24	0.6	0.6	12	211	22
Trinity Bay	317	225	26	356	59	1.5	0.3	12	708	32
Trinity River	1,099	572	62	877	124	4.3	0.5	27	2,110	82
West Bay	344	212	30	405	68	1.6	0.9	21	706	44
White Oak Bayou	110	128	24	365	69	1.5	1.3	29	488	54
Total Project Area	**4,238**	**3,010**	**481**	**6,420**	**1,110**	**26.3**	**14.2**	**355**	**10,900**	**749**
Median	134	121	22	301	51	1.2	0.5	13	445	32
Maximum	1,099	572	62	877	124	4.3	1.9	39	2,110	82
Minimum	25	25	4	65	11	0.3	0.1	5	94	9

Source: Newell et al., 1992

intense source zones for pesticides. Loading estimates by land use type for a year with average rainfall are given in TABLE 6.3.

The geographic distribution of loadings was determined based on land use and runoff data. The load maps produced for this project (FIGURES 6.19–6.23) identified subwatersheds with high nonpoint source load generation. As expected from land use findings, the highly urbanized areas in Houston, Baytown, Texas City, and Galveston contributed the highest loads per unit area for all water quality constituents. Of these constituents, fecal coliform bacteria and oil and grease loads were almost entirely associated with the urban areas. Loading estimates for the individual subwatersheds for a year with average rainfall are given in TABLE 6.4.

Discussion

The amount of NPS pollution was found to be very sensitive to the amount of runoff. The runoff and loads for a wet year were 40-60 percent higher than those found for the average year. Significantly, a large individual storm event (equal to storm size that occurs on the average once per year) was found to contribute approximately 15 to 20 percent of the total annual nonpoint source load to the bay. These data indicated that a significant portion of the annual loads occur during a few of the largest rainfall events during the year.

The geographic approach used in the study of Newell et al. indicated that the highest erosion rates, and thus greatest sources of sediment were occurring in a wedge-shaped area, having a point at the mouth of the Ship Channel and reaching westward through Houston to the watersheds upstream of Barker/Addicks reservoirs. The high sediment loads were attributed to a combination of erosion in urban land use areas in the Houston vicinity and of barren land in the rural western watersheds.

Compared to the pollutant loads generated by urban areas, agricultural loadings were smaller. Much of the lower watershed involved in agriculture is devoted to rice production, which may result in significantly lower pollutant loads of sediment, nutrients, and pesticides when compared to row crops (McCauley, 1991).

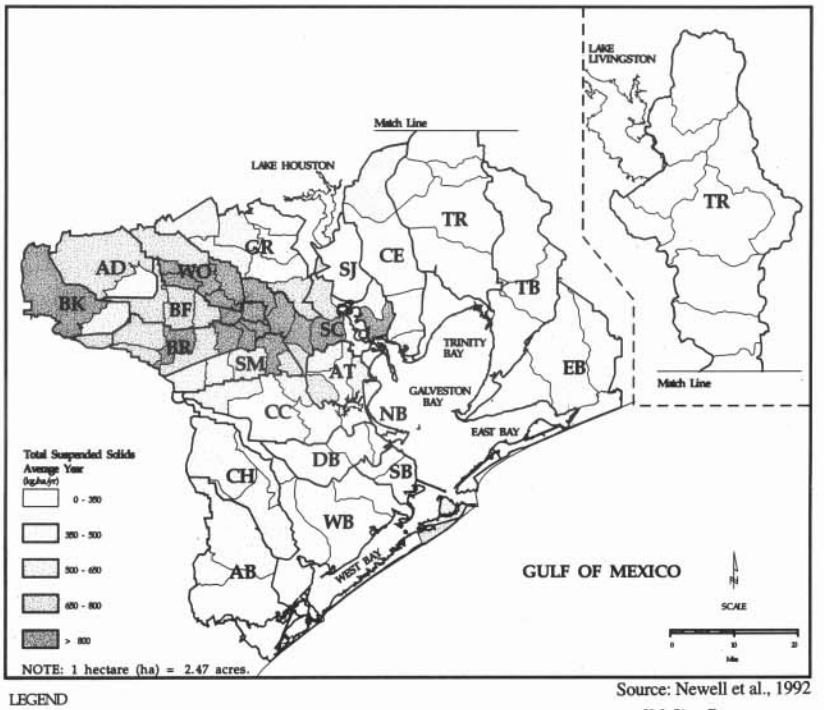
While high pollutant concentrations could occur seasonally (for example, nutrients just after fertilizer application), low concentrations have been observed during much of the growing season (Brown et al., 1978). During the growing season water in rice fields is impounded behind small dikes, limiting potential for erosion and pollutant release. The complicated hydrology of rice fields and the variable water quality over time make it very difficult to estimate an average NPS-related concentration in rice-field runoff.

Note that the forgoing information addresses the source of NPS pollutants. What happens to these pollutants once they reach a bayou, river, or the bay is a separate and difficult issue. Actual impacts of local NPS pollutants on the bay are difficult to assess without analyzing the change in pollutant concentrations in Galveston Bay itself. For example, NPS loads enter the bay intermittently as relatively brief slugs of pollutants in large volumes of runoff, from numerous entry points. The amount, timing, and duration of these NPS events are determined by rainfall conditions. Discharge from Lake Livingston and Lake Houston complicates this assessment, as the reservoirs change the timing and water quality of the discharge from the Trinity and San Jacinto rivers to the bay.

Septic Tanks

Septic tanks near Galveston Bay have the potential to contribute nutrients and human pathogens to waters of the estuary (see Chapter Nine). The soils in the immediate watershed virtually assure numerous septic tank failures, since the fine-grained clays have an extremely slow percolation rate. Overall, however, septic tanks do not likely contribute a substantial portion of the total fecal coliform bacteria loading to Galveston Bay (Jensen, 1992). Leaks from failing septic systems do affect local areas, particularly tributaries such as Dickinson Bayou, where limited dilution occurs. Also, numerous (perhaps most) septic tank failures go unreported, inhibiting estimates of their impact on the bay.

Malfunctioning septic tanks were included in a study reported by Guillen et al. (1994). During 1992 a total of 166 septic tank violations were reported to designated municipal agents and/or the Texas Natural Resource Conservation Commission. Using common industry estimates of the average flow from a malfunctioning septic system Guillen et al. estimated that a total of 4,445,030 gallons of partially treated effluent from faulty septic systems had

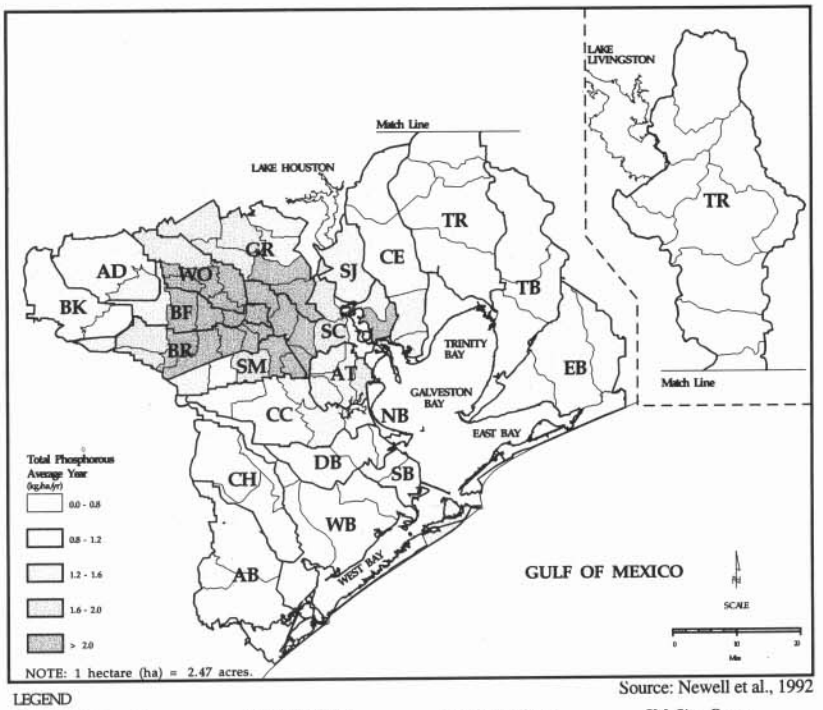


Source: Newell et al., 1992

LEGEND

AB Austin/Bastrop Bayou	CC Clear Creek	GR Greens Bayou	SM Sims Bayou
AD Addicks Reservoir	CE Cedar Bayou	NB North Bay	TB Trinity Bay
AT Armand/Taylor Bayou	CH Chocolate Bayou	SB South Bay	TR Trinity River
BF Buffalo Bayou	DB Dickinson Bayou	SC Ship Channel	WB West Bay
BK Barker Reservoir	EB East Bay	SJ San Jacinto River	WO White Oak Bayou
BR Brays Bayou			

FIGURE 6.19. *Total suspended solids in stormwater runoff from Galveston Bay subwatersheds in a year with typical rainfall. A major constituent is sediment, particularly from construction sites and barren or eroding lands.*



Source: Newell et al., 1992

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AB Austin/Bastrop Bayou	CC Clear Creek	GR Greens Bayou	SM Sims Bayou
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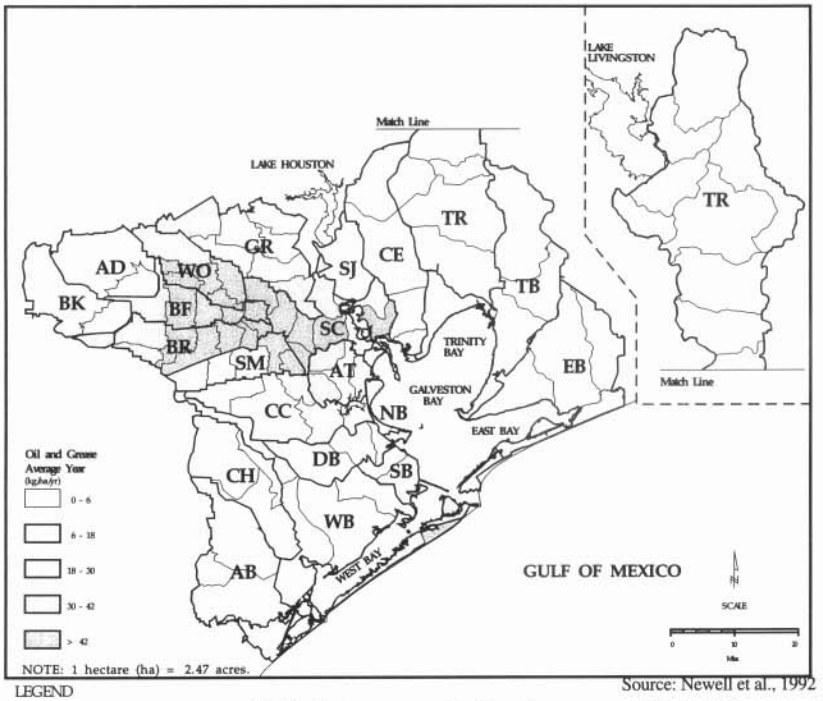
BK Barker Reservoir	EB East Bay	SJ San Jacinto River	WO White Oak Bayou
BR Brays Bayou			

FIGURE 6.20. *Total phosphorus in stormwater runoff from Galveston Bay subwatersheds in a year with typical rainfall. Phosphorus, a nutrient which can overstimulate algae growth, tends to attach to sediment particles.*



Source: Newell et al., 1992

LEGEND

AB Austin/Bastrop Bayou	CC Clear Creek	GR Greens Bayou	SM Sims Bayou
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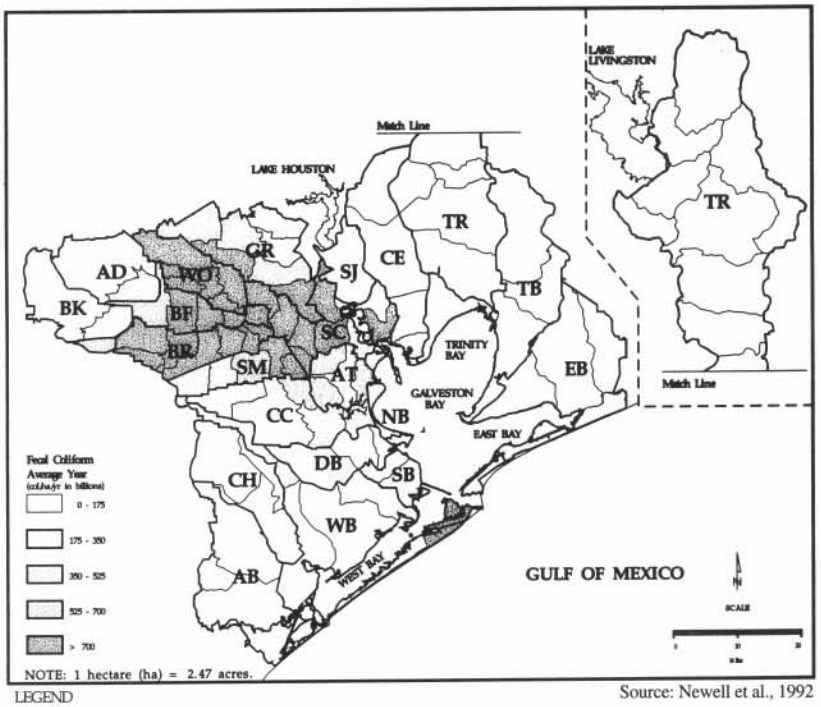
BF Buffalo Bayou	DB Dickinson Bayou	SC Ship Channel	WB West Bay
BK Barker Reservoir	EB East Bay	SJ San Jacinto River	WO White Oak Bayou

FIGURE 6.21. *Oil and grease in stormwater runoff from Galveston Bay subwatersheds in a year with typical rainfall. Loading from this source totals some 40 percent of the historic* Exxon Valdez *spill annually. Oil and grease contain numerous specific compounds, many of which are toxic. Sources include engine drippings and purposeful dumping of motor oil.*



Source: Newell et al., 1992

LEGEND

AB Austin/Bastrop Bayou	CC Clear Creek	GR Greens Bayou	SM Sims Bayou
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BF Buffalo Bayou	DB Dickinson Bayou	SC Ship Channel	WB West Bay
BK Barker Reservoir	EB East Bay	SJ San Jacinto River	WO White Oak Bayou

FIGURE 6.22. *Fecal coliform bacteria in stormwater runoff from Galveston Bay subwatersheds in a year with typical rainfall. These bacteria indicate contamination from warm-blooded animal or humans sources, including pets, wildlife and sewage. Not included are sewage sources from septic tanks and municipal sewage system bypasses and overflows.*

al. estimated that a total of 4,445,030 gallons of partially treated effluent from faulty septic systems had discharged into the Galveston Bay watershed during 1992. The exact chemical composition and final amount that eventually reached waterways via overland flow or storm sewers was unknown. The majority (83 percent) of complaints occurred in the San Jacinto Watershed (excluding the area above the Lake Houston dam). The majority of problems were associated with poor system design and/or insufficient soil drainage.

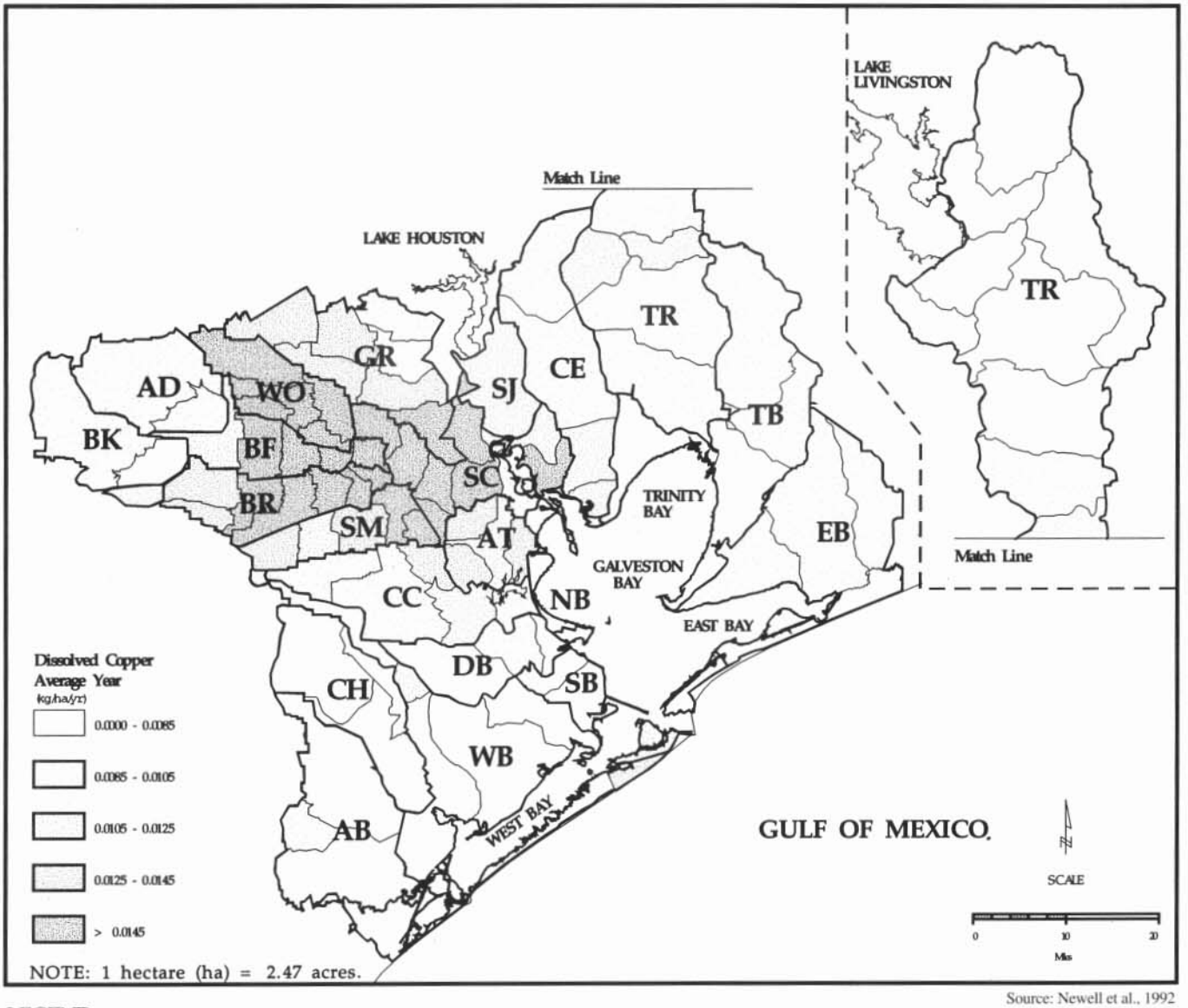
Marina/Boater Impacts

Evidence exists from studies in other parts of the country that marinas and their associated boats can be sources of pollutants, including heavy metals, fecal coliform bacteria, and nutrients (North Carolina Department of Environment, Health, and Natural Resources, 1991). Improperly designed marinas with poor circulation can also reduce flushing and, during times of minimal water movements, concentrate pollutants, deplete oxygen, and cause serious environmental harm, including fish kills.

Galveston Bay, particularly in the Clear Lake area, contains a very high concentration of recreational vessels (see Chapter Four). Until recently, there were few locations to pump out boat sewage and, consequently, much of the boat sewage was discharged directly into Galveston Bay and/or Clear Lake. However, recently a private entrepreneur has built both portable and stationary sites in Clear Lake (Maritime Sanitation, 1992).

Four recreational marinas and one boat canal subdivision were studied by Guillen et al. (1993) during May and July, 1992. These included the Galveston Yacht Club, Lafayette Landing, Houston Yacht Club, South Shore Harbor, and Jamaica Beach. Surface water and recently-deposited sediment samples were collected from four locations at each marina site. These locations included an inside station (furthest away from outlets to adjacent water bodies), an entrance station at the opening of the marina, a near-field station (within 0.25 mi from the entrance), and a far-field site (usually ≥ 0.5 mi from the entrance). General conclusions were:

> Fecal coliform bacteria concentrations generally increased as one progressed from open waters inward in each marina system. State water



Source: Newell et al., 1992

LEGEND

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SC Ship Channel
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SM Sims Bayou
TB Trinity Bay
TR Trinity River
WB West Bay
WO White Oak Bayou

FIGURE 6.23. *Dissolved copper in storm water runoff from Galveston Bay sub watersheds in a year with typical rainfall.*

quality standards for fecal coliforms were exceeded at the inner stations and state shellfish standards (14 colonies per 100 mL) were violated at the Houston Yacht Club. The outer stations of the Clear Lake marinas may also have been influenced by human activities unrelated to boats, for example urban runoff and septic system failures.

Dissolved oxygen generally decreased as one progressed from open waters inward in each marina system. Lowest levels were recorded at the South Shore Harbor inner station. Dissolved oxygen at the inner stations of Jamaica Beach and South Shore Harbor violated the state water quality standard of 4.0 mg/L.

Copper and lead showed apparently increasing contamination toward the inner stations of each marina. This suggested that long term accumulation of copper and lead in sediments may be occurring.

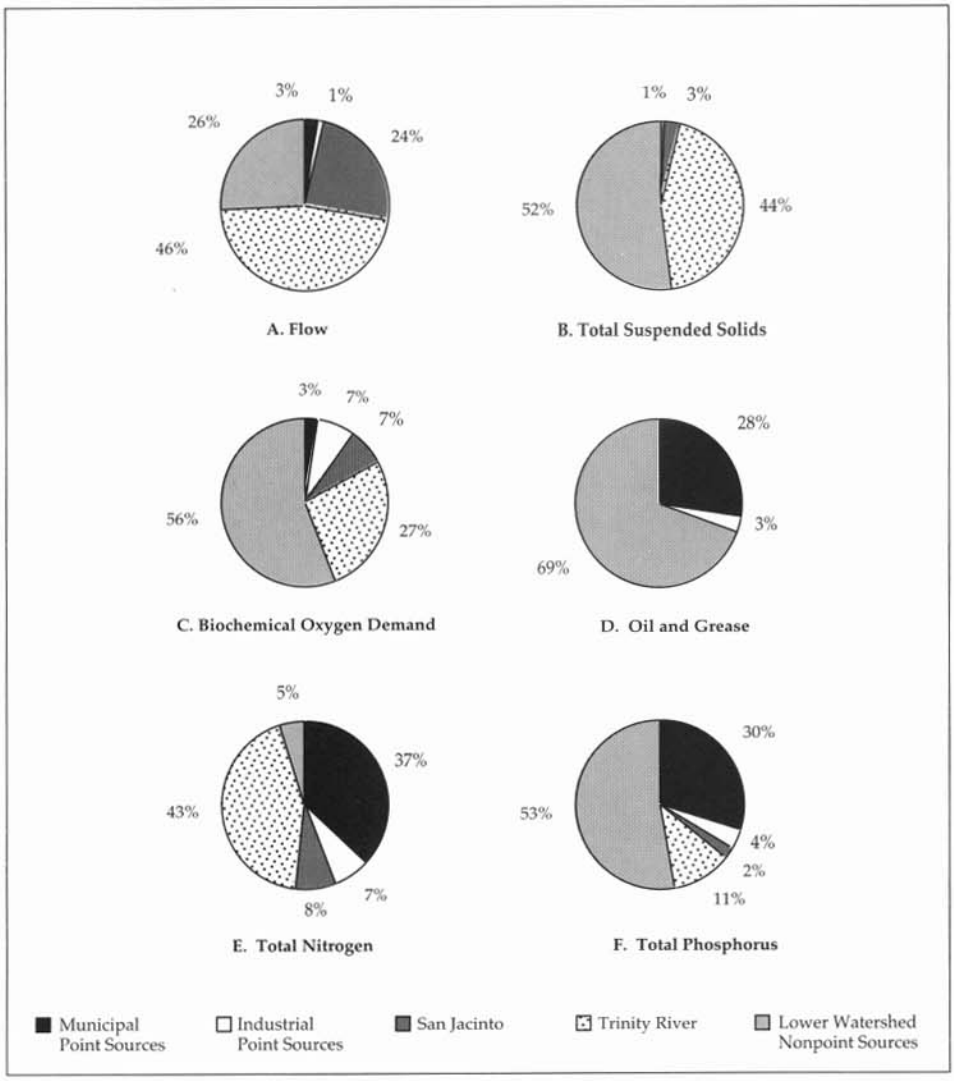


FIGURE 6.24. *Bay-wide analysis: the relative contribution of selected constituents to the Galveston Bay system from five major sources. These estimates represent a synthesis of various recent studies described in this chapter.*

POLLUTANT LOADING TO GALVESTON BAY: A SYNTHESIS

Galveston Bay is affected by diverse major influences on the quality of its water and sediments. The complex physical, chemical, and biological processes in the bay make these influences difficult to tease apart. However, the managers of the bay, who seek to identify and alter the most negative influences, have great interest in determining the relative roles of the major sources of pollution. Managers are interested in both the entire system and in portions of the system such as the upper Houston Ship Channel, which have traditionally received the greatest wastewater volume.

Relative Contributions From Five Sources

In this section, relative loadings from five of the bay's major pollution sources were compared for each of several key water quality constituents. The sources considered for this analysis were:

Municipal Point Sources. Approximately 559 permitted wastewater treatment plants provide a total flow of approximately 135 trillion gallons per year. Loadings were derived from Armstrong and Ward (1994) excepting pesticides (Goodman, 1989).

Industrial Point Sources. Some 247 facilities in the immediate watershed provide about 39 billion gallons of "process water" per year (not including cooling water). Loadings were derived from Armstrong and Ward (1994), excepting pesticides (Goodman, 1989).

The San Jacinto River. This second-largest river feeding the bay delivers flow from 2,828 sq mi of watershed draining into Lake Houston. (Note that some of the loadings from the San Jacinto watershed originate from upstream point sources). Loadings were derived from Armstrong and Ward (1994) excepting pesticides (Newell et al., 1992).

The Trinity River. Some 26,000 sq mi of watershed (including Dallas and Fort Worth) are drained by the Trinity. Net loadings were measured at Romayor, Texas, located several miles downstream of the Lake

Dissolved arsenic levels were generally low and did not exceed state criteria for chronic (long-term) exposure. There was nonetheless an apparent increasing trend of arsenic contamination toward the inner stations of each marina. This suggests that long-term accumulation of arsenic in sediments may be occurring.

Guillen et al. (1993) concluded that most water quality impacts associated with marinas are localized. Dissolved oxygen levels were generally depressed, severely at the Jamaica Beach finger canals and at South Shore Harbor. Oxygen problems were least severe at the more openly designed Galveston Yacht Club and at the Houston Yacht Club, which employ bulkheads that do not extend to the bottom. The Houston Yacht Club design allows water to enter the marina from below the bulkhead and also at the marina entrance. The other facilities' primary flushing corridor is limited to main entrances only.

Livingston dam. (As with the San Jacinto River, loadings represent a mixture of nonpoint and point sources). Loadings were derived from Armstrong and Ward (1994) excepting pesticides (Newell et al., 1992).

Local nonpoint sources from the lower watershed. Runoff from the 4,600 sq mi watershed immediately surrounding the bay reaches the estuary from a variety of bayous, small streams, stormwater outfalls, and overland drainage. Loadings were derived from Newell et al. (1992), excepting PCBs (Armstrong and Ward, 1994) and PAHs (national means reported by Cole et al., 1984).

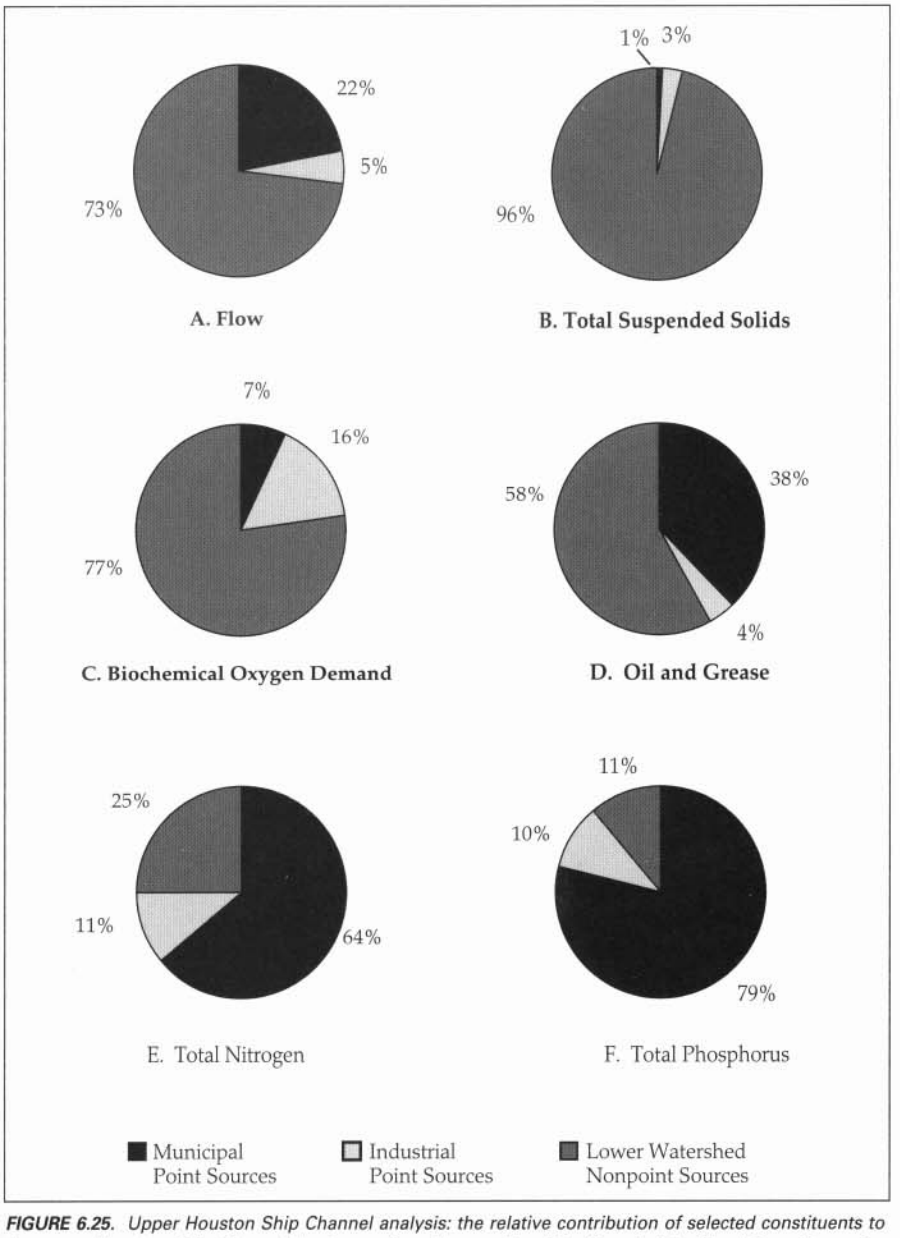


FIGURE 6.25. *Upper Houston Ship Channel analysis: the relative contribution of selected constituents to the upper Houston Ship Channel (upstream from the mouth of the San Jacinto River) from five major sources. These estimates represent a synthesis of various recent studies described in this chapter.*

Reflecting the interests of bay managers, loading estimates for the five pollutant sources were calculated for two different geographic areas: 1) for the entire bay system; and 2) for the upper Houston Ship Channel only, upstream from the mouth of the San Jacinto River. Geographically, all sources within the watershed were used for the baywide analysis, while the Houston Ship Channel analysis utilized an appropriate set of subwatersheds based on known hydrology. These were: Buffalo Bayou (including Addicks and Barker reservoirs), Brays Bayou, Greens Bayou, Sims Bayou, White Oak Bayou, and the local Houston Ship Channel drainage (see Newell et al., 1992). Data from the Texas Natural Resource Conservation Commission water quality segments 1005, 1006, 1007, 1013, 1014 were used to estimate point source loads to the channel.

Other potential sources of pollutants not considered in this comparison include groundwater, constituents in rainfall itself, boats, mobile animal sources, and oil and chemical spills (some of these are considered in the next section). Internal bay sources, such as the cycling of contaminants from the sediments to the water and net transport from the Gulf to the bay were also not evaluated. The comparison was intended to show the relative contribution of the most important inputs to the Galveston Bay system.

Loadings to the Entire Galveston Bay System

Loadings to the bay system are given in TABLE 6.5, with relative contributions from the five sources shown in the form of pie charts for selected constituents (FIGURE 6.24). As described in Chapter Four, the Trinity River is the largest source of flow to Galveston Bay. Over an entire year, point sources contribute less than five percent of the total flow into the bay.

Local nonpoint sources are the largest source of total suspended solids to the bay, contributing slightly over 50 percent of the 914 million kg/yr of sediment. The Trinity River, even with the effects of the Lake Livingston reservoir, was a close second. Point sources contributed less than one percent of the total suspended solids loading to the bay. The location of sediment delivery is important–for example sediment loading to the Trinity delta is highly desirable to maintain wetlands.

Local nonpoint sources also generated over half of the bay's annual BOD loading, with point sources providing less than ten percent of the total loading. Municipal point sources were the source of about one-third of the nitrogen and phosphorus load to

TABLE 6.5. Bay-Wide Analysis: Relative Contributions of Pollutants From Five Major Sources.

Point Source Constituent	Municipal Point Sources	Industrial Point Sources	San Jacinto River	Trinity River	Lower Watershed Nonpoint Sources	Total
Flow						
Million ac-ft/yr	0.4	0.1	2.8	5.5	3.0	11.8[1]
(% of Total)	(3)	(1)	(24)	(46)	(25)	(100)
Total Susp. Solids						
Million Kg/yr	2.7	7.0	25.4	398.4	481.0	914.5
(% of Total)	(0)	(0)	(3)	(44)	(53)	(100)
BOD						
Million Kg/yr	1.4	3.3	3.5	13.0	26.3	47.5
(% of Total)	(3)	(7)	(7)	(27)	(55)	(100)
Oil and Grease						
Million Kg/yr	5.7	0.6	0.0	0.0	14.2	20.5
(% of Total)	(28)	(3)	(0)	(0)	(69)	(100)
Total Nitrogen						
Million Kg/yr	7.1	1.3	1.5	8.2	1.1	19.2
(% of Total)	(37)	(7)	(8)	(43)	(6)	(100)
Total Phosphorus						
Million Kg/yr	3.6	0.4	0.2	1.3	6.4	11.9
(% of Total)	(30)	(4)	(2)	(11)	(54)	(100)
Total Arsenic						
1,000 Kg/yr	16.3	3.8	3.9	50.7	29.0	103.7
(% of Total)	(16)	(4)	(4)	(49)	(28)	(100)
Total Cadmium						
1,000 Kg/yr	5.6	0.8	2.7	14.2	5.5	28.8
(% of Total)	(20)	(3)	(9)	(49)	(19)	(100)
Total Chromium						
1,000 Kg/yr	21.9	10.2	46.7	119.7	10.0	208.5
(% of Total)	(11)	(5)	(22)	(57)	(5)	(100)
Total Copper						
1,000 Kg/yr	18.8	9.1	65.4	129.1	49.5	271.9
(% of Total)	(7)	(3)	(24)	(47)	(18)	(100)
Total Lead						
1,000 Kg/yr	23.0	2.4	43.9	365.2	138.4	572.9
(% of Total)	(4)	(0)	(8)	(64)	(24)	(100)
Total Mercury						
1,000 Kg/yr	0.2	0.0	0.8	2.8	0.9	4.6
(% of Total)	(3)	(1)	(17)	(60)	(19)	(100)
Total Zinc						
1,000 Kg/yr	83.9	30.0	232.1	639.0	396.9	1381.9
(% of Total)	(6)	(2)	(17)	(46)	(29)	(100)
PCBs						
Kg/yr	0.0	15.7	0.0	38.0	61.3	115.0
(% of Total)	(0)	(14)	(0)	(33)	(53)	(100)
Pesticides						
Kg/yr	588.0[2]		170	575	749	2082
(% of Total)						(100)
PAHs						
Kg/yr	-	0.0	-	-	371.0	>371
(% of Total)						(100)

[1]Note this value is about 15 percent higher than given in Chapter Five; point sources were include here and different sources of data were consulted

[2]This represents the combined municipal and industrial point source loading

the bay. The Trinity River contributed 43 percent of the total nitrogen load, while the local nonpoint sources yielded 54 percent of the total phosphorus load.

The Trinity River was the largest source of all seven of the metals analyzed, ranging from a 46 percent to 64 percent contribution. Industrial sources were minor contributors bay-wide (less than five percent in all cases) while municipal dischargers were responsible for between ten and 20 percent of the total arsenic, cadmium, and chromium loading. Local nonpoint sources were also significant contributors and provided between 18 percent and 29 percent of the metals loading for total arsenic, total cadmium, total copper, total lead, total mercury, and total zinc. Note that these data were based on analytical methods for metals whose overall accuracy has been questioned (described previously in this chapter).

For PCBs, the analysis performed by Armstrong and Ward (1994) indicated that the local tributary loadings (consisting mostly of local nonpoint sources with some point sources) contribute 61 kg/yr of PCBs to the bay, the largest source. Different results were produced using data from Cole et al., (1984). In that study, one of 86 nationwide urban runoff samples showed PCBs with a concentration of 0.03 µg/L. Applying this value to the Galveston Bay watershed yielded PCB washoff of less than one kg/yr. The reason for this discrepancy is not known.

Loadings to the Upper Houston Ship Channel

Loadings to the upper Houston Ship Channel (upstream from the mouth of the San Jacinto River) are given in TABLE 6.6, with relative contributions from the five sources shown in the form of pie charts for selected constituents (FIGURE 6.25). Results for this portion of the bay system reflect a high percentage of the total point and nonpoint sources entering the system, but none of the effects from the bay's two largest rivers.

Almost all (96 percent) of the total suspended solids loadings to the Houston Ship channel were caused by local nonpoint sources, compared to about 50 percent for the entire bay system.

Although numerous major municipal and industrial point sources discharge to the upper Houston Ship Channel, point sources were

responsible for only 22 percent of the total annual BOD loading, with nonpoint sources contributing 77 percent of the load. This reflects substantial BOD reductions in recent years (see FIGURE 6.27). Municipal point sources were the largest contributors of nitrogen and phosphorus, with 64 percent and 79 percent respectively. Industrial dischargers were responsible for only 11 percent of the total nitrogen loading and ten percent of the total phosphorus loading to the channel.

Municipal point sources contributed over half of the total loading for three metals (total arsenic, total cadmium, and total chromium) to the Houston Ship Channel. Nonpoint sources were responsible for most of the total lead, total mercury, and total zinc loadings to the channel. This finding contrasts with the bay-wide domination of the Trinity River metals loadings. Loadings from the Trinity are delivered in low concentrations in a high volume of water, while loadings to the Houston Ship Channel, a limited area with limited circulation, may contribute to higher ambient concentrations, particularly in sediments.

Point sources of PCBs on the upper Houston Ship Channel totaled 15.7 kg/yr (Armstrong and Ward, 1994), while the Trinity River provided 38 kg/yr. The best estimate for the total PCB loading to the bay (114.7 kg/yr using Armstrong and Ward's estimate) corresponds to between 0.1 and 13 percent of the total PCBs now trapped in the bay's sediment. The lack of comprehensive data for the Trinity River, San Jacinto River, and point sources prevented a comprehensive analysis for pesticides or PAHs.

Besides the recent analysis presented here, Winslow and Associates (1986) also estimated the sources of pollutant loadings to the Houston Ship Channel for BOD, total suspended solids, ammonia-nitrogen, and total Kjeldahl nitrogen. Two different calculation methods were used to analyze the nonpoint source data they collected, and point sources/collection system loadings were divided into overflows, bypasses, wet weather municipal point source flows, dry and transitional municipal point source flows, and industrial point sources.

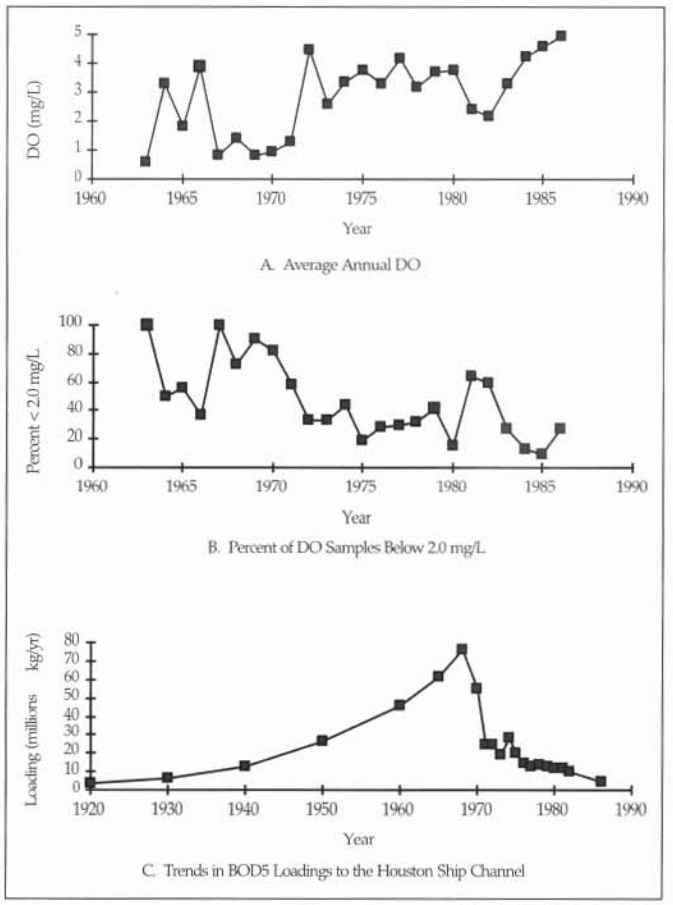
The Winslow and Associates study broadly agrees with the analysis presented here. Using a land use-based "individual component method" for nonpoint sources, they determined that urban runoff was responsible for most of the Ship Channel loading: 73 percent of the annual carbonaceous BOD load to the channel, 90 percent of the TSS, 21 percent of the ammonia, and 52 percent of the TKN. Overflows and bypasses contributed 11 percent or less of these loadings in 1986; since that time the collection system has been improved to reduce the frequency and volume of overflows and bypasses. Municipal point source loadings accounted for about ten percent of the BOD and 66 percent of the ammonia loading. Industrial point sources accounted for less than seven percent of the BOD and five to six percent of the ammonia and TKN loading to the channel.

Other Pollutant Sources

Other sources of pollutants, in addition to those considered in the previous analysis, are likely to have a role in determining water quality in the estuary. A preliminary investigation of rainfall and dustfall loadings was prepared using sampling data reported in Browne et al. (1992). Using typical concentrations for urban and rural settings, loadings from rainfall and dustfall were estimated and compared to the total loadings shown in TABLE 6.5. This comparison indicated that rainfall accounted for less than 15 per-

TABLE 6.6. Upper Houston Ship Channel Analysis: Relative Contributions of Pollutants From Major Sources.

Constituent	Municipal Point Sources	Industrial Point Sources	Lower Watershed Nonpoint Sources	Total
Flow				
Million ac-ft/yr	0.3	0.1	1.0	1.4
(% of Total)	(22)	(5)	(73)	(100)
Total Susp. Solids				
Million Kg/yr	2.6	7.1	208.0	217.7
(% of Total)	(1)	(3)	(96)	(100)
BOD				
Million Kg/yr	1.0	2.2	10.9	14.1
(% of Total)	(7)	(16)	(77)	(100)
Oil and Grease				
Million Kg/yr	5.7	0.6	8.9	15.2
(% of Total)	(38)	(4)	(59)	(100)
Total Nitrogen				
Million Kg/yr	7.1	1.3	2.7	11.1
(% of Total)	(64)	(11)	(24)	(100)
Total Phosphorus				
Million Kg/yr	3.6	0.4	0.5	4.5
(% of Total)	(79)	(10)	(11)	(100)
Total Arsenic				
1,000 Kg/yr	16.3	3.8	10.3	30.4
(% of Total)	(54)	(13)	(34)	(100)
Total Cadmium				
1,000 Kg/yr	5.6	0.8	1.9	8.3
(% of Total)	(68)	(9)	(23)	(100)
Total Chromium				
1,000 Kg/yr	21.8	10.3	3.5	35.6
(% of Total)	(61)	(29)	(10)	(100)
Total Copper				
1,000 Kg/yr	18.8	9.2	17.4	45.4
(% of Total)	(41)	(20)	(38)	(100)
Total Lead				
1,000 Kg/yr	23.1	2.3	48.7	74.1
(% of Total)	(31)	(3)	(66)	(100)
Total Mercury				
1,000 Kg/yr	0.00	0.06	0.31	0.37
(% of Total)	(0)	(16)	(84)	(100)
Total Zinc				
1,000 Kg/yr	84.4	29.6	139.9	253.9
(% of Total)	(33)	(12)	(55)	(100)



Source: Armstrong and Ward, 1994; Stanley, 1992

FIGURE 6.27. *Dissolved oxygen improvements in the upper Houston Ship Channel resulting from improved wastewater treatment. Increased dissolved oxygen (a), and a reduction in the frequency of dissolved oxygen depletion below 2.0mg/L (b) resulted from a greater than 95 percent reduction in BOD loading (c). Data is for segment 1006 (Greens Bayou to San Jacinto River). In spite of these improvements, low dissolved oxygen (particularly near the bottom) remains a concern throughout the upper ship channel.*

cent of the total loading for three indicator parameters: total nitrate/nitrite (12 percent), lead (less than one percent), and cadmium (nine percent). Surprisingly, the reported dustfall rate of 32 tons per sq mi per month for the Gulf Coast was estimated to contribute almost 23 percent of the total sediment load to the bay if the entire 600 sq mi area of the bay is assumed to be subject to this deposition rate. In reality, much lower deposition rates are probably experienced in the open bay or at seaward locations farther from sources.

Groundwater may also affect the quality of Galveston Bay. Jensen (1992) reports the contribution of septic tanks to the fecal coliform loading to the bay as negligible. Groundwater pollution from hazardous waste sites has been identified as a possible source of toxicants, but data from existing groundwater regulatory programs has not been compiled to provide bay-wide groundwater loading. Chapter Nine identifies contamination of Clear Creek by toxic organics in the vicinity of the Brio Superfund Site. Future work on this topic is planned as part of the Texas Clean Rivers Program.

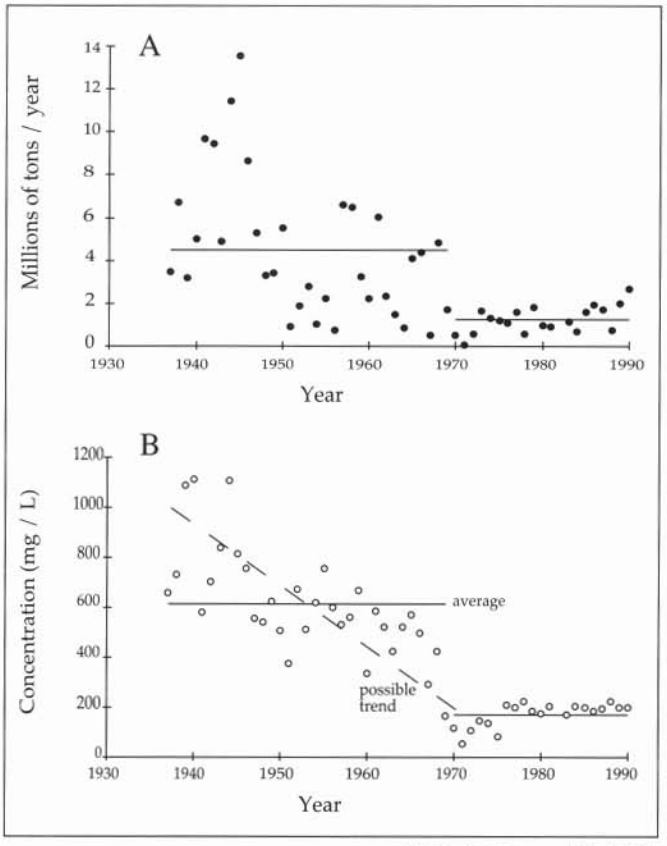
Finally, three recent incidents have resulted in major spilled cargoes in the Houston Ship Channel inside of the Galveston Bay Estuary:

> In 1989, the Tank Barge *Coastal 2514* spilled 6,000 barrels of oil slurry.
>
> In 1990, the Tank Barge *Apex Marine 3417* released 700,000 gallons of number five oil.
>
> Also in 1990, the Bottle Barge *Duval II* spilled 2,800 tons of molten sulfur.

These and numerous smaller oil and chemical spills constitute another source of pollution.

Patterns at the Ecosystem Level

Water quality is controlled by a number of interrelated processes, **feedback loops** and numerous components which are difficult to measure. This complicates the analysis of cause-and-effect mechanisms at the ecosystem level. Because of this complexity, many of the observed trends are difficult to explain. In Galveston Bay, however, three systematic trends have been linked



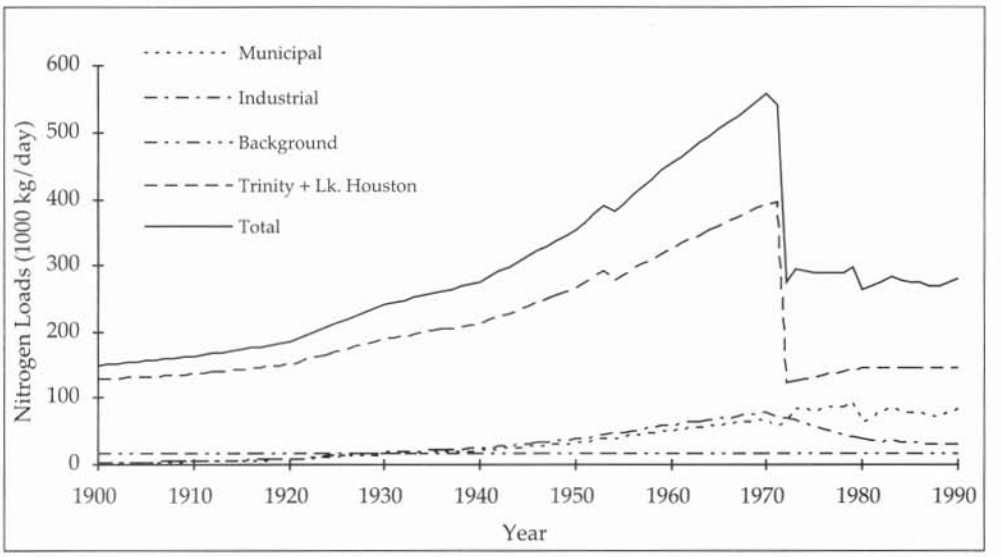
Source: Armstrong and Ward, 1994

FIGURE 6.26. *Historical variation in the silt load of the Trinity River at Romayor. This location is just downstream of Lake Livingston, a major reservoir with nearly the same water volume as Galveston Bay. The data reveal a major reduction in Trinity River silt coinciding with completion of the reservoir, which reached normal pool level in 1973. Lake Livingston, and Lake Houston on the San Jacinto, serve as efficient sediment traps and thereby also capture other constituents associated with silt particles, for example phosphorus.*

to cause-and-effect mechanisms. These trends, described below, illustrate ecosystem responses to external changes in human activity.

Reduced TSS Concentrations Due to Lake Livingston

As shown in FIGURE 6.26, the current sediment load in the Trinity River is about two-thirds less than the historical sediment load (1930s and 1970s). Two possible mechanisms involved are: 1) the construction of Lake Livingston; and 2) changing land use practices and construction of other reservoirs in the upper part of the Trinity River watershed (Ward and Armstrong, 1992).



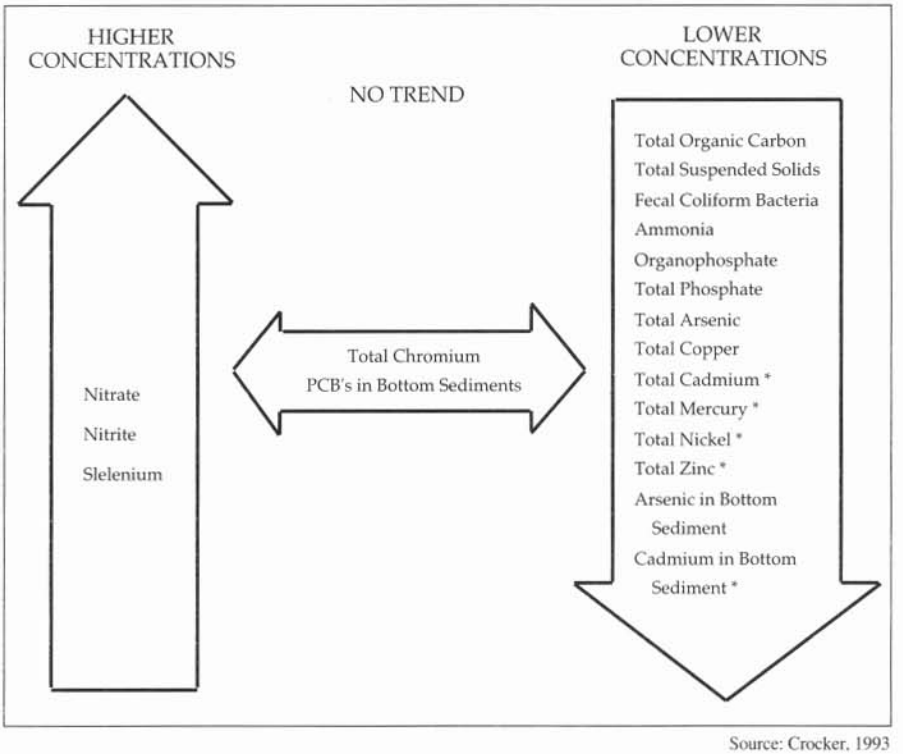
Source: Jensen et al., 1992

FIGURE 6.29. *Nitrogen loads in the Galveston Bay system. Reduced nitrogen loading in the 1970s resulted from the construction and upgrading of treatment works triggered by the Federal Water Quality Act. This, combined with the influence of reservoir construction, resulted in nitrogen reductions to approximately 1930s levels. "Background" does not include the Trinity River of Lake Houston.*

Lake Livingston construction began in 1968 and water reached design pool level about three years later. To put this reservoir in perspective, it is useful to note that Lake Livingston and Galveston Bay are almost the same volume: two million ac-ft for the lake vs. 2.2 million ac-ft for the bay. The lake has an average hydraulic residence time of 4-5 months, giving it a theoretical sediment-trapping efficiency of more than 50 percent.

Changes in land use practices in the upper watershed are difficult to quantify, although there has been a definite increase in no-till agriculture and implementation of erosion control programs by the U.S. Soil Conservation Service. In addition, a total of 28 major reservoirs have been constructed in the upper Trinity watershed above Lake Livingston with a cumulative storage capacity of about six million ac-ft. Most of these reservoirs were constructed in the 1950s and 1960s and now trap large quantities of sediment that once were carried to the bay.

If a two-thirds reduction in sediment load from the Trinity River is applied to the data in TABLE 6.5, then it appears that the changes in the Trinity River have decreased the overall sediment load to the bay by 40 to 50 percent. Over the same time period, total suspended solids concentrations in the open bay have also declined to a level about one-third of their value 25 years ago. Although in-bay factors may have also contributed to this decline, the primary mechanism is probably reduced sediment loads from the Trinity River.



Source: Crocker, 1993

FIGURE 6.28. *Water quality trends in the upper Houston Ship Channel. For most constituents at most locations, improvements have resulted from improved wastewater treatment (asterisks denote improvement at upstream stations only). For trends by station, see FIGURE 6.12.*

Improved Houston Ship Channel Water Quality from Wastewater Treatment

As described in the introduction, the Houston Ship Channel was one of the most polluted bodies of water in the world in 1970, due to the discharge of massive volumes of pollutants from industrial, municipal, and nonpoint sources. In 1968, over 76 million kilograms of biochemical oxygen demand were discharged to the upper channel every year, effectively inhibiting the presence of aquatic life.

Then in 1971, the Environmental Protection Agency and the forerunner of the Texas Natural Resource Conservation Commission implemented a stringent program to improve wastewater treatment. Industries were the first to respond, followed by upgraded municipal discharges in the early 1980s (such as the start-up of the City of Houston's 69th Street Plant in 1983). By 1990 the BOD loading to the channel had been reduced by over 95 percent to 3.1 million kg/yr (FIGURE 6.27). The current BOD loading is approximately the same as the loading to the channel in the 1920s (Armstrong and Ward, 1994), an amazing water pollution control achievement.

The effect of BOD reduction on the water quality of the Houston Ship Channel has been significant. The average surface dissolved oxygen concentration in the lower channel is now above five mg/L, while the percentage of samples below two mg/L has been reduced considerably (FIGURE 6.27). The concentration of a number of other pollutants in the channel has also been reduced, and most constituents that have increased in concentration are also associated with improved wastewater treatment (FIGURE 6.28).

Changing Nitrogen Loads to the Bay

Jensen et al. (1991) provided a long-term estimate for the change in total nitrogen loads to the bay (FIGURE 6.29). Their period of record was from 1900 to 1990, and they included simplified estimates for local industrial point sources, local municipal point sources, "background" concentrations (local nonpoint sources), and Lake Houston/Trinity River. Note that the Lake Houston/Trinity River data reflect a combination of point sources and nonpoint sources from the upper watersheds.

The analysis identified a four-fold increase in total nitrogen loading to the bay from 1900 to 1973, primarily a result of slowly increasing nitrogen concentrations in the Trinity River. Only 10-20 percent of the total increase during this 73-year period was caused by higher loadings from local industrial and municipal point sources that started growing rapidly after 1950.

After 1973, several things happened that greatly reduced nitrogen loads to the bay. Most importantly, the Lake Livingston dam was constructed and reduced overall nitrogen loadings by over 50 percent (due to sedimentation, **denitrification**, and phytoplankton uptake). Starting in the early 1970s, there was also a reduction in industrial nitrogen loadings, although this reduction was dwarfed by the overall reduction caused by Lake Livingston.

Finally, total nitrogen loads from municipal sources leveled off after 1973. Further reductions were limited by the nature of the treatment process. Secondary treatment does not include nitrogen removal (while waste treatment processes result in the conversion of ammonia to nitrate, total nitrogen is unchanged). Because some of the channel dischargers were already on secondary treatment, the overall effect of improved wastewater treatment in the 1970s was much more apparent for BOD than total nitrogen.

The long-term reduction in nitrogen loading is a significant process for Galveston Bay, because primary productivity of phytoplankton (the basis for the entire food chain) is conventionally thought to be nitrogen-limited in coastal marine systems. During the same time period that nitrogen loads were reduced, there was an apparent decline in phytoplankton abundance (as measured by chlorophyll-*a* reductions of over 50 percent in the past 20 years). Overall ramifications include a possible reduction in dissolved oxygen in some areas of the bay possibly due to less photosynthetic activity, and a speculated (and debated) future crash in oyster populations due to lack of food supply (see Chapter Seven).

SUMMARY

The Galveston Bay system is characterized by good water quality in open bay waters. Water and sediment quality problems, where they occur, are primarily found in the western, urbanized tributaries. Water quality in these locations has shown significant improvement over the past 20 years because of improved wastewater treatment by point source dischargers. Nonpoint sources, therefore, represent the greatest challenge for future water quality improvements.

Significant water quality improvements have been made in the bay's largest and most problematic urban tributary–the upper Houston Ship Channel. Prior to 1970 much of the Ship Channel above the mouth of the San Jacinto River was a lifeless body of water with little or no dissolved oxygen. A 95 percent reduction in the discharge of biological oxygen demand has reduced loadings to the levels seen in the 1920s. As a result, dissolved oxygen concentrations have increased significantly, permitting the return of some aquatic life in the upper Houston Ship Channel (see Chapter Eight). Despite improvements, some reaches of the upper Houston Ship Channel continue to exhibit low dissolved oxygen levels in the one to two mg/L range, particularly near the bottom.

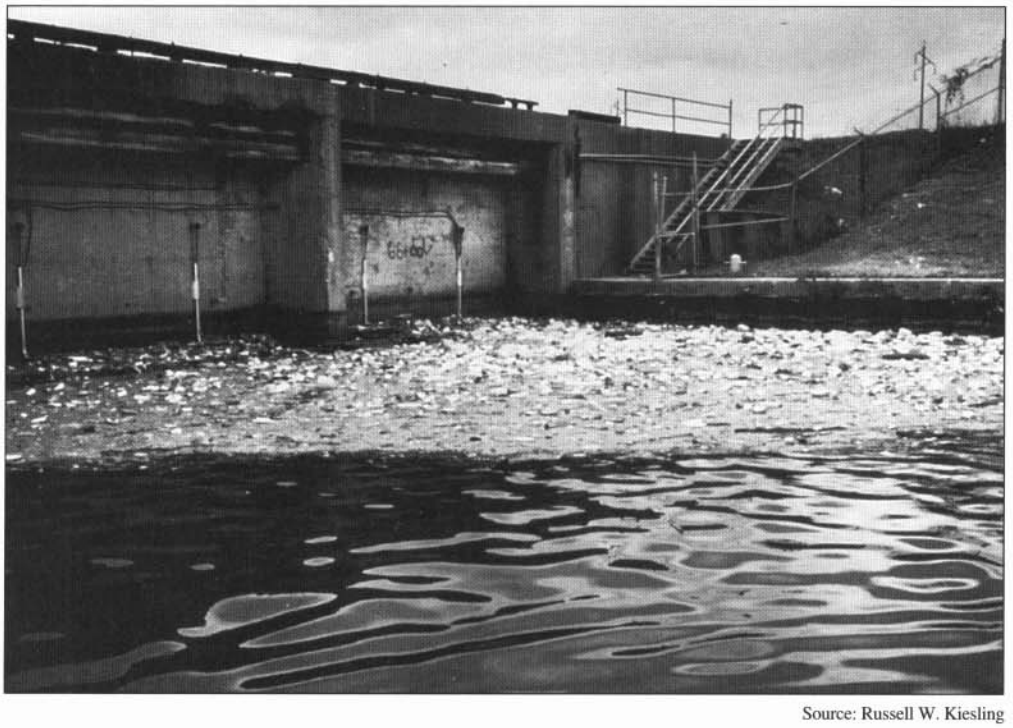
Although data are sparse, metals have apparently also undergone a general decline in both water and sediments of the upper estuary where contamination has traditionally been greatest. However, possible shortcomings in the traditional analytical methods for metals make interpretation of metals data difficult. If the decline in metals is real, the possible explanations include improved industrial wastewater treatment, and removal of contaminated sediments by upland confinement of dredged material.

PCBs and PAHs have been identified as particular water quality problems due to bioaccumulation by aquatic organisms (see Chapter Nine). Available data indicate that: 1) most of the PCBs and PAHs are derived from urban runoff, although there is one discharger of PCBs to the bay; 2) some of the water samples collected in the Houston Ship Channel violate state criteria for safe concentrations of PCBs; and 3) the total concentration of PCBs and PAHs now stored in bay sediments is probably much higher than the annual delivery of these compounds to the bay.

A bay-wide analysis of five major sources of pollutants and other water quality constituents revealed that the Trinity River (which includes both point and nonpoint sources) was responsible for almost half of the sediment, nitrogen, and metals loadings to the bay. These loads are delivered in diluted concentrations and do not appear to be elevating ambient levels in either water or sediments.

Source: Galveston Bay National Estuary Program

The bay's greatest water quality challenge is control of nonpoint sources of pollution. Storm water washing over streets, parking lots, and residential neighborhoods contains such contaminants as oil and grease, fertilizers, herbicides, and pesticides. With each rain, storm sewers (above) discharge these materials to the urban bayous (below), where floatable trash becomes an eyesore.



Source: Russell W. Kiesling

Local nonpoint sources contributed more than half of the sediment, BOD, oil and grease, and phosphorus loadings, often to portions of the bay with limited flushing. Industrial point sources contributed less than seven percent of any of the total loading of any pollutant, including heavy metals and BOD, while municipal point sources were responsible for about one-third of the total oil and grease, total nitrogen, and total phosphorus loads.

The same pollutant source analysis, applied to just the upper Houston Ship Channel above the mouth of the San Jacinto river, revealed an even more dramatic dominance of nonpoint sources for some constituents (e.g. BOD). Municipal point sources, however, dominated the loading to this area for nutrients and metals, with industry contributions of most conventional parameters relatively minor.

Overall, the open bay is cooler, less saline, and much clearer than it was 30 years ago. Although the temperature and salinity changes do not have a simple explanation, the reduction in total suspended solids is probably due to the completion of Lake Livingston in 1973. This reservoir, which holds about the same volume of water as Galveston Bay, traps sediments from the upper watershed, reducing suspended solids concentrations in the bay to about one-third their value in the late 1960s.

Lake Livingston is probably also responsible for a 40-50 percent reduction in total nitrogen loads to the bay and the subsequent decline in nitrate and ammonia concentrations in open bay waters. Although wastewater treatment improvements likely also had role, the overall annual nutrient reduction caused by Lake Livingston is probably several times larger than the reduction from any other cause. All told, the Lake Livingston dam has appeared to reverse the steadily increasing trend of nitrogen loadings to the bay noted since 1900 (primarily from the Trinity River), and now nitrogen loads to Galveston Bay are about what they were in the 1930s.

Lower nitrogen concentrations in the open bay are probably the main reason for the observed 50 percent reduction in phytoplankton biomass (indicated by chlorophyll-*a* over the past 30 years). A continued decrease in phytoplankton populations, if it occurs, could affect the bay's food web (reducing the oyster food supply, for example), or could be hailed as a success story for management, returning the bay to a more nearly pristine nutrient and productivity level.

FOR MORE INFORMATION

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CHAPTER SEVEN

Wetlands and Reefs: Two Key Habitats

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. Several specific habitat types have been identified and described in the Galveston Bay system (see FIGURE 2.4). The importance of these habitats, their internal functions, and their interconnectedness were presented in Chapter Three as a conceptual model of the bay ecosystem. The continued productivity and biological diversity of the estuarine system is dependent upon the maintenance of varied and abundant high-quality habitat.

Of the bay's habitats, two in particular are important to the health of the bay and are emphasized in this chapter. First, wetlands (including submerged aquatic vegetation) serve important biological, hydrological, and ecological functions in the bay ecosystem. Second, oyster reefs are important as indicators of the overall condition of the ecosystem and are the basis for an important commercial fishery. Besides the discussion presented here, note that several other chapters refer to other aspects of these habitats, such as the circulation effects of oyster reefs (Chapter Five), and the productivity of marshes (Chapter Eight).

WETLANDS

Wetlands are transitional areas 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 include rainfall and runoff, water table fluctuations, streamflow, **evapotranspiration**, waves and longshore currents, astronomical and wind tides, storms and hurricanes, deposition and erosion, subsidence, faulting, and sea-level rise (White and Paine, 1992; see Chapter Five). 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 astronomical inter-tidal zone along the shore, to the higher wind-tidal zone and infrequently-flooded storm-tidal zone. The continuing action of physical processes and the proximity to salt and fresh water sources determine the location and composition of the plant communities that–more than any other attribute–define wetlands.

In addition to being formed by physical processes, wetlands have in turn become important elements of many processes that keep the bay ecosystem healthy. Hydrologically, wetlands fringing

Source: Galveston Bay National Estuary Program

Wetlands, shown here in Christmas Bay, are indispensable to ecosystem function. They provide nursery areas for marine species, feeding habitats for birds, and they export critical nutrients and organic matter to other bay habitats.

the shoreline are valuable filtering zones for polluted runoff and help protect the bay from excessive organic 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. The relatively long residence times associated with wetlands help to treat the water by removing organics and permitting excess sediment to settle out before reaching the bay. Finally, well-developed vegetated wetlands also provide a barrier between open water and land, preventing or reducing shoreline erosion.

Biologically, marshes are an important source of nutrients and carbon exported to biological consumers in open bay waters and the bay bottom. Wetlands are among the most productive biological systems on the planet, and they may be more important to the Galveston Bay system than is true for many other bays (Sheridan et al., 1989 and Chapter Eight).

Among the most important wetland functions is their role as habitat for many species of plants, fish, birds, and wildlife. Many of Galveston Bay's principal fishery species rely on wetlands during at least some part of their life cycle. These species include brown shrimp, white 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, ranging from microbes to vertebrates, that comprise a large part of the food web (see Chapter Three). Several bird species, such as snowy egrets, roseate spoonbills, tricolored herons, black skimmers, and great egrets use the marsh as feeding habitat.

General Classification

For convenience, wetlands and aquatic habitats can be classified in five overall categories:

Estuarine systems (salt or brackish water)

Palustrine systems (generally fresh water)

Lacustrine systems (lakes)

Riverine systems (rivers)

Marine (open ocean)

The estuarine system dominates Galveston Bay wetlands, comprising 89 percent of the wetland and deep-water habitats in 1989 (White and Paine, 1992; White et al., 1993). The palustrine system was a distant second at six percent, followed by the lacustrine (four percent), riverine (0.5 percent), and marine (0.4 percent) systems.

Within this classification scheme, wetlands can be further

Source: Bureau of Economic Geology

Brackish-marsh community in the Brazoria National Wildlife Refuge southwest of Hoskins Mound. Although dominant species are Spartina patens *and* Distichlis spicata, Spartina alterniflora *occurs along the tidal channel.*

Source: Bureau of Economic Geology

Fresh-marsh community in the Trinity River valley north of Interstate Highway 10.

Source: Texas Parks and Wildlife Department

Cypress swamps, bottom-land hardwoods, and associated riparian (floodplain) forests, contribute important nutrients as well as dissolved and particulate organic matter to the estuarine system. In addition, they provide valuable habitat supporting numerous fish and wildlife species. Mature bottomland forests are of prime concern on a national basis due to their accelerating loss and high habitat value.

subdivided into hydrologic subsystems, such as intertidal and subtidal, and into classes based on vegetation and substrate. It should be noted that this classification of wetlands does not necessarily coincide with "jurisdictional" wetlands subject to Corps of Engineers jurisdiction under Section 404 as determined by the *1987 Wetland Delineation Manual*. Wetlands encompass a variety of plant communities. In Galveston Bay, five community types dominate: emergent wetlands including salt-water marshes, brackish water marshes, and fresh-marshes; forested wetlands (swamps); and submerged aquatic vegetation beds (such as seagrass beds). These communities are described below.

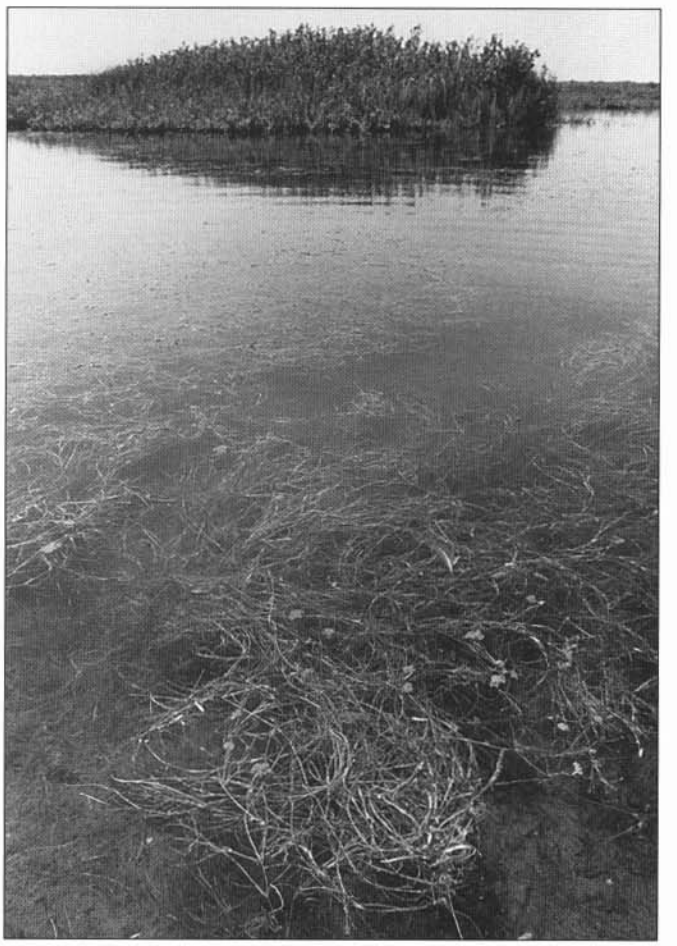
Salt Marsh

Salt-marsh communities are found in high-salinity areas, along protected estuarine shorelines. Prevalent species in the salt-marsh community include *Spartina alterniflora* (smooth cordgrass), *Batis maritima* (saltwort), *Distichlis spicata* (saltgrass), and *Salicornia spp.* (glasswort). *S. alterniflora*, which lives in the intertidal zone, dominates the low-salt-marsh community. At higher elevations, *Spartina patens* (marshhay or saltmeadow cordgrass) and *Spartina spartinae* (Gulf cordgrass) occur, although they are more common in brackish marshes (White and Paine, 1992).

In wind-tidal sand flats, vegetation is limited because of intermittent salt water flooding and subsequent evaporation that concentrates salt. Algal mats are abundant in these areas, while emergent vegetation is limited to salt-tolerant species such as shoregrass (*Monanthochloe littoralis*), saltwort, and glasswort (White and Paine, 1992).

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 salt-marsh species. In general, the brackish marsh is dominated by *Spartina patens* (marshhay or salt meadow cordgrass) and *Distichlis spicata* (seashore saltgrass; Harcombe and Neaville, 1977). Other species include needlegrass rush (near tidal drains), common reed and big cordgrass (on levees), seashore paspalum and longtom (in fresher areas), and isolated clumps of saltmarsh bulrush and Olney bulrush.



Source: Galveston Bay National Estuary Program

Submerged meadows composed mainly of widgeon grass and shoalgrass are a key element of the lower bay environment, shown here in Christmas Bay. Only a remnant of this habitat type remains baywide, the destruction resulting from a combination of locally increased turbidity, increased bay depth, high pollutant loads, fishing and boating disturbance, dredging, and tropical storms and hurricanes.

Fresh Marsh

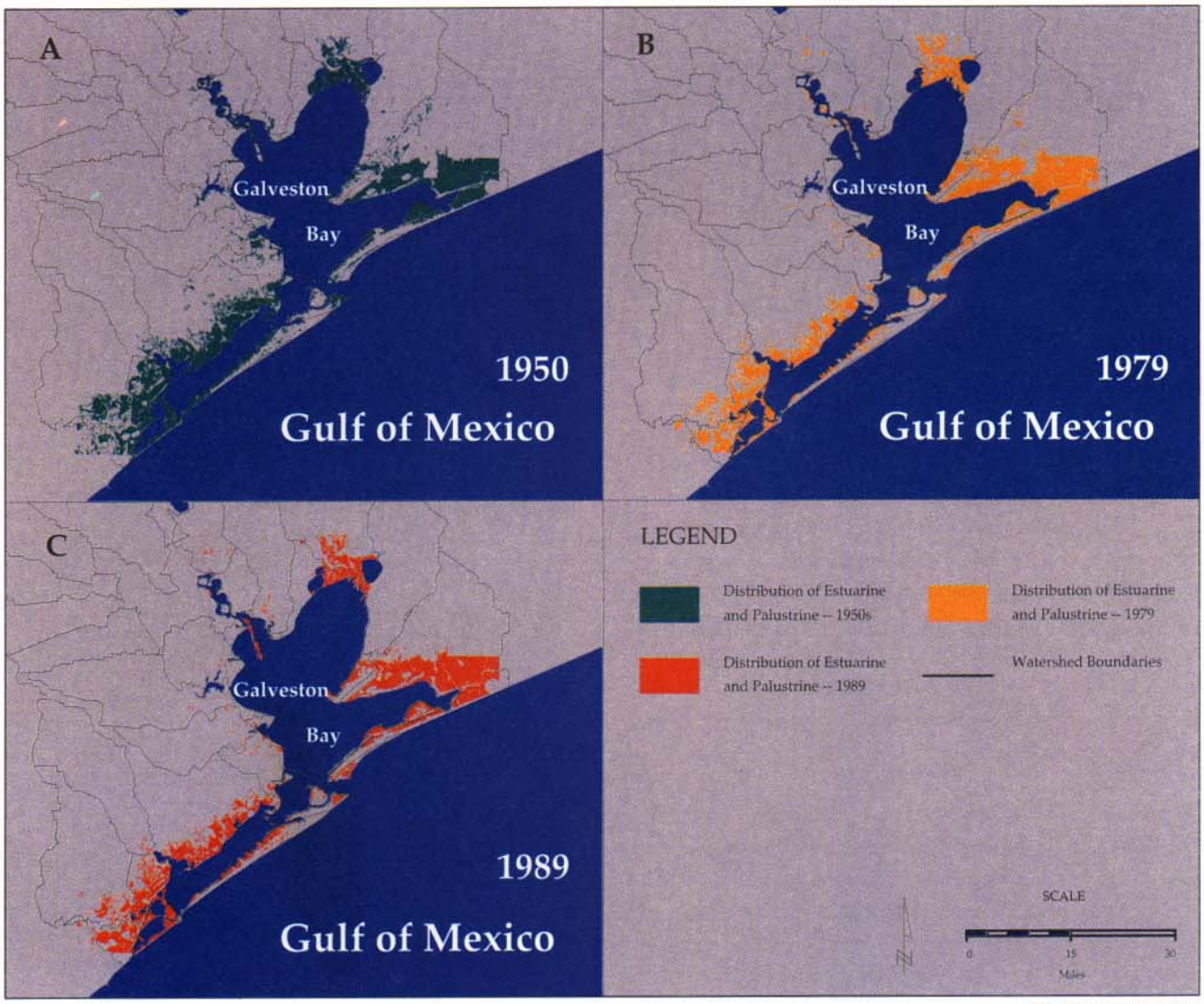
Fresh marshes are primarily found in areas that are affected by saltwater flooding only during large tropical storms or hurricanes. The fresh water in these marshes is sufficient to maintain a low enough salinity for such species as *Zizaniopsis miliacea* (marsh millet or giant cutgrass), *Sagittaria falcata* (coastal arrowhead), and *Eleocharis quadrangulata* (squarestem spikesedge). In lower, wetter areas, water hyacinths 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).

Swamps

Forested wetlands include woodlands or forested areas with saturated soils or which are inundated by water much of the year. In the Galveston Bay system, this community is located almost exclusively in the Trinity River valley. The swamp community primarily consists of *Taxodium distichum* (bald cypress), with some button bush, water elm, and water hickory (White and Paine, 1992).

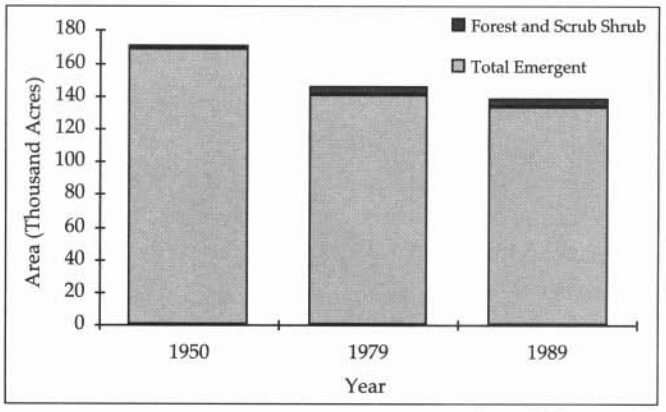
Submerged Aquatic Vegetation

Historically, continuous beds of submerged aquatic vegetation flourished in three locations: 1) around the Trinity River Delta, consisting of *Ruppia maritima* (widgeon grass), and *Vallisneria americana* (tape grass); 2) along the west shoreline from Seabrook to San Leon, also consisting of widgeon grass; and 3) the southern shoreline of West Bay, with relatively long narrow beds of *Halodule wrightii* (shoalgrass) mixed with widgeon grass (Renfro, 1959; Pullen, 1960). A remnant of this latter habitat can be still be found in Christmas Bay, with shoalgrass and widgeon grass being the primary species. *Halophila engelmannii* (clovergrass) and *Thalassia testudinum* (turtlegrass) are also found, but to a limited extent (Pulich and White, 1991). *Thalassia* and perhaps other seagrasses ocurred in West Bay, but are now gone (Pulich and White, 1991). Submerged aquatic vegetation does not normally fall within the def-



Source: White et al., 1993

FIGURE 7.1. *Changes in the distribution of emergent wetlands bordering Galveston Bay since the 1950s. Wetland types mapped include estuarine (salt or brackish water) and palustrine (generally fresh water). These maps are based on a digitized wetlands classification of aerial photographs.*



Source: White et al., 1993

FIGURE 7.2. *Changes in the extent of wetlands in Galveston Bay over time. The figures reveal an overall loss of 17 to 19 percent of the wetlands present in 1950, but encouragingly, the rate of loss has declined.*

inition applied to emergent wetlands like salt marshes, but their high importance and severe declines in the Galveston Bay system make them quite important in this system.

The Need to Determine Wetland Status and Trends

Understanding where wetlands are located and how they have changed over time is critical if they are to be effectively protected and managed. Some broad trends are available to characterize wetland losses. For example, nationally, three-fourths of the estuarine wetlands classified by Dahl and Johnson (1991) were "intertidal emergent," typified by *Spartina* salt marshes. These authors estimated a relatively small 1.5 percent loss from the mid 1970s to the mid 1980s for this important habitat type, nationwide.

For Galveston Bay, most scientists suspected emergent wetlands were being lost at a rate higher than the national trend. However, until recently, no figures have been available to characterize losses. To provide this needed information, the Galveston Bay National Estuary Program commissioned a study by White et al. (1993) to determined the status and trends of Galveston Bay wetlands.

In the study, wetlands were delineated on aerial photographs through stereoscopic interpretation using procedures developed for the U. S. Fish and Wildlife Service National Wetlands Inventory program. Field reconnaissance was an integral part of the interpretation process. Following the classification procedures of Cowardin et al. (1979), wetlands were classified by system, subsystem, and class for the 1950s, 1979, and 1989, and by subclass, water regime, and special modifier for the years 1979 and 1989 (White et al., 1993). Upland habitats were delineated on 1979 and 1989 maps. More than 180 field sites were examined as part of an effort to characterize wetland plant communities and define wetland map units in the Galveston Bay system (White and Paine, 1992). Most of the following discussion summarizes the results from this comprehensive study.

Distribution of Wetland Communities

Based on the work of White et al. (1993), vegetated wetlands were found to total 138,600 ac (216.6 sq mi), or about 25 percent of all of the open-bay and adjacent bay habitats. As would be expected, the majority of these wetlands were estuarine intertidal emergent wetlands (salt or brackish marshes) and constituted 83 percent or 108,200 ac. Palustrine emergents (fresh or inland marshes) comprised 22,200 ac. The total area of forested wetland habitat amounted to 5,650 ac, or four percent of the vegetated wetland system. Fresh water scrub/shrub wetlands totaled 2,000 ac (less than two percent of vegetated wetlands), and estuarine scrub/shrub wetlands encompassed 550 ac (0.4 percent). Areal extents of the various types are shown in FIGURE 7.1, while trends are summarized in FIGURE 7.2.

Submerged aquatic vegetation had a total mapped area of 700 ac (adjusted for photo-interpretation errors) in the Galveston Bay project area (White et al., 1993). Of this total, 386 ac were mapped in Christmas Bay, with most of the remaining areas near the Trinity River delta. The total area of submerged vegetation is thought to be larger than actually measured because of unmappable areas on the margins of the Trinity River delta.

Wetlands Loss Over Time

Overall Trend

The aerial photo-interpretation analyses performed by White et al., (1993) indicated gains and losses in different classes of wetlands, with an overall net decreasing trend since the 1950s (see FIGURE 7.2). More than 33,000 ac of vegetated wetlands have been lost during this period, amounting to about 19 percent. (The actual loss in all wetlands is somewhat less, perhaps closer to 17 percent, because delineations of wetlands in some areas on the 1950s vintage black-and-white aerial photographs included peripheral upland areas, which inflated the 1950s wetland acreages).

This rate of loss is substantially higher than the national rate of loss of estuarine wetlands. One encouraging sign, however, is that the rate of loss decreased over time from 1,000 ac/yr between 1953 and 1979, to about 720 ac/yr between 1979 and 1989. The rate of loss between 1979 and 1989 is even lower (<500 ac/yr) if inaccuracies in wetland interpretation of the 1979 photographs are taken into account.

The area of mapped emergent wetlands (marshes) decreased from 165,500 ac in the 1950s to 130,400 ac in 1989, producing a bay-wide net loss of 35,100 ac, or 21 percent of the 1950s resource (FIGURE 7.3 indicates the several types of losses). As in the case of vegetated wetlands, this amount of loss in emergent wetlands is thought to be overestimated; the actual loss is probably less than 19 percent.

Trend by Wetland Classes

A large portion of the overall losses in wetlands, can be attributed to the loss of fresh-water marshes (TABLE 7.1 and White et al., 1993). Note that the values show the net loss and gain for each type of wetland as opposed to a gross loss. 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.

Total scrub/shrub wetlands decreased by 900 ac, representing a 25 percent loss of the 1950s resource. Forested wetlands, on the other hand, increased by 3,600 ac–almost twice the 1950s area. Almost all of this gain was in the Trinity River valley. Much of the gain in forested wetland area was due to: 1) growth of shrubs and trees in areas previously mapped as scrub/shrub wetlands; and 2) photointerpretation inconsistencies on the different sets of photographs. In addition, 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.

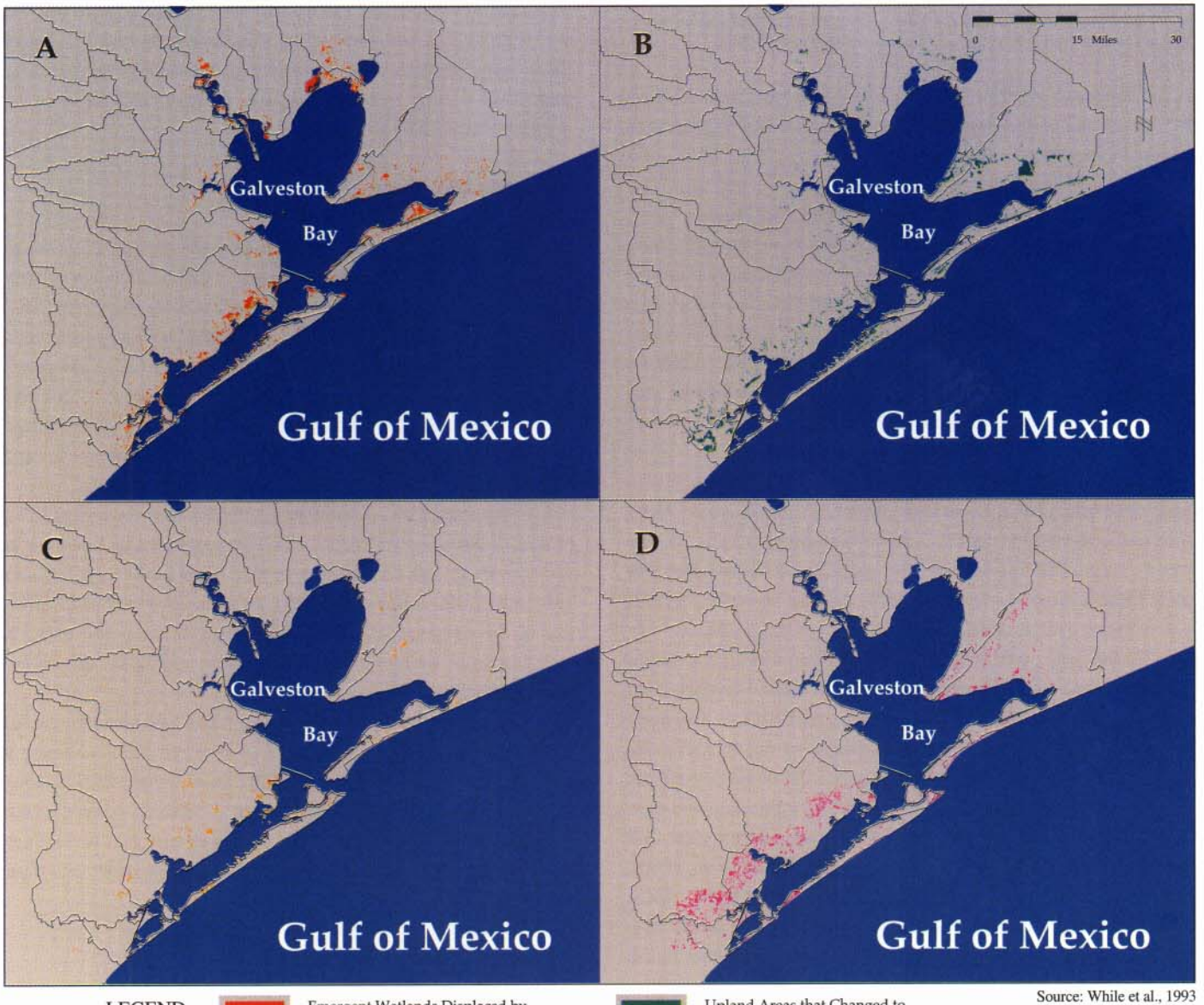
Submerged aquatic vegetation habitat decreased from 2,500 ac in the 1950s to 700 ac in 1987 (FIGURE 7.4). Accordingly, the decline in this habitat type is 1,800 ac, or over 70 percent of the 1950s habitat (White et al., 1993).

Causes of Wetlands Loss

Four main causes of the wetland losses are: 1) man-induced subsidence and associated relative sea-level rise; 2) direct conversion for agricultural, urban, industry, and transportation purposes; 3) dredge-and-fill activities; and 4) isolation projects. These factors are discussed in more detail below.

Effect of Subsidence and Sea Level Rise

Subsidence and sea level rise has resulted in the drowning of numerous wetland areas throughout the bay system, and has also



Source: While et al., 1993

FIGURE 7.3. *Types of wetland conversions taking place from the 1950s to 1989. Leading causes of wetland losses were conversion to open water and barren flats, and conversion to rangeland (also see FIGURE 7.7).*

TABLE 7.1. Estimated Net Change in Areas of Vegetated Wetland Classes Between 1950s and 1989.

Wetland Class	Net Change in Wetland Area 1950s-1989(ac)
Estuarine bay marshes, salt and brackish water[1]	+ 8,200
Estuarine bay marshes, salt and brackish water/unconsol. shore	-16,200
Estuarine, intertidal scrub/shrub	+ 4,700
Fresh-water marshes, meadows, depressions, or drainage areas	-26,800
Swamps, woodlands in floodplains, depressions, meadow rims	+ 3,500
Willow thicket, river banks	- 1,400

Source: White et al., 1992

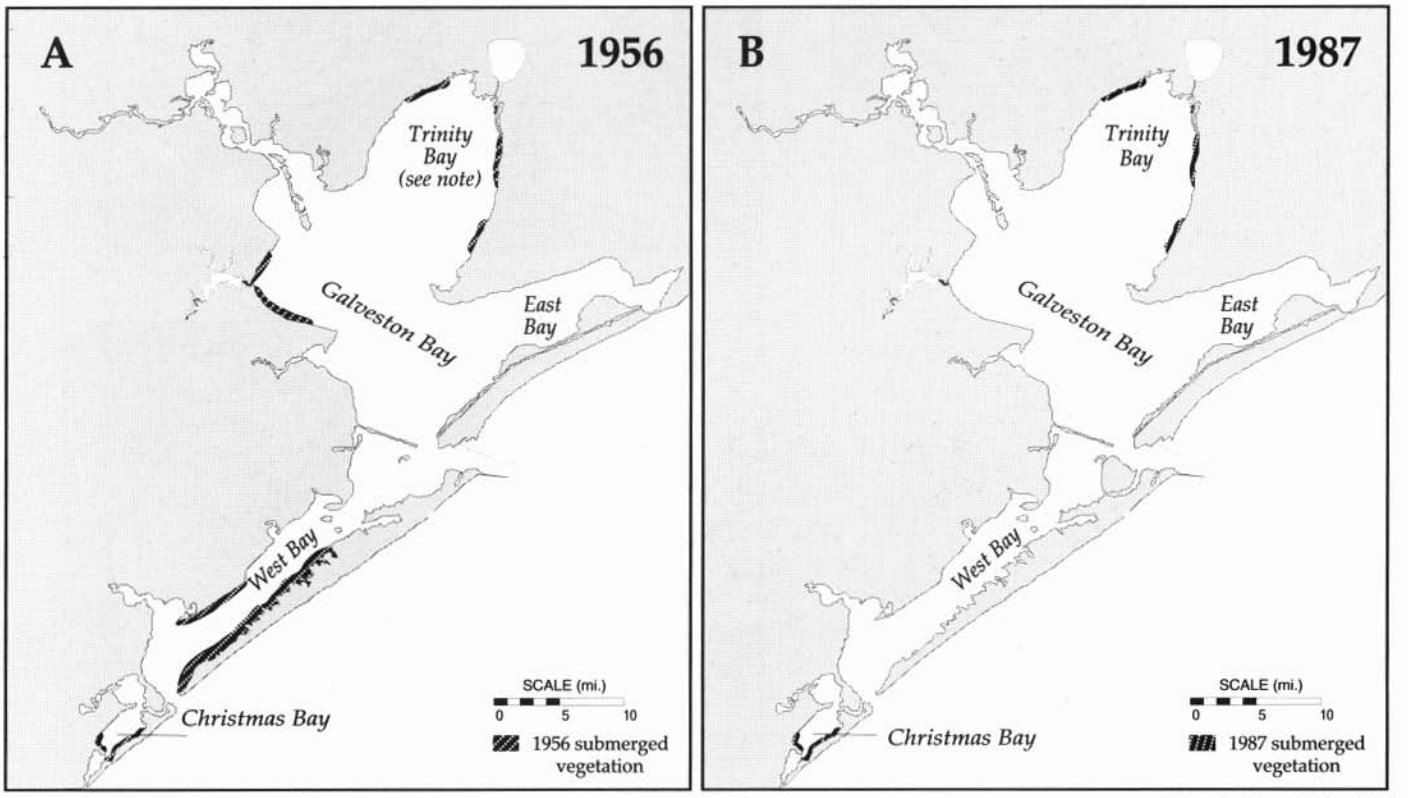
[1]The apparent increase in "estuarine bay marshes, salt and brackish water" areas are in large part due to reclassification of fresh-water marshes and other marsh types to this category

resulted in creation of new wetlands by inundation of uplands. Overall, losses exceed gains. About 26,400 ac of 1950s marsh were converted to open water/barren flat habitats by 1989 (see FIGURE 7.3a). Most of this conversion was due to subsidence caused by pumping of groundwater and relative sea level rise combined with consolidation (shrinking) of clay layers in the underlying aquifers (see Chapter Five).

In certain parts of the bay system, the effects of man-induced subsidence and associated relative sea-level rise have been particularly severe. Wetland areas affected by subsidence include the north, west, and south margins of Galveston Bay and the northeast part of West Bay. For example, more than 3,600 ac of marshland in the Virginia Point area (Jones Bay and Swan Lake) were replaced by open water and barren mud flat between the 1950s and 1989 (FIGURE 7.5).

The Clear Lake area offers another example of the effect of land-surface subsidence and the subsequent intrusion of open water and shallow flats into vegetated wetlands (FIGURE 7.6). Since the 1950s, there has been a complete loss of fresh water wetlands along Armand Bayou (McFarlane, 1991). Subsidence along active surface faults also contributed to replacement of marshes by water and barren flats in some areas.

Losses in emergent wetlands in some areas were partly offset by gains in emergent wetlands in other areas. Bay-wide subsidence/sea level rise was probably responsible for converting part of approximately 21,000 ac of previously upland areas to wetland areas (see FIGURE 7.3b). 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 and Christmas 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



Source: Pulich and White, 1991

FIGURE 7.4. *Locations and losses of submerged aquatic vegetation in Galveston Bay. Best estimates indicate at least a 70 percent loss of this habitat type. Although present, submerged aquatic vegetation was not mapped in Christmas Bay and Trinity Bay locations in 1956. The 1987 distribution of submerged vegetation in these locations is shown for comparison purposes.*

over areas previously mapped as intertidal flats. This type of change was common in intertidal sand flats on the barrier islands.

Conversion to Upland Land Uses

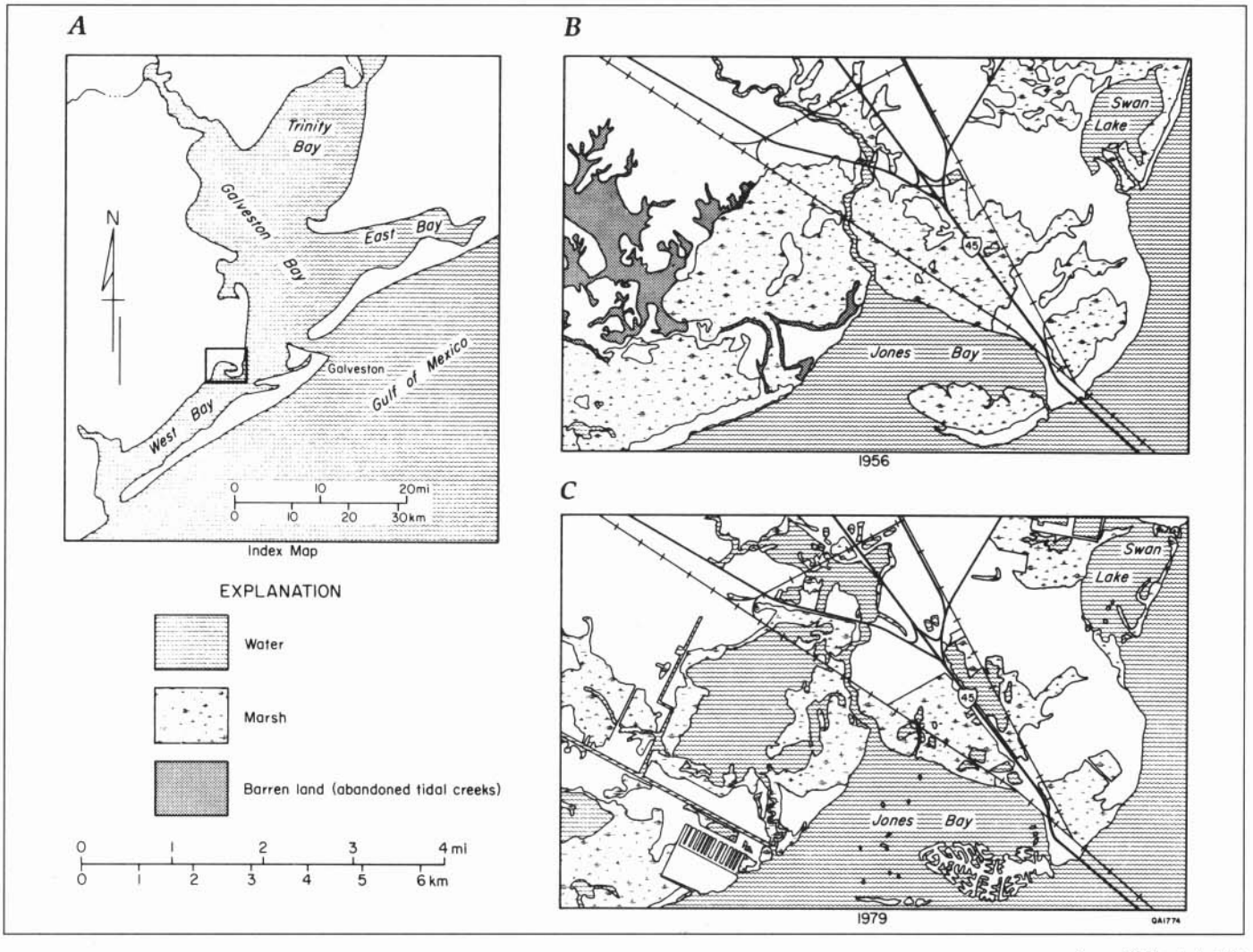
Draining of wetlands has also caused a significant loss of wetlands since 1950 (see FIGURE 7.3c). Much of this loss has occurred in fresh water marshes as opposed to the saltwater or brackish marshes. The gross lost area is 35,600 ac, which accounts for much of the total loss in estuarine and fresh water emergent wetlands. It should be noted that part of this loss can be attributed to photo-interpretation problems.

Conversion to upland range was the most significant human land use change affecting wetlands, with 25,000 ac of wetlands lost between the 1950s and 1989 (FIGURE 7.3d; FIGURE 7.7). Most of this change occurred landward from West and Christmas Bays. While some of the conversion appeared to be natural, much of the change may be attributable to drainage ditches constructed to reduce flooding and increase the area available for livestock grazing.

Conversion to cropland and pastureland claimed 3,600 ac, mostly in the Hitchcock, Oyster Bayou and Hoskins Mound 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 which affected photointerpretation, most of the loss may be due to direct conversion to upland range and cropland.

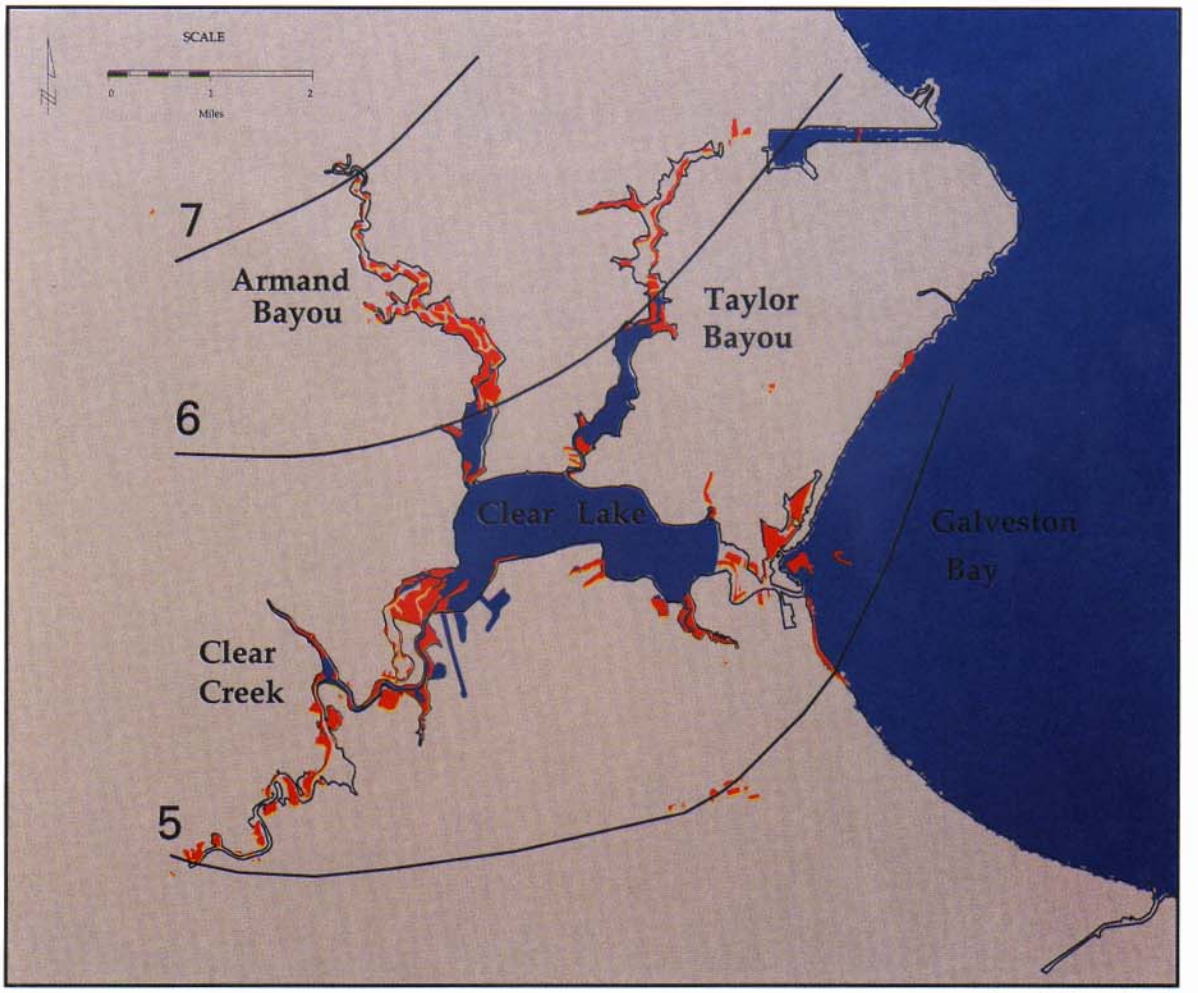
Conversion of wetlands to urban upland areas totaled 5,700 ac, and were concentrated in the south and west side of the bay, particularly around the Virginia Point area. Other areas where urbanization of wetlands occurred were in the Galveston, Texas City, League City, and Sea Isle areas.

Other upland conversions since the 1950s included dredged material disposal areas, with a net loss of 500 ac, and conversion to oil and gas production, resulting in a net loss of 800 ac. Much of the dredged material disposal losses were associated with the Gulf Intracoastal Waterway, while oil and gas production losses were concentrated in the Virginia Point, Texas City, and High Island areas.



Source: White, et al., 1985

FIGURE 7.5. *Changes in the distribution of wetlands between 1956 (b) and 1979 (c) near Jones Bay and Swan Lake, shown inset in (a). Land subsidence due to groundwater pumping resulted in the drowning of some 3,600 ac of marshland.*



Source: White et al., 1993

LEGEND

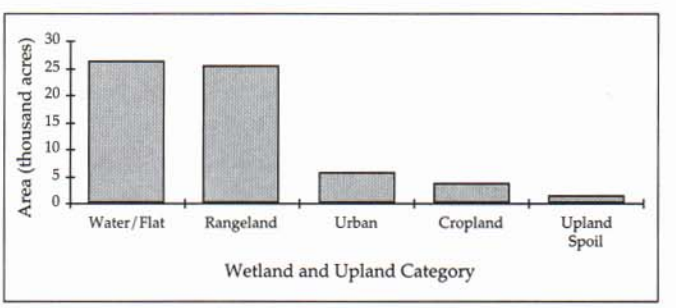
Emergent Wetlands Displaced by Water

Contours (in feet) for Subsidence between 1906 and 1987

FIGURE 7.6. *Relationship between subsidence and losses of emergent wetlands in the Clear Lake system. Contours indicate subsidence in feet between 1906 and 1987. Red indicates emergent wetlands displaced by open water. The loss of wetlands along Armand Bayou was practically complete, as a result of the increase in water depth.*

Dredge and Fill Influences

The relative impact of dredging and filling on marshes is difficult to quantify due to the lack of a good early-century baseline. In addition, there was no regulatory protection of wetlands until implementation of the Section 404 program in 1972. Ward (1993) estimated the total loss in marshland due to dredge and fill activities by analyzing available records from federal dredging projects, available maps of the bay over time, and U.S. Army Corps of Engineers Section 10/404 dredge-and-fill permits since the 1940s (see Chapter Five for more discussion of Section 10/404 projects). Based on this information, he estimated that a total of 7,070 ac of marshland had been lost to dredging, filling, and disposal activities since 1900. Of this loss, 2,920 ac was lost due to creation of designated disposal areas, 860 ac to navigation channels, and 3,290 to private dredge and fill operations under the Corps Section 10/404 permit program (note that the Section 10/404 permit data only extend back to the 1940s). The total area of wetlands lost was up to



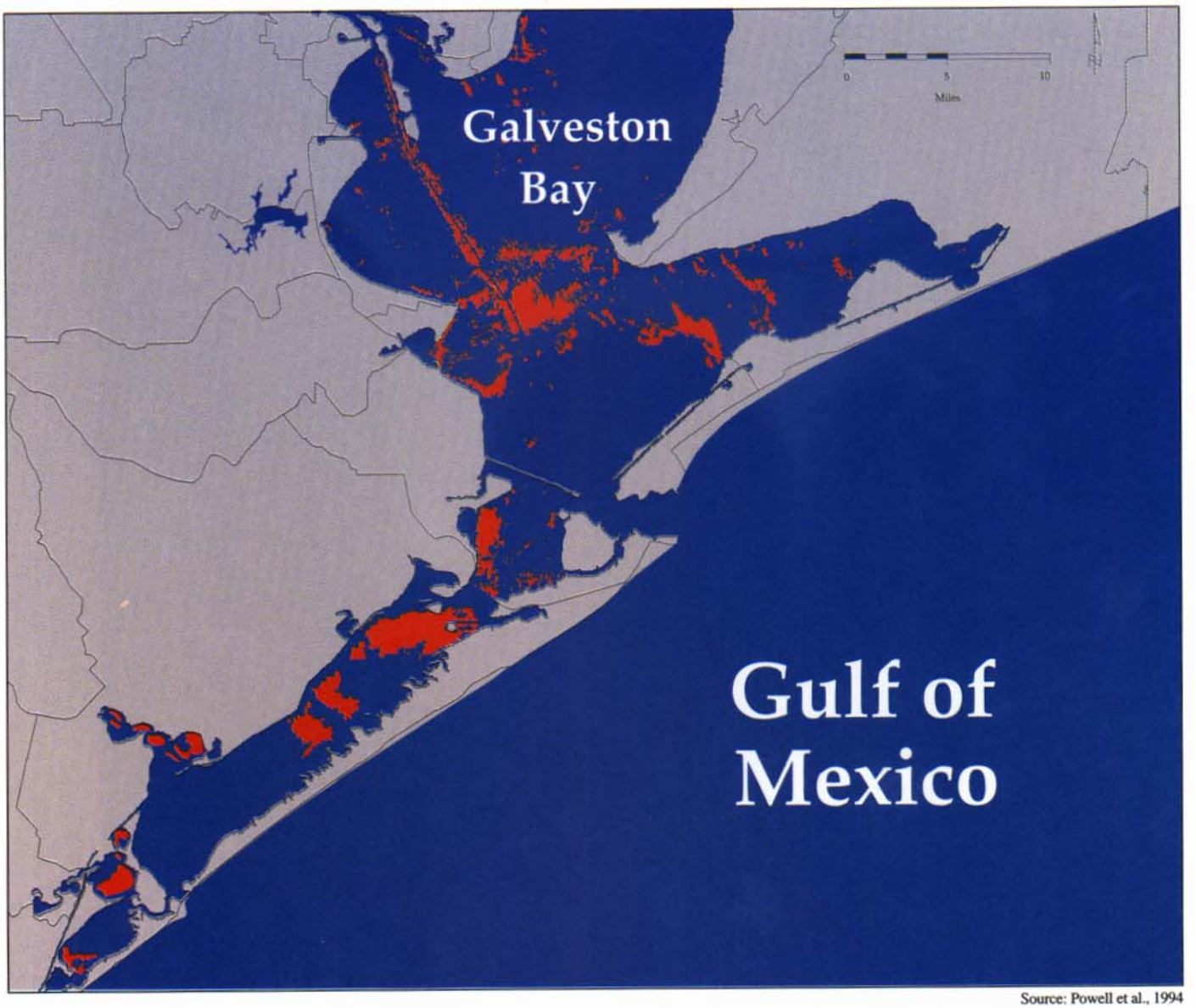
Source: White et al., 1993

FIGURE 7.7. *Extent of Galveston Bay marshes converted to other types of habitats.*

five percent of the total wetland area estimated to be present representing up to 20 percent of the net losses.

Isolations

As described in Chapter Five, several large-scale modifica-



Source: Powell et al., 1994

FIGURE 7.8. *Oyster reefs and shell-dominated bottom in Galveston Bay, shown in red. This map is based on a survey which used state-of-the-art sonar, global positioning, and geographic information system technologies.*

tions 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 ac of shallow bay bottom and 10,000 ac of marshland from the estuarine system. Other estuarine marshlands that have been isolated from the bay include:

1,100 ac in the Trinity River delta for the Delhomme hunting area;

2,500 ac on the west side of Trinity Bay and Trinity River delta for HL&P Cedar Bayou Generating Station's cooling pond;

About 2,000 ac on the north shore of East Bay for salt water barriers; and

About 700 ac in the Moses Lake and Dollar Bay area for the Texas City flood control project (although some limited exchange with bay waters occurs).

While these isolation projects have not resulted in a total conversion of these marshes to upland land uses, there has been an overall reduction of 16,000 ac of estuarine marshland from the Galveston Bay system since 1900 due to isolation and open-water habitat (Ward, 1993).

Changes in Submerged Aquatic Vegetation

The exact reasons for the decline in submerged aquatic vegetation are not known, although they may include some of the mech-

TABLE 7.2. Areal Extent of Oyster Reefs in Galveston Bay, Comparing 1971 and 1991 Survey Results.

Location	Extent of Reef 1991 (ac)	Contrast Between Comparable Reef Areas[1] Mapped in 1971 and 1991 1971 (ac)	1991 (ac)	1971-1991 % Increase
East Bay	2,900	2,660	2,900	9.0
Trinity Bay	1,250	540	840	55.6
Redfish Bar	3,300	1,850	3,090	67.0
North Redfish Bar in Central Galveston Bay	1,430	400	700	75.0
Red Bluff/Morgans Point Embayment	300	150	200	33.3
Clear Lake Embayment	270	220	260	18.2
Dickinson Embayment	2,100	1,370	1,910	39.4
Pelican Island Embayment	2,070	N/A	N/A	N/A
West Bay	7,400	N/A	N/A	N/A
West Bay Satellite Bays	2,980	N/A	N/A	N/A
Houston Ship Channel	2,700	240	1,310	445.8
TOTAL	**26,700**	**7,430**	**9,300**	**25.2**

Source: Powell et al., 1994

[1]See text for discussion of differences in methodology between the 1971 and 1991 surveys.

anisms described above. Pulich and White (1991) suggested that the most plausible reasons included: 1) subsidence and Hurricane Carla in western Galveston Bay; and 2) 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 submerged growth in Galveston Bay, as in other estuaries. In addition, submerged aquatic vegetation requires a low-energy environment with limited erosional forces. Subsidence has removed natural submerged wave barriers (**berms**) which created protected areas for submerged aquatic vegetation. Increased wave energy and erosional forces experienced in locales where submerged aquatic vegetation formerly existed may have reduced the potential for re-establishment.

OYSTER REEFS

As described in previous chapters, oysters create reef habitats that are important from a commercial, hydrological, and ecological point of view. Reef and unconsolidated shell sediments comprised a total of 26,700 ac in 1991 (Powell et al., 1994). The oyster reefs of Galveston Bay can be divided into naturally-occurring reefs that have existed over historic time, and reefs that originated through 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 small more-or-less circular bodies; and 4) barrier reefs extending across or nearly across the bay.

Reefs originating from human influences include those associated with: 1) dredged material banks next to navigation channels; 2) oil and gas development; 3) oyster leases; and 4) natural accretion in areas not previously conducive to reef development because of modifications in current flow. The reef types resulting from human activity account for a substantial fraction of all of the present-day reefs in Galveston Bay. In many areas of the bay, they account for 80 to 100 percent of the entire reef area.

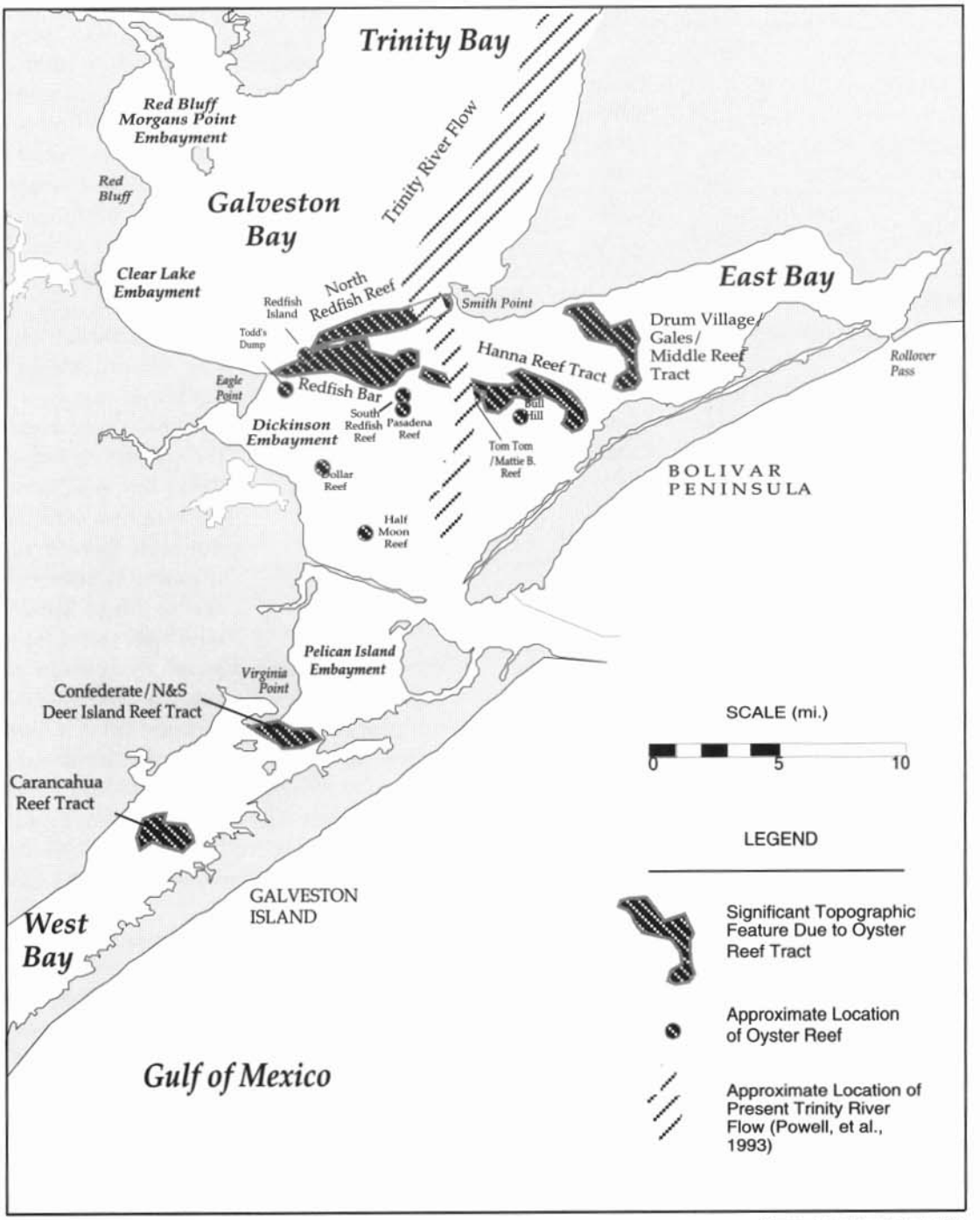
Reef Distribution and Trends

Oyster reefs and shell-dominated bay bottom were surveyed by Powell et al. (1994). The surveyed area included the majority of West Bay, East Bay, Trinity Bay, and Galveston Bay. Of the surveyed area, about 53 percent was in Galveston, East and Trinity Bays. The remaining 47 percent was in West Bay and the Pelican Island Embayment (the term embayment refers to sectors of Galveston Bay proper separated by significant points, islands, or man-made dikes and channels). A summary of the report prepared by Powell et al. (1994) is presented below. Chapter Eight includes a discussion of the status and trends of the oyster as a species, while this discussion emphasizes the habitat value of oyster reefs.

Locations of reefs and unconsolidated shell sediments in the bay are indicated in TABLE 7.2, FIGURE 7.8 (detailed locations), FIGURE 7.9a (general locations with reef names), and FIGURE 7.9b (reef gains and losses).

The area of oyster reef and oyster shell bottom identified in the recent oyster survey was substantially greater than depicted on earlier Texas Parks and Wildlife Department charts from the 1970s prepared by Benefield and Hofstetter (1976). Comparing all but the West Bay area, the recent survey identified 14,210 ac of oyster reef compared to the 7,424 ac 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 (FIGURE 7.9b). 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; 3) and 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. However, technology used by Powell et al. allowed more extensive mapping of the bay (particularly in deeper areas) than was previously possible using primarily manual and visual methods. Existing information, including the wisdom of working oystermen, indicates that little



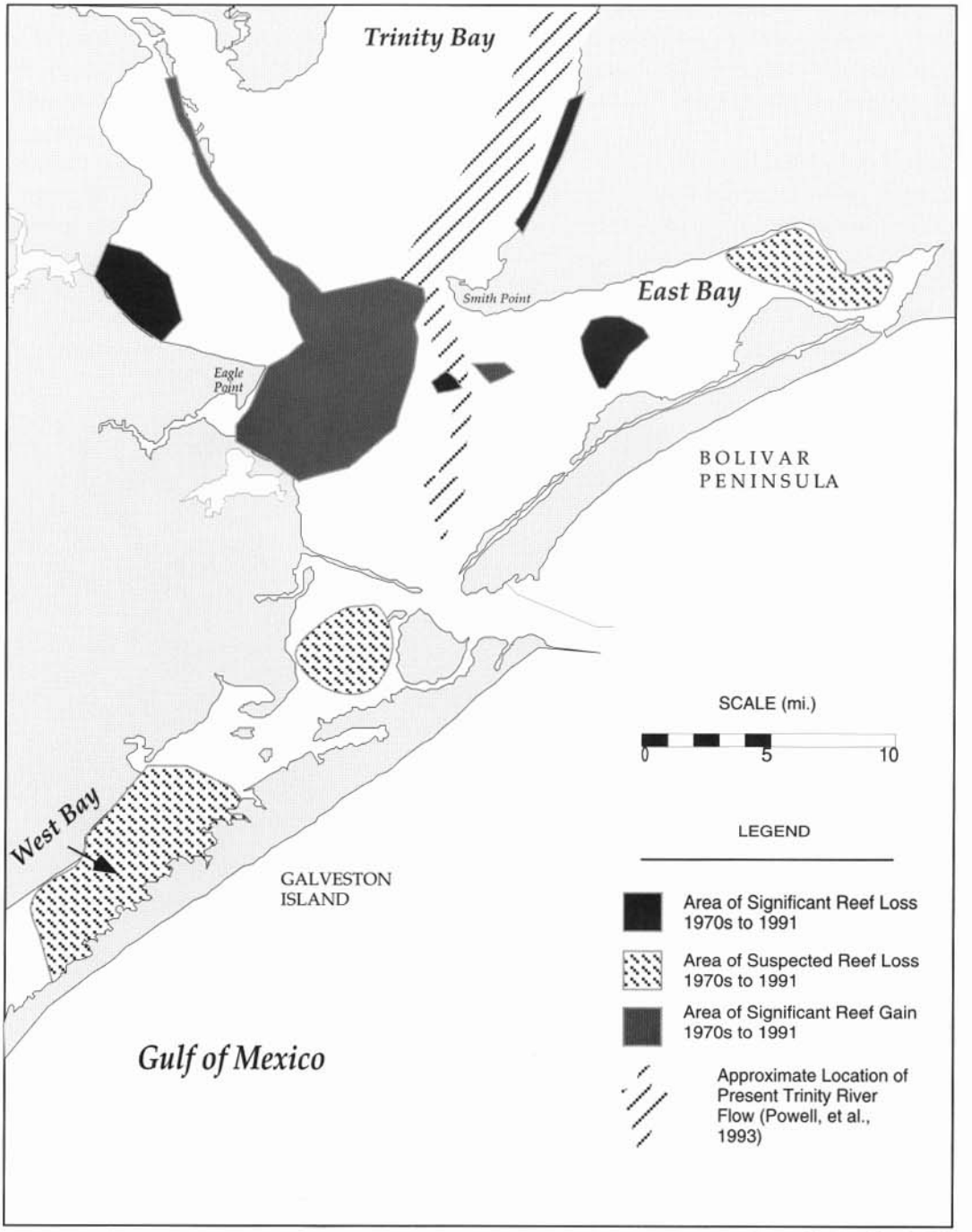
Source: After Powell et al., 1994

FIGURE 7.9a. *Diagrammatic representation of major Galveston Bay oyster reefs. Commercial and other named reef tracts are identified in relation to net Trinity River current flow. Significant oyster reef gains and losses, 1970s to 1991, are shown in (b).*

loss of previously-mapped 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.

Reefs originating through human activities, whether associated with dredged material banks from channels, oil field development, or purposeful creation (i.e., artificial reefs), appear not to vary in quality from natural reefs. Rates of accretion and loss were location-specific rather than dependent on the mode of origin of the reef. Clearly, artificial reefs can be markedly successful, if sited correctly to enhance reef growth (Powell et al., 1994).

There were substantial changes in bathymetric relief attributable to oysters in only one area, Redfish Bar, which has essentially moved south since the turn of the century (Powell et al., 1994). Relief on the remaining barrier reefs has not changed perceptibly. The reason for the disappearance of the original Redfish Bar cannot be precisely identified, nor are data sufficient to describe possible recovery of the many smaller reefs in East Bay and Trinity Bay that were impacted by shell dredging prior to 1970.



Source: After Powell et al., 1994

FIGURE 7.9b. *Diagrammatic representation of significant oyster reef gains and losses, 1970s to 1991.*

Large-Scale Impacts to Oyster Reef Habitat

Certain components of the Galveston Bay reef system 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 structure, **standing crop** and productivity of their phytoplanktonic food supply, salinity, and disease and predation (see Chapter Eight). Some of the most important large-scale changes to oyster habitat are presented below and shown above in FIGURE 7.9b.

Effects of the Oyster Fishery

No evidence exists for a substantial impact by the commercial oyster fishery on the bathymetric relief of existing oyster reefs (Powell et al., 1994). Supporting evidence provided from the survey included the following: 1) some of the most heavily-fished reefs have clearly not varied much in relief since an original 1850s survey (U.S. Coast Guard Service, 1855); 2) on the average, heavily fished reefs have accreted more area in the past 20 years than reefs not fished; 3) relief did not uniformly vary between reefs that are both open and closed to harvest for public health reasons–some

of each had relatively high relief (one to 1.5 m) and low relief (<0.5 m), primarily controlled by local conditions and individual reef history; and 4) the most significant areas of reef loss were in areas of the bay closed for oyster harvesting (see Chapter Nine for a discussion of reef closures).

The data demonstrated several likely impacts on reef area by the fishery. Most leases today contain reef or semi-consolidated shelly areas, and at least some of this material originated from purposeful and inadvertent shell transplanting by the lease holders. The accretion or loss of these reef areas were, once again, dependent on siting in relation to natural factors affecting oysters; they were not dependent upon mode of origin. Movement of shell off reef edges, if anything, has appeared to aid in reef growth–many reefs in naturally favorable areas were accreting area at their margins. An unknown portion of this marginal accretion was due to shell movement by the fishery, but there was no evidence of reef loss by this mechanism. Accordingly, the areal extent of reefs has probably been increased by fishing activities (Powell et al., 1994). The evidence suggests that judicious siting of new leases and requirements for private shell planting on leases could substantially increase the acreage of reef in the Galveston Bay system.

As a result of circulatory changes in the estuary (discussed below) some reefs are no longer optimally located for continued high productivity. Conversely, some areas with few oysters could now support productive reef if sufficient hard substrate became available. Observations suggest that naturally, reefs build only slowly out onto muddy bottom, due to the influence of several negative 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, suggesting a conservative management approach for these areas.

Effects of Subsidence

Regional subsidence has increased the depth of Galveston Bay and changed its shape (see Chapter Five). Influences on oysters were reported by Powell et al. (1994) as threefold: 1) most reefs are now detached from the shoreline, a likely result of subsidence and shoreline retreat; 2) the increase in water depth (particularly for barrier reefs) has reduced the extent to which reefs are intertidally and subaerially exposed, while drowning the natural alongshore berms that can develop into reefs; and 3) areas of high subsidence, such as the Clear Lake Embayment, have suffered reef attrition due to siltation (FIGURE 7.9b). The Clear Lake area, however, must not be adequate to support reef growth any longer–otherwise reef growth would have kept up with siltation.

Effects of Channelization

Channelization, dike construction, and loss of the original Redfish Bar (see Chapter Five) have substantially altered bay circulation patterns. The pre-1900 circulation pattern in Galveston and Trinity Bays is unknown, but the breaching of Redfish Bar by the Houston Ship Channel likely produced major circulatory changes influencing oysters. Prior to 1900, Redfish Bar had three primary channels, only one of which (West Pass) admitted 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. Other changes have probably also been important, for example, the Texas City Dike has probably reduced circulation in West Bay.

Source: Texas Sea Grant College Program

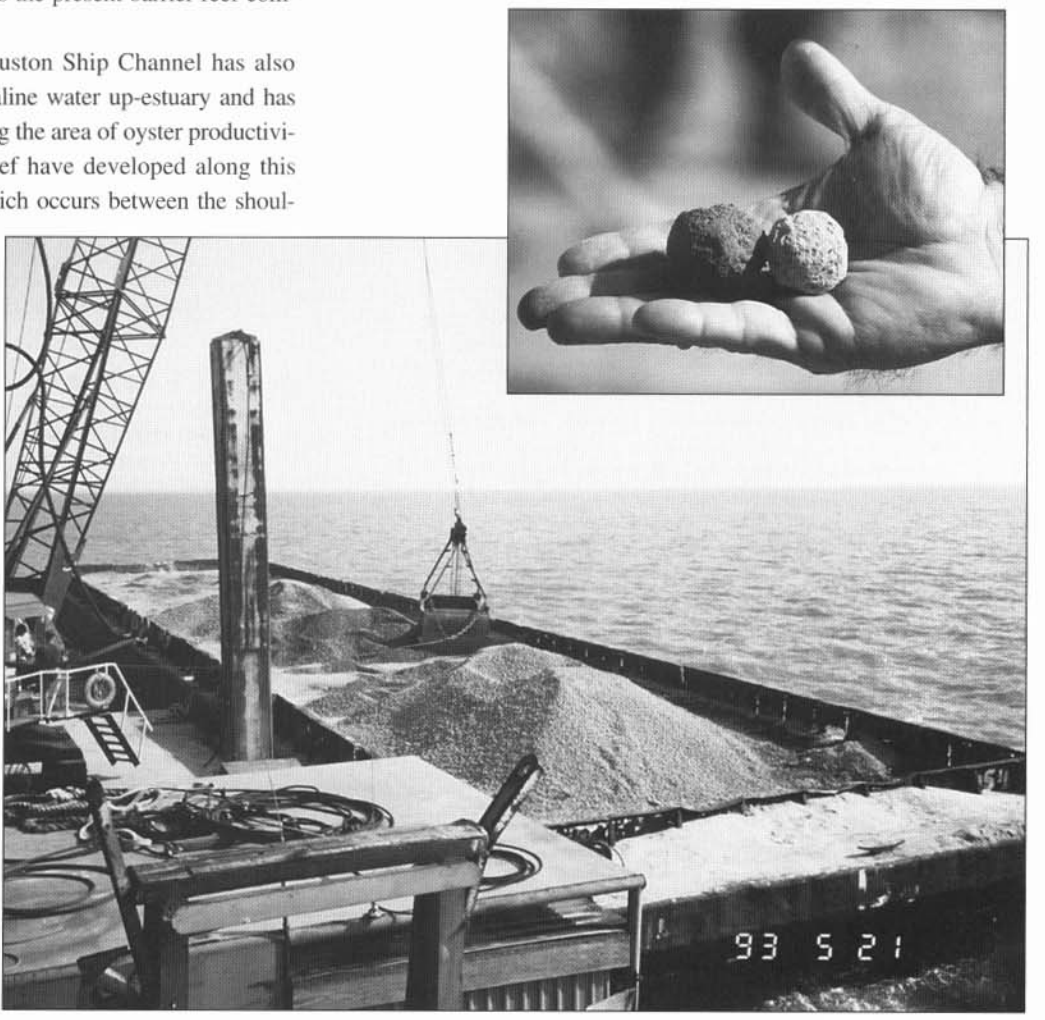
Oysters are harvested with oyster dredges (upper right). The live oysters are then separated from shell (predominating in this haul) and shucked for sale. Oysters require a hard substrate (generally shell) to grow, and changes in bay circulation can result in the demise of old reefs and the creation of new ones.

Bay-wide changes in circulation have resulted from these alterations. Today, the bulk of the Trinity River flow exits Trinity Bay along the southern shore, wraps immediately 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 (FIGURE 7.9a). 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 circulatory barrier.

For oysters, the result has been a destruction of the original equilibrium between reefs and the bay circulation (Powell et al., 1994). Ultimately, this change resulted in: 1) loss of a number of small reefs along the southern shore of Trinity Bay; 2) the demise of the Hanna Reef tract in the vicinity of Mattie B. Reef and Tom Tom Reef, the present outlet for much of the Trinity River flow;

and 3) the accretion of reef along the southern edge of South Redfish Reef, along the western and northern margin of Pasadena Reef, and along the southern edge of Bull Hill and associated reefs (FIGURE 7.9b). These latter three areas adjoin the present route of outflow of the Trinity River as it crosses the present barrier reef complex in the bay.

On the positive side, the Houston Ship Channel has also increased the penetration of more saline water up-estuary and has increased current velocities, extending the area of oyster productivity northward. Over 2,500 ac 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 (FIGURE 7.9b). Curiously, the data reveal the importance of the coincidence of two bathymetric features for development of reef along channels: both a channel and a dredged material disposal bank are required. Observation of channels in which the dredged material disposal banks were placed on only one side show that reef development is predominantly or exclusively on that side. In the reach from buoy 63 to Morgans Point, all reef development is in this small zone parallel to the channel. The reefs resulting from these alterations have greatly benefited the commercial fishery.



Source: Houston Lighting and Power

Oyster studies suggest reefs can develop in some bay locations currently devoid of oysters due to lack of hard substrate. The Galveston Bay National Estuary Program, in conjunction with Houston Lighting and Power and the Port of Houston Authority, undertook a pilot project in which golf ball-sized pellets of coal ash were placed in the bay for reef-substrate. Preliminary results indicate this activity can make use of an industrial byproduct to benefit the bay.

SUMMARY

Wetlands and oyster reefs are two important habitat types within the Galveston Bay ecosystem. Wetlands have declined substantially over the past four decades, while oyster reefs appear to have increased.

Wetland losses are reflected by acreages of 171,000 in the 1950s; 146,500 in 1979; and 138,600 in 1989. The rate of loss, however, decreased over time from 1,000 ac/yr between 1953 and 1979, to less than 700 ac/yr between 1979 and 1989. Adjustments for photointerpretation errors reduce this rate even more. Most of the loss of estuarine marsh has been caused by subsidence and subsequent conversion to open bay/barren flats. For fresh water marshes, human activities have been responsible for most of the loss, particularly conversion to upland range. Other major alterations have resulted from a series of projects that have isolated a total of 16,000 ac of formerly estuarine marshland and shallow water from the bay. The closure of Turtle Bay (now called Lake Anahuac) in 1936 is the most prominent example of isolation.

Historically, continuous beds of submerged aquatic vegetation flourished around the Trinity River Delta, along the west shoreline from Seabrook to San Leon, and in West Bay. Only a remnant of this habitat remains in the submerged aquatic vegetation meadows of Christmas Bay, a secondary bay of west Galveston Bay. The exact reasons for the decline are still unknown, although increased turbidity, subsidence, increased erosion through wave energy, pollution, nutrient fluctuations, and human impacts have been identified as potential causes.

Overall, Galveston Bay has grown substantial oyster reef in the last 20 years. The location and mechanisms of reef accretion suggest that natural responses to changes in circulation and salinity by the oyster populations are primarily responsible, rather than the direct production of new reef by man. For example, the Houston Ship Channel has increased the penetration of saline water up-estuary, increasing the overall area of oyster reef by about 2,500 ac, to the great benefit of oyster populations and the oyster fishery.

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CHAPTER EIGHT

The Bay's Living Resources

Ah, my dear friend, would that you were here just now to see the snipes innumerable, the blackbirds, the gallinules, and the curlews that surround us;—that you could listen as I now do, to the the delightful notes of the mockingbird, pouring forth his soul in melody as the glorious orb of day is fast descending towards the western horizon;—that you could gaze on the great herons which, after spreading their broad wings, croak aloud as if doubtful regarding the purpose of our visit to these shores!

–John James Audubon, upon visiting Galveston Bay in 1837

Galveston Bay is home to a myriad of organisms that live in a variety of estuarine habitats and which interact with the bay in a variety of ways. Fish and wildlife resources provide some of the Bay's greatest values, economically, recreationally, and aesthetically. Individual species, ranging from microbes to alligators, can also serve as useful indicators of the overall condition of the ecosystem; therefore considerable scientific and regulatory resources are devoted to studying their populations. Quite naturally, most monitoring efforts are directed at the species of greatest concern to humans–particularly seafood species.

Historical accounts indicate that several Galveston Bay fish and wildlife species, including sea turtles, snook, striped bass, and the saltwater terrapin, have either disappeared or declined dramatically in the last 150 years. This provides reason for concern about conditions in the bay causing these declines–are these conditions likely to cause declines in other species? On the other hand, long-term commercial and recreational fishing harvest records (some dating back to the 1890s) show harvest fluctuations over time, but no dramatic species decline (see seafood landings in Chapter Four).

Based on a major review of living resources in the estuary (reported in this chapter), the Texas Parks and Wildlife Department concluded that the overall "health" of the bay system is fair to good. There were no observed wholesale declines in species population abundance over the past ten to 20 years and the energy and material transfers throughout the food web were occurring more or less naturally (Green et al., 1992). In fact, there were significant increases in some populations, including American alligator, red drum, spotted seatrout, Atlantic croaker, black-bellied plover, willet, sanderling, western sandpiper, olivaceous cormorant, and brown pelican. To now, Galveston Bay has clearly escaped major biological losses seen in some of the Atlantic estuaries.

Recent trends for several bay species, however, do raise concerns. Population declines have been observed over the past decade for white shrimp, blue crab, mottled duck, and some shoreline-feeding birds. The major decline in submerged aquatic vegetation and 17–19 percent loss of estuarine wetlands described in Chapter Seven are troublesome issues; estuarine species that depend upon these key habitats could be affected if these trends continue (Green et al., 1992). As these habitats have declined, fishing activity and recreation usage of the bay continues to increase, placing added strain on the resource.

This chapter summarizes findings from several recent studies of the bay's living resources. Discussion begins with a description of the bay's food web, a concept that reveals the interdependence among bay species and the importance of external materials and processes to estuarine species populations (see also Chapter Three). 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: phytoplankton, zooplankton, benthic organisms, oysters, finfish, shrimp and crabs, birds, amphibians and reptiles, and finally, mammals. Objective data on most of these topics is of recent vintage, rarely predating the 1970s. Therefore, we lack a larger historical perspective on the findings reported here.

Much of the material in this chapter falls in the realm of population dynamics. What controls the population size of a given

Source: Frank S. Shipley

A semipalmated sandpiper surveys the placid waters of a mud flat.

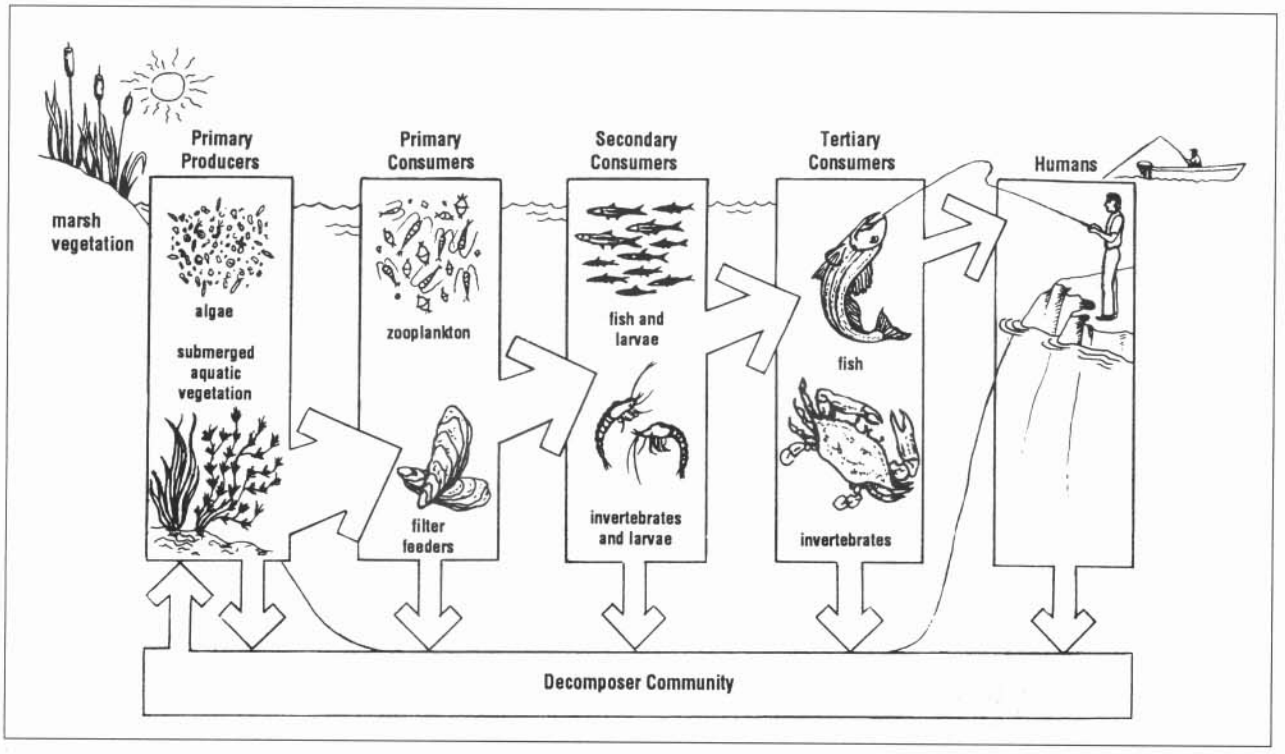
species? Among the relevant factors are habitat (both quantity and quality) degree of environmental contamination, and a host of natural forces such as predation, competition for food or space, diseases and parasitism. Population regulation can be controlled seasonally; it can also operate on just one of several life stages. While estuarine populations may frequently be limited by abiotic factors of the physical environment (hurricanes; salinity), this is not an unswerving rule; most often, the underlying mechanisms remain hidden. Therefore, managers of estuarine populations (who are responsible for species management regardless of how much is understood) work with the tools available, including harvest regulations for commercial and recreational species, habitat protection, and actions to keep the environment free from contaminants. Trial and error can help determine management actions that work for a given species, while science continues to search out the underlying mechanisms.

THE ESTUARINE FOOD WEB

The estuarine food chain has been described by Monroe and Kelly (1992):

> *Life in an estuary does not happen in random order; rather, it is organized and structured. From the simplest microscopic plants to the largest animals, organisms are connected to each other in chains of "who eats whom" known as a food web.*
>
> *In a food web, plants and animals are connected by energy flow. At the bottom of the web, green plants and some bacteria utilize the energy of sunlight to combine carbon dioxide and water into simple foods. In this process known as photosynthesis, plants and photosynthetic bacteria convert or "fix" inorganic carbon into molecules of carbohydrates. In doing this, they store the energy of sunlight in organic chemical bonds. As small animals consume these plants and bacteria and are in turn eaten by predators, the energy passes through the food web.*
>
> *Plants and photosynthetic bacteria are known as primary producers in a food web because they produce the first forms of food. Animals that eat plants are known as primary consumers, and animals that eat other animals are called secondary or tertiary consumers.*

Some of the paths of energy flow in a typical estuarine food web are depicted in simplified form in FIGURE 8.1.



Source: Alliance for Chesapeake Bay, 1992

FIGURE 8.1. *The estuarine food web begins with solar energy converted to green plant tissue. As grazers, the primary consumers use this tissue directly, in turn supporting predators at several levels. An important part of this system is the detrital pathway; decaying organic matter originating at each step supports a diverse group of decomposers.*

Primary Production

The various levels in the food web all ultimately rely upon energy captured from the environment by green plants, the primary producers. In Galveston Bay, there are six main primary producer communities ranging from phytoplankton (algae) in open bay habitat to trees and perennials in woodlands and swamps bordering the estuary (TABLE 8.1). Each of these flora types is responsible for a portion of the production (generation of organic matter through photosynthesis) that sustains primary consumers and their predators.

Sheridan et al. (1989) used literature values to estimate primary production for six main classes of flora, and concluded that phytoplankton, benthic microflora, plants in salt and brackish marshes, and trees in woodlands and swamps all contribute roughly the same order of magnitude of organic food to the estuary. Fresh water marshes were a much smaller contributor. Although submerged vegetation had the highest productivity per square kilometer, their small areal extent in the bay made them less significant in terms of the amount of fixed energy produced. A good deal of uncertainty is involved in making these estimates.

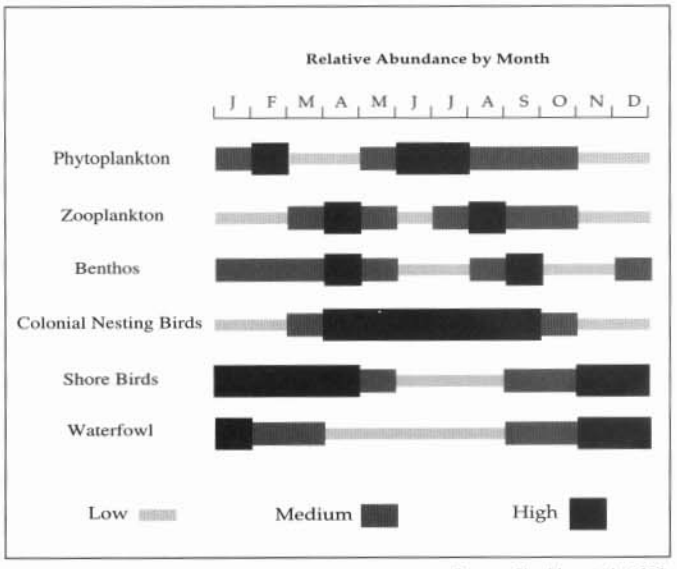
TABLE 8.1. Primary Productivity in the Galveston Bay System.

Flora	Average Estimated Primary Productivity (g dry/m^2/yr)	Areal Coverage (km^2)	Estimated Annual Production (metric tons)
Phytoplankton	350	1,425	498,750
Benthic microflora	500	1,425	712,500
Submerged vegetation	2,600	1	2,600
Fresh water marsh	820	40	32,800
Salt-brackish marsh	1,100	370	407,000
Woodlands/swamps	700	500	350,000

Source: Sheridan et al., 1989

Much of the primary production identified by Sheridan et al. is separated in time and space from the primary consumers. For example, woodlands, swamps, and fresh water marshes probably export less than ten percent of their primary productivity to in-bay consumers because of their relative isolation, whereas salt water marshes may export 35-40 percent (Texas Department of Water Resources, 1981; Gosselink et al., 1979). In addition, the nutritional quality of the primary production is lowest for higher-order plants in marshes, swamps, and seagrass meadows, and highest for phytoplankton.

Because a substantial amount of the overall productivity reaching the estuary is of lower quality, the majority of the primary consumers in the bay system are species that consume the detritus of primary production rather than living plant material. Many of these species also consume the bacterial and fungal decomposers associated with decaying organic matter. These detritivores include many benthic organisms such as marine worms, bivalves, gastropods, crustaceans, and bottom feeding fishes and **macroinvertebrates** (Sheridan et al., 1989; Gosselink et al., 1979).



Source: Sheridan et al., 1989

FIGURE 8.2. *Living things at all levels in Galveston Bay's food web vary in abundance with the seasons. Seasonal reproduction patterns and species movements (for example juvenile shrimp migrating to the Gulf of Mexico) are the basis for much of the variability. These abundance patterns represent evolutionary adaptations to the dynamic processes of the estuary.*

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 very productive 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.

Indicator Species

Food web theory provides a context for selecting particular **indicator species** at different trophic levels to indicate the overall condition of the ecosystem. "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 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, marshes, and other wetlands.

> 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 and stressed environments.

> Economically important groups generally utilizing middle trophic levels. These include finfish and most shellfish. Example species include red drum, sand seatrout, Atlantic croaker, southern flounder, white shrimp, brown shrimp, and blue crab.

> Species of special interest including top carnivores such as dolphins, sharks, and waterbirds; abundant prey species; and endangered species.

Species within each of these categories are marked by variability occurring on different time scales. One important scale is seasonal (FIGURE 8.2); many species are migratory or time their reproduction based upon seasonal water temperatures or food supplies. Investigations focusing upon population dynamics must account for this source of natural variability, before long-term trends relating to changing bay conditions or human activities can be deciphered. One key challenge to biologists is obtaining a long enough data record to partition the various sources of variability affecting species numbers.

PHYTOPLANKTON

Phytoplankton are microscopic single-celled algae that drift with the motion of the currents, constituting an important and high-quality source of energy to consumers. Problems can result from large changes in phytoplankton abundance. For example, excessive reproduction of phytoplankton, usually caused by enhanced levels of nutrients, results in algae blooms. Algae blooms can exert high oxygen demand on the water through nocturnal respiration and decomposition following death (in the daytime, algae are net producers of oxygen, as a by-product of photosynthesis). The oxygen depletion accompanying eutrophication can suffocate other aquatic organisms and generally degrade the environment. Conversely, a shortage of phytoplankton depletes the food supply of primary and higher consumers such as oysters, shrimp, fish, and birds.

Phytoplankton research in Galveston Bay began in the late 1950s and peaked in the 1970s with Trinity Bay impact studies related to cooling water discharges of the Cedar Bayou electrical power generating station. Key studies include Hohn (1959), Armstrong and Hinson (1973), Strong (1977), and Zotter (1979). Research on phytoplankton biomass includes Zein-Eldin (1961), Strong (1977), Mullins (1979), Krecji (1979), and Smith (1983). The Texas Department of Water Resources studied phytoplankton as part of a fresh water inflow study (1981). Most of these studies had limited spatial and temporal coverage, and no documented phy-

toplankton studies have been conducted on the bay since 1985.

Types of Phytoplankton in Galveston Bay

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).

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). This has important food web implications; nanoplankton are much more susceptible to immediate grazing by zooplankton than larger phytoplankton, causing Texas phytoplankton populations to be more vulnerable to consumers (Stockwell and Buskey, in preparation).

In general, phytoplankton *densities* in Galveston Bay are lower than in many other Texas estuaries (Texas Department of Water Resources, 1981), which are, in turn, 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. These topics are addressed below.

Production Rates

Most phytoplankton productivity studies in Galveston Bay were performed in the early 1970s and concentrated in areas influenced by the Cedar Bayou Generating Station outfall. These studies went beyond measurements of abundance and taxonomic distribution, also measuring the rate of photosynthesis from the phytoplankton using the Carbon-14 uptake method. After a review of the available information, Buskey and Schmidt (in Green et al., 1992) concluded "there is no evidence for long-term trends in primary production patterns in the Galveston Bay estuary based on these data from the 1970s. There is considerable spatial and seasonal variability in primary production, but the overall annual mean of primary production is always 35 mg C/m^3/hr, except for the study of Strong (1977), whose mean value was nearly 55 mg C/m^3/hr."

TABLE 8.2. Annual Phytoplankton Primary Production Estimates for Selected North American Estuaries.

Estuary	Primary Production (g C/m^2/yr)
Hudson River Plume, New York	550
Pamlico River, North Carolina	500
Puget Sound, Washington	465
Corpus Christi, Texas (1987-1988)	430
Galveston Bay, Texas	**365**
Narragansett Bay, Rhode Island	220
South Bay, San Francisco Bay, California	210
Corpus Christi Bay, Texas (1981-1983)	174
Wassaw Sound, Georgia	90
Average of 45 estuary systems	**255**

Source: Buskey and Schmidt, in Green et al., 1992

Galveston Bay appears to have slightly above average phytoplankton primary production rates, compared to most other estuaries in the U.S. (TABLE 8.2; Green et al., 1992). Primary productivity for Galveston Bay was estimated using an assumed production rate of 40 mg/C/m^3/hr, 12 hours of daylight, and a two meter average depth; this yields an estimated primary productivity rate per unit area of the bay of 365 g C/m^2/year.

In most estuarine situations, phytoplankton primary production is controlled by light, temperature, and nutrients. In Chesapeake Bay, for example, serious water quality problems have been documented as a result of excess nutrient loadings, and point and nonpoint management regulations have been implemented to reduce nutrient import to Chesapeake waters. Nitrogen is most often the limiting nutrient in coastal systems (Buskey and Schmidt in Green et al., 1992). Besides large-scale impacts of nutrients, marked seasonal effects are also observed in temperate estuaries, where lower production in the winter months results from lower water temperatures and reduced light.

Texas estuaries differ from temperate U. S. estuaries in being wind-dominated and shallow, resulting in low, but variable water clarity (the long-term average secchi depth is only about half a meter). The phytoplankton response in this environment is by no means fully understood. The low average water clarity may impose some light limitations on photosynthesis (Harding et al., 1986; Armstrong, 1987; McFarlane et al., 1989; Baca et al., 1982), but little information exists to define exactly how this works (Whitledge and Ray, 1989). However, since wind constantly mixes the bay (and its phytoplankton) when it is in its most turbid condition, phytoplankton may continue to photosynthesize to some extent, making productivity rates poorly predictable based on water clarity alone (Marsh, 1974). The tendency is for small blooms to occur throughout the year, apparently unrelated to locations or seasons (Stockwell, 1989). Overall, Galveston Bay appears to be less susceptible to nutrient over-enrichment and related algae blooms and dissolved oxygen problems than are many Atlantic estuaries.

Trends in Space and Time

Buskey and Schmidt (in Green et al., 1992) concluded it was impossible to verify any spatial trends in phytoplankton distribution based on the series of unrelated and limited special studies conducted from 1957 to the 1992. Data compiled by Ward and Armstrong (1992) indicated some possible areas of high chlorophyll-*a* abundance, such as in 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 dominated; whereas higher salinity sites were dominated by diatoms.

Concerning temporal trends, Buskey and Schmidt noted the difficulty in drawing long-term conclusions about phytoplankton abundance patterns. Several short-term phytoplankton studies, extending over a one or two-year period, evaluated temporal changes in phytoplankton abundance using chlorophyll-*a* as an indicator of biomass. In one early study, Zein-Eldin (1961) found no seasonal trend in average biomass at several Galveston Bay stations after taking chlorophyll-*a* samples once a week for a 20-month period in the late 1950s (FIGURE 8.3). Of note is the fact that several years of extreme drought ended in the middle of 1957, followed by higher flow in late 1957.

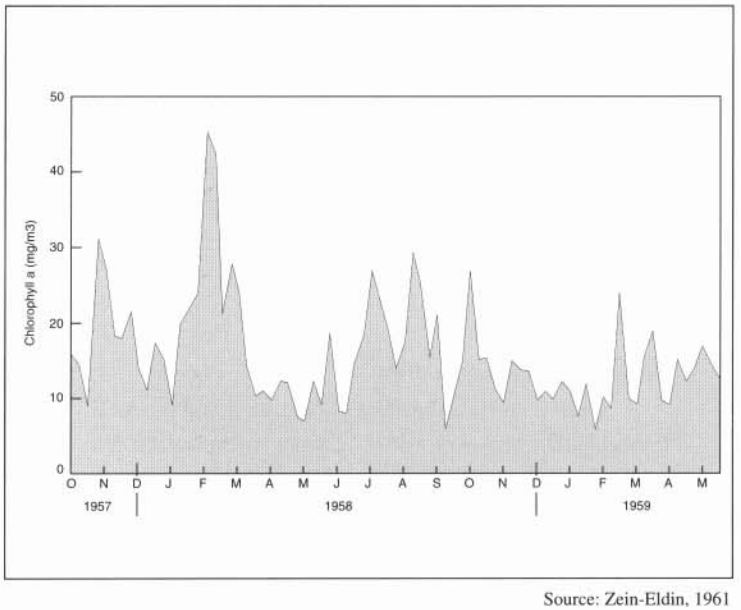
Possible Increases, 1950s–1970s

There is some indirect evidence of an increase in chlorophyll-*a* from the late 1950s to the 1970s (Buskey and Schmidt in Green, 1992). *Mean* chlorophyll-*a* concentration from the Zein-Eldin study in the late 1950s was 16 mg/m^3, which compares closely to an overall mean of 13 mg/m^3 and 17 mg/m^3 for stations in Trinity Bay measured by Mullins (1979) and Strong (1977), respectively. However, the *maximum* concentration of chlorophyll-*a* from the 1950s Zein-Eldin study was 45 mg/m^3, compared to higher maximum concentrations measured in three Trinity Bay studies in the 1970s: 70 mg/m^3 (Mullins, 1979), 120 mg/m^3 (Krecji, 1979), and 85 mg/m^3 (Strong, 1977). Smith (1983) found a maximum concentration of 45 mg/m^3 chlorophyll-*a* in the late 1970s.

Declines, 1970s to Present

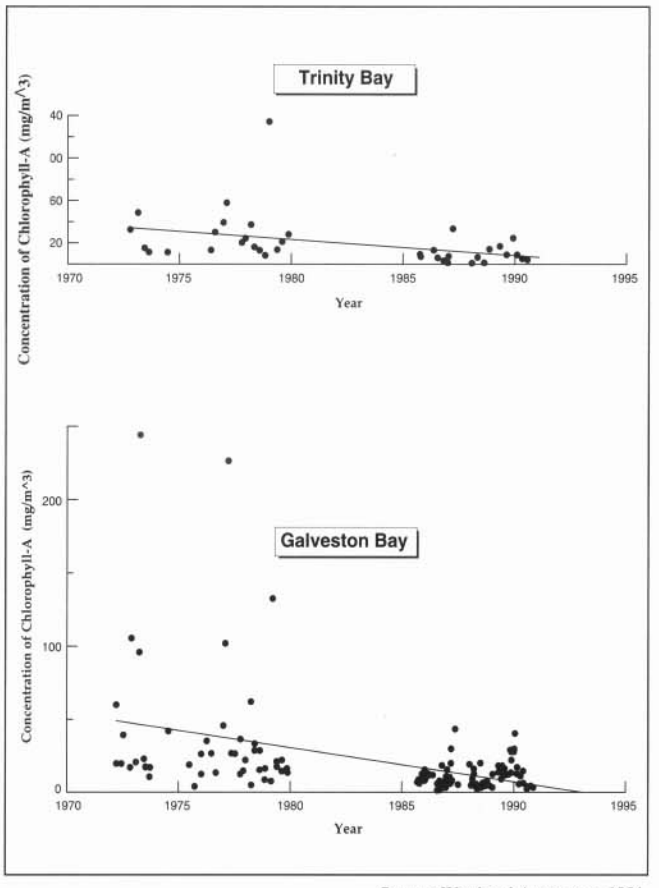
Since the 1970s, however, the existence of a routine monitoring program for chlorophyll-*a* has allowed better trend analyses, even though this parameter remains merely an indicator of actual phytoplankton biomass. A clear decline emerged from analysis of this data by Ward and Armstrong (1992): mean chlorophyll-*a* concentrations fell by about 50 percent throughout much of the bay from 1969 to 1990 (see FIGURE 6.8b). This decline occurred in numerous individual hydrographic segments; data from lower Galveston Bay and from Trinity Bay are given in FIGURE 8.4. For each of these segments, mean chlorophyll-*a* from the 1970 to 1980 period was 30-35 mg/m^3, compared to ten to 15 mg/m^3 for 1985 to 1991.

This is a considerable decline in phytoplankton, but falls short of a precipitous "crash" to unmatched lows. Rather, implications of the chlorophyll measurements are that phytoplankton biomass may have reached levels slightly lower than values typical of Galveston Bay from 1957 to 1959. Current phytoplankton conditions are only slightly lower than the mean value observed during the late 1950s by Zein-Eldin.



Source: Zein-Eldin, 1961

FIGURE 8.3. *Chlorophyll-a variation in Galveston Bay over a two-year period in the late 1950s. Phytoplankton abundance, indicated by chlorophyll measurements, is marked by unpredictable variability in short-term studies. Chlorophyll-a apparently increased (from the values shown here) to higher levels in the early 1970s, followed by a decline (FIGURE 8.4). Wind mixing and low water clarity tend to forestall seasonal algae "blooms" more frequent in some other U. S. estuaries.*



Source: Ward and Armstrong, 1991

FIGURE 8.4. *Chlorophyll-a, an indicator of phytoplankton biomass, has declined throughout much of Galveston Bay since the early 1970s. Data are shown for Trinity Bay and central Galveston Bay. A leading hypothesis for this reduction is reduced nutrients (particularly nitrogen) resulting from improved wastewater treatment and creation of reservoirs on the Trinity and San Jacinto Rivers.*

Probable Causes of Trends

Why did phytoplankton apparently increase from the late 1950s to the early 1970s, then decline from the early 1970s to the

present? The complex dynamics of phytoplankton, combined with the lack of long-term direct measurement data makes the explanations discussed below somewhat speculative.

Buskey and Schmidt (in Green et al., 1992) suggested the earlier increase may have been caused by a combination of increasing nutrients and a change in predator populations. An increase in nutrient concentrations from the 1950s to 1970s probably resulted from increased point and nonpoint source discharges as the Houston metro area developed. Buskey and Schmidt reported that Galveston Bay had lower zooplankton abundance than other Texas bays in the 1970s (see zooplankton section, below) and speculated a link to "industrial discharges." If their hypothesis is correct, then improvements in industrial discharges after 1970 could have allowed a resurgence in zooplankton populations, which subsequently increased phytoplankton grazing. Unfortunately, not enough data are available to confirm the posited temporal change in zooplankton populations (Buskey and Schmidt in Green et al., 1992).

Ward and Armstrong (1992) evaluated several potential causes for the decline in chlorophyll-*a* observed after 1970:

Declining inorganic nutrient supply

Increased toxicity or adverse environmental conditions

Increased predation on phytoplankton

Decreases in chlorophyll-*a* dominated organisms

Laboratory artifacts, due to alterations in methodology

They concluded nutrient reduction was the most plausible explanation. Chlorophyll-*a* declines paralleled an observed 50 percent reduction in nutrients due to curtailed point source loadings in the early 1970s, the trapping of Trinity River nutrients due to construction of Lake Livingston in the early 1970s, and changes in land use in the upper watershed (see Chapter Six).

Finally, the decline in phytoplankton might be influenced by an increased population of filter-feeders such as oysters or clams. 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 (see Chapter Seven).

Nuisance Blooms and Red Tides

Nuisance blooms of various green algae and non-toxic **dinoflagellates** occur occasionally, mainly in tributaries which have low circulation and high nutrient (e.g. nitrogen) sources. Such blooms have been noted both in winter (for example in Clear Lake) and summer (for example Dickinson Bayou and Clear Lake) during calm conditions when light penetration improves. These blooms can be accompanied by oxygen depletion, particularly in enclosed situations, and can be triggered by summer low-flow conditions. Almost certainly, resulting oxygen depletion in the bay's bayous and stream tributaries is more widespread than currently acknowledged, due to a lack of oxygen measurements at night and during early morning hours when this depletion would be expected.

Toxic blooms (as determined by fish kills) are uncommon events within Galveston Bay. Fish kills and water discoloration caused by **red tide** blooms are periodically observed in the Gulf of Mexico but only occasionally noted inside Galveston Bay. For example, a major outbreak of the toxic red tide *Ptychodiscus brevis* occurred off much of the Texas coast 1986–1987 (detailed in Trebatoski, 1988). This incident resulted in one of the largest fish kills in recent times, but no evidence exists that this bloom entered any of Galveston Bay's inlets, as it entered several other Texas bays to the south.

Within the bay, most red tide blooms are caused by the dinoflagellate *Gonyaulax monilata*, and are of limited duration. This species produces a reddish-brown hue and toxins that can result in fish kills. One of the most notable red tides to affect the bay occurred in 1984 (Harper and Guillen, 1989).

ZOOPLANKTON

Zooplankton are microscopic drifting animals that feed on phytoplankton or smaller zooplankton. 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 (primarily net size) by different researchers. The time of day that samples are collected is also important, as many estuarine zooplankton are diurnal vertical migrators (Minello and Matthews, 1981). Therefore, daytime zooplankton samples often underestimate total zooplankton population densities. The longest running data set extends from 1967 to 1980 for an area in Trinity Bay near the Cedar Bayou Generating Station (Buskey and Schmidt in Green et al., 1992).

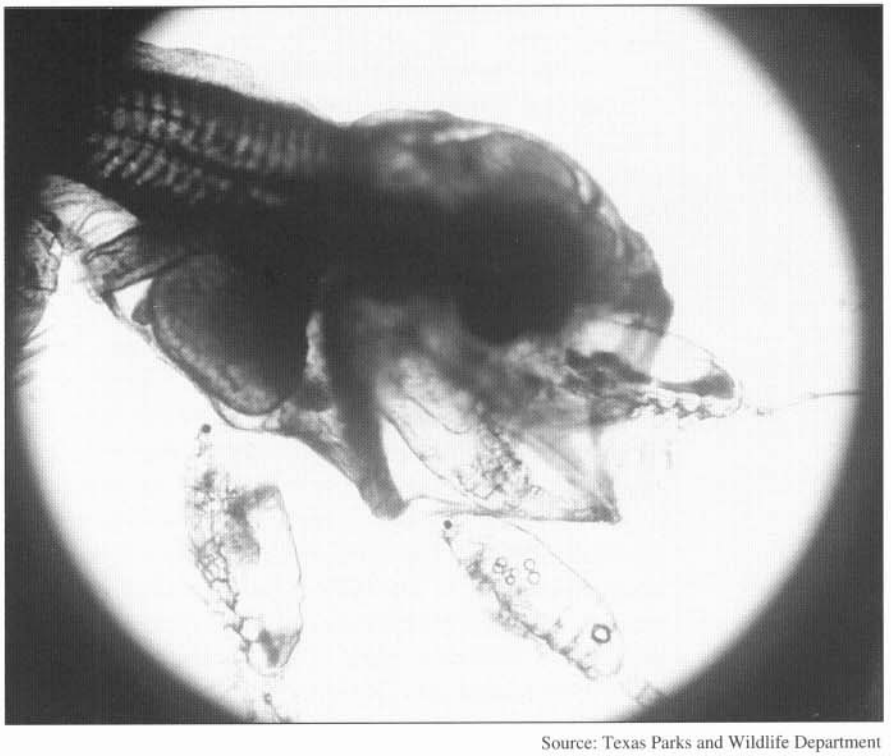
Like phytoplankton, zooplankton are often classified by size. Categories include **macrozooplankton** (visible range), **mesozooplankton**, **microzooplankton** (20-200 µm in size fraction), and **nanozooplankton** (2-20 µm). While some research has focused on the first two categories, few studies have focused on the smaller microzooplanton, even though they are probably responsible for grazing more phytoplankton biomass than the mesozooplankton (Buskey, 1989). The dominant zooplankton and mesozooplankton species in the Trinity Bay study include copepods, larval marine worms, and larval barnacles. *Acartia tonsa* (a copepod) is the domiant zooplankton species in Galveston Bay and other Texas estuaries (Lee et al., 1986).

Factors controlling zooplankton abundance are not well understood in Texas estuaries. However, some predictable changes can be correlated with changes in salinity. Large increases in zooplankton populations are often observed after extensive flushing of estuaries from high river runoff (Buskey, 1989). Other factors include food limitation during some parts of the year and effects of predators such as **ctenophores** (Day et al., 1987).

Data collected by the University of Texas Marine Science Institute reveal that 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 exact reasons for the high variability are unknown, although Buskey and Schmidt have speculated a link to industrial discharges. Based on several studies, they suggested that, in general, shallow, subtropical bays along the Texas coast may have lower zooplankton abundances than temperate estuaries.

BENTHIC ORGANISMS

Benthos refers to organisms that live in, on, or near the bottom, including plants, invertebrates, and fish of all sizes. Epifauna live on the surface of the bay bottom, while infauna burrow into the bottom, either superficially through fine sediments or deeper in vertical tubes. Many researchers focus on the benthic infauna, consisting largely of marine worms, brackish-water clams, other mollusks, and small crustaceans. Sampling of benthic invertebrates is performed by dredging or coring to collect sediment samples and then using sieves to separate organisms from the sediment. Because there is considerable variation in sampling techniques, it is difficult to compare absolute abundances reported in different studies.



Source: Texas Parks and Wildlife Department

A larval red drum feeds on zooplankton under the microscope. The plankton present in estuaries include algae, diatoms, larval fish and invertebrates, eggs of various species, and larger jellyfish and ctenophores.

Many benthic organisms are **filter feeders** that strain suspended organisms and organic matter from the water column, such as oysters feeding on phytoplankton. Deposit feeders, such as some worms, feed by ingesting sediments from the bay bottom and extracting nutrients. Still other benthic organisms graze on top of the sediments or are predators on other benthos.

Benthic organisms are an important component of the estuarine food web, fed upon by fish and birds, including Atlantic croaker, spot, mullet, drum, ducks, and other marsh birds. Recent research has determined that marsh benthos have a larger effect on estuarine fisheries than previously thought: juveniles of many fish species consume benthic organisms in tidally-flooded marshes (Zimmerman in Green et al., 1992). Overall, the benthic environment is heterotrophic–that is based on imported organic matter. Detritus that supports the benthic community originates from primary production in other parts of the estuary and its watershed.

Sediments are, of course, the matrix of the benthic environment. Within the sediment, a layering occurs, with oxidizing sediments on top, perhaps to a depth of several centimeters. Below this layer, and visible in benthic cores, is a darker-appearing reducing environment with little or no oxygen. This pattern influences many important benthic chemical process, shaping benthic ecology and benthic-pelagic chemical coupling–the chemistry of sediment/water equilibria. Particularly in shallow estuaries like Galveston Bay, this chemistry is important in both natural processes and in determining the fate, effects, and bio-availability of many pollutants. Sediments have an affinity for toxic pollutants and other materials that tend to accumulate on the bottom of the bay through sedimentation.

For several reasons, benthic organisms are good environmental indicators. Their relative immobility means they are continually exposed to any pollutants bound to sediments. Being on the bottom, they are first to experience the effect of oxygen depletion, since anoxia is generally most severe near the bottom (for example in the Houston Ship Channel). The high benthic community diversity under normal conditions tends to be replaced by a suite of fewer, more tolerant species in response to environmental stress, a pattern easy for a benthic ecologist to recognize.

Below are discussions on the extensive open-bay benthic community, and the community in more limited marsh areas on the Bay's shorelines. The marsh benthic community may be an especially important component of the overall marsh habitat, serving as a food supply for numerous species. The estuary has been losing salt marsh habitat through conversion to open-bay habitat due, in large part, to localized shoreline subsidence and the associated incursion of the sea.

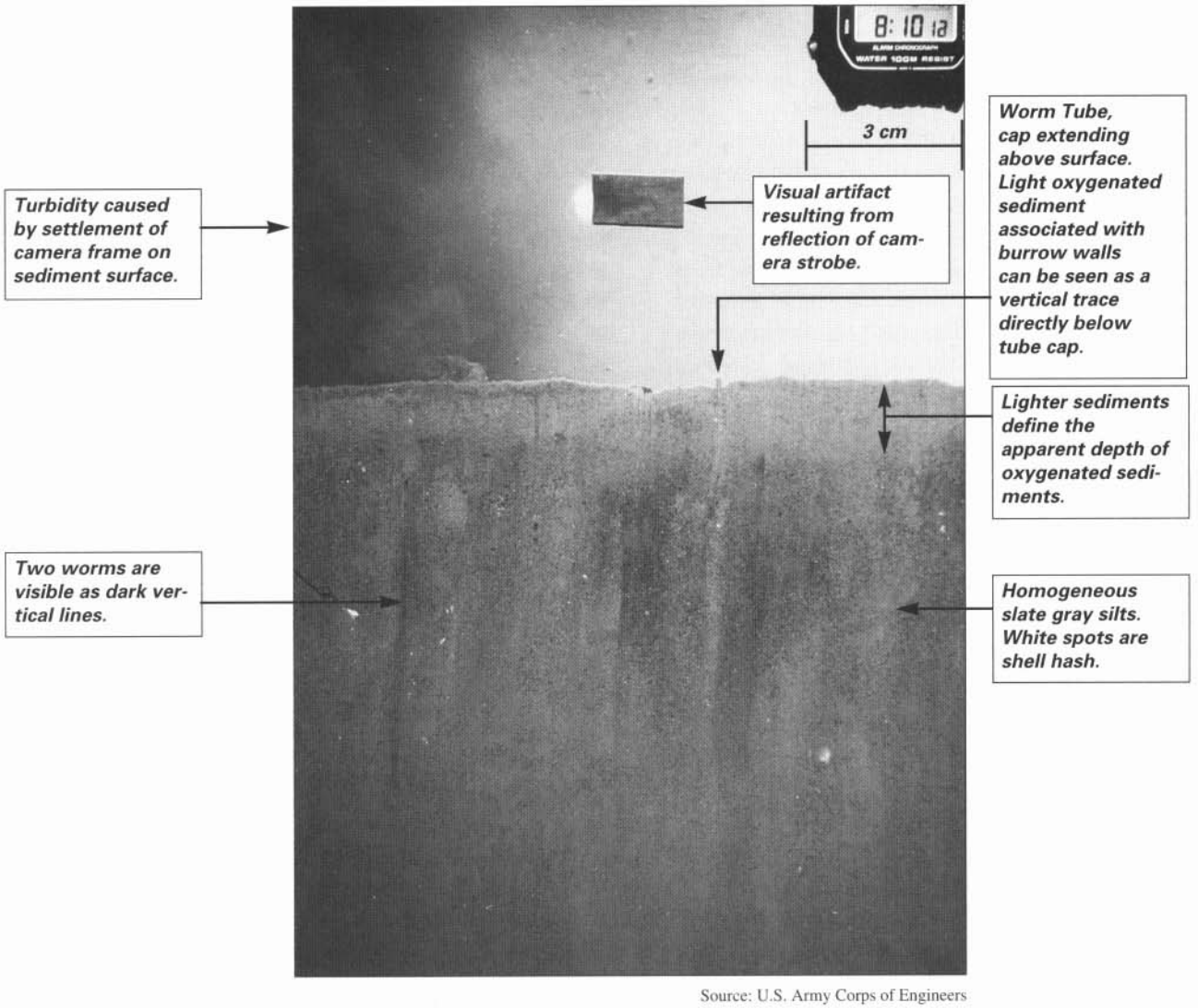
Open Bay Benthos

Parker (1960) defined several **macrobenthic** assemblages, primarily mollusks, and correlated them with salinity and substrate

characteristics. Most of his work was performed from 1950 to 1957, a period of drought in Texas. During 1976 and 1977, White et al. (1985) collected single 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), molluscs, and crustaceans. Muddy bottoms supported a richer polychaete community, while sandy bottoms supported more crustaceans. They 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). Galveston Bay and West Bay had twice the species richness of Trinity Bay or East Bay. Clear Lake, the San Jacinto River, and Houston Ship Channel had much lower species diversity than any of the open bay stations.

Recently, Ray et al. (1993) reported interim results from a four-year study of benthic assemblages in the lower and upper portions of the estuary that focused on potential impacts of dredged materials. Ray et al. concluded that observed patterns in benthic assemblages were primarily attributable to the prevailing salinity regime, and secondarily influenced by substrate type (for example shell hash compared to mud). In general, the benthic infauna were described as "opportunistic species adapted to a dynamic salinity regime and variable physical conditions typical of shallow Gulf of Mexico estuaries."

Spatially, open-bay benthos generally increase in abundance



Source: U.S. Army Corps of Engineers

For this photograph, a special apparatus was inserted into the bottom of Galveston Bay, revealing a cross section of sediment to a depth of several inches. Several features of typical soft sediment habitat are revealed. The light-colored layer on the sediment surface corresponds to oxygenated sediments, here less than one centimeter deep. To the right of center at the sediment-water interface is a worm tube cap extending above the surface, and causing the light oxygenated sediments to penetrate downward along the tube. Beneath the oxygenated sediments are fine-grained silts, punctuated by lighter bits of shell. (The dark rectangle top center is a camera strobe reflection).

from the Trinity Bay-Upper Bay region to the Lower Galveston-West Bay region (Harper in Green et al., 1992). This is opposite of the trend observed in San Antonio Bay, which is south of and has higher salinity than Galveston Bay (Matthews and Marcin, 1973; Harper, 1973, Harper and Hopkins, 1976).

Temporally, a seasonal trend is observed, with peak abundances in 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, fresh water flood events can alter this cycle.

Marsh Benthos

Marsh areas are vital ecological components in **nutrient cycling**, **carbon flux**, and sediment binding, and are habitat for many types of plants and animals (see Chapters Three and Seven). In Galveston Bay, brown shrimp, white shrimp, blue crab, red drum, spotted seatrout, southern flounder, and Gulf menhaden all depend upon the marsh portion of the benthic community.

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). Mollusks comprised less than three percent of infaunal abundance at any one site. 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 between plants (Zimmerman in Green et al., 1992). The local benthic assemblage was strongly affected by salinity, a significant influence bay-wide.

Spatially, Zimmerman found the highest densities and greatest species richness in the mid-salinity marshes near Moses Lake and Smith Point. In the low-salinity marshes associated with the upper bay/Trinity River delta, marine worms dominated the infaunal community, while small crustaceans were absent. In the high salinity lower bay, benthic abundance and richness values fell between the other upper-bay and mid-bay systems.

Temporally, marsh infauna displays a seasonal periodicity, with peak yearly abundances in late winter and early spring and lower abundances in the fall (Zimmerman in Green et al., 1992; based on annual data from a long-term study of marshes near the Galveston Island State Park). The abundance of benthic predators is the primary cause for this seasonal pattern; shrimp, crab, and fish predators are more abundant in warm weather.

Zimmerman et al. (1991) indicated that marshes which are drowning (as a result of subsidence and the associated relative rise in sea level) have higher secondary productivity than stable marshes, until they are succeeded by open-bay habitat. This creates a temporarily beneficial situation for fish, invertebrates, birds, reptiles, and mammals that use the marsh, due to increase in: 1) estuarine area; 2) the duration of access due to flooding; and 3) the interface between the marsh and open bay. Therefore, secondary productivity increases for a short period, until the drowning marsh is converted to open-bay habitat, at which point the secondary productivity and habitat diversity decline.

Man-Made Perturbations to Benthos

Urban and Industrial Runoff

Carr (1993) conducted a sediment quality triad study of Galveston Bay for the Galveston Bay National Estuary Program, in which a series of sediment samples were analyzed for three parameters: 1) contaminants; 2) toxicity; and 3) benthic abundance and diversity. This study is reported primarily in Chapter Six (see FIGURE 6.16). For benthos, the "significantly altered level" was defined as samples with fewer than ten species and total abundance less than 100 organisms.

Carr's study analyzed six stations directly associated with urban and/or industrial runoff: Burnett Bay in the Houston Ship Channel; Kemah Flats near the outfall of Clear Lake; near Texas City; Black Duck Bay near local industrial treatment lagoons; Swan Lake; and Dollar Bay. Two of these stations, Burnett Bay and Black Duck Bay, had significantly altered levels of benthic organisms from "contaminant-induced degradation" (Carr, 1993). Both of these small, partially-enclosed bays are located on the upper Houston Ship Channel. The other four urban/industrial stations did not exhibit a significantly altered benthic community.

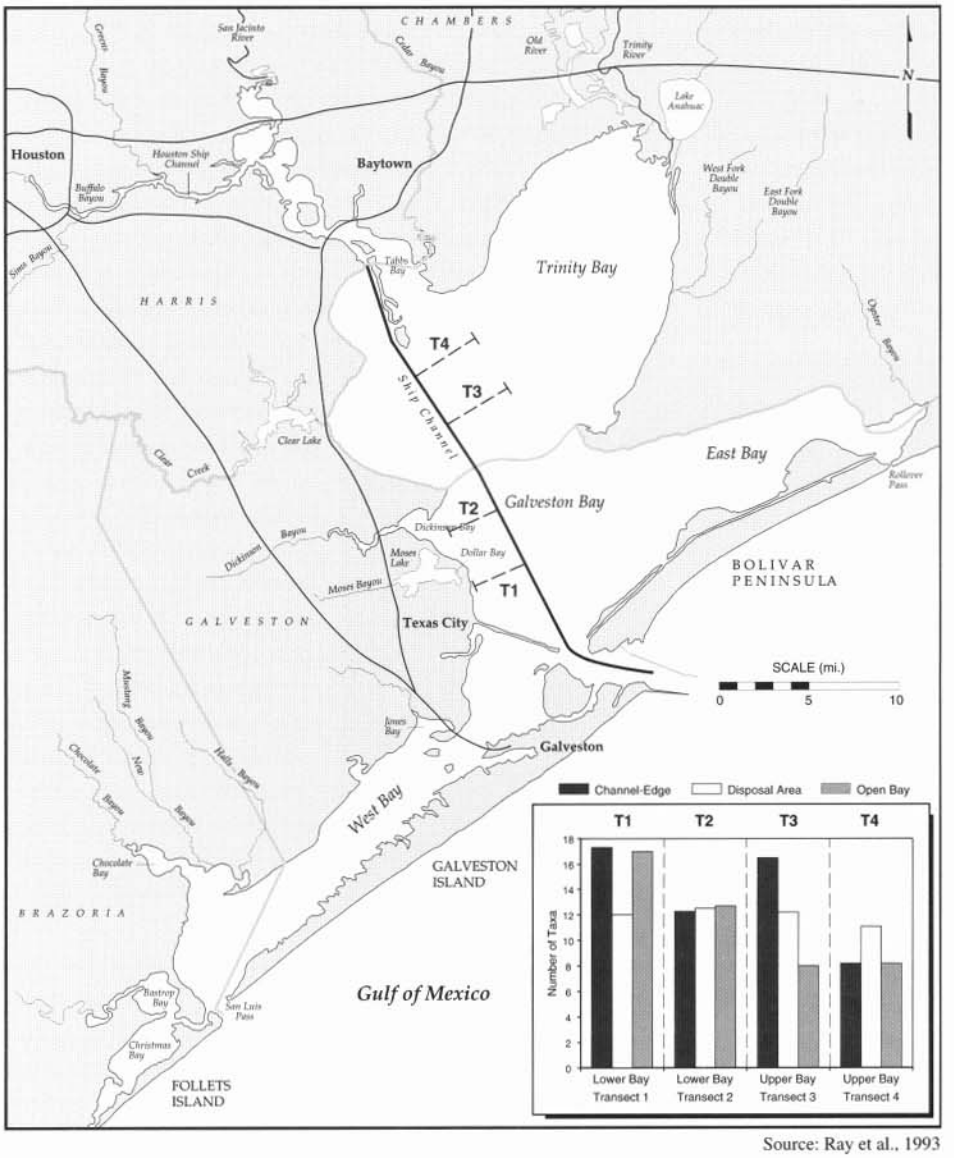
For comparison, 13 of Carr's stations, located in open bay waters away from local runoff and petroleum production platforms, showed fewer community impacts. Of these 13 stations, three were selected because they had known elevations of either copper, lead, strontium, or chromium; the study revealed toxicity effects at these stations. Of the remaining ten stations representative of open bay conditions, only one showed "significantly altered levels of benthic organisms" as defined in the study. This station, located in East Bay, did not have contaminant-induced degradation; however, East Bay was determined by White et al. (1985) to have lower species richness than most other parts of the open bay.

Cedar Bayou Generating Station

As part of Houston Lighting and Power's Cedar Bayou Generating Station project in the 1970s, investigators established several benthic sampling stations near intake and discharge points as well as several reference stations (Williams, 1972; and McBee, 1975). No effect from the power plant's effluent could be detected, although some improvement in Cedar Bayou was observed because upstream brine discharges were diluted by bay water drawn upstream to the power plant intake (Harper in Green et al., 1992).

Oyster Shell Dredging

Although oyster shell dredging has not been conducted in Galveston Bay for over 20 years, data from San Antonio Bay suggest that this practice had long-term effects. In San Antonio Bay, some holes caused by oyster shell dredging were still visible after



Source: Ray et al., 1993

FIGURE 8.5. *Benthic infauna (sediment-dwelling organisms) are an important indicator community in Galveston Bay. Benthic diversity along four transects extending from the Houston Ship Channel to the open bay is indicated here. In general, the more stable salinities of the lower bay system support slightly higher benthic community diversity.*

24 years (Harper and Hopkins, 1976). About five years were required to obtain near-normal levels of macrobenthos in dredged holes. No direct research assessing impacts of shell dredging has been performed in Galveston Bay.

Dredging for Navigation Channels

Ray et al. (1993) documented benthic assemblages along four transects running perpendicular to the Houston Ship Channel as part of a four-year Corps of Engineers study. They used a specialized camera system to obtain images of the vertical sediment cross-section at the sediment-water interface (see photo page 163), along with conventional box coring methods to analyze benthic communities. Their preliminary findings indicate that dramatic differences in benthic community structure do not occur between the channel-edge, dredged material disposal area, and undisturbed open-bay habitats (FIGURE 8.5).

A companion study by Clarke et al. (1993) was performed to measure the rate of recovery of benthic populations after placement of a stiff Pleistocene clay on open-bay bottoms to simulate dredged material disposal in Galveston Bay. Two 23-ac experimental plots, one in the upper bay and one in the lower bay, were constructed along with four undisturbed reference plots. Preliminary data during the first 15-21 weeks of the test revealed some weathering of hard clay sediments. Recruitment of benthic taxa to the disturbed bay bottoms occurred rapidly, although in a patchy fashion. Overall benthic assemblage densities remained depressed after the initial 15-21 week period, but signs of recovery were observed for biomass and taxa in one of the mounds located in lower Galveston Bay.

Oil Field Brine

Releases of oil field produced water (highly concentrated brines containing dissolved oil-related constituents; see Chapter Six) have significant impacts on benthic assemblages in the vicinity of produced water outfalls (Mackin, 1971; Armstrong et al., 1979; Nance, 1984; Harper, 1986; and Roach et al., 1993a, 1993b). In most of these studies, the area immediately around the outfall was found to contain hydrocarbons in the sediments, and sediments were devoid of benthic organisms up to 50 meters away. The abundance of benthic organisms increased with distance away from the discharge to a maximum located 500–1500 meters away.

Roach et al. (1993a, 1993b) evaluated impacts of produced water discharges on benthic organisms at two locations in Galveston Bay, one representing a shoreline/open bay habitat and one a tributary habitat. Sampling stations nearest to the tributary outfall exhibited an absence of any benthic organisms, while greatly depressed populations were observed adjacent to the shoreline discharge. In both cases the outfall was determined to have contaminated the adjacent sediments to the extent that benthic infauna were absent or only minimally colonizing the sediments.

OYSTERS

Two oyster species inhabit Texas Coastal waters: the Gulf oyster (*Ostrea equestris*), which prefers higher salinity waters associated with open bays, Gulf passes, and the Gulf; and the

Eastern oyster (*Crassostrea virginica*), which grows abundantly in the brackish waters of enclosed bays and is commercially important (Quast et al., 1988).

The life cycle of the Eastern oyster begins with a free-swimming larval stage that eventually attaches to a hard substrate (frequently existing reef shell), forming an oyster spat. The spat commences a growth period that is classified into sub-adult and adult phases. Oysters generally spawn when the water temperature reaches and stays at or above 20° C; in the Galveston Bay system this usually occurs in June or July after the ambient temperature has increased to 25° C. Oyster larvae, spat, sub-adults and adults are all filter feeders on phytoplankton.

Source: Texas Sea Grant College Program

Typical oyster reef, seen through non-typically clear water over a shallow bay reef.

Physical Factors

Oysters are most successful in habitats that provide a firm substrate for attachment, good water circulation, and suitable water temperature and salinity. The most suitable substrate is generally the shell (of both living and dead oysters) associated with existing reefs. Several layers of live oysters result, with the youngest on the top. These natural reefs are primarily of four types: 1) alongshore reefs oriented parallel to shore and located near or attached to the shoreline; 2) reefs extending perpendicular from the shoreline or a point nearshore out into the bay; 3) patch reefs composed of one or more relatively small more-or-less circular bodies; and 4) barrier reefs extending across or nearly across the bay.

Specific water flow requirements for Texas oysters are not known (Quast et al., 1988). Galtsoff (1964) determined that for maximum feeding, current velocities fast enough to exchange water above a reef three times an hour are required. Oysters can tolerate water temperatures as low as one °C and as high as 36°C, however, optimum water temperatures for growth, reproduction, and survival of Texas oysters ranges from 20 to 30°C.

While oysters are typically found in areas where long-term salinity ranges between ten and 30 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 eight ppt (Hofstetter, 1983). Oysters in Trinity Bay have survived salinity less than five ppt for two to three weeks but experienced over 90 percent mortality when exposed to near-fresh water with less than two ppt salinity for three weeks (Quast et al., 1988). A short term lowering of salinity (five to ten ppt for two to six weeks) is beneficial to oysters because it reduces predation by oyster drills and stone crabs. Such salinity reductions also reduce the infection rate and effects of **dermo**, caused by *Perkinus marinus* (see below).

Before reservoirs were constructed on the rivers that emptied into Texas bays, large floods reached and passed through the bays relatively quickly (Hofstetter, 1977). While salinity was reduced to the point where oysters were sometimes killed, the duration of the "freshet" was relatively short, and oyster populations reestablished themselves relatively quickly. With the reservoirs in place, the salinity is still reduced, but the duration of the freshet is extended. Longer freshets are more destructive than rapidly passing floods, thereby potentially increasing the stress on oyster populations (Hofstetter, 1977).

Biological Factors

Oysters are stressed by competition, parasites, diseases, and predation from other organisms. The most important of these biological stresses in Galveston Bay is infection by "dermo," *Perkinsus marinsus* (Powell et al., 1994), a protozoan parasite that ranges from Delaware to Mexico. Mortality of market oysters in Galveston Bay resulting from this parasite can range from ten percent to 50 percent annually, and the mortality rate increases with increasing temperature. In a May, 1992 survey of Galveston Bay oyster populations, Powell et al. (1994) found that the highest prevalence of *Perkinsus marinsus* was found in West Bay, where over 50 percent of the oysters were infected. The authors noted

that this infection rate was lower than the rates reported by others because of the unusually low salinity conditions that occurred during the four months prior to sampling.

Oysters compete with other benthic organisms for space and nutrients and are food sources for several predators. Competitors include barnacles, mussels, worms, and algae (Quast et al., 1988). Predators that feed on oysters include stone crabs, mud crabs, blue crabs, the southern oyster drill, and some finfish. In the oyster survey conducted in 1992, the southern oyster drill was only found in West Bay and on Half Moon Reef. Highest crab abundances on oyster reefs (mostly mud crabs) were found in West Bay, the southwestern portion of Redfish Bar to Smith Point, and in the Red Bluff area (Powell et al., 1994).

Trends in Space and Time

A review of old maps of the Texas coast archived in the General Land Office indicated an extensive loss of shoreline (intertidal) oyster reefs in Galveston Bay. However, recent research by Powell et al. (1994) indicated an increase in overall oyster reef area since the 1970s. Chapter Seven includes a discussion of the change in oyster reef habitat since the 1970s and shows the current location of reefs in Galveston Bay.

The abundance of spat, small and market oysters decreased in the Galveston Bay system between 1956 and 1977 (Quast et al., 1988). After a sharp increase in abundance between 1980 and 1982, abundance continued to decline through 1987. For example, oysters were measured using a 35-liter oyster dredge at three sites on Redfish Bar between 1956 and 1984 (Hofstetter, 1977). The annual mean number of oyster spat was 113 between 1956-1966, 34 between 1967 and 1977, and 44 between 1978 and 1984. Between 1956 and 1982, the annual mean number of market oysters (greater than 76 mm) in Galveston Bay samples generally fluctuated between 20 and 40 individuals (Hofstetter, 1977). Responding to high fresh water inflow, 1982 samples peaked at 68 individuals per sample, and then declined to pre-1982 levels again in 1984.

Landings of Galveston Bay oysters have fluctuated through the years, with a marked increase after 1960 (see Chapter Four). Fishing pressure has increased significantly, however, and Quast et al. (1988) concluded that the oyster was overfished in Texas (although recent research indicates that the oyster harvest has not harmed the oyster reef habitat–see Chapter Seven). From 1982-1986 about 81 percent of the Galveston Bay oyster harvest came from public reefs, with the remainder from private oyster leases issued by the state.

Vitality of Reefs

The results of a reef survey, a health survey, and computer modeling simulations suggest that the most productive region of Galveston Bay for oysters is the area associated with the salinity gradient produced by the Houston Ship Channel (Powell et al., 1994). Areas along the channel produced the healthiest oyster populations, as measured by density, size-frequency distribution, and reproductive state. In addition, the study indicated the South Redfish Reef and Houston Ship Channel could be important natural brood areas, producing larvae for the bay as a whole. Current flow and food availability appear to be the key determinants of local variations in population health.

Reefs near Pelican Island and central West Bay are supporting much lower production than would be expected from known conditions and historical indicators (Galtsoff, 1931). The Texas City Dike is probably responsible for at least of a portion of the low oyster productivity in these areas because it restricts circulation in West Bay (Powell et al., 1994).

Additional research performed by Powell et al. (1994) addressed the relationship between food supply and oyster populations in Galveston Bay. They suggested that large oysters (greater than 90 cm) are relatively rare in Galveston Bay, and that overall, Galveston Bay now has a planktonic food supply just barely adequate to support a market-size population. Since phytoplankton, the primary food supply for oysters, has shown declining populations since the 1970s, there is speculation that the amount of future oyster harvests may be affected.

FINFISH, SHRIMP, AND CRAB POPULATIONS

The Galveston Bay system maintains important recreational and commercial fisheries for shrimps, crabs, and fishes. During the last 100 years, the total landings from the estuary have doubled, mostly due to shrimp and crabs (total landings of other species have remained essentially unchanged, excepting decreases for striped bass and grouper). How have the various bay species fared under this increased fishing intensity?

Two types of information are available regarding Galveston Bay finfish and shellfish populations: 1) commercial and recreational landings of shrimps, crabs, oysters, and finfish (presented in Chapter Four); and 2) scientific measurements of indicator species conducted by marine fisheries organizations. Note that the first type of data is fishery-dependent (the results are based upon both the intensity of fishing effort and the abundance of the organisms), while the data of the second type are fishery-independent (scientific capture studies based only on the abundance of organisms) and provide better information to estimate actual population sizes. Fishery independent scientific studies (Green et al., 1992; Green et al., 1993) are the focus of this section.

Scientific trawling studies by the Texas Parks and Wildlife Department have identified about thirteen species of shrimp, seventeen species of crab, and over 150 finfish species in the bay (McEachron et al., 1977; Parker, 1965; Loeffler in Green et al., 1992). In one two-year trawl study for fish, six species were found to account for 91 percent of the total number of fish collected: Atlantic croaker (51 percent); bay anchovy (22 percent); star drum (8 percent); spot (4 percent); sand seatrout (3 percent); and sea catfish (3 percent). These six species, plus striped mullet, accounted for 74 percent of the fish biomass collected, whereas Atlantic croaker alone represented 34 percent of the total fish biomass (Sheridan et al., 1989). TABLE 8.3 lists the common and scientific

TABLE 8.3. List of Common and Scientific Names of Commercial and Recreational Finfish and Shellfish Species Caught or Landed in Texas.

Common Name	Scientific Name	Common Name	Scientific Name
Finfish		Pinfish	*Lagodon rhomboides*
Alligator gar	*Lepisosteus spatula*	Red drum	*Sciaenops ocellatus*
Atlantic croaker	*Micropogonias undulatus*	Seatrout	
Atlantic cutlassfish	*Trichiurus lepturus*	Sand seatrout	*Cynoscion arenarius*
Atlantic moonfish	*Selene setapinnis*	Silver seatrout	*Cynoscion nothus*
Atlantic needlefish	*Strongylura marina*	Spotted seatrout	*Cynoscion nebulosus*
Atlantic spadefish	*Chaetodipterus faber*	Shark	
Atlantic stingray	*Dasyatis sabina*	Atlantic sharpnose	*Rhizoprionodon terraenovae*
Black drum	*Pogonias cromis*	Blacktip	*Carcharhinus limbatus*
Bluefish	*Pomatomus saltatrix*	Bull	*Carcharhinus leucas*
Blue catfish	*Ictalurus furcatus*	Scalloped hammerhead	*Sphyrna lewini*
Channel catfish	*Ictalurus punctatus*	Smooth dogfish	*Mustelis canis*
Cobia	*Rachycentron canadum*	Sheepshead	*Archosargus probatocephalus*
Flounder		Silver perch	*Bairdiella chrysoura*
Gulf flounder	*Paralichthys albigutta*	Lane snapper	*Lutjanus synagris*
Southern flounder	*Paralichthys lethostigma*	Southern stingray	*Dasyatis americanus*
Florida pompano	*Trachinotus carolinus*	Spot	*Leiostomus xanthurus*
Freshwater drum	*Aplodinotus gruniens*	Striped burrfish	*Chilomycterus schoepfi*
Gafftopsail catfish	*Bagre marinus*	Tripletail	*Lobotes surinamensis*
Gulf butterfish	*Peprilus burti*		
Hardhead catfish	*Arius felis*	**Shellfish**	
Kingfish		Crab	
Gulf kingfish	*Menticirrhus littoralis*	Blue crab	*Callinectes sapidus*
Southern kingfish	*Menticirrhus americanus*	Stone crab	*Menippe mercenaria*
Ladyfish	*Elops saurus*	Eastern oyster	*Crassostrea virginica*
Mackerel		Shrimp	
King mackerel	*Scomberomorus cavalla*	Brown	*Penaeus aztecus*
Spanish mackerel	*Scomberomorus maculatus*	White	*Penaeus setiferus*
Menhaden	*Brevoortia patronus*	Pink	*Penaeus duorarum*
Mullet		Rock	*Sicyonia brevirostris*
Striped mullet	*Mugil cephalus*	Seabob	*Xiphopenaeus kroyeri*
White mullet	*Mugil curema*	Squid	
Ocellated flounder	*Ancylopsetta quadrocellata*	Brief squid	*Lolliguncula brevis*
Permit	*Trachinotus falcatus*	Long-finned squid	*Loligo pealei*
Pigfish	*Orthopristis chrysoptera*		

Source: Sheridan et al., 1989

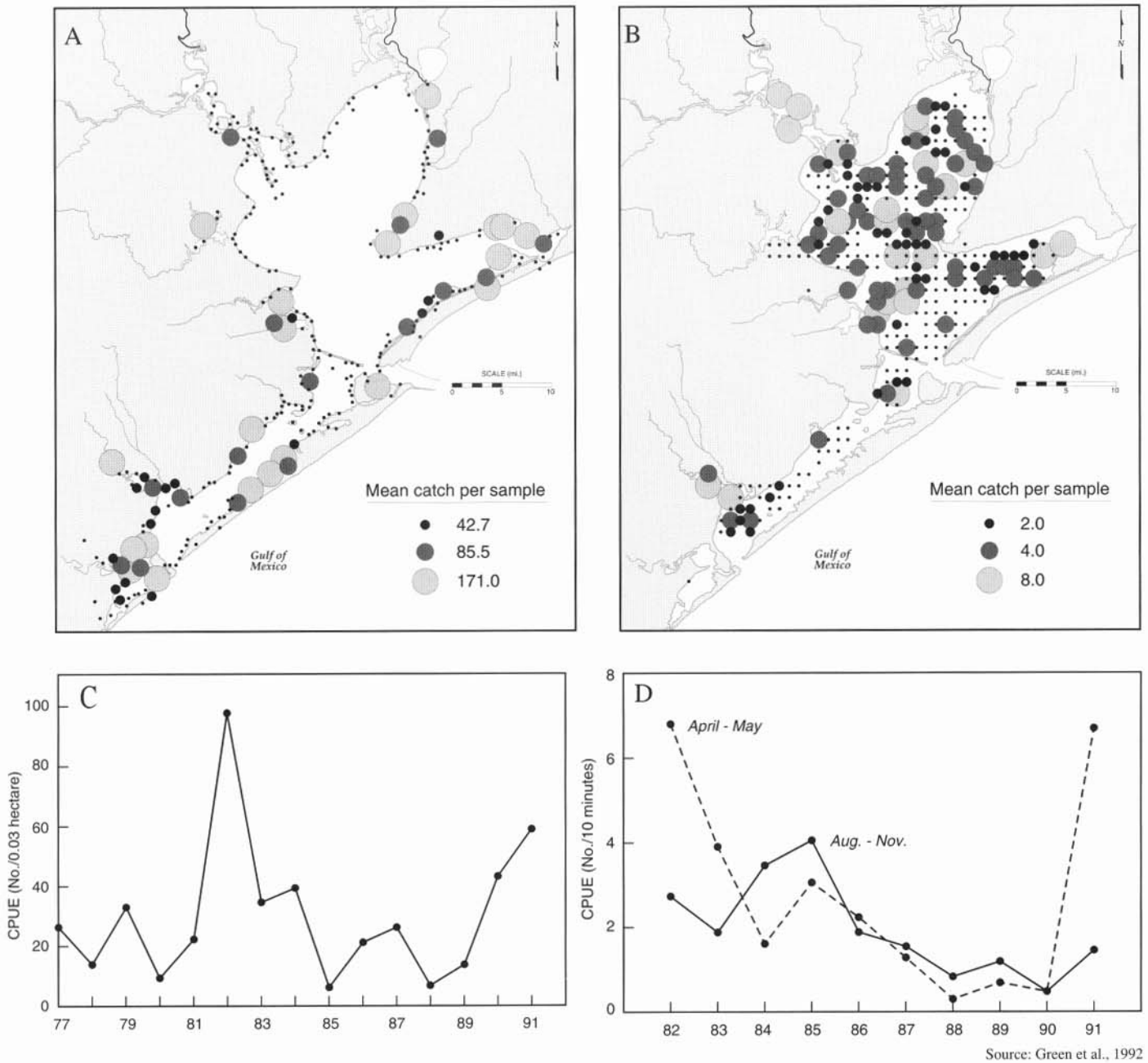
names of commercial and recreational finfish and shellfish reportedly caught or landed in Texas.

The Texas Parks and Wildlife Department sampling data indicated that the "overall health of the Galveston Estuary appears to be fair to good" (Green et al., 1992). There were significant increases in some finfish populations, including red drum, spotted seatrout, and Atlantic croaker. Certain species have shown some evidence of potential decline, such as white shrimp (although recent data indicates a rebound) and large size classes of the blue crab.

Methodology and Data

The Texas Parks and Wildlife Department utilizes several techniques, including: 1) seines for collecting smaller organisms in near-shore environments; 2) trawls for collecting organisms found on or near the open bay bottoms; 3) gill nets for catching larger fish near shore; and 4) oyster dredges for sampling macro-benthic shellfish and encrusting organisms. Raw data are compiled to estimate the mean catch per sample for comparing spatial trends, and the **catch per unit effort** (CPUE) for temporal trends. CPUE is defined as the number of individual fish/shellfish caught for a given area seined or time trawled.

Throughout the following section, spatial distributions of finfish and shellfish are illustrated in "bubble charts," in which the size of each bubble is proportional to organism numbers (CPUE, mean



Source: Green et al., 1992

FIGURE 8.6. *White Shrimp abundance distributions and temporal trends. Young-of-the-year are shown in (a), caught with bag seines along the shoreline (35-55 mm size, June-November, 1977-1989), while (c) reveals the corresponding abundance trend over time. First-time spawners are shown in (b), caught with trawls in open bay waters (110-130 mm size, August-November, 1982-1990), and (d) presents the corresponding time trend. The decline in spawners has prompted management concerns for this species (see text).*

catch per sample), with locations determined by latitude-longitude coordinates taken during sampling. Each map represents a particular species age class, with shoreline bubbles corresponding to bag seines and open-water bubbles relating to otter trawl samples.

Temporal trends are defined using graphs of CPUE vs. year. Most graphs represent a ten to 15-year time span for a specific size class of a particular species. In addition to the data, a statistical trend line and associated 95 percent confidence interval is presented for some species (see FIGURES 8.10–8.11). Typical size classes from youngest to oldest are: 1) young-of-the-year; 2) juveniles; 3) first time spawners; and 4) adults.

Selected Species Summaries

The spatial distribution and temporal trends for several selected species are presented in this section. White shrimp and blue crab were selected because of their observed decline in relative abundance. Two finfish were selected for detailed graphical presentation. The spotted sea trout is a recreational species and top carnivore, and the bay anchovy is an important element of the lower food web in the open bay. More detailed information (maps, CPUE graphs, and other data) on these four species and ten additional species are presented in Green et al. (1992).

White Shrimp

The near-shore and open-bay distribution of white shrimp is depicted in FIGURE 8.6. Young-of-the-year white shrimp emerge from marsh areas in East Bay, West Bay and Christmas Bay during June-December. In the open bay, first-time spawning shrimp cluster in the mid to upper bay.

A strong decline in white shrimp was observed from 1982 through 1990, leading to concern about the condition of the bay's white shrimp population (Walton and Green, 1993; Green et al., 1993). Similar declines were noted in the Aransas Bay, Corpus Christi Bay, and Laguna Madre estuaries. However, recent sampling results from 1991 show a large rebound to 1983 population levels (Walton and Green, 1993). The rebound is probably at least partially the result of increased fresh water inflow due to extremely wet conditions in 1990 and 1991, and management actions discussed below.

Source: Texas Parks and Wildlife Department

Shrimp tagging studies by the Texas Parks and Wildlife Department help managers to assess population stocks, migration, and survivorship. This information can then be used to determine biologically appropriate harvest regulations.

Source: Texas Parks and Wildlife Department

The blue crab fishery in Galveston Bay has expanded in recent years, resulting in declines in adult size classes, particularly due to capture of adult males in the upper, river-influenced portion of the estuary.

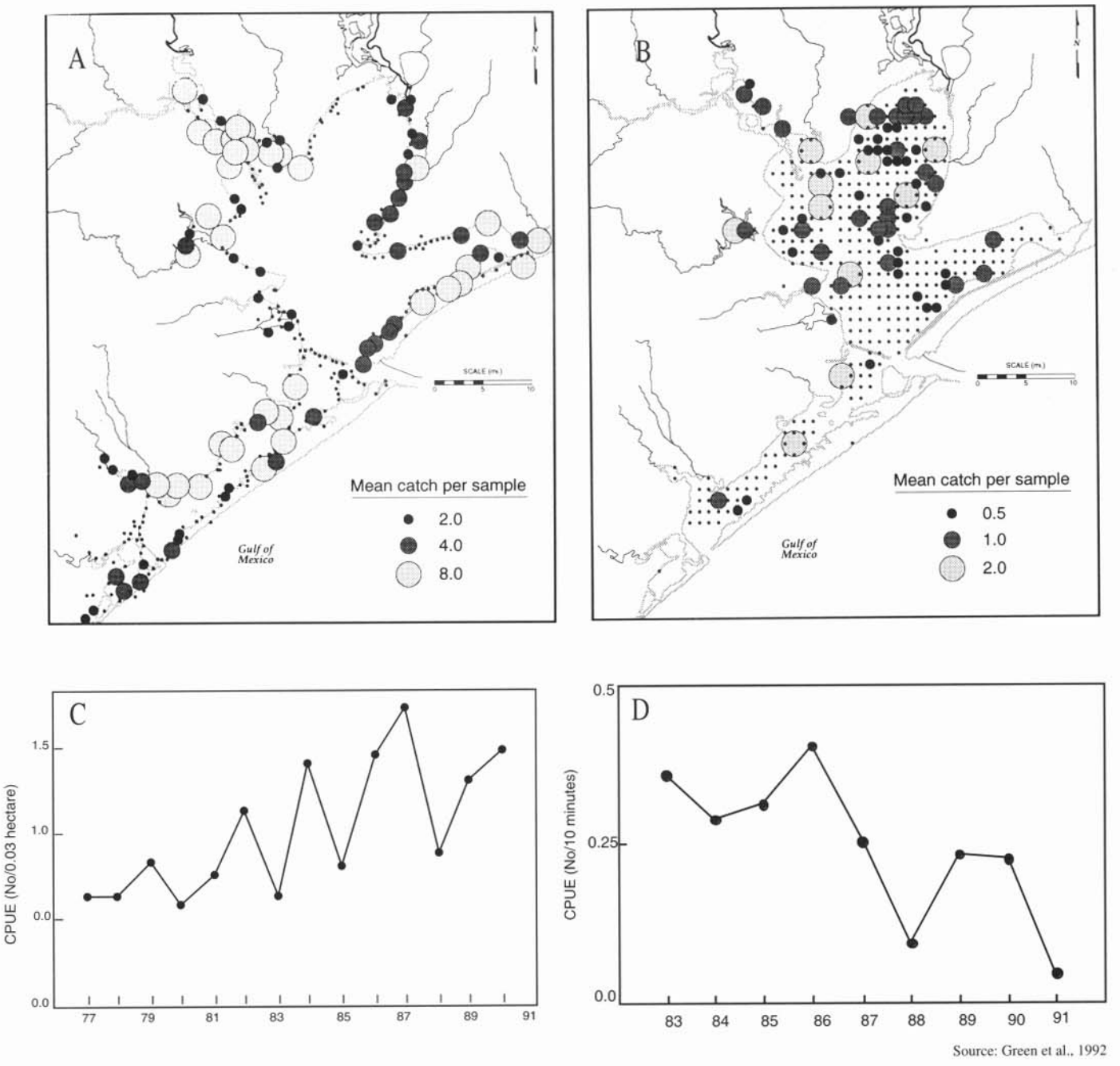
Three potential causes for the observed decline in white shrimp, 1982–1992 were discussed by Walton and Green (1993): overfishing, pollution, and low fresh water inflows. Overfishing was deemed the most obvious possibility for the decline. Several other factors such as loss of wetlands, a change in the food chain, and increased predation were considered but ruled out because similar species such as brown shrimp did not exhibit a similar decline.

Based on the supposition that over-harvest can be a factor for white shrimp, changes in fisheries regulations have been implemented by the Texas Parks and Wildlife Department at various times to protect the white shrimp resource. Shrimping in nursery areas was prohibited in 1979, except for "grandfathered" shrimpers, who continued to shrimp these areas until 1989. Night shrimping was banned during spring months in 1990. Most importantly, starting in 1990, all shrimping was banned for two summer months in the Gulf of Mexico, a major white shrimp spawning area.

Blue Crab

More blue crabs are landed in Galveston Bay than in any other Texas estuary (Walton and Green, 1993). Blue crab landings have increased from about 200,000 pounds per year in 1960 to over three million pounds per year in 1990 (see Chapter Four). This trend is partly because of the increasing value of blue crabs.

The population analysis indicated a more complex seasonal trend for this species than for many estuarine organisms. Small near-shore juveniles (less than 25 mm in width) peaked in March, while larger near-shore blue crab populations peaked in the summer. Smaller open-bay crabs indicated a peak abundance in April,



Source: Green et al., 1992

FIGURE 8.7. *Blue crab abundance distributions and temporal trends. Young-of-the-year are shown in (a), caught with bag seines along the shoreline (25-45 mm size, January-December, 1978-1989), while (c) reveals the corresponding abundance trend over time. First-time spawners are shown in (b), caught with trawls in open bay waters (120-140 mm size, January-December, 1983-1990), and (d) presents the corresponding time trend. The decline in spawners was related to overharvest, particularly of males in the upper estuary.*

and larger sizes (greater than 120 mm) peaked in June. Higher near-shore abundance for young-of-the-year blue crabs was noted in the area above Morgans Point, the eastern fringe of Trinity Bay, north of Bolivar Peninsula, and around fringes of West Bay. For open-bay trawls, more young-of-the-year blue crabs were found in Trinity Bay (FIGURE 8.7).

Blue crabs had different temporal trends for different size classes: smaller crabs increased in abundance from 1983 to 1990 while the larger sizes decreased. For example, the mean size of crabs collected in trawl samples dropped from 91 mm in 1982 to 71 mm in 1988 (Mambretti et al., 1990). Recruitment did not appear to be a problem, as smallest crab sizes increased in number (Green et al., 1992). Because blue crabs are mobile and widely dispersed off the entire Texas coast, strong recruitment might continue even if the in-bay adult population were reduced (Walton and Green, 1993).

These results indicated a blue crab decline in the lower salinity upper-bay zone, directly implicating overfishing of male blue crabs (Walton and Green, 1993). Females need to migrate to higher salinity water to spawn, while males do not. Therefore, males spend more time in fresher parts of the bay and consequently are targeted by fishermen in the upper estuary. In addition, male

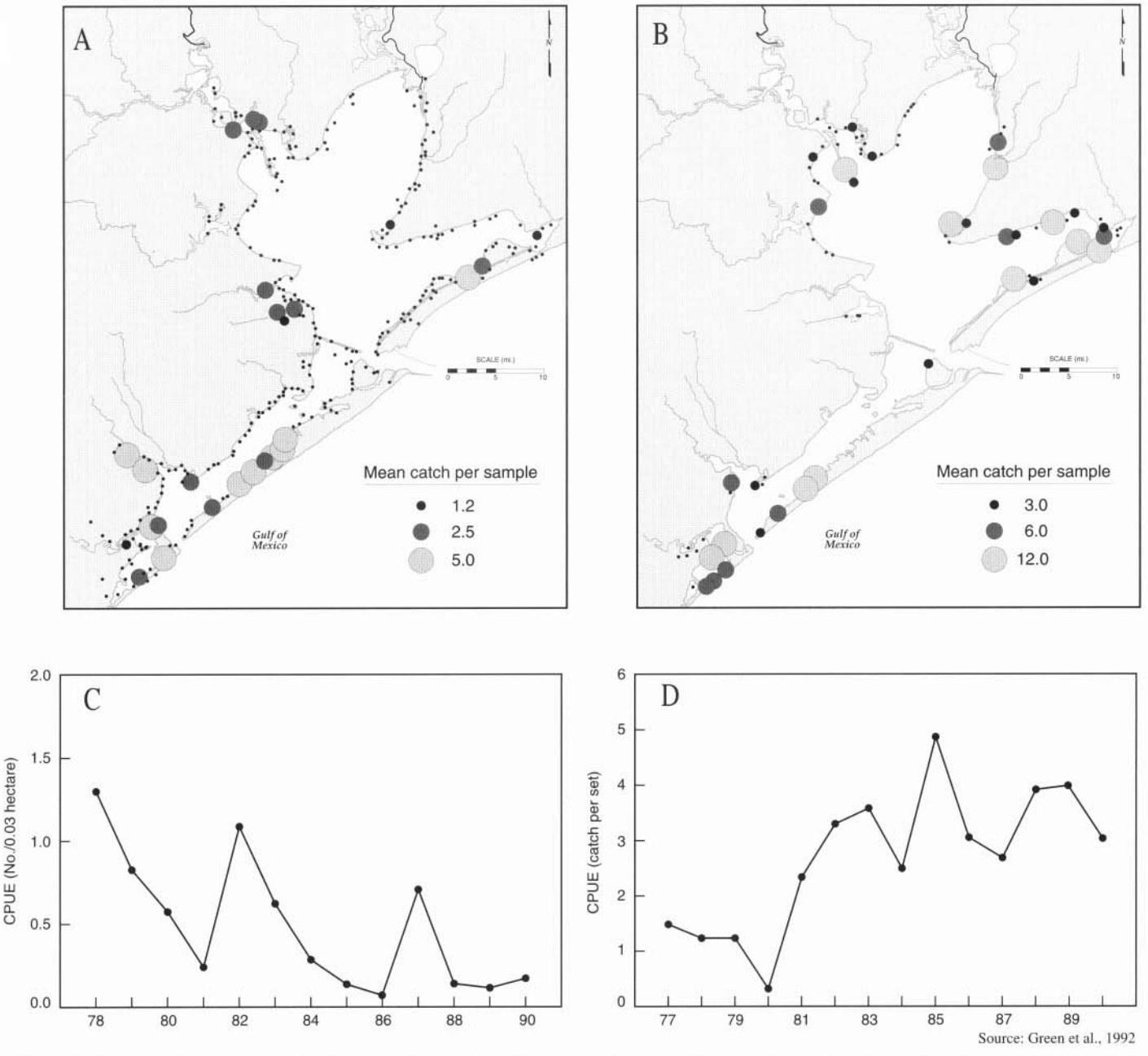


FIGURE 8.8. *Spotted seatrout abundance distributions and temporal trends. Young-of-the-year are shown in (a), caught with bag seines along the shoreline (35-75 mm size, July-December, 1978-1989), while (c) reveals the corresponding abundance trend over time. First-time spawners are shown in (b), caught with gill nets (> 450 mm size, Spring 1977-1990), and (d) presents the corresponding time trend. The increase in the adult size class represents a recovery from overharvest.*

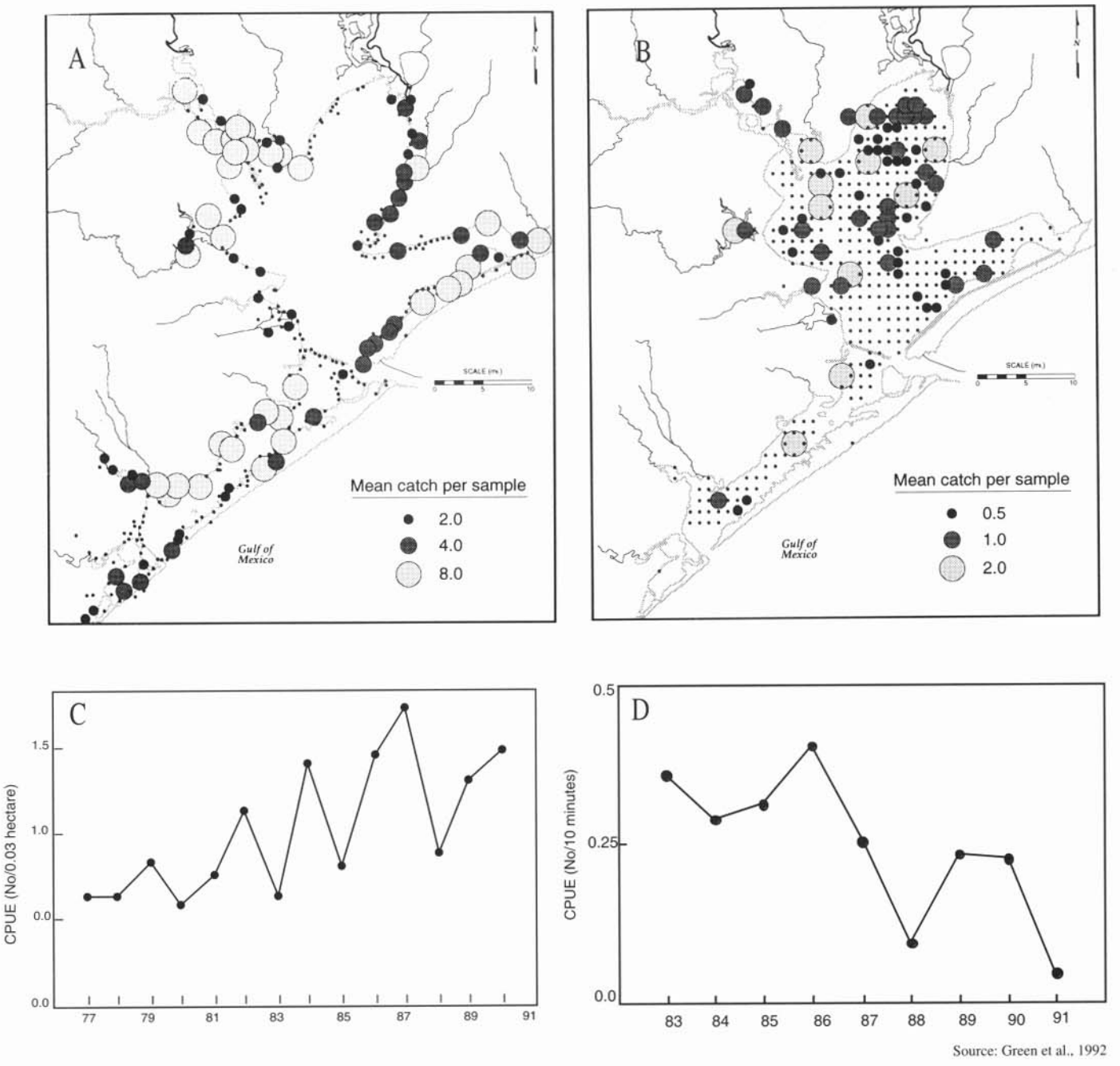
blue crabs are more valuable than females, due to their larger size.

An alternative explanation for the blue crab decline involves a possible decline in the import of organic detritus to the middle and lower portions of the estuary, associated with wetlands loss. Such a loss of detritus could represent a decreased available food supply for the blue crab (Green et al., 1992). The duration of the blue crab population decline prior to 1983 is unknown, as little detailed fisheries information is available for this species. Similar declines have been noted in Aransas Bay and Laguna Madre, although these are much smaller fisheries in terms of total blue crab landings.

Current harvesting regulations include: 1) crab traps must be marked; 2) the number of crab traps per fisherman is restricted in certain areas; 3) egg-bearing females must be released; and small crabs (less than five inches) must be released, except for use as bait.

Red Drum and Spotted Seatrout

Red drum and spotted seatrout are the premier recreational game species of the bay. Both were already in a state of reduced abundance due to overfishing when intensive scientific studies of these populations were initiated. Regulations passed to protect red drum and spotted seatrout included: no commercial sale since 1981; banning of all nets in 1988; implementation of minimum and maximum sizes (maximum limits for red drum only, to protect spawners); and daily bag limits for recreational fishermen in 1982. These species showed increases in first-time spawners and remaining adults after these regulations were implemented, despite several



Source: Green et al., 1992

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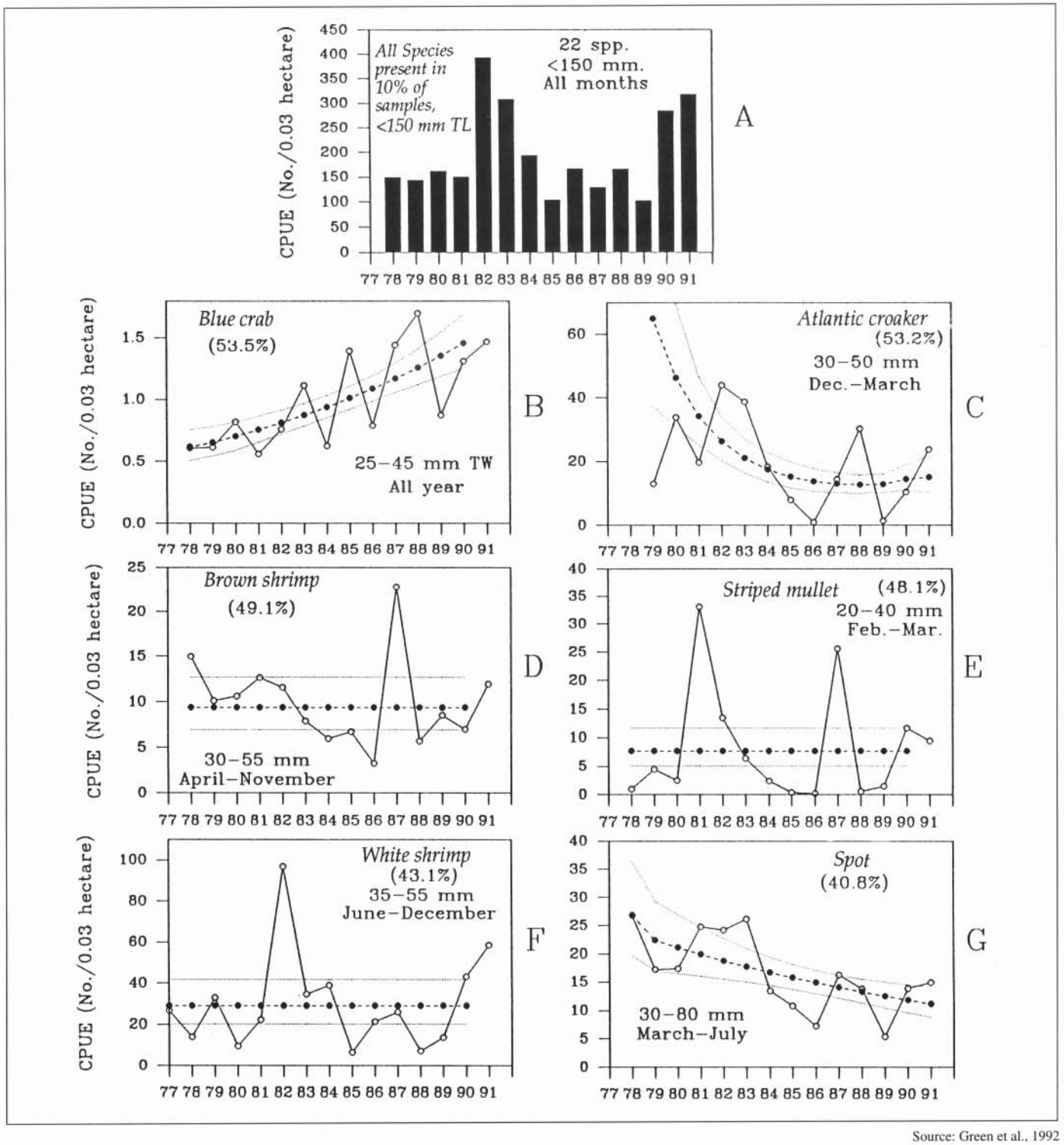
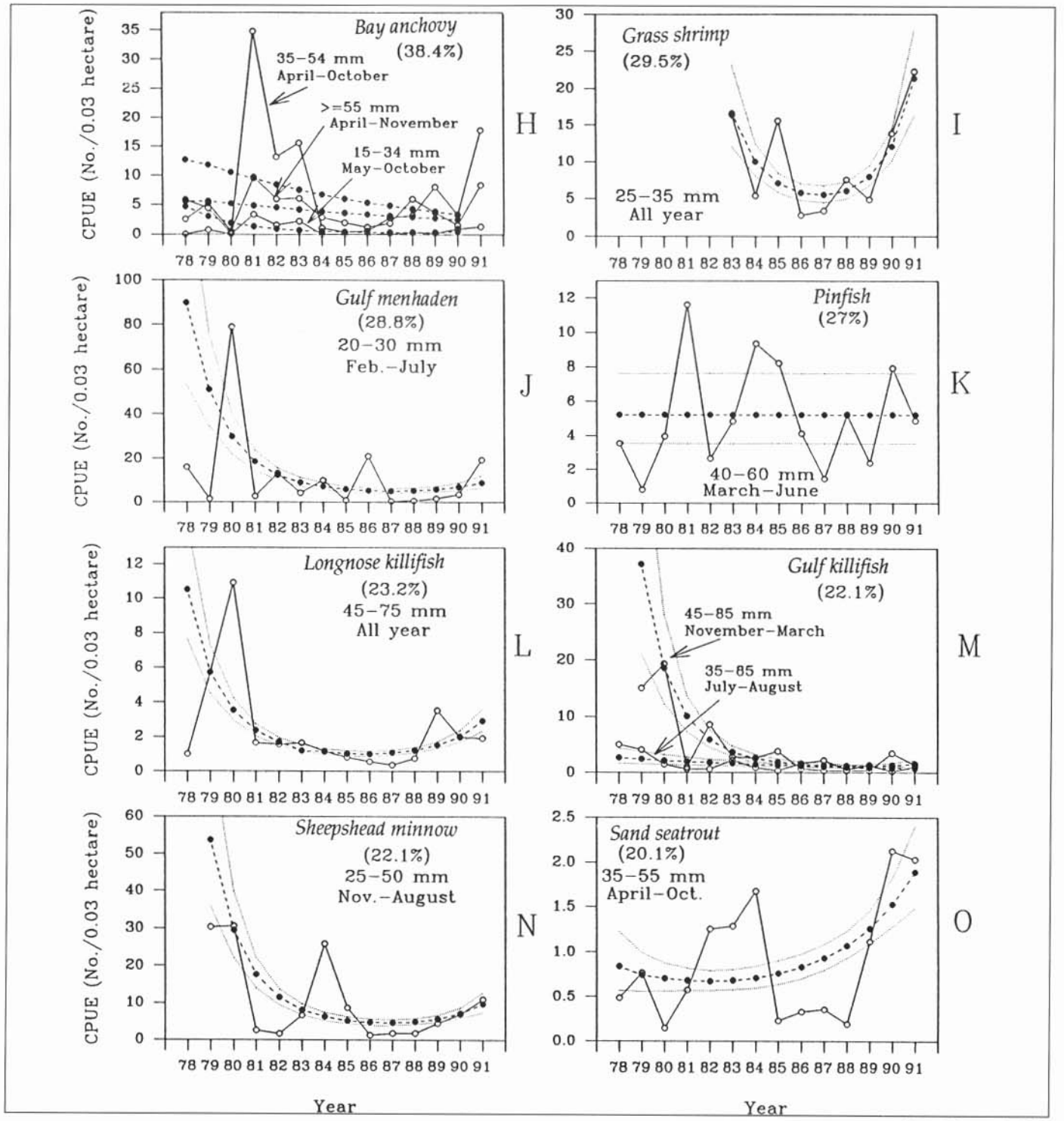


Source: Green et al., 1992

FIGURE 8.10. *Mean annual catch per unit effort (CPUE) is shown for fourteen selected species (b-o, including facing page) caught by bag seine and a time trend for all these species combined is given in (a). Shown on the individual species plots is a trend line (solid dots) and corresponding 95 percent confidence interval. Note size ranges, for comparison to FIGURE 8.11, which includes larger sizes of some of the same species.*

In the case of red drum, young-of-the-year were found throughout the estuary with the highest concentrations in Christmas Bay, Bastrop Bay, Chocolate Bay, West Bay, East Bay, around Smith Point, and near the Clear Lake area. The geographic distributions of juvenile and first-time spawning red drum were similar; the highest catches for both size classes were concentrated in East Bay, around Christmas Bay, Bastrop Bay and the northern part of upper Galveston Bay.

The causes of variability for red drum were incompletely understood, but several factors may have been important. Recent losses of protected areas with grass and mud bottoms, important to juveniles, may have exerted an influence. Fluctuations in shrimp,



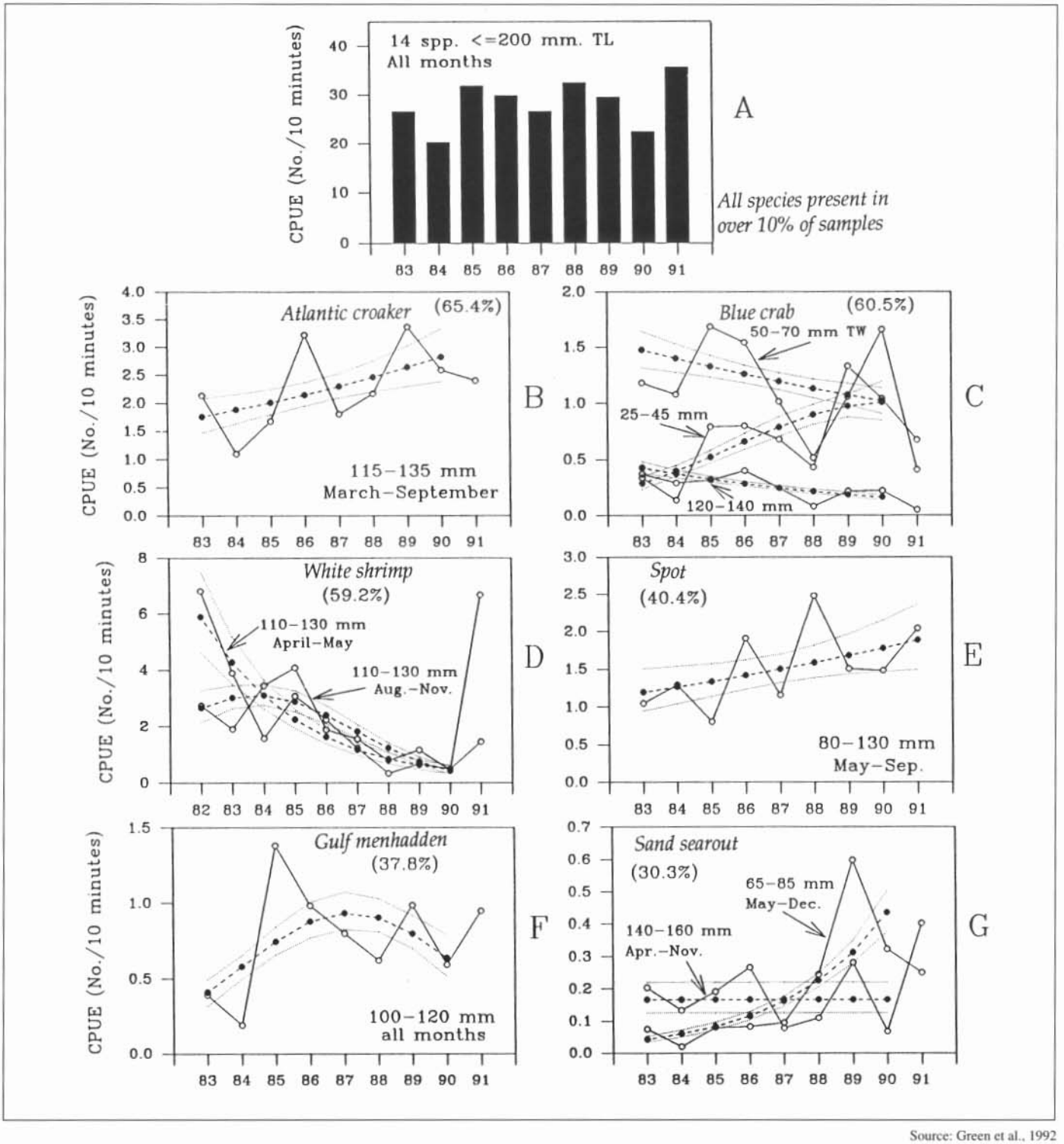
Source: Green et al., 1992

a primary food source, could also have driven changes in numbers. For this species, population trends are further complicated by regulation and stocking efforts to rehabilitate the species. Close to five million red drum fry were stocked in the estuary in 1979, and over one million in 1983, perhaps reflected in the peak catches of young fish in those years and, to some degree, in subsequent peaks in the two larger size classes. However, no such peak appeared in 1985 when over one and a half million fingerlings were stocked, possibly because most of them were released later in the year and were not of sufficient size to be included in the 25–65 mm size range.

Bay Anchovy

Bay anchovy are planktonic feeders which provide an important prey item for larger fish species. Although third in abundance (in terms of numbers of fishes caught) this species is probably the most numerically abundant fish in the bay, prevalent both nearshore and offshore.

The distribution maps for bay anchovy (FIGURE 8.9) reveal

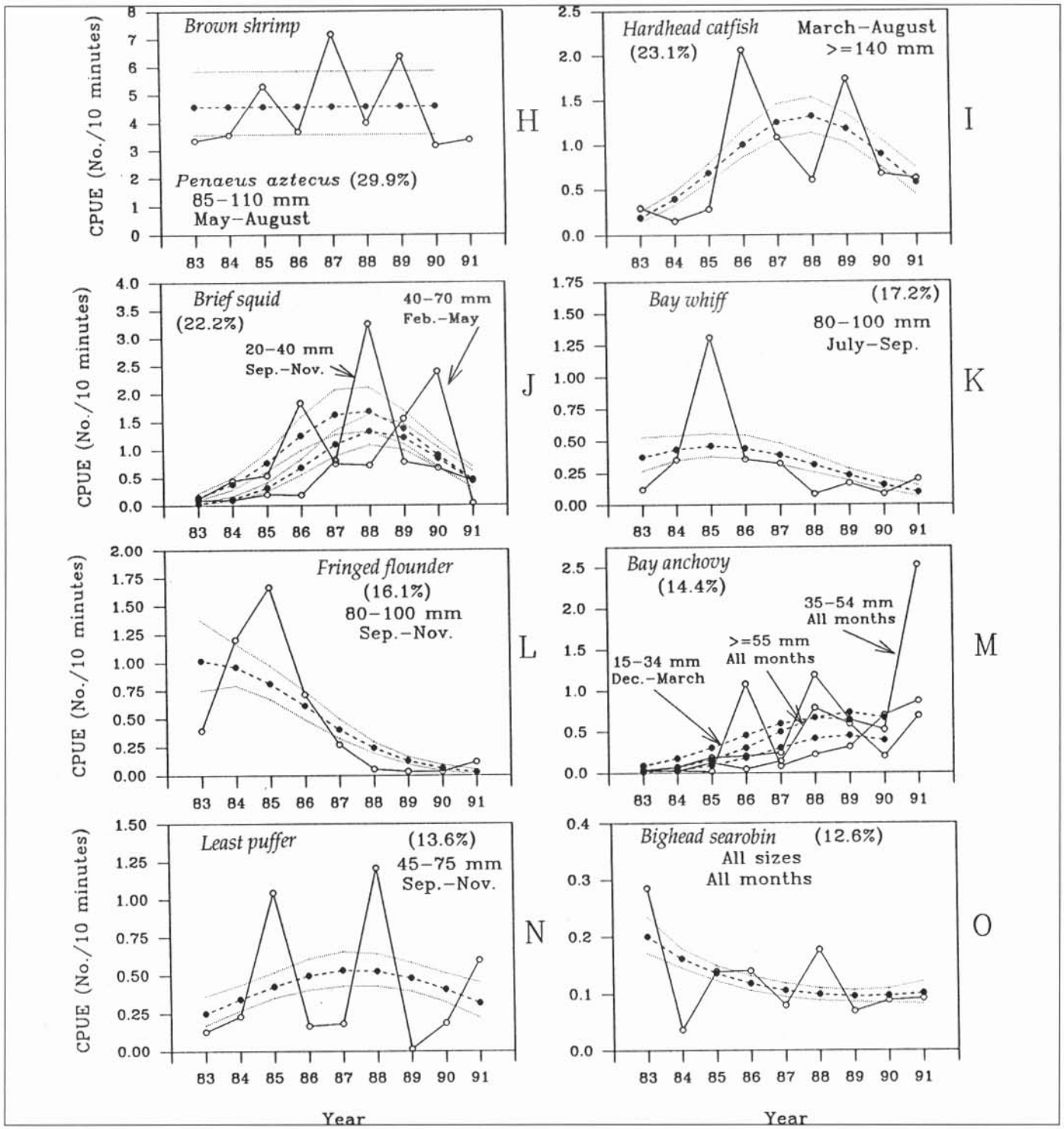


Source: Green et al., 1992

FIGURE 8.11. *Mean annual catch per unit effort (CPUE) is shown for fourteen selected species (b-o, including facing page) caught by trawl, and a time trend for all these species combined is given in (a). Shown on the individual species plots is a trend line (solid dots) and corresponding 95 percent confidence interval.*

that first-time-spawners (35-54 mm) were associated with bay margins, particularly West Bay and East Bay, while first-time spawners in the open-bay were more abundant in the lower estuary. Changes in seasonality may be partially responsible for the differing results for bag seine CPUEs (warm months analyzed) and trawl CPUEs (cold months analyzed).

When analyzed for temporal trends, three classes of bay anchovy (15-34 mm, 35-54 mm, >55 mm) decreased in population from 1978 to 1990 for the bay margins. In the open bay, however, this fish showed an increasing trend. Once again, these results may be affected by the different time periods that are represented in the analyses done on data from different gear types. Regardless, this



Source: Green et al., 1992

potential decline in a major prey species along the shores, combined with the observed decline for some shore-feeding birds (see page 184), suggests the issue be further investigated.

Striped Mullet

Striped mullet are one of the most abundant fish species in shallow Texas waters. Young mullet use the back-bays of the estuary as nursery areas, where they feed on detritus and epiphytic algae. In Galveston Bay, striped mullet were evenly distributed throughout the bay for both bay margin habitats and the open bay. Young-of-the-year had peaks in the winters of 1981 and 1987 and first-time spawners showed an overall increasing trend. Adults decreased from 1975 to 1979, then remained constant. No mechanisms have been identified to account for these changes.

Other Species

The Texas Parks and Wildlife Department also identified the status and trends for other key indicator species (Green et al., 1992;

TABLE 8.4. Estuarine Fish and Shellfish Species in Galveston Bay: Results of Species Trend Studies

Species	Observations
Apparent Decline:	
Blue Crab	Chronic recent decline for older age classes; intensive harvest likely involved
White Shrimp	Chronic decline for older age classes; overharvest, habitat loss, pollution implicated; apparent very recent population rebound
Grass Shrimp	Strong decrease in adults followed by recent increase; other life stages inconclusive
Striped Bass	Long term decline
Green Turtle	Long term decline
Diamondback Terrapin	Long term decline
No Apparent Trend:	
Brown Shrimp	No apparent consistent trend
Southern Flounder	No significant trend for young of the year or adults
Gulf Menhaden	Variability among age classes and sampling period; no long-term pattern
Pinfish	Variability among gear types and sampling period; no long-term pattern
Bay Anchovy	Different gear types yield conflicting results; possible slight increase 1984-1990
Black Drum	Young of the year decreased 1978-1990; adults increased
Sand Seatrout	Variability among age classes, gear type, and sampling period; no long-term pattern
Apparent Increase:	
Red Drum	General increase in spawners and adults; harvest restrictions likely helped
Spotted Seatrout	General increase in spawners and adults; harvest restrictions likely helped
Atlantic Croaker	Linear increase in adults; no consistent trend for juveniles

Source: Green et al., 1992

Green et al., 1993; FIGURES 8.10–8.11). The most notable trends for Galveston Bay shellfish and finfish are summarized in TABLE 8.4.

Probable Causes of Fish and Shellfish Declines

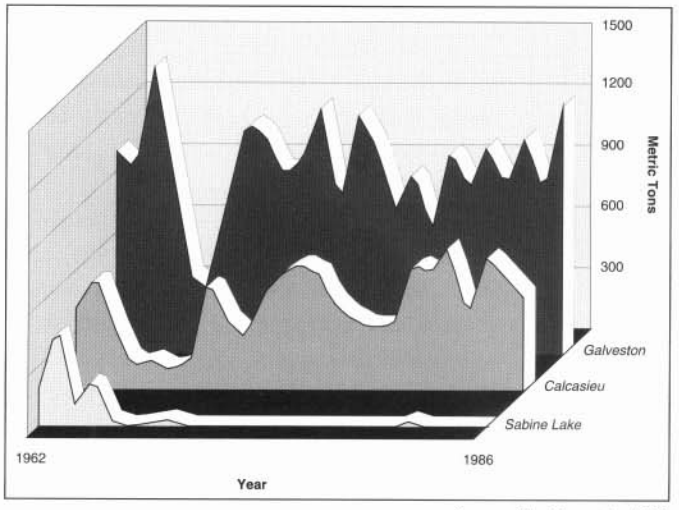
The declines noted above for white shrimp and blue crab populations raise some concerns for these species and for potential bay conditions which may have influenced the declines (Walton and Green, 1993). In addition, anecdotal information exists for several other species (such as tarpon, snook, and striped bass), indicating long-term declines compared to 1800s levels. Some reasons for declines were discussed above, such as overfishing, loss of marsh habitat, changes in fresh water inflow, and changes in riverine organic loads to the bay.

Below, the role of wetlands and fresh water inflow is addressed in more detail. In addition, several other studies have been performed to evaluate various impacts on Galveston Bay's living resources from commercial and recreational **bycatch**, cooling water systems, fish kills, and pollution in the Houston Ship Channel. Currently, there is little information to quantitatively link mortality from any of these sources to population limitations of species bay-wide, but clearly the magnitude of the impacts from some of these sources could have important effects.

The Role of Wetlands and Fresh Water Inflow

Future changes in fresh water inflow could potentially have a great effect on shrimp populations. High fresh water inflows result in increased nutrient availability and diatom blooms that can sometimes be associated with increases in brown and white shrimp populations (Walton and Green, 1993; Gunter and Hildebrand, 1954; and Gunter and Edwards, 1969). In Sabine Lake, changes to inflow resulting from damming the Neches and Sabine rivers and concurrent isolation of wetlands may have been responsible for the permanent collapse of a 300 metric ton/year white shrimp fishery in Sabine Lake (Sheridan et al., 1989). At the time of collapse, comparable fisheries in Galveston Bay and Lake Calcasieu were not affected (FIGURE 8.12). Possibly acting through a climatic link to inflow, a correlation has also been observed between El Niño events and higher shrimp productivity (Green et al., 1993), but no causative relationships have been confirmed. It remains uncertain how global climatic events like El Niño or the Southern Ocean Oscillation Event affect estuarine organisms locally.

Future wetland losses are also a concern for shrimp. In nearshore Louisiana, a decline in landings of brown shrimp was directly linked to the loss of nearby salt marsh (Turner, 1977). But paradoxically, increased populations of some aquatic organisms over the long-term record (i.e. over the last 30 years) may also reflect the long-term loss in wetlands. A relative sea-level rise (i.e. a "drowning" marsh) temporarily increases access to marsh areas for many species with a corresponding temporary increase in secondary production when compared to stable marshes. This can be seen in the long-term recruitment trends of several commercial



Source: Sheridan et al., 1989

FIGURE 8.12. *The permanent collapse of the white shrimp fishery in Sabine Lake resulted from diversion of the Neches and Sabine Rivers (altering fresh water inflow), and isolation of wetlands serving as critical nursery areas. White shrimp production in Sabine Lake is compared to Galveston Bay and Lake Calcasieu during the same period.*

species: Gulf-wide harvesting of young Gulf menhaden has increased over 200 percent in the past 30 years while populations of young shrimp have increased over 50 percent (Sheridan et al., 1989). Based partially on these results, Sheridan et al. (1989) concluded that "the effects of marsh disintegration are beginning to show up."

Valuable fisheries and wildlife habitat has been lost in Galveston Bay due to an apparent rise in sea level (on the order of 1.5 to two feet since the turn of the century–see Chapter Five) in combination with surface subsidence caused by pumping of oil and groundwater. While most of the near-shore and bay bottom subsidence has all but stopped, the Environmental Protection Agency has predicted that a general sea level rise will continue, perhaps at an increased rate. If this predicted sea level rise occurs, then much more marsh will be lost than is gained by the rising water level. The net loss of marsh would be due to local topography and the presence of urbanization that would prevent the conversion of low-lying upland areas to marsh (FIGURE 8.13).

Shrimp Trawl Bycatch

Bycatch is a broad term to describe unwanted incidental harvesting of organisms during pursuit of a different species. A recent study to assess shrimp trawl bycatch in Galveston Bay was conducted by the National Marine Fisheries Service Galveston Laboratory during the 1992 shrimp season (Martinez et al., 1993).

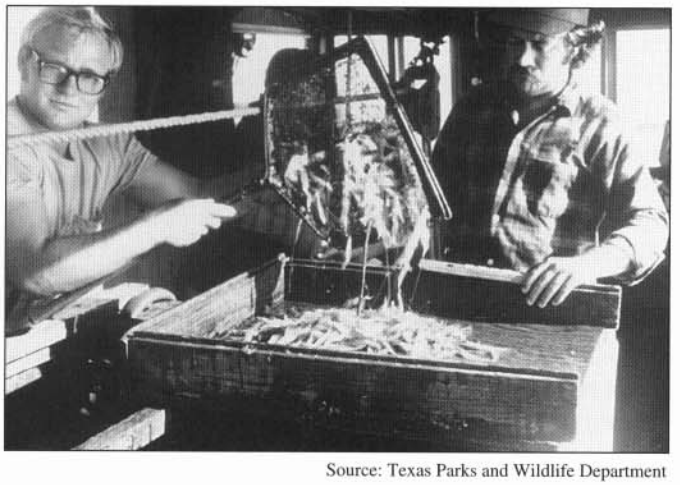
Both commercial and bait fishing industries were evaluated. Overall, one fish was captured as incidental bycatch for every 1.9 shrimp landed during the March to November shrimping season. In terms of biomass, 2.6 kg of fish were collected for every one kg of shrimp. By using shrimp landings data, the total bycatch from shrimping (fish plus crabs and squid) in the Galveston Bay system was estimated at about four million kg during the 1992 fishing season.

These bycatch data represented the sum of all fish and invertebrates captured in the shrimp trawls, including those culled overboard which survived in some unknown proportion. Almost all of the fishermen who participated in this study utilized culling boxes (plywood enclosures with flow-through seawater) on their vessels. The catch from each net haul was generally placed in these culling boxes to minimize mortality of live-bait shrimp being sought (bait operations) and facilitate ease of separating shrimp from bycatch. No specific tests were performed to determine the survival rate of the discarded organisms.

Dominant bycatch species captured included Atlantic croaker, Gulf menhaden, sand seatrout, bay anchovy, sea catfish, spot, brief squid, and blue crab. Recreational finfish species (southern flounder, red drum, and spotted seatrout) were captured infrequently in shrimp trawls, a conclusion supported by previous studies.

Recreational Bycatch

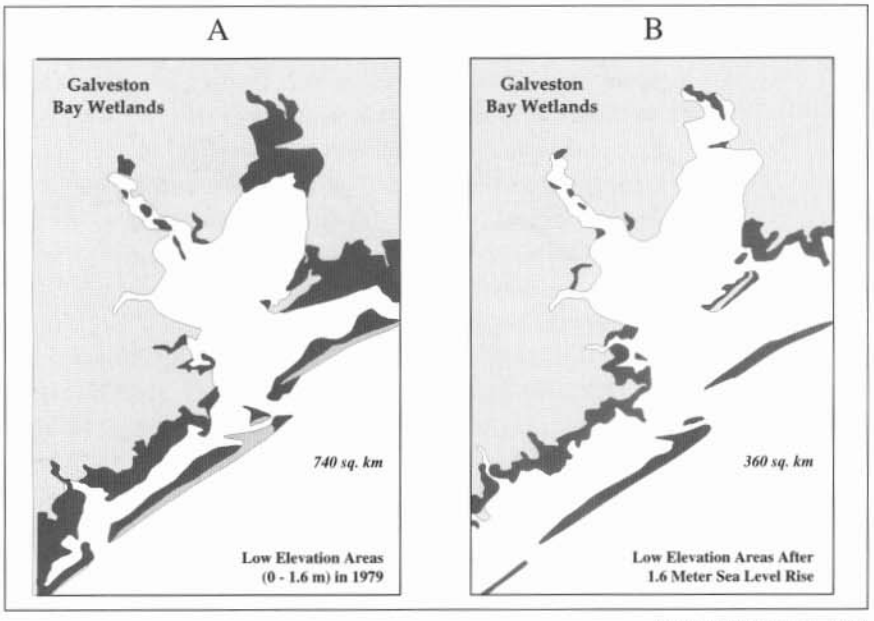
Based on federal and state fisheries data, Saul et al. (1992) concluded that recreational sport-boat fishermen caught and released about two fish for every fish retained. When applied to the



Source: Texas Parks and Wildlife Department

About three pounds of bycatch (fish and other non-target species) are caught for each pound of shrimp harvested. The net haul (below) is culled on board (above), with the bycatch returned to the bay.

Source: Texas Sea Grant College Program



Source: Sheridan et al., 1989

FIGURE 8.13. *Predicted changes in wetland areas if a 1.6-m sea level rise occurs. Wetlands in 1979 (a) are compared to a predicted condition in the year 2100 (b).*

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 less than 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 seven days of being hooked, handled, and released. Although total biomass of recreational bycatch (including survivors) was not estimated by Saul et al., it is probably around 1-2 million kg/yr, or less than half the total shrimp bycatch biomass of four million kg/yr (assuming recreational bycatch of an average of 2.4 million fish/yr at an estimated 0.5-1 kg/fish).

Impacts From Cooling Water Systems

Cooling water systems for such industries as power generation can cause incidental mortality of bay organisms through **impingement** and **entrainment**. Impingement occurs when organisms are collected by a screen at a water intake structure. Entrainment occurs when organisms too small to be intercepted at the intake screens pass through the plant. There are five major electricity generation facilities around Galveston Bay operating cooling water systems, each of which utilize U.S. Environmental Protection Agency-defined "Best Available Technology" impingement and entrainment control systems. Such systems control impingement and entrainment losses by limiting the approach velocity of the water to the intake screens, and by providing a pathway for the larger organisms to be diverted around the plant.

The impact of cooling water use on fishery resources was studied using historical data (Palafox and Wolford, 1993). Using 1978-1979 data from five 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. They also concluded that only one other facility besides the five HL&P generating stations (a chemical facility in Texas City) could have a major effect on finfish and shellfish in the bay due to impingement.

To gauge the relative significance of impingement, Palafox and Wolford (1993) compared the projected biomass of sport and commercial species impinged at five HL&P plants to the biomass of commercial and sportfish landings reported by the Texas Parks and Wildlife Department. The 1978 to 1979 time period had the most extensive data for comparison. For the species of interest, more biomass was landed by commercial and recreational fisherman than were impinged on the cooling system screens. The weight of impinged brown shrimp and white shrimp was nearly 11 percent of the commercial landing, while impinged blue crabs from these locations represented nearly 17 percent of the commercial landings bay-wide. The weight of red drum, sand seatrout, and spotted seatrout were all less than three percent of the recreational landings. In general, commercially and recreationally

Source: Texas Parks and Wildlife Department

Four of the top ten Coastal fish kills reported in the nation 1980-1989 occurred in the Galveston Bay system, with 50 million fish killed in a single event. The typical kill occurs in an area of limited circulation in the warm months. The predominant cause is lack of oxygen, not toxicity.

important species such as spotted seatrout, black drum, red drum, and southern flounder were infrequently impinged and only in low quantities.

It should be noted that the above comparison of commercial and sportfish landings to entrainment levels does not consider survival rates of entrained organisms. The data show considerable but varied survival, depending on species, time of day, season, and plant location. In particular, plant location clearly affected survival rates: survival at the Cedar Bayou station was much greater than the survival rates reported for the Robinson station near San Leon. In general, crustaceans had higher survival rates than fish.

Source: Frank S. Shipley

Shorebirds and this pair of pintail ducks are just a few of the bird species which depend upon the habitats provided by Galveston Bay.

None of the historical studies 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 drawn through the cooling systems.

Both detrimental and beneficial effects were observed from the discharge of heated effluent from the Cedar Bayou Generating Station. Gulf menhaden showed negative effects from elevated temperatures of 30°C, and bay anchovy, sea catfish, sand seatrout, and spot avoided zones with water temperatures greater than 35°C. On the other hand, large numbers of fish were found congregated in the discharge canal and near the outfall during the winter (Palafox and Wolford, 1993).

Fish Kills

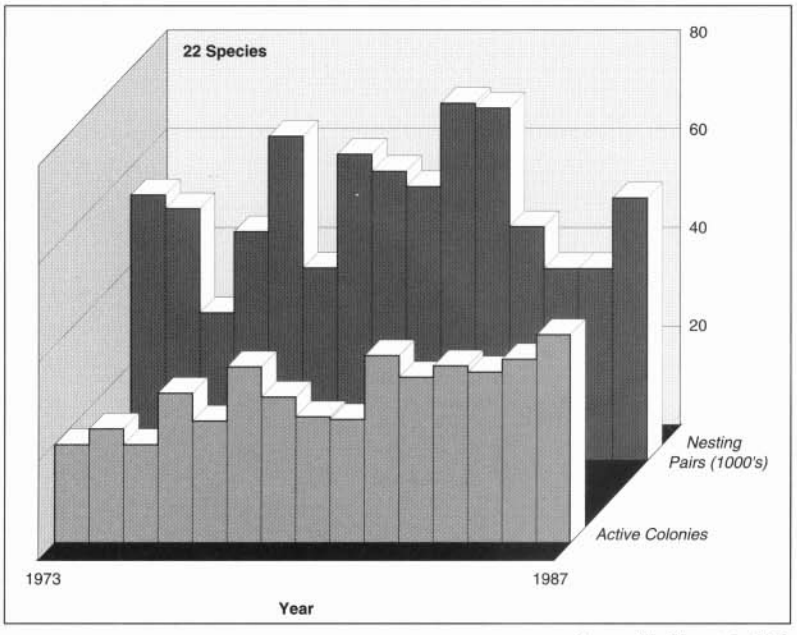
The Gulf Coast has some of the nation's largest and most frequent fish kill events, partially because of the hot climate and physical features such as low circulation. In a national study, Galveston Bay had the highest number of reported major fish kills (28) in the United States from 1980 to 1989 (Lowe et al., 1991) with over 100 million fish killed. Seventeen of the 28 kills were related to low dissolved oxygen.

Palafox and Wolford (1993) reviewed 220 Galveston Bay fish kills which occurred over the past 20 years, with the following findings:

> Fifty-six fish kills (25 percent) were related to point source pollution. Primary causes were unknown spills at electric power generation facilities, sewage treatment plant by-passes, pipeline leaks and unknown spills at chemical plants, ocean dumping, and seismic detonations. Almost all of the fish mortality attributed to point sources occurred from May to October, with peaks in May and September.
>
> Forty-three kills (20 percent) were caused by nonpoint sources, including undefined runoff events and other nonpoint influences contributing to low dissolved oxygen. Gulf menhaden was the species most often killed in nonpoint source events. These occurred most often from June through September with a peak in August.

TABLE 8.5. Dominant Species in the Upper Houston Ship Channel.

Common Name	Scientific Name
Brown shrimp	*Penaeus aztecus*
White shrimp	*Penaeus setiferus*
Grass shrimp	*Palaemonetes pugio*
Blue crab	*Callinectes sapidus*
Gulf menhaden	*Brevoortia patronus*
Threadfin shad	*Dorosoma petenese*
Bay anchovy	*Anchoa mitchilli*
Sheepshead minnow	*Cyprinodon variegatus*
Gulf killifish	*Fundulus grandis*
Longnose killifish	*Fundulus similis*
Inland silverside	*Menidia beryllina*
Spot	*Leiostomus xanthurus*
Atlantic croaker	*Micropogonias undulatus*
Striped mullet	*Mugil cephalus*
White mullet	*Mugil curema*
Sailfin molly	*Poecilia latipinna*



Source: Sheridan et al., 1989

FIGURE 8.14. *Trends for colonial nesting birds. These species include the herons and ibises, terns, cormorants, roseate spoon bill, and black skimmer.*

> One hundred and twenty-one fish kills (55 percent) could not be classified as to cause based on the report records.

Fish kills most often occurred in tributaries to Clear Lake and East Bay, and within West Bay, San Jacinto Bay, Dickinson Bayou, and Clear Lake. Although fish kills from freezes can be significant, these kills were not included in the references presented above.

The Upper Houston Ship Channel–Biological Suitability

Early studies of the Houston Ship Channel determined that the area above the confluence of the San Jacinto River was virtually lifeless (Chambers, 1960). By the mid 1970s, considerable improvement could be seen between the San Jacinto River and Greens Bayou (Segment 1006), but the upper portion from Greens Bayou to the Turning Basin (Segment 1007) was still devoid of fishes, crabs, and shrimps.

Since the late 1960s, municipal and industrial point source waste loadings of BOD have decreased by over 95 percent (see Chapter Six), resulting in utilization of the channel by a variety of organisms (Seiler et al., 1991). The lower portion of the landlocked reach now supports a viable fish population year-round (TABLE 8.5). In the winter, the upper channel has a species richness and abundance that exceeds the lower portion of the landlocked reach, and it also maintains a viable shoreline assemblage during the summer months. Seiler et al. (1991) also concluded that although the upper Houston Ship Channel currently possesses a "no aquatic life" designation, the increased utilization by fish, shrimp, and crabs may have implications on the future use designations of the channel.

The return of estuarine species to the upper Houston Ship Channel is encouraging, but does not indicate a complete recovery to conditions characteristic of other portions of the bay. Biological diversity remains generally lower, dissolved oxygen is still depressed (particularly near the bottom) and toxic contamination of sediments and organisms continues to be observed.

BIRDS

Bird populations in Galveston Bay have significant commercial, recreational, ecological, and aesthetic values. In addition, many bird species are predators on fish, shellfish, or benthic organisms, and therefore are important indicators of the health of the food web and the status of different bay habitats.

Observers have noted 139 bird species associated with Galveston Bay wetlands and open-bay habitats (Arnold, 1984).

Source: Robert W. McFarlane

Source: Robert W. McFarlane

Forester's terns nest in a smooth cordgrass marsh on a dredged-material disposal island in Drum Bay (left). The wind- and wave-driven wrack composed of hollow, jointed cordgrass stems lodges in the marsh and provides a dry platform for nests (right). The nests and underlying wrack float up and down with the tide but can float free and blow away on exceptionally high storm tides.

TABLE 8.6. Estuarine-Dependent Bird Species Utilizing Galveston Bay: Results of Species Trend Studies.

Species	Observations
Apparent Decline:	
Tricolored Heron	Fewer total birds nesting in more colonies; no trend in the Christmas Bird Count
Snowy Egret	Decrease in numbers and numbers per nesting colony; Christmas Bird Count showed increase
Black Skimmer	Decrease in numbers and numbers per nesting colony; no trend in the Christmas Bird Count
Roseate Spoonbill	Decrease in numbers and numbers per nesting colony; Christmas Bird Count showed increase
Mottled Duck	Mid-winter Waterfowl Transects showed decrease; Christmas Bird Count showed increase
Northern Pintail	Mid-winter Waterfowl Transects showed decrease; Christmas Bird Count showed increase
Blue-winged Teal	Mid-winter Waterfowl Transects showed decrease; Christmas Bird Count showed increase
No Apparent Trend:	
Great Egret	Constant or increasing total number nesting in more colonies with fewer birds
American Avocet	No change on Bolivar Flats Survey; increase in Christmas Bird Count
Dunlin	No change on Bolivar Flats Survey; increase in Christmas Bird Count
American Coot	No discernible trend
Green-winged Teal	No discernible trend
Northern Shoveler	No apparent trend; variability suggests local movements
American Widgeon	No apparent trend; variability suggests local movements
Canvasback	No trend based on Christmas Bird Count
Fulvous Whistling Duck	No trend based on Christmas Bird Count
All Blackbirds	No trend or insufficient data
Apparent Increase:	
Olivaceous Cormorant	Increase in total numbers and colonies; Christmas Bird Count showed variable increase
Forster's Tern	Increase in colonies and Christmas Bird Count
Black-bellied Plover	Apparent increase based on Bolivar Flats Survey and Christmas Bird Count
Willet	Apparent increase based on Bolivar Flats Survey and Christmas Bird Count
Sanderling	Apparent increase based on Bolivar Flats Survey and Christmas Bird Count
Western Sandpiper	Apparent increase based on Bolivar Flats Survey and Christmas Bird Count
Mallard	No change or possible increase in wintering population
Gadwall	No change or possible increase in wintering population
All Scaup	Christmas Bird Count showed increase
Ruddy Duck	Christmas Bird Count showed increase
Bufflehead	Christmas Bird Count showed increase
Wood Duck	Christmas Bird Count showed increase
Ring-necked Duck	Christmas Bird Count showed increase
Black-crowned Night Heron	Increase in colonies and Christmas Bird Count

Source: Green et al., 1992

TABLE 8.7. Colonial Waterbird Nesting Locations in Brazoria, Chambers, Galveston and Harris Counties for 1990.

Colony Name	Number of Species	Number of Breeding Pairs
Brazoria County		
Follets Island	2	70
Drum Bay	10	470
Bastrop Bay	2	120
West Bay Bird Island	4	215
San Luis Island # 1	0	0
Arcadia Reef	5	125
Chambers County		
Catfish Acres	5	870
Trinity River Mouth	6	3,320
East of Lost Lake	4	425
Vingt-et-un Island	9	380
Galveston County		
Scholes Field	1	80
Redfish Island	2	42
Smith Point Island	12	1,602
Rollover Pass	10	1,438
Moses Lake Spoil Islands	4	82
Dickinson Bay Spoil Island	2	550
Bolivar Flats	1	2
Marker 52 Spoil Island	1	30
Jigsaw Island	2	270
North Deer Island	14	4,829
Down Deer Island	1	70
South Deer Island	7	620
Ganges Bayou	1	62
Little Pelican Island	15	15,574
Pelican Island	4	10,448
Fort San Jacinto	1	4
Magnolia Compress #15	1	4
Farmers Copper	1	50
McAllis Point	1	20
Maggies Point	3	230
Snake Cove Point	2	26
Bay Harbor Bar	4	330
Oxen Bayou Point	2	90
Mensell Bayou Point	6	823
Starvation Point	2	17
Eckert Bayou Point	4	613
Hoeckers Point	2	85
Dana Cove	1	25
Carancahua Cove	6	682
Live Oak Grove	1	4
San Luis Pass	2	210
Harris County		
Sheldon Reservoir	5	1,110
Baytown Tunnel	2	60
Alexander Island	10	793
Exxon Baytown North Gate	1	32

Source: Jones and Neuse, Inc., 1992

Data from the Texas Colonial Waterbird Surveys from 1973 to 1990 were used to evaluate trends for birds utilizing Galveston Bay living resources and habitats. The Christmas Bird Count represented another source of data. The Christmas Bird Count is a winter bird census conducted by the Audubon Society, utilizing amateurs to enumerate birds in prescribed areas. Population trends for colonial waterbirds, waterfowl, shorebirds, and special species of interest were summarized from three primary sources: Walton and Green (1993), Slack et al. (in Green et al., 1992), and Sheridan et al. (1989). TABLE 8.6 summarizes the overall trends for different birds of the Galveston Bay estuary.

Colonial Waterbirds

Overall, there is no significant trend in the number of total colonial waterbirds around Galveston Bay, nor is there a trend in number of species present from 1973 to 1990. The number of pairs of colonial-nesting waterbirds has varied from about 39,000 pairs in 1978 and 1982 to a high of 71,200 in 1985 (FIGURE 8.14). The number of active colonies, found in association with gravel and shell bars, marshes, cypress stands, dredged material islands, and industrial and developed locations, has increased from 20 in 1973 to 42 in 1987 (see TABLE 8.7 for data from 1990). The three most common species in the 1986 nesting season were the laughing gull, royal tern, and cattle egret.

The results of this overall analysis, while encouraging, could potentially obscure patterns of concern for individual species. An analysis performed in 1992 indicated that some particular colonial species were indeed declining in numbers (Slack et al. in Green et al., 1992). Subsequently, Slack et al. performed a more detailed statistical analysis which identified a long-term structural change in Galveston Bay's bird community (Green et al., 1992; Walton and Green, 1993). Population trends for three different groups of colonial waterbirds were evaluated: 1) an inland species group, 2) an open-water group, and 3) a marsh group.

The inland group consisted of fresh water marsh feeders and generalists such as little blue herons, white ibises, cattle egrets, white-faced ibises, and great blue herons. No significant change in number of individuals or percentages of these birds in colonies was observed during the period 1973-1990.

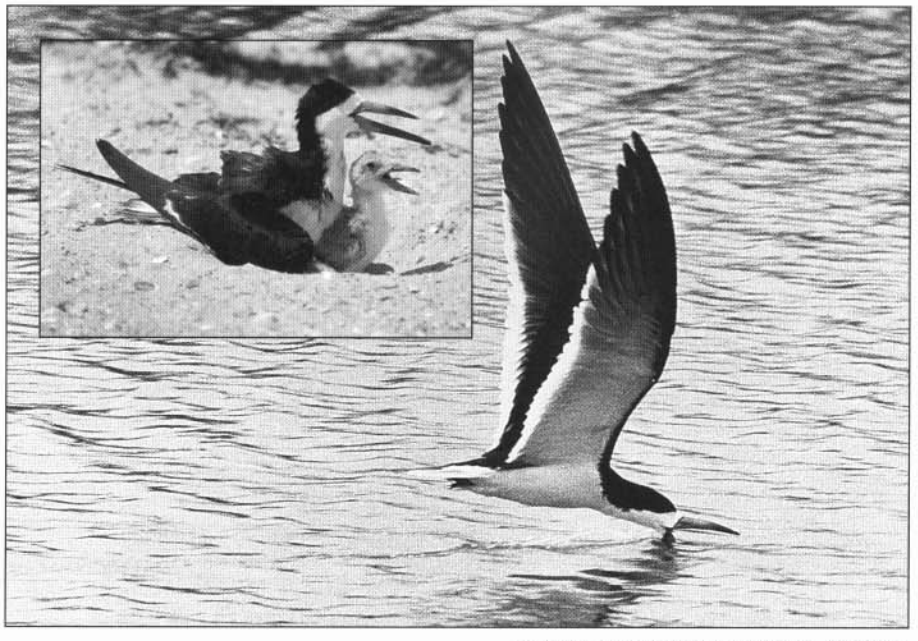
Open-water birds included royal terns, Caspian terns, olivaceous cormorants, Forster's terns, and Sandwich terns. These species depend primarily upon fish caught from open-bay habitats. Both the number of individuals and number of colonies increased during the study period.

Species in the marsh group were waders that feed on small fish and benthic invertebrates along shoreline marsh edges. Species included snowy egrets, roseate spoonbills, tricolored herons, black skimmers, and great egrets. For these species, the number of colonies increased, but number of individuals per colony decreased enough to represent an overall decline in numbers. This decline is of particular concern in view of the 17-19 percent reduction in wetlands needed by these species (Chapter Seven). These species nest in colonies but spread out within the bay system for

feeding. Nesting colony locations are ample, but the feeding habitat losses may have influenced populations.

Waterfowl

An annual average of 11,500 waterfowl were observed in the Galveston Bay system, based upon data for 1978 and 1984-1987 (Sheridan et al., 1989). The most commonly observed species were all migratory: the green-winged teal, ring-necked duck, lesser scaup, red-breasted merganser, and ruddy duck. Because of the nature of these and other migratory species, population regulation is impossible to evaluate by studying populations at any one location. That is, they could be winter-limited (influenced by conditions in Galveston Bay and other wintering areas) or breeding-limited by habitat or other factors to the north. However, reductions in numbers utilizing a winter area, while not necessarily reflecting population reductions, could nevertheless reflect decreased habitat utilization in response to habitat loss or deterioration.



Source: Frank S. Shipley; inset Robert W. McFarlane

Black skimmers utilize the unique foraging method of skimming the water surface in flight. Inset is an adult with its chick and simple nest scrap on a sand-and-shell beach at San Luis Pass on Galveston Island.

Migratory waterfowl such as northern pintail and blue-winged teal have declined in population continent-wide, most probably due to loss of wetland breeding habitat on the Great Plains, or conditions in the Central and South American wintering grounds. Texas-related factors for the decline in these species are therefore difficult to evaluate (Cain and Feierabend, 1988). Controls on pesticide use have reduced pesticide-related mortality, while avian cholera mortalities increased in the 1980s. Poisoning from lead shot is a problem for some species, such as mottled duck (Moultan et al., 1988), although steel shot is now exclusively used in the coastal area.

Only the fulvous whistling duck, mottled duck, and wood duck breed in the vicinity of the bay system. Data on mottled duck populations were somewhat contradictory. The long-term Christmas Bird Count data indicated a generally flat trend line from 1964 to 1989, while the Texas Parks and Wildlife Department and U. S. Fish and Wildlife Service Mid-Winter Waterfowl Survey shows a strong downward trend for the period 1986 to 1991 (Slack et al. in Green et al., 1992). Part of the reason for the discrepancy is the large scatter shown in the data, particularly for the Mid-Winter Waterfowl Survey. Additional data are required to confirm which surveys are more representative of actual mottled duck population trends.

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). Snow geese may be increasing to the point where populations will be affected by overcrowded breeding grounds.

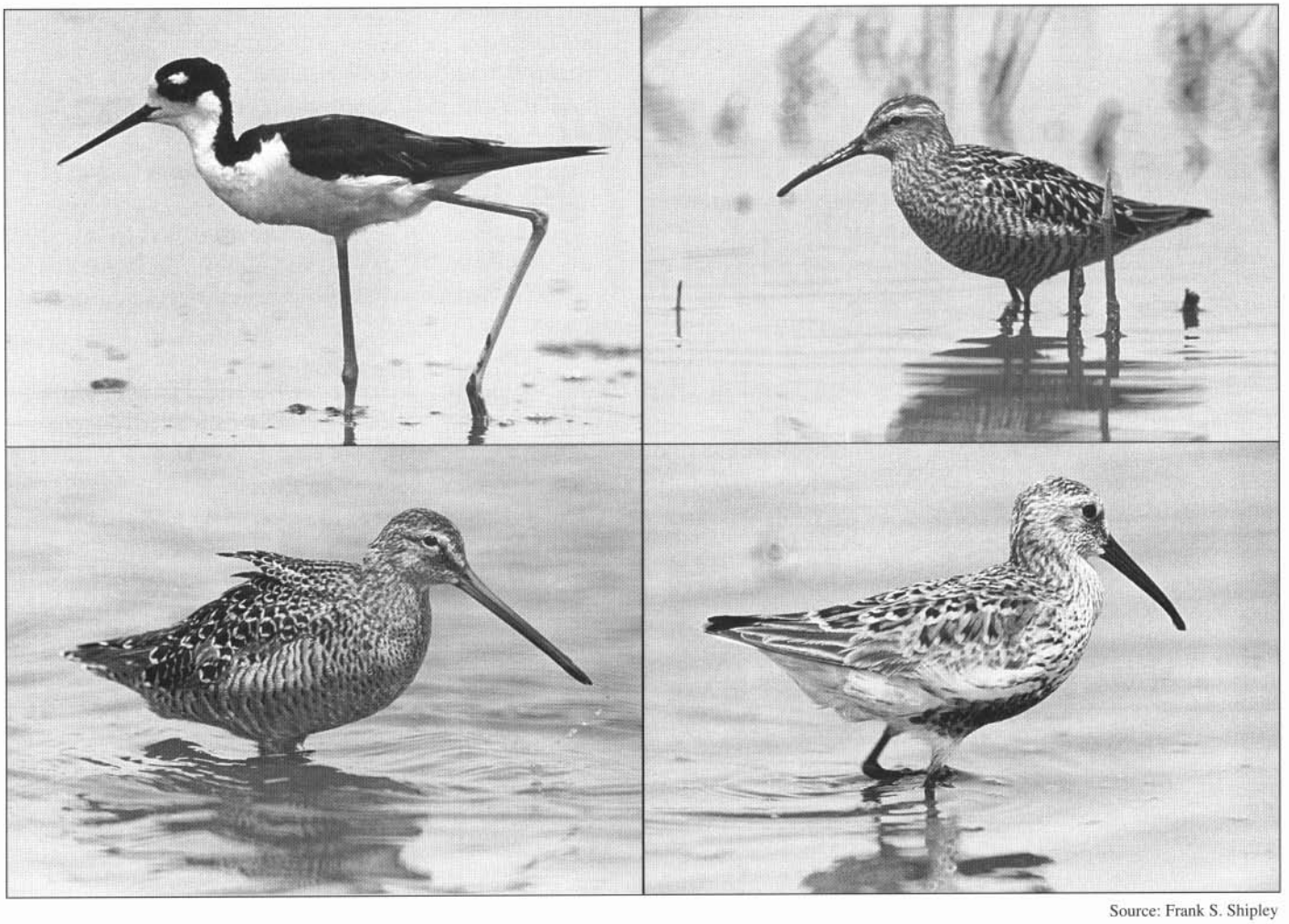
Shorebirds

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. Many of these species are probers, inserting their elongated bills into the sediments to capture benthic infauna on the intertidal mud flats and associated shallow-water areas. One species, the American avocet, sweeps the water surface for plankton in the shallows. Intertidal flats on Bolivar Peninsula and on either end of Galveston Island are the primary habitats for these shorebirds.

The most common shorebirds are the black-bellied plover, American avocet, willet, sanderling, western sandpiper, dunlin, and dowitchers (see photo page 186). The Christmas Bird Counts and the Bolivar Flats Shorebird Survey (special surveys conducted by the U. S. Fish and Wildlife Service's Clear Lake Office) indicate a possible increase in shorebirds, although the data are difficult to interpret due to lack of standardization.

Threatened or Endangered Bird Species

Brown pelicans, an endangered species which declined in the 1960s due to the toxicity and bioconcentration of pesticides, have shown increases in Galveston Bay during the past few years, probably because of the reduction/and or elimination of specific pesticides known to be harmful. Two roosting sites, but no nesting sites, are known according to the 1990 Colonial Water Bird Survey. The bald eagle, an endangered species, has nesting sites in Chambers, Galveston, and Harris counties. The arctic peregrine



Source: Frank S. Shipley

Four shorebird species of Galveston Bay (clockwise from upper left): the black-necked stilt, stilt sandpiper, long-billed dowitcher, and dunlin. These and other shorebird species utilize mudflat habitats such as Bolivar Flats in migration.

falcon and piping plover are listed as threatened in some of the counties around the bay, but do not nest in the area.

AMPHIBIANS AND REPTILES

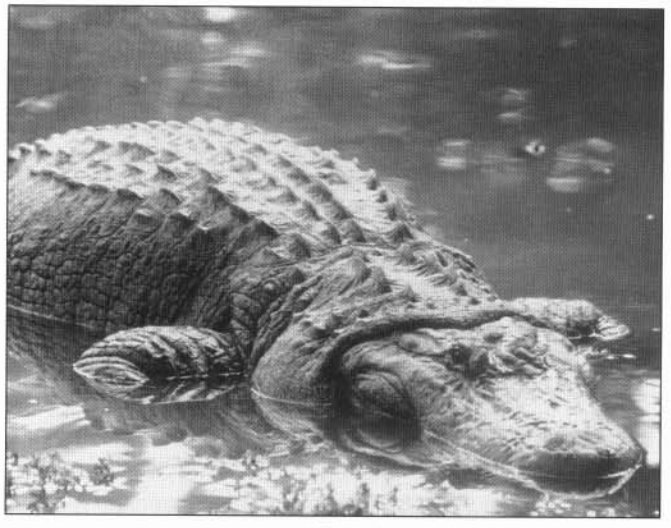
A total of 92 species of amphibians and reptiles have been observed in four counties adjacent to Galveston Bay. Of particular interest is the American alligator, which has increased in population since counts were initiated in 1971. The alligator has increased throughout much of its U. S. range, due to initial harvest bans, followed by reinstated, limited harvests as populations increased. In Texas, harvest has been overseen by the Texas Parks and Wildlife Department. During 1984 to 1986, 655 alligators were legally harvested from the Galveston Bay system, with most taken from the fresh water marshes in Chambers County.

Sea turtles were once present in the bay in relatively large numbers and supported a commercial fishery in Galveston in the 1890s. Today, sea turtles that reside in Texas waters have been identified as threatened or endangered species: leatherback sea turtle, Kemp's ridley sea turtle, loggerhead sea turtle, and green sea turtle. During the 1980-1991 period, a total of 27 sea turtles were found in Galveston Bay (Caillouet et al., 1991). Eighteen sightings were observations of dead stranded turtles, with three turtles found in shrimp trawls. Sightings were concentrated around Bolivar Roads and the Texas City Dike, the San Luis Pass/Chocolate Bay/Christmas Bay area, and Rollover Pass. Kemp's ridley sea turtle comprised 16 of the 27 sightings.

Little is known about the behavior and habitat selection of Texas sea turtles. Currently, the National Marine Fisheries Service is using satellite, radio, and sonic tracking of sea turtles in estuarine and offshore waters to provide more data on turtle biology. Management activities of interest include special precautions prior to marine seismic blasting, use of **turtle excluder devices** (TEDs) by shrimp trawlers, and the National Marine Fishery Service Head Start Program, a recently terminated program to hatch, rear, and release young sea turtles.

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



Source: Texas Parks and Wildlife Department

Increasing numbers of alligators throughout the southern U.S. have brought the species back from remnant populations. Alligators are now harvested in an open season in Texas, their high numbers even supporting "Gatorfest," an annual extravaganza in Chambers county, where most alligators in the Galveston Bay area are found.

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.

About 100 bottlenose dolphins are permanent residents of Galveston Bay and reside primarily around Bolivar Roads (Wursig and Henningsen, 1991). Many more dolphins are transient users of the bay, and over 1,000 different individuals have been observed in Galveston Bay during the past four years.

Based largely on research from Sarasota Bay, Florida, dolphins consume about 3.5-5 percent of their body weight in fish per day, with striped mullet being the primary prey. Assuming an average body weight of 180 kg, a single dolphin is estimated to consume almost 2800 kg of fish per year. When this value is applied to Galveston Bay dolphins, it is estimated that the 100 year-round residents of the bay could consume about 280,000 kg of fish per year.

SUMMARY

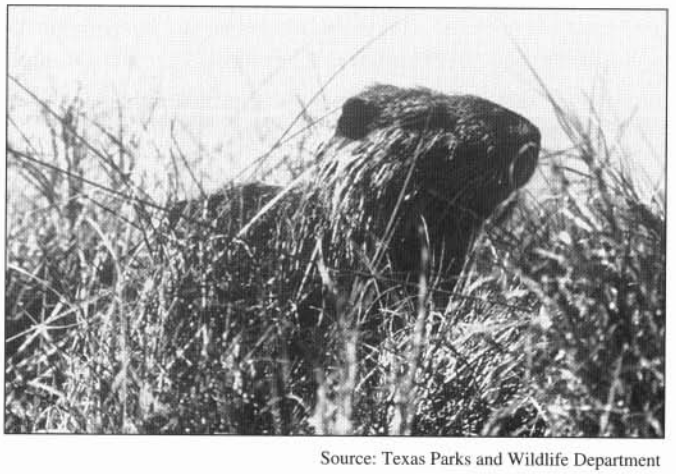
A wide variety of fish, wildlife, plant, and invertebrate populations either reside in or periodically utilize Galveston Bay and its associated habitats. These species compose the estuary's food web, capturing solar energy in the carbon bonds of carbohydrate compounds (green plants) thereby creating the food supply for higher level consumers and predators, including humans. The detrital pathway, with decaying organic matter at its base, is an important part of this process.

Most of the Bay's species appear to be in good health, with some exceptions posing management concerns. Phytoplankton abundance has changed significantly through the years, apparently in response to increases in nutrients peaking in the late 1960s, followed by nutrient reductions due to improved pollution control and the construction of reservoirs on the Trinity and San Jacinto Rivers. Today, plankton abundance is similar to levels seen prior to the major urban expansion on the bay's western shores.

Benthic communities have excellent value as indicators of environmental stress. This stress is evident in some Galveston Bay locations due to urban/industrial runoff and petroleum production facilities which discharge toxic compounds. Over wide expanses of the bay, however, the benthic community remains abundant and diverse, following a natural gradient of increasing diversity from the upper bay system seaward. Oyster reefs, if anything, have expanded in recent years. Some of the most productive reefs now occur on the shoulders of the open-bay reach of the Houston Ship Channel, where current velocities and salinity structure favor reef development.

Commercial fish and shellfish populations are generally stable, and fish, crabs, and shrimp have partially reestablished themselves in the once-lifeless Houston Ship Channel following significant reductions in municipal and industrial discharges. However, two species, white shrimp and blue crab, appear to be suffering from commercial overfishing. The Texas Parks and Wildlife Department has responded by banning the harvesting of shrimp in areas where white shrimp are believed to spawn during two crucial summer months, and is considering new fishing limitations for blue crabs. The rebound of red drum and spotted seatrout populations clearly show that Texas fisheries harvest and restocking programs can work.

The total number of all colonial waterbirds has remained relatively stable since the early 1980s. However, the composition of the colonial waterbird community is thought to be changing–there are now fewer wading marsh feeders. In this regard, birds are a sensitive indicator; continued wetlands loss from human development and from relative sea-level rise could greatly reduce the biological abundance and diversity of the bay in the future. As discussed in Chapter Seven, these processes have been responsible for most of the 17-19 percent loss in wetland areas that has occurred since the mid 1950s.



Source: Texas Parks and Wildlife Department

Nutria are an exotic species introduced into the United States from South America. Originally imported for their fur-bearing value, these animals rapidly spread through Gulf Coast wetlands where they encountered few predators. Voracious herbivores, they frequently decimate valuable emergent marsh habitat. Such "eat-outs" leave the sediment exposed and susceptible to high rates of erosion.

FOR MORE INFORMATION

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CHAPTER NINE

Public Health

Seafood (from Galveston Bay) is generally safe to eat, with the caveat that higher levels of contaminants in the Upper Bay can pose some risk to individual consumers, depending on the frequency and amount of seafood consumed and the biological characteristics of the consumer doing the eating.

–Frank Shipley, ***Knowing the State of the Bay: The Need for a Continuing Process,*** **1993**

Is it safe to swim in Galveston Bay? Can I eat the seafood? To citizens of Texas and the Galveston Bay region, these are compelling questions. News accounts of bay-related health threats get high attention from both the public and the media. For example, dioxin contamination in the upper bay system has led to specific recommendations by the Texas Department of Health to avoid certain seafoods taken from that limited area. Similarly, the Texas Department of Health advises against consumption of any fish from the bay's Clear Creek tributary, due to the discovery (near the Brio Superfund Site) of two suspected cancer-causing chemicals, and a third tied to nervous disorders. And, about half the bay remains permanently or provisionally closed to shellfish harvesting due to potential risk from pathogenic bacteria.

How do conditions in Galveston Bay affect public health? In this chapter, this topic is addressed under three headings: 1) the human health aspects of pathogens (disease-causing microbes), including shellfish closures and the safety of contact recreation (swimming, wade-fishing, jet skiing, etc.); 2) concentrations of toxic chemicals in fish and shellfish from the bay; and 3) the potential risks involved in consuming the bay's seafood, including discussion of the limitations inherent in determining risk.

Two studies provide the main background for this characterization. Jensen (1992) reviewed the current status of regulations for shellfish harvesting areas, shellfish bed closures, sources of bacterial contamination, and the incidence of known pathogenic organisms in the bay. Brooks et al. (1992) reviewed existing data regarding toxic chemicals in selected Galveston Bay organisms and, based on new field samples of fish and shellfish, performed an assessment of chemical risk associated with consumption of Galveston Bay seafood.

PATHOGENS

One important health concern related to human use of Galveston Bay arises from the potential presence of human pathogens in bay waters. Exposure to these pathogens could occur through contact and non-contact recreation or through the consumption of molluscan shellfish, primarily oysters. History provides valid reasons for concern about such menaces as infectious hepatitis, dysentary, ***Vibrio*** infections 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.

In general oyster consumption, in the absence of a regulatory program, would represent a higher risk than contact recreation due to the fact that oysters naturally filter microbes from the water in feeding, and because they are commonly consumed raw.

Indicator Organisms

Ideally, 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 enumerat-

ing the many different kinds of human pathogens. Instead, *indicator organisms* have been used 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 as Indicator Organisms

A number of possible indicators of human pathogens in water are available, including: fecal coliform bacteria, total coliform bacteria, *E. coli* (a particular bacteria species), fecal streptococcus, and **enterococcus**. The *Texas Surface Water Quality Standards* (Texas Water Commission, 1991), the Texas Natural Resource Conservation Commission water quality monitoring program, and the Texas Department of Health Shellfish Sanitation Program currently use fecal coliform bacteria as the indicator, but have used total coliform in the past. For water testing purposes, fecal coliform bacteria are defined as those coliforms which ferment lactose with gas and acid formation at an elevated temperature of 44.5 °C. Total coliform bacteria, on the other hand, comprise aerobic and facultative anaerobic and other bacteria that respond at 35 °C.

Fecal coliform bacteria naturally occur in the intestines of mammals and birds, their fecal material containing some one million organisms per gram. Each human produces from 100 to 400 billion coliform organisms per day. Since 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. Conversely, the presence of fecal coliforms indicates contamination that could (but may not) involve more serious pathogens. The use of fecal coliform bacteria as an indicator in drinking and recreational waters has nearly a century of successful application in protecting public health, including about 50 years use in shellfish regulation.

Problems with the use of Fecal Coliforms as Indicators

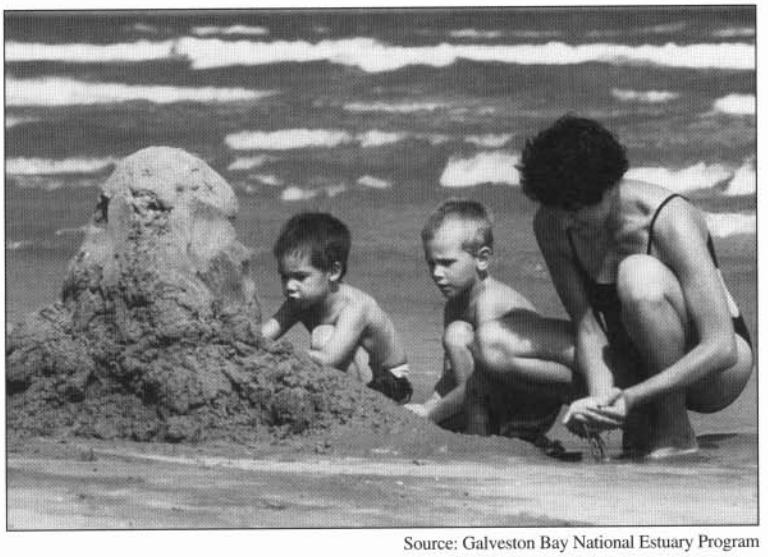
The use of fecal coliforms as an indicator has its limitations. There are some bacterial pathogens which are unrelated to human wastes and therefore not detected in the routine tests (*Vibrio vulnificus* is an example discussed in this chapter). Conversely, many *non-fecal* coliforms common in soil and on the surface of plants cannot be distinguished from fecal coliforms by the tests commonly used. Positive fecal coliform test results have been found for numerous food processing wastes and fish growing ponds, all with no mammalian waste sources. Elevated levels are also found in runoff from agricultural fields with very limited mammalian and avian populations. Thus, elevated concentrations of organic materials from a wide range of sources can support bacterial populations, and the total and fecal coliform tests need to be interpreted with caution.

The fecal coliform test has generally supplanted the total coliform test since the 1970s, in spite of the "false positive" problems resulting from organisms which are not of enteric origin. Studies on contact recreation conducted by the Environmental Protection Agency found that positive fecal coliform tests were not well-correlated with the concentration of actual pathogens.

Sources of Indicator Bacteria

Recent studies suggest that the primary and overwhelming source of fecal coliform bacteria to Galveston Bay is runoff from upland areas, with urbanized areas being one of the major components (see Chapter Six). Part of the reason fecal coliform levels are high in urbanized areas is the contribution from sewer leaks and overflows. However, urban area runoff (even when the collection systems are not leaking) generally has high fecal coliform levels, and runoff occurs in much greater volumes than sewage sources.

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). Flow from shoreline septic systems is small–each tank can be conservatively expected to release 150 gal/day with a fecal coliform count of 2 x 10^6 colony per 100 mL, not enough to provide a substantial combined load to the bay. For point sources, disinfection required under permit regulations is generally effective. The only time that point sources become a significant portion of the flow to Galveston Bay is during dry weather, at which time fecal coliform levels are at their lowest due to the lack of runoff.



Source: Galveston Bay National Estuary Program

Is the water safe for swimming? The safety of contact recreation, like enjoyment of the Gulf Beach shown here, depends upon bacteria concentrations. Bacteria in some western bay tributaries such as Clear Creek and Dickinson Bayou can exceed safe levels, but these areas are nevertheless popular for water skiing, jet skiing, and other watersports.

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 (Texas Department of Health et al., 1990), with low incidence of pathogenic organisms.

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. This contact recreation is not currently routinely regulated. The Texas Department of Health does not have a program for regulating contact recreation, nor does it have a public education program regarding contact recreation.

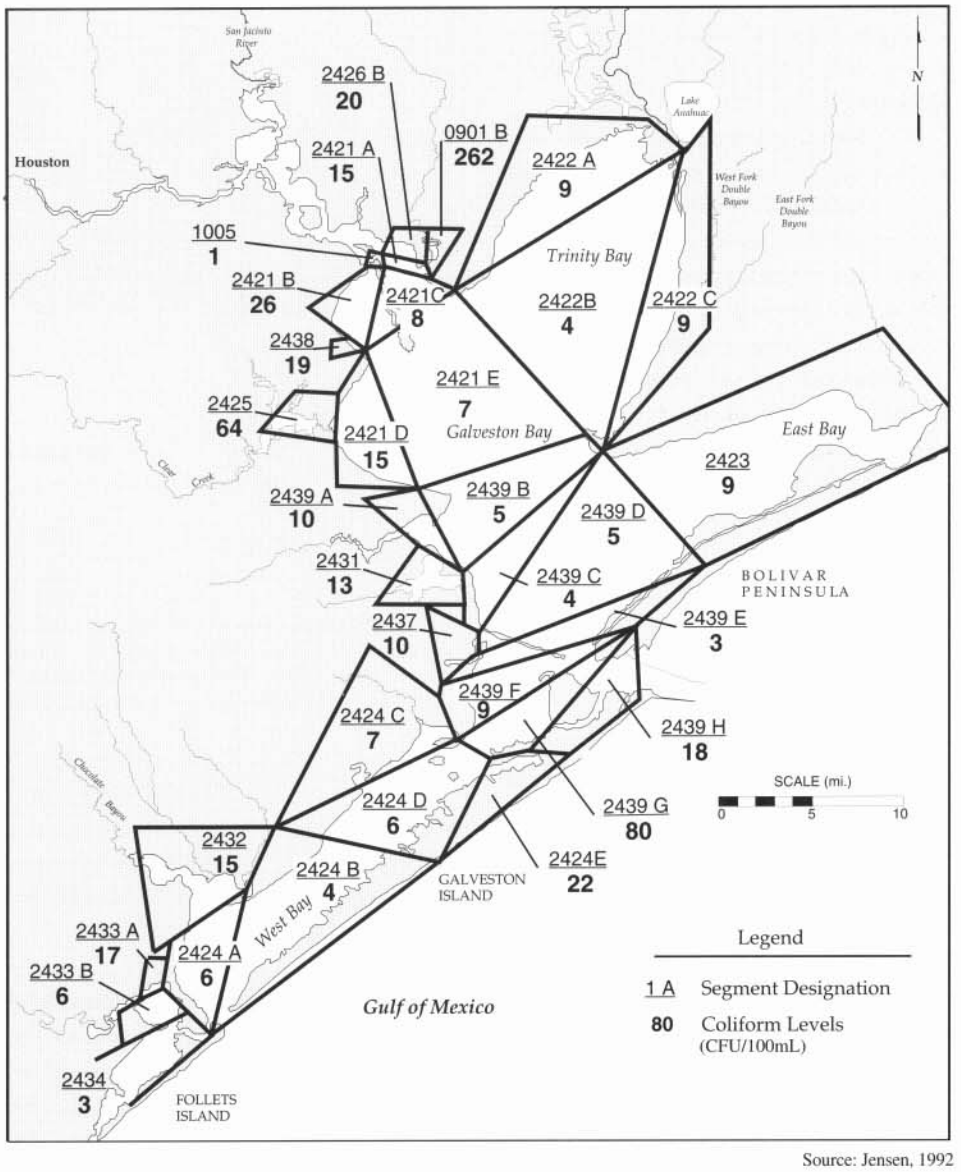
The Texas Natural Resources Conservation Commission indirectly addresses contact recreation by establishing "designated uses" and related water quality standards (Texas Water Commission, 1991). This program is aimed at water quality management rather than determining any risks to the public engaged in contact recreation. These standards and the Texas Natural Resource Conservation Commission water quality monitoring data can be used to evaluate whether the designated use is being met, and more specifically, whether water quality generally supports the use of bay waters for contact recreation (see box page 195). The criterion for this designation is the fecal coliform test, as determined by the membrane filter method.

How frequently is the Texas Natural Resource Conservation Commission criterion for contact recreation violated? Data compilations were conducted during two Galveston Bay National Estuary Program projects carried out by the University of Texas (Ward and Armstrong, 1992) and by Espey, Huston, and Associates (Jensen, 1992). Findings indicated that–over the long term–all *open bay areas* of the system met the Texas water quality criterion for contact recreation of 200 **colony forming units** (CFU) per 100 mL (FIGURE 9.1). This comparison was developed by calculating the long-term geometric mean of the available fecal coliform data from the late 1960s to 1991 and comparing this geometric mean to the 200 CFU per 100 mL standard. (Note that this method does not meet the sampling criteria specified in the *Standards* themselves – in general data were too sparce to conduct such a study.) Over the short term, of course, bacteria levels at any time and place would be determined by the actual events related to contamination.

A second analysis of the same bacteria data is presented in FIGURE 9.2, showing the percentage of samples that exceed the 200 CFU per 100 mL standard for contact recreation and the 14 CFU per 100 mL standard for "oyster waters." None of the segments shown in FIGURE 9.2 have more than a 50 percent exceedence rate relative to the 200 CFU per 100 mL standard for contact recreation. In general, the open waters of Galveston Bay appear to be safe for contact recreation.

Problem Areas for Contact Recreation

In bay tributaries with poor circulation and more numerous surrounding sources of contamination, the picture is somewhat different. The following urbanized bayous on the western side of the bay currently have a Texas Natural Resource Conservation Commission contact recreation designation, but were found by



Source: Jensen, 1992

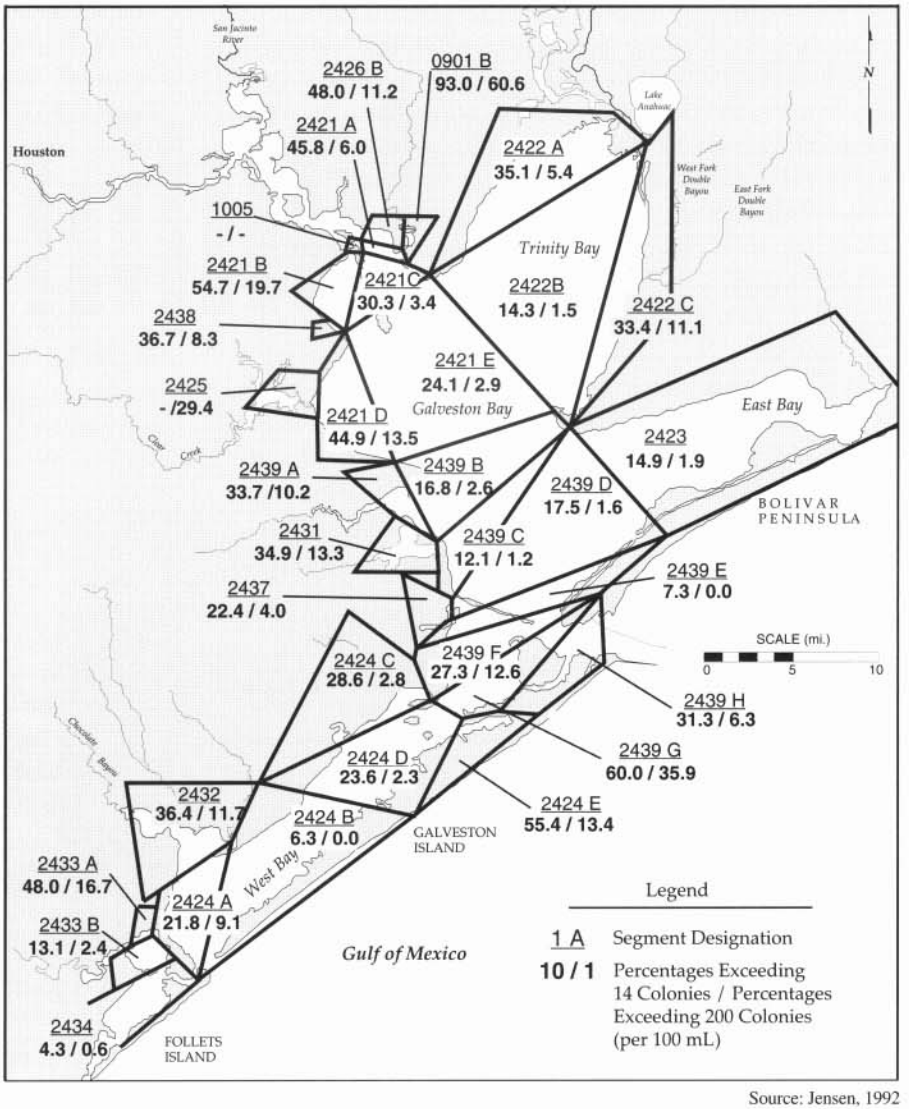
FIGURE 9.1. *Long-term mean fecal coliform bacteria concentrations in Galveston Bay generally show that open-water portions of the bay meet contact recreation standards specified in the Texas Surface Water Quality Standards. Problem areas occur in urbanized tributaries, particularly on the western shoreline. Depiction of these long-term values tends to mask temporary exceedences of bacterial standards, as would occur in some locations following runoff.*

Jensen (1992) to exceed the contact recreation criterion for a 30-year analysis: Cedar Bayou Tidal, Buffalo Bayou Tidal, Clear Creek Tidal, Dickinson Bayou Tidal, Bastrop Bayou Tidal, Sims Bayou, Brays Bayou and Hunting Bayou.

However, this 30-year analysis has limited use in predicting current bacteria levels. Data used to calculate the geometric mean included samples from the 1960s when severe wastewater treatment plant overloading and gross pollution of the areas' urbanized streams was occurring. As shown by Ward and Armstrong (1992) the fecal coliform concentrations in the western tributaries that Jensen analyzed fell significantly during the 1970s and 1980s as waste treatment improved.

Current fecal coliform concentrations are therefore probably lower in many of the western tributaries than the long-term means shown in FIGURES 9.1 and 9.2. Based on more recent monthly sampling performed by the Texas Natural Resource Conservation Commission, the only tidally-affected stream segments that are designated for contact recreation and may not meet the 200 CFU per 100 mL standard are (Galveston Bay National Estuary Program, 1993):

> Buffalo Bayou Tidal (mean of 8,309 CFU per 100 mL),
>
> Clear Creek Tidal (mean of 334 CFU per 100 mL)
>
> Dickinson Bayou Tidal (mean of 445 CFU per 100 mL)



Source: Jensen, 1992

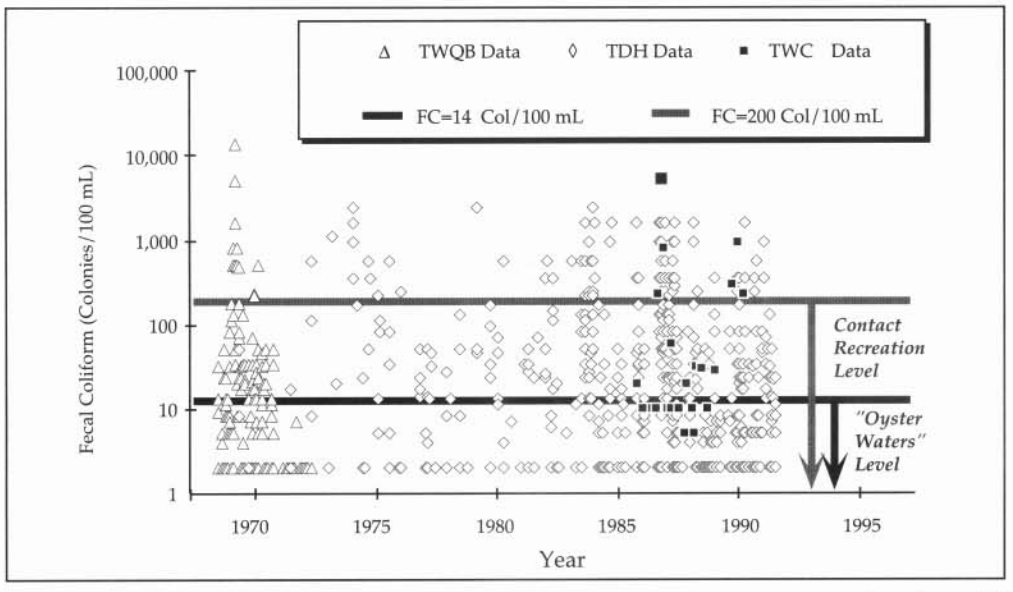
FIGURE 9.2. *Bacteria in relation to oyster and contact recreation criteria. Long-term mean fecal coliform bacteria levels in Galveston Bay are expressed as a percentage exceeding the criteria in* Texas surface Water Quality Standards. *Data indicate few violations in open-water areas on a long-term basis. Temporary higher bacteria levels are generally associated with runoff to the bay.*

The overall trend in fecal coliform bacterial concentrations appears to be one of decline, with much data scatter at specific locations. Ward and Armstrong (1992) showed a generally decreasing trend in fecal coliform concentrations in most of the bay over the past 20 years. Jensen (1992) indicated that despite major population increases in the urban areas of the watershed since the 1960s, no evidence of a systematic increase in fecal coliforms could be identified in Galveston Bay. FIGURE 9.3 illustrates this point with the available fecal coliform data for Galveston Bay near Seabrook for the period 1965 - 1992. Total coliform data collected in the same area from 1958 - 1980 show a similar high variability that obscures possible long-term trends. The improvements in sewage treatment over the last several decades have likely helped to reduce overall bacterial contamination.

In summary, potential contact recreation risks exist in the western tributaries (some with septic tank problems) which still have a moderate potential to infect humans engaged in water-related activities. Some of the more popular areas for contact recreation in the bay are not currently sampled for fecal coliform bacteria. The open bay waters, by contrast, generally have low bacterial concentrations.

Non-Contact Recreation

Non-contact recreational activities in Galveston Bay include such water-based activities as power-boating and sailing. While contact with the water during these activities is limited, some contact may occur. The Texas Department of Health does not have a program regulating non-contact recreation. However, the water quality standards set by the Texas Natural Resource Conservation Commission recognize the limited human health risks associated with non-contact recreation. One designated use under the water quality standards is "non-contact recreation" and, as for contact



Source: Jensen, 1992

FIGURE 9.3. *Fecal coliform bacteria concentrations in Galveston Bay off Seabrook exhibit large variability, caused mainly by rainfall runoff conditions. Trends are not generally discernible for localized areas of the bay like this, but taken over larger areas, coliform bacteria have shown a probable decline. Criteria for "oyster waters" (14 CFU per 100 mL) and for contact recreation (200 CFU per 100 mL) are shown.*

recreation, the criterion for this designation is the fecal coliform test as determined by the membrane filtration test.

The non-contact designation allows ten times greater fecal coliform bacterial concentration than the contact criterion. It is defined as a fecal coliform count less than 2000 CFU per 100 mL of water expressed as a geometric mean based on a minimum of five samples collected over a 30-day period; *and* fecal coliform content exceeding 4000 CFU per 100 mL in no more than ten percent of all samples based on at least five samples taken during any 30-day period; *and* if ten or fewer samples are analyzed, only one sample can exceed 4000 CFU per 100 mL.

All segments designated for contact recreation and oysters waters are also expected to meet the 2000 CFU per mL non-contact recreation criterion. In addition, the following segments are designated for non-contact recreation use: Segment 1005-Houston Ship Channel/San Jacinto River; Segment 2437-Texas City Ship Channel; and Segment 2438-Barbours Cut. The 2000 CFU per 100 mL criterion is also applied to Segment 1006-Houston Ship Channel, and Segment 1007-Houston Ship Channel/Buffalo Bayou.

Jensen (1992) found that the following segments violated the 2000 CFU per 100mL non-contact criterion: Segment 1005 -Houston Ship Channel/San Jacinto River; Segment 1007-Houston Ship Channel/Buffalo Bayou; Segment 1013-Buffalo Bayou Tidal; and Segment 1014-Buffalo Bayou Above Tidal. In addition, Sims Bayou, Brays Bayou and Hunting Bayou exceeded the non-contact recreation criterion. These are all urbanized tributaries with limited circulation surrounded by potential sources of bacteria.

Shellfish Bed Closures

The consumption of oysters, especially raw, can pose a significant health risk, since oysters can concentrate pathogens in their gut as they feed. The Texas Department of Health has a program that restricts the harvesting of oysters to protect the public from this health risk (see box on page 196), while the Texas Natural Resource Conservation Commission carries out a program to maintain water quality in areas designated for shellfish harvest.

Use of Indicator Tests

Fecal coliform bacteria are used in the Texas Department of Health program as an indicator, and the test procedure has evolved over the years. Prior to the late-1970s, the Texas Department of

TEXAS NATURAL RESOURCE CONSERVATION COMMISSION CRITERIA FOR CONTACT RECREATION

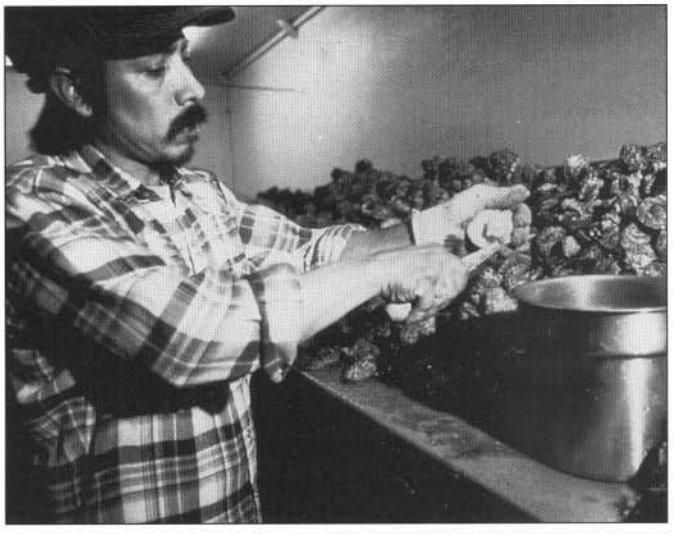
The following criteria are utilized by the Texas Natural Resource Conservation Commission to apply to a designated use of surface waters for contact recreation (Texas Water Commission, 1991):

Less than 200 colony forming units (CFU) per 100 milliliters (mL) of water as a geometric mean based on five samples collected over a 30-day period; and

Less than 400 CFU per 100 mL in more than ten percent of all samples, based on at least five samples, taken during any 30-day period; and

If ten or fewer samples are analyzed, only one sample can exceed 400 CFU per 100 mL.

According to the Texas Surface Water Quality Standards, "a designation of contact recreation is not a guarantee that the water so designated is completely free of disease-causing organisms."



Source: Galveston Bay National Estuary Program

Oysters—delicious seafood and basis of an important bay economy. Their harvest in Galveston Bay is regulated by the Texas Department of Health to reduce the risk of disease to consumers.

Source: Texas Sea Grant College Program

Health used the Total Coliform concentration obtained with the **Most Probable Number** (MPN) test. Subsequently, both total and fecal coliform MPN test data were used by Texas Department of Health until about 1983. Since 1983, only fecal coliform MPN data have been used by Texas Department of Health.

The Texas Natural Resource Conservation Commission does not regulate oyster harvest, but the *Texas Surface Water Quality Standards* maintain an "oyster waters" designation for water quality protection of reefs. Oyster waters are to have a median less than 14 CFU per 100 mL of water, and not more than ten percent of the samples on a per station basis may exceed 43 CFU per 100 mL. The Texas Natural Resource Conservation Commission uses the membrane filtration test method in conjunction with the *Standards* (the *Standards* do not specify the use of MPN or membrane filtration methods). The difference between the membrane filter and MPN tests used by these two agencies have prevented their data from being strictly comparable.

Under the Texas Natural Resource Conservation Commission program, the following segments are designated as "oyster waters:" Segment 2420-Upper Galveston Bay; Segment 2422-Trinity Bay; Segment 2423-East Bay; Segment 2424-West Bay; Segment 2432-Chocolate Bay; Segment 2433-Bastrop Bay; Segment 2434-Christmas Bay; Segment 2435-Drum Bay; and Segment 2439-Lower Galveston Bay. These include essentially all of the open bay and some of the side bays. FIGURE 9.2 shows areas which exceeded the 14 CFU per 100mL criterion for oyster waters (but does not distinguish between areas that are designated for this use and areas which are not). Note that this analysis was based upon long-term

TEXAS DEPARTMENT OF HEALTH CATEGORIES FOR SHELLFISH GROWING AREAS

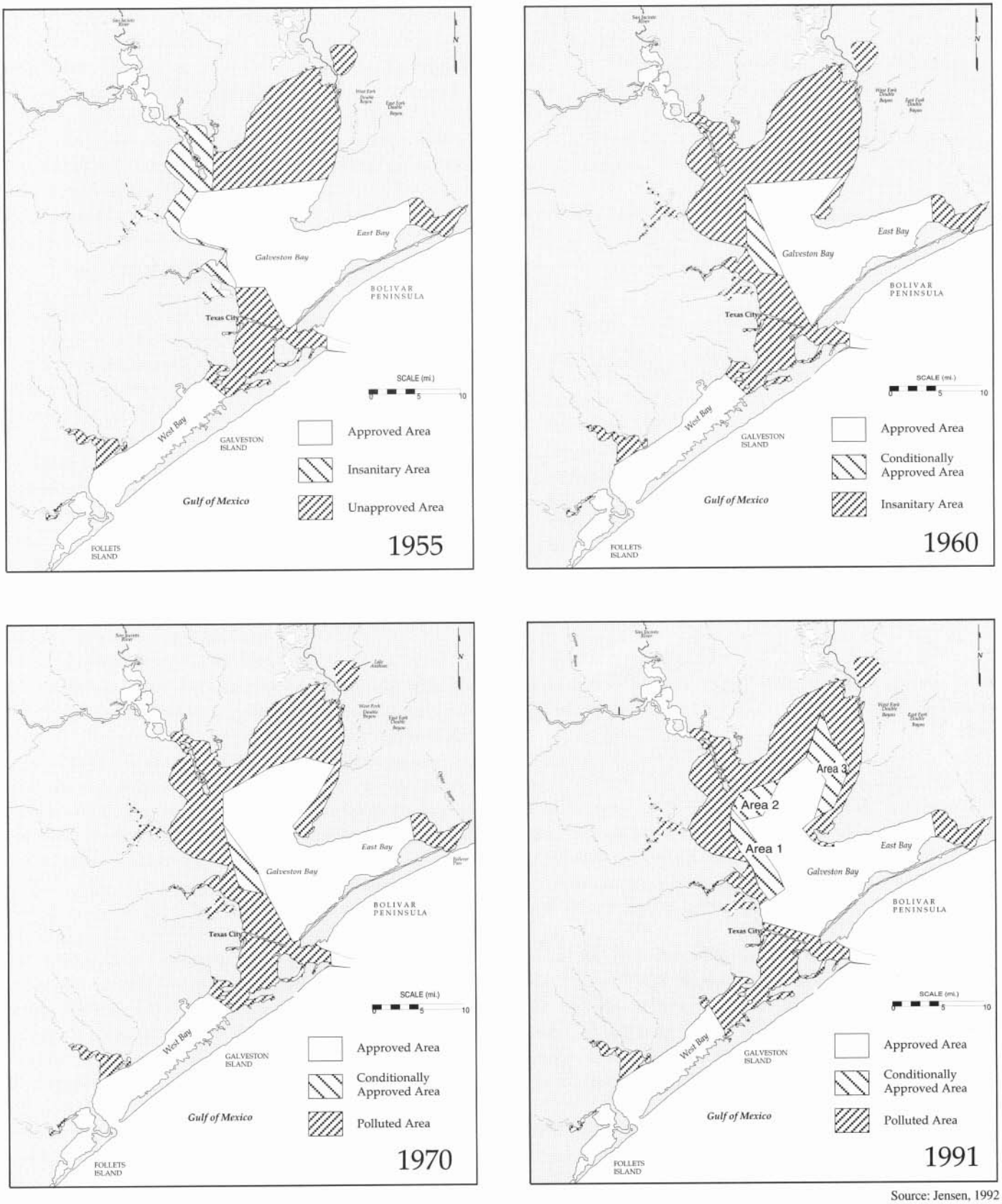
Approved areas lack significant contamination risk from human and/or animal fecal matter and are acceptable for direct market harvesting under all but very unusual situations.

Restricted areas are subject to some limited pollution, as indicated by a sanitary survey, and are unacceptable for harvesting without cleansing of the shellfish before entry into the market.

Conditionally Approved areas are subject to intermittent microbiological pollution which occasionally makes them unacceptable for harvesting– they are closed until conditions once again meet the approved area criteria.

Prohibited areas are small areas immediately surrounding sewage treatment outfalls discharging near the reefs; harvesting is not allowed from prohibited areas for any reason.

Texas law established the term *polluted area*, which is used in the Texas Department of Health orders and maps; however the criteria used by Texas Department of Health are the same as established for *restricted* areas in the National Shellfish Sanitation Program. Use of the term "polluted" applies only to the indicator tests and does not imply that waters are polluted according to common usage of the term.



Source: Jensen, 1992

FIGURE 9.4. *Four maps of shellfish harvest closures covering 36 years reveal that the area of the bay subject to closure has remained about the same over the years, in spite of constant regulatory and biological changes. The approximately 200,000 acres currently subject to closure (about half the bay) includes about 21 percent of the bay's oyster reefs. These maps are produced by the Texas Department of Health as a regulatory tool.*

means (not medians, as required under the *Standards*).

Overall, the fecal coliform test used by the Texas Department of Health has been successful in assuring the good quality of shellfish from Galveston Bay sold for human consumption. However, limitations on the indicator approach discussed earlier in this chapter apply also to its use for oyster harvest regulation. Fecal coliform testing produces many false positive results, and fails to indicate risk from naturally occurring non-intestinal pathogens such as *Vibrio vulnificus*. Therefore, the validity of using only coliforms to regulate shellfish growing areas may be questionable (Jensen, 1992).

TABLE 9.1. Outbreaks of *Vibrio* Diseases Associated with Activities in Galveston Bay.

Age	Sex	County	Organism	Date	Outcome	Exposure	Activity
32	F	Galv.	*vulnificus*	9/83	recovered	water	sex
54	M	Harris	*parahaemolyticus*	6/86	recovered	wound	stepped on sharp object in water
57	M	Harris	*cholerae* non01	7/87	died	wound	pinched by crab
31	F	Wharton	*parahaemolyticus*	9/87	recovered	wound	walking
72	M	Harris	*vulnificus*	10/87	recovered	water	fishing
34	M	Brazoria	*cholerae* non01	8/89	recovered	wound	wade fishing
28	M	Harris	*vulnificus*	4/90	recovered	wound	windsurfing
4	F	Hender.	*vulnificus*	7/90	recovered	water	swimming
67	M	Harris	*vulnificus*	8/90	recovered	wound	fishing
46	M	Harris	*parahaemolyticus*	9/90	recovered	wound	swimming
78	M	Galv.	*parahaemolyticus*	5/91	recovered	wound	fishing
11	M	Galv.	*vulnificus*	8/91	recovered	water	playing in water

Source: Jensen, 1992

Shellfish Closure Trends

Maps are periodically produced by the Texas Department of Health as a regulatory tool to designate shellfish classification in Texas bays. There have been 40 shellfish classification maps issued for Galveston Bay by the Texas Department of Health since classification began in Texas. Four maps covering 36 years are shown in FIGURE 9.4.

Overall, the extent of the bay subject to shellfish harvest closure has remained about the same. However, this does not imply that conditions on the reefs themselves have necessarily remained the same–the maps reflect regulatory policies as well as field measurements. Besides elevated bacterial levels, areas closed over the years have resulted from changes in classification methods, testing procedures, and terminologies.

The history of shellfish sanitation for Galveston Bay illustrates these changes. Most of Trinity Bay, the northern and southwestern parts of Galveston Bay, the eastern part of East and West Bays, and Chocolate Bayou in West Bay were all originally classified as "unapproved oyster areas." In 1955, the unapproved area in Trinity Bay was reduced and the northern and western parts of Galveston Bay were changed to "unsanitary oyster areas" (FIGURE 9.4), causing a significant reduction in the unapproved area. In August of 1958, the unapproved areas in both Trinity Bay and Galveston Bay was once again expanded and the unsanitary area in Galveston Bay was once again labeled unapproved. However, two months later, the unapproved label was changed back to insanitary and the central part of Galveston Bay was reclassified as a conditionally approved oyster area. This classification remained the same in 1960. The 1960 map was changed slightly in 1970; most notable is the reclassification of unsanitary areas to prohibited or polluted areas after a 1969 Texas Department of Health comprehensive sanitary survey.

The most current classifications of Galveston Bay areas were issued by Texas Department of Health on November 1, 1991 (FIGURE 9.4). Portions of the eastern southwestern, western, northwestern, and northern shorelines were classified as "polluted" (see box on page 196 for explanation of this term). As for Trinity Bay, the northern, northeastern, and eastern portions were similarly classified. Also, all areas within a 50 yard radius of recreational cabins located in the bays were closed for shellfish harvesting. There were three areas that were classified as conditionally approved areas. These areas remain subject to classification changes based upon meteorological conditions which influence runoff.

In all, about half the bay's total area (about 200,000 acres) is subject to some form of shellfish harvest restriction by the Texas Department of Health. However, this area does not encompass a like proportion of the bay's economically important reefs; only about 21 percent of the oyster reefs in the bay are classified as prohibited or polluted.

Vibrio

The bacterial genus *Vibrio* contains 11 species which 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 of which is *Vibrio vulnificus*, which can cause rapid and devastating infection in humans. These bacteria cannot be detected with the fecal coliform test, and therefore present a problem. *Vibrio vulnificus* exists naturally, being most common in warm waters with a temperature range of 10° to 30°C and a salinity range of five to 30 ppt – conditions representative of Galveston Bay.

Out of 176 *Vibrio* infections reported statewide between May of 1981 and September of 1991, 68 were reported in counties surrounding Galveston Bay, but only 12 were specifically identified as associated with Galveston Bay (Jensen, 1992; TABLE 9.1).

Contact recreation and food consumption were roughly equal sources of *Vibrio* infection, which accounted for 75 percent of the reported cases. No known regulatory mechanism exists to eliminate *Vibrio* risk; however the risk is small.

No evidence of temporal trend or relationship between *Vibrio* and fecal coliform bacteria data has been identified in Galveston Bay. A study performed in Cow Trap Lake, confirmed this conclusion (Texas Department of Health et al., 1990). Cow Trap Lake was selected because it exhibited elevated fecal coliform levels from non-human sources. Only low levels of pathogens were encountered in the lake, indicating a very low likelihood of transmission of disease from consumption of oysters from the lake. However, the oysters from the study area exceeded National Shellfish Sanitation Program market criterion (230 fecal coliform per 100 grams) in three of the four study phases.

TOXICANTS IN SEAFOOD ORGANISMS

In addition to being a critical type of information needed for reducing human health risks related to seafood consumption, data on concentrations of toxic chemicals in estuarine organisms are important indicators of ecosystem health.

A study by Brooks et al. (1992) provided information on toxic chemicals in finfish, shellfish, and birds in Galveston Bay, including the results of new field sampling. Supplementary information was also available from the National Oceanic and Atmospheric Administration National Status and Trends Study, a nationwide monitoring program for toxic chemicals in oysters and mussels. Oysters are good indicators of the presence of toxic chemicals in the environment because they do not move around, and because they filter large volumes of water and therefore have the potential to concentrate materials from the estuary.

Literally millions of compounds exist which could affect living organisms in an estuarine environment; those described below address several categories most likely to be present.

PAHs–Polynuclear Aromatic Hydrocarbons

PAHs are toxic compounds, some of which are carcinogens, that are "fat-binding" in living organisms and therefore have the potential to accumulate. PAHs are related to petroleum and combustion of petroleum and other organic compounds. Cycloalkanes, branched alkanes, n-alkanes, and aromatic compounds are the predominant hydrocarbons present in petroleum. Major sources in the coastal environment include drilling operations and petroleum production, transportation activities, coastal and/or riverine inputs, and

HYDROCARBON CONTAMINATION OF GALVESTON BAY: A SAMPLING OF STUDIES

Studies conducted from the Houston Ship Channel to San Luis Pass show that PAH concentrations in tissues of organisms in upper Galveston Bay are generally higher than in the lower bay. Total PAHs ranged from 11.0 to 236,000 ng/g (parts per billion), and included fluoranthene, pyrene, benzo(b)fluoranthene, benzo(e)pyrene, benzo(a)pyrene, chrysene, phenanthrene, and 1-methyl phenanthrene.

Oysters from polluted and unpolluted sites were analyzed between 1969 and 1971 (Fazio, 1971). Total PAHs ranged from 11 to 237 ng/g. Highest PAHs in tissues from contaminated sites were fluoranthene (7.8 ng/g), pyrene (6.5 ng/g), benzo(b)fluoranthene (2.2 ng/g), benzo(e)pyrene (2.1 ng/g).

Oysters collected in the late 1970s near Morgans Point, near the entrance of the Houston Ship Channel, had concentrations of benzo(a)pyrene from 0.07 to 0.14 ng/g (Murray et al., 1980). Oysters collected near San Luis Pass in the study did not have detectable concentrations of benzo(a)pyrene.

Oysters from Morgans Point, contained a total of 236,000 ng/g hydrocarbons (Ehrhardt, 1972). Concentrations of aromatic hydrocarbons were higher than those of alkanes.

Another oyster study from Morgans Point (Anderson, 1975) reported concentrations of 160,000 ng/g total hydrocarbons. Oysters collected a few miles away from the Houston Ship Channel had lower concentrations (26,000 ng/g), while oysters collected in West and East Bays had less than 2,000 ng/g of total hydrocarbons in their tissues.

Oysters collected from Galveston Bay from 1976 - 1978 as part of a nationwide study (Farrington et al., 1980) contained 940 ng/g fluoranthene and 1,010 ng/g pyrene.

A 1988 study (Fox, 1988) reported that total PAHs were higher at sites located closer to urban areas. Oysters collected near the Houston Yacht Club (615 ng/g) and Confederate Reef near the City of Galveston (610 ng/g), had annual average concentrations that were higher than samples collected from Todd's Dump (134 ng/g) located in the middle of Galveston Bay, and Hanna Reef in East Bay (111 ng/g). Pyrene, fluoranthene, chrysene, phenanthrene, and 1-methyl phenanthrene were the most frequently detected PAHs.

combustion of all forms of fossil fuels, including atmospheric fallout of the combustion products. PAHs are also introduced into the environment from some organic chemical reactions, and fires–both natural and from waste incinerators or other combustion sources. Because of the persistent and "fat-binding" nature of PAHs, it is not surprising that they have been frequently detected as a widespread (as opposed to localized) pollutant.

Brooks et al. (1992) conducted a survey of five species of seafood organisms from four locations in the bay (see FIGURE 9.5 and the section on seafood risk page 202). The study analyzed for 24 individual PAHs and revealed total PAHs ranging from nondetectable to 1253 ng/g (parts per billion). Oysters had higher total PAH concentrations than fish (all four sites) and crabs (all except Hannah Reef). 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 oysters to be among the highest 25 percent throughout the Gulf of Mexico.

The Brooks study also revealed some information about the origin of PAHs. Alkylated PAHs were low at all sites when compared to total PAHs (except at Eagle Point), indicating a combustion source. Alkylated and high molecular weight PAHs in fish from Eagle Point probably resulted from the *Apex* barge oil spill of 1990.

A total of more than ten additional studies of oysters, fish, and birds from Galveston Bay generally indicated that PAH concentrations in tissues of these organisms were higher in upper Galveston Bay than in the lower bay (see box on page 199). For example, a 1987 study (King et al., 1987) reported on double-crested cormorants, a fish-eating waterbird near the top of the food web which winters on the upper Houston Ship Channel. At the beginning of the wintering season, birds contained only naphthalene and fluoranthene. At the end of the wintering season, birds contained eight aromatic hydrocarbons.

Results of the National Status and Trends Study (findings summarized in Brooks et al. 1992) show that PAHs measured in oysters from upper Galveston Bay and near the City of Galveston were ten to one hundred times higher in concentration than for non-urban portions of the bay. Overall concentrations ranged from 54 to 2,400 ng/g. Of interest, the prevalence of two particular PAHs (pyrene and fluoranthene) suggested that the major source of PAHs in the Galveston Bay area was combustion products.

Chlorinated Hydrocarbons

Most attention to this class of toxic compounds has been focused on pesticides and PCBs (polychlorinated biphenyls). Pesticides include DDT (and related degradation compounds DDD and DDE); aldrin (which degrades to dieldrin); and heptachlor (which degrades to heptachlor epoxide, endrin, and lindane). The use 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.

The study by Brooks et al. (1992) analyzed for a suite of chlorinated hydrocarbons and PCBs, including total BHCs, total chlordane, dieldrin, total DDTs, and total PCBs. The findings from this project are given in TABLE 9.2.

Other studies also reveal that, in spite of the current bans, a variety of organochlorine residues exist in Galveston Bay organisms and sediment and water samples. About 12 different studies on chlorinated hydrocarbons in organisms from Galveston Bay have been conducted (see box on page 201), with a good review provided in Brooks, et al. (1992). Compounds most commonly found were PCBs, DDT metabolites, and occasionally, dieldrin, HCB and chlordane. Of these, PCBs are perhaps of most concern, due to the results of the Galveston Bay National Estuary Program seafood risk analysis study, also reported in this chapter.

Dioxin and Furans

These compounds (polychlorinated dibenzo-p-dioxins and

TABLE 9.2. Chlorinated Hydrocarbons in Oyster, Crab, and Fish Tissue from Four Sites in Galveston Bay.

Compound	Findings
BHCs	Higher in oysters than crabs or fish tissue; highest in fish livers. Highest at Morgans Point (8.85 ng/g); similar at Eagle Point, Hanna Reef, and Carancahua Reef. Levels for oysters within range reported by National Status and Trends Program.
Chlordane	Similar in fish, crabs, and oysters; higher in fish livers. Highest at Morgans Point (58 ng/g) and decreased down-bay. Levels for oysters within range reported by National Status and Trends Program.
DDT	Similar in fish, crabs, and oysters; higher in fish livers. Highest at Morgans Point (average 87 ng/g) and decreased down-bay. Levels for oysters within range reported by National Status and Trends Program (which found DDT in Galveston Bay oysters among the highest 25 percent of concentrations Gulf-wide).
Dieldrin	Similar in fish and oysters; lower in crabs; highest in fish livers. No down-bay decreasing trend (range two to 11 ng/g). Levels for oysters within range reported by National Status and Trends Program .
PCBs	Similar in oyster and fish, slightly higher in crabs; much higher in fish liver. Decrease from Morgans Point down-bay (range 176–612 ng/g). Levels for oysters within range reported by National Status and Trends Program.

Source: Brooks et al., 1992

polychlorinated dibenzofurans) are extremely persistent in the environment, and can affect human health at low concentrations. As a result of dioxin found in seafood organism tissue in Galveston Bay, a seafood consumption advisory for catfish and blue crabs was issued by the Texas Department of Health in September, 1990 for a portion of the upper bay system. Under the advisory, no one should consume more than one seafood meal (not to exceed eight ounces) each month from this area; and women of child-bearing age and children should not consume *any* catfish or blue crabs from this area. The sea catfish to which the advisory applied is not generally consumed.

One study in the late 1980s reported concentrations of 54.8 pg/g (parts per trillion) dioxin in blue crabs and 3.2 pg/g in blue catfish collected at the San Jacinto Monument. Further downstream at Morgans Point, concentrations were 14.8 pg/g in sea catfish and 6.2 pg/g in oysters. A follow-up study was conducted in 1990, finding up to 3.97 pg/g in crabs, oysters, and red drum in upper Galveston Bay.

Trace Metals

Metals in Galveston Bay organisms rarely differ substantially from levels noted for other Gulf of Mexico estuaries. For example, the average concentrations of cadmium, chromium, copper, manganese, and lead in oysters collected from six different sites under the National Status and Trends Program differed by ten percent or less from the Gulf-wide average. Silver was 23 percent higher, nickel 16 percent higher, and selenium was 14 percent higher than the Gulf-wide averages. (Apparently, the Galveston Bay oysters exceeded the Gulf-wide average because of low selenium oysters taken in Mississippi and Florida). Oysters from other Texas and Louisiana bays are also similar in arsenic and mercury content to those in Galveston Bay. Zinc, however, was 35 percent higher in Galveston Bay oysters than the Gulf-wide average. Concentrations of zinc in oysters showed a clear correlation with human activities, whereas other metals did not.

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

SOME STUDIES OF CHLORINATED HYDROCARBONS IN GALVESTON BAY

These toxic compounds, mainly persistent pesticides, tend to accumulate through the food chain to high levels. Their persistence has resulted in their continued presence in Galveston Bay, even though many are out of general use due to product bans enacted as their ecosystem effects became widely known beginning in the late 1960s.

Tests on oysters collected 1965 - 1972 (Butler, 1973) determined that DDT residues were the most commonly detected organochlorines. Overall averages for DDT in oysters were 6.16 ng/g for oysters from Trinity Bay, and 23.9 ng/g for those from Galveston Bay. Dieldrin was the second most frequently encountered chlorinated pesticide–oysters averaged 14.5 ng/g, while the average for oysters from Trinity Bay was lower (2.86 ng/g). Similar concentrations of dieldrin were reported for clams from Trinity Bay in 1975.

Oysters collected at four sites scattered throughout the bay contained detectable concentrations of PCBs, DDT residues, dieldrin, transnonachlor, alpha-chlordane, and heptachlor epoxide. Oysters from the Houston Yacht Club reef, in upper Galveston Bay, had higher concentrations of organochlorides than oysters from the other sites (Hanna Reef, Todd's Dump, and Confederate Reef). HCB and PCP (two other chlorinated hydrocarbons) have also been found in oysters from Galveston Bay at Morgans Point.

A fish tissue study conducted during the mid-1970s (Strawn et al., 1977) found PCB concentrations of 50 - 500 ng/g in mullet, croaker, and Florida pompano collected in Trinity Bay. Lower concentrations were found in juvenile croakers (nine to 43 ng/g).

Studies in the late 1980s (King, 1989a; 1989b) found significant concentrations of chlorinated hydrocarbons in fish that are food items for two birds that use Galveston Bay: black skimmer and olivaceous cormorant. These fish were tidewater silverside, sheepshead minnow and striped mullet.

Other studies were conducted in the mid- to late 1980s on chlorinated pesticides in tissues of waterbirds nesting in upper Galveston Bay, including olivaceous and double-crested cormorants, laughing gulls, and black skimmers (King and Krynitsky, 1986; King et al., 1987). PCB concentrations ranged from 930 to 4,430 ng/g, and dieldrin concentrations ranged from 100 - 160 ng/g. These concentrations are one to two orders of magnitude higher than those in fish. Since these fish-eating birds are at the top of the aquatic food chain, bioaccumulation of organic contaminants is expected. Chlordane, HCB, and heptachlor epoxide were also found to be present in waterbird tissues.

Source: Galveston Bay National Estuary Program

Seafood in the raw. Dumped on the deck of a shrimp trawler, the crabs, shrimp, and fish of Galveston Bay illustrate the basis for a thriving seafood economy. The risk associated with eating any seafood item from the bay can be estimated, but the decision about what to eat can only be made by the individual consumer.

zinc were lower in the study by Brooks et al., and did not correlate with urban and industrial areas, as determined in the National Status and Trends work. In general, Brooks et al. found no strong relationship between metals in fish flesh and proximity to industrialization (or any other geographical trend). Tissue concentration ranges determined by Brooks et al. were: silver 0.09–0.14 µg/g; arsenic 0.45–0.89 µg/g; cadmium 0.168–0.310 µg/g; chromium 0.022–0.211 µg/g; copper 9.888–33.819 µg/g; mercury 0.079–0.123 µg/g; nickel 0.04–0.20 µg/g; lead 0.04–0.06 µg/g; selenium 0.88–2.27 µg/g; and zinc 68.7–115.2 µg/g.

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. Tissues were analyzed for arsenic, antimony, chromium, copper, cyanide, selenium, silver, and zinc. Concentrations of arsenic ranged from 0.25 to 4.2 mg/kg, antimony ranged from 3.3 to 4.2 mg/kg, chromium ranged from 0.48 to 12 mg/kg, copper ranged from 0.48 to ten mg/kg, cyanide from <0.51 to 1.9 mg/kg, selenium from 0.61 to 14 mg/kg, silver from 0.48 to 1.5 mg/kg and zinc from 4.8 to 51 mg/kg. Antimony, arsenic and selenium concentrations exceeded Environmental Protection Agency fish tissue criteria, while chromium, copper, cyanide, silver, and zinc concentrations were below the Environmental Protection Agency criteria.

Arsenic and mercury in Galveston Bay oysters collected under the National Status and Trends Program were less than one-half the Gulf-wide average but the Gulf-wide averages are greatly affected by several sites in Florida that produce oysters greatly enriched in arsenic and mercury, and by a site in Lavaca Bay which is enriched in mercury. Oysters from other Texas and Louisiana bays are similar in arsenic and mercury content to those in Galveston Bay.

HUMAN HEALTH RISKS ASSOCIATED WITH SEAFOOD CONSUMPTION

Seafood from Galveston Bay is quite popular. Texas A&M figures from several recent studies indicate that Galveston Bay seafood landings account for more than 30 percent of the state-wide bay system total (Brooks et al., 1992), and more than 65 percent for oysters (Haby et al., 1989). Yet the question is asked again and again, "is it safe to eat?"

Generally, but not always, the answer is "yes." 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. But this issue requires some qualification, presented in this section. Seafood from the bay contains generally low but variable concentrations of toxic chemicals that can represent health risks of some concern under certain conditions.

Seafood Advisories

Two **seafood advisories** (see box below) have recently been issued for the Galveston Bay system. The first was based upon dioxin contamination in a limited area of the upper bay. The Texas Department of Health 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 (rarely consumed anyway) or blue crabs from this area. The advisory was issued because of low levels of dioxin found in samples of these two species, 3.2 parts per trillion to 14.8 parts per trillion. Samples of other species did not show levels of dioxin above the low levels which trigger an advisory under risk assessment protocols (Thompson, 1993a). This advisory was conservative in the sense that most of the data on tissue concentrations of dioxin were below the Environmental Protection Agency screening level, and none of the samples exceeded the Federal Drug Administration guidelines for issuing a warning.

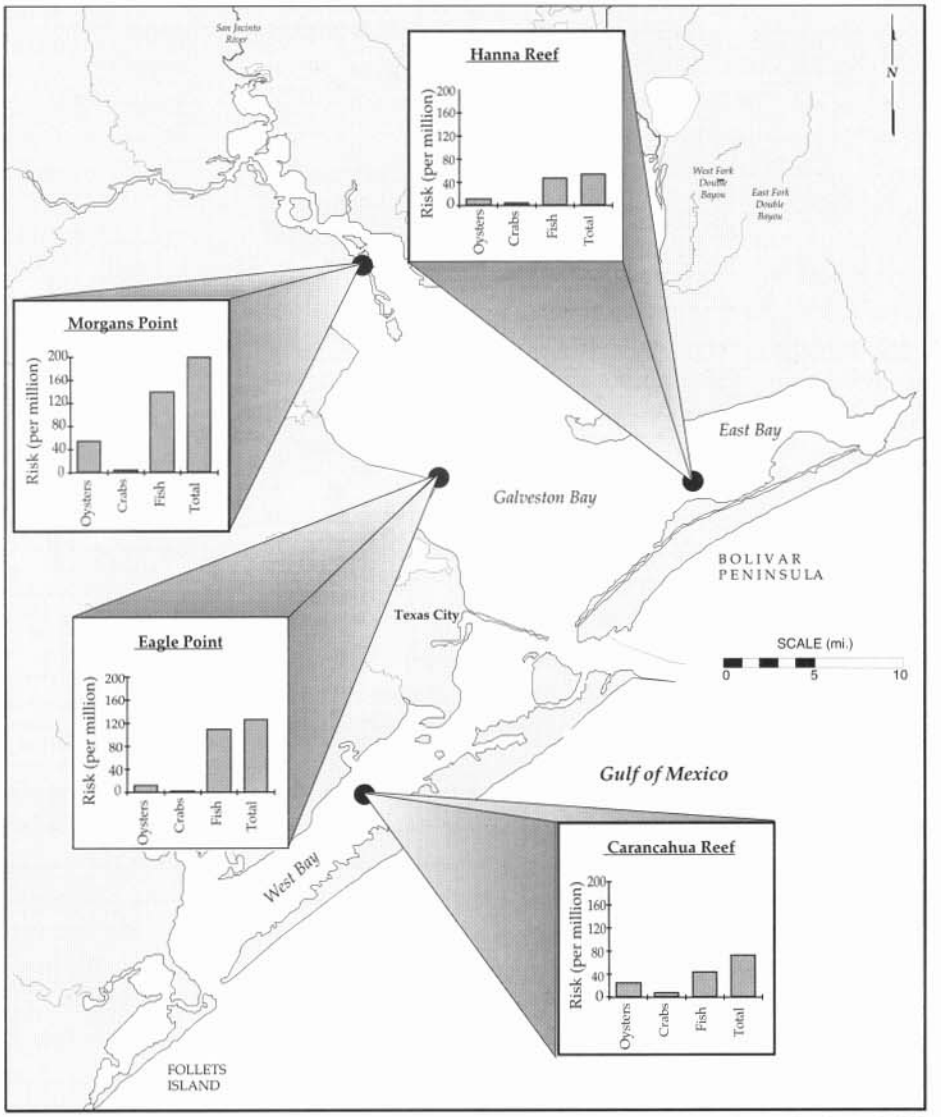
The second advisory was based on three toxic compounds

TEXAS DEPARTMENT OF HEALTH SEAFOOD ADVISORIES

Seafood consumption advisories or area closures are issued by Texas Department of Health 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 based on information provided. 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.

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, included dichloroethane and trichloroethane–both of which are believed to cause cancers of the liver and kidneys–and carbon disulfide, which can cause nervous disorders (Texas Department of Health, 1993). The contaminated fish were found in the vicinity of the former Brio Refining Company, a U. S. Environmental Protection Agency Superfund site where a cleanup of toxic industrial compounds is in the early stages.

Consumption advisories serve to protect seafood consumers. However, one shortcoming in the current regulatory system is a lack of routine tissue monitoring to determine risks. Therefore, a study was carried out by Texas A&M University to sample Galveston Bay seafood organisms from widely scattered locations, and estimate the potential risk to consumers. Contaminant concentrations in these seafood samples were reported above; below are reported the results of risk estimation. The risk estimates resulting from this study exceeded a benchmark used by EPA Region 6 to flag possible problems, for consumers of large amounts of seafood from the upper bay.



Source: Brooks et al., 1992

FIGURE 9.5. *Lifetime carcinogenic risks from eating Galveston Bay seafood from the locations indicated. The graphs show expected cases of cancer attibuted to toxic contaminants in oysters, crabs, and fish from these locations. For a perspective on the significance of these findings, see TABLE 9.7.*

The Galveston Bay National Estuary Program/Texas A&M Seafood Study

This project was a screening survey of Galveston Bay seafood organisms, designed to determine contaminant concentrations and potential risk to seafood consumers (Brooks et al., 1992). The sampling design called for the analysis of contaminants in five species of seafood organisms from four sites (TABLE 9.3; FIGURE 9.5.) Heavy metals, hydrocarbons, pesticides, and PCBs were measured in oysters, blue crabs, spotted seatrout, black drum, and southern flounder. Edible portions of the seafood were of greatest interest, but some analyses were conducted for fish livers, where metabolism and a high lipid content tend to concentrate contaminants.

The project relied on sensitive analytical methods that can discriminate trace amounts of specific contaminants. Based on contaminant levels found in the seafood organisms, risk to consumers was estimated using a scientific procedure to determine the probability of adverse health effects from eating seafood contaminated with the toxic agents of concern. The chief goal was to characterize the types of hazards associated with the contaminants and to estimate the probability that those hazards could affect exposed populations or individuals. The risk assessments calculated for this study closely follow guidelines of the Environmental Protection Agency.

The 15.0 g/d (grams per day) *average* total seafood consumption rate assumed for the study was partitioned into fish (12.3 g/d), oysters (1.6 g/d) and crabs (1.1 g/d) based on data from Puget Sound (Tetra Tech, 1988) and Texas seafood statistics (Quast et al., 1989). The *high* seafood consumption rate used in the study was based on consumption estimates for the top five percent of consumers (TABLE 9.4). It should be noted that the Environmental Protection Agency uses a value of 6.5 g/d as an average consumption rate. The Environmental Protection Agency figure is derived from a national average for seafood consumption while Brooks' consumption figure of 15.0 g/d was intended to more accurately reflect local seafood consumption rates.

It is important to note that risk assessment is a controversial

and evolving field (see box on page 205 for a discussions of some of the specific limitations and assumptions). Risk estimates rely on statistical averages for an entire population; the more an individual differs from the average the less they apply. These estimates also have considerable uncertainty. They depend upon experimental and epidemiological information about hazardous properties of chemicals, combined with information concerning the magnitude of human exposure to these chemicals. Some researchers have suggested that the risk assessment procedures in use today for chemical contaminants are so conservative that they may be invalid (Ames et al., 1987; Lehr, 1990), implying that the vast majority of seafood from Galveston is safe to eat (Thompson, 1993b).

In spite of their controversial nature, risk assessment studies provide us with the only method we have to assess the safety of different activities like consuming seafood. "Safety" is a relative term referring to an activity with acceptably low risk–but "acceptably low" to one person may not be to another. Therefore, the significance of risk can only be determined by each individual, reviewing the best information available, and comparing one kind of personal risk to another. An understanding of risk is also necessary to determine how safety can be increased by addressing the sources of contaminants.

Two types of risks were evaluated in the Galveston Bay National Estuary Program/Texas A&M study: cancer risks and non-cancer risks. Cancer risk (primarily from organic toxicants) is expressed as the probability for a 154-lb human to contract cancer as a result of eating the assumed amount of seafood over a 70-year lifetime. For example, risk expressed as 7.4×10^{-5} (the cumulative risk associated with seafood from Carancahua Reef) equates to one person in 740,000 contracting cancer as a result of eating the seafood. The non-cancer health hazard (primarily from trace metals) is expressed as a ratio of the dose of contaminants from the seafood portion to a "reference dose" established as a threshold for human health concern. A value of greater than one represents a potential concern.

TABLE 9.3. Categories of Compounds Potentially Contributing to Risk to Consumers of Galveston Bay Seafood, Based on Preliminary Risk Estimates.

Priority	Toxic Class	Chemical or Compound Group
High	Carcinogens	Arsenic
		Polycyclic Aromatic Hydrocarbons (PAHs): anthracene; thioanthene; pyrene; benzo(a)pyrene; benzo(b)fluoranthene; chrysene; benzo(k)fluoranthene
		Polychlorinated Biphenyls (PCB)
		DDT and derivatives (DDD and DDE)
	Noncarcinogens	Cadmium, Lead, Phenanthrene
Medium	Carcinogens	Benzene hexachloride (BHC)
		Chlordane
		Dieldrin
	Noncarcinogens	Mercury, Copper
Low	Carcinogens	
	Noncarcinogens	Antimony, Chromium, Nickel, Selenium, Silver, Zinc

Source: Brooks et al., 1992

Seafood Consumption Risk Findings

For cancer risk, consumers eating *average* amounts of seafood from some locations in Galveston Bay (15 g/day, or about a pound per month) were at risk above a benchmark level of 1×10^{-4} (one in 10,000) previously used by the Environmental Protection Agency to flag possible problems (equal to 100 extra cancer deaths per million people). The risk from oysters at Morgans point and fish at Morgans and Eagle Points was estimated to be higher than risk from oysters or fish from other locations (TABLE 9.5 and FIGURE 9.5). These risks were higher in the upper Bay, where effects from the upper Houston Ship Channel and the Trinity River would be expected (see FIGURE 9.5). In comparison to average levels of seafood consumption, the person who consumes *large quantities* of seafood (147.3 g/day or about ten pounds per month) would exceed the Environmental Protection Agency benchmark risk at all sites examined in the study.

TABLE 9.4. Average and High (95th Percentile) Consumption Rates for Fish, Crabs and Oysters Used in Risk Assessment Calculations.

Seafood Category	Average Value	High Exposure Value
Fish	12.3 g/day	94.5 g/day
Oysters	1.6 g/day	31.3 g/day
Crabs	1.1 g/day	21.5 g/day
Total	**15.0 g/day**	**147.3 g/day**

Source: Brooks et al, 1992

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 products (such as engines, burning, etc.) that were not directly associated with release of oil to the bay (Brooks et al., 1992).

The Galveston Bay National Estuary Program study did not include dioxin, due to the costs of dioxin analysis. However, a previous Environmental Protection Agency study (Crocker and Young, 1990) addressed tetrachlorodibenzo-p-dioxins and -dibenzofurans (dioxins and furans) at sites in Arkansas, Louisiana and Texas. They estimated a risk level for 2,3,7,8-tetrachlorodibenzo-p-dioxin of 2.14×10^{-4} for sea catfish at Morgans Point, 4.6

RISK ASSESSMENT IN THE GALVESTON BAY STUDY: SOME LIMITATIONS

Determining the concentration of a chemical in edible portions of seafood

Sources of uncertainty in the tissue analyses included:

> Organisms were collected during an unusual flood, possibly affecting "normal" fish distribution and contaminant levels;
>
> Sampling took place over a several month period, and included some alternates species when sampling success was poor; and
>
> Sampling coincided with the Apex barge spill–some tissue samples clearly showed petroleum compounds related to the spill.

Choosing assumptions for average seafood consumption rates

> For the entire consumer population: 15 g/day (about a pound per month) for marine seafood corresponding to the amount cited in the *Texas Surface Water Quality Standards.*
>
> For high-amount consumers: 147.3 g/day (about ten pounds per month), corresponding to the top five percent of consumers (including subsistence fishermen).

Determining how much of the chemical is absorbed from seafood eaten

> All the chemical present in edible portions was assumed to be absorbed by the consumer. In reality, preparation, cooking, and digestive efficiency would tend to reduce the effective dose.
>
> The study also assumes that the average consumer will get all of their seafood from Galveston Bay and will eat this seafood every day for 70 years. In reality, we get seafood from many different bays and oceans, and many people do not eat seafood from this area for a total of 70 years.

Determining average consumer weight

The project assumed 70 kg (154 lb) based on standard Environmental Protection Agency methods. Generally, a smaller person would be more susceptible to a given chemical dose.

Determining cancer-causing potency

The project used the most sensitive five percent of the general population to the given chemical. Dose-response relationships upon which these assumptions were based have other elements of uncertainty:

> Potency information is sometimes derived from animals studies, which may react differently from humans. For example, it takes 5,000 times the dose of dioxin that is lethal to a guinea pig to have the same effect on a hamster (Tschirley, 1986).
>
> Other potency information is derived from knowledge about similar chemicals.

Adding the effects from multiple chemicals

The risk from different compounds were added together in this study to yield a cumulative risk. However, some researchers question the assumption that potential carcinogenic effects of multiple chemicals are additive. For example, the Environmental Protection Agency's Science Advisory Board recently recommended that the risk from potential carcinogens should be considered additive only when it is demonstrated that they have the same mechanisms of action and the same receptor organ. This would have the effect of reducing the risk estimates produced by the Galveston Bay National Estuary Program/Texas A&M study. On the other hand, not all compounds were included in the study, for example dioxin (known to be present in the upper estuary) was not included because of analytical expense and the existence of previous studies. Including additional compounds would tend to increase the estimates of risk.

x 10^{-5} for blue catfish at San Jacinto Monument, 8.8 x 10^{-5} for oysters at Morgan's Point, and 7.93 x 10^{-4} for blue crabs at San Jacinto Monument.

The Environmental Protection Agency study assumed a consumption rate of 6.5 g/d, while the Galveston Bay National Estuary Program study assumed consumption rates of 15 g/d for the average consumer and 147.3 g/d for high seafood consumers. Thus, the two studies are not directly comparable, but added together, would yield an estimate higher than those presented in this chapter. Calculating an average of the four Environmental Protection Agency risk estimates, and adding this to the estimates for risk to average and high consumers of seafood from Morgans Point (Brooks et al., 1992), yields estimates of 3 X 10^{-4} for average consumers and 2.6 X 10^{-3} for high consumers. This estimate includes consideration of arsenic, PAHs, BHC, total chlordane, dieldrin, total DDTs, total PCBs, and dioxins and furans.

For non-cancer risk, Brooks et al. indicated no exceedences of health-based standards at average seafood consumption rates, but some exceedences for high seafood consumption rates, primarily related to oysters (TABLE 9.6). There were no significant differ-

TABLE 9.5. Carcinogenic Risk Estimates for Galveston Bay Seafood from Four Different Areas of the Bay.

Site	Fish Consumption Rate		Oysters Consumption Rate		Crabs Consumption Rate	
	Average	High	Average	High	Average	High
Hanna Reef	4.1×10^{-5}	3.1×10^{-4}	9.5×10^{-6}	1.9×10^{-4}	3.6×10^{-6}	7.0×10^{-5}
Morgans Point	1.4×10^{-4}	1.0×10^{-3}	5.5×10^{-5}	1.3×10^{-3}	4.9×10^{-6}	9.6×10^{-5}
Eagle Point	1.1×10^{-4}	8.2×10^{-4}	1.3×10^{-5}	2.5×10^{-4}	2.7×10^{-6}	5.3×10^{-5}
Carancahua Reef	4.3×10^{-5}	3.3×10^{-4}	2.5×10^{-5}	4.8×10^{-4}	6.5×10^{-6}	1.3×10^{-4}

Source: Brooks et al., 1992

TABLE 9.6. Non-Carcinogenic Risk Index Estimates for Galveston Bay Seafood from Four Different Areas of the Bay.

Site	Fish Consumption Rate		Oysters Consumption Rate		Crabs Consumption Rate	
	Average	High	Average	High	Average	High
Hanna Reef	0.10	0.79	0.10	1.95	0.01	0.21
Morgans Point	0.11	0.84	0.14	2.76	0.02	0.30
Eagle Point	0.11	0.82	0.12	2.35	0.01	0.24
Carancahua Reef	0.10	0.77	0.17	3.31	0.03	0.50

Source: Brooks et al., 1992

TABLE 9.7. Cumulative Risk Estimates[1] for Chemicals of Concern Measured in Fish, Crabs, and Oysters from Galveston Bay.

Site	Non-Carcinogenic Risk Index Values[2]		Carcinogenic Risk Values[3]	
	Average Consumption	High Consumption	Average Consumption	High Consumption
Hanna Reef	0.21	**2.95**	5.4×10^{-5}	**5.7×10^{-4}**
Morgans Point	0.27	**3.90**	2.0×10^{-5}	**2.3×10^{-3}**
Eagle Point	0.24	**3.41**	**1.3×10^{-4}**	**1.1×10^{-3}**
Carancahua Reef	0.24	**4.58**	7.4×10^{-5}	**9.4×10^{-4}**

Source: Brooks et al. 1992

[1]Multiple chemical exposure via multiple categories of seafood for the chemicals measured in this study. Any risk from dioxins should be added to these values to give a total cumulative risk.

[2]All trace metals except arsenic were evaluated.

[3]Chemicals evaluated were arsenic PAHs BHC, chlordane, dieldrin, DDT and its derivatives, and total PCBs

BOLD means risk estimate exceeds EPA benchmark level

ences in the non-carcinogenic risk level between any of the locations for fish, oysters or crabs. While the level of chemical contaminants in oysters was higher than fish, the average lifetime risk was about the same because the amount of fish consumed was assumed to be higher. TABLE 9.7 summarizes both cancer and non-cancer risks for all four locations.

What do the risk levels mean? To place them in perspective, consider that approximately 25 percent of all people contract cancer. Performing some activity at the 1×10^{-4} benchmark risk level will increase the overall probability that one contracts cancer from 0.2500 (25 percent) to 0.2501 (infinitesimally higher). In other words, we are subject to lots of cancer risk anyway. TABLE 9.8 (adapted from Wilson, 1979; Crouch and Wilson, 1982; Lehr, 1990) provides some examples of common activities and the associated cancer risks, including consumption of Galveston Bay seafood.

SUMMARY

Open-water portions of Galveston Bay generally conform to Texas water quality criteria for contact recreation. Areas where recent fecal coliform bacteria levels exceeded the state standard are in western, developed tributaries of the bay: Buffalo Bayou Tidal, Clear Creek Tidal, and Dickinson Bayou Tidal. In some of these areas, contact recreation is common and unregulated. Bacteria data show no increasing trend that could be associated with human activities in the watershed.

Source: Texas Sea Grant College Program

Galveston Bay's finest. Future comprehensive management of Galveston Bay can assure we maintain the ecological and human life support capacity of this premier estuary.

While many regulatory changes have taken place over the years in shellfish harvesting regulation, the area of the bay subject to shellfish closure has remained about the same for four decades. Wet weather runoff appears to be the most significant source of bacteria, but concentrations in the open bay tend to be localized and of short duration. For example, many of the conditionally approved areas for oyster harvesting are reopened within a few days after heavy rain events. Many of the shellfish closures result from either a small portion of the data exceeding higher values, generally after rains, or a judgment made about the potential for upland facilities to introduce pathogens.

As a water quality and public health indicator, the fecal coliform test currently being used has significant limitations. While it has a long history of protecting public health, limitations result from the frequent presence of naturally occurring bacteria which "pass" the test and lack of a good correlation with both true pathogens from animal wastes and with naturally occurring pathogens, particularly *Vibrio*.

No total prohibitions on seafood consumption due to toxic contamination currently exist in Galveston Bay. However, a seafood consumption advisory for catfish and crabs was issued by the Texas Department of Health in September 1990 for the upper bay system and upper Houston Ship Channel as a result of dioxin measured in these species. A second advisory was issued in late 1993 for all fish from Clear Creek, as a result of several industrial chemicals found in fish tissue. Currently lacking for the Galveston Bay system is a routine seafood testing and risk assessment program that would effectively identify health issues.

A one-time risk assessment study of seafood organisms from four locations in the bay indicated that the upper bay system (Morgans Point) was the most contaminated site, with contamination generally decreasing down-bay. The risk associated with consumption of average amounts of seafood sometimes exceeded a benchmark risk level used by EPA Region 6 to flag possible problems. For high–consumption populations, risk exceeded the benchmark at all locations. PAHs and PCBs appear to be responsible for most of the carcinogenic risk associated with consumption of Galveston Bay seafood, with oysters the most contaminated species and crabs the least.

In reality, science cannot currently determine the true risk to bay users or seafood consumers resulting from contamination–either by bacteria or by toxic materials. Decisions about individual risk remain with the individual, with risk estimates available as one source of information.

TABLE 9.8. Comparative Risks Associated with Various Activities.

Activity	Risk Level	Additional Cancer Deaths per Million People Doing Activity	Source of Risk
One Chest X-Ray	1.0×10^{-6}	1	Cancer by Radiation
Eating Galveston Bay Seafood Every Day for 70 yrs. (Average Consumption)	**7.0×10^{-5}**	**70**	**Cancer from PCBs, PAHs**
Eating Four Tablespoons of Peanut Butter Every Day for 70 Years	5.6×10^{-4}	560	Cancer from Aflatoxin (natural carcinogen)
Eating Galveston Bay Seafood Every Day for 70 yrs. (High Consumption)	**1.2×10^{-3}**	**1200**	**Cancer from PCBs, PAHs**
Breathing Air Pollution in New York for 70 yrs.	1.3×10^{-2}	12,775	Cancer from Air Pollution
Smoking for 70 yrs.	2.1×10^{-1}	210,000	Cancer, Heart Disease

Source: adapted from Wilson, 1979; Crouch and Wilson, 1982; Lehr, 1990

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EPILOGUE

The Future of Comprehensive Management

What will happen to the project's science consensus as it moves into the heavy seas of policy, to be confronted by non-environmental analyses and competing values?...

–William S. Tuohy on the San Francisco Estuary

The scientific attention focused on Galveston Bay following its congressional designation as an "Estuary of National Significance" has resulted in an unprecedented accumulation of new knowledge about the estuary, its processes, and its problems. As a result, we now perceive the "State of the Bay" with far greater clarity than before. But from the beginning, the knowledge was sought to support problem-solving. How, then, do we put our knowledge to work?

The research findings presented here serve as the factual foundation for a document that will help determine the future of Galveston Bay. *The Galveston Bay Plan* is a Comprehensive Conservation and Management Plan, destined to become a blueprint for restoring and maintaining the Galveston Bay ecosystem. Its purpose is to identify the most pressing of the bay's problems and to establish goals and objectives for resolving them. *The Galveston Bay Plan* prescribes specific actions to protect and enhance the estuary–its water and sediment quality, living resources, and surrounding land and water resources (EPA, 1989).

What will *The Galveston Bay Plan* accomplish? Regulation

Source: Galveston Bay National Estuary Program

Galveston Bay—what of its future?

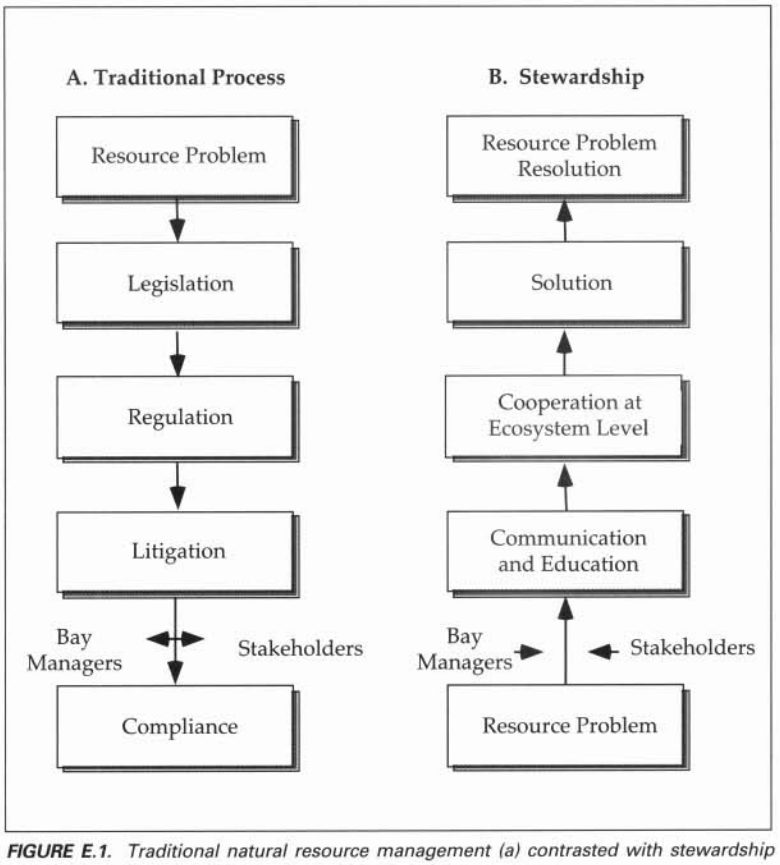

FIGURE E.1. *Traditional natural resource management (a) contrasted with stewardship (b). Traditionally, individual problems prompted legislation and creation of a system of diverse regulatory mandates. Authority derived from a top-down, command-and control approach, requiring continuous bureaucratic energy and resulting in a semi-adversarial relationship with stakeholders (quite effective for some problems). Stewardship, conversely, begins with stakeholders and resource managers agreeing upon the problems–in the context of the entire ecosystem. Necessary consensus-building takes longer and is more difficult than the traditional process, but helps stimulate a self-perpetuating sense of personal responsibility for public resources.*

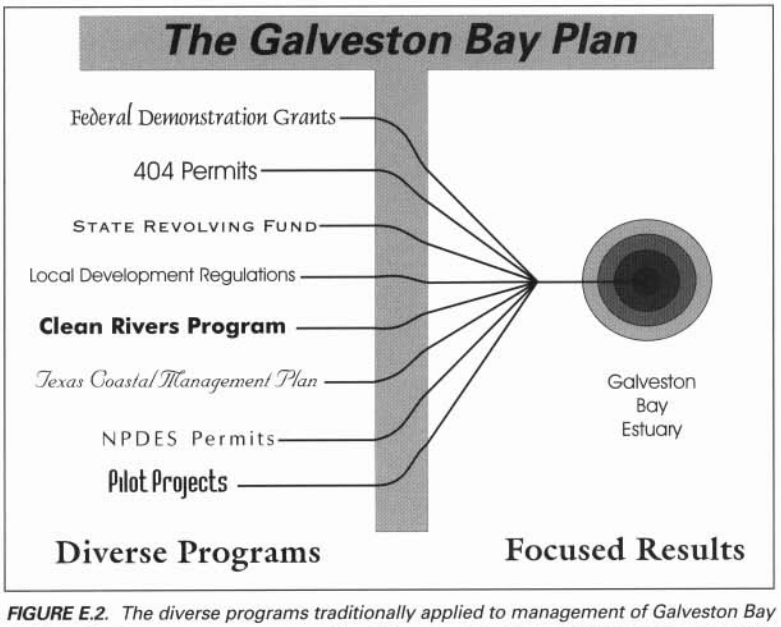

FIGURE E.2. *The diverse programs traditionally applied to management of Galveston Bay (left) reside in numerous agencies.* The Galveston Bay Plan, *utilizing the stewardship process depicted in FIGURE E.1, helps focus these programs on the Bay's documented problems (right). This integration of programs promotes the solving of problems that are systematic and exceed the scope any single governmental entity.*

of point sources of pollution from cities and industries has dominated Galveston Bay management for 25 years. As the findings reported in this book demonstrate, this management has produced remarkable improvements in the upper Houston Ship Channel and other degraded waters—a continuing success story. But in bay-wide importance, the point source issue has now given way to more pervasive and difficult issues, not well suited to traditional regulatory solutions (these are the seventeen priorities described in Chapter One). Habitat losses, diffuse pollution from land runoff, and human health and shoreline management issues all point to a need for non-traditional management measures in the future.

Therefore, *The Galveston Bay Plan* incorporates a philosophy diverging from traditional resource management (FIGURE E.1). The traditional approach involves a collection of narrowly defined initiatives operating in semi-isolation from one another. These initiatives begin with a mandate from government and end with litigation or compliance by the users of the bay. *The Galveston Bay Plan*, in contrast, begins with stakeholder agreement on the problems. Stakeholder involvement is central to each step in the planning process, leading to a coordination of governance at the ecosystem, rather than resource, level.

The ecosystem approach to managing Galveston Bay is clearly necessary. Numerous bay processes reported in this book have proven to be interrelated, involving the bay itself, its tributaries to some distance upstream, and the watersheds where humans carry on their daily activities. This interconnectedness shapes the management planning process; solutions to the bay's problems can only be effective if they, like the problems, operate at a systems level. To be effective, both scientific and resource conservation activities must be interdisciplinary.

This is also true at the level of bay governance, where environmental problem-solving has traditionally been limited by the narrow and diverse scopes of involved agencies (Hadden, 1993). These agencies have traditionally pursued agendas specific to their mission in a system that provides checks and balances of power, but which discourages integrated regional planning and results in sub-optimal use and management of the resources. Artificial distinctions of jurisdiction do not correspond to problems defined by natural distinctions of hydrology and ecology.

Inevitably, the *Galveston Bay Plan* encompasses water quality, habitat, wildlife, and human health aspects of the estuary, all concerns over which no single agency presides. *The Galveston Bay Plan* provides a focus necessary to integrate the diverse programs and jurisdictions for improved stewardship–a regional solution for a regional problem (FIGURE E.2). Who will implement the *Galveston Bay Plan*? Who will pay for the work? Can it last? These are questions that science cannot address.

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Glossary

Abiotic–The non-living, or physical part of an environment.

Accretion–Accumulation of sediments by deposition, as for a river delta or along a shoreline.

Aerobic–In the presence of, or utilizing oxygen.

Algae Bloom–Population explosion of phytoplankton in response to changing environmental conditions, including nutrient over-enrichment from wastewater and nonpoint sources. Blooms can result in oxygen depletion and biological impacts; see also *eutrophication*.

Ambient–Prevailing environmental conditions, as opposed (for example) to measurement in a laboratory or waste stream. In an estuary, ambient conditions are receiving water conditions in the bay itself, representing an integration of the various sources of impact to the system.

Amphipod–A member of the crustacean order Amphipoda. These numerous small (but generally visible) flea-like forms (flattened from side to side) are abundant in marine environments.

Anaerobic–Lacking oxygen, for example submerged sediments below a narrow oxygenated layer. Also refers to metabolic function in the absence of oxygen, present in some microbe species.

Annelid–Worms of the invertebrate phylum Annelida which are segmented (as distinguished from non-segmented roundworms and flatworms). Most estuarine worms are polycheates, a group dominating the bay bottom habitat.

Anoxia–Absence of oxygen; see also *anaerobic*, *hypoxia*.

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 results from materials in rain or snowfall, combined with dry dust fallout. Increasingly, atmospheric sources are recognized as a significant source of nutrients and contaminants to coastal systems.

Autotrophic–A species or ecosystem sustained entirely by food created within, for example a green plant or an estuary which is a net exporter of organic matter. Contrasts with *heterotrophic*–a species or ecosystem which imports energy (e.g. a predator or estuary which receives substantial organic matter from upstream).

Base Flow–The volume of flow in a stream or river during dry conditions (as opposed to conditions influenced by storm runoff).

Bathymetry–Underwater topography defined by patterns in depth.

Benthic–Associated with sediments on the bottom of a water body.

Berm–An elongated ridge elevated above the surrounding area; could be natural (for example an underwater longshore bar created by currents) or man-made (a ridge of sediment disposed along a navigation channel or an upland feature constructed to manage runoff).

Bioaccumulate–The accumulation of a contaminant in the tissues of a living organism due to uptake from the environment.

Biochemical Oxygen Demand (BOD)–The degree to which organic compounds consume oxygen in water, based on a five-day laboratory test in which loss of oxygen in a sample results from bacterial respiration and chemical processes. BOD is a traditional water quality measurement applied to wastewater such as treated sewage.

Bioconcentrate–The magnification of contaminant concentrations in living things due to increased tissue concentrations at each successive trophic level in a food chain. Bioconcentration generally (but not always) occurs due to a contaminant being soluble in fatty tissues and not in water.

Biogenic–Created by biological processes.

Biomass–Physical mass (weight) of living tissue. This is a biological measurement used to establish the importance of certain groups of living things in an ecosystem, as opposed to *numbers* of individuals. For example, the biomass of phytoplankton (standing crop) is an important measurement in describing an estuarine food chain.

Bioturbation–The disturbance of sediments due to displacement by living things. For example, bioturbation resulting from burrowing of organisms in the benthic habitat increases sediment aeration and influences contaminant equilibria with the overlying water.

Bivalve–Member of the invertebrate class Bivalvia, including the shellfish groups with two hinged shells, such as oysters.

Blue-Green Algae–Primitive algae with a bacteria-like cell structure, lacking a nucleus and other organelles. These species manufacture photosynthetic pigments but lack chloroplasts (the specialized photosynthetic organelles in higher plants). In some situations, an increase in blue-green algae can indicate an environmental stress such as pollution.

Bulkhead–A man-made vertical wall on the shoreline which replaces the natural gradual depth gradient. Bulkheads are normally constructed to stabilize shorelines and prevent wave damage to upland property.

Bycatch–The incidental harvesting of organisms of one species

during pursuit of another, most often applied to the numerous species of fish and shellfish captured incidentally in shrimp trawls.

Carbon Flux–Transport of organic compounds in an ecosystem, including trophic dynamics, chemical transformations, and physical movements.

Catch Per Unit Effort (CPUE)–The numbers or biomass of organisms caught in a fishery survey, corrected for the level of effort expended (e.g. area seined or time trawled). CPUE provides a better estimate of actual populations than uncorrected figures such as commercial landings.

Channelization–The conversion of shallow coastal areas to deeper dredged navigation channels.

Circulation–Estuarine current patterns, determined by bathymetry, hydrology, fresh water inflow, channels and islands, and geophysical forces.

Coarse Particulate Organic Matter (CPOM)–Unprocessed carbon compounds input to an aquatic system, for example leaf litter.

Colonial Nesting–The propensity for some bird species, for example most egrets and herons, to nest in dense colonies.

Colony Forming Units (CFU)–Bacterial colonies on laboratory media resulting from filtering and culturing bacteria from a water sample. The count of CFUs is an index to the bacterial concentration in the water: each colony in the laboratory culture is inferred to have arisen from reproduction of a bacterium in the original sample.

Commensal–A relationship among two or more species in which one or both benefits from the other without causing harm. Commensal relationships (for example certain crabs living among oysters) result from a coevolutionary history.

Community–Natural, intermingled plant and animal populations which share a given space, compete for resources, and interact with one another in an ecosystem.

Competition–Patterns in distribution, abundance, and behavior in a natural community resulting from competition for a limited resource (e.g. food or space).

Contact Recreation–Human activity involving bodily contact with water, and therefore the potential for increased risk to health when contaminants or pathogens are present. In Galveston Bay, contact activities like wade-fishing and sail-boarding are more common than swimming, traditionally perceived as the principle form of contact recreation.

Copepod–A member of the crustacean subclass Copepoda; including small but generally visible species. Free living forms are common in benthic and planktonic samples, while some are parasitic (e.g. "fish lice").

Cordgrass–Group of several wetland plant species common to both brackish and salt estuarine marshes. Smooth cordgrass, *Spartina alterniflora*, is the dominant plant species of the fringing salt marshes of the Gulf Coast.

Coriolis Force–A force resulting from the earth's rotation which affects fluids like the oceans and the atmosphere, causing hurricanes and whirlpools to rotate counter-clockwise in the northern hemisphere, clock-wise in the southern hemisphere. The coriolis force, through its effect on water currents, contributes to the similarity of geography among Texas bay systems.

Crustacean–Member of the aquatic class Crustacea of the phylum Arthropoda. A heterogeneous and important estuarine group including shrimp, crabs, barnacles, and others.

Ctenophore–Member of the invertebrate phylum Ctenophora (comb jellies; sea walnuts, unrelated to the true "jellyfish"). Ctenophores are bioluminescent members of the plankton assemblage up to several inches in size, with eight rows of cilia and which prey on smaller plankton. The phosphorus jelly is a common inhabitant of Texas bays.

Cubic Feet Per Second (cfs)–Standard unit for measurement of stream flow or wastewater discharge.

Decomposer–An organism which consumes dead organic matter. Decomposers are a major (perhaps dominant) component of the estuarine food chain.

Delta–The fan-shaped mass of sediments deposited where a river discharges to a larger, slower moving water body. Deltas are important for their wetland habitat values.

Demersal–Animals living in the water but feeding on the bottom; for example bottom-feeding fish such as the croaker.

Denitrification–Natural chemical conversion of dissolved nitrogen (nitrite) to gaseous nitrogen, removing it from an aquatic system.

Denivellation–Wind forcing of water resulting in water depth changes. Denivellation in Texas estuaries can produce more extreme water level fluctuations than do tides.

Density Current–Currents resulting from salt water being heavier than fresh water. For example, seawater from the Gulf intrudes landward along the bottom of the Houston Ship Channel, displacing lighter, fresher waters seaward.

Deposit Feeder–An organism which ingests bottom sediments and digests the contained microorganisms and organic matter.

Dermo–A disease of oysters caused by the parasitic protozoan *Perkinsus marinsus*. This disease has a substantial influence on Texas oysters, being more severe in seasonally warmer waters.

Detritivore–An organism that derives nutrients and energy by consuming decaying organic matter.

Detritus–Decaying organic material.

Diatom–A group of phytoplankton species utilizing silica as a structural component of the cell wall; a dominant component of the plankton in Galveston Bay.

Dinoflagellate–Unicellular, generally motile species of algae with two whip-like flagella arranged in a characteristic pattern. This group includes some common plankton species and also red tide organisms such as *Gonyaulax monilata* and *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.

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 which influence the saturation level. A high deficit can be an indicate a water quality problem.

Ecological Niche–The way a species "makes its living;" where it lives, what it consumes, and how it avoids consumption by predators or displacement by other species.

Ecosystem–A natural system including the sum total of all living things, the non-living environment and its physical forces, and the relationships among these, including processes such as predation, competition, energy flow, and nutrient cycling. An estuary is an ecosystem.

Ecotourism–Tourism supported by natural ecological attributes of an area, for example bird-watching.

Effluent–Wastewater discharged to a receiving water.

Embayment–Portions of open water or marsh defined by natural topographical features such as points or islands, or by human structures such as dikes or channels.

Emergent Wetlands–Marshes in which vegetation is rooted underwater and the tops exposed (as contrasted with submerged vegetation or upland habitats).

Enterococcus–Bacteria species which are enteric in man or animals, some of which are pathogens. Enterococci are considered a possible replacement for fecal coliform bacteria as an indicator of water contamination.

Entrainment–Transport of living organisms in a water current, as occurs when organisms enter a cooling water intake structure.

Epibenthic–Located at the surface of the sediments on the bay bottom, generally referring to algae.

Epifauna–Organisms living on a surface, for example the bay bottom or submerged leaves of a rooted aquatic plant.

Epiphytic–Organisms growing on, and supported in part by a plant, for example epiphytic algae growing on the surface of submerged aquatic vascular plants.

Estuary–A semi-enclosed body of water having a free connection with the open sea and within which seawater is diluted measurably by fresh water from land drainage.

Estuarine Debris–Trash in a bay or along its shoreline. Debris consists of tires, construction wastes, household trash, and above all, plastic. Debris degrades aesthetic values and represents a hazard to wildlife (e.g. entanglement or mistaken consumption as food).

Eutrophication–A process of nutrient over-enrichment of a water body, resulting in overgrowth of algae, frequently followed by algae die-offs and oxygen depletion.

Evapotranspiration–Uptake of water by living plants, transport to leaf surfaces, and evaporation to the atmosphere.

Exotic Species–Species not native to an ecosystem, 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.

Fecal Coliform Bacteria–Enteric bacteria which ferment lactose with gas and acid formation at a temperature typical of warm-blooded animals. In water, fecal coliforms are commonly used as an indicator of contamination, and are normally measured using filtration and culture on disk media (but see also *Most Probable Number*).

Feedback Loop–A self-regulatory process in a biological or physical system whereby extremes in a particular condition trigger forces to moderate that condition and maintain a steady state, for example population size (environmental) or body temperature (physiological).

Filter Feeder–Organism (for example the oyster) which feeds by pumping 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.

Flocculant–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 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, based on the food chain principal, but more accurately reflecting the complexities of branching energy transfer among various species at different trophic levels.

Foraminifera–Group of single-celled plankton species characterized by a calcareous skeleton, persistent beyond death.

Freshet–An influx of fresh water inflow, for example following seasonally high precipitation.

Gastropod–Member of the class Gastropoda of the phylum Molluska. These are the snails and similar organisms with an asymmetrical, spirally-coiled shell.

Geographic Information System (GIS)–A computer system which links geographic reference data to attribute datasets, with the capability to display features and analytical outcomes on maps. GIS tools are increasingly being applied to

ecosystem, watershed, and landscape studies, both in ecological research and for environmental management planning.

Green Algae–A common algae type in estuaries, with nucleated cells and photosynthetic pigments contained in organelles called chloroplasts.

Groundwater–Water beneath the earth's surface, occurring in aquifers at one or more depth levels.

Guild–A group of species with similar ecological niches; that is, they "make their living" in a similar way within an ecosystem. For example, the planktivorous fishes would constitute an estuarine species guild.

Gyre–Circular, rotational current pattern, established by winds or other physical forces.

Habitat–The environment chosen by a species to live in, providing life requisites such as food and shelter.

Herbivore–Plant-eater.

Heterotrophic–A species or entire community/ecosystem which acquires its energy by import rather than producing it's own food. Secondary consumers are heterotrophic, as are estuaries which receive substantial organic inputs (energy subsidies) from upstream. Contrasts with *autotrophic*– a species or ecosystem capable of being sustained by creation of its own food (e.g. a green plant or an estuary which is a net exporter of organic matter due to high primary productivity).

Hydrologic Cycle–The continuous cycle of water in the biosphere as solid, liquid, and gas. Marked by evaporation from oceans to the atmosphere, precipitation to the earth's surface, replenishment of groundwater, runoff, uptake by plants, and storage in oceans and ice caps.

Hypoxia–Depletion of dissolved oxygen in water to low levels, for example less than two mg/L. Hypoxia could result from natural or human introduction of oxygen-demanding compounds, or from eutrophication resulting from nutrient overenrichment.

Impervious Cover–Land surfaces with a low capacity for soil infiltration, for example paving, roofs, roadways, or other human structures. The presence of impervious cover increases runoff and affects the quantity and composition of nonpoint source pollution.

Impingement–The accumulation of organisms on a water intake screen, for example at a power plant cooling-water intake.

Indicator Species–A species which, through its population size or condition, mirrors environmental conditions within an ecosystem. For example, eastern oysters are a good indicator species in estuaries by virtue of their wide distribution, inability to move about, and sensitivity to conditions of interest like salinity and contaminant concentrations.

Infauna–Animals living within submerged sediments.

Inflow–The water feeding an estuary, generally referring to river sources.

Intertidal–The portion of shoreline between low and high tide lines, intermittently submerged.

Isopod–A member of the crustacean order Isopoda, small but generally visible species flattened from top to bottom (the pillbug is a terrestrial isopod). Isopods are common benthic and epibenthic invertebrates.

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.

Macroalgae–Algae large enough to be visible.

Macrobenthos–Bottom-dwelling invertebrates large enough to be visible.

Macroflora–Plants large enough to be visible.

Macroinvertebrates–Invertebrates large enough to be visible, for example those retained on a 0.5 mm screen. Most benthic studies concentrate on this size range.

Macrophyte–A higher green plant, for example rooted aquatic vegetation.

Macrozooplankton–Animals in the water which drift with the currents and are large enough to be visible.

Meiofauna–Bottom-dwelling microscopic animals in the 0.002 to 0.02 inch size range. Most benthic studies concentrate on the larger benthic macroinvertebrates, hence less is known of the meiofauna, in part composed of nematodes, copepods, and juvenile forms of larger invertebrates.

Meroplankton–The portion of the plankton assemblage composed of temporarily planktonic life stages of non-planktonic species. These are primarily larvae or juveniles of such species as oysters, crabs, shrimp, and barnacles.

Mesozooplankton–Planktonic animals 200 µm to two millimeters in size.

Microalgae–Planktonic, epiphytic, or epibenthic algae smaller than visible size range.

Microfauna–Animals which will pass through a 0.002 inch mesh screen.

Microflora–Microscopic plants.

Microzooplankton–Planktonic animals in the 20 to 200 µm size range.

Mollusk–Member of the invertebrate phylum Molluska, containing mainly shelled creatures (bivalves like oysters, the various gastropod snails) and squid and octopus species.

Most Probable Number (MPN)–Measurement of fecal coliform indicator bacteria based on gas production in tubes. An alternative to the more standard fecal coliform test involving

filtration and culture on disk media (see also *fecal coliform bacteria*).

Mysid–A family of small shrimp common in marine environments and utilized for standardized laboratory toxicity testing.

Nanoplankton–Members of the plankton assemblage two to 20 µm in size.

Nanozooplankton–Animal members of the plankton two to 20 µm in size.

National Pollution Discharge Elimination System (NPDES)–A regulatory program created under the Water Quality Act and administered by the EPA. The NPDES was originally enacted to eliminate all point source pollution by the mid-1980s through a process of wastewater permitting and regulation. The program, while not successful in eliminating point source pollution, has done much to improve water quality in the U.S.

Nekton–Aquatic animals of the water column with sufficient powers of locomotion to overcome currents (contrasted with plankton which, although some can swim, are at the mercy of currents). Fish are members of the nekton.

Nonpoint 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 nonpoint 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. Emergent marshes and seagrass beds are examples of highly productive nursery habitats.

Nutrient Cycle–Chemical transformation of nitrogen, phosphorus and silica compounds in continuous cycles of organic and inorganic phases in an ecosystem.

Opportunistic Species–Species which exploit diverse aspects of the environment as conditions change, flexible in life requirements and generalists by nature. Able to quickly adopt to temporarily available resources such as food supplies.

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–The discharge point for a wastewater stream, for example from a sewage treatment plant or refinery.

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. For example, sharks of the open ocean.

Penaeid shrimp–Members of the shrimp family Penaeidea, including the well-known commercial species (brown, pink, and white shrimp).

Percolation Rate–A property of sediments measured by the volume of water which 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.

Polycyclic Aromatic Hydrocarbons (PAHs)–A family of organic compounds deriving from fossil fuels and their combustion. The higher molecular weight PAHs are an 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. Porewater 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 which has been filtered from the mantle cavity of bivalve mollusks such as oysters, but not processed through the digestive tract.

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 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, for example 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 was not the receiving water (for example groundwater discharge to an estuary as wastewater).

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 contaminants 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.

Salinity–Salt concentration in marine waters, ranging from zero to about 33 parts per thousand (ppt) in estuaries. Salinity originated as an oceanographic term and does not have a precise chemical definition, since the proportions of various ions vary in the different waters of the world.

Salinity Gradient–A spatial salinity transition, for example from a fresh river mouth to ocean inlet. "Steep" gradients can occur between adjacent water masses of differing salinity, as occurs in a density current.

Seafood Advisory–Warning issued by a public health authority recommending avoidance or reduced intake of certain species which 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 seagrasses have 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, for example at an inlet.

Siltation–The accumulation of sediments transported by water. Siltation is an ongoing process of one to three feet accumulation per century in Galveston Bay.

Silvicultural–Use and management of forest resources.

Spat–Young 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 *productivity*–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 of 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 tribu-

tary or bayou, as opposed to a major river.

Supersaturation–A concentration of a gas in water (for example oxygen) above the equilibrium concentration. This occurs when the gas enters solution more quickly than release from the liquid to 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 equilibria 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 which feeds on materials in water suspension, for example oysters which filter plankton.

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 such as salts, which are non-filterable and remain following evaporation of the water.

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, for example, can be used to establish toxicity both for effluent and for ambient waters and sediments.

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 mechanical devices attached to otter trawls, used to deflect sea turtles from the catch. TEDs are in wide use in offshore shrimping operations to prevent turtle losses.

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.

Washover Fan—the fan-shaped deposits of sediment resulting from deposition by water currents, for example 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 econogical 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.

Zooplankton—Animals which are suspended in and transported by water.

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