HISTORICAL TRENDS

WATER QUALITY AND FISHERIES: GALVESTON BAY

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U.S. DEPARTMENT OF COMMERCE
National Oceanic and Atmospheric Administration
COASTAL OCEAN OFFICE
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WATER QUALITY AND FISHERIES: GALVESTON BAY

A Report to the
National Ocean Pollution Program
and the
National Sea Grant College Program

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Preface

Despite great interest in — and large expenditures for — estuarine water quality and fisheries management, there have not been evaluations of the long-term trends in conditions of most of our estuaries. Consequently, little is known about the effectiveness of past and present management programs.

This is one of several products of a study of long-term trends in water quality and fishery resources in three important U.S. estuaries: 1) Narragansett Bay, Rhode Island, 2) the Albemarle-Pamlico Sound system in North Carolina, and 3) Galveston Bay, Texas. The project had four specific objectives:

1. To document long-term trends in water quality and, where possible, identify causes, consequences and significance.
2. To assess whether problems are similar or unique to each estuary.
3. To assess whether progress is being made in improving conditions in water quality and fishery resources and whether there are examples of success that would be useful for estuarine managers and researchers elsewhere.
4. To glean examples of the useful integration of research and policy.

The three estuaries chosen for this study have sufficient long-term data to permit trend analyses and inter-estuarine comparisons. In two of them, monitoring programs have been carried out for at least two decades. The Texas Department of Health and the Texas Water Commission and its predecessors, the Water Quality Board and the Department of Water Resources, have been monitoring dissolved oxygen, nutrients, metals and bacteria at many stations in Galveston Bay and along the Houston Ship Channel since the late 1960s. Likewise, there is a twenty-five year record of water quality from 20-30 stations in the Pamlico River Estuary in North Carolina. In the third estuary, Narragansett Bay, no routine monitoring program has been carried out, but enough independent studies have incorporated water quality parameters to permit construction of a comparable long-term data set. In addition to water quality data bases, there are catch statistics and records of management efforts for important fisheries in each bay.

These estuaries are characterized by a range of pollution problems, some of which are unique to each, while others are shared by all. Narragansett Bay and Galveston Bay represent heavily industrialized, urban estuaries with a long history of pollution. They are subjected to intense port and shipping activities, massive industrial discharges and major domestic sewage loadings from urbanized centers of population: Houston in Galveston Bay; and Providence, Central Falls and East Providence in Narragansett Bay. In contrast, the Albemarle-Pamlico Sound system is a relatively undeveloped estuary without major shipping lanes, industrial activity or a densely urbanized coastline. Instead, it is characterized by extensive wetlands along its shoreline with agriculture and forests as the major land use types within its watershed. Yet it also is perceived as having a history of water quality problems.

This is one of three separate — but comparable — reports that have been prepared on trends in pollutant loadings, water quality and pertinent fisheries for each of the estuaries. The other two are:

Stanley, Donald W. 1992. Historical Trends: Water Quality and Fisheries, Albemarle-Pamlico Sounds, With Emphasis on the Pamlico River Estuary. University of North Carolina Sea Grant College Program Publication UNC-SG-92-04. Institute for Coastal and Marine Resources, East Carolina University, Greenville, NC. 215 pp.

Desbonnet, A. and V. Lee. 1991. Historical Trends: Water Quality and Fisheries, Narragansett Bay. The University of Rhode Island Coastal Resources Center Contribution No. 100 and National Sea Grant Publication #RIU-T-91-001. Graduate School of Oceanography, Narragansett, RI. 101 pp.

Support for this research was provided by the National Ocean Pollution Program Office of the National Oceanic and Atmospheric Administration, U.S. Department of Commerce. The project was administered as Grant R/SF-2 through the UNC Sea Grant College Program, North Carolina State University, Raleigh, NC.

Several persons in Texas state agencies provided courteous and friendly assistance as I sought to collect the information needed for the study. Even more valuable were their insights and historical perspectives on the issues associated with the ecology of Galveston Bay. During one visit to the state in December 1987, Dr. Neal Armstrong, a member of the faculty of the University of Texas at Austin, provided a summary of the research that has gone on in the bay, and Dr. Gary Powell and his associates at the Texas Water Development Board detailed the history of the State's role in managing the bay. Also, Kirk Wiles of the Texas Board of Health outlined that agency's role in regulating shellfishing bed closures in the bay, and Dr. Brian Cain of the U.S. Fish and Wildlife Service discussed concerns about pollution related to dredging in the Houston Ship Channel.

Among those who provided data used in the report was Ms. Sylvia von Fange of the Texas Water Commission Library. She and her staff were particularly helpful, allowing me to ship books and reports back to North Carolina for photocopying. Other library and agency personnel who gave assistance included Debra E. Bunch (Texas Parks and Wildlife Department Library), Virginia Hall (Texas State Department of Agriculture Library), I.J. Shenkir (Feed and Fertilizer Control Service, Texas Agricultural Extension Service), and the staffs of the Houston Public Library and the U.S. Government Documents Section of the North Carolina State University Library.

Many hundreds of hours were spent tabulating data for the tables and graphs in the report. East Carolina University students and staff involved in this task included Ray Taft, Jeff Taft, Sharon Reid, Colleen Reid, Deborah Daniel, Anne Anderson and Kay Evans. I thank K. Teague, G. Powell, and D. Beckett for reviewing an earlier draft. Mark Hollingsworth provided invaluable assistance in the preparation of the final draft.

Greenville, North Carolina D.W.S.
December, 1991

Chapter 1

Profile of the Galveston Bay System

> *In the short run, the bay's deterioration is a direct benefit to many, but its protection is a recognizable value to relatively few. For one thing, 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 waters bear a close resemblance to cafe au lait. Its flat and timbered 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 the visual evidence alone, a resource worth saving.*
>
> Smith (1972)

It is not the purpose of this chapter to provide a thorough description of the physics, chemistry, and biology of the Galveston Bay system. Rather, it is a brief sketch intended to focus the reader's attention on the features of the bay which are most relevant to the water quality and fisheries data that will be presented later. Several more comprehensive reports on the ecology of the bay are available. One is the U.S. Fish and Wildlife Service Biological Services Program summary of environmental literature entitled *Texas Barrier Islands Region Ecological Characterization: Environmental Synthesis Papers* authored by Shew et al. (1981). Other useful Fish and Wildlife Service products include *An Annotated Bibliography of the Fish and Wildlife Resources of Galveston Bay* by Christman et al. (1978), and the *Gulf Coast Ecological Inventory: User's Guide and Information Base* by Beccasio et al. (1982). Another important source is Armstrong's (1987) report on *The Ecology of Open-Bay Bottoms of Texas: A Community Profile*. It is particularly valuable because it provides comparisons between Galveston Bay and other Texas estuaries. Finally, the Galveston National Estuary Program, begun in 1989, has provided a number of technical reports and other documents. All publications from this program, as well as many other published and unpublished works concerning the Bay, can be found at the Galveston Bay Information Center. The Center is located at the Jack K. Williams Library on the Galveston Texas A&M campus.

The Physical Environment

The Galveston Bay system (sometimes referred to as the Trinity-San Jacinto estuary) covers about 1,430 square kilometers and includes East Bay, Galveston Bay, Trinity Bay, West Bay and several smaller bays (Figure 1.1). The gentle slope of the coastal area of southeast Texas continues through the estuaries; thus, they tend to be very shallow. Trinity and upper Galveston bays average 1.6 m in depth while lower Galveston Bay averages 2 m with areas up to 4 m. The contiguous East and West bays are even shallower, averaging slightly more than 1 m in depth. Bolivar Roads, the main tidal channel through the barrier islands, normally has depths exceeding 10 m. Depths in the dredged channels range up to 12 m (Texas Department of Water Resources 1981a).

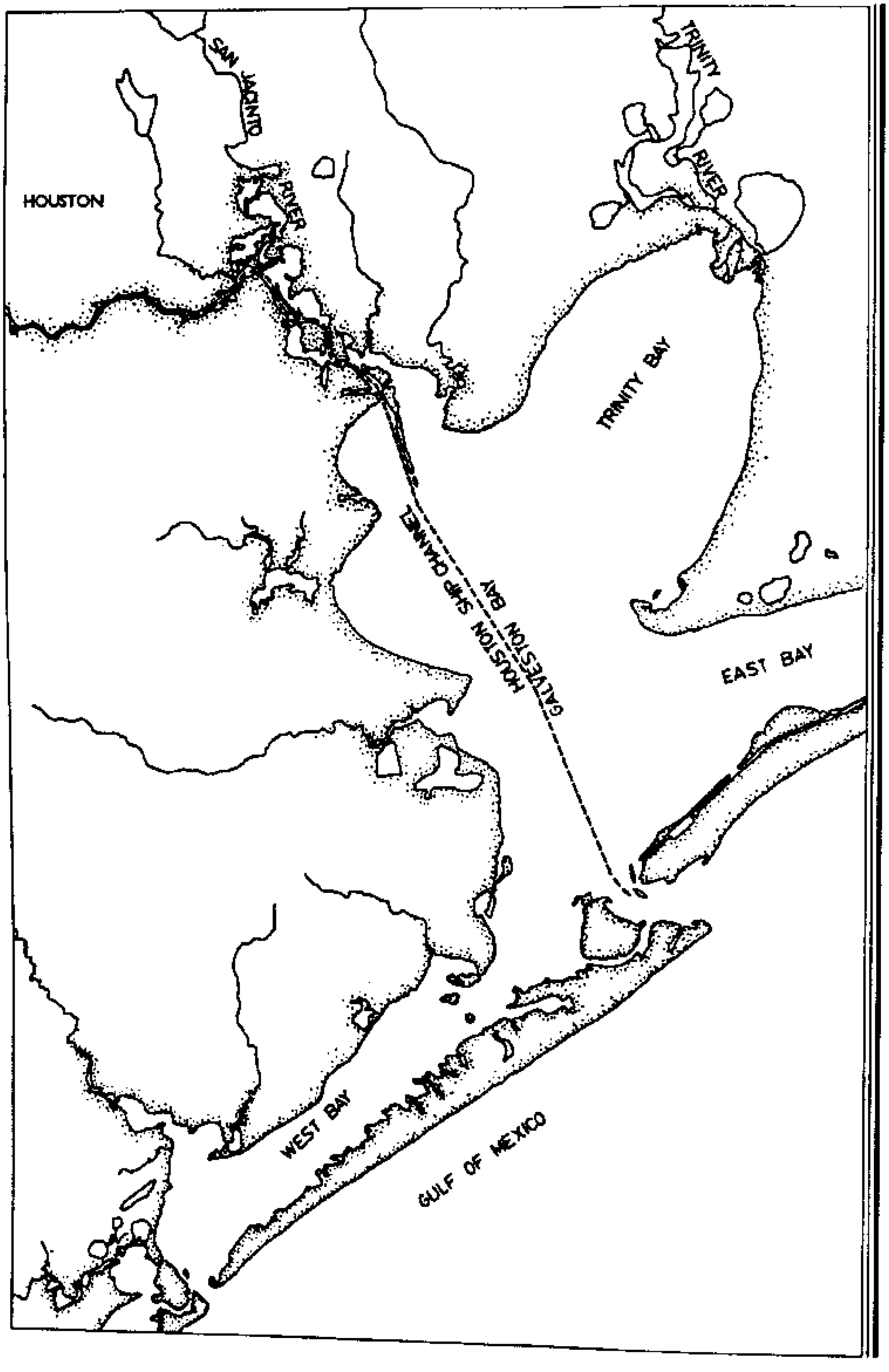

Figure 1.1. *Map of Galveston Bay system.*

Geological Origin and Evolution

The present estuaries along the Texas coast had their beginnings during the last major glacial epoch, about 30,000 years ago. During that period, sea level is estimated to have dropped more than 50 meters, and the coastline moved some 80 km seaward of its present-day location. Then, between 18,000 and 4,500 years ago, the ice retreated. Sea level rose, and large barrier islands were deposited as the Trinity and San Jacinto rivers continued to meander through the river plain. As the sea level rose and the barrier islands formed, the river valleys were filled with water, creating Galveston Bay and other nearby estuaries. Since then, depositional processes have continued, and the bays have become more shallow. Wind and water forces have continually changed the barrier islands, the tidal deltas, and the bottom features of the bay (Fisher et al. 1972).

In 1979 wetlands associated with the Galveston Bay estuary consisted of 35.5 km^2 of forested wetlands, 146.6 km^2 of freshwater marsh, 473.5 km^2 of salt marsh, and a number of freshwater ponds and lakes totaling 91.4 km^2 (King et al. 1986). Land subsidence, resulting from excessive groundwater withdrawals and from withdrawal of shallow oil deposits, has been occurring in the Galveston Bay area since the early part of this century. The City of Houston and the Texas City area have experienced subsidence of nearly 122 cm, while other areas around the bay have undergone as much as 244 cm of subsidence (Texas Water Quality Board 1975b; Fisher et al. 1972). Between surveys in 1956 and 1979, Galveston Bay lost approximately 16% of its marshes and an estimated 95% of its submerged vegetation. The problem of wetland loss will be exacerbated in the future due to continuing subsidence of coastal areas and to sea level rise. (Sheridan et al. 1988).

Climate

Galveston Bay lies in the climatic zone classified as subtropical, characterized as having humid weather with warm summers. The climate is also predominantly marine because of the proximity of the Gulf of Mexico. Polar Canadian air masses frequent the basin in winter causing brief

Table 1.1. *Hydrologic data for Galveston Bay (Armstrong 1987). Values are averages for the period 1941-1976.*

Parameter	Value	Percent of total	Reference
A. Drainage Area			
Trinity	**46,540 km^2**	**79.15**	**1**
San Jacinto	**10,230 km^2**	**17.40**	
Coastal	**2,028 km^2**	**3.45**	
Total	**58,798 km^2**	**100.00**	
B. Surface area			
Trinity Bay	**36,585 ha**	**27.08**	**1**
Galveston Bay	**53,016 ha**	**39.25**	
East Bay	**17,685 ha**	**13.09**	
West Bay	**27,803 ha**	**20.58**	
Total	**135,089 ha**	**100.00**	
C. Volume			
Trinity Bay	**.687 km^3**	**23.60**	**2**
Galveston Bay	**1.311 km^3**	**45.04**	
East Bay	**.224 km^3**	**7.69**	
West Bay	**.689 km^3**	**23.67**	
Total	**2.911 km^3**	**100.00**	
D. Average Depth	**2.1 m**	**2**	
E. Precipitation onto Estuary Surface	**134.80 cm/yr^1**		**3**
	1.93 km^3/yr^1		**2**
F. Evaporation from Estuary Surface	**118.80 cm/yr^1**		**3**
	1.70 km^3/yr^1		**2**
G. Gaged inflows (54,250 km^2)			
Trinity basin	**6.61 km^3/yr^1**	**79.15**	**1**
San Jacinto basin	**1.97 km^3/yr^1**	**17.40**	
San Jacinto-Brazos	**0.13 km^3/yr^1**	**3.45**	
Total	**8.71 km^3/yr^1**	**100.00**	
H. Ungaged inflows (6,875 km^2)			
	3.13 km^3/yr^1		**3**
I. Net inflow (I = G + H + E - F)			
	12.29 km^3/yr^1		

[1] **Hofstetter (1977)**

[2] **Armstrong (1987)**

[3] **Texas Department of Water Resources (1981)**

periods of cool, foggy and rainy weather (Texas Department of Water Resources 1981a). The mean July temperature is 33.9°C and the mean January temperature is 7.2°C with below freezing temperatures occurring on an average of 7 days a year. Rainfall averages about 127 cm/year and is fairly evenly distributed throughout the year. Excessive rainfall can occur in a short time period when slow-moving thunderstorms or tropical disturbances pass over the area in late summer. The mean annual relative humidity in the Houston area averages around 80%. Winds are predominantly from the north in the winter and from the southeast the remainder of the year (Texas Water Quality Board 1975b).

Freshwater Inflows

Drainage areas contributing freshwater to the Galveston Bay system include the Trinity and San Jacinto River basins, the Trinity-San Jacinto coastal basin, and parts of the Neches-Trinity and San Jacinto-Brazos coastal basins (Table 1.1). The Trinity River basin is by far the largest of these, with a drainage area of 46,540 km². From its headwaters in southeastern Archer County, Texas, the West Fork Trinity River flows in a southeasterly direction to its confluence with the Clear Fork Trinity River near downtown Fort Worth. From here, the West Fork Trinity continues in a generally easterly direction until its merger with the Elm Fork Trinity River in the eastern part of the city of Dallas. At this point, the Trinity River begins and flows in a southeasterly direction to Trinity Bay (Figure 1.2). The river is about 1150.435 km, dropping some 381 m from source to mouth.

In 1985 there were a total of 37 major reservoirs within the Galveston Bay watershed (Table 1.2). All but 4 of the 29 reservoirs on the Trinity River are located in the upper half of the basin, in the Dallas-Fort Worth area. Lake Livingston is the largest reservoir in the basin and is the only lake on the main stem of the Trinity between Dallas and Galveston Bay. There are no major natural lakes in the basin (Wurbs 1985; Texas Department of Water Resources 1981a). There are several other reservoirs in various stages of planning or construction in the Trinity Basin. The

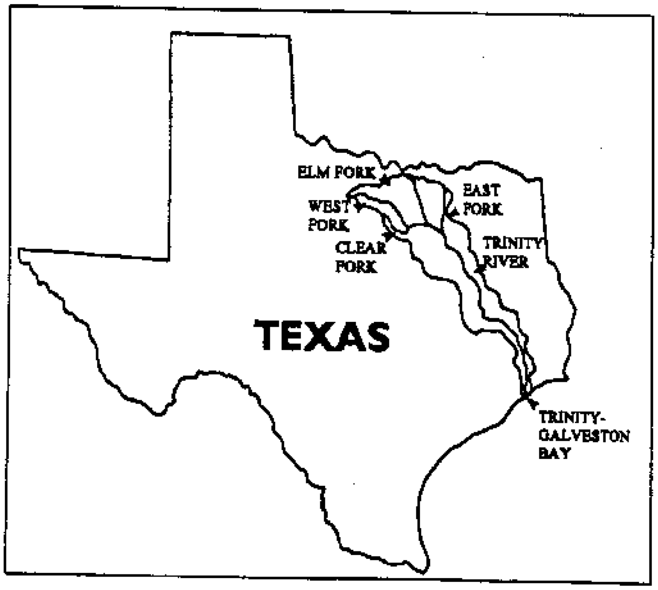

Figure 1.2. *Map of Trinity River Basin. From Warshaw (1975).*

most controversial is the Wallisville Reservoir, which would dam the Trinity just upstream from its mouth. Construction of Wallisville Reservoir was halted in 1973, when it was about 75% completed, due to environmental litigation (Wurbs 1985; U.S. Army Corps of Engineers 1988).

The San Jacinto River basin has a much smaller drainage area — 10,230 km^2. Emptying into the Houston Ship

Table 1.2. *Major reservoirs in the Galveston Bay basin (Wurbs 1985; Texas Department of Water Resources 1981; Corps of Engineers 1988). "R" = Recreation; "M" = Municipal Water Supply; "P" = Steam-Electric Power; "A" = Agricultural Water Supply; "Mi" = Water Supply for Mining; "F" = Flood Control.*

Name	Owner/Operator	Uses	Year Built	Surface area (acres)	Total capacity (acre-ft)
Trinity River Basin					
Kiowa	Lake Kiowa, Inc.	R	1968	560	7,000
Halbert	City of Corcicana	M,R	1921	650	7,420
Trinidad	Texas Power and Light	P	1925	740	7,450
Terrell City	City of Terrell	M,R	1955	830	8,710
White Rock	City of Dallas	R	1910	1,120	10,740
Waxanachie	Ellis County	M	1956	690	13,500
North	Dallas Power and Light	P	1957	800	17,000
Weatherford	City of Weatherford	M	1957	1,210	19,470
Houston County	Houston County	M	1966	1,280	19,500
Forest Grove	Texas Utilities Service	P	1937	2,710	22,840
Mountain Creek	Dallas Power and Light	P	1937	2,710	22,840
Amon G. Carter	City of Bowie	M	1956	20,050	29,000
Anahuac	Chambers & Liberty Cos. Navigation District	A,Mi	1914	5,300	35,300
Worth	City of Fort Worth	M	1914	3,560	38,130
Arlington	City of Arlington	M	1957	2,270	45,710
Fairfield	Industrial Generating Service	P	1969	2,350	50,600
Wallisville	Corps of Engineers	M,R	——	19,700	58,000
Bardwell	Corps of Engineers	F,M,R	1965	6,040	137,060
Eagle Mountain	Tarrant County	M,A	1934	9,200	190,300
Navarro Mills	Corps of Engineers	F,M,R	1963	11,700	206,200
Benbrook	Corps of Engineers	F,M,R	1952	7,630	258,600
Joe Pool	Corps of Engineers	F,M,R	1986	7,470	304,000
Bridgeport	Tarrant County	M	1965	33,750	386,420
Grapevine	Corps of Engineers	F,M,R	1952	12,740	425,500
Ray Hubbard	City of Dallas	M	1968	22,740	490,000
Cedar Creek	Tarrant County	M	1965	33,750	679,200
Lavon	Corps of Engineers	F,M,R	1953	29,450	748,200
Lewisville	Corps of Engineers	F,M,R	1954	39,080	981,800
Ray Roberts	Corps of Engineers	F,M,R	1987	36,900	1,064,600
Livingston	City of Houston, Trinity River Authority	M,A,R	1968	82,600	1,750,000
Trinity-San Jacinto Coastal Basin					
Cedar Bayou	Houston Power and Light	P	1972	2,600	20,000
San Jacinto River Basin					
Sheldon	Texas Parks & Wildlife	R	1943	1,700	5,420
Lewis Creek	Gulf States Utilities	I	1969	1,010	16,400
Houston	City of Houston	M,A,R,Mi	1954	12,240	140,520
Addicks	Corps of Engineers	F	1948	220	204,500
Barker	Corps of Engineers	F	1945	220	207,000
Conroe	San Jacinto River Authority	M,Mi	1973	20,980	429,800
San Jacinto-Brazos Coastal Basin					
Galveston County	Galveston County	M,I	1949	810	7,310

Channel about 14.48 km above Morgan's Point, the San Jacinto depends for its flow almost entirely upon overflow at the dam on Lake Houston, which is the principal water supply reservoir for the City of Houston. During a year of unusually low rainfall, such overflow is negligible. On the other hand, in a wet year overflow from Lake Houston provides over 60% of the total freshwater inflow into the ship channel (Texas Water Quality Board 1975b).

While the San Jacinto is generally the most important source of freshwater to the lower Houston Ship Channel, the principal source of inflow to the upper channel during dry periods is wastewater discharge. This is primarily because of the small watershed of Buffalo Bayou, the lower reach of which was widened and deepened in the early part of this century to form the ship channel. The wastewater input volume does not fluctuate much seasonally (Texas Water Quality Board 1975b). When freshwater inflow is moderate to high, there is well defined salinity stratification in the confined portion of the ship channel. When inflow is low, mixing tends to be more complete due to tidal action (Texas Water Quality Board 1977).

Smaller coastal drainage areas also contribute freshwater to the bay system. One of these, the Neches-Trinity, is bounded on the east by the drainage of Oyster Bayou. Two others are the Trinity-San Jacinto and San Jacinto-Brazos coastal basins. In total, these coastal drainages encompass about 2,000 km^2.

Galveston Bay receives the largest amount of freshwater inflow of all the bays along the Texas coast, in part because the drainage areas lie in the eastern part of the state where precipitation is much greater than farther west. Annual rainfall amounts diminish 10 mm for every 9.5 km as one moves east to west across Texas (Armstrong 1987). The combined annual freshwater inflow to the bay from all drainage areas averages 11.61 km^3 per year (Table 1.1). About 78% of this is from the Trinity River Basin. The peak freshwater influx normally corresponds with spring rains and usually over 70% of the total annual inflow occurs between January and June (Shew et al. 1981). The seasonal variability is much greater for the Trinity than for the San Jacinto, because withdrawals from Lake Houston by the City of Houston tend to dampen oscillations in the San Jacinto's natural flow pattern. Major impacts from the spring peak inflows from the Trinity include overbank flooding of marsh areas, extension and building of bay head and oceanic deltas, flushing of the bays, and reduction of salinities (Texas Department of Water Resources 1982b).

In addition to the overland runoff, there is an additional input of 1.93 km^3 each year from precipitation directly onto the bay and an evaporative loss of 1.7 km^3. Thus, the net inflow (combined inflows + precipitation - evaporation) amounts to approximately 12.3 km^3/year. This amounts to an average basin areal yield of 2,256 m^3/ha (Armstrong 1987).

Tidal Exchange, Circulation and Flushing

Three inlets connect the Galveston Bay system with the Gulf of Mexico (Figure 1.1). Two are natural tidal inlets: San Luis Pass between Follets Island and Galveston Island, and Bolivar Roads between Galveston Island and Bolivar Peninsula. Rollover Pass, dug across the base of Bolivar Peninsula in 1955, connects East Bay and the Gulf. Approximately 80% of the tidal exchange in the Galveston Bay system occurs through Bolivar Roads. Less than 20% of the tidal exchange occurs through the San Luis Pass, and Rollover Pass exchanges less than 1% of the flow carried by Bolivar Roads (Shew et al. 1981).

Normal lunar tidal range averages 40 cm in lower Galveston Bay, decreasing to approximately 30 cm in East, West, Trinity, and upper Galveston bays. Since the lunar tide range is small, the effect of wind is proportionately large in comparison to other estuaries with larger lunar tides. Thus, observed water level fluctuations in the bay depend a great deal on the wind tide amplitude and on whether the lunar and wind tides are in or out of phase with one another (Shew et al. 1981). Because of the shallow depths throughout the estuary, wind can play a major role in the generation of waves and longshore currents. Thus, wind is a major factor influencing erosion, accretion and other changes in shoreline configurations (Texas Department of Water Resources 1982b).

An analysis of net circulation patterns (simulated by a tidal hydrodynamic model) by the Texas Department of Water Resources (1982b) indicated that the dominant circulation in Galveston Bay is a net movement of water along the Houston Ship Channel. Shifting winds associated with the higher incidence and greater intensity of weather fronts during the winter increases flushing in Galveston Bay, in comparison to summer months when the winds are more unidirectional. The circulation patterns in Trinity, East and West bays are generally dominated by internal circulation currents. East Bay has comparatively poor circulation because of its alignment perpendicular to the prevailing winds and limited tidal exchange with the Gulf (Shew et al. 1981). West Bay, aligned similarly to East Bay, nevertheless probably has better circulation and flushing due to greater volumes of tidal exchange through Bolivar Roads and San Luis Pass (Espey, Huston and Associates 1978). Armstrong (1982), using the single layer model calculation, estimated the average freshwater residence time of Galveston Bay to be 40 days.

Salinity and Temperature

Mean salinity in the Galveston Bay complex is around 17 ppt (Martinez 1975), but is highly variable, both spatially and temporally. Trinity Bay is generally the least saline area because of the Trinity River's outflow. Salinity along the western part of Galveston Bay is typically higher than on the east, because of the Trinity River inflow from the east and because of the partial barrier formed by the dredge spoil along the Houston Ship Channel (Espey, Huston and Associates 1978). The ship channel is the primary path for salinity intrusion into upper Galveston Bay. While vertical stratification is generally absent in the bay, the ship channel and other dredged channels are exceptions. In West Bay, salinity gradients are generally small due to the low freshwater input and the large exchange with the Gulf of Mexico at either end (Espey, Huston and Associates 1978). In East Bay, the major flow of freshwater is from the east, so that the salinity gradient is from east to west (low to high) (Shew et al. 1981). Salinity usually fluctuates with time as a result of freshwater inflows that vary by several orders of magnitude. In a typical year, the seasonal average salinity range is approximately 11 ppt (Martinez 1975).

Mean water temperature for the entire bay complex averages about 22°C. Seasonally, water temperatures closely follow the seasonal change in air temperature. The monthly average minimums typically occur between December and February (approximately 12°C), and the maximum occurs in August or September (approximately 29°C) (Shew et al. 1981). At any given time, water temperatures differ as much as 8°C within the bay. The lowest temperatures are usually near the mouth of the Trinity River while the highest are in the protected embayments near shore during low river inflow. Vertical temperature gradients are normally negligible in all areas of the bays except in the dredged channels, where they may be quite pronounced (Espey, Huston and Associates 1978).

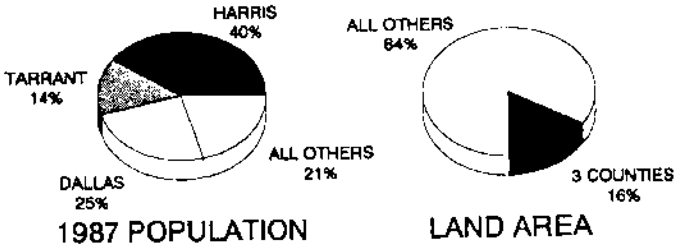

Figure 1.3. *Population and land area distribution (1987) in the Galveston Bay watershed. Data from* The Texas Almanac *(1988).*

Principal Uses

The rise of the Houston metropolitan area as a major population and industrial center has been a fairly recent development; most of its growth has taken place in the last 60 years. One hundred years ago, the four-county region surrounding the bay had less than 80,000 inhabitants. Galveston, not Houston, was the center of shipping and commerce of southeast Texas. And cotton, not petrochemicals, was the major commodity (Texas Water Quality Board 1975b).

Much of the growth and development of the Houston area is attributable to the completion of the Houston Ship Channel in 1914, in combination with the discovery of oil in the region by the 1920s. 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. Houston soon replaced Galveston as the center of commercial and industrial activity. Galveston Island and its beaches have since developed into an important tourist area (Texas Water Quality Board 1975b).

By 1930, over 80% of the ocean-going tonnage from the Port of Houston was in the form of oil and related chemicals. By this time, many large oil companies had established their offices in the area, and refineries were well developed along the upper channel. 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. It has subsequently risen to first place (Texas Water Quality Board 1975b).

Population Distribution

Population distribution is extremely uneven across the Galveston Bay watershed. Out of 43 counties lying wholly or partly in the basin, just three (Harris, Tarrant and Dallas) contain nearly 80% of the total basin population. Put another way, 80% of the basin population lives on only 16% of the basin land area in these three counties (Figure 1.3). These counties

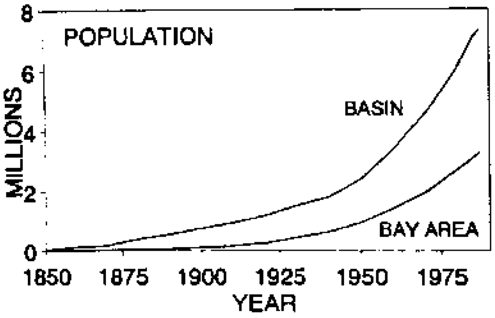

Figure 1.4. *Population Growth in the Galveston Bay area since 1850. "Bay Area" includes Chambers, Harris, Galveston, and Brazoria counties. Data are from Androit (1983) and* The Texas Almanac *(1988).*

are the centers of the two largest urban areas in Texas: 1) Houston (Harris County), situated at the upper end of Galveston Bay, and 2) Dallas-Fort Worth (Dallas and Tarrant Counties), located some 643.6 km up the Trinity River. The Dallas-Fort Worth area is known as the *Metroplex*.

Houston is the 9th largest metropolitan area in the United States (as of 1986) and was the fastest growing in the late 1970s and early 1980s (Texas Water Commission 1988b). The region has exhibited boomtown characteristics over most of the past 5 decades (Figure 1.4). In 1985 over 3.2 million people lived in the four counties surrounding the bay (Chambers, Brazoria, Galveston and Harris). The majority (2.8 million) were concentrated along the northwest shore of the bay in Harris County, which is dominated by Houston, the most populous Texas City, and fourtth in the U.S., with 1.7 million persons in 1985 (*Texas Almanac* 1988).

Houston's population gains during the 1970s and early 1980s were remarkable. Growth between 1970 and 1980 averaged 3.7% annually, and between 1980 and 1982 Houston's population grew at by an incredible 12%. Since 1982, however, population growth has slowed considerably. Migration has accounted for a large part of the population changes in the Houston area during the past several decades (*Texas Almanac* 1988).

The eastern shore of Galveston Bay is far less intensely developed than the western shore. Chambers County, which surrounds most of Trinity Bay, is primarily agricultural, with extensive rice and row-crop farmlands, cattle range, and timber. The 1985 population of this county was only about 19,000.

Industry and the Port of Houston

The production of oil, natural gas, and petrochemical products (e.g., plastics) dominates the Houston area economy. Nearly one-half of the total chemical production in the U.S. takes place in the four-county area surrounding the bay. More than 500 chemicals are produced there, including 55% and 34% of the total polypropylene and polyethylene production, respectively. Thirty percent of the total U.S. petroleum

Table 1.3. *Galveston Bay commercial landings catch composition (1982-1986 averages). Data are from Osburn et al. (1987).*

Species	lbs	kg	% of total catch	% of finfish catch	% of shellfish catch
Finfish	**564,792**	**256,190**	**4.9**		
1. Flounder	150,100	68,085	1.3	26.6	
2. Black Drum	108,171	49,066	0.9	19.1	
3. Mullet	88,780	40,271	0.8	15.7	
4. Sheepshead	70,090	31,793	0.6	12.4	
5. Croaker	27,460	12,456	0.2	4.9	
6. Other Food Fish	61,931	28,092	0.5	11.0	
7. For Bait, Reduction and Animal Food	58,260	26,427	0.5	10.3	
Shellfish	**10,917,440**	**4,952,152**	**95.1**		
1. Blue Crabs	1,841,300	835,412	16.0		16.9
2. Oysters	3,880,800	1,760,331	33.8		35.6
3. Brown and Pink Shrimp	1,878,480	852,079	16.4		17.2
4. White Shrimp	3,316,860	1,504,528	28.9		30.4

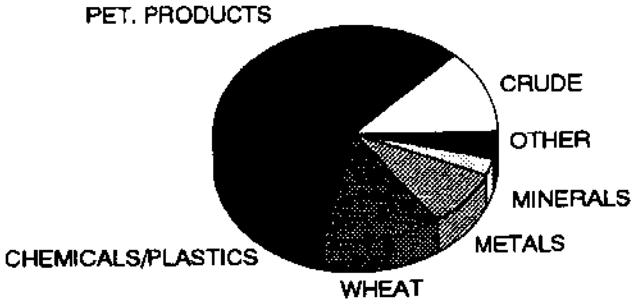

Figure 1.5. *Major categories of cargo transported on the Houston Ship Channel in 1984. Data are from U.S. Army Corps of Engineers' annual reports of* Waterborne Commerce in the United States.

industry is located adjacent to the bay. Most of this industrial development is concentrated in two areas: one along the upper Houston Ship Channel, the other in the Texas City vicinity along the southwestern shore of the bay.

Nationally, the Port of Houston is the third largest in terms of total shipping tonnage (Ditton et al. 1988). The port is located along the upper Houston Ship Channel, and it is a 40.2-km-long complex of public and private facilities. Over 4,700 ships visited the port in 1987, transporting an estimated 99.858 million metric tons of cargo.

The dominance of petroleum and related industries around the bay is reflected in the types of commerce on the ship channel (Figure 1.5). The major cargo types are refined petroleum products (37%), chemicals and plastics (21%), crude petroleum (13%) and wheat (13%). The wheat, petroleum products and chemicals and plastics are primarily exported, while the crude petroleum, various mineral ores, steel products and motor vehicles are the main imports (Liebow et al. 1980).

To accommodate the waterborne commerce associated with this highly industrialized area, a total of 201.125 km of navigation channels have been dredged throughout Galveston Bay (Diener 1975). The principal channels within this network are the Gulf Intracoastal Waterway, Houston Ship Channel, Texas City Channel, the channel to Liberty, and the Galveston Channel. It has been estimated that between 1867 and 1986 about 75.11 km^2 of habitat in the bay was disrupted or eliminated by navigation projects (King et al. 1986).

The Houston Ship Channel (Figure 1.1) extends approximately 80.45 km from the Port of Houston to the Gulf of Mexico. It

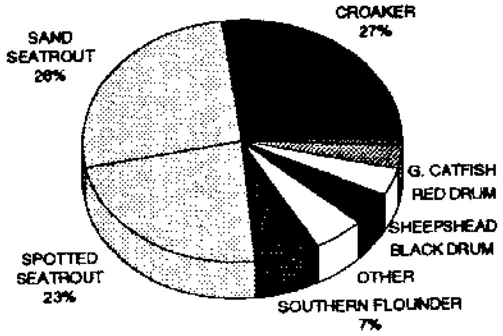

Figure 1.6. *Composition of catch, as numbers of fish caught, by Galveston Bay recreational fishermen (averaged for 1974-1985 period). Data are from Osburn and Ferguson (1986).*

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 Morgan's Point, and crosses the bay to the Gulf of Mexico. The narrow, confined, 40.225 km long portion of the channel between the Port of Houston's ship-turning basin near downtown Houston and Morgan's Point is one of the most heavily industrialized water bodies in the world.

Commercial Fisheries

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 (Table 1.3), which was about one-third of the state total (Osburn et al. 1987). The annual finfish catch is a relatively small part (4.9%) of the total harvest, averaging about one-half million pounds per year. Four species account for nearly 75% of the total finfish harvest. In decreasing order of importance they are southern flounder (*Paralichthys lethostigma*), black drum (*Pogonias cromis*), mullet (*Mugil cephalus*), and sheepshead (*Archosargus probatocephalus*). Other commercial species in the bay include spotted seatrout (*Cynoscion nebulosus*), red drum or redfish (*Sciaenops ocellata*), Atlantic croaker (*Micropogon undulatus*) and gafftopsail catfish (*Bagre marinus*). Spotted seatrout and red drum were banned from the commercial harvest in September 1981.

Shrimp, oysters, and blue crabs have been the dominant shellfish species, making up nearly 95% of the total annual bay catch. Three kinds of shrimp -- white, brown and pink -- together accounted for nearly half the total seafood harvest between 1982 and 1986. Over three million pounds of white shrimp (*Penaeus setiferus*), along with 1.9 million pounds of brown and pink shrimp (*Penaeus aztecus* and *Penaeus duorarum*), were caught in an average year. The Virginia oyster (*Crassostrea virginica*) was the single most important species harvested in the bay during the period (3.9 million pounds/year). Finally, there were about 1.8 million pounds of blue crabs (*Callinectes sapidus*) in an average year's harvest (Osburn et al. 1987).

Offshore, in the Gulf of Mexico, the annual shrimp harvest is much greater than that within the bay itself. Since these animals live in the bay as juveniles, it is reasonable to argue that this catch should be included in an assessment of the bay productivity (Armstrong 1987). It is impossible to accurately assign the Gulf catch to individual estuaries, but an indication of the Galveston Bay contribution is the catch for Zone 18, a 12,950 km^2 area located offshore from the bay. Between 1959 and 1976, the shrimp catch in this zone averaged nearly 4.536 million kg/year (Texas Department of Water Resources 1981). The 1986 harvest of shrimp from all areas off the Texas coast was 34.4736 million kg (Osburn et al. 1987). It has been estimated that the Galveston Bay system is responsible for 30% of the brown shrimp and 41% of the white shrimp in this catch (Texas Water Commission 1988b).

Most of the oyster reefs in the Galveston Bay system are located in the central portions of East Bay and Galveston Bay, where fresher waters of the major tributaries mix with saline waters of the Gulf. The most recent survey of the bay's oyster reefs was that of Benefield and Hofstetter (1976). They mapped 160 reefs totaling 3,076 ha. The largest reef complex (971 ha) is around Redfish Bar, between Eagle Point and Smith Point, in central Galveston Bay. Trinity Bay supports very few reefs due to the frequent floods on the Trinity River and unsuitable bay substrate (King et al. 1986).

Oysters are harvested from both public reefs (3,047 ha) and private oyster leases (951 ha) in the bay. From 1982 to 1986, approximately 81% of the reported commercial landings were from the public reefs, while the remaining 19% were taken from the private leases. Private oyster leases were originally granted to encourage reef development and private oyster culture. But today few oyster leases in the bay are being used exclusively for oyster culture. Instead, lease operators harvest oysters transplanted from polluted reefs to private leases. Transplanting from polluted reefs is permitted to reduce the amount of oysters in polluted waters and therefore discourage the illegal harvest and marketing of contaminated oysters. Transplanted oysters must be depurated (held in unpolluted waters until contaminants are naturally cleared) before they can be sold for public consumption. Transplanting and depuration are coordinated and monitored through a cooperative effort by the Texas Parks and Wildlife Department and the Texas Department of Health. About 21% (653 hectares) of the oyster reefs in Galveston Bay are classified as polluted and therefore off-limits for harvesting, by the Texas Department of Health (Benefield and Hofstetter 1976; Texas Parks and Wildlife Department 1988).

Recreation

In addition to the important commercial fishery in the bay, there is also a significant sport fishery. In fact, commercial fishing on average accounts for only about 14% of the total catch within the bay, with the remainder (86%, 498,960 kg in 1986) going to the sport catch (Texas Department of Water Resources 1981b; Texas Water Commission 1988b). The bay supports approximately 2 million man-hours of sport fishing annually, creating economic benefits estimated at $364 million in 1986 (Texas Water Commission 1988b).

About three-quarters of the annual sport fishing effort, and catch, occurs between 15 May and 20 November. Atlantic croaker (*Micropogonias undulatus*), sand seatrout (*Cynoscion arenarius*), and spotted sea trout (*Cynoscion nebulosus*) are the most popular sport fishes. Together they comprised 76% of the total catch (numbers) between 1974 and 1985 (Osburn and Ferguson 1986) (Figure 1.6).

Recreational boating is popular on the Texas coast in general and Galveston Bay in particular. The Clear Lake-Galveston Bay area has been referred to as the "yacht capitol of Texas." Residents in the four-county area around the bay in 1986 held 104,000 boat licenses and were served by 38 marinas and 8,000 boat slips. The bay system accounts for 30% of the total number of marinas on the Texas coast and 63% of the total wet slips in commercial marinas (Texas Water Commission 1988b).

In addition, the bay is used for other forms of recreation, such as duck hunting, swimming, camping, picnicking and sightseeing. No direct quantitative measures of these activities are available, but an indirect indication of their relative importance is the amount of money spent. In 1986, the figure was $122 million, about one-third the amount spent on sport fishing, and 55% of the total expenditures of this type on the Texas coast (Texas Water Commission 1988b).

Two national wildlife refuges and several state parks facilitate recreational activities in the bay area. The Brazoria Refuge is at the extremity of West Bay and the Anahuac Refuge is adjacent to East Bay. Galveston Island State Park fronts on West Bay and the Gulf of Mexico. San Jacinto State Park borders the Houston Ship Channel above Morgan Point (King et al. 1986).

Chapter 2

Bay Issues and Management: An Overview

> *If strong laws and institutional presence were all that was needed to get the job done, the waters of Galveston Bay would be clean.*
>
> Smith (1972)

Major Environmental Concerns

Over the past two decades there have been several major issues for the Galveston Bay system that have been mentioned in almost every assessment of the bay's ecological health. Various research and management programs have attempted to deal with these problems, but none of them have been totally resolved. The summary below is taken primarily from the recent Texas Water Commission (1988b) document nominating Galveston Bay as an *Estuary of National Significance*, the first step in yet another attempt to develop a "comprehensive" management plan to protect the bay.

Wastewater Discharges

The Galveston Bay system directly receives more than half the permitted discharges in the State of Texas. More than 50% of the U.S. petrochemicals production and more than 30% of the country's petroleum refining takes place along the bay's shores. Four thousand vessels cross the bay each year on their way to Houston, the nation's third largest port. In addition, partially treated municipal sewage from nearly three million Houston area residents imposes a heavy BOD and nutrient burden.

So far, the most obvious impacts of these industrial and municipal loads have been in the confined portions of the Houston Ship Channel above Morgan's Point, but there continue to be worries that open waters of the bay system are suffering from some (largely unquantified) forms of degradation, and that conditions will worsen in the future. Toxic materials effects are part of the concern, but to date there is generally a lack of data from which to quantify the impacts. Eutrophication symptoms have never developed to any great extent in the open bay, despite the heavy nutrient and BOD inputs. Light limitation caused by high turbidity has been hypothesized as the reason why this bay has not responded as much to nutrients as some other bays, but not many details of nutrient cycling have been quantified for the estuary.

In short, the basic issue is whether Galveston Bay can support a major industrial/urban complex and still maintain good enough water quality to sustain the traditional living resources for which estuaries are so prized.

Channelization

Since the natural depth of Galveston Bay is only about 1.8 m, the establishment and continued growth of the Port of Houston have depended on maintenance of dredged channels across the bay. Millions of cubic yards of sediment are scooped out of the Houston Ship Channel, and other channels in the bay, every two or three years, depending on the degree of silting, by the U.S. Army Corps of Engineers (Figure 2.1). The channelization issue is at the forefront at this time (1989) because of a proposed new round of dredging to widen and deepen the channel (*See* Chapter 3).

There are three major concerns associated with the channel dredging. The first is loss of habitat. Dredging opponents point out that dredge spoils deposited alongside the channel cover productive estuary bottom. The second concern has to do with the effect of the channels on circulation and salinity in the bay. Deep channels allow higher salinity water to enter the upper areas of the bay. Also, the dredge spoil banks may partially disrupt normal freshwater/seawater mixing patterns. The fear is that these changes could affect oysters and other organisms that need freshwater inflow to avoid marine predators and disease. Finally, there is concern that dredging will resuspend toxic metals and organic compounds deposited on the bottom from decades of wastewater discharge from Houston and the heavily industrialized upper ship channel (*See* Chapter 4).

Freshwater Inflow

This is another issue at the forefront today. Freshwater is a relatively scarce, and therefore valuable, natural resource in Texas. Hence, there is great competition for it. Overall about 75% of the state's freshwater is used for agricultural purposes and 20% is allocated for industrial and domestic uses. That leaves only about 5% for the bays and estuaries. For Galveston Bay, the percentage is somewhat higher than this state average, because the bay's watershed lies in east Texas, the wettest region of the state. But water needs in the Houston area continue to increase as more people and industries arrive.

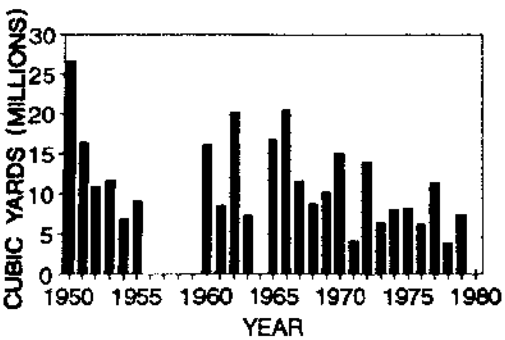

Figure 2.1. *Cubic yards of dredge spoil removed from the Houston Ship Channel and from other areas in Galveston Bay. Data are from the U.S. Army Corps of Engineers* Annual Report of the Chief of Engineers on Civil Works Activities *(1951-1979).*

To meet these demands, it was proposed over twenty-five years ago that a major reservoir be built on the lower Trinity River at Wallisville. The dam would be just above the river's mouth, impounding a 2266 ha lake to serve as: 1) a water supply for Houston, 2) a saltwater barrier for rice farmers, and 3) a navigational channel for a small upriver port. But it has been charged that these projected benefits are nothing more than "bloated, deceptive promises" based on "manipulated statistics, congressional chicanery, inaccurately calculated costs, and the subversion of federal environmental law" (Robison 1986). Bay scientists and some managers worry that further diversion of Trinity River water could have the same basic effect as more channelization. That is, the natural freshwater/saltwater balance would be upset, threatening the bay's valuable oyster harvest. The researchers also contend that more reservoirs will reduce the amount of nutrients and sediments coming into the bay, possibly reducing algal and animal productivity and preventing buildup of marshes. Still, after more than two decades, the debate over Wallisville goes on. As of February, 1989, the Texas Water Commission was investigating the possibility of transferring water from the Sabine River (near the Texas-Louisiana border) to Houston as a substitute for the dispute-ridden reservoir project (Scarlett 1989).

Loss of Habitat

Comparison of digitized wetlands maps of the Galveston-Houston area prepared from photographs taken in 1956 and 1979 give some evidence of the rate of wetlands losses around the bay. Among the changes noted are: 1) decreases in freshwater marshes (-63.2 km^2), salt- and brackish-water marshes (-41.5 km^2), and beaches/bars (-4.3 km^2) and increases in freshwater ponds and lakes (+35.3 km^2), forested wetlands (+9 km^2), and uplands (+6.5 km^2). Although reasons for gains and losses in some areas are unclear, many of the changes are attributed to human activities, including construction of channels, impoundments, and "made" land, as well as to land-surface subsidence (Longley and Wright 1984).

It has been predicted that the problem of wetlands loss around Galveston Bay could become more serious in the future due to continuing subsidence of coastal areas and to sea level rise from planetary warming. In 1985, the bay system was surrounded by approximately 290 square miles of land (mostly marsh) from 0 to 5 feet above mean sea level. With a sea level rise of 5 feet by the year 2100 as projected for this area, that 290 square miles would be converted to open bay, with a maximum replacement potential of 140 square miles (the 5-to-10 foot elevation lands). This corresponds to a 50% loss in potential marsh land, much of which is already modified by housing and industry (Sheridan et al. 1988).

The Bay Managers: State and Local

Texas has many governmental entities which influence the allocation and protection of water resources. Several are state agencies, but there are many more regional, county and municipal bodies organized as authorities, councils, boards, etc. Many of the water quality programs cut across state agency and local/regional lines and overlap jurisdictions. For this reason, coordination of environmental programs in the state is sometimes difficult due to a lack of effective

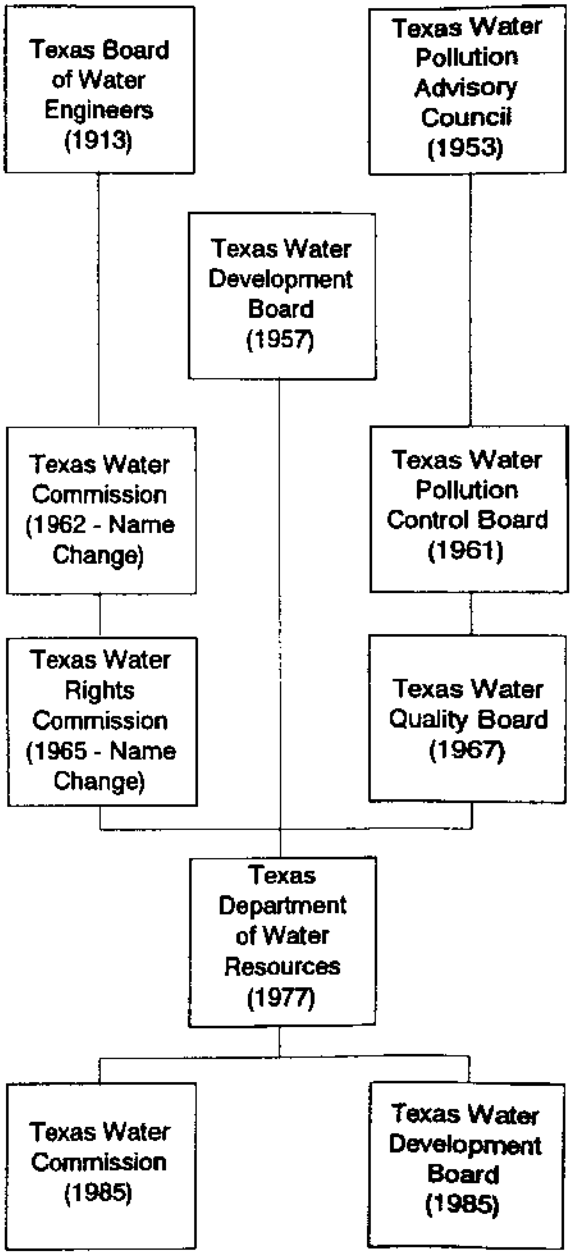

Figure 2.2. *Evolution of Texas water agencies. Redrawn from Smerdon et al. (1988).*

communication between agencies which have different statutory authorities (Texas Water Commission 1988b). There has been no shortage of criticism of the state's past efforts to manage its estuaries (e.g., Carter 1970; Smith 1972; King and Kendall 1987; Wiggins and Anderson 1987; Smerdon et al. 1988).

State Agencies

Organization of the state agencies has undergone numerous changes since the Board of Water Engineers was established, primarily for the regulation of water rights, in 1913 (Figure 2.2). Three separate water agencies emerged by the 1960s. One handled water rights and legal questions (Water Rights Commission); another was a planning agency that managed loan funds (Water Development Board). The third was responsible for pollution control and water quality (Water Quality Board). This was the first major statewide effort in the water pollution field (Texas General Land Office 1976; Smerdon et al. 1988). The Texas Water Quality Board:

1. set water quality criteria and regulated waste discharges and private sewage facilities;
2. was responsible for issuing regulations to prevent the spill or discharge of oil and other hazardous substances into the coastal waters of Texas, as well as arranging the prompt removal of spills or discharges that did occur; and
3. was the lead state agency for the areawide waste treatment management program, which was a part of the federal pollution control scheme that emerged in the early 1970s (Texas General Land Office 1976).

The Water Quality Board existed from 1967 until 1977, when it and the two other water agencies created in the 1960s were combined to form the Texas Department of Water Resources. This single water agency continued until 1985 when, in another reorganization, it was divided into two agencies: 1) the Texas Water Development Board, responsible for long range planning/development of water resources and financing of water resource and wastewater treatment projects; and 2) the Texas Water Commission, responsible for all other water activities, including pollution control.

The legislative act which created the Water Commission assigned to it most of the previous Department of Water Resources functions, along with responsibility for other programs previously administered by the Texas Department of Health and the Public Utility Commission. It also changed the focus of the agency's work toward a greater emphasis on enforcement.

The Water Quality Division of the Water Commission is responsible for efforts to prevent and control water pollution. It is organized into three Sections:

1. Standards and Evaluation: One task of this section is assessment of existing water quality and identification of problem areas through a Statewide Monitoring Network in lakes, rivers and estuaries. It also prepares *Waste Load Evaluations* for specific river and estuarine segments, compiles the biennial statewide *Water Quality Inventory*, and develops water quality standards.
2. Wastewater Permits: Personnel in this section process wastewater permit applications. They also evaluate U.S. Army Corps of Engineers draft permits to determine if water quality standards will be violated by the proposed activities.
3. Wastewater Enforcement: This section enforces wastewater discharge permits. Resolution of noncompliant activities involves negotiation with permittees, administrative enforcement actions, litigation, and technical support (Texas Water Commission 1989).

In addition to the Water Commission, there are several other state agencies which have roles in managing the bay. The Texas Parks and Wildlife Department has most of the responsibility for the bay's fish and wildlife resources. Programs of this department include: 1) the Fisheries Monitoring Program to compile commercial landings data; 2) on-site pollution/fish kill investigations; 3) fisheries enhancement; 4) fish and game regulations enforcement; and 5) the shell, sand, and gravel removal permit program.

The Texas Department of Health works with the Water Commission to design wastewater treatment plants. The Department also runs the Shellfish Sanitation Program, which involves opening and closing areas of the bay for shellfish harvesting and inspecting shellfish plants to ensure that sanitary conditions are met.

Regional and Local Management

The Gulf Coast Waste Disposal Authority (GCWDA) is a special government entity created by the Texas legislature in 1969. Its jurisdiction is the three-county area (Harris, Galveston, and Chambers) surrounding Galveston Bay. Its purpose is to prevent water pollution by providing for disposal of wastes on a regional basis. GCWDA enforces its own and other agency rules concerning waste disposal, regulates septic tank installation, and may contract with industry to supply pollution control systems. GCWDA can construct, acquire, and operate disposal systems. It conducts studies concerning the control of water pollution and is authorized to prepare a master plan for pollution abatement, waste disposal, and wastewater treatment. Technical assistance to municipalities and other government bodies is another function of GCWDA (Smith 1972).

Local Environmental Groups

Local citizens, sometimes in conjunction with national environmental organizations, have also been active from time to time as specific bay-related issues arose. For example, the Bayou Preservation Association, a early 1970s homeowners coalition in Houston, successfully fought Corps of Engineer plans to straighten the Buffalo Bayou upstream from the ship channel for flood prevention (Smith 1972). About the same time, a suit was filed in federal court to stop construction of the Wallisville Dam by the Corps. The suit was filed by the national Sierra Club and its Houston Chapter, the Houston Sportsmen's Club, the Houston Audubon Society, the Texas Shrimp Association, and two individuals.

More recently, in early 1988, the Galveston Bay Foundation was organized. Inspired by a speech in Houston by a board member of the very successful Chesapeake Bay Foundation, this new organization has been described as not being an environmental group in the conventional sense of the term. Rather, it represents the viewpoint of many different groups who use the bay, such as commercial and recreational fishermen, the boating and yachting community, industry and business, and the private citizen (Dawson 1987; Robison 1988). To accomplish its goals, the Foundation plans to: 1) educate, 2) lobby to the extent possible, 3) litigate as necessary, and 4) encourage, conduct and/or fund research about the bay ecosystem (Galveston Bay Foundation 1988). Two of the Foundation's first efforts will be formal opposition to the Corps of Engineers proposal to deepen and widen the Houston Ship Channel, and developing a position on another contested Corps project, the Wallisville Dam (Robison 1988).

Multidisciplinary, Management-Oriented Research Projects

The Galveston Bay Project: 1968-1974

The Galveston Bay Project was intended to be a comprehensive study of Galveston Bay which would provide the basis for a sound water quality management plan for the bay. A consortium of three universities - the University of Texas at Austin, Texas A & M, and Texas Technological University - prepared the Galveston Bay Work Plan in 1966 (Texas A & M University et al. 1966). According to this plan, the specific goals of the study would be: 1) to determine the freshwater inflow needed to sustain a desirable aquatic environment; 2) to evaluate the cost of achieving incremental levels of water quality; 3) to determine the social benefits associated with incremental improvements in water quality; 4) to determine the benefits to marine life associated with incremental improvements in water quality; and 5) to determine the optimum management program for the Galveston Bay system.

The Texas Water Quality Board began to implement the plan in June, 1967. The project was managed jointly by personnel of the board and two engineering firms. Funding came primarily from the state of Texas and the U.S. Department of the Interior through the Federal Water Pollution Control Administration, and later the Environmental Protection Agency. The U.S. Army Corps of Engineers also contributed services.

The original Bay Work Plan drawn up in 1966 was modified several times during the course of the study. In late 1967 it was decided to redirect selected elements in the plan toward a more practical "physical planning program". This involved more emphasis on municipal wastewater collection systems and wastewater treatment plants, both municipal and industrial. Thus, activities such as the selection and evaluation of alternative treatment systems received more attention, while other program elements, such as land use planning, were reduced. Other modifications in the plan were made when the U.S. Congress passed, in 1972, Public Law 92-500, entitled the *Federal Water Pollution Control Act Amendments of 1972*. The Galveston Bay Project was changed in scope to help provide the type of input needed by the state of Texas to fulfill its planning requirements under PL 92-500.

The report summarizing the Galveston Bay Project results (Texas Water Quality Board 1975b) lists these accomplishments:

1. A system of self-reporting on industrial effluents was developed by the Texas Water Quality Board.
2. An eight-county regional sewerage system plan was adopted for the Houston area.
3. A water quality sampling network in the bay was established.
4. Mathematical models were developed to predict the effects on the receiving waters of varying waste load levels.
5. A study of sediment loadings in the bay and Houston Ship Channel was made to evaluate the sources and fates of pollutants associated with the sediments.
6. Oxygenation studies were made to evaluate the processes affecting reaeration in the bay. This information was used to refine the dissolved oxygen model.
7. A water reuse study was accomplished to determine the optimum use of available supplies of used water.
8. A ground-water investigation report was prepared to determine the availability of groundwater from principal aquifers in the area.
9. Toxicity studies were conducted.
10. Waste load evaluations, required by PL 92-500, were made for most stream segments within the Galveston Bay watershed.
11. Much of the data gathered by the project was used to help determine the waste discharges which could be allowed with each of approximately 500 new permits to discharge issued in the study area.
12. Water quality improved in the Houston Ship Channel between 1968 and 1974. The yearly mean dissolved oxygen in the Turning Basin (upper end of the channel) rose from 0.30 mg/liter to 2.60 mg/liter. The summary noted that the DO

in the bay itself had never been as critical as in the channel, and that the bay waters were continuing to maintain a healthy dissolved oxygen level.

13. The relative levels of "net plankton" (at about the mid-point of the channel between Morgan's Point and the Turning Basin) increased between 1972 and 1974.

14. A significant reduction in waste loads to Galveston Bay occurred during the project period. The BOD load in the ship channel in 1974 was about 37% of the load that had existed in 1968.

Management Conference for Galveston Bay

With the nomination, and acceptance, of Galveston Bay to the National Estuary Program in 1987-1988, a second major integrated effort at managing the bay got underway. The goal is to develop "Comprehensive Conservation and Management Plans" for nationally significant estuaries threatened by pollution, development, or overuse. EPA is the federal agency responsible for overseeing and funding the program.

In general, the goals of the Galveston Project will be to maintain ambient water quality in the bay and to enhance estuarine productivity. Current and proposed projects are intended to prevent water quality deterioration in the Houston Ship Channel and to improve certain parameters such as dissolved oxygen concentrations where possible. Efforts to prevent man-induced wetlands losses and control shoreline erosion will also be studied during the project (Texas Water Commission 1988b).

Chapter 3

The Houston Ship Channel: Growth and Pollution

History of Houston and the Ship Channel

Houston, the perennial boom town, has for over 140 years sustained the ethic that motivated its founding by two New York real estate speculators: "liberated capitalism," the belief in the superiority and sacredness of the individual's right to promote, speculate, build, buy and sell without outside restraint or control.

Carleton and Kreneck 1979

The Houston area was an uninhabited swamp before 1836. In that year Augustus and Kirby Allen, land speculators from New York, bought a nine square mile tract of land at the junction of Buffalo and White Oak bayous, twenty-five miles upstream from Galveston Bay. The city was born in a real estate ad, drawn up by the brothers to promote it as a point "which must ever command the trade of the largest and richest portion of Texas" and a place that was to be "the great interior commercial emporium of Texas" (Sibley 1968). Houston did not remain in obscurity for long. The Allens had shrewdly chosen to name it after Sam Houston, the hero of the Battle of San Jacinto, so as to convince the Texas Republic to move its capitol there in 1837.

Their plan worked, and although the capitol was moved from Houston to Austin only two years later, Houston began to grow. Between then and 1900 its development centered around cotton, railroads and timber. Cotton was king in nineteenth-century Houston, and middlemen helped develop the city as a center for shipping the "white gold" to Northeastern and British textile mills by means of rail and steamboat. Timber was also moved through Houston by a railroad line linking the city with the East Texas Piney Woods to the north. By the 1890s a network of railroads made transportation by rail more important than by the bayou and gave the town its motto: "Houston, Where Seventeen Railroads Meet at the Sea" (Carleton and Kreneck 1979).

In the spring of 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). Audubon collected several ivory billed woodpeckers, and called them "abundant" in the area. Another description of the bayou from about the same time is of interest because it was somewhat prophetic:

> "Its banks are high and lined with the cypress knee which shoots up along the edge of the water. In passing over this singular body of water, which is confined, with few exceptions, to precipitous banks on either side, covered with massive timber, whose rich dense foliage throws a melancholy, somber shade over its dark and sluggish waters. Throughout its whole extent it bears a strong resemblance to a canal." (Farrar 1926).

Later that same year, on December 31, 1837, the steamboat *Laura* became the first to visit Houston. In part, this was a publicity stunt to prove that Buffalo Bayou was navigable (McComb 1981). The *Houston Telegraph* published an extra edition telling about the ship coming up to the newly-formed city. In 1839, a committee was appointed to plan the clearing of major obstacles such as logs and sandbars from a portion of the bayou. City officials passed an ordinance establishing the Port of Houston, which included "all roads on the banks of the Buffalo Bayou as well as all wharves and landings within the city limits." The Congress of the Republic of Texas granted the city the right to remove obstructions from and improve navigation on the bayou in 1842. By the time Texas was annexed by the United States in 1845, Houston was permanently established on the only dependably navigable waterway in Texas.

The latter half of the nineteenth century saw the beginning of efforts to significantly widen and deepen Buffalo Bayou to accommodate larger vessels, and development of an intense ports rivalry between Houston and Galveston. Dredging in upper Galveston Bay began in the early 1870s when local interests cut a channel 4.3 mdeep and 45.7 m wide through Morgan's Point into upper Galveston Bay for a distance of five miles. Meanwhile, federal participation in building the Houston Ship Channel had originated with the River and Harbor Act of 1872, which provided for the U.S. Army Corps of Engineers to provide funds to dredge a deeper channel all the way from Houston to Bolivar Roads at the Gulf entrance to Galveston Bay. The project was completed in 1876. Now, ships drawing 2.7 m of water could use the port at Houston, and a city newspaper bragged that its merchants were "free of the extortions of . . . Galveston's hideous wharf monopoly" (Sibley 1968).

Nevertheless, Galveston was emerging as a major port. Lying just inside Bolivar Roads at the seaward end of Galveston Bay, it required only short dredge cuts to be linked to the Gulf. By 1896, Galveston was a deep-water port, with a 7.6 m channel and jetties to help prevent shoaling of the cuts through Bolivar Roads (Sibley 1968). By the year 1907, Galveston ranked second among all U.S. ports in the value of foreign exports, second only to New York. Cotton was the predominant article of export (Alperin 1977). Another port was established in the 1890s with the dredging of a 4.9 m deep channel from deep water in Galveston Harbor across to Texas City, on the southwestern edge of the bay.

The deep water channel to Galveston brought Houston close to a major crisis in its economic development, and Houstonians launched a deep-water movement of their own in the late 1890s. Then, a devastating hurricane swept across Galveston in 1900, decimating the island and killing thousands of people. This natural disaster added weight to Houston's arguments in favor of a more protected port, but work on a deeper channel was proceeding slowly. Finally, in 1910, a new Federal Rivers and Harbors Act changed the name of the project to the "Houston Ship Channel," and by 1912, financing was assured and work on the channel got underway in earnest (Alperin 1977).

The work was completed a year ahead of schedule and on November 10, 1914, President Woodrow Wilson pushed a pearl-topped button in Washington to set off a cannon on the banks of the turning basin near downtown Houston, formally marking the opening of the Houston Ship Channel to (Sibley 1968). The channel was 82.1 km in length, and had a maximum depth of 7.9 m and a maximum width of 45.7 m. Warehouses and wharves began to line the banks of the upper ship channel from the Turning Basin downstream to Morgan's Point. The first regularly scheduled steamship service was inaugurated August 22, 1915 (Bernard Johnson 1975).

By the mid-1920s, pressure was on to have the channel deepened even further, to widen some portions, and to construct a new Turning Basin (Smith 1972). This was necessitated by the discovery of oil in the area and the concurrent development of the internal combustion engine. These developments and the resource requirements of World War I combined to produce a heavy demand for products from this region. By 1927, 83% of the ocean-going tonnage from the Port of Houston was in the form of oil and related chemicals. Only 20 years before, cotton had been the main commodity (Bernard Johnson 1975).

The River and Harbor Act of 1935 authorized further enlargement of the channel to a depth of 9.8 m and a width of 121.9 m. Refineries were well developed along the channel. By this time Texas led all states in refining of petroleum with Harris County leading all other counties. Many large oil companies had established their offices in the area, as had oil supply services and other related industries (Bernard Johnson 1975).

During and after World War II, new major industries were established, including a primary steel producer and a major ordinance plant. Construction of countless miles of pipelines accompanied by continued development of chemical and petrochemical industries further established the channel area as a major production and distribution center. Between 1940 and 1948, Texas rose from tenth to sixth place in chemical production and has subsequently risen to first place (Bernard Johnson 1975). The channel has since been enlarged to a depth of 12.2 m; the width has remained at 121.9 m (King et al. 1986).

Substantial increases in the tonnage of cargo moving through the channel have followed each of these ship channel enlargements (Figure 3.1). For example,

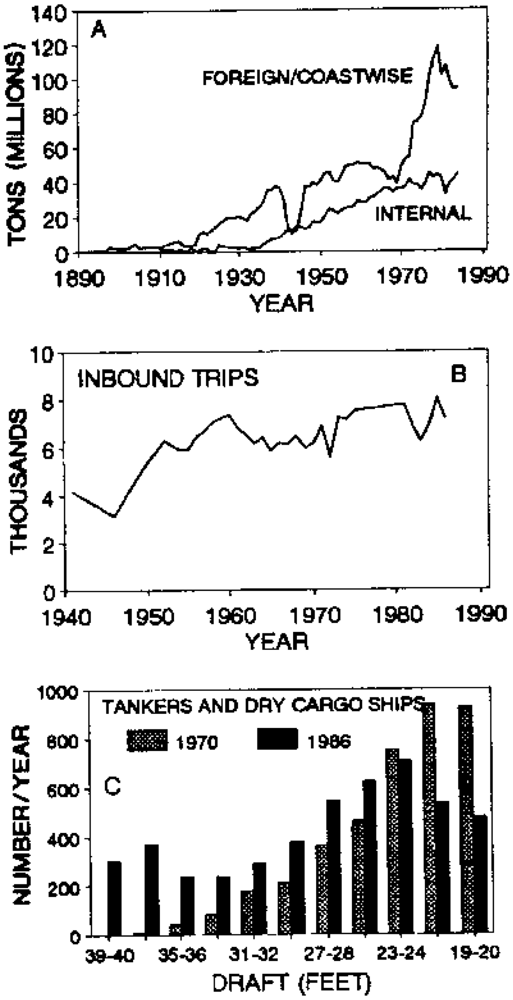

Figure 3.1. A. *Trends in waterborne commerce on the Houston Ship Channel. "Internal" refers to cargo transported only within the bay: "Foreign / Coastwise" cargo originated from, or was bound for ports outside the bay.* **B.** *Number of ships entering and leaving Galveston Bay through the Bolivar Roads Pass.* **C.** *Changes in the frequency distribution of various sized tankers and dry cargo ships (as measured by draft in feet) entering and leaving Galveston Bay. The data are from U.S. Army Corps of Engineers annual reports of Waterborne Commerce in the United States (1922-1986).*

since it was deepened and widened in 1966, the tonnage of cargo borne by ships on the channel has about doubled, from around 70 million tons/yr to about 140 million tons/yr. The increase has come not so much as a result of increased numbers of ships, but rather primarily because larger, deeper draft vessels have been able to enter the bay (Figure 3.1).

A $350 million plan to increase the dimensions of the ship channel once more — to 15.2 m deep by 182.9 m wide in most areas — was put forth by the U.S. Corps of Engineers in 1966. The sponsor of the project, the Port of Houston, argued that it is needed to permit Houston to continue to compete successfully with other deep water Gulf ports (Rice Center 1988). One projection is that the enlarged channel would nearly double the volume of grain exported from Houston, as larger vessels would cause the rerouting of Corn Belt grain away from New Orleans and other lower Mississippi ports (*Houston Post* 1987).

But work on this project has never begun, because of widespread opposition from most environmental groups and some Federal and State agencies, including the U.S. Fish and Wildlife Service, the Texas Parks and Wildlife Commission, the Texas Land Commission, the state attorney general's office, and the Texas Department of Agriculture. The project has become one of the most controversial, complex, and protracted battles in the history of the ship channel.

The U.S. Fish and Wildlife Service conducted a study to determine the expected impact of the ship channel enlargement. In October1986 it released a report in which it was concluded that the plan should "not be submitted to Congress for authorization because of severe, long-term impacts that cannot be mitigated with any predictability". The agency based its objection to the plan on the following areas of concern:

1. the anticipated loss of 60%-80% of the Galveston Bay oyster fishery due to increased salt water intrusion;
2. the loss of productivity associated with the disposal of dredged material on 44.3 km^2 of bay bottom;
3. the cumulative adverse effects of the project when superimposed upon previous alterations to the estuarine system and alterations from the implementation of future navigation and water supply projects; and
4. the potential for remobilization of toxic chemical contaminants in dredged material placed in a confined bay, with subsequent fishery losses caused by chemically-related mortality (U.S. Fish and Wildlife Service 1986).

There is evidence that the dredging of channels, along with increased withdrawal of Trinity River water, has substantially altered salinity patterns, mixing and circulation, and the distribution of some organisms, in the bay. Bernard Johnson (1975) noted that before dredging started in the 1850s, the main body of Galveston Bay was divided into two basins by Redfish Reef. Reports from the time indicate that this shell reef consisted of a chain of small islands covered in some areas with brush, with one main channel about 2 meters deep near Edward's Point. The upper portion of Galveston Bay including Trinity Bay must have been considerably fresher than today, especially at times of high river flow. Evidence for this comes from surveys that have shown few fossil oyster reefs in the upper bay, whereas many reefs were found on Redfish Reef and in the southern part of the bay. Today, however, active oyster reefs are found in the upper bay, especially along the path of the Houston Ship Channel. River flow has decreased due to man's use of the river water, and the dredged channels have increased the circulation between the two portions of the bay. This indicates better mixing in this part of the bay; that is, freshwater does not predominate for such long periods of time in the upper bay as before, when Redfish Reef was more effective in hindering mixing of fresh and salt waters (Bernard Johnson 1975).

Pollution in Buffalo Bayou and the Ship Channel

Pollution of Buffalo Bayou and other streams near Houston had become a concern very early in the city's history. In the 1830s large amounts of sand washed into the bayou in front of Houston's Main Street with every heavy rain. Problems with silting and water pollution appeared, and the success of industry intensified the pollution. On March 8, 1841, the city council took its first action to prevent industrial wastes from endangering navigation. An ordinance was passed forbidding deposits of sawdust on the banks of Buffalo Bayou or White Oak Bayou (Bernard Johnson 1975).

Before 1881, Houstonians obtained water from the bayous and from rain which was stored in cisterns and barrels, but in that year the Houston Water Works Company came into operation, providing piped water from a reservoir created by damming the Buffalo Bayou. But the water works was not very successful, as the supply was often inadequate for fighting fires and citizens complained about the quality of the drinking water. The Water Works Company began to drill artesian wells in 1888, and by 1891 it operated fourteen wells to supply a 18.1 km^2 area through 64.4 km of pipe. To meet the demands of firefighting, however, the company resorted to its old source, again placing Buffalo Bayou water in the mains (McComb 1981).

In 1893, people complained that tap water was no better than bayou water; fish died in the bayou as a result of creosote poisoning; "tar water" flowed from the pipes. Physicians noted a rise in "bowel" trouble, and even the wife of the president of the Water Company complained about the water. The president of the company promised more wells. But the trouble persisted. The Houston Cotton Exchange, referring to the bayou as "an immense cesspool, reeking with filth and emitting a stench of vilest character," asked the city council to halt pollution. The city engineer asserted that solids from toilets appeared in the bayou, and a reporter noted a sewer outlet dumping forty thousand gallons daily from the Houston and Texas Central shops into the stream *above* the Water Works dam (McComb 1981). Individuals and organizations like the Houston District Medical Association, waged a war of words with the president of the Water Company over the next six years, but conditions remained about the same.

In the late 1890s, some improvements finally seemed imminent. The city approved a $300,000 bond issue for a sewer system which would use advanced sewage methods in operation in only a few other places in the world. The reason for the city's sudden interest in waste treatment was an announcement by the Army Corps of Engineers that Houston had better clean the sewage out of Buffalo Bayou if it wanted federal help in constructing a ship channel. The system that was built consisted of collection pipes and pumps to convey the sewage to a treatment facility where it was filtered through various layers of broken stone, gravel, coke and sand. Heavy matter stayed on the surface of the beds where it dried and was later removed with rakes. The filtered effluent flowed in a long canal leading to Buffalo Bayou. At the opening inspection of the system the consulting engineer bragged about the purity of the effluent and demonstrated his conviction by dramatically drinking some of the treated water, declaring it quite palatable (McComb 1981).

But just a few years after its completion in 1902, the new facility was in a state of almost total inoperability, having been abused and neglected. On a tour of the facility, the Houston mayor found that the filters processed only half of the sewage, that sand beds were clogged and five feet deep in water, and that one of the beds was not in use at all because it leaked into the keeper's house. At the spot where the consulting engineer had drank, the mayor noted the malodorous atmosphere and commented, "Well, I do not know how the water looked when [he] drank it, but I readily relinquish any claim that I may have on any portion of it to [him] or anyone else who desires the quaff from it" (McComb 1981).

Yet this finding apparently did not spur substantial repairs. By 1916 it was estimated that 70% to 80% of the city's sewage was going directly into Buffalo Bayou. The same year, a reporter from the *Houston Post* found 35 private sewers draining into the bayou. By this time, however, a main impetus for cleaning up the bayou had been removed. The city no longer obtained its drinking water from the reservoir on Buffalo Bayou, having converted its entire system to artesian wells. In addition, the main body of the ship channel had already been built and there was no longer anything compelling the city to clean up its waste. It was far easier and cheaper to simply dump it into the water and let it move down to the bay. Buffalo Bayou was on its way to becoming a virtual open sewer (Smith 1972).

Although the municipalities built more sewage treatment plants and made some moves to clean the streams and prevent pollution, the efforts were not successful, especially after 1940, when Buffalo Bayou became even more seriously contaminated. Growing at increasingly rapid rates (more than 2,000 newcomers a month by the early 1970s), Houston was hard put to update its collection system and waste treatment plants. In addition to the approximately 150 sewage treatment plants which discharged raw or partially treated municipal and industrial wastes directly into the channel, or indirectly to its side channels and tributaries, the phalanx of petrochemical, chemical, steel-making and paper-making plants dumped raw or partially treated industrial wastes into these waters. In 1945, after complaints by residents and a polio scare, the U.S. Public Health Service inspected a sidearm of the bayou and found flowing into the stream enough raw sewage to equal that produced by a town of 54,000 people. Buffalo Bayou was 80% sewage. Only four industries responded to suggestions for improvements, and the Public Health Service investigator found himself maligned as having a personal interest in chlorine sales, since he recommended the disinfection of sewage (Environmental Protection Agency 1980; McComb 1981).

Apparently there was still no improvement during the 1950s and early 1960s, despite the creation of new federal, state and local institutions to deal with water pollution problems. Texas created a state water pollution control program in 1961, with a permit system for pollution discharges. Ironically, the City of Houston had no program for monitoring or enforcing water pollution until 1971. But Harris County, in which the city is located, had acted back in 1953 to create a Air and Water Pollution Control Section. Its director, Dr. Walter A. Quebedeaux became known as a reformer in pollution control. This intrepid investigator once had garbage dumped on his head from the stern of an Italian tanker while he was out in a rowboat searching for an oil leak (McComb 1981), but his cleanup and enforcement proposals faced continuous opposition from other local and state authorities (Smith 1972).

In spite of these new institutions, the ship channel remained critically polluted.

Smith (1972) concluded that the performance of the various governmental authorities in the two decades preceding 1970 had been a "dismal failure." Laws dealing with water pollution remained unenforced. Many industries along the ship channel dumped wastes far in excess of their permits, yet only a handful of prosecutions against these polluters had been started by the state. Municipal authorities in the Galveston Bay area were even more lax, Smith contended. The federal government had also moved too slowly to make its authority felt, doing "virtually nothing to secure compliance with federally approved standards or to initiate enforcement of laws on the books."

Ship Channel Cleanup: 1965-Present

The Situation in the Late 1960s

Dr. Quebedeaux, the Harris County pollution-control officer, reported in 1964 that most of Houston's sixty-four sewage treatment plants worked poorly and twenty-two operated at near capacity or beyond. The same year, the Texas Water Pollution Control Board claimed that most of the water in some tributary bayous came from treatment plants, and that 90 million gallons of sewage effluent flowed daily into the ship channel. In 1966 fire, feeding upon flammable material floating on the water, swept across the channel and burned a shipyard worker to death. In 1967 a Baylor Medical School doctor warned, "It's just plain sewer water. You shouldn't bathe in this water. You shouldn't even get it on your skin. You shouldn't have anything to do with it. It should be put in a closed pipe and carried out to sea." A commissioner of the Federal Water Control Administration commented after a 1967 inspection that "The Houston Ship Channel, in all frankness, is one of the worst polluted bodies of water in the nation. In fact, on almost any day this channel may be the most badly polluted body of water in the entire world. Most days it would top the list." A group of students from San Jacinto College even went so far as to hold a funeral service for the ship channel in mid-October, 1970. A large crowd gathered at San Jacinto Park next to the channel and a Harris County Health Department official read the death certificate. "Death," he said, "was caused by strangulation by municipal sewage and industrial slops in utter disregard of statutes". (Environmental Protection Agency 1980; McComb 1981).

By 1968, the load of pollution placed on the upper and lower Houston Ship Channel in terms of biochemical oxygen demand (BOD) — a measure of the organic matter in water which consumes oxygen during biological processes that break it down — was 208,656 kg per day, or the equivalent untreated sewage load produced in one day by a city of 2 million people. Approximately 69% of this load came from the concentration of industrial plants pouring improperly treated wastes into the channel, and 31% came from the inadequately treated sewage of local municipalities. In 1969, state water quality specialists measured dissolved oxygen levels of zero from the City of Houston's malfunctioning Northside Sewage Treatment Plant downstream to the San Jacinto Monument. Not only were there no fish and aquatic life along this upper channel 25.7 km segment, but water quality degradation had also caused frequent and massive fish kills in the upper portion of Galveston Bay (Environmental Protection Agency 1980).

Concentrations of the plant growth nutrients nitrogen and phosphorus in the channel were extremely high compared to those in Galveston Bay. For example, phosphate phosphorus (PO_4-P) levels had been measured as high as 15 mg/liter in the channel, while typical concentrations out in the bay were around 0.2 mg/liter. In addition to the phosphorus problem, levels of nitrogen, especially ammonium nitrogen, were consistently above 3 mg/liter, compared to typical open-bay levels of 0.1 mg/liter, or less. Contributions of inorganic nitrogen and phosphate phosphorus to the bay from the Houston Ship Channel for the 1968-1970 period were estimated to be approximately 6,350.4 kg and 19,958.4 kg, respectively (Texas Water Quality Board 1977). The concern was that these high nutrient loadings might adversely impact phytoplankton algae growth patterns farther out in Galveston Bay (Espey et al. 1971).

In addition, petrochemical and chemical wastes discharged at certain locations along the upper channel had colored the water black. Industrial oil spills from tanker transfer operations degraded the shoreline, and sludge from organic solids settled on the bottom, sending foul-smelling gas bubbles to the surface, also creating a tremendous dissolved oxygen demand.

Fecal coliform bacteria counts, a measure of bacterial pollution from human and animal wastes, posed a severe health threat. The state water quality standard for the upper ship channel was 2,000 fecal coliform organisms per 100 ml, but as late as 1973, fecal coliform readings at one monitoring station on the upper channel averaged over 72,000 organisms per 100 ml, and were sometimes as high as 2.2 million organisms per 100 ml (Environmental Protection Agency 1980).

The Houston Enforcement Conference

Several times in the late 1960s teams of federal officials had visited the Houston Ship Channel, "reaped publicity by pointing to it with shocked disbelief, and then returned to Washington and forgotten about it" (Smith 1972). But an important milestone in the history of pollution in the channel came in June 1971, when U.S. Environmental Protection Agency personnel, along with state and local officials, descended upon Houston for a six-day meeting formally known as the Federal Conference on Pollution Affecting Shellfish Harvesting in Galveston Bay.

The Federal Water Quality Act of 1965 had required Texas and all the other states to establish water-quality standards, subject to approval by the federal government, for all interstate waters within their jurisdictions, including Galveston Bay. Texas responded quickly with a set of relatively strong standards, requiring that the ship channel be kept at "an esthetically acceptable quality, that it be aerobic, and that the main portion of it be suitable for noncontact body recreation (the regulations were more strict for the open waters of the bay). Enacted in 1967, these channel standards proved to be little more than a sham according to one critic (Smith 1972), since state and local authorities were doing so little to bring enforcement. EPA had three courses of action it could pursue to seek enforcement of the standards. It could: 1) warn the state to come into compliance within 180 days; 2) convene a standard-enforcement conference, but only if requested to do so by the governor of the state; or 3) call a shellfish conference, by which the federal government could try to make a case that the shellfish industry had suffered from pollution.

EPA decided to pursue the shellfish enforcement conference remedy, even though their case was weak. Oyster harvests in the bay had been down in 1968 when federal officials had begun to consider a shellfish conference. Oyster production nearly doubled during the next two years, following the opening of more oystering grounds and a decrease in the size limit for harvestable oysters by Texas state agencies. As a result, federal officials shelved the shellfish conference idea, fearing that they would not be able to make a convincing argument. But it was decided to go ahead with the conference in 1971 because of pressure from concerned citizens and environmental groups, and a newly-released, critical Ralph Nader task force report. The focus of the meeting was EPA's contention that pollution, primarily from discharges into the Houston Ship Channel, was causing about half of the bay to be closed to oyster harvesting, thereby making a substantial dent in the economic returns of the shellfish industry (Environmental Protection Agency 1971a, 1971b).

Thus, to no one's surprise, the Houston conference did not conclude that economic harm to shellfish was occurring. In fact, state and federal evidence showed there was no substantial economic injury to Galveston Bay's shellfish taken from approved areas, and that these shellfish were, moreover, likely safe to eat. However, a joint state and federal program, based on an exhaustive EPA report of conditions in the channel and the bay presented during the conference, triggered a new and increased effort to abate pollution in the Galveston Bay system.

As a result, the Texas Water Quality Board agreed in December, 1971, to approve a pollution plan for the Houston Ship Channel's industries and municipalities which was expected to cost $800 million over a twenty-year period (Environmental Protection Agency 1980). A primary goal of the plan was to eventually limit the total pollution discharges into the channel to 15,876 kg of BOD a day, about one-sixth the load allowed under existing permits, with a slice of the total allocated to each municipal and industrial discharger. It had been calculated that this reduced BOD load would assure a minimum of one ppm dissolved oxygen in the ship channel (Smith 1972).

To achieve this goal, hundreds of millions of dollars would have to be spent to build and upgrade municipal and industrial wastewater treatment plants. Between 1973 and 1979, the EPA awarded $42.4 million to Houston and the cities of Pasadena and Bellaire to upgrade and expand several existing waste treatment plants to provide advanced secondary treatment, and also construct ancillary equipment such as sludge dryers, sludge handling equipment and an interceptor sewer system. These activated sludge secondary facilities were designed to remove 95% of the BOD and 93% of the total suspended solids in their discharges. In addition, between 1977 and 1979, the EPA awarded the City of Houston $165.7 million to construct the 69th Street Wastewater Treatment Plant, the largest and most advanced secondary sewage treatment facility in the Houston Metropolitan Area and one of the biggest activated sludge facilities in the United States (Environmental Protection Agency 1980).

CHAPTER 4

The Houston Ship Channel: Water Quality Trends

BOD Loading

For the purpose of setting water quality standards, the Texas Water Commission divides that part of the Houston Ship Channel between the Turning Basin and Morgan's Point into three segments. Beginning at the upper end, Segment 1007 includes the portion of the channel from the Turning Basin down to Green's Bayou; Segment 1006 extends from that point on down to the San Jacinto River; and Segment 1005 extends from there downstream to Morgan's Point. These three segments make up the "confined" part of the ship channel. Even though the channel extends beyond Morgan's Point across Galveston Bay to the Gulf of Mexico, it is the portion above Morgan's Point that is widely known as "the Houston Ship Channel" (Texas Water Quality Board 1977). This chapter concerns only this part of the channel above Morgan's Point.

The Texas Water Development Board began to follow ship channel trends in BOD loading in the late 1960s. Details about how the numbers were computed are not given in most of the reports. The basic procedure seems to have been to compute a BOD loading for each industrial or municipal discharge by multiplying averaged BOD values (mg/liter) times averaged daily wastewater discharge rates. The individual BOD loads were then summed to give the total daily BOD load for the whole channel. Actually, in most of the reports, two totals were presented; one for municipal wastes (sewage treatment plants), and another for the industrial wastes.

> *The Houston Ship Channel is not a swimming pool. It can never be a mecca for Sunday sailors and swimmers, for regardless of the increasing cleanliness of it's water, a sailboat and a human being are no match for immense ocean-going ships and tankers which have barely enough room to pass each other. Nevertheless, the plain fact is that we've improved an industrial stream that was once a sick pesthole, and by doing so, have improved water quality conditions in Galveston Bay, the most productive estuary in Texas.*
>
> Texas State officials, quoted in EPA (1980)

There are some discrepancies in the early 1970s BOD loadings given in the various reports (Table 4.1). The value for 1971 reported in the *Galveston Bay Project Summary Report* by the Texas Water Quality Board (1975b) is two-to-three times higher than numbers from two other soures. For 1970, both of the Water Quality Board reports (1975 and 1977) gave values that were about three times that in a 1984 Texas Department of Water Resource report summarizing historical trends in BOD loading to the ship channel. A less serious discrepancy involves the 1972 data, where the range in reported values is between 120,469 and 153,000 lb/day BOD. In other years, there were only minor differences in the numbers in the different reports. I do not know the reason for these differences. However, a retrospective review of available data, its sources, reliability and completeness was made by the Texas Department of Water Resources before publishing the 1984 *Wasteload Evaluation for the Houston Ship Channel*. The Texas Water Commission considers the data denoted by asterisks in Table 4.1 (and plotted in Figure 4.1) to be the most accurate available (D.E. Beckett, personal communication).

There has been an impressive downward trend in the ship channel BOD loading during the past two decades (Figure 4.1). In 1968 the combined municipal and industrial load was about 460,000 lbs/day. By 1971 the total had been reduced to around 100,000-150,000 lbs/day, due primarily to improvements in the industrial waste treatment. Both industrial and municipal loading gradually declined through the 1970s and 1980s so that by 1986 the total load was only about 25,000 lbs/day, or around 5% of what it had been eighteen years before.

Historically, a large majority of the total BOD discharge to the ship channel has come from only a few of the hundreds of discharges. The most significant ones during the period November 1975-October 1976 were five sewage treatment plants in Houston. They contributed 63% of the total loading at that time. The Houston Northside Plant was the largest, with 53% of the total (Texas Water Quality Board 1977). By late 1986, the number of permitted discharges to the channel had grown to 675 (534 domestic and 141 industrial), but 70% of the total wastewater flow, and two-thirds of the total BOD, originated from only six of the facilities. Gulf Coast Waste Disposal Authority, Washburn Tunnel Plant, discharged the greatest BOD load (5,766 lb/day), followed by Houston's 69th Street WWTP (2,841 lb/day), Houston's

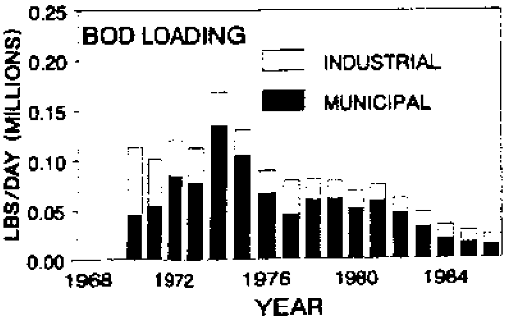

Figure 4.1. *Trends in BOD$_5$ loading to the Houston Ship Channel between 1968 and 1986. See Table 4.1 for data sources.*

Table 4.1. *BOD loading data for the Houston Ship Channel. Data Sources: 1) Texas Water Quality Board (1975b); 2) Texas Water Quality Board (1977); 3) Texas Department of Water Resources (1984b). *This data used in Figure 4.1.*

Year	Source	Municipal	Industrial	Total
1968	1			**460,000**
	2	140,000	320,000	**460,000**
1969	1			**356,000**
1970	1			**300,000**
	2	140,000	192,000	**332,000**
	*3	45,318	68,086	**113,404**
1971	1			**332,000**
	2	57,000	95,000	**152,000**
	*3	55,180	46,515	**101,695**
1972	1			**123,675**
	2	103,000	50,000	**153,000**
	*3	84,769	35,700	**120,469**
1973	1			**119,000**
	2	77,000	42,000	**119,000**
	*3	77,947	35,250	**113,197**
1974	1			**171,000**
	2	133,000	37,000	**170,000**
	*3	134,414	34,689	**169,101**
1975	2	106,000	19,000	**125,000**
	*3	104,859	25,986	**130,845**
1976	2	60,000	27,000	**87,000**
	*3	66,906	22,579	**89,485**
1977	*3	44,832	33,996	**78,828**
1978	*3	59,659	21,368	**81,027**
1979	*3	61,028	18,194	**79,222**
1980	*3	50,990	18,451	**69,441**
1981	*3	58,656	16,704	**75,360**
1982	*3	46,869	14,569	**61,438**
1983	*3	33,260	15,067	**48,328**
1984	*3	20,316	14,307	**34,623**
1985	*3	16,287	12,360	**28,648**
1986	*3	14,360	10,956	**25,316**

Sims Bayou WWTP (2,234 lb/day), Houston's Northside WWTP (2,046 lb/day), Exxon-Baytown Refinery Outfall #1 (1,914 lb/day) and St. Regis Paper Company (1,321 lb/day) (Texas Water Commission 1987b).

From 1968 to around 1975, the ship channel industrial polluters were much more successful than the municipalities in reducing their BOD contributions. This caused a dramatic shift to occur in the relative proportions of the total load attributable to these two source categories. In 1968, industry contributed 69% of the total pound-per-day BOD loading to the channel, and municipal dischargers contributed 31%. In 1972, this ratio changed sharply; municipalities now accounted for 67% of the BOD loading, while industry's share dropped to 33%. In 1981, this disparity was even greater; the municipal contribution jumped to 77% while industry's share dropped to 23%. By 1986, however, the municipal plants had made more progress, so that the ratio stood at 55% municipal and 45% industrial. A 1980 Environmental Protection Agency summary report entitled *Lower Houston Ship Channel and Galveston Bay, Texas: A Water Quality Success Story*, praised industries role in eliminating most of the BOD load by noting that :

> "In terms of pollution abatement, industry - long excoriated as the destroyer of the channel and Galveston Bay - no longer wears the black hat. For it has cleaned up its wastewater to the point that Harris County's Dr. Quebedeaux, known in the past as a vocal critic of industrial polluters, could say with confidence in 1976: "There are still some cases where industry needs to use better techniques. But the industrial segment, as a whole, has come a long way." (Environmental Protection Agency 1980)

Powelson (1978) attempted to identify and analyze the major factors responsible for the dramatic decline in industrial BOD loading to the ship channel between 1968 and 1976. He concluded that the reduction resulted from several interdependent factors, including: 1) low permitted BOD volumes, 2) *Operation Clean-Sweep*, 3) industrial anticipation of future strict legislation, 4) regional collective treatment plants, and 5) the 1972 Federal Water Pollution Control Act Amendments. Here are Powelson's findings summarized:

1. Low permitted BOD volumes as early as 1968 encouraged some of the dischargers to improve treatment facilities without being coerced through governmental enforcement. Powelson contends that during that period of time the Texas Water Quality Board rarely referred permit violators to Civil or District Courts, but rather tended to pursue compliance through negotiation.

2. *Operation Clean Sweep* was an enforcement policy initiated by the Texas Water Quality Board in November 1968. Its objective was to systematically investigate every waste discharge in Texas, to determine whether or not the discharger was in compliance with existing permits, and to specify any corrections needed "for protection of the waters of the State." By July 1972, over 1,500 dischargers had been surveyed, with 238 of these appearing before the Texas Water Quality Board. The program was criticized for concentrating on small-town municipal discharges rather than large industries, and for levying fines that were insignificant for large industries. However, the incentive to avoid adverse publicity seems to have resulted in many industries complying with instructions given by the Texas Water Quality Board for improvement of treatment facilities.

3. Powelson speculated that several industries, including Petro-Tex, Lubrizol, Shell Oil, and U.S. Gypsum, reduced their

BOD loading in anticipation of future rigorous regulations by state and federal agencies. Shell Chemical Company, for example, was one of the largest BOD dischargers in 1968, with an average loading of 43,000 lbs/day. At that time it had already started construction on additional treatment facilities, including an effluent incinerator for secondary solids, an oil separator, and pH controls. The consequences of these alterations was a decline in the BOD loading to 1,400 lbs/day by 1975. The company received no enforcement orders of any kind during this period. Developing, or maintaining, a positive public relations image may have played a role also. Powelson pointed out that by the late 1960s, it was becoming increasingly common for large industries, particularly oil refineries, to stress expensive treatment facilities in their advertising.

4. The Gulf Coast Waste Disposal Authority (GCWDA) was created by the Texas legislature in 1969 to help control water pollution in the Galveston Bay area. The nine-member Board of Directors is composed of three representatives from each of the three bay area counties under its jurisdiction (Harris, Chambers, and Galveston). GCWDA is one of the few authorities in the U.S. which gives industries the incentive to weigh the costs of individual treatment versus the costs of contracting a large regional collective authority, with its inherent economics of scale. The powers of the Waste Authority are broad; it can acquire in any legal manner, construct, improve, maintain, use or operate any facility needed to pursue its purpose. Additionally, the Authority has the power to tax up to 10 cents per $100 valuation if approved by the voters, and may issue revenue bonds to construct treatment plants. Finally, it may conduct hearings, investigations, and inspections, with the ability to sue for violations of Texas Water Quality Board permits.

Generally, the industrial participants pay the debt service on municipal bonds, as well as plant operation and maintenance costs. Industries also pay a management fee to the authority. The chief benefit to the public is that a government agency can monitor and control the dischargers. Industry also gets some advantages; its interest rate on the bonds is lower than it would be on industrial bonds. As of 1975, the industries contributed 70% of the revenue, and the State of Texas contributed 24%. Municipal users and administrative fees accounted for the remaining 6% of the budget.

The Authority maintains that one advantage of the central treatment of various types of waste is that the large-scale central facility, with sophisticated back-up and emergency facilities, is better designed to absorb occasional disruptions in its facilities. But critics have charged that industries are much less accountable for their own pollution and that the large flow masks the toxic pollutants of some industries, making them harder to detect and control.

In 1975, the main treatment plant operated by the GCWDA was the Washburn Tunnel Plant in Pasadena which began operation in 1973. This plant initially contracted with five industries to treat their wastes in a single biological waste treatment facility.

5. The 1972 Federal Amendments had an impact on the treatment facility improvements of some firms. One example was Southland Paper, an industry not affected by *Operation Clean Sweep*. It was reviewed, but was never called before the Water Quality Board, presumably because improvements in its treatment facility were progressing on schedule. Southland indicated to Powelson during his survey that the 1972 Federal Amendments influenced the company's abatement schedule. Between 1967 and 1977, its BOD load decreased from 6,400 lbs/day to 2,300 lbs/day. Another factor may have been the age of the

plant; that is to say, this was a new plant, built in 1967, which had installed relatively advanced treatment at the start.

It is noteworthy that the uppermost segment of the ship channel was not referred to in the title of the 1980 EPA report on the BOD reduction "success" story. Most of the industrial discharges, from which most of the BOD had been eliminated, were located in the middle segment of the ship channel, about a third of the way between the Turning Basin and Morgan's Point. Farther upstream, near or above the turning basin, were most of the Houston municipal wastewater discharges, including the largest - the Houston Northside plant. The fact was that in the 1970s there had not been nearly as much improvement in these plants, so that conditions were still rather poor in the uppermost ship channel segment. Designed to handle 55 million gallons per day (MGD), the Northside plant in 1975-76 was receiving 70-100 MGD, and it released nearly half the total BOD load to the ship channel (Texas Water Quality Board 1977). Installation of new sludge handling equipment in 1975-76 did bring down the plant's BOD loading by a great amount (Figure 4.2). This was the major factor in the downward trend in total BOD loading to the ship channel between 1974 and 1977 (Figure 4.1).

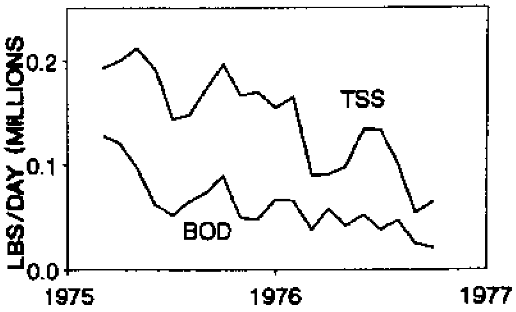

Figure 4.2. *Effluent BOD$_5$ and total suspended solids loading to Buffalo Bayou by the City of Houston Northside Sewage Treatment Plant during the period March 1975 to October 1976. From Texas Water Quality Board (1977).*

The domestic loading did not decrease any further, however, between 1977 and the early 1980s. A *Wasteload Evaluation* for the ship channel by the Texas Department of Water Resources (1984b) cited two reasons for this: "First, a number of domestic dischargers have not yet finished construction of wastewater treatment facilities capable of meeting the effluent limitations recommended by the 1974 Houston Ship Channel Waste Load Evaluation. Second, rapid population growth in the Houston area has caused a significant increase in domestic wastewater flows. . . The City of Houston treatment plants are being renovated and expanded under the timetable dictated in an enforcement order issued by the Texas Department of Water Resources. The Houston 69th Street Wastewater Treatment Plant began operation in October 1983, alleviating a portion of the loading to the Houston Northside facility. By the middle of 1984, the loading to the Houston Ship Channel that has resulted from the overloaded Houston Northside wastewater treatment plant should be significantly reduced."

Indeed, by 1986 the municipal loading was down significantly from those of the early 1980s (Figure 4.1). Besides the new 69th Street plant, there was another factor that probably contributed to this decline; namely, the economic recession that hit Houston in the early part of the decade. Between 1983 and 1986, the total flow from the municipal wastewater plants actually declined slightly, due to population emigration (Texas Water Commission 1987b).

Dissolved Oxygen

Standards for dissolved oxygen concentration have existed for segments of the Houston Ship Channel since 1967

(Texas Water Quality Board 1976; Policy Research Institute 1986). As early as 1973 they were set at 1.5 mg/liter in Segment 1007 (the Turning Basin area); 2.0 mg/liter in Segment 1006, from Green's Bayou down to the San Jacinto River; and 4.0 mg/liter from there on down to Morgan's Point (Segment 1005) (Texas Water Quality Board 1977). A 1984 Wastelaod Evaluation for the ship channel recommended that the standard for Segment 1007 be reduced from 1.5 to 1.0 mg/liter. It was stated in the report that this could be done without affecting the desired water uses (Texas Department of Water Resources 1984b).

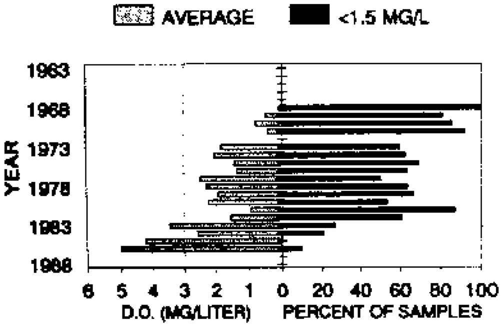

Figure 4.3. *Trends in annual mean surface dissolved oxygen (mg / liter) in Houston Ship Channel Segment 1007 (Turning Basin). See Appendices 2 and 3 for station locations.*

These rather modest dissolved oxygen standards for the ship channel are based on designated "uses to be protected" for the different segments that are an outgrowth of the controversial "zoning" of the channel by the Texas Water Pollution Control Board in 1964. In October of that year the Board adopted the policy that the upper part of the ship channel was to be considered as existing principally for purposes of navigation and industry, and not for recreation or for the support of marine life. The portion from the San Jacinto Monument to Morgan's Point would serve as a buffer zone to protect and preserve Galveston Bay for fishing and recreational activities (Williams 1972).

But until recently, even these low standards for Segment 1007 and 1006 were often violated. Figures 4.3-4.5 show the trends in annual mean surface water dissolved oxygen in the ship channel since 1963 (*See* Appendices 2 and 3 for description of data sources and stations). The Turning Basin, at the head of the channel, has historically had the lowest D.O. Relatively isolated from tidal exchange with Galveston Bay, this region depends on Buffalo Bayou inflow following periods of stormwater run-off to flush the heavy BOD

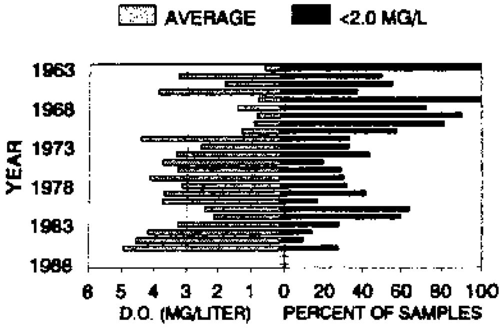

Figure 4.4. *Trends in annual mean surface dissolved oxygen (mg / liter) in Houston Ship Channel Segment 1006 (Greens Bayou to San Jacinto River). See Appendices 2 and 3 for station locations.*

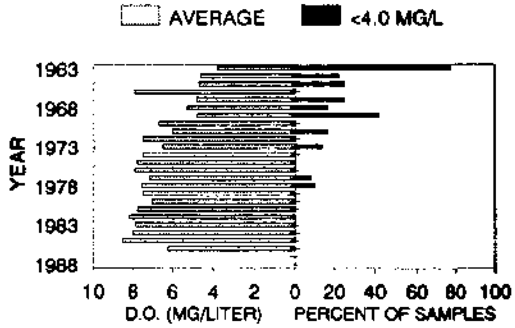

Figure 4.5. *Trends in annual mean surface dissolved oxygen (mg / liter) in Houston Ship Channel Segment 1005 (San Jacinto River to Morgan's Point). See Appendices 2 and 3 for station locations.*

load it receives from the Houston municipal waste plants. During periods when fresh water input is moderate to low, most of the oxygen in the Turning Basin is consumed by decomposing organic wastes. High ambient temperatures and calm weather that characterize summer low flow periods also contribute to oxygen depletion.

In the 1960s and 1970s the annual average dissolved oxygen in Segment 1007 increased slowly, but declined again in the late 1970s and early 1980s, following the same trends as the BOD loading. The 1968 annual average was <0.5 mg/liter, compared to mid-1970s values around 1-2 mg/liter. Since 1981, however, dissolved oxygen in this segment had improved rapidly. By 1985-1986 it was up to between 4 and 5 mg/liter. The percentage of samples violating the standard also has fallen rapidly in recent years. In most years during the 1960s and 1970s 40% to 80% of all the samples were below 1.5 mg/liter. In fact, many had undetectable dissolved oxygen. But 1981, the percentage of violations has decreased rapidly to less than 10% in 1985 and 1986.

Farther down the ship channel, in Segment 1006, there has also been improvement in oxygen conditions, although they were never as low as in the Turning Basin area. Since 1963 the annual mean has risen from around 1 mg/liter to 4-5 mg/liter (Figure 4.4). Most of the improvement had taken place by 1973, perhaps a reflection of the early efforts to remove BOD by some of the industries in this segment. The percentages of standard violations have declined, but still, in recent years 10%-30% of the samples have fallen below the 2.0 mg/liter standard.

Decreasing BOD loading in the upper ship channel has also led to increases in oxygen in Segment 1005 between the San Jacinto River and Morgan's Point. This segment receives most of its oxygen demanding wastes from the segments farther upstream rather than from industries along its shores. Also, situated closer to the bay, it has better tidal flushing. A third factor is flushing by the San Jacinto River, which empties into the channel at the upper end of this segment. Thus, historical dissolved oxygen concentrations have been relatively high here (Figure 4.5). In the 1960s the annual means were around 4-5 mg/liter. Since then they have increased to about 8 mg/liter. Again, the cause of the improvement is decreased BOD loading from Segments 1006 and 1007 farther up the channel. The 4 mg/liter standard for this segment is seldom violated.

Nitrogen and Phosphorus

There have never been standards for nitrogen and phosphorus in the ship channel or any other part of the Galveston Bay system. But there has been concern about ammonia nitrogen levels, since nitrification (oxidation of ammonia to nitrate nitrogen) is an oxygen consuming, biological process. The Texas Department of Water Resources, and more recently the Water Commission, have attempted to control ammonia nitrogen in the ship channel by means of the Wasteload Allocation Process. This involves setting limits on the NH_4 concentrations in the discharges from waste treatment plants (Policy Research Institute 1986), but does not set a standard for waters in the ship channel. In recent years, the discharge concentrations were supposed to be in the 3-5 mg/liter (as NH_3-N) range for the sewage treatment plants (Texas Department of Water Resources 1984b). But the measured ammonia concentrations in a 1985 Intensive Survey of some of the municipal and industrial effluents ranged up to 50 mg/liter (Texas Water Commission 1987b).

Nevertheless, better waste treatment has led to significant decreases in ship channel ammonia nitrogen concentrations during the past two decades (Figures 4.6-4.8). At the turning Basin (Segment 1007), NH_4-N averaged around 4-5 mg/liter in the early 1970s. It came down a little during the next decade, but has shown the most improvement since 1983, dropping from 4 mg/liter to around 1.5 mg/liter (Figure 4.6). In Segment 1006, upstream from the San Jacinto River, NH_4-N also decreased, from about 5 mg/liter in 1970 to less than 1 mg/liter by 1986. Most of the decline here seems to have taken place in the mid-'70s. There was actually little change from about 1977 through 1982, with the concentrations remaining at about 1.5 mg/liter. Finally, in the most downstream ship channel segment, 1005, NH_4-N went from around 1.5 mg/liter in 1970 to less than 0.3 mg/liter in 1986.

In the early 1970s, nitrate nitrogen (NO_3-N) was not very concentrated in the ship channel, compared to ammonia. But as the ammonia nitrogen declined, the nitrate nitrogen levels increased, especially in the two upper segments. The result was that by 1986, nitrate concentrations were equal to, or greater than, the ammonia concentrations. For example, in Segment 1007, the 1973 nitrate was only about 0.2 mg/liter, or about 5% of the total dissolved inorganic nitrogen (DIN - the sum of ammonia plus nitrate). In 1986, however, the nitrate averaged nearly 2 mg/liter, which was about two-thirds of the DIN total. Undoubtedly, one important reason for this shift was that nitrification became more pronounced, especially in the upper channel segments, as the dissolved oxygen concentrations rose.

The consequence of this increased nitrification rate is that the DIN concentrations have not declined as much in the channel as would be indicated from the

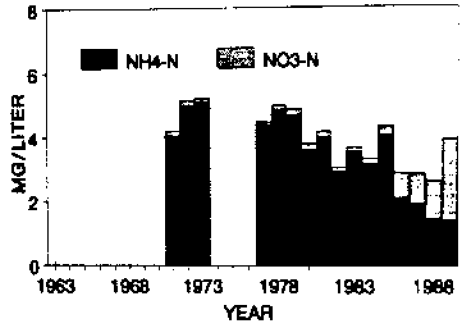

Figure 4.6. *Trends in ammonia (NH_4-N) and nitrate (NO_3-N) nitrogen concentrations in Houston Ship Channel Segment 1007 (Turning Basin). See Appendices 2 and 3 for station locations.*

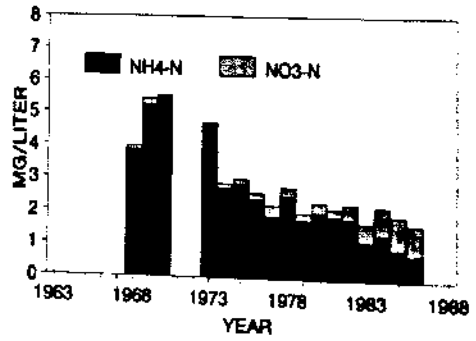

Figure 4.7. *Trends in ammonia (NH_4-N) and nitrate (NO_3-N) nitrogen concentrations in Houston Ship Channel Segment 1006 (Greens Bayou to San Jacinto River). See Appendices 2 and 3 for station locations.*

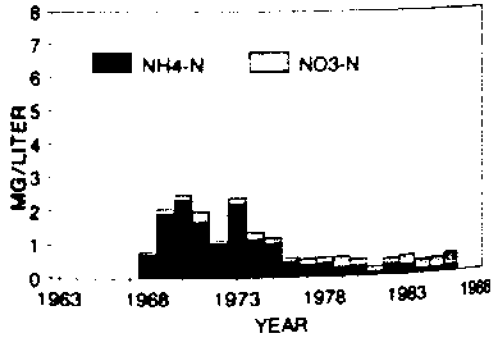

Figure 4.8. *Trends in ammonia (NH_4-N) and nitrate (NO_3-N) nitrogen concentrations in Houston Ship Channel Segment 1005 (San Jacinto River to Morgan's Point). See Appendices 2 and 3 for station locations.*

ammonia nitrogen data alone. Apparently, the improved waste treatment processes employed to remove much of the ship channel BOD load have not been nearly so effective in removing nitrogen. This comes as no surprise, since it is well known that conventional secondary sewage treatment processesremove only 25-45% of the nitrogen in sewage (Gakstatter et al. 1978).

Phosphorus concentrations in the ship channel have shown about the same temporal spatial trends as those for nitrogen (Figures 4.9-4.11). Both total phosphorus (TP) and phosphate phosphorus (PO_4-P) are more concentrated in the upper channel segments, and both have declined substantially since the late 1960s. For example, in Segment 1007, TP was about 3 mg/liter in the early 1970s, but now is down to around 1.5 mg/liter (annual averages). Phosphate phosphorus has decreased from 2.3 mg/liter in 1977 to 1.2 mg/liter in 1986. The similarity in the TP and PO_4-P concentrations indicated that most of the TP is inorganic. In other words, only a small fraction of the TP is particulate or dissolved organic phosphorus.

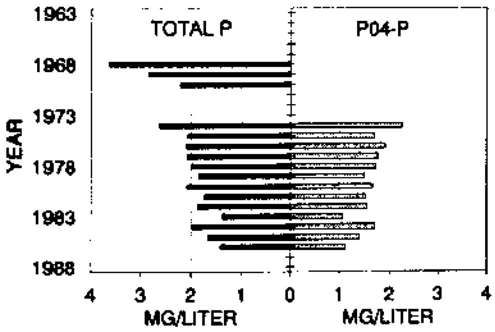

Figure 4.9. *Total phosphorus and phosphate phosphorus (PO_4-P) trends in Houston Ship Channel Segment 1007 (Turning Basin). See Appendices 2 and 3 for station locations.*

Metals

Petrochemical industries along the Houston Ship Channel use large quantities of metals as catalysts in a variety of manufacturing processes, such as the production of styrene (chromium, copper, iron, and zinc) and polyethylene (chromium and nickel). Zinc chromate, which has algicidal properties, is added to cooling water to prevent fouling of the cooling equipment by algae. In addition, some metals are present in significant amounts in municipal wastewater discharges. Thus, it is rea-

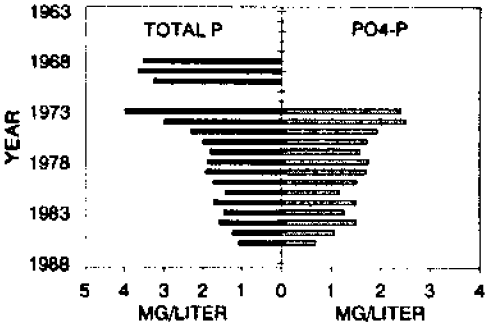

Figure 4.10. *Total phosphorus and phosphate phosphorus (PO_4-P) trends in Houston Ship Channel Segment 1006 (Greens Bayou to San Jacinto River). See Appendices 2 and 3 for station locations.*

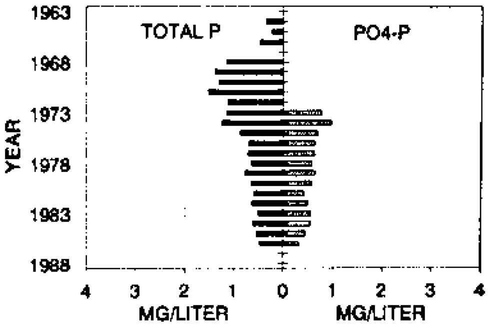

Figure 4.11. *Total phosphorus and phosphate phosphorus (PO_4-P) trends in Houston Ship Channel Segment 1005 (San Jacinto River to Morgan's Point). See Appendices 2 and 3 for station locations.*

sonable to assume that toxic materials would be a major issue for the Galveston Bay system. In fact, however, these pollutants have been studied not nearly as thoroughly as BOD loading and oxygen, nutrients, and freshwater inflow. In fairness, it should be kept in mind that the same applies to most other estuaries around the nation, including those in other highly industrialized areas. Some of the reasons for this are the lack of reliable, sensitive measurement techniques in the past; high analytical costs; and uncertainty about the degree of toxicity of a given concentration of a particular metal or organic pollutant. Also, the chemical behavior of toxic metals in aquatic ecosystems is very complex, involving exchanges among water, sediments and organisms. The rates of these exchanges are determined by a number of physical/chemical conditions, and the toxicity of the metals varies, depending on their chemical form in the environment.

Heavy metals have been sampled more often than toxic organic compounds in the Galveston Bay system, and as would be expected, most of the metals samples have come from the water and sediments in the Houston Ship Channel. Since 1974 the Texas Water Quality Board and the Water Commission have sampled sediments at four sites in the ship channel. They also take water samples quarterly at six ship channel stations. Routinely the water samples come from one foot beneath the surface, and the sediment samples are taken with either an Eckman or Petersen-type dredge, which samples the upper few inches of sediment (Texas Water Commission 1986c). Earlier data, from the late 1960s and early 1970s, were reported by Copeland and Fruh (1970) and Hann and Slowey (1972).

A 1969 grab sample survey of effluents showed that thousands of pounds of some metals were being discharged per day into the Houston Ship Channel. Of the five metals analyzed, zinc was being released at a rate of 7,886 pounds/day, followed by copper (2,332 pounds/day), lead (1,630 lb/day), cadmium (1,098 lb/day) and chromium (336 lb/day). A few industries and/or municipal waste plants, were responsible for high percentages of the total production of each metal. For example the Houston Northside Sewage Treatment Plant and three ship channel industries accounted for about two-thirds of the zinc load; and over 95% of the cadmium came from one industry (Environmental Protection Agency 1971a).

But in the late 1960s and early 1970s, metals waste loads from the industrial plants probably began to decline. At least this was the conclusion reached in a 1977 Texas Water Quality Board report comparing the 1969 data with data collected between 1972 and 1974 (Table 4.2). The report's authors called the general pattern of reduction by these selected industries "representative," and concluded that it mainly reflected recent improvements in the treatment afforded industrial wastewater.

As would be expected, reduced metals loading to the ship channel has led to more

Table 4.2. *Comparison of trace metals discharged to the Houston Ship Channel by selected dischargers in 1969 and 1972-1973. All values are pounds per day. From Texas Water Quality Board (1977).*

Metal	Discharger	1969	1973
Cadmium	Stauffer	2.0	0.1
Chromium	Goodyear	6.0	3.7
	Petro-Tex	10.0	111.0
	Stauffer	2.0	0.1
	Tenneco	18.0	10.1
	Houston Northside	47.0	27.0
Copper	Tenneco	20.0	1.4
Lead	Stauffer	2.0	0.1
Zinc	Armco	146.0	32.0
	Tenneco	38.0	18.0
	Houston Northside	1,030.0	184.0

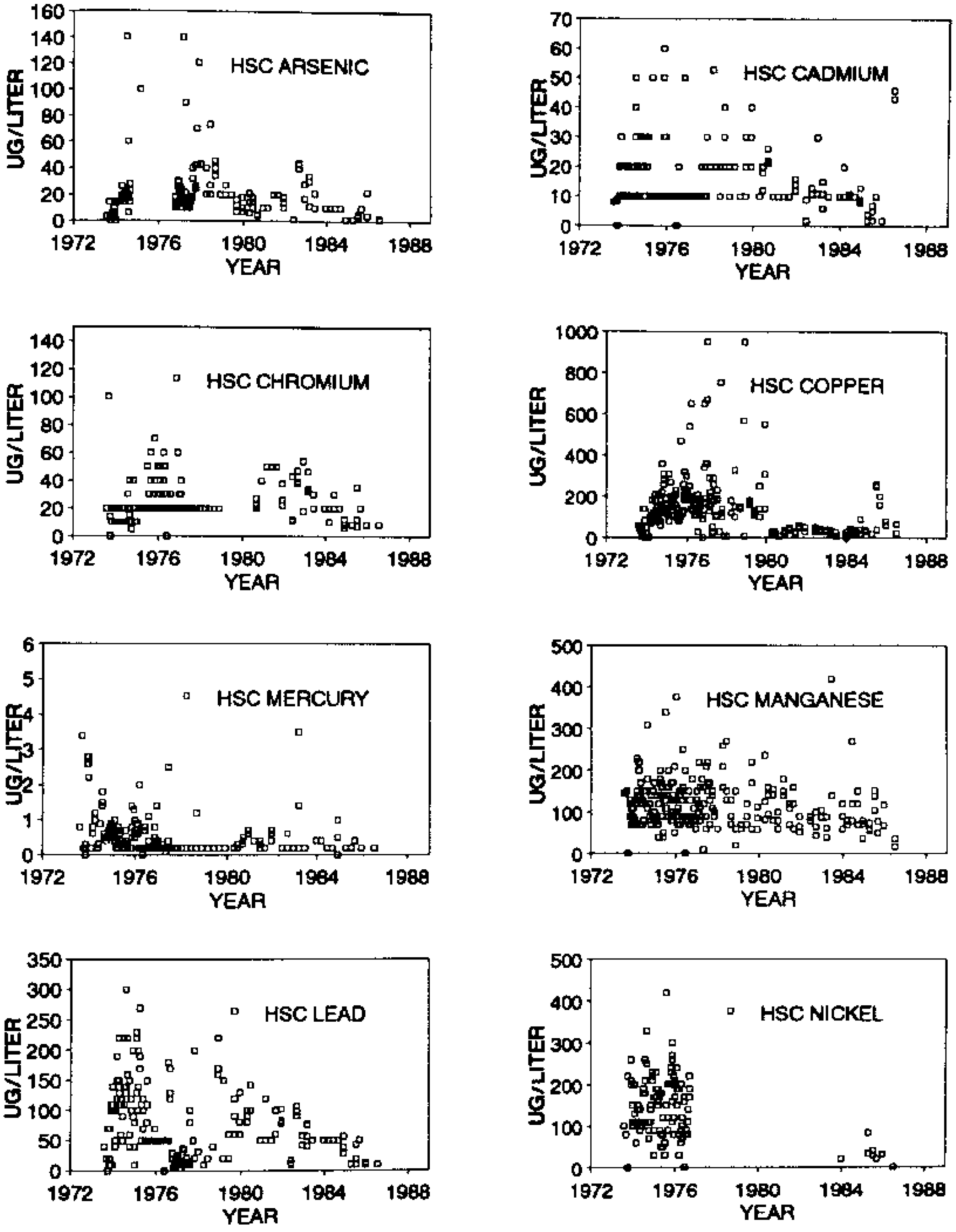

Figure 4.12. *Metals concentrations in Houston Ship Channel water, 1974-1986. Data are for Texas Water Commission Segments 1005, 1006, and 1007.*

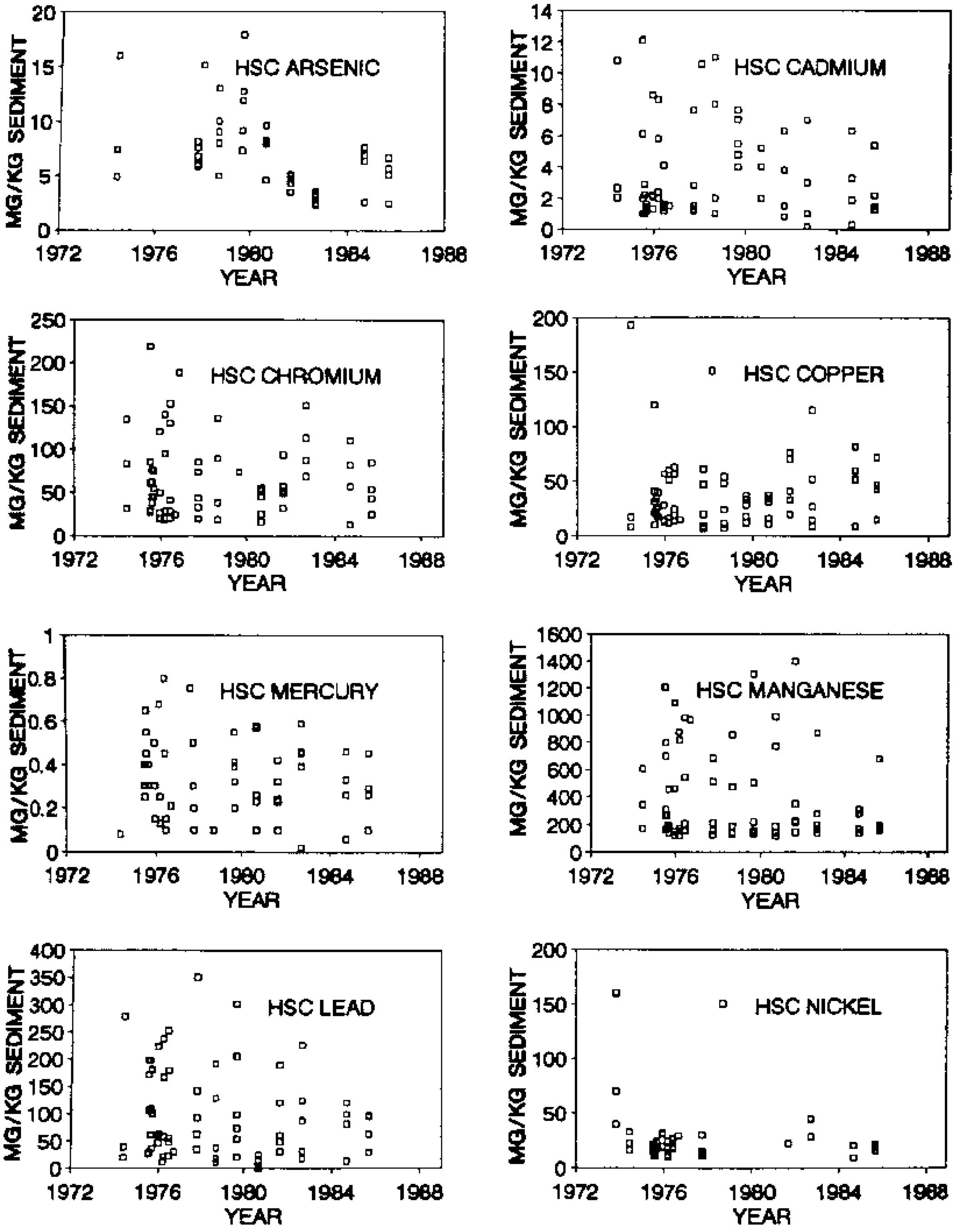

Figure 4.13. *Surface sediment metals concentrations in the Houston Ship Channel, 1974-1986. Data are for Texas Water Commission Segments 1005, 1006, and 1007.*

substantial declines in concentrations of these materials in the water than in the sediments. Figures D4.12 and D4.13 show plots of all the data collected by the Texas Water Quality Board and Water Commission between 1974 and 1987. Arsenic, chromium, and lead have shown the strongest declines in the water samples. In the 1970s arsenic was frequently greater than 30 µg/liter, but since 1984 almost all the readings have been below 10 µg/liter. Maximum chromium levels have decreased from 70-100 µg/liter to around 40 µg/liter, and lead levels have fallen from a maximum of 300 µg/liter in 1974 to a maximum of 100 µg/liter in 1986 (Figure 4.12).

Arsenic, cadmium and lead levels in the ship channel sediments appear to be trending downward, but for the other metals there are no obvious trends (Figure 4.13). Before 1982 about half the arsenic values were above 8 mg/kg sediment; since then they have all been below 8. Average lead levels in the 1984 and 1985 samples were also down by about 50% from those taken a decade earlier. Similarly, cadmium concentrations seem to have declined modestly since the 1970s. In 1986 the maximum was 6 mg/kg sediment, compared to 11 mg/kg sediment in 1974 and 1978.

Both water column and sediment values for a given metal have ranged widely, but there are several factors that could explain this. One is that the highest concentrations are probably very localized because, as was noted above, some of the metals are discharged in large quantity by only a few industries. Second, the data plotted in Figure 4.13 are for the whole ship channel (Segments 1005-1007). It has been shown by Hann and Slowey (1972) that, in the early 1970s at least, there was a clear trend of decreasing sediment metals concentrations as one moved down the ship channel. This is a reflection of the high concentration of municipal and industrial outfalls along the upper one-third of the channel. Finally, as White et al. (1985) pointed out, estuarine sediment concentrations of many of the metals are naturally highest in muddy sediments and lowest in sandy sediments.

Nevertheless, sediment concentrations of several of the metals have remained substantially above screening levels for dredged sediment disposal proposed by the U.S. EPA (1974) (Figure 4.13). Most of the arsenic, cadmium and lead samples collected by the Texas Water Quality Board and Water Commission since 1974 have been above the screening levels, while nickel, manganese and mercury levels have usually been below the EPA thresholds. About 25% of the chromium and copper values were above the thresholds.

Knowledge of the impacts that metals and other toxics have had on Galveston Bay organisms is very sketchy. Copeland and Fruh (1970) showed that various species diversity indices were inversely related to the calculated concentrations or discharges from the Houston Ship Channel. It was also demonstrated that estuarine waters that were more concentrated in wastewater discharges exhibited a toxic or growth depressing effect on natural and pure cultures of phytoplankton. Further work showed that unknown toxic materials being introduced via the Trinity River and the Houston Ship Channel depressed phytoplankton growth rates.

King et al. (1986) criticized the monitoring for organic contaminants in ship channel sediments performed by the U.S. Army Corps of Engineers before dredging. Sediments are normally analyzed for 21 parameters, but nine of these are chlorinated hydrocarbons that have been banned from use in the United States. King et al. contended that since levels of these contaminants have been declining since 1972 in most locations that are monitored through the National Contaminant

Biomonitoring Program (Cain 1981; Cain and Bunck 1983; Schmitt et al. 1983), they should be dropped from the Corp's routine monitoring of channel sediment. On the other hand, they argued, there are some chemicals that are not currently monitored, but which should be included: selenium, phthalate esters, phenols, polycyclic aromatic hydrocarbon (PAH) compounds, and chlorinated styrenes. A preliminary study by the U.S. Fish and Wildlife Service has shown that volatile (2 or 3 ringed) polycyclic aromatic hydrocarbons (PAH) were below limits of detection in the ship channel. But it was suspected that larger (4 and 5 ring), less volatile PAH compounds, which were not measured, may be present in concentrations high enough to cause "significant contamination" of bay sediment. However, this conclusion was based on indirect evidence -- no actual measurements of these compounds had been made at the time of this report (King et al. 1986).

Plankton, Benthos, Fish, and Public Perceptions

Although the Houston Ship Channel had been "irrevocably altered in terms of its capacity to support certain kinds of wildlife" according to a Texas Water Quality Board report (1977), it "is inhabited by a substantial portion of the biological community that characterizes the Galveston Bay complex as a whole." "Furthermore," the report stated, "The numbers and kinds of organisms present have increased in the past five years [1972-1977], due largely to water quality improvement resulting from reductions in waste discharges." The report went on to describe in detail the changes in abundance for different kinds of organisms in the ship channel. Here is a summary of the findings:

1. Both pollution-tolerant and other kinds of phytoplankton algae grew in the ship channel. The highest species and individual counts were found at Morgan's Point. It is almost certain that phytoplankton production in the channel is limited by contaminants, as both nitrogen and phosphorus are present in amounts to support a much larger standing crop of phytoplankton. Copeland and Fruh (1970) toxicity test results - as described above - were cited as supporting evidence for this conclusion.

2. Zooplankton concentrations also decline up the channel from Morgan's Point. Probable reasons for this pattern include the gradient in dissolved oxygen, and less availability of food (algae, bacteria, or other zooplankton), and increased toxicity upstream.

3. The earliest studies of the ship channel benthos were by Chambers and Sparks (1959). They found no living organisms in samples from the deep (dredged) portion of the channel. More recently (1972-1976), benthic organisms were still scarce or completely absent at the Turning Basin, but were present in samples taken farther down the channel.

4. The low concentrations of oxygen and higher levels of some toxic materials in the upper channel depress nektonic life there. Oxygen depletion and toxic substances, probably aggravated in their effects by sudden temperature and salinity changes during heavy storm runoff periods, have also been responsible for fish and invertebrate kills. There is good evidence, however, that water quality is becoming more suitable for a variety of nekton. Shrimp and crabs were being caught on the water intake screens at an industrial facility 11.5 miles downstream from the Turning Basin as early as October 1971. "We counted 8,000 organisms in 1973, 78,000 in 1975, and almost 117,000 in 1977, a 75% increase at this upper channel location," a Texas Department of Water Resources biologist was reported to have said. In November, 1972, fish and crabs

began to be collected from another intake 20 miles below the Turning Basin (Texas Water Quality Board 1977).

Accounts from newspaper articles written in the early-to-mid 1970s were used by EPA in its 1980 summary of ship channel pollution cleanup. These stories suggest that there were some changes in the public's perception of the channel and Galveston Bay. The following is from that report, entitled *A Water Quality Success Story: Lower Houston Ship Channel and Galveston Bay, Texas* (U.S. EPA 1980).

> It didn't take long for people working and living along the channel to notice and appreciate these improvements. In late 1972, the executive vice president of the Pasadena Chamber of Commerce was invited to eat at Diamond Shamrock's snack bar, where he was served shrimp cocktail made with fresh shrimp from the channel. "They were delicious," he said, "and I haven't had any ill effects." A year later, an officer with a company even farther upstream wrote to the Texas Water Quality Board: "(Your) hard work in improving the Houston Ship Channel is paying off. We recently repaired a condenser using ship channel water for cooling. Part of the blockage was shrimp and crab. We know they were showing up downstream, but this is the first we've heard of this type of marine life this far upstream." According to a diver working these waters, "not too long ago the channel water ate the zipper right out of my diving suit in two or three months, but not it takes a year or more. I can see much better underwater, the water tastes as if it had fresh water mixed in with it, and the odor is much better, too." A boat captain and the founder of a canoe club were also impressed. According to the captain, "this stream is cleaner than I've ever seen it. The sea life is improving and coming farther up the channel. Fact is, I have to scrape barnacles off my hull that weren't able to grow a few years back." "I agree with that," said the canoe club director. "Our club folded up because of pollution, but now we've reorganized because the channel is much, much improved — and there's plenty of fish and aquatic life. While we know that the channel is a busy transportation artery," he added, "we're still going to give it a sportsman's try."

In an article which appeared in the November 2, 1975 issue of the *Houston Chronicle*, outdoor staff writer Joe Doggett had more good news for local sportsmen. "Up to last week," he wrote, "I would have vowed that a fisherman would be more apt to catch typhus than tarpon from the upper reaches of the Houston Ship Channel . . . but an employee of a power plant in Pasadena rewrote my thinking when he discovered hundreds of baby tarpon milling around the plant's warm water discharge pipe at the junction of the ship channel and Vince Bayou . . ." Shortly after, Doggett, who admitted that he was "immediately skeptical," drove out to the site to see for himself. "We fished for several hours and saw hundreds of tarpon within a hundred-yard stretch. Most of them were about a foot long, but some were as small as five or six inches, and others looked close to 10 pounds. We jumped about 10 fish each and landed two, and I was goggled at the sight of so many tarpon being so close to where they had no business being."

CHAPTER 5

The Trinity River

Water Quality in the River in 1975

Since 1975 the state of Texas has submitted *Water Quality Inventories* to the U.S. EPA every year, or more recently, every other year. These reports summarize existing water quality problems in the state, fulfilling requirements of Section 305(b) of the Federal Water Pollution Control Act passed by Congress in 1972.

The Trinity is one of 23 inland and coastal basins designated by the Water Commission for purposes of water quality management and planning. Like the others, the Trinity is subdivided into segments (Figure 5.1). All the numbers assigned to the Trinity segments begin with the prefix 08, and there are 35 segments in the basis. The principal segments are described in Table 5.1. Generally, the low-numbered segments are farthest downriver.

In the first Inventory, it was reported that:

> The main stem of the Trinity River receives all the municipal and industrial effluent from the Dallas-Fort Worth area and during low flow conditions, these effluents comprise the total flow of the upper Trinity. . . The East Fork of the Trinity is totally dominated by sewage effluent and imposes a vast waste load on the main stem. The Elm Fork tributary and Ten Mile Creek also add waste loads. The result is extremely low dissolved oxygen readings and coliform bacteria violations for quite some distance down the main stem of the Trinity (well into Segment 804).
>
> Many reservoirs in the Trinity Basin are experiencing rapid eutrophication and resulting nuisance algal conditions and high pH levels due to critical concentrations of nutrients contributed by municipal effluents.
>
> (Texas Water Quality Board 1975a)

> *The overall condition of parts of the river, particularly the East Fork, is disgraceful. Even though I was prepared mentally for what I was going to see . . . it was amazing. Water in the East Fork runs as a thick sludge —almost black in color with no fish. But the Trinity River has a lot of potential. It's coming back. The river is downright beautiful in some places. I think it's worth saving.*
>
> R. Irwin, U.S. Fish and Wildlife Service,
> quoted in *Houston Post* article (1985).

Another indication of the poor water quality in the Trinity in 1975 was the low ranking of some of its segments, compared to other streams in Texas. For example, Segments 804 and 805, between Lake Livingston and Fort Worth, were ranked as the sixth and fourth worst (out of 288) in the state. Segment 803, Lake Livingston, was the 15th worst. Farther upstream, stretches of the West Fork of the Trinity below Lake Worth (Segment 806), and the East Fork of the Trinity (Segment 819) were also poorly ranked. None of these segments met the stream standards applicable at that time, and some were deemed unsuitable for contact recreation or

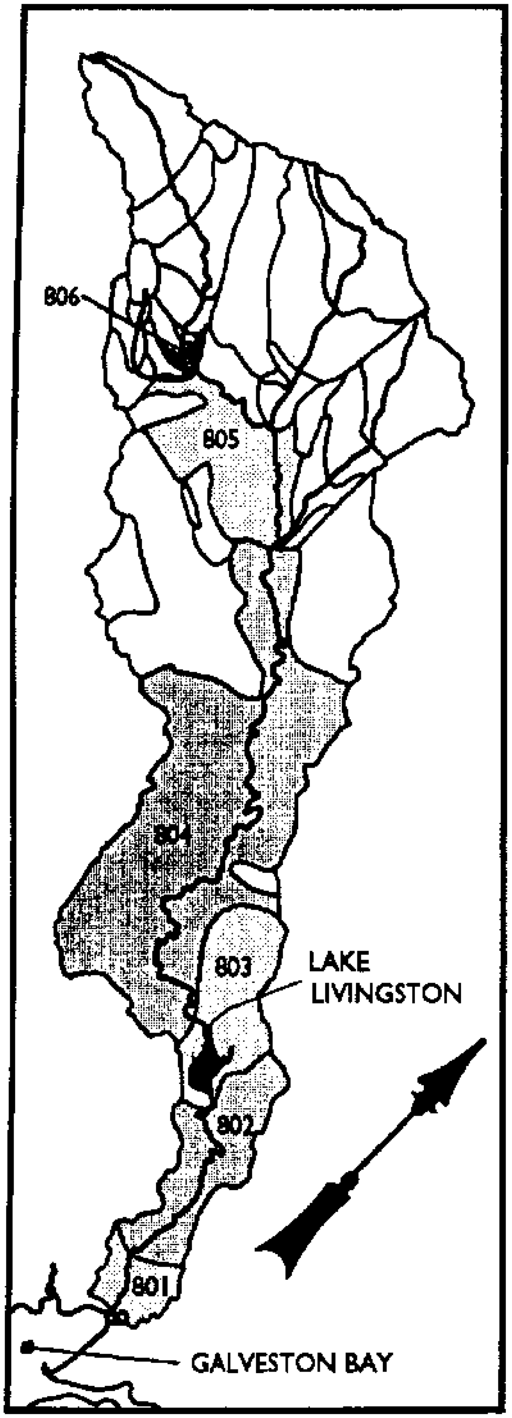

Figure 5.1. *Trinity River Basin segments, as designated by the Texas Water Commission for management purposes. Redrawn from Texas Department of Water Resources (1981b).*

domestic raw water withdrawal (Texas Water Quality Board 1975a).

In addition to low dissolved oxygen and high coliform counts, the Trinity River below the Metroplex area has historically carried very heavy loads of nitrogen and phosphorus. In the 1970s, total nitrogen averaged about 15 mg/liter in the Dallas area under low flow conditions, and total phosphorus was 8-10 mg/liter (Figure 5.2). Typical total nitrogen and phosphorus loads in this river segment were around 35,000-40,000 pounds per day and 15,000-20,000 pounds per day, respectively (Texas Department of Water Resources 1978).

An early Texas Department of Health report in 1925 had described fish kills along the Upper Trinity River where there were heavy loads of organic materials discharged from the packing houses and wastewater facilities of Dallas and Fort Worth. The state began a fish kill inventory in 1970, and an analytical study of the thirteen kills documented between 1970 and 1985 indicated that most kills in the Trinity are caused by low dissolved oxygen levels (Texas Water Commission 1987a).

A 1972-74 study by the Texas Parks and Wildlife Department showed that the Upper Trinity River fishery was depauperate in a segment downstream from the Metroplex, with an average of less than one species per sampling period and a total of only four species (Figure 5.3). Fish were totally absent during four of the six collecting periods. Farther downriver, the fishery improved gradually and was relatively healthy in the Lower Trinity above Lake Livingston (Texas Parks and Wildlife Department 1974).

In a 1975 report, it was concluded that there had been no improvement in water quality in the upper Trinity River (Segment 0805) in the preceding 15 years (Warshaw 1975). This conclusion was based on a lack of trend in either dissolved oxygen or total suspended solids (Table 5.2) at a station 20

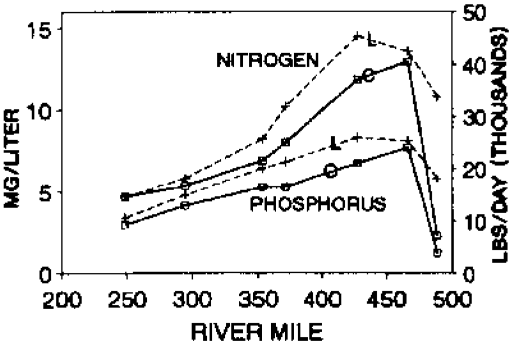

Figure 5.2. *Historical low-flow nutrient concentrations (C) and loads (L) in the Trinity River between Dallas and State Highway 7 near Crockett, Texas (1972-1975). River Miles indicate distance upstream from Galveston Bay. Redrawn from from Texas Department of Water Resources (978).*

Table 5.1. *Locations of selected segments of the Trinity River Basin, as designated by the Texas Water Commission.*

Number	Name and Location
0801	**Trinity River Tidal**: from the confluence with Anahuac Channel in Chambers County to a point 3.1 km downstream of U.S. 90 in Chambers County.
0802	**Trinity River below Lake Livingston**: from a point 3.1 km downstream of U.S. 90 in Chambers County to Livingston Dam in Polk/San Jacinto County.
0803	**Lake Livingston**: from Livingston Dam to a point 1.8 km upstream of Boggy Creek in Houston/Leon County, up to the normal pool elevation of 131 ft.
0804	**Trinity River Above Lake Livingston**: from a point 1.8 km upstream of Boggy Creek in Houston/Leon County to a point 100 m upstream of SH 31 in Henderson/Havarro County.
0805	**Upper Trinity River/Lower West Fork Trinity River**: from a point 100m upstream of Beach Street at Forth Worth in Tarrant County to Lake Worth Dam in Tarrant County
0806	**East Fork Trinity River**: from the confluence with the Trinity River in Kaufman County to Rockwall-Forney Dam in Kaufman County.

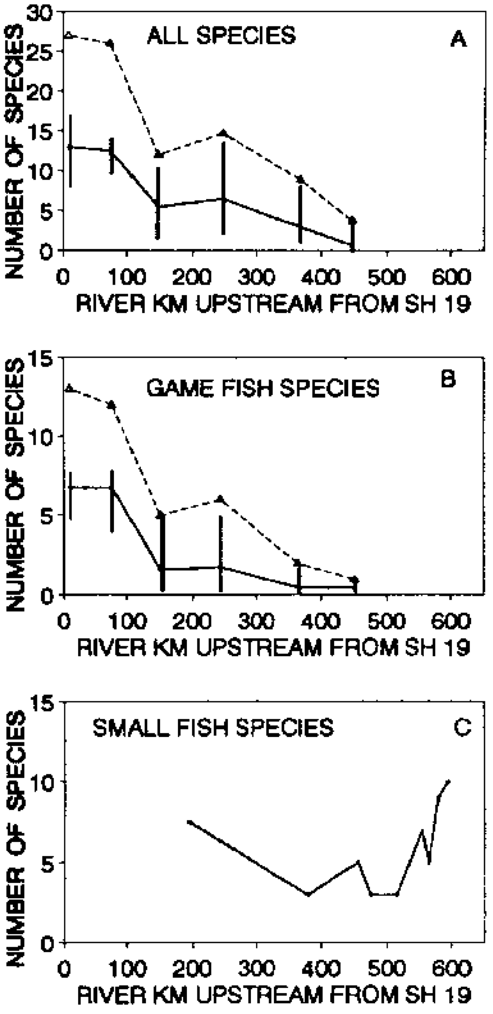

Figure 5.3. *Number of fish species collected in the Trinity River, July 1972-April 1974 (from Texas Parks and Wildlife Department 1974). Vertical bars in panels A and B represent the range. and dots represent the mean for individual collections. Triangles on dotted line represent the total number of species collected during the entire study period. Panel C is the number of small fish species collected by Irwin (1985) by seining in the Trinity River, August 1985. Redrawn from Texas Water Commission (1987a).*

miles below the Dallas-Fort Worth area that had been monitored since 1957 by the Geological Survey and the State Health Department.

Cleanup Activities: 1975-1985

The North Central Texas Council of Government (NCTCOG) is a regional organization responsible for water quality management in a 3,375 square mile area surrounding the Dallas-Fort Worth Metroplex. It includes all of Dallas and Tarrant Counties, and parts of Collin, Denton, Ellis, Johnson, Kaufman, and Rockwall counties. In 1970 the council developed the *Upper Trinity River Basin Comprehensive Sewerage Plan*, the first regional plan in the country approved by the EPA pursuant to the 1965 Federal Water Pollution Control Act. The plan called for abandonment of many smaller wastewater treatment plants and consolidation of service by designated major joint systems. By 1985 most of what the *Comprehensive Sewerage Plan* recommended had been implemented.

However, unprecedented growth in the Dallas/Fort Worth area has occurred in recent years, so that the council continues to struggle to increase treatment plant capacity rapidly enough to keep up with the growth (North Central Texas Council of Government 1985). More people were added to the region during the five-year period from 1980-1985 than in the previous ten years from 1970-1980 (Figure 5.4). In 1985 the region's population stood at 3.9 million, and was projected to reach between 4.5 and 5 million by the year 2,000 (NCTCOG 1985).

Since its creation in 1966, one of the highest priority of the NCTCOG has been the cleanup of the Trinity River through improvement in dissolved oxygen levels. The Council reported in 1985 that the composite BOD loadings and concentration for the 24 major plants in the Dallas/Fort Worth area had decreased substantially since 1970, even though average annual wastewater flows had increased by over 100% during the same period (NCTCOG 1985).

Table 5.2. *Trends in dissolved oxygen and total suspended solids at Trinity River Station 0805.0100 during 1957-1973 (Warshaw 1975).*

Year	Flow cfs	DO mg/l	TDS mg/l
1957	6,513	4.1	329
1958	3,932	3.1	328
1959	1,407	3.2	474
1960	1,551	4.5	467
1961	1,504	3.2	420
1962	2,599	3.4	397
1963	938	3.6	539
1964	848		525
1965	3,928		323
1966	3,774		387
1967	997		463
1968	3,798	6.2	312
1969	3,786	4.6	372
1970	2,777	3.9	373
1971	774	2.6	416
1972	2,892	2.9	400
1973	3,445	3.3	332

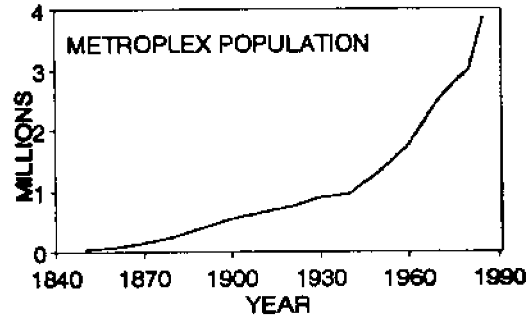

Figure 5.4. *Population trends in the North Central Texas Council of Government Planning Region. This region includes all of Dallas and Tarrant Counties, and portions of six other counties comprising the Dallas/Fort Worth Metroplex. Modified from North Central Texas Council of Government (1985).*

The historical wastewater flows, BOD$_5$ loadings, and dissolved oxygen levels in Trinity River Segments 0804 and 0805 between 1970 and 1985 are shown in Figures 5.5 and 5.6. The loadings are based on monthly self-reporting data, and the instream oxygen data were collected by the Texas Department of Water Resources. Segment 804 wastewater flows and BOD$_5$ loading have gradually increased since 1970, but this is a relatively rural part of the basin, and the flow and BOD loads are minuscule compared to those farther upriver in Segment 0805. There, population growth in the Fort Worth-Dallas Metroplex more than doubled the wastewater flow between 1970 and 1984, from 180 MGD to 380 MGD. However, improved wastewater treatment resulted in an impressive decline in the BOD$_5$ loading to this segment (Figure 5.6). In 1983 and 1984, the loads were around 25,000 pounds per day, compared to 90,000-105,000 pounds per day in the mid-1970s. In 1984, about 95% of the wastewater flow and over 99% of the BOD$_5$ were from municipal sewage treatment plants; industrial sources made very minor contributions to the totals (Texas Water Commission 1986b).

Between 1978 and 1985, Trinity River dissolved oxygen levels improved significantly just downstream from the major treatment plants in the Dallas-Fort Worth area (Figure 5.7), although there were still low summertime values at the CAM 4 sampling site below Dallas. This was attributed to a continuing problem of overloaded facilities where construction to either expand or improve treatment had not kept up with increased wastewater volumes (NCTCOG 1985).

The reduced BOD loading from the Dallas-Fort Worth area also resulted in improved oxygen conditions farther downstream in the Trinity (Figures 5.5 and 5.6). In the 1970s Segment 0805 dissolved oxygen readings were mostly between 3.5-6.5 mg/liter (annual means); but in the 1980s the annual averages have risen to 5-8 mg/liter. Also, the minimum oxygen levels have risen above the 3.0 mg/liter standard for this river segment. Farther downriver, in Segment 0804, both the minimum and annual average oxygen levels have im-

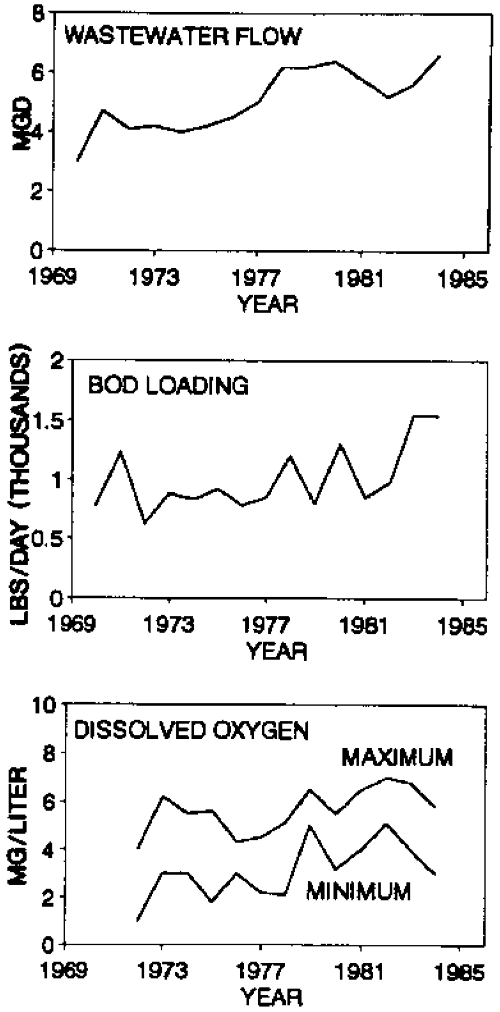

Figure 5.5. *Historical total wastewater flows (MGD), BOD$_5$ loading (pounds/day), and dissolved oxygen (mg/liter) in Trinity River Segment 0804. Values plotted are annual averages, and the dissolved oxygen data is from Station 0804.0600 at State Highway 31 west of Trinidad, Texas. Data from Texas Water Commission (1986b).*

proved also (Figure 5.5). However, the State standard for that segment, (5 mg/liter) is not always met. In fact, the annual minimums have been below 5 mg/liter in most years (Texas Water Commission 1986b).

Goss (1987) presented trends analysis results for several parameters sampled in the Trinity River near Crockett Texas between 1964 and 1885. This USGS streamflow and water quality station is about 100 km upriver from Lake Livingston, in Segment 0804. Trends were defined as monotonic changes with time, and tests for trends were conducted using the Seasonal Kendall procedure as described by Smith et al. (1982) and Crawford et al. (1983). Results of the tests were that BOD showed a small downtrend (Table 5.3), but there were uptrends in nitrogen and phosphorus. In 1986, it was estimated that wastewater treatment plants in Dallas and Fort Worth were discharging about 39,000 pounds of NH_3-N per day. This was nearly twice the instream NH_3-N load measured in the Dallas area ten years earlier (Texas Water Commission 1986b; Texas Department of Water Resources 1978). Thus, the improvements in wastewater treatment in the Fort Worth-Dallas region in the 1970s and 1980s reduced the BOD loading but had little effect on nutrient loading, which is typical for secondary biological treatment processes.

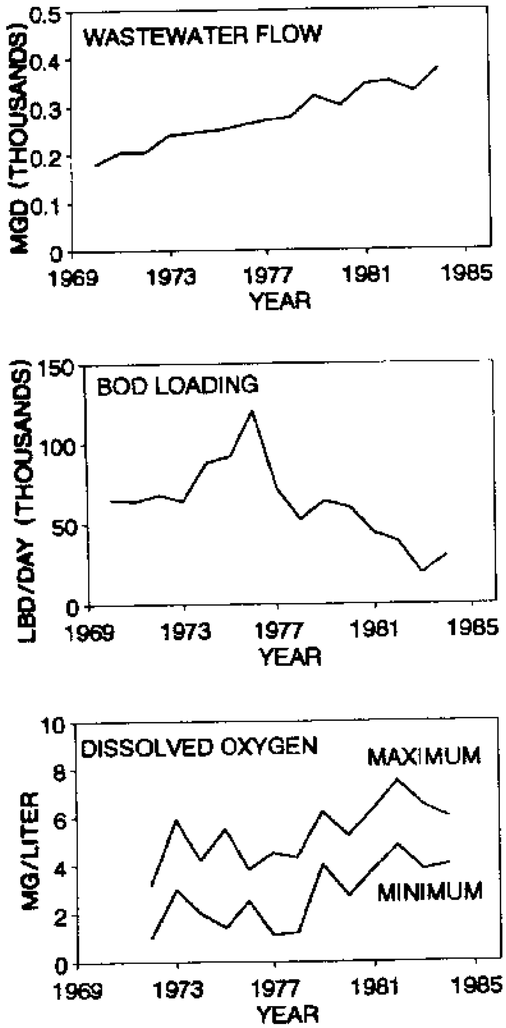

Figure 5.6. *Historical total wastewater flow (MGD), BOD_5 loading (pounds/day), and dissolved oxygen (mg/liter) in Trinity River Segment 0805. Values plotted are annual averages, and the oxygen data is for Station 0805.0100 at State Highway 34 southwest of Rosser, Texas. Data from Texas Water Commission (1986b).*

Some improvement in the health of the Trinity River fishery has occurred, as indicated by the results of a 1985 study by the U.S. Fish and Wildlife Service (Irwin 1985). A longitudinal pattern still existed, with lowest species diversity in the Metroplex area, and greater species diversity upstream from Fort Worth and downriver from Dallas to Lake Livingston. But there were more fish found at the sties in the Dallas-Fort Worth vicinity than in the earlier study described above (Figure 5.3). Beginning in 1979 the flathead catfish (*Pylodictis olivaris*), a highly desirable game fish that is sensitive to environmental disturbance, appeared in samples from some of the upper reaches. It was concluded that this improvement in the fishery was attributable to more favorable oxygen conditions in the river (Irwin 1985). Ironically, the enhanced condition of the fishery in the upper reaches seems to have made this area more susceptible to fish kills in the early 1980s (Texas Water Commission 1987a).

Does Dallas-Fort Worth Pollution Impact Galveston Bay?

As will be shown below, Trinity Bay, the upper area of the Galveston Bay system that receives Trinity River Basin water, is relatively clean, at least in terms of BOD and nutrient loadings. There appear to be two major factors responsible for this: 1) the great distance (over 500 miles) between the bay and the Fort Worth/Dallas metroplex, and 2) Lake Livingston.

As would be expected, the longitudinal trend in Trinity River dissolved oxygen is toward increasing concentrations the farther one goes downstream from the Metroplex area (Texas Water Commission 1987a). The form of this profile is well known as a "dissolved oxygen sag curve," and is typical in any stream receiving discharges containing oxygen demanding substances. The remarkable thing about the Trinity sag curve is its length, approximately 300 river miles from Fort Worth to Lake Livingston (Figure 5.8).

Historically, a nutrient "loss" phenomenon has been observed to occur during low flow conditions in the mid-portion of the upper Trinity River (Figure 5.2 and Texas Department of Water Resources 1978). These losses represent about one-half to two-thirds of the nitrogen load and about one-half the phosphorus load generated in the Metroplex area (Figure 5.2). Several physical and biological processes have been hypothesized to be responsible for the losses:

Table 5.3. *Trend test results for water-quality constituents in the Trinity River near Crockett, Texas, February 1964 to August 1985. + = uptrend; - = downtrend; --- = no trend. From Goss (1987).*

Constitutent	Concentration unit	Median rate of change per year	Percent per year
Total nitrogen	mg/liter	+0.22	+4.89
Total organic nitrogen	mg/liter	+0.11	+9.52
Ammonia nitrogen	mg/liter	+0.01	+2.07
Nitrite nitrogen	mg/liter	+0.01	+9.11
Nitrate nitrogen	mg/liter	+0.20	+6.51
Organic + ammonia N	mg/liter	+0.03	+1.73
Total phosphorus	mg/liter	+0.02	+1.62
BOD	mg/liter	-0.13	-2.38
Dissolved oxygen	mg/liter	---	---

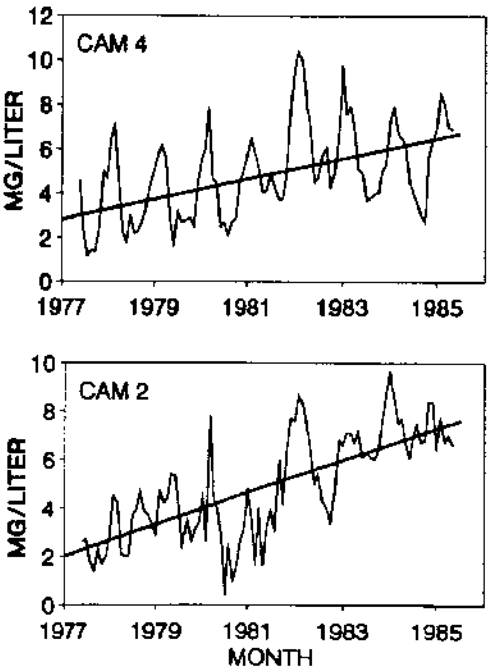

Figure 5.7. *Dissolved oxygen trends at two sites on the Trinity River below major wastewater treatment facilities in the Fort Worth / Dallas area. CAM-2 (Continuous Automated Monitoring System Station 2) is in the West Fork Trinity River at Beach Street, Forth Worth; CAM-4 is in the Trinity River at South Loop 12, Dallas. Data from North Central Texas Council of Government (1985).*

1) uptake by periphyton and macrophytes, 2) loss to the sediments through algal die-off and suspended sediment affinity, and 3) nitrogen losses to the atmosphere through ammonia stripping and denitrification.

In 1975-76 the Trinity River Authority made a study to try to determine which of these processes are the important causes of the instream nutrient losses. A typical low-flow nutrient loss profile from that study is depicted in Figure 5.9. Sediment and water concentrations of N and P showed similar trends. Highest concentrations were in the upper portion of the river, and they decreased going downstream. The study concluded that much of the ammonia nitrogen and phosphate phosphorus losses were due to phytoplankton uptake and nitrification (conversion of ammonia to nitrate). Chlorophyll *a* trends in the river lend support to this hypothesis, in that the algal biomass tends to be highest in the mid-river area downstream from the heavy nutrient loading zone (Figure 5.10). Ammonia volatilization was found to account for less than 5% of the total nitrogen loss. Denitrification was thought to be a major nitrogen sink because of anoxic conditions in the sediments, but this was not quantified in the study (Texas Department of Water Resources 1978).

Thus, the Trinity River between Fort Worth/Dallas and Lake Livingston has been characterized as "one long, effluent dominated loading-and-recovery zone" (Trinity River Authority 1974). The self-purification in the Trinity is not complete, however; certain problems remain in the water entering Lake Livingston, a reservoir on the river about 80 miles upstream from Galveston Bay. Built in 1968, the lake is a water supply and recreational impoundment managed jointly by the Trinity River

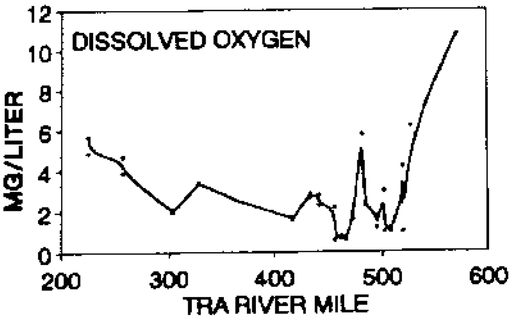

Figure 5.8. *Dissolved oxygen profile on the Trinity River for summer low-flow conditions. From Trinity River Authority (1974).*

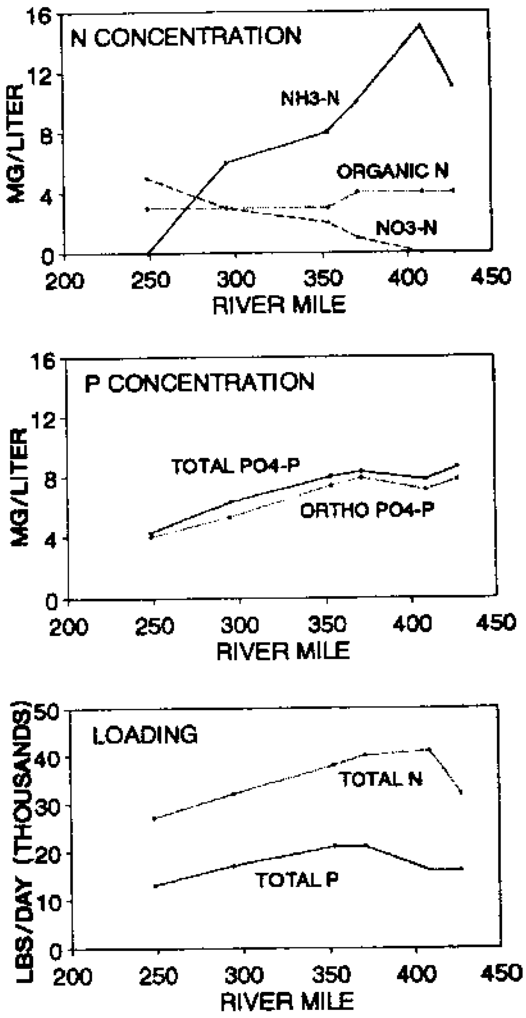

Figure 5.9. *Low-flow nutrient profiles for mid-Trinity River sampling conducted on October 18, 1975. "River Miles" represent distance upstream from Galveston Bay. From Texas Department of Water Resources (1978).*

Authority and the City of Houston. It is by far the largest reservoir in the Trinity River Basin, with a surface area of 82,600 acres and a storage capacity of 1.75 million acre-feet (Wurbs 1985).

Carlson's (1977) trophic state indices, based on Secchi disc depth, total phosphorus concentration, and chlorophyll *a* levels, have been calculated for Texas reservoirs in recent years and presented in the semi-annual *Water Quality Inventory* reports (Texas Department of Water Resources 1980, 1982a, 1984a; Texas Water Commission 1986). Between 1980 and 1986, the sum of the indices computed for Lake Livingston averaged about 230, and there was little variation. These sums placed this lake among the most eutrophic of all the reservoirs in Texas included in the sampling (Table 5.4). High chlorophyll *a* and high total phosphorus were the causes of this relatively eutrophic ranking. Between 1976 and 1985, total phosphorus concentrations in the reservoir averaged 318 µg/liter.

In 1976 it was reported that:

> Lake Livingston has exhibited severe eutrophic conditions since its impoundment. Algal blooms, together with large areas of macrophytes (water hyacinth, duckweed, hydrilla and coontail), are common in the reservoir. Nutrient levels are high and hypolimnetic anoxia persists for a large portion of the year (Hydroscience 1976).

The authors of this report calculated nitrogen and phosphorus mass balances for the lake (Table 5.5). The budgets showed that the principal nutrient source is the Trinity River, which supplies about 39.6 million pounds nitrogen/year and 10.8 million pounds phosphorus/year. Direct wastewater dischargers and land runoff to the lake is minor (<0.2 million pounds nitrogen/year and <0.1 million pounds phosphorus/year). On the order of 90% of the total annual loading occurred during the high river flow period from January through June. For 1975 there was a 29% loss of total nitrogen and a 52% loss of total phosphorus through the lake, based on a comparison of the measured inputs and estimated outputs. This overall nutrient loss is attributed to several mechanisms. The largest nutrient sink is settling of particulate materials to the sediments. The effect of this is reduced somewhat by the release of inorganic nutrients from the sediments during periods of bottom water anoxia. However, the nutrient settling rate far exceeds the nutrient release rate (Hydroscience 1976). The second nutrient sink is

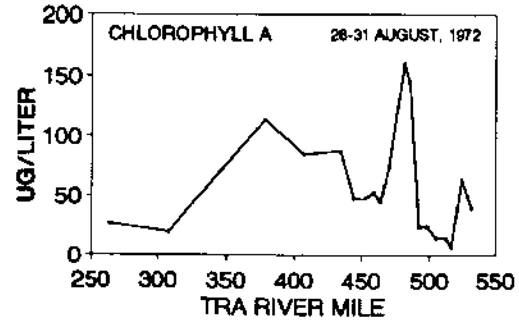

Figure 5.10. *Chlorophyll* a *concentration profile on the Trinity River for summer low-flow conditions. From Trinity River Authority (1974).*

Table 5.4. *Trophic status calculations and relative rankings for Lake Livingston, 1980-1986. Data from Texas Department of Water Resources (1980, 1982a, 1984a) and Texas Water Commission (1986a).*

	Carlson Indices				Ranking (Lake Livingston/ Most eutrophic in State)
Year	Secchi	Chlorophyll *a*	TP	Sum	
1980	---	---	---	230	85/87
1982	---	---	---	234	73/82
1984	45	89	96	230	88/98
1986	48	89	93	230	85/98

Table 5.5. *Summary of 1975 mass balances for nitrogen and phosphorus in Lake Livingston. Data are from* Hydroscience *(1976).*

Gains/Losses	(lbs/year)	(lbs/year)
Gains		
River inflow	39.6	10.8
($NO_2 + NO_3 = 7.0$)		
($NH_3 = 5.5$)		
(Organic N = 16.0)		
($PO_4 = 3.4$)		
Wastewater discharges	<0.2	<0.1
Nitrogen fixation	9.6	
Sediment regeneration	2.8	0.7
Total	**52.2**	**11.6**
Losses		
River outflow	28.4	5.2
($NO_2 + NO_3 = 7.0$)		
($NH_3 = 5.5$)		
(Organic N = 16.0)		
($PO_4 = 3.4$)		
Macrophyte production	7.6	2.5
Denitrification	0.8	
Total	**36.8**	**7.7**

associated with the macrophyte uptake of nutrients, but this pathway was not quantified. Of course, some of this nutrient would be returned to the water column later via remineralization. An additional postulated, but unquantified, loss mechanism is denitrification, the biological conversion of inorganic nitrogen to nitrogen gas.

In summary, a large part of the oxygen-demanding organic waste and nutrient loads originating in the Fort Worth-Dallas region is dissipated upstream from Galveston Bay. Oxidation of labile organic matter, and reoxygenation of the water occurs gradually over the 500-mile course of the river between Dallas and Lake Livingston. Some ammonia nitrogen is converted to nitrate nitrogen in the Trinity via nitrification, and a substantial amount is probably lost via denitrification, especially in the upper river segment where bottom water and sediments are often hypoxia or anoxic. Some fraction of the instream phosphorus load is lost via sedimentation. Farther downstream, Lake Livingston traps substantial quantities of the remaining nitrogen and phosphorus. Consequently, river water entering Trinity Bay contains very much lower concentrations of nutrients and organic matter than would be the case if there were not such a great distance, and a large reservoir, between the bay and the major source of these materials.

CHAPTER 6

Trends in Galveston Bay Water Quality

For decades the bay in our backyard has been dredged, netted and scraped for its seafood. It has been dumped with every imaginable discharge our homes and cities and industries have produced. Its nourishing rivers have been strangled with dams, and yet the bay, thanks to its power of self-renewal, has not died

Robison (1989)

Dissolved Oxygen

High BOD or low dissolved oxygen have never been found to be problems in the open waters of the Galveston Bay system. Gloyna and Malina (1964) presented limited data on dissolved oxygen and BOD for Trinity Bay, but concluded that "at present time (1963) there seems to be no major pollution nor problems of public health significance with Trinity Bay." "If one were to use dissolved oxygen as the sole measure of good water quality in Galveston Bay," wrote Espey et al. (1971), "the overall condition would be good. At most times of the year the dissolved oxygen is equal to or above the specified minimum (5-6 mg/liter for the different bay regions)." This report did mention, as others have, that bottom waters in the Houston Ship Channel were sometimes below these minimums. In a section entitled *Historical Trends of Water Quality in the Galveston Bay System*, the report stated that:

> Based on historical data taken by the Texas State Department of Health and the recent Galveston Bay Project, some comments on observed trends in BOD, dissolved oxygen, and total coliforms can be made. BOD data obtained in the Galveston Bay system over the past seven years (1964-1971) has not varied significantly. Although BOD values are low considering the multitude of wastes entering from the Houston Ship Channel, toxic constituents may have resulted in a depressed measurement throughout the bay. Dissolved oxygen trends in . . . (the bay)... were also remarkably constant. In Trinity and upper Galveston Bay, the trend over the past seven years has been toward a gradual increase in dissolved oxygen. East Bay has been the only part of the system not experiencing any coliform problem (over the preceding seven years). Lower Galveston Bay experienced the highest coliform concentrations. Levels in Trinity Bay, especially the northern shoreline area, were above the standard considered suitable for shellfish harvesting.
>
> Based on the trends observed in these three parameters, it appears that conditions for most of the bay system have not deteriorated. However, it is questionable whether or not there has been any improvement. For instance, increased oxygen levels could indicate the bay is undergoing enrichment, and algal photosynthesis is resulting in an upward trend in dissolved oxygen levels. Different BOD analysis methods between the Texas Department of Health and the Galveston Bay Project could account for some of data variability. Fortunately, flushing resulting

from the inflows of major tributaries, tidal exchange with the Gulf of Mexico, and the natural assimilative capacity of this productive estuarine system has been active in preventing any widespread water quality problems thus far (Espey et al. 1971).

Comparison of the earlier data with that taken more recently by the Texas Department of Water Resources and Water Commission shows that since 1971 surface water oxygen conditions in the bay have not changed substantially. Figure 6.1 gives the annual means, along with the individual data, for selected stations in Galveston, Trinity, East and West Bays. In all the areas, oxygen is seldom below 6 mg/liter, and the lowest readings naturally tend to occur during the warmer months (denoted by solid dots in plots), when water temperatures are highest and oxygen saturation levels are lowest. Wintertime values mostly are in the 8-12 mg/liter range. Trends in oxygen, as reflected by the annual means, are not apparent at any of these sites.

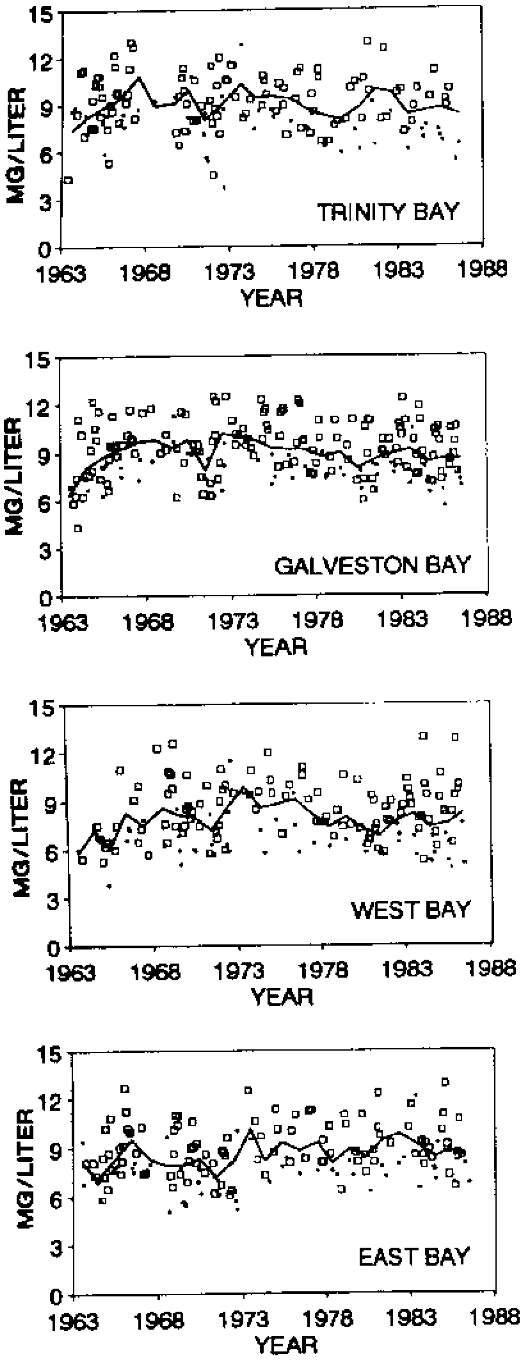

Figure 6.1. *Dissolved oxygen trends in four areas of the Galveston Bay system, 1963-1986. Open boxes are winter (October-May) data, and dots represent summer (June-September) data. Annual mean concentrations are depicted by the solid lines. Station locations are given in Appendices 2 and 3.*

Nitrogen and Phosphorus

U.S. Geological Survey discharge and water quality data were used in a Texas Department of Water Resources study

Table 6.1. *Range of expected nitrogen and phosphorus loading to Galveston Bay from the Trinity River, San Jacinto River, and the Houston Ship Channel. TP = total phosphorus; DIN = dissolved inorganic nitrogen (From Texas Department of Water Resources 1981a).*

		Loading (10^6 kg/yr)		
Source	Flow (10^6 acre-ft)	DIN	Organic N	TP
Trinity River	5.42(78%)	0.5-3.5	2.0-6.3	0.6-1.6
San Jacinto R./ Lake Houston	0.88(12%)	0.1-0.4	0.2-1.0	0.1-0.3
H. Ship Channel	0.47 (7%)	0.6-3.5	0.2-1.6	0.5-2.3
Other	--.-- (3%)	----	—	—

(1981a) to calculate the potential nutrient loading contributions from the Trinity River, the San Jacinto River tributaries, and the Buffalo Bayou (Houston Ship Channel) tributaries. Loadings (in kilograms per day) were calculated by multiplying maximum and minimum concentrations observed for each of the twelve months over the period 1970 through 1977 times the mean monthly discharges for each stream. The results of these calculations are summarized in Table 6.1. The Trinity River, which contributes 78% of the gaged freshwater inflow to the estuary was estimated to contribute 0.5-3.5 million kg dissolved inorganic nitrogen and 0.6-1.6 million kg total phosphorus per year, depending on the flow. The ship channel, and its tributaries upstream from the San Jacinto River, contributes only 6.8% of the total flow. However, the nitrogen and phosphorus concentrations were high enough in the 1970s that inorganic nitrogen and total phosphorus loadings from this source were comparable to that from the Trinity River (Table 6.1). Nutrient inputs from other sources, including marsh exchange and precipitation, are minor relative to the freshwater inputs (Table 6.2). Thus, the authors of the study concluded, it could be expected that upper Galveston Bay and Trinity Bay would experience higher nutrient concentrations than other portions of the estuary (Texas Department of Water Resources 1981a).

Table 6.2. *Estimated annual nutrient inputs to Galveston Bay (Armstrong 1987). All values are 10^6 kg/yr, except areal loading, which is g/m^2 of estuarine surface per year. Freshwater loadings computed by multiplying average annual concentrations (1970-1977) times annual average freshwater inflows (1942-1976).*

Nutrient	Freshwater Inflows	Marshes	Precip.	Total	Areal Loading
Nitrogen	11.58	0.16	0.34	12.08	8.40
Phosphorus	3.63	0.13	0.04	3.81	2.66

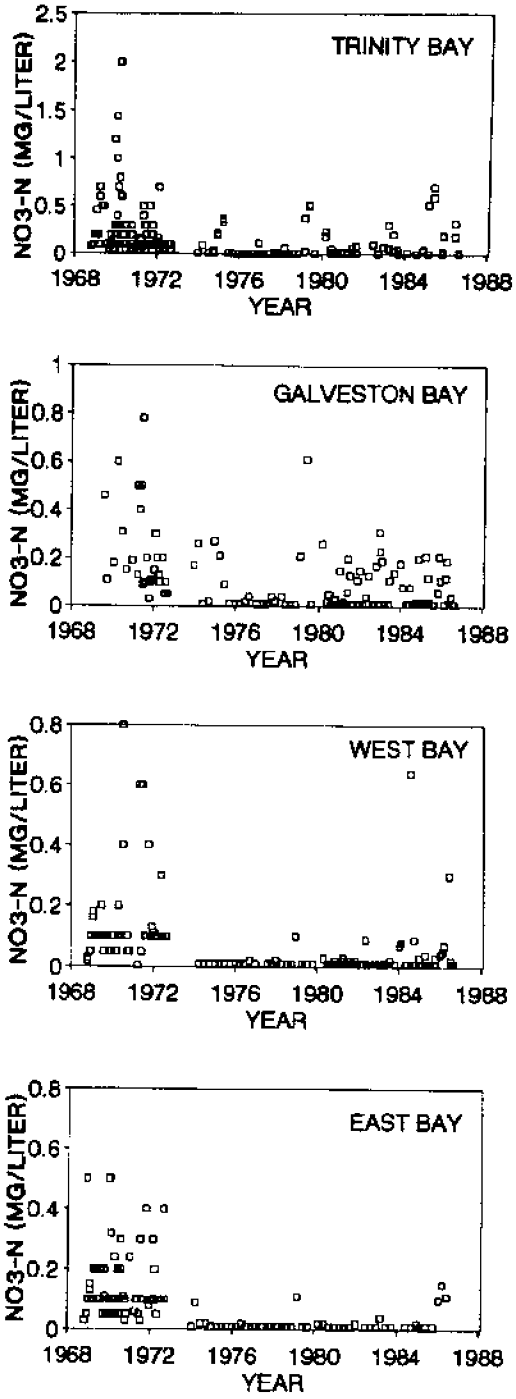

Figure 6.2. *Nitrate nitrogen (NO_3-N) concentration trends in four areas of the Galveston Bay system, 1968-1986. Station locations are given in Appendices 2 and 3.*

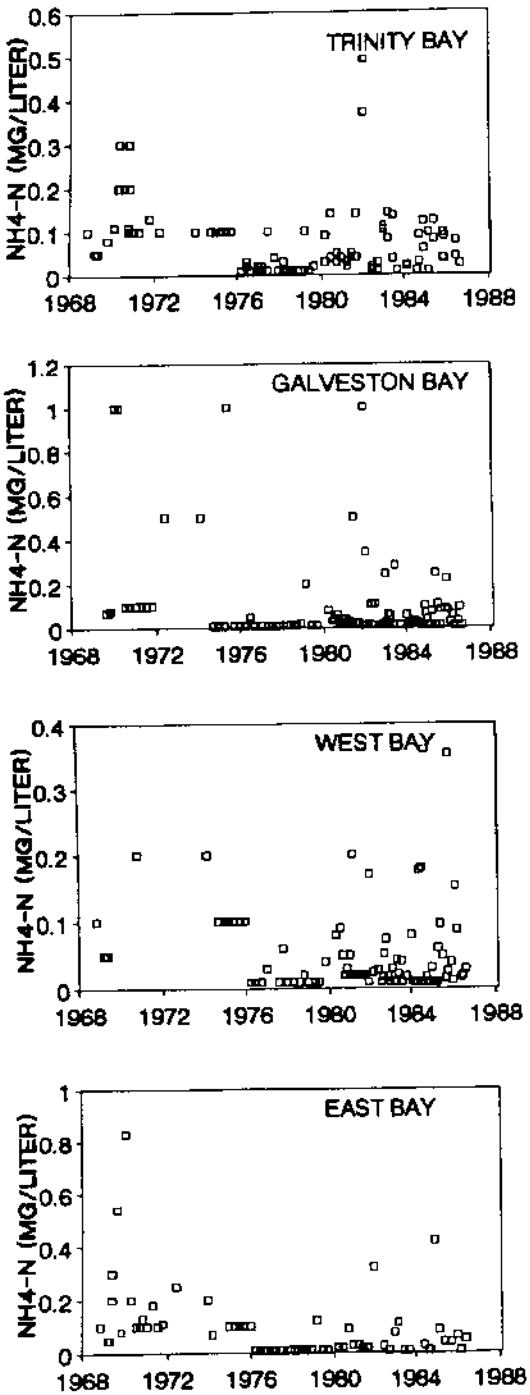

Figure 6.3. *Ammonia nitrogen (NH_4-N) concentration trends in four areas of the Galveston Bay system, 1968-1986. Station locations are given in Appendices 2 and 3.*

Figures 6.2 and 6.3 are compilations of ammonia (NH_4-N) and nitrate (NO_3-N) data for representative stations in four regions of the bay system. The Trinity Bay plot includes data from two stations close to one another in the upper part of the bay, the Galveston Bay data is from a station near Redfish Bar, and the West and East Bay plots include data from one station in each of these areas (*see* Appendices 2 and 3 for station locations). All of the data since 1974 have come from the Texas Department of Water Resources and Water Commission sampling programs.

The nitrate concentrations appear to have declined after 1972, but this may be an artifact related to the use of more than one data set in these plots (Figure 6.2). Unfortunately, there is no easy way to determine if this is so. However, there are no obvious trends in the nitrate data between 1974 and 1986. There are some other general points which can be inferred from this data set. First, there is a trend of decreasing nitrate nitrogen as one goes down the salinity gradient from the Trinity Bay toward the Gulf of Mexico. The Trinity Bay nitrates are often greater than 0.2 mg/liter, while those at the other end of the system, in East and West bays, are seldom above 0.2 mg/liter (Figure 6.2). This inverse relationship between nitrate and salinity is common in river-dominated estuaries, since river water usually has much higher nitrate levels than ocean water. Second, the nitrate levels in this system do not seem abnormally high in comparison to other estuaries along the Gulf Coast or the Atlantic Coast of the U.S. (Nixon 1983).

Ammonia nitrogen concentrations have been less than 0.1 mg/liter in most of the samples taken from all four regions in the bay. Higher concentrations are most often found at the Trinity Bay stations and at the station in upper Galveston Bay (Figure 6.3). Occasionally, there are unusually high values, possibly caused by high freshwater inflow associated with storms, or perhaps the result of sediment resuspension during storm events. There have been no obvious up or down trends in the ammonia concentration data. Except for the occasional high values, these ammonia data are similar to those from other U.S. East Coast and Gulf Coast estuaries (Nixon 1983; Boynton et al. 1982).

Other than an apparent decrease in total phosphorus in Trinity Bay, there have been no obvious trends in phosphorus concentrations in the bay system over the past two decades. The total phosphorus data in Figure 6.4 are from three sources: 1) Pullen et al. (1971) and Pullen and Trent (1969) for 1964-1966; 2) the Galveston Bay Project for 1968-1972 (Huston 1971); and 3) Texas Water Development Board and Water Commission for the period 1974-1986. Unfortunately, again, there is evidence that these data sets may not be comparable. The first set (Pullen et al. 1971; and Pullen and Trent 1969) seems to be consistently lower than the second, which in turn, seems to have given higher values than the third. Of course, it is possible that these differences represent real trends, but I suspect not. Total phosphorus analysis usually requires some type of digestion (oxidation) process to convert the organic P to phosphate P, and it is well known that in the past some digestion procedures were used that gave incomplete conversion of the more refractory organic P constituents. Presumably, the data from the period 1974-86 were analyzed by the same procedure. If this is assumed to be the case, then it can be surmised that there have been no noticeable trends in total phosphorus in the bay since that time.

Phosphate phosphorus (PO_4-P) has been monitored by the Water Development Board and Water Commission since 1974 (Figure 6.5). Once again, this data set gives no indication of a change in the abundance of phosphorus in the Galveston

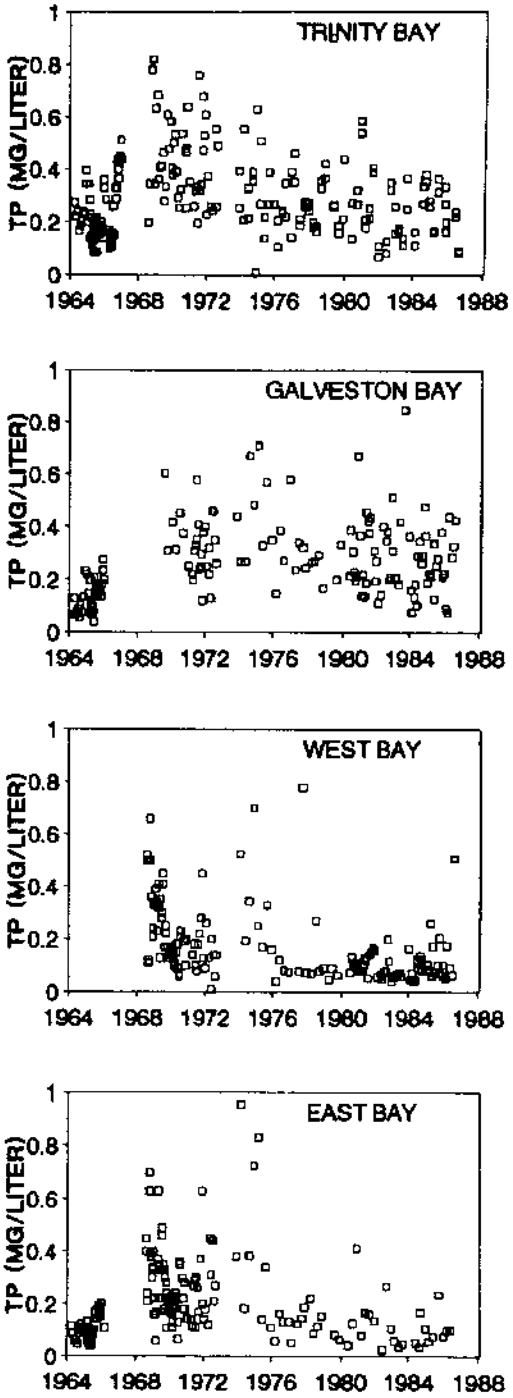

Figure 6.4. *Trends in total phosphorus concentrations in four areas of the Galveston Bay system, 1963-1986. Station locations are given in Appendices 2 and 3.*

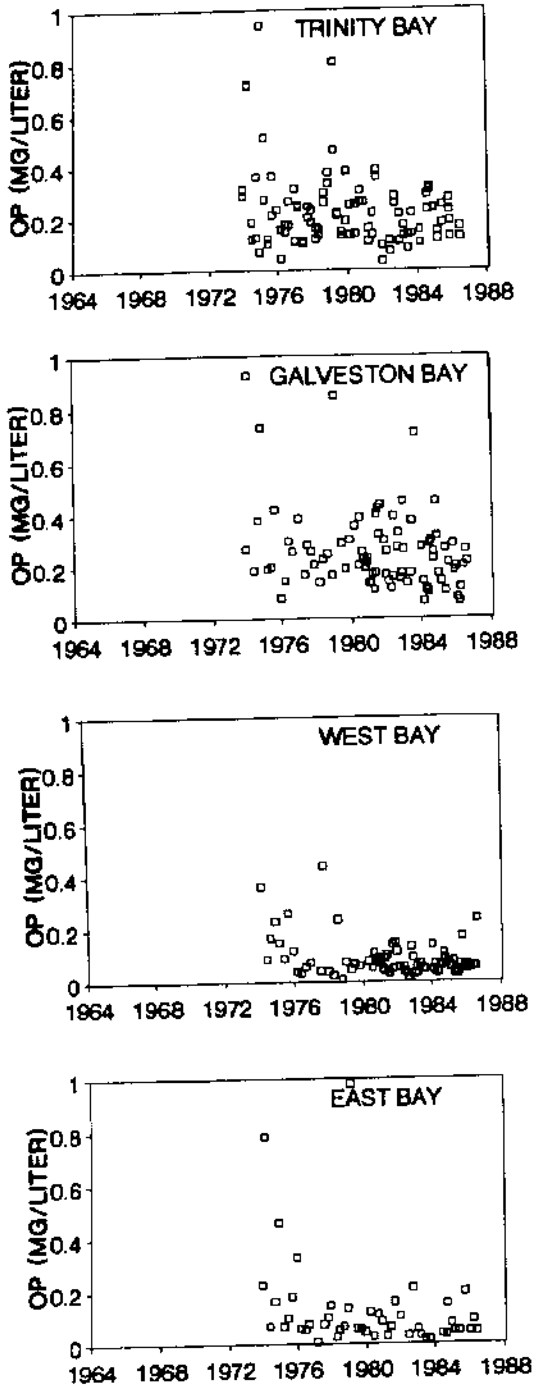

Figure 6.5. *Trends in phosphate phosphorus concentrations in four areas of the Galveston Bay System, 1974-1986. Station locations are given in Appendices 2 and 3.*

Bay system. Concentrations in Trinity Bay and upper Galveston Bay have averaged around 0.2 mg/liter, while in East and West Bays, phosphate has averaged about 0.1 mg/liter. This spatial gradient is probably due to mixing of phosphate rich waters from the Trinity River and the Houston Ship Channel with phosphate-poor Gulf of Mexico water. The East and West Bay data are comparable to those from other moderately enriched estuaries, whereas the Trinity and upper Galveston Bay values seem typical for some of the more heavily enriched urban estuaries in the U.S. (Nixon 1983).

Metals

Hann and Slowey (1972) carried out one of the first studies of heavy metals in the bay. Unlike some earlier studies, their's used the more accurate atomic absorption spectrometry method of analysis, and enough stations were sampled to give a good indication of the spatial patterns. The range of values found for eight of the metals in the top six inches of the bay sediments were as follows: arsenic, 0.8 to 5.4 mg/kg; cadmium, <0.2 to 5 mg/kg; chromium, 9 to 120 mg/kg; copper, 4 to 96 mg/kg; lead, 5 to 50 mg/kg; manganese, 52 to 935 mg/kg; mercury, 4 to 590 mg/kg; and nickel, <1 to 57 mg/kg [values based on dry weights of sediments]. In general, these early 1970s results agreed well with those from a 1960s study by Davis (1968). With the exception of four stations, most metals were distributed fairly uniformly throughout the bay system. Three of these were in upper Galveston Bay near Morgan's Point and the fourth was in the Texas City Channel. The authors of the report speculated that the proximity of these stations to industrial and urban inputs probably accounted for their higher levels. Lowest values were found in upper Trinity Bay where a hard sandy bottom existed.

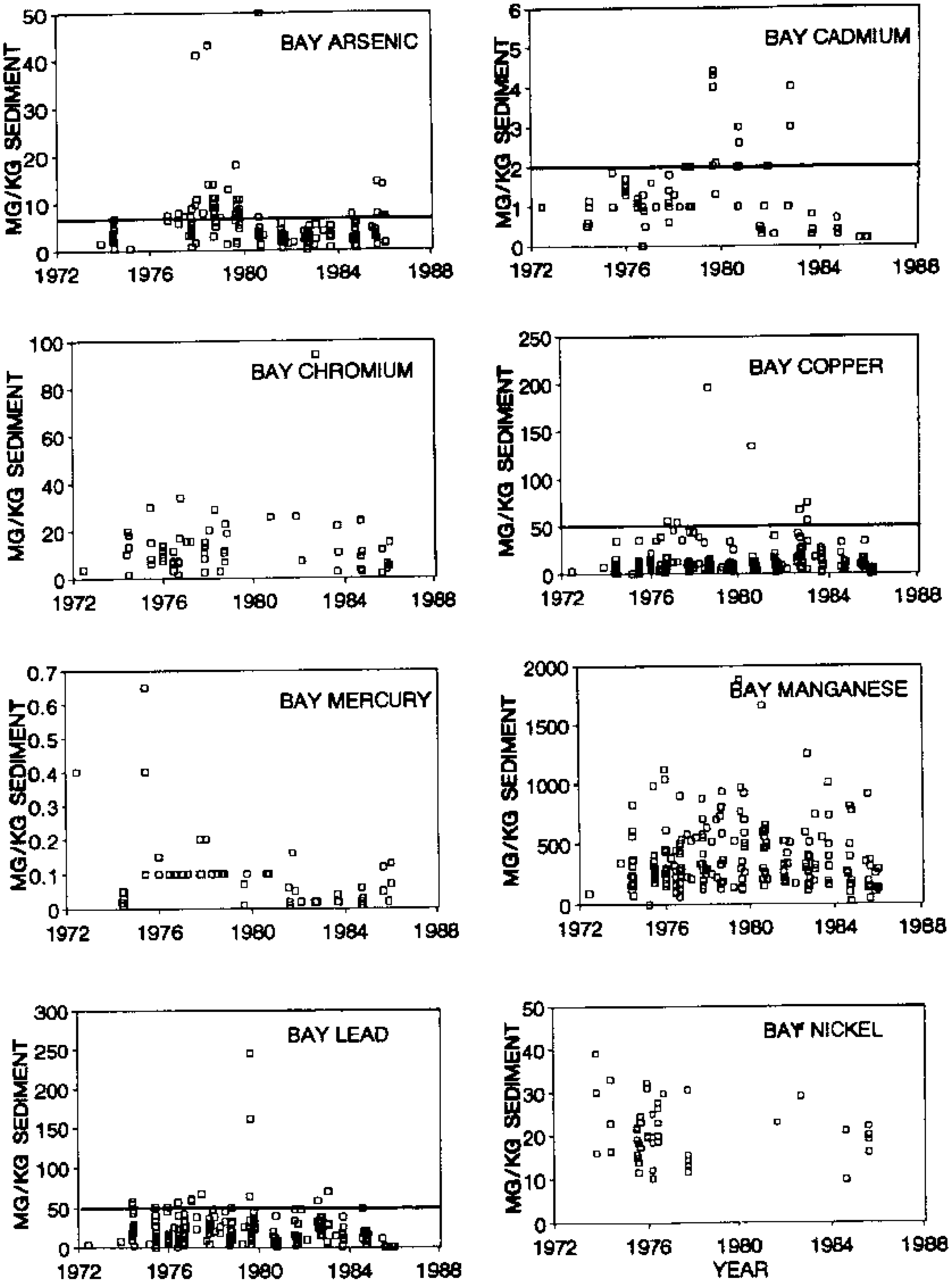

Figure 6.6. *Surface sediment metals concentrations in Galveston Bay, 1974-1986. Horizontal lines denote screening levels proposed by the U.S. EPA (1974) for dredged sediment disposal in the Galveston Bay region. Station locations are given in Appendices 2 and 3.*

Sediment metals data collected in the bay by the Texas Water Development Board and the Water Commission since 1974 are generally in the same ranges given above for the Hann and Slowey data, and have tended to follow the same spatial patterns. The data in Figure 6.6 are from five Water Commission stations around the bay: two in Trinity Bay and one each in Trinity Bay, East Bay and in upper Galveston Bay. For most metals the bay concentrations are lower than those in the ship channel above Morgan's Point (*see* Figure 4.13) and are generally below the screening levels proposed by the U.S. EPA (1974) for dredged sediment disposal. In particular, cadmium, chromium, mercury and lead are considerably lower in the bay than in the ship channel. Bay cadmium has averaged around 1 ppm, compared to 4 ppm in the channel, and bay chromium is only about one-fifth the ship channel levels, on average. Mercury in the bay averages less than 0.1 ppm, compared to 0.3 ppm in the ship channel, and almost all the bay lead samples were less than 50 ppm, whereas most in the ship channel were above this value. Comparison of the five bay stations showed that, as expected, the upper Galveston Bay station generally had the highest metals concentrations. Many of the data in Figure 6.6 that are above the EPA screening levels were from this station. Not shown in these plots are Water Commission data from the Texas City area in the southwest corner of Galveston Bay. But a cursory examination of the 1974-1986 data from that region indicated that it has continued to have higher sediment metals levels than most other areas in the bay. The data do not give any evidence of trends in the bay sediment metals concentrations. Unfortunately, no single station has been sampled with enough regularity to permit a statistical test for trends.

Another difficulty in interpreting the Texas Water Commission sediment metals data is that it is not normalized to sediment texture (i.e., mud vs. sand), which is known to strongly influence the background levels of metals in estuarine sediments. However, White et al. (1985) took this factor into account in their analysis of U.S.G.S. metals data from Galveston Bay. By doing so, they were able to distinguish anomalously high levels from those due simply to high mud content in the sediments. While their study did not address trends, it does provide information about spatial variability in bay metals. Generally speaking, their results confirm those from the other studies described above. Namely, highest (in some cases anomalously high) metals concentrations were in the sediments of upper Galveston Bay and other areas close to anthropogenic sources.

Red Tides and Other Algal Blooms

Historically, excessive growth of phytoplankton has not occurred with any regularity in the open waters of the Galveston Bay system. To the contrary, most workers have emphasized the modest cell densities and productivity of phytoplankton in the bay (Copeland and Fruh 1970; Oppenheimer et al. 1973), despite the abundant nutrients. The discrepancy has generally been attributed to light limitation resulting from high turbidity (Armstrong 1987), although there have been no studies to test this hypothesis. There are not enough phytoplankton data for the bay to permit a statistical test for temporal trends.

Gulf of Mexico and Texas bay waters periodically experience fish kills and water discoloration due to red tide organisms. Most of these events are limited in duration and are caused by blooms of *Gonyaulax monilata* (Texas Water Commission 1988a). One such outbreak, in the summer of 1949, affected Offats Bayou on Galveston Island. Apparently, fishermen and local residents had observed red tide-like symptoms and accompanying phenomena for almost every summer during the preceding 15-20 years (Connell and Cross 1950). *Ptychodiscus brevis* red tides have occurred also, although infrequently, along the Texas Coast. One of the most recent lasted from August 1986 until February 1987. It was first seen near the western end of Galveston Island, and from there the bloom quickly spread nearly 300 miles southward, down the Texas coast into Mexican waters. Along this path, the red tide infected coastal Gulf waters and some of the bays; however, Galveston Bay was spared (Texas Water Commission 1988a). No conclusions were reached concerning the cause of the red tide, despite intensive study by Texas state agency personnel.

Chapter 7

Trends in the Bay's Fisheries

> *Although critical estuarine habitats are being lost, abundances of most important species do not yet seem to be affected. Landings of fishery organisms and abundance of waterfowl and colonial nesting birds fluctuate annually, but appear reasonably stable.*
>
> Sheridan et al. (1988)

Galveston Bay has supported a commercial fishery for over a century, and as was the case in other states along the Gulf and Atlantic Coasts, problems for the industry began to develop early. C. H. Stevenson's 1893 *Report on the Coast Fisheries of Texas*, prepared for the U.S. Fish Commission, is a valuable source of information on the early history of the bay fisheries. He first gave a general account of the fishery, and then discussed some of the problems. The following is excerpted from the report:

> At present, bay seining is the most important fishery in Texas. Few large boats can venture into the shallow waters of Upper Galveston, Trinity, East, or West Bays. Using skiffs and very large seines, the bay fishermen surround and catch schools of menhaden, which are used for their oil and as fertilizer. The oyster industry is second in extent, but will doubtless rank first within a few years. Only about 4% of the 1890 catch came from the Gulf of Mexico proper. All of the Texas fisheries have increased in extent since 1880 except for shrimp. The growth is due primarily to the development of the methods of marketing the catch. This has been aided greatly by better rail transportation in the region, along with the capability to manufacture ice.
>
> Believing that the fish are caught in greater quantities than their natural fecundity can make good, there is a desire on the part of many persons, especially those interested in developing the sporting fisheries in Texas, to restrict in some way the use of seines. While the supply of fish may be decreasing, yet there does not appear to be an urgent necessity for very great restrictions. The cessation of the seine fishery in the bays for a few months from May to August, which is the plan generally urged, would throw entirely out of employment over 350 men, removing from the coast towns a monthly revenue of more than $12,000, and taking from the market a cheap and wholesome article of food.

In addition to taking measures to prevent over fishing, the fishery managers were experimenting with fish stocking in Texas coastal waters. As the first Texas Fish Commissioner, one of Stevenson's early projects involved building fish hatcheries, and importing German carp, rainbow trout, California salmon, and shad for stocking the states depleted streams. In the spring of 1890, 745 lobsters, 7-10 inches long were sent to Galveston to be "planted" in the Gulf near the city of Galveston, but it was noted later that only "two or three of these have since been obtained, and the experiment cannot be considered a success" (Stevenson, 1893).

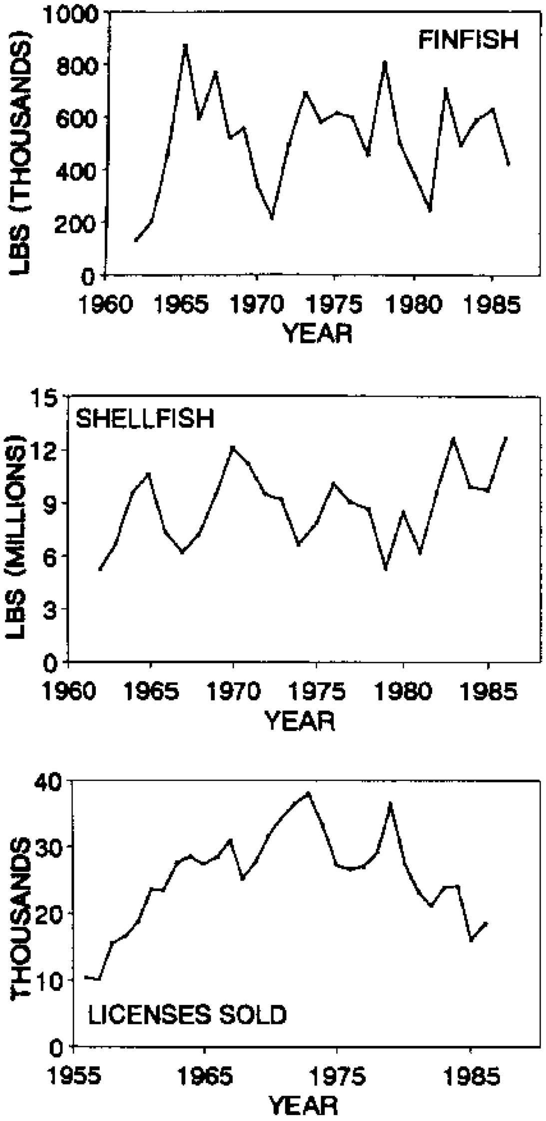

Figure 7.1. *Galveston Bay trends in commercial finfish and shellfish landings. Also plotted are the numbers of commercial saltwater licenses sold in Texas in each fiscal year from 1956 through 1986 (Osburn et al. 1987).*

There is a section in Stevenson's report devoted to Galveston Bay. I read all of it, hoping to find some mention of water quality in the bay. But there was none, which I suppose could be interpreted to mean that it was not considered to have a major impact on the fishery at that time.

Commercial Fisheries

The Database

Commercial landings of marine species from Texas bays and the Gulf of Mexico off Texas have been collected from seafood dealers since 1887 (Perret et al. 1980). However, the early data were collected sporadically, and in many instances probably underreported the catch. For example, in 1907 the fish commissioner ceased to report the landings except for pounds of fish and oysters upon which a new special tax was levied. As can be seen in the data for that period, the amount of reported landings diminished slightly at first; possibly to avoid the tax. However, in 1908, the commissioner added Harris County as a reporting station. Prior to 1915, wholesale statistics were not recorded. This means that many more pounds of fish, shrimp, and oysters may have been taken from the bay for private or wholesale use than were actually reported (Texas Game, Fish and Oyster Commission 1937).

Since 1936, the Texas Parks and Wildlife Department has monitored the landings and value of the marine fishes, oysters, crabs and shrimp through a mandatory self-reporting system known as the Monthly Marine Products Report (MMPR), which is completed by seafood dealers. Since 1956, the National Marine Fisheries Service has collected landings data on shrimp through seafood dealer reports and shrimp-vessel crew interviews (Prytherch 1980), while the Parks and Wildlife Department has continued to collect data on fishes, crabs and oysters. An informal data exchange between agencies permitted the compilation of total self-reported landings of marine species. Beginning 1 April, 1985, Parks and Wildlife and the National Marine Fisheries Service instituted a formal cooperative agreement to collect and exchange commercial fisheries statistics (Osburn et al. 1987).

Except for oyster harvests, none of the Galveston Bay commercial landings data before 1962 were used in this report. Unfortunately, the landings reports before 1962 did not separate fish caught in Galveston Bay from those caught in the Gulf and subsequently "landed" in bay ports. Another reason for not using earlier data is that before the early 1960s there were inconsistencies in the reporting procedures (Texas Department of Water Resources 1981a). For example, penaeid shrimp harvest data from the turn of the century to the late 1940s are incomplete and include only the white shrimp harvest. Exploitation of the brown shrimp began in 1947 with night trawling and rapidly increased throughout the 1950s; however, separation of the two species in the fisheries statistics was not begun until after 1957. *Texas Landings*, compiled by the U.S. Department of Commerce (1969-1979) and the U.S. Department of Interior (1962-1968), reports total annual catches (by species) from Galveston Bay and from the Gulf of Mexico. Data for the period 1980-1986 came from Osburn et al. (1987).

Finfish

Over the past 25 years total annual finfish harvests in the bay have fluctuated between 100,000 and 200,000 pounds in the poor harvest years and between 600,000 and 850,000 pounds in the most productive years (Figure 7.1). Lowest catches were in 1962, 1963, 1970, 1971 and 1981, while 1965-67 and 1978 were high catch years. Overall, there is no obvious trend in the finfish total landings.

For most individual species the landings have been highly variable (Figure 7.2). Much of the variability during recent years can be explained in part by the Texas State Legislature's ban on the sale of red drum and spotted seatrout beginning in September, 1981. This action was taken to stem the apparent decline in the abundances of these two species after the mid-1970s, caused by increased fishing pressure, both from commercial and sports fishermen. Spotted seatrout and red drum had comprised 45-75% and 5-10%, respectively, of the Texas sport landings, but catch rates by private-boat fishermen were beginning to decline. Also, Texas Parks and Wildlife monitoring had shown that the stocks of these two species were declining (Osburn and Ferguson 1986). Subsequent monitoring has established that the declines of these stocks has stabilized, but it is too early to tell if they will rebound (Rice et al. 1988).

The commercial landings of other bay species increased sharply following the prohibition of red drum and spotted seatrout. For example, flounder catches went from less than 50 million pounds/year in 1981 to about 200 million pounds/year in 1982 (Figure 7.2). Mullet landings also increased greatly, from less than 5,000 pounds in 1981 to 120,000 pounds in 1982. There were also increases in sheepshead and black drum, croaker, and gafftopsail catfish. Some of these increases were temporary, however. By 1986, black drum and sheepshead landings were at their lowest and next to lowest levels, respectively, since 1977. Meanwhile, flounder and mullet landings remained relatively high. These shifts present an interesting example of the interrelationships between commercial and sports fishing in an estuary.

Shrimp and Blue Crabs

Shellfish harvests in the bay have averaged about 8 million pounds per year since 1962, with shrimp leading the catch in most years. Shrimp harvests have ranged from lows between 2 and 3 million pounds in the late 1960s to over 6 million pounds in 1984 and 1986 (Figure 7.3). Although there is considerable fluctuation from year to year, there seems to have been

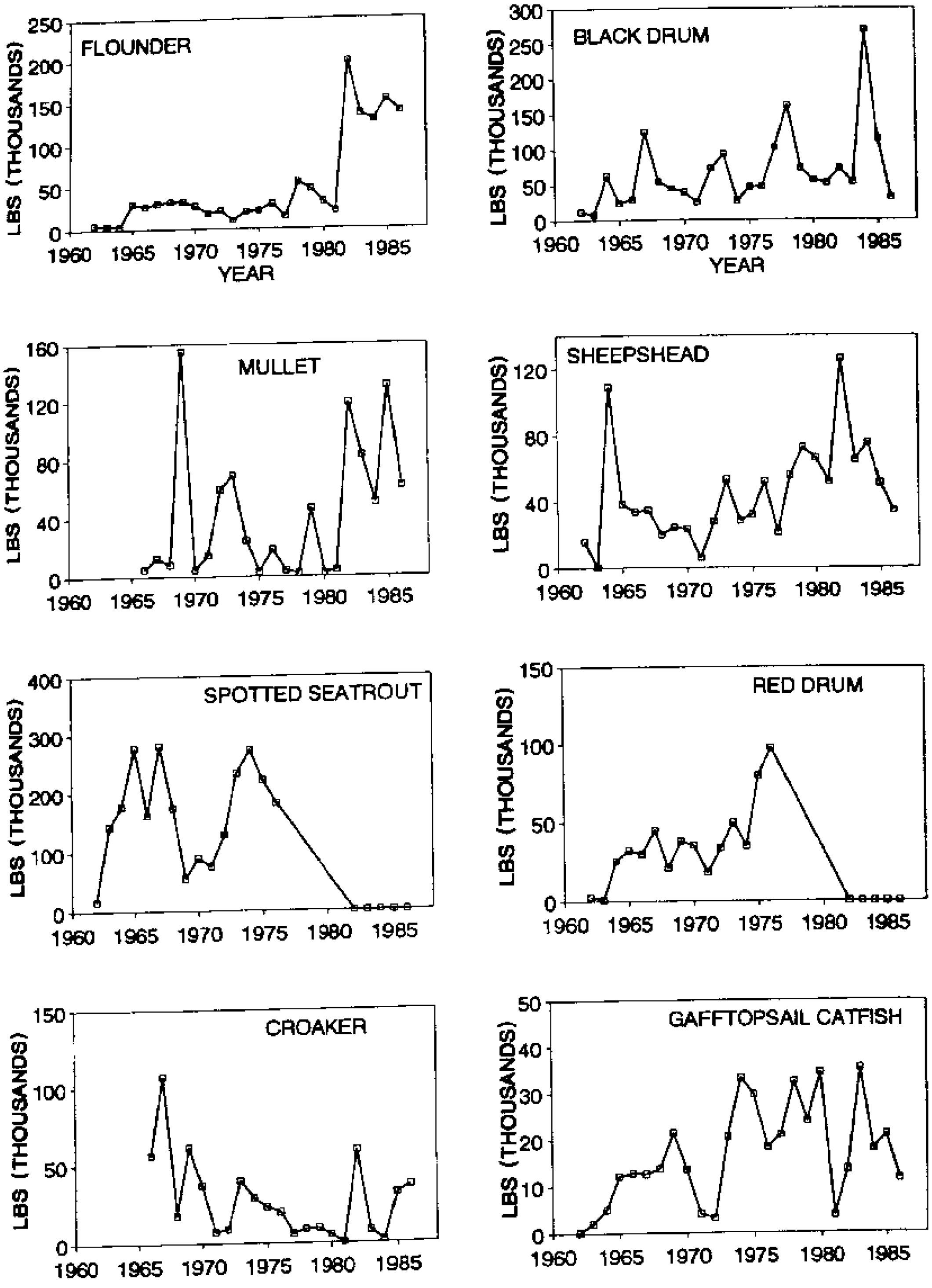

Figure 7.2. *Galveston Bay trends in commercial landings of the eight most important finfish species.*

an overall trend of gradually increasing shrimp landings in Galveston Bay since 1962.

Blue crab landings in the bay rose rapidly during the 1960s, then generally declined through 1981, and have subsequently risen sharply again to an all time high in 1986 (Figure 7.3). The 1962 catch was only 300,000 pounds, but by 1970 it had risen to 2.6 million pounds. The 1981 catch was about 600,000 pounds, the lowest since 1962, but from then until 1986 there were increases every year. The 1985 and 1986 increases were the largest ever for this estuary. It is difficult to see any clear long-term trend in these data.

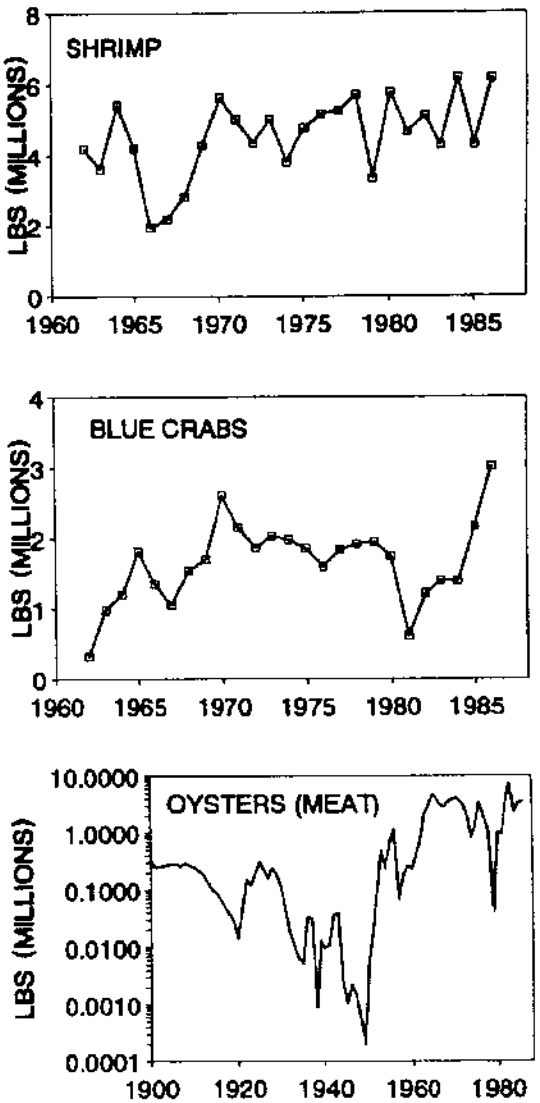

Figure 7.3. *Galveston Bay commercial landings of shrimp, blue crabs, and oysters.*

Oysters

Galveston Bay oysters are an important commercial species, spend their entire lives in the bay, are not able to flee polluted waters, and have the capacity to concentrate some potentially lethal pollutants. Thus, they ought to be an ideal organism to study in terms of the long-term effects of changes in water quality on the fishery resources of the bay. Coincidentally, the oyster fishery in Galveston Bay seems to have been monitored, researched, and analyzed more thoroughly over the past 30 years than any other bay fishery.

R.P. Hofstetter, the leader of much of the long-term effort to track oyster populations in the bay, has indicated that it arose from conflicts between the oyster fishery and a related industry -- shell dredging:

> In 1951, shell dredging companies operating within the bay proposed to . . . dredge several passes through two "barrier" reefs . . . The purpose was to improve water circulation and encourage oyster growth . . . Since no current information on the status of the oyster reefs was available . . . [Game and Fish Commission] personnel were requested to investigate. This was the beginning of oyster studies in Galveston Bay by the Coastal Fisheries Division. Although the dredging was evaluated and judged unnecessary, it was decided that further studies would be useful.
>
> By the mid-1950s . . . shell dredging operations, which had been centered in Trinity Bay, moved closer to the main reefs as shell deposits in the upper bay became exhausted. Expan-

> sion of the shell industry along with growth of the oyster fishery made conflicts inevitable, and it became necessary to develop a shell management program based upon a knowledge of the oyster resource. Studies originally intended as a short-term evaluation of the shell-dredging proposal evolved into a long-term program to obtain information needed for the management of both industries
>
> (Texas Parks and Wildlife Department 1988).

Two valuable reports summarizing the knowledge gained from these studies are Hofstetter's (1977) *Trends in Population Levels of the American Oyster*, and the recently completed *Texas Oyster Fishery Management Plan Source Document* by the Texas Parks and Wildlife Department (1988). The discussion below relies heavily on material presented in these two reports.

The abundance of spat, young oysters and market size oysters at several locations in Galveston Bay has been monitored regularly since 1956. Samples, consisting of 0.035 m^3 of unculled oysters, are collected using a "Texas style" oyster dredge. Live oysters are culled from the sample, measured, and grouped into classes designated as spat (<25 mm), small (26-75 mm) and market size (76 mm and over). Since the amount of area covered by the reefs has not been followed, these data are not necessarily representative of the total quantity of oysters in the bay, but rather changes in densities over time for the reef areas sampled (Texas Parks and Wildlife Department 1988).

First, annual mean numbers of spat (5-25 mm) in Galveston Bay samples generally declined from the late 1950s through 1977 before increasing gradually through 1984 (Figure 7.4). Annual mean number of spat in open waters (waters containing oysters approved by TDH for harvest), has varied since 1984 (Figure 7.5). Since 1985 however, highest numbers of spat were seen during July through November. Annual mean number of small oysters (26-75 mm) generally declined from the late 1950s through 1977 before increasing to a peak in 1981 and declining through 1984 (Figure 7.6). Annual mean number of small oysters in open waters continued to decline between 1985 and 1987 (Figure 7.7). Finally, annual mean number of market oysters (>76 mm) in Galveston Bay samples generally fluctuated between 20 and 40 individuals per sample between 1956 and 1981 before peaking at 68 individuals/sample in 1982 (Figure 7.8). Mean number of market oysters declined to pre-1982 levels in 1984. Annual mean number of market oysters in open water samples has declined since 1985. Monthly mean number of market oysters is generally highest just prior to the opening of the oyster season, declines through the season and increases before the next season opens (Figure 7.9) (Texas Parks and Wildlife Department 1988).

Oysters were not harvested commercially from Texas bays to a great extent prior to 1870. Before 1880 there were no efficient methods for transporting oysters inland from coastal communities and the sale of oysters was restricted to local markets. The growth of oystering paralleled the development of shipping and processing industries along the coast (Stevenson 1893).

Historical trends in the Galveston Bay oyster harvest are depicted in Figure 7.3. Hofstetter noted an apparent 10-12 year cyclical fluctuation (unexplained) in the pattern of oyster landings between 1900 and 1972. From 1900 through 1910, annual oyster production ranged from 244,000 to 336,000 pounds of shucked oyster meats. After 1911, harvests dropped substantially, ranging from almost 100,000 pounds in 1914 down to slightly below 15,000 pounds in 1920. Within two years production had

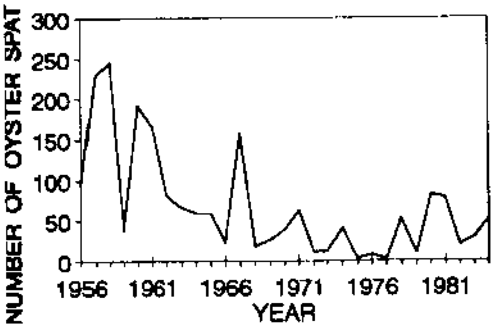

Figure 7.4. *Annual mean number of oyster spat in 0.035 m³ oyster dredge samples collected quarterly at three Redfish Bar sites in central Galveston Bay during 1956-1984 (Texas Parks and Wildlife Department 1988).*

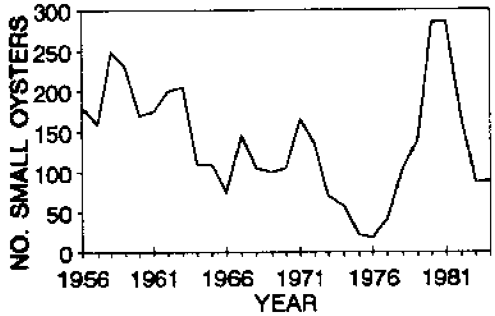

Figure 7.6. *Annual mean number of small oysters in 0.035 m³ dredge samples collected quarterly at three Redfish Bar sites in central Galveston Bay during 1956-1984 (Texas Parks and Wildlife Department 1988).*

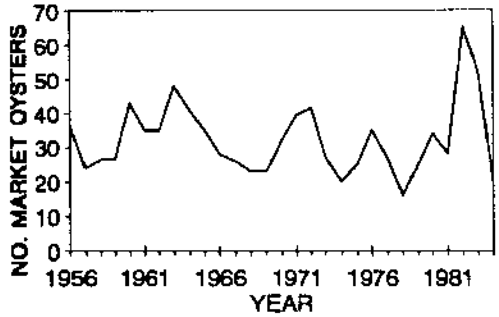

Figure 7.8. *Annual mean number of market oysters in 0.035 m³ oyster dredge samples collected quarterly at three Redfish Bar sites in Central Galveston Bay during 1956-1984 (Texas Parks and Wildlife Department 1988).*

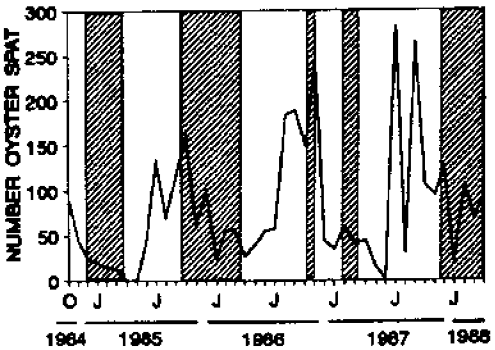

Figure 7.5. *Mean monthly number of oyster spat per 5-minute tow time collected in Galveston Bay from unpolluted waters. Shaded areas indicate open fishing seasons (Texas Parks and Wildlife Department 1988).*

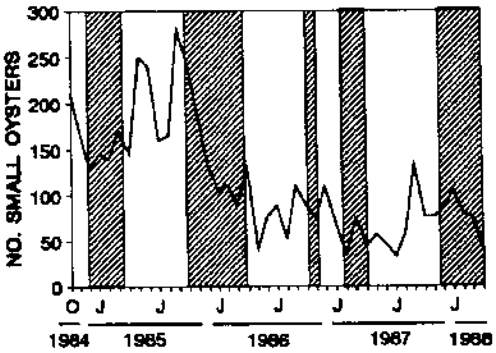

Figure 7.7. *Mean monthly number of small oysters per 5-minute tow time collected in Galveston Bay from unpolluted waters. Shaded areas indicate open fishing seasons (Texas Parks and Wildlife Department 1988).*

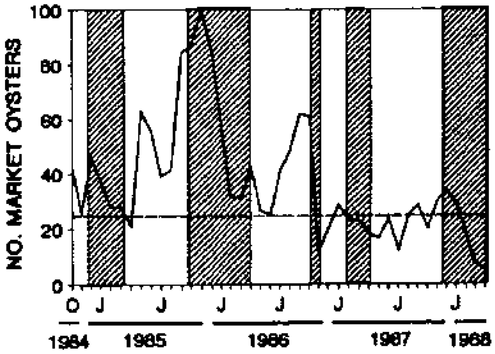

Figure 7.9. *Mean monthly number of market oysters per 5-minute tow time collected in Galveston Bay from unpolluted waters. Shaded areas indicate open fishing seasons. Broken line represents historical depletion level (Texas Parks and Wildlife Department (1988).*

jumped about ten times to almost 150,000 pounds, ranging upwards to over 300,000 pounds in 1925 and staying above 100,000 pounds through 1930. The harvest plummeted in the 1930s to a low of 5,000 pounds in 1935, climbed above 30,000 pounds for two years, then dropped to 800 pounds in 1938. Aside from 1942 and 1943 when harvests ranged above 37,000 pounds, production remained close to 10,000 pounds per season in the early 1940s, falling to 1,000 or 2,000 pounds in the late 1940s and finally reaching bottom in 1948 when no harvest was reported. In the 1950s production increased, with over 1 million pounds reported for the first time in 1956.

A prolonged flood in 1957 caused lower harvests for a few years but production rose in 1961, reaching 1 million pounds again in 1962 and attaining a new record high of over 4 million pounds in 1965. Until 1972 harvests ranged close to 3 million pounds per season (Hofstetter 1977). After 1972, the harvests declined for two years to 750,000 pounds in 1974, rose to 3.25 million pounds in 1976, and then declined steadily to 40,000 pounds in 1979, the lowest value in 20 years. A rising trend in the early 1980s was capped by an all-time high 7 million pound harvest in 1983. Finally, the catch fell back to about 2.5 million pounds in 1984 and has fluctuated around 3 million pounds since (Figure 7.3 and Texas Parks and Wildlife Department 1988).

Causes of fluctuations in commercial fisheries landings can never be completely quantified because there are so many factors which contribute to the variability. But in their proposed oyster fishery management plan, Texas Parks and Wildlife Department (1988) summarized the important factors affecting the oyster catch as follows:

1. Data on fishing effort are not reliable, although the numbers of fishermen, their gear and activity have changed greatly in the past 100 years.

2. Many types of irregular events can cause short-term fluctuations. These include mass mortalities from freezes, toxic phytoplankton blooms, hypersalinity, harvest restrictions, world wars, hurricanes, tropical storms, and economic considerations like inflation.

3. Long-term events that may cause more gradual changes in landings include trends in gear used, water quality deterioration from pollutants or long-term climatic-hydrographic changes.

4. The veracity of the catch statistics can be affected by changes in reporting rates by oyster dealers.

The most noticeable long-term feature of the Galveston Bay oyster harvest data (Figure 7.3) is the sudden rise in annual catches during the early 1960s. In the opinion of the experts, three factors contributed to this change:

1. Decrease in the minimum legal harvestable size: In February, 1963, the Texas Game and Fish Commission reduced the legal oyster size from 3.5 inches to 3 inches, because studies had shown that oyster survival dropped sharply among oysters over 3 inches. The immediate effect was to nearly double the quantity of oysters available to fishermen. However, this change in the legal size seems not to have affected the market oyster stocks (Hofstetter 1977).

2. Increase in fishing gear efficiency: The oyster dredge was introduced into the Texas fishery in 1913. However, tonging continued to be the major harvest method until the 1960s when it was supplanted by the dredge skiff, a small open boat propelled by outboard motor and equipped to pull a dredge and hoist it aboard. In earlier years this "power dredging" was prohibited in Galveston Bay waters less than 6 feet deep, but this rule was rescinded in 1963. Tongers were numerous in the mid-1950s while the shallow portions of the bay were closed to power dredging, and in

1954-58 tonging accounted for 34%-56% of the harvest. By the 1960s tongers produced less than 10% of the harvest and after 1963 around 1% was tonged (Hofstetter 1977).

3. Underreporting: Hofstetter (1977) and Texas Department of Parks and Wildlife (1988) cautioned that the low landings reported before 1960 are due in part to underreporting. In particular:

> The initiation of mandatory self-reporting in 1936 was followed by a decline in reported landings. Prior to 1937 most of the landings information was voluntarily supplied by major oyster dealers. Since 1937 all seafood dealers have been required to report all seafood products purchased from commercial fishermen to Texas Parks and Wildlife Department on a monthly basis. Reported landings increased noticeably between 1962 and 1963 when Parks and Wildlife began to actively monitor and enforce reporting requirements
>
> (Texas Parks and Wildlife Department 1988).

Past research and monitoring of the Galveston Bay oyster fishery have provided no concrete evidence of links between pollution and either abundance or harvest of oysters. Hofstetter (1977) reviewed what had been learned by the mid-1970s. He discussed four classes of pollutants that had been investigated. Here are his conclusions, supplemented by other information I have gleaned from the more recent literature.

1. Heavy metals: Thousands of kilograms of heavy metals are discharged into the Houston Ship Channel daily. Flushing of the channel could distribute these heavy metals into the bay, possibly contaminating oysters. However, 1969 and 1970 analyses of bay oysters yielded trace metal concentrations that did not reflect any significant effect from the industrial waste sources upon approved oyster growing areas (Casper 1971 was cited).

2. Petroleum Hydrocarbon Residues: In addition to concentrations of petrochemical industries in the Houston Ship Channel and along the western shores of the bay, there are several oil and gas production fields within Galveston Bay. Many of the wells are on, or near, oyster reefs. The Environmental Protection Agency (1971a) cited the ship channel as a major source of oil and petrochemical waste with contributions from vessel pollution and from oil well pumping in the bay. Its survey in 1970 found 23-26 ppm hydrocarbon residues in oysters from approved shellfish harvesting areas, 30 ppm in oysters from a conditionally approved area, and 237 ppm in oysters from a closed area at Morgan's Point near the entrance of the Houston Ship Channel into the bay. However, sampling of oysters from 18 stations by the Food and Drug Administration in May 1971 showed that the levels of toxic fractions of hydrocarbons were not of public health significance, nor were there visible signs of oil or odors of petroleum distillates (Casper 1971). Anderson (1975) found that Galveston Bay oysters accumulated a wide variety of petroleum hydrocarbons when exposed to various concentrations of refined and crude oils, but released hydrocarbons from their tissues within 52 days when placed in oil-free sea water.

3. Pesticide Residues from Agriculture: In 1965 croplands around Galveston Bay received about 6 million kg of pesticides, including 3.3 million kg of Toxaphene, 1.9 million kg of Sevin, 700,000 kg of DDT, 300,000 kg of Parathion and 200,000 kg of Dieldrin (Childress 1965). Of the 47 oyster samples collected in Trinity and East Bays during 1965-72, approximately 60% contained DDT residue, 2% contained Dieldrin and none contained Endrin, Toxaphene or PCB. Of the 71 oyster samples

from Galveston Bay, 85% contained DDT, 44% contained Dieldrin but no Endrin, Toxaphene or PCB appeared (Butler 1973). Generally, a clearly defined trend towards declining DDT residues was observed in oyster samples from all areas of the Texas coast. By 1971 samples containing 100 to 1,000 ppb DDT had decreased 75% (Butler 1973). Chlorinated hydrocarbon levels in Galveston Bay were of no known public health significance (Casper 1971).

4. Municipal Sewage Contamination: Of all pollutants, sewage contamination has probably had the greatest observable effect on the fishery, causing the State Health Department to close various sections of Galveston Bay because of high coliform bacteria concentrations in oysters or in waters overlying oyster beds.

Oyster beds in Galveston Bay may be closed for two reasons. The first is that the waters are determined to be polluted on a more-or-less permanent basis. The polluted waters are indicated on maps that have been produced by the Texas Department of Health from time to time since 1951. The second reason for closing oyster beds is that bacteria counts in runoff water flowing into the bay go up when it rains, and the department can temporarily close otherwise approved oystering areas. After the rains stop and the oysters have had time to cleanse themselves, the bay is returned to its normal classification map. Large areas of otherwise approved oystering areas in the bay may be closed temporarily because of excessive freshwater inflow. Table 7.1 summarizes the data on closings of this type in the bay between 1969 and 1985. Most of the closings in recent years have been due to excess freshwater inflows (R.E. Thompson, personal communication).

Table 7.1. *Closings and openings of oyster fishing areas in Galveston Bay due to excessive freshwater inflow, 1969-1985.*

Month/Year	Trinity Bay	Galveston Bay	East Bay	West Bay
Feb.-Mar 1969	21	21	21	0
Mar-Apr. 1973	22	22	15	15
Apr.-Aug. 1973	118	118	22	22
Jan.-Mar. 1974	48	48	48	0
Jun. 1976	6	6	6	
Jul-Aug. 1979	12	12	12	12
Jun. 1981	7	7	7	7
Jul. 1981	8	8	8	8
Jan.-Apr. 1983	76			
Aug.-Sep. 1983	42	42	42	42
Oct.-Jan 1984/85	21	21	21	82
Mar.-Apr. 1985	17	17	17	21

The permanently closed, polluted, or unsanitary oystering areas in the bay have changed over the years. In 1883, Spencer Baird of the U.S. Fish Commission prepared a map of oyster beds in Galveston Bay. Bernard Johnson (1975) noted that in 1971 the beds were in the same location as shown on the 1883 map, except for those in West Bay. Hofstetter (1977) speculated that the decline of the West Bay reefs was caused primarily by increased salinity resulting from changes in circulation patterns in the bay following dike and channel construction.

A sanitary survey in 1943 showed that an area of West Bay between Texas City and Galveston should be declared grossly polluted. In February 1944 an outbreak of food poisoning occurred at a oyster dinner in Galveston in which cases of gastro enteritis were traced to the consumption of raw oysters gathered from polluted areas (Wise et al. 1944). In the late 1940s most of the bay was unapproved for commercial oystering. This has been cited frequently as a cause for the decline of the oyster catch in the bay during the 1940s (Hofstetter 1977).

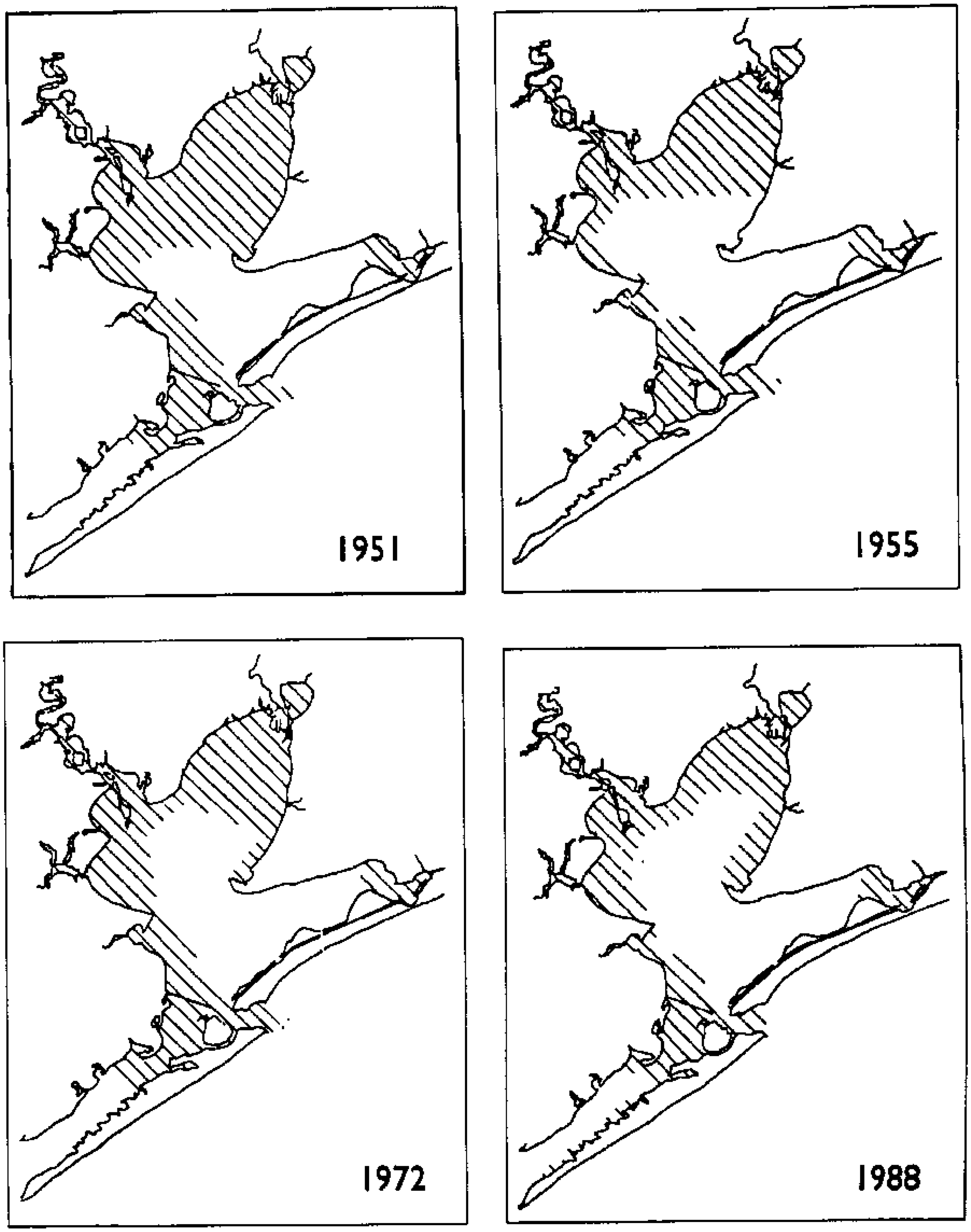

Figure 7.10. *Changes in areas closed to oystering in Galveston Bay, 1951-1972. Areas between Galveston Island and the Texas City Dike, Chocolate Bay, upper East Bay, and upper Galveston and Trinity Bay within slashed line were clsoed in all years. From Hofstetter (1977).*

The first map showing areas approved and unapproved for oystering were produced by the Texas Department of Health following a survey in 1951. At that time, new sections of the bay were approved for oystering (Texas Department of Health 1952), and the annual catch began to increase shortly thereafter. It is not clear from the literature whether or not these openings resulted from improved sanitation, but I suspect not. Wise et al. (1948) indicated that large volumes of raw sewage were still being discharged into the bay in the late 1940s from Houston, Galveston and Texas City municipal treatment plants.

Although changes have been made in approved oystering areas since the mid-1950s (Figures 7.10), most of the major public reefs were, and have remained, in approved waters (Texas Department of Health 1958, 1967).

It was concluded in 1971 that "detailed evaluation of over 3,000 bacteriological samples from 84 water sampling stations and related hydrographic and meteorological data in addition to over 750 oyster samples collected by the Texas State Department of Health since 1963 indicates that the shellfish industry has a quality product available. There has been no consumer complaint or confirmed case of illness traced to the consumption of Galveston Bay oysters" (Casper 1971).

The recently completed oyster fishery management plan for Texas bays provides insight on the perceived threats faced by these shellfish today in Galveston Bay. Historically, the Texas Legislature has managed the state's oyster fishery, but limited authority has been delegated to the Texas Parks and Wildlife Department and to the Texas Department of Health. Parks and Wildlife may close areas to oyster harvest when it is determined they are being overworked, damaged, being reseeded or restocked. The Health Department closes areas to harvest when they are determined to be polluted, either on a permanent or temporary basis. (Texas Parks and Wildlife Department 1988). In 1985 the State legislature directed the Parks and Wildlife Department to prepare a new Oyster Fishery Management Plan that will result in "optimum yield" for the oystering industry. Optimum yield is defined as "the amount of oysters that the fishery will produce on a continuing basis to achieve the maximum economic benefits . . . as modified by any relevant social or ecological factors." (p. 5, Texas Parks and Wildlife Department 1988).

The following are some of the recommendations made in this plan for future management of the oyster fishery:

1. Area closures in unpolluted waters, as well as specific time period restrictions (time-of-day and seasonal), and size limits should continue to be the primary management tools for managing the oyster industry. No change in the current minimum size limit (3 inches) for harvestable oysters is recommended.
2. Penalties for violating regulations should be increased.
3. An industry-financed shell recovery and cultch replacement program should be implemented for natural reefs. The Department should continue to aggressively protect and enhance oyster habitat and water quality via all available resource protection agencies and programs.
4. Monitoring of oyster population trends and commercial landings and effort should continue.

The Importance of Freshwater Inflow

A recurring theme of estuarine fishery management in Texas has been the importance of freshwater inflow, and related variables such as salinity regime. nutrient supply, and phytoplankton and zooplankton productivity. Although somewhat anecdotal, notes in the *Annual Summary*

Table 7.2. *Excerpts from Annual Summary reports of Texas commercial fisheries landings (U.S. Department of Commerce [1969-1979]; U.S. Department of Interior [1963-1968])*

Fishery Year	Excerpts from Comments
Oyster	
1965	There were no reports of 'oyster kills' or meat discolorations during 1964 or 1965
1967	The hot, dry, arid conditions in the Galveston watershed throughout the spring and fall harvest seasons cut the yield of meatssome 6 to 7 percent below that obtained in 1966
1969	Freshwater input into the Galveston Bay system was somewhat below the desired level
1971	Meat yields were less than normal as sustained hot, dry weather was prevalent throughout the spring and much of the fall season
1972	Many reefs were closed during March and April because of flood waters
1973	Heavy floods during the spring and early summer killed many small reefs in Galveston Bay and caused intermittent closing of all reefs during the spring
1974	Decline due largely to heavy mortalities from freshwater kills in fall 1973 and spring 1974
1975	Increase resulting from the recovery of reefs damaged by freshwaters in the fall and spring of the 1973-1974 season
1976	Increase resulting from reef recovery from the 1974 freshwater kill and increased fishing because of strong market demand
1977	Decline attributed to heavy fishing pressure in 1976 and cold rough weather during the fall season of 1977
1978	Decline attributed to heavy fishing pressure in 1977
1979	Heavy floods in 1978 and 1979 resulted in the closure of most public reefs
Blue Crabs	
1965	The first legal restrictions were imposed on the crab industry in mid-1965 . . . illegal to possess an egg-bearing female for sale or personal use
1966	There was a steady decline in crab populations in all major areas throughout 1966
1967	A steady decline in crab populations was evident until late fall when freshwater intrusion improved ecological conditions
1968	An incentive . . . was the extremely short supply of crab meat due to a tremendous decline in blue crab populations in most other major producing areas in the country
1977	Most of the increase was attributed to increase fishing pressure
1977	Increase resulted largely from higher prices which led to heavy fishing
Finfish	
1964	In recent years, the closing of more inshore water to net fishing has caused a general decline in the volume of domestic edibile fish landings
1968	Red snapper landings have been on a downward trend mainly due to reduced fishing effort by Texas fishermen as a result of a lack of abundance on grounds normally fished
1977	Drop resulted from very cold, rough waters in late 1977 and the short supply of good fish in the Texas bays
1979	The 1979 harvest reflected the continuing decline in the population of of major species in the State. The heavy floods, a severe fuel shortage, and the Mexican oil spill plagued the Texas fisheries in 1979

reports of Texas landings since 1962 suggest that climate-related events, along with over fishing and market economics, are the major factors affecting year-to-year variations in the seafood catches (Table 7.2). Over and over, researchers have sought to quantify the physical, chemical and biological effects of fluctuating inflow, particularly in the Galveston Bay system. Freshwater inflow has been studied, and written about, as much as, or more than, each of the other factors, including pollution, that affect the Galveston Bay system fisheries. Undoubtedly, interest in the subject has been sustained partly because of perceived dangers from the long-standing proposal to dam the Trinity River at Wallisville. The following synopsis of some of the early research is from a 1981 Texas Department of Water Resources Report entitled *A Study of the Influence of Freshwater Inflows.*

> Diener (1975) concluded that the optimum salinity range in the bay is 10-17 ppt and that an estimated 2,000 cfs of Trinity River inflow during March through October is necessary to maintain the habitats. Copeland et al. (1972) estimated that the upper Trinity Bay habitats were up to 72% dependent upon river-borne organic matter to support the observed high secondary productivity in the area. More specifically, Parker et al. (1975) concluded that a minimum 1.3 million acre-feet per year of Trinity River inflows may provide sufficient nutrients to sustain a low level of phytoplankton and marsh plant production in the Trinity Delta and bay area. However, Soloman and Smith (1973) suggested that while the bay is highly dependent upon the river inflows for salinity maintenance, the bay may not be as dependent upon river-borne nutrients.
>
> Although an inverse correlation has been reported between Trinity River flows and the bay's density of crustaceans (Baldauf et al. 1970), Cooper (1970) noted that excessive retardation of freshwater flow acted as a stress which had synergistic effects with increased effluent loading. Using 1956 through 1968 commercial fisheries statistics, Parker and Blanton (1970) hypothesized a reduction in seafood landings when average winter salinities exceed summer salinities as a result of high spring/summer freshwater inflows to the estuary. In another attempt to correlate fisheries with inflows, Armstrong and Hinson (1973) reported that an analysis of 1959 through 1964 records indicates that Galveston Bay displacement rates exceeding twice per year apparently cause a decrease (i.e., negative correlation) in total commercial harvests.

Texas politicians apparently were receptive to the ecologists message about the importance of freshwater inflow, as the State legislature passed resolutions in 1973 and 1975 declaring that "a sufficient inflow of freshwater is necessary to protect and maintain the ecological health of Texas estuaries and related living marine resources" (Texas Department of Water Resources 1981a). Subsequently, the 1975 legislature enacted a bill mandating comprehensive studies of the effects of freshwater inflow upon the bays and estuaries of Texas. Presumably, the study results would help to insure that the estuaries would not be short-changed in the future as various interests competed for the state's limited supply of freshwater.

This turned out to be the most thorough study of the subject to date, and a series of reports were prepared, one for each of the State's major estuaries, including, of course, the Galveston Bay system (Texas Department of Water Resources 1981b). Once again, it was found that a large part of the year-to-year variation in finfish and shellfish harvest in Galveston Bay, as well as in the adjacent offshore waters, can be explained by differences in freshwater inflow. Step-wise multiple regression techniques were used to examine the relationships between seasonal harvests and freshwater inflows to the bay. The harvests of most species were determined to show statistically significant changes as inflows changed, but the direction of the effects was variable. For example, increased freshwater inflow in spring (April-June) was positively related to offshore shrimp harvest, but the same spring inflow increase was negatively related to inshore harvests of oysters, blue crabs, and red drum. In other words, the different species require different seasonal inflow regimes for optimal productivity. Therefore, the study report concluded, management decisions regarding freshwater inflow control would need to be based on balancing these divergent needs, or giving preference to the needs of one or two particular fisheries components. A choice could be made on the basis of which species production is more ecologically characteristic and/or economically important to the estuary (Texas Department of Water Resources 1981b).

Much has been written about the year-to-year effects of Trinity River freshwater inflow on Galveston Bay oyster abundance and harvests. Lower than normal salinity caused by river floods has been the major cause of short-term declines in oyster abundance in the bay. For example, Hofstetter (1977) documented in detail the close coupling between salinity and spat setting and oyster mortality during the 1960s and 1970s. Best spat sets occurred when spring salinities ranged between 17-24 ppt and the poorest sets occurred when salinities dropped below 8 ppt. Also, salinities below 3 ppt affected oyster feeding and increased mortality. Oyster populations in the upper bay (i.e., Trinity Bay) were periodically reduced, or totally destroyed by the spring flooding. Oysters in middle Galveston Bay and in East Bay were killed only in severe flooding such as 1957 and 1973. These two floods led to strong declines in harvests in the late 1950s and in 1973-1975 (Figure 7.3).

Before impoundments were erected on the Trinity River, flood waters reached and flowed through Galveston Bay very quickly (Hofstetter 1977). Salinities were reduced to near freshwater levels, but the freshet was usually of short duration. These brief freshets killed many oysters but when salinity levels increased again, oyster populations could rapidly reestablish themselves, taking advantage of the clean fresh cultch provided by the oysters that died. Since impoundments have been built, flood waters have been impounded and released at a slower rate over a longer period of time. Salinity levels in the bay still drop to lethal levels (1-3 ppt) but the duration of the freshet is extended. Extended freshets are more destructive than rapidly passing floods (Hofstetter 1977) and as a result, oyster populations are not able to reestablish themselves as quickly.

On the other hand, increased salinity in the lower bay probably has led to increased oyster reef predation and disease losses (Hofstetter 1977; Martin 1987; Sheridan et al. 1988). The infectious protozoan *Perkinsus marinus* (or *Dermocystidium marinum*) causes extensive mortality of seed and market sized oysters in the higher salinity (>20 ppt) areas of the bay. Also, there is a predator -- the oyster drill (*Thais haemastoma*) -- which is widespread in the higher salinity (>15 ppt) areas of the bay (King et al. 1986).

Recreational Fisheries

The Database

The Texas Parks and Wildlife Department has conducted surveys of private-boat sport fishermen in Texas marine waters since 1974. These surveys monitor the species composition, size, number, and landings per unit of effort for the economically important species landed by fishermen on a yearly basis in the Gulf of Mexico off Texas, and in the bays, including Galveston Bay. A report by Osburn and Ferguson (1986) included a compilation of all these survey data used in the Galveston recreation fishing trend plots described below. This report also describes in detail the survey methods used to obtain the estimates.

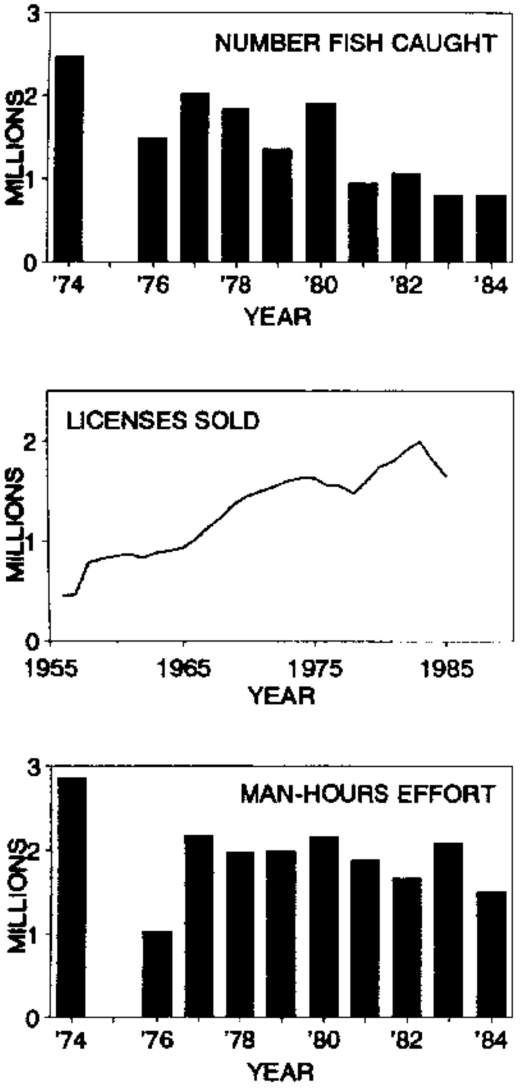

Figure 7.11. *A. Annual catch of fish in Galveston Bay by private-boat sport fishermen, 1974-1985.* ***B.*** *Number of recreational fishing licenses sold in Texas, 1958-1985. C. Man-hours of effort for private-boat sport fishermen in Galveston Bay, 1974-1985. All data are from Osburn and Ferguson (1986).*

Trends in Recreational Fishing

Private-boat sport fishing effort, as measured by man-hours spent fishing, decreased only slightly since the 1970s in Galveston Bay (Figure 7.11). This is contrary to the general pattern for the state, which is one of increasing fishing pressure in the bays and passes, reflected both by the number of man hours and also by the number of fishing licenses sold (Figure 7.11 and Osburn and Ferguson 1986). But the numbers of fish caught declined both in Galveston Bay and for the state as a whole. Percentage-wise, the decreases from 1974 to 1985 were about the same: 64% for Galveston Bay and 73% for the State.

Declines in catches in nearly all the most popular sport fish in Galveston Bay contributed to the overall decline (Figure 7.12). Sand seatrout, spotted seatrout, and croaker, which comprise the bulk of the catch, have all declined by about two-thirds. Flounder, sheepshead, and black drum catches have fluctuated widely, but overall were not very different in 1984-85 than in 1974-75. The prohibition on commercial harvesting of spotted seatrout and red drum in the bay in 1981 apparently had little short-term impact on the private-boat sport catches, as they continued to decline slowly.

Osburn and Ferguson (1986) hypothesized that the declining landings in Galveston Bay were due partly to declining

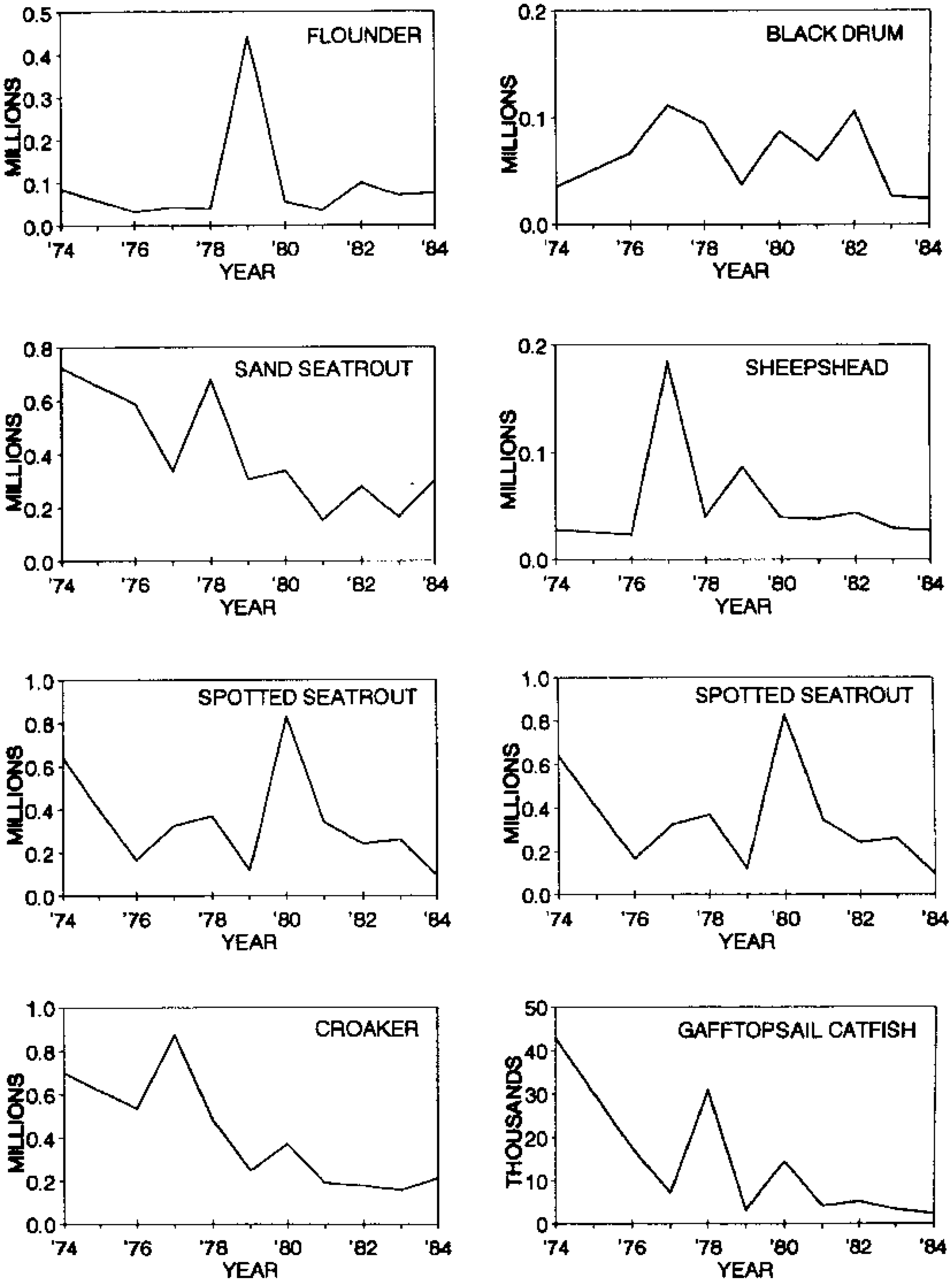

Figure 7.12. *Annual catches of major recreational species in Galveston Bay by private-boat sport fishermen, 1974-1985. Data from Osburn and Ferguson (1986).*

fish availability. They cited as evidence for this both the decline in catch rates by private-boat fishermen and data from the Texas Parks and Wildlife Department fisheries-independent monitoring program. But the data from this monitoring, given in Rice et al. (1988), do not appear to support the hypothesis (Figure 7.13). The "catch rates" (number of each fish species caught per hour with gill nets, or fish density per hectare as determined with bag seines), are tabulated for each of the major bays in the State, including Galveston Bay. For both Galveston Bay and all the Texas bays combined ("coastwide" values) there are no obvious long-term trends in the catch rates, at least for all fish species combined. But there were downward trends in spotted seatrout and red drum, according to the authors of the report (Rice et al. 1988). Short-term decreases in both the sport fishing catches and the catch-rate monitoring data between 1983 and 1984 were attributed to a severe fish kill along the Texas coast in the 1983-1984 winter, caused by unusually cold temperatures (Osburn and Ferguson 1986; Rice et al. 1988).

Fish Kills and Diseases

Bernard Johnson (1975) summarized Galveston Bay fish kill data for the period 1962-1974 (Table 7.3). More detail as to location, time of year, and cause is given in the report from which this summary information was taken. Most (>75%) of the kills occurred during the summer (June-September). Most of the kills in "Galveston Bay" were actually in the semi-enclosed harbor at Texas City; there were very few in the open waters of the bay (Bernard Johnson 1975). Most of the kills in the ship channel were attributed to either oxygen depletion or sewerage operations. For the Galveston Bay kills, the causes included oxygen depletion, pesticides, petrochemicals, bacterial infections, and in many cases were unknown. The "other areas" data in

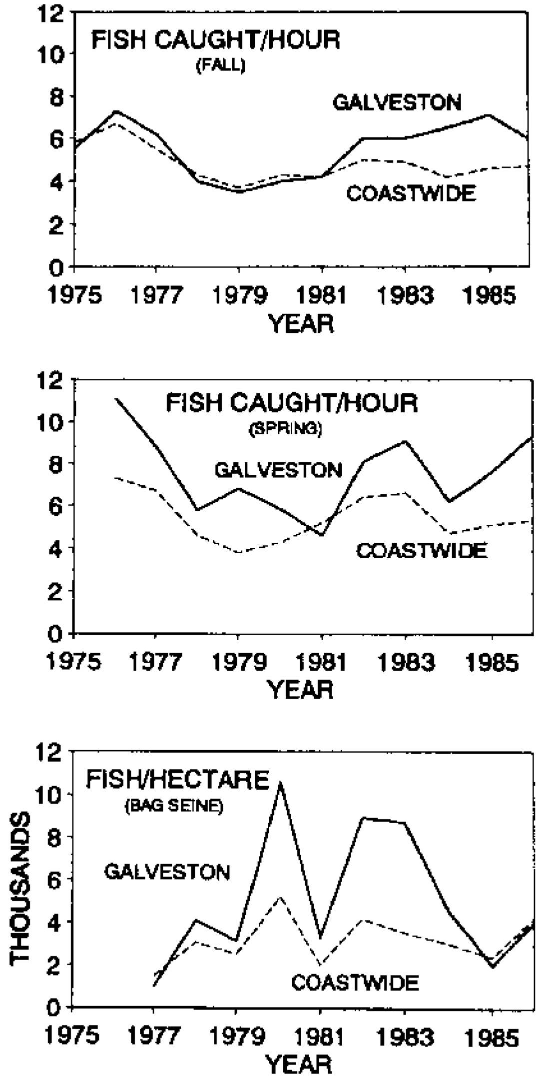

Figure 7.13. *Catch-rate data for Galveston Bay and for all Texas estuaries ("coastwide") combined, 1975-1986.* ***Top, Middle.*** *Gill net samples were taken in the fall (F) and in the spring (S) of each year.* ***Bottom.*** *Seine-bag samples were collected in each estuary 6-10 times per month. See Rice et al. (1988) for details.*

Table 7.3 are for enclosed bayous and lakes, drainage ditches, rivers and marinas contiguous to Galveston Bay. Here also, there were a wide range of causes for the fish kills, including sewerage, pesticides, petrochemicals, and oxygen depletion. Many of the kills in these areas also were from unknown causes. The numbers of fish estimated to have been killed ranged very widely, from a few dozen to as high as 20 million in one incident. In most cases, the numbers were between 1,000 and 100,000.

There was a tremendous increase in the number of reported incidents and fish killed in Galveston Bay during the early 1970s (Table 7.3), but this probably is misleading. That was a period when there was a great deal of research and monitoring effort on the bay, so that undoubtedly there was more effort to document fish kills than there had been in the past. This is a problem common to the fish kill data from most other regions; i.e., unequal sampling effort over a long period of time (Stanley 1985). Thus, unfortunately, these Galveston Bay fish kill data are of little use in assessing water quality trends.

Table 7.3. *Summary of fish kills in the Galveston Bay area, 1962-1973. Data are from Bernard Johnson (1975).*

	Ship Channel		Galveston Bay	
Year	No. Kills	No. Fish	No. Kills	No. Fish
1962				
1963	1		6	19,000
1964	2	100,200	1	30
1965	5	15,300	6	13,000
1966	1	2,000	2	3,000
1967			2	1,000
1968	2	31,000		
1969	1			
1970	6	1,253,200	4	13,000
1971	3	23,000	9	2,795,900
1972	7	1,110,000	7	1,261,100
1973	2	512,000	6	426,530
1974	3	21,000	3	1,511,000

	Other Areas		Total	
Year	No. Kills	No. Fish	No. Kills	No. Fish
1962	8	10,000	8	10,000
1963	6	61,000	13	25,100
1964			3	100,230
1965	8	7,106	19	35,406
1966	4	250	7	5,250
1967	6	8,800	8	9,800
1968	4	2,050	6	33,050
1969	16	1,513,215	17	1,513,215
1970	22	4,273,650	31	5,539,850
1971	50	22,461,760	62	25,280,660
1972	45	46,470,522	59	48,841,622
1973	34	40,570,604	42	41,503,134
1974	23	8,125,795	29	3,657,735

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Appendices

Appendix 1. Chronological History of Army Corps of Engineers Activities in the Galveston Bay System

Galveston Harbor and Channel

Aug. 5, 1886: Construct 2 rubblestone jetties at entrance to Galveston Harbor.

June 13, 1902: A channel 1,200 by 30 feet from Bolivar Roads (outer end of old inner bar near Fort Point) to 51st St.

Mar. 3, 1905: Purchase or construct hydraulic pipeline dredge.

Mar. 2, 1907: Extension of jetties to present project length and construction and operation of a dredge.

Mar. 2, 1907: Extension of Galveston Channel from 51st to 57th Sts., with depth of 30 feet and width of 700 feet.

June 25, 1919: Conditional extension of Galveston Channel between 51st and 57th Sts., 30 feet deep and 1,000 feet wide.

July 27, 1916: Extend seawall at Galveston from angle at 6th St. and Broadway to vicinity of Fort San Jacinto.

July 18, 1918: Deepen harbor channel to 35 feet and widen to 800 feet.

Sept. 22, 1922: Further extension of seawall at Galveston to a junction with south jetty; and repairing seawall in front of Fort Crokett reservation.

Jan. 21, 1927: Deepen Galveston Channel to 32 feet; and maintain Galveston Harbor channels to dimensions of 800 feet wide, 35 feet deep on outer bar and 34 feet deep on inner bar.

Aug. 30, 1935: Maintain State Highway Ferry Landing Channels to dimensions of 12 by 100 feet.

Aug. 30, 1935: Construct 13 groins along gulf shore from 12th to 61st Sts. in city of Galveston at a limited cost of $234,000 (10 groins constructed).

Aug. 30, 1935: Deepen Galveston Channel to 34 feet (Bolivar Roads to 43d St.).

Aug. 30, 1935: Deepen Galveston entrance channel to 36 feet.

April 4, 1938: Completion of project for construction of 13 groins.

June 30, 1935: Deepen Galveston Harbor to 38 feet from gulf to a point 2 miles west of seaward end of north jetty; thence 36 feet to Bolivar Roads; revoking authority for maintenance of ferry channels; and Galveston channel to 36 feet deep from Bolivar Roads to 43d St.

May 17, 1959: Construct extension of Galveston Seawall from 61st St., southwesterly 16,300 feet along gulf shore.

July 3, 1958: Deepen Galveston Harbor to 42 feet from gulf to a point 2 miles west of seaward end of north jetty and 40 feet thence to Bolivar Roads to 43d St.

Houston Ship Channel

Mar. 5, 1905: Easing or cutting off sharp bends and construction of a pile dike.

Mar. 2, 1919: A channel 30 feet deep, widen bend at Manchester and enlarge turning basin.

Mar. 3, 1925: A light-draft extension of channel to mouth of White Oak Bayou.

July 3, 1930: Widen channel through Morgan Point and to a point 4,000 feet above Baytown and widen certain bends.

Aug. 30, 1935: Deepen to 32 feet in

main channel and turning basin, and a 400-foot width through Galveston Bay.

Aug. 30, 1935: Deepen to 34 feet in main channel and widen from Morgan Point to turning basin.

Mar. 2, 1945: Branch channel 10 by 60 feet behind Brady Island.

Mar. 2, 1945: Widen channel from Morgan Point to lower end of Fidelity Island with turning points at mouth of Hunting Bayou and lower end of Brady Island.

Mar. 2, 1945: Widen channel from lower end of Fidelity Island to Houston turning basin and dredge off-channel silting basins.

June 30, 1948: Deepen to 36 feet from Bolivar Roads to and including main turning basin at Houston, Texas, including turning points at Hunting Bayou and Brady Island.

July 3, 1958: Deepen to 40 feet from Bolivar Roads to Brady Island, construct Clinton Island turning basin, a channel 8 by 125 feet at Five Mile Cut, and improve shallow-draft channel at Turkey Bend.

July 14, 1960: Barbour Terminal at Morgan Point.

Oct. 27, 1965: Restoring existing locally dredged channel from mile 0 to 0.34 to 36 feet deep and dredging a 15-12 ft. channel from mile 0.34 to 2.81, in Greens Bayou.

Texas City Channel

Mar. 4, 1913: A channel 300 by 30 feet and construct a pile dike 28,200 feet long north to channel.

July 3, 1930: A harbor 800 by 30 feet at Texas City, and construct a rubblemound dike.

Aug. 30, 1935: Extension of rubblemound dike to shoreline.

Aug. 30, 1935: Deepen channel and harbor to 32 feet.

Aug. 30, 1935: Deepen channel and harbor to 34 feet.

Aug. 26, 1937: Extended harbor 1,000 feet southward, 800 by 34 feet.

June 30, 1948: Deepen channel and harbor to 36 feet, widen channel to 400 feet and harbor to 1,000 feet and changing name of project to "Texas City Channel, Texas."

July 14, 1960: Deepen channel and turning basin to 40 feet and construct 16-foot Industrial Barge Canal.

Oct. 12, 1972: Widen the existing main turning basin to 1,200 feet including relocation of the basin 85 feet to the east; provide a 40-foot deep channel in the Industrial Canal at widths of 300-400 feet, with a turning basin at the head of the canal 40 feet deep, 1,150 feet long, and 1,000 feet wide, and easing of the bend at the entrance to the canal, and deauthorization of shallow-draft Industrial Barge Canal not incorporated in the plan of improvement above.

Trinity River and Tributaries

Mar. 3, 1905: Anahuac Channel.

July 25, 1912: 6-foot channel to Liberty.

Sept. 22, 1922: Abandon improvements above Liberty and terminate all improvements by lock and dam, leaving a 6-foot channel from Liberty to mouth.

Mar. 2, 1945: Provides for a navigable channel from the Houston Ship Channel near Red Fish Bar in Galveston Bay to Liberty, Texas, with project depth of 9 feet deep and 200 feet wide in Galveston and Trinity Bays to the mouth of Trinity River and 9 feet deep and 150 feet wide in the river section, with a turning basin at Liberty.

July 24, 1946: Modification of the project to provide for a channel 9 feet deep and 150 feet wide from the Houston Ship Channel near Red Fish Bar in Galveston Bay extending along the east shore of Trinity Bay to the mouth of the Trinity River at Anahuac, including protective spoil embankment on the bay side of the channel in lieu of the 9 by 200-foot channel in Galveston and Trinity Bays.

Oct. 23, 1962: Provides for the multiple-purpose Wallisville Reservoir, including a navigation lock in the Wallisville dam at Channel Mile 28.30 and advancement of the Channel to Liberty from one mile below Anahuac (Mile 23.2) to the Texas Gulf Sulphur Company's slip at Channel Mile 35.8, and incorporation into existing project Anahuac Channel and mouth of Trinity River Projects.

Oct. 27, 1965: Reevaluation of navigation benefits.

Appendix 2. Water Quality Data Sources

Four water quality data sets were used for the trend analyses in this study. One is the Bureau of Commercial Fisheries (later the National Marine Fisheries Service) data, collected over a ten-year period from January 1958 through December 1976. Second, there is Galveston Bay Project data, which was collected on a monthly basis from July 1968 through August 1972, with the exception of a four-month period between November 1970 and February 1971. The third set of data is from the Texas Water Development Board (later the Texas Department of Water Resources and the Texas Water Commission). Finally, the Texas Department of Health Resources sampled the bay regularly beginning in 1963. The Texas Water Development Board/Department of Water Resources/ Water Commission data set covered the longest period of time (1972-present), and was the most thorough in terms of number of stations and sampling frequency. However, it was useful to combine their data set with those from the other agencies, wherever possible, so that the time series analyses could be extended back into the 1960s.

The objectives of the National Marine Fisheries Study were: "(1) to summarize bottom temperature, salinity, dissolved organic nitrogen, total phosphorus, and dissolved oxygen data in relation to three habitats and five bay areas; and (2) to determine the temporal and spatial distributions and ranges of these parameters and some of the relations and mechanisms affecting their distributions" (Pullen et al. 1971). Sampling frequency ranged between weekly and every other month. Before 1964, only temperature and salinity were measured. Dissolved oxygen (DO), total phosphorus (TP), and dissolved organic nitrogen (DON) were measured between 1964 and 1966. Pullen and Trent (1969) cited Marvin et al. (1960) for the TP and DO methods. They also stated that the DON was determined by Kjeldahl analysis, and that temperature and salinity were measured by means of either a salinometer (Industrial Instruments Model RS-5; accuracy +/- 0.3 ppt, +/- 0.5 °C), or by titration of water samples (accuracy +/- 0.2 ppt). It is important to note that all the water samples and *in situ* measurements were taken from the lower 0.3 m of the water column. There were no stations in the Houston Ship Channel north of Morgan's Point, and none in West Bay. The techniques for measuring each parameter are described in Pullen and Trent (1969), which also contains a compilation of the raw data. Data from the period 1963-66 are analyzed and summarized in Pullen et al. (1971).

Details concerning the origin, objectives, and evolution of the Galveston Bay Project (1968-1972) sampling program are given above (*See* Chapter 2). Up until November 1970, thirty-five stations were sampled; nine of these were in the Houston Ship Channel above Morgan's Point. After March 1971, only 15 stations in the bay proper were sampled. Detailed information about the sample collection and analytical methods can be found in Espey et al. (1971), Chapter 5.

The Texas Water Quality Board began monthly monitoring in the Houston Ship Channel in January 1972. In September 1977, the agency merged with two other state agencies to become the Texas Department of Water Resources. It was reorganized again in 1985, becoming the Texas Water Commission. Monitoring of the ship channel and other areas of the bay by this agency has continued up to the present. Stations are visited for routine hydrographic measurements (e.g., salinity, temperature, dissolved oxygen) and samples are collected on a monthly, quarterly, or annual basis for BOD, nitrogen, phosphorus, fecal coliforms, and other analyses.

Before 1963, the State Department of Health had made pollution surveys in the bay area, primarily for shellfish sanitation purposes. In the fall of 1962, the Bayshore Rod and Gun Club appeared before the newly-created Texas Water Pollution Control Board and requested a pollution survey of Galveston Bay and contiguous waters. The primary interest was to evaluate to what degree industrial and municipal wastes were affecting water sports and fishing, both sport and commercial, in the bay. Consequently, between 1963 and 1967, there was a "Water Quality Survey of Galveston Bay," made for the State Water Quality Board (formerly the Texas Water Pollution Control Board) by the State Department of Health. The results were presented in Texas Department of Health reports (1968, 1969). The Department of Health continues to monitor the bay for fecal coliforms and related parameters.

Fortunately, there are several sites in the Galveston Bay system near which all -- or most -- of these programs had sampling stations. Ten such sites were chosen to be representative of the various regions in the bay. I have designated these locations as "Stations" 1-10. Their locations, and the corresponding agency station numbers are given on the following page in Table A1. The first five are in the upper Houston Ship Channel (upstream of Morgan's Point). Numbers One and Two are in Texas Water Commission Segment 1007; Three and Four are in Segment 1006; and Five is in the uppermost segment. 1005. There are also two sites in Trinity Bay (Stations 7 and 8), one in East Bay (Station 10), one in West Bay (Station 9), and one about mid-way down Galveston Bay near the Redfish Bar oystering grounds (Station 6).

Appendix 3. Locations of Sampling Stations Used for Galveston Bay Water Quality Trend Analysis

GBP = Galveston Bay Project; T = Texas Water Quality Board/Texas Department of Water Resources/Texas Water Commission; TDH = Texas Department of Health; NMFS = National Marine Fisheries Service.

STATION	LOCATION
STATION 1	
+ GBP	(29°44.9'-95°17.2') Station 11, In Houston Ship Channel near Public Wharf 2, north side
+ T	(29°44'57"-95°17'22") Station1007.08, H. Ship Channel, Turning Basin
+ TDH	Station HSC-00X10, Houston Ship Channel, Turning Basin
+ NMFS	No station near this location
STATION 2	
+ GBP	(29°43.4'-95°13.2') Station 35, In H. Ship Channel opposite FL "165"
+ T	(29°43'09"-95°14'33") Station 1007.03, Houston Ship Channel, Sims Bayou, across from US Gypsum
+ TDH	Station HSC-00X18 Houston Ship Channel, Below Sims Bayou
+ NMFS	No station near this location
STATION 3	
+ GBP	(29°44.8'-95°10.5') Station 10, In Houston Ship Channel near Phillips 66 dock and flashing light
+ T	(29°44'46"-95°10'01") Station 1006.02, Houston Ship Channel, Greens Bayou near Todd Shipyard and CM-152
+ TDH	Station HSC-00X31, Houston Ship Channel, Greens Bayou
+ NMFS	No station near this location
STATION 4	
+ GBP	(29°45.1'-95°05.7') Station 9, In H. Ship Channel near flashing light "133"
+ T	(29°45'13-95°05'39') Station 1006.01, Houston Ship Channel, monument under powerline above USS Texas
+ TDH	(29°45.5'-95°05.5') Station HSC-00X37, Houston Ship Channel, at Battleship Texas
+ NMFS	No station near this location
STATION 5	
+ GBP	(29°40.5'-94°58.8') Station 33, In Houston Ship Channel at Morgan Point
+ T	(29°40'58"-95°58'55") Station 1005.01, H. Ship Channel, Morgan Point
+ TDH	(29°40.2'-95°58.7') Station HSC-00X45, H. Ship Channel, Morgan Point
+ NMFS	29°39.5'-94°57.3', Station 99

Appendix 3 *continued*

STATION	LOCATION
STATION 6	
+ GBP	(29°29.3'-94°51.8') Station 41, In Houston Ship Channel near FL “51A” (Junction of Trinity River Channel)
+ T	(29°30'50"-94°52'45") Station 2439.0025, Lower Galveston Bay, Redfish Island (South end CM 2)
+ TDH	(29°29.5'-94°52.2') Station GAL-00284, Houston Ship Channel Marker 53
+ NMFS	(29°28.4'-94°48.0') Station 38
STATION 7	
+ GBP	(29°42.9'-94°43.6') Station 38, Buoy #1 in Anahuac Channel
+ T	(29°41'58"-94°44'09") St. 2422.0100, Trinity Bay, Anahuac Channel Marker 1
+ TDH	(29°41.8'-94°44.2') Station TRI-1316B, Marker Number 1, Anahuac Channel
+ NMFS	(29°42.5'-94°44.2') Station 88
STATION 8	
+ GBP	(29°39.9'-94°47.2') Station 26, Humble Oil Well 95 - flashing red light
+ T	(29°39'54"-94°49'12") Station 2422.0200, Trinity Bay, Exxon Well C-1 (200 yds. N)
+ TDH	(29°40.6'-94°47.2') Station TRI-0023, Between Umbrella Pt. and Double Bayou
+ NMFS	(29°40.6'-94°49.2') Station 87
STATION 9	
+ GBP	(29°13.3'-94°59.7') Station 14, Marked pile E. of Carancahau Reef in West Bay
+ T	(29°13'45"-95°00'00") Station 2424.0100, West Bay, Carancahau Reef. First tall piling in channel through reef
+ TDH	(29°13.3'-94°59.7') Station WES-00A59, Carancahau Reef
+ NMFS	No station near this location
STATION 10	
+ GBP	(29°28.2'-94°42.6') Station 29, USGS tide gage near Hanna Reef
+ T	(29°29'28") Station 2423.01, East Bay, halfway between Marsh and Elm Points
+ TDH	(29°30.7'-94°37.9') Station EAS-00147, East Bay, between Elm Grove Pt. and Stephenson Pt.
+ NMFS	(29°30.0'-94°41.1') Station 28

* U.S. G.P.O.:1992-313-153:60522