An Environmental Inventory of the Armand Bayou Coastal Preserve

Galveston Bay
National Estuary Program

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Robert W. McFarlane, Ph.D.
Principal Investigator

EXECUTIVE SUMMARY

The goal of this report was to gather and integrate existing data, identify data gaps, and describe the environmental attributes of Armand Bayou relevant to the development of a management plan for the Armand Bayou Coastal Preserve. Armand Bayou can be influenced by events anywhere within, as well as beyond, its watershed.

The physical characteristics of the coastal preserve area have changed drastically due to 5 to 9 feet of land-surface subsidence across the watershed since 1906. The lower reach of the bayou has changed from a wetland-bordered freshwater stream to a brackish tidal lake nearly devoid of wetlands. Mud Lake has expanded from 100 acres in 1956 to more than 325 acres today. All of the 275 acres of wetlands present in 1956 have been lost; replacement wetlands, of a different nature, amount to 24 acres, for a net loss of 91 percent.

The water quality of Armand Bayou is poor. It is ranked as the second-highest stream on the Texas coast for hypoxia, a condition of low oxygen produced by algae responding to elevated nutrient levels. Annual and monthly levels for total and ortho- phosphorus are persistently above thresholds characteristic of eutrophic streams. Ammonia and nitrate nitrogen exceed eutrophic thresholds during the cooler months but appear to be removed from the bayou by accelerated algal growth during warm months. Fecal coliforms are a problem of long standing. No investigation of toxicants in the water or sediments has been undertaken.

The 60 square mile (38,400 acre) watershed receives 48 inches of rainfall annually and contributes approximately 80,000 acre-feet (71.4 million gallons per day, MGD) of freshwater inflow to Clear Lake. This rainfall varies greatly, even between localities very close together, and episodes of exceptionally heavy precipitation occur. Most of the watershed lies within the city limits of Pasadena, Deer Park, La Porte and Houston and has 38 percent residential-urban and 6 percent industrial land use. Point source discharges have declined in number, from 6 to 3, but the volume of wastewater discharged has increased 35 percent, to 6.2 MGD, over the past decade. Point source stormwater discharges were 1.8 MGD in 1989.

Controversial issues in recent years have involved the accelerated and increased delivery of residential-area stormwater to the bayou and the removal of irrigation water from the bayou. The current water quality monitoring station at Bay Area Boulevard does not reflect the

input of nutrients and pollutants from Horsepen Bayou, a major tributary which receives the bulk of treated wastewater effluent discharged into the bayou. The quarterly or semi-annual monitoring of recent years is inadequate to determine stream conditions. A 24-hour water quality survey during the warm season is needed to determine the extent of oxygen sag during hours of darkness. An additional monitoring station that will reflect the contribution of pollutants from Horsepen Bayou is needed. Monthly sampling should be resumed for 2 to 3 years to establish an adequate baseline of information. An investigation of toxicants in water and sediment samples should be conducted.

The flora and fauna of Armand Bayou are poorly known and population trends cannot be determined. The freshwater biota upstream of Bay Area Boulevard, and in the tributaries, is virtually unknown. The lower reach is potentially a valuable nursery habitat for certain commercial and recreational finfishes and shellfishes. A survey of these species in Mud Lake should be undertaken. The extent of bottomland forest flooding and value of this forest habitat as a contributor of detritus and nutrients, and as a sink for nutrients and pollutants, should be determined.

INTRODUCTION

Armand Bayou, a small coastal stream on the western shore of Galveston Bay, has been incorporated into the joint Texas General Land Office/Texas Parks & Wildlife Department Coastal Preserves Program. The Texas Legislature has provided a mechanism by which the General Land Office can lease appropriate, state-owned, coastal lands to the Parks & Wildlife Department to be managed as preserves. The Parks & Wildlife Department has authority to acquire lands for parks and wildlife management areas and habitats for nongame and endangered species, and to establish scientific areas for the purpose of preserving flora and fauna of scientific or educational value.

The Texas Coastal Preserve Program was devised to ensure long-range protection, enhancement, and public use of unique coastal natural resources. The Program seeks to achieve these goals by identifying unique coastal areas, including their fragile biological communities and important colonial waterbird nesting sites, in need of protection and actively involving all concerned and knowledgeable persons and organizations.

A crucial step toward the protection of a coastal preserve will be the development of a management plan for the preserve. This environmental inventory is designed to assist in the preparation of the management plan. Conservationists, preservationists, and environmentalists have demonstrated considerable fervor regarding Armand Bayou but essential questions remain. What are the actual resources to be preserved? What are the current conditions within the waterway? The bayou has been variously described as "Texas' last pristine bayou" (Houston Chronicle, 8/16/89), "the only bayou intact in its entire flood plain" (Chronicle, 4/24/89), and "a rare untouched 3000 acres of wilderness" (Daily Pasadena Citizen, 12/3/88). Yet the bayou is the recipient of substantial quantities of treated domestic wastewater and industrial- and residential-area stormwater. The electronic and print media have devoted considerable attention to the bayou in recent years as plans were revealed to increase the volume of treated wastewater or untreated residential stormwater discharged into it, or remove water to irrigate a golf course.

The goal of this report is to gather and integrate existing data currently held by the relevant agencies, identify data gaps, and describe the environmental attributes of the bayou relevant to development of a management plan for the coastal preserve. Specific topics to be addressed include human occupancy, physical habitat alterations, water quality trends, freshwater inflows, infrastructure, hydrological and meteorological influences, and the living resources.

I. STRUCTURE AND FUNCTION OF THE ECOSYSTEM

The boundaries of the coastal preserve extend from the confluence of Armand Bayou with Clear Lake (at NASA Road 1) upstream to the limit of tidal influence (Figure 1). The exact limit of upstream tidal influence is uncertain. The Texas General Land Office considers the limit to be approximately 2000 feet upstream of the confluence of Armand Bayou and Spring Gully (point A in Fig. 1). This establishes the preserve as approximately 6.8 miles in length. Alternatively, the Texas Water Commission has designated this point to be approximately 0.5 miles south of Genoa-Red Bluff Road, adjacent to the Baywood Country Club (point B in Fig. 1). Following the sinuous bayou path, this point increases the length of the preserve to 7.9 stream miles. The lateral boundaries are the mean high tide line, the limit of state ownership.

The tidal stretch of the bayou is designated as Segment 1113 by the Texas Water Commission. The non-tidal upstream portion of Armand Bayou itself and its several tributaries (Horsepen Bayou, Big Island Slough, Spring Gully, Willow Springs Gully) are not designated stream segments. The coastal preserve is an aquatic preserve, permanently or cyclically covered by tidal waters.

The Armand Bayou portion of the Galveston Bay ecosystem which is being incorporated into the coastal preserve has a linear structure. It is an open system which receives substantial inputs of freshwater, sediment, and nutrients from the surrounding upland areas and tributaries. It receives inputs of tidal energy and larval and juvenile forms of marine life from the bay itself. Galveston Bay has primary, secondary, and tertiary bay components. Lower Galveston Bay is a primary bay in this system; it is closest to the tidal inlet at Bolivar Roads and exchanges water and organisms directly with the Gulf of Mexico. Consequently, it experiences high salinities, from 20 to 30 parts per thousand (ppt). Upper Galveston Bay and Trinity Bay constitute a secondary bay; the width of the bay is constricted between Eagle Point and Smith Point and oyster reefs span this gap. As a secondary bay, this segment receives the brunt of freshwater, sediment, and nutrient input. Salinities are lower, frequently 10 to 20 ppt at the connection to the lower bay, approaching zero at the mouths of the Trinity and San Jacinto Rivers.

Tertiary bays are one step further removed from the sea. They are usually small, well-enclosed, basins which exchange material and organisms with secondary bays (Britton & Morton, 1989). Salinity ranges from fresh to slightly brackish but marine organisms pre-dominate. Clear Lake is a classic example of a tertiary bay. It has a tightly constricted connection to upper Galveston Bay which restrains tidal influences. The lower reach of Armand Bayou, called Mud Lake, is broad and shallow and closely couples the bayou to Clear Lake, providing feeding grounds for the inhabitants of the tertiary bay.

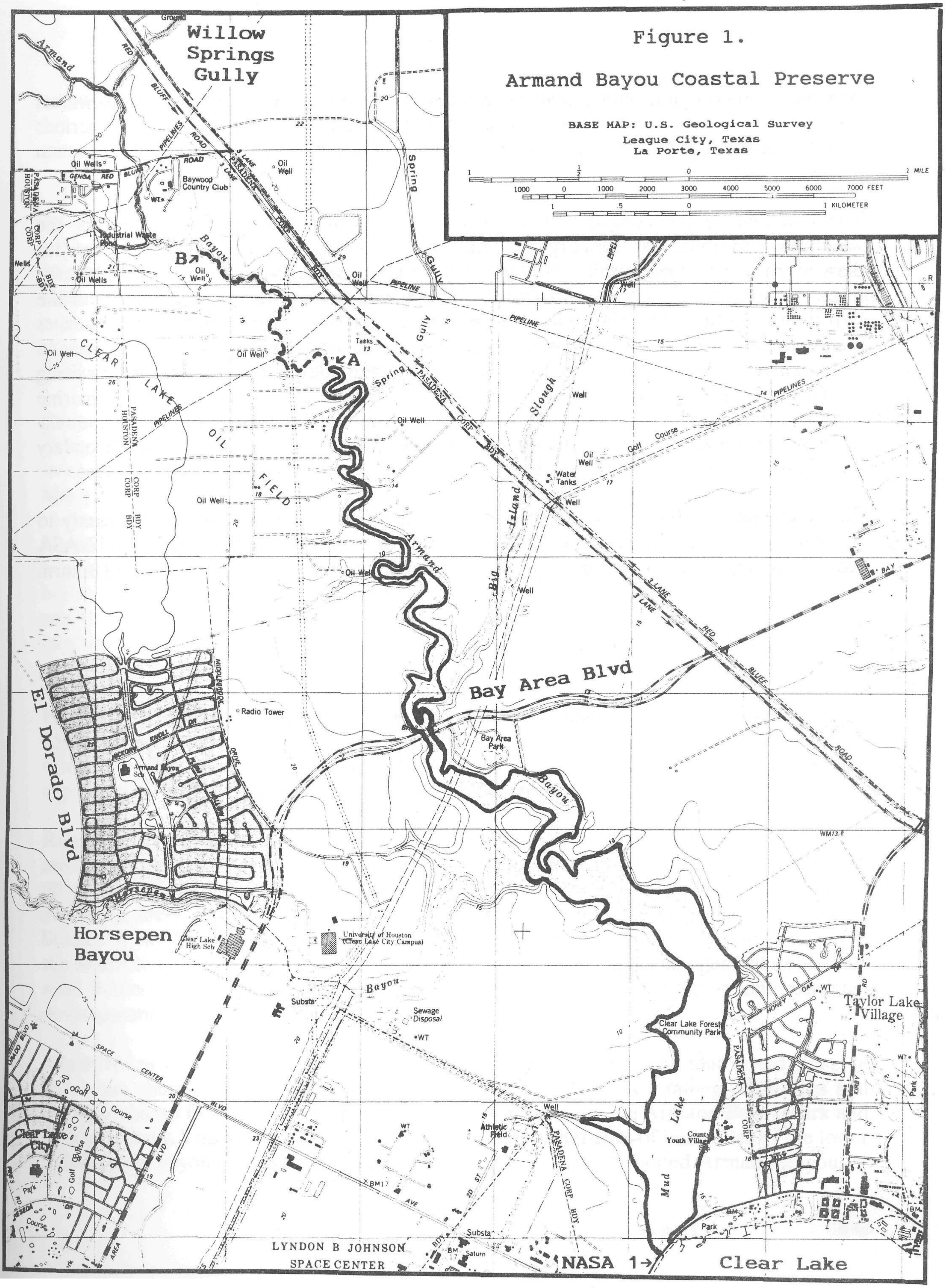


Figure 1.
Armand Bayou Coastal Preserve
BASE MAP: U.S. Geological Survey
League City, Texas
La Porte, Texas
Willow Springs Gully
Spring Gully
Big Island Slough
Armand Bayou
Bay Area Blvd
El Dorado Blvd
Horsepen Bayou
Taylor Lake Village
Mud Lake
Clear Lake
NASA 1
LYNDON B JOHNSON SPACE CENTER
Clear Lake Forest Community Park
University of Houston (Clear Lake City Campus)
Bay Area Park
Clear Lake Oil Field
Baywood Country Club
Industrial Waste Pond
Clear Lake High Sch
Clear Lake City

Armand Bayou is significantly influenced by activity anywhere within its watershed. Its waters originate from direct precipitation and runoff from upland areas. During extended periods of drought, flow in the bayou ceases except for supplementary waters provided by human activity.

The functions of the ecosystem follow its linear structure. The coastal prairies of the watershed contribute dissolved organic matter and both large and small particles of detritus derived from the decomposition of plant and animal remains. Partially decomposed leaves from the water-tolerant trees and shrubs of the fluvial woodlands along the banks of the bayou are flushed into the waterway with each flooding event. Streamside marshes manufacture more organic material for the detrital-based food chain. Detritus, colonized and conditioned by bacteria and fungi, forms the nutrient and energy source for organisms living in and on the mud bottoms of Mud Lake and Clear Lake. At this point, juvenile marine organisms find a rich feeding ground within Clear Lake. As they grow larger they gradually foresake this tertiary bay and reverse their initial migration, slowly traversing the secondary and primary bays of the estuary before returning to the sea to mature and reproduce.

To understand the importance of the Armand Bayou Coastal Preserve, it is necessary to understand the watershed connections and the role of estuarine components beyond NASA Road 1. To accomplish this task, major environmental components will be examined in turn.

II. ENVIRONMENTAL ELEMENTS

A. HUMAN OCCUPANCY

Humans have occupied and influenced this bayou for hundreds of years (Herzberg, 1988). Nomadic Indians were the first to exploit the richness of the diverse habitats - coastal prairie, gallery forest, marsh and estuary - which merge in close proximity here. Other than creating the kitchen middens which attract modern archeologists, these first colonists most likely had little impact on the ecosystem.

European settlers introduced the plow to the prairie soils and began to produce more lasting change to the landscape. Early pioneers grew sugar cane, vegetables and fruits and harvested trees for decades. The land has benefited from some long-term ownership. The 84-acre Martyn farm was purchased in 1879 and remained in the family until 1964, when it was sold to the Friendswood Development Company and later became part of the Armand Bayou Nature Center. Oilman Jim West began to buy ranch property in the watershed in the 1920s, acquiring thousands of acres of old homesteads which he maintained as a game preserve before selling the land to the Humble Oil and Refining company in the late 1930s. Until the construction of Bay Area Boulevard in 1967, the bayou was accessible only by boat. The bayou was known as Middle Bayou, lying between Clear Creek and Taylor Bayou, for most of its mapped history.

Humble Oil, through its subsidiary, Friendswood Development Co., began development of 15,000 acres of its property to create Clear Lake City. Development accelerated when NASA selected the West ranch for the Manned Spacecraft Center. Single-family dwellings expanded exponentially and the local population swelled. Major changes in land use resulted.

Rapid development occurred throughout the 1960s. The City of Pasadena obtained annexation rights and extended its jurisdiction to cover the entire bayou in 1969. Most of the 60 square miles of the watershed fall within the city limits of 4 local city governments - Pasadena, Deer Park, La Porte, and Houston; the remainder lies within Harris County. Studies by the U.S. Geological Survey revealed that substantial subsidence had occurred in the watershed. A subsidence district was created in 1975. Floodplain management ordinances soon limited development below 13 feet above mean sea level. These actions restricted development of 800 acres along the bayou.

The 1970s produced a grass-roots effort to create a park on the bayou that would preserve its unique character as an urban "wilderness." By 1974, 10 tracts totalling 2119 acres had been purchased from Friendswood Development Co. to create the Armand Bayou Park and Nature Center. This served to preserve the natural characteristics of both sides of the lower reach of the bayou. It was at this time that the waterway was renamed Armand Bayou.

B. PHYSICAL HABITAT ALTERATIONS

1. Subsidence

Subsidence is the lowering of the elevation of the surface of the land. In this area, subsidence has been caused by the withdrawal of groundwater, that is, water located beneath the earth's surface, and, to a lesser extent, depletion of shallow petroleum reserves. Between 1906 and 1987 the land surface within the Armand Bayou watershed experienced substantial subsidence - as much as 9 feet along the northern perimeter, and 5 feet in the south (HGCSD, 1987). Subsidence poses a threat to both human resources and natural ecosystems in low-lying coastal areas such as this.

The subsidence has not occurred at a uniform rate (HGCSD, 1987). Between 1906 and 1943 the land surface sank approximately 1.0 feet at Pasadena but only 0.4 feet near Clear Lake. Subsidence developed into a serious problem during the 1950s, following industrial development along the Houston Ship Channel. As industry and the public began to withdraw greater amounts of water from the underlying Chicot and Evangeline aquifers, subsidence became more noticeable. Between 1943 and 1973, the land sank 7 feet in Pasadena and 4 feet near Clear Lake and the Johnson Space Center.

Community and business leaders began discussing possible remedies to the subsidence problem during the 1950s, and took action to obtain surface water in the 1960s, but a negotiated solution was a long time in coming (HGCSD, 1989). In 1975, the Texas Legislature created the Harris-Galveston Coastal Subsidence District "for the purpose of ending subsidence which contributes to or precipitates flooding, inundation, or overflow of any area within the district, including without limitation rising waters resulting from storms or hurricanes."

In 1976, the Subsidence District adopted an interim plan designed to have an immediate impact on the subsidence problem in the area most vulnerable to the damaging effects of subsidence. The interim plan focused on southeastern Harris County and all of Galveston County as the area of concentrated emphasis. The two counties were divided into eight regulatory areas. Area 1 includes Baytown, the Ship Channel, southeast Harris County outside of Interstate Loop 610, and most of Galveston County; the Armand Bayou watershed is totally enclosed within Area 1.

The interim plan emphasized development of surface water supplies and water conservation. Texas City industries had imported surface water from the Brazos River as early as 1948, and Lake Houston began providing San Jacinto River water to the southeast Houston area in 1954. The Coastal Water Authority began importation of Trinity River water in 1976. Area 1 groundwater use dropped from 139.4 down to 22.1 million gallons per day (MGD) between 1976 and 1988, despite increased demand. The City of Houston recently completed a 100 MGD expansion of a water treatment plant near the Houston Ship Channel and a 50 MGD plant near Ellington Field to provide for future demand. The City of Deer Park constructed a surface-water treatment plant with 6 MGD peak capacity, expandable to 12 MGD. In 1985, the Subsidence District introduced its final plan (HGCSD, 1985). Entities in Area 1 were required to reduce their groundwater use to just 10 percent of total water demand by 1990. The goal was met.

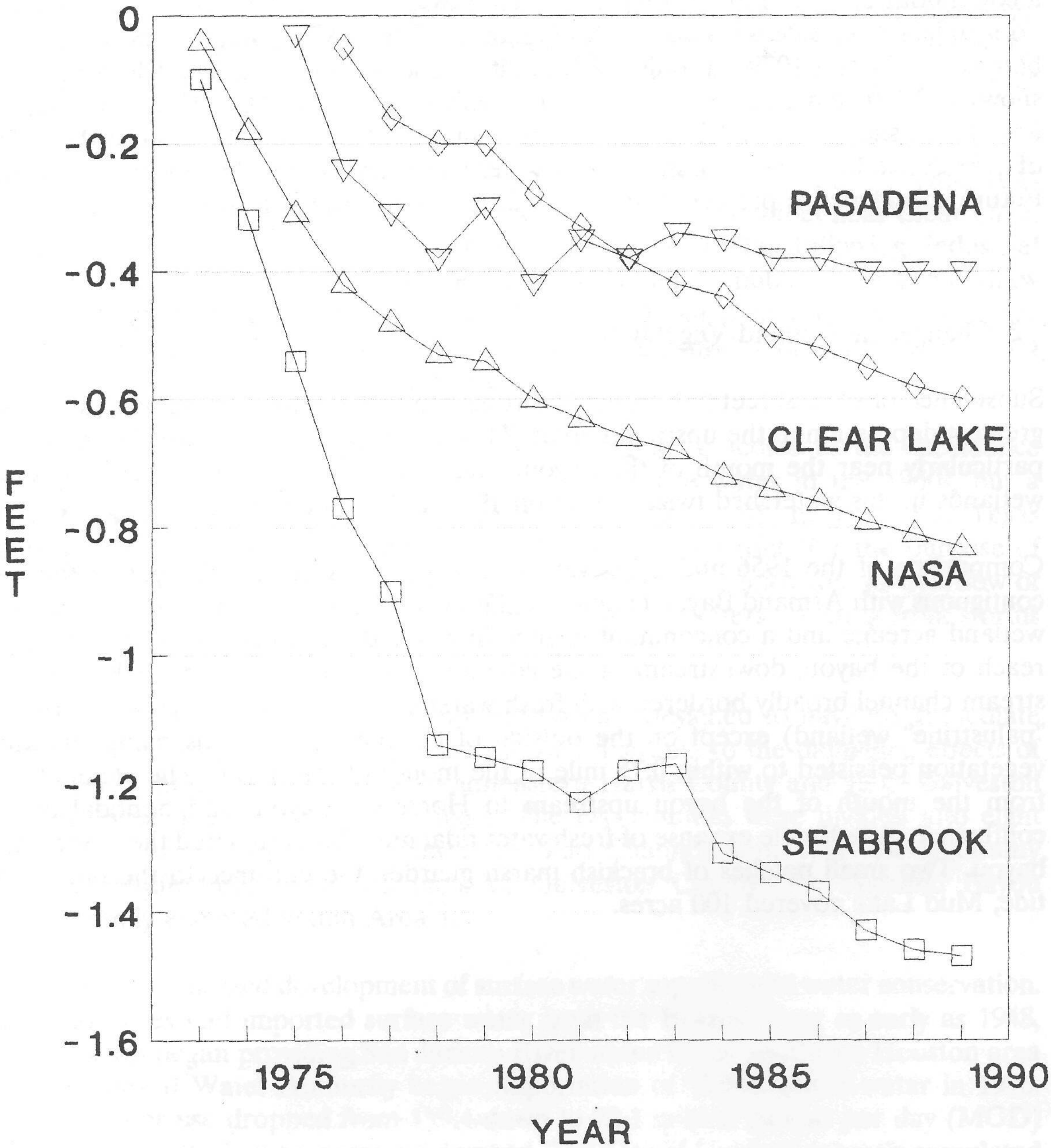
The Subsidence District has installed four borehole extensometers within the Armand Bayou watershed, located at Pasadena, Clear Lake, NASA, and Seabrook. These monitors provide a continuous record of elevation change (HGCSD, 1990). The Pasadena monitor indicates no significant subsidence since 1980 (Figure 2). The NASA monitor reveals a 0.6 ft loss between 1974 and 1979 but only 0.2 ft additional loss since then. The Clear Lake monitor shows a 0.4 ft loss from 1976 to 1982 but only 0.2 ft since then. The Seabrook monitor indicates a sharp loss of 1.2 ft between 1973 and 1981 but only 0.2 ft since then. The rate of subsidence has clearly diminished. Aquifer water levels have begun to rise significantly. Future subsidence is projected to be less than one additional foot by the year 2020.

2. Changes in Wetland Vegetation

Subsidence of several feet has occurred throughout the Armand Bayou watershed, with the greatest depression in the upstream areas. This subsidence can affect drainage in the basin, particularly near the mouth of the bayou. The U.S. Fish & Wildlife Service has mapped wetlands in this watershed twice, based on 1956 and 1979 aerial photography (USDIa, b).

Comparison of the 1956 and 1979 wetland maps reveals drastic changes in the wetlands contiguous with Armand Bayou (Figure 3). There has been a 91.3 percent reduction in total wetland acreage and a concomitant change in wetland types (Table 1). In 1956 the lower reach of the bayou, downstream of the confluence with Big Island Slough, was a narrow stream channel broadly bordered with fresh-water emergent marsh vegetation (one type of "palustrine" wetland) except on the outside of channel curves. This palustrine emergent vegetation persisted to within 0.75 mile of the mouth of the bayou. The channel was tidal from the mouth of the bayou upstream to Horsepen Bayou, and nontidal above that confluence. A half-mile expanse of freshwater tidal mud flat dominated the lower end of the bayou. Two small patches of brackish marsh guarded the entrance to the bayou. At high tide, Mud Lake covered 100 acres.

Figure 2.
RECENT SUBSIDENCE NEAR
ARMAND BAYOU WATERSHED



HGCSD Extensometer Data

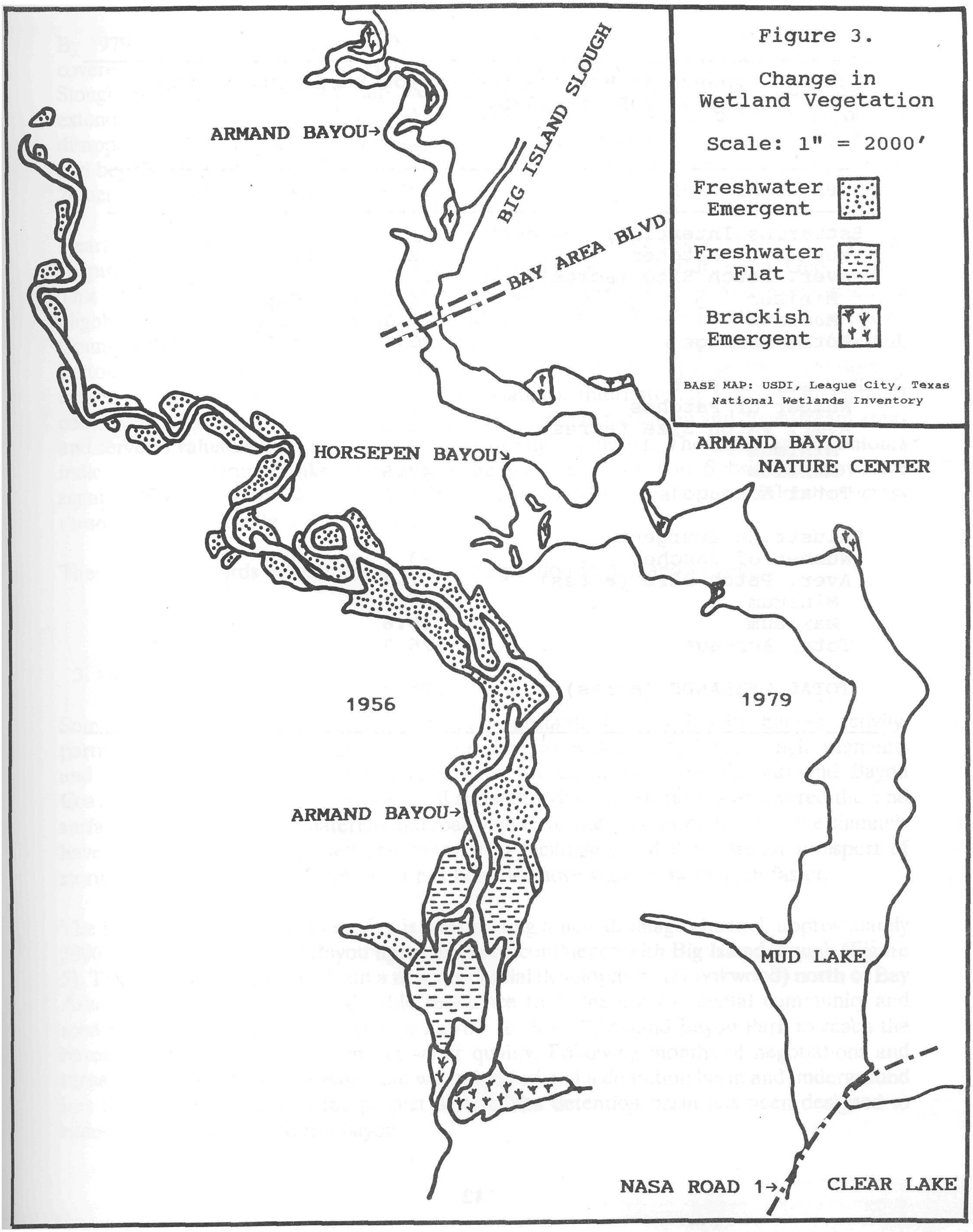


Figure 3.
Change in Wetland Vegetation
Scale: 1" = 2000'
Freshwater Emergent
Freshwater Flat
Brackish Emergent
BASE MAP: USDI, League City, Texas National Wetlands Inventory
ARMAND BAYOU→
BIG ISLAND SLOUGH
BAY AREA BLVD
HORSEPEN BAYOU→
ARMAND BAYOU NATURE CENTER
1956
1979
ARMAND BAYOU→
MUD LAKE
NASA ROAD 1→
CLEAR LAKE

Table 1. Change in Wetland Vegetation Bordering Armand Bayou, 1956 to 1979.

TYPE OF WETLAND	1956	1979	LOSS
Estuarine Intertidal Emergent			
Number of Patches	2	10	
Aver. Patch Size (acres)	12.7	2.4	
Minimum	4.3	0.8	
Maximum	21.1	3.7	
Total Acreage	25.4	24.0	5.6%
Palustrine Flat			
Number of Patches	3	0	
Aver. Patch Size (acres)	24.4		
Minimum	1.4		
Maximum	47.8		
Total Acreage	73.1	0	100%
Palustrine Emergent			
Number of Patches	23	0	
Aver. Patch Size (acres)	7.7		
Minimum	0.7		
Maximum	49.6		
Total Acreage	176.8	0	100%
TOTAL WETLANDS (acres)	275.3	24.0	91.3%

By 1979, all of this freshwater emergent marsh had drowned and disappeared. Mud Lake covered 325 acres upstream to Horsepen Bayou, and continued upstream to Big Island Slough and beyond. The tidal flats were no longer exposed at low tide, and tidewaters extended upstream beyond Spring Gully. The brackish marsh at the mouth of the bayou had disappeared but tiny patches had gained a foothold in Horsepen Bayou, upper Mud Lake, and beyond Big Island Slough. Total wetland acreage had shrunk from 275 acres in 1956 to 24 acres in 1979.

Nearly all of the Armand Bayou shoreline is bordered by water-tolerant trees and shrubs (Figure 4) which create a "fluvial woodland" (White et al., 1985; Bur. Econ. Geol., 1989). This vegetation was omitted from the 1956 USDI wetland map and categorized as oligohaline, semi-permanent, non-tidal uplands in the 1979 USDI wetland map. The Harris County Soil Survey (USDA SCS, 1976), indicates 2 soil types here; a nearly level, forested, bottomland soil (Nahatche-Voss-Kaman association), and a nearly level to gently sloping, loamy, forested soil (Midland-Beaumont association). Intermittently flooded, this habitat could contribute substantial amounts of organic material to the bayou and downstream areas and serve as valuable foraging areas for fishes during inundation. The topographic contours indicate rather abrupt banks of 10 to 15 ft height along the bayou. Subsidence may have significantly lowered this land-water interface, however. The lateral extent of flooding across these forests is variable and unknown.

There are no records of submerged aquatic vegetation in Armand Bayou.

3. Drainage

Some natural drainage channels have been substantially modified by human activity, particularly in the upper reaches of the watershed, as evidenced by long, straight segments and 90-degree turns. Such modifications have not occurred within the Armand Bayou Coastal Preserve. Residential, commercial and industrial construction have covered the land surface with impermeable materials and roadways have altered flow patterns. Some channels have been enlarged, deepened and bermed to facilitate rapid downstream transport of stormwater runoff. The overall result has been to move water downstream faster.

The Friendswood Development Co. is constructing a new drainage channel, approximately 3000 feet long, to Armand Bayou upstream of its confluence with Big Island Slough (Figure 5). This project, designed to drain a new residential development (Brookwood) north of Bay Area Boulevard, ignited considerable resistance from the environmental community and media coverage because it traverses a narrow section of Armand Bayou Park to reach the bayou and potentially would impact water quality. Following months of negotiations and threatened court action, the easement was relocated and a detention basin and underground box culvert were added to the project design. The detention basin has been designed to reduce pollutant loads to the bayou.

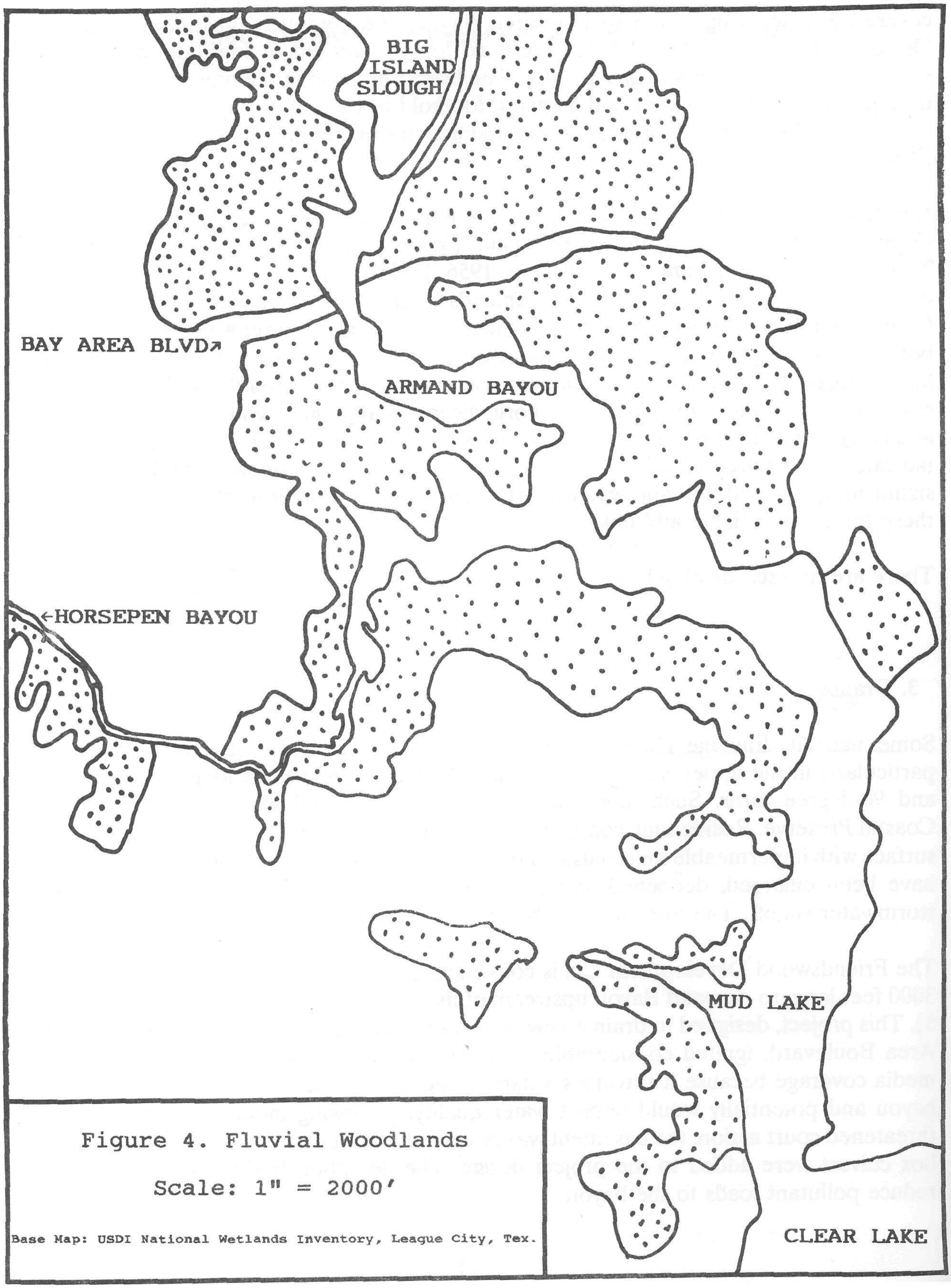


Figure 4. Fluvial Woodlands

Scale: 1" = 2000'

Base Map: USDI National Wetlands Inventory, League City, Tex.

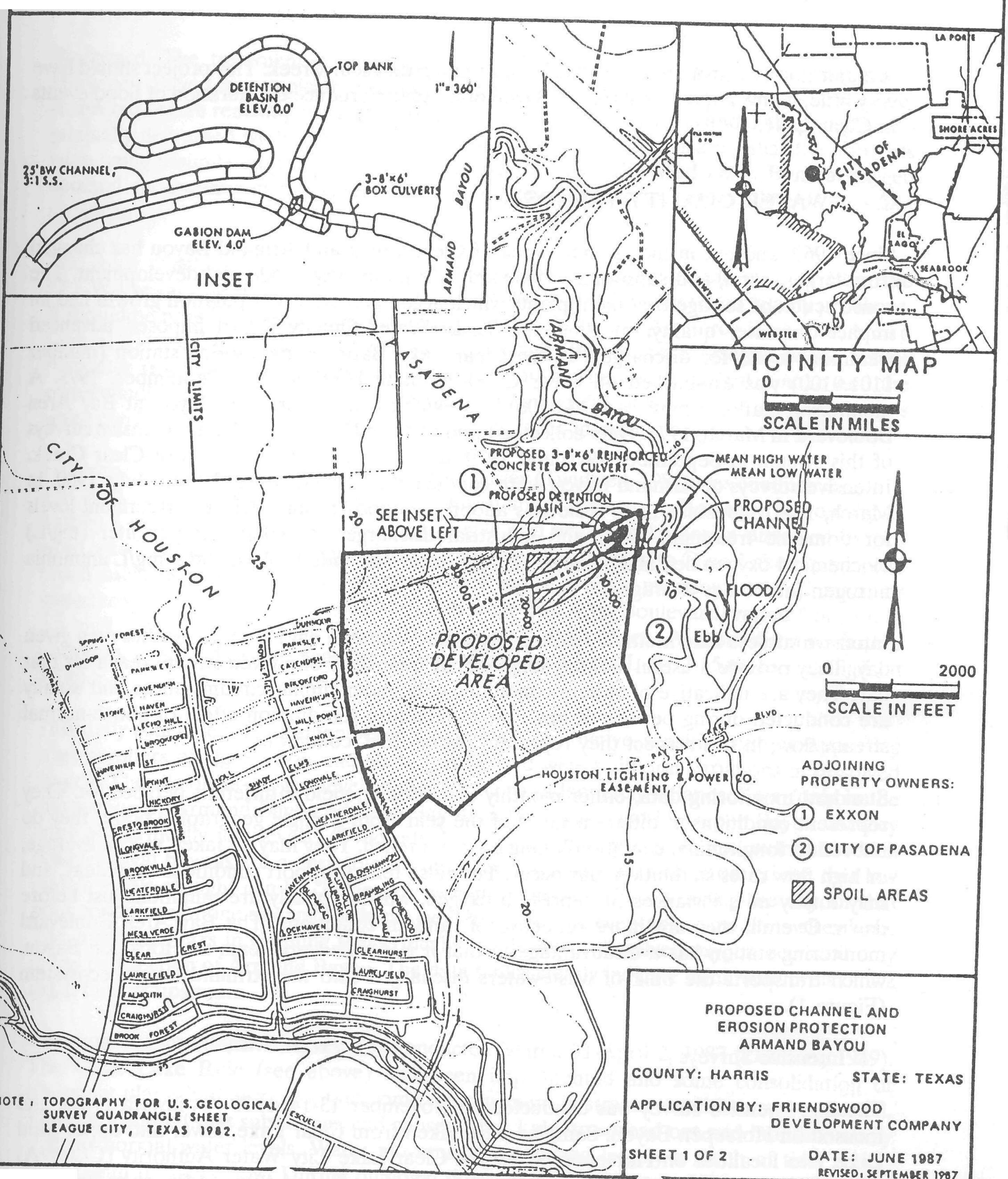


Figure 5. Drainage Channel from Brookwood to Armand Bayou

Source: U.S. Army Corps of Engineers

A major flood control project is under construction on Clear Creek. This project should have very little, if any, impact on Armand Bayou other than to reduce the duration of flood events in Clear Lake.

C. WATER QUALITY TRENDS

Since 1960 land use in the drainage area of Clear Creek and Armand Bayou has changed from largely rural, and substantially wooded, to high density residential development. The construction of sewage treatment plants which accompanied this population growth had an impact on water quality. In 1969, the Texas Water Quality Board imposed advanced treatment levels for dischargers in the Clear Lake Basin. A monitoring station (number 1101.0100) was established on Clear Creek at State Highway 3 in September, 1973. A monitoring station (number 1113.0100) was established on Armand Bayou at Bay Area Boulevard in March, 1976. Data collected monthly from Clear Creek led to intensive surveys of this stream in September 1976 and 1979 and a waste load evaluation of Clear Creek. Intensive surveys of Armand Bayou were conducted in November, 1979, and July, 1980. In March, 1981, the Clear Lake Rule was adopted, imposing more stringent treatment levels for domestic treatment plant and industrial discharges: 5 milligrams per liter (mg/L) biochemical oxygen demand (5-day), 12 mg/L total suspended solids, and 2 mg/L ammonia nitrogen (all 30-day averages).

Intensive surveys take multiple readings (typically 4 times a day) at multiple sites on a given day. They provide a useful one-day longitudinal "snapshot" of a given stream reach for that day. They are indicative of stream conditions only under similar circumstances and usually are conducted during periods of low flow to minimize the dilution effect of above-normal stream flow; in this respect they represent "worst-case" conditions.

Standard monitoring data, either monthly or quarterly, yield a different perspective. They represent conditions at different times of the year from a single geographic point; they do not reflect longitudinal conditions along a stream reach. They may be taken at low, average, or high flow rates so dilution may occur. They also tend to report conditions at midday, and may totally miss instances of depressed oxygen, which typically are minimum just before dawn. Overall, they are more reflective of random conditions. The Bay Area Boulevard monitoring station has a disadvantage in that it is situated upstream of Horsepen Bayou, which transports the bulk of wastewaters discharged into the Armand Bayou ecosystem (Figure 1).

1. Intensive Surveys

The first intensive survey was conducted on November 13-14, 1979 (Twidwell, 1980), and focused on Horsepen Bayou. Samples were taken from Clear Lake, lower and upper Mud Lake, two localities on Horsepen below the Clear Lake City Water Authority (CLCWA) sewage treatment plant, Horsepen at Bay Area Boulevard, and Armand Bayou at Bay Area

Boulevard. The treatment plant effluent was within its limitations. Dissolved oxygen in Horsepen Bayou was typically depressed about 2 mg/L by the wastewater effluent but recovered before reaching Armand Bayou. Nutrients (nitrate nitrogen and orthophosphorus) gradually decreased while chlorophyll a increased downstream indicating that the nutrients were being assimilated into algal biomass by phytoplankton in Mud Lake. Benthal oxygen demand measurements indicated that the oxygen demand of the sediments was not significant.

The study concluded that Horsepen Bayou was able to assimilate the effluent from the CLCWA sewage treatment plant without the development of serious water quality problems. It should be noted that three other treatment plants (Ellington Air Force Base STP, Metro Central STP, and Bayfield PUD STP) also discharged effluent into Horsepen Bayou before the water reached the CLCWA plant. The relationship between nutrient uptake and the corresponding increase in algal biomass signaled potential problems in the summer months when conditions were more conducive to aquatic plant growth.

Following the first survey, a broader intensive survey (Twidwell, 1981) was conducted on July 1-3, 1980, sampling 7 stations on Armand Bayou and 7 stations on Horsepen Bayou. Again nutrients were found to be assimilated by algae and wide oscillations in dissolved oxygen were noted. All stations from upper Horsepen Bayou downstream to Clear Lake experienced broad oscillations in dissolved oxygen, from 4 mg/L in early morning to 15-21 mg/L by midafternoon. Armand Bayou, just upstream from Bay Area Boulevard, varied from 1.6 to 2.5 mg/L on the bottom, and 2.5 to 8.6 mg/L near the surface. A short distance farther upstream, dissolved oxygen near the surface rose from 3.5 mg/L at 11:15am to 16.5 mg/L at 3:25pm.

This study concluded that Armand Bayou was a very productive, sensitive system supporting large numbers of algae whose metabolism produced wide temporal variations in dissolved oxygen. The dissolved oxygen levels appeared to be "adequately balanced" for "only in the mid-section of Armand Bayou between Bay Area Boulevard and Horsepen Bayou did they approach critically low levels" (Twidwell, 1981). This implies that excess nutrients which produce algal blooms are a desirable condition because they increase productivity, that low oxygen levels at night can be "balanced" by high oxygen conditions during the day, or that poor conditions in one stream reach can be "balanced" by acceptable conditions elsewhere. The conclusion errs in claiming that critically low levels of dissolved oxygen occurred only in the mid-section of Armand Bayou. The data tables clearly indicate minimum levels of 1-2 mg/L farther upstream.

The most recent intensive survey was conducted March 31-April 2, 1987 (Ottmers, 1989). The Clear Lake Rule (see above) had been implemented and some consolidation of treatment plants had occurred, thus some improvement in stream conditions was expected. The report noted that subsidence had caused Mud Lake to spread out and inundate many trees at normal water levels. Water movement was judged largely a result of tidal action rather than tributary flow. During outgoing tides, water from Armand Bayou and nutrient laden water from Horsepen Bayou mixed freely in the upper reaches of Mud Lake. On incoming tides, some of this enriched water was pushed back into both Armand Bayou and Horsepen Bayou. Nutrients trapped in this back and forth movement produced prolific algal growth in the area between upper Mud Lake, lower Horsepen Bayou, and Armand Bayou at Bay Area Boulevard. Wind and wave action in Mud Lake provided aeration which helped maintain dissolved oxygen levels. No station exhibited depressed dissolved oxygen in either surface or bottom waters. All 15 sampling stations had supersaturated dissolved oxygen for some, if not most, of the day.

Table 2 compares the 1980 and 1987 values for four nutrients from upstream to downstream zones, with tributary data at the appropriate interval. The threshold values beyond which each nutrient is considered "elevated" by the Texas Water Commission (TWC, 1988, 1990) are shown. The values represent composite samples from each site on two days, 7 years apart. Ammonia nitrogen demonstrates substantial improvement except for a persistent problem on Horsepen Bayou between El Dorado Boulevard and Bay Area Boulevard which may represent non-point source introduction from two drainage ditches which drain residential areas and the Clear Lake Golf Course. Nitrate nitrogen was formerly introduced in the same stretch but, in 1987, substantial nitrate discharges from the Metro Central STP upstream masked any input from the residential areas and golf course. All nitrogen was assimilated by the bayou and Mud Lake before reaching Clear Lake.

Both total phosphate and ortho-phosphate remain problematic in the entire basin. Concentrations have been lowered in the upper basin but have worsened by an order of magnitude or more on Horsepen Bayou. While both phosphate measurements have been lowered by assimilation in Mud Lake, neither declined to the threshold level.

Table 2. Longitudinal Stream Comparison of Nutrients

LOCALITY mg/L	AMMONIA NITROGEN Threshold>0.15		NITRATE NITROGEN Threshold>0.4	
	1980	1987	1980	1987
Armand Bayou				
Genoa-Red Bluff Rd	.12	.09	.05	.15
below Spring Gully	.14	.02	.09	.06
Big Island Slough				
Red Bluff Rd	.08	.02	.01	.41
Bay Area Blvd	.03	<.02	.04	.54
lower reach	.08	<.02	.09	.13
Horsepen Bayou				
El Dorado Blvd	.06	.06	.13	12.60
Bay Area Blvd	.17	.22	1.55	8.87
lower reach	.36	<.02	<.01	.02
Mud Lake				
upper	<.02	<.02	.08	.02
lower	<.02	<.02	<.01	.02

mg/L	TOTAL PHOSPHATE Threshold>0.4		ORTHO-PHOSPHATE Threshold>0.2	
	1980	1987	1980	1987
Armand Bayou				
Genoa-Red Bluff Rd	.85	.44	.72	.32
below Spring Gully	.99	.31	.85	.16
Big Island Slough				
Red Bluff Rd	1.81	.59	1.45	.33
Bay Area Blvd	1.00	.82	.69	.53
lower reach	.94	.72	.63	.40
Horsepen Bayou				
El Dorado Blvd	.31	4.76	.08	2.55
Bay Area Blvd	.41	4.07	.21	3.77
lower reach	.94	1.87	.65	1.57
Mud Lake				
upper	.89	.55	.59	.25
lower	.81	.47	.58	.24

2. Monitoring Long-term Trends

Long-term data are available only for the Bay Area Boulevard sampling station on Armand Bayou (Station 1113.0100), dating back to March, 1976. Samples were obtained monthly from December, 1976, to March, 1979, quarterly from 1980 to 1987, and semi-annually since 1988. For the purposes of this report, the data were assembled in a year-by-month matrix to determine annual (all months of a given year) and monthly (all years for a given month) means, standard deviation, and sample size. Sample sizes used to determine means were small, ranging from 2 to 12, typically 4 to 6, and standard deviations were large.

Data were analyzed as provided by the Texas Water Commission, without independent evaluation of the TWC quality assurance and quality control program. Sample size is likely to be a more serious problem than errors in the data set. Sample size of one or two per year (for trends) or per month (for seasonal comparison), or entire years without data, were common. The data were analyzed to determine the presence of trends. The annual average for a given parameter was considered the dependent variable; the year the data were obtained was the independent variable. Simple linear regressions were performed to answer two questions. Given that values for a given parameter vary considerably, how much does introduction of a second parameter (time, as year of data collection) reduce this variability? This reduction was estimated by the coefficient of determination, $\underline{r^2}$. These coefficients were typically very low with these data.

The next question asked if there was a linear relationship between the annual average for a given parameter and the year the data were collected. Were averages increasing or decreasing, getting better or worse? This was determined with the correlation coefficient, $\underline{r}$. Correlation coefficients range from +1 to -1; a coefficient of 0 indicates there is no relationship between the average and the year it was measured. The null hypothesis states there is no correlation and the coefficient is zero. The alternative hypothesis, that there is a correlation, is accepted if the null hypothesis can be rejected, that is, it is not equal to zero. There is always a chance that the null hypothesis will be rejected when it is, in fact, true. Thus we want to determine the probability of claiming that a relationship exists when it does not.

Usually a risk of 1 in 20 is acceptable (a probability of 0.05, or 5% chance, expressed as $P<.05$). The lower the risk, the better, and the more faith we can place in the trend being real. Sometimes a greater risk, say 1 in 10, or 10% chance of claiming a trend that does not exist, can still be informative (expressed as a weak trend, $P<.10$). Very weak trends, with a high risk of 1 in 5, or 20% chance of claiming a trend that does not really exist (expressed as $P<.20$) also have been noted in this report. Critical values for the correlation coefficient were obtained from a statistical table. Significance is affected by sample size; that is, a given correlation coefficient may be significant at a specific risk level with a large number of samples but insignificant with a smaller number of samples. The significance level for most trends was very poor and all trends should be interpreted with caution. No inference of cause and effect can be made for any comparisons.

Selected parameters will be addressed individually below.

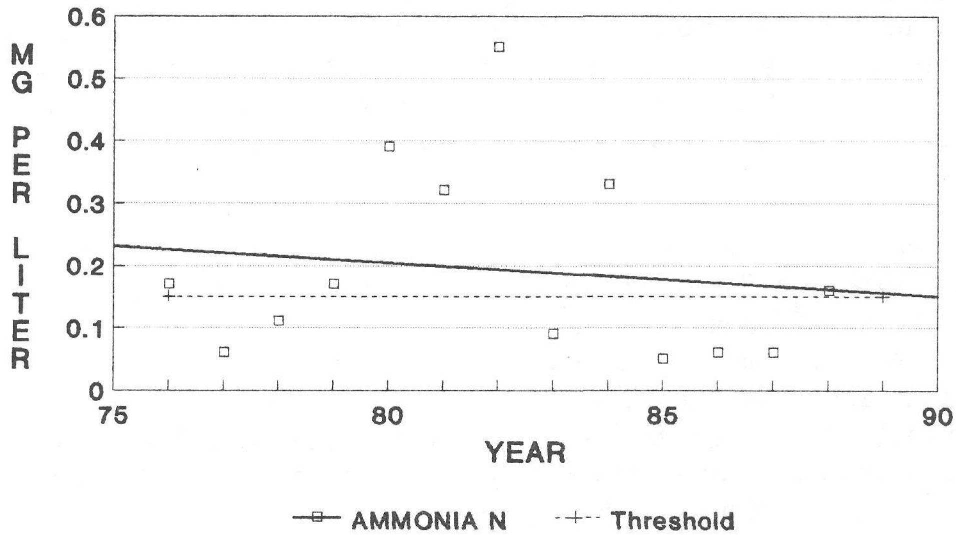
Ammonia Nitrogen - Annual averages ranged from 0.049 to 0.950 mg/L, with 7 of 13 (53.8%) exceeding the 0.15 mg/L threshold. The slightly downward trend shown in Figure 6 is not significant. Monthly averages exceeded 0.15 mg/L for 5 months (November to March). Monthly values were higher during cooler months (November to April average = 0.282 mg/L) than warmer months (May to October average = 0.048 mg/L), which may reflect the greater ability of algae to utilize ammonia at higher temperatures and with more daylight (Fig. 7). Of 71 individual values, 24 (33.8%) were greater than 0.15 mg/L, 3 (4.2%) were greater than 1.0 mg/L, and the maximum was 1.97 mg/L.

Nitrate Nitrogen - Annual averages ranged from 0.078 to 0.855 mg/L, but only one exceeded the 0.4 mg/L threshold. The weak trend (Fig. 8) indicates increasing concentrations and there is greater than 90% certainty that the correlation coefficient (r=0.511) is not due to chance alone. Monthly averages exceeded the threshold in only three months (Nov to Jan). Monthly values for nitrate mimicked ammonia (Fig. 9), being higher in cooler months (November to April average = 0.428 mg/L) than warmer months (May to October average = 0.041). Of 67 individual values, 14 (20.9%) were greater than 0.4 mg/L, and 3 (4.5%) were greater than 1.0 mg/L, with the highest = 1.63 mg/L.

Total Phosphorus - Annual averages ranged from 0.414 to 3.242 mg/L, all exceeding the 0.4 mg/L threshold. Monthly averages ranged from 0.423 to 2.180 mg/L, all exceeding the threshold. There is no apparent seasonal trend evident in the monthly averages. The minimum individual value was 0.221 mg/L, 53 of the 69 values (76.8%) exceeded 0.4 mg/L, 12 (17.4%) were greater than 1.0, and the maximum was 11.0 mg/L. There is no significant trend to phosphorus concentrations. A very weak trend (Fig. 10) indicates increasing concentrations but there is only 80% certainty that the correlation coefficient (r=0.381) is not due to chance alone.

Ortho-Phosphorus - Annual averages ranged from 0.319 to 1.096 mg/L, all exceeding the 0.2 mg/L threshold. Monthly averages ranged from 0.329 to 0.709 mg/L, all exceeding the threshold. There is no apparent seasonal trend. The minimum individual value was 0.109 mg/L, 62 of 69 values (89.9%) exceeded 0.2 mg/L, 8 (11.6%) were greater than 1.0 mg/L, and the maximum was 1.68 mg/L. All individual values since July, 1980, have exceeded the threshold. There is no significant trend to ortho-phosphorus concentrations. A very weak trend (Fig. 11) indicates increasing concentrations but there is less than 90% certainty that the correlation coefficient (r=0.434) is not due to chance alone.

Figure 6.
Trend for Ammonia Nitrogen



Correlation Coefficient r = -.134

Figure 7.
Seasonality of Ammonia

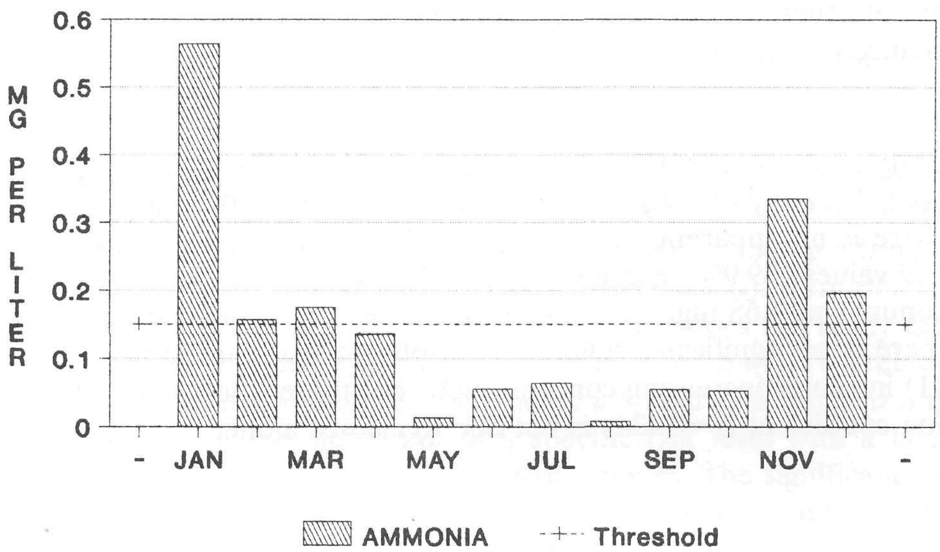
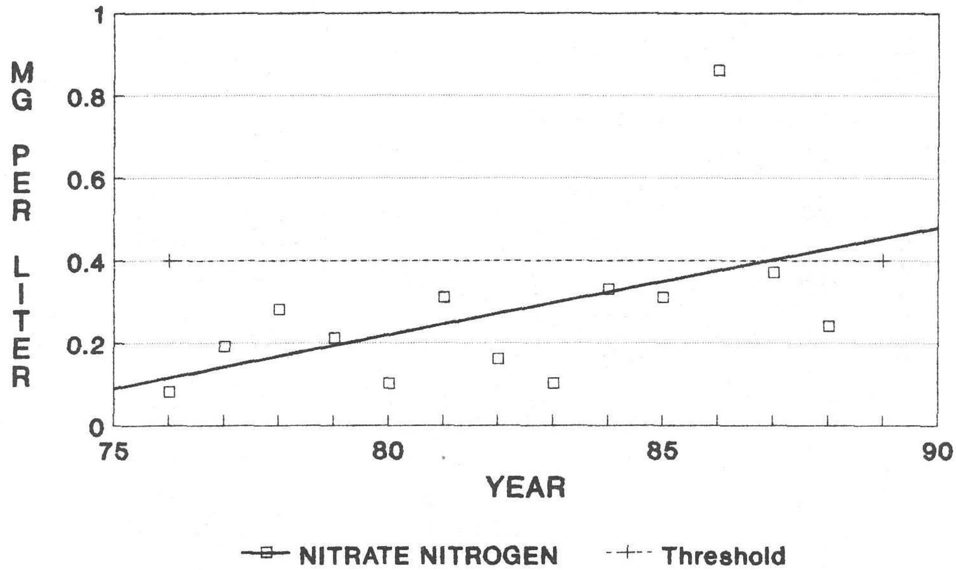


Figure 8.
Trend for Nitrate Nitrogen



Correlation Coefficient r = .511

Figure 9.
Seasonality of Nitrate Nitrogen

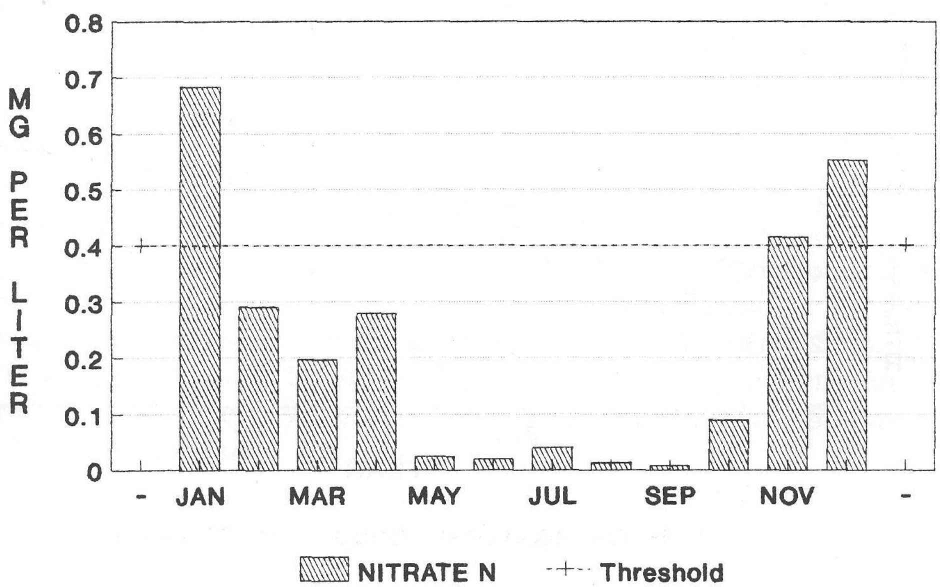
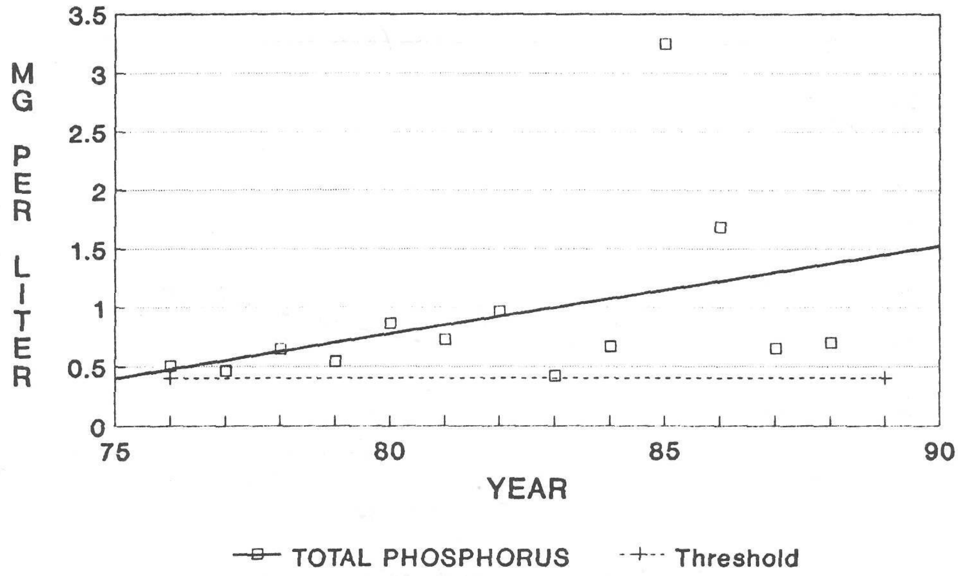
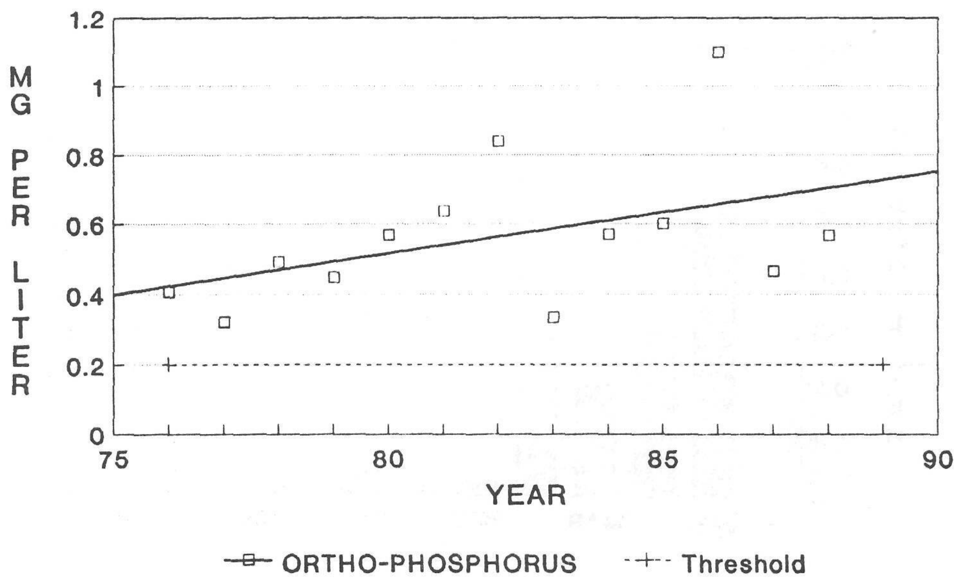


Figure 10.
Trend for Total Phosphorus



Correlation Coefficient r = .381

Figure 11.
Trend for Ortho-Phosphorus



Correlation Coefficient r = .434

Chlorophyll-a - There are no chlorophyll data from August 1980 to September 1985. Threshold values for chlorophyll are 50 micrograms per liter (μg/L) for individual values and 20 μg/L for averages. Annual averages from 1976 to 1988 ranged from 7.63 to 86.5 μg/L, exceeding the threshold in 7 of 8 years (87.5%). Monthly averages ranged from 19.7 to 137.7 μg/L, all exceeding the threshold. Individually, 27 of the 49 values (55.1%) exceeded the 50 μg/L threshold, with a maximum of 196 μg/L. The decreasing trend shown in Fig. 12 is not significant (r=-.425). The monthly averages show an interesting seasonal pattern (Fig. 13) as concentrations rise in March, peak in April, and steadily decline to December, except for a peak in October, and another in January.

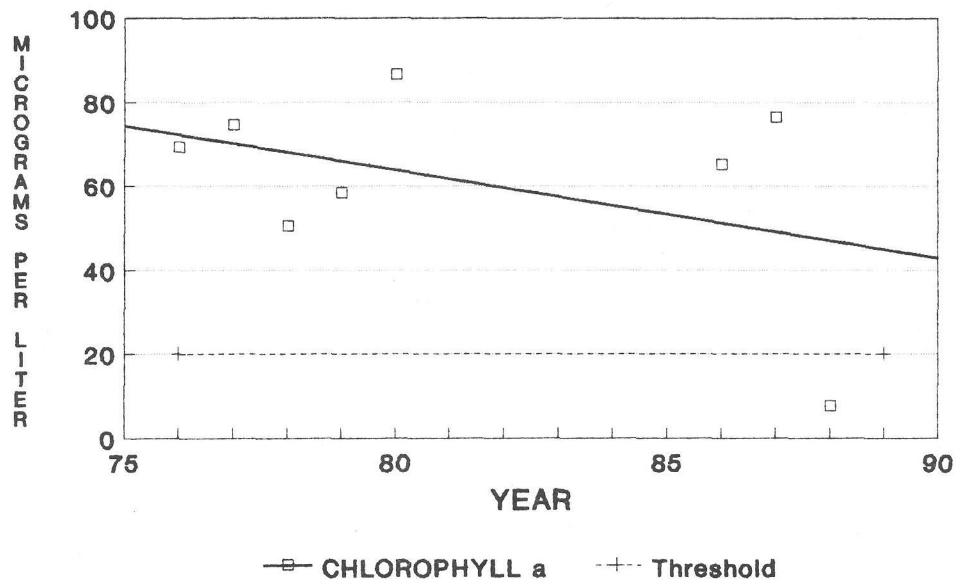
Dissolved Oxygen - Neither the Environmental Protection Agency nor the Texas Water Commission have established a threshold that determines when hypoxia (low dissolved oxygen) becomes anoxia (the absence of oxygen). For example, while 0 mg/L is obviously anoxic, is 0.1 or 0.5 mg/L sufficient for aerobic organisms so that the water may be considered hypoxic?

Dissolved oxygen is frequently stratified, with depletion of oxygen occurring along the bottom, due to oxygen demand of bottom sediments and oxygen replenishment at the water-air interface. The average difference in dissolved oxygen between surface water (1 ft deep) and the bottom (variable 3- to 7-foot depth according to freshwater flow, tide, and channel location) on 50 days was 1.81 mg/L. The maximum difference was 8.0 mg/L; on only two days was there no difference; and on 5 days dissolved oxygen was higher on the bottom than at the surface. Calculation of annual averages was based on surface values only.

There are several thresholds for dissolved oxygen. The criterion established by the Texas Water Commission for Armand Bayou (classified as high quality aquatic habitat) is a minimum of 4.0 mg/L. The TWC uses minimum values of 0 mg/L, and averages less than 4.5 mg/L, to indicate that anoxic conditions may exist (TWC, 1990). Supersaturation of oxygen, which is frequently associated with algal blooms resulting from excess nutrients, is indicated when the maximum dissolved oxygen exceeds 12 mg/L (TWC, 1990). Supersaturation, which is not detrimental, is sometimes accompanied by wide diurnal fluctuations in dissolved oxygen, and hypoxia may occur during dark periods of the day.

Annual averages ranged from 5.8 to 10.7 mg/L. Monthly averages ranged from 6.4 to 10.7 mg/L. Only 2 of 70 values (2.9%) were below 4.0 mg/L. Eleven values (15.7%) exceeded 12 mg/L, with the maximum being 12.7 mg/L. Monitoring surveys of this nature are unlikely to reveal the extent of daily oscillations, as demonstrated by the intensive surveys (Section C.1 above). The downward trend shown in Figure 14 is not significant (r=-.250). The seasonality of dissolved oxygen is shown in Figure 15. The apparent distinction between cooler months (December to May, average = 9.5 mg/L) and warmer months (June to November, average = 7.5 mg/L) is not significant.

Figure 12.
Trend for Chlorophyll



Correlation Coefficient r = -.425

Figure 13.
Seasonality of Chlorophyll

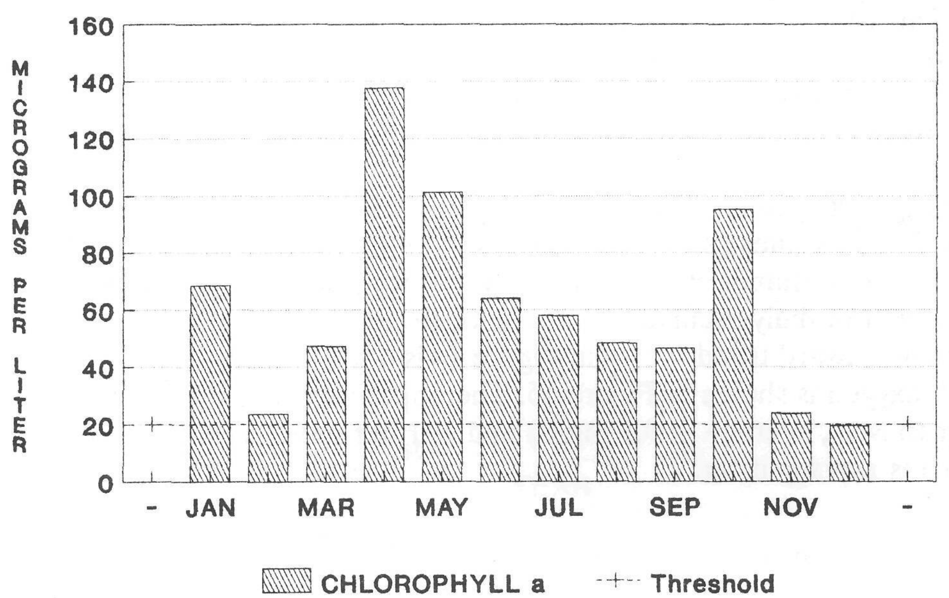
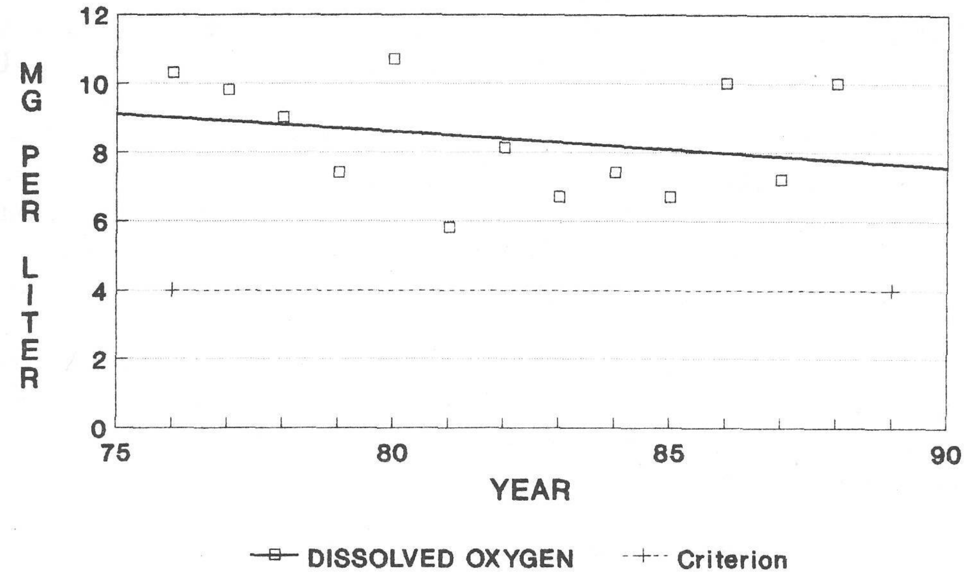
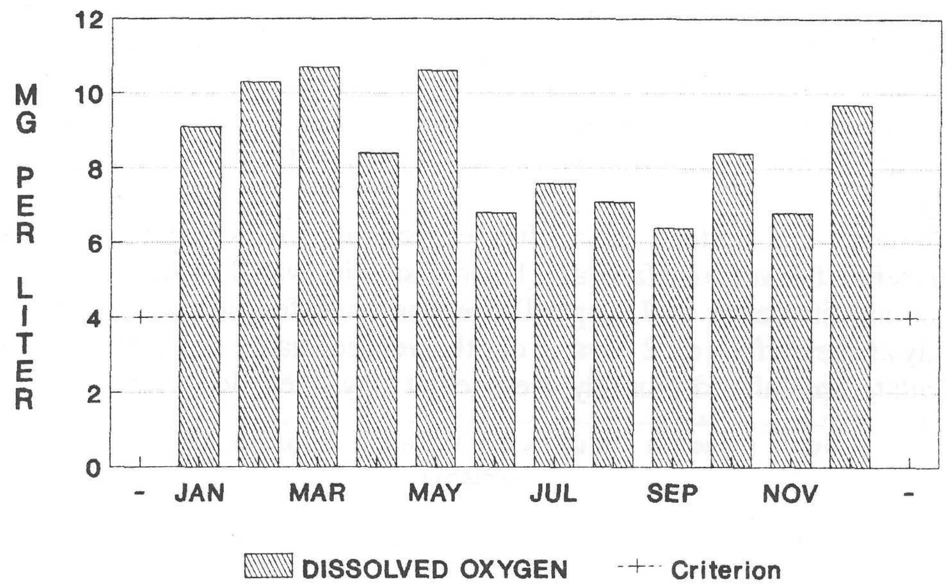


Figure 14.
Trend for Dissolved Oxygen



Correlation Coefficient r = -.25

Figure 15.
Seasonality of Dissolved Oxygen



Using monthly averages, dissolved oxygen concentrations seem to track chlorophyll concentrations during the warmer months but not in cool months (Fig. 16). Using individual values, any relationship is even more obscure (Fig. 17).

Sulfate - Annual averages ranged from 52.3 to 510.3 mg/L. Monthly averages ranged from 66.0 to 350.8 mg/L. The maximum individual value was 1110 mg/L. There is no criterion or threshold for sulfate. The rising trend shown in Figure 18 is not significant (r=0.122).

Chloride - Measurement of this parameter in Armand Bayou is complicated by its natural occurrence in seawater. Therefore the periodic monitoring data from Bay Area Boulevard reflect chloride picked up by precipitation runoff, chloride added to the bayou in treated wastewater effluent, and chloride from the brackish waters of the bay. The intensive survey data are better able to provide an estimate of the longitudinal stream gradient (Table 3).

Upper Armand Bayou and tributaries have relatively low values but Big Island Slough appears to be receiving effluent containing chloride. Horsepen Bayou has low chloride levels. There is no water quality criterion for chloride in Armand Bayou. There is no permitted brine discharge into Armand Bayou.

Total Dissolved Solids - This parameter is also complicated by brackish water in the tidal reach and is presented with a longitudinal comparison (Table 3). It demonstrates increased loading in Big Island Slough.

Salinity - This parameter is estimated from the specific conductance of the water samples. It is usually stratified and highly variable. A wedge of denser salt water usually lies on the bottom of the channel, advancing and ebbing with the tide. Light to moderate precipitation may add fresh runoff which remains near the surface. Heavy precipitation may force the wedge out of the tributary completely. The intensive surveys (for example, Ottmers, 1989) detected daily shifts in Armand Bayou as great as 3 ppt as far upstream as Bay Area Boulevard and 4.4 ppt in the mouth of Horsepen Bayou. Conversely, shifts at the lower end of Mud Lake were negligible. The leading edge of the salt wedge appears to advance and retreat within the lower reach of Armand and Horsepen Bayous.

Surface (1 ft deep) and bottom (3 to 7 ft deep) salinities were measured on 44 days. The average difference between surface and bottom salinity was 0.8 parts per thousand (ppt), with a maximum difference of 7.0 ppt. There was no difference on 13 days (29.5%), and higher salinity at the surface on 2 days. A depth-averaged value or a single surface value was used to calculate annual and monthly averages at Bay Area Boulevard.

Figure 16.
Dissolved Oxygen and Chlorophyll
(Monthly Averages)

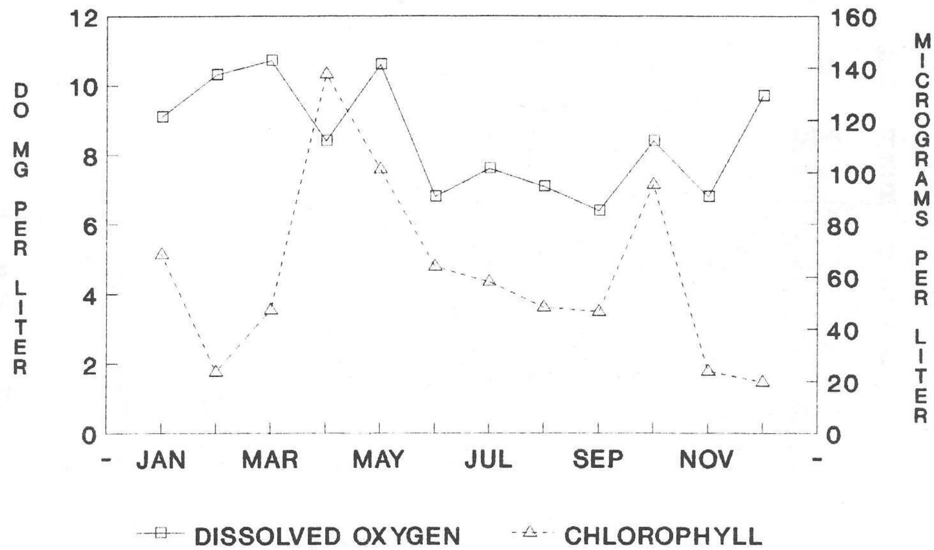


Figure 17.
Dissolved Oxygen and Chlorophyll
(Individual pairs of values)

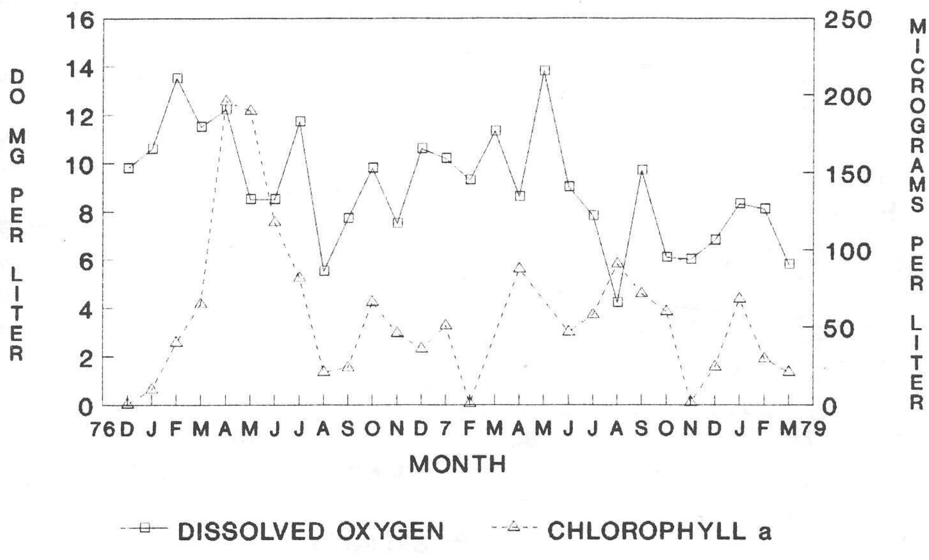
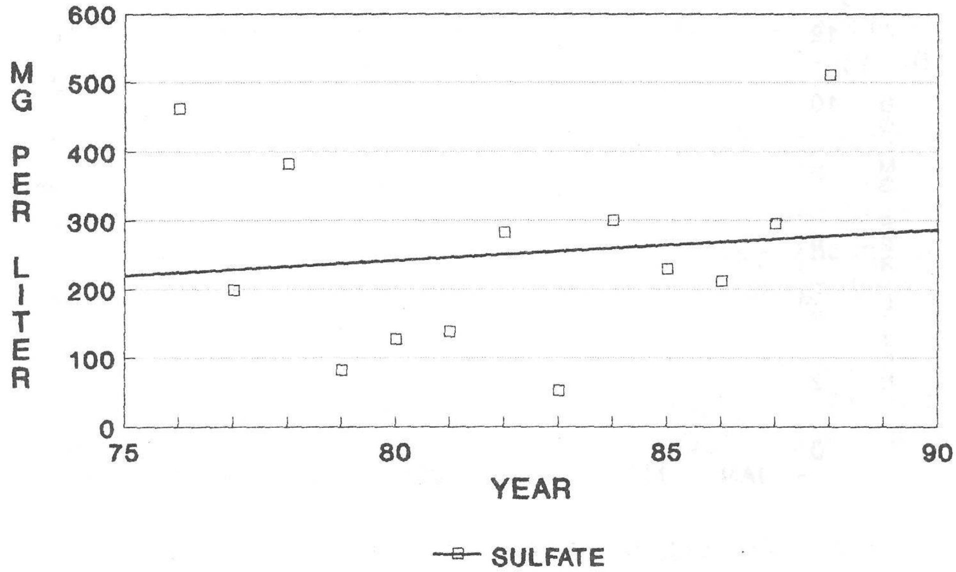
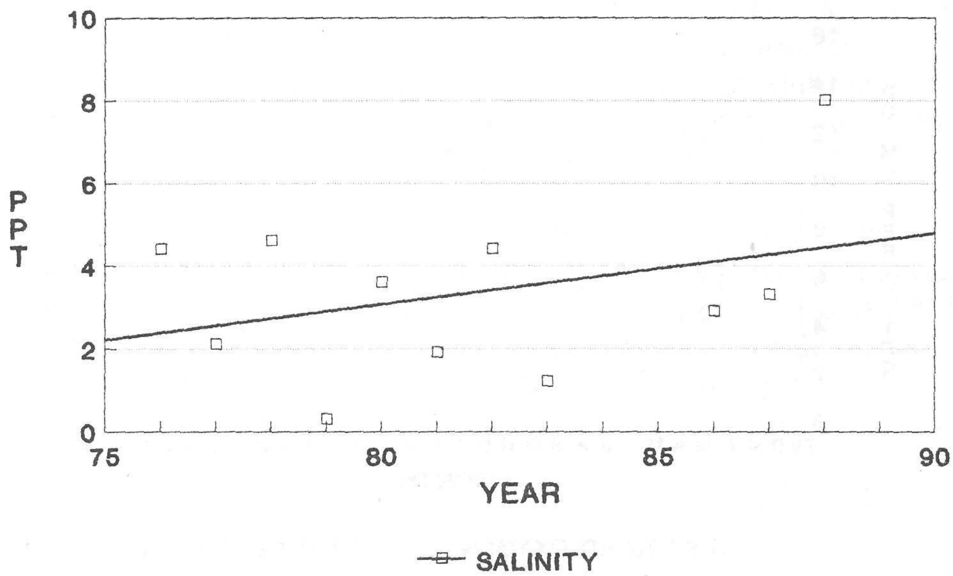


Figure 18.
Trend for Sulfate



Correlation Coefficient r = .122

Figure 19
Trend for Salinity



Correlation Coefficient r = .34

Table 3. Longitudinal Stream Comparison of Chloride and Total Dissolved Solids (TDS).

LOCALITY	CHLORIDE mg/L		TDS mg/L	
	1980	1987	1980	1987
Armand Bayou				
Fairmont Parkway	-	83	-	494
Willow Springs Gully				
Red Bluff Road	-	107	-	572
Genoa-Red Bluff Road	101	95	467	544
Spring Gully				
Red Bluff Road	-	157	-	646
below Spring Gully	124	198	507	616
Big Island Slough				
Fairmont Parkway	126	346	710	1046
Red Bluff Road	391	629	878	1370
Bay Area Blvd	1240	2384	-	4590
lower reach	1880	4416	3467	8520
Horsepen Bayou				
El Dorado Blvd	172	179	507	682
Bay Area Blvd	170	196	578	678
lower reach	1300	2334	2441	4450
Mud Lake				
upper	2350	4422	4271	8220
lower	3600	4929	6176	9130

Average annual salinity ranged from 0.29 to 8.0 ppt. Monthly averages ranged from 0.5 to 6.9 ppt. The increasing trend shown in Figure 19 is insignificant (r=0.34).

Fecal Coliforms - Annual and monthly geometric means were calculated using logarithmic transformations. Contact recreation is a designated water use for Armand Bayou and the criterion is 200 fecal coliform bacteria per 100 ml of water, and/or 10% of the measurements greater than 400/100ml. Annual averages ranged from 78 to 4724 per 100 ml; 6 years (46.2%) exceeded the 200/100ml criterion (4 exceeded the 400/100ml criterion), and the highest year exceeded the 2000/100ml criterion established for non-contact recreation.

Monthly averages ranged from 34 to 5510 fecal coliforms per 100 ml; the 200/100ml criterion was exceeded 6 months (50%) of the year, the 400/100ml criterion was exceeded twice, and the non-contact recreation criterion of 2000/100ml was exceeded once. Individually, 32 of 68 samples (47.1%) exceeded the contact recreation criterion of 200/100ml, 25 (36.8%) exceeded the 400/100ml criterion, 12 exceeded the non-contact recreation criterion of 2000/100ml, and the maximum contamination found was 32,000 per 100ml. The downward trend shown in Figure 20 was not significant (r=-.119). There is no apparent seasonal pattern to the contamination (Fig. 21).

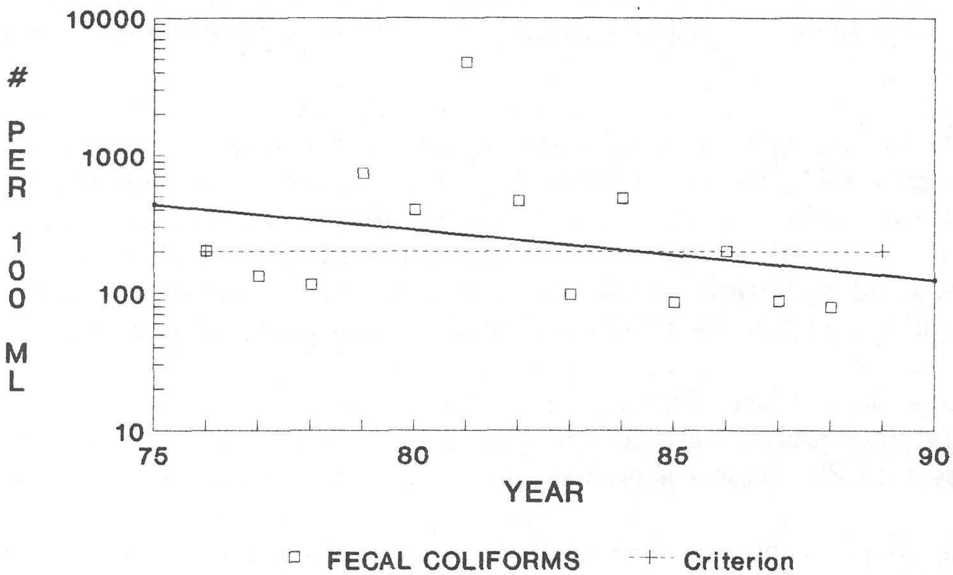
3. Eutrophication

The 9th Edition of the Texas Water Quality Inventory (Texas Water Commission, 1988, p.258) characterized the potential water quality problems for the Armand Bayou Tidal segment (1113) as:

> "Supersaturated dissolved oxygen levels occur periodically [that is, 26-44% of the time]. Total and orthophosphorus levels are persistently [100% of the time] elevated, inorganic nitrogen levels are occasionally [11-25%] elevated, and chlorophyll a is periodically elevated. Fecal coliform bacteria are periodically elevated."

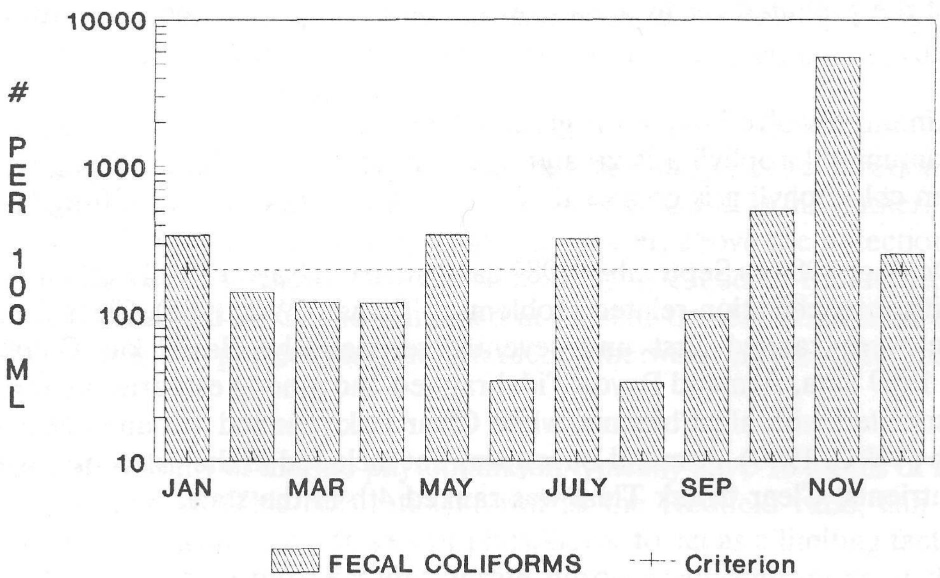
Designated water uses for this segment are (1) contact recreation, and (2) high quality aquatic habitat. The inventory examined the 4 most recent years of routine stream monitoring data. If more than 10% of the dissolved oxygen measurements were less than 3.0 mg/L, a station was determined not fishable. If the log average of each station's fecal coliform bacteria level was greater than 200/100ml and/or 10% of the measurements were greater than 400/ 100ml, a station was determined not swimmable. Armand Bayou Tidal was judged fishable and swimmable. Conditions were such that the segment was designated as "effluent limited", implying that conventional wastewater treatment is adequate to protect existing stream conditions.

Figure 20.
Trend for Fecal Coliforms



Correlation Coefficient r = -.119

Figure 21.
Seasonality of Fecal Coliforms



The TWC considers significant violations of water quality standards to be: (1) greater than 25% of monitoring values exceed [are less than] the dissolved oxygen criterion; (2) greater than 50% of values for chloride, sulfate, and total dissolved solids exceed the criteria; and (3) the log average of fecal coliform bacteria exceed twice the established criterion. Armand Bayou Tidal experiences supersaturation, and limited hypoxia, rather than anoxia. Since Armand Bayou is not a domestic water supply, there are no criteria established for chloride, sulfate, or total dissolved solids. In recent years, fecal coliform averages have not exceeded 400/100ml.

The inventory notes (p.2) that eutrophication, or excessive plant production, in estuaries may cause problems not specifically addressed by the designated uses and numerical criteria of the surface water quality standards. Estuaries exhibiting the highest degree of eutrophication were Clear Creek Tidal (Segment 1101) and Armand Bayou Tidal (Segment 1113). Texas has not adopted numerical criteria for nutrients. For comparative purposes, the initial screening guidelines used by TWC considered nutrients to be elevated if:

Ammonia + Nitrate Nitrogen are greater than	1.0 mg/L
Total Phosphorus is greater than	0.2 mg/L
Dissolved Phosphorus is greater than	0.1 mg/L

Additional, more stringent, thresholds are applied to estuarine waters. Nutrients are considered elevated if:

Ammonia nitrogen is greater than	0.15 mg/L
Nitrate nitrogen is greater than	0.4 mg/L
Total phosphorus is greater than	0.4 mg/L
Ortho-phosphorus is greater than	0.2 mg/L

Evidence of the potential for hypoxia (low dissolved oxygen) associated with algal blooms occurs if:

Maximum dissolved oxygen is greater than	12 mg/L
Maximum chlorophyll a is greater than	50 μg/L
Mean chlorophyll a is greater than	20 μg/L

Based on October 1983 to September 1987 data, Armand Bayou Tidal ranked second among estuaries with eutrophication-related problems in Texas (TWC, 1988). Clear Creek Tidal and Clear Lake were ranked first and seventh, respectively. Based on October 1985 to September 1989 data, Armand Bayou Tidal ranked 2nd among estuaries in Texas exhibiting hypoxia associated with algal blooms, while Clear Lake ranked 4th and Clear Creek Tidal ranked 12th (TWC, 1990). Armand Bayou was not included in the list of estuaries exhibiting elevated nutrients; Clear Creek Tidal was ranked 4th in the state.

This is somewhat paradoxical. Armand Bayou is notable for its hypoxia, which is generally considered to result from algal growth stimulated by eutrophication, or excess nutrients, but the bayou is not judged to contain elevated nutrients. Algal growth is stimulated by available nutrients, increased water temperatures, and increased daylength. Growth is retarded by toxicants and limiting factors (any constituents which inhibit further growth by their scarcity). Nitrogen and phosphorus are both fertilizers but nitrogen is frequently scarcest in estuarine waters and the limiting factor.

Both total phosphorus and orthophosphorus are abundantly available (Figures 10 and 11). Ammonia and nitrate nitrogen are also available (Fig. 6 & 8) but both demonstrate seasonal scarcity (Fig. 7 & 9). Figure 22 shows the seasonal availability for these two forms of nitrogen. Both are very abundant during the winter and nearly disappear during the summer.

Figure 23 demonstrates the seasonal cycle of water temperature. The values represent a single day in each month, not averages. The concentration of chlorophyll a on those same days is also shown in Figure 23. As spring temperature rose in 1977, chlorophyll (as a surrogate for algae) followed, but chlorophyll peaked in April and May and sharply declined thereafter. It is possible, but unlikely, that algal growth and chlorophyll were inhibited by higher water temperature. A second burst of growth occurred during the autumn months, perhaps indicating a different species dominating the algal community. Comparing the nitrogen peaks in Fig. 22 with the algae peaks in Fig. 23, it seems possible that the rapid growth of algae exhausted the available supply of nitrogen. Alternatively, the disappearance of nitrogen from the water column may lead to the decline of algae. Cause and effect are difficult to discern in this instance.

The correlation between nitrate nitrogen and chlorophyll was very low ($r=-0.324$, $P>.10<.20$) when all 27 data pairs were included. When the maximum value for nitrate nitrogen (1.63 mg/L), which was double the next highest value (0.83 mg/L) and septuple the average (0.233 mg/L), was considered an outlier and omitted, the correlation became highly significant ($r=-0.475$, $P<.02$). Nitrate nitrogen declined to the detection limit (0.01 mg/L) at all chlorophyll concentrations greater than .070 mg/L.

There was a strong correlation ($P<.001$) between nitrate nitrogen concentrations and water temperature, both with (corr. coeff. $r=-0.691$) or without ($r=-0.773$) the outlier. Nitrate was present at concentrations an order of magnitude, or greater, above the detection limit (0.01 mg/L) at temperatures lower than 20°C. Concentrations declined to the detection limit as water temperature reached 20°C, and remained at or near the detection limit above 25°C. The concordance was not perfect and the interaction between nutrient, temperature and algae is complex.

The molecular constituents of marine phytoplankton typically have 16 atoms of nitrogen for each atom of phosphorus. This N:P ratio, known as the Redfield ratio, can be used to indicate the potential of available nitrogen or phosphorus to act as a limiting factor affecting algal populations. Ammonia nitrogen and nitrate nitrogen concentrations at the Armand

Bayou monitoring station were summed to determine gram-atoms of nitrogen; orthophosphorus concentrations were used to calculate gram-atoms of phosphorus. The Redfield ratio was calculated for 66 sample dates with adequate data. The ratios ranged from 0.05 to 12.82, with an average value of 2.19; the ratio exceeded 8.0 only twice. This indicates that nitrogen potentially is a limiting factor at all times, and phosphorus seldom, if ever, acts to limit algal growth at this location.

The seasonality of the Redfield ratio and chlorophyll-a are shown in Figure 24. The N:P ratio clearly is unimodal, peaking in November and declining steadily to a minimum in July. Chlorophyll-a, on the other hand, is tri-modal, with a minor peak in January, a major peak in April, and an intermediate peak in October. The presence and magnitude of these peaks varied somewhat from year to year. The Redfield ratio was a fair predictor of chlorophyll-a concentrations (corr. coeff. $r=0.336$; $P=0.026$; $N=44$). Conversely, chlorophyll concentrations were useless for predicting nitrogen concentrations, but water temperature ($r=0.694$; $P=0.000$) and phosphorus concentrations ($r=0.497$; $P=0.001$) were reliable. Used jointly in a multiple regression, water temperature and phosphorus concentration accounted for 67% of the variation in nitrogen concentrations ($r=0.817$; $P=0.000$).

It may be concluded that phosporus is present in high concentrations at all seasons but nitrogen is removed from the system, by an unknown mechanism, from May to October. Daily oscillations of dissolved oxygen, from supersaturation to hypoxia, are frequently observed. Armand Bayou is eutrophic during the winter months, from November to March. An increase in nitrogen loading may exceed the assimilation capacity of this estuary and increase the duration of eutrophic conditions.

Figure 22.
Monthly Variation in Nitrogen

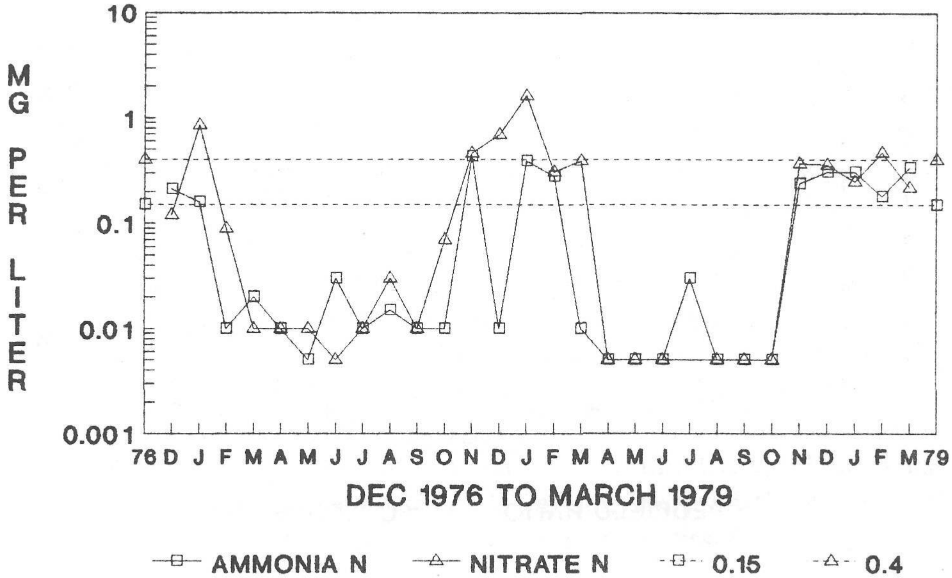


Figure 23
Monthly Variation in Temperature
and Chlorophyll

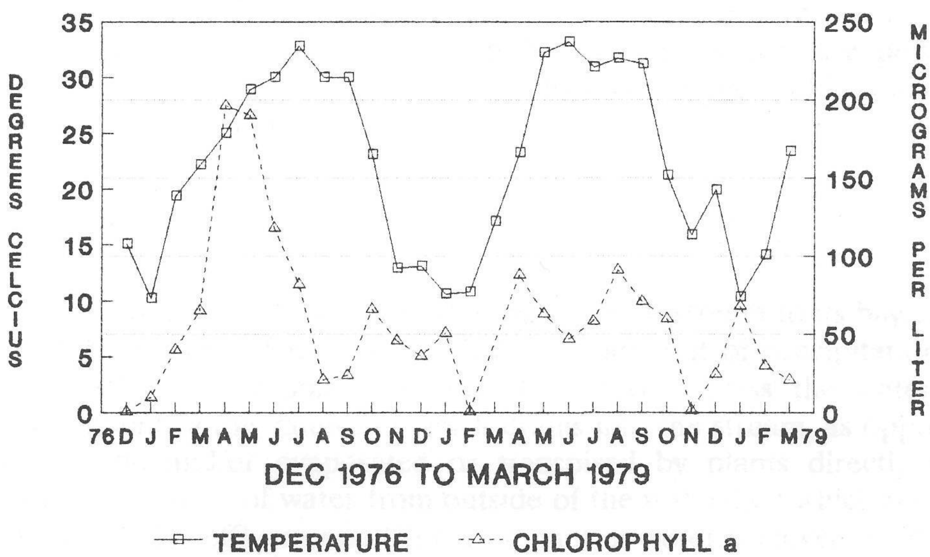
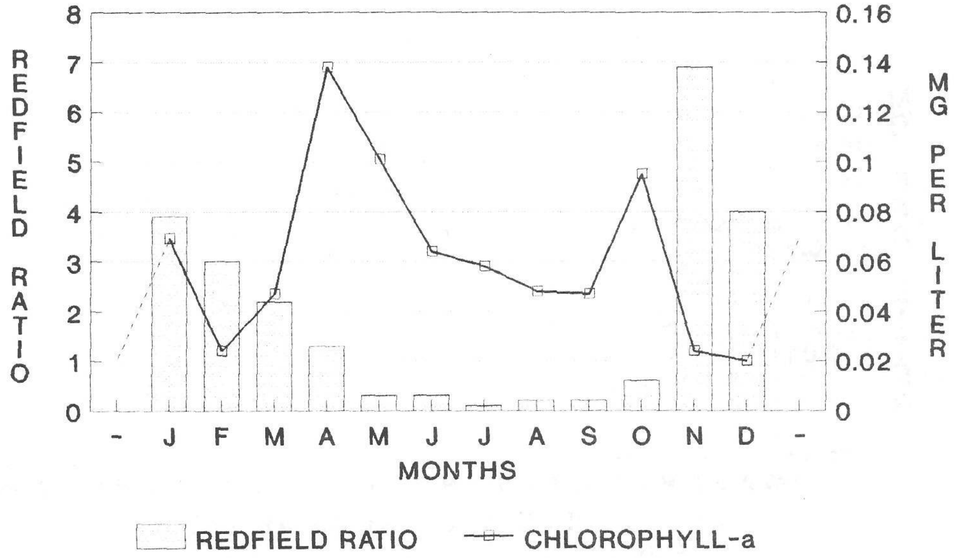


FIGURE 24
SEASONALITY OF REDFIELD RATIO
AND CHLOROPHYLL-a



4. Toxicants

There are no data for heavy metals, polychlorobiphenyls (PCBs), polycyclic aromatic hydrocarbons (PAHs), pesticides, or oil and grease in water or sediments for Armand Bayou.

5. Local Comparison

For this report, two comparisons are made to place the water quality information for Armand Bayou in perspective. First, all of the data from the Armand Bayou watershed are presented in Table 4 to provide an overview of the basin. All intensive surveys and monitoring stations are included. As previously noted, the available data are very limited and the single, long-term monitoring station lies upstream of the Horsepen Bayou tributary.

The estimated average for dissolved oxygen is an approximation due to two biases inherent to the method. This parameter is stratified and represented by multiple samples on some sample dates (the intensive surveys). This biases the averages by overweighting data from those days. Furthermore, surface and bottom samples are pooled with all others but they do not represent independent samples. A more accurate estimate would be provided by entering depth-averaged values. The same is true for conductivity, which is used to derive salinity and, occasionally, total dissolved solids. Conductivity is stratified due to the saltwater wedge on the bottom and is subject to the same biases as dissolved oxygen.

It is clear that, overall, the average values for ammonia (0.14 mg/L) and nitrate nitrogen (0.21 mg/L) did not exceed their elevated nutrient thresholds, 0.15 and 0.4 mg/L, respectively. Note, however, that chlorophyll (59 μg/L average, 196 μg/L maximum) substantially exceeded the thresholds (20 and 50 μg/L, respectively).

Second, direct comparisons with Clear Creek, Taylor Bayou, and Clear Lake are provided in Table 5. If one assumes that Clear Creek is polluted, for it is restricted to non-contact recreation and suffers both hypoxia and elevated nutrients, then Armand Bayou does not live up to its reputation as a "pristine" stream. In fact, Taylor Bayou experiences better conditions regarding temperature, transparency, dissolved oxygen, pH, ammonia, nitrate, phosphorus, and fecal coliforms.

D. FRESHWATER INFLOWS

The volume of freshwater which is transported by a coastal stream to its bay is determined by five factors: (1) the size of its watershed, (2) the amount of precipitation which falls within its watershed, (3) the soil type or surface cover across the watershed, which determines the amount of this rainwater which drains into the stream, as opposed to being absorbed by the soil and/or evaporated or transpired by plants directly back to the atmosphere, (4) the amount of water from outside of the watershed which is imported and discharged as wastewater effluent and (5) the amount of water removed from the stream,

Table 4. Parameter Summary for Armand Bayou, Segment 1113.

Parameter (Unit)		Number of Samples	Average Value	Maximum Value	Minimum Value
Temperature	(°C)	221	23.7	35.0	8.9
Transparency, Secchi	(inches)	15	13	24	6
Conductivity, Field	(micromho)	202	7639	27900	250
Dissolved Oxygen	(mg/L)	221	8.6	16.9	1.6
pH	(SU)	200	8.4	9.4	6.9
Ammonia NH3-N, Total	(mg/L)	92	.14	1.97	.01
Nitrite NO2-N, Total	(mg/L)	66	.04	.79	.01
Nitrate NO3-N, Total	(mg/L)	88	.21	1.63	.01
Total Kjeldahl N	(mg/L)	23	2.2	3.0	1.2
Total Phosphorus, wet	(mg/L)	90	.84	11.00	.22
Ortho-Phosphorus,	(mg/L)	90	.54	1.68	.11
Total Organic Carbon	(mg/L)	61	19	54	10
Chloride	(mg/L)	83	2052	10500	18
Sulfate SO4	(mg/L)	79	264	1110	4
Fecal Coliform FCBR	(/100ml)	68	221	32000	10
Chlorophyll <u>a</u> corrected	(μg/L)	59	59	196	1
Pheophytin <u>a</u>	(μg/L)	60	8	50	0

Table 5. Local Comparison of Average Values.

Parameter	Clear Creek Tidal	Armand Bayou Tidal	Taylor Bayou Tidal	Clear Lake
Temperature	21.9	23.7	22.2	22.9
Transparency	13	13	15	16
Conductivity	13025	7639	13153	18522
Dissolved Oxygen	7.1	8.6	7.9	8.2
pH	8.0	8.4	8.1	8.3
Ammonia NH3-N	.40	.14	.08	.15
Nitrite NO2-N	.07	.04	.04	.02
Nitrate NO3-N	.37	.21	.06	.11
Total Kjeldahl N	1.24	2.2	2.38	1.38
Total Phosphorus	.92	.84	.39	.53
Ortho-Phosphorus	.73	.54	.24	.41
Total Organic Carbon	16	19	21	14
Chloride	3312	2052	4051	5917
Sulfate	396	264	603	781
Fecal Coliform	218	221	86	57
Chlorophyll <u>a</u>	42	59	51.8	40
Pheophytin <u>a</u>	9	8	3.7	5

for irrigation or other purposes, which is not returned to the stream. Each of these factors will be addressed in turn.

The Texas Water Development Board (TWDB) has estimated the fresh-water inflow to Clear Lake. One watershed unit (11130) used by TWDB includes Armand Bayou, Taylor Bayou, and the smaller bayous along the southern shore of Clear Lake. This area encompasses 80.0 square miles. The TWDB estimates are given in Table 6 as monthly and annual inflows based on 1977-1987 precipitation and discharges. There are no diversions of water in this unit. The runoff curve number used in the calculations was 88.5.

1. Watershed

The flat terrain of this watershed (highest point 35+ ft) and the extreme subsidence which has occurred lead to differing estimations of the watershed boundary. For purposes of this report, the map prepared by the Harris County Flood Control District (July 1984) was judged to be most accurate. Each of the 33 subwatershed boundaries on this 1:24,000 scale map was measured with a compensating polar planimeter. The total watershed encompasses 60.031 sq miles, or 38,420 acres (Figure 25). All of the soils in the watershed are poorly drained, very slowly permeable, clayey and/or loamy soils.

2. Precipitation

The nearest National Weather Service precipitation station is positioned in Deer Park at the northern perimeter of the watershed. The monthly distribution of rainfall is listed in Table 7 and shown in Figure 26. There is little difference between the 30-year long term average (1951-1980) and recent rainfall (1977-1987). Long-term trend data (characterized as "normal" precipitation by NWS) for Deer Park (49.6 in.), Alvin (48.0 in.) and Galveston (40.2 in.) was used to construct annual rainfall isopleths for the watershed area. The isopleths have a NE-SW orientation and indicate 49 inches of precipitation in the northwest, 48 inches centrally, and 47 inches at the southeast end of the watershed. Thus, on average, the watershed receives 48 inches of precipitation annually.

The Harris County Flood Control District has installed 3 rain gauges within the watershed; on Armand Bayou at Bay Area Boulevard (Sta. 250) and Genoa-Red Bluff Road (Sta. 220), and on Big Island Slough at Fairmont Parkway (Sta. 230). These 3 stations form a triangle with sides of 2.7, 2.9 and 3.9 miles in length. Thus these stations are rather close together but in their first 3 years (1987-89) of operation they have revealed some startling differences in precipitation. Variation between years is expected and has occurred, with differences between low and high annual rainfall of 29.0, 25.1, and 22.5 inches for stations 220, 230, and 250, respectively. Large variation within years has also been shown, with differences of 8.1, 12.6, and 19.1 inches of annual rainfall between stations 220 and 250, only 3.9 miles apart (Fig. 27).

Table 6. TWDB Estimated Freshwater Inflow to Clear Lake.
(includes Armand Bayou, Taylor Bayou, and south shore

Month	Modeled Inflow ac-ft	Return Flow ac-ft	Total ac-ft
January	7518	526	8044
February	6698	464	7162
March	5913	480	6393
April	3231	455	3686
May	7258	506	7765
June	16450	518	16968
July	12856	538	13394
August	7005	518	7523
September	14085	550	14635
October	6866	543	7409
November	10069	494	10563
December	5205	524	5729
Annual	103,153	6,116	109,269

Table 7. Monthly Distribution of Precipitation at Deer Park

Month Inches	Long-term Trend 1951-1980	Recent Trend 1977-1987
January	3.72	3.97
February	3.16	3.22
March	2.56	2.86
April	3.67	2.07
May	4.24	4.91
June	5.21	6.27
July	4.81	5.22
August	4.73	4.72
September	6.00	6.14
October	3.69	3.57
November	4.16	5.04
December	3.65	3.11
Annual	49.60	51.10 Inches

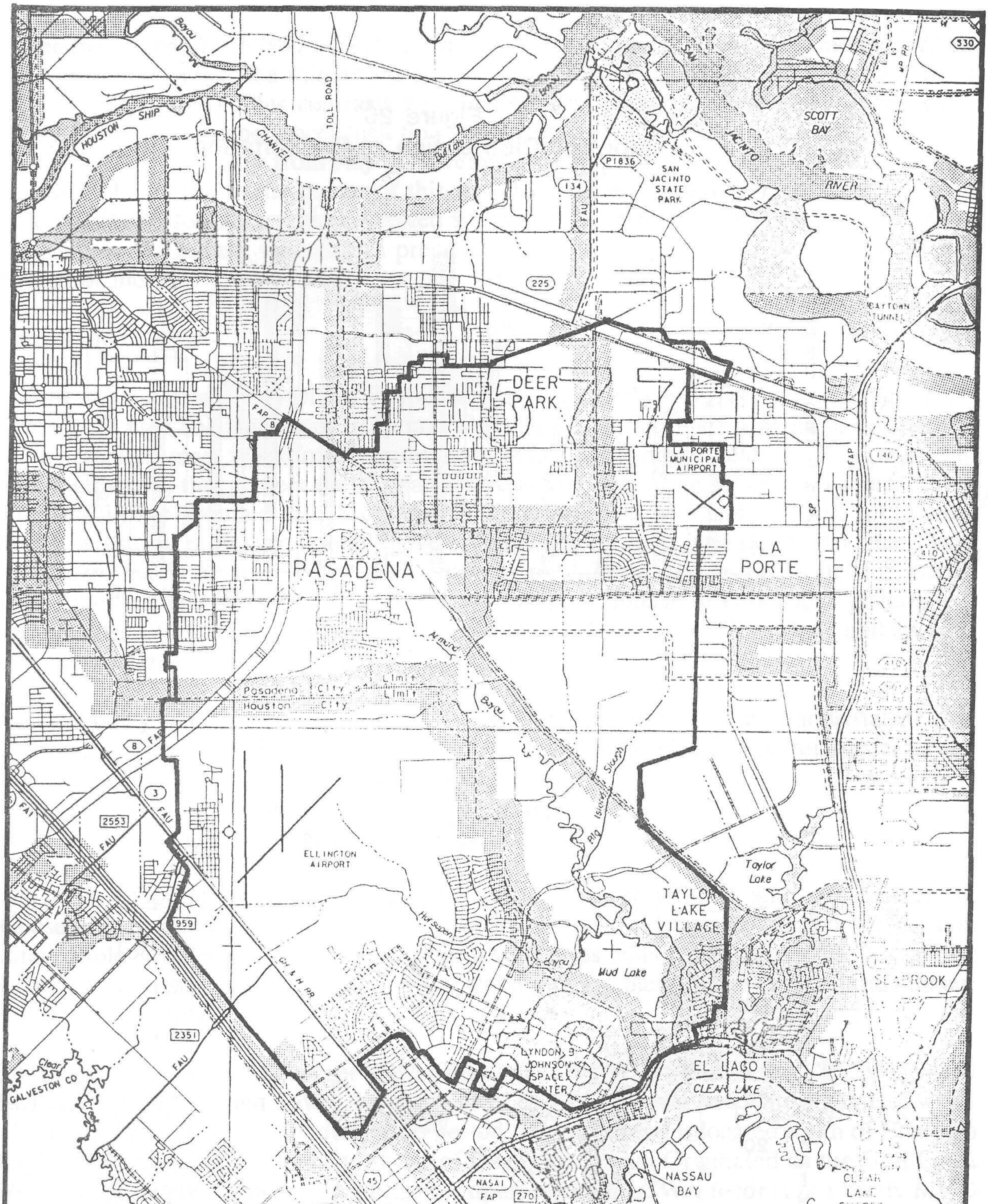


Figure 25. Armand Bayou Watershed

Scale: 1" = 2 miles

Base Map: SDHPS Harris County 102

Figure 26
Monthly Distribution of Precipitation

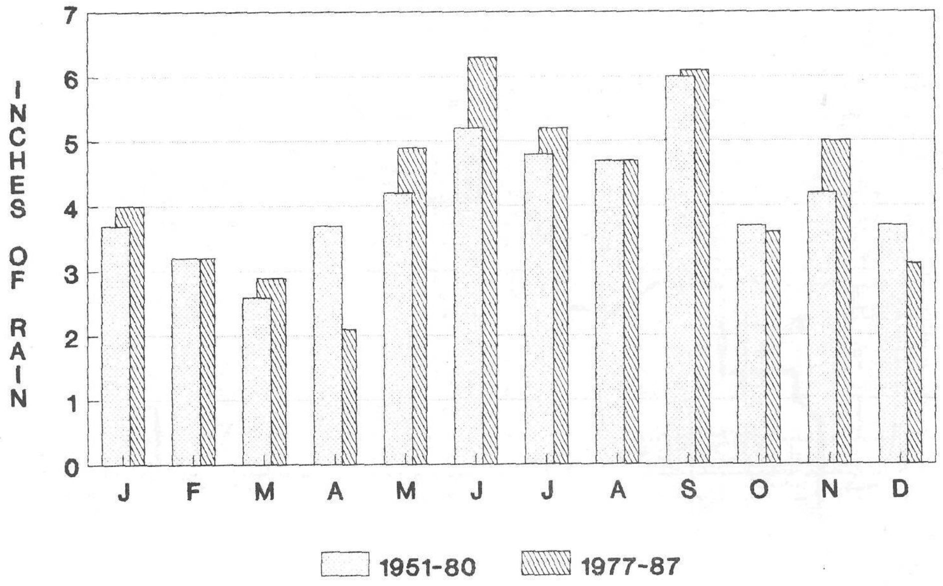
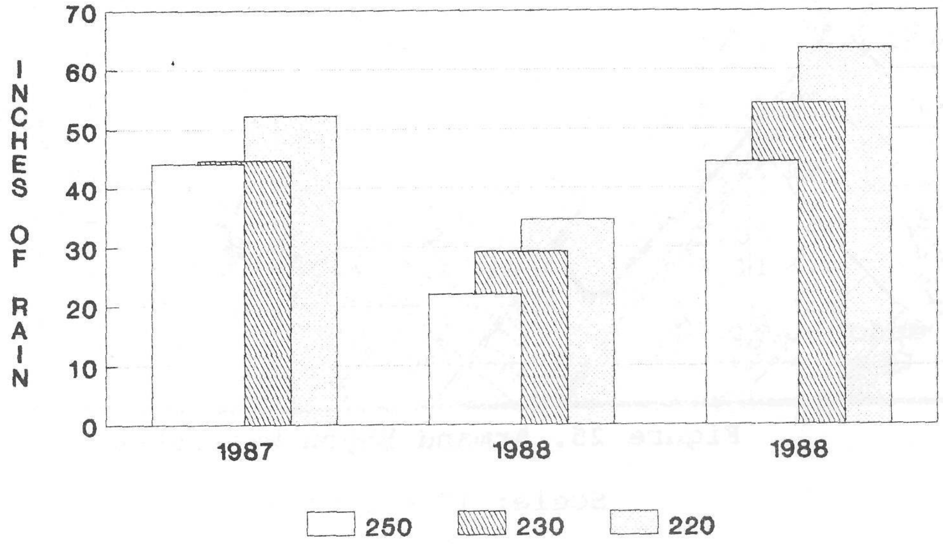


Figure 27.
Annual Rainfall Variation
Between Stations



During the 11-year 1977-1987 period, annual precipitation ranged from 34.13 inches to 62.18 inches, nearly double. The rainfall varied from 2 to 6 inches per month, without extended dry periods (Fig. 26). This contrasts with major river inflow to this estuary, such as the Trinity River, which experiences high flow from north-east Texas precipitation from March to June and very low flow from July to November. During a 4-day period, June 23-26, 1989, 16 inches of rain fell in the center of this watershed. The northern perimeter received 15 inches while the southern region received 9 inches. During this event 6.9 inches fell within 36 hours. Such extreme variation in precipitation renders estimation of freshwater inflow difficult or inexact.

3. Runoff

Stormwater runoff will vary with soil type, vegetative ground cover, recent precipitation and human land use. The Bureau of Economic Geology (1989) has mapped land use within the watershed. This map, based on topographic contours, is slightly smaller (55.76 sq mi) than others (60 sq mi) that correct the drainage pattern to reflect more subtle road construction, etc. Land use is grouped into 8 categories: range-pasture, woodland-timber, residential-urban, industrial, park-recreational, government land, oil field, and education site. These categories mix vegetative cover with ownership and are not appropriate for runoff determinations. For example, oil fields are typically grasslands in this area, and government land includes Ellington Airport and NASA, which include substantial grassland and lawn, as does the University of Houston-Clear Lake.

Approximately 38 percent of the land is residential-urban and 6 percent is industrial, neither of which will retain much precipitation. Eight percent is woodland. The remainder of the watershed has substantial grass vegetation.

4. Water Discharges

Two types of point source discharges, treated wastewater effluent and stormwater, are released into tributaries of Armand Bayou. There are no releases of brine or production water. Table 8 reviews the volumes of water involved (as million gallons per day, MGD) for the past 10 years. A trend to regional or central treatment plants has decreased the number of discharge points.

The largest wastewater discharger is the Clear Lake City Water Authority (CLCWA) which discharges into Horsepen Bayou downstream of Bay Area Boulevard. The volume of water released increased 38 percent during the period. Metro Central is located south of Ellington Airport and releases into the headwaters of Horsepen Bayou. Originated by the Gulf Coast Waste Disposal Authority, the plant is now operated by CLCWA for Harris County MUD 67, Gulfway MUD, Bayfield PUD, and the City of Houston. The volume of its discharge has increased 484 percent over the period and this is the treatment plant most likely to grow. This facility is designated as the regional treatment plant and its current capacity is 5 MGD. Additional land is available for it to grow to 40-50 MGD capacity when needed.

Table 8. Point Source Discharges into Armand Bayou Tributaries

WASTEWATER (MGD)

	CLCWA	METRO	ELLING -TON	COLLEGE VIEW	FAIR- MONT	BAY- FIELD	COUNTRY -WIDE	TOTAL
1980	3.506	.224	.151	.290	.392	.045		4.608
1981	3.787	.453	.239	.341	.799	.182		5.801
1982	3.512	.717	.219	.251	.713			5.412
1983	3.549	.816	.252	.178				4.795
1984	3.858	.793	.099	.156			.008	4.914
1985	4.454	1.069	.120	.206			.012	5.861
1986	4.542	1.083	.160	.238			.013	6.276
1987	4.403	1.059	.162	.187			.013	5.284
1988	4.383	1.099	.136				.054	5.672
1989	4.842	1.309					.072	6.223

STORMWATER (MGD)

	LYONDELL	OXYPETROCHEM	TOTAL
1983	.695		.695
1984	.387		.387
1985	.556		.556
1986	.601		.601
1987	1.593		1.593
1988	.823	.086	.909
1989	1.488	.333	1.821

The Ellington plant was built by the Air Force for Ellington AFB and inherited by the City of Houston in 1984 and dismantled in 1988. Located near the Metro Central plant, it formerly discharged into Horsepen Bayou. The College View MUD plant, which discharged into Willow Springs Bayou, passed to the City of La Porte in 1986 and was dismantled in 1987. The City of La Porte also closed its Fairmont Park plant, which discharged into Big Island Slough, in 1982. Both areas are now served by a central treatment plant which discharges into another watershed. The Bayfield MUD, dismantled in 1982, formerly discharged into a flood control ditch connected to Horsepen Bayou. The Countrywide Partnership treatment facility discharges into a drainage ditch connected to Willow Springs Gully.

There are two significant point source dischargers of stormwater. In Bayport, Lyondell, formerly the El Paso Polyolefins Co. and then Rexene Products Co., discharges large quantities of stormwater into Big Island Slough. Since 1988, Cain Chemical, Inc., now OxyPetrochemical, has also discharged stormwater into Big Island Slough. Other intermittent dischargers include ICI Americas, Inc. in Bayport, the Hughes Sand Pits, Inc., and NASA-Ellington Field.

In 1989, an average 6.2 million gallons per day of treated wastewater was discharged into Armand Bayou from point sources. This is equivalent to 6,944 acre-feet of water per year. This estimate is greater than the 6,116 acre-ft of return flow estimated by the TWDB for a 33 percent larger watershed (Table 6). This water is imported into the watershed from groundwater and surface water sources. An additional 1.8 MGD (2016 acre-ft/yr) of stormwater runoff is discharged from point sources.

5. Water Withdrawals

There are no reservoirs on Armand Bayou and no agricultural or municipal interests which withdraw water. In 1989 the Baywood Country Club requested authority to withdraw water to irrigate 80 acres of golf course. The Texas Water Commission issued a permit in 1990 to withdraw 150 acre-feet of water per year during periods when bayou flow exceeds 2 cubic feet per second (900 gallons per minute) below the diversion point. The water will be temporarily stored in three off-channel reservoirs totaling 5.5 acre-feet capacity.

6. Extra-Watershed Connections

The headwater of Armand Bayou is connected to the headwater of Little Vince Bayou in the vicinity of East Beltway and Spencer Highway. Since the connector lies at the high point of local topography, 35 ft above sea level, there is unlikely to be substantial interchange of water between the watersheds.

E. INFRASTRUCTURE

Much urban development has benefitted from major infrastructure projects which provide economic incentive, ease transportation bottlenecks, and often facilitate growth. In the Clear Lake area, construction of the Interstate 45 highway and creation of the Johnson Space Center were early catalysts. Today, deaccession of Ellington Air Force Base and the subsequent industrial development of the airport as a result of new space projects serves as a similar stimulus on a smaller scale. Highway expansion continues with East Beltway 8 and Clear Lake City Boulevard. On a smaller scale, the City of Pasadena plans to extend Center Street south and southwest, crossing Red Bluff Road to reach the Fairmont Parkway, adjacent to Armand Bayou.

Armand Bayou, once a barrier to travel and accessible only by boat, has been spanned by NASA Road 1, Bay Area Boulevard, Genoa-Red Bluff Road, Fairmont Parkway and other roadways. Water enthusiasts are attracted to the area because of its access to Galveston Bay.

There are three issues involved. What is the present quality of Armand Bayou water? How much stormwater drainage can be added to the bayou without lowering its quality? How much water can be removed from the bayou for irrigation without changing its salinity profile?

The question of current water quality was addressed in Section C above. The question of additional stormwater has not been answered adequately. High-traffic highways often lead to greater residential density. The conversion of grasslands or woodlands to residential areas greatly increases the quantity of stormwater runoff, since less of it soaks into the ground, and degrades the quality of that runoff, since it picks up motor oil, fertilizers, and pesticides associated with urban lifestyles. One developer has plans to convert another 2000 acres (5% of the watershed) into residential areas. One solution, already employed, is to provide detention ponds that will retard runoff and decrease pollutants before the water reaches the bayou.

Additional wastewater effluent will also influence the bayou and downstream areas. A tentative plan to eventually discharge as much as 50 MGD from the Metro Central plant into Horsepen Bayou already has been proposed. Wastewater will be collected miles beyond the watershed and brought to the plant for treatment. Even when efficiently operated, within permit limits, a plant of that size will add substantial quantities of nutrients and pollutants to the bayou ecosystem.

The question of bayou water diversion also remains unanswered. How much irrigation water returns to the bayou? What nutrients, herbicides, or pesticides has it picked up enroute? Flood control improvements currently underway will increase the rate of water movement down the bayou. The ecological effects of this action may be inadequately addressed.

F. HYDROLOGICAL AND METEOROLOGICAL INFLUENCES

The combined effect of land subsidence and sea-level rise are causing historic shorelines to creep inland. As described in section B above, subsidence in this area has greatly slowed and is no longer a major problem. Sea-level will have less effect on the Armand Bayou ecosystem in the future because of the steepness of the current bayou shoreline. A five foot rise in sea level will deepen the water but not greatly expand the submerged bottom laterally. The 5-ft and 10-ft contour lines are immediately adjacent to the present shoreline and lateral expansion will be contained. Any existing wetlands would be drowned but no original wetlands remain from 1956 and few new marshes have been established.

Major precipitation events can be very local or widespread. The effects cannot be predicted without the aid of a real-time telemetered monitoring system, as employed by the Harris County Flood Control District. The impact of hurricanes varies with their forward speed, wind speed and wind angle to the shoreline. Each storm is unique and the National Weather Service uses complex computer models and multiple scenarios to predict their impacts. Massive water movements may scour organisms, sediments and nutrients from the bayou. Ecosystem impact is unpredictable.

The still, high water-mark recorded for Hurricane Carla, the largest storm is Texas' history, was 10.4 feet above mean sea level at the mouth of Mud Lake. There was some flooding at the junction of Armand and Horsepen Bayous, but flooding upstream did not reach the juncture of Armand Bayou and Spring Gully (Fisher et al., 1972).

G. LIVING RESOURCES

There have been many studies of the biota of Galveston Bay, some studies of the biota of Clear Lake, but virtually no studies of the biota of Armand Bayou.

As an example, the Coastal Fisheries Branch of the Texas Parks and Wildlife Department samples the fisheries of Galveston Bay monthly. The sample locations are randomly chosen from an established grid system. Clear Lake is included within the system. However, random samples mean there is no systematic sampling of the same localities with the same collecting gear in a repetitious time sequence. The sampling scheme works very well for Galveston Bay as a whole entity, for which it was designed; it works poorly for Clear Lake, which is inadequately sampled; it does not work at all for Mud Lake and Armand Bayou, which are not sampled. The scheme does identify the organisms which reside in Clear Lake and may enter Mud Lake, and provides estimates of their relative abundance and diversity.

Other studies contribute to our knowledge of the inhabitants of Clear Lake and support inferences regarding the biota of Mud Lake. There are no studies which address the freshwater biota of Armand Bayou and its tributaries. The first study of Clear Lake was reported by Chin (1961) who made 363 otter trawl collections between January 1958 and

January 1959, obtaining nearly 52,000 specimens. He verified that Clear Lake was an estuarine nursery area. Twelve species formed 98 percent of the total organisms collected and 3 species rotated as the most abundant species throughout the year. The Atlantic croaker was most abundant from mid-December to mid-May, when it was supplanted by brown shrimp until July, when it was replaced by white shrimp until mid-December. Five species - Atlantic croaker, brown shrimp, southern flounder, Gulf menhaden, and spot - were most abundant in spring. As summer water temperature reached 30°C these species declined. Five other species reached their maximum abundance after water temperature peaked - white shrimp, sand seatrout, hardhead catfish, gafftopsail catfish, and bay whiff - and declined in autumn and winter.

In that same year, 1958, another group sampled 10 localities in Clear Lake, Clear Creek, Taylor Lake, Mud Lake and Armand Bayou. From their 228 samples, the stomach contents of 5019 bony fishes representing 40 species were analyzed (Diener et al, 1974). The data were pooled and those fishes specifically caught in Armand Bayou and Mud Lake were not identified.

In 1961, Clear Lake was sampled again and compared with Trinity Bay and Offatts Bayou on Galveston Island (Chapman, 1963). Slightly saline Clear Lake yielded fewer species but 4 times as many individuals as higher salinity Offatts Bayou with the same fishing effort. Comparing closed-habitat Clear Lake with open-habitat Trinity Bay at equal salinities, more shrimp, crabs, and fish were caught in Clear Lake than Trinity Bay (157.7 vs 88.4 per 5-minute trawl). Samples were collected from February to December and among the 19,709 organisms collected in Clear Lake, the numerically most abundant species, in descending order, were white shrimp, Atlantic croaker, brown shrimp, bay anchovy, sand seatrout, largescale menhaden, spot, and blue crab.

Mock (1964) in 1963 studied bottom sediments in Clear Lake and listed 5 species of mollusks found; the bivalves were common rangia, brown rangia, Mitchell's macoma, and dwarf surf clam, and one gastropod, the sharp-knobbed nassa. All 5 species were found in high salinity water near the outlet to Galveston Bay but only one, the surf clam, was found in low salinity water. Mock noted that only a single species of unidentified annelid worm was found.

Mock (1966) collected shrimp along shorelines at the mouth of Clear Creek in 1965 to demonstrate the natural, vegetated shoreline produced 2.5 times more brown shrimp and 14 times more white shrimp than bulkheaded shoreline.

Pullen (1969) described hydrological conditions in Clear Lake for 1958-1966, reporting temperature, salinity, dissolved organic nitrogen, total phosphorus, and oxygen. Salinity ranged from 0.1 to 23.7 ppt, and the lower end of Mud Lake was noted as having lower salinities than anywhere in Clear Lake.

The Clear Creek Basin Water Quality Study conducted during summer by students from Clear Creek High School was initiated in 1971 (CCBWQS, 1971, 1972, 1975a, 1975b). Biological investigations were included in 1974 and 1975. Planktonic organisms were identified to the generic level, and the fishes and macroinvertebrates collected in a shrimp trawl were identified to the specific level. These qualitative studies are the only information on plankton from the Clear Lake watershed. They also added two fishes, rainwater killifish and spotted sunfish, to the species list.

White et al. (1985) reported on benthic samples collected from Clear Lake in 1976. One mollusk, Mulinia lateralis; 5 polychaetes, Mediomastus californiensis, Streblospio benedicti, Stenoninereis rudolphi, Parandalia fauveli, Podarkeopsis levifuscina; and 2 crustaceans, Edotea montosa, Oxyurostylis salinoi, were added to the species list.

Two environmental reports (Espey, Huston 1977a, 1977b) added 2 fishes and an oligochaete, Peloscolex sp., a polychaete, Capitella capitata, an isopod, Edotea sp., and chironomids to the list. Another environmental report (Guthery et al., 1977) added the polychaetes Neanthes succinea and Polydora sp.

Klotz (1977) conducted the only study of zooplankton and primary productivity, and the first study that focused on Armand Bayou. He studied 4 stations from Bay Area Boulevard downstream to the outlet of Mud Lake. Gross primary productivity varied from 4000 to 8000 kcal/m^2 /yr; net primary productivity varied from 3000 to 7000 kcal/m^2 /yr, both of which were considered low for Texas bays. He found the zooplankton community to be depauperate, composed of Pleurobrachia, Acartia, Cyclops, polychaete larva, a gammarid amphipod, and a hydrachnid.

The Armand Bayou Nature Center has recently begun investigations of the aquatic life of Armand Bayou (R. Gray, 1988, unpublished list of fishes and invertebrates; D. Myers, pers. comm.). They have added 5 fishes and a mollusk to the species list, several with freshwater affinities.

1. Aquatic Life

Appendix Table A.1 lists the fishes which have been identified from the Clear Lake estuary. The list is compiled from the references noted above and data from the Coastal Fisheries monitoring program of the Texas Parks and Wildlife Department. Theoretically, any of these species could occur in Armand Bayou, particularly in Mud Lake during periods of saltwater intrusion. Those species which are known to have occurred in Armand Bayou are preceded with an asterisk. Appendix Table A2 lists the macroinvertebrates of the Clear Lake estuary. Classes and families of animals which have been noted but not specifically identified are included. Appendix Table A3 lists the planktonic organisms of the Clear Lake estuary. There does not appear to be any information regarding aquatic life in Armand Bayou upstream of Bay Area Boulevard.

Although seagrasses formerly occurred in Galveston Bay adjacent to Clear Lake along the Seabrook and Kemah shoreline, there is no evidence that they ever occurred in Clear Lake (Pulich & White, 1989). There are no reports of submerged aquatic vegetation in Mud Lake or Armand Bayou.

More (1965) noted that Mud Lake was a good nursery area for southern flounder but its use by juvenile spotted seatrout was sporadic. He noted there was no submerged aquatic vegetation.

2. Birds

There is no quantitative information regarding the water birds which are associated with Armand Bayou. The Armand Bayou Christmas Bird Count does not segregate data for Armand Bayou itself from the remainder of the 15-mile diameter count circle. There are no colonial waterbird nesting sites in the area.

3. Endangered and Threatened Species

The following endangered and threatened species potentially may be associated with the aquatic habitat of the Armand Bayou Coastal Preserve (TPWD, 1988):

ENDANGERED
- Bald Eagle
- Brown Pelican
- Paddlefish

THREATENED
- Reddish Egret
- White-faced Ibis
- American Swallow-tailed Kite
- Wood Stork
- Arctic Peregrine Falcon
- Alligator Snapping Turtle
- Creek Chubsucker

The checklist of common birds for the Armand Bayou Nature Center lists the bald eagle, American swallow-tailed kite, and wood stork as occurring at the site. The piscivorous bald eagle and wood stork would be directly associated with the Coastal Preserve. The insectivorous swallow-tailed kite would be associated with the prairie habitat of the nature center, rather than the bayou.

It is possible that the brown pelican, reddish egret, white-faced ibis, and peregrine falcon may occasionally appear on Armand Bayou but normally it would not be considered primary habitat for these species.

The paddlefish is known to inhabit coastal streams and brackish water and has been collected in the San Jacinto River (Lee et al., 1980). It prefers large bodies of water. It has never been collected in Clear Lake and would be unlikely to ascend Armand Bayou.

The creek chubsucker is a freshwater species that has been found in tributaries of the San Jacinto and Trinity Rivers (Lee et al., 1980). It is not known to occur in Armand Bayou, which is unlikely habitat since it connects only to brackish water.

The alligator snapping turtle is an inhabitant of deep, freshwater lakes and rivers (Garrett & Barker, 1987). Although it occasionally enters brackish water, it would be more likely to do so near the mouth of a large river, rather than a small coastal stream, such as Armand Bayou.

In summary, Armand Bayou is unlikely to be a significant habitat for endangered species. Only two, the bald eagle and wood stork, are expected to seasonally use the coastal preserve on occasion.

CONCLUSIONS

1. Armand Bayou is influenced by activity and events anywhere within its 60 square mile watershed. In the future it may be affected by activity beyond its watershed, as sewage generated elsewhere is brought to the Metro Central regional wastewater treatment plant. This will introduce additional nutrient enriched wastewater effluent into the Armand Bayou ecosystem.

2. The coastal preserve watershed has experienced 5 to 9 feet of land surface subsidence since 1906; the rate of subsidence has declined substantially and future subsidence should be negligible.

3. Subsidence has extended the zone of tidal influence, changed the lower reach of the bayou from a freshwater to a brackish water environment, increased the size of Mud Lake from 100 acres to more than 325 acres, and decreased wetlands from 275 acres in 1956 to 24 acres in 1979, a 91 percent loss.

4. Flood control improvements continue to move water downstream faster, limiting infiltration time and pollutant removal.

5. The quality of bayou water is poor, and in clear contrast to its designated uses - high quality habitat and contact recreation. The current sampling station does not reflect the input of pollutants from Horsepen Bayou. Quarterly or semi-annual monitoring is inadequate to determine stream conditions. The bayou is eutrophic all year in regards to phosphorus, and seasonally, in winter, with nitrogen. High chlorophyll and dissolved oxygen levels are persistent indicators of enrichment. No information on toxicants exists.

6. The number of point source discharges has declined from 6 to 3, but the rate of treated wastewater discharge has increased 35 percent over the past decade, to 6.2 MGD in 1989. An additional 1.8 MGD of stormwater is released from point sources into the bayou. The rate of discharge from sewage treatment plants will continue to increase.

RECOMMENDATIONS

1. The extent of bottomland forest flooding and value of this forest as a contributor of detritus and nutrients, and as a sink for nutrients and pollutants, should be determined. These fluvial forests should be examined to determine if different forest types exist on the different soils.

2. Establishment of an additional monitoring station that will reflect the contribution of pollutants from Horsepen Bayou is needed. Monthly sampling should be resumed for 2 to 3 years to establish an adequate baseline of information.

3. An investigation of toxicants in water and sediment samples should be conducted.

4. Investigations of the utilization of Mud Lake by commercial and recreational finfishes and shellfishes should be undertaken.

5. Investigations of the freshwater flora and fauna should be initiated, especially upstream of Bay Area Boulevard and into the lower reaches of Horsepen Bayou, Big Island Slough, and Spring Gully.

6. A 24-hour water quality survey should be conducted during the warm season to determine the extent of oxygen sag during hours of darkness.

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APPENDIX

Table A1. Fishes of the Clear Lake Estuary
(* - Species Known to Inhabit Armand Bayou)

Achirus lineatus, Lined Sole
* Adinia xenica, Diamond killifish
Alosa chrysochloris, Skipjack herring
* Anchoa mitchilli, Bay anchovy
Archosargus probatocephalus, Sheepshead
Arius felis, Hardhead catfish
Astroscopus y-graecum, Southern stargazer
Bagre marinus, Gafftopsail catfish
Bairdiella chrysoura, Silver perch
* Brevoortia patronus, Gulf menhaden
Chaetodipterus faber, Atlantic spadefish
Citharichthys spilopterus, Bay whiff
Cynoscion arenarius, Sand seatrout
* Cynoscion nebulosus, Spotted seatrout
* Cyprinodon variegatus, Sheepshead minnow
* Dorosoma cepedianum, Gizzard shad
Dorosoma petenense, Threadfin shad
Elops saurus, Ladyfish
* Fundulus grandis, Gulf killifish
Fundulus pulvereus, Bayou killifish
Fundulus similis, Longnose killifish
* Gambusia affinis, Mosquitofish
Gobiesox strumosus, Skilletfish
Gobioides broussoneti, Violet goby
Gobionellus boleosoma, Darter goby
* Gobionellus bosci, Naked goby
Gobionellus hastatus, Sharptail goby
Gobionellus shufeldti, Freshwater goby
* Lagodon rhomboides, Pinfish
* Leiostomus xanthurus, Spot
Lepisosteus osseus, Longnose gar
* Lepisosteus spatula, Alligator gar
Lepomis punctatus, Spooted sunfish
Lucania parva, Rainwater killifish
Menidia beryllina, Inland silverside
* Menidia peninsulae, Tidewater silverside
* Micropogonias undulatus, Atlantic croaker
Morone chrysops, White bass
* Mugil cephalus, Striped mullet

Table A1. Fishes of the Clear Lake Estuary (continued)
(* - Species Known to Inhabit Armand Bayou)

Mugil curema, White mullet
Myrophis punctatus, Speckled worm eel
Oligoplites saurus, Leatherjacket
Opisthonema oglinum, Atlantic thread herring
Opsanus beta, Gulf toadfish
* Paralichthys lethostigma, Southern flounder
Peprilus burti, Gulf butterfish
* Poecilia latipinna, Sailfin molly
Pogonias cromis, Black drum
Polydactylus octonemus, Atlantic threadfin
Prionotus tribulus, Bighead searobin
* Sciaenops ocellatus, Red drum
Sphoeroides parvus, Least puffer
Stellifer lanceolatus, Star drum
* Symphurus plagiusa, Blackcheek tonguefish
* Syngnathus scovelli, Gulf pipefish
Trichiurus lepturus, Atlantic cutlassfish
Trinectes maculatus, Hogchoker
Urophycis floridana, Southern hake

Table A2. Macroinvertebrates of the Clear Lake Estuary
(* - Species Known to Inhabit Armand Bayou)

Foraminiferans
Nematotodes
Ctenophores
  * Pleurobrachia sp., Comb jelly
Annelid worms
  Polychaetes
    Capitella capitata
    Mediomastus californiensis
    Neanthes succinea
    Parandalia fauvelli
    Podarkeopsis levifuscina
    Polydora sp.
    Stenoninereis rudolphi
    Streblospio levifuscina
    Streblospio benedictii
  Oligochaetes
    Peloscolex sp.
Mollusks
  Gastropods
    Nassarius acutus, Sharp-knobbed nassa
  Bivalves
    Macoma mitchilli, Mitchill's macoma
    Mulinia lateralis, Dwarf surf clam
    * Rangia cuneata, Common rangia
    Rangia flexuosa, Brown rangia
Arthropods
  Crustaceans
    Ostracods
    Copepods
      Acartia sp.
      Cyclops sp.
    Cirripeds
    Isopods
      Edotea sp.
    Amphipods
    Decapods
      Penaeus aztecus, Brown shrimp
      Penaeus setiferus, White shrimp
      Xiphopencus sp., Seabob

Table A2. Macroinvertebrates of the Clear Lake Estuary (continued)
(* - Species Known to Inhabit Armand Bayou)

* Palaemonetes pugio, Grass shrimp
Macrobrachium ohione, River shrimp
* Callinectes sapidus, Blue crab
Crangonid
Portunid crabs
Xanthid crabs
Chironomids

Table A3. Planktonic Organisms of the Clear Lake Estuary
(* - Species Known to Inhabit Armand Bayou)

Bacteria
- * Bacillis sp.
- * Spirillum sp.
- * Streptococcus sp.

Blue-green Algae
- * Agmenellum sp.
- * Anabaena sp.
- * Anacystis sp.
- * Gomphosphaeria sp.
- Lyngbya sp.
- * Oscillatoria sp.
- Prabaena sp.
- * Tetrahedron sp.

Flagellates
- Chromulina sp.
- * Lobomonas sp.
- Monas sp.
- Naelgeria sp.
- Oikomonas sp.
- Peridinium sp.
- * Trachelomonas sp.
- Euglena sp.

Ciliates
- Oxytricha sp.
- Paramecium sp.
- Pilidium sp.
- Stentor sp.

Green Algae
- * Ankistrodesmos sp.
- Closterium sp.
- Crucigenia sp.
- Mougeotia sp.
- Protococcus sp.
- * Scenedesmus sp.
- * Selenastrum sp.
- Staurastrum sp.

Table A3. Planktonic Organisms of the Clear Lake Estuary (cont'd)
(* - Species Known to Inhabit Armand Bayou)

Diatoms
- Campylooliscus sp.
- Coscinodiscus sp.
- Cyclotella sp.
- * Diatoma sp.
- * Fragilaria sp.
- Frustulia sp.
- Gyrosigma sp.
- Navicula sp.
- Nitzschia sp.
- * Staureneis sp.
- Surirella sp.
- Synedra sp.

Nematodes
- Chronogaster sp.

Crustaceans
- * Brachyura sp.
- Stilomysis sp.