TRINITY-SAN JACINTO ESTUARY:
A Study of the Influence of Freshwater Inflows

The preparation of this report was financed in part through funds made available by Senate Bill 137 of the 64th Texas Legislature.

Texas Department of Water Resources
LP-113

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PREFACE

The Texas Water Plan of 1968 tentatively allocated specific annual amounts of water to supplement freshwater inflow to Texas' bays and estuaries. These amounts were recognized at the time as no more than preliminary estimates of inflow needs based upon historical inflows to each estuary. Furthermore, the optimal seasonal and spatial distribution of the inflows could not be determined at the time because of insufficient knowledge of the estuarine ecosystems.

Established public policy stated in the Texas Water Code (Section 1.003 as amended, Acts 1975) provides for the conservation and development of the State's natural resources, including "the maintenance of a proper ecological environment of the bays and estuaries of Texas and the health of related living marine resources." Both Senate Concurrent Resolution 101 (63rd Legislature, 1973) and Senate Resolution 267 (64th Legislature, 1975) declare that "a sufficient inflow of freshwater is necessary to protect and maintain the ecological health of Texas estuaries and related living marine resources."

In 1975, the 64th Texas Legislature enacted Senate Bill 137, a mandate for "comprehensive studies of the effects of freshwater inflow upon the bays and estuaries of Texas..." Reports published as a part of the effort were to address the relationship of freshwater inflow to the health of living estuarine resources (e.g., fish, shrimp, etc.) and to present methods of providing and maintaining a suitable ecological environment. The technical analyses were to characterize the relationships which have maintained the estuarine environments historically and which have provided for the production of living resources at observed historic levels.

This report is one in a series of reports on Texas bays and estuaries designed to fulfill the mandate of Senate Bill 137. Six major estuaries on the Texas coast are part of the series, including (1) the Nueces estuary, (2) the Mission-Aransas estuary, (3) the Guadalupe estuary, (4) the Lavaca-Tres Palacios estuary, (5) the Trinity-San Jacinto estuary, and (6) the Sabine-Neches estuary. Reports in the S.B. 137 series are designed to explain in a comprehensive, yet understandable manner, the results of these planning efforts.

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CHAPTER I

SUMMARY

Concepts and Methods

The provision of sufficient freshwater inflow to Texas bays and estuaries is a vital factor in maintaining estuarine productivity, and a factor contributing to the near-shore fisheries productivity of the Gulf of Mexico. This report analyzes the interrelationships between freshwater inflows and estuarine productivity, and establishes the seasonal and monthly freshwater inflow needs, for a range of alternative management policies, for the Trinity-San Jacinto estuary of Texas.

Simplifying assumptions must be made in order to estimate freshwater inflow requirements necessary to maintain Texas estuarine ecosystems. A basic premise developed in this report is that freshwater inflow and estuarine productivity can be examined through analysis of certain "key indicators." The key physical and chemical indicators include freshwater inflows, circulation and salinity patterns, and nutrients. Biological indicators of estuarine productivity include selected commercially important species. Useful species are generally chosen on the basis of their wide distribution throughout each estuarine system, a sensitivity to change in the system, and an appropriate life cycle to facilitate association of the organism with estuarine productivity.

Description of the Estuary and the Surrounding Area

The Trinity-San Jacinto estuary consists of Trinity Bay, Galveston Bay, East Bay, West Bay and several smaller bays. Areas contributing inflow to the estuary include the entire Trinity and San Jacinto River Basins and the Trinity-San Jacinto Coastal Basin, plus parts of the Neches-Trinity and San Jacinto-Brazos Coastal Basins.

The major marsh areas of the Trinity-San Jacinto estuary are associated with the Trinity River delta. Active delta plains are covered with salt, brackish, and freshwater marshes. Most of the shorelines associated with the Trinity-San Jacinto estuary are balanced between shoreline erosion and sediment deposition.

Land use in the area is dominated by urban and industrial uses. The City of Houston and the petro-chemical industrial complex are predominant features.

Inland areas and marshes contiguous to the Trinity-San Jacinto estuary system provide terrestrial and aquatic habitat for many species of wildlife including the endangered American alligator, the whooping crane, the Atlantic ridley turtle, the brown pelican, and the Houston toad. Wildlife resources of the area enhance the opportunities for sightseeing, nature studies, and esthetic benefits accruing to the naturalists. In addition, more than 149 thousand acres of marshland are available to outdoor sportsmen for hunting opportunities. These marsh areas support populations of migratory game birds for the hunting esthusiasts.

The Trinity-San Jacinto estuary has historically been the overall leading fisheries resource base in Texas. The annual commercial bay harvest of finfish and shellfish in this estuary has averaged 8.9 million pounds (4.1 million kg; 96.1 percent shellfish) during the 1962 through 1976 interval. However, a large portion of each estuary's production of fish and shellfish is caught in the Gulf by commercial and sport fishermen. When these harvests are considered, the total contribution of the estuary to the Texas coastal fisheries (all species) is estimated at 46.7 million pounds (21.2 million kg; 87.4 percent shellfish) annually for a recent five year period (1972-1976). Penaeid shrimp species dominate the shellfish harvests.

Total economic impact of the estuary's commercial fish and shellfish harvests on the State are estimated at $185.9 million per year, using an input-output analysis and 1976 dollar values. Similarly, the estuary's total sport and recreational fishing impact on Texas is estimated at $13.4 million annually.

Hydrology

Sources of freshwater inflow to the Trinity-San Jacinto estuary include gaged inflows from the contributing rivers and streams; ungaged runoff; return flows from municipal, industrial and agricultural sources; and precipitation on the estuary. To acquire accurate inflow measurements, gaged stream flows require adjustment to reflect any withdrawals or return flows downstream from gage locations. Ungaged runoff is estimated by computerized mathematical models using field data for calibration and verification. Rainfall is estimated as a distance-weighted average of the daily precipitation recorded at weather stations surrounding the estuary.

Freshwater inflows in terms of annual and monthly average values over the 1941 to 1976 period varied widely from the mean as a result of recurrent drought and flood conditions. On the average, total freshwater inflow to the estuary is computed at 11.34 million acre-feet (14 billion m^3) annually.

In general, the water quality of gaged inflows to the estuary from the Trinity River is good. No parameters were found in violation of existing Texas stream standards. Inflows from Buffalo Bayou and other urban drainage ways, however, contain significant nutrient loadings. Studies of past water quality in and around the estuary have noted the occurrence of heavy metals in sediment samples. Locally, bottom sediment samples from the Trinity-San Jacinto estuary have exceeded the U. S. Environmental Protection Agency criteria for metals in sediment (prior to dredging) for arsenic, cadmium, copper, lead and zinc.

Circulation and Salinity

The movements of water in the shallow estuaries and embayments along the Texas Gulf Coast are governed by a number of factors, including freshwater inflows, prevailing winds, and tidal currents. An adequate understanding of mixing and physical exchange in these estuarine waters is fundamental to the assessment of the physical, chemical, and biological processes governing these important aquatic systems.

To fully evaluate the tidal hydrodynamic and salinity transport characteristics of estuarine systems using field data, the Texas Department of Water Resources developed digital mathematical models representing the important mixing and physical exchange processes of the estuaries. These models are designed to simulate the tidal circulation patterns and salinity distributions in shallow, irregular, non-stratified estuaries. The basic concept utilized to represent each estuary is the segmentation of the physical system into a grid of discrete elements. The models utilize numerical analysis techniques to simulate the temporal and spatial behavior of circulation and salinity patterns in an estuary.

To properly evaluate the transport of water and nutrients through a deltaic marsh, it is necessary to describe and compute estimates of the complex tidal and freshwater inflow interactions. A mathematical model based upon the physical laws of conservation of mass and momentum has been developed to simulate the passage of water and nutrients through the Trinity deltaic system. The computations are based upon use of a finite difference approximation to the equations which describe the governing physical relationships.

The marsh inundation model is applied to the Trinity River delta. The delta system is represented as a series of interconnected shallow channels which are subject to varying levels of inundation, depending upon the tidal and riverine flow rates. The representation of the Trinity River delta includes the non-tidally influenced flood plain of the Trinity River from the stream gages near Lost Lake and Lake Charlotte to the Wallisville levee.

The model coefficients for calibration of the hydrodynamic model reflecting each delta's hydraulic characteristics, were determined by simulating the flow conditions and water inundation depths in each delta, comparing them with actual observed conditions, and adjusting the coefficients until adequate agreement between observed and simulated conditions was achieved.

The numerical tidal hydrodynamic and salinity mass transport models were applied to the Trinity-San Jacinto estuary, with the model representation of the system including Galveston Bay, Trinity Bay, East Bay, West Bay, and numerous smaller bays, San Luis Pass and Bolivar Roads. The hydrodynamic and mass transport models were calibrated and verified for the estuary.

The extent of marsh inundation due to tidal and river floods in the Trinity River delta was investigated utilizing the verified inundation model for this system. The flooded surface area of the Trinity delta was determined under both high and low tidal amplitudes, for four typical floods which occurred on the Trinity River after the filling of Lake Livingston.

Statistical analyses were undertaken to quantify the relationship between freshwater inflows from the Trinity and San Jacinto Rivers and salinities from Trinity and Galveston Bays. Utilizing gaged daily river flows and observed salinities, a set of monthly predictive salinity equations was derived utilizing regression analyses for the indicated areas of the estuary. These equations predicted the mean monthly salinity as a function of the mean monthly freshwater inflow rate.

Nutrient Processes

The deltaic marshes are important sources of nutrients for the estuarine system. Periodic inundation events are natural and necessary in order for the deltaic marshes of the Trinity-San Jacinto estuary to deliver their potential nutrient materials (e.g., plant detritus) to the open waters of the bays. This will occur as a floodwave of freshwater moving across the delta sweeping decayed macrophytic and dried algal material out of the system. A sudden inundation event over the delta marshes, following a period of dry emersion, results in a short period of high nutrient release from the established vegetation and sediments. During periods of high river discharge and/or extremely high tides that immediately follow prolonged dry periods, the contribution of carbon, phosphorus, and nitrogen from the deltaic marshes to the estuarine system can be expected to increase dramatically.

Aerial photographic studies of the Trinity River delta have provided insight into on-going wetland processes. Dredging and diking have combined to reduce the extent of marsh flooding of the Trinity delta. The natural Trinity River deltaic wetland has been significantly modified by recent construction projects. Extensive over-grazing and drainage improvement of marsh areas adjacent to the estuary is resulting in the displacement of some native marsh vegetation. The direct loss of wetlands due to these activities will probably have an adverse impact on the food-chain productivity of the Trinity-San Jacinto estuary.

Primary and Secondary Bay Production

The community composition, distribution, abundance, and seasonality of the phytoplankton, zooplankton, and benthic invertebrates of the Trinity-San Jacinto estuary were employed as "indicators" of primary and secondary productivity. The estuarine communities identified are typical in that they were composed of a mixture of freshwater, marine, and endemic species (i.e., species restricted to the estuarine zone).

Seven phytoplankton divisions represented by 132 taxa were collected from Trinity Bay. A clear distinction in community composition was discovered between locations having significantly different salinity conditions.

A total of 70 zooplankton species representing nine phyla were identified. Correlation analysis revealed no significant relationships between zooplankton standing crops and freshwater inflows. However, these factors did exhibit a regulating influence on species composition, seasonal occurrence, and distribution of zooplankton in Trinity Bay as evidenced by comparing stations.

Six phyla represented by 72 benthic species were collected from Trinity Bay. Although not statistically correlated with inflows or salinity, the benthic community appears to be similarly influenced by these factors.

The phytoplankton, zooplankton, and benthic populations in any body of water respond to a combination of physical and chemical seasonal controlling factors. Thus, it is difficult to single out the influence of any one of these factors on the entire community. In Texas estuaries, there is always a collection of species which are capable of maintaining high standing crops, regardless of the salinity, as long as it is relatively stable over the species lifecycle, and provided that other physiological requirements for that particular species group are met. If freshwater inflow is decreased, either partially or totally, the community composition will generally shift toward the more marine forms.

Fisheries

Virtually all of the Gulf fisheries species are estuarine-dependent. Commercial inshore harvests (1962-1976) from bays of the Trinity-San Jacinto estuary rank first in shellfish and fourth in finfish of eight major Texas estuarine areas. In addition, the sport or recreational finfish harvest has been estimated at six times larger than the commercial finfish harvest in the estuary. For the 1972 through 1976 interval, the average annual sport and commercial harvest of fish and shellfish dependent upon the estuary is estimated at 46.7 million pounds (21.2 million kg; 87.4 percent shellfish).

Although a large portion of each Texas estuary's fisheries production is harvested offshore in collective association with fisheries production from other regional estuaries, inshore bay harvests are useful as relative indicators of the year to year variations in an estuary's surplus production. These variations are affected by the seasonal quantities and sources of freshwater inflow to an estuary through ecological interactions involving salinity, nutrients, food (prey) production, and habitat availability. The effects of freshwater inflow on the Trinity-San Jacinto estuary are also reflected in the offshore harvests of the penaeid shrimp fishery. Therefore, the fisheries species can be viewed as integrators of their environment's conditions and their harvests used as relative ecological indicators, insofar as they reflect the general productivity and 'health" of an estuarine ecosystem.

A time series analysis of the commercial bay fisheries landings (1962 through 1976) and the commercial offshore penaeid shrimp harvests (Gulf Area No. 18, 1959 through 1976) was undertaken to estimate the commercial harvests as functions of the seasonal freshwater inflows to the estuary. Regression equations derived in the analysis provide numerical estimates of the effects of variable seasonal inflows, contributed from the major freshwater sources, on the production of seafood organisms dependent on the estuarine ecosystem. The analysis also supports existing scientific information on the seasonal importance of freshwater inflow to the estuary. All significant inshore and offshore harvest responses to winter (January-March) inflow are estimated to be negative for increased inflow in this season. With exception of the inshore brown and pink shrimp component's positive response to Trinity delta inflow, all other significant inshore harvest responses are estimated to relate negatively to increased summer (July-August) inflow. Offshore all shrimp and brown and pink shrimp fisheries components also relate positively to increased summer inflow, but negatively to increased spring (April-June) inflow. However, offshore white shrimp and inshore red drum, oyster and blue crab harvests relate positively to increased spring season inflow. Significant harvest responses to increased autumn (September-October) inflow are positive, except for the negative responses of the oyster and brown and pink shrimp fisheries components. Increased late fall (November-December) inflow relates positively to several fisheries components (e.g., finfish, spotted seatrout, and red drum), but again is negatively related to oyster harvest.

Where the estimated seasonal inflow needs of the fisheries components are similar, the components reinforce each other; however, where components are competitive by exhibiting opposite seasonal inflow needs, a management decision must be made to balance the divergent needs or to give preference to the needs of a particular fisheries component. A choice could be made on the basis of which species' production is more ecologically characteristic and/or economically important to the estuary. Whatever the decision, a freshwater inflow management regime can only provide an opportunity for the estuary to be viable and productive because there are no guarantees for estuarine productivity based on inflow alone, since many other biotic and abiotic factors are capable of influencing this production. However, most of these other factors are largely beyond human control, whereas man's acivities can restrict freshwater inflows to the detriment of fish and wildlife resources.

Estimated Freshwater Inflow Needs

A methodology is presented which combines the analysis of the component physical, chemical and biological elements of the Trinity-San Jacinto estuary into a sequence of steps which results in estimates of the freshwater inflow needs for the estuary based upon specified salinity, marsh inundation and commercial fishery harvest objectives.

Monthly mean salinity bounds are established at locations in the estuary near the inflow points of the San Jacinto and Trinity River Basins. The upper and lower limits on monthly salinity provide a salinity range within which viable metabolic and reproductive activity can be maintained and normal historical salinity conditions are observed.

Marsh inundation needs, for the flushing of nutrients from riverine marshes into the open bays, are computed and specified for the Trinity River delta. The San Jacinto River delta is limited in areal extent and far smaller than the Trinity delta. As a result, no inflow requirements for inundation of the San Jacinto River delta are specified from the San Jacinto River Basin. The Trinity River delta is frequently submerged by floods from the Trinity River. Based upon historical conditions and gaged streamflow records, freshwater inflow needs for marsh inundation are estimated and specified at 750 thousand acre-feet (924 million m^3) in each of the months April, May and October. These volumes correspond to flood events with peak flow rates of 29,500 ft^3/sec (836 m^3/sec).

Evaluation of Estuarine Alternatives

Estimates of the freshwater inflow needs for the Trinity-San Jacinto estuary are computed by representing the interactions among freshwater inflows, estuarine salinity, and fisheries harvests within an Estuarine Linear Programming Model. The model computes the monthly freshwater inflows from the San Jacinto and Trinity River Basins which best achieve a specified objective.

The monthly freshwater inflow needs for the Trinity-San Jacinto estuary were estimated for each of the three following alternatives:

Alternative I (Subsistence): minimization of the annual combined freshwater inflow while meeting salinity viability limits and marsh inundation needs;

Alternative II (Maintenance of Fisheries Harvest): minimization of annual combined freshwater inflow while providing predicted annual commercial bay harvests of red drum, spotted seatrout, shrimp, blue crab, and bay oysters at levels no less than their 1962 through 1976 mean values, satisfying marsh inundation needs, and meeting salinity viability limits; and

Alternative III (Shrimp Harvest Enhancement): maximization of the predicted offshore commercial harvest of shrimp (in Gulf Area No. 18) while meeting salinity viability limits, satisfying marsh inundation needs, and utilizing an annual freshwater inflow from each of the Trinity and San Jacinto River Basins at a level no greater than their individual average annual historical (1941-1976) inflows.

Under Alternative I (Subsistence), the Trinity-San Jacinto system, which has functioned as both a commercial shellfish and finfish producing system in the past, could continue to be an important fisheries producing estuary with substantially less freshwater inflow. Freshwater inflows totaling 6.85 million acre-feet (8,446 million m^3; 67 percent estimated from gaged areas) annually are predicted to satisfy the basic salinity gradient and marsh inundation needs, with resulting predicted increases in the combined commercial finfish and shellfish harvests of 16 percent, above average values for the period 1962 through 1976 (Figure 1-1).

Under Alternative II (Maintenance of Fisheries Harvests), the predicted annual commercial bay harvests of red drum, spotted seatrout, shrimp, blue crab and bay oysters are required to be at least as great as historical (1962-1976) average levels. The marsh inundation needs and salinity bounds must also be satisfied. To satisfy these criteria, an annual freshwater inflow of 7.19 million acre-feet (8,865 million m^3; 68 percent from gaged areas) is needed (Figure 1-1). The predicted combined finfish and shellfish annual commercial harvest (offshore shrimp included) for this Alternative is approximately 16 percent higher than the historical average.

Under Alternative III (Shrimp Harvest Enhancement), the Trinity-San Jacinto estuary's annual freshwater inflow needs are estimated at 7.02 million acre-feet (8,656 million m^3; 68 percent from gaged areas), distributed in a seasonally unique manner, to achieve the objective of maximizing the annual predicted commercial harvest of shrimp in the offshore area (Gulf Area No. 18) adjacent to the estuary (Figure 1-1). Annual inflows from the San Jacinto River Basin are limited by the average annual 1941 through 1976 historic inflow from the basin, thus indicating that some additional inflow from the basin would enhance the harvest. Annual inflow need from the Trinity River Basin, however, was 40 percent less than the historical (1941-1976) mean. The objective of harvest enhancement is achieved with a predicted 15 percent increase over the mean 1959 through 1976 harvest of penaeid shrimp in offshore Gulf Area No. 18, and an equal percentage gain in the total commercial shellfish and finfish harvest (inshore fisheries included) (Figure 1-1).

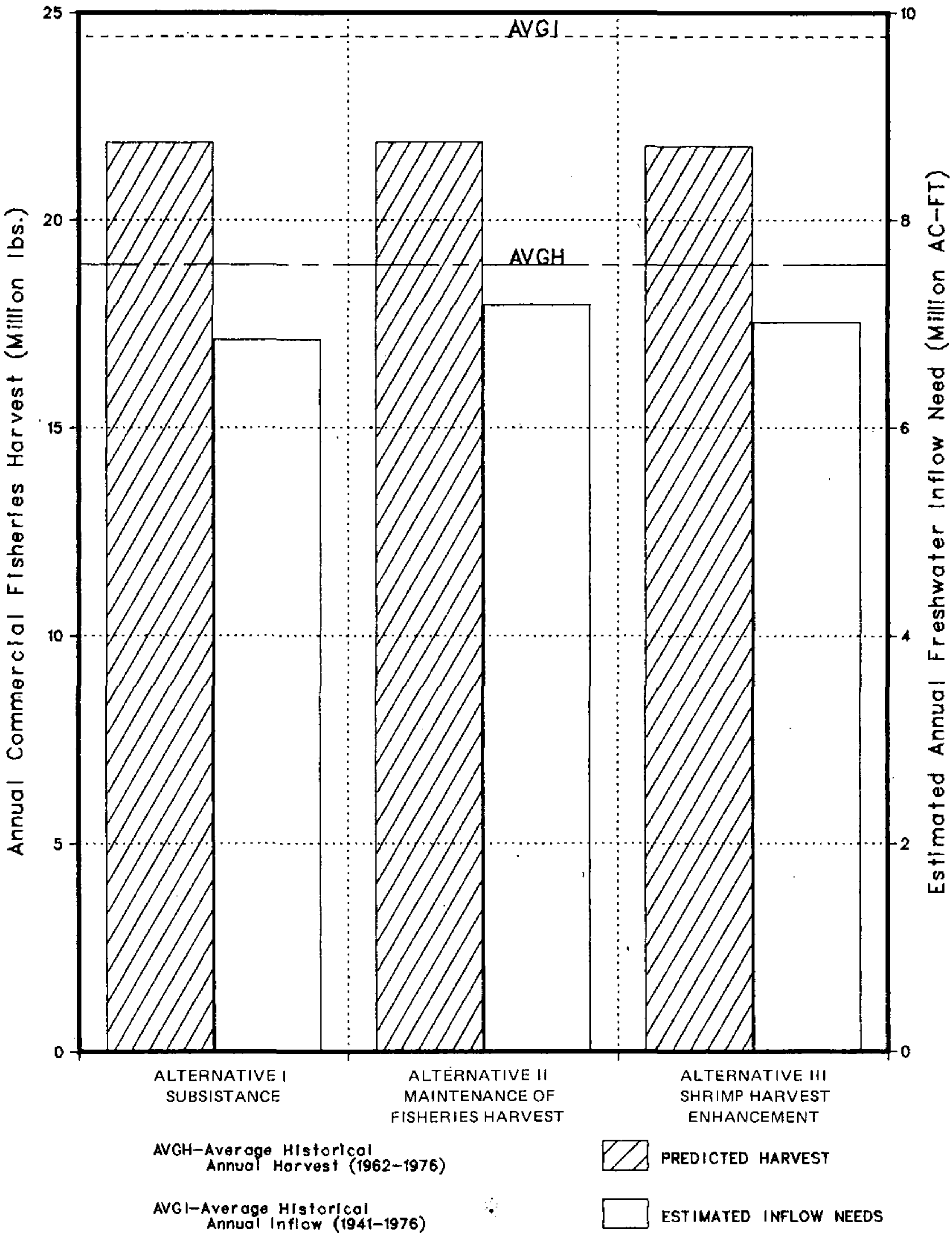


Figure 1-1. Predicted Annual Commercial Fisheries Harvest and Estimated Inflow Needs Under Three Alternatives for the Trinity-San Jacinto Estuary

The monthly distribution of the inflow needs for each of the Alternatives and the average historical monthly freshwater inflows for the period 1941 through 1976 are given in Figure 1-2.

Estuarine Circulation and Salinity Patterns

The numerical tidal hydrodynamic and salinity mass transport models were applied to the Trinity-San Jacinto estuary to determine the effects of the estimated freshwater inflow needs for Alternative I[1/] upon the average monthly net flow circulation and salinity characteristics of the estuarine system. The monthly simulations utilized typical tidal and meteorological conditions observed historically for each month simulated.

The net circulation patterns simulated by the tidal hydrodynamic model indicate that the dominant simulated current in Galveston Bay is a net water movement along the Houston Ship Channel. This dominant current influences circulation in the other areas of Galveston Bay. The simulated net water movements in Trinity, East, and West Bays were generally dominated by internal circular currents. The simulated monthly circulation patterns indicated that the currents in the Trinity-San Jacinto estuary are wind dominated.

The simulated salinities in the Trinity-San Jacinto estuary for the estimated monthly freshwater inflow needs under Alternative I vary over a wide range. Salinities throughout the estuary are lowest in the month of May, with average simulated salinities of less than 20 parts per thousand (ppt) over the entire estuary except near San Luis and Bolivar Passes. The highest levels of simulated salinities occur during the month of August, when salinities in Galveston Bay near Bolivar Pass exceed 30 ppt. The simulated salinities for Trinity Bay are generally less than 15 ppt throughout the year. The major portion of Galveston Bay has simulated salinities of between 15 and 20 ppt; however, during the high freshwater inflow months of April and May, the salinities in the bay are between 10 and 15 ppt.

Since the middle portion of Galveston Bay has simulated salinities in all months below a target maximum allowable concentration of 20 ppt, the freshwater inflow needs established by the Estuarine Linear Programming Model would be adequate to sustain the salinity gradients specified, within the objectives, throughout the estuary.

The estimated monthly freshwater inflow needs derived in this report are the best statistical estimates of the monthly inflows satisfying specified objectives for commercial fisheries harvest levels, marsh inundation and salinity regimes. These objectives cover a range of potential management policies.

A high level of variability of freshwater inflow occurs annually in Texas estuaries. Fluctuations in inflows are expected to continue for any average level of inflow into the estuary which may be specified. Some provision should be made, however, in any estuarine management program to prevent an increase (over historical levels) in the frequency of low inflows detrimental to the estuarine-dependent organisms.

1/ The alternative having the lowest inflow level and thus the alternative that would impinge most heavily upon salinities.

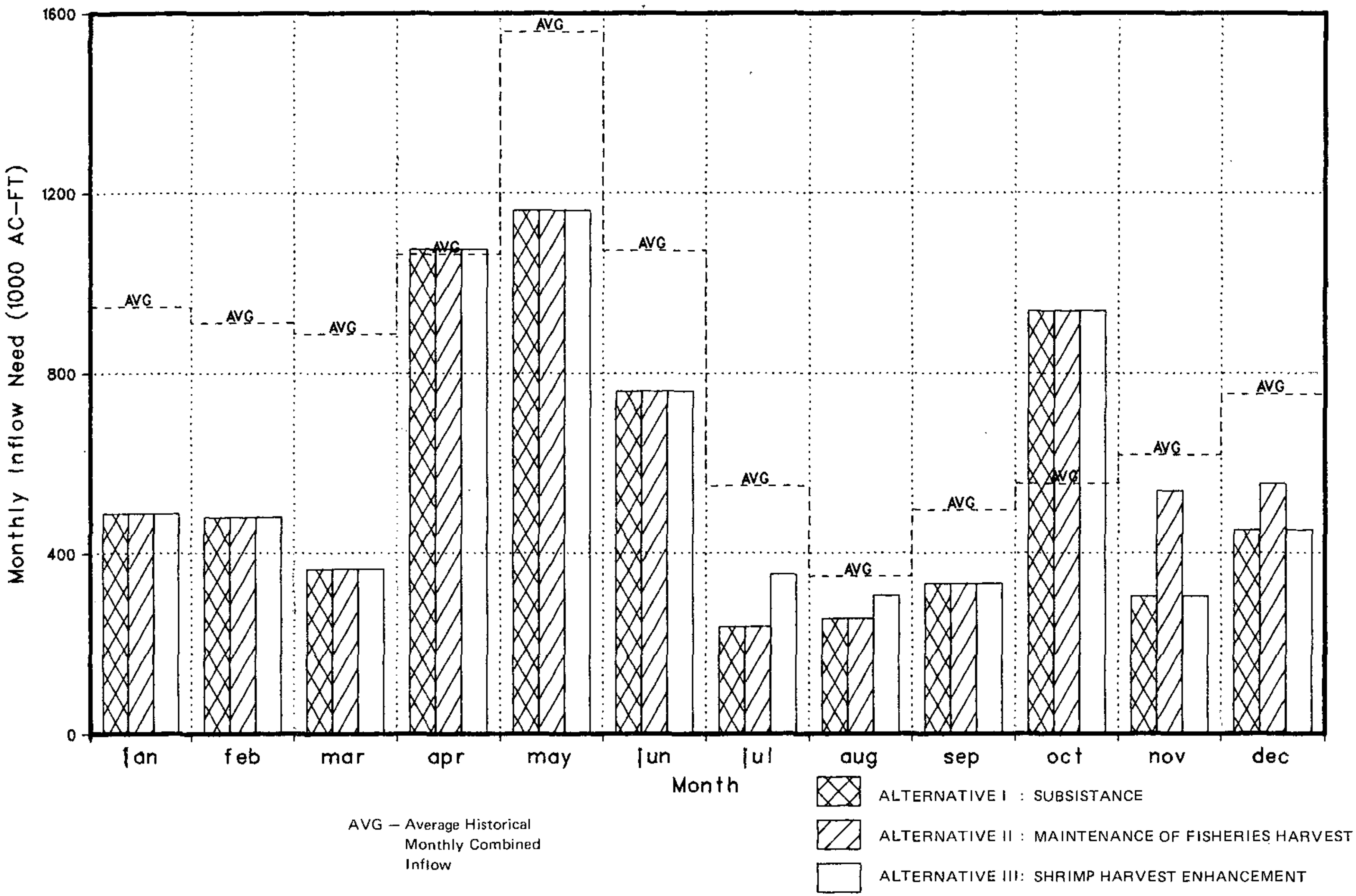


Figure 1-2. Estimated Monthly Freshwater Inflow Needs for the Trinity-San Jacinto Estuary Under Alternatives I, II, III

CHAPTER II

CONCEPTS AND METHODS FOR DETERMINING THE INFLUENCE OF FRESHWATER INFLOWS UPON ESTUARINE ECOSYSTEMS

Scope of Study

Senaté Bill 137 (64th Texas Legislature) mandates a comprehensive study of environmental variables, especially freshwater inflow, which affect Texas estuarine ecosystems. This report presents the results of the studies of the Trinity-San Jacinto estuary. In succeeding chapters, biotic and abiotic factors are conceptually related, enabling the use of numerical analysis for the identification of maintenance needs. Many estuarine maintenance needs are directly related to freshwater inflow and associated quality constituents. In some cases, these needs may be exceeded in importance by the basic availability of substrate and/or habitat in the ecosystem.

Fundamental to these discussions is the concept of seasonal dynamics; that is, the environmental needs of an estuarine ecosystem are not static annual needs. In fact, dynamic equilibrium about the productive range is both realistic and desirable for an estuarine environment. Extended periods of inflow conditions which consistently fall below maintenance levels can, however, lead to a degraded estuarine environment, loss of important "nursery" functions for estuarine-dependent fish and shellfish resources, and a reduction in the potential for assimilation of organic and nutritive wastes. During past droughts, Texas estuaries severely declined in their production of economically important fishery resources and began to take on characteristics of marine lagoons, including the presence of starfish and sea urchin populations (199). Chapter II and succeeding chapters will address a broad range of estuarine concepts; emphasis is placed primarily on those concepts germane to the discussion of freshwater inflow needs of the Trinity-San Jacinto estuary.

Estuarine Environment

Introduction

The bays and estuaries along the Texas Gulf Coast represent an important economic asset to the State. The results of current studies carried out under the Senate Bill 137 mandate will provide decision makers with important information needed in order to establish plans and programs for each of the State's major estuarine systems.

Physical and Chemical Characteristics

Topography and Setting. A Texas estuary may be defined as the coastal region of the state from the tidally affected reaches of terrestial inflow sources to the Gulf of Mexico. Shallow bays, tidal marshes, bayous, creeks and other bodies of water behind barrier islands are included under this definition. Estuarine systems contain sub-systems (e.g., individuals bays), lesser but recognizable units with characteristic chemical, physical and biological regimes. Primary, secondary, and tertiary bays, although interrelated, all require study for proper understanding and management of the complete system.

The primary bay of an estuary is directly connected to the Gulf of Mexico. This area of the estuary is generally saline (seawater) to brackish, depending upon the proximity to areas of exchange between the bay and Gulf waters. Secondary bays empty into the primary bay of an estuary and are thus removed from direct flow exchange with the Gulf. In secondary bays, the salinities are usually lower than the primary bay. In terms of energy input to the estuarine systems, the most productive and dynamic of estuarine habitats are the tertiary bays. Tertiary bays are generally shallow, brackish to freshwater areas where sunlight can effectively penetrate the water column to support phytoplankton, benthic algae, and other submerged vegetation. Substantial chemical energy is produced in these areas through photosynthetic processes. These nutritive biostimulants are distributed throughout the estuarine system by inflow, tides, and circulation.

Texas has about 373 miles (600 kilometers) of open-ocean or Gulf shoreline and 1,419 miles (2,290 kilometers) of bay shoreline, along which are located seven major estuarine systems and three smaller estuaries (Figure 2-1). Eleven major river basins, ten with headwaters originating within the boundaries of the state, have estuaries of major or secondary importance. These estuarine systems have a total open-water surface area of more than 1.5 million acres (607,000 hectares) with more than 1.1 million acres (445,000 hectares) of adjacent marshlands and tidal flats (480). Physical characteristics of the Trinity-San Jacinto estuary are described in Chapter III.

Hydrology. A primary factor distinguishing an estuary from a strictly marine environment is the input of freshwater from various sources. Sources of freshwater inflow to Texas estuaries include: (1) gaged inflow (as measured at the most downstream flow gage of each river system), (2) ungaged runoff, and (3) direct precipitation on the estuary's surface.

The measurement of each of these sources of freshwater inflow is necessary to develop analytical relationships between freshwater inflow and resulting changes in the estuarine environment. Gaged inflow is the simplest of the three sources to quantify; however, gaged records do require adjustment to reflect any diversions or return flows downstream of gage locations.

Computation of ungaged inflow requires utilization of a variety of analytical techniques, including computerized mathematical watershed models, soil moisture data, and runoff coefficients developed from field surveys. Direct precipitation on an estuary is assumed to be a distance-weighted average of the daily precipitation recorded at weather stations in the coastal regions adjacent to each bay.

The hydrology of the Trinity-San Jacinto estuary is described in Chapter IV.

Water Quality. The factors which affect the water quality of aquatic ecosystems and their importance to the various biological components include nutrients, such as nitrogen and phosphorus; the basic cellular building block,

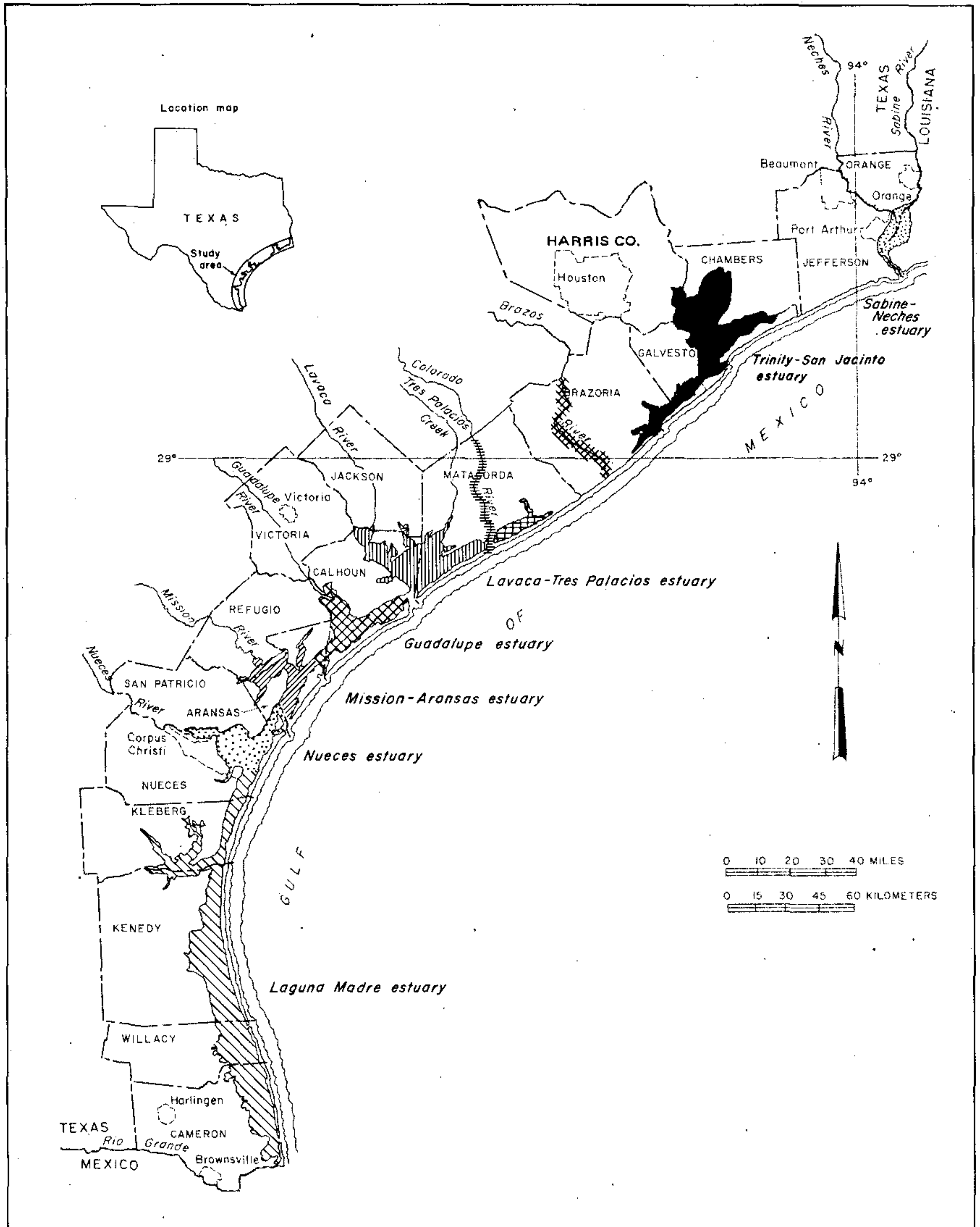


Figure 2-1. Locations of Texas Estuaries

Base from Official State Highway Map of Texas, 1971 carbon; trace elements necessary for biological growth; the presence of sufficient concentrations of dissolved oxygen for respiration of aerobic organisms; and the occurrence of toxic chemicals that may inhibit growth and productivity. (Figure 2-2). The presence of pollutants can have significant impacts upon estuarine water quality. Economic and business development activities may result in changes to the physical and chemical quality of the runoff. Waste loads which enter the aquatic ecosystem can be of several types, including predominantly municipal and industrial effluent and agricultural return flow. The presence of toxic chemicals can have a detrimental impact upon the quality of estuarine waters and the indigenous aquatic ecosystem.

Water quality considerations are discussed in Chapter IV and Chapter VI.

Biological Characteristics

An estuarine ecosystem comprises a myriad of life forms, living interdependently, yet all dependent on the "health" of the aquatic environment. Among the general groupings of life forms that occur in the estuary, the most prominent are bacteria, phytoplankton (algae), vascular plants (macrophytes), zooplankton, benthic infauna, shellfish and finfish.

Salinity, temperature, and potentially catastrophic events (e.g., hurricanes) are factors that largely control and influence species composition in these ecosystems. While the number of species generally remains low, numbers of organisms within a single species may be high, fluctuating with the seasons and with hydrologic cycles (212, 77, 207). The fluctuating conditions provide for a continuing shift in dominant organisms, thereby preventing a specific species from maintaining a persistent dominance.

Natural stresses encountered in an estuarine ecosystem are due, in part, to the fact that these areas represent a transition zone between freshwater and marine environments. Biological community composition changes, with respect to the number of species and types of organisms, when salinity is altered (Figure 2-3). The number of species is lowest in the estuarine transition zone between freshwater and marine environments. The species composition of a community may vary taxonomically from one geographic locality to another; however, most species have a wide distribution in Texas bays and estuaries.

Biological aspects of the Trinity-San Jacinto estuary are described in detail in Chapters VII and VIII.

Food Chain. To evaluate the effects of freshwater inflow on an estuary, it is necessary to consider the significant interactions among dominant organisms for each of the estuary's trophic (production) levels. A complicated food web consisting of several food chains exists among the trophic levels of an estuarine ecosystem, with water the primary medium of life support (44, 164, 46, 112, 187, 240). The aquatic ecosystem can be conceptualized as comprising four major components, all interrelated through various life processes (Figure 2-2):

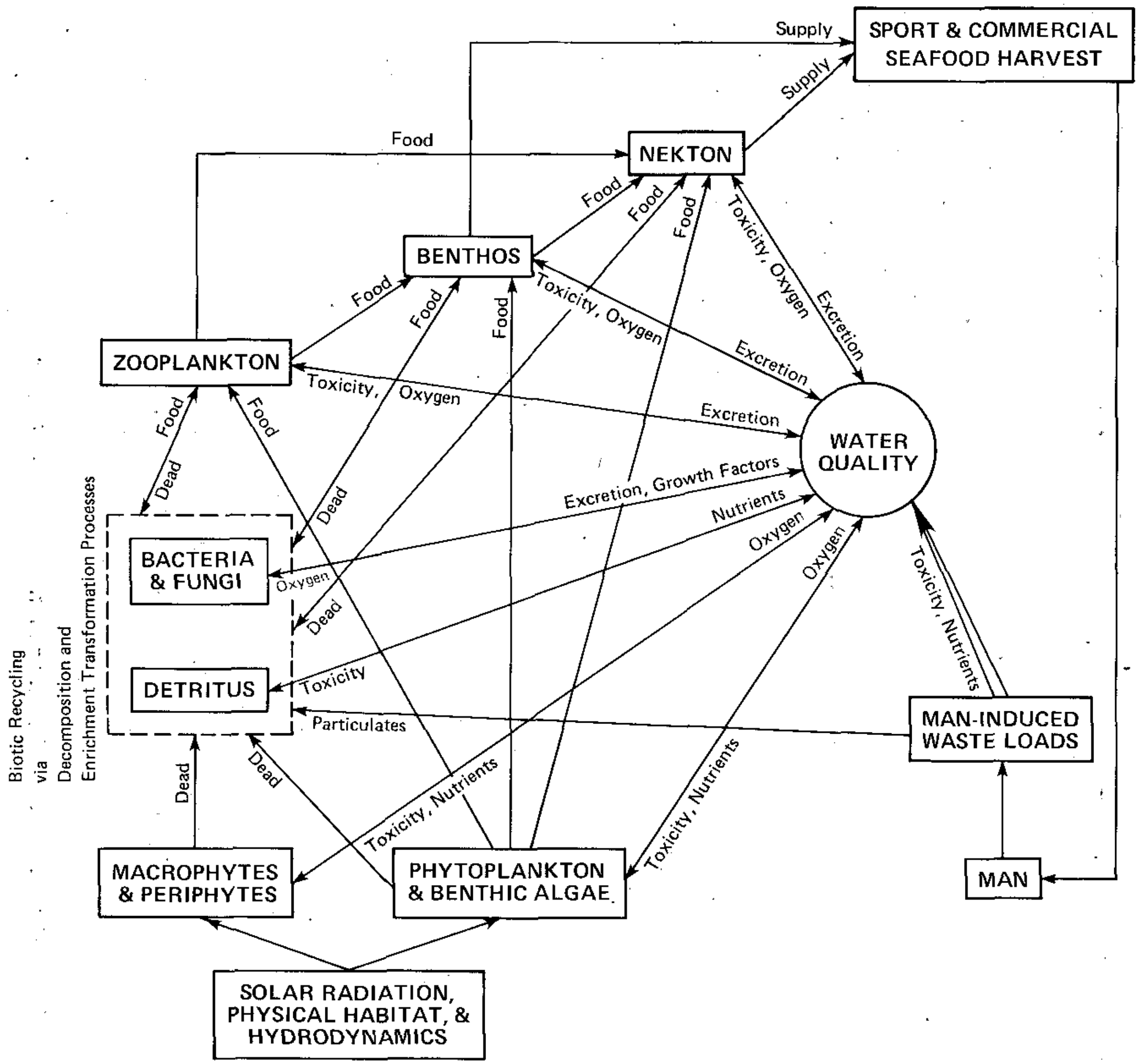


Figure 2-2. Component Schematic Diagram of a Generalized Texas Estuarine Ecosystem.

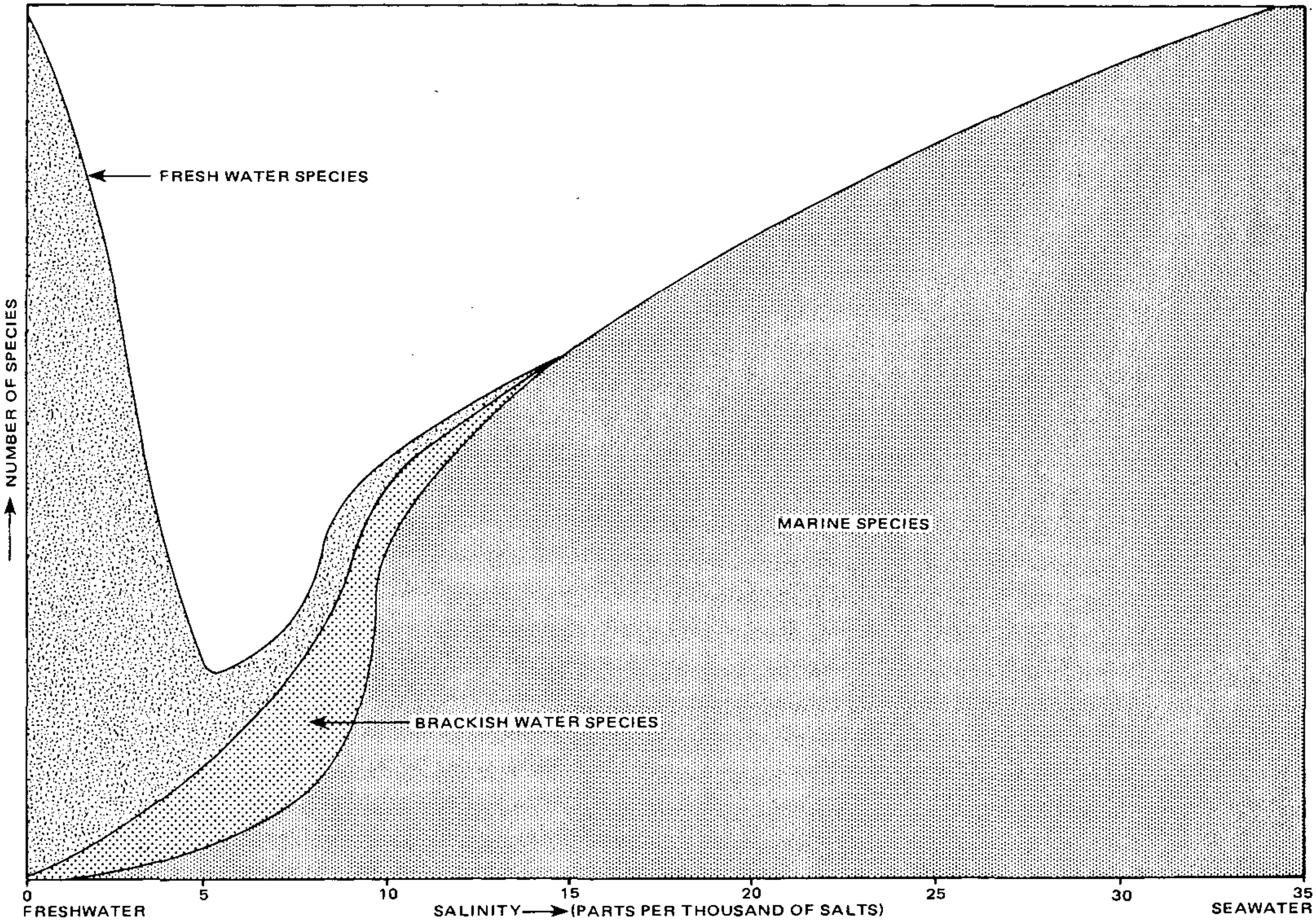


Figure 2-3. Species Composition of Estuarine Environments (212)

1. Chemical parameters including basic substances essential to life such as carbon dioxide (CO_2), nitrate (NO_3), ammonia (NH_3), phosphate (PO_4), and dissolved oxygen (DO),
2. Producers including autotrophic organisms such as vascular plants and algae that can transform basic substances into living cellular material through utilization of sunlight by photosynthesis,
3. Consumers (herbivores, omnivores, and predators) including heterotrophic organisms such as zooplankton, shellfish, and fish species that utilize other biota as basic food material, and
4. Decomposers including bacteria in both liquid and solid (sediment) phases and fungi.

The trophic relationships occurring in an estuarine system typical of those along the Texas Gulf Coast are large in number and complex in scope (Figure 2-4). The river inflow provides a major source of nutrients and organic materials, both of which contribute to supporting the extensive populations of omnivore and filter feeding species which dominate the lower trophic levels of the system. Exact quantitative relationships among the estuarine organisms and the aquatic environment are extremely complex and many are still unknown.

Life Cycles. Many organisms of estuarine systems are not permanent residents, in that they spend only part of their life cycle in the estuary. Migration patterns constitute an integral part of the life history of many estuarine-dependent species (218). These migrations occur in seasonal cycles and most are involved with spawning (reproduction). Larval and postlarval organisms may migrate into the estuary because of food and physiological requirements for lowered salinity (139, 534), and/or for protection against predators and parasites (144, 197). Juvenile forms use the shallow "nursery" areas during early growth (92), migrating back to the Gulf of Mexico in their adult or subadult life stage.

For high marsh productivity to occur, the timing of freshwater inflow, inundation (irrigation) of marshes, and nutrient stimulation (fertilization) of estuarine plants must coincide with the subtropical climatic regime of the Gulf region. Nature's seasons provide environmental cues, such as increases or decreases in salinity and temperature, that enable estuarine-dependent species to reproduce and grow successfully in the coastal environments. These species have adapted their life cycles to the natural schedule of seasonal events in the ecosystem and also to reduce competition and predation. Coincidence of seasonal events, such as spring rains, inundation of marshes and increased nutrient cycling is made more complex by both antecedent events and ambient conditions. For example, winter inundation and nutrient stimulation of marshes may not be as beneficial to the estuarine system as similar events in the spring because low winter temperatures do not support high biological activity. Consequently, the growth and survival of many economically important seafood species will be limited if antecedent events and ambient conditions are unfavorable and far from the seasonal optimum. Further, the entire ecosystem can lose productivity through disruption of energy flow and become altered by slight, but chronic stresses (547).

Virtually all (97.5%) of the Gulf fisheries species are considered estuarine-dependent (93); however, the seasonal aspects of their life cycles are quite different. Some species, such as the redfish, spawn in the fall and the young are particularly dependent on migration to and utilization of the

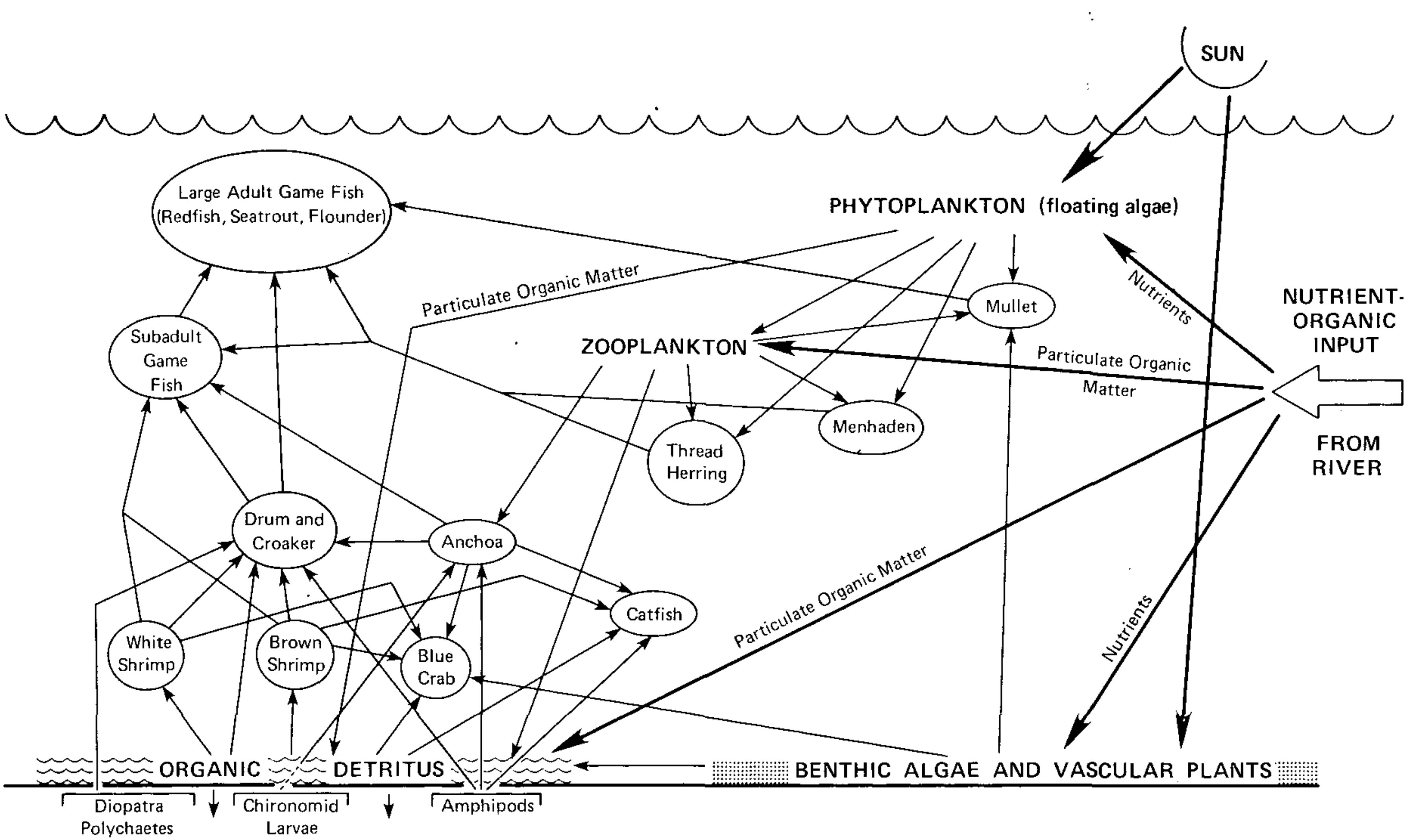


Figure 2-4. Simplified Trophic Relationships in a Texas Estuary [After WRE (540)]

"nursery" habitats during this season. Others, such as the penaeid shrimp, spawn primarily in the spring and early summer, and their young move inshore to shallow, low salinity estuarine areas for growth and development at this time. Not all estuarine-dependent species are migratory between the marine and estuarine environments; however, there are few true year-round residents (e.g., bay oysters) capable of completing their life cycle totally within the estuary (179).

Habitat. The marsh wetlands adjacent to each Texas estuary are among the most important areas of the estuarine ecosystems. They may be characterized as tracts of soft, wet land located adjacent to or near the bay margins and along the channels of inflowing drainages, such as a river mouth with its associated delta. Depending upon the specific location, estuarine marsh communities may be frequently inundated by tidal fluctuations or only occasionally inundated by the seasonal flooding of inflowing streams. Texas estuarine marshes are dominated by salt-tolerant vegetation, such as the cord grass Spartina, which produces significant quantities of organic material (i.e., detritus) that forms the base of the trophic structure (foodweb) and provides input to the productivity in higher trophic levels (fish, shrimp, oysters, etc.). Vascular plant production of several delta marshes along the Texas Gulf Coast has been measured at about 100 million pounds dry weight per year (or 45,500 metric tons/yr) each, with production exceeding 15,000 dry weight lbs/acre/year (or 1,680 $g/m^2/yr$) in the most productive areas (54). Throughout the world, only tropical rain forests, coral reefs, and some algal beds produce more abundantly per unit of area (187, 343).

Marsh production has been shown to be a major source of organic material supporting the estuarine food web in coastal areas from New England to the Gulf of Mexico (40, 112, 163). Because of high plant productivities an estuarine marsh can assimilate, if necessary, substantial volumes of nutrient-rich municipal and industrial wastes (530, 531) and incorporate them into the yield of organic material which supports higher trophic level production, such as fishery species. Such high food density areas serve as "nursery" habitats for many economically important estuarine-dependent species, as well as providing food and cover for a variety of water fowl and mammals. Delta marshes may serve other beneficial functions acting as a temporary floodwater storage area and/or aiding in erosion control by absorbing potentially destructive wave energy.

Relationships between productivity and habitat are discussed in Chapters VI, VII, and VIII.

Summary

Texas has seven major estuarine systems and several smaller estuaries that are located along approximately 373 miles (600 km) of coastline. These estuarine systems have a total open-water surface area of more than 1.5 million acres (607,000 ha), including many large shallow bays behind barrier islands. At least 1.1 million acres (445,000 ha) of adjacent marshes, tidal flats, and bayous provide "nursery" habitats for juvenile forms of marine species and produce nutrients for the estuarine systems.

The ecosystems which have developed within these estuaries are in large part dependent upon the amount, as well as the seasonal and spatial distribution of freshwater inflow and associated nutrients. Freshwater flows enter the bays from rivers and streams and from local rainfall runoff. Freshwater dilutes the saline tidal water of the Gulf and transports nutritive and sedimentary building blocks that maintain marsh environments and contribute to estuarine production of fish and shellfish.

The health of estuarine aquatic organisms is largely dependent upon water quality. Pollutants and toxic materials create physiological (metabolic) stresses that can inhibit reproduction and growth, and may have long-lasting effects on the estuary.

An estuarine ecosystem is a complex interrelationship of abiotic and biotic constitutents. Basic inorganic elements and nutrients are assimilated by primary-producer organisms, such as algae. These organisms in turn are consumed by predators in higher trophic levels. Organic material is made available for reuse in the ecosystem by decomposers, such as bacteria and fungi.

Many species inhabiting Texas estuaries are not permanent residents. Juveniles enter the estuary in larval or postlarval forms and remain during early growth. Fish and shellfish species, in particular, may have migratory life cycles, with the adults spawning in the Gulf of Mexico and juveniles migrating to the estuaries.

Estuarine wetlands and river deltas are the most important habitat areas for juvenile forms of many aquatic species. These marsh systems contribute nutrients to the estuaries while providing nursery habitats for many species of estuarine organisms.

Evaluation of Individual Estuarine Systems

Introduction

In order to better understand the basic relationships among the numerous physical, chemical and biological factors governing Texas estuarine systems, and the importance of freshwater to these systems, the Texas Department of Water Resources has conducted studies on the effects of freshwater inflow on nutrient exchange, habitat maintenance, and production of living organisms. Technical methods developed and used in these studies are described in this report. These methods were developed to quantitatively express (1) the inundation/dewatering process of river delta marshes, (2) the biogeochemical cycling and exchange of nutrients, (3) the estuarine salinity gradient, and (4) the production of fisheries. Mathematical models have been developed for high-speed computers using data collected from each estuarine system. These computer techniques allow the analyst to rapidly simulate (1) the hydrodynamics of river deltas, (2) the tidal hydrodynamics of the bay systems, and (3) the transport of conservative constituents (salinity) within the estuaries. These mathematical simulation techniques have quantified, insofar as possible at this time, the interrelationships among physical, chemical, and biological parameters that govern the productivity within these systems.

Mathematical Modeling

The concept of mathematical modeling is fundamental to understanding the techniques utilized in this study for evaluation of freshwater inflow effects upon an estuary. In general, a mathematical model is a specific set of mathematical relationships describing real-world relationships of a system or its component parts, be that system physical, economic or social. A mathematical model (representation of a prototype system) may undergo several stages of development and refinement before it is found to be a satisfactory descriptive and predictive tool of a particular system. A rigorous data acquisition program must be undertaken to gather sufficient information to test and apply the model. A simplified flow diagram of the model development and application process is presented in Figure 2-5.

Model development begins with problem conception. The governing equations for each aspect of the problem are constructed to form a congruous system of equations that can be solved by the application of ordinary solution techniques. The governing equations are then coded into algorithmus, data input and output requirements are determined, and the necessary computer files are created.

Several independent sets of input and output data, as prescribed by the formulation and construction steps, must be acquired and prepared in proper format. The data should be of sufficient spatial extent and temporal duration to insure coverage of all anticipated boundary conditions and variations.

Calibration of the model consists of its application utilizing one or more of the input data sets, followed by comparison of the simulated model responses with the corresponding observed real-world conditions. Adjustment of the input equation coefficients may be necessary until the simulated and observed responses agree within appropriate predetermined tolerances.

Once a model has been satisfactorily calibrated, an independent set of input values (not previously used in the calibration process) should be used to simulate a new set of response values. A comparison of the simulated responses with the observed data should yield close agreement. Close agreement within predetermined tolerance levels indicates model "validation". It is then possible to simulate conditions for which comparative response data are not currently available, with a high degree of confidence over the range of conditions for which the model has been calibrated and validated. However, a calibrated model that has not been validated in the manner described here may still give a reasonable simulation; but the degree of response confidence is less. The computer model, if properly applied and its output judiciously interpreted, can be a valuable analytical tool.

The mathematical models used to evaluate the hydrology and salinity of the Trinity-San Jacinto estuary are described in detail in Chapter V.

Key Indicators of Estuarine Conditions

The large number of complex interactions of physical, chemical, and biological parameters make it difficult to completely define the interrelationships of an estuarine ecosystem. Major environmental factors and identifiable biological populations can be used, however, as "key indicators" to understand

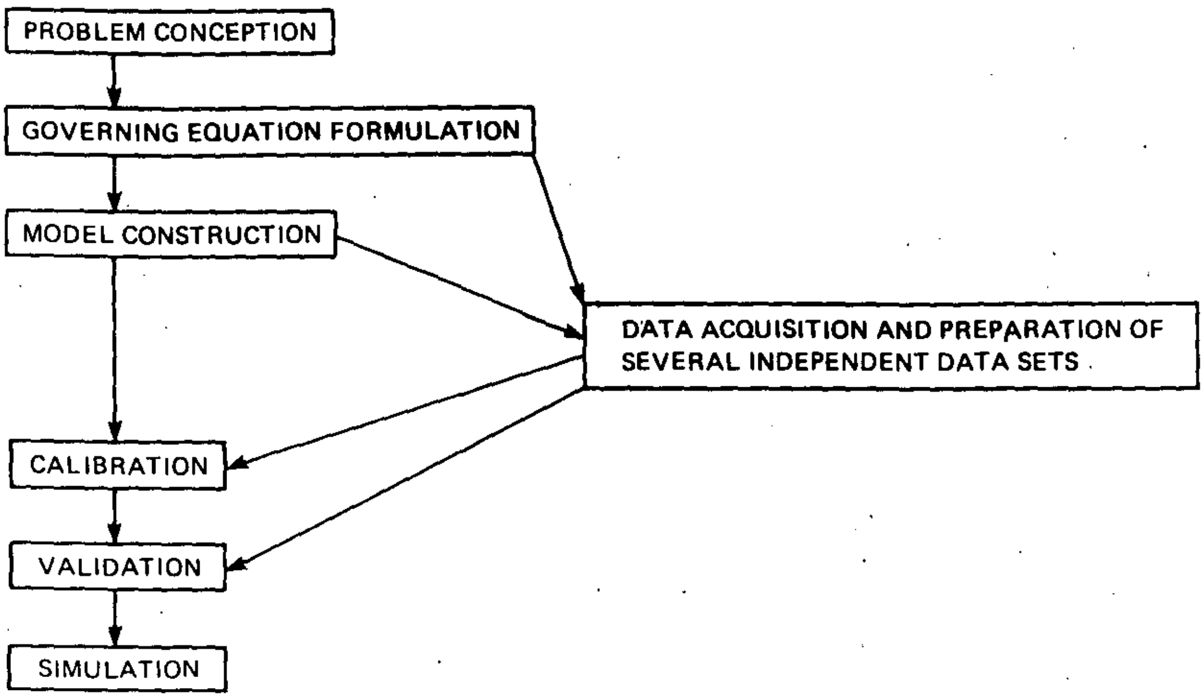


Figure 2-5. Flow Diagram of Model Development

and demonstrate the response of higher food chain organisms, such as shellfish and finfish, to major changes in the ecosystem (233, 187). Physical and chemical constituents of prime importance to the estuarine ecosystem include freshwater inflow, circulation and salinity patterns, and nutrients. Chapters IV, V and VI quantify each of these factors to assess their relationship in estuarine productivity.

Physical and Chemical Indicators. (1) Freshwater Inflow. Freshwater is one of the most important environmental parameters influencing estuarine systems. Freshwater inflows serve the following major functions:

1. Salinity gradient control,
2. Transport of sedimentary and nutritive building blocks, and
3. Inundation of the deltaic marshes.

Salinity gradients throughout an estuary are directly related to the quantity of freshwater inflow; freshwater decreases salinities near an inflow point, while salinities at points further away are influenced only gradually with time. Salinities in the estuaries are determined by balance among several factors, including freshwater inflow, tidal exchange and evaporation.

Freshwater inflow also transports sediments and nutrients into the estuarine system. During flood stage, many square miles of marsh habitat are inundated and inorganic nutrients deposited in the marsh. These nutrients are converted to an organic state by primary production and bacteriological action and then drawn into the overylying water column. The subsidence of the floodwaters and the subsequent dewatering of the marshes results in the movement of organic nutrients from the marsh into the nearby tertiary and secondary bays. However, large volumes of freshwater inflow can also be detrimental, depressing biological productivity and flushing even the primary bay of an estuarine system. Flood events may resuspend and transport sediments, increasing turbidity and causing a rapid decrease in the standing crop of phytoplankton, zooplankton, benthos and fisheries populations. The period of time necessary for recovery of the estuarine system after such an event is governed by variables such as season of the year, temperature, food availability and subsequent freshwater inflows.

(2) Critical Period. An understanding of the concept of "critical period" is necessary in order to understand the importance of freshwater inflow to Texas estuarine systems (117, 175). There are basically two types of critical periods that must be considered--long term and seasonal. The first, or more general type, is that resulting from extended years of drought with extreme low freshwater inflow, creating stressful or lethal conditions in the estuary. A second type of critical period occurs on a seasonal basis, whereby lowered freshwater inflow affects the growth and maturation of delta marsh habitats, the utilization of "nursery" areas by juvenile fish and shellfish, and the transport of sediment and nutritive substrate materials (especially detritus) to the estuary.

Long-term critical periods of multi-year droughts affect entire estuarine systems, while short-term critical periods relate to habitat-specific or species-specific seasonal needs. Where seasonal needs conflict between estuarine-dependent species and limited freshwater is available for distribution to an estuary, a management decision may need to be made to give preference to selected species. This decision could be made on the basis of historical dominance of the system by one or more species, that is, whether the estuarine system has historically been a finfish or a shellfish producing area.

The physical characteristics of each estuarine system are a reflection of long-term adaptations to differing salinity, nutrient, and sedimentary balances. Among such distinctive characteristics are bay size, number and size of contributing marshes, extent of submerged seagrass communities, species diversity, and species dominance. The timing of freshwater inflows can be extremely important, since adequate inflow during critical periods can be of greater benefit to ecological maintenance than abundant inflow during noncritical periods.

(3) Circulation. The movement of waters within an estuary largely determines the distribution of biotic and abiotic constituents in the system. To study the movement of estuarine waters under varying conditions, tidal hydrodynamic mathematical models have been developed and applied to individual Texas estuaries (173). Each model computes velocities and water surface elevations at node points of a computational grid superimposed on an estuary. Estuarine characteristics along any given vertical line (the water column) are assumed to be homogeneous.

The tidal hydrodynamic model takes into account bottom friction, submerged reefs, flow over low-lying barrier islands, freshwater inflow (runoff), any other inflows, ocean tides, wind, rainfall, and evaporation. The model may be used to study changes in erosion and sedimentation patterns produced by shoreline development and to evaluate the dispersion characteristics of waste outfalls. The primary output from the tidal hydrodynamic model is a time-history of water elevations and velocity patterns throughout the estuary. Output data are stored on magnetic tape for later use.

The tidal hydrodynamics model is described in detail in Chapter V.

(4) Salinity. A knowledge of the distribution of salinities over time at points throughout an estuary is vital to the understanding of environmental conditions within the system. To better assess the variations in salinity, a salinity transport mathematical model has been developed (173, 174) to simulate the salinity changes in response to dispersion, molecular diffusion and tidal hydrodynamics. This model is a companion model to the hydrodynamic model described previously.

The mass transport model is used to analyze the salinity distributions in shallow, non-stratified, irregular estuaries for various conditions of tidal amplitude and freshwater inflow. The model is dynamic and takes into account location, magnitude, and quality of freshwater inflows; changing tidal conditions; evaportion and rainfall; and advective transport and dispersion within the estuary. The primary output of the model is the tidal-averaged salinity change in the estuary due to variations in the above mentioned independent variables. This model, in conjunction with the tidal hydrodynamic model, can also be used to assess the effects of development projects such as dredging and filling on circulation and salinity patterns in an estuary.

In this study, relationships between inflow and salinity were established using the statistical technique of regression analysis. Regression analysis is a method of estimating the functional relationship among variables. The relative accuracy of such a predictive model, commonly measured in terms of the correlation coefficient, is dependent upon the correlation of salinities to inflow volumes. The statistical relationship between salinity and inflow can generally be represented as an reciprocal function (Figure 2-6). This functional form plots as a straight line on log-log graph paper.

The statistical regression models differ from the salinity transport model in that the transport model analyzes the entire estuary to a resolution of one nautical mile square, while each statistical model represents the salinity at only a single point in the estuary. These models compliment each other, however, since a statistical model is considered more accurate near a river's mouth and the salinity transport model provides better predicted salinities at points in the open bay.

The salinity transport model and the statistical regression models are described in Chapter V.

(5) Nutrients. The productivity of an estuarine system depends upon the quantity of necessary nutrients such as carbon, nitrogen and phosphorus. Thus, the transportation and utilization of these nutrients in the system is of major importance. The most significant sources of nutrients for Gulf estuaries are the tidal marshes and river deltas (40, 163). A hypothetical cross-section of a typical salt water marsh is illustrated in Figure 2-7. Note the typical low channel banks which may be inundated by high tides and high river flows. Inorganic materials and organic detritus transported and deposited in salt marshes by river floods are assimilated in the marshes through biological action and converted to organic tissue. This conversion is accomplished by the primary producers (phytoplankton and macrophytes) of the marsh ecosystem. The primary producers and organic materials produced in the marsh are then transported to the bay system by the inundation and subsequent dewatering process. This process is controlled by the tidal and river flood stages.

To properly evaluate the transport processes through a deltaic river marsh it is necessary to estimate the complex tidal and freshwater inflow interactions. A mathematical model (set of equations) based upon the appropriate physical laws was developed for determining flows, water depths, and nutrient transport in the Trinity River delta (61, 64). This model applies in cases of both low-flow and flood conditions. The results of freshwater inflows upon the marsh inundation and dewatering processes are estimated through the application of this marsh inundation model (see Chapter V).

Biological Indicators. Terms like "biological indicators", "ecological indicators", "environmental indicators", and others found in the scientific literature often refer to the use of selected "key" species. Usually such key species are chosen on the basis of their wide distribution throughout the system of interest (e.g., an estuary), a sensitivity to change in the system (or to a single variable, like freshwater inflow), and an appropriate life-cycle to permit observation of changes in organism densities and productivity in association with observations of environmental change.

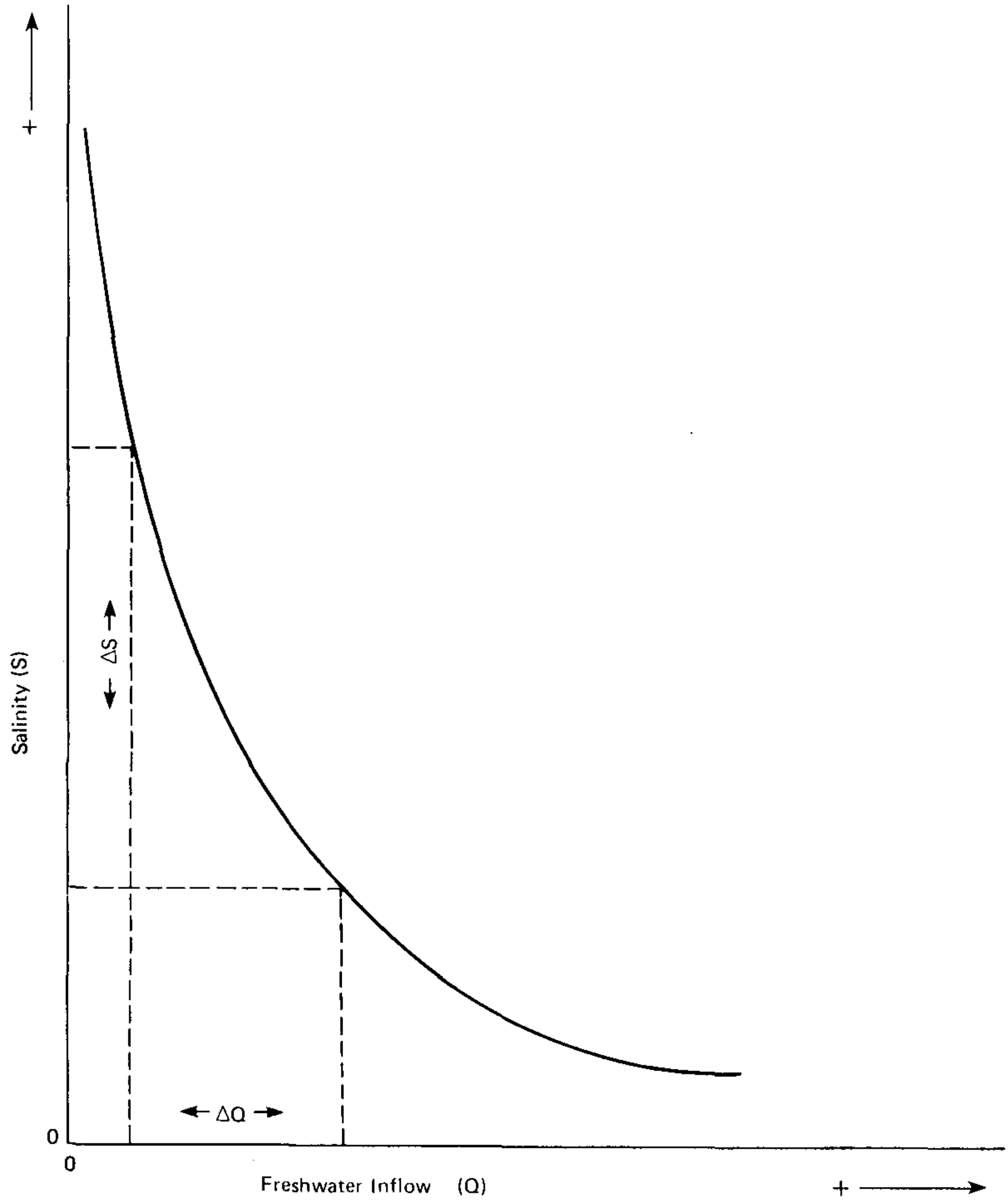


Figure 2-6. Typical Variation of Freshwater Inflow Versus Salinity in a Texas Estuary

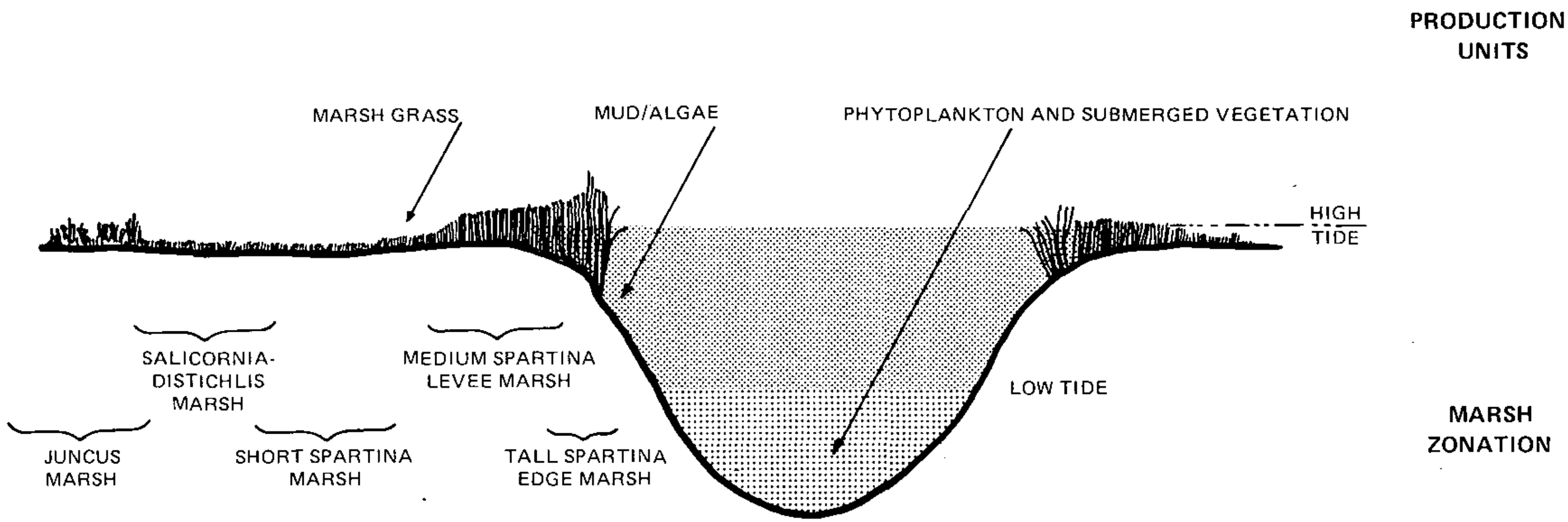


Figure 2-7. Zonation of a Salt Marsh in a Texas Estuary (275)

Dr. Eugene Odum has remarked that "ecologists constantly employ such organisms as indicators in exploring new situations or evaluating large areas" (187). Odum also notes that large species often serve as better indicators than small species because a larger and more stable biomass or standing crop can be supported with a given energy flow. The turnover of small organisms may be so great that the particular species present at any one moment may not be very useful as a biological indicator.

In the 1975 American Fisheries Society Water Quality Statement, Dr. H. E. Johnson stated that "fisheries provide a useful indicator of the quality and productivity of natural waters. Continuous high yield of fish and shellfish is an indicator of environmental conditions that are favorable for the entire biological community. In a number of recent environmental crises, fish and shellfish have served as either the link between pollution and human problems or an early warning of an impending contamination problem."

If every estuarine floral and faunal species could be monitored and integrated into a research program, the maximum data base would be achieved; however, there are always time and financial limitations that make this impossible. It is believed that the use of indicator or key species that emphasize the fishery species is reasonable and justified, especially when one considers the type of ecosystem and the availability of time and money which limit the number of environmental variables that may be investigated in depth. Use of several diverse species avoids problems most commonly associated with a single chosen indicator, wherein data may be dependent upon that particular species' sensitivity. The "key" species approach is used in these studies of the Texas bays and estuaries.

(1) Aquatic Ecosystem Model. Attempts to understand the complex interactions within Texas estuarine ecosystems have lead to the development of a sophisticated estuarine ecologic model (ESTECO; 540, 275). The model was formulated to provide a systematic means of predicting the response of estuarine biotic and abiotic constituents to environmental changes. Ecological modeling techniques involve the use of mathematical relationships, based on scientific evidence, to predict changes in estuarine constituents.

While the principal focus of the ESTECO model is to simulate those quantities that are considered to be the most sensitive indicators of the primary productivity of an estuarine environment (i.e., salinity, dissolved oxygen, nutrients, and algae), the higher trophic levels are also taken into account. The trophic categories included in the model are phytoplankton, zooplankton, benthos, and nekton (fish). Since the life cycles of algae and the higher forms of biota that depend on them, as well as the life cycles of bacteria and other decomposers, are intimately related to water quality, a complex set of physical, chemical and biological relationships have been included in the ESTECO model which link the various abiotic constituents to several forms of estuarine biota.

While the estuarine ecologic model provides a valuable conceptual tool for understanding estuarine ecosystems, the validity of the current version of ESTECO in predicting long-term estuarine constituents has not yet been proven. As presently structured, the estuarine ecologic model is capable of producing useful results over short time periods, but lacks the refinement necessary to accurately represent the long-term phenomena which occur in the estuarine system. Also, the comprehensive data to accurately calibrate the estuarine ecologic model for simulation periods in excess of one year are not yet available. Further refinement of the model is anticipated as these data become available.

At present, the most serious deficiency of the estuarine ecological model is its inability to accurately describe and predict the standing biomass of commercially important finfish and shellfish which spend portions of their life cycles in the estuary. Thus, for purposes of this study, statistical analysis techniques are used to predict the productivity of the higher trophic levels under various freshwater inflow conditions. The statistical models are described below.

(2) Statistical Models. An investigation of the effects of freshwater inflow on an estuary necessitates the use of existing information on the system's hydrology and biology. In most cases, numerical analysis of this information allows the demonstration of statistical relationships between freshwater inflow and dependent environmental variables such as fishery production. The use of linear regression analysis allows the development of a variety of descriptive and predictive relationships between seasonal freshwater inflows and commercial harvest of finfish and shellfish. The specific regression equations for estimating harvest of spotted seatrout, red drum, black drum, white shrimp, brown and pink shrimp, blue crab, and bay oyster as a function of the reported quantities of seasonal freshwater inflow are computed using data from each estuarine system (Chapter VIII). These regression equations can be used to compute estimates of the estuarine productivity, in terms of harvested fisheries biomass, as a function of seasonal freshwater inflow. However, there are variations in the historical harvest data which are not explained by variations in seasonal freshwater inflow. These variations may be due to other factors such as temperature, predation and disease.

The described relationships are useful in defining the possible impacts and interactions between freshwater inflows and the biomass production in various trophic levels. Many of the complicated relationships among trophic levels within an aquatic ecosystem are not yet completely understood and data about them are not available, so the mathematical representations required to describe such phenomena have not been adequately defined. Therefore, regression techniques are applied in these studies as a useful tool in understanding these interactions.

(3) Finfish Metabolic Stress Analysis. The health of organisms in an estuarine ecosystem is dependent upon a number of factors. Wohlschlag (320, 321) and Wakeman (538) have reported on the stress of salinity changes upon the metabolic activities of several Texas estuarine fish species. For example, Wakeman measured the maximum sustained swimming speeds of four estuarine fish species (i.e., spotted seatrout, sheepshead, and black and red drum) at 28 degrees celsius over a range of salinities (10-40 parts per thousand, ppt) normally encountered in the estuary to determine their optima. All of these species are of commercial and recreational importance; therefore, results of these metabolic research studies are valuable in the planning and management of the Texas estuarine systems and their production of renewable fish resources. Salinity ranges and salinity optima have also been determined for

several other estuarine-dependent fish and shellfish species (including shrimp, crabs, and oysters), and are presented in Chapter IX.

Analyzing the Estuarine Complex

Synthesis of Competing Estuarine Responses. The development of environmental modeling techniques has increased the capability of the planners to make intelligent and comprehensive evaluations of specified development alternatives and their impact on aquatic ecosystems. Due to the tremendous complexity of aquatic ecosystems and their importance in water resources planning, sophisticated mathematical techniques are being continually developed and used for assessment of alternative projects and programs.

Any desired management objective for the biological resources of an estuary must include a value judgment concerning competing interests. Where seasonal salinity needs are competitive among estuarine-dependent species (e.g., one species prefers low salinities in the spring and another prefers high salinities in the same season) a management decision may be required to specify a preference to one or more species' needs. Such a decision could be made on the basis of which organism has been more characteristic of the estuary of interest. Additionally, needs for freshwater in the contributing river basins must be balanced with the freshwater needs of the estuary.

Techniques for the synthesis of inflow alternatives are further discussed in Chapter IX.

Determination of Freshwater Inflow Needs. (1) Estuarine Inflow Model. In order to establish an estimate of the freshwater inflow needs for an estuary, mathematical techniques are applied to integrate the large number of relationships and constraints, such that all of the information can be used in consideration of competing factors. The relationships and constraints in this formulation consist of:

1) statistical regression equations relating annual fisheries harvest to seasonal inflows,
2) upper and lower bounds for the inflows used in the regression equations for harvest,
3) statistical regression equations relating seasonal salinities to seasonal freshwater inflows,
4) upper and lower bounds on the seasonal inflows used in computing the salinity regression relationships, and
5) environmental bounds on a monthly basis for the salinities required to maintain the viability of various aquatic organisms.

Constraints (2) and (4) are required so that the inflows selected to meet a specified objective fall within the ranges for which the regression equations are valid. Thus, in this analysis errors are avoided by not extrapolating beyond the range of the data used in developing the regression relationships.

The constraints listed above are incorporated into a special linear programming (LP) model, to determine the monthly freshwater inflows needed to meet specified marsh inundation, salinity, and fisheries objectives. The optimization procedure used to assess alternative objectives is formulated in a computer code based upon the simplex algorithm (42) for the solution of linear programs. A linear program may be used to reach an optimum solution to a problem where a desired linear objective is maximized (or minimized) subject to satisfying a set of linear constraints.

The output from the LP model provides not only the seasonal freshwater inflows needed to maximize the desired objective function, which in this case is stated in terms of marsh inundation, salinity, and fisheries harvested, but also the predicted harvest levels and salinities resulting from the model's freshwater inflow regime. The harvests that are predicted under such a regime of freshwater inflows can be compared with the average historical harvests to estimate changes in productivity.

Use of the estuarine inflow model is described in Chapter IX.

(2) Model Interactions. The estuarine linear programming model incorporates salinity viability limits and commercial fisheries harvest factors considered in determining interrelationships between freshwater inflows and estuarine key indicators, including the marsh and river delta inundation requirements. The schedule of flows for marsh inundation and for maintaining salinity and productivity levels are combined into one constraint in the model by taking the largest of the minimum required values for the two purposes. Thus, if the flow in March required for inundation is greater than the flow needed for salinity gradient control and fisheries harvest (production), then the March inflow need only be equal to the inundation requirement. A seasonal schedule of inflows needed by the estuary to meet the specified objectives is thus derived.

A process for synthesis of estimated freshwater inflow needs for the Trinity-San Jacinto estuary is discussed in Chapter IX.

Techniques for Meeting Freshwater Inflow Needs. The freshwater inflows needed to maintain an estuary's ecology can be provided from both unregulated and regulated sources. The natural inflows from uncontrolled drainage areas and direct precipitation will possibly continue in the future at historical levels, since man's influence will be limited, except in those areas where major water diversions or storage projects will be located. Inflows from the major contributing river basins, however, will probably be subject to significant alteration due to man's activities. A compilation and evaluation of existing permits, claims and certified filings on record at the TDWR indicate that should diversions closely approach or equal rates and volumes presently authorized under existing permits and claims presently recognized and upheld by the Texas Water Commission, such diversions could equal or exceed the total annual runoff within several major river systems during some years, particularly during drought periods. Total annual water use (diversions) do not yet approach authorized diversion levels in most river basins, as evidenced by both mandatory and voluntary comprehensive water use reporting information systems administered by the TDWR. With completion of major new surface-water development and delivery systems, such as the major conveyance systems to convey water from the lower Trinity River to the Houston-Galveston area, however, freshwater inflows to some bay systems may be progressively reduced and/or points of re-entry (in the form of return flows) may be significantly altered.

(1) Freshwater Inflow Management. The freshwater runoff from the regulated watersheds of the upstream river basins may be managed in several ways to insure the passage of necessary flows to the estuaries. These include the granting of water rights for surface-water diversion and storage consistent with the freshwater inflow needs of the estuary.

Water Rights Allocation. Adjudication of surface-water rights in Texas is an extremely important factor in addressing the issue of allocation and possibly ultimately the appropriation of State water specifically for estuarine maintenance.

In 1967, the Texas Legislature enacted the Water Rights Adjudication Act, Section 11.301 et seq. of the Texas Water Code. The declared purpose of the Act was to require a recordation with the Texas Water Commission of claims of water rights which were unrecorded, to limit the exercise of those claims to actual use, and provide for the adjudication and administration of water rights. Pursuant to the Act, all persons wishing to be recognized who were claiming water other than under permits or certified filings were required to file a claim with the Commission by September 1, 1969. Such a claim is to be recognized only if valid under existing law and only to the extent of the maximum actual application of water for beneficial use without waste during any calendar year from 1963 to 1967, inclusive. Riparian users were allowed to file an additional claim on or before July 1, 1971 to establish a right based on use from 1969 to 1970, inclusive.

The adjudication process is complex and, in many river basins, extremely lengthy. The procedures were designed to assure each claimant, as well as each person affected by a final determination of adjudication, all of the due process and constitutional protection to which each is entitled. Statewide adjudication is currently approximately 72 percent complete. Although the adjudication program is being accelerated, several years will be required to complete adjudication for the remaining basins. Final judgments have been rendered by the appropriate District Courts and certificates of adjudication have been issued in portions of the Rio Grande, Colorado, San Antonio and Guadalupe Basins.

Recognition of the freshwater needs of the estuaries, allocation and possible direct appropriation of State water to meet these needs, and equitable adjudication of water rights and claims are intertwined—a fact which must be recognized by all involved in identifying coastal issues and resolving coastal problems.

Operations of Upstream Reservoirs in Contributing Basins. The control of surface-waters through impoundment and release from large storage reservoirs is a potential source of supplementary waters for the Texas estuaries. The Texas Water Plan specified a plan for the delivery of up to 2.5 million acre-feet (3.1 billion m^3) of supplemental water annually to Galveston, Matagorda, San Antonio, Aransas, and Corpus Christi Bays through controlled releases from the coastal component of the proposed Texas Water System. Conceptually, the Texas Water System would conserve and control water from basins of surplus, and transport them, together with water from other intrastate, interstate, and potential out-of-State sources, to areas of need throughout Texas. This volume of supplemental water would probably not be required every year; however, during periods of extended drought it would be available to supplement reservoir spills, reservoir releases not diverted for use, properly treated and managed return flows, unregulated runoff of major rivers below reservoirs and runoff from adjacent coastal areas, and precipitation that falls directly on the bays and estuaries.

Although the Texas Water Plan tentatively provides a specific amount of supplemental water inflow for estuaries on an annual basis, it was, (and is still) clearly recognized that the amount specified is not more than a preliminary estimate. Furthermore, the optimum seasonal and spatial distribution of these supplemental inflows could not be determined at that time because of insufficient knowledge of the estuarine ecosystems.

Attention must be given to the possibilities of providing storage capacity in existing and future reservoir projects specifically for allocation to estuarine inflows, with releases timed to provide the most benefit to the estuary. Development of institutional arrangements whereby repayment criteria for such allocated storage are determined and associated costs repaid will be needed. Potential transbasin diversions to convey "surplus" freshwater from "water-rich" hydrologic systems to water-deficient estuaries will also have to be studied and costs will have to be computed. Additionally, structural measures and channel modifications which might enhance marsh inundation processes using less freshwater will have to be evaluated. These are all a part of planning to meet the future water needs of Texas.

(2) Elimination of Water Pollutants. The presence of toxic pollutants in freshwater inflows can have a detrimental effect upon productivity of an estuarine ecosystem by suppressing biological activity. Historically, pollutants have been discharged into rivers and streams and have contaminated the coastal estuaries. Imposition of wastewater discharge and streamflow water quality standards by State and Federal governmental agencies has had and will continue to have a significant impact upon pollutants entering estuarine waters. Presence of toxic pollutants in the Texas estuaries will continue for the foreseeable future in some areas as compounds deposited in sediments become resuspended in the water column by dredging activities and when severe storms cause abnormally strong currents. This report does not include a comprehensive assessment of water pollution problems in the Trinity-San Jacinto estuary, but other ongoing studies by the Department of Water Resources do address such problems.

(3) Land Management. The uses of watershed areas are of particular importance to the contribution of nutrient materials from the land areas surrounding Texas estuaries. In coastal areas, significant contributions of nutrients are provided to the estuary by direct runoff. Removal of marsh grasses in coastal areas through overgrazing by livestock and through drainage improvement practices can result in substantial reductions in the volume of

nutrients contributed to an estuary. This report does not consider land management techniques in detail, although land management is an alternative technique in any coastal zone management plan.

Summary

The provision of sufficient freshwater inflow to Texas bays and estuaries is a vital factor in maintaining estuarine productivity and a factor contributing to the near-shore fisheries productivity of the Gulf of Mexico. The methodology for establishing freshwater inflow needs described in this report relies heavily on the use of mathematical and statistical models of the important natural factors governing the estuaries. Mathematical models relating estuarine flow circulation, salinity transport, and deltaic marsh inundation processes were developed based upon physical relationships and field data collected from the system, and utilized to assess effects of freshwater inflows.

Simplifying assumptions must be made in order to estimate freshwater inflow requirements necessary to sustain Texas estuarine ecosystems. A basic premise described in this report is that freshwater inflow and estuarine productivity can be examined through analysis of certain "key indicators." The key physical and chemical indicators include freshwater inflows, circulation and salinity patterns, and nutrients. Biological indicators of estuarine productivity include selected commercially important species. Indicator species are generally chosen on the basis of their wide distribution throughout each estuarine system, a sensitivity to change in the system, and an appropriate life cycle to facilitate association of the organism with the estuarine factors, particularly seasonal freshwater inflows.

An estuarine inflow model is used in these studies to estimate the monthly freshwater inflows necessary to meet three specified fish harvest (production) objectives subject to the maintenance of salinity limits for selected organisms. Where seasonal needs compete between estuarine-dependent species, a choice must be made to give preference to one or more species' needs. Additionally, society's economic, social, and other environmental needs for freshwater in the contributing river basins must be balanced with the freshwater needs of the estuary.

CHAPTER III

DESCRIPTION OF THE ESTUARY AND THE SURROUNDING AREA

Physical Characteristics

Introduction

The Trinity-San Jacinto estuary covers about 600 square miles (1,600 square kilometers) and includes East Bay, Galveston Bay, Trinity Bay, West Bay and several smaller bays (Figure 3-1). Water depth at mean low water varies from less than six feet (1.8 m) in West Bay to over 10 feet (3.1 m) in Galveston Bay. Depths in the dredged channels range up to 40 feet (12 m).

The study area lies in the Upper Coast climatological division of Texas in the warm temperate zone. Its climatic type is classified as subtropical (humid with warm summers). The climate is also predominantly marine because of the proximity of the Gulf of Mexico. Polar Canadian air masses frequent the basin in winter causing brief periods of cool, foggy and rainy weather (373).

Rainfall is fairly evenly distributed throughout the year. Excessive rainfall can occur in a short time period when slow-moving thunderstorms or tropical disturbances pass over the area in late summer.

Influence of Contributory Basins

Drainage areas contributing inflow to the Trinity-San Jacinto estuary include the Trinity and San Jacinto River Basins, the Trinity-San Jacinto Coastal Basin, and parts of the Neches-Trinity and San Jacinto-Brazos Coastal Basins (Figure 3-2).

The Trinity River Basin, largest of the contributory basins, has a total drainage area of 17,969 square miles (46,540 km^2). From its headwaters in southeastern Archer County, the West Fork Trinity River flows in a southeasterly direction to its confluence with the Clear Fork Trinity River near downtown Fort Worth. From here, the West Fork Trinity continues in a generally easterly direction until its merger with the Elm Fork Trinity River in the eastern part of the City of Dallas. At this point, the Trinity River begins and flows in a southeasterly direction to Trinity Bay. Major tributaries of the West Fork include Clear Fork Creek, Village Creek, and Mountain Creek. Major tributaries of the Elm Fork Trinity River include Spring Creek, Clear Creek, and Denton Creek. Major tributaries of the Trinity River below the confluence of West Fork and Elm Fork include White Rock Creek, East Fort Trinity River, Cedar Creek and Richland Creek.

Average annual runoff in the upper Trinity River Basin ranges from about 150 acre-feet per square mile (714.3 m^3/ha) in the headwaters of the West Fork to 400 acre-feet per square mile (1,905 m^3/ha) in the headwaters of the East Fork. Average annual runoff in the middle of the basin is about 300

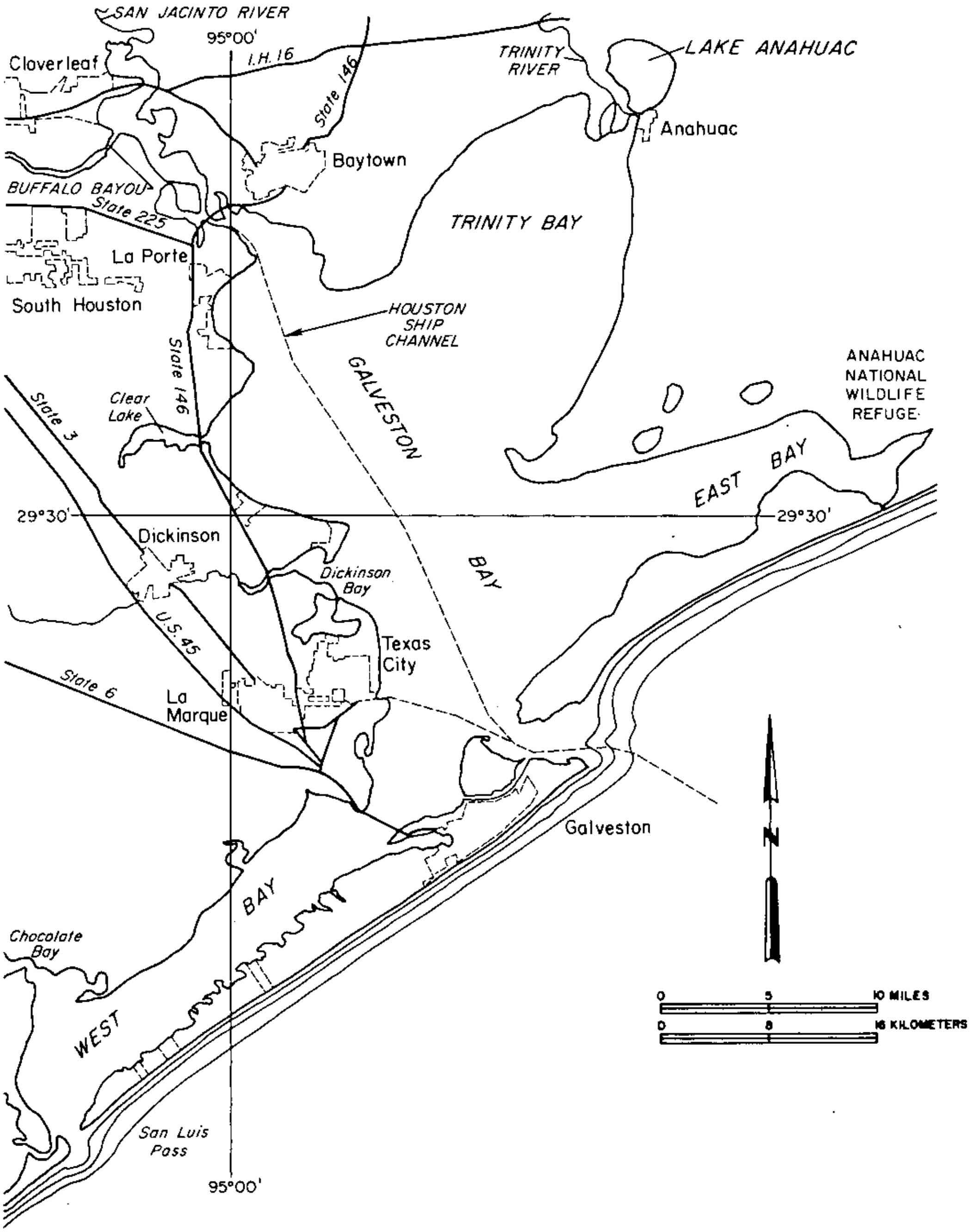


Figure 3-1. Trinity-San Jacinto Estuary

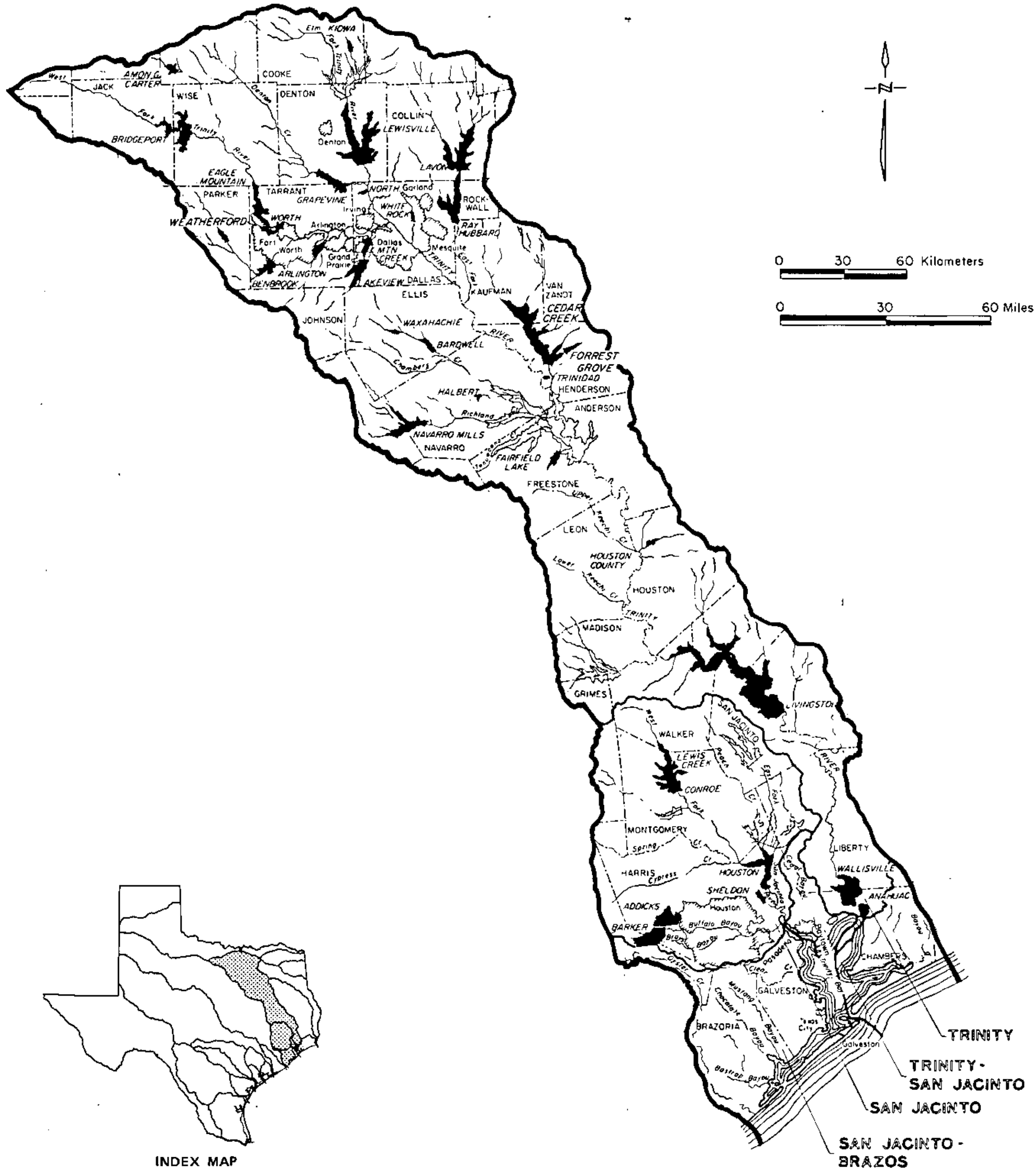


Figure 3-2. Basins Contributing to the Trinity-San Jacinto Estuary

acre-feet per square mile (1,222.9 m^3/ha) and increases to over 550 acre-feet per square mile (2,619.4 m^3/ha) near the mouth. However, during the drought year of 1956 average annual runoff for the entire basin was less than 60 acre-feet per square mile (285.8 m^3/ha).

The San Jacinto River basin has a total drainage area of 3,976 square miles (10,298 km^2). The two major branches of the San Jacinto River include the West Fork and East Fork with drainage areas of 1,750 and 1,050 square miles (4,532 km^2 and 2,720 km^2), respectively. Average annual runoff is about 350 acre-feet per square mile (1,667 m^3/ha) within the city limits of Houston, Texas. The lowest runoff rate also occurred in 1956 with a basin average of about 70 acre-feet per square mile (333 m^3/ha).

Contributing areas of the Neches-Trinity Coastal Basin are bounded on the east by the drainage area of Oyster Bayou. Total drainage area contributing to the estuary system is 430 square miles (2,048 m^3/ha).

Total drainage area of the Trinity-San Jacinto Coastal Basin is 247 square miles (640 km^2). The major stream in this area is Cedar Bayou.

Total drainage area contributing runoff in the San Jacinto-Brazos Coastal Basin to the estuary is 961 square miles (2,489 km^2). This basin is bounded on the west by the drainage area of Chocolate Bayou. Major streams within this coastal area include Clear Creek, Dickinson Bayou, Moses Bayou, Highland Bayou, Hells Bayou and Mustang Bayou.

Most of the coastal basins are less than 25 feet (7.5 m) above mean sea level. The drainage is poorly defined and is affected by irrigation and drainage canals. Runoff generally exceeds 900 acre-feet per square mile (4,286 m^3/ha).

There are a total of 35 major reservoirs existing or under construction within the contributing area of the Trinity-San Jacinto estuary (Table 3-1).

Geologic Resources

Sedimentation and Erosion. The Trinity-San Jacinto estuary's main source of sediment is the Trinity River. Headwaters of the Trinity River carry sediment ranging from 0.70 acre-feet/square mile (3.33 m^3/ha) to 1.06 acre feet/square mile (5.05 m^3/ha) annually as it flows through the North Central Prairie, Western Cross Timbers, Grand Prairie, and Eastern Cross Timbers physiographic provinces (262, 273). Within the Blackland Prairie the annual sediment production rate is 0.77 to 0.85 acre-feet/square mile (3.7 to 4.1 m^3/ha). As the Trinity River flows southward into the East Texas Timberlands the annual sediment production rate decreases to 0.16 acre-feet/ square mile (0.76 m^3/ha). The East Fork of the San Jacinto River contributes an average of 0.037 acre-feet/square mile (0.18 m^3/ha) of sediment annually. Most, if not all, of this sediment is trapped by Lake Houston thus keeping it from entering Galveston Bay (274).

As the Trinity River enters Trinity Bay flow velocities decrease and the sediment transport capability is reduced; thus, sediment is deposited near the headwaters, forming a bay-head delta. The delta which formed at the mouth of

Table 3-1. Reservoirs of Contributing Basins, Trinity-San Jacinto Estuary

Reservoir Name	Type of Use(s) a/	Year Dam Completed	Surface Area b/ Acres	Conservation Pool Elevation ft (msl)	Conservation Pool Storage c/: thousand ac-ft	Flood Control Storage thousand ac-ft	Total Storage thousand ac-ft
Trinity River Basin							
Bridgeport	W.S.,R	1932	13,000	836.0	386,420		386,420
Amon G. Carter	W.S.,R	1956	1,540	920.0	20,050		20,050
Eagle Mountain	W.S.,R	1932	9,200	649.1	190,460		190,460
Worth	W.S.,R	1914	3,560	594.3	38,130		38,130
Weatherford	W.S.,R	1957	1,210	896.0	19,470		19,470
Benbrook	W.S.,R,F.C.	1950	3,770	694.0	88,250	76,550	164,800
Arlington	W.S.,R	1957	2,275	550.0	45,710		45,710
Lakeview d/,f/	W.S.,R	—	7,470	522.0	176,900	127,100	304,000
Mountain Creek	W.S.,R	1936	2,710	457.0	22,840		22,840
Kiowa	R	1970	560	700.0	7,000		7,000
Lewisville	W.S.,F.C.,R	1955	23,280	515.0	464,500	525,200	989,700
Grapevine	W.S.,F.C.,R	1952	7,380	535.0	188,550	246,950	435,500
North e/	W.S.,R	1957	800	510.0	17,000		17,000
White Rock	W.S.,R	1911	1,119	458.0	10,740		10,740
Lavon	W.S.,F.C.,R	1953	21,400	492.0	456,500	291,700	748,200
Ray Hubbard	W.S.,R	1969	22,745	435.5	490,000		490,000
Trinidad e/	W.S.,R	1925	740	284.5	7,450		7,450
Terrell	W.S.,R	1955	830	504.0	8,712		8,712
Forrest Grove e/,d/	W.S.,R	—	1,502	359.0	20,038		20,038
Cedar Creek	W.S.,R	1966	33,750	322.0	679,200		679,200
Waxahachie	W.S.,R	1956	690	531.5	13,500		13,500
Bardwell	W.S.,F.C.,R	1966	3,570	421.0	54,900	85,100	140,000
Halbert	W.S.,R	1921	650	368.0	7,420		7,420
Navarro Mills	W.S.,F.C.,R	1963	5,070	424.5	63,300	148,900	212,200
Fairfield e/	W.S.,R	1969	2,350	310.0	50,600		50,600
Houston County	W.S.,R	1966	1,282	260.0	19,500		19,500
Livingston	W.S.,R	1969	82,600	131.0	1,750,000		1,750,000
Wallisville d/	W.S.,R	—	19,700	4.0	58,000		58,000
Anahuac e/	Ir.	1914	5,300	5.0	35,300		35,300
San Jacinto River Basin							
Lewis Creek e/	W.S.,R	1969	1,010	267.0	16,400		16,400
Conroe	W.S.,R	1973	20,985	201.0	430,260		430,260
Houston	W.S.,R	1954	12,240	43.8	146,700		146,700
Sheldon	W.S.,R	1943	1,700	50.5	5,420		5,420
Barker	F.C.	1945	—	—	—	207,000	207,000
Addicks	F.C.	1948	—	—	—	204,500	204,500

a/ W.S. - Water Supply (may include municipal, manufacturing, irrigation, steam electric power and/or mining uses)
R. - Recreation
F.C. - Flood control
Ir. - Irrigation only
b/ At conservation pool elevation
c/ Includes sediment storage
d/ Under construction
e/ Off channel reservoirs depending upon diversions from adjacent streams and/or reservoir releases for firm supply
f/ Land purchase initiated only

the Trinity River is of a type which develops under conditions of high sediment inflow into a relatively quiescent body of water (i.e., Trinity Bay).

The major marsh areas in the Trinity-San Jacinto estuary are associated with deltas. Delta plains are covered with fresh, brackish, and saline marshes. In order for marshes to propagate there must be a balance between sediment deposition and compactional subsidence. If there is excessive vertical accretion, marsh vegetation is replaced by mainland grasses, shrubs, and trees. Where subsidence is more rapid than deposition, the plants drown and erosion by waves and currents deepen the marsh to form lakes or enlarged bay areas. At present, marsh surface-water level relationships of the Trinity delta are stable. Sedimentation rates and subsidence apparently are near equilibrium. Other important sources of estuarine sediments include:

(1) Direct runoff or drainage from contiguous land and marsh areas to the estuary;
(2) Wind blown sediments, important in areas near sand dunes and non-urbanized areas; and
(3) Normal ecological and biological processes producing organic sediment from the marine life and aquatic vegetation, often making up a large percentage of total estuarine sediments.

The mainland shore is characterized by near vertical bluffs cut into Pleistocene sand, silt, and mud (Figure 3-3). Erosion of these bluffs furnishes sediment to the adjacent lakes, marshes, and bays. The type of sediment deposited depends on whether the adjacent bluff is composed of predominantly sand or mud. Energy levels (erosional capacity) in the Trinity-San Jacinto estuary are dominated by wind action since the range of astronomical tides is only bout 0.5 foot (0.15 m). Winds blowing across the bay generate tides of two or three feet (0.6 or 1 m) and cause a change in water level at the shoreline (302). These changes in water levels produced by the wind are called wind tides.

Shoreline and vegetation changes within the Trinity-San Jacinto estuarine system and in other areas of the Texas Gulf Coast are the result of natural processes (305, 302). Shorelines are in a state of erosion, accretion, or are stabilized either naturally or artificially. Erosion produces a net loss in land; accretion produces a net gain in land; and equilibrium conditions produce no net change in land area.

Most of the shoreline areas associated with the Trinity-San Jacinto estuary are balanced between erosion and deposition (Figure 3-4). The nature of beaches is an indicator of the extent of shoreline stability. Sediments of the mainland beaches are a mixture of sand, shell, and rock fragments, with shell and rock fragments the most common constituents. This is an indication that little sand is currently being supplied to these beaches by rivers.

Processes that are responsible for the present shoreline configuration and that are continually modifying shorelines in the Trinity-San Jacinto estuary include astronomical and wind tides, longshore currents, normal wind and waves, hurricanes, river flooding, and slumping along cliffed shorelines. Astronomical tides are low, ranging from about 0.5 foot (0.15 m) in the bays to a maximum of about two feet (0.6 m) along the Gulf shoreline. Wind is a major factor in influencing coastal processes. It can raise or lower water

Figure 3-3. Geologic Map

Base from U.S. Geological Survey, 1:1,000,000, 1965

Geology adapted from Geologic Map of Texas (Darton, Stephenson and Gardner, 1937)

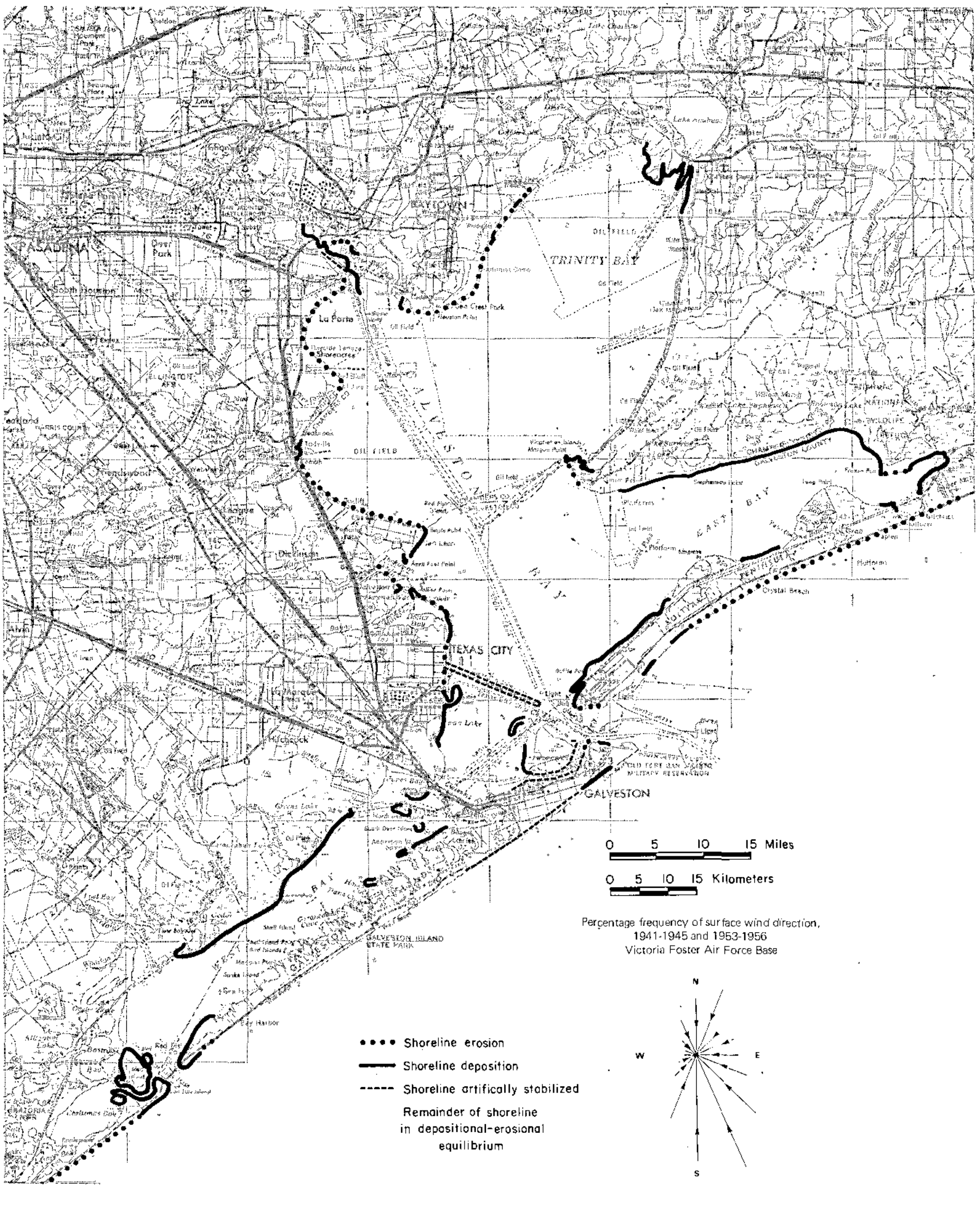


Figure 3-4. Shoreline Physical Processes, Trinity-San Jacinto Estuary (302)

level along the Gulf and/or mainland shore according to the direction it is blowing. Wind also generates waves and longshore currents (205, 110, 344).

The seasonal threat of wind and water damage associated with tropical cyclones occurring in the Gulf of Mexico exists each year from June through October. Wind damage from hurricanes and associated tornadoes can be costly, but the most severe losses occur from the flooding brought by heavy rains and high storm surges along the Coast. Gulf and mainland shorelines may be drastically altered during the approach, landfall, and inland passage of hurricanes (110, 227). Storm surge flooding and attendant breaking waves may erode Gulf shorelines tens to hundreds of feet. Washovers along the barrier islands and peninsulas are common, and salt-water flooding may be extensive along the mainland shorelines.

Flooding of rivers and small streams normally corresponds with spring thunderstorms and the hurricane season. Some effects of flooding include: (1) overbank flooding into marsh areas of the floodplain and onto delta plains; (2) progradation of bayhead and oceanic deltas; (3) flushing of bays and estuaries; and (4) reduction of salinities.

Mineral and Energy Resources. Resources of the Texas coastal zone include oil and natural gas (Figure 3-5), which serve not only for fuel but also provide raw material for many petrochemical processes.

The production of oil, natural gas, and natural gas liquids plays a prominent role in the total economy of the area surrounding the Trinity-San Jacinto estuary (301). In addition to the direct value of these minerals, oil and gas production supports major industries within the area and elsewhere in the coastal zone by providing readily available fuels and raw materials.

Notably absent in the Texas coastal zone are natural aggregates and bulk construction materials (e.g., gravel and stone for crushing). At the same time the demand for these materials is high in the heavily populated and industrialized areas of the coastal zone; therefore, a large portion of such materials must be imported from inland sources. Shell from the oyster *Crassostrea*, and smaller amounts from the clam *Rangia* is used as a partial substitute for aggregate. Some high quality sand deposits have potential specialty uses in industry, such as for foundry sands, glass sands, and chemical silica (304).

Dredged shell, with physical properties suitable for use as aggregate and road base, has chemical properties suitable for lime, cement, and other chemical uses. If shell were not used, these resources would have to be transported approximately 170 miles (270 km) from the nearest Central Texas source. Shell resources are finite, and at present rates of consumption they will be depleted in the near future. Substitute materials will then have to be imported, either from inland sources or by ocean barge from more distant locations.

Groundwater Resources. Groundwater resources in the area of the Trinity-San Jacinto estuary occur in a thick sedimentary sequence of interbedded gravel, sand, silt, and clay. The stratigraphic units included in this sequence are the Jackson Group, the Catahoula, Oakville and Goliad Formations of Tertiary

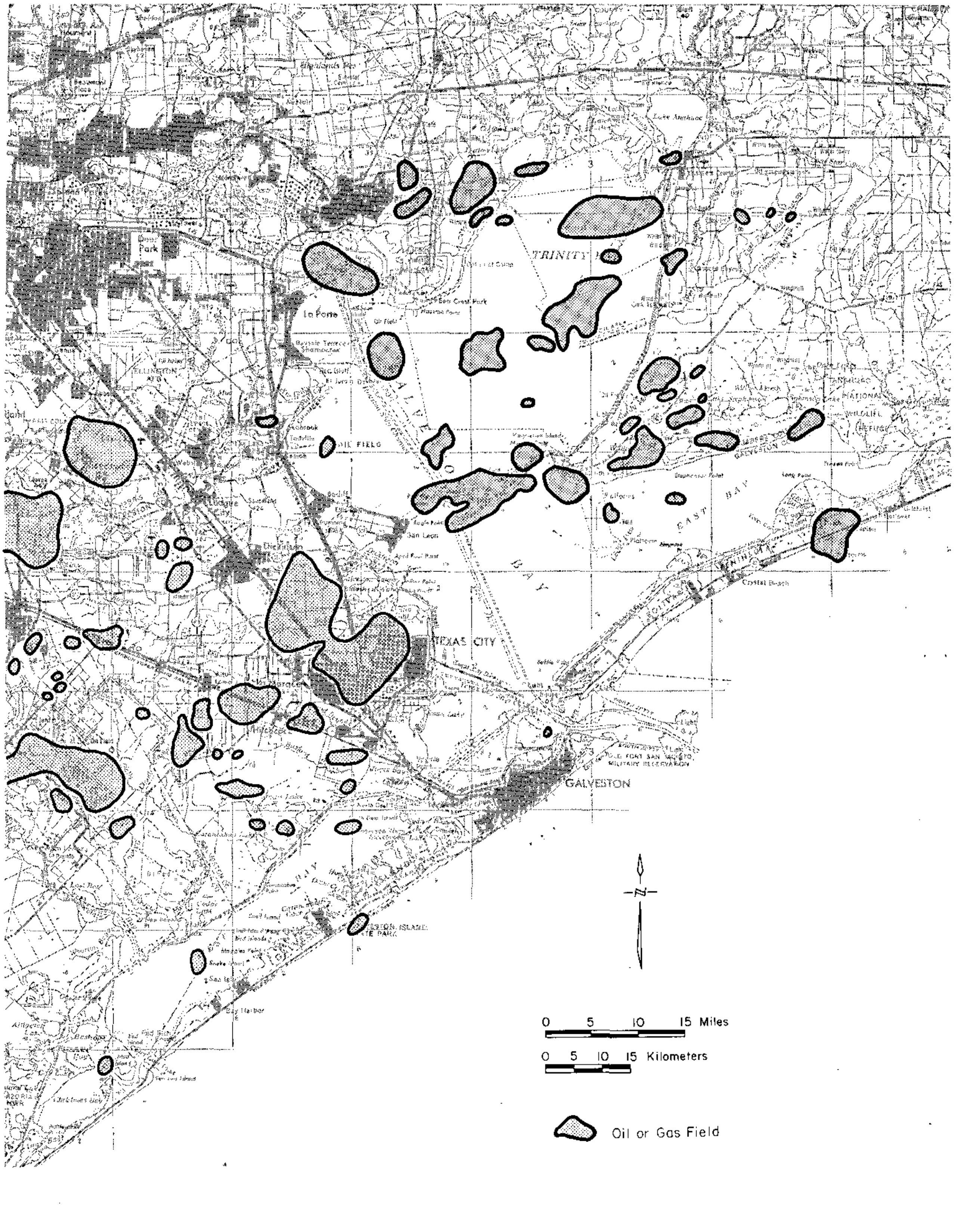


Figure 3-5. Oil and Gas Fields, Trinity-San Jacinto Estuary (302)

Age and the Lissie and Beaumont Formations of Quaternary Age. These ancient sedimentary units are not uniform in composition and thickness, but were deposited by the same natural processes that are now active in shaping the coastline. Thick layers of sand and gravel representing ancient river channel deposits grade laterally into silt and clay beds which were deposited by the overbank flooding of ancient rivers. Individual beds of predominantly sand and clay interfinger with each other and generally are hydrologically connected laterally and vertically. Because of this interconnection, groundwater can move from one bed to another and from one formation to another. The entire sequence of sediment with the exception of the Jackson Group, functions as a single aquifer, which is referred to as the Gulf Coast Aquifer.

Near the Trinity-San Jacinto estuary this fresh (up to 1,000 mg/l total dissolved solids) to slightly saline (1,000 to 3,000 mg/l total dissolved solids) portion of the aquifer extends to a maximum depth of about 3,000 feet (914 m). The most productive part of the aquifer is from 400 to 1,200 feet (122 to 336 m) thick (277).

Excessive pumping of groundwater can cause land surface subsidence and saltwater encroachment, which are both irreversible. Locally the shallow aquifer may contain saltwater, whereas the deeper aquifer sands may have freshwater. Excessive pumping of freshwater will allow saline waters to encroach into the freshwater zone, contaminating wells and degrading the general groundwater quality. The principal effects of subsidence are activation of surface faults, loss of ground elevation in critical low-lying areas already prone to flooding, and alteration of natural slopes and drainage patterns (Figure 3-6).

Natural Resources

The Texas coastal zone is experiencing geological, hydrological, biological and land use changes as a result of man's activities and natural processes. What was once a relatively undeveloped expanse of beach along deltaic headlands, peninsulas, and barrier islands is presently undergoing considerable development. Competition for space exists for such activities as recreation, seasonal and permanent housing, industrial and commercial development, and mineral and other natural resource production (305).

The Trinity-San Jacinto estuary includes areas in both the Coastal Prairie and the Coastal Marshland resource areas (373). The native vegetation consists of coarse grasses with a narrow fringe of trees along the streams. Much of the area is in urban and industrial land use (Figure 3-7). The City of Houston and the petro-chemical industrial complex are the predominant features of the surrounding area. Marshes are confined to strips along the coast and inlets, with vegetation composed of saltgrass, cordgrass and spikesedge. Soils are generally acid, sometimes saline, clays and loams. Pines grow on the well-drained upland with some hardwoods along the streams.

Agricultural land use includes irrigation of rice, dryland crops, and ranching activities (269, 376). Results of rice irrigation return flow studies (379) indicate that about 30 percent of the water applied for irrigation returns as surface flow to the drainage system. Soybeans are the major dryland crop with small acreages of grain sorghum and cereal grains.

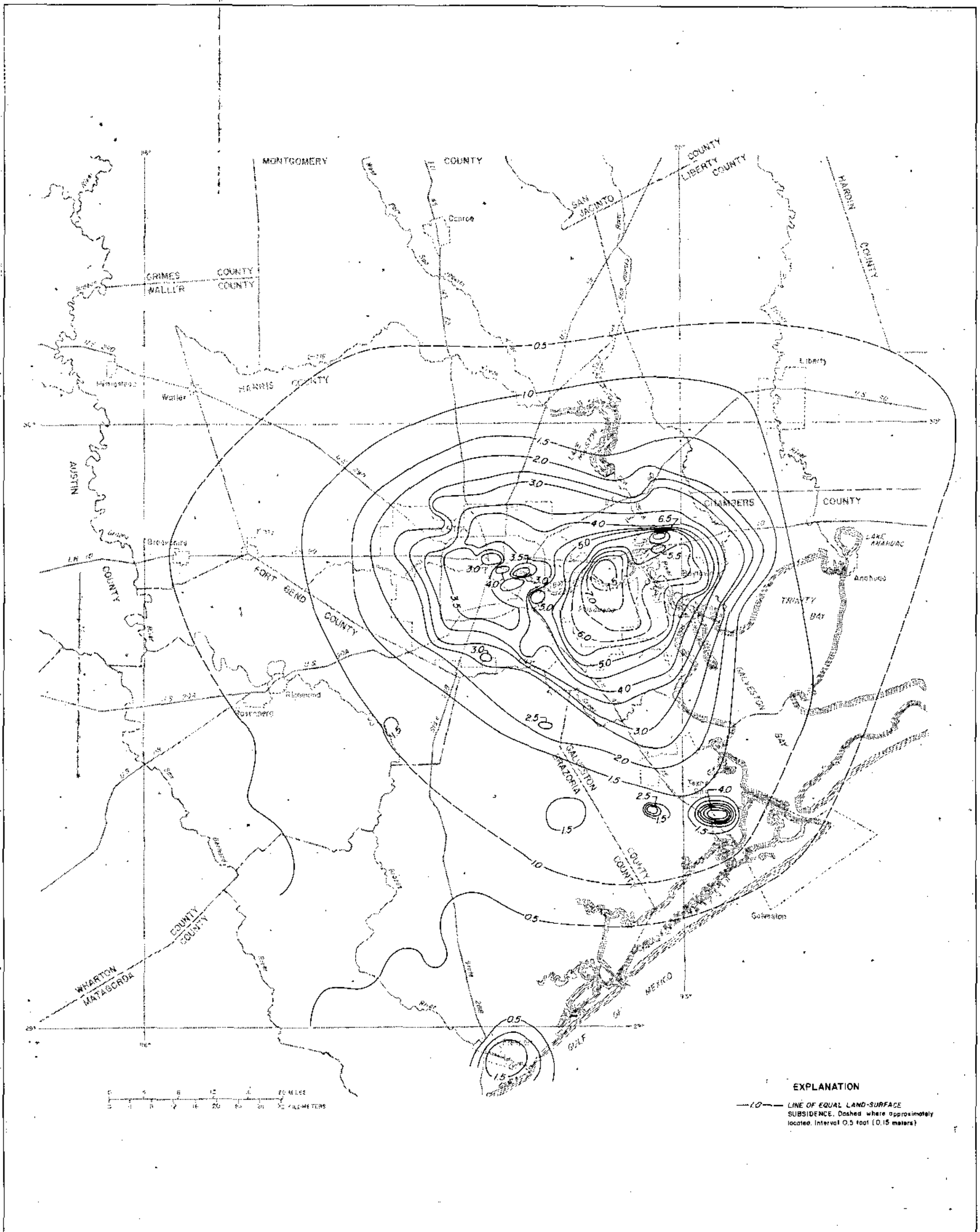


Figure 3-6. Land Surface Subsidence in the Houston Area, 1943-1973 (302)

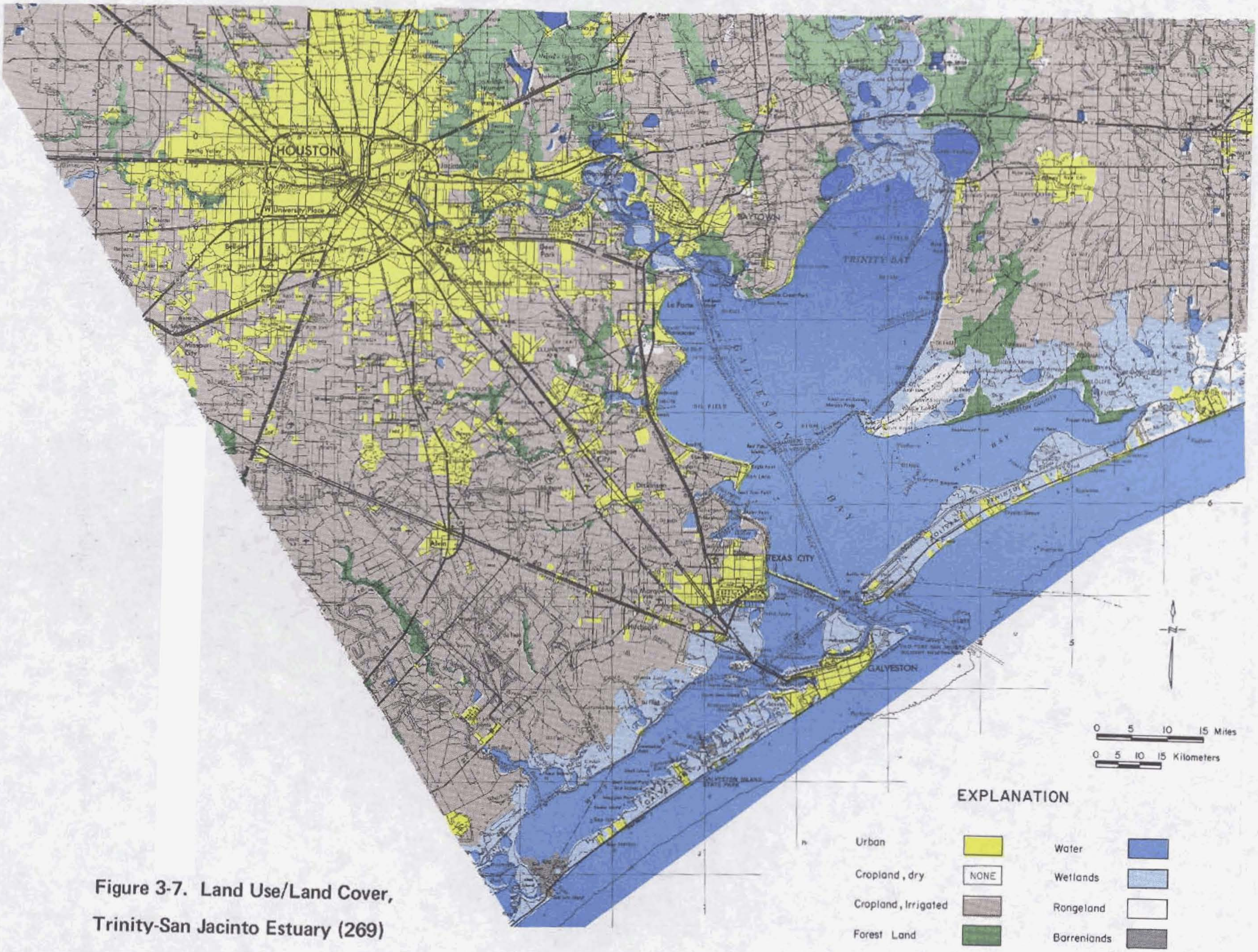


Figure 3-7. Land Use/Land Cover, Trinity-San Jacinto Estuary (269)

In the immediate vicinity of the Trinity-San Jacinto estuary, the U. S. Department of the Interior manages the Anahuac National Wildlife Refuge. In addition, the State of Texas has a fish hatchery, three State parks and the Sheldon Wildlife Management area. Archeological sites within the area indicate utilization of the region from the Archaic to Historic stages (370). Important historic sites (Figure 3-8) include the Presidio San Augustin de Ahumada and the Mission Nuestra Senora de la Luz. Founded in late 1756 or early 1757, both the mission and presidio which were established for the conversion of the Bidai and Orcoquizac Indians were officially discontinued in 1772 (297, 298, 378).

Natural resources of the Trinity-San Jacinto estuary system and adjoining inland areas provide a wide variety of recreational opportunities for visitors to the area. Water-oriented recreational activities such as fishing, boating, skiing, and swimming are amply available to the recreationists, with approximately 357.5 thousand surface acres (144,676 ha) of bay water for recreational use. The fishing resources of the bay system include many fish species preferred by sport fishing enthusiasts. Sports creel studies conducted by the Texas Parks and Wildlife Department (284, 295) estimate that sport fishermen caught more than 3.2 million fish (all species) totaling over 2.8 million pounds (1.2 million kg) during the period September 1974 through August 1975. Over 75 percent of the species composition of the sport harvest (number of fish) was attributed to three species: (1) Atlantic croaker (26.6 percent); (2) spotted seatrout (25.7 percent); and (3) sand seatrout (22.6 percent). Other species included red drum, black drum, southern flounder, sheepshead, and gafftopsail. Spotted seatrout accounted for 39.9 percent of the harvest by weight.

Inland areas and marshes contiguous to the Trinity-San Jacinto estuary system provide terrestrial and aquatic habitat for many species of wildlife including the endangered American alligator, the whooping crane, the Atlantic ridley turtle, the brown pelican, and the Houston toad. Wildlife resources of the area enhance the opportunities for sightseeing, nature studies, and esthetic benefits accruing to the naturalists. In addition, more than 149 thousand acres (60,298 ha) of marshland are available to outdoor sportsmen for hunting opportunities. These marsh areas support populations of migratory game birds for the hunting enthusiasts.

The Trinity-San Jacinto estuary system has historically been the overall leading fisheries resource base in Texas. The annual commercial bay harvest of finfish and shellfish in this estuary has averaged 8.9 million pounds (4.1 million kg; 96.1 percent shellfish) during the 1962 through 1976 interval. However, a large portion of each estuary's production of fish and shellfish is caught in the Gulf by commercial and sport fishermen. When these harvests are considered, the total contribution of the estuary to the Texas coastal fisheries (all species) is estimated at 46.7 million pounds (21.2 million kg; 87.4 percent shellfish) annually for a recent five year period (1972-1976). Penaeid shrimp species dominate the shellfish harvests.

Data Collection Program

The Texas Department of Water Resources realized during its planning activities that, with the exception of data from the earlier Galveston Bay Study, limited data were available on the estuaries of Texas. Several limited research programs were underway; however, these were largely independent of

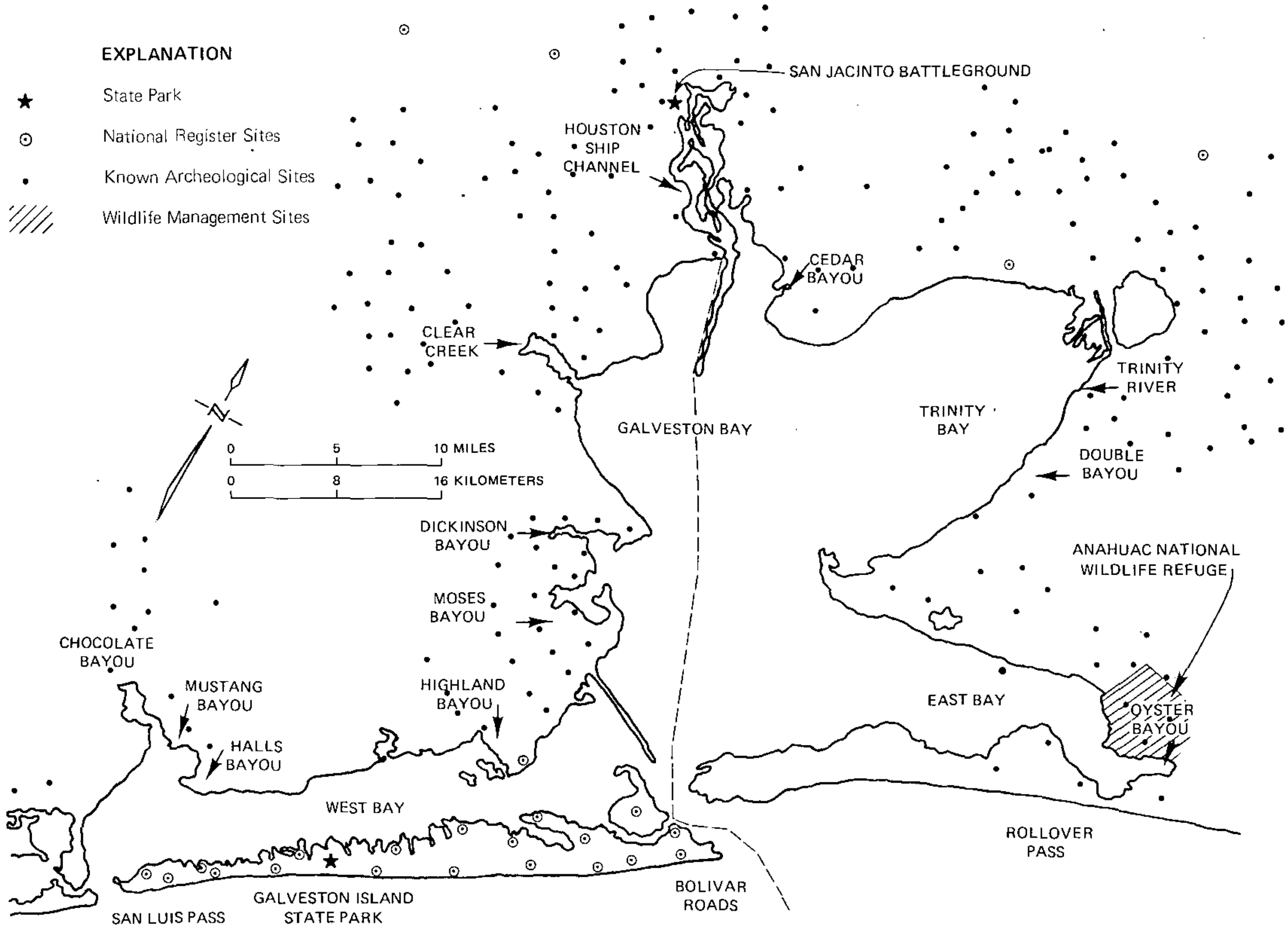


Figure 3-8. Natural Resources, Trinity-San Jacinto Estuary (378)

one another. The data collected under any one program were not comprehensive, and since sampling and measurement of environmental and ecological parameters under different programs were not accomplished simultaneously, the resulting data could not be reliably correlated. In some estuaries, virtually no data had been collected.

A program was therefore initiated by the Department, in cooperation with other agencies, to collect the data considered essential for analyses of the physical and water quality characteristics and ecosystems of Texas' bays and estuaries. To begin this program, the Department consulted with the U. S. Geological Survey and initiated a reconnaissance-level investigation program in September 1967. Specifically, the initial objectives of the program were to define: (1) the occurrence, source and distribution of nutrients; (2) current patterns, directions, and rates of water movement; (3) physical, organic and inorganic water characteristics; and (4) the occurrence, quantity, and dispersion patterns of water (fresh and Gulf) entering the estuarine system. To avoid duplication of work and to promote coordination, discussions were held with other State, Federal and local agencies having interests in Texas estuarine systems and their management. Principally, through this cooperative program with the U. S. Geological Survey, the Department has continued to collect data in all estuarine systems of the Texas Coast (Figures 3-9 and 3-10, Table 3-2).

Calibration of the estuarine models (discussed in Chapter V) required a considerable amount of data. Data requirements included information on the quantity of flow through the tidal passes during some specified period of reasonably constant hydrologic, meteorologic, and tidal conditions. In addition, a time history of tidal amplitudes and salinities at various locations throughout the bay was necessary. Comprehensive field data collection was undertaken on the Trinity and San Jacinto estuary on July 20-23, 1976. Tidal amplitudes were measured simultaneously at numerous locations throughout the estuaries (Figure 3-9). Tidal flow measurements were made at several different bay cross-sections. In addition, conductivity data were collected at many of the sampling stations shown in Figures 3-9 and 3-10. Studies of past and present freshwater inflows to Texas' estuaries have used all available sources of information on the physical, chemical, and biological characteristics of these estuarine systems in an effort to define the relationship between freshwater and nutrient inflows and estuarine environments.

Economic Characteristics

Socioeconomic Assessment of Adjacent Counties

The economic significance of the natural and man-made resources associated with the Trinity-San Jacinto estuary is reflected in the direct and indirect linkages of the bay-supported resources to the economies of Brazoria, Chambers, Galveston and Harris Counties. Trends in population, earnings by industry sector, and personal income levels are presented for the four counties.

Population. The population of the four county study area experienced a growth of approximately 2.3 percent annually between 1970 and 1975. Brazoria and Harris Counties grew the fastest, at average annual rates of 2.5 percent and

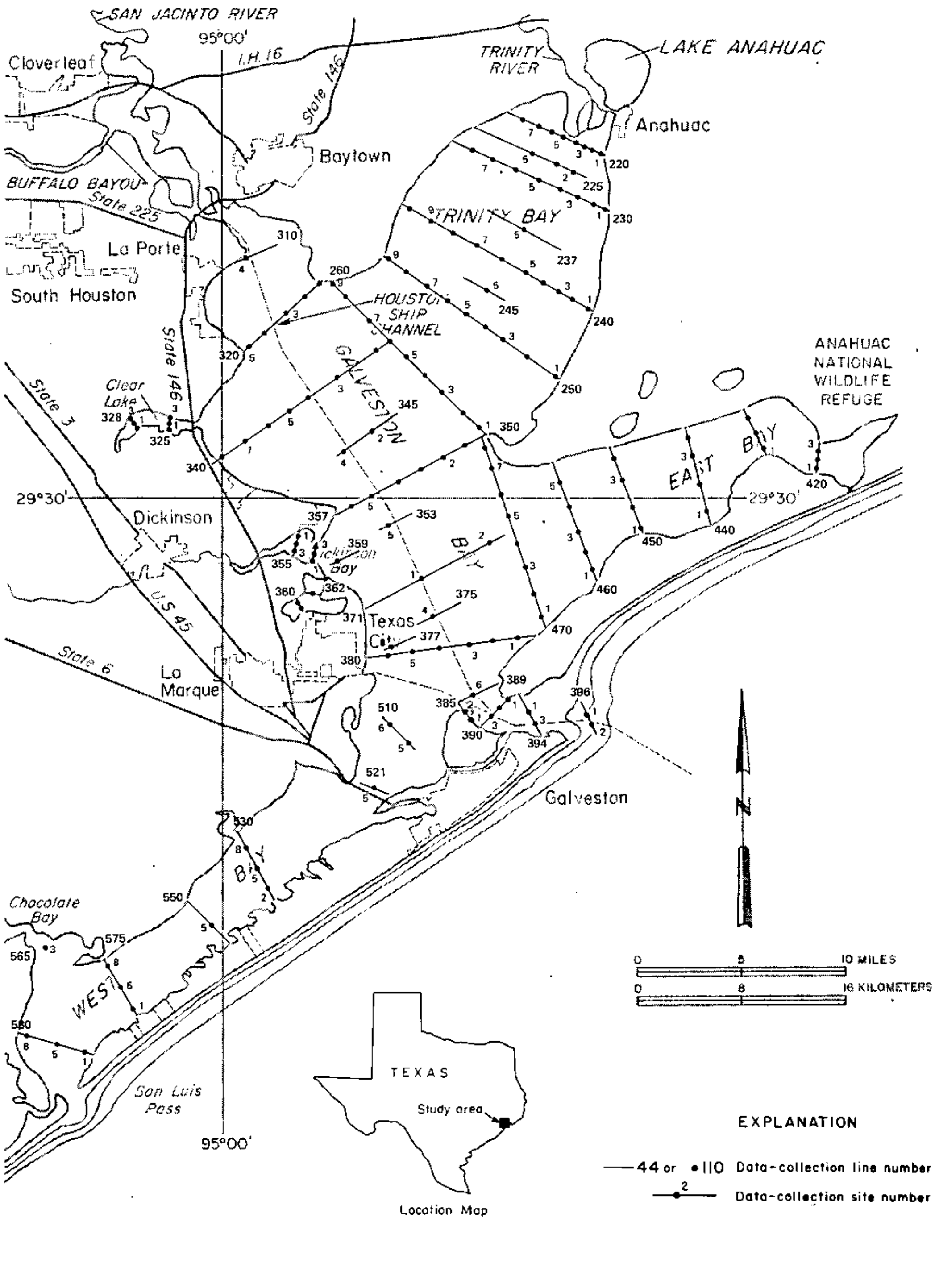


Figure 3-9. Data-Collection Sites in the Trinity-San Jacinto Estuary

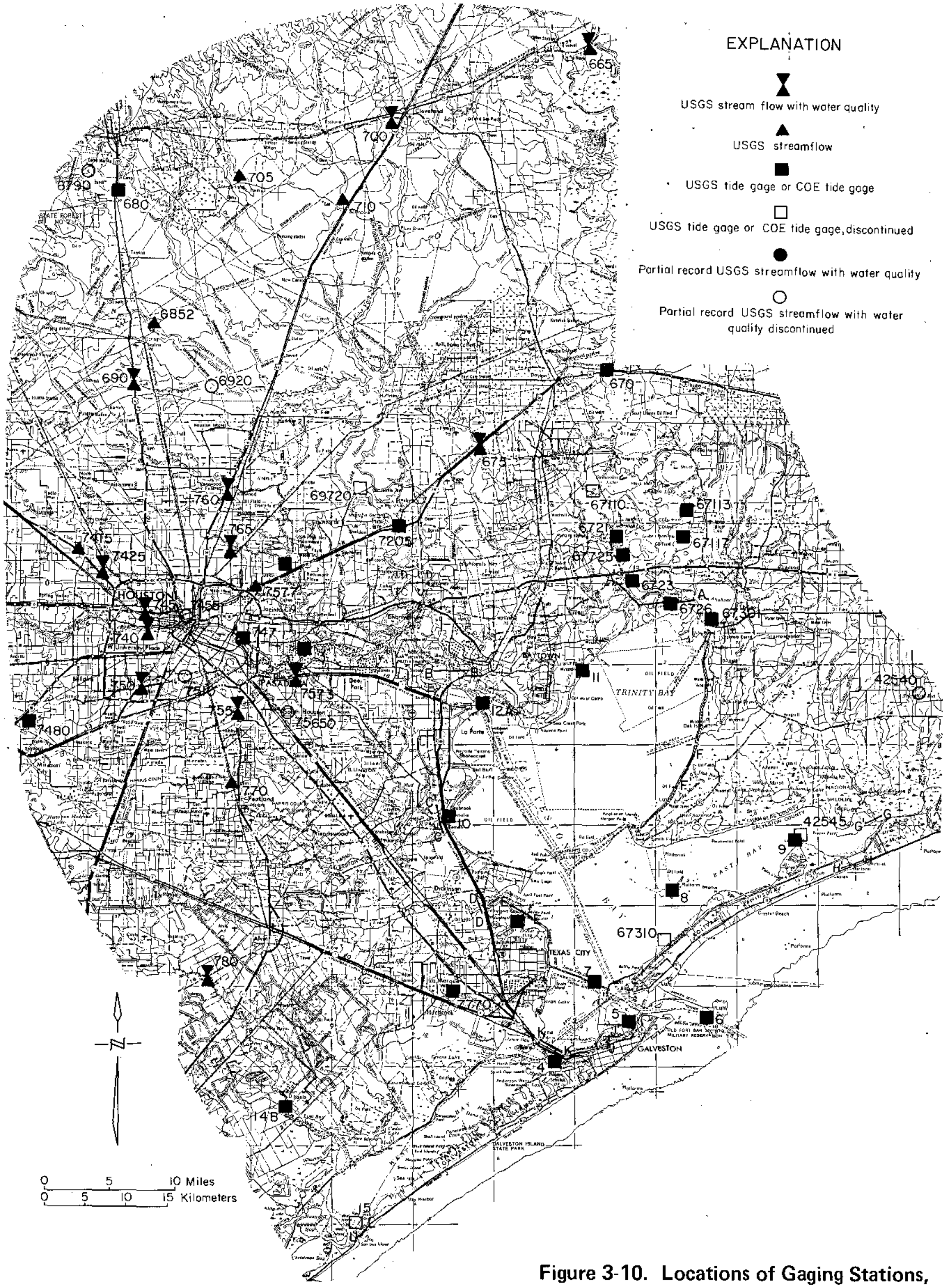


Figure 3-10. Locations of Gaging Stations, Trinity-San Jacinto Estuary

Table 3-2. U. S. Geological Survey (USGS) or Corps of Engineers (COE) Gages, Trinity-San Jacinto Estuary

Station Number	Station Description	Period of Record	Operating Entity	Type of Record
	<u>Stream Gages</u>			
42540	East Bayou nr. Stowell, Tx.	1967-72	USGS	Continuous Recording
66500	Trinity River at Romayor	1924-	USGS	Continuous Recording
67500	Cedar Bayou nr. Crosby, Tx.	1971-	USGS	Continuous Recording
68000	West Fork San Jacinto River nr. Conroe	1961-	USGS	Continuous Recording
68520	Spring Creek at Spring	1939-	USGS	Continuous Recording
69000	Cypress Creek nr. Westfield	1944-	USGS	Continuous Recording
69720	Lake Houston nr. Sheldon	1954-	USGS	Continuous Recording
70000	East Fork San Jacinto River nr. Cleveland	1939-	USGS	Continuous Recording
70500	Caney Creek nr. Splendora	1943-	USGS	Continuous Recording
71000	Peak Creek at Splendora	1943-	USGS	Continuous Recording
73700	Piney Creek nr. Piney Point	1963-	USGS	Continuous Recording
74150	Cole Creek at Deihl Road, Houston	1964-	USGS	Continuous Recording
74250	Brickhouse Gulley at Costa Rica Street, Houston	1964-	USGS	Continuous Recording
74500	Whiteoak Bayou at Houston	1936-	USGS	Continuous Recording

(continued)

Table 3-2. U. S. Geological Survey (USGS) or Corps of Engineers (COE) Gages, Trinity-San Jacinto Estuary (cont'd.)

Station Number	Station Description	Period of Record	Operating Entity	Type of Record
75000	Brays Bayou at Houston	1936-	USGS	Continuous Recording
75500	Sims Bayou at Houston	1952-	USGS	Continuous Recording
75730	Vince Bayou at Pasadena	1971-	USGS	Continuous Recording
75770	Hunting Bayou at Hwy. 610	1964-	USGS	Continuous Recording
76000	Greens Bayou nr. Houston	1952-	USGS	Continuous Recording
76500	Halls Bayou at Houston	1952-	USGS	Continuous Recording
76700	Greens Bayou at Ley Road	1962, 1964, 1971-	USGS	Continous Recording
77000	Clear Creek nr. Pearland	1963-	USGS	Continuous Recording
78000	Chocolate Bayou nr. Alvin	1959-	USGS	Continuous Recording
	<u>Partial Record Stream Gages</u>			
67900	Lake Creek nr. Conroe	1968-	USGS	Limited Data
69200	Cypress Creek nr. Humble	1970-	USGS	Limited Data
74550	Little White Oak Bayou at Houston	1971-	USGS	Limited Data
75100	Brays Bayou at Scott Street	1971-	USGS	Limited Data
75650	Berry Bayou at Forest Oaks Street	1964-	USGS	Limited Data

(continued)

Table 3-2. U. S. Geological Survey (USGS) or Corps of Engineers (COE) Gages, Trinity-San Jacinto Estuary (cont'd.)

Station Number	Station Description	Period of Record	Operating Entity	Type of Record
	Tide Gages			
4	Railroad Causeway to Mainland	1962-	COE	Continuous Recording
5	Galveston Harbor, Ft. Point	1968-	COE	Continuous Recording
6	Galveston Bay Entr. Channel, So.	1962-	COE	Continuous Recording
7	North Texas City Dyke	1962-	COE	Continuous Recording
8	Hanna Reef, Moody Pass	1962-	COE	Continuous Recording
9	Marsh Point, Sun Oil Channel	1962-	COE	Continuous Recording
10	Seabrook, Texas Parks & Wildlife	1970-	COE	Continuous Recording
11	Trinity Bay, Point Barrow	1962-	COE	Continuous Recording
12A	Morgan Point, Barbours Cut	1962-65	COE	Continuous Recording
13	Texaco Oil Dock, Galenda Park	1962-	COE	Continous Recording
14B	Chocolate Bayou, Lost Lake, AMOCO Dock	1975-	COE	Continuous Recording
15	Highway Bridge, San Louis Lake	1968-	COE	Continuous Recording
42545	Galveston Bay nr. Marsh Point	1975-76	USGS	Continuous Recording
67000	Trinity River nr. Liberty	1922-	USGS	Continuous Recording

(continued)

Table 3-2. U. S. Geological Survey (USGS) or Corps of Engineers (COE) Gages, Trinity-San Jacinto Estuary (cont'd.)

Station Number	Station Description	Period of Record	Operating Entity	Type of Record
67110	Big Caney Creek nr. Mont Belvieu	1976-77	USGS	Continuous Recording
67113	Sulfur Barge Canal nr. Wallisville	1976-77	USGS	Continuous Recording
67117	Lake Charlott nr. Wallisville	1976-	USGS	Continuous Recording
67210	Old River nr. Mont Belvieu	1977-	USGS	Continuous Recording
67230	Old River Lake nr. Wallisville	1976-	USGS	Continuous Recording
67725	Lost River nr. Wallisville	1976-	USGS	Continuous Recording
67260	Old River Cutoff Channel nr. Wallisville	1976-	USGS	Continuous Recording
67301	Anahuac Channel at Anahuac	1976-	USGS	Continuous Recording
67310	Galveston Bay nr. Crystal Beach	1975-76	USGS	Continuous Recording
697205	San Jacinto nr. Sheldon	1970-	USGS	Continuous Recording
74700	Buffalo Bayou at 69th Street, Houston	1961-	USGS	Continuous Recording
74800	Keegans Bayou at Roark Rd., Houston	1964-	USGS	Continuous Recording
77650	Moses Lake - Galveston Bay nr. Texas City	1967-	USGS	Continuous Recording
77700	Highland Bayou at Hitchcock	1963-	USGS	Continuous Recording

2.4 percent, respectively; while Chambers and Galveston Counties increased at more modest rates of 1.0 percent and 1.4 percent annually. During the same period, the State of Texas was gaining population at an annual growth rate of 1.7 percent.

In 1975, the population of the four county area was 2,279,400. Harris County accounted for 86.1 percent followed by Galveston County with almost eight percent. Population forecasts for the period 1970 to 2030 indicate that the population of the study area can be expected to increase 214 percent by the year 2030. Harris County is projected to remain the most populated county in the area, and also the second fastest growing, with an annual rate of growth (2.0 percent) exceeded only by Brazoria County (2.1 percent). Estimates of future population for the four county area are presented in Table 3-3.

Income. Real personal income for the four county study region comprised approximately 21 percent or $7.52 billion of the state's estimated personal income in 1970. Harris County accounted for more than 87 percent of the regional estimate, followed by Galveston (7.8 percent), Brazoria (4.6 percent), and Chambers (.6 percent).

Employment. In 1970, an estimated 820,862 persons were employed in the study area, and almost 87 percent of these (711,749) worked in Harris County. Chambers County had the lowest employment, only 0.5 percent of the regional total.

Seventy-six percent of the region's employed labor force is distributed among eight major industrial sectors (Table 3-4). More workers are involved in wholesale and retail trade than any other sector -- over 182 thousand or 22.2 percent of the total. Manufacutring is also a major employer in the area, accounting for 168 thousand workers, over 20 percent of the labor force.

Industry. The "basic" industries in the area, i.e., those which produce tangible output largely for export, are manufacuturing, agriculture-forestry-fisheries, and mining (Table 3-5). These sectors account for over 24 percent of all employment in the study area. In addition to the basic sectors are the service sectors: wholesale and retail trade, professional services, construction, civilian government, and amusement and recreation. These sectors employ over 52 percent of the region's workers. The service sectors provide goods and services to the basic industries as well as to the general public and are, in varying degrees, dependent upon them.

The most important basic sector of the regional economy, in terms of total earnings, as well as employment, is manufacturing (Table 3-5). Most of the manufacturing activity is concentrated in the production of machinery products, chemicals and petroleum refining and related products.

Table 3-3. Population Estimates and Projections, Area Surrounding Trinity-San Jacinto Estuary, 1970-2030 (272)

County	1970	1975	1980	1990	2000	2010	2020	2030	1970-2000 Annual % Change	1970-2030 Annual % Change
Brazoria	108,312	122,800	140,300	176,900	218,400	262,500	314,500	375,000	2.4	2.1
Annual % Change	2.5	2.7	2.3	2.1	1.9	1.8	1.8			
Chambers	12,187	12,800	13,600	14,900	16,500	18,600	21,500	25,700	1.0	1.3
Annual % Change	1.0	1.2	.92	1.0	1.2	1.5	1.8			
Galveston	169,812	182,000	197,200	226,000	257,600	291,600	333,500	384,800	1.4	1.4
Annual % Change	1.4	1.6	1.4	1.3	1.3	1.4	1.4			
Harris	1,741,912	1,961,800	2,243,400	2,763,500	3,357,100	4,005,300	4,746,200	5,601,300	2.2	2.0
Annual % Change	2.4	2.7	2.1	2.0	1.8	1.7	1.7			
Area Total	2,032,223	2,279,400	2,594,500	3,181,300	3,849,600	4,578,000	5,415,700	6,386,800	2.2	1.9
Annual % Change	2.3	2.6	2.1	1.9	1.7	1.7	1.7			
State Total	11,198,655	12,193,200	13,393,100	15,593,700	18,270,700	21,540,600	25,548,400	30,464,900	1.6	1.7
Annual % Change	1.7	1.9	1.5	1.6	1.7	1.7	1.8			

Table 3-4. Employment by Industrial Sector, Area Surrounding Trinity-San Jacinto Estuary, 1970 (266)

Sector	1970					
	Brazoria	Chambers	Galveston	Harris	Total	Percent of Total Employment of Study Area
Wholesale and Retail Trade	6,707	974	12,225	162,540	182,446	22.2
Manufacturing	11,765	521	13,156	143,039	168,481	20.5
Professional Services	5,483	604	13,087	115,339	134,513	16.4
Construction	5,303	507	6,390	63,348	75,548	9.2
Agriculture, Forestry, and Fisheries	1,475	587	1,033	5,666	8,761	1.1
Mining	975	342	629	20,246	22,192	2.7
Civilian Government	468	166	3,213	24,617	29,469	3.6
Amusement and Recreation	180	4	464	5,729	6,377	.78
All Other	6,455	586	14,814	171,225	193,080	23.5
Total	39,811	4,291	65,011	711,749	820,862	100.0

Table 3-5. Earnings by Industrial Sector, Area Surrounding Trinity-San Jacinto Estuary, 1970 (265)

Sector	1970					
	Brazoria	Chambers	Galveston	Harris	Area Total	Percent of Total Earnings in Study Area
	(Thousands of 1967 Dollars)					
Wholesale and Retail Trade	35,926	5,425	67,132	1,169,536	1,278,019	19.9
Manufacturing	98,738	4,116	103,565	1,288,845	1,495,264	23.2
Professional Services	19,516	2,235	47,754	551,470	620,975	9.6
Construction	34,944	3,474	43,166	560,727	642,310	10.0
Agriculture, Forestry, and Fisheries	6,342	2,624	4,554	32,725	46,246	.72
Mining	10,219	3,727	6,758	285,038	305,741	4.7
Civilian Government	26,456	3,111	59,359	595,922	684,847	10.6
Amusement and Recreation	709	17	1,873	30,300	32,899	.51
All Other	32,936	2,937	81,742	1,213,186	1,330,801	20.7
County Totals	265,785	27,666	415,902	5,727,749	6,437,102	100.0

The mineral wealth of the area is also an important factor in its economy. In 1976, the four counties produced over $1.5 billion worth of oil, gas, stone, clay, sand and gravel, cement, magnesium and lime. These mineral products supply raw materials for the petroleum refining and petrochemical industries and other manufacturers, as well as inputs for the construction sector of the economy.

The area surrounding the Trinity-San Jacinto estuary produces a significant portion of the coastal region's agricultural output, with 1977 annual receipts from crops and livestock of $108.2 million. All four counties were rice and soybean producers; other major regional crops were grain sorghum, cotton and corn. Crop production accounted for 72 percent of regional farm income, and the remaining 28 percent originated from livestock and poultry enterprises. In addition, the bay-supported commercial fishing industry provides fish and shellfish seafoods to local and regional markets.

Summary. The four county area possesses abundant natural and man-made resources. Examination of projected trends in population, industrial composition and earnings, and personal income provides an insight into the future course of the area's economy. Just as the current strength of the economy can be attributed to the diversity of the area's industrial structure, the future health of the region will depend on the extent to which such diverse industrial activities as manufacturing, agriculture, tourism, commercial fishing, and oil and gas mining are able to coexist in the bay environment.

The economic outlook for the study area is bright due primarily to the growth potential of the petrochemical complex, but also attributable to the industry mix and diversity of the region. The manufacturing base of the area should broaden and be supported by large-scale mining, agricultural and agribusiness operations. This should be accompanied by major increases in employment and earnings in the trade, service and government sectors of the regional economy. The water-oriented outdoor recreational potential of the area must be expanded as well to keep pace with the rest of the economy. If this potential is not maintained and enhanced, it could slow the economic progress of the area and restrict rapidly increasing income levels and job opportunities.

Economic Importance of Sport and Commercial Fishing

Introduction. Concurrent with the biological and hydrological studies of the Trinity-San Jacinto estuary system, analyses have been performed to compute estimates of the quantities of sport and commercial fishing and the economic impacts of these fisheries upon the local and state economies. The sport fishing estimates are based upon data obtained through surveys of a sample of fishing parties and upon the analytic methods presented below. The commercial fishing estimates were based on data from published statistical series about the industry.

Sport Fishing Data Base. In cooperation with the Texas Parks and Wildlife Department, three types of sample surveys were conducted for the purpose of obtaining the data necessary for these studies of sport fishing in the Trinity-San Jacinto estuary. The surveys included: (1) personal interviews;

(2) roving counts; and (3) motor vehicle license plate counts (295). Personal interviews of a sample of sport fishing parties on randomly selected weekend days were conducted at major access points to the Trinity-San Jacinto estuary for the purpose of obtaining sample data pertaining to fish catch, cost of fishing trip, and personal opinion information. Concurrent with the personal interview survey, counts of sport fishermen and boat trailers were made at a statistically randomized sample of boat ramps and wade-bank areas to estimate the number of sport fishing parties in the bay area. Data for the personal interview sample and fishermen counts conducted during the period September 1, 1976 through August 31, 1977 were used in this analysis. A motor vehicle license plate survey was conducted during the summer of 1977 to obtain additional information on sport fishing visitation patterns by county of origin.

Sport Fishing Visitation Estimation Procedures. Estimates of total sport fishing parties were made using data obtained from the personal interview survey and the fishermen and boat trailer counts from the roving count survey. The fishing party was selected as the unit of measurement because expenditures were reported for parties as opposed to individuals. Sample data from the personal interview survey were analyzed to determine the average number of fishermen per party, the average number of hours fished per party, and the proportion of boat fishermen actually fishing in the study area. Each of these average computations was stratified according to calendar quarter and fishing strata (boats or wade-bank).

The roving count sample survey consisted of boat trailer counts at each of the designated boat ramps within the study area (estuary system). An adjustment of the boat trailer count was made to correct for those boats which were not fishing in the estuary system. Sample data from the boat party personal interview survey were used to estimate the proportion of boat parties that were fishing in the study area.

The estimated number of fishing parties at the Trinity-San Jacinto estuary for the study period is stated as follows:

$$T = Z + W$$

where:

T = Estimated total annual fishing parties,
Z = Estimated number of boat fishing parties, and
W = Estimated number of wade-bank fishing parties.

Each of the components of the total fishing party estimating equation is defined and explained below:

$Z = \sum_{k=1}^{4} z_k$; (k = 1, 2, 3, and 4) and pertains to the calendar quarters of the year beginning with September 1, 1976.

where:

Z = Estimated number of boat parties fishing in the Trinity-San Jacinto estuary for the period September 1, 1976 through August 31, 1977.

z_k = Estimated number of boat parties fishing in the Trinity-San Jacinto estuary during the kth calendar quarter of the study period.

$$W = \sum_{k=1}^{4} w_k; \ (k = 1, 2, 3, \text{ and } 4) \text{ as explained above.}$$

where:

W = Estimated number of wade-bank parties fishing in the Trinity-San Jacinto estuary for the period September 1, 1976 through August 31, 1977.

W_k = Estimated number of wade-bank parties fishing in the Trinity-San Jacinto estuary during the kth calendar quarter of the study period.

The equation and definitions presented above give the results of the sample estimates of the types of fishing in the estuary. The typical quarterly sample analysis and individual computing methods are stated and defined below for the general case, for weekends. Since roving count and interview data were not collected on weekdays in this study period, weekday analyses were based on the weekday/weekend visitation distribution as observed in the motor vehicle license plate survey. The results for weekdays and weekend days were summed to obtain estimates for the entire quarter.

For boat fishing:

$$z_k = \frac{B_k \cdot H_k \cdot D_k \cdot \sum_{i=1}^{r} \sum_{j=1}^{m} \frac{X_{ij}}{N_{ik}}}{\bar{A}_k}$$

where:

z_k = Estimated number of boat fishing parties on weekend days in quarter k,

B_k = Estimated proportion of trailers for which there were boat parties fishing in the study area in quarter k, on weekend days,

H_k = Number of hours subject to being surveyed per weekend day in quarter k (14 hours per day in fall, 12 hours per day in winter, 14 hours per day in spring, and 15 hours per day in summer),

r = Number of sample boat sites within the study area,

D_k = Weekend days in quarter k,

x_{ij} = Number of trailers counted per hour on weekend days at site i on day j, in quarter k,

N_{ik} = Number of times site i was surveyed on weekend days during quarter k, and

$\bar{A}_k$ = Average number of hours fished per boat party on weekend days in quarter k.

No data were collected for wade-bank and pier fishing in this study period; therefore, the estimate of wade-bank and pier parties was based on the relation of wade-bank to boat fishing and pier to boat fishing as observed in a 1975 study of Galveston Bay (295).

These typical terms for each fishing type were summed as described above to obtain the total annual sport fishing visitation estimate in parties. The number of persons per party, cost per party per trip and county of origin of each party were also computed.

Sport Fishing Visitation Estimates. Results from the visitation estimation equations indicate that 305.8 thousand fishing parties visited the estuary during the period September 1, 1976 through August 31, 1977, (Table 3-6). Seasonal visitation as a percentage of annual visitation ranged from a high of more than 37 percent for the summer quarter to a low of approximately 13 percent during the winter quarter. The distribution of fishing parties by strata indicates that wade-bank fishing accounted for 46.8 percent of annual visitation followed by boat fishing with 45.1 percent (Table 3-6).

Sport Fishing Visitation Patterns. Although the personal interview information included the county of residence of the interviewee, the number of interviews (558 in all) was too small to estimate a general visitation pattern to the estuary system. Thus, an intensive survey was undertaken in the summer of 1977 to observe, in conjunction with the roving count, the motor vehicle license plate numbers of fishing parties. From the license plate numbers, the vehicle's registration county, presumably the fishing party's county of residence, could be determined. In this way, the effective sample size was increased.

The results of the survey show that over 86 percent of fishermen at the Trinity-San Jacinto estuary came from the following five counties -- Harris (61.6 percent of the summer 1977 visitation), Galveston (12.8 percent), Brazoria (5.6 percent), Jefferson (4.6 percent), and Fort Bend (1.7 percent). A more general visitation pattern distinction of "local" and "nonlocal" was also made. "Local," for the purposes of this study, includes counties within approximately 60 miles of the estuary area. For the Trinity-San Jacinto estuary, these counties are Brazoria, Chambers, Harris, Galveston, Liberty, Waller, Fort Bend, and Montgomery. "Non-local" comprises all other Texas counties and out-of-state visitors.

Since it is expected that the proportions of local and nonlocal bay sport fishermen vary from season to season, an attempt was made to estimate this pattern for seasons other than the summer period. The only information available on visitation patterns for all seasons was the sample of personal interview data which, in addition to the small number of observations, was felt to be biased toward local parties. Thus, the summer license survey visitation pattern was compared to the summer interview pattern, for the purpose of computing an adjustment factor. This was applied to the remaining quarters of

Table 3-6. Estimated Seasonal Sport Fishing Visitation to the Trinity-San Jacinto Estuary, 1976-1977 a/

Season b/	Boat	Wade-Bank	Pier	Total - All Strata
		thousands of parties		
Fall	36.8 (2.50)	27.2 (2.06)	4.7 (1.94)	68.7 (2.29)
Winter	13.5 (2.14)	22.5 (1.83)	3.6 (1.88)	39.6 (1.94)
Spring	35.9 (2.38)	40.5 (2.05)	6.5 (2.13)	82.9 (2.20)
Summer	51.7 (2.69)	53.0 (1.95)	9.9 (2.66)	114.6 (2.35)
Total All Seasons	137.9 (2.51)	143.2 (1.98)	24.7 (2.27)	305.8 (2.24)

a/ The figures in parenthesis indicate the average number of fishermen per party for the respective fishing type and quarter.

b/ Fall = September, October, and November
Winter = December, January, and February
Spring = March, April, and May
Summer = June, July, and August

interview data to remove the bias toward local data and provide a more accurate reflection of year-round visitation patterns (Table 3-7).

Sport Fishing Direct Expenditures. During the interview, a question was asked of the party head for total expected cost of the trip for the entire group, including food, lodging, and gasoline. The personal interview survey sample of fishing party expenditure data was grouped by origin (local or nonlocal). The average cost per party for the various fishing types and origins (Table 3-8) was applied to the adjusted visitation distribution estimates (Table 3-7) and visitation estimation by type (Table 3-6) to obtain an estimate of total sport fishing expenditures (Table 3-9). More than 39 percent of the estimated total expenditures ($4.13 million) were made during the summer and nine percent were made during the winter quarter (Table 3-9).

Sport Fishing Economic Impact Analysis. Sport fishing expenditures exert an effect upon the economies of the local regions where fishing occurs and upon the entire State because of transportion expenses, sport fishing equipment sales, and service sector supply and demand linkages directly and indirectly associated with fishing expenses. The direct, or initial, business effects are the actual expenditures for goods and services purchased by sport fishing parties. For this analysis, variable expenditures for transportation, food, lodging, and other materials and services purchased were classified by economic sector. Specifically, the expenditures that vary with size of party, duration of trip, and distance traveled; i.e., variable expenditures, were classified into: recreation (including marinas, boat rental fees, and boat fuel); fisheries (bait); eating and drinking establishments; lodging services; and travel (gasoline and auto service stations). Equipment expenditures for boat insurance, boats, motors, trailers, and fishing tackle are not available. Thus, this analysis is an understatement of the total business associated with sport fishing in the Trinity-San Jacinto estuary.

Indirect impacts are the dollar values of goods and services that are used to supply the sectors which have made direct sales to fishing parties. Each directly affected sector has supplying sectors from which it purchases materials and services. The total amount of these successive rounds of purchases is known as the indirect effect. The total business effects of purchases of supplies and services by fishing parties upon the regional and state economies include the direct and indirect incomes resulting from the direct fishing business. Each economic sector pays wages, salaries and other forms of income to employees, owners and stockholders who in turn spend a portion of these incomes on goods and services. In this study, the method used to calculate this total impact is input-output analysis, using the Texas Input-Output Model (276) and regional input-output tables derived from the State model (282).1/

The expenditure data collected by personal interviews of a sample of fishing parties at the Trinity-San Jacinto estuary (Table 3-9) indicated only the magnitude of variable expenditures by sport fishermen. To estimate the sectorial distribution of all expenditures, the interview data were supplemented with data from estimated retail sales in 1975 by marine sport fishing

1/ Input-output relationships were estimated for Calhoun, Victoria, Jackson, Refugio, and Wharton Counties.

Table 3-7. Estimated Seasonal Sport Fishing Visitation Patterns at the Trinity-San Jacinto Estuary, 1976-1977

Visitation	Fall	Winter	Spring	Summer	Total-Annual
			thousands of parties		
Local	57.4	39.6	76.6	98.2	271.8
Nonlocal	11.3	--	6.3	16.4	34.0
Total Visitation	68.7	39.6	82.9	114.6	305.8

Table 3-8. Estimated Average Cost per Sport Fishing Party by Type and Origin, Trinity-San Jacinto Estuary, 1976-1977

Average Cost per Party	Boat	Wade-Bank	Pier	Weighted Average
		1976 dollars		
Local	15.75	7.53	7.37	11.20
Nonlocal	34.27	31.86	19.35	31.98

Table 3-9. Estimated Sport Fishing Expenditures by Season and Fishing Party Type, Trinity-San Jacinto Estuary, 1976-1977

Season a/	Boat	Wade-Bank	Pier	Total	Percent
		thousands of 1976 dollars			
Fall	691.2	313.1	43.7	1,048.0	25.4
Winter	212.1	169.5	27.0	408.6	9.9
Spring	616.2	379.8	53.4	1,049.4	25.4
Summer	951.8	583.7	89.7	1,625.2	39.3
Total	2,471.3	1,446.1	213.8	4,131.2	100.00

a/ Fall = September, October and November
Winter = December, January and February
Spring = March, April and May
Summer = June, July and August

related industries in the West Gulf of Mexico region (Mississippi delta to Mexican border) (517). To account for different origins and types of fishing parties, variable expenditures were analyzed for each of the four types of fishing parties: local boat parties; local wade-bank parties; nonlocal wade-bank parties; and nonlocal boat parties. Variable expenditures, except for travel, were classified as having been made within the local region, since that is the site at which the service is produced. For the travel sector, it was assumed that one-half of the expenditures occurred within the local area and one-half occurred elsewhere in the state en route to the study area.

The results of the survey show that variable sport fishing expenditures in the local area of the Trinity-San Jacinto estuary were over $4.0 million. In addition, there was an estimated $125 thousand spent outside the region, within Texas (Table 3-10). Most of the expenditure impact, over 96 percent, accrues to the region. However, when the total impacts are calculated, the regional gross impact of over $9.16 million accounts for only 68 percent of the gross dollar value statewide (Table 3-11). This spreading of impact results from business and industry market linkages among regional establishments and suppliers throughout the State.

A significant portion (over 36 percent) of the direct expenditures by sport fishermen in the region results in increased personal incomes for regional households directly affected by the sport fishing industry. From these data it is estimated that regional households received an increased annual income of over $2.73 million from the sport fishing business in the area (Table 3-11). Statewide, the income impact amounted to over $3.82 million, annually.

The input-output analysis estimated a total of 255 full time job equivalents directly related to sport fishing in the Trinity-San Jacinto estuary region in 1976 through 1977. Statewide, an additional eleven full time job equivalents were estimated to be directly related to the expenditures for sport fishing. The total employment impact to the state economy was 450 full time job equivalents (Table 3-11).

Revenues to state and local governments (including schools) are positively impacted by the increased business activity and gross dollar flows from sport fishing business. The total statewide state tax revenues amounted to $139 thousand, with $91.3 thousand collected in the local region. Most of the state revenues were received from the rest of the State and not from the surrounding estuarine region. However, the total tax revenue impacts for local jurisdictions were concentrated within the region where an estimated $155.6 thousand resulted from direct, indirect and induced sport fishing expenditures (Table 3-11). In addition, local governments outside the Trinity-San Jacinto estuary region collected an estimated $41 thousand in taxes on travel expenditures by fishing parties in 1976 through 1977.

The data show that sport fishing in the Trinity-San Jacinto estuary region has a larger economic impact within the region than areas outside the region, $4.22 million compared to $9.13 million, respectively. However, data necessary to analyze the effects of sport fishing equipment business were not available. Thus, the annual statewide gross output impact of over $13.38 million represents a contribution to the State's economy from only the variable expenditures by sport fishermen in the estuary region and does not include the effects of purchases of sport fishing equipment.

Table 3-10. Estimated Sport Fishing Variable Expenditures by Sector, Trinity-San Jacinto, Estuary, 1976-1977

	Bait	Travel	Food	Lodging	Recreation a/	Total
	thousands of 1976 dollars					
Total	947.2	909.9	1,014.6	308.6	950.9	4,131.2 b/

a/ Marinas, boat fuel, and boat rental.
b/ Adjusted for travel expenditures outside the study area of $125.1 Expenditures in the region = $4,006.1 thousand.

Table 3-11. Direct and Total a/ Economic Impact from Sport Fishing Expenditures, Trinity-San Jacinto Estuary, 1976-1977 b/

	Direct c/		Total	
	Regional	State	Regional	State d/
Output (thousands)	$4,006.1	$4,131.2	$9,162.7	$13,385.8
Employment (Man-Years)	255	266	368	450
Income (thousands)	1,477.1	1,539.5	2,732.6	3,829.4
State Tax Revenues (thousands)	e/	35.7	91.3	139.0
Local Tax Revenues (thousands)	e/	53.5	155.6	217.4

a/ Total = direct, indirect, and induced
b/ Values in 1976 dollars
c/ Direct impacts for the region and state differ due to the travel expenditure adjustment
d/ Statewide expenditures include the regional impacts
e/ Data not available

Economic Impact of Commercial Fishing. The analysis of the commercial fishing industry in the Trinity-San Jacinto estuary was somewhat limited by the availability of estuary-specific data. Estimates made of the estuary's total contribution to Texas commercial fisheries harvests were based on the inshore-offshore catch distribution. However, the specific markets into which the fisheries catches were marketed are not known. Thus, for this portion of the analysis it was assumed that the markets were in Texas and that the statewide average prices were appropriate and applicable.

The average annual commercial fishing contribution of the estuary was estimated at 827,700 pounds (375,440 kg) of finfish and 40,792,500 pounds (18.5 million kg) of shellfish for the period 1972 through 1976. Using 1976 average dockside finfish and shellfish prices ($.357 per lb. and $1.456 per lb., respectively), the direct commercial value of fish and shellfish attributed to the estuary was estimated at $59.69 million (1976 dollars) (469). Shrimp, blue crab, and oysters constituted approximately 97 percent of this value.

The Texas economy-wide total business resulting from commercial fish catch attributed to the Trinity-San Jacinto estuary was estimated using the 1972 Texas Input-Output Model fisheries sector multipliers. Total value of the catch was $59.69 million, direct employment in the fisheries sector was 2,174, and direct salaries to fisheries employees was $19.94 million (Table 3-12).

Gross Texas business resulting from fishing, processing, and marketing the catch attributed to the estuary was estimated at $185.93 million. Indirect supporting and marketing activities provided an additional 2,173 full time job equivalents regionally and an additional 2,446 full time job equivalents statewide. Gross personal income in Texas attributed to the estuarine fishing and supporting sectors was estimated at $51.13 million, state taxes at $1.69 million, and taxes paid to local units of governments throughout Texas, as a result of this fishery business, at $2.35 million (Table 3-12).

Summary of Economic Impact of the Sport and Commercial Fisheries. Analyses have been performed to compute estimates of the quantities of sport and commercial fishing and the economic impact of these fisheries upon the local and state economies.

Sport fishing expenditures exert an effect upon the economies of the local regions where fishing occurs and upon the entire State because of transportation expenses, sport fishing equipment sales, and service sector supply and demand linkages directly and indirectly associated with fishing expenses. Direct business effects include expenditures for goods and services purchased by sport fishermen (transportation, food, lodging, equipment). Indirect impacts are the dollar value of goods and services that are used to supply the sectors which make these direct sales to fishing parties. Other indirect impacts include wages, salaries and other forms of income to employees, owners and stockholders.

The method of input-output analysis, using both the Texas Input-Output Model and regional tables derived from the state model, was used to calculate the total impact. The results showed that variable sport fishing expenditures in the local area were greater than $4.0 million. In addition, there was an estimated $125 thousand spent outside the region, within Texas.

Table 3-12. Direct and Total a/ Economic Impact of Commercial Fishing in the Trinity-San Jacinto Estuary

	Fishing Sector	Total	
		Regional	State
Output (1000's 1976 $)	59,689.4	126,839.9	185,932.4
Employment (Man-Years)	2,174	3,815	4,619
Income (1000's 1976 $)	19,942.2	42,237.6	51,131.8
State Tax Revenues (1000's 1976 $)	226.8	1,199.8	1,689.2
Local Tax Revenues (1000's 1976 $)	268.6	2,047.3	2,345.8

a/ Total = direct, indirect and induced

Over 36 percent of the direct expenditures by sport fishermen in the region resulted in increased personal incomes for regional households directly affected by the sport fishing industry. Statewide, the income impact amounted to over $3.82 million, annually. In addition, the total employment impact to the State economy was 450 full-time job equivalents.

Revenues to State and local government (including schools) were positively impacted by the increased business activity and gross dollar flows from the sport fishing industry. The total statewide State tax revenues amounted to over $139.0 thousand.

Estimates were made of the total (inshore-offshore) commercial fisheries harvest dependent upon the Trinity-San Jacinto estuary. The average annual commercial fisheries contribution was estimated at 41,620,200 pounds (18.9 million kg) of finfish and shellfish for the period 1972 through 1976. The total value of the catch was $59.69 million (1976 dollars), direct employment in the commercial fisheries sector was 2,174, and direct salaries to employees was $19.94 million.

CHAPTER IV

HYDROLOGY

Introduction

Detailed studies of the hydrology of areas draining to the Trinity-San Jacinto estuary are necessary to estimate historical freshwater inflows from contributory areas, only a portion of which are gaged. Two major river basins contribute to the Trinity-San Jacinto estuary, the Trinity and San Jacinto Basins. Additionally, small coastal basins, including a portion of the Neches-Trinity Coastal Basin, Trinity-San Jacinto Coastal Basin, and the San Jacinto-Brazos Coastal Basin, contribute to the estuary. The previous chapter of this report (Chapter III, "Influence of Contributory Basins") describes upstream reservoirs in the major basins. The present chapter deals with aspects of the quality and quantity of freshwater inflow from a historical perspective.

Freshwater Inflows

Freshwater inflow contributions to the Trinity-San Jacinto estuary consists of (1) gaged inflow from the Trinity and San Jacinto River Basins and San Jacinto-Brazos Coastal Basin; (2) ungaged runoff; (3) return flows from municipal, industrial and agricultural sources in ungaged areas; and (4) direct precipitation on the estuary. The following paragraphs will consider each of these individually. In addition to freshwater inflow, evaporation from the bay surface is considered to arrive at a freshwater inflow balance.

Gaged Inflows from the Trinity Basin

The Trinity River Basin has a total gaged drainage area of 17,186 square miles (44,755 km^2). This inflow enters the estuary through the Trinity delta at the northern edge of Trinity Bay. Gaged contributions of the Trinity River Basin to the estuary have averaged 5,381,000 acre-feet/year (6,608 million m^3/yr) over the period 1941 through 1976 (Table 4-1). Gaged yield from the Trinity Basin (1941-1976) has averaged 313 acre-feet per square mile (1,490 m^3/ha). Gaged Trinity Basin inflows have accounted for 55 percent of the combined inflow1/ and 47 percent of the total freshwater inflow2/ to the Trinity-San Jacinto estuary over the 1941 through 1976 period (Table 4-2).

1/ Combined inflow = (gaged inflow) + (ungaged inflow) + (return flows from ungaged areas) - (diversions below last gage)

2/ Total freshwater inflow = (combined inflow) + (direct precipitation on the estuary).

Table 4-1. Monthly Freshwater Inflow, Trinity-San Jacinto Estuary, 1941-1976 a/

MONTH	GAGED TRINIT. FLOW	GAGED S.JAC. FLOW	GAGED SJ-BRZ FLOW	TOTAL GAGED FLOW	UNGAGED INFLOW	RETURN FLOWS	TRINITY RIVER DIVERSIONS	COMBINED INFLOW	PRECIPITATION ON BAY	TOTAL FRESHWATER INFLOW	BAY EVAPORATION LOSSES	FRESHWATER INFLOW BALANCE
					thousands of acre-feet							
AVERAGE OVER ALL YEARS												
JANUARY	523	187	8	719	212	17	1	948	113	1062	65	997
FEBRUARY	480	175	8	664	242	5	1	912	104	1017	63	953
MARCH	579	118	6	704	172	15	5	887	86	974	77	896
APRIL	624	183	7	815	245	29	25	1065	126	1192	90	1101
MAY	1059	198	12	1269	294	32	36	1559	138	1698	118	1579
JUNE	652	165	13	831	249	34	42	1073	136	1209	146	1062
JULY	256	74	9	340	183	69	42	550	152	703	160	542
AUGUST	103	42	8	153	173	54	32	349	168	517	175	342
SEPTEMBER	145	86	11	243	223	50	21	496	157	653	154	499
OCTOBER	230	106	7	344	193	23	4	555	122	678	144	534
NOVEMBER	316	135	7	459	150	12	2	619	124	743	105	637
DECEMBER	409	122	8	539	196	20	2	754	135	889	78	810
TOTALS	5376	1591	104	7080	2532	360	213	9767	1561	11335	1375	9952
MONTHLY AVERAGE	448	133	9	590	211	30	18	814	130	945	115	829

a/ Rounding errors may result in small differences between Tables 4-1 and 4-2

Table 4-2. Annual Freshwater Inflow, Trinity-San Jacinto Estuary, 1941-1976 a/ b/

YEAR	GAGED TRINIT. FLOW	GAGED S.JAC. FLOW	GAGED SJ-BRZ. FLOW	TOTAL GAGED FLOW	UNGAGED INFLOW	RETURN FLOWS	TRINITY RIVER DIVERSIONS	COMBINED INFLOW	PRECIPITATION ON BAY	TOTAL FRESHWATER INFLOW	BAY EVAPORATION LOSSES	FRESHWATER INFLOW BALANCE
1941	10336	3982	159	14477	4899	122	120	19378	2348	21726	1121	20605
1942	9206	1722	77	11005	2574	136	145	13570	1717	15287	1268	14019
1943	3853	1234	65	5152	2651	152	192	7763	1756	9519	1267	8252
1944	8142	2331	161	10634	3860	151	191	14454	1818	16272	1267	15005
1945	12275	3151	138	15564	4438	154	184	19972	2137	22109	1267	20842
1946	9865	4416	206	14487	6238	160	183	20702	2891	23593	1238	22355
1947	5286	1505	81	6872	1561	162	162	8413	1230	9643	1266	8377
1948	3799	544	70	4413	1109	171	240	5453	996	6449	1266	5183
1949	5303	2608	218	8129	4807	192	259	12869	2187	15056	1239	13817
1950	6962	2012	90	9064	1874	187	220	10905	1270	12175	1414	10761
1951	1503	228	44	1775	713	206	277	2417	1184	3601	1385	2216
1952	2302	773	82	3157	2019	205	249	5132	1444	6576	1386	5190
1953	3975	1366	123	5464	2179	203	230	7616	1585	9201	1474	7727
1954	1272	386	34	1692	356	276	279	2045	800	2845	1592	1253
1955	1782	409	47	2238	1768	320	214	4112	1578	5690	1532	4158
1956	918	121	15	1054	599	326	106	1873	1040	2913	1592	1321
1957	11885	1740	133	13758	3772	319	143	17706	1683	19389	1443	17946
1958	5928	1006	67	7001	2312	351	183	9481	1519	11000	1414	9586
1959	4733	1979	198	6910	3993	348	191	11060	1755	12815	1652	11163
1960	5413	2950	128	8491	2767	373	215	11416	1523	12939	1534	11405
1961	6250	3157	188	9595	4070	368	235	13818	1869	15687	1503	14184
1962	3603	587	65	4255	939	419	271	5342	1177	6519	1532	4987
1963	1522	438	42	2002	677	445	266	2858	865	3723	1208	2515
1964	2199	681	58	2938	1395	448	219	4562	1204	5766	1238	4528
1965	4673	630	53	5356	1038	469	239	6625	1119	7744	1533	6211
1966	6173	1562	143	7878	3655	514	204	11843	1935	13778	1031	12747
1967	2066	224	41	2331	801	533	265	3400	1103	4503	1295	3208
1968	7906	2302	163	10371	3295	551	244	13973	1636	15609	1270	14339
1969	7423	1350	106	8879	2187	562	252	11376	1578	12954	1327	11627
1970	3030	962	105	4097	2957	575	266	7363	1735	9098	1358	7740
1971	2258	359	67	2684	1109	615	259	4149	1293	5442	1574	3868
1972	2487	1373	128	3988	2507	625	220	6900	1399	8299	1445	6854
1973	11039	4021	245	15305	5802	559	211	21455	2241	23696	1406	22290
1974	7581	2552	160	10293	2882	632	251	13556	1597	15153	1502	13651
1975	7222	1627	96	8945	2229	610	221	11563	1873	13436	1418	12018
1976	3538	1215	111	4864	1306	695	205	6660	1387	8047	1485	6562
TOTAL	193708	57503	3907	255118	91338	13154	7830	351780	56472	408252	49742	358510
AVERAGE	5381	1597	109	7087	2537	365	217	9772	1569	11340	1382	9959
MEDIAN	5009	1369	100	6891	2270	349	220	8947	1578	10321	1396	8981
PERCENT	47.5 +	14.1 +	1.0 =	62.5 +	22.4 +	3.3 −	2.0 =	86.2 +	13.9 =	100.0 :	12.2	
PERCENT	55.1 +	16.4 +	1.2 =	72.6 +	26.0 +	3.8 −	2.3 =	100.0 :	16.1			

a/ Units are thousands of acre-feet
b/ Rounding errors may result in small differences between Tables 4-1 and 4-2

Gaged Inflows from the San Jacinto Basin

The total gaged drainage area of the San Jacinto River Basin is 3,520 square miles (9,167 km^2), of which 1,741 square miles (4,534 km^2) were gaged above Lake Houston prior to 1953. An additional 2,828 square miles (7,365 km^2) of drainage area have been gaged since 1953.

The magnitude of San Jacinto River Basin flow passing into the estuary is dependent on the spills from Lake Houston. To determine the portion of the San Jacinto River flow that enters the estuary through Lake Houston, the magnitude of spills was developed by means of a reservoir operation study from 1954 through 1976 (Figure 4-1). Over the period 1941 through 1976, average annual gaged inflow to the estuary from the San Jacinto River Basin was 1,597,000 acre-feet (1,970 million m^3) (Table 4-2). Gaged yield from the San Jacinto River Basin (1941-1976) has averaged 454 acre-feet per square mile (2,162 m^3/ha). Gaged San Jacinto River Basin inflows accounted for 16 percent of the combined inflow and 14 percent of the total freshwater inflow over the 1941 through 1976 period.

Gaged Inflows from the San Jacinto-Brazos Coastal Basin

The total gaged drainage area of the San Jacinto-Brazos Coastal Basin is 126.1 square miles (328 km^2). The Clear Creek gage at Pearland (USGS Gage #08077000) and Chocolate Bayou gage near Alvin (USGS Gage #08078000) were utilized for determining gaged freshwater inflow. Over the period 1941 through 1976, average annual inflow to the estuary from the San Jacinto-Brazos Coastal Basin was 109,000 acre-feet (130 million m^3) (Table 4-2). Gaged yield from the San Jacinto-Brazos Coastal Basin (1941-1976) has averaged 865 acre-feet per square mile (4,119 m^3/ha). Gaged basin inflows accounted for 1.2 percent of the combined inflow and 1.0 percent of the total freshwater inflow over the 1941 through 1976 period.

Ungaged Runoff Contributions

Ungaged drainage areas contributory to the Trinity-San Jacinto estuary include some 2,640 square miles (6,875 km^2)1/ in the San Jacinto-Brazos Coastal Basin, the Trinity-San Jacinto Coastal Basin, Neches-Trinity Coastal Basin, the Trinity River Basin, and the San Jacinto River Basin. To facilitate the study of inflow contributions, the ungaged drainage area immediately contributing to the Trinity-San Jacinto estuary and above Lake Houston was divided into 45 subbasins (Figure 4-2). Using a Thiessen network (387) the weighted daily precipitation was determined for each subbasin (Table 4-3). A water yield model which uses daily precipitation, Soil Conservation Service average curve numbers, and soil depletion index (Beta) to predict runoff from small watersheds was calibrated with the 16 gaged subbasins located within the contributing drainage area (374). Statistical correlations between annual and monthly gaged total inflow and simulated runoff were used to determine the "goodness of fit" of the calibration procedure. The calibrated model was then applied to the ungaged subbasin to calculate the ungaged runoff (Table 4-3).

1/ With the installation of one coastal gage in 1972, the ungaged drainage area decreased to 2,575 square miles (6,706 km^2).

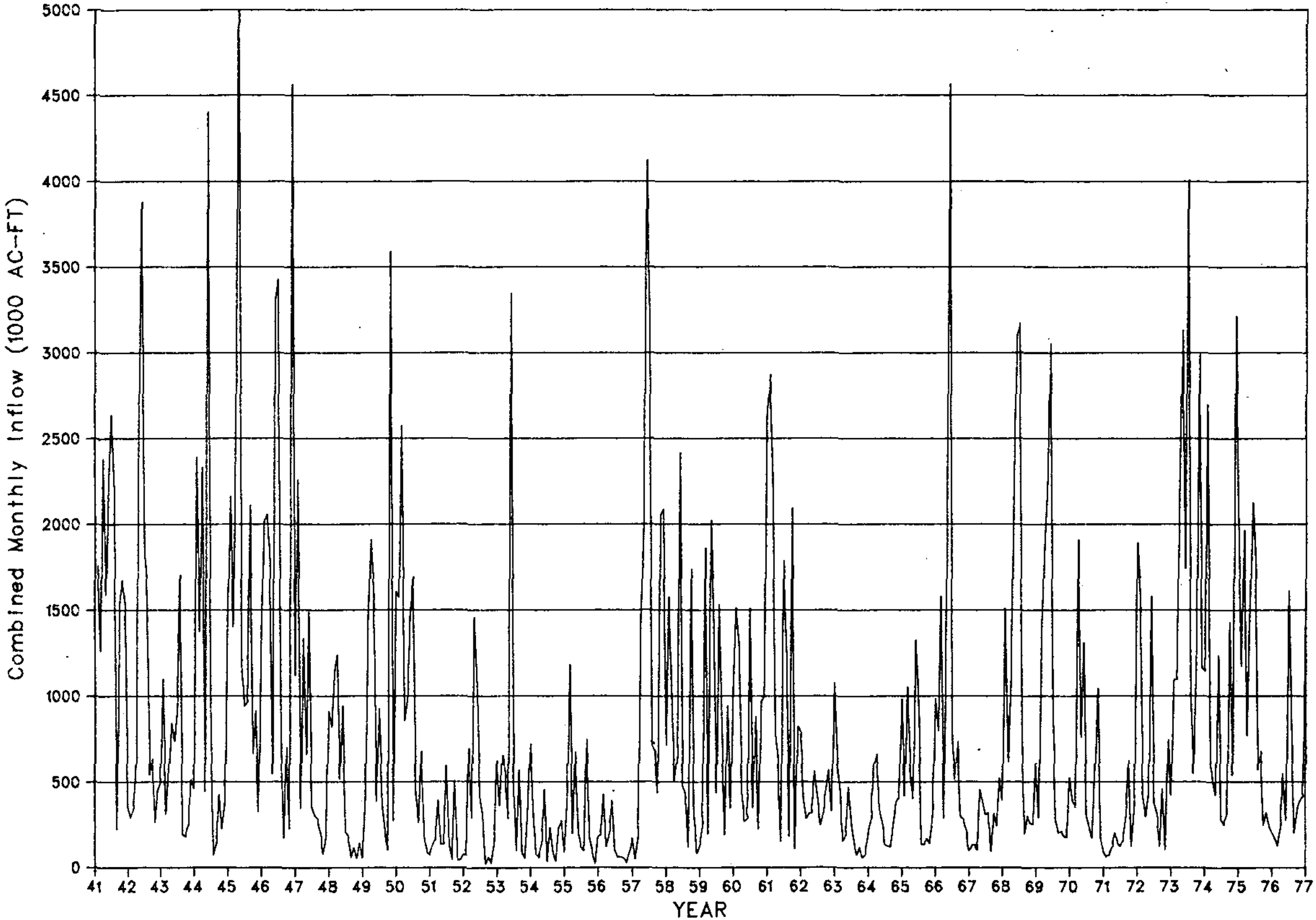
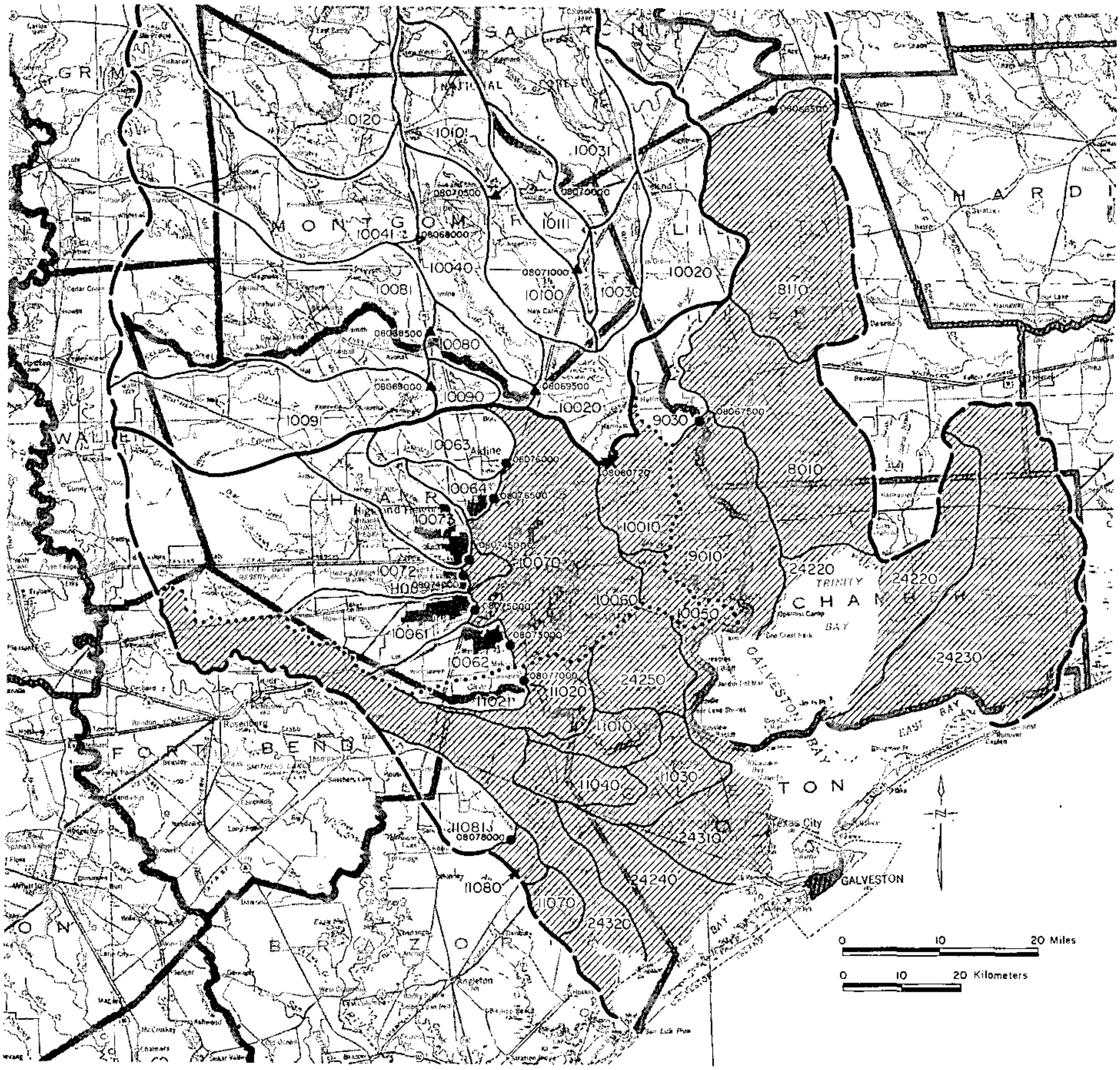


Figure 4-1. Combined Monthly Inflow to the Trinity-San Jacinto Estuary, 1941-1976



EXPLANATION

U.S.G.S. GAGING STATIONS

▲ 08069000 Streamflow into Lake Houston

● 08078000 Streamflow into Ungaged Areas

★ 08080720 Reservoir Contents Gage

Ungaged Area

Boundary of Area Contributing to Lake Houston

• • • • • San Jacinto River Basin Boundary

11020 Subbasin Number (See Table 4-3)

Figure 4-2. Ungaged Areas Contributing to Trinity-San Jacinto Estuary

Table 4-3. Runoff from Ungaged Areas, Trinity-San Jacinto Estuary

Subbasin Description	Drainage Area (mi^2)	Weighted Precipitation: NWS a/ Station No.	Weighted Precipitation: Weight b/ Factor	Average Runoff ac-ft/mi^2 (1941-1976)	Average Curve Number c/ / Beta $x10^{-6}$ d/	Explained Variation: Annual r^2	Explained Variation: Monthly r^2	Gaged: USGS Station No.	Gaged: Period of Record
8010 Wallisville Trinity River tidal	501.0	5196 0235	.68 .80	1133	87/68.1	-	-	-	-
8110 Liberty Trinity River above tidal	282.0	5196 8265	.559 .441	820	83/77.9	-	-	-	-
9010 Cedar Bayou tidal-drains City of Baytown and surrounding area	52.0	0235 4307	.80 .20	1010	85/75.8	-	-	-	-
9020 Cedar Bayou above tidal	64.9	5196	1.00		84/103.0	.96	.75	08067500	1972-76
10010 San Jacinto River tidal 200 yards below IH10 bridge to Lake Houston	60.0	5196 4323 4305 4307	40 10 30 20	685	80/86.7	-	-	-	-
10050 Houston ship channel Morgans Pt. to San Jacinto, including tidal portion of San Jacinto River to 200 yds. below IH10 bridge	50.0	4307	1.00	706	80/84.4	-	-	-	-
10060 Houston Ship channel ungaged tidal portion San Jacinto River and tributaries confluence to turning basin	340.2	4307 4305 4323 8928	.36 .34 .21 .09	910	85/65.6	-	-	-	-
10070 Houston ship channel turning basin	27.3	4305 4323	.61 .39	678	80/81.7	-	-	-	-
11010 Clear Creek tidal	50.0	0204 4307	.82 .08	904	85/63.7	-	-	-	-
11020 Clear Creek above tidal	81.2	0204 4307	.32 .68	917	85/67.1	-	-	-	-
11030 Dickenson Bayou tidal	60.0	0204	1.00	852	84/66.8	-	-	-	-
11040 Dickenson Bayou	50.0	0204	1.00	852	84/66.8	-	-	-	-

a/ National Weather Service
b/ Percentage of area of influence expressed as a factor (387)
c/ An assigned parameter for a particular hydrologic soil-cover complex (374)
d/ Soil moisture depletion coefficient (374)

(continued)

Table 4-3. Runoff from Ungaged Areas, Trinity-San Jacinto Estuary(cont'd)

Subbasin Description	Drainage Area (mi²)	Weighted Precipitation: NWS a/ Station No.	Weighted Precipitation: Weight b/ Factor	Average Runoff ac-ft/mi² (1941-1976)	Average Curve Number c/ / Beta x10⁻⁶ d/	Explained Variation: Annual r^2	Explained Variation: Monthly r^2	Gaged: USGS Station No.	Gaged: Period of Record
11070 Chocolate Bayou tidal	20.0	0204	1.00	755	82/73.4	-	-	-	-
11080 Chocolate Bayou above tidal	52.7	0204	1.00	757	82/73.4	-	-	-	-
24220 Trinity Bay including Mouth of Trinity River	170.0	0235	1.00	1208	88/63.7	-	-	-	-
24230 East Bay	260.0	0235	1.00	1208	88/63.7	-	-	-	-
24240 West Bay	40.0	0204	1.00	672	80/80.0	-	-	-	-
24250 Clear Lake	80.0	4307 0204	.91 .09	694	80/84.2	-	-	-	-
24260 Tabbs - Black Duck Scott Burnett and San Jacinto Bays	48.0	4307	1.00	706	80/89.4	-	-	-	-
24310 Moses Lake drains Texas City	111.0	0204	1.00	1019	87/59.8	-	-	-	-
24320 Chocolate Bay	210.0	0204	1.00	852	84/66.8	-	-	-	-
24360 Barbours Cut - Bayport Channel	30.0	4307	1.00	947	85/67.2	-	-	-	-
10061 Brays Bayou at Houston	88.4	8728 1838 4325	.15 .40 .45	934	85.3/66.0	.64	.66	08075000	1941-76
10062 Sims Bayou at Houston	64.0	4307 4325	.40 .60	-	83.7/70.3	.86	.82	08075500	1953-76
10063 Greens Bayou at Houston	72.7	4327 4323	.33 .67	-	76.4/95.4	.64	.45	08076000	1953-76
10064 Halls Bayou at Houston	24.7	4327 4323	.10 .90	-	82.27/74.8	.72	.54	08076500	1953-76
10072 Buffalo Bayou at Houston	385.0	4331 4305 4325	.56 .31 .13	-	78.7/86.3	.80	.55	08074000	1941-56 1962-74
10073 White Oak Bayou at Houston	84.7	2206 4305 4331 4327 4323	.023 .046 .158 .707 .066	684	80.4/83.1	.69	.55	08074500	1941-76

a/ National Weather Service
b/ Percentage of area of influence expressed as a factor (387)
c/ An assigned parameter for a particular hydrologic soil-cover complex (374)
d/ Soil moisture depletion coefficient (374)

(continued)

Table 4-3. Runoff from Ungaged Areas, Trinity-San Jacinto Estuary(cont'd)

Subbasin Description	Drainage Area (mi^2)	Weighted Precipitation: NWS a/ Station No.	Weighted Precipitation: Weight b/ Factor	Average Runoff ac-ft/mi^2 (1941-1976)	Average Curve Number c/ / Beta $x10^{-6}$ d/	Explained Variation: Annual r^2	Explained Variation: Monthly r^2	Gaged: USGS Station No.	Gaged: Period of Record
11021 Clear Creek at Pearland	38.8	4307 8728	.60 .40	–	81.0/83.4	.82	.80	08077000	1948-59 1964-76
11081 Chocolate Bayou near Alvin	87.3	0204	1.00		85.4/61.6	.70	.62	08078000	1947-57 1960-76
Trinity River at Romayor	17,186.0	–	–	315	–	–	–	08066500	1941-76
80720 Lake Houston spills (7/53 - 12/76)	2,828.0	–							
10020 Lake Houston	328.0	8265 5196 6280 4323	.33 .16 .45 .06	416	72/118.2	–	–	–	–
10030 East Fork San Jacinto River	73.0	6280	1.00	414	72/121.5	–	–	–	–
10031 East Fork San Jacinto River near Cleveland	325.0	3298 1956 8265 6280 4382 7651	.607 .081 .249 .025 .025 .008	484	75.3/91.8	–	.79	08070000	1941-76
10040 West Fork San Jacinto River	172.0	1956 6280 9076 4323	.231 .542 .094 .133	442	73.3/116.1	–	–	–	–
10041 West Fork San Jacinto River near Conroe	809.0	1956 6024 9076 0244 0635 3298 4382	.126 .392 .028 .150 .072 .014 .216	–	73.2/93.9	–	.70	08068000	1941-76
10042 West Fork San Jacinto near Humble	1,741.0	1956 6024 9076 0244 0635 3298 4382 4323 6280 2206 4080 9448 4327 4704	.090 .218 .180 .073 .033 .006 .100 .022 .074 .060 .017 .089 .009 .028	–	–	–	–	08069500	1941-53
10080 Spring Creek	29.0	6280 9076 4323	.64 .28 .08	403	72/121.3	–	–	–	–
10081 Spring Creek near Spring	409.0	0244 2206 4080 6024 9076 9448	.016 .029 .073 .151 .568 .163	–	73.0/92.0	–	.78	08068520	1941-76
10090 Cypress Creek	37.0	9076 4323	.240 .760	405	72/115.7	–	–	–	–

a/ National Weather Service
b/ Percentage of area of influence expressed as a factor (387)
c/ An assigned parameter for a particular hydrologic soil-cover complex (374)
d/ Soil moisture depletion coefficient (374)

(continued)

Table 4-3. Runoff from Ungaged Areas, Trinity-San Jacinto Estuary(cont'd)

Subbasin Description	Drainage Area (mi^2)	Weighted Precipitation: NWS a/ Station No.	Weighted Precipitation: Weight b/ Factor	Average Runoff ac-ft/mi^2 (1941-1976)	Average Curve Number c/ / Beta x10^{-6} d/	Explained Variation: Annual r^2	Explained Variation: Monthly r^2	Gaged: USGS Station No.	Gaged: Period of Record
10091 Cypress Creek near Westfield	285.0	2206 4323 4327 4704 9076 9448	.324 .021 .053 .172 .124 .306	-	71.4/102.2	-	.69	08069000	1945-76
10100 Caney Creek	98.0	6280	1.00	413	72/121.5	-	-	-	-
10101 Caney Creek near Splendora	105.0	3298 1956 6280	.053 .860 .087	-	74.2/91.9	-	.71	08070500	1944-76
10110 Peach Creek	41.0	6280	1.00	451	73/115.5	-	-	-	-
10111 Peach Creek near Splendora	117.0	6280 1956 8265	.460 .504 .036	-	72.8/97.8	-	.63	08071000	1944-76
10120 Honea above Conroe Reservoir	445.0	0244 0635 1956 3298 4382 6024	.015 .107 .158 .028 .393 .299	440	73/115.7	-	-	-	-

a/ National Weather Service
b/ Percentage of area of influence expressed as a factor (387)
c/ An assigned parameter for a particular hydrologic soil-cover complex (374)
d/ Soil moisture depletion coefficient (374)

During the period 1941 through 1976, ungaged runoff averaged 2,537,000 acre-feet/year (3.13 billion m^3/yr) and runoff yield averaged 961 acre-feet/mi^2 (4,576 m^3/ha)1/. Ungaged inflow accounted for 26 percent of the combined inflow and 22 percent of the total freshwater inflow to the Trinity-San Jacinto estuary over the 1941 through 1976 period (Table 4-2).

Ungaged Return Flows

Return flows from municipalities and industries within the ungaged subbasins were estimated from data provided by the Texas Department of Water Resources (TDWR) self-reporting system. Irrigation return flows in ungaged areas were calculated using agency data collected in rice irrigation return flow studies (376, 379). Average return flows over the 1941 through 1976 period were approximately 365,000 acre-feet per year (450.6 million m^3/yr). Estimated ungaged return flow accounted for four percent of the combined inflow and three percent of the total freshwater inflow to the Trinity-San Jacinto estuary over the 1941 through 1976 period (Table 4-2).

Diversions

Reported diversions for municipal, industrial and irrigation use within the ungaged subbasins were provided by the Texas Department of Water Resources (TDWR) reported water usage system. Average diversions over the 1941 through 1976 period were approximtely 217,000 acre-feet per year (267.9 million m^3). Estimated diversions accounted for 3.8 percent of the combined inflow and 3.3 percent of the total freshwater inflow to the Trinity-San Jacinto estuary (Table 4-2) over the 1941 through 1976 period.

Combined Inflow

A category called combined inflow was obtained by aggregating gaged Trinity River Basin and San Jacinto River Basin inflow, gaged San Jacinto-Brazos Coastal Basin contributions, ungaged runoff, and estimated ungaged return flows. Over the period 1941 through 1976 combined inflows averaged 9,772,000 acre-feet per year (12.05 billion m^3/yr) (Table 4-2). Combined inflow accounted for 86 percent of the total freshwater inflow to the Trinity-San Jacinto estuary over the 1941 through 1976 period. Average monthly distributions of combined inflow are shown in Figure 4-3.

Precipitation on the Estuary

Direct precipitation on the 353,730 acre (143,153 ha) surface area of Trinity-San Jacinto estuary was calculated using Thiessen-weighted precipitation techniques (387). Over the 1941 through 1976 period, annual mean precipitation amounted to 1,569,000 acre-feet per year (1.93 billion m^3/yr). Direct precipitation accounted for 14 percent of the total freshwater inflow to the Trinity-San Jacinto estuary over the period 1941 through 1976 (Table 4-2).

1/ Ungaged drainage area held constant at 2,640 sq. mi. (6,875 km^2).

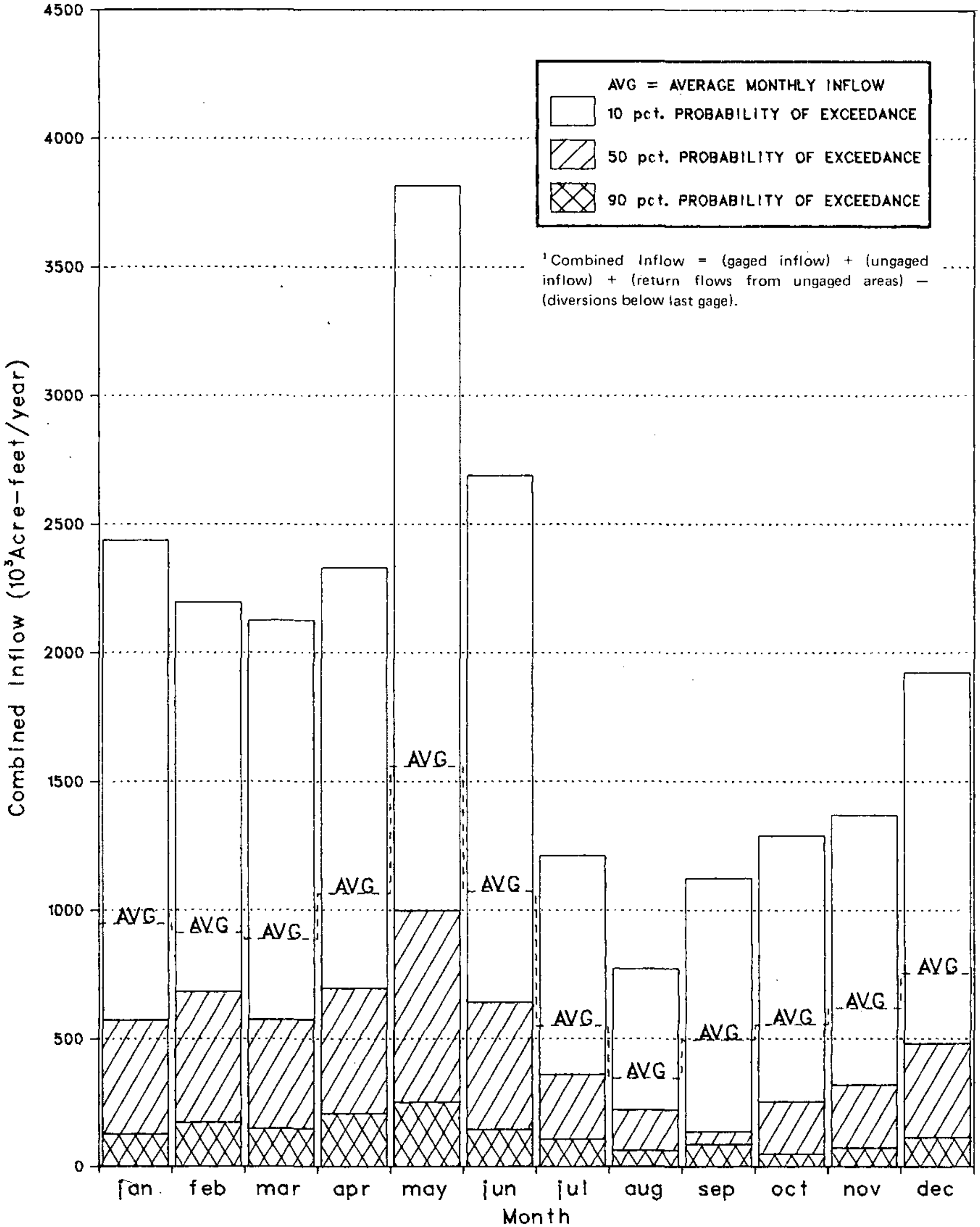


Figure 4-3. Monthly Distribution of Combined Inflow,[1] Trinity-San Jacinto Estuary, 1941-1976

Total Freshwater Inflow

Total freshwater inflow includes gaged Trinity River Basin and San Jacinto River Basin inflows, gaged San Jacinto-Brazos Coastal Basin contributions, ungaged runoff, return flows from ungaged areas and direct precipitation on the estuary. For the 1941 though 1976 period, average annual freshwater inflow amounted to 11,340,000 acre-feet (14.00 billion m^3). Average monthly distributions of total freshwater inflow are shown in Figure 4-4.

Bay Evaporation Losses

Gross surface evaporation rates for the estuary were calculated from Texas Department of Water Resources pan evaporation data (377). Since the reduction in evaporation due to estuarine salinity is never in excess of a few percent (over an extended period of time), salinity effects were omitted in the estimation of evaporation rates. Over the period 1941 through 1976, mean evaporation over the 353,730 acre (143,153 ha) estuary surface averaged 1,382,000 acre-feet per year (1.70 billion m^3/yr). When compared to total freshwater inflow, evaporation on the estuary's surface was about 12 percent of total inflow over the 1941 through 1976 period.

Freshwater Inflow Balance

A freshwater inflow balance for the period of 1941 through 1976 is shown in Table 4-2. A negative number in some years indicates evaporation exceeding total freshwater inflow (during periods of extreme drought). For the 1941 through 1976 period, the mean freshwater inflow balance amounted to 9,959,000 acre-feet per year (12.28 billion m^3/yr).

Variations in Inflow Components through Drought and Flood Cycles

Although previous paragraphs have described the components of freshwater inflow in terms of annual and monthly average values over the 1941 through 1976 period, there have been wide variations from the mean as a result of recurrent drought and flood conditions. Monthly inflows and their corresponding exceedance frequencies are shown in Table 4-4. The "50%" column for each component inflow represents a 50 percent probability that the corresponding inflow will be exceeded in the given month. These values can be compared to average values given in Table 4-1. Columns marked "10%" (probability of exceedance) indicate component values for wet year conditions, one year in ten. Columns marked "90%" (probability of exceedance) indicate component values for drought conditions, one year in ten. Further illustration of near limit probabilities are provided in Figures 4-3 and 4-4 for combined inflow and total freshwater inflow, respectively.

Quality of Gaged Inflows

Ten USGS gaging stations monitor the quality of inflows to the Trinity-San Jacinto estuary. Three representative stations have been selected for this analysis: Station No. 08066500 (Trinity River at Romayor), Station No. 08074000 (Buffalo Bayou at Houston), and Station No. 08078000 (Chocolate Bayou

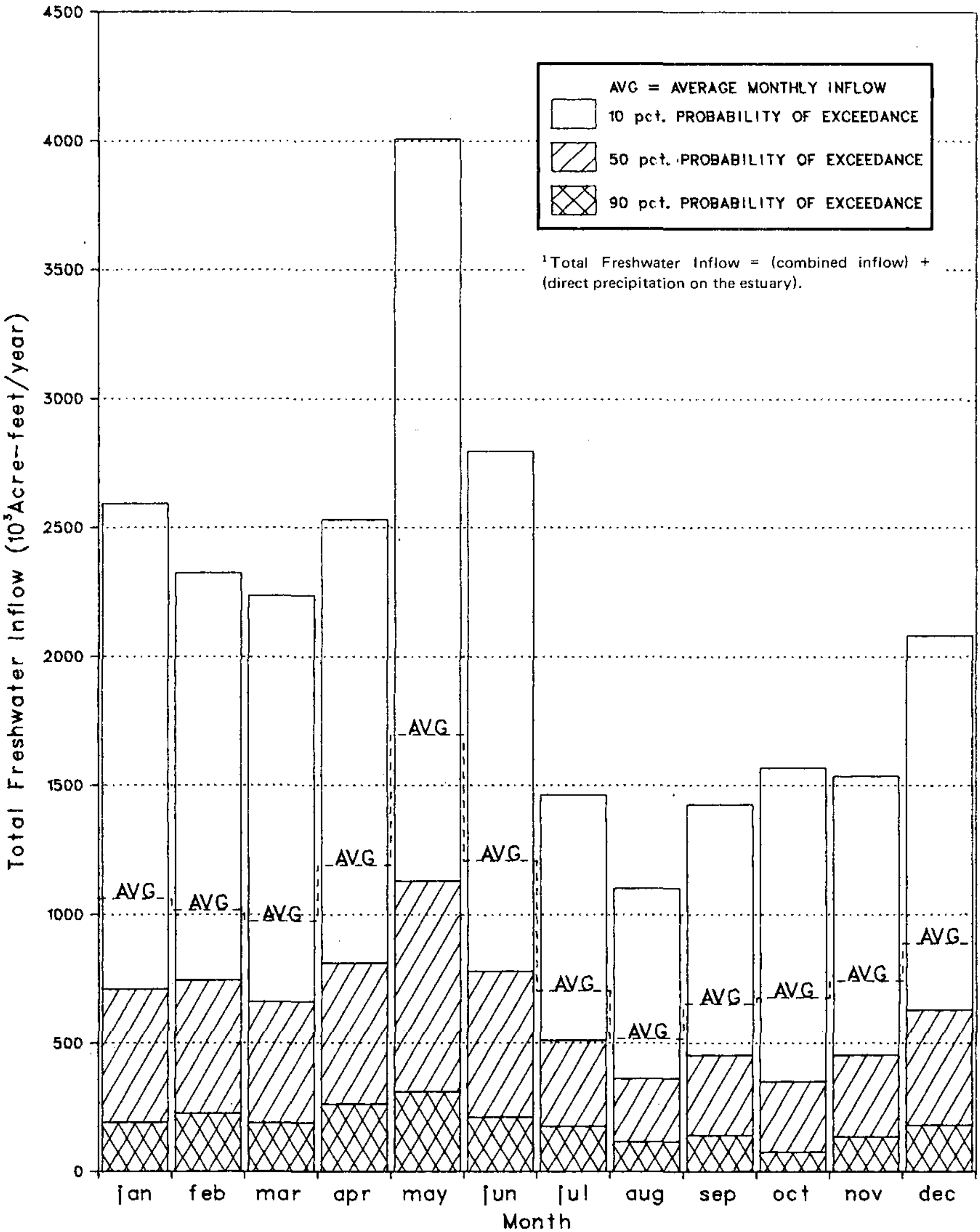


Figure 4-4. Monthly Distribution of Total Freshwater Inflow[1], Trinity-San Jacinto Estuary, 1941-1976

Table 4-4. Monthly Inflows to the Trinity-San Jacinto Estuary for Corresponding Exceedance Frequencies a/, b/

Month	Gaged Trinity Basin Inflow			Gaged San Jacinto Basin Inflow			Gaged San Jacinto-Brazos Basin Inflow			Total Ungaged Inflow			Ungaged Inflow			Combined Inflow			Precipitation on Bay			Total Freshwater Inflow			Bay Evaporation Losses		
	10%	50%	90%	10%	50%	90%	10%	50%	90%	10%	50%	90%	10%	50%	90%	10%	50%	90%	10%	50%	90%	10%	50%	90%	10%	50%	90%
January	1,402	289	58	586	80	10	22	4	0	1,978	389	73	679	106	15	2,438	573	130	221	96	40	2,592	710	194	84	64	49
February	1,130	319	87	595	87	11	23	5	0	1,597	442	118	944	114	12	2,197	638	176	216	86	30	2,325	745	229	85	62	44
March	1,403	353	88	338	61	10	15	3	0	1,704	441	112	531	65	6	2,126	575	152	204	64	17	2,237	661	192	98	77	59
April	1,359	406	122	440	85	17	16	4	1	1,793	529	157	757	106	14	2,331	696	210	259	98	37	2,530	811	265	122	88	63
May	2,563	632	155	556	99	17	28	8	2	3,047	798	205	852	127	12	3,816	998	254	301	97	31	4,008	1,130	312	142	119	97
June	1,635	401	95	417	50	6	34	8	1	2,075	513	123	797	86	7	2,689	641	148	319	93	26	2,795	779	214	178	145	117
July	596	150	37	193	31	5	22	7	2	800	214	56	510	71	8	1,212	361	109	311	121	45	1,463	511	178	201	159	124
August	218	69	22	93	21	5	18	5	1	320	110	38	492	49	3	772	224	65	322	133	52	1,102	362	118	207	173	146
September	334	86	22	194	37	8	25	7	2	556	146	39	774	89	7	1,124	139	90	376	113	29	1,426	453	143	189	152	122
October	550	111	23	215	28	4	16	2	0	809	160	32	605	36	0	1,290	256	52	306	80	15	1,569	351	79	177	142	114
November	718	152	33	306	36	4	20	2	0	1,009	213	47	467	51	0	1,370	321	76	246	98	39	1,537	454	138	132	104	82
December	1,093	234	48	374	58	8	23	5	0	1,489	309	61	551	111	10	1,923	482	116	256	115	50	2,082	629	183	103	77	58

a/ Units are thousands of acre-feet
b/. Exceedance frequencies indicate the probability that the corresponding monthly inflow will be exceeded during the given month

near Alvin). The range of water quality parameters that were experienced in the 1977 water year are tabulated in Figure 4-5. During the period, four to 12 samples were available for most parameters.

Student's t-tests were performed on the data to determine if any statistical difference (two-tailed test) was evident among the sample means for the three gaging stations. It was found that for many parameters, differences between the mean values were not statistically significant. However, sample means from Buffalo Bayou at Houston were significantly higher (statistically) than the other two stations for total ammonia nitrogen, total nitrate nitrogen, total organic nitrogen, total phosphorus, and biochemical oxygen demand, reflecting its urban runoff contribution. Sample means from the Trinity River at Romayor were significantly lower (statistically) than the other two stations for silica, sodium, fluoride, total organic carbon and biochemical oxygen demand; and higher for dissolved oxygen. The sample mean from Chocolate Bayou near Alvin was significantly higher (statistically) than the other two stations for magnesium.

In general, the water quality of Trinity River flows draining to the Trinity-San Jacinto estuary is very good. Inflows from Buffalo Bayou and other urban drainage ways reflect significant nutrient loadings. Inflows from Chocolate Bayou indicate slight contamination from unknown sources. Lack of sampling data on the quality of inflows from the San Jacinto River below Lake Houston make comparisons difficult, but quality is believed to be good. No parameters were found in violation of Texas stream standards.

Quality of Estuarine Waters

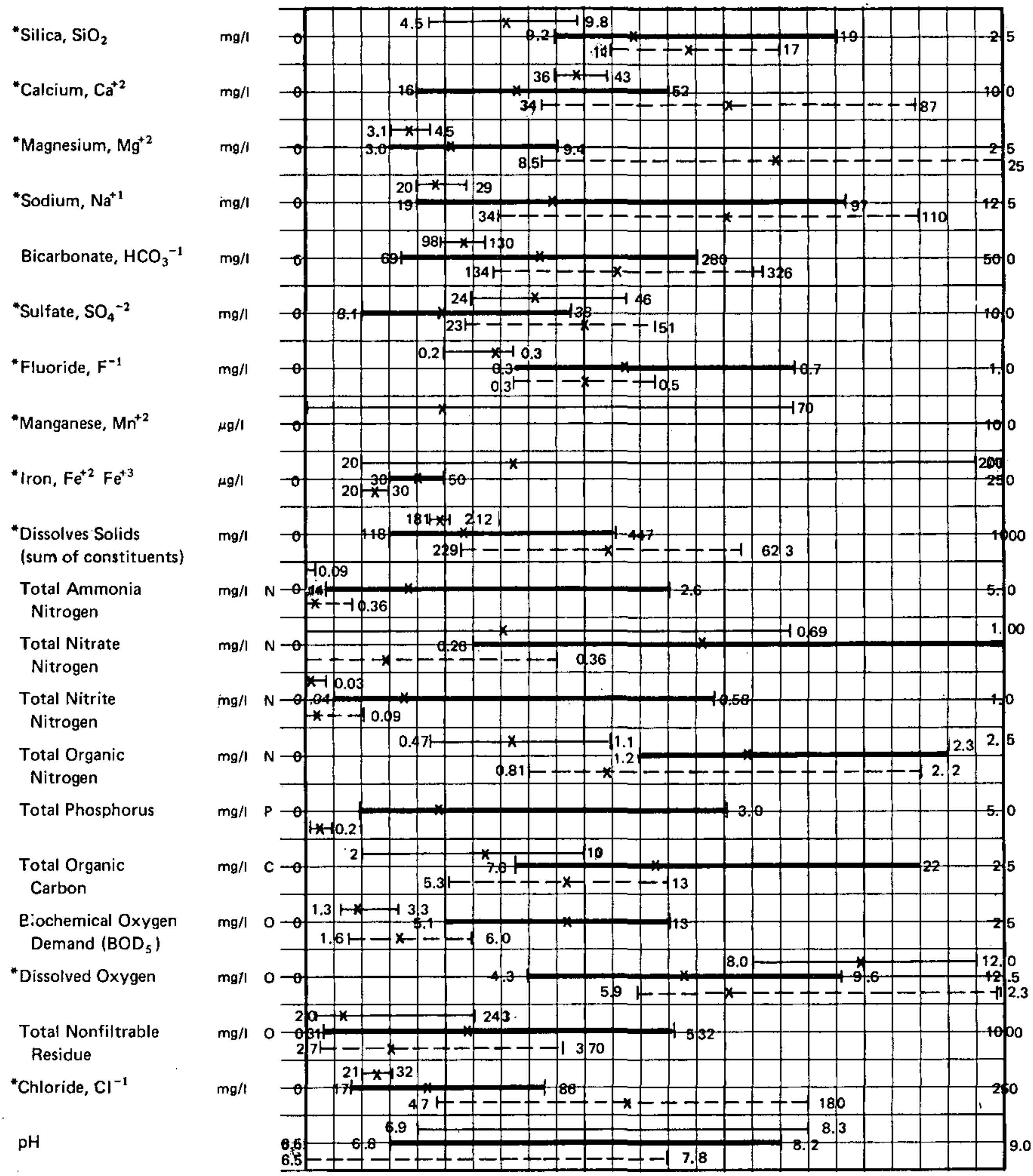
Nutrient Concentrations in the Trinity-San Jacinto Estuary

Historical concentrations of carbon, nitrogen, and phosphorus in Texas estuarine systems are largely unknown. Until 1968, water quality parameters in the open bays had not been monitored on a regular long-term basis. A regular program of water quality data collection in Texas estuaries was initiated by the cooperative efforts of the U. S. Geological Survey and the Texas Department of Water Resources. Manpower and monetary constraints now limit the number of sites and frequency of sampling.

While insufficient data precludes a determination of seasonal nutrient concentrations in the estuary, the data available from 1975 through 1977 can be used to determine general concentrations of carbon, nitrogen and phosphorus (CNP) in the Trinity-San Jacinto estuary.

The estuary was divided into five major segments for the analysis: (1) Upper Galveston Bay (which includes those sampling stations north of sampling line 350); (2) Lower Galveston Bay (which includes those sampling stations at and south of sampling line 350); (3) Trinity Bay; (4) West Bay; and (5) East Bay (Figure 4-6). Only those sample sites located away from major population or industrial centers in open bay waters were considered, since nutrient concentrations near these locales might bias resultant concentrations in open waters.

Freshwater discharges from the Trinity River and contributions from the deltaic marshes of the Trinity delta have been a major source of nutrients for



1 ├──┤ 5 Range of values reported at USGS Station 08066500, Trinity River at Romayor.
4 ┣━━┫ 6 Range of values reported at USGS Station 08074000, Buffalo Bayou at Houston.
2 ├ ─ ─ ┤ 6 Range of values reported at USGS Station 08078000, Chocolate Bayou near Alvin.
─X─ Mean of reported values.
* Dissolved fraction only.

Figure 4-5. Range of Values for Water Quality Parameters, Gaged Inflow to Trinity-San Jacinto Estuary, October 1976-September 1977

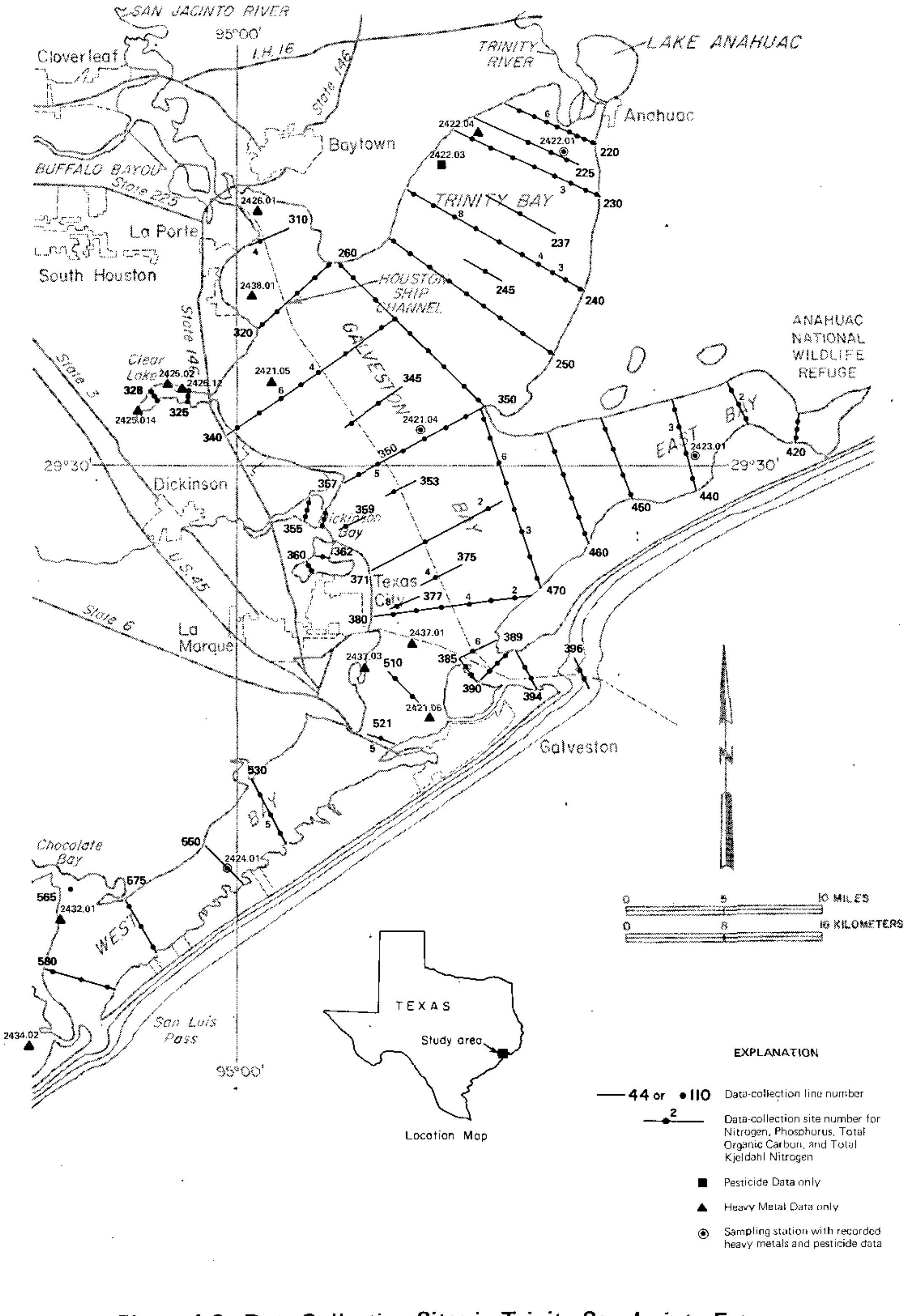


Figure 4-6. Data-Collection Sites in Trinity-San Jacinto Estuary

the Trinity-San Jacinto estuary. The Trinity River accounts for 78 percent of the gaged freshwater inflow to the estuary. The watercourses that drain the City of Houston empty into the Houston Ship Channel, and subsequently contribute inflow to Upper Galveston Bay. This inflow constitutes only 6.9 percent of the gaged flow to the estuary, yet CNP concentrations are high enough that total nutrient loadings from this source outweigh those from the Trinity River inflows. From this discovery it would be expected that Upper Galveston Bay and Trinity Bay would experience higher nutrient concentrations than other portions of the estuary, a result that is generally borne out by the water quality data (as discussed below).

The CNP data for each of the five distinct portions of the estuary were tabulated, averaged, and subjected to standard statistical methods for comparison of the means (student's t-test) to determine which of the portions of the estuary, if any, consistently exhibited CNP concentrations significantly different from others. Frequency histograms of grouped nitrogen, phosphorus, organic carbon and total Kjeldahl nitrogen data were also plotted in Figures 4-7 through 4-10.

Ammonia nitrogen, nitrite nitrogen and nitrate nitrogen were summed for each sample to arrive at total available nitrogen concentrations. Ammonia nitrogen and total organic nitrogen were summed for each sample to arrive at total Kjeldahl nitrogen concentrations.

Total organic carbon ranged from 3.3 mg/l to 17 mg/l. Student's t-test analyses revealed that the concentrations of organic carbon in Upper Galveston Bay were significantly higher (95 percent confidence level) than those in Lower Galveston and West Bays. There was no significant difference between the concentrations found in Upper Galveston Bay and Trinity Bay segments. In addition, student's t-test analyses revealed that the concentrations of organic carbon in Trinity Bay were significantly higher (95 percent confidence level) than those concentrations in Lower Galveston Bay and West Bay.

Total Kjeldahl nitrogen ranged from 0.11 mg/l to 1.61 mg/l. Student's t-test analyses revealed that the concentrations of total Kjeldahl nitrogen in Upper Galveston Bay were significantly higher (95 percent confidence level) than those concentrations of total Kjeldahl nitrogen in Trinity Bay, Lower Galveston Bay, and West Bay. In addition, the total Kjeldahl nitrogen concentrations in Trinity Bay were also significantly higher (95 percent confidence level) than those concentrations in Lower Galveston and West Bays. The concentrations in East Bay were significantly higher (95 percent confidence level) than those concentrations found in Trinity Bay.

Total phosphorus concentrations ranged from 0.08 mg/l to 0.55 mg/l. Student's t-test analyses revealed that the concentrations in the Upper Galveston Bay segment were significantly higher (95 percent confidence level) than those concentrations of phosphorus in all other remaining bay segments. Likewise, the concentrations in Trinity Bay were also significantly higher (95 percent confidence level) than Lower Galveston Bay, East Bay and West Bay.

Total nitrogen concentrations ranged from 0.03 mg/l to 0.67 mg/l. Student's t-test analyses revealed that the concentrations of nitrogen in the Upper Galveston Bay segment were significantly higher (95 percent confidence level) than those concentrations in all other segments but East Bay. Also,

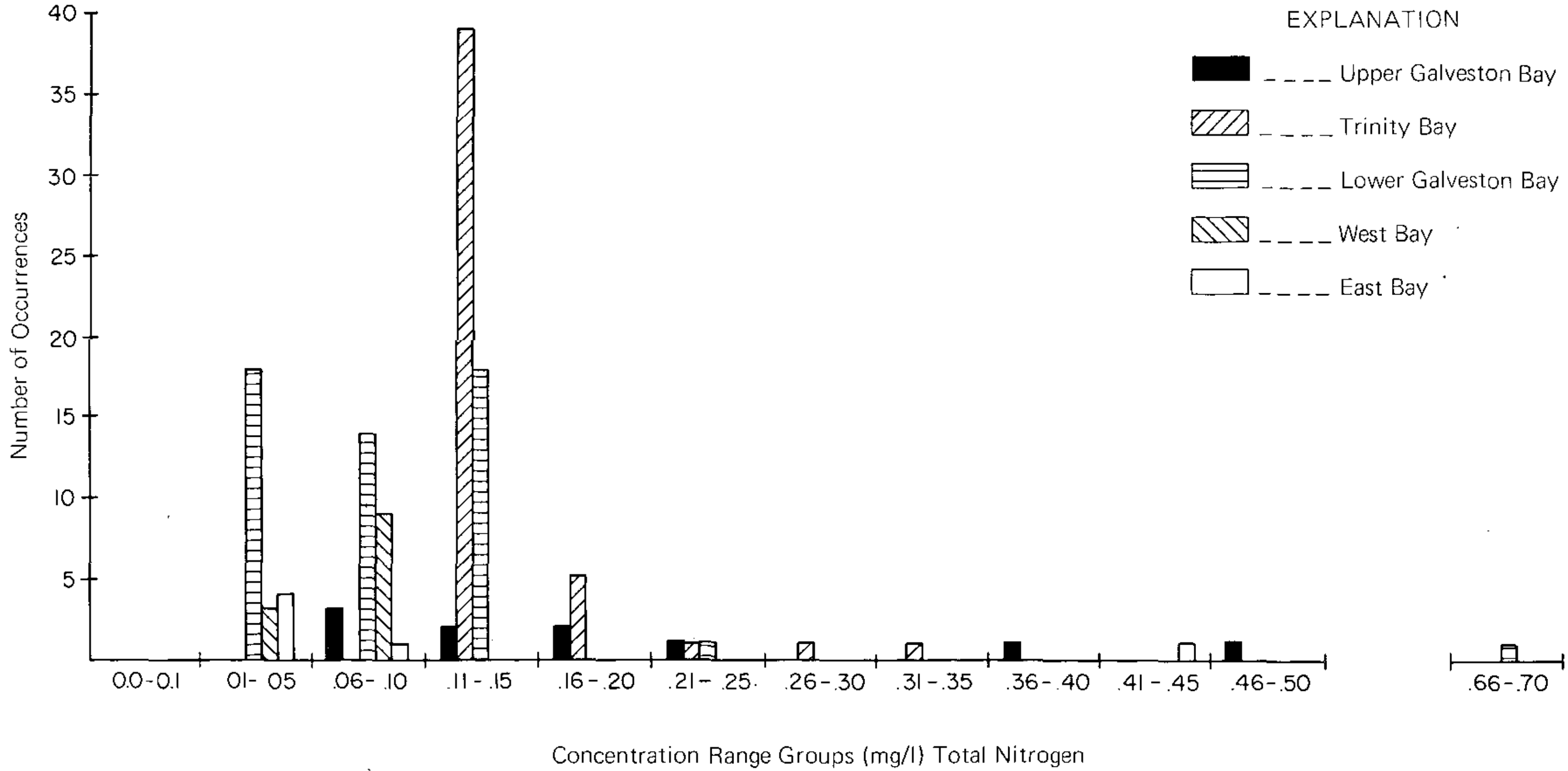


Figure 4-7. Distribution of Total Nitrogen (as N) Concentrations Occurring in the Trinity-San Jacinto Estuary, 1968-1977

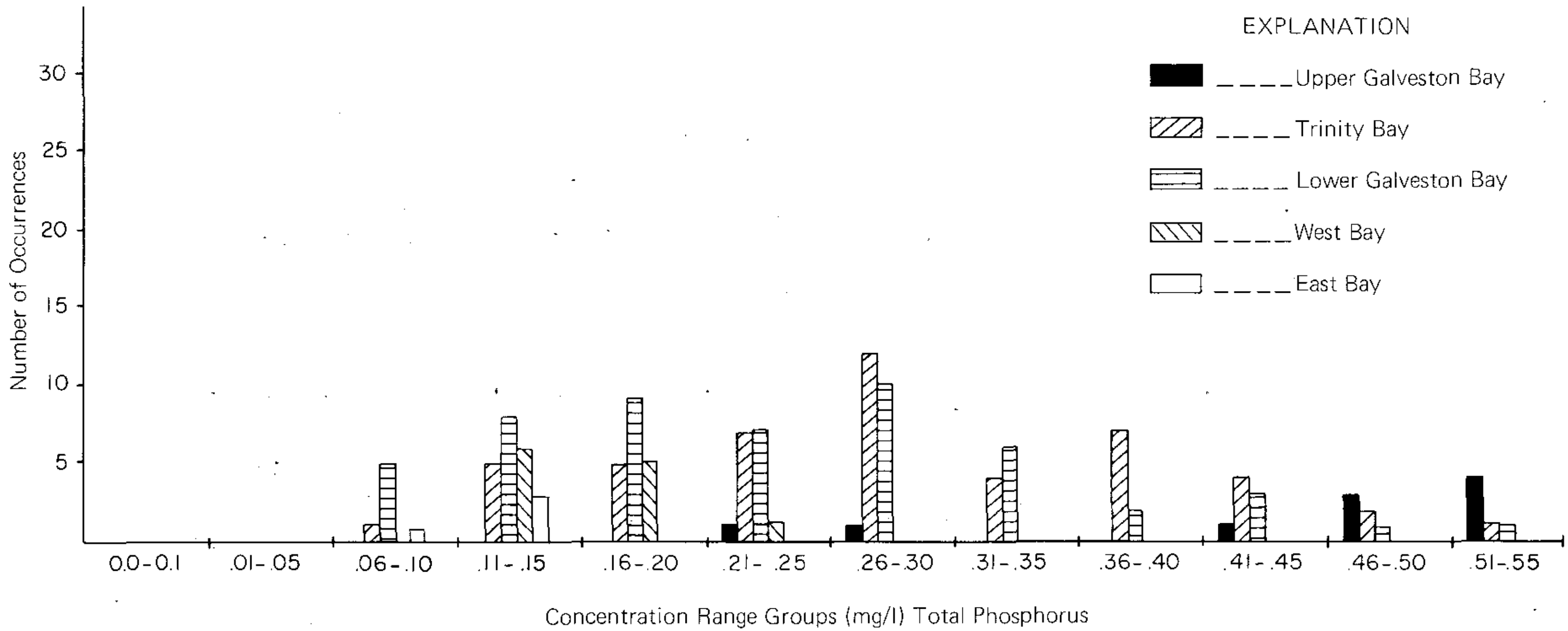


Figure 4-8. Distribution of Total Phosphorus (as P) Concentrations Occurring in the Trinity-San Jacinto Estuary, 1975-1977

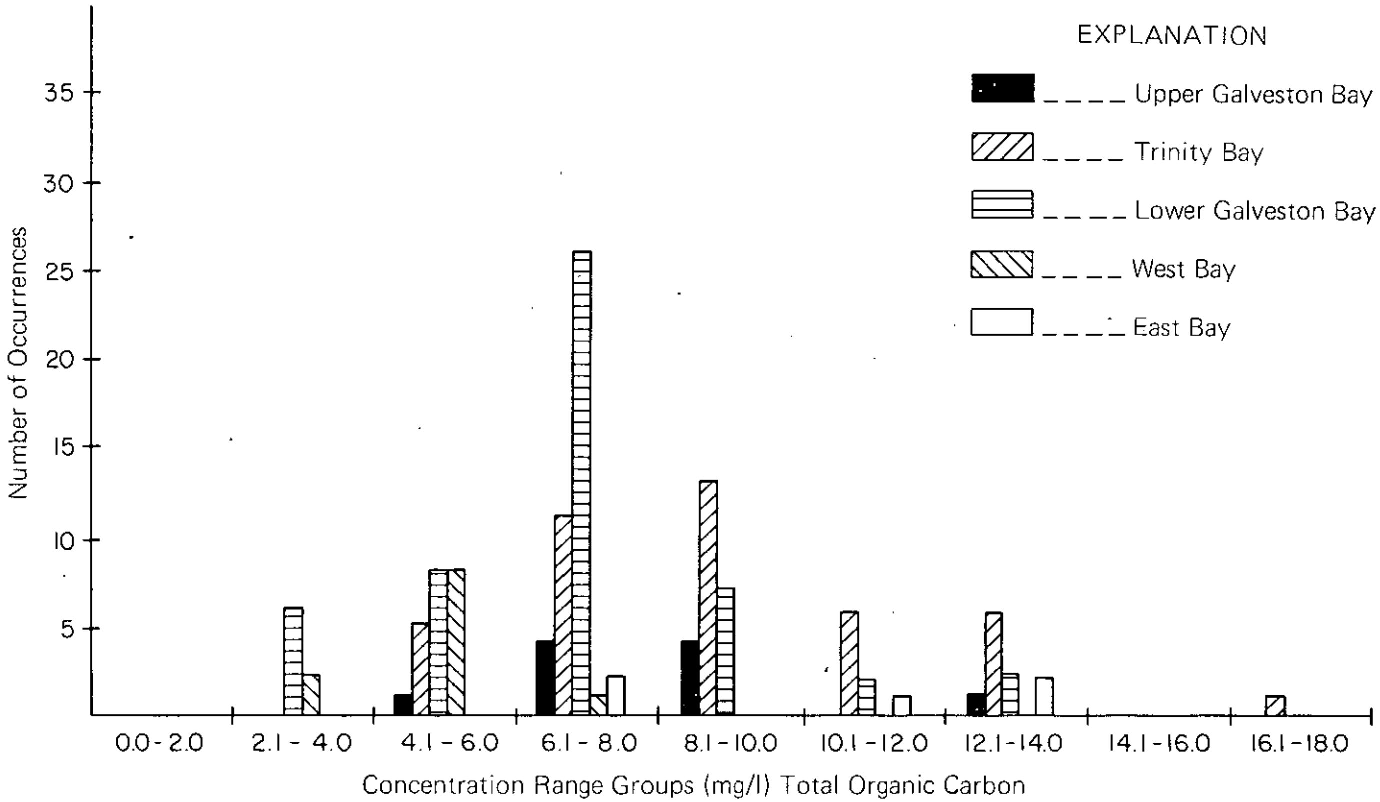


Figure 4-9. Distribution of Organic Carbon Concentrations Occurring in the Trinity-San Jacinto Estuary, 1975-1977

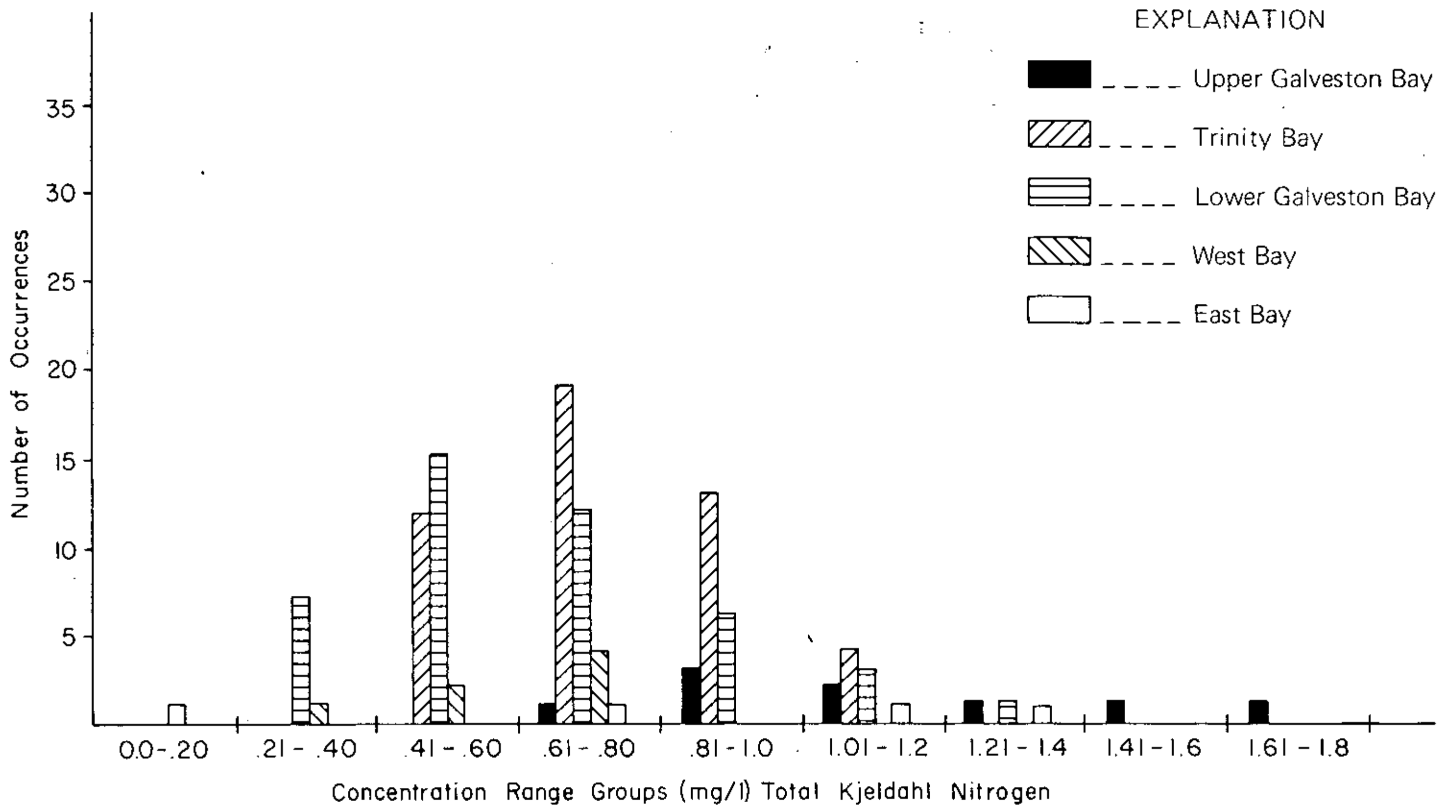


Figure 4-10. Distribution of Total Kjeldahl Nitrogen Concentrations Occurring in the Trinity-San Jacinto Estuary, 1975-1977

the concentrations of nitrogen in Trinity Bay were significantly higher (95 percent confidence level) than those concentrations in the Lower Galveston and and West Bays.

Heavy Metals

The scope of this section is not intended to be a comprehensive analysis of the sources from which heavy metals originate in the area. The purpose is to summarize the available data on the heavy metals and give the range of values that have been found in sampling efforts.

Samples of the bottom sediments in the Trinity-San Jacinto estuary were collected by the Texas Department of Water Resources at 16 data collection sites shown in Figure 4-6 for the period of record 1974 through 1978. The heavy metals detected included arsenic (As), cadmium (Cd), copper (Cu), lead (Pb), manganese (Mn), nickel (Ni), zinc (Zn), and mercury (Hg).

Statistical analyses were not possible due to the limited number of samples for the test period from 1974 to 1978. The range of values for heavy metals detected in Galveston Bay, Trinity Bay, Clear Lake, West Bay, East Bay, Texas City Ship Channel, Tabbs Bay, Bayport Channel, Christmas Bay and Chocolate Bay are listed in Table 4-5.

Accumulation of metals in bottom deposits may not be detectable in overlying water samples, yet still exert an influence from time to time. Wind and tide induced water movements, ship traffic and dredging activities are some physical processes that can cause mixing of materials from the sediment into the water. Chemical changes resulting from seasonal temperature fluctuations, oxygenation, and respiration, can influence the rate of movement and distribution of dissolved substances between water and sediment. Microorganisms living on the bottom (benthos) also play an important role in the circulation of metals by taking them up from the sediment, sometimes converting them to more toxic forms. Heavy metals in sediment and water may pose a threat to fish and shellfish as these organisms generally concentrate certain toxic metals in their bodies when feeding in polluted areas. Reduction of productivity in the area may be the result of toxic effects of heavy metals upon organisms, and may have an ultimate effect on man if he is exposed to heavy metals through edible fish and shellfish. Sediment samples from some areas of the Trinity-San Jacinto estuary exceed the U. S. Environmental Protection Agency criteria for metals in the sediments (prior to dredging). The following constituents have been found in violation of these standards in at least one sample: arsenic, cadmium, copper, lead, and zinc (Table 4-5).

Pesticides and Herbicides

Samples of the bottom sediments in the Trinity-San Jacinto estuary were collected at five data collection sites shown in Figure 4-6 for the period from 1974 to 1978 through the Texas Department of Water Resources sampling program. The data were analyzed for pesticides and herbicides concentrations. The parameters detected were heptachlor and heptachlor expoxide but at levels below or equal to detection limit of 0.1 $\mu g/kg$. Statistical analyses were not possible due to the limited number of samples available.

Table 4-5. Ranges of Metals in Sediment Compared to USEPA (1974) Dredge Criteria a/

Station Location b/ & USGS Station Number: / Parameter	Galveston Bay			Trinity Bay		Clear Lake			East Bay	Dredge Criteria
	2421.04	2421.05	2421.06	2422.01	2422.04	2425.012	2425.02	2425.014	2423.01	
	Units are mg/kg									
Arsenic	2.12-14.0*	4.5-43.0*	2.57-7.10*	5.7-10.0*	0.55-3.0	4.2-43*	3.4-14*	4.7-12.0*	3.43-9.0*	5
Cadmium	0.52-<2.0	0.5-<2.0	0.83-1.9	0.01-<2.0	<0.6-1.7	0.5-<2.0	0.5-<3.0*	0.9-<2.0	0.510-1.3	2
Copper	4.0-14.0	6.0-18.0	7.02-15.2	1.0-8.0	1.0-10.4	31.0-64.0*	33.0-196*	26-44	2.05-7.0	50
Lead	3.4-24.6	11.2-61.1*	17.1-32.8	7.3-25.4	2.75-13.8	21.6-39.8	15.0-67.6*	24.0-64.6*	4.0-22.4	50
Manganese	183.9-327	151.0-330.0	308.3-502.3	288.8-876	64.9-1121.9	178-355	225-799	168.2-340	126.6-184.5	--
Mercury	<0.10	<0.10-0.20	<0.10	0.10	<0.10	0.05-<0.10	<0.10-0.20	0.07-0.20	<0.10	1
Nickel	5.0-10.7	7.0-28.0	12.5-20.7	7.3-23.0	2.4-19.0	13.2-25	13.1-33	12.1-29.0	5.3-16.5	50
Zinc	25.1-53.0	25.7-106.0*	41.7-68.0	19.6-61.4	9.4-36.2	51.3-82.0*	40.3-12540*	50-77*	28.0-56.4	75

a/ Includes data from reference (277)
b/ See Figure 4-6 for station locations
* Denotes at least one sample in violation of EPA's dredge spoil criteria

Table 4-5. Ranges of Metals in Sediment Compared to USEPA (1974) Dredge Criteria a/ (cont'd.)

Station Location b/ & USGS Station Number: / Parameter	Texas City Ship Channel		Tabbs Bay	Bayport Channel	Chocolate Bay	Christmas Bay	West Bay	Dredge Criteria
	2437.01	2437.03	2426.01	2438.01	2432.01	2434.02	2424.01	
	Units are mg/kg							
Arsenic	3.6-11.0*	7.1-11.0*	3.5-9.6*	2.36-5.0*	4.58-9.0*	6.0*	3.36-4.1	5
Cadmium	0.01-2.4*	1.0-2.4*	<1.0-3.5*	<1.0-1.03	0.9-1.5	<1.0	0.59-1.87	2
Copper	0.01-21.8	14.8-60.5*	9.6-17.3	6.5-13.8	5.5-11.0	7.0	5.9-14.0	50
Lead	0.05-50.0*	38.7-60.1*	26.6-57.8*	6.0-30.8	15.3-47.3	10.0	10.8-50.5*	50
Manganese	354.8-1043.6	256.0-397.0	227.4-434.7	185.1-352.0	500-983.6	363	196.0-345.8	—
Mercury	<0.10	<0.10	0.40	<0.10	<0.10	<0.10	0.20	1
Nickel	21.0-27.8	19.3-26.6	17.5-25.3	10.9-23.6	14.5-37.0	—	11.6-22.4	50
Zinc	29.8-80.1*	56.2-84.0*	61.2-104.9*	23.2-64.6	34.5-90.2*	35.0	17.8-70.2	75

a/ Includes data from reference (277)
b/ See Figure 4-6 for station locations
* Denotes at least one sample in violation of EPA's dredge spoil criteria

Summary

Sources of freshwater inflow to the Trinity-San Jacinto estuary include gaged inflows from the contributing rivers and streams; ungaged runoff; return flows from municipal, industrial and agricultural sources; and precipitaiton on the estuary. Measurement of sources of freshwater inflow adds to the understanding of inflow timing and volumes and their influence on bay productivity. To acquire accurate inflow measurements, gaged stream flows require adjustment to reflect any withdrawals or return flows downstream from gage locations. Ungaged runoff is estimated by computerized mathematical models using field data for calibration and verification. Rainfall is estimated as a distance-weighted average of the daily precipitation recorded at weather stations surrounding the estuary.

Freshwater inflows in terms of annual and monthly average values over the 1941 to 1976 period varied widely from the mean as a result of recurrent drought and flood conditions. On the average, total freshwater inflow to the estuary is estimated at 11.34 million acre-feet per year (14 billion m^3).

In general, the water quality of gaged inflows to the estuary from the Trinity River is good. Inflows from Buffalo Bayou and other urban drainage ways reflect significant nutrient loadings. No parameters were found in violation of existing Texas stream standards. Studies of past water quality in and around the estuary have noted the occurrence of heavy metals in sediment samples. Locally, bottom sediment samples from the Trinity-San Jacinto estuary have exceeded the U. S. Environmental Protection Agency criteria for metals in sediment (prior to dredging) for arsenic, cadmium, copper, lead and zinc.

Basic hydrologic data described in this Chapter (Chapter IV) is used as input to modeling studies discussed in Chapters V, VIII, and IX.

CHAPTER V

CIRCULATION AND SALINITY

Introduction

The estuaries and embayments along the Texas Gulf Coast are characterized by large surface areas, shallow depths and irregular boundaries. These estuarine systems receive variable influxes of freshwater and return flows which enter through various outfall installations, navigation channels, natural stream courses, and as runoff from contiguous land areas. After entering the estuary, these discharges are subject to convective movements and to the mixing and dispersive action of tides, currents, waves and winds. The seaward flushing of the major Gulf Coast estuaries occurs through narrow constricted inlets or passes and in a few cases, through dredged navigable channel entrances. While the tidal amplitude at the mouths of these estuaries is normally low, the interchange of Gulf waters with bay waters and the interchange of waters among various segments have a significant influence on the circulation and transport patterns within the estuarine system.

Of the many factors that influence the quality of estuarine waters, mixing and physical exchange are among the most important. These same factors also affect the overall ecology of the waters, and the net result is reflected in the benefits expressed in terms of the economic value derivable from the waters. Thus, the descriptions of the tidal hydrodynamics and the transport characteristics of an estuarine system are fundamental to the development of any comprehensive multivariable concept applicable to the management of estuarine water resources. Physical, chemical, biological and economic analyses can be considered only partially complete until interfaced with the hydrodynamic and transport characteristics of a given estuarine system.

The following sections of Chapter V will address the development and application of the hydrodynamic, mass transport, and marsh inundation models used to evaluate the circulation and salinity patterns of the Trinity-San Jacinto estuary.

Description of the Estuarine Mathematical Models

Description of Modeling Process

A shallow estuary or embayment can be represented by several types of models. These include physical models, electrical analogs and mathematical models, each of which has its own advantages and limitations. The adaptation of any of these models to specific problems depends upon the accuracy with which the model can simulate the prototype behavior to be studied. Furthermore, the selected model must permit various alternatives to be studied within an efficient and economical framework.

A mathematical model is a functional representation of the physical behavior of a system or process presented in a form available for solution by any acceptable method. The mathematical statement of a process consists of an input, a transfer function and an output. The output from a given system or component of a system is taken to be related to the input or some function of the input by the transfer function.

Because of the nonlinearities of tidal equations, direct solutions in closed form seldom can be obtained for real circumstances unless many simplifying assumptions are made to linearize the system. When boundary conditions required by the real system behavior become excessive or complicated, it is usually convenient to resort to a numerical method in which the system is discretized so that the boundary conditions for each element can be applied or defined. Thus it becomes possible to evaluate the complex behavior of a total system by considering the interaction among individual elements satisfying common boundary conditions in succession. The precision of the results obtained depends; however, on the time interval and element size selected and the rate of change of the phenomena being studied. The greater the number of finite time intervals used over the total period of investigation, the greater the precision of the expected results.

Numercial methods are well adapted to discretized systems where the transfer functions may be taken to be time independent over short time intervals. The development of high-speed digital computers with large memory capacities makes it possible to solve the tidal equations directly by finite difference or finite element techniques within a framework that is both efficient and economical. The solutions thus obtained may be refined to meet the demands of accuracy at the burden of additional cost by reducing the size of finite elements and decreasing the time interval. In addition to the constraints imposed on the solution method by budget restrictions or by desired accuracy, there is an optimum size of element and time interval imposed by mathematical considerations which allow a solution to be obtained which is mathematically stable, convergent, and compatible.

Mathematical Model Development

A mathematical model to simulate the tidal and circulation patterns in the Trinity-San Jacinto estuary was developed by Tracor, Inc. for the Texas Water Quality Board's Galveston Bay Project (390-420). This model was modified by personnel of the Engineering and Environmental Systems Section for use as a long-range water resources planning tool. A conservative transport model designed to simulate salinity distributions in the Trinity-San Jacinto estuary was adapted from a similar model developed by Masch (173) for the Lavaca-Tres Palacios estuary. These models are designed to simulate the tidal and circulation patterns and salinity distributions in a shallow, irregular, non-stratified estuary. The two models are sequential (Figure 5-1) in that the tidal hydrodynamic model computes temporal histories of tidal amplitudes and flows. These are then used as input to the conservative mass transport model to compute vertically averaged salinities (or concentration of any other conservative material) under the influence of various source salinities, evaporation, and rainfall. Both of these models have "stand alone" capabilities, although it must be recognized that the mass transport model ordinarily cannot be operated unless the tidally generated convective inputs are available.

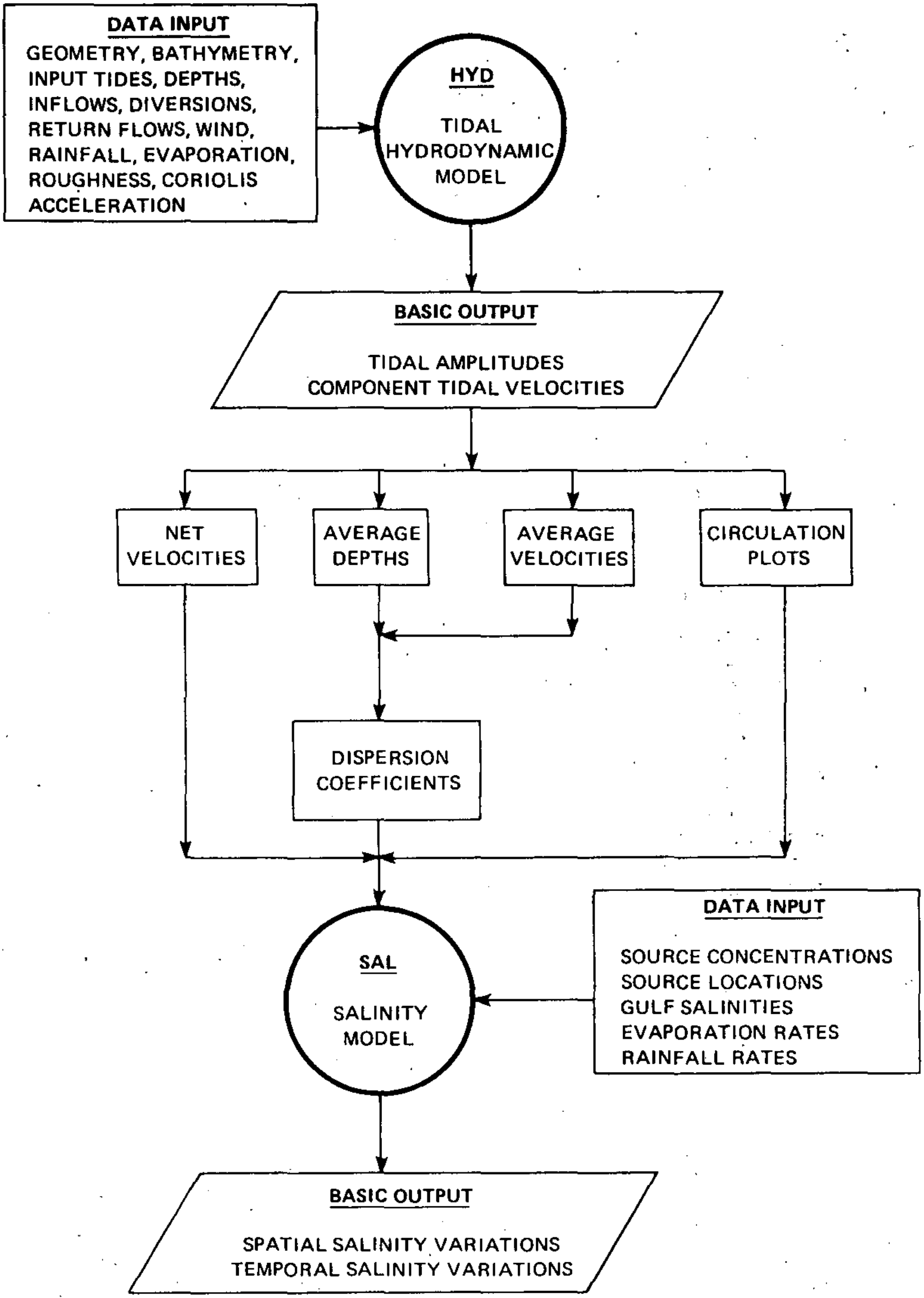


Figure 5-1. Relationship Between Tidal Hydrodynamic and Salinity Models (173)

Hydrodynamic Model. Under the assumption that the bays are vertically well-mixed, and the tidally generated convection in either of the two area-wise coordinate directions can be presented with vertically integrated velocities, the mathematical characterization of the tidal hydrodynamics in a bay system requires the simultaneous solution of the two-dimensional dynamic equations of motion and the unsteady continuity equation. In summary, the equations of motion neglect the Bernoulli terms but include wind stresses and the Coriolis acceleration, and can be written as:

$$\frac{\partial q_x}{\partial t} - \Omega\, q_y = -\, gd\, \frac{\partial h}{\partial x} - fq\, q_x + K\, V_w^2 \cos\ \Theta \qquad [1]$$

$$\frac{\partial q_y}{\partial t} + \Omega\, q_x = -\, gd\frac{\partial h}{\partial y} - fq\, q_y + K\, V_w^2\ \sin\Theta \qquad [2]$$

The equation of continuity for unsteady flow can be expressed as

$$\frac{\partial q_x}{\partial x} + \frac{\partial q_y}{\partial y} + \frac{\partial h}{\partial t} = r - e \qquad [3]$$

where

x,y = horizontal Cartesian coordinates
t = time
q_x, q_y = vertically integrated x and y components of flow per unit width, respectively (x and y taken in the plane of the surface area)
g = acceleration due to gravity
h = water surface elevation with respect to mean sea level (msl) as datum
d = total water depth (h-z)
z = bottom elevation with respect to msl
q = $(q_x^2 + q_y^2)^{1/2}$ = magnitude of flow per unit width
f = dimensionless bed resistance coefficient from the Manning Equation
V_w = wind speed at a specified elevation above the water surface
Θ = angle between the wind velocity vector and the x-axis
K = dimensionless wind stress coefficient
Ω = Coriolis parameter = $2\omega\sin\phi$
ω = angular velocity of the earth = 0.73×10^{-4} rad/sec
ϕ = latitude = 29.5° for the Trinity-San Jacinto estuary
r = rainfall intensity
e = evaporation rate.

The numerical solution utilized in the hydrodynamic model of the Trinity-San Jacinto estuary involves an explicit computational scheme where equations [1], [2], and [3] are solved over a rectangular grid of square cells used to represent in a discretized fashion the physiography and various boundary conditions found in this bay system (Figure 5-2). This explicit formulation of the hydrodynamic model requires for stability a computational time step, $\Delta t < \Delta s/(2gd_{max})^{1/2}$, where Δs is the cell size and d_{max} the maximum water depth encountered in the computational matrix. The numerical solutions of the basic equations and the programming techniques have been described previously (173).

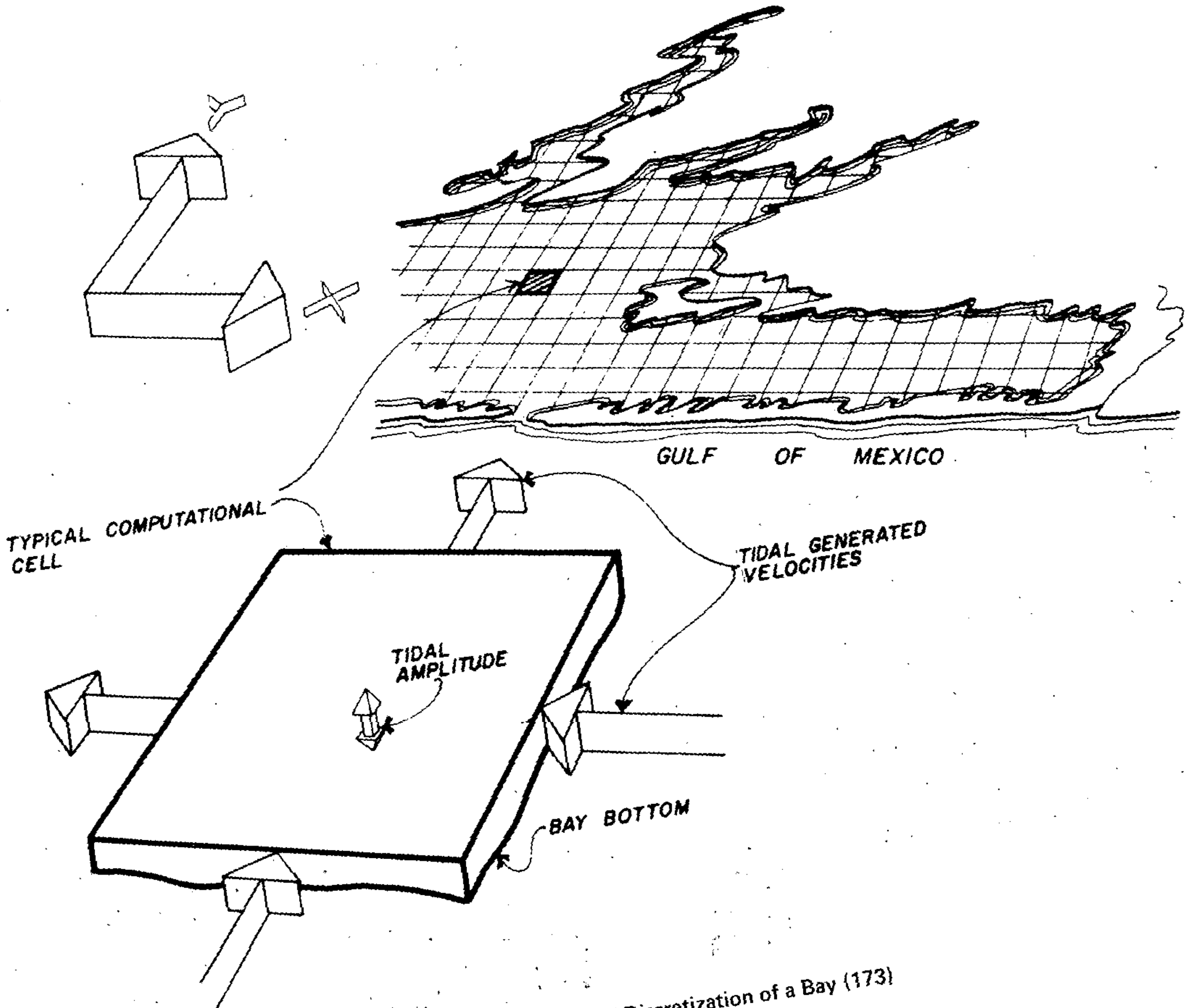


Figure 5-2. Conceptual Illustration of Discretization of a Bay (173)

The following data comprise the basic set for applying the tidal hydrodynamic model. Time varying data should be supplied at hourly intervals.

Physical Data

- topographic description of the estuary bottom, tidal passes, etc.
- location of inflows (rivers, wastewater discharges, etc.)

Hydrologic - Hydraulic Data

- tidal condition at the estuary mouth (or opening to the ocean)
- location and magnitude of all inflows and withdrawals from the estuary
- estimate of bottom friction
- wind speed and direction (optional)
- rainfall history (optional)
- site evaporation or coefficients relating surface evaporation to wind speed.

Conservative Mass Transport Model. The transport process as applied to salinity can be described through the convective-dispersion equation which is derivable from the principle of mass conservation. For the case of a two-dimensional, vertically-mixed bay system, this equation can be written as:

$$\frac{\partial(C\bar{d})}{\partial t} + \frac{\partial(\bar{q}_x C)}{\partial x} + \frac{\partial(\bar{q}_y C)}{\partial y} = \frac{\partial}{\partial x}\left[D_x \frac{\partial(C\bar{d})}{\partial x}\right] + \frac{\partial}{\partial y}\left[D_y \frac{\partial(C\bar{d})}{\partial y}\right] + K_e C\bar{d} \qquad [4]$$

where C is the tidally averaged salinity or TDS concentration; $\bar{q}_x$ and $\bar{q}_y$ are the net flows over a tidal cycle in the x and y directions, respectively; D_x and D_y are the corresponding dispersion coefficients evaluated at a scale representative of total tidal mixing; and $\bar{d}$ is the average depth over a tidal cycle. The term $K_e C\bar{d}$ is a first order reactive term included to represent the buildup of concentration due to evaporation from the bay surface, and K_e is a coefficient determined volumetrically in accordance with methods described by Masch (173). The primary difference in the form of Equation [4] given above and that reported previously (173), is that Equation [4] is written in terms of net flows per foot of width rather than tidally averaged velocities.

The numerical technique employed in the salinity model involves an alternating direction implicit (ADI) solution of Equation [4] applied over the same grid configuration used in the tidal hydrodynamic model to determine the net flows and tidally averaged depths. Because of its implicit formulation the ADI solution scheme is unconditionally stable and there are no restrictions on the computational time step, Δt. However, to maintain accuracy and to minimize round-off and truncation errors, a condition corresponding to $\Delta t/\Delta \bar{s}^2 \leq \frac{1}{2}$ was always maintained throughout this work. Details of the numerical solution of Equation [4] and programming techniques have also been previously described by Masch (173).

The basic data set required to operate the conservative mass transport model consists of a time history of tidal-averaged flow patterns, i.e., the output from the tidal hydrodynamic model, the salinity concentrations of all inflows to the estuary, and an initial salinity distribution within the estuary.

Marsh Inundation Model. The marsh inundation model, DELTA, is a one-dimensional mathematical model capable of simulating basic hydrologic and nutrient transport characteristics in a deltaic system. DELTA is adapted to simulate single events such as log-flow periods, high tides, flood events (or any type of related event) with a duration of less than 22 days. Through the application of constant freshwater inputs and a repetitious tidal cycle, a "steady-state" event covering longer periods of time may be examined. DELTA is made up of two smaller models, a hydrodynamic submodel, HYDELT, and a mass-transfer submodel, MTDELT.

(1) HYDELT. For the calculation of tides in estuaries and tidal rivers, HYDELT assumes that all flow momentum is concentrated in the longitudinal component of the channel and that when inundated, the flood plain serves principally as volume storage and carries relatively little longitudinal momentum. Neglecting Coriolis acceleration and surface wind-stress, the governing equations are the conservation of longitudinal momentum and continuity for one-dimensional tidal flows:

$$\frac{\partial Q}{\partial t} + \frac{\partial}{\partial x} \left(\frac{Q}{A}\right) + gA \frac{\partial H}{\partial x} + \frac{gn^2 \, Q |Q|}{2.22 \, AR^{4/3}} = 0 \qquad [1]$$

and

$$\frac{\partial H}{\partial t} + \frac{1}{B} \frac{\partial Q}{\partial x} - \frac{Q_f}{A_s} = 0 \qquad [2]$$

In equations [1] and [2], Q is the flow in the conveyance channel; A is the cross-sectional area of the conveyance channel; H is the water level; R is the hydraulic radius; n is Manning's roughness parameter; B is the lateral width; A_s is the surface area including lateral storage; z is the height of channel bottom above an arbitrary datum; Q_f is the lateral discharge into the channel; g is the acceleration of gravity; x is the distance in the longitudinal direction; and t is time.

Solution of Equations [1] and [2] utilize the "leapfrog" method of finite differences whereby water depths, inundated surface areas, and lateral channel discharges are determined at the center of each segment, while longitudinal flow quantities and velocities are determined at segment boundaries (Figures 5-3 and 5-4). This solution technique has been proven to be stable for hyperbolic systems, such as those described by Equations [1] and [2], so long as $\Delta t < (\Delta x/c)$; where Δt is the solution time step, and c is the maximum phase velocity of a wave.1/

(2) MTDELT. The mass-transfer submodel, MTDELT, used in conjunction with the hydrodynamic submodel, simulates the influence of exchange rates on nutrient levels in the deltaic system. MTDELT can simulate organic nitrogen, ammonia, nitrite, nitrate, total phosphorus, total carbon, and two species of algae.

MTDELT uses the one-dimensional mass continuity equation:

$$\frac{1}{A} \frac{\partial}{\partial t} (AC) + \frac{1}{A} \frac{\partial}{\partial x} (AUC) = \frac{1}{A} \frac{\partial}{\partial x} \left(AE_L \frac{\partial C}{\partial x}\right) \pm S \qquad [3]$$

1/ c is approximated as $(gD)^{1/2}$ + U, where D is water depth and U is the local water velocity.

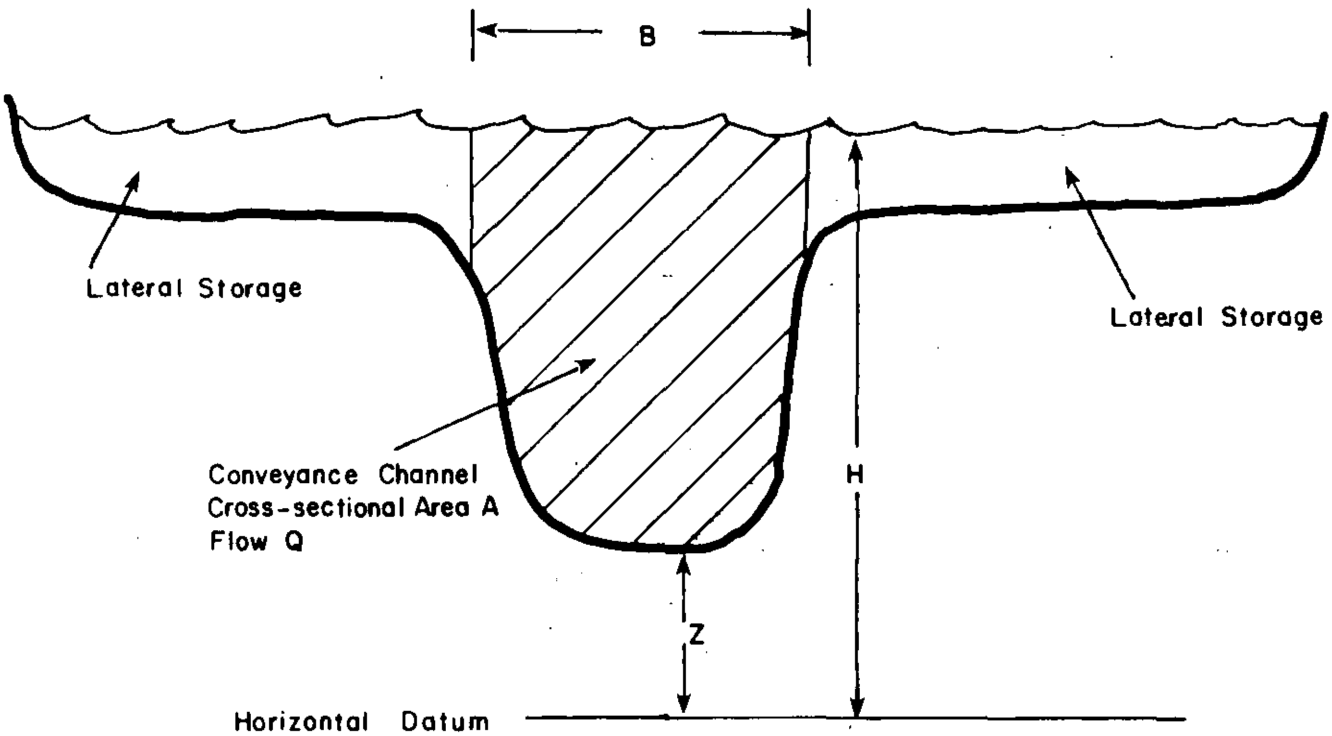


Figure 5-3. Definition of Variables in Cross Section (173)

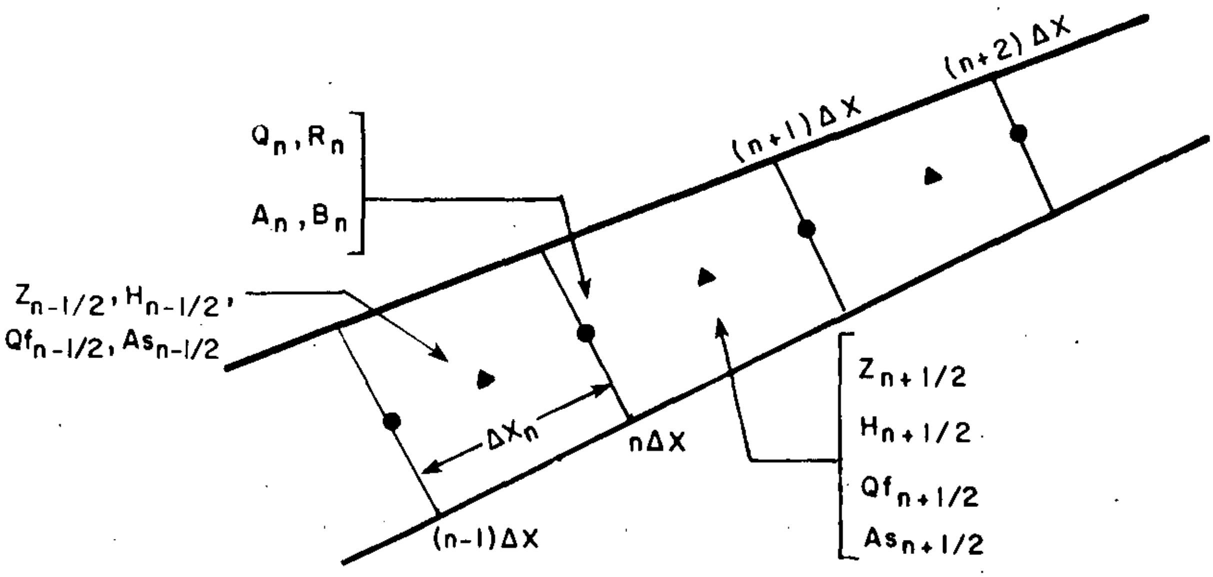


Figure 5-4. Definition of Finite-Difference Segmentation for Hydrodynamic Model (173)

In equation [3], C is the constituent concentration; E_L is the longitudinal dispersion coefficient, and S represents sediment transfer, biological reactions, plant intake, influent sources, and withdrawal sinks.

(3) Calibration and Validation of the Marsh Inundation Model. The hydrodynamic submodel, HYDELT, was calibrated and validated for the Trinity River Delta by Hauck (52, 62).

Trinity River Delta. For the purpose of inundation analysis, the area of the Trinity River delta of concern is that region shaded in Figure 5-5. (The segmentation schematic utilized for the Trinity delta is also shown on this same figure). This shaded area is considered to be biologically the most important area of the Trinity marsh systems, bounded on the south by the Wallisville levee and continuing northward to the beginning of the cypress swamp area. The eastern boundary is the Trinity River, and the area extends westward from the river to the beginning of the uplands. Included within this area are all major marsh regions subject to inundation from river flow. This marsh area is highly productive and inundation to a minimum depth of 0.5 ft. (0.15 m) continually for two days should result in the flushing of nutrients into Trinity Bay.

Another large productive marsh region lies to the south of the Wallisville levee. However, this region is omitted from the study area because it is not significantly influenced by Trinity River water elevations due to the presence of the levee, but rather tidal elevations, independent of river flow, determine water levels in this region.

The periods chosen for simulation were selected based on tides and freshwater inflow and on the availability of data to verify the velocities and water depths predicted by the model. The availability of adequate verification data restricted the period of study to October 1975 through February 1977. The majority of verification data consists of water elevations (river stage or tide record) from continuous recording gages operated by the U.S. Geological Survey (USGS), U.S. Corps of Engineers (USCE) and TDWR. From October 1975 through September 1976, water elevation records were available from the gage at the confluence of the Old and Lost Rivers (section 34) and from the gage on the Trinity River at Liberty (section 92). Beginning October 1976 through February 1977 tide records were available from the gages on Anahuac Channel at Anahuac (section 48), on the Old River Cutoff Channel (section 24), on Lake Charlotte (section 165), on the Sulphur Barge Channel (section 162) and on the Lost River near Wallisville (section 200). Unfortunately, the tide records from the Lake Charlotte and Lost River gauges were often unuseable as verification data. The Lake Charlotte gage does not record water elevations below 1.1 ft. (0.3 m) and the Lost River gage was not operating reliably during a majority of the period. Daily stage readings for the stream gage at Liberty were also available for this time period. In addition, for January 1977 tide data are available from the Old River gage near Mont Belview (same location as Old and Lost River gage, section 34).

In addition, from November 30 through December 2, 1976, an intensive hydrologic and biologic study was conducted jointly by USGS, TDWR and Espey, Huston & Associates personnel. For various portions of this three-day period, instantaneous velocity and flow measurements were taken

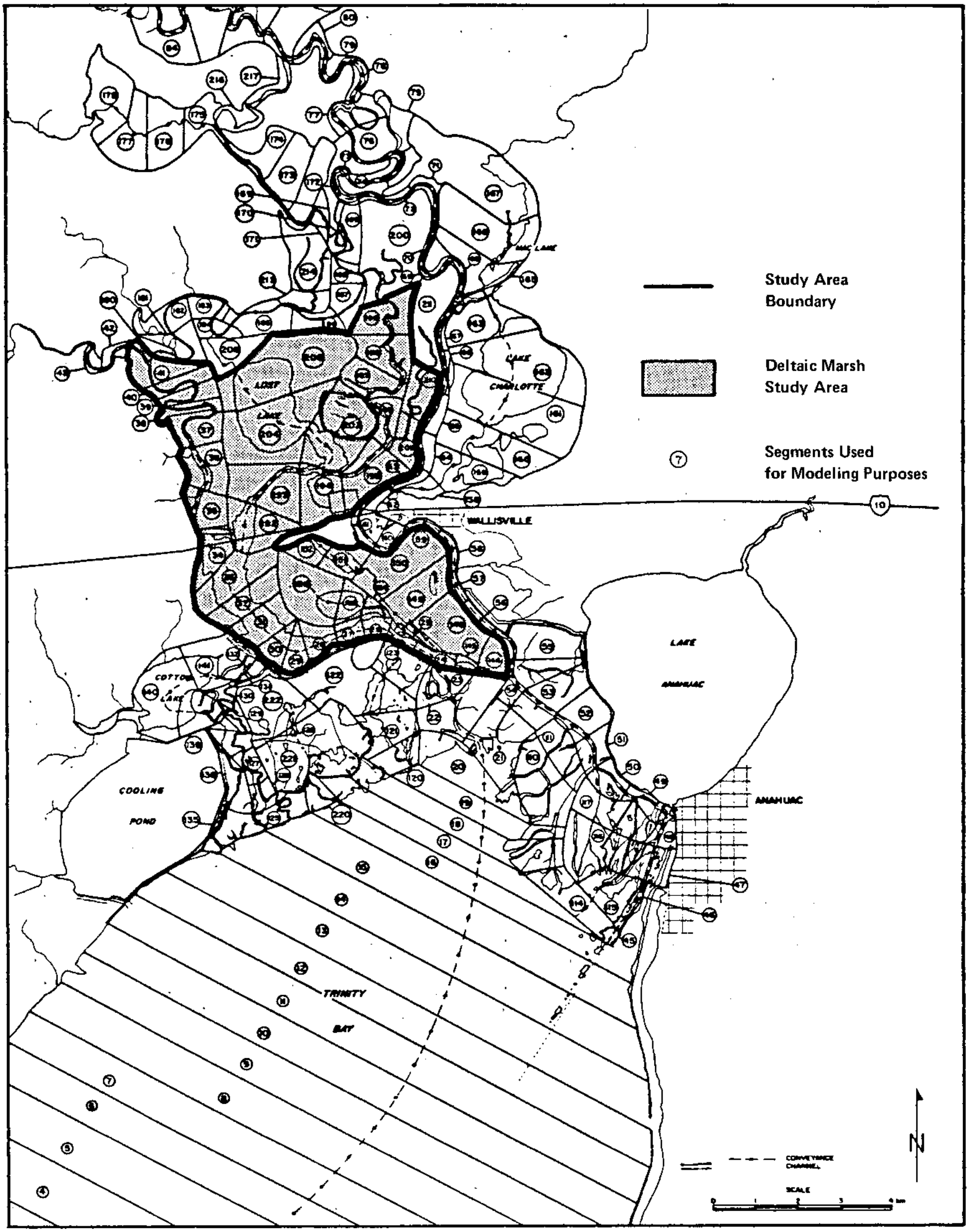


Figure 5-5. Deltaic Systems Boundaries of the Trinity Delta (52)

at time intervals of from one to six hours at the following locations: Old River Cutoff (section 144), Trinity River above Jack's Pass (section 53), Long Island Bayou above mouth (section 22), Long Island Bayou at levee breach (section 23), Anahuac Channel (section 47), Cove Bayou (section 120), Cross Bayou (section 125), Lake Pass (section 158), Cotton Bayou (section 132), Lost River near Interstate Highway 10 (section 192), Old River near Interstate Highway 10 (section 33), Mac Lake (section 165) and the Cutoff (section 169).

Low Flow Simulations. To initially test the segmentation of the physical system, the hydrodynamic model was used to simulate two low flow equilibrium1/ periods. Because of the large size of the system being simulated, it takes a "start-up time" of 24 to 36 hours for the simulated system to recover from the inaccuracies of the assumed initial conditions and to show proper response to the boundary conditions and mathematical equations. For this reason the first 24 hours of each simulation is not presented.

The first low flow equilibrium period selected was from April 14 through April 21, 1976. During this time period, the flow in the Trinity River at Romayor was approximately 1,600 ft^3/sec (45.3 m^3/sec) with an additional 40 ft^3/sec (1.1 m^3/sec) of inflow determined as entering below this gaging location, and diversions totaling 500 ft^3/sec (14.2 m^3/sec) were calculated to occur below Liberty. The tide at Morgan's Point during this time was initially semidiurnal changing to diurnal (Figure 5-6). There was a strong southeast wind during most of this period, particularly on April 15-18, while a light northerly wind prevailed on April 21. The wind influence on the bay results in the water elevation set-up on April 15-18.

The results of the simulation were compared with the measured water elevation records at the Liberty gage and the Old and Lost Rivers gage as shown in Figure 5-7 and 5-8, respectively. The measured and simulated river stages at Liberty compare favorably, though only minor tidal influence is observed at this location. The major discrepancies occur on the first and last days of the simulation. On the first day, the error is due to the "start-up time" of the model, that is, the river flow is still adjusting from the assumed initial conditions. As the boundary inflow from the Romayor gage (section 108) reaches the Liberty gage location (section 92) an increase to approximately the proper water elevation is observed. The last day of simulation, April 21, is the beginning of passage of a large flood. The increase in stage was not adequately accounted for in this steady-state case. The simulated and recorded tides for the gage at the Old and Lost Rivers also compare favorably. The phase error is small, approximately one hour. Tidal amplitudes also are adequately simulated. For a majority of the simulation period the error between simulated and recorded tides is less than 0.2 feet (0.06 m) with a maximum discrepancy of 0.5 ft. (0.15 m) occurring on April 18.

1/ "Low flow equilibrium" or "steady state" refers to the condition when the streamflow over the desired period was nearly constant. Such a condition eliminates the streamflow variability in the system, and permits an assessment of how adequately the model replicates tidal variations through the system.

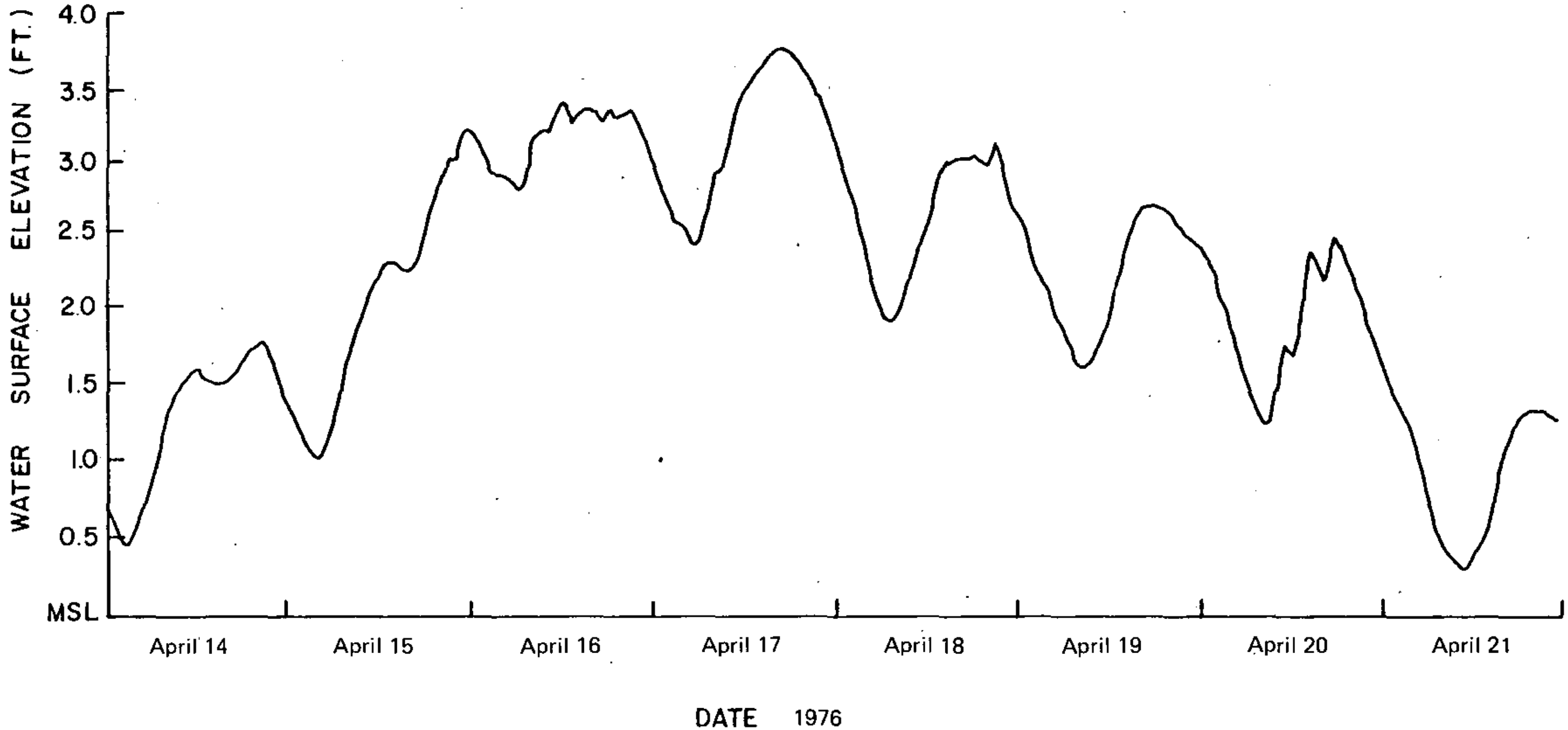


Figure 5-6. Driving Tide Record at Section 2, Morgan's Point Gage, April 14-21, 1976 (52)

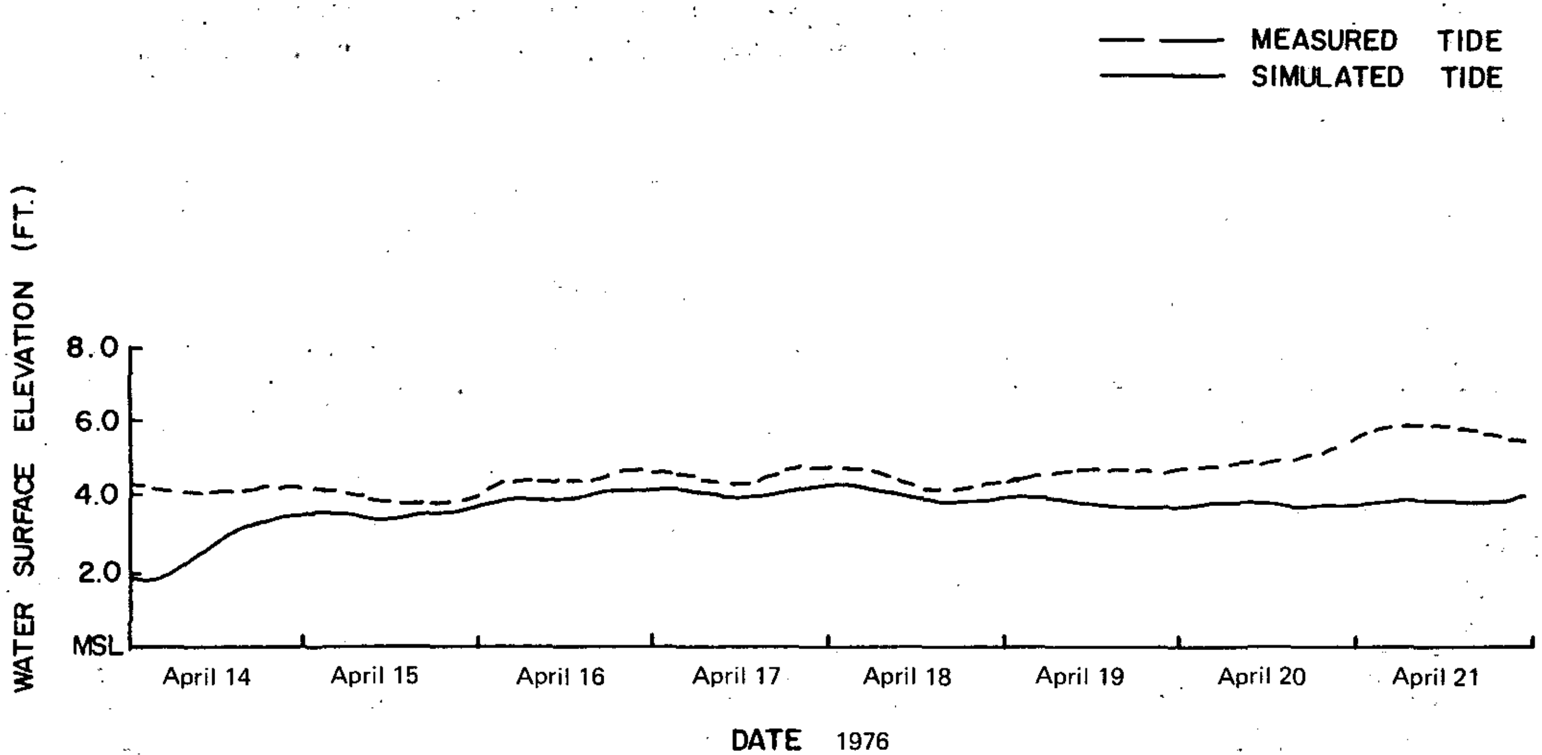


Figure 5-7. Comparison of Observed and Simulated Water Stage at Section 92, Trinity River at Liberty Gage, April 14-21, 1976 (52)

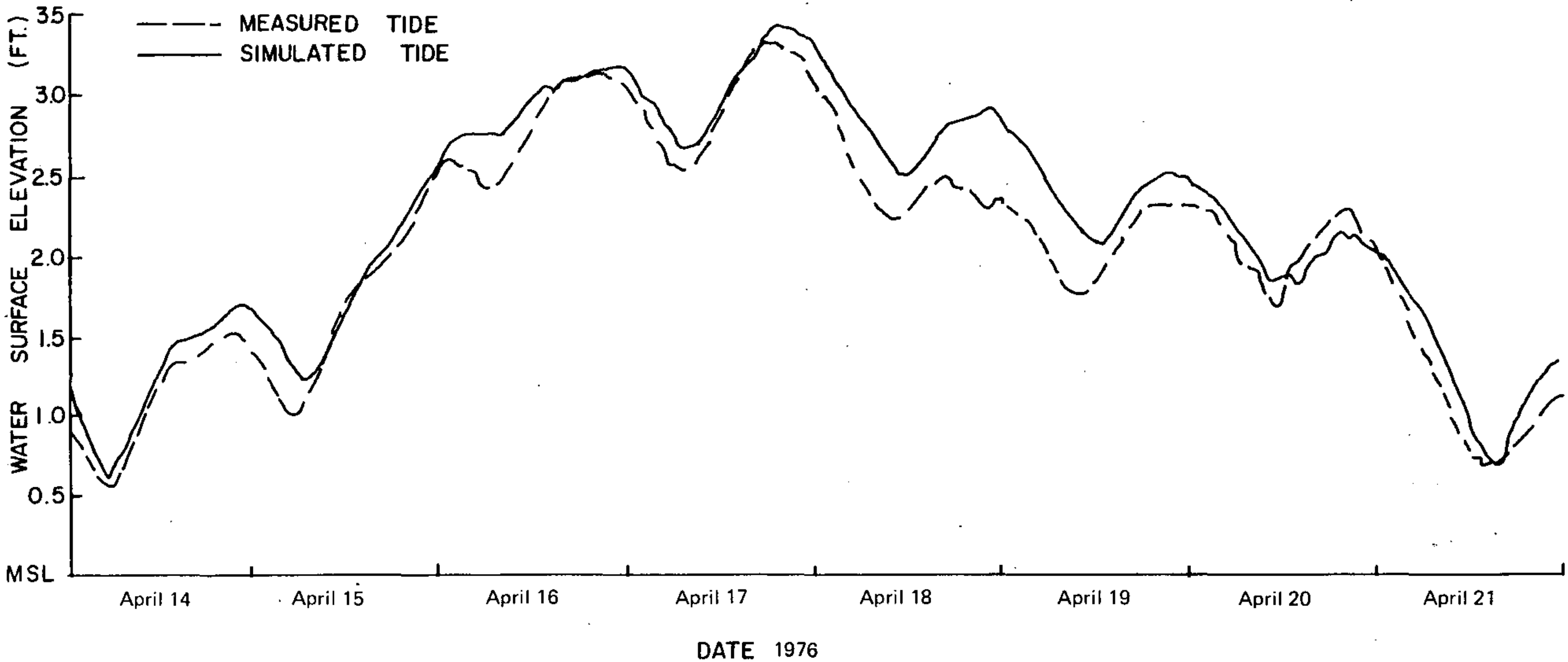


Figure 5-8. Comparison of Observed and Simulated Tidal Elevations at Section 34, Old and Lost River Gage, April 14-21, 1976 (52)

The second low-flow equilibrium case selected was the period from November 16 through November 23, 1976. During this period the Trinity River gage at Romayor was not recording, but based on the flows at Goodrich gage located 23 river miles above the segmentation, a river flow of 1,200 ft^3/sec (34 m^3/sec) was determined as the input at the upper boundary of the segmentation (section 108). Diversions for this period were calculated to be only 60 ft^3/sec (1.7 m^3/sec). Some additional runoff was required due to a 1- to 2-inch rain which occurred over the lower Trinity watershed on November 19-20. Because of tidal influences at the Liberty gage for river flows below 10,000 ft^3/sec (283 m^3/sec), the water stage records at Liberty could not be used as a completely reliable source to estimate flows for this low water period. But in lieu of any other information and based on the one-foot river stage rise from November 20-22, a hydrograph with a peak discharge of 1,000 ft^3/sec (28 m^3/sec) was input at segment 95. This additional inflow is not of significant magnitude to appreciably alter most of the tide records in the deltaic system, so this simulation is still considered a low-flow equilibrium case. The driving tide as recorded at Point Barrow during this period was initially semidiurnal changing to diurnal (Figure 5-9) and winds were light and from the north.

The results of the simulations were compared with the tidal records for the Old River Cutoff Channel gage, the Anahuac Channel gage and the Sulphur Barge Channel gage as shown in Figures 5-10 through 5-12. The Lake Charlotte gage did not properly record the tides of this period which were almost entirely below the elevation this gage can record, and the Lost River gage was not functioning properly during this time interval. So neither gage was employed for verification of data.

The simulated and recorded tides for the Old River Cutoff and Anahuac Channel gage locations, Figures 5-10 and 5-11, respectively, compare favorably as far as tidal amplitude and phase. However, a datum error of approximately 0.3 ft. (0.9m) is apparent at both locations. The measured tide is consistently lower than the simulated tide at both gages. A comparison of the model driving tide from the Point Barrow gage with these two gages also indicates that the driving tide is higher than the measured tides at the Old River Cutoff and the Anahuac Channel gage. It seems unlikely during this period of light winds that mean water elevations would decrease in the upstream direction, as this implies. It is more likely that there is a datum error, resulting from subsidence of gages or from a survey error when setting gage datums.

The simulated and recorded tides at the Sulphur Barge Channel gage compare satisfactorily (Figure 5-12). The simulated tide lags the measured tide by approximately two hours. For the first four days tidal amplitudes are well simulated, though for the last four days significant errors are apparent. The simulated tidal troughs are deeper than the measured troughs and this error may be due to ungaged local runoff dampening the tidal amplitude and raising the water elevation in the Sulphur Barge Canal.

Flood Simulations. During this study period, two floods occurred and caused an appreciable rise in water elevation in the delta region. Though these floods inundated essentially the entire marsh area, the conditions of one-dimensional flow as implicitly assumed in the computer

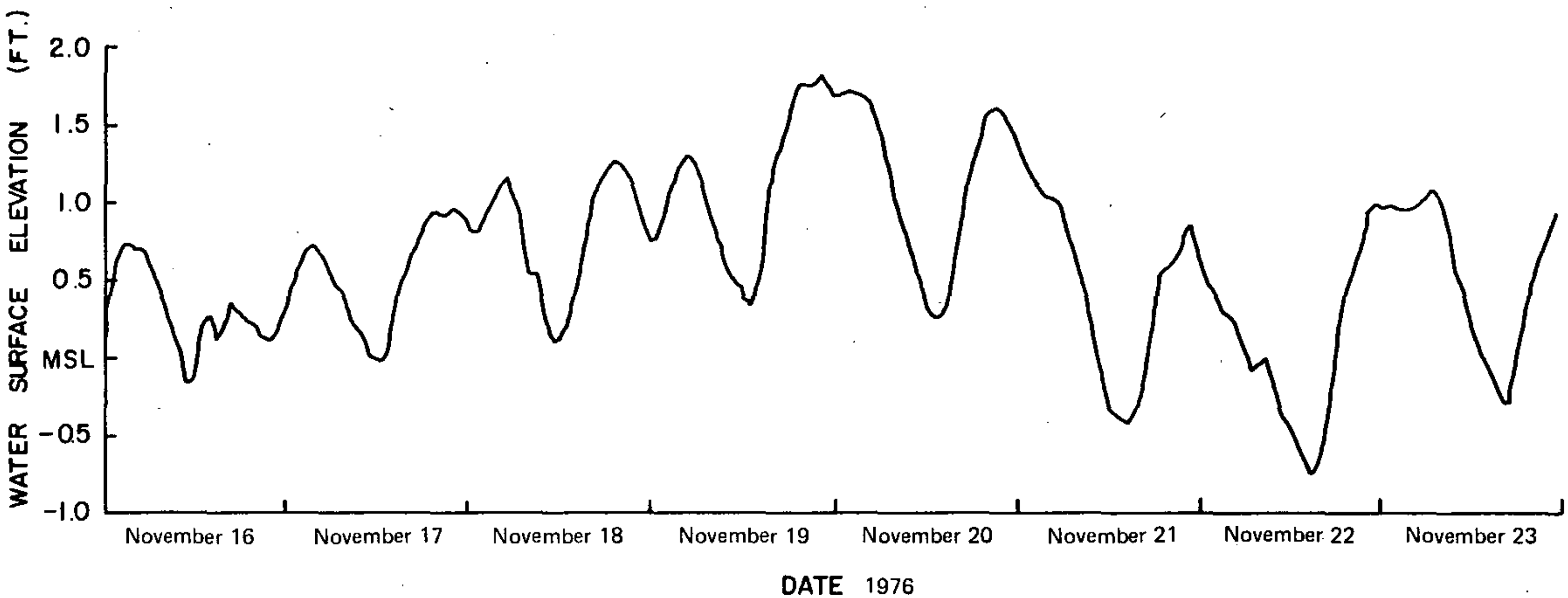


Figure 5-9. Driving Tide Record at Section 8, Point Barrow Gage, November 16-23, 1976 (52)

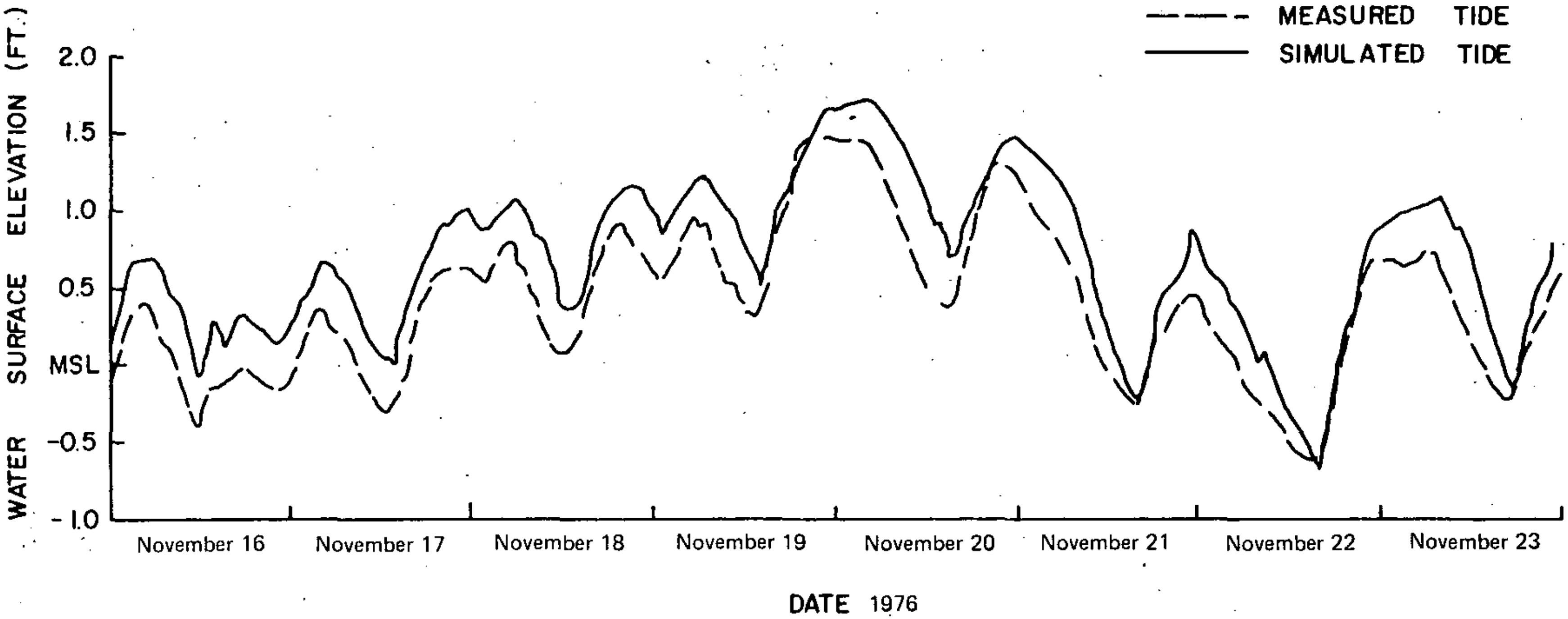


Figure 5-10. Comparison of Observed and Simulated Tidal Elevations at Section 24, Old River Cutoff Channel, November 16-23, 1976 (52)

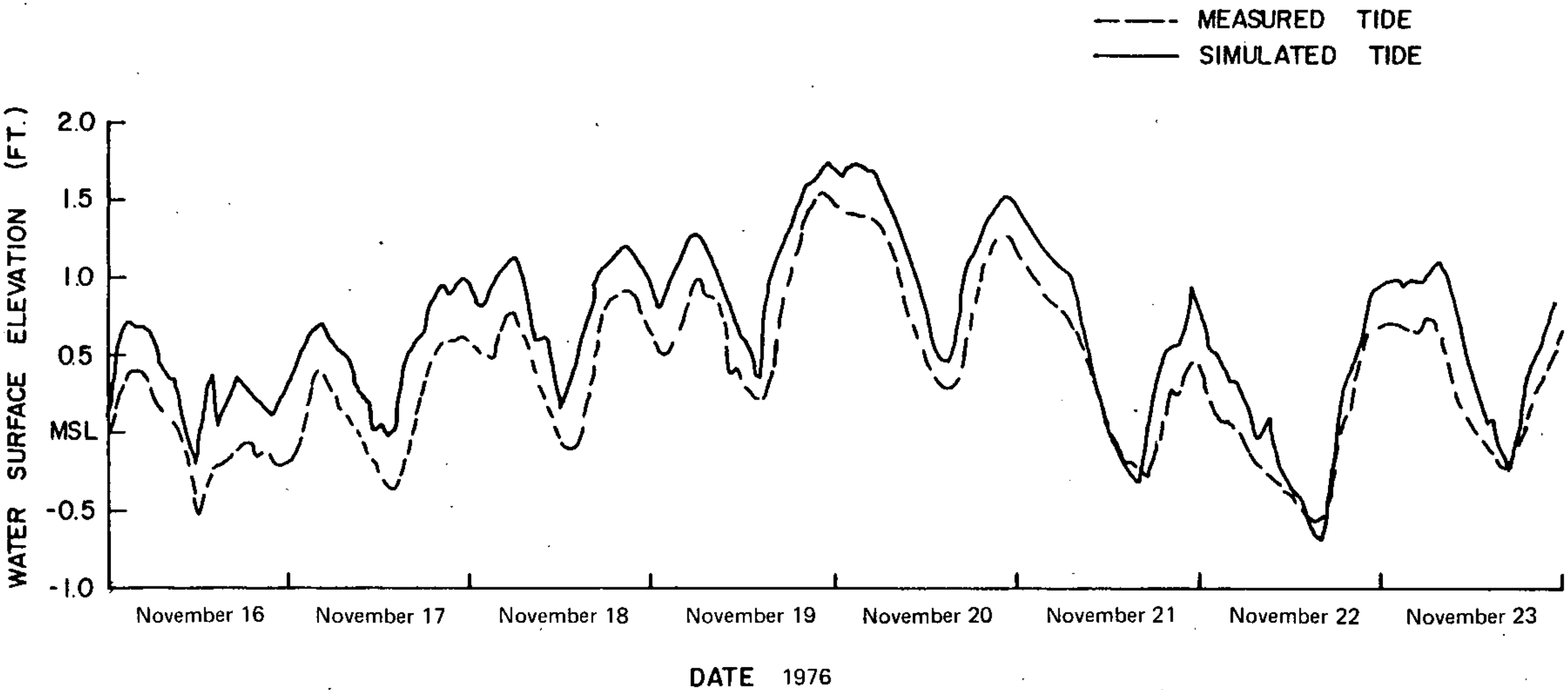


Figure 5-11. Comparison of Observed and Simulated Tidal Elevations at Section 48, Anahuac Channel Gage, November 16-23, 1976 (52)

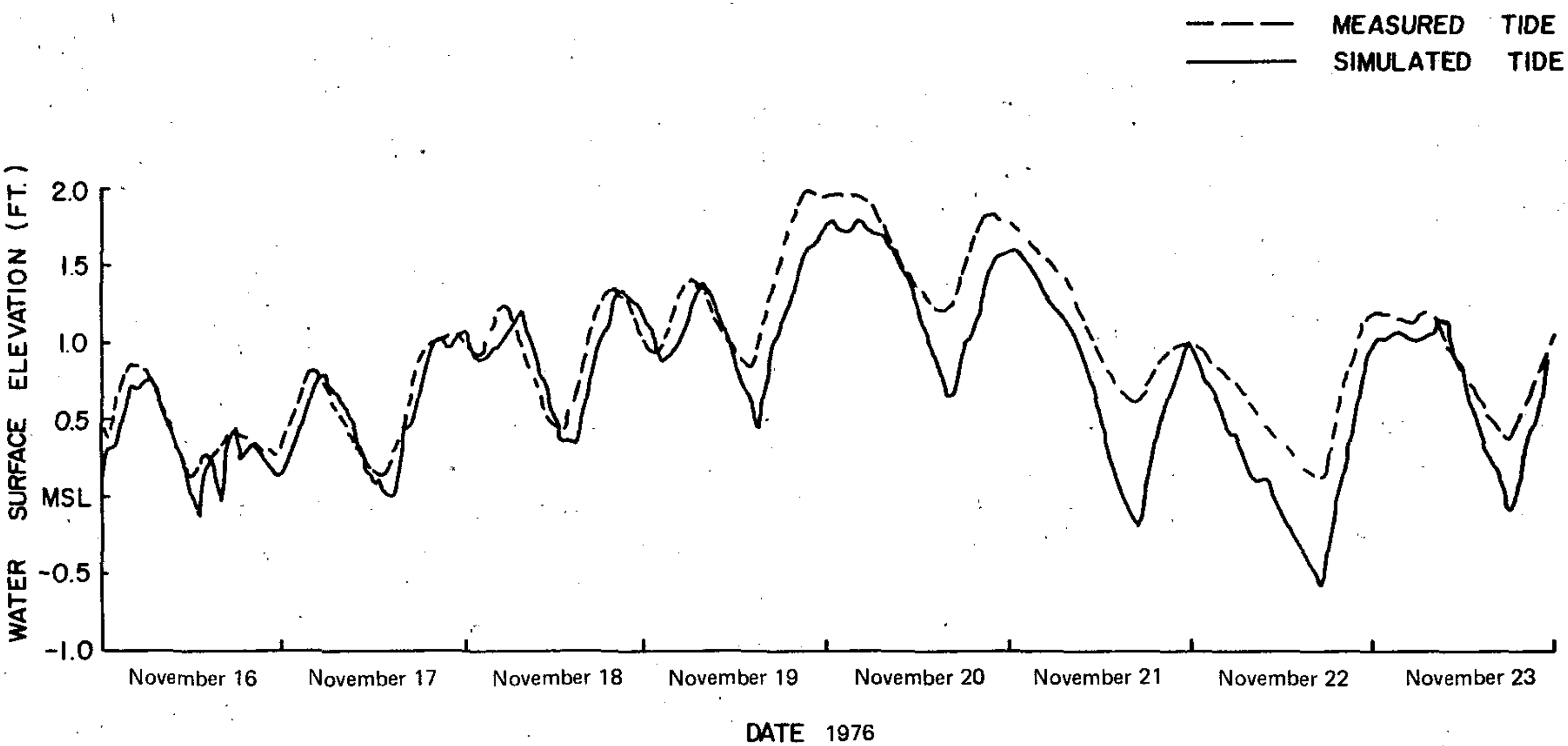


Figure 5-12. Comparison of Observed and Simulated Tidal Elevations, at Section 165, Sulphur Barge Channel Gage, November 16-23, 1976 (52)

code were apparently not violated in the physical system. As for the low-flow equilibrium cases, the first day of the simulation was omitted because of the required "start-up time". Because of the long duration of both of these floods, three to four weeks, only that portion of the flood which resulted in significant influences on the delta was simulated.

The first of these floods was simulated as the period June 1 through June 16, 1976. This simulation case represents a nearly ideal flood case from a meteorological viewpoint. Heavy rains of as much as five inches occurred over much of the Trinity watershed on May 31 and June 1, and no other significant rains occurred during the remainder of the simulation period. period. Errors due to rainfall on the lower watershed during the flood per se are minimal. For the entire period winds were of moderate speed from the northeast on the first nine days and shifting to the southeast for the last seven days. The driving tide at Morgan's Point during this time was initially diurnal, changing briefly to semidiurnal and then returning to diurnal (Figure 5-13). Because special calculations were performed by the USGS, flows in the Trinity River at Romayor plus estimates of the additional inflow occurring between the Romayor and Liberty gages were available. A maximum daily-average flow of 33,200 ft^3/sec (940 m^3/sec) was measured at the Romayor gage on June 3. A listing of the daily flows used as input to the model are presented in Table 5-1. Withdrawal at section 86 for irrigation purposes was calculated to be 1,000 ft^3/sec (28 m^3/sec).

The comparison of simulated and measured water elevations for the Liberty gage and the Old and Lost River gage are shown in Figures 5-14 and 5-15. The flood passage as recorded at the Liberty gage is satisfactorily simulated. The simulated water elevation does show significant error over the last four days, June 13-16; however, for the remainder of the period, simulated elevations are within two feet (0.6 m)of recorded elevations. The simulated and measured water elevations at the Old and Lost River gage also compare favorably. The simulation does indicate rising water elevations before they were measured, particularly June 3-5. The peak water elevation and its duration are simulated quite accurately as is the gradual subsidence of the flood.

The simulated flood levels in the delta at four day intervals on June 1, 5, 9, 13 and 17, 1976 are presented in Figures 5-16 through 5-20, respectively. This sequence of figures indicates the water level above bank elevation at hour 0000 CST for each day mentioned and depicts the rise and subsequent fall of water levels with the passage of the flood. On June 1 (Figure 5-16) moderate levels of inundation are indicated because of the relatively high tides of this period. By June 5 (Figure 5-17) flood waters are causing increased water levels in the upper delta and along the Trinity River, and by June 9 (Figure 5-18) the maximum water levels are occurring throughout the delta area. The June 13 and 17 simulations (Figures 5-19 and 5-20) indicate water levels as the flood waters recede.

The second flood was simulated for the period December 12-27, 1976. Due to heavy rainfall of approximately 5.0 inches (13 cm) on the deltaic region during this period and because the streamflow gage at Romayor was inoperative, it was difficult to estimate flow in the Trinity River. The gaged flow from the Goodrich gage was used as the headwater flow condi-

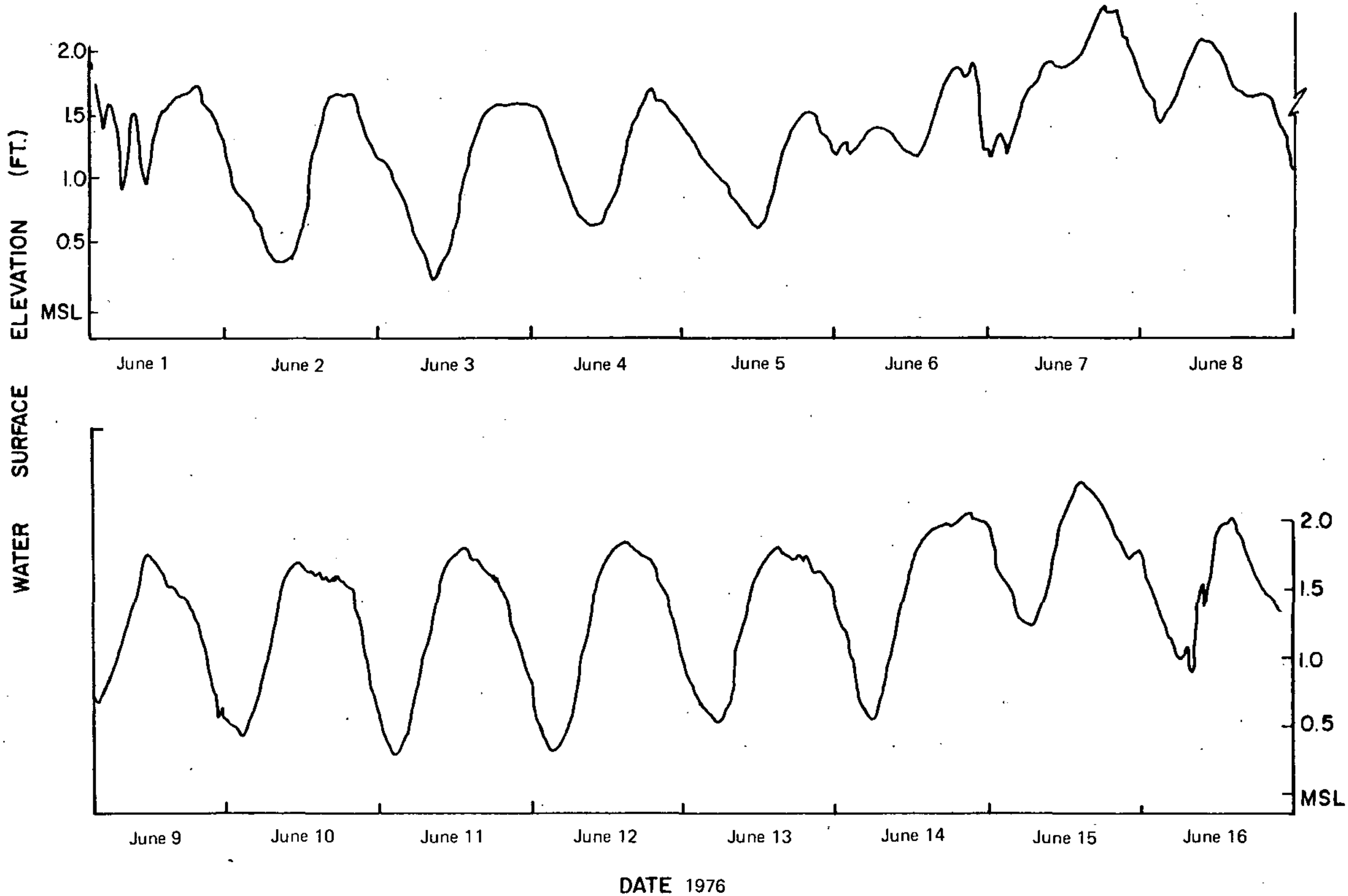


Figure 5-13. Driving Tide Record at Section 2, Morgan's Point Gage, June 1-16, 1976 (52)

Table 5-1. Daily Flow a/ Records for the Trinity River, June 1-16, 1976 (52)

DATE	TRINITY HEADWATER a/ Segment 108	ADDITIONAL INFLOW b/ Segment 95
	(ft^3/sec)	
June 1	16,900	1289
June 2	31,500	1384
June 3	33,200	1050
June 4	32,800	1035
June 5	31,800	983
June 6	29,100	947
June 7	27,600	968
June 8	24,900	760
June 9	23,100	660
June 10	21,100	454
June 11	17,800	240
June 12	13,800	137
June 13	9,010	95
June 14	5,830	79
June 15	3,780	83
June 16	3,730	154

a/ All flows from USGS special computations
b/ Flows supplement Goodrich gaged flows in order to produce measured stage at Liberty

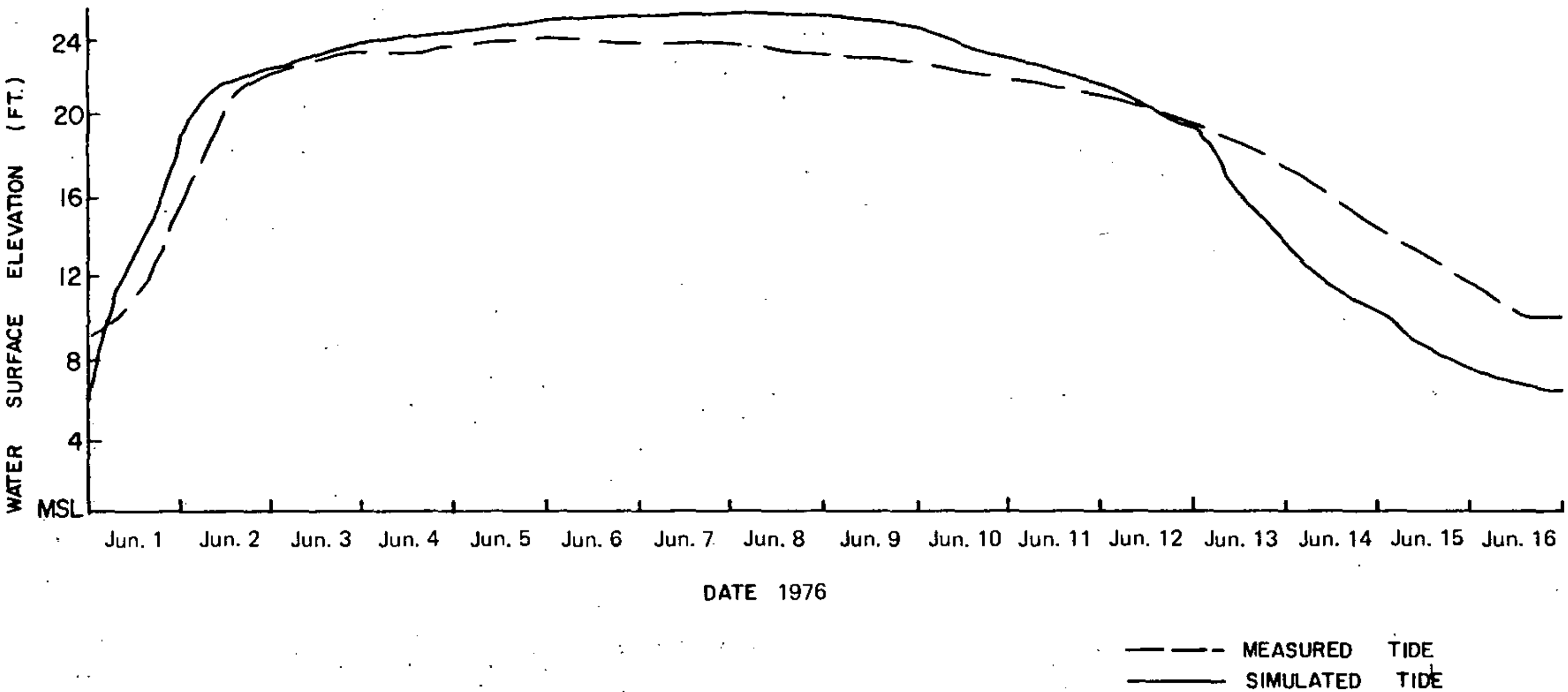


Figure 5-14. Comparison of Observed and Simulated Water Stage at Section 92, Trinity River at Liberty Gage, June 1-16, 1976 (52)

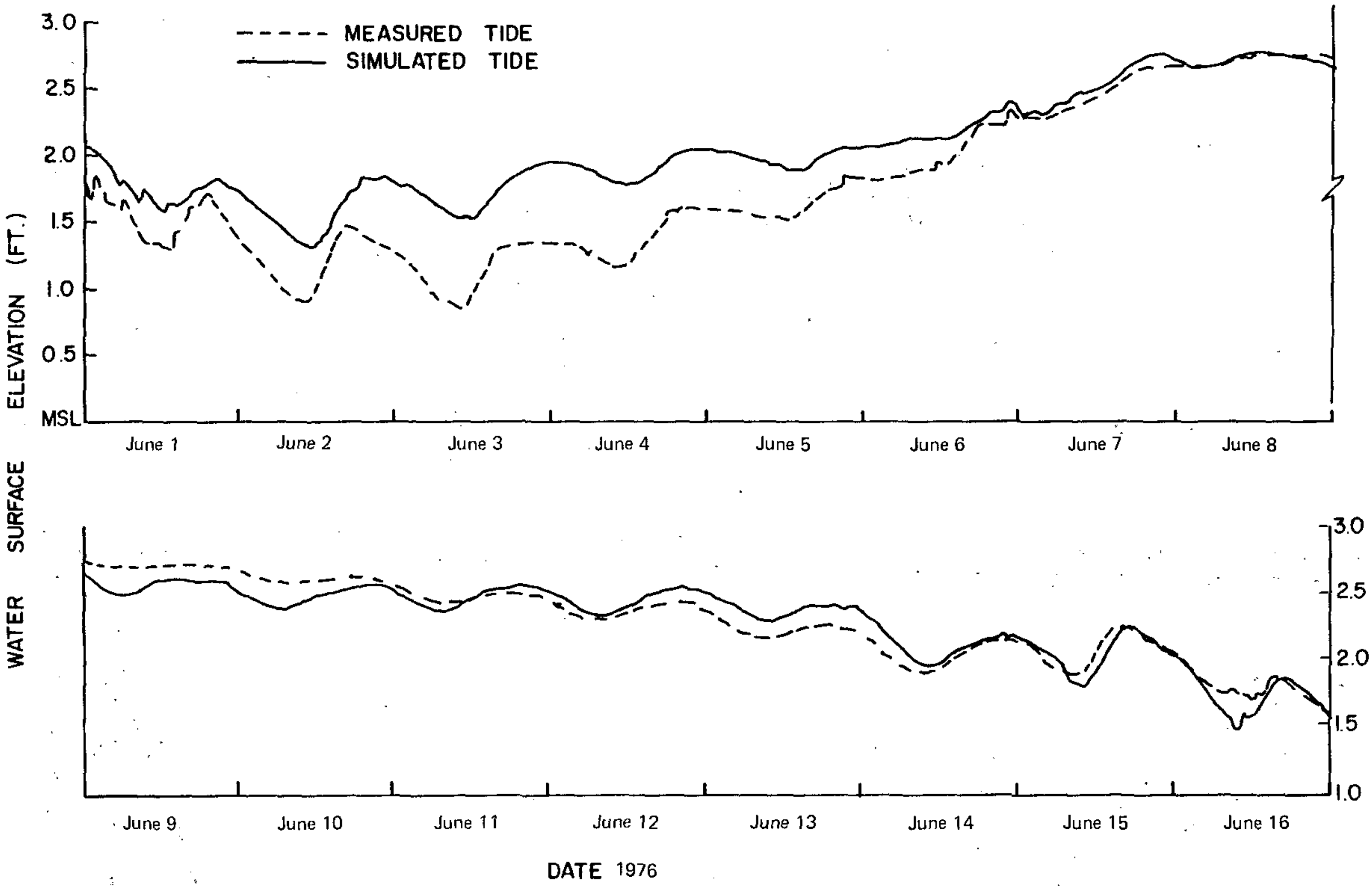


Figure 5-15. Comparison of Observed and Simulated Tidal Elevations at Section 34, Old and Lost River Gage, June 1-16, 1976 (52)

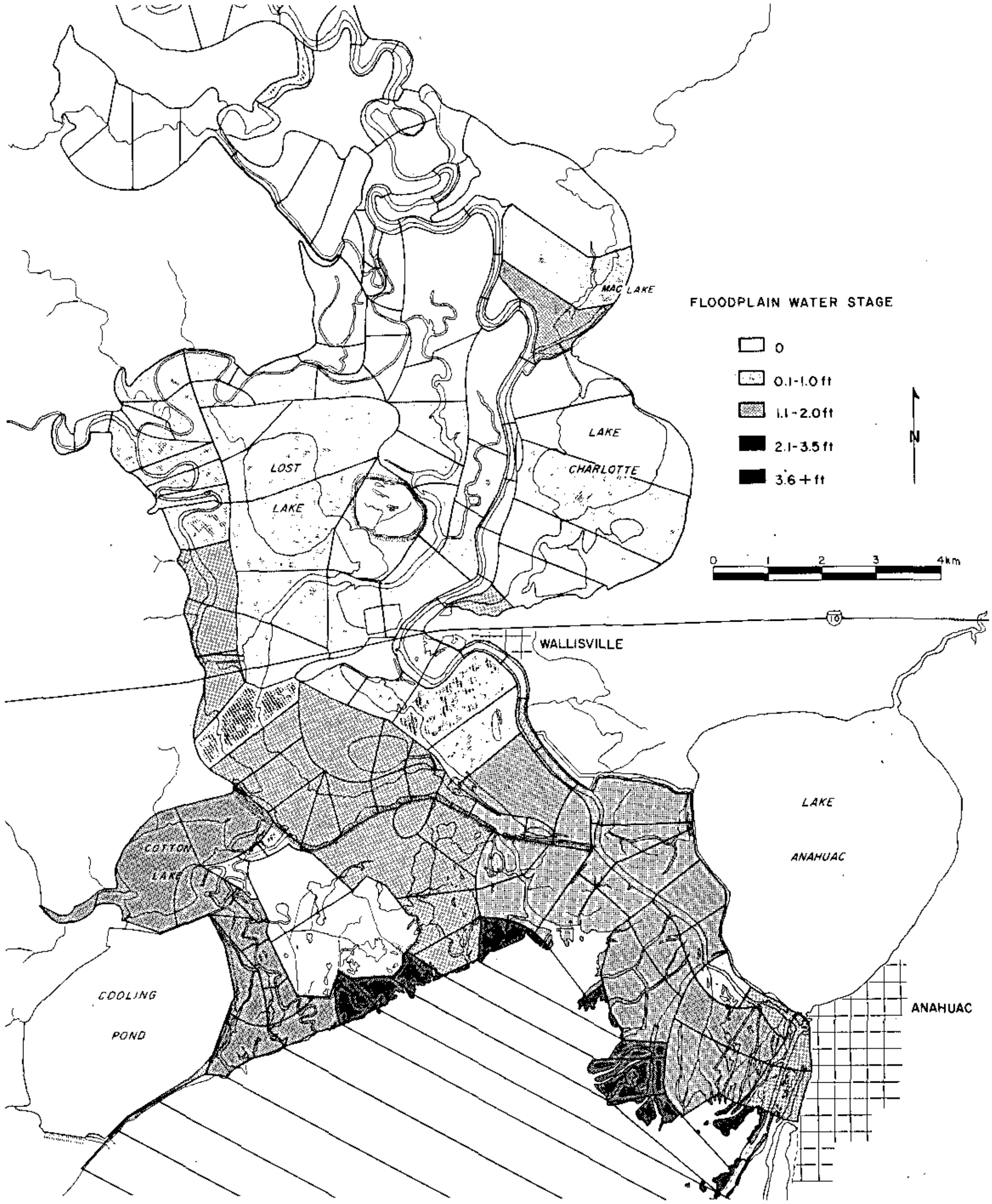


Figure 5-16. Trinity Delta System Showing Inundation Areas, June 1, 1976 (52)

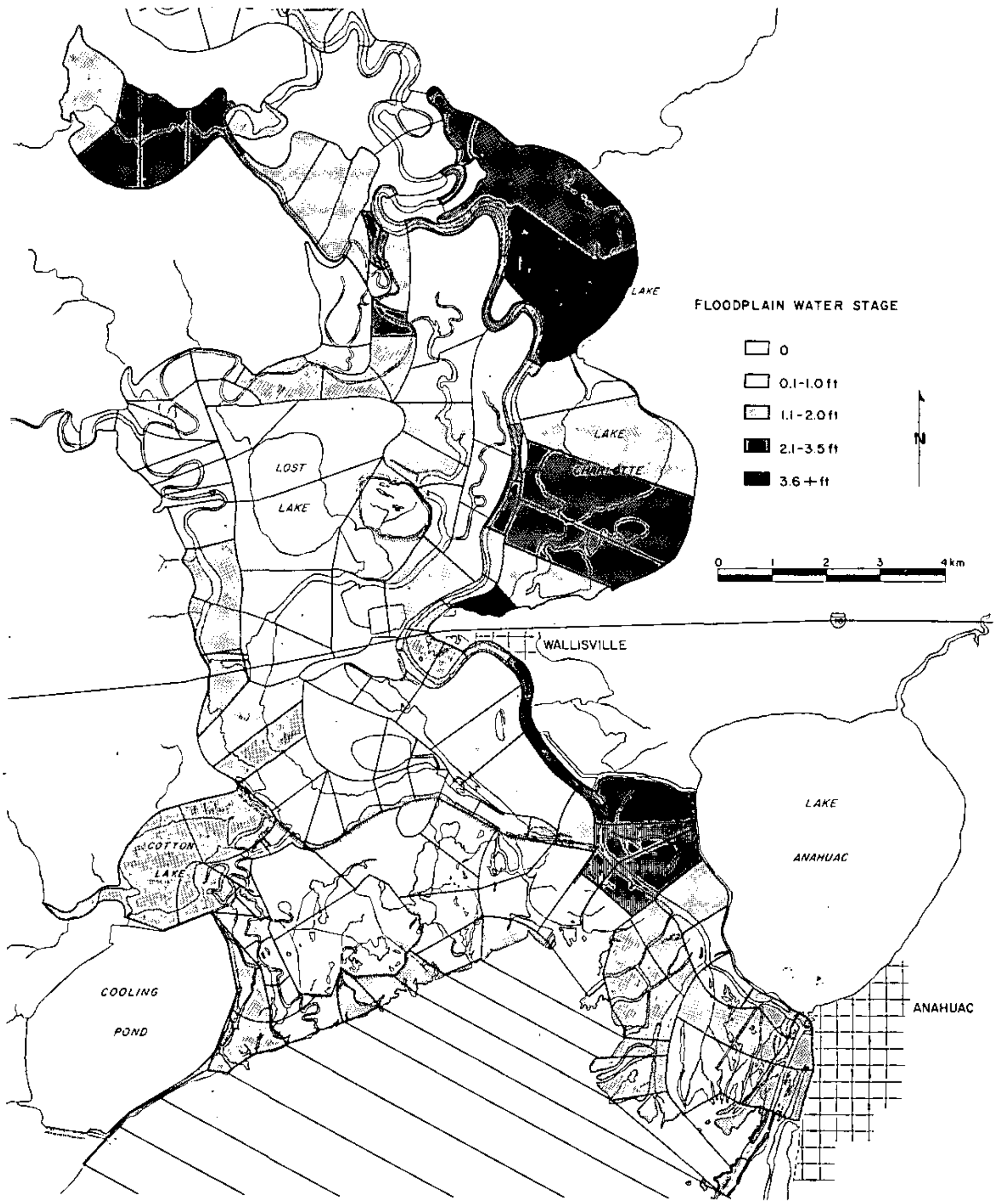


Figure 5-17. Trinity Delta System Showing Inundation Areas, June 5, 1976 (52)

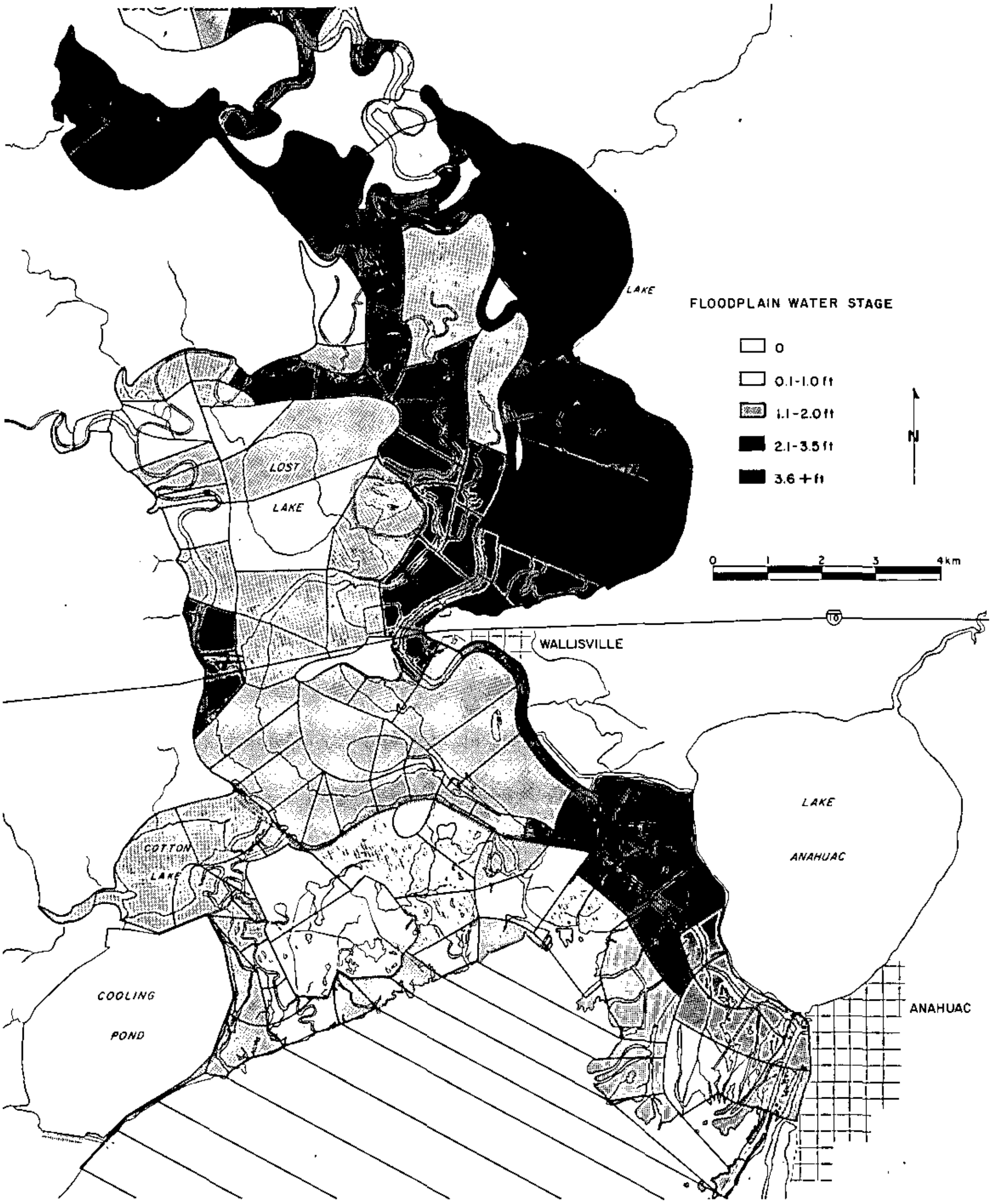


Figure 5-18. Trinity Delta System Showing Inundation Areas, June 9, 1976 (52)

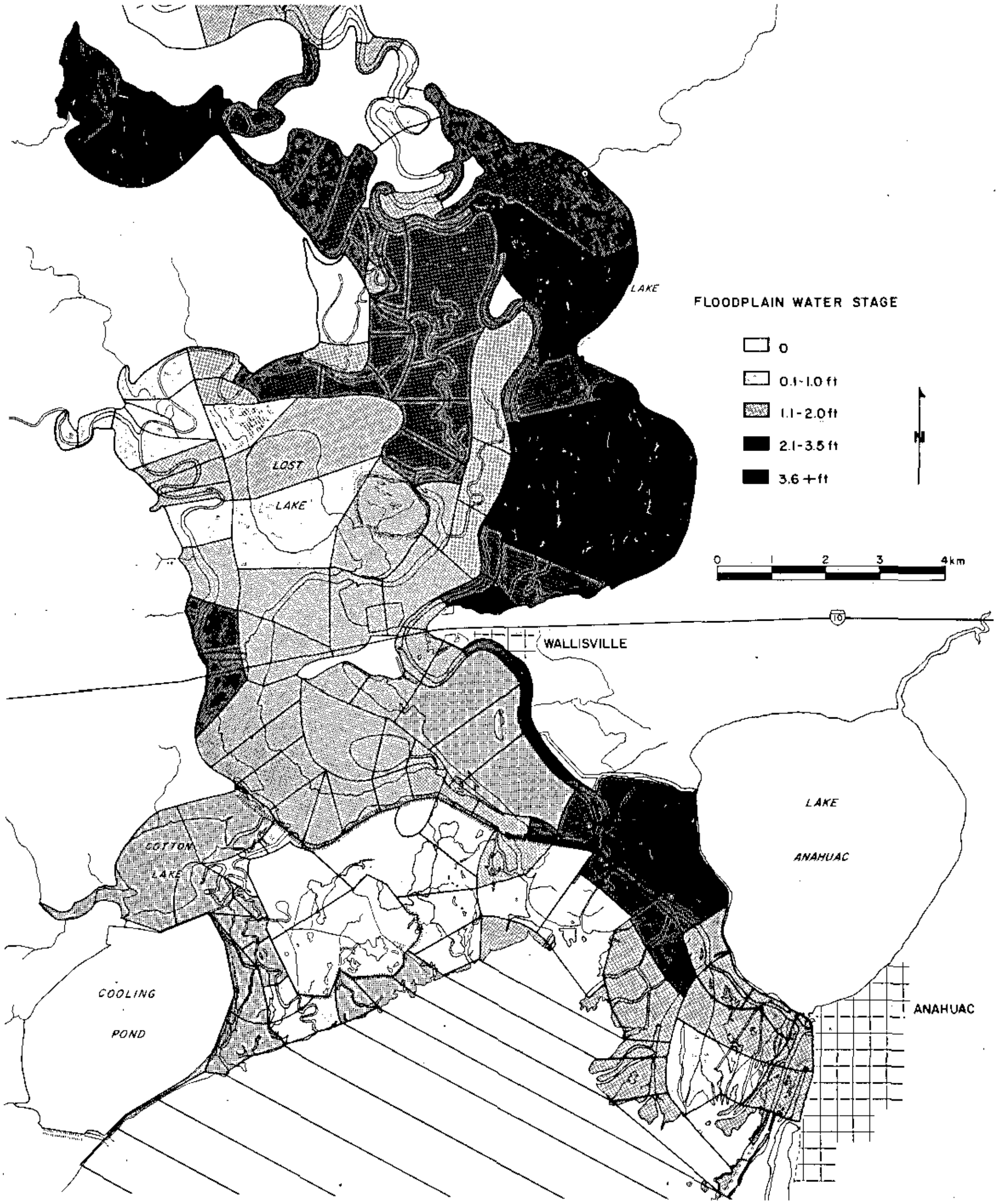


Figure 5-19. Trinity Delta System Showing Inundation Areas, June 13, 1976 (52)

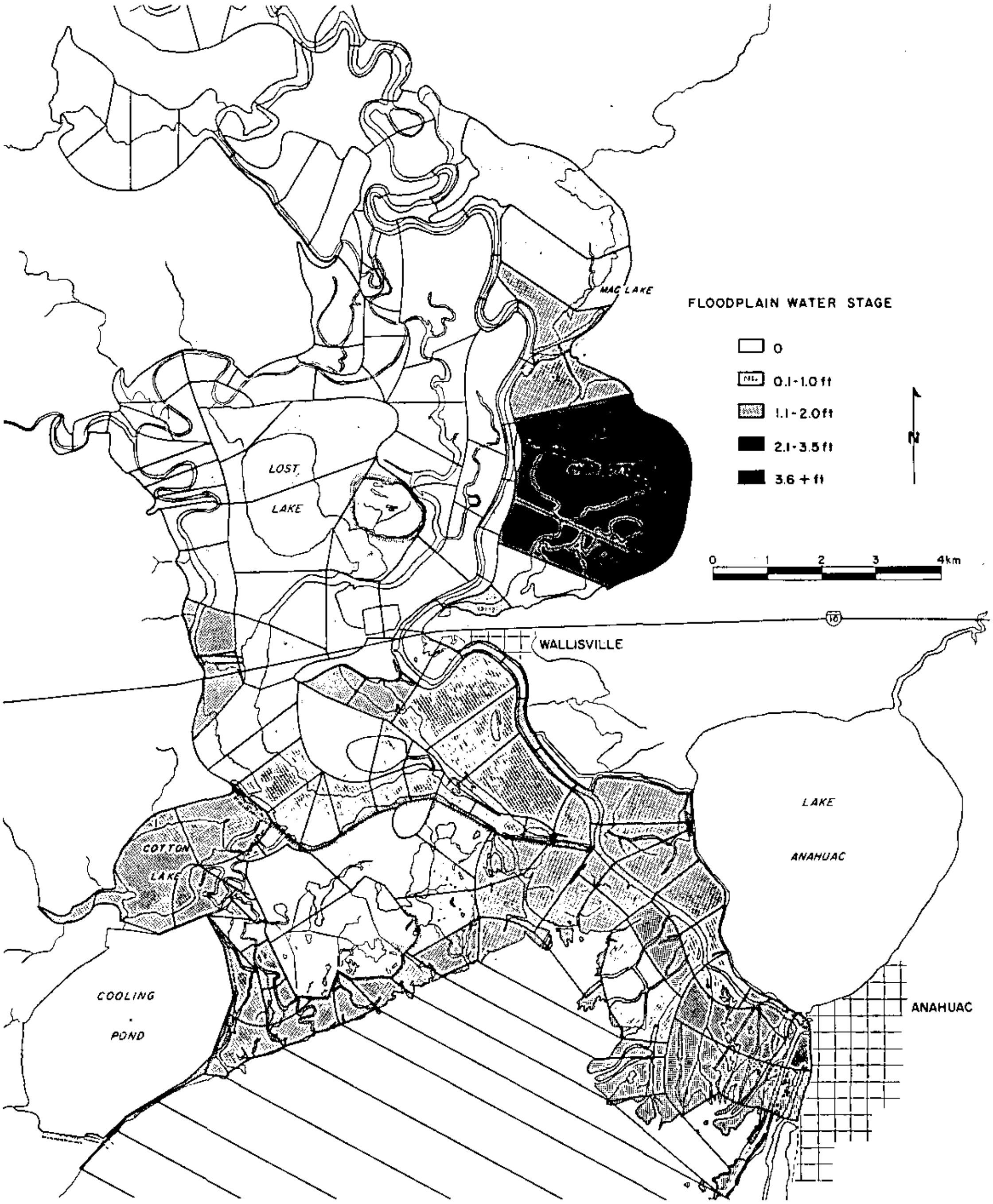


Figure 5-20. Trinity Delta System Showing Inundation Areas, June 17, 1976 (52)

tions at section 108 and a maximum daily-average flow of 26,800 ft^3/sec (759 m^3/sec) was recorded on December 16. Based on the daily staff readings at Liberty, it was apparent that considerable inflow occurred between the Goodrich and Liberty gages due to the heavy rains on the lower watershed. An additional hydrograph was used as input at Segment 95, and the hydrograph shape was constructed to supplement the Goodrich flows in a manner that would produce the proper water stage at Liberty. The daily inflows from both inflow locations are presented in Table 5-2. Withdrawals averaged over 60 ft^3/sec (1.7 m^3/sec) for this period. The driving tide at Point Barrow began as semidiurnal, became diurnal, and returned to semidiurnal (Figure 5-21). During this period, winds were generally from the north or east and of moderate speed, with the exception of a strong north wind on December 20 which resulted in the water setdown apparent in the driving tide at the same time.

Simulated and measured water elevations are compared at the gages at the Old River Cutoff Channel, the Anahuac Channel, Lake Charlotte, and the Sulphur Barge Channel (Figures 5-22 through 5-25, respectively). The Lost River gage was not recording properly during this period.

In general, the simulated and measured tides compare favorably at both the Old River Cutoff Channel and Anahuac Channel gages. The approximately 0.3 ft. (0.09 m) datum error at both gages, previously mentioned with respect to the November 16-23 case, is still apparent in this simulation. The most significant discrepancies occurred during the lower tidal amplitude on December 21 and 26. Overall tidal amplitude and phase are adequately simulated at both locations, though the simulation during the wind setdown condition is poor.

The flood passage as recorded at the Lake Charlotte gage (Figure 5-24) is accurately simulated. Water elevation and phasing of the flood is quite good. The short rise in water elevation measured at this gage on December 12 is most likely due to local runoff from a 1.5 inch (3.8 cm) rain that occurred on that day. At the Sulphur Barge Channel gage, the simulated and measured water elevations exhibit poor agreement (Figure 5-25). The phasing of the flood is adequate, but the water elevation is as much as 3.0 feet (1 m) in error. This error can not be adequately explained. Input conditions were set to produce proper water elevations at the Liberty gage, and elevations at the Lake Charlotte gage just off the river were accurately simulated. However, about two miles upstream from the Lake Charlotte area, the simulations at the Sulphur Barge gage show significant error. Whether this is due to significant unaccounted runoff (Spinks Creek empties into the marsh in this area) or whether the error is purely a simulation error can not be determined from this single flood case. Further investigation of other flood cases, as data becomes available, is required.

The simulated flood water levels in the delta are presented at four-day intervals on December 12, 16, 20, 24 and 28 (Figures 5-26 through 5-30). As for the first flood, this sequence of figures depicts water levels above bank elevation at hour 0000CST for each day mentioned for the deltaic portion of the computer segmentation. Prior to flood passage, some tidal inundation of the deltaic marsh areas is indicated on December 12 (Figure 5-26). The next two figures in the sequence, for December 16 and December 20, indicate the increased rise in water elevations with the

Table 5-2. Daily Flow Records for the Trinity River, December 12-27, 1976 (52)

DATE	TRINITY HEADWATER a/ Segment 108	ADDITIONAL INFLOW b/ Segment 95
	(ft³/sec)	
Dec 12	20,500	0.
Dec 13	22,500	0.
Dec 14	23,000	0.
Dec 15	25,200	0.
Dec 16	26,800	0.
Dec 17	25,300	0.
Dec 18	23 700	750.
Dec 19	23,000	2500.
Dec 20	20,900	4300.
Dec 21	16,300	5800.
Dec 22	9,250	4500.
Dec 23	6,629	3300.
Dec 24	5,480	4300.
Dec 25	4,860	5800.
Dec 26	4,500	5800.
Dec 27	3,660	4800.

a/ Flows from USGS gage on Trinity River at Goodrich
b/ Flows supplement Goodrich gaged flows in order to produce measured stage at Liberty

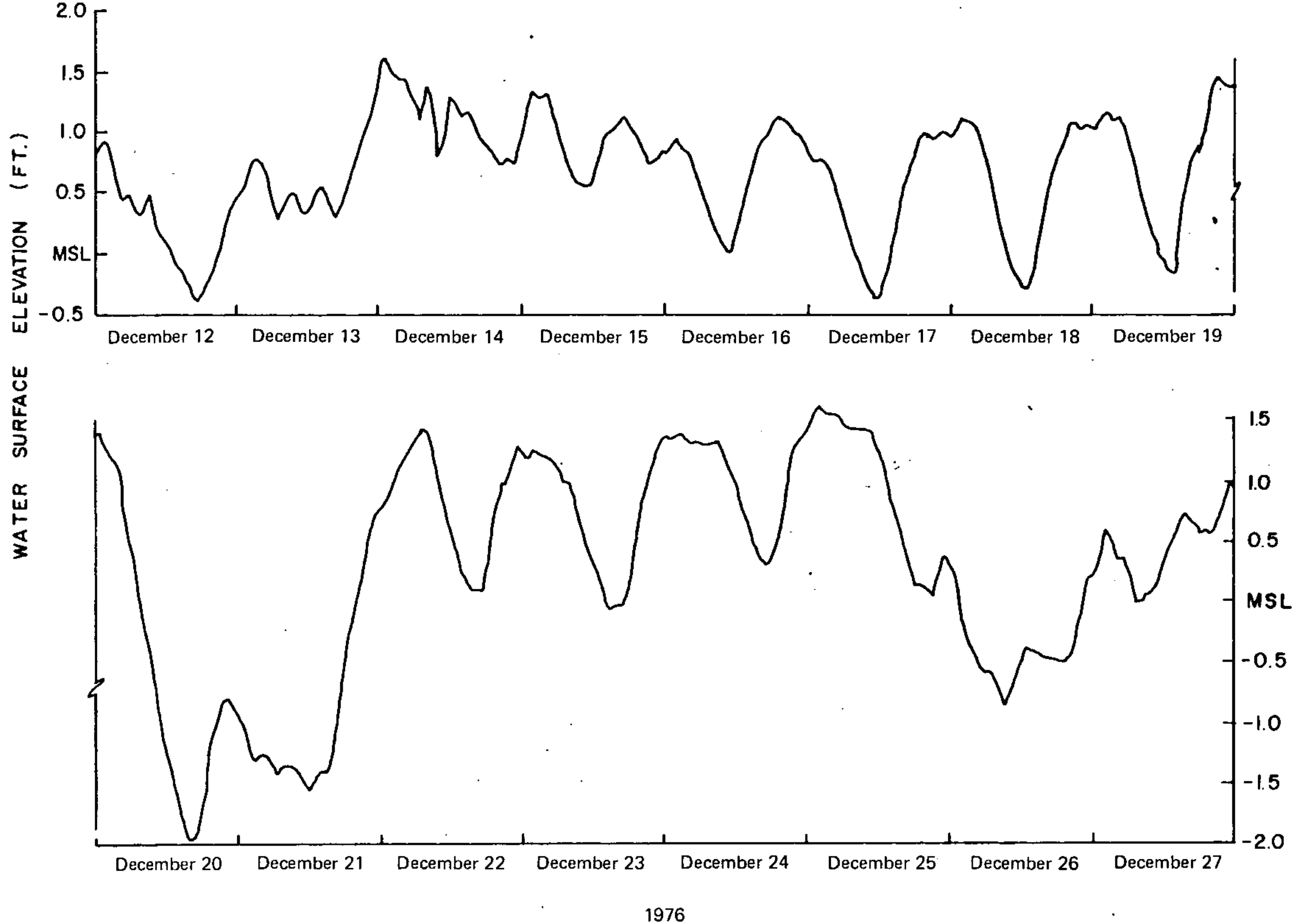


Figure 5-21. Tidal Elevation Record at Section 8, Point Barrow Gage, December 12-27, 1976 (52)

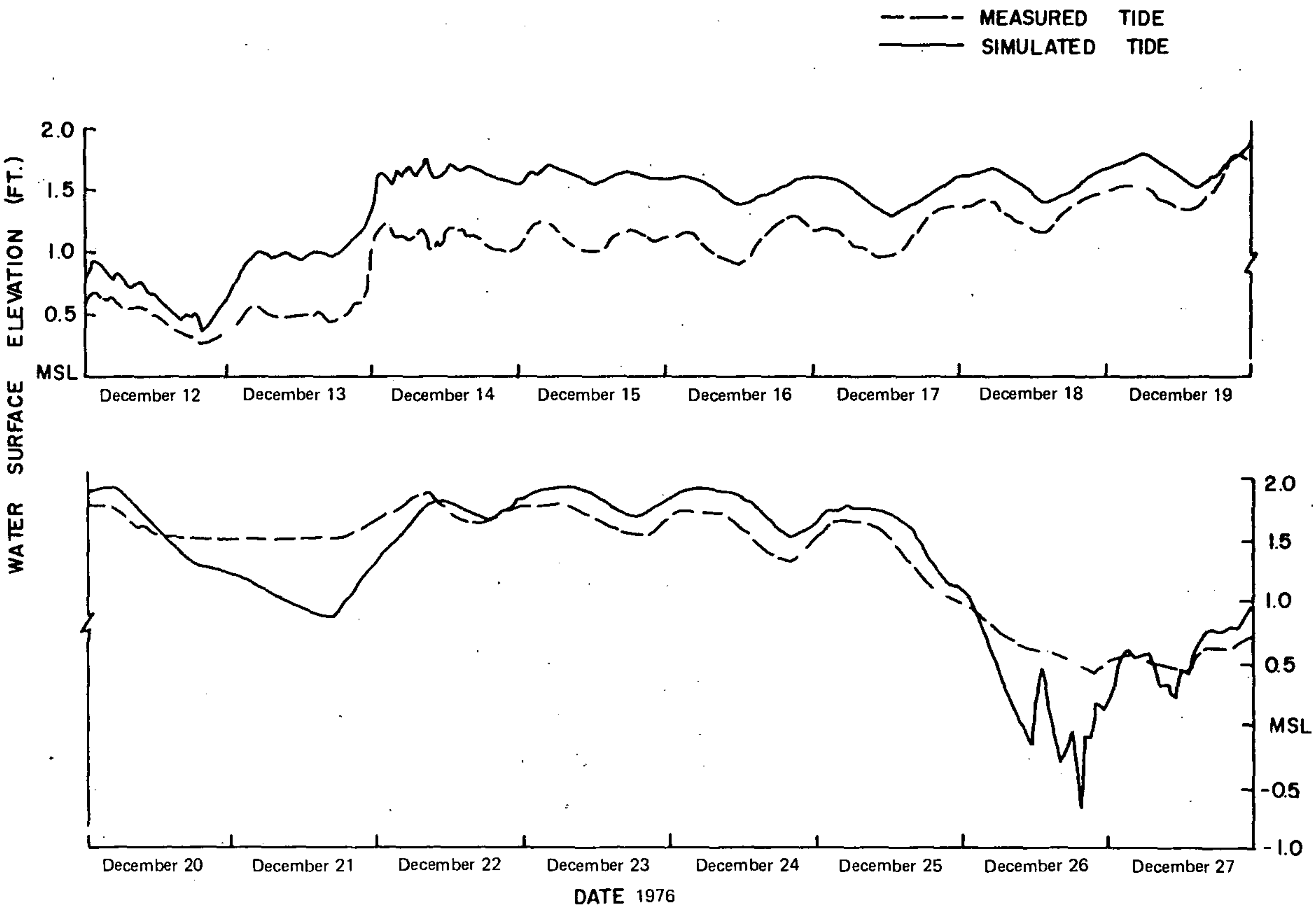


Figure 5-22. Comparison of Observed and Simulated Tidal Elevations at Section 24, Old River Cutoff Channel Gage, December 12-27, 1976 (52)

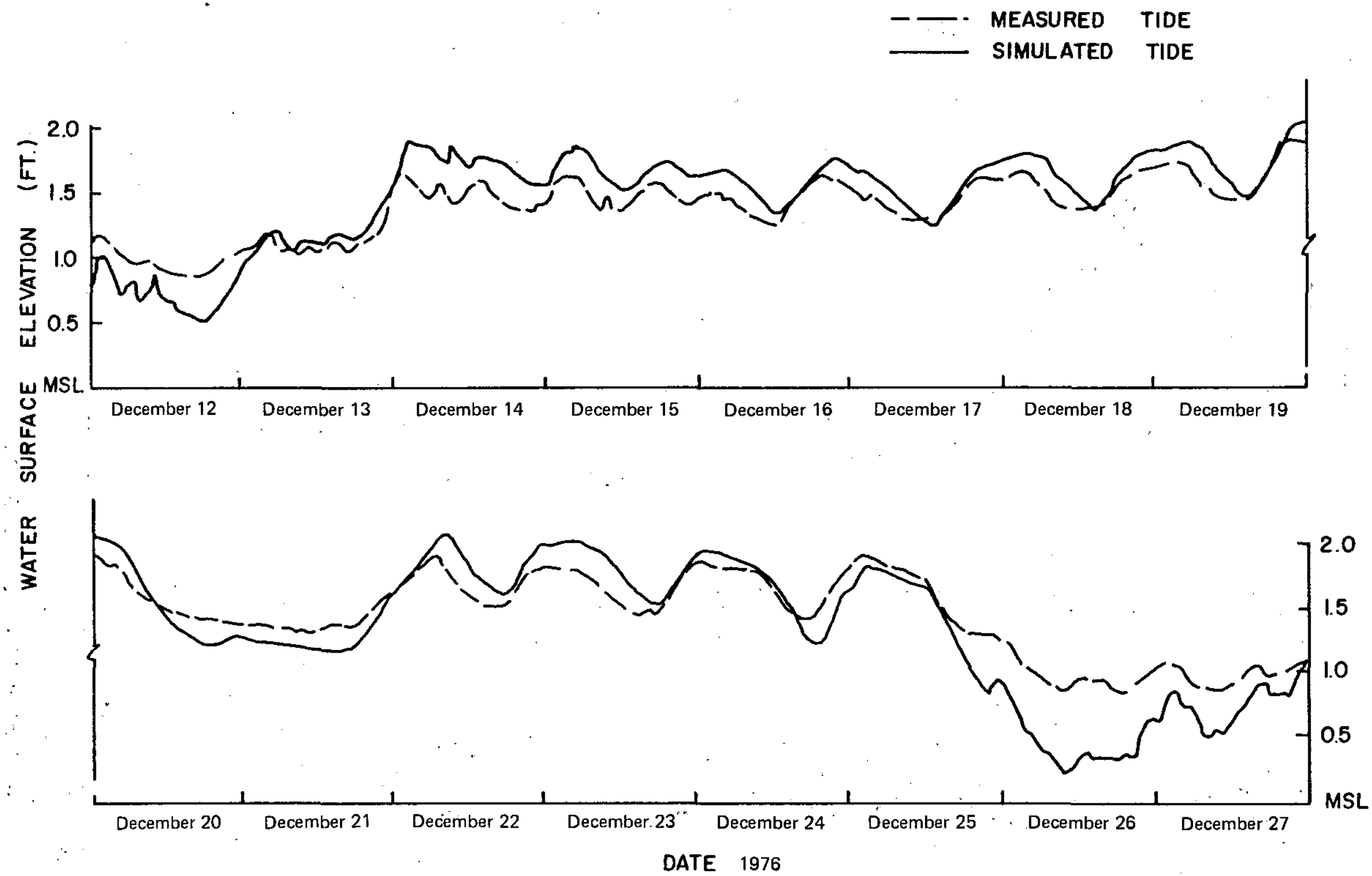


Figure 5-23. Comparison of Observed and Simulated Tidal Elevations at Section 48, Anahuac Channel Gage, December 12-27, 1976 (52)

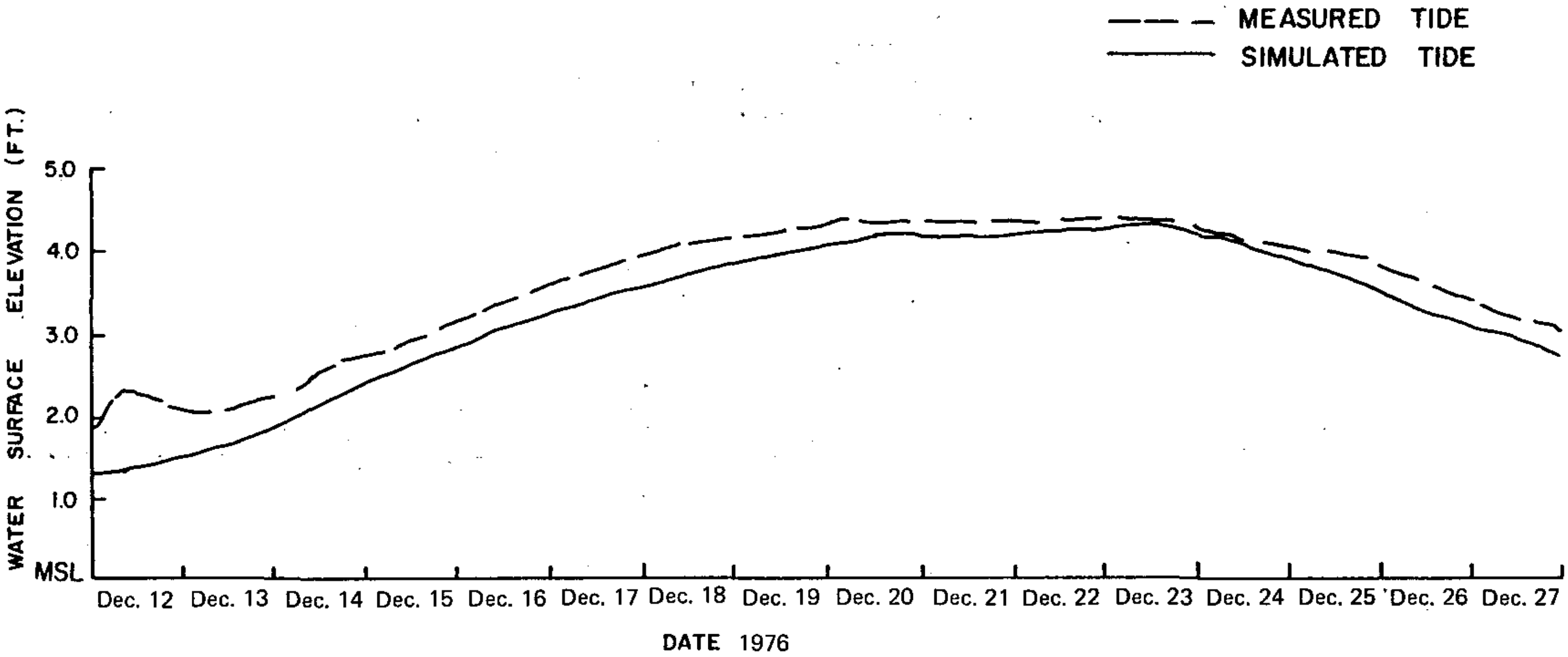


Figure 5-24. Comparison of Observed and Simulated Tidal Elevations at Section 162, Lake Charlotte Gage, December 12-27, 1976 (52)

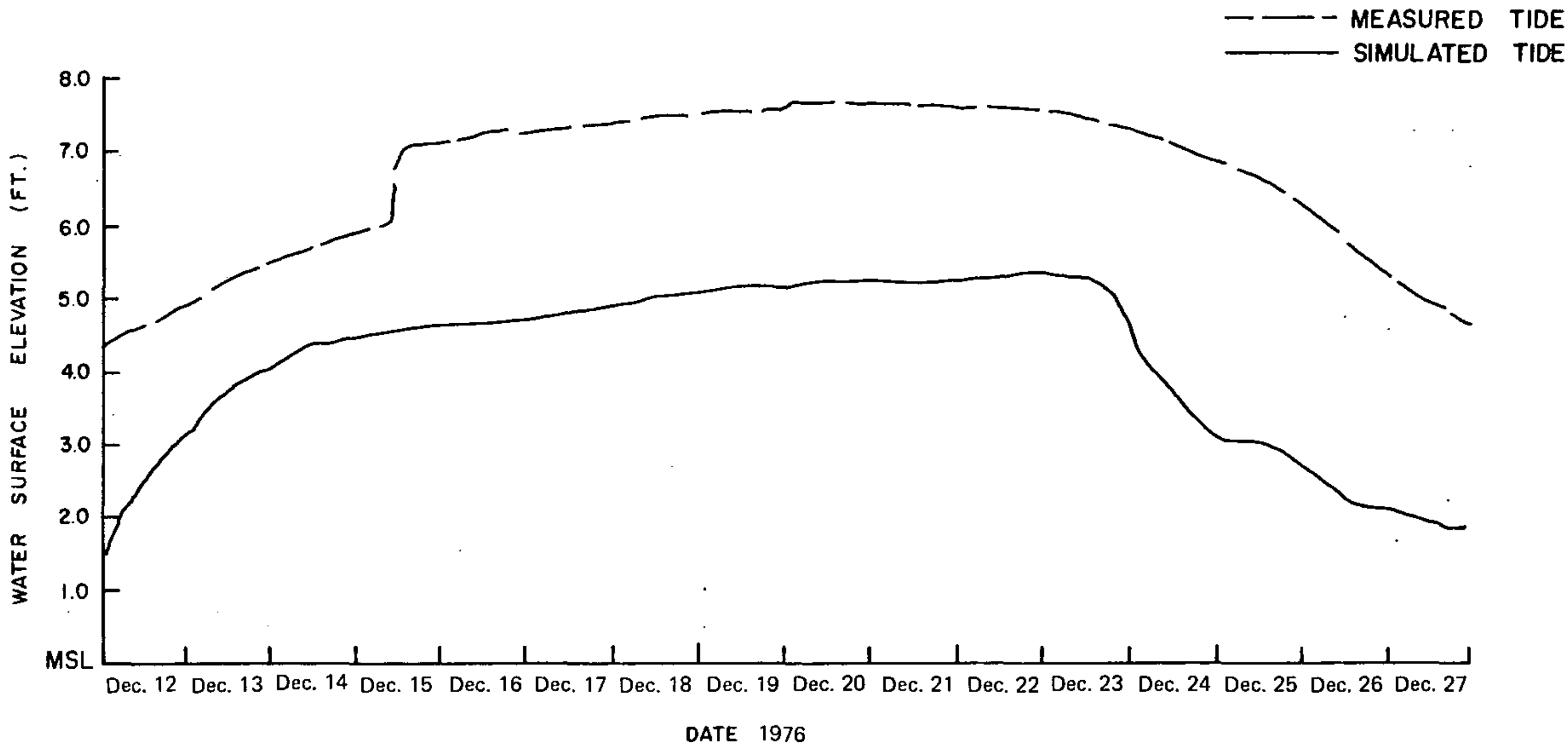


Figure 5-25. Comparison of Observed and Simulated Tidal Elevations at Section 165, Sulphur Barge Channel Gage, December 12-27, 1976 (52)

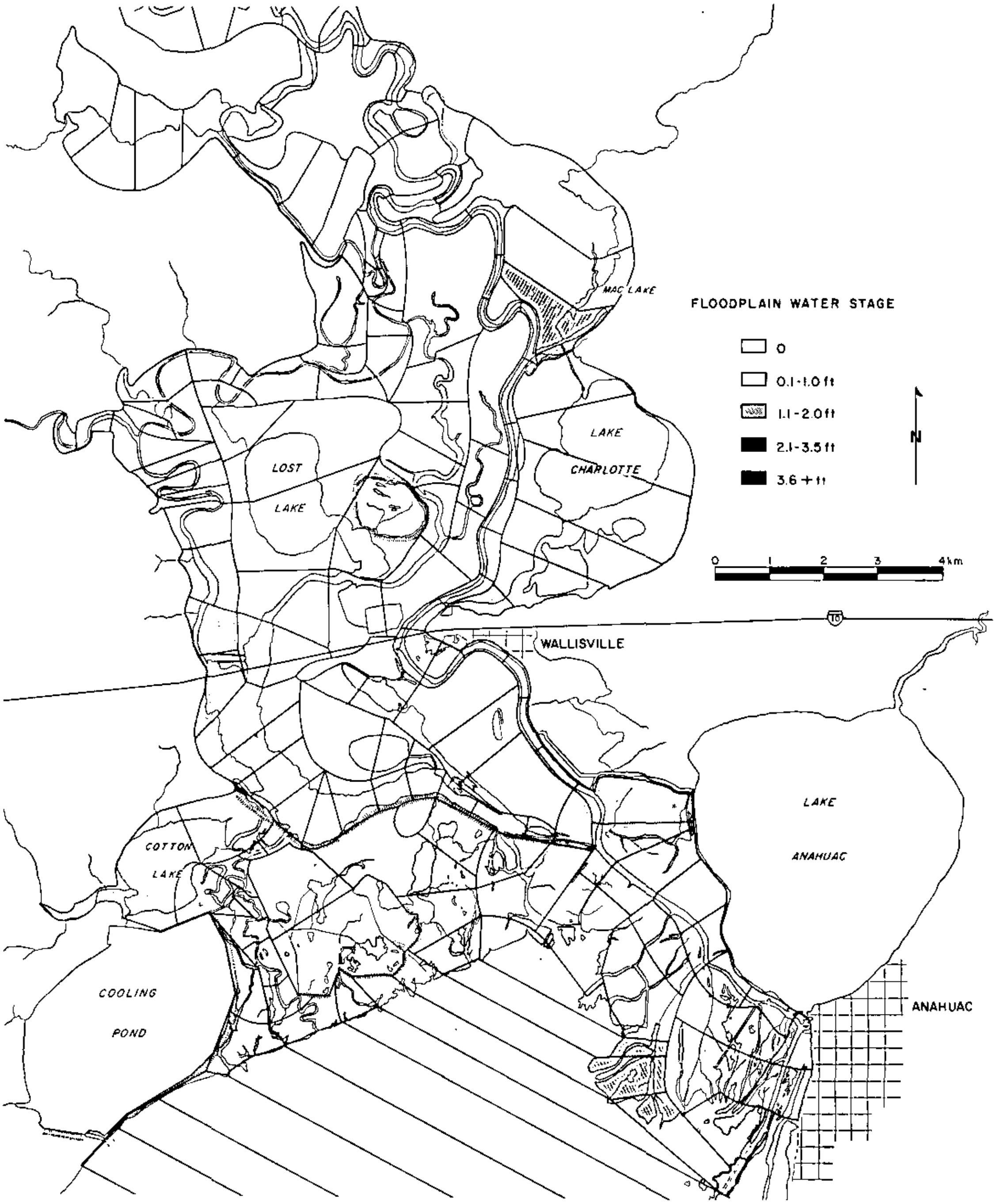


Figure 5-26. Trinity Delta System Showing Inundation Areas, December 12, 1976 (52)

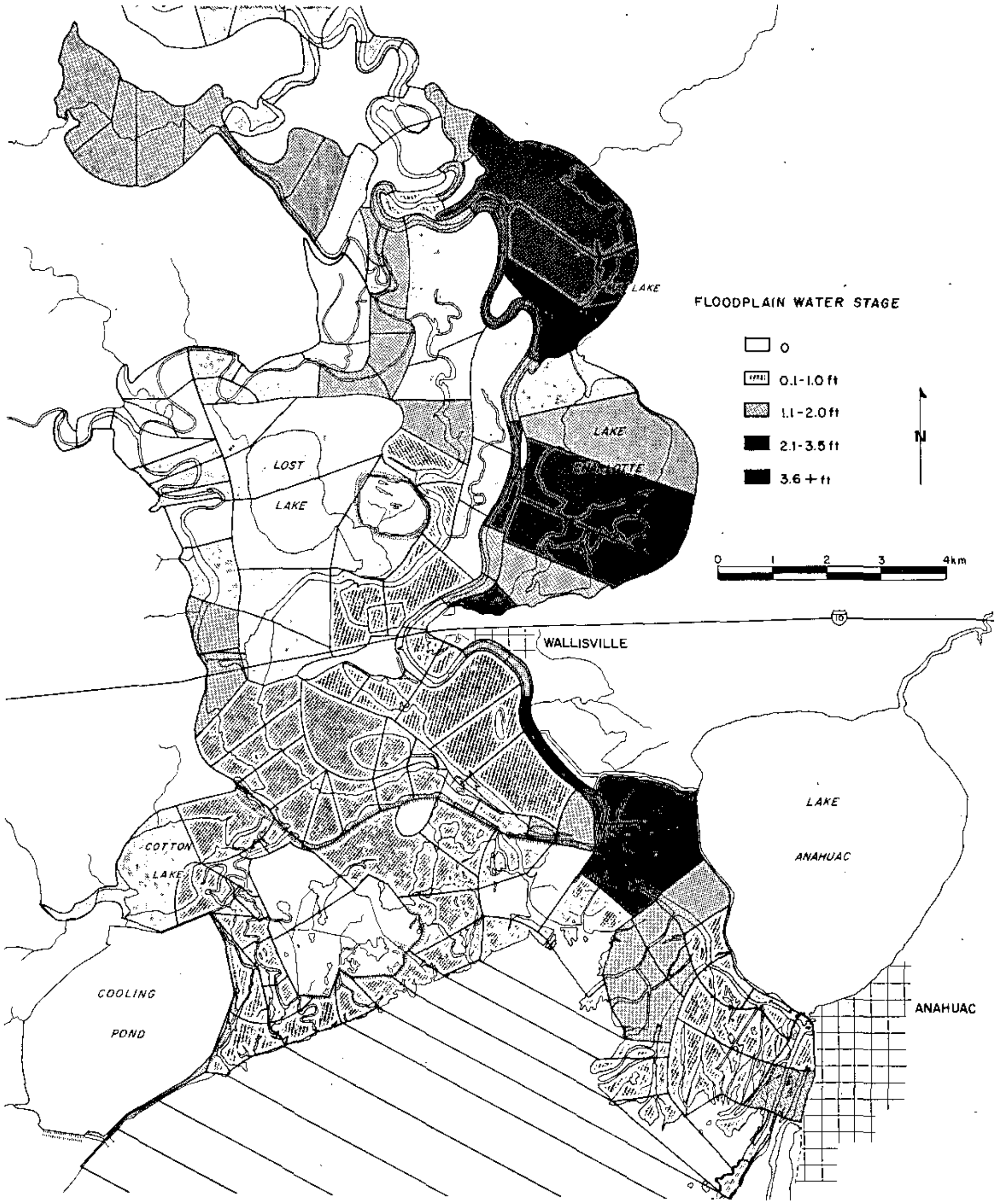


Figure 5-27. Trinity Delta System Showing Inundation Areas, December 16, 1976 (52)

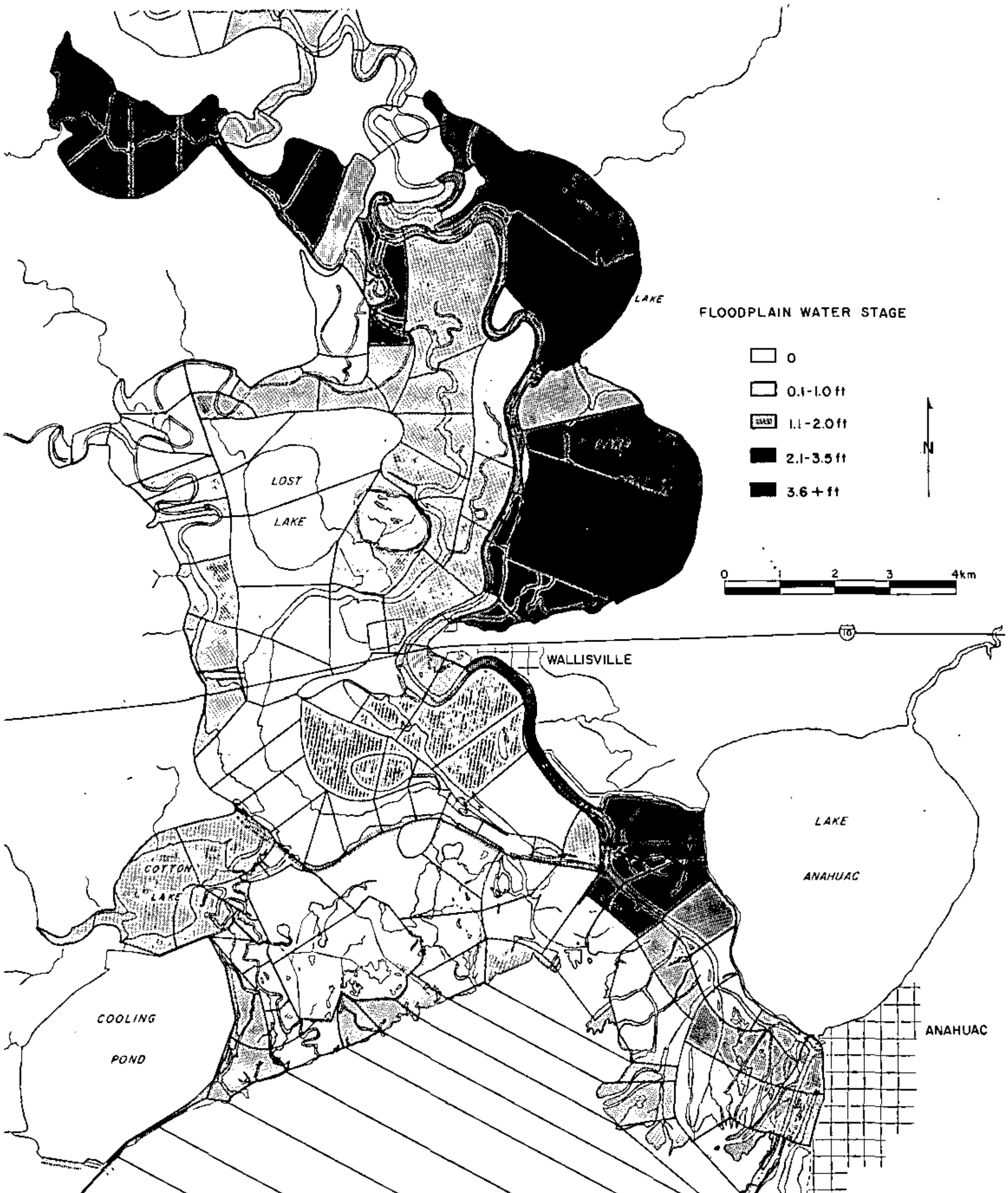


Figure 5-28. Trinity Delta System Showing Inundation Areas, December 20, 1976 (52)

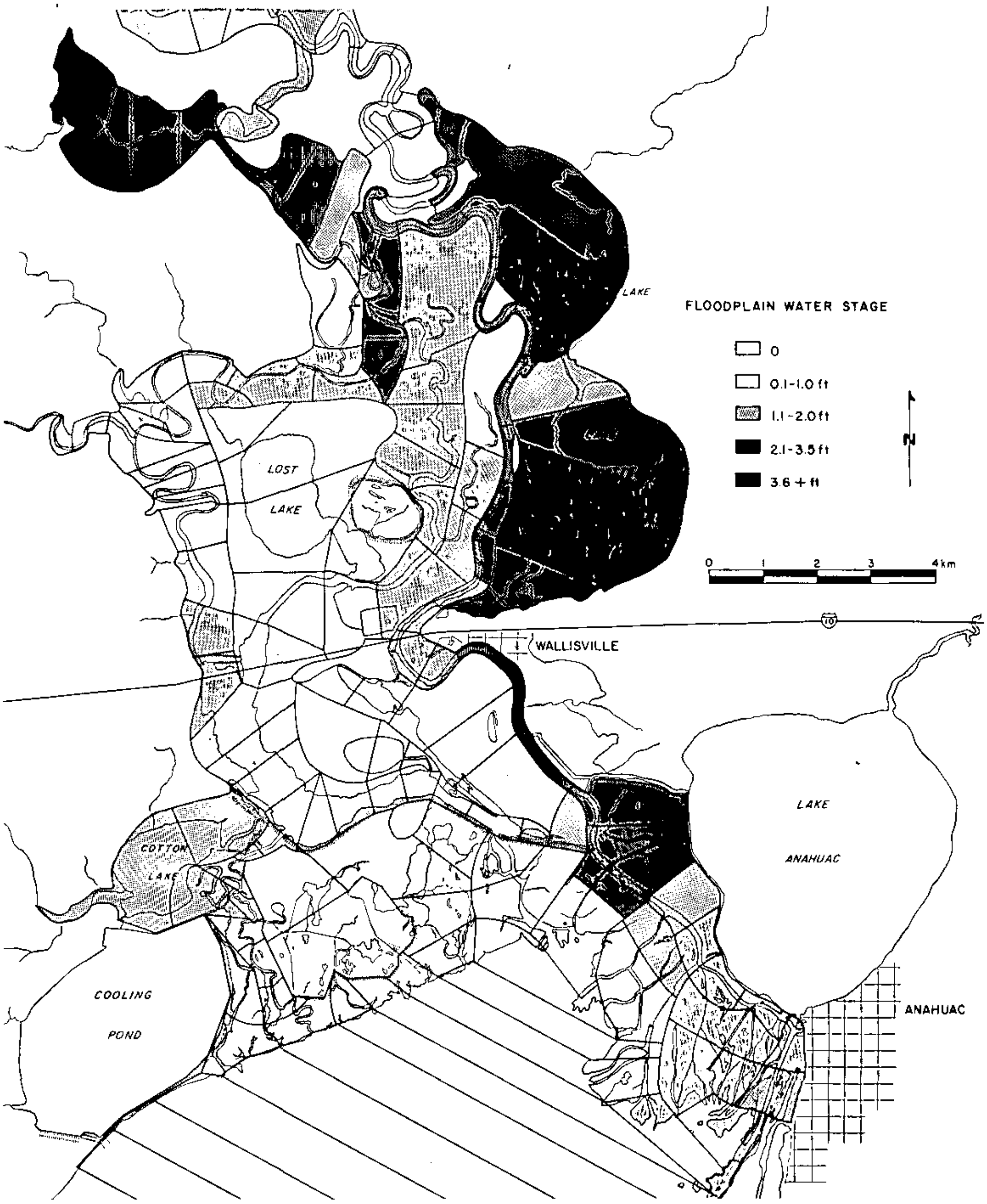


Figure 5-29. Trinity Delta System Showing Inundation Areas, December 24, 1976 (52)

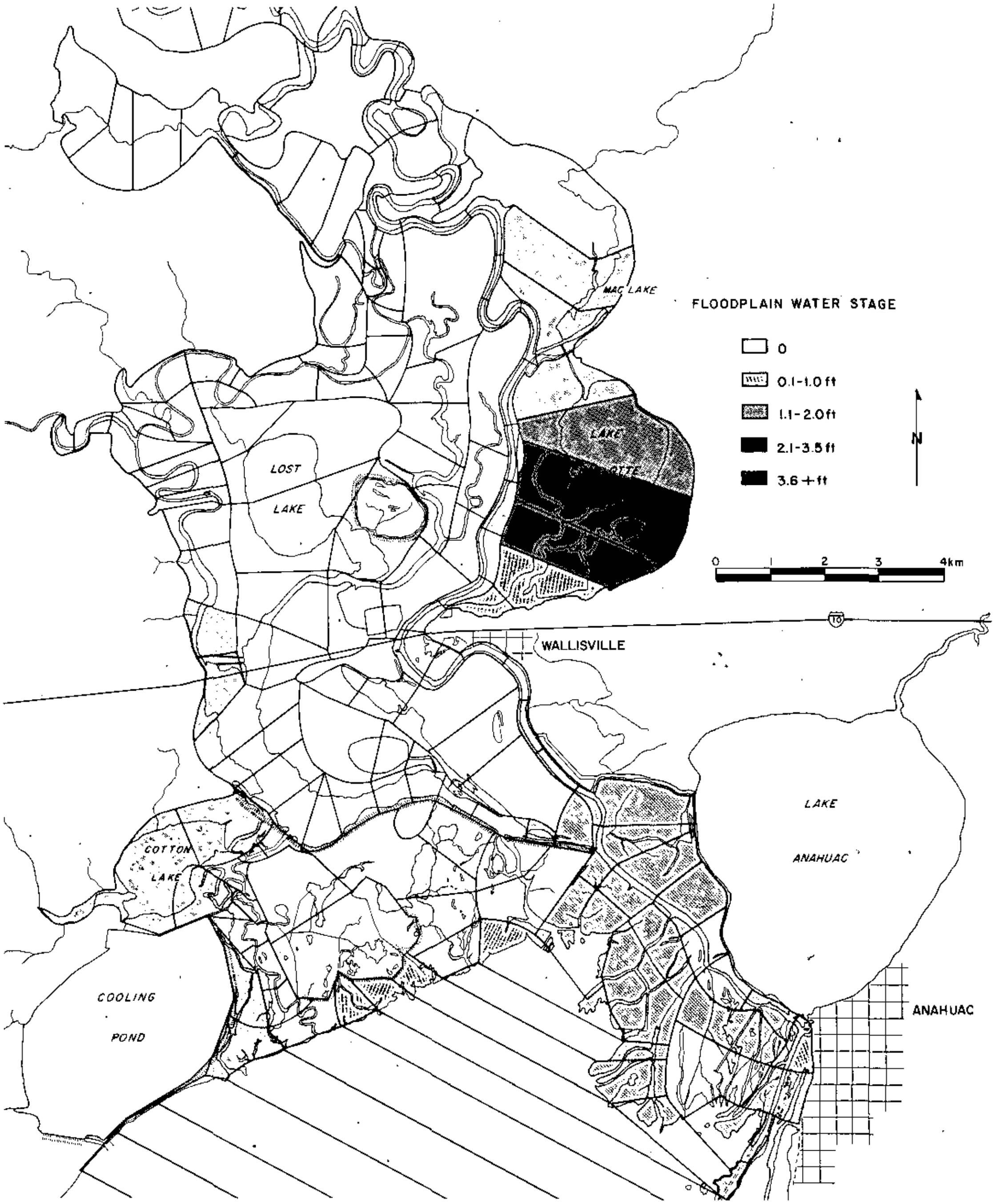


Figure 5-30. Trinity Delta System Showing Inundation Areas, December 28, 1976 (52)

passage of the flood crest. Maximum levels of inundation occur on approximately December 24 (Figure 5-29). A rapid receding of flood waters occurs as indicated on Figure 5-30 for December, 28. Because of a combination of wind setdown on the bay water elevations on December 26 and 27 and the gradual receding of the flood stage, the delta flood levels lower quite rapidly.

Intensive Study Simulation. An intensive diurnal biological and hydrodynamic study was conducted by the USGS, TDWR and EH&A from November 30 through December 3, 1976. During this period two diurnal field programs were conducted, one from approximately 1100 CST November 30 to 1000 CST December 1 and the other from 1100 CST December 2 to 1000 CST December 3. In order to take advantage of the flow verification data obtained during this study, a simulation was conducted for the period November 26 through December 3, 1976. Streamflow was nearly constant at approximately 2,400 ft^3/sec (68 m^3/sec) with diversions calculated to be 60 ft^3/sec (1.7 m^3/sec). The driving tide at Morgan's Point was diurnal during the entire period (Figure 5-31). The wind during this time was light except for November 28 and 29 when moderately strong north winds persisted. A large wind setdown is apparent in the driving tide on these same two days.

The simulated and measured tides for the gages on the Old River Cutoff Channel, Anahuac Channel and the Sulphur Barge Channel are presented in Figures 5-32 through 5-34, respectively. Due to the low tides, the Lake Charlotte gage was not recording during this period and the Lost River gage was not recording properly, so neither of these records are available. The measured and simulated tides at the Old River Cutoff Channel and at Anahuac Channel compare favorably. The tidal amplitude is reproduced accurately and the tide phasing is within a couple of hours. As in a previous simulation, the 0.3 ft. (0.09 m) datum error between measured and simulated tides is evident at both gages. Besides the datum error, the major simulation inaccuracy occurs during the low tides resulting from the wind setdown. Taking into account the 0.3 ft. (0.09 m) datum difference, the simulated tide is approximately one foot too low during setdown conditions.

The simulated and measured tidal amplitude and phase also compare favorably at the Sulphur Barge Channel gage (Figure 5-34). As at the two previous gage locations, the low tide period is poorly simulated. In addition, the simulated tide is approximately 0.3 ft. (0.09 m) higher than the measured tide for most of the period. This error was not apparent in the previous simulations and can not be easily explained. Water elevation in the Sulphur Barge Channel is controlled by a combination of tides and river stage. Since the streamflow gage at Romayor was inoperative at this time, input flows for the Trinity River were estimated from the measured flow at the Goodrich and the Liberty gages on November 30 and December 1 during the intensive inflow study. An over estimate of river flow would result in a mean water elevation that is too high, which could be an explanation of the 0.3 ft. (0.09 m) error.

As noted previously, flow measurements from several sampling sites provide a source of additional verification data. In fact, flow measurement is a more preferable form of verification data than water-level records, since the objective of the modeling work is the simulation of transport

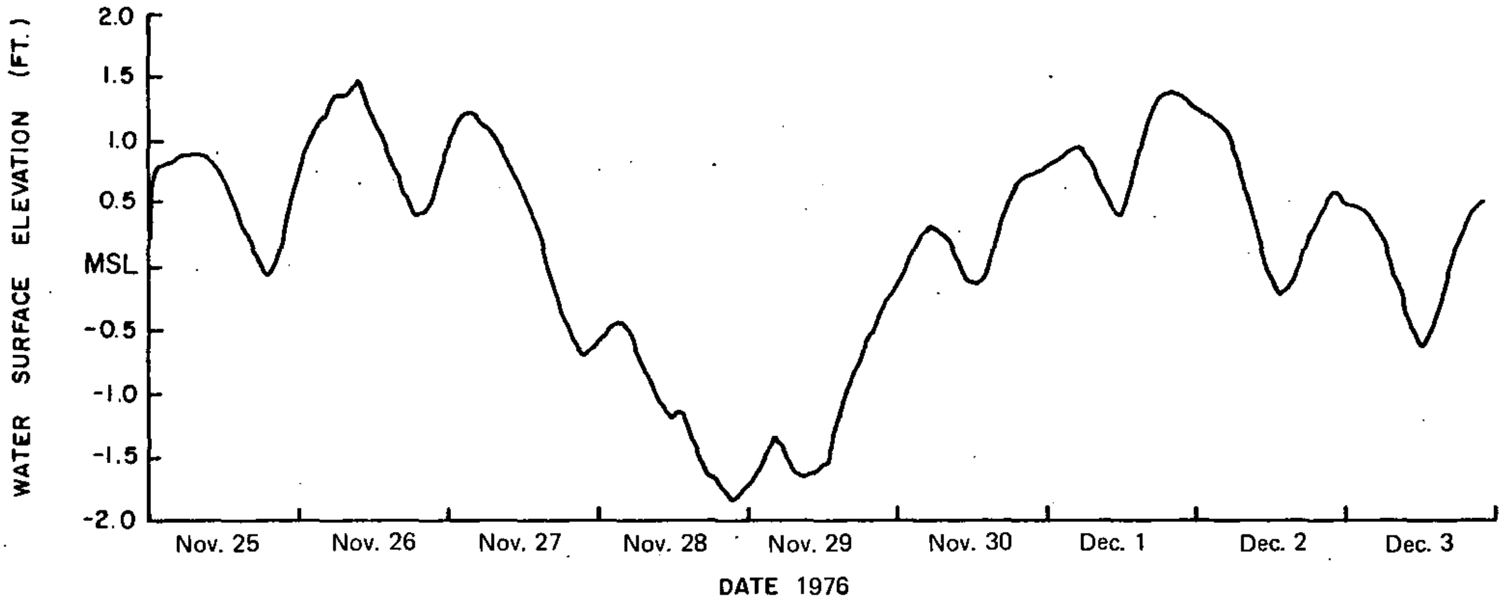


Figure 5-31. Driving Tide Record at Section 2, Morgan's Point Gage, November 25-December 3, 1976 (52)

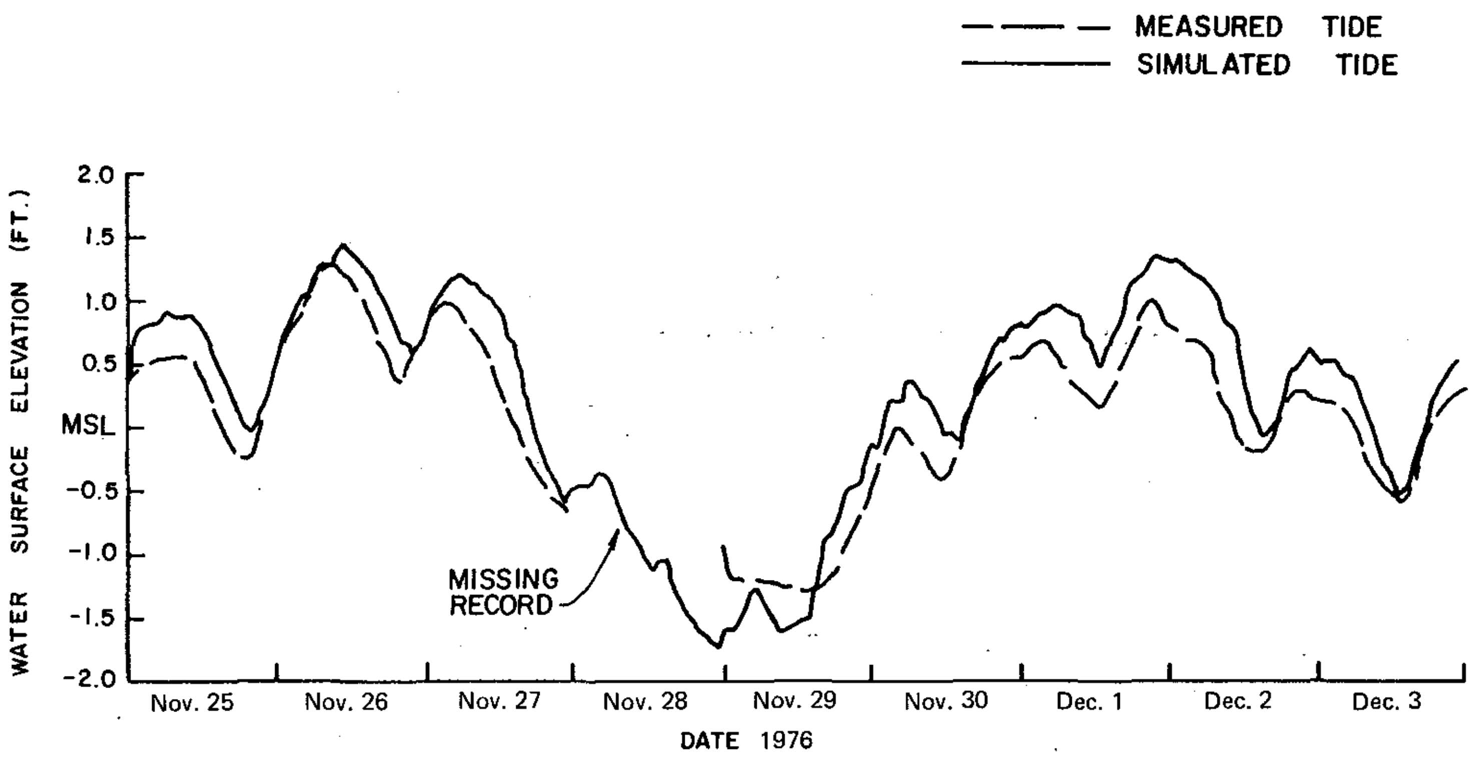


Figure 5-32. Comparison of Observed and Simulated Tidal Elevations at Section 24, Old River Cutoff Channel Gage, November 25-December 3, 1976 (52)

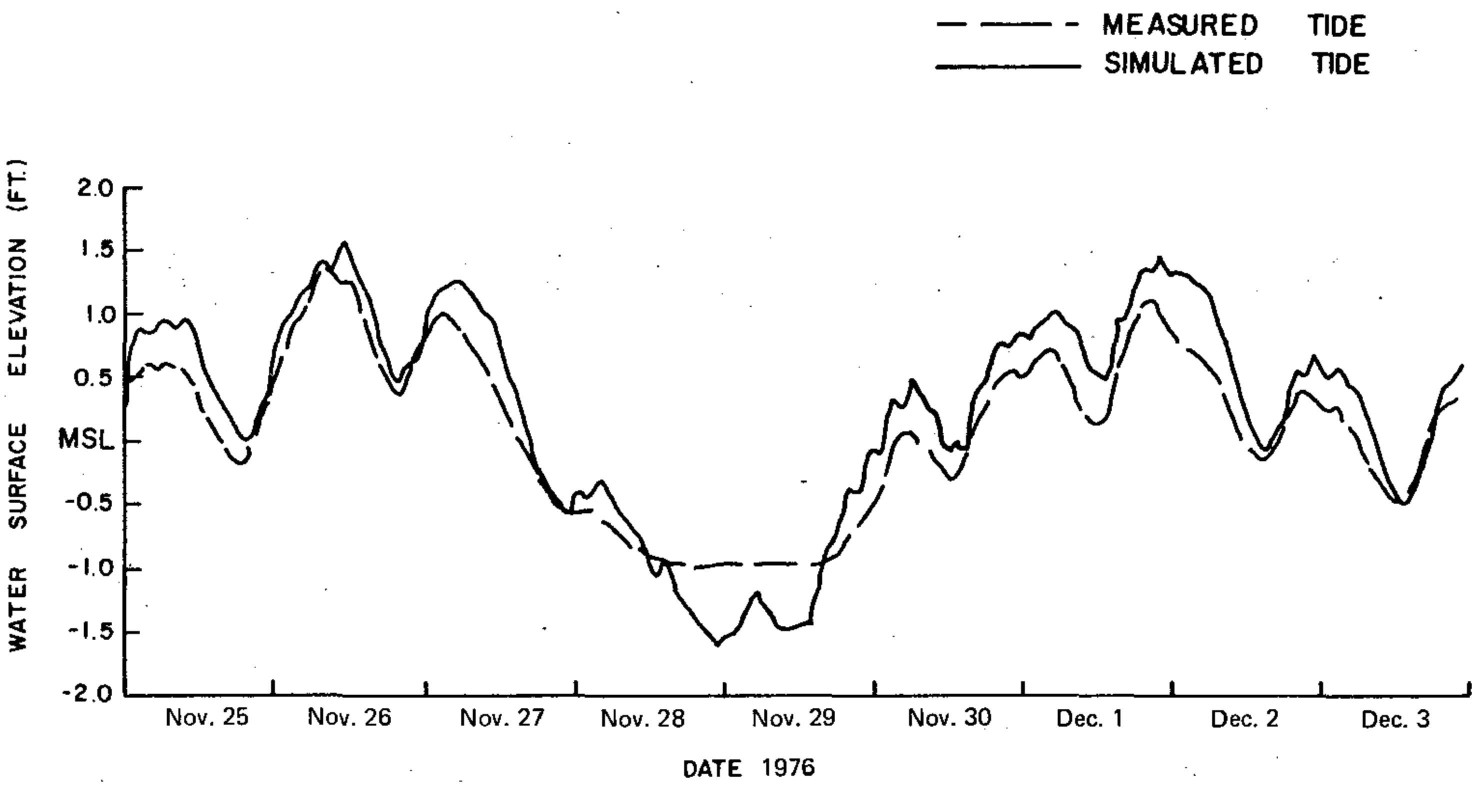


Figure 5-33. Comparison of Observed and Simulated Tidal Elevations at Section 48, Anahuac Channel Gage, November 25-December 3, 1976 (52)

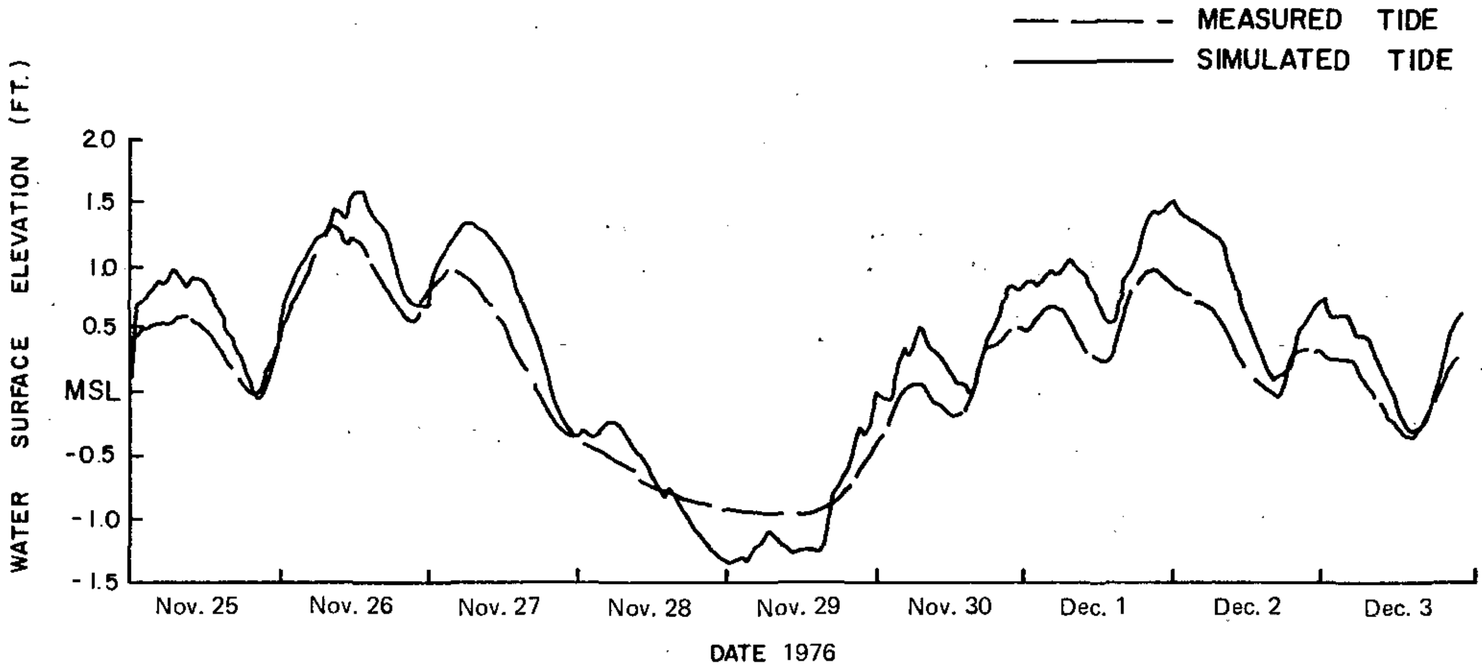


Figure 5-34. Comparison of Observed and Simulated Tidal Elevations at Section 165, Sulfur Barge Channel, November 25-December 3, 1976 (52)

in the system. However, the individual measurements of velocity required to obtain flows are subject to complex turbulent fluctuations and in areas where relatively fresh river flows mix with highly saline tidally influenced waters, bi-directional flows can occur, i.e., the lower density freshwater on the surface flows in one direction while heavier saline water at lower depths flows in the opposite direction. This should be kept in mind when comparing point-measured flows to the smoothed flows of the model.

For the first diurnal study (November 30 and December 1) the sampling sites were located at the Old River Cutoff (section 144), Trinity River above Jack's Pass (section 53), Anahuac Channel (section 47), Lake Pass (section 158), Mac Lake (section 165) and the Cutoff (section 169) (Figure 5-35). At this time, the system was recovering from the wind setdown conditions of November 28 and 29. The reliability of the simulation varies from location to location. The Old River Cutoff simulation is good; flows and direction correlate with measured values at all times. At the Trinity River above Jack's Pass and the Anahuac Channel the flow magnitudes correlate well; however, the simulation indicates a reversal in flow direction for a brief period which was not observed in the physical system. At Lake Pass and Mac Lake there are at times significant errors in flow magnitude and in direction, but overall the simulation satisfactorily reproduces the measured values. The poorest simulation was the Cutoff where measured and simulated flow direction are the same, but simulated flows are approximately an order of magnitude too large. With the exception of the Cutoff, the simulation of flows for this period is satisfactory.

For the second diurnal study conducted on December 2 and 3, a greater number of locations were measured. Included in the study were sites on the Cutoff (section 169), the Old River (section 33), the Lost River (section 192), Cotton Bayou (section 132), Trinity River above Jack's Pass (section 53), Lower Long Island Bayou (section 22), Upper Long Island Bayou (section 23), Cross Bayou (section 115) and Cove Bayou (section 120). Again the Cutoff location is the site of the poorest simulation. At this location the flow direction is in general correctly simulated flows are approximately an order of magnitude too large. At Cross Bayou, Cove Bayou and Cotton Bayou simulated flows are of approximately the proper magnitude, though errors in flow direction do occur. At the remaining locations on the Lost River, the Old River, Trinity River above Jack's Pass, the Upper Long Island Bayou and the Lower Long Island Bayou the simulated and measured flows compare favorably. There do exist some discrepancies in flow and direction, but most of this error is the result of errors of 1 and 2 hours in the tide phasing. However, a significant error does occur at the Trinity River above Jack's Pass where a reversal in flow for two hours that is indicated by the simulation did not occur in the physical system. Overall, this diurnal period was simulated favorably; the Lost River and Old River site measurements show especially good comparison with the simulation results.

This particular case provides a good test of the simulating capabilities of the model, since the extremely low tides resulting from wind setdown provided somewhat abnormal antecedent conditions from which the system may still be recovering during the diurnal studies. Considering the dynamic influence of tides and winds on this area and the fact that even

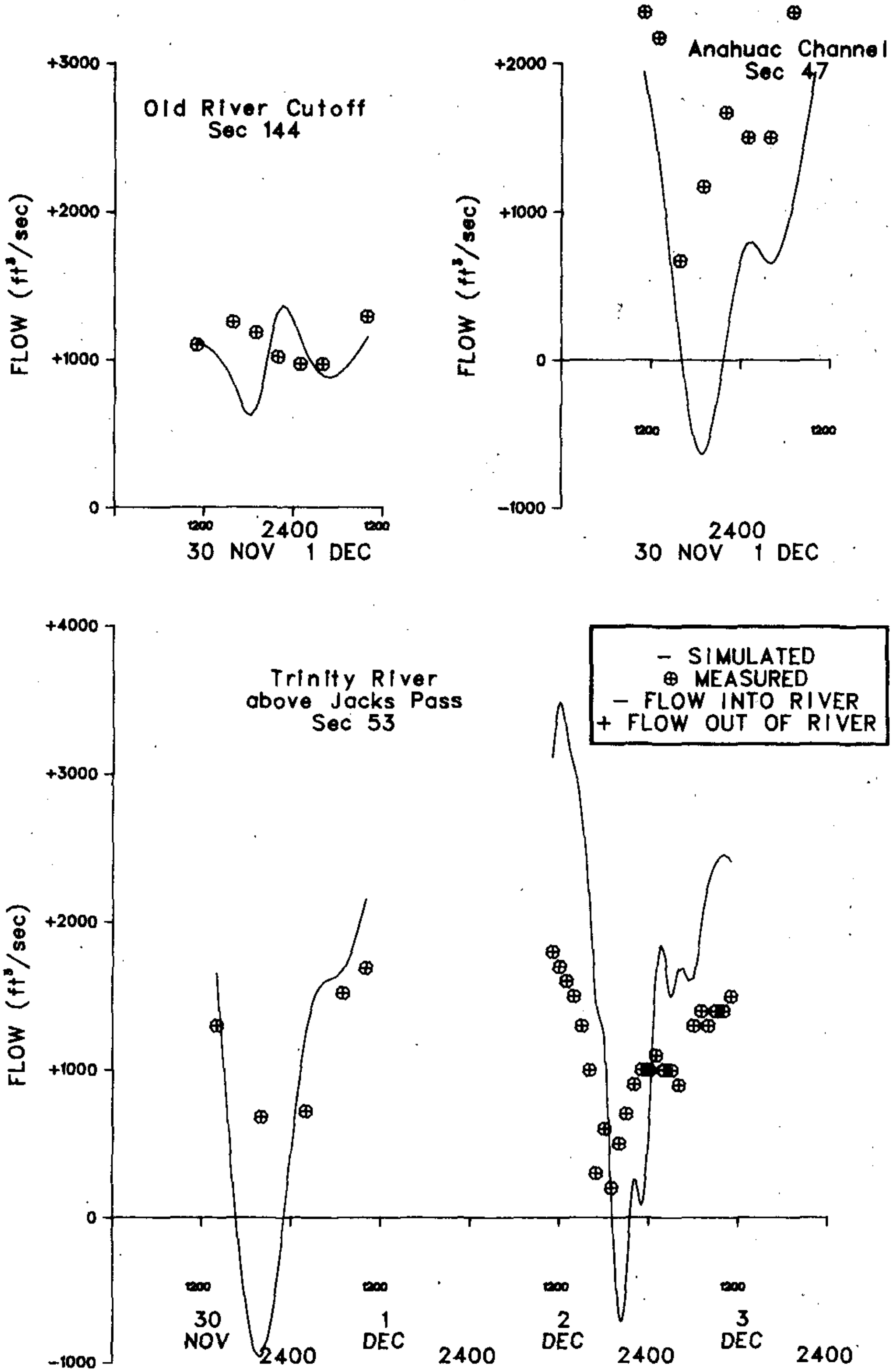


Figure 5-35. Comparison of Observed and Simulated Flows, Trinity-San Jacinto Estuary, November 30-December 3, 1976 (52)

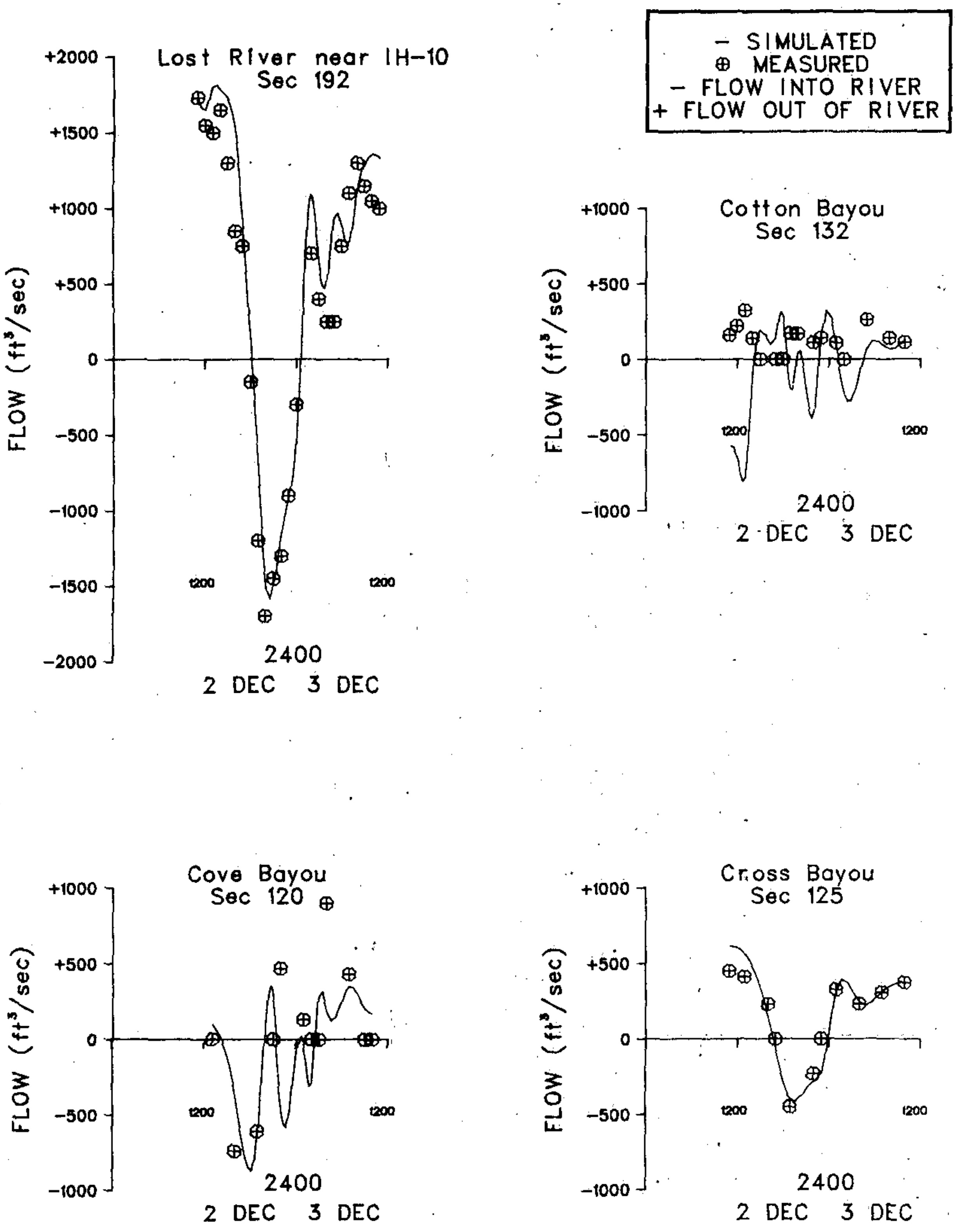
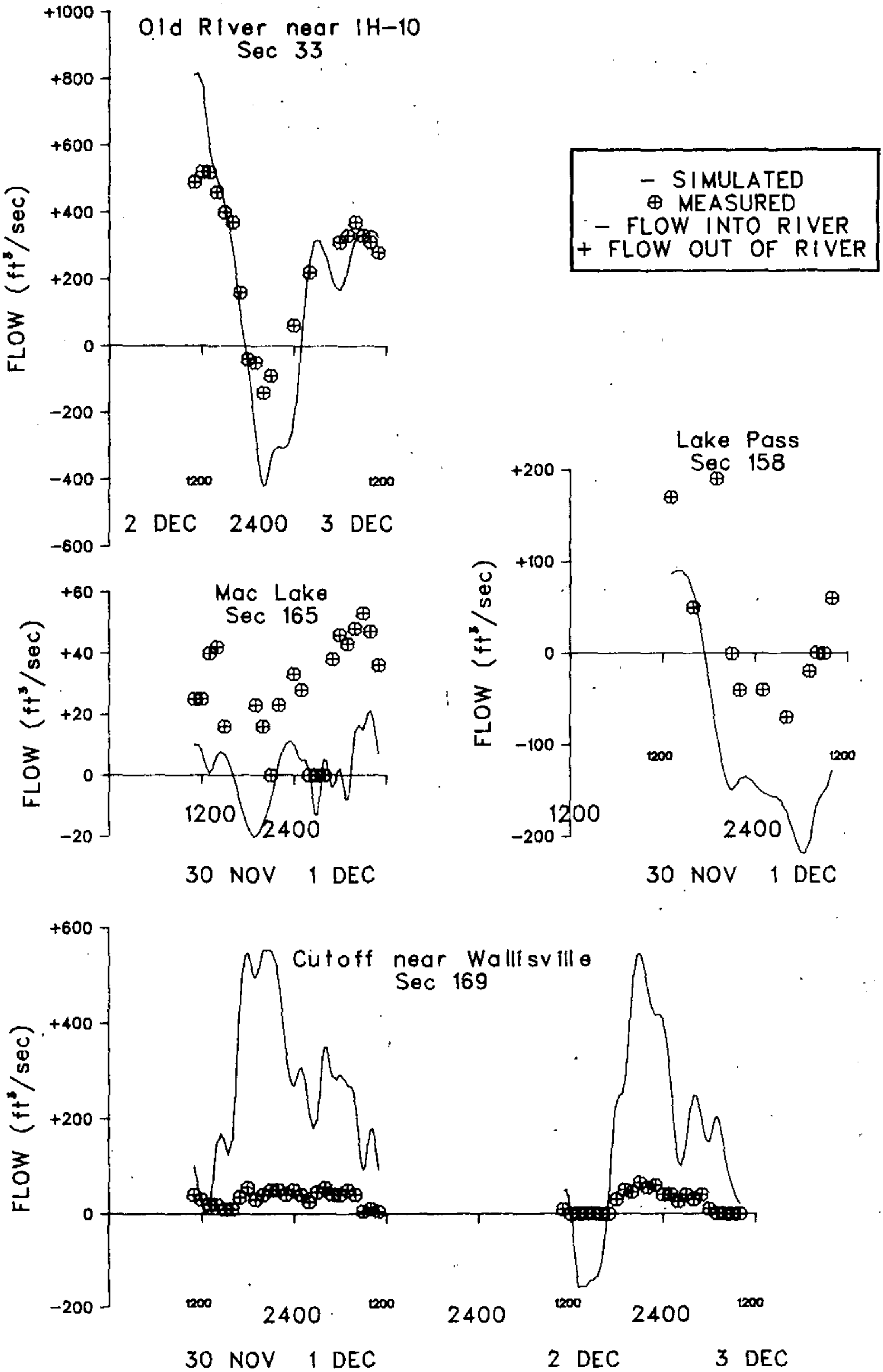


Figure 5-35. Cont.



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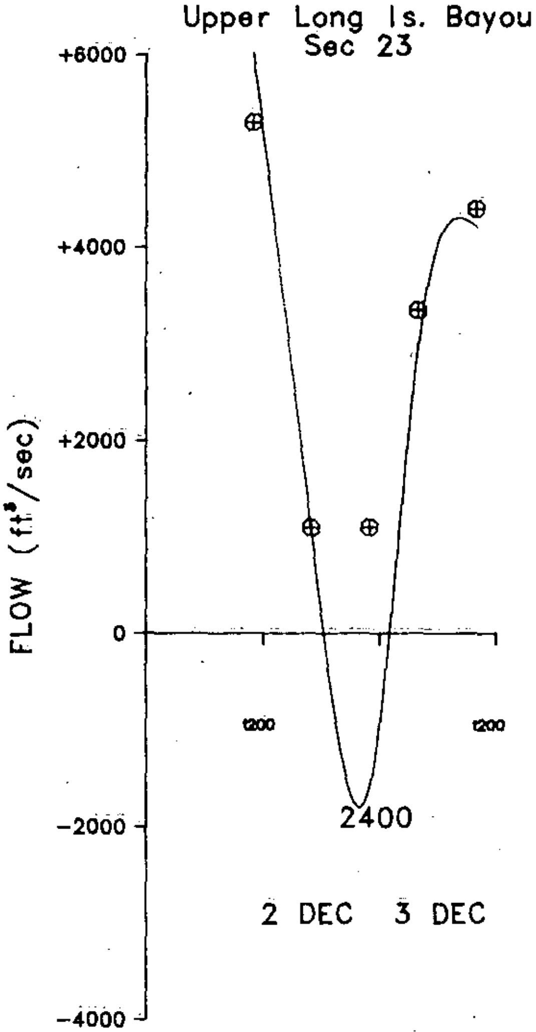
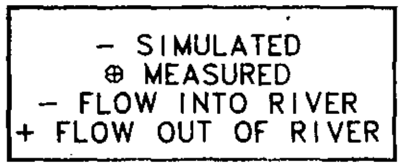




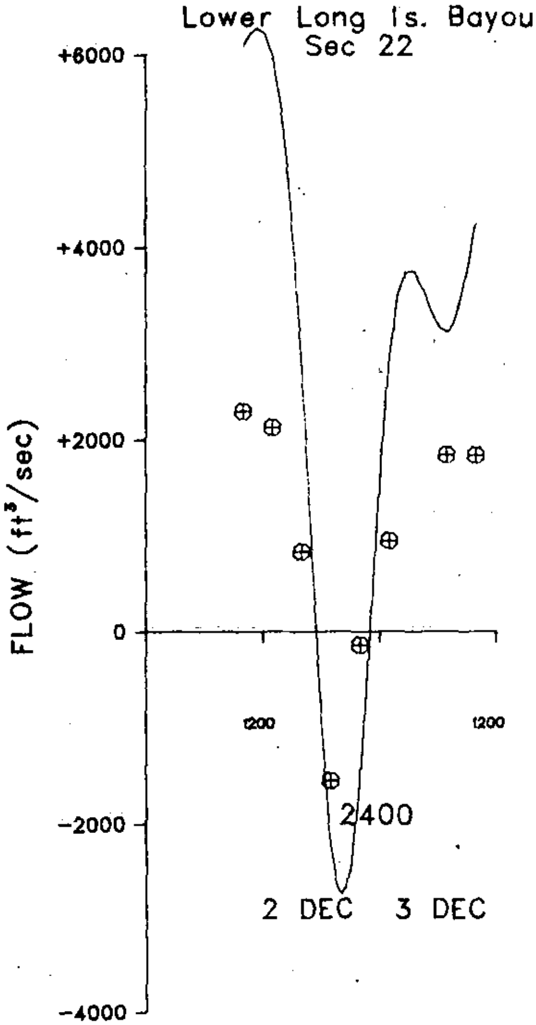


Figure 5-35. Cont.

slight tidal phase errors can result in considerable error when comparing nearly instantaneous simulated and measured flows, the magnitudes and direction of flow compare favorably at most sampling sites. Large discrepancies do occasionally occur, especially at the Cutoff, but the model is capable of simulating flow direction and magnitude at most locations in the delta in a satisfactory manner.

A major objective of this study was to apply a one-dimensional hydrodynamic model to the flow regime within the Trinity River Delta and test the efficiency of the model by simulating periods for which tidal elevation and flow verification data were available for the system. This objective has been realized to the extent that the test applications indicate the model is capable of replicating observed water surface elevations within acceptable limits to predict flow regimes necessary for inundation of the marsh areas. Amplitude and phase of the tidal record were replicated accurately at several tide gage locations in the system. A slight (0.3 ft. or 0.09 m) displacement of the observed and simulated tidal records was in constant evidence at the Anahuac Channel and the Old River Cutoff gages. A study of relative water levels in the system, independent of model results, strongly suggests the discrepancy is in the data and not an error in the model.

Limitations of available flow data prevent an unqualified judgement on the model's ability to predict absolute levels of flow throughout the system. However, the model did exhibit the ability to replicate proper flow direction and periodicity. The major discrepancy in the model simulations occurred during the periods of strong north winds, which results in wind setdown in bay and deltaic waters and periods of low flow such as the onset of flow reversal at slack tide. This could be due to the occurrence of bi-directional flow or simply because the flows are below the threshold of the model's capabilities since the model was designed to predict the occurrence and extent of marsh inundation during periods of high tides and/or moderately high streamflow conditions.

Application of Mathematical Models, Trinity-San Jacinto Estuary

Hydrodynamic and Mass Transport Models

The computational grid network used to describe the Trinity-San Jacinto estuary is illustrated in Figure 5-36. The grid is superimposed on a map showing the general outline of the estuary. Included in the grid network are the locations of islands (solid lines), submerged reefs (dash lines), inflow points, and tidal excitation cells. The x-axis of the grid system is aligned approximately parallel to the coastline, and the y-axis extends far enough landward to cover the lower reaches of all freshwater sources to the bay. The cell size (one square nautical mile) is based on (1) the largest possible dimension that would provide sufficient accuracy, (2) the density of available field data, and (3) computer storage requirements and computational time. Similar reasoning is used in selection of the computational time step except that the maximum possible time step in the hydrodynamic model is constrained by the criterion for mathematical stability. In the indexing scheme shown in Figure 5-36, cells are numbers with the indices $1 \leq i \leq IMAX = 45$ and $1 \leq j \leq JMAX = 32$. With this arrangement, all model parameters such as water depths,

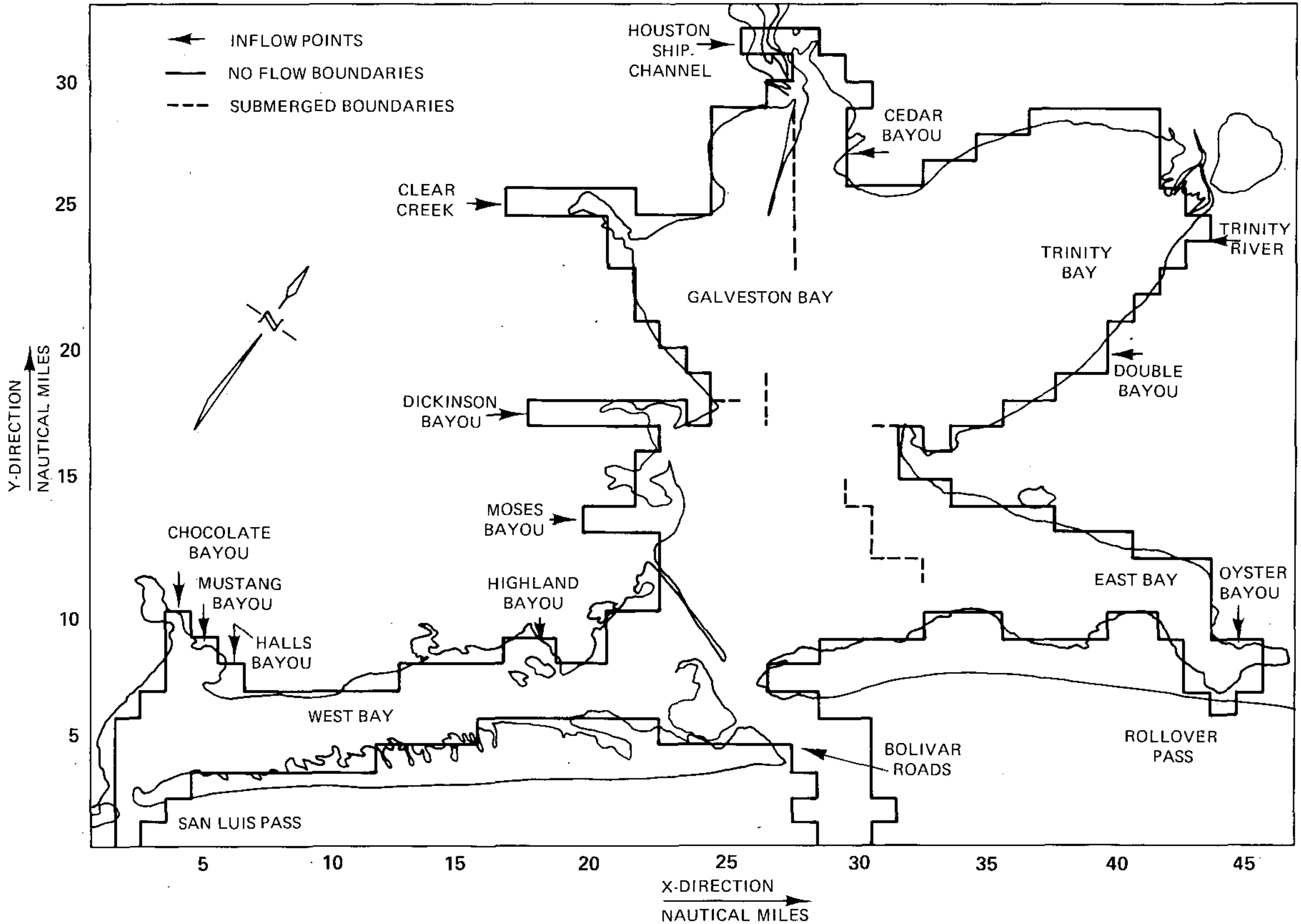


Figure 5-36. Schematic Computational Grid, Trinity-San Jacinto Estuary (173)

flows in each coordinate direction, bottom friction, and salinity can be identified with each cell in the grid.

The basic data necessary for the development, verification and calibration of the mathematical models include Gulf tides, measured tide at discrete points throughout each estuary, gaged freshwater inflows, estimate of ungaged and return flows, wind magnitude, direction and duration, evaporation, and measurements of conservative constitutents (chlorides, specific conductance or total dissolved solids, TDS) throughout the estuary and at each inflow source. Such a compilation of data for a specified period of time is referred to as a "data package". Through successive applications of the model to several independent data packages, the model is calibrated and verified. Data packages necessary for the calibration and verification of the estuary models are obtained through a cooperative program with the U.S. Geological Survey. Especially important is the comprehensive data collection effort conducted in the estuary during July 1976.

A representative sample of the results of the calibration of the Trinity-San Jacinto Estuary models using data obtained during the July 1976 field study are presented in Figures 5-37 to 5-39 to demonstrate the ability of the models to simulate observed values of tidal amplitude, flow, and salinity throughout a tidal cycle at several locations in the estuary.

To test the model's abilities to simulate the salinity response of the estuary over an extended time period, an operation schedule was developed to calculate the variation in salinity distribution during 1974 through 1976. The two-year period was divided into 39 consecutive hydrologic sequences[1/]. The minimum time period used as a hydrologic sequence was seven days. Seasonal averages were used for the meteorological and tidal inputs. The results of the model operation showed reasonable agreement with observed data (Figures 5-40 to 5-45). Perfect agreement could not be expected since the simulated results represented average salinity conditions for the time period covered by the hydrologic sequence while the measured data were an instantaneous response of the estuary to the specific tidal, freshwater inflow, and meteorological conditions present at the time of the measurement.

Marsh Inundation Model

Studies were performed on the Trinity River delta in an effort to delineate flow distribution patterns and establish areas that would be subject to the previously defined inundation criterion of 0.5 feet (0.15 m) of depth per 48 consecutive hours.

In the Trinity delta study, estimates were made of the percentage of the delta surface area subject to inundation through the interaction of varying freshwater inflows and selected tides. The Trinity delta study area is the shaded area shown in Figure 5-5. This shaded area is considered to be biologically the most important area of the Trinity marsh systems, bounded on the

1/ A hydrologic sequence is defined as a time period for which the daily inflow to the estuary can be reasonably represented by the mean daily inflow during that period, i.e., the variation in daily flow about the mean daily flow is small when compared to the magnitude of the mean daily flow.

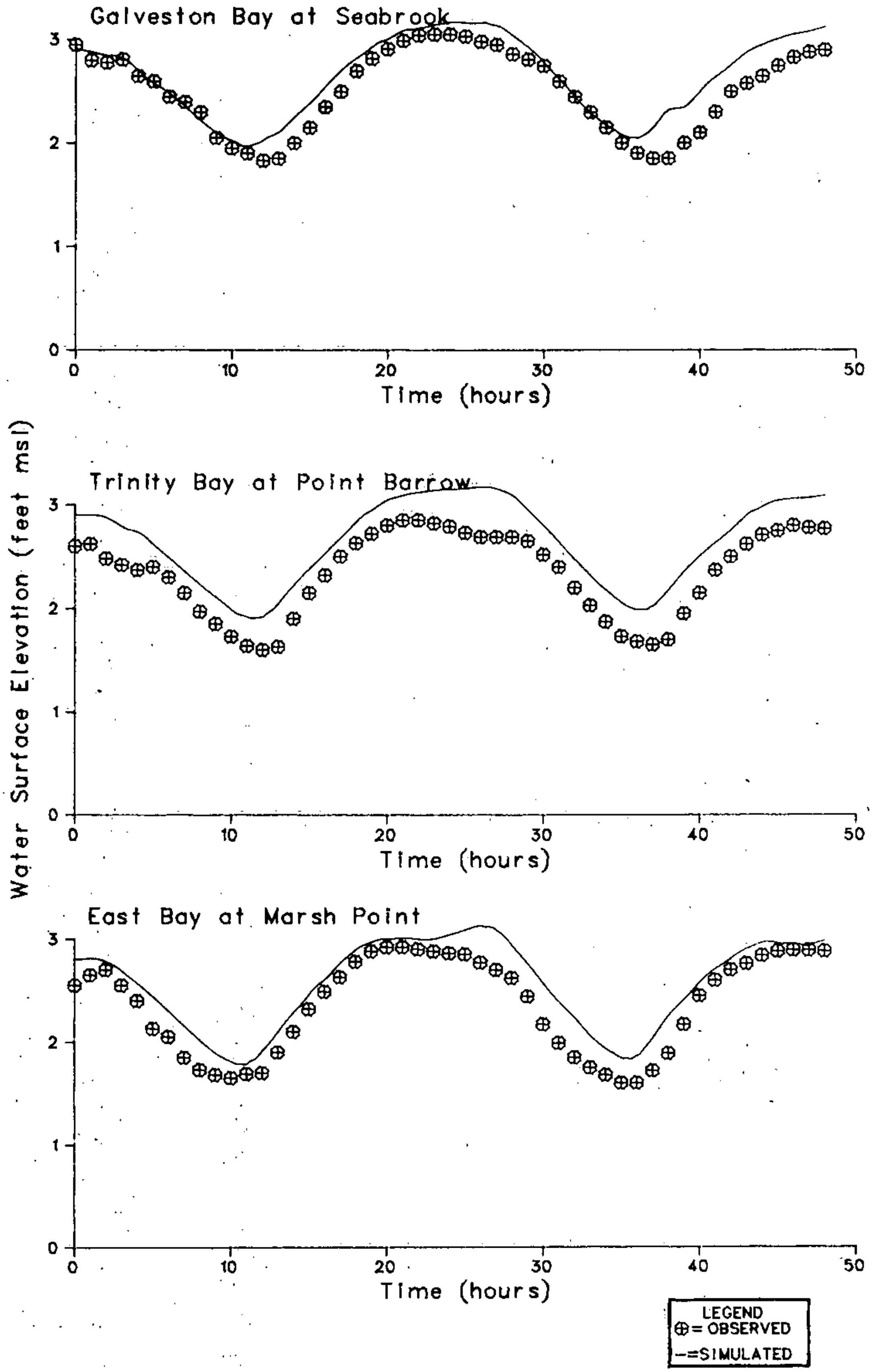


Figure 5-37. Comparison of Observed and Simulated Tidal Elevations, Trinity-San Jacinto Estuary, July 21-23, 1976

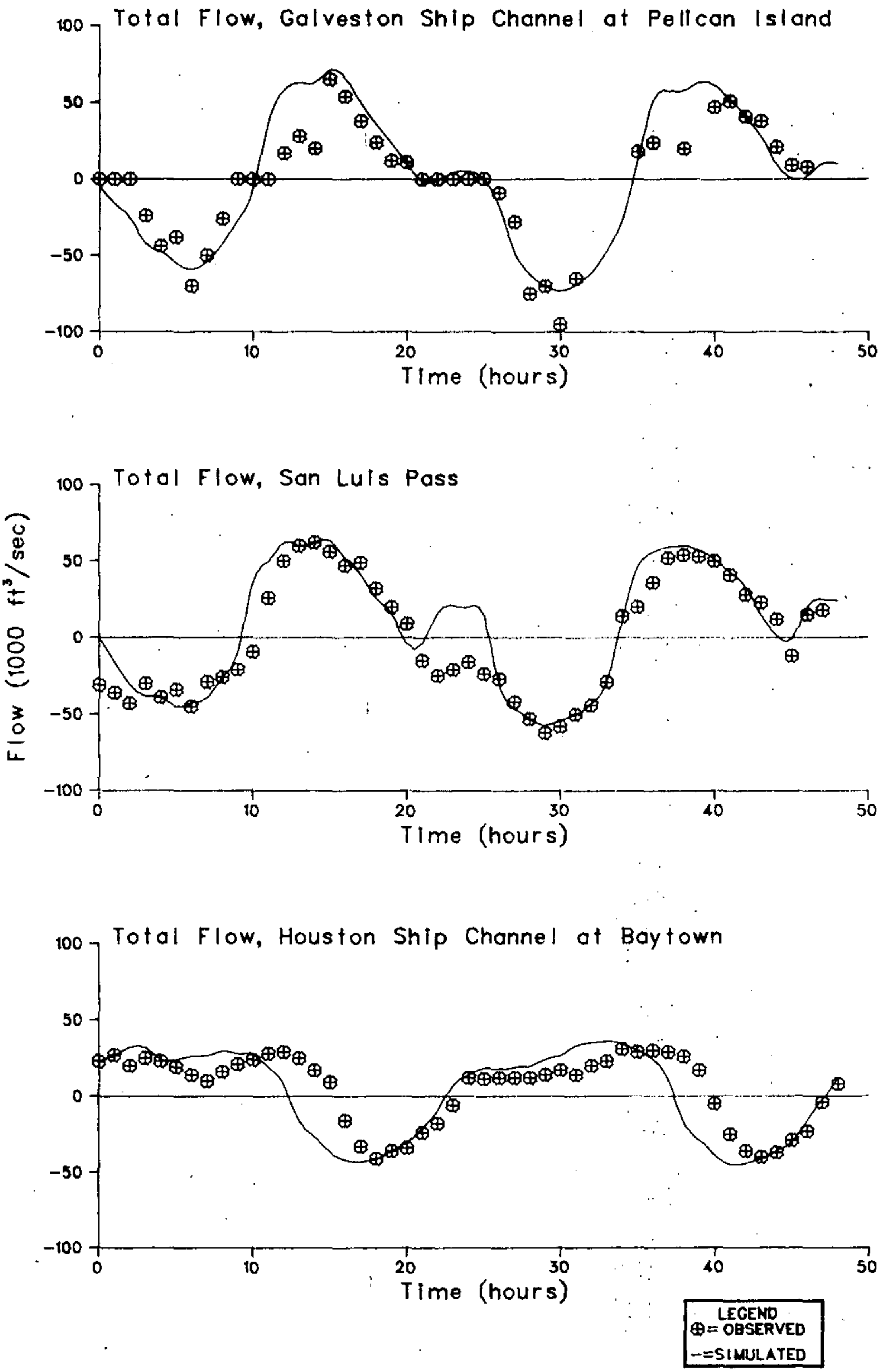


Figure 5-38. Comparison of Observed and Simulated Flows, Trinity-San Jacinto Estuary, July 21-23, 1976

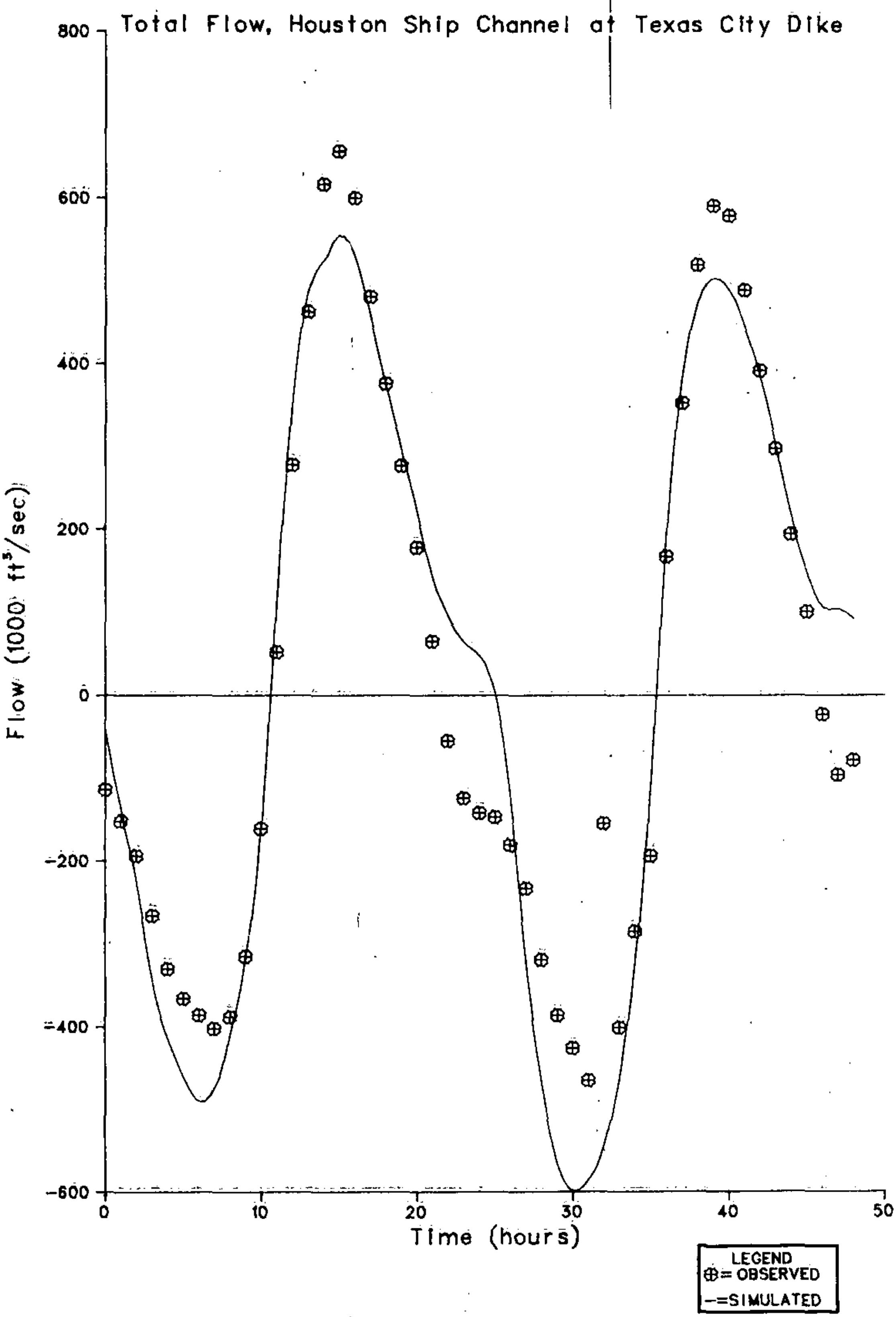


Figure 5-38. Cont.

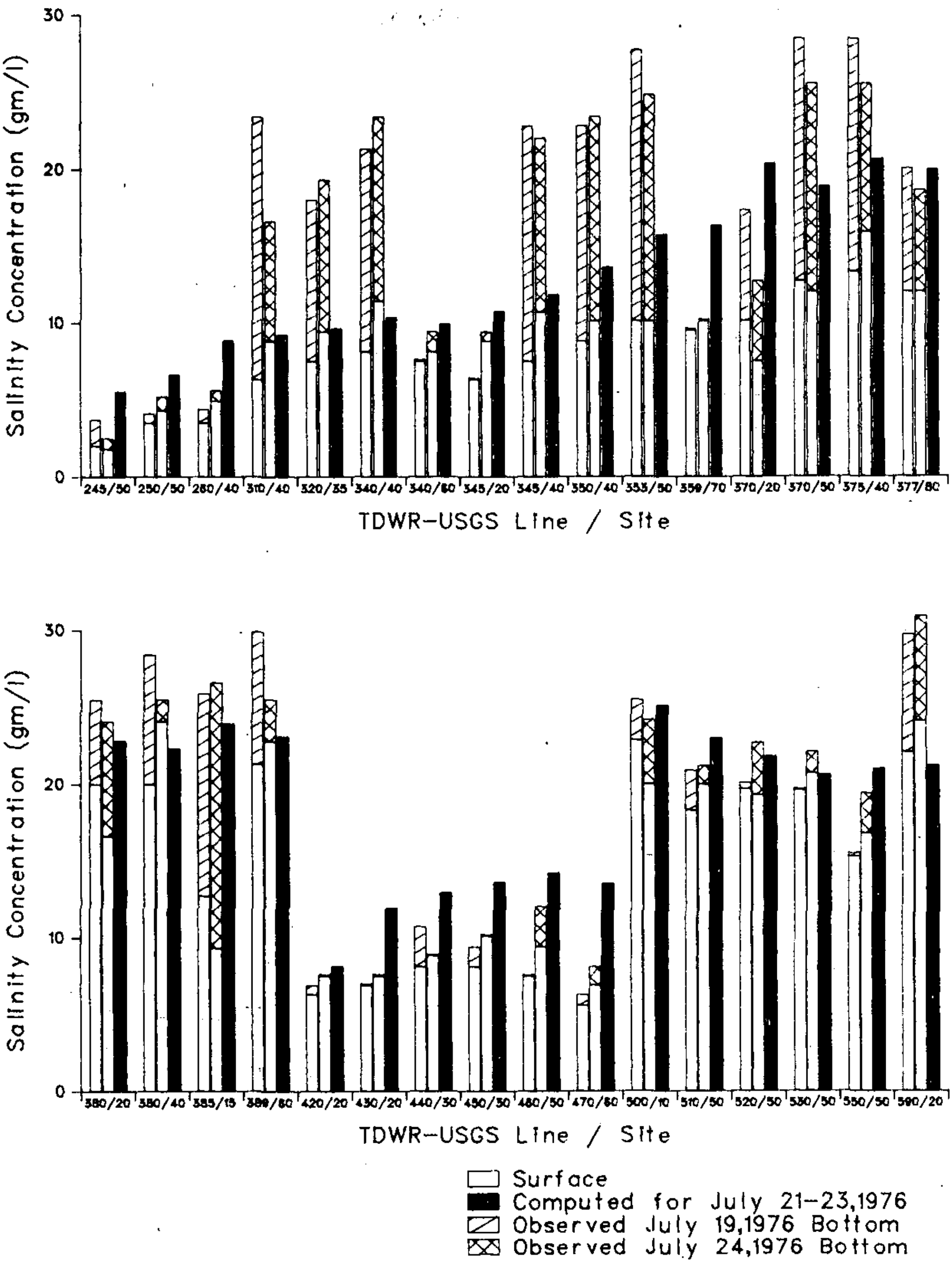


Figure 5-39. Comparison of Observed (Surface and Bottom) and Simulated Salinities, Trinity-San Jacinto Estuary, July 19-24, 1976

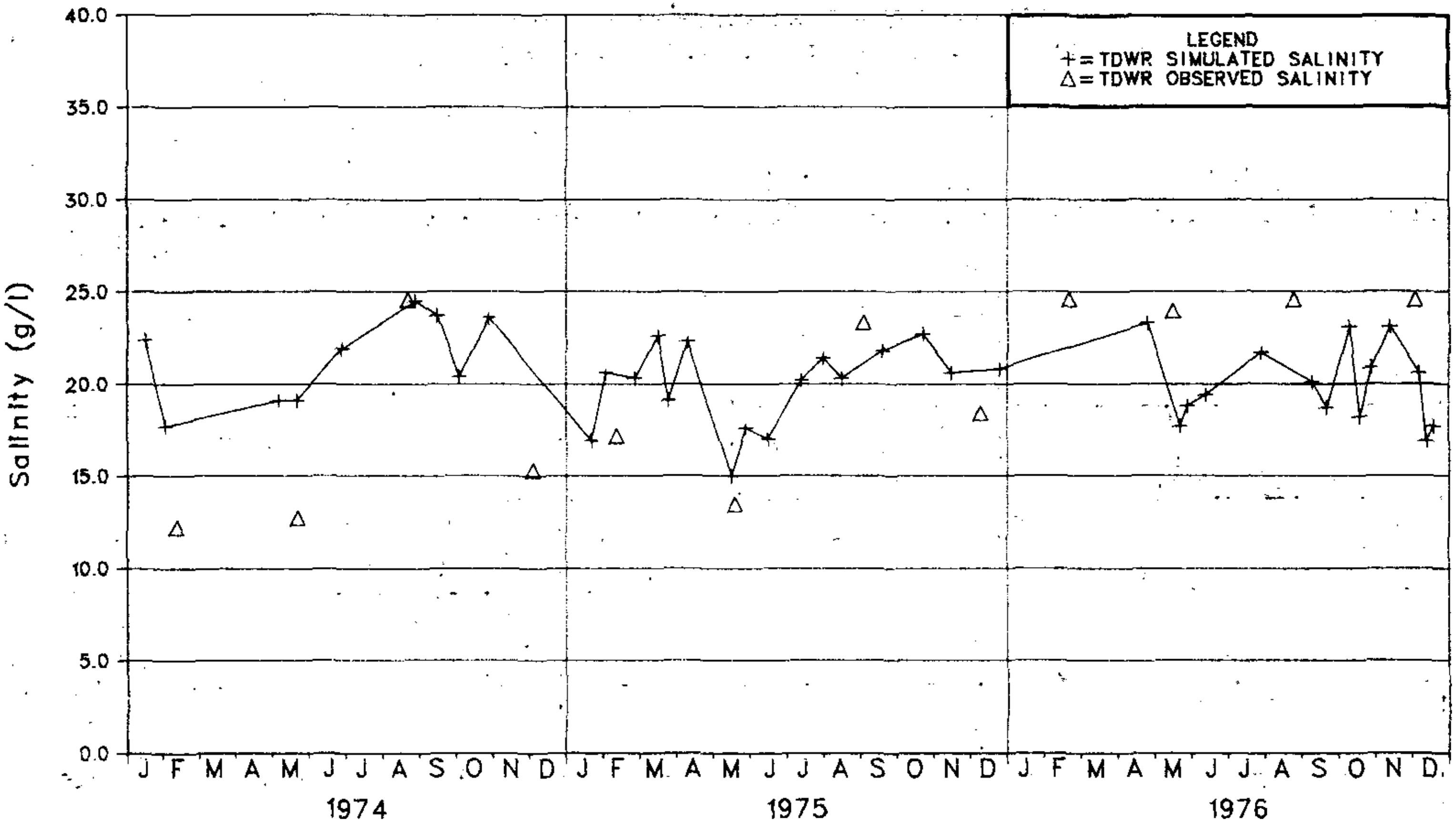


Figure 5-40. Comparison of Observed and Simulated Salinities, Galveston Bay, TDWR Station No. 2421.0300

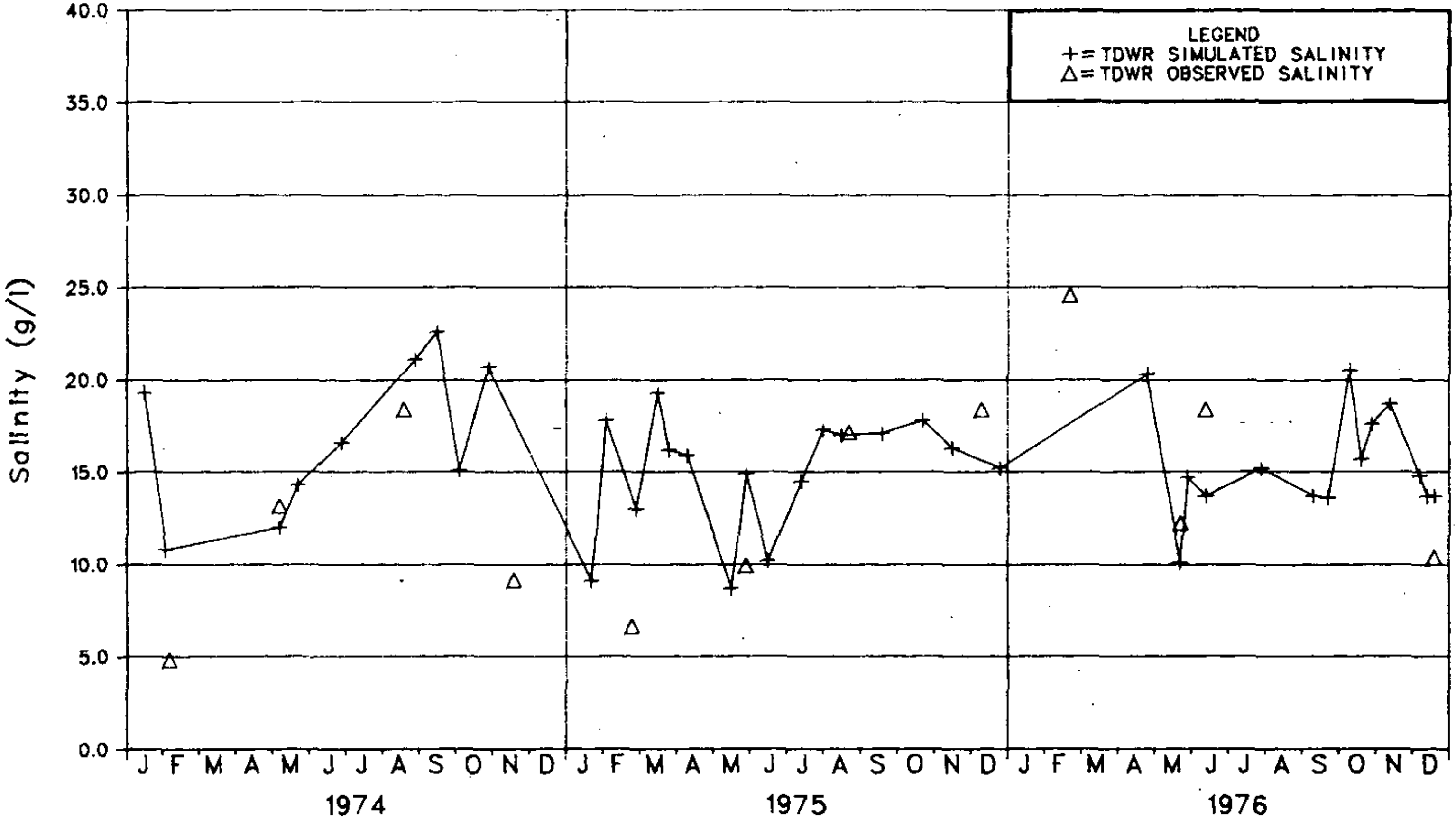


Figure 5-41. Comparison of Observed and Simulated Salinities, Galveston Bay, TDWR Station No. 2421.0200

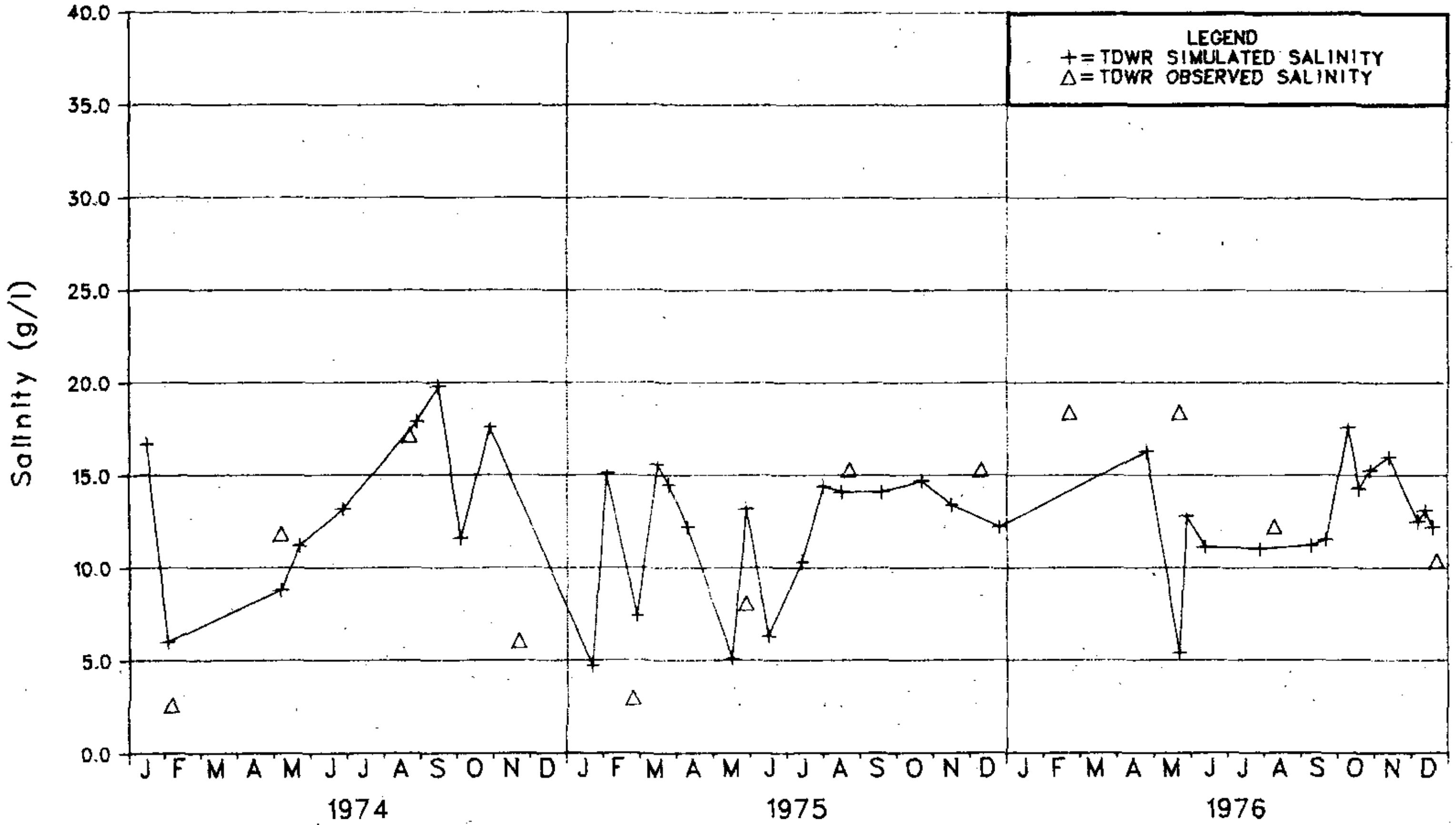


Figure 5-42. Comparison of Observed and Simulated Salinities, Galveston Bay, TDWR Station No. 2421.0400

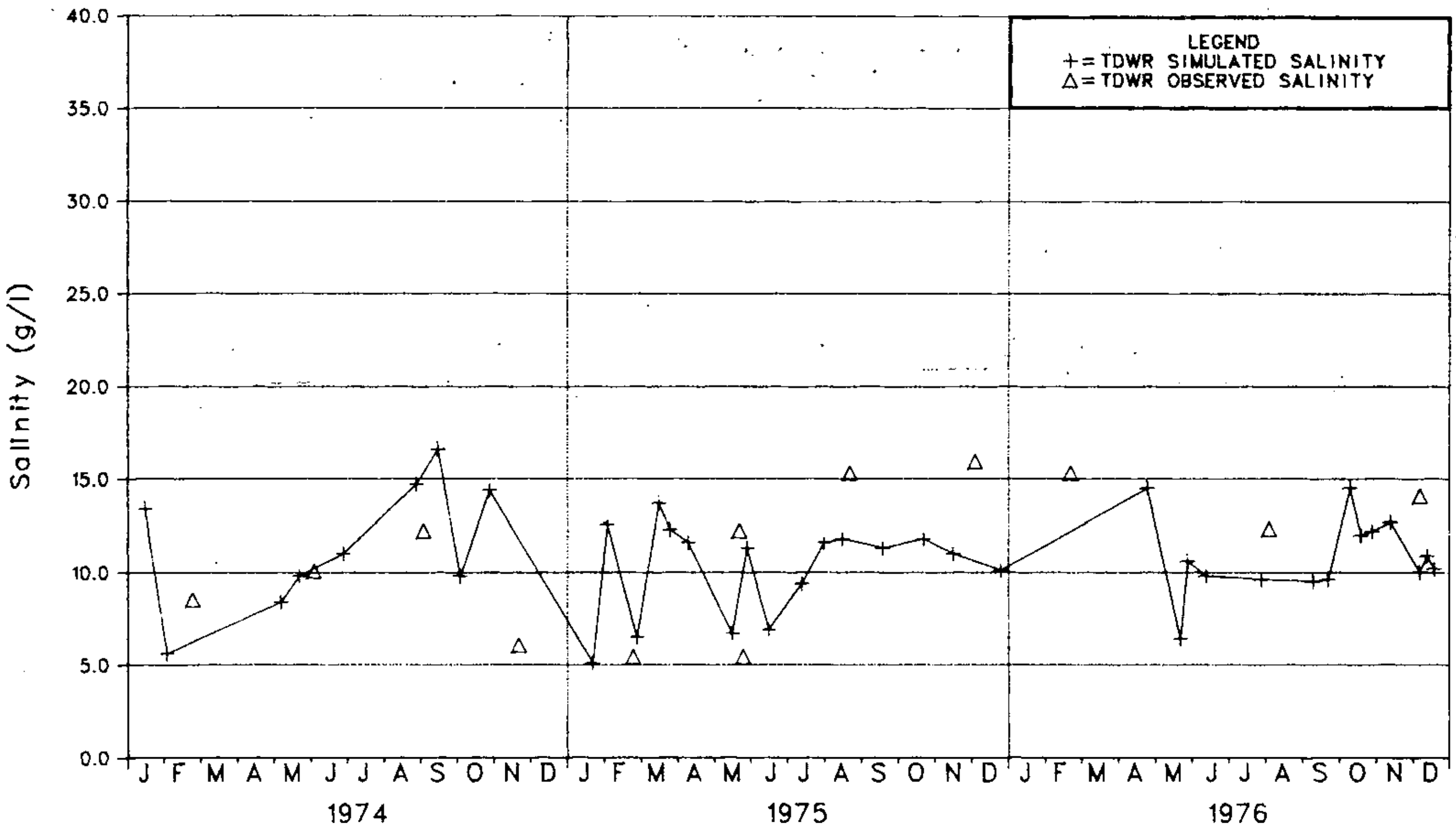


Figure 5-43. Comparison of Observed and Simulated Salinities, Galveston Bay, TDWR Station No. 2421.0100

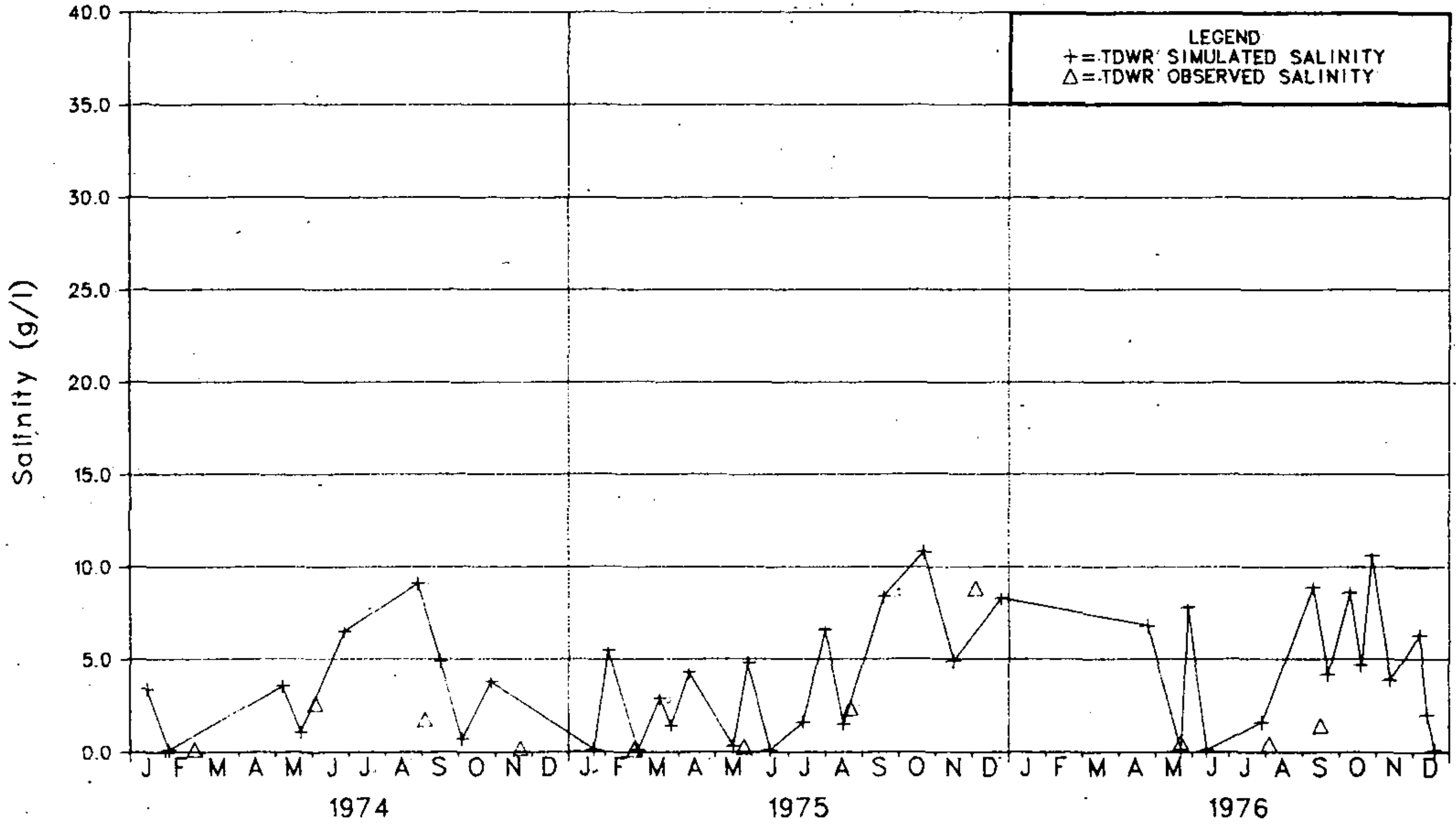


Figure 5-44. Comparison of Observed and Simulated Salinities, Galveston Bay, TDWR Station No. 2422.0100

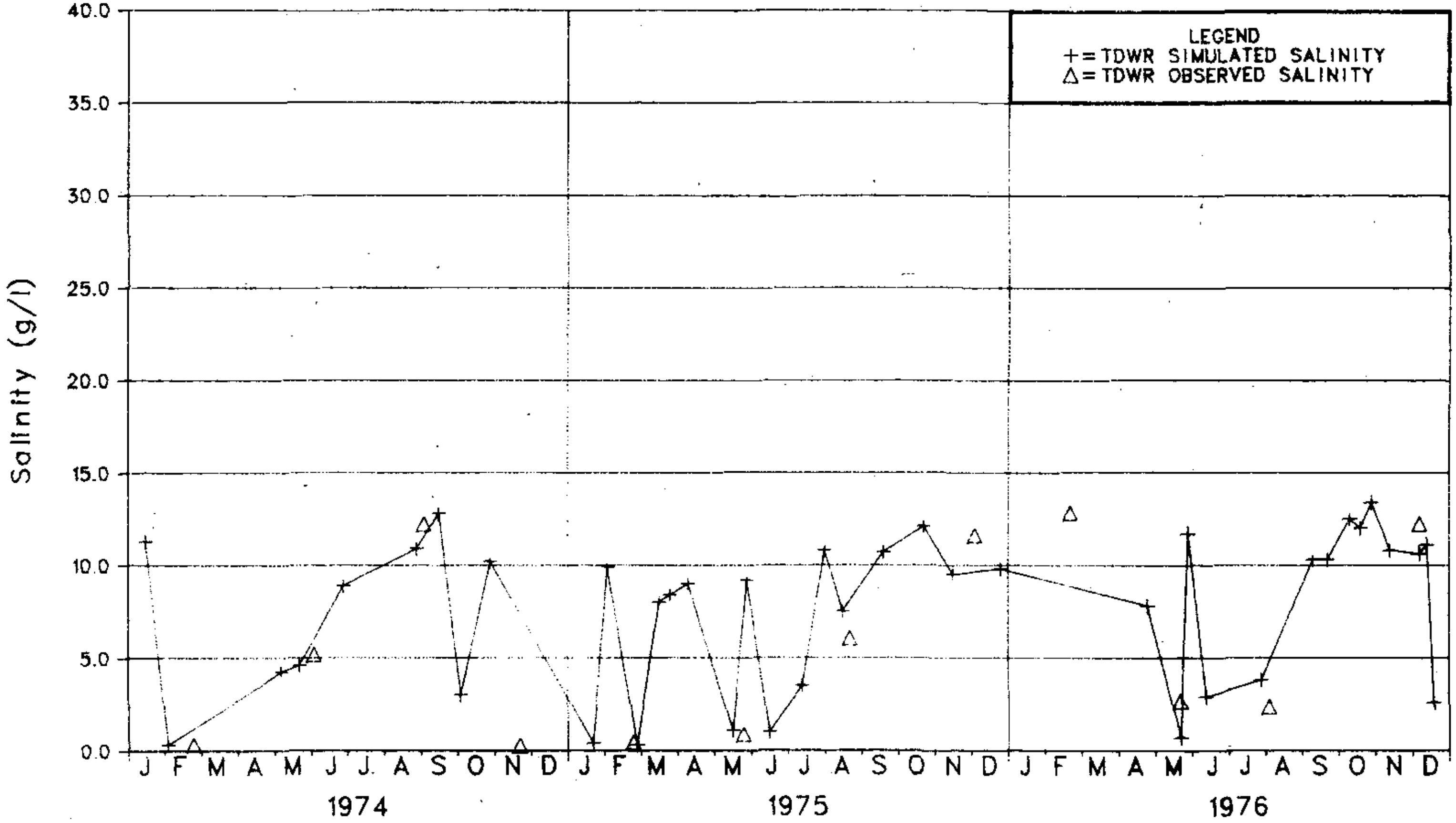


Figure 5-45. Comparison of Observed and Simulated Salinities, Galveston Bay, TDWR Station No. 2422.0200

south by the Wallisville levee and continuing northward to the beginning of the cypress swamp area. The eastern boundary is the Trinity River, and the area extends westward from the river to the beginning of the uplands. Included within this area are all major marsh regions subject to inundation from river flow. This marsh area is highly productive and inundation should result in the flushing of nutrients into Trinity Bay.

Hydrographic input into the model was taken from an idealized hydrograph that was constructed from parameters derived from five flood events which occurred on the Trinity River after Lake Livingston had filled. Details of this hydrograph can be found in the Trinity River delta inundation study (52). Six flood peaks, ranging in magnitude from 10,000 ft^3/sec (283 m^3/sec) to 35,000 ft^3/sec (991 m^3/sec) in increments of 5,000 ft^3/sec (142 m^3/sec), were selected to fulfill the freshwater inflow requirements of the model. In addition, two independent tide records from the Morgan's Point tide gage were selected which correspond to the low and high tide conditions. Each of the six flood cases were simulated with both a high and low driving tide in an effort to differentiate those areas which would be inundated as a result of high flows, and those areas which would be inundated as a result of the interaction of high freshwater inflows and high tidal amplitude.

Driven by low tide conditions the model shows that no inundation will occur within the study area during floods of less than 20,000 ft^3/sec (566 m^3/sec). From flood peaks of 20,000 ft^3/sec (566 m^3/sec) to 30,000 ft^3/sec (850 m^3/sec) the percent of study area inundation will increase from 5 to 22 percent, and Trinity River floods with peak discharges in excess of 30,000 ft^3/sec (850 m^3/sec) will sharply increase the percentage of study area inundated (Figure 5-46). A 35,000 ft^3/sec (991 m^3/sec) flood will inundate 79 percent of the marsh study area during low tide conditions.

High tide conditions, on the other hand, will cause some inundation within the study area for all six of the flood peaks simulated (Figure 5-46). The model predicts that increases in flood peaks from 10,000 ft^3/sec (283 m^3/sec) to 20,000 ft^3/sec (566 m^3/sec) will moderately increase the amount of the study area that will be inundated. Between floods peaks of 20,000 ft^3/sec (566 m^3/sec) and 25,000 ft^3/sec (708 m^3/sec), however, the area inundated increases dramatically from 44 to 91 percent, respectively. The two remaining flood peaks simulated, 30,000 ft^3/sec (850 m^3/sec) and 35,000 ft^3/sec (991 m^3/sec) will completely inundate the study area.

With low tidal conditions at Morgan's Point, the model predictions indicate that a flood peak in excess of 30,000 ft^3/sec (850 m^3/sec) will be required to achieve a high percentage of inundation of the study area. When tides are higher than normal, however, the study area will be inundated by floods of lesser magnitude. A flood peak of 25,000 ft^3/sec (708 m^3/sec) would appear to be the most judicious use of water for inundation purposes when the Morgan's Point tide stage is above normal.

As a result of these studies, curves were developed relating the percentage of marsh area inundated to a function of flow, for both low and high tides. These results are presented in Figure 5-46 and Table 5-3.

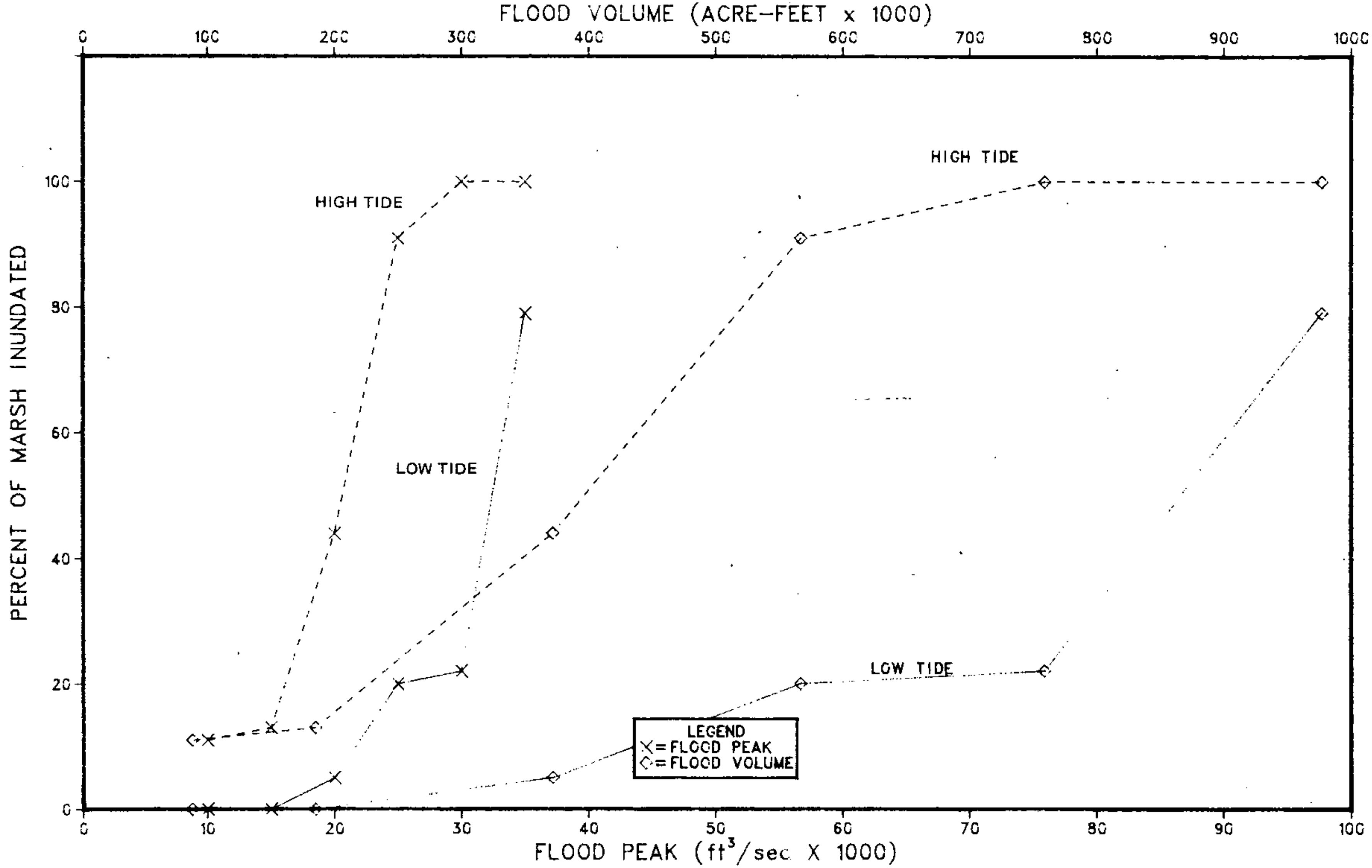


Figure 5-46. Simulated Trinity Delta Marsh Inundation, High and Low Tides

Table 5-3. Trinity Delta Inundation Study

Peak Discharge	Flood Duration	Flood Volume	Total Discharge	Inundation 1/			
				Percent		Acres	
				Low	High	Low	High
10,000	9	87,572	44,150	0	11	0	940
15,000	16	184,961	93,250	0	13	0	1,097
20,000	19	371,906	187,500	5	44	405	3,629
25,000	21	567,281	286,000	20	91	1,639	7,585
30,000	21	758,689	382,500	22	100	1,864	8,328
35,000	21	976,874	492,500	79	100	6,589	8,328

a/ Inundation of 0.5 feet for 48 consecutive hours

Freshwater Inflow/Salinity Regression Analysis

Changes in estuarine salinity patterns are a function of several variables, including the magnitude of freshwater inflow, tidal mixing, density currents, wind induced mixing, evaporation and salinity of source inflows. In the absence of highly saline inflow and neglecting wind effects, the volumes of antecedent inflow and the tidal mixing are the most important factors affecting salinity. Salinities immediately inside the Gulf passes vary markedly with flood and ebb tide; the influence of tidal mixing attenuates with distance traveled inside the estuary from the Gulf pass.

The dominance of the effect of freshwater inflow on estuary salinity increases with an increase in proximity to freshwater inflow sources. The areal extent of the estuary influenced by freshwater inflow varies in proportion to the magnitude of freshwater inflow except during conditions of extreme drought. Regression analyses of measured salinities versus freshwater inflow are carried out to verify and quantify such a relationship.

The average daily salinities were assumed to be related to gaged streamflows by one of the following relationships:

$$S_t = a_0 + a_1 Q_{t-k}^{-b} + a_2 \left(\sum_{i=1}^{n} Q_{t-i} \right)^{-b} \qquad [1]$$

or

$$S_t = a_0 \left(Q_{t-k}\right)^{a_1} \left(\sum_{i=1}^{n} Q_{t-i} \right)^{a_2} \qquad [2]$$

where S_t is the average salinity of the t-th day; Q_{t-k} or Q_{t-i} is gaged streamflow k or i days antecedent to the t-th day; b is a positive number between zero and one; n is an integer; and a_0, a_1 and a_2 are regression coefficients. The term $\sum_{i=1}^{n} Q_{t-i}$ in Equations [1] and [2] represents the antecedent inflow conditions, while Q_{t-k} represents the present inflow condition taking into consideration streamflow time lag between the gage and the estuary. The regression coefficients were determined using a step-wise multiple regression procedure (16).

The regression equations developed for Trinity Bay used salinities obtained by the Texas Department of Water Resources (TDWR) at statewide monitoring network station No. 2422.03 (Figure 4-6) and gaged streamflows recorded for the Trinity River near Romayor (Table 5-4). The daily average salinity is related to the daily gaged streamflow by

$$S_t = -1.62 + 2528.5 \left(\sum_{i=1}^{29} Q_{t-i} \right)^{-0.5} \qquad [3]$$

where S_t and Q_{t-i} are salinity and streamflow in ppt and ft^3/sec, respectively. With a correlation coefficient (r) of 0.88 and an explained variation (r^2) of 0.77 percent, the regression is tested to be highly significant ($\alpha = .01$).

Table 5-4. Description of Data for Regression Analysis, Trinity-San Jacinto Estuary

Bay	Salinity		Inflow		No. of Observations for Regression
	Station a/	Period of Record	USGS Station	Period of Record	
Trinity	TDWR Monitoring Station 2422.03	May 1969 to Sep. 1977	Trinity River near Romayor	Jan. 1925 to Sep. 1977	33
Galveston	TDWR Monitoring Station 1005.01	May 1969 to Dec. 1977	Derived San Jacinto Basin inflow	Jan. 1941 to Dec. 1976	82

a/ See Figure 4-6 for station locations

Monthly salinity-inflow relationships were derived using equation [3] to generate daily salinities for the period of streamflow record, 1925 through 1976. The computed daily salinity values were averaged monthly over the study period, and the averages were related to the monthly average flows by the geometric equation

$$S_m = C_0 \, (Q_m)^{C_1} \exp \, (ts_e) \qquad [4]$$

where S_m and Q_m are monthly average salinity and gaged flow in ppt and ft^3/sec, respectively, C_0 and C_1 are regression coefficients, and (ts_e) is a random component (66). The frequency analyses for Trinity-San Jacinto estuary indicate that both monthly salinity data and monthly gaged streamflows are approximately log-normal distributed. Therefore, the random component has a normal distribution and can be expressed by ts_e (66), where t is a standard normal deviate with zero mean and unit variance, and s_e is the standard error of estimate of ln (S_m) on ln (Q_m). Resulting correlation coefficients of equation [4] for Trinity Bay (Table 5) for the twelve months (r) ranged from 0.82 to 0.92, which are highly significant ($\alpha = .01$).

The average condition of [4] over a 12-month period, i.e., the relationship of the mean monthly averages, is fitted to the equation

$$S_y = 656.8 \, Q_y^{-0.576} \qquad [5]$$

where S_y and Q_y are mean monthly average salinity, and gaged flow in ppt and ft^3/sec, respectively. The equation and the 95 percent confidence limits of S_y versus Q_y are plotted in Figure 5-47. The other statistics of equation [5] are listed in Table 5-5.

The analysis for Galveston Bay, used the salinities obtained by the Texas Department of Water Resources (TDWR) at statewide monitoring network station No. 1005.01 (Morgan's Point) and the derived San Jacinto River Basin monthly inflow as described in Chapter IV, (Hydrology). The monthly inflows to daily flow by were uniformly divided into daily flows. Daily salinity is related to daily flow by

$$S_t = 0.61 + 3404.7 \, \left(\sum_{i=0}^{29} Q_{t-i}\right)^{-0.5} \qquad [6]$$

The correlation is highly significant with a correlation coefficient (r) of 0.72.

Using equation [6] to generate mean daily salinity for the period of streamflow record, 1941 through 1976, the relationships between computed monthly mean salinities and monthly mean streamflows were determined as shown in Table 5-6. The average condition of the relationships can be fitted to the equation

$$S_y = 217.4 \, Q_y^{-0.355} \qquad [7]$$

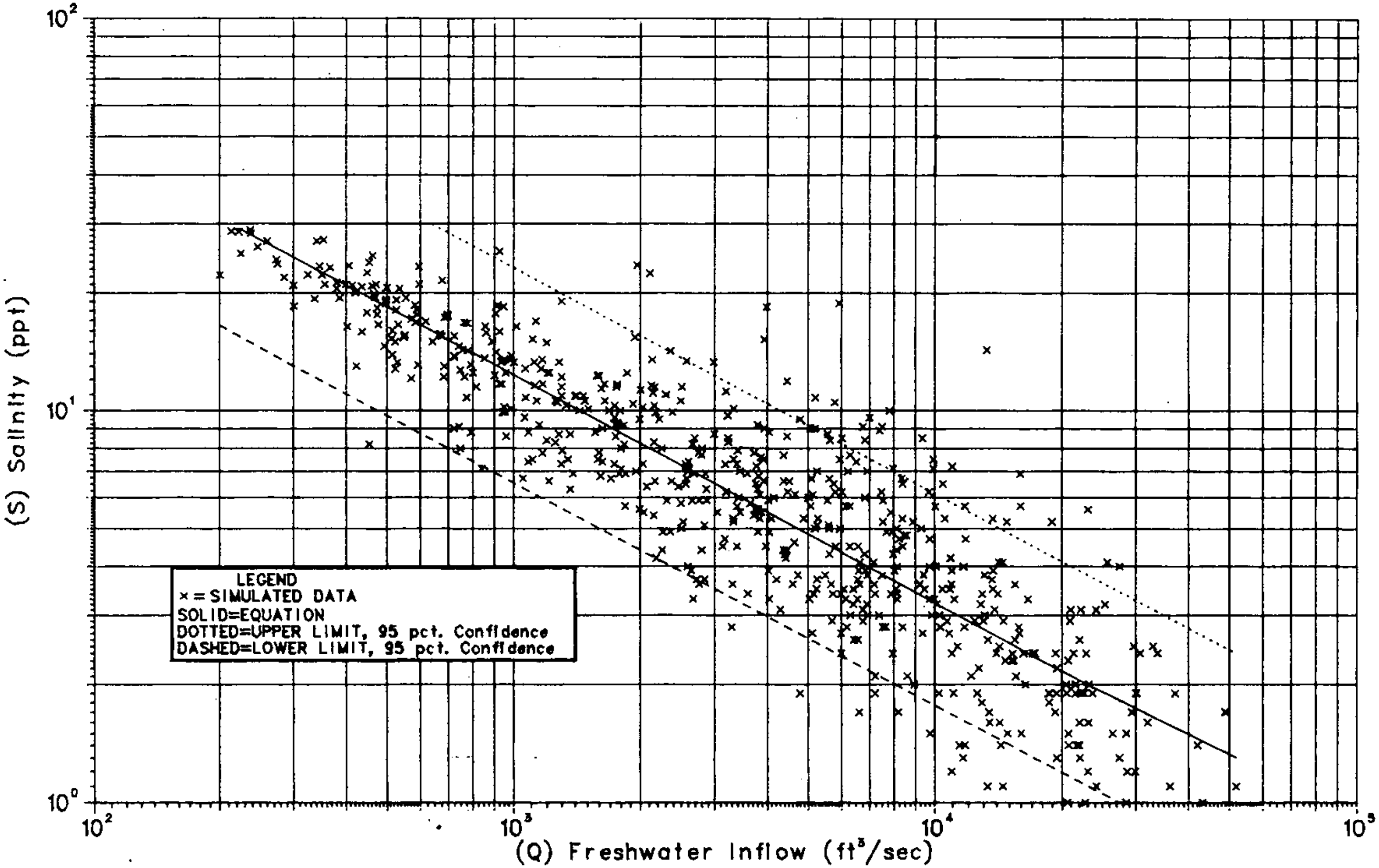


Figure 5-47. Average Monthly Salinity Versus Average Monthly Gaged Inflow, Trinity Bay, 1925-1976

Table 5-5. Results of Salinity Regression Analysis, Trinity Bay

Station	Class	Regression Equation (S in ppt and Q in ft³/sec)		Correlation Coefficient r	Explained Variation r^2	Standard Error of Estimate s_e	F-test
TDWR 2422.03	Daily	$S_t = 1.62 + 2528.5 \left(\sum_{i=1}^{29} Q_{t-i} \right)^{-0.5}$		0.88	0.77	3.11	**
	Jan.	$S = 775.1\ Q^{-0.590}$,	$350 \leq Q \leq 30,000$	0.91	0.83	0.309	**
	Feb.	$S = 987.7\ Q^{-0.622}$,	$450 \leq Q \leq 37,700$	0.87	0.76	0.343	**
	Mar.	$S = 663.5\ Q^{-0.582}$,	$530 \leq Q \leq 42,100$	0.90	0.81	0.315	**
	Apr.	$S = 1037.9\ Q^{-0.627}$,	$420 \leq Q \leq 65,700$	0.84	0.71	0.398	**
	May	$S = 746.9\ Q^{-0.589}$,	$1,280 \leq Q \leq 62,000$	0.82	0.68	0.410	**
	Jun.	$S = 1175.5\ Q^{-0.673}$,	$460 \leq Q \leq 45,100$	0.87	0.76	0.422	**
	Jul.	$S = 677.2\ Q^{-0.616}$,	$230 \leq Q \leq 28,500$	0.94	0.89	0.241	**
	Aug.	$S = 626.5\ Q^{-0.587}$,	$200 \leq Q \leq 10,100$	0.94	0.88	0.197	**
	Sep.	$S = 290.3\ Q^{-0.440}$,	$210 \leq Q \leq 14,900$	0.92	0.85	0.290	**
	Oct.	$S = 204.9\ Q^{-0.393}$,	$180 \leq Q \leq 14,900$	0.82	0.67	0.343	**
	Nov.	$S = 483.6\ Q^{-0.514}$,	$270 \leq Q \leq 30,800$	0.83	0.69	0.406	**
	Dec.	$S = 674.7\ Q^{-0.555}$,	$350 \leq Q \leq 43,200$	0.88	0.77	0.353	**
	All	$S = 656.8\ Q^{-0.576}$		0.89	0.80	0.382	**

** Indicates a statistical significance level of $\alpha = 0.01$ (highly significant) where S_y and Q_y are mean monthly average salinity and gaged flow, respectively. The equation and the 95 percent confidence limits of S_y versus Q_y are plotted in Figure 5-48. The other statistics of equation [7] are listed in Table 5-6.

The above freshwater inflow-salinity relationships can be used to provide preliminary estimates of the response of the estuary to proposed freshwater inflow regimes. Such a technique allows a quick screening of the inflow regimes that have the least desirable impact on salinity patterns in the estuary. Only the most promising inflow regimes then remain to be analyzed in detail using the estuarine tidal hydrodynamic and salinity transport models.

In future studies, the regression equations developed here may be useful in determining the impact of modified long-term freshwater inflow patterns on the estuary, including the imposition of alternative river basin development and management plans on the hydrology of the contributing river basins.

Summary

The movements of water in the shallow estuaries and embayments along the Texas Gulf Coast are governed by a number of factors, including freshwater inflows, prevailing winds, and tidal currents. An adequate understanding of mixing and physical exchange in these estuarine waters is fundamental to the assessment of physical, chemical, and biological processes governing these important aquatic systems.

To fully evaluate the tidal hydrodynamic and salinity transport characteristics of estuarine systems using field data, the Texas Department of Water Resources developed digital mathematical models representing the important mixing and physical exchange processes of the estuaries. These models are designed to simulate the tidal circulation patterns and salinity distributions in shallow, irregular, non-stratified estuaries. The basic concept utilized to represent each estuary is the segmentation of the physical system into a grid of discrete elements. The models utilize numerical analysis techniques to simulate the temporal and spatial behavior of circulation and salinity patterns in an estuary.

To properly evaluate the transport of water and nutrients through a deltaic marsh, it is necessary to describe and compute estimates of the complex tidal and freshwater inflow interactions. A mathematical model based upon the physical laws of conservation of mass and momentum has been developed to simulate the passage of water and nutrients through the Trinity deltaic system. The computations are based upon use of a finite difference approximation to the equations which describe the governing physical relationships.

The marsh inundation model is applied to the Tinity River delta. The delta system is represented as a series of interconnected shallow channels which are subject to varying levels of inundation, depending upon the tidal and riverine flow rates. The representation of the Trinity River delta includes the non-tidally influenced flood plain of the Trinity River from the stream gages near Lost Lake and Lake Charlotte to the Wallisville levee. The San Jacinto River delta is much smaller in areal extent than the Trinity delta, and was not considered of sufficient significance to warrant extensive analysis of its inundation characteristics.

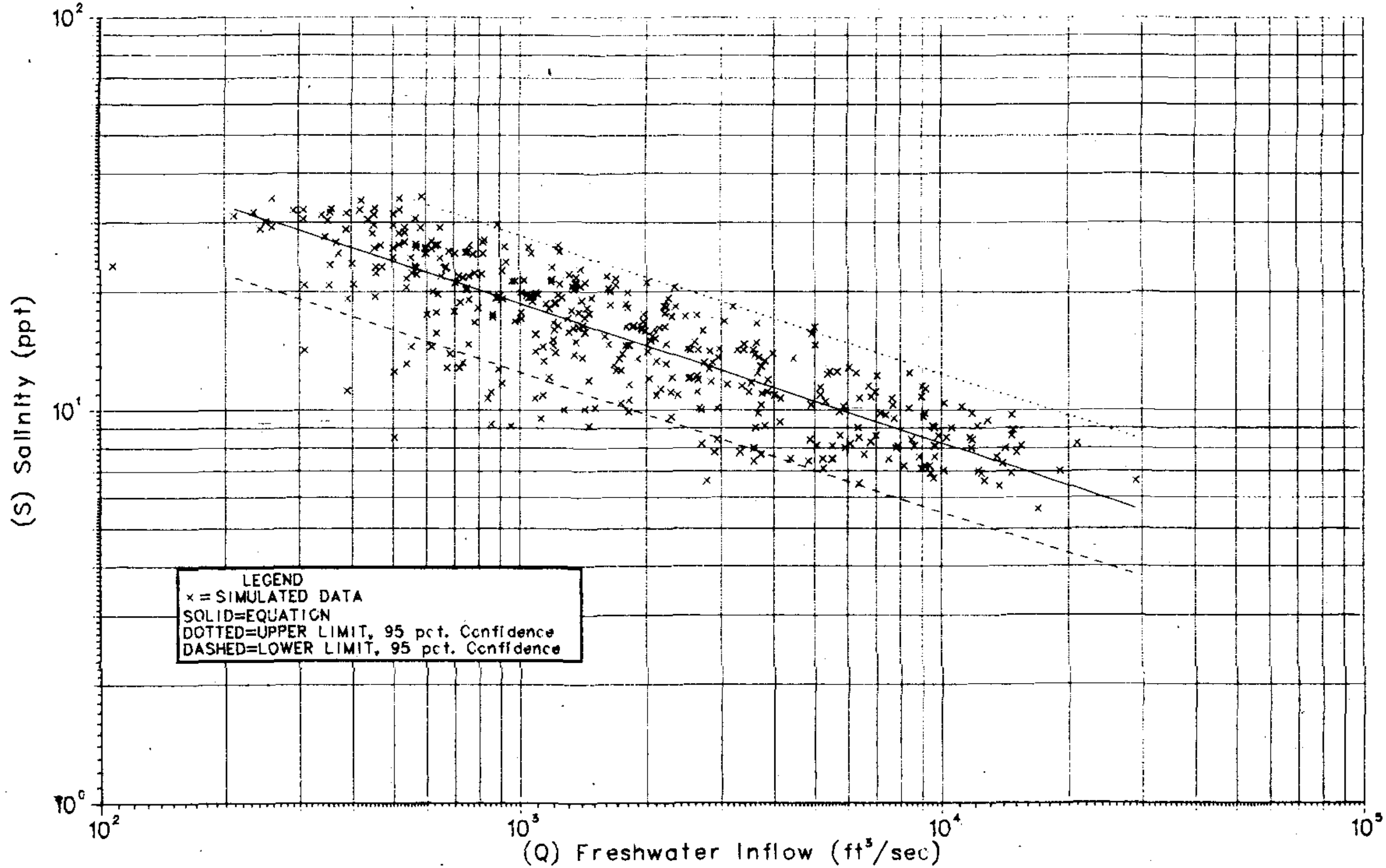


Figure 5-48. Average Monthly Salinity Versus Average Monthly Gaged Inflow, Galveston Bay, 1941-1976

Table 5-6. Results of Salinity Regression Analysis, Galveston Bay

Station	Class	Regression Equation (S in ppt and Q in ft³/sec)	Correlation Coefficient r	Explained Variation r^2	Standard Error of Estimate s_e	F-test
TDWR 1005.01	Daily	$S_t = 0.61 + 3403.7 \left(\sum_{i=0}^{29} Q_{t-i}\right)^{-0.5}$	0.72	0.52	5.76	**
	Jan.	$S = 355.3\ Q^{-0.413}$, $300 \le Q \le 13{,}560$	0.96	0.92	0.140	**
	Feb.	$S = 163.5\ Q^{-0.323}$, $150 \le Q \le 13{,}700$	0.84	0.71	0.265	**
	Mar.	$S = 152.7\ Q^{-0.318}$, $150 \le Q \le 9{,}630$	0.73	0.54	0.296	**
	Apr.	$S = 221.8\ Q^{-0.352}$, $500 \le Q \le 15{,}500$	0.87	0.75	0.209	**
	May	$S = 228.2\ Q^{-0.364}$, $400 \le Q \le 15{,}100$	0.88	0.78	0.208	**
	Jun.	$S = 141.6\ Q^{-0.313}$, $240 \le Q \le 16{,}970$	0.82	0.68	0.264	**
	Jul.	$S = 454.9\ Q^{-0.453}$, $440 \le Q \le 9{,}430$	0.85	0.73	0.229	**
	Aug.	$S = 215.5\ Q^{-0.359}$, $340 \le Q \le 11{,}840$	0.82	0.67	0.188	**
	Sep.	$S = 195.0\ Q^{-0.330}$, $420 \le Q \le 12{,}890$	0.89	0.79	0.154	**
	Oct.	$S = 181.1\ Q^{-0.337}$, $200 \le Q \le 21{,}060$	0.90	0.81	0.205	**
	Nov.	$S = 240.8\ Q^{-0.360}$, $250 \le Q \le 29{,}040$	0.85	0.72	0.284	**
	Dec.	$S = 378.7\ Q^{-0.417}$, $350 \le Q \le 9{,}640$	0.87	0.76	0.247	**
	All	$S = 217.4\ Q^{-0.355}$	0.89	0.80	0.382	**

** Indicates a statistical significance level of $\alpha = 0.01$ (highly significant)

The correct model coefficients for calibration of the hydrodynamic model, reflecting the delta's hydraulic characteristic, were determined by simulating the flow conditions and water inudation depths in the delta, comparing them with actual field data, and adjusting the coefficients until adequate agreement between observed and simulated conditions was achieved.

The numerical tidal hydrodynamic and salinity mass transport models were applied to the Trinity-San Jacinto estuary, with the model representation of the system including Galveston Bay, Trinity Bay, East Bay, West Bay, and numerous smaller bays, San Luis Pass and Bolivar Roads. The hydrodynamic and mass transport models were calibrated and verified for the estuary.

The extent of marsh inundation in the Trinity River delta was investigated utilizing the verified inundation model for this system. The surface area of the Trinity delta flooded was determined for four typical flood hydrographs, which occurred on the Trinity River after the filling of Lake Livingston, under high and low tidal amplitudes.

Statistical analyses were undertaken to quantify the relationship between freshwater inflows from the Trinity and San Jacinto Rivers and salinities from Trinity and Galveston Bays. Utilizing gaged daily river flows and observed salinities, a set of monthly predictive salinity equations were derived utilizing regression analyses for the indicated areas of the estuary. These equations predicted the mean monthly salinity as a function of the mean monthly freshwater inflow rate.

CHAPTER VI

NUTRIENT PROCESSES

Introduction

Biological productivity is keyed to a variety of physical and chemical processes. These include favorable conditions of temperature, salinity, and pH, as well as a sufficient energy source (e.g., sunlight and tides) to drive the biological processes. In addition, readily available supplies of inorganic materials are essential, the most obvious being carbon, nitrogen, and phosphorus (CNP). No less important, but required in smaller amounts are silicon, sodium, potassium, manganese, chlorine, and sulfate ions. Other essential elements are required in trace amounts.

In the majority of aquatic ecosystems, these elements are available in quantities necessary to support biological production. A deficiency of any one, however, may be sufficient to limit biological productivity. In most cases, nutrients required in the largest amounts are quickly depleted from the surrounding medium. Their concentrations can consequently be considered among the most important factors relating to biological productivity. The ratios of the three most important elements -- carbon, nitrogen, and phosphorus -- to lesser ones are such that a deficiency of any one of the three will act as a limiting factor regulating the level of productivity in the system.

CNP (carbon to nitrogen to phosphorus) ratios vary from organism to organism. Carbon is normally required in the greatest quantity followed by nitrogen and phosphorus. Generally, oceanic species have a reported value of 106:16:1 (142). Nitrogen to phosphorus ratios for a variety of phytoplankton species are usually in the range of 10-12:1 (142). Nitrogen and phosphorus are considered to be the "critical" nutrients in aquatic ecosystems since carbon is rarely, if ever, limiting due to the readily available supply of atmospheric CO_2 and the ability of autotrophic organisms to use this form.

The amount of nitrogen required in an aquatic ecosystem is generally greater than phosphorus; biological productivity is therefore most likely to be nitrogen-limited. This has been reported to be the case in a number of estuaries (530, 532, 159, 220, 225, 133), including those in Texas (368, 369).

Nutrients can be brought into the estuary in either particulate or dissolved forms. Both forms may be composed of organic and inorganic components. Particulate nutrients may exist in the form of detritus from decaying vegetation, sewage and industrial waste effluents, or nutrients adsorbed onto silt, clay, and various mineral particles. In general, some form of mixing is necessary to keep particulate materials (especially the larger ones) in suspension. Mixing forces may be in the form of wind-driven circulation, as in the shallow bays of the Texas coast, or as induced currents from the rivers and streams that feed the estuaries.

The three natural sources of nutrients to the estuaries are streams and rivers, rain, and seawater. Seawater is not usually considered as a nutrient source; however, there may be a considerable exchange of seawater with bay water, depending upon prevailing conditions, and some nutrients may enter from this source. Rainfall probably does not act as a major nutrient source either, although soluble ammonia may be available in the atmosphere at times. On the Texas coast, the major source of nutrients is freshwater inflow from the rivers and streams that empty into the estuary. Inflows suspend and transport nutrients of natural and man-made origin.

The following sections describe the methodology used to determine the nutrient contribution of the Trinity and San Jacinto Rivers to the Trinity-San Jacinto estuary, the importance of deltaic marshes to biological primary production, and finally the role deltaic marshes play in trapping, storing, and converting inorganic nutrients to plant biomass and the subsequent transport of this biomass to the estuarine systems.

Nutrient Loading

Attempts to determine the amount of nutrient loading from a riverine source to an estuary have been conducted by Smith and Stewart (229). The basic methodology includes a determination of mean annual flow magnitudes and mean annual concentrations of the nutrient species; simple multiplication is used to arrive at a loading in pounds (or kilograms) per year. The U. S. Geological Survey (USGS), in cooperation with the Texas Department of Water Resources, has maintained daily stream discharge records of the major rivers and tributaries that empty into Texas bays and estuaries. Nutrient concentration and water quality data have been collected systematically for these rivers only since the late 1960's.

Nutrient contributions to the Trinity-San Jacinto estuary are derived primarily from (1) river inflow; (2) local ungaged runoff; and (3) biogeochemical cycling in deltaic and peripheral salt or brackish water marshes. In addition, nutrients may be contributed by point source discharges or return flows. The adjacent Gulf of Mexico, by comparison, is nutrient-poor; resulting concentration gradients are such that a net transport of nutrients out of the bay/estuary system toward the Gulf normally occurs. Numerous complicating factors such as the magnitude of freshwater inflows, winds, currents, and biological activity all contribute to the complexity of processes that may be occurring at any time.

The Trinity River contributes freshwater and nutrients to the northeast arm of the estuary, Trinity Bay, near Wallisville, Texas. White Oak, Caney, Peach, Spring, and Cypress Creeks along with the east and west forks of the San Jacinto River empty into Lake Houston northeast of the City of Houston. Downstream, the San Jacinto River channel is the common watercourse that carries freshwater and nutrient contributions from the basin to the estuary. Greens, Hunting, Halls, White Oak, Brays, and Sims Bayous drain areas in and around Houston and contribute discharge and nutrients to Buffalo Bayou, known as the Houston Ship Channel in its downstream reach.

The mean annual total discharge measured at the closest non-tidally influenced gage for the major freshwater inflow sources to the Trinity-San Jacinto estuary is about 6.93 million acre-feet (8,550 million m^3). The Trinity River contributes an average annual inflow of 5.42 million acre-feet (78.2 percent of the total) to the estuary. Contributions from the San

Jacinto River and its tributaries to Lake Houston are about 0.88 million acre-feet (12.6 percent). Since significant diversions are made from Lake Houston to supply the water needs of the City of Houston, the amount of freshwater contributed to the estuary from this source is much less, usually negligible. Mean annual contributions from Buffalo Bayou upstream from the Houston Ship Channel and those streams contributing to it are 0.47 million acre-feet (6.8 percent), including return flows from the City of Houston. There are three additional sources of gaged freshwater inflow to the Trinity-San Jacinto estuary: (1) Cedar Bayou, 56 thousand acre-feet/year (0.8 percent); (2) Clear Creek, 26 thousand acre-feet/year (0.4 percent); and (3) Chocolate Bayou, 78 thousand acre-feet/year (1.1 percent).

U. S. Geological Survey discharge and water quality data over the period of record 1970 through 1977 were used to calculate the potential nutrient loading contributions from the Trinity River, the San Jacinto River tributaries, and the Buffalo Bayou tributaries. The results of analyses of nutrient loadings from each freshwater inflow source should be interpreted as estimates based on limited data. The estimated loadings reflect the order of magnitude and range that might be expected during periods of similar climatic and streamflow conditions.

Studies were conducted in the Trinity River delta to gain insight into nutrient contributions from this brackish intertidal marsh to the Trinity estuary. The studies involved seasonal intensive field sampling efforts over a one or two day period and laboratory tests using vegetation/sediment cores taken from the delta. As is the case with riverine water quality, an analysis of the deltaic marsh contribution is inadequate based upon data collected over one to two years on a seasonal basis. More data are needed, particularly for extreme events such as floods, hurricanes, and droughts, in order to refine these analyses.

Water quality data collected by the U. S. Geological Survey indicated mean monthly organic nitrogen concentrations in the Trinity River at Romayor, ranged from 0.39 mg/l to 0.79 mg/l. Mean monthly organic nitrogen concentrations in Cedar Bayou, Trinity River, and the West Fork San Jacinto River were consistently within a similar concentration range (Figure 6-1). Mean monthly organic nitrogen concentrations in Buffalo Bayou and its tributaries throughout the City of Houston generally ranged from 1.0 mg/l to slightly more than 2.0 mg/l. Unusually high mean organic nitrogen values observed in Halls Bayou during October and August may not have been representative of the true mean. (The October mean is based on only two data points. The August mean includes an unusually high organic nitrogen value of 16.0 mg/l recorded in 1977; excluding this data point, the mean monthly concentration for August is calculated to be 1.02 mg/l, in line with those values observed for other nearby watercourses in the City of Houston drainage.) No obvious seasonal patterns of organic nitrogen concentration variation are apparent from the data.

The majority of the mean monthly inorganic nitrogen concentrations in the Trinity River, the West Fork San Jacinto River, Cedar Bayou, and Chocolate Bayou were less than 1.0 mg/l. The one exception was a value of 1.47 mg/l for May in Chocolate Bayou (Figure 6-2). This appears to be the peak of a springtime rise in inorganic nitrogen concentrations for this watercourse. With the exception of Greens Bayou, mean monthly inorganic nitrogen concentrations in watercourses that empty into the Houston Ship Channel ranged between 2 mg/l to

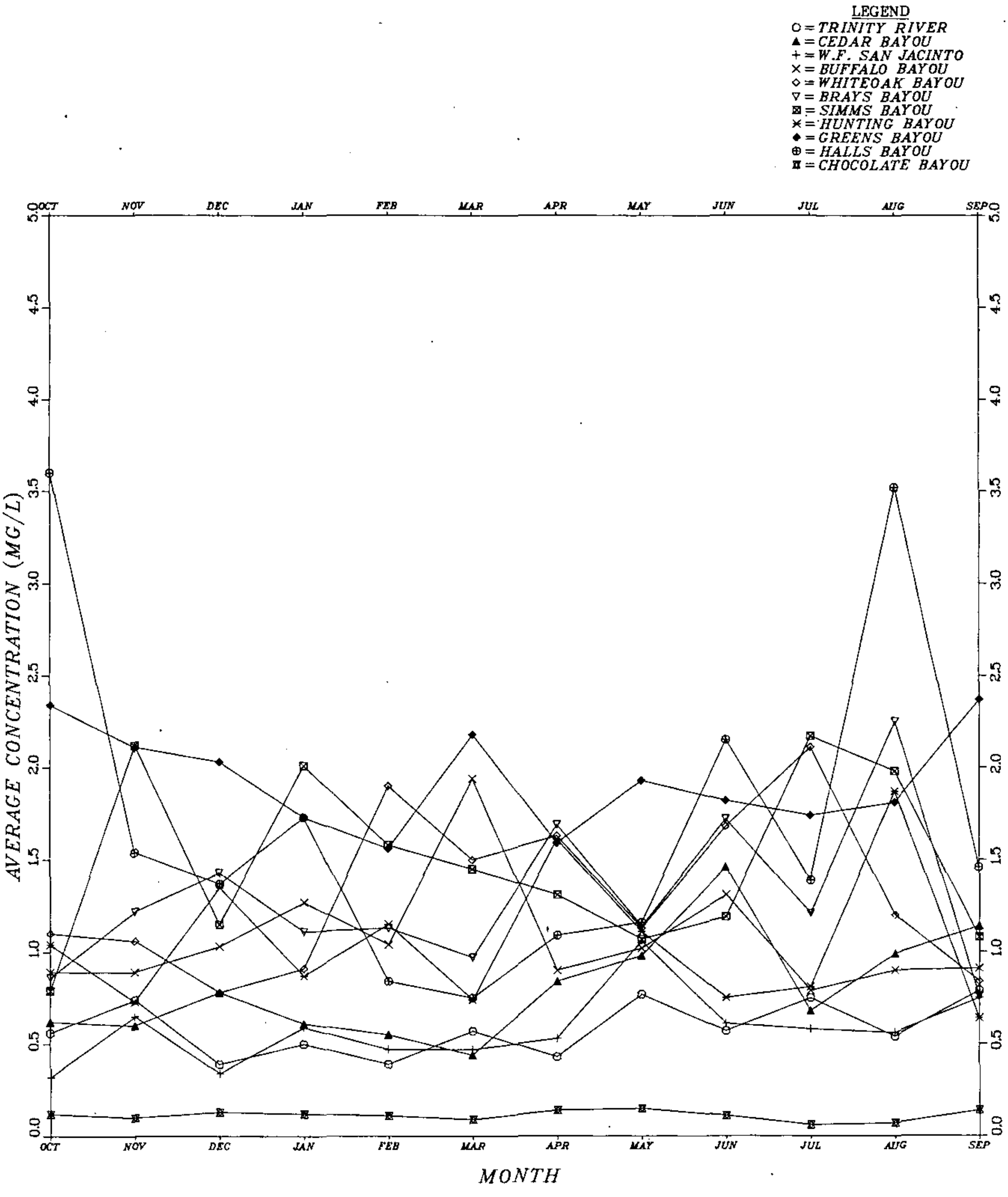


Figure 6-1. Mean Monthly Organic Nitrogen Concentrations in Streams Contributing to the Trinity-San Jacinto Estuary, 1970-1977

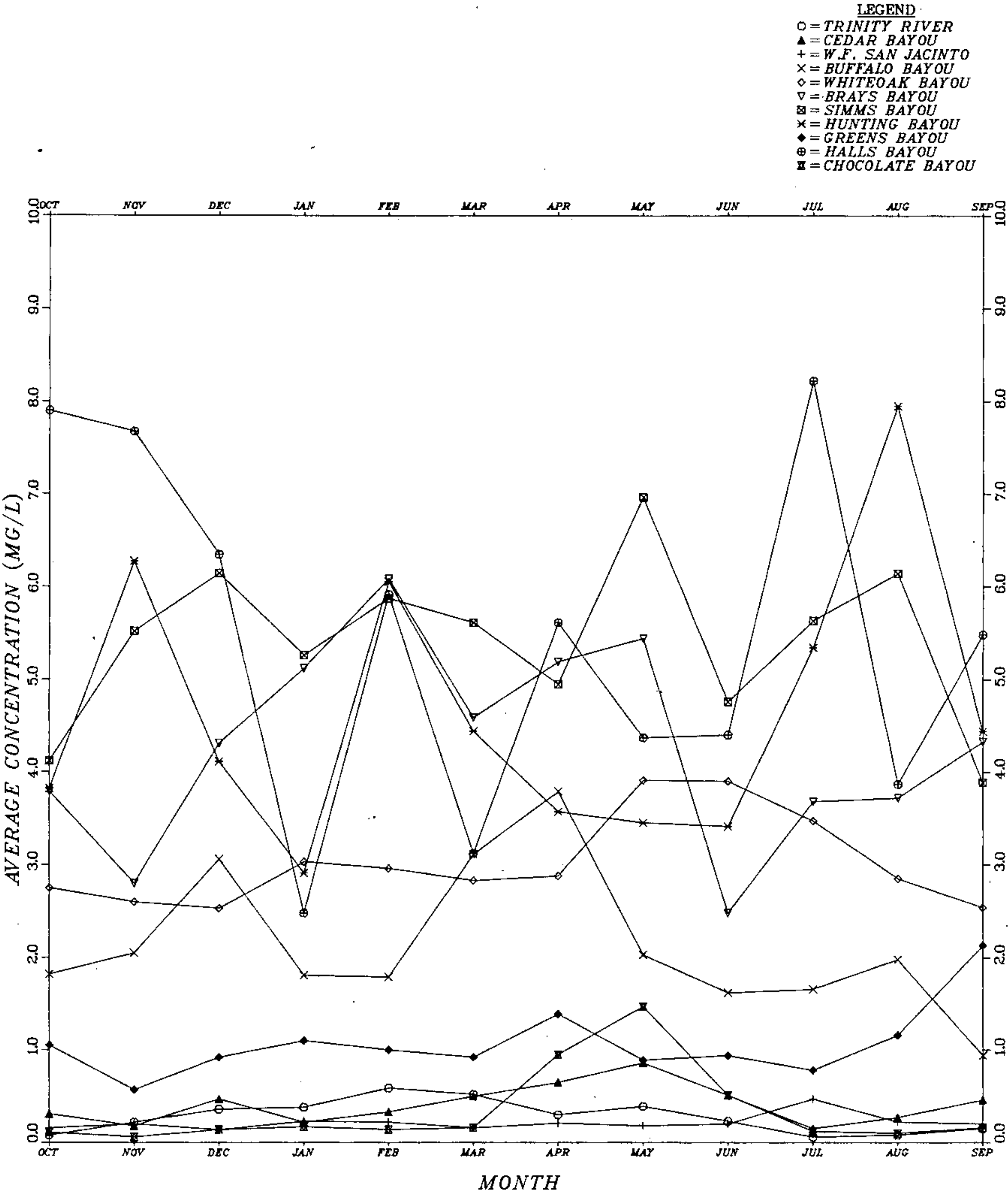


Figure 6-2. Mean Monthly Inorganic Nitrogen Concentrations in Streams Contributing to the Trinity-San Jacinto Estuary, 1970-1977

slightly higher than 8 mg/l. Concentrations in Greens Bayou were generally 1.0 mg/l or less. With the exception of Chocolate Bayou, there are no apparent seasonal trends for inorganic nitrogen concentrations in these watercourses.

Mean monthly total phosphorus concentrations less than 1.0 mg/l occurred in the Trinity River, Cedar Bayou, the West Fork San Jacinto River and Chocolate Bayou (Figure 6-3). Mean monthly total phosphorus concentrations in the other watercourses ranged from 1.0 mg/l to 5.0 mg/l. Halls Bayou, however, is an exception as several concentration values exceeded 5.0 mg/l. Halls Bayou is also the only watercourse where a seasonal trend may be evident, with the highest concentrations occurring in the fall and the lowest occurring in winter.

Mean monthly total organic carbon (TOC) concentrations ranged from 6.0 mg/l to 27 mg/l (Figure 6-4). Concentrations in the Trinity River and West Fork San Jacinto River were as a rule lower than those in the other watercourses. The distinction is less obvious for TOC than it is for the nitrogen and phosphorus parameters. There are no apparent seasonal trends for TOC in any of these watercourses.

The potential ranges for nutrient contributions from each stream influent to the Trinity-San Jacinto estuary are presented in Tables 6-1 through 6-4. Nutrient contributions (in kilograms per day) were calculated using the maximum and minimum concentration observed for each of the twelve months over the period of record (1970 through 1977) and the mean monthly discharges for each stream. Nutrient concentration data were not readily available for several of the tributary streams to the San Jacinto River above Lake Houston, nor were suitable data available for the reach of the San Jacinto River below Lake Houston. USGS water quality data have been recorded only for the West Fork San Jacinto River. Texas Department of Water Resources statewide water quality monitoring network data were available for the East Fork San Jacinto River. Carbon, nitrogen and phosphorus (CNP) concentrations in the East Fork were within the concentration range of reported observations from the West Fork in the U. S. Geological Survey records. The range of CNP values reported in the USGS data for the West Fork San Jacinto River were assumed to be representative of the concentrations expected in the East Fork San Jacinto River, Spring Creek, Cypress Creek, Caney Creek, and Peach Creek where discharge measurements but not water quality data were available. The mean monthly discharges of these six tributaries to Lake Houston were summed for each of the twelve months to arrive at a total monthly inflow. The CNP ranges reported by the USGS for the West Fork San Jacinto River were applied to these monthly totals to determine potential nutrient loading into Lake Houston. These values are presented in Tables 6-1 through 6-4 under the heading: San Jacinto River/Lake Houston. At present the percentage of these values passed through Lake Houston to the estuary is unknown. The data are presented for comparison of the potential nutrient contribution of the San Jacinto River system with the other streams that contribute to the estuarine system.

The Trinity River, which contributes 78 percent of the gaged freshwater inflow to the estuary, is also responsible for contribution of the bulk of the nutrient loading, thus demonstrating the importance of freshwater discharge in the transport of nutrients to the estuarine system. The watercourses that drain the City of Houston empty into the Houston Ship Channel, and subsequently contribute inflow to Upper Galveston Bay. This inflow constitutes only 6.9 percent of the gaged flow to the estuary, yet CNP concen-

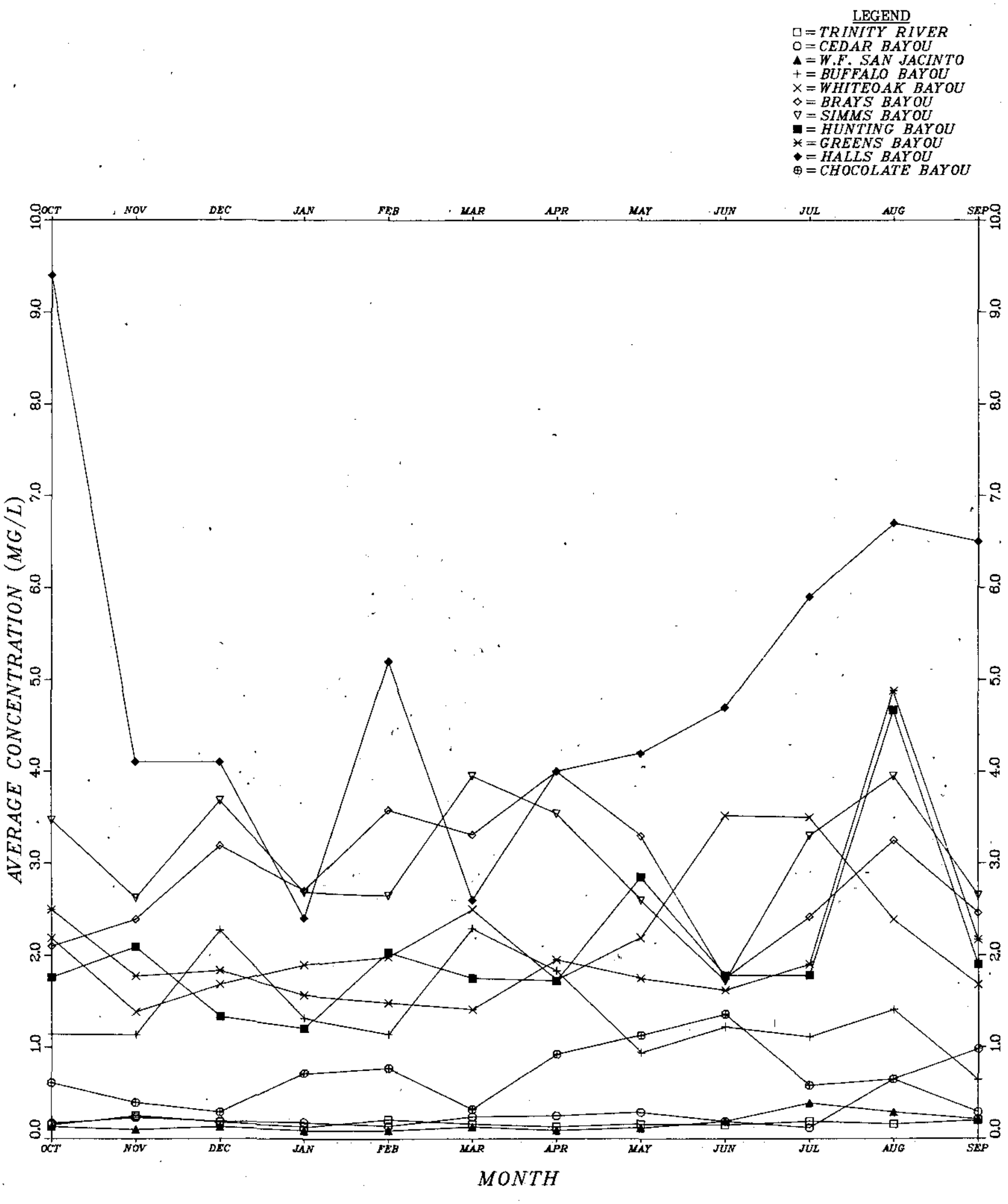


Figure 6-3. Mean Monthly Total Phosphorus Concentrations in Streams Contributing to the Trinity-San Jacinto Estuary, 1970-1977

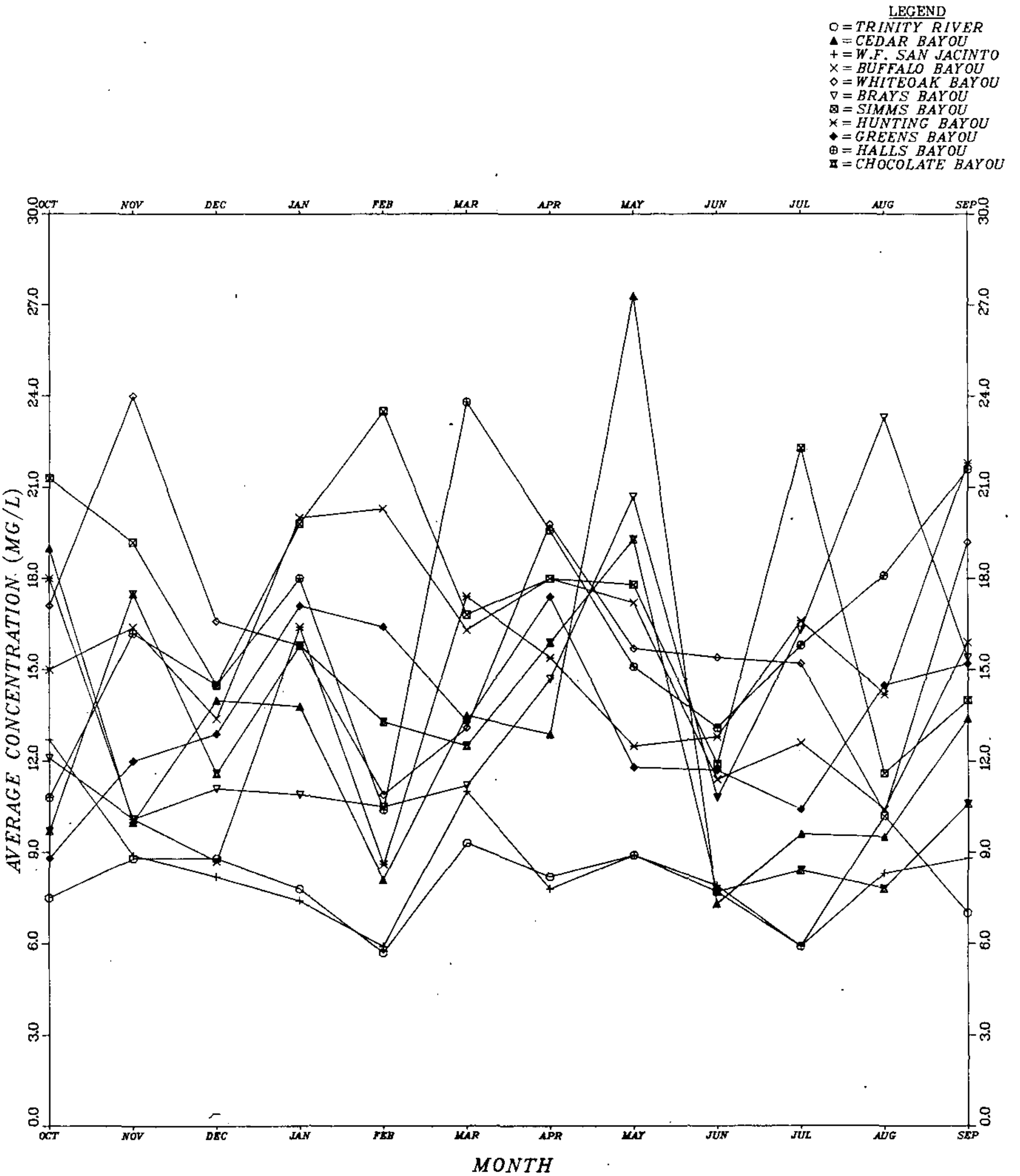


Figure 6-4. Mean Monthly Total Organic Carbon Concentrations in Streams Contributing to the Trinity-San Jacinto Estuary, 1970-1977

Table 6-1. Range of Expected Inorganic Nitrogen Loading to Trinity-San Jacinto Estuary Based on Mean Monthly Gaged Discharges

		Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
		kilograms per day											
Trinity River	high	11,454	21,939	1,687	16,113	27,210	10,819	1,501	972	1,389	2,510	5,418	17,230
	low	2,813	3,011	337	537	4,535	1,056	0	40	58	179	1,761	562
Cedar Bayou	high	87	72	80	443	385	323	20	22	207	57	81	355
	low	37	7	12	30	74	65	6	5	28	40	23	23
San Jacinto River/Lake Houston	high	1,277	1,970	650	2,454	1,061	2,180	1,079	502	419	557	1,238	762
	low	681	229	217	94	367	67	131	0	183	144	232	166
Buffalo Bayou	high	2,058	2,362	3,425	5,336	2,766	2,741	1,580	1,789	1,004	2,697	5,573	5,479
	low	799	528	565	192	1,241	365	479	309	330	470	605	448
White Oak Bayou	high	1,243	1,159	607	975	1,902	2,322	886	420	1,061	804	1,789	877
	low	200	500	341	325	293	179	148	291	128	106	153	68
Brays Bayou	high	2,382	2,943	1,315	1,856	3,385	2,203	1,914	957	2,164	1,558	3,438	2,313
	low	568	1,242	370	715	450	186	294	451	483	133	381	138
Simms Bayou	high	1,531	2,987	1,029	1,136	3,244	4,447	1,079	988	1,727	1,578	2,073	2,048
	low	222	519	289	320	312	72	105	209	85	74	147	184
Hunting Bayou	high	307	613	297	264	504	522	327	497	711	291	431	297
	low	18	110	52	81	81	74	76	62	103	85	81	82
Greens Bayou	high	687	504	228	389	590	578	326	191	617	403	353	662
	low	181	106	33	84	120	23	39	65	97	147	187	73
Halls Bayou	high	254	796	263	679	677	680	1,070	433	794	572	447	701
	low	102	247	14	147	105	20	277	4	114	241	180	190
Chocolate Bayou	high	75	62	77	495	637	383	55	79	100	79	15	78
	low	17	5	1	27	92	90	14	5	20	7	8	13

Table 6-2. Range of Expected Organic Nitrogen Loading to Trinity-San Jacinto Estuary Based on Mean Monthly Gaged Discharges

		Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
		kilograms per day											
Trinity River	high	13,263	15,701	2,474	21,484	41,226	26,389	10,504	3,604	4,687	7,710	13,546	16,106
	low	5,426	2,366	450	5,908	24,323	5,278	6,860	2,592	4,456	717	8,367	0
Cedar Bayou	high	240	159	64	396	412	945	112	171	349	127	253	283
	low	58	29	26	84	70	176	29	14	87	70	44	82
San Jacinto River/Lake Houston	high	3,234	3,528	1,570	4,058	6,531	3,052	992	800	1,256	1,078	2,747	3,116
	low	1,745	870	541	849	2,041	671	316	58	850	233	2,399	0
Buffalo Bayou	high	2,216	1,736	4,110	1,103	2,151	1,827	764	762	1,465	878	1,242	1,389
	low	119	8	34	197	323	208	127	99	161	201	240	108
White Oak Bayou	high	499	884	549	834	654	949	1,165	336	335	435	831	305
	low	48	189	38	58	70	58	36	44	56	38	44	20
Brays Bayou	high	1,076	582	547	912	866	1,291	684	554	385	354	880	845
	low	30	162	72	82	123	118	89	306	89	73	91	51
Simms Bayou	high	1,229	623	701	609	504	533	831	659	296	279	844	447
	low	34	60	38	61	98	220	47	0	47	49	38	32
Hunting Bayou	high	113	150	62	126	228	121	69	191	65	119	55	147
	low	9	5	7	17	23	24	8	14	16	17	6	9
Greens Bayou	high	306	313	192	593	348	173	147	153	796	129	140	185
	low	22	38	18	52	77	42	32	15	25	118	20	70
Halls Bayou	high	384	141	57	205	266	331	229	110	212	268	227	115
	low	11	17	8	27	18	18	0	10	21	103	15	30
Chocolate Bayou	high	302	322	102	337	1,051	1,040	269	306	533	182	135	129
	low	43	53	8	91	115	175	81	79	137	70	38	23

Table 6-3. Range of Expected Total Phosphorus Loading to Trinity-San Jacinto Estuary Based on Mean Monthly Gaged Discharges

		Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
		kilograms per day											
Trinity River	high	3,215	12,905	495	6,445	8,245	4,486	3,430	972	1,331	1,793	5,689	4,120
	low	1,407	860	225	2,417	4,535	2,639	1,286	324	810	717	1,626	936
Cedar Bayou	high	60	25	34	171	158	68	23	182	111	40	71	72
	low	34	17	16	15	12	55	6	6	39	13	37	33
San Jacinto River/Lake Houston	high	553	550	839	849	857	2,046	600	451	432	629	658	829
	low	298	137	81	0	286	101	153	44	65	107	232	99
Buffalo Bayou	high	1,583	1,962	2,512	2,148	1,564	2,076	1,019	1,211	571	1,631	3,064	4,013
	low	483	400	320	366	518	349	331	202	410	445	497	478
White Oak Bayou	high	760	791	679	399	857	2,048	821	456	838	644	701	785
	low	183	205	246	272	50	129	25	144	106	118	135	68
Brays Bayou	high	1,285	1,488	887	1,417	2,466	1,519	1,139	1,166	1,393	843	1,499	2,395
	low	173	679	321	528	333	106	180	268	199	218	212	169
Simms Bayou	high	819	1,480	739	905	1,225	941	1,052	628	1,044	726	764	1,285
	low	149	312	280	244	130	110	47	48	83	80	76	242
Hunting Bayou	high	124	132	100	116	441	283	82	134	176	135	125	103
	low	27	57	25	37	125	40	29	51	44	51	31	42
Greens Bayou	high	573	522	225	390	600	535	383	280	343	412	280	516
	low	57	137	27	139	70	26	44	64	85	176	66	93
Halls Bayou	high	261	882	159	542	840	735	500	588	794	617	392	548
	low	58	176	19	35	69	28	235	59	79	350	147	76
Chocolate Bayou	high	41	32	20	44	76	71	35	38	70	65	34	43
	low	17	7	4	17	19	33	9	10	30	12	8	18

Table 6-4. Range of Expected Total Organic Carbon Loading to the Trinity-San Jacinto Estuary Based on Mean Monthly Gaged Discharges

		Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
		kilograms per day											
Trinity River	high	221,044	172,068	22,491	375,962	453,488	263,890	87,894	64,798	63,656	80,681	176,099	224,734
	low	118,500	86,034	17,093	53,709	272,093	163,611	50,378	31,994	28,935	46,616	59,603	86,148
Cedar Bayou	high	6,029	1,301	2,842	5,444	8,232	3,259	1,024	1,529	4,361	3,026	2,994	4,373
	low	1,232	1,055	510	1,089	1,873	1,857	829	282	1,396	3,026	230	2,315
San Jacinto River/Lake Houston	high	36,599	41,234	32,487	61,343	53,062	36,895	10,030	13,098	15,700	32,325	46,423	36,463
	low	26,811	10,079	27,073	15,100	22,858	17,776	4,143	2,620	6,803	16,522	20,116	13,259
Buffalo Bayou	high	26,906	26,411	13,700	15,097	25,416	14,950	7,644	6,277	153,836	13,171	18,218	13,120
	low	9,496	9,810	6,279	4,065	8,602	5,897	3,720	3,676	9,303	5,519	7,287	5,865
White Oak Bayou	high	7,367	5,121	2,313	5,439	4,057	5,821	3,119	1,321	6,517	4,175	10,907	7,414
	low	2,852	466	1,214	1,632	2,705	2,587	1,642	1,080	1,676	1,461	3,116	1,701
Brays Bayou	high	5,380	6,468	2,641	5,522	11,329	5,317	6,608	1,643	6,225	5,983	5,865	4,508
	low	1,734	1,455	1,339	1,921	4,665	2,620	2,506	726	3,172	1,686	1,043	2,141
Simms Bayou	high	5,772	9,609	2,930	3,827	5,762	4,390	4,025	1,955	3,479	4,469	6,052	3,724
	low	1,303	3,376	1,249	2,105	2,641	2,383	1,428	484	1,600	1,815	1,242	2,048
Hunting Bayou	high	1,563	573	1,874	1,117	1,176	1,617	995	860	1,529	970	666	402
	low	205	265	187	349	698	590	216	207	1,000	970	274	402
Greens Bayou	high	3,695	4,140	1,666	3,758	3,097	2,602	2,029	1,975	2,470	1,764	3,312	2,249
	low	981	1,409	625	289	1,819	882	518	440	1,386	306	612	741
Halls Bayou	high	2,195	1,411	1,985	1,852	2,230	1,176	1,529	1,176	2,381	1,029	2,266	1,274
	low	604	176	441	662	695	492	412	278	390	82	355	701
Chocolate Bayou	high	6,039	5,527	2,830	5,478	7,963	4,398	2,602	2,166	4,665	2,793	3,161	4,290
	low	1,466	691	512	1,117	3,822	2,837	2,255	790	2,266	1,653	969	1,565

trations are high enough that total nutrient loadings from this source outweigh those from the Trinity River inflows. From this discovery it could be expected that Upper Galveston Bay and Trinity Bay would experience higher nutrient concentrations than other portions of the estuary, a result that is generally borne out by the water quality data.

Marsh Vegetative Production

An estuarine marsh is a complex living system which provides: (1) detrital materials (small decaying particles of plant tissue) that are a vital basic food source for the estuary, (2) "nursery" habitats for the young of economically important estuarine-dependent fisheries species, (3) maintenance of water quality by filtering upland runoff and tidal waters, and (4) shoreline stabilization and other buffer functions.

Perhaps the most striking characteristics of a marsh is the large amount of photosynthesis (primary production) within the system by the total plant community (i.e., macrophytes, periphytes, and benthic algae); thus, estuarine marshes are recognized as among the world's most productive areas (187, 188). Marshes of the Atlantic and Gulf coasts are no exception since the inhabiting rooted vascular plants have adapted advantageously to the estuarine environment and are known to exhibit high biomass production (343, 537, 39, 211, 345, 338, 428, 10). As a result, the marshes are large-scale contributors to estuarine productivity, providing a major source of particulate (i.e., detrital) substrate and nutrients to the microbial transformation processes at the base of the food-web which enrich the protein levels and food value for consuming organisms (43, 44, 240, 190, 546, 164, 163, 40, 201, 46, 140, 234, 106, 105, 112). Recent research has demonstrated a correlation between the area of intertidal salt marsh vegetation and the commercial harvests of penaeid shrimp (424). For Texas estuaries, the statistical relationship indicates at least 30 pounds of shrimp harvested (heads-off weight) per acre of intertidal marsh (33.6 kg/ha).

Marsh areas may be of greater ecological value if sectioned into small tracts by the drainage channels of transecting bayous and creeks (78). The rationale for this suggestion is found in "edge-effect" benefits; that is, a higher edge length to marsh area ratio provides more interface and a greater opportunity for exchange of nutrients and organisms across the boundary between open aquatic and marsh habitats. Deltaic marshes at the headwaters of an estuary generally exhibit a dendritic pattern of drainage channels and are especially important because they form a vital link between an inflowing river and its resulting estuary. Here, the direct effects of freshwater inflow/salinity fluctuations are primarily physiological, affecting both seed germination and plant growth, and are ultimately reflected in the competitive balance among plant species and the presence of vegetative "zones" in the marsh (332, 203, 198, 185, 103, 228).

The Trinity-San Jacinto estuary receives its major input from the Trinity River and the marshes of the Trinity delta. Adams (60) has delineated nine vegetation zones which represent the major distinguishable vegetative communities in the delta. The above ground net primary production of the rooted vascular plants (macrophytes) is estimated at 96.6 million dry weight pounds per year (43,824 metric tons/year) over the 13,379 acre (5,414 ha) study area.

Annual net production (ANP) varies from a low of 1,918 dry weight pounds per acre (215 g/m^2) in sampled stands of arrowhead (Sagittaria graminea) to a high of 26,623 dry weight pounds per acre (2,984 g/m^2) in sampled stands of the common reed Phragmites communis. The average ANP over the entire study area is estimated to be 7,222 dry weight pounds per acre (819.5 g/m^2) with approximately 51 percent of the total ANP occurring in the lower delta marshes south of Old River Lake and west of the Trinity River, 20 percent in the middle delta marshes south of IH-10 between Old River Lake and the Trinity River, and 29 percent in the upper delta marshes north of IH-10. The predominant macrophytes in the Trinity delta include Spartina patens, Aster subulatus, Echinochloa muricata, Alternanthera philoxeroides, Paspalum lividum, Phragmites communis, Persicaria punctata, and Sagittaria graminea (Table 6-5).

While the nine vegetation zones delineated by Adams (60) comprise a total of 13,379 acres (5,414 ha), they represent only 27 percent of the total 49,879 acres (20,185 ha) of Trinity deltaic wetlands. The remaining 73 percent (36,501 acres or 14,771 ha) includes many unvegetated areas and consists of cypress swamps (16,873 acres or 6,828 ha), fresh to brackish lakes (8,550 acres or 3,460 ha), diked areas (6,341 acres or 2,566 ha), and small components of mud flats, dredged material, upland vegetation and surface waters such as marsh ponds, bayous, and river areas (4,737 acres or 1,917 ha).

In addition, Adams (60) measured net periphyton production ranging from a low of 1.38 dry weight pounds per acre per day (0.155 g/m^2/d) to a high of 11.54 dry weight pounds per acre per day (1.293 g/m^2/d), averaging 4.78 dry weight pounds per acre per day (0.536 g/m^2/d) overall. Assuming that about 13,600 acres (5,500 ha) of the delta were inundated, the periphyton ANP can be estimated at 23.7 million dry weight pounds (10,760 metric tons) or about 65,000 dry weight pounds per day (29.5 metric tons/d).

Although the high productivity of these deltaic marsh habitats results in significant quantities of detritus for potential transport to the estuary, actual detrital transport is dependent on the episodic nature of the marsh inundation and dewatering process. Cooper (29) suggests that the vast majority of the primary production in the higher, irregularly-flooded vegetative zones goes into peat production and is not exported. The lower, frequently-flushed vegetative zone characterized by Spartina alterniflora may contribute about 45 percent of its net production to the estuarine waters (240).

Borey et al. (214) have studied the factors affecting detritus export from estuarine marshes of Chambers County to adjacent bay areas of the Trinity-San Jacinto estuary. Measuring carbon export during 24 diurnal periods over an annual interval, they estimate carbon export at 4 to 6.5 percent of net primary production. In addition, they conclude that this level of export is within the 0 to 21 percent range reported for other marshes and indicates that export is only 45 to 70 percent of the available ANP from the marsh vegetation. Major factors affecting export were determined to be (1) degree of inundation (flooding), (2) vegetation structure, (3) aquatic consumption, and (4) hydrological regime; however, tidal range did not seem to be an important factor of export magnitude in this case.

In many coastal areas the production and nutritive contribution of emergent vascular plants to the estuarine ecosystems is supplemented or even

Table 6-5. Scientific and Common Names of Important Plant Species Occurring in the Trinity River Delta (60)

Scientific Name	Common Name
Acnida tamariscina	Water hemp
Alternanthera philoxeroides	Alligator weed
Ambrosia trifida	Giant ragweed
Ammania coccinea	Tooth-cup
Aster subulatus	Saltmarsh aster
Baccharis halimifolia	Sumpweed
Bacopa monnieri	
Celtis laevigata	Sugarberry
Cyperus articulatus	Sedge
Cyperus odoratus	Sedge
Echinochloa muricata v. muricata	Barnyard grass
Eichornia crassipes	Water hyacinth
Gaura filiformis	Gaura
Gleditsia triacanthos	Honey locust
Heterotheca pillosa	Gold aster
Hymenocallis sp.	Spider lily
Iva annua	Marsh-elder
Leptochloa fascicularis	Sprangletop
Leptochloa uninerva	Sprangletop
Paspalum lividum	Longtom
Paspalum vaginatum	Paspalum
Persicaria punctata	Water smartweed
Pluchea purpurascens	Marsh fleabane
Phragmites communis	Common reed
Rhynchospora corniculata	Horned rush
Sagittaria graminea	Arrowhead
Salix nigra	Black Willow
Sapium sebiferum	Tallow tree
Scirpus americanus v. longispicatum	Bulrush
Scirpus maritimus	Salt-marsh bulrush
Sesbania drummondii	Rattlebush
Spartina alterniflora	Smooth cordgrass
Spartina patens	Saltmeadow cordgrass
Spartina spartinae	Gulf cordgrass
Sphenoclea zeylanica	Chicken spike
Typha sp.	Cat-tail
Vigna luteola	Pea-vine

largely replaced by vast submerged seagrass beds. This is particularly true for estuarine areas on the South Texas coast (e.g., Laguna Madre). An established seagrass community is highly productive, provides valuable habitat (food and cover) to economically important estuarine-dependent fish and shellfish, and stabilizes the bottom of the estuary (181, 136, 12).

The areal extent of seagrasses (i.e., Halodule beaudettei and Ruppia maritima) in the Trinity-San Jacinto estuary has been estimated by Diener (480) at 18,100 acres (7,323 ha). Gloyna and Malina (313) found that primary production rates in Galveston Bay grass flats range from 35.6 to 303 pounds per acre per day (4 to 34 $g/m^2/d$). There is essentially no submerged vegetation in the open waters of the estuary's bays; virtually all occurs in shallow peripheral areas and coves where light to moderate stands of shoal grass (H. beaudettei) and widgeon grass (R. maritima) are found in waters of less than five feet (1.5 m) depth (289). Renfro (278) reported in 1959 that there was little submerged vegetation in the estuary, except for a dense stand of Ruppia on the relatively firm sediments of the west side of upper Galveston Bay from Seabrook north to Red Bluff where the productive beds extended from shore out to an average of about 200 yards (183 m). In addition, Pullen (279) notes that the Ruppia beds in upper Galveston and Trinity Bays are extremely important habitats for spotted seatrout (Cynoscion nebulosus), and that Hurricane Carla (September 8-14, 1961) caused extensive damage to grass beds in the estuary. It is of interest to note that seatrout harvest in 1962 was very low, and remained below average in 1963 (see Chapter VIII).

Marsh Nutrient Cycling

Deltaic and other brackish and salt marshes are known to be sites of biological productivity. Emergent macrophytes and blue-green algal mats serve to trap nutrients and sediment as flow velocities decrease. These nutrients are incorporated into the plant biomass during growth periods and are sloughed off and exported to the bay as detrital material during seasons of plant senescence and/or periods of inundation and increased flows into the open bay. The Trinity River delta is characterized by a diversity of habitats and species ranging from the predominantly intertidal brackish marshes south of the Wallisville levee to the freshwater cypress bottoms and oxbows that occur northward to Liberty, Texas.

Studies by Armstrong et al. (306, 312), Dawson and Armstrong (311), Armstrong and Brown (310), and Armstrong and Gordon (308, 309) have been conducted for the purpose of determining the role of plants and deltaic sediments in nutrient exchange processes. In most cases these patterns seem to be similar from species to species. Armstrong et al. (312) found the rates of nutrient exchange for marsh macrophytic species and associated sediments in the Trinity delta were similar in magnitude but somewhat lower than exchange rates reported for other Texas coastal marsh systems (Table 6-6). Portions of the marsh habitat were sufficiently diverse to allow comparison of CNP exchange rates among the vegetation and sediment cores from the intertidal zone and the nearby freshwater-dominated zone containing very different types of vegetation (Table 6-7). Both fresh and brackish areas of the marsh exported particulate organic material; however, the rates from the predominantly freshwater/cypress dominated area around Mac Lake were substantially lower than those from laboratory reactor samples collected from the intertidal zone below the Wallisville levee. The results from the study also indicate an active

Table 6-6. Summary of Nutrient Exchange Rates (312)

	DOC a/	POC b/	VSS c/	Nitrogen Total	Nitrogen Organic	P d/	Tide Range	Inundation Regularity
			(kg/ha/d)					
Saltwater Marsh								
Pomeroy et al (204)						-0.1	large	high
Reimold (210)						-6.3	large	high
Settlemyer and Gardner (225)			-18.4			-0.18	medium	high
Hall et al (107)	-0.23	+1.6					medium	high
Odum and de la Cruz (189)			-2 to 28				large	high
Brackish Marsh								
Stevenson et al (235)				-0.029		-0.025	medium	medium
Armstrong and Hinson (6)								
Lavaca Bay								
Flood Drainage	-12.6			-1.3	-1.2	-0.1	small	low
Small Net Exchange	- 0.94		- 1.5	-0.21	-0.21	<-0.01	small	low
Normal w/Drying	-27.3		-83.6	-1.2	-1.1	-0.16	small	low
Dawson and Armstrong (311)								
Normal Tidal Exchange	- 2.3			-0.39		-0.08	small	low
Following Drying	- 5.9			-2.1		-0.19	small	low
Armstrong and Brown (310)								
Sediment Only				-0.74		-0.1	none	none
Armstrong and Gordon (309)								
Nueces Bay (Reactors)	- 1.62		- 3.08	-0.08		-0.03	small	high
San Antonio Bay (Reactors)	- 2.42		- 3.54	-0.02		-0.08	small	high
Copano Bay (Linear Marsh)	- 3.75		- 0.86	-0.06		0.00		
Armstrong and Gordon (308)								
Colorado River Delta (Reactors)	- 0.46		- 0.18	0.0	0.0	0.00	none	none
Armstrong et al (312)								
Trinity River Delta (Reactors)	0.0		- 0.86	0.01	0.0	0.02	none	none
Trinity River Delta (Linear Marsh)	- 1.36		0.40	-0.05		-0.02		

a/ DOC - Dissolved Organic Carbon
b/ POC - Particulate Organic Carbon
c/ VSS - Volatile Suspended Solids
d/ P - Phosphorus

Table 6-7. Summary of Nutrient Exchange Rates for Plant Types from the Lower Trinity River Delta Marshes Corrected for Wall Effects (312)

Nutrient	Mac Lake: *Lythrum lanceolatum*	Mac Lake: *Rhynchospora macrostachya*	Lower Delta: *Rhynchospora macrostachya*	Lower Delta: *Spartina patens*	Lower Delta: *Scirpus americanus*	Lower Delta: *Sagittaria lancifolia*
			(kg/ha/d)			
Salinity	1.0	2.	19	-68.	15.	38.
Total Suspended Solids a/	-0.136	-0.096	-3.854	-7.587	-4.843	-2.274
Volatile Suspended Solids	-0.013	-0.003	-0.641	-1.465	-0.587	-0.754
Biochemical Oxygen Demand (5 day) a/	0.000	0.000	-0.008	-0.096	-0.017	-0.019
Total Organic Carbon	-0.004	-0.002	0.283	-0.449	0.260	-0.100
Total Kjeldahl Nitrogen a/	0.000	0.000	0.007	0.024	0.006	0.012
Total Kjeldahl Nitrogen	0.000	0.000	0.001	0.002	0.005	0.008
Particulate Total Kjeldahl Nitrogen	0.000	0.000	0.007	0.007	0.002	0.004
Organic Nitrogen	0.000	0.000	0.000	0.001	0.005	0.008
Ammonia-Nitrogen	0.000	0.000	0.016	0.026	0.017	0.018
Nitrite-Nitrogen	0.000	0.000	0.000	0.001	0.000	0.000
Nitrate-Nitrogen	0.000	0.000	0.075	0.126	0.078	0.080
Total Phosphorus a/	0.000	0.000	0.018	0.036	0.025	0.020
Total Phosphorus	0.000	0.000	0.018	0.024	0.026	0.018
Particulate Total Phosphorus	0.000	0.000	0.033	0.061	0.033	0.048
Ortho Phosphorus	0.000	0.000	0.014	0.039	0.026	0.022

a/ Results for unfiltered samples.

uptake of nitrogen and phosphorus species in the intertidal marsh zone while there appears to be no net uptake or release of these nutrients from the samples collected in the Mac Lake area. There is also evidence that attached algae, found in laboratory samples collected from the lower delta, dominate the exchange process.

The results from the linear marsh model containing a cross-section of the lower delta vegetation and sediment are believed to be more representative of actual CNP exchange rates than those calculated from the laboratory core reactor studies (Table 6-8). These results also compare favorably with those reported in the literature for other Texas coastal marshes.

Hauck and Ward (62) determined that the ten square mile (2,590 ha) marsh lying to the south of the Wallisville levee is primarily intertidal and largely uninfluenced by Trinity River water elevations. Applying CNP exchange rates given in Table 6-8, this portion of the marsh might potentially export as much as 11,000 kg/d of total organic carbon (TOC) under the proper combination of seasonal conditions and tidal elevation (inundation). Likewise, proper conditions could result in the release of 250 kg/d total phosphorus, 114 kg/d inorganic nitrogen, and 205 kg/d organic nitrogen. Results from the linear marsh model suggest that under certain conditions the lower delta may act as a TOC and nitrogen sink.

The deltaic marshes are important sources of nutrients for the estuary. Periodic inundation events are necessary in order for the Trinity delta marshes to deliver their potential nutrient stores to the open waters of the bay. This will occur as the water moving across the delta sweeps decayed macrophytic and dried algal mat material out of the system. Following a period of emersion, a sudden inundation event over the delta marshes will result in a short period of high nutrient release from the established vegetation and sediments (311). This period may last for one or two days and is followed by a rapid decrease in release rates toward the seasonal equilibrium. During periods of high river discharge and/or extremely high tides that immediately follow prolonged dry periods, the contribution of carbon, phosphorus, and nitrogen from the deltaic marshes to the estuarine system can be expected to increase dramatically.

Wetlands Processes

The concept of the coastal zone as an area of general environmental concern has come about only during the past decade or so. Landmark legislation along these lines includes the Coastal Zone Management Act of 1972 which emphasizes that "...it is the national policy to preserve, protect, develop, and where possible, to restore or enhance, the resources of the Nation's coastal zone for this and succeeding generations..." More recently, Executive Order 11990 of May 24, 1977, ordered federal agencies with responsibilities in, or pertaining to, the coastal zone to "...take action to minimize the destruction, loss or degradation of wetlands, and to preserve and enhance the natural and beneficial values of wetlands..."

In pursuit of this goal, the Texas Department of Water Resources has funded aerial photographic studies with the Texas A&M Remote Sensing Center to provide baseline characterization of key coastal wetlands in Texas in order to comparatively evaluate the various components of the marsh systems. The fol-

Table 6-8. Exchange Rates of Carbon, Nitrogen, and Phosphorus in the Linear Marsh from the Trinity River Delta (312)

Nutrient	Stage: Normal	Stage: Flood	Stage: Low	Stage: Low
	(kg/ha/d)			
Total Suspended Solids	-65.49	-52.19	15.228	-37.79
Volatile Suspended Solids	- 3.941	- 9.11	3.384	11.28
Biochemical Oxygen Demand (5 Day)	0.742	- 1.18	1.523	0.82
Total Organic Carbon	- 0.464	2.07	-2.82	- 4.23
Total Kjeldahl Nitrogen a/	- 0.046	- 0.041	-0.028	- 0.085
Total Kjeldahl Nitrogen	- 0.046	0.083	-0.028	- 0.028
Ammonia-Nitrogen	- 0.0023	- 0.059	-0.0085 b/	- 0.006
Nitrite-Nitrogen	b/	b/	b/	- 0.014 b/
Nitrate-Nitrogen	b/	0.094	0.0113	- 0.024 b/
Total Phosphorus a/	- 0.0417	0.0041	0.071	- 0.096
Total Phosphorus	-0.035	-0.046		- 0.003
Ortho Phosphorus	- 0.0058 b/	-0.021	0.032	b/

a/ Results from unfiltered samples.
b/ Some or all data below detectable limits.

lowing description of the Trinity River delta is a by-product of seasonal aerial photographic studies conducted during the 1978-1979 growing season (258).

The Trinity River delta is a relatively stable system whose outlet lies along the eastern side of an extensive deltaic wetland which fronts some 10 miles (16 km) along upper Trinity Bay. Signs of man's activities are readily apparent throughout the delta, extending from Trinity Bay northward to Devers Canal. Left to its own devices, the lower river would quite probably have slowly extended its delta bayward in the long term. However, the river outlet has been channelized and aligned, with spoil banks lining the extreme tip. Construction of Livingston Dam upstream, coupled with dredging and diking downstream, have combined to reduce flooding of the Trinity delta except under extreme flood conditions.

The natural deltaic wetland has been significantly modified by three recent construction projects. The construction of Lake Anahuac, an irrigation storage reservoir just north of the town of Anahuac, provided water for rice farming and in turn encouraged conversion of large areas of wetlands southeast of the Trinity River delta to rice culture. Construction of the 2 miles x 3 miles (3 km x 5 km) cooling pond along the northwestern edge of Trinity Bay has resulted in a direct loss of productive wetland area. (The associated thermal power plant receives influent water from the San Jacinto estuary some seven miles [11 km] to the southwest and discharges into Trinity Bay). Completion of Wallisville Dam and impoundment of Wallisville Reservoir will also result in the loss of a sizeable area of viable wetlands. The direct, irreplaceable loss of wetlands will most certainly impact the food chain productivity of the Trinity-Jan Jacinto estuary.

The long-range condition of the wetlands environment will be considerably affected by the kinds of decisions which are made over the next few years. The proper environment would, in the case of the deltaic marshes, be one in which there is a healthy seasonal cycle of emergence-to-maturation-to-senescence-to-detrital utilization. Acre for acre, the wetlands are among the most productive areas on earth. Therefore, the direct and indirect impacts of water, power, and navigational development; oil and gas production; and expansion of agricultural and cattle-raising activities in the coastal zone should be of consuming interest.

Summary

The deltaic marshes are important sources of nutrients for the estuarine system. Periodic inundation events are natural and necessary in order for the marshes of the Trinity-San Jacinto estuary to deliver their potential nutrient stores to the open waters of the bays. This will occur as the slug of freshwater moving across the delta sweeps decayed macrophytic and dried algal mat material out of the system. A sudden inundation event over the delta marshes, following a period of emersion, results in a short period of high nutrient release from the established vegetation and sediments. This period may last one or two days and is followed by a period in which release rates decrease rapidly until they approach the seasonal equilibrium. During periods of high river discharge and/or extremely high tides that immediately follow prolonged dry periods, the contribution of carbon, phosphorus, and nitrogen from the deltaic marshes to the estuarine system can be expected to increase dramatically.

Aerial photographic studies of the Trinity River delta have provided an insight into on-going wetland processes. Construction of Livingston Dam upstream, coupled with dredging and diking downstream, have combined to reduce flooding of the Trinity delta except under extreme flood conditions. The natural Trinity River deltaic wetland has been significantly modified by three recent construction projects: (1) Lake Anahuac, (2) a large thermal power plant cooling pond, and (3) Wallisville Dam and Reservoir (uncompleted). The direct loss of wetlands due to these construction activities will most certainly impact the food-chain productivity of the Trinity-San Jacinto estuary. The long-range condition of the wetlands environment will be considerably affected by the kinds of decisions which are made over the next few years with regard to water, power, and navigational development; oil and gas production; and expansion of agricultural and cattle-raising activities in the coastal zone.

CHAPTER VII

PRIMARY AND SECONDARY BAY PRODUCTION

Introduction

A large number of environmental factors interact to govern the overall biological productivity in a river fed, embayment-type system such as the Trinity-San Jacinto estuary. In order to describe the "health" of an estuarine ecosystem, the food-web and its trophic levels (e.g., primary and secondary bay production) must be monitored for a long enough period to establish seasonality, distribution of production, and community composition. Ecological variables which were studied and are discussed herein include the abundance (counts per unit volume or area), distribution, and species composition of the phytoplankton, zooplankton, and the benthic invertebrates.

All biological communities are energy-nutrient transfer systems and can vary only within certain limits regardless of the species present. In a much simplified sense, the basic food supply (primary production) is determined by a number of photosynthetic species directly transforming the sun's energy into biomass that is useful to other members of the biological community not capable of photosynthesis. Thus, the concept of primary and secondary productivity emerges. Fundamentally, primary productivity represents the autotrophic fixation of carbon dioxide by photosynthesis in plants; secondary productivity represents the production of herbivorous animals which feed on the primary production component. The integrity of biological systems then stems mainly from the nutritional interdependencies of the species composing them. These interdependencies form a functional trophic structure within the estuary (Figure 7-1).

The phytoplankton (free-floating plant cells) form a portion of the base of this trophic structure as primary producers. Estuaries benefit from a diversity of phytoplankton by experiencing virtually year-round photosynthesis and production. Shifts in community composition and replacement of many species throughout the seasonal regime provide an efficient adaptation to seasonal changes in biotic and abiotic factors. Secondary production evolves as the phytoplankton producers are consumed in turn by the zooplankton (tiny, suspended or free-floating animals) and filter-feeding fishes; planktonic detritus is also utilized by many benthic invertebrates.

Characteristically, each estuary has identifiable phytoplankton, zooplankton, and benthic communities. Since these organisms respond to their total environment in a relatively short time-span, they can be employed as "indicators" of primary and secondary production, especially in the open bay areas. Therefore, the main objectives of this analysis are to describe the community composition, distribution, density, and seasonality of the following important ecological groups: phytoplankton, zooplankton, and benthic invertebrates.

Data presented in this report for each of the lower food chain categories (i.e., phytoplankton, zooplankton, and benthos) were obtained from a study

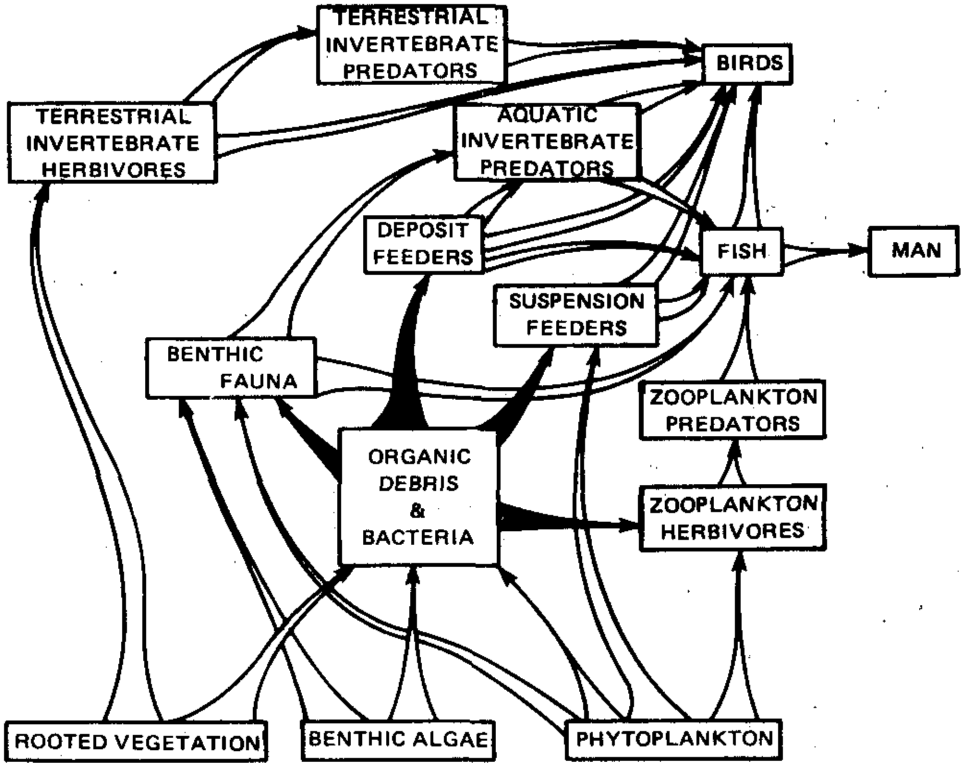


Figure 7-1. Estuarine Food-Web Relationships Between Important Ecological Groups (77)

performed by Espey, Huston and Associates, Inc. (63) under interagency contract with the Texas Department of Water Resources. The objective of the study was to determine species diversity and standing crops of the phytoplankton, zooplankton, and soft-bottom benthic assemblages of Trinity Bay.

Hydrographic, chemical, and biological samples were collected monthly from Trinity Bay from September 1975 through August 1976 at six stations ranging from the mouth of the river over the extent of the bay (Figure 7-2). In-situ profiles of salinity, conductivity, temperature, and dissolved oxygen were obtained at each sampling site. Surface water samples were analyzed for nitrite nitrogen, nitrate nitrogen, ammonia, organic nitrogen, ortho-phosphate, total phosphorous, and total organic carbon.

Phytoplankton

Data Collection

Seven divisions represented by 132 phytoplankton species were collected from the Trinity Bay system: Bacillariophyta - diatoms [54 taxa]; Chlorophyta - green algae [45 taxa]; Cyanophyta - blue-green algae [14 taxa]; Pyrrophyta - dinoflagellates [9 taxa]; Euglenophyta - [7 taxa]; Cryptophyta - [2 taxa]; and Chrysophyta - golden-brown algae [1 taxon]. It may be of interest to note that many of the species collected, especially the Chlorophyta, are considered to be freshwater forms and their presence is perhaps an indicator of the prevailing low salinity regime found in the Trinity Bay system.

Surface and bottom phytoplankton samples were collected at each station and these data were pooled in the following analysis. Phytoplankton concentrations in a single (pooled) sample ranged from 10,200 cells/l at site 5 (November 1975) to 1,276,000 cells/l at site 1 (February 1976) (Figure 7-3). Mean monthly densities ranged from 33,200 cells/l in November 1975 to 488,800 cells/l in July 1976. A smaller peak was recorded in February 1976 (354,800 cells/l). The seasonal maxima in later winter and midsummer were dominated by diatoms and blue-green algae, respectively.

Species diversity values exhibited a great deal of variability. For example, a diversity value of 2.0 was calculated for the February 1976 sample at site 1; the following month the diversity value increased to 3.8. An extremely large bloom of the diatom <u>Skeletonema costatum</u> (723,400 cells/l) occurred in February at this site while no "blooming" populations were observed in March. Similarly, a July bloom of the blue-green algae <u>Oscillatoria</u> at station 5 (311,200 cells/l) produced a diversity value of 2.6; in August the value increased to 4.2. In general, major blooms (greater than 20,000 cells/l) caused low species diversities; high diversity values were usually found in the absence of blooming populations.

Over the 12-month study period the mean percentage representation of each phytoplankton division for all stations was as follows:

Diatoms	41.6%
Green algae	24.2%
Blue-green algae	23.0%

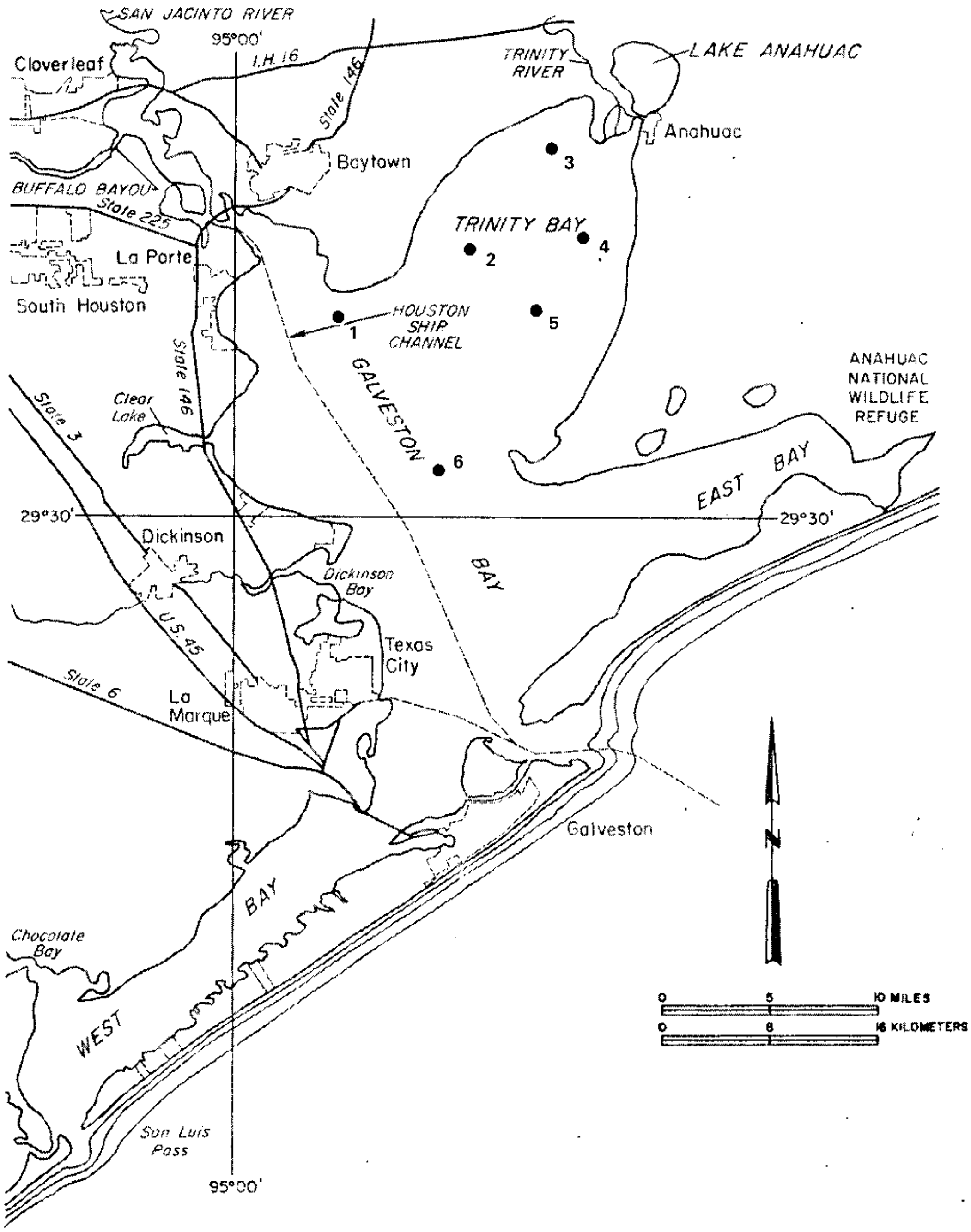


Figure 7-2. Trinity-San Jacinto Estuary Hydrologic and Biologic Sample Sites (56)

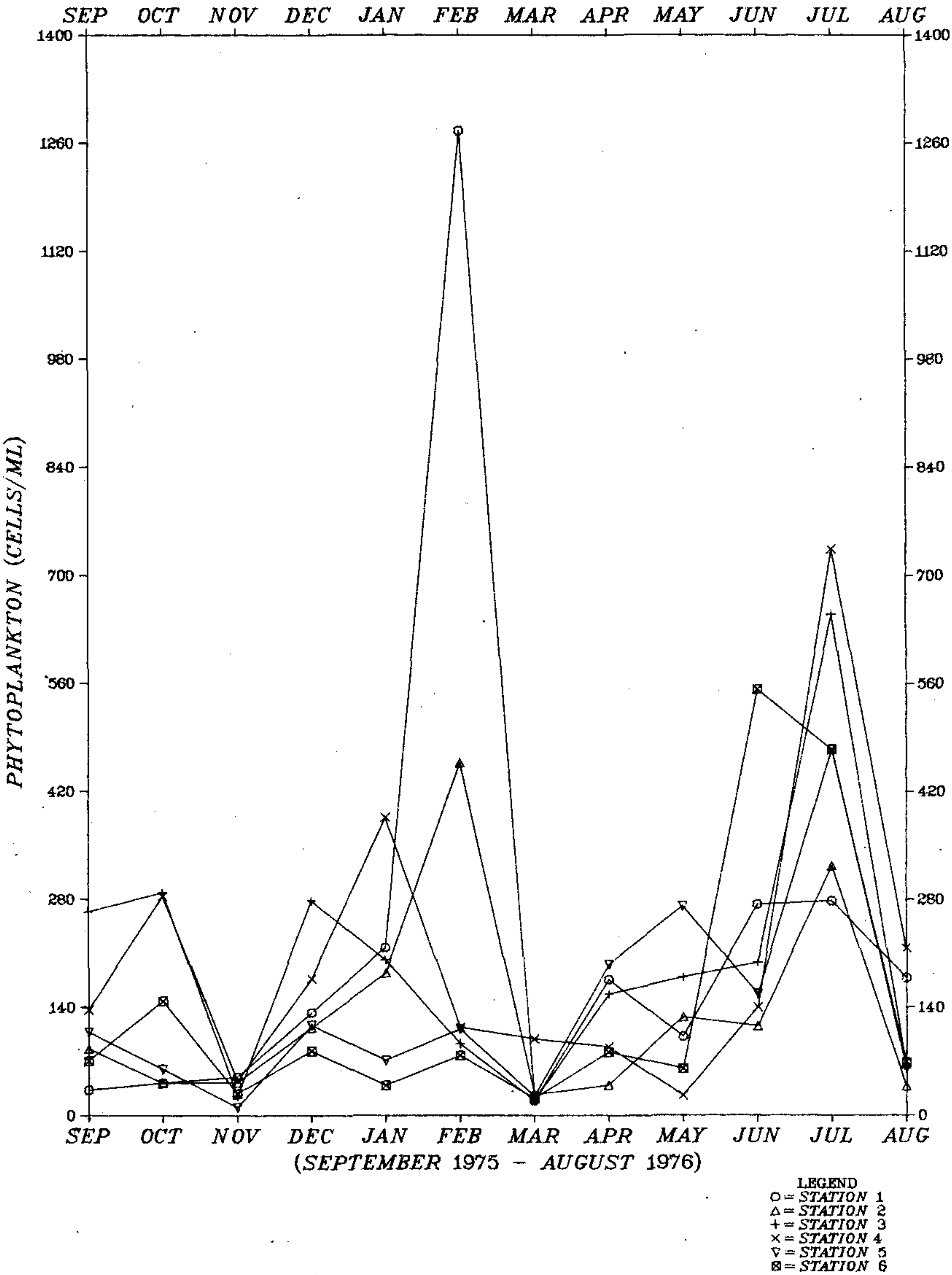


Figure 7-3. Mean Monthly Phytoplankton Densities in Trinity Bay, September 1975-August 1976

Dinoflagellates	5.9%
Euglenoids	2.6%
Others	2.7%

The seasonal succession of Trinity Bay phytoplankton groups, averaged over all stations, is shown in Figure 7-4. The diatom component was particularly large in February and April 1976 samples. As previously mentioned, a bloom of the diatom Skeletonema costatum was responsible for the February peak. The April peak was due largely to blooming populations of Thalassionema nitzschoides and Navicula abunda. The blue-green algae comprised over 70 percent of the total standing crop in July 1976 due to large numbers of Oscillatoria. Populations of Prorocentrum caused the dinoflagellate representation to rise to 32 percent in January 1976 samples. No other major compositional shifts were observed during the sampling period.

The percent abundance of the major phytoplankton groups was averaged over all sampling dates (Table 7-1). Stations 3, 4, and 5 under the direct influence of the Trinity River, had a relatively low representation of diatoms; the green and blue-green algae appeared to be the most prevalent at these stations. The opposite was true for stations 1, 2 and 6.

The average monthly densities of the five most prominent phytoplankton taxa are listed in Table 7-2. The blue-green algae Oscillatoria and the diatom Skeletonema costatum produced conspicuous blooms in July and February, respectively. The halophilous freshwater diatom Cyclotella meneghiniana was ubiquitous throughout the year but reached maximum densities in January 1976; another diatom Nitzschia closterium was most prevalent in May-June samples. Ankistrodesmus, a green algae, was also ubiquitous throughout the year.

Results of Analyses

Trinity Bay phytoplankton densities observed during the Espey, Huston and Associates study were similar to values reported for other marine areas and estuaries of Texas. Average standing crop for the 12-month study was 171,400 cells/l. Moseley et al. (19) state that phytoplankton densities of 730,000 cells/l occurred in Cox Bay, while Espey, Huston and Associates (49) reported phytoplankton densities of 133,000 cells/l from Sabine Lake. Standing crops observed by Holland et al. (325) in the Nueces and Mission-Aransas estuaries ranged from 55,000 cells/l in Copano Bay to 790,000 cells/l in Nueces Bay.

Some of the green and blue-green algae collected are representative of typical forms found in freshwater reservoirs of the southwestern United States. Diatoms and dinoflagellates found in Trinity Bay were a mixture of freshwater, brackish, and marine species that frequently occur in coastal areas of the Gulf of Mexico. Although euglenoids are generally regarded as freshwater organisms, species such as Euglena and Eutreptia are frequently tolerant of salinity.

Phytoplankton species vary markedly in their ability to withstand changes in salinity. Accurate halobion classification of most species found in Trinity Bay is impossible due to insufficient culture experimentation on salinity optima and tolerances. Chu (22) noted that although cell division can continue in freshwater for most estuarine species, most freshwater species cannot grow in salinities exceeding 2 ppt. Foerster (67) found, however, that

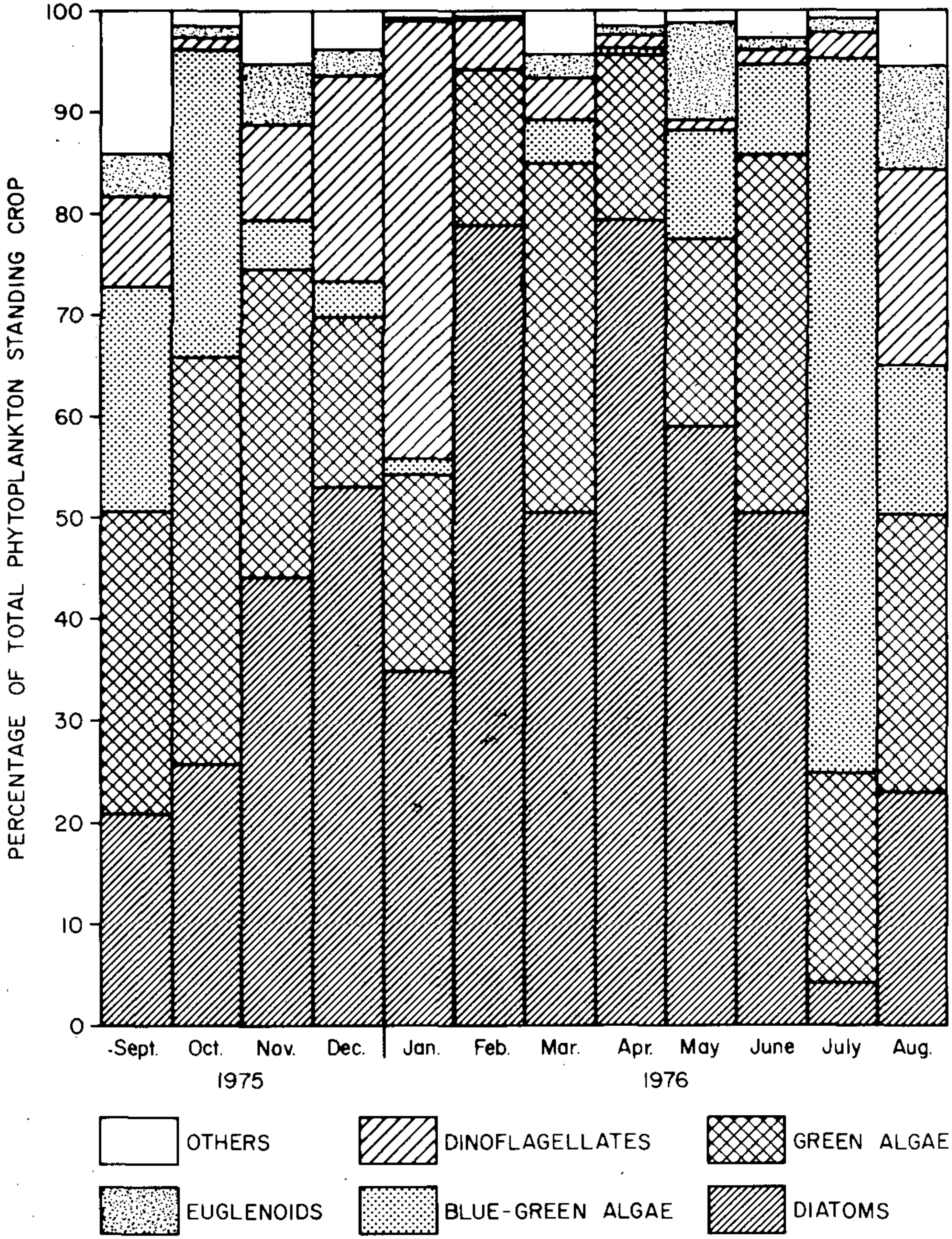


Figure 7-4. Seasonal Succession of Trinity Bay Phytoplankton Groups

Table 7-1. Abundance of Phytoplankton Groups by Station in Trinity Bay, September 1975 - August 1976

Group \ Station	1 a/	2	3	4	5	6
			(percent)			
Diatoms	61.5	53.3	25.8	21.9	43.8	49.3
Green algae	17.2	18.2	27.0	35.5	21.4	21.9
Blue-green algae	6.5	17.1	36.5	28.6	26.0	23.2
Dinoflagellates	7.0	7.2	4.1	4.3	4.7	2.2
Euglenoids	5.4	2.5	2.4	1.3	2.3	1.5
Others	2.4	1.7	4.2	3.4	1.8	1.9
Total Standing Crop	100.0	100.0	100.0	100.0	100.0	100.0

a/ Refer to Figure 7-2 for locations of Stations 1 through 6.

Table 7-2. Average Monthly Density of Major Phytoplankton Species in Trinity Bay, September 1975 - August 1976

Species	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug
					number/ml							
Blue-green Algae												
Oscillatoria	0.1	0.8	0	0	0	0	0.1	0	0	1.6	309.8	0.5
Diatoms												
Skeletonema costatum	0	0	0	35.3	6.9	207.8	3.6	2.1	0	0	0	0
Cyclotella meneghiniana	1.6	1.6	1.5	10.8	61.1	2.6	0.5	1.4	2.5	15.5	2.7	4.6
Nitzschia closterium	4.6	0	0	0.2	0.1	3.6	1.3	4.5	26.8	57.6	1.5	2.0
Green Algae												
Ankistrodesmus	25.8	54.8	1.5	1.5	0.3	1.7	0.7	0.7	0.5	8.2	7.7	1.7

many freshwater species can resume growth after exposure to seawater if placed in a freshwater medium.

Estuarine plankton were divided by Perkins (200) into three components: "(1) autochthonous populations, the permanent residents; (2) temporary autochthonous populations, introduced from an outside area by water movements, are capable of limited proliferation only and are dependent upon reinforcement from the parent populations; and (3) allochthonous populations, recently introduced from freshwater or the open sea, are unable to propagate and have a limited survival potential." The Trinity bay system supports a phytoplankton population derived from the entire range described above. The Euglenophyta (e.g., Euglena and Trachelomonas) are representative of the permanent autochthonous populations. Temporary autochthonous species include diatoms (e.g., Skeletonema costatum) and dinoflagellates (e.g., Prorocentrum). The allochthonous element is difficult to define but is probably represented by diatoms and green algae derived from both marine and fresh environments.

Freshwater inflows from river sources may act to transport freshwater phytoplankton species into the estuarine system. Although river flows function to lower salinities and to transport nutrients, detritus, and dissolved organic materials into the bay, the rate of river flow through an estuary can also have contrasting effects. More nutrients and freshwater plankton may be imported to the system with increased flow rates, thus increasing standing crops and primary production. At very high flow rates or flood conditions, however, the high turbidities, salinity changes, and flushing out of indigenous populations may depress phytoplankton abundance and productivity.

Correlation analysis of combined river inflow (gaged and ungaged) versus mean phytoplankton standing crops from the Trinity Bay study, however, revealed a lack of correlation ($\alpha > 0.05$). This was due, in part perhaps, to the atypical Trinity River inflows during this period. Normally, peak periods of inflow occur in late spring and early fall. However, in 1975 the fall maximum was absent and the spring 1976 peak was sustained well through July (Figure 7-5).

A more detailed analysis was performed in which the monthly combined river inflows were compared to average monthly phytoplankton densities at stations 3, 4, and 5 (lagged one month). The analysis revealed a very highly significant ($\alpha = 0.01$) correlation coefficient ($r^2 = 0.778$), implying that about 60.5 percent of the variations in phytoplankton standing crops at these stations were due to fluctuations in river inflows.

Winsborough and Ward (56) utilized data collected from the Espey, Huston and Associates study and discovered a clear distinction in community composition between these stations (3, 4, and 5), dominated by the outflow of the Trinity River, and the more saline stations 1, 2, and 6. The green algae were predominant at the former while diatoms dominated collections at the latter (Figures 7-6 and 7-7). Results were compared with an earlier study of Galveston Bay reported by Copeland and Fruh (32). The Galveston Bay study included phytoplankton collections in February, April, July, and October 1969 in Trinity Bay. The number of species identified by Copeland and Fruh were about half those encountered in the Espey, Huston and Associates study. The predominance of the green algae was not noted at the river-influenced stations.

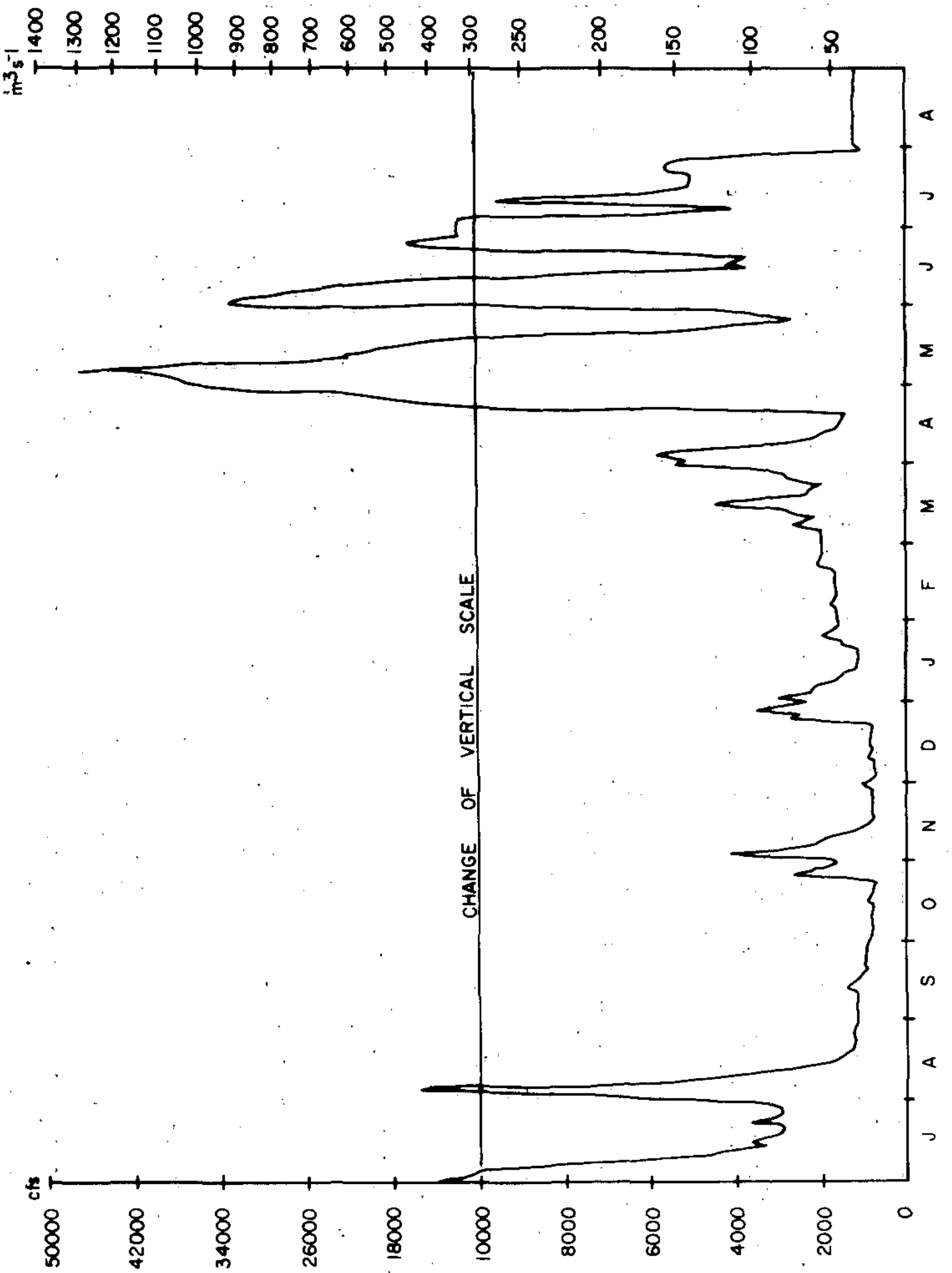


Figure 7-5. Daily Discharge of Trinity River at Romayor, July 1975-August 1976 (56)

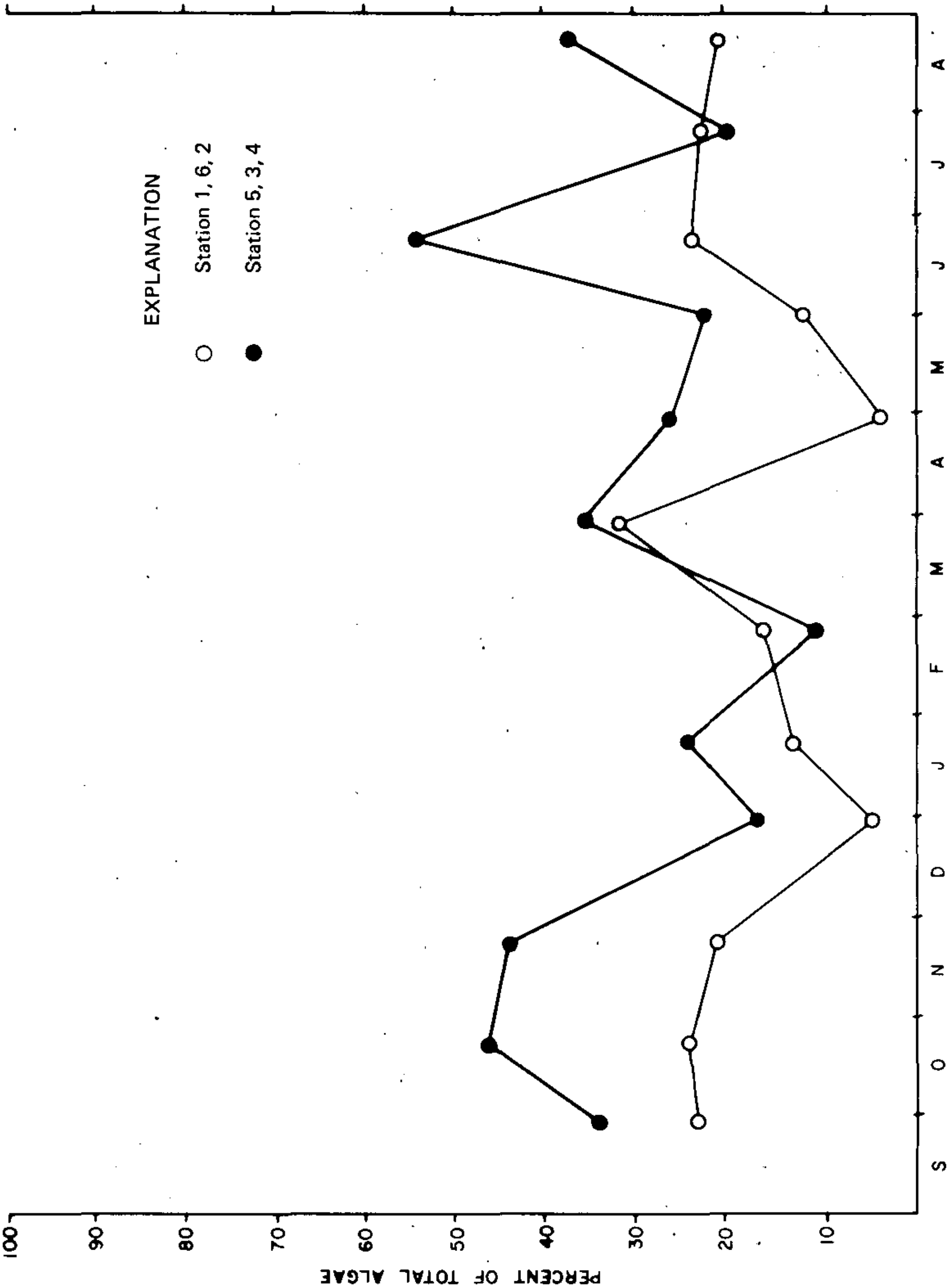


Figure 7-6. Proportion of Chlorophyta (Green Algae) to Total Algae (56)

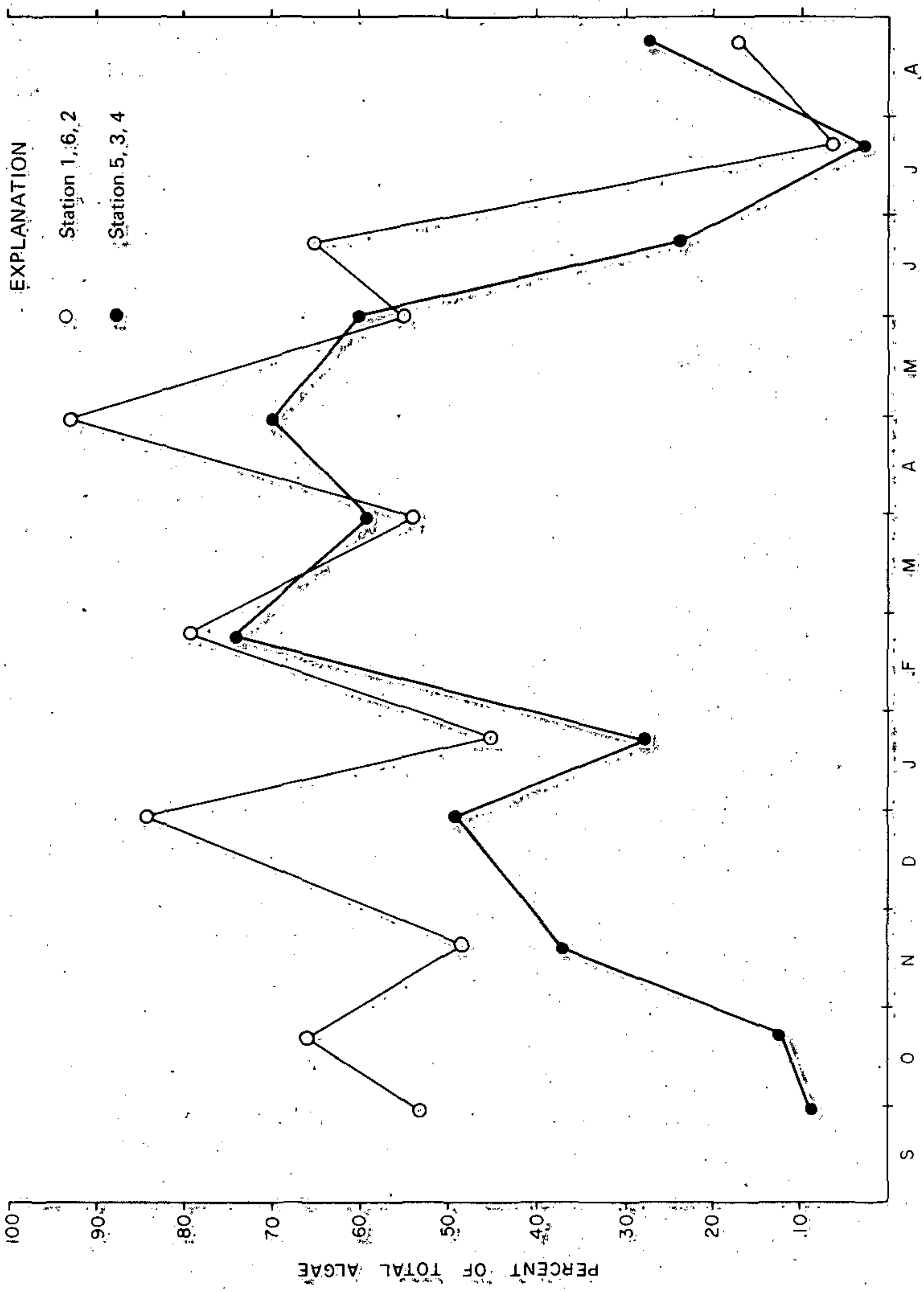


Figure 7-7. Proportion of Bacillariophyta (Diatoms) to Total Algae (56)

Zooplankton

Data Collection

A total of 70 zooplankton species representing nine phyla were identified during the 12-month study (63). The most prominent phylum was the Arthropoda which accounted for 55 percent of the organisms identified. The rotifers accounted for 21 percent, the protozoans for 15 percent, and the annelids for three percent. The remaining four phyla (Nematoda, Mollusca, Chaetognatha, and Chordata) accounted for a combined total of six percent. The freshwater zooplankton assemblages included such organisms as the cyclopoid copepods of the genus Cyclops and rotifers, including Asplancha, Brachionus, and Keratella. The brackish or estuarine species were commonly represented by the calanoid copepods Acartia spp. or the cyclopoid copepods Oithona spp. Marine species from the neritic Gulf waters were represented by the calanoid copepod Labidocera aestiva, the bioluminescent dinoflagellate Noctiluca scintillans, and the chordate larvacean Oikopleura.

Zooplankton standing crops in a single sample ranged from 155 organisms/m^3 at station 3 in July 1976 to 426,101 organisms/m^3 at station 6 in April 1976 (Figure 7-8). Station 6, off Smith Point, averaged 44,583 organisms/m^3, while Station 3, near the mouth of the Trinity River averaged 5,925 organisms/m^3. The overall mean density for all stations was 21,971 organisms/m^3 for the 12-month study.

Zooplankton populations experienced greater seasonal fluctuations than phytoplankton. Peaks in standing crops occurred in April and August 1976. Mean monthly densities showed tremendous variation--up to two orders of magnitude--over short periods of time. The mean monthly density for all stations ranged from 1,235 organisms/m^3 in December 1975 to 190,560 organisms/m^3 in April 1976.

The zooplankton community of Trinity Bay can be summarized as follows:

1. Calanoid copepods of the genus Acartia. (Acartia tonsa was the dominant species in this system).
2. Immature copepods, i.e., naupliar larvae and copepodites.
3. Other Copepods with the exception of Acartia (e.g., Cyclops and Oithona).
4. Immature barnacles, i.e., nauplii and cyprids.
5. Rotifers, primarily freshwater forms, such as Asplancha, Brachionus, and Keratella.
6. Miscellaneous crustaceans including ostracods, cladocerans, etc.
7. Protozoans, primarily Tintinnopsis and Noctiluca scintillans.
8. Others (e.g., immature gastropods, insect larvae, etc.).

The dominant organisms during the study were the barnacle nauplii, the calanoid copepod Acartia tonsa, and the copepodites. The combined standing crops of these three organisms comprised over 70 percent of the total zooplankton populations for all months except April 1976 during the study (Figure 7-9). April collections were dominated by copepod nauplii and the protozoan Noctiluca scintillans.

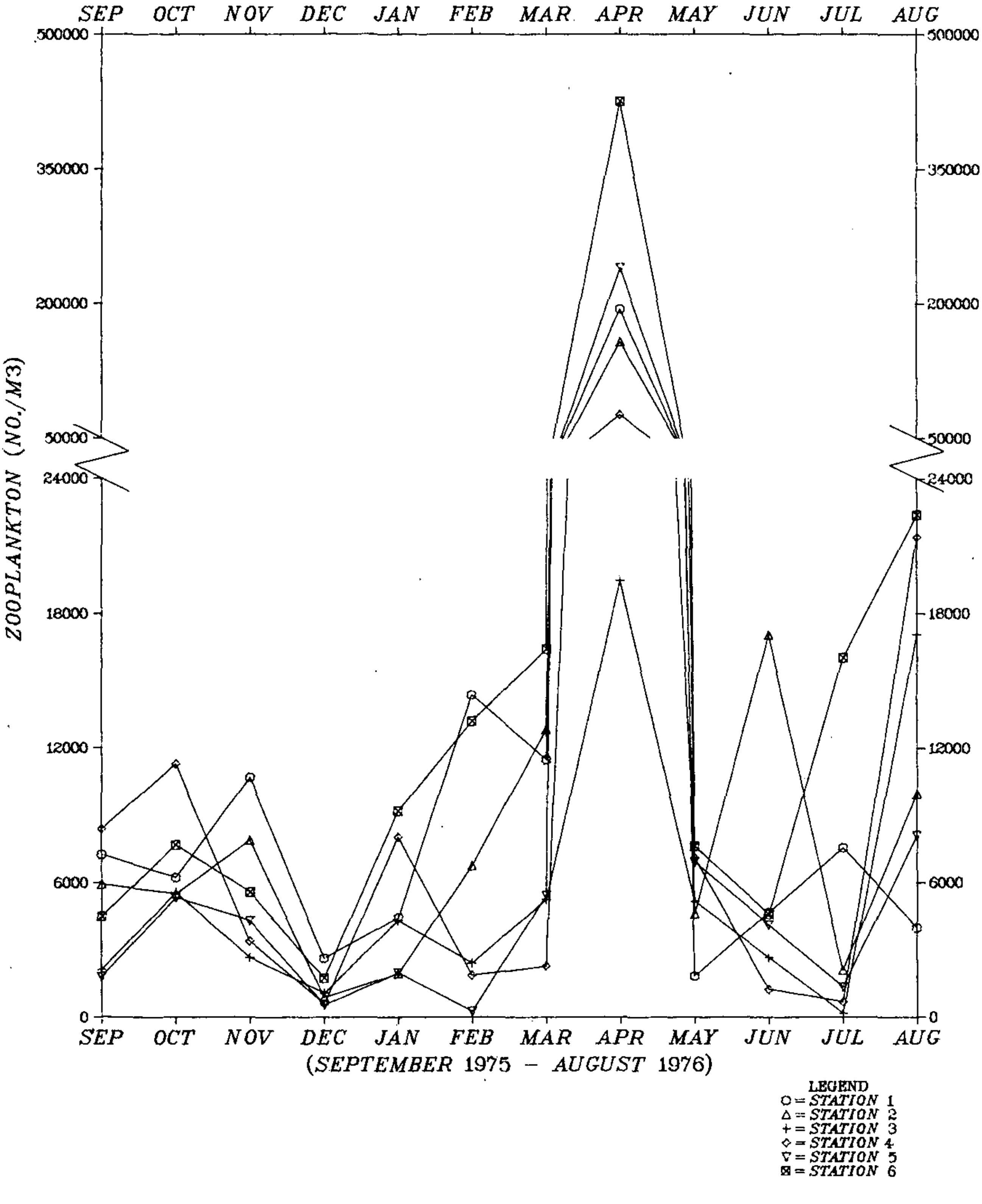


Figure 7-8. Mean Monthly Zooplankton Densities in Trinity Bay, September 1975-August 1976

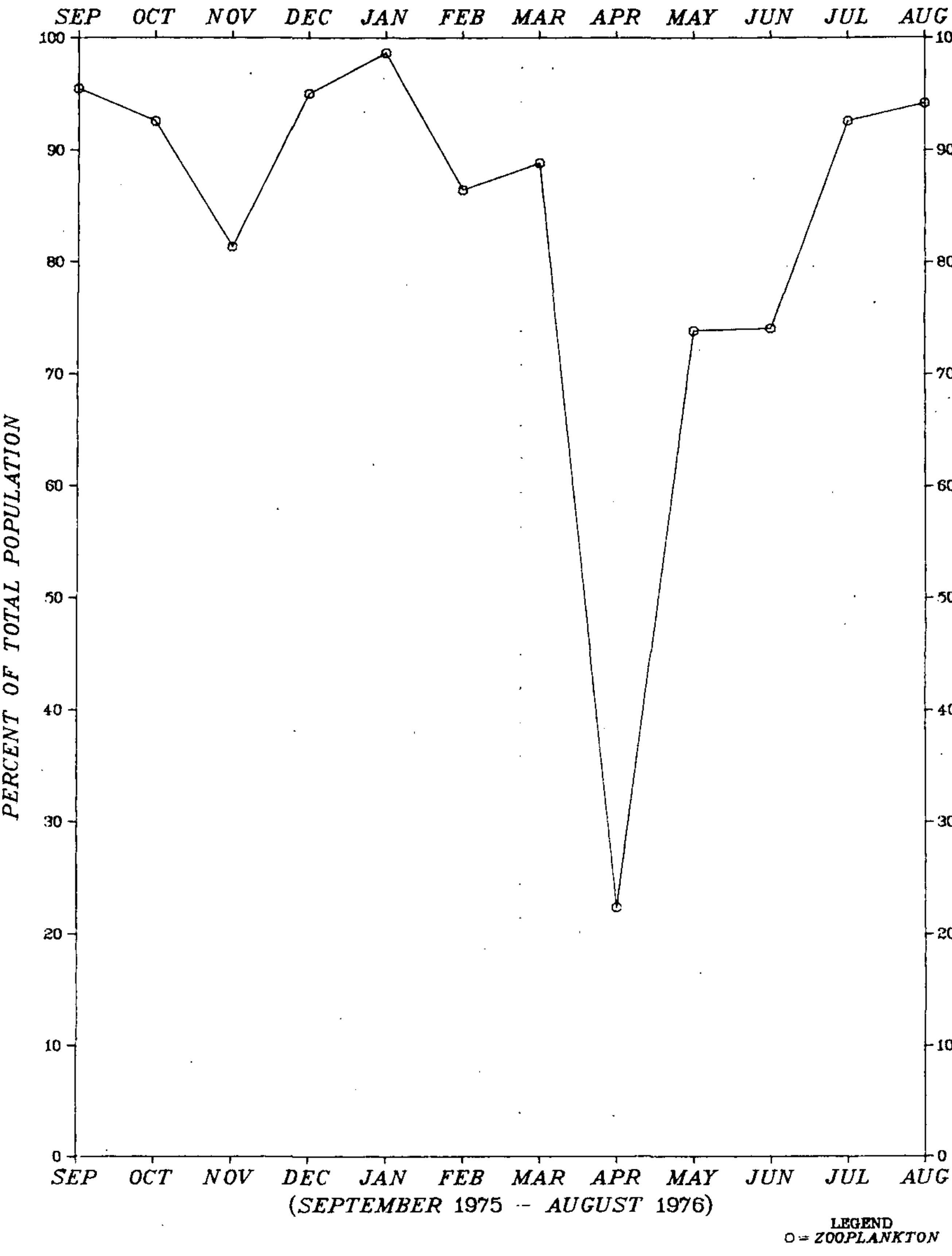


Figure 7-9. Combined Proportion of *Acartia tonsa*, Barnacle Nauplii, and Copepodites to Total Zooplankton Populations in Trinity Bay, September 1975-August 1976

Acartia tonsa reached peak densities in summer and early fall months of the study. The immature barnacles, including the naupliar and cypris forms were prominent in late winter and early spring which corresponds to the period of greatest spawning activity of the barnacle. The immature copepods were most abundant in October and November 1975 and April through July 1976.

Results of Analyses

Estuarine zooplankton actually represent two separate categories: the holoplankton and the meroplankton. Holoplankton are true zooplankton that spend their entire life cycle as animal plankton (e.g., copepods, cladocerans, larvaceans, chaetognaths, and ctenophores). Meroplankton, however, represent only certain life stages of animal species that are otherwise not considered planktonic (e.g., larval stages of barnacles, oysters, shrimp, crabs, and fish).

Many zooplankton species found in Trinity Bay are widely distributed along the coasts of the United States, while others may even have a world wide distribution. For example, Green (77) reports that Acartia tonsa may be found in the Central Baltic Sea area; Brachionus quadridentata is also known from parts as distant as the Aral Sea of Russia.

Other zooplankton studies conducted in estuaries and bays along the Texas coast have produced similar results to this study. As previously mentioned, barnacle nauplii and the calanoid copepod Acartia tonsa were the dominant zooplankton forms in Trinity Bay. This agrees with studies in Sabine Lake (421, 49), in Lavaca Bay (293), in San Antonio Bay (291), and in the Nueces and Mission-Aransas estuaries (325). Maximum and minimum mean monthly densities in Trinity Bay were also similar to results from the studies mentioned above (Table 7-3). Mean monthly zooplankton standing crops from the Trinity Bay study are compared with combined (gaged and ungaged) river inflow in Figure 7-10.

Freshwater inflow can influence zooplankton in several ways. Estuarine zooplankton standing crop composition can be altered by importation of freshwater species. Inflows can also transport zooplankton food resources into the system in the form of phytoplankton and detritus. However, zooplankton communities may also be adversely affected by increased river inflows. Sudden shifts in salinity and flushing out of autochthonous populations can decrease zooplankton standing crops. As reported by Perkins (200) the primary factor influencing the composition and abundance of estuarine zooplankton is development rate versus flushing time. Saltwater intrusions, on the other hand, act to (1) import marine zooplankton into the system; (2) import marine phytoplankton as a food source; and (3) increase salinity.

Correlation analyses revealed no significant statistical relationships between zooplankton populations and river inflows. However, freshwater inflow/salinity changes were important factors regulating the species composition, seasonal occurrence, and distribution of zooplankton communities during the Trinity Bay study. Diversities at stations 3, 4 and 5, closest to the river's mouth, were directly related to the rate of river flow; that is, diversity changes were closely allied to the presence or absence of freshwater taxa. Stations 1, 2 and 6 were located in areas of considerable mixing of

Table 7-3. Range of Mean Monthly Zooplankton Densities (individuals/m^3)

System	Minimum	Maximum
Trinity Bay (63)	1,235 (Dec. 1975)	190,560 (Apr. 1976)
Nueces Bay (325)	832 (Oct. 1973)	8,027,855 (Feb. 1974)
Corpus Christi Bay (325)	1,722 (Dec. 1972)	53,657,037 (Mar. 1973)
Copano Bay (325)	1,296 (Sep. 1974)	53,536 (Feb. 1973)
Aransas Bay (325)	2,497 (Dec. 1972)	3,008,679 (Feb. 1974)
Sabine Lake (49)	381 (Apr. 1975)	20,042 (Oct. 1974)
Lavaca Bay (293)	1,980 (Oct. 1973)	27,846 (Feb. 1974)
San Antonio Bay (291)	820 (Jun. 1973)	46,296 (Feb. 1973)

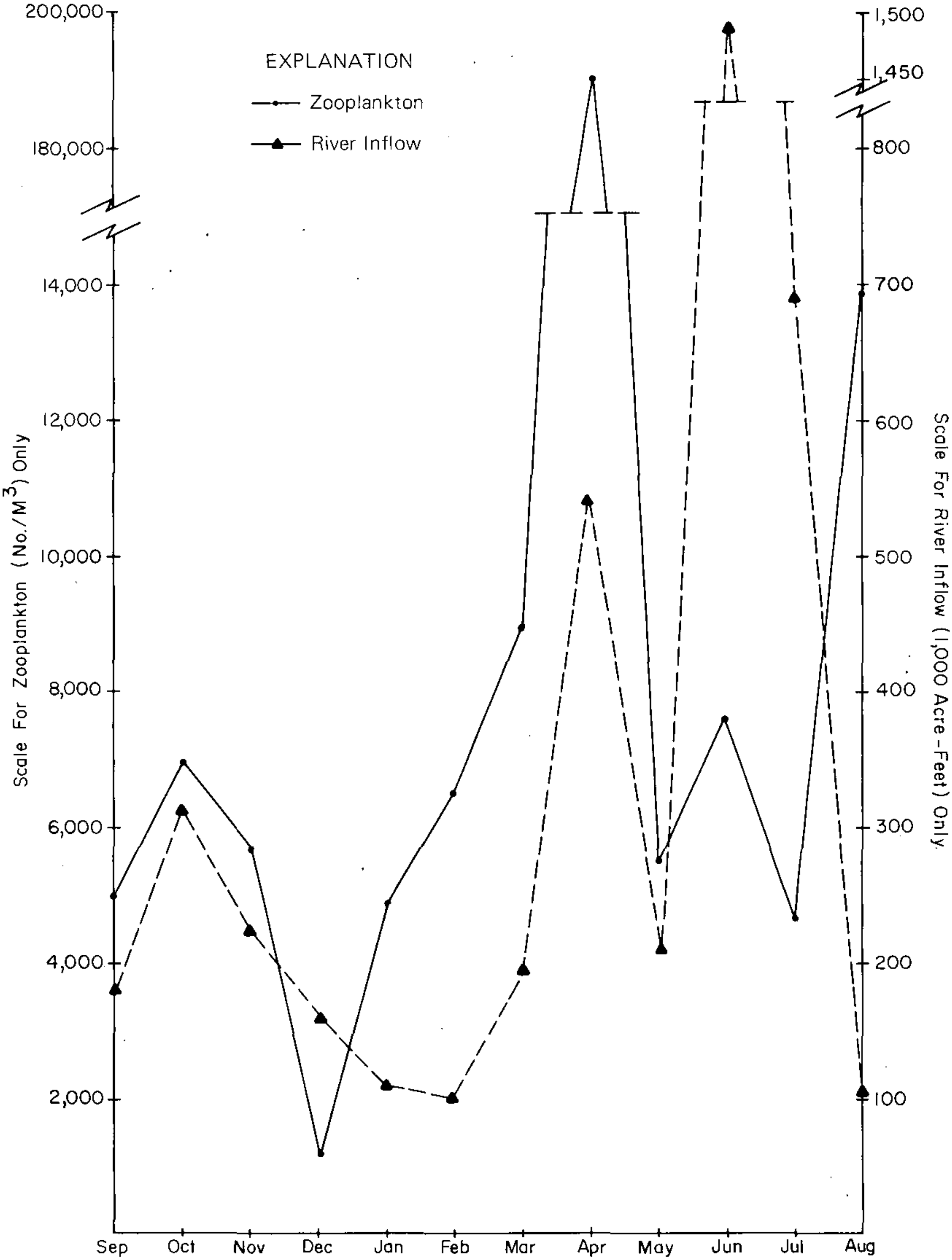


Figure 7-10. Mean Monthly Zooplankton Densities Versus River Inflow in Trinity Bay, September 1975-August 1976

water masses and zooplankton; communities consisted mainly of brackish water species and species preferring more saline waters.

The ecological niches for zooplankton are such that optimal conditions for growth and survival occur at different times of the year for different species. Optimal conditions for a given species result in high numbers of individuals for that species as long as favorable conditions last. If conditions are favorable for more than one species at the same time, the dominant or more competitive species will be found in the highest numbers followed by smaller increases in populations of the other species involved. Because the species in an area can vary in density and species predominance as well as fluctuate seasonally during the year, reliable conclusions on the plankton populations of an area can only be drawn on the basis of long-term investigations with regular catches.

Benthos

Data Collection

A total of 4,608 organisms representing 72 species in six phyla were identified from benthic samples collected during the 12-month Espey, Huston and Associates study (63). Triplicate samples were collected at each station with a 6 x 6-inch Ekman dredge. Results discussed herein are reported as individuals/m^2.

The most prominent phyla were the Annelida which accounted for 49 percent of the species identified, followed by the Arthropoda with 25 percent, and the Mollusca with 20 percent. The remaining three phyla, the Bryozoa, Rhynchocoela, and Chordata, comprised a total of six percent of the species identified.

Mean monthly densities ranged from a high of 1,463 individuals/m^2 in September 1975 to a low of 409 individuals/m^2 in August 1976. The overall mean density for the 12-month study was 945 individuals/m^2. Occasional peak populations in individual samples precluded any correlation between samples. For example, standing crops ranged from 129 individuals/m^2 at station 5 to 2,222 individuals/m^2 at nearby station 6 in May 1976 (Figure 7-11).

Bottom salinities generally followed the pattern of river discharges during the year with highest values recorded during the fall and winter when sustained freshwater inflows were low. In almost all months the lowest salinities were recorded at stations, 3, 4 and 5, presumably because of the more direct river influence.

The polychaetes dominated benthic collections at all stations (Figure 7-12). Seventy-four percent of the overall collections were comprised of polychaetes; the molluscs accounted for 15 percent, and others, including arthropods, rhynchocoels, chordates, and bryozoans, accounted for 11 percent. Stations 3, 4 and 5 exhibited greater numbers of molluscs than the stations farthest removed from the mouth of the river. While the molluscs and "others" comprised 34 percent of the total standing crop at stations 3, 4 and 5, they only accounted for 14 percent at stations 1, 2 and 6. Conversely, the polychaetes dominated stations 1, 2 and 6 with 86 percent of the catches and accounted for only 61 percent of the collections at stations 3, 4 and 5.

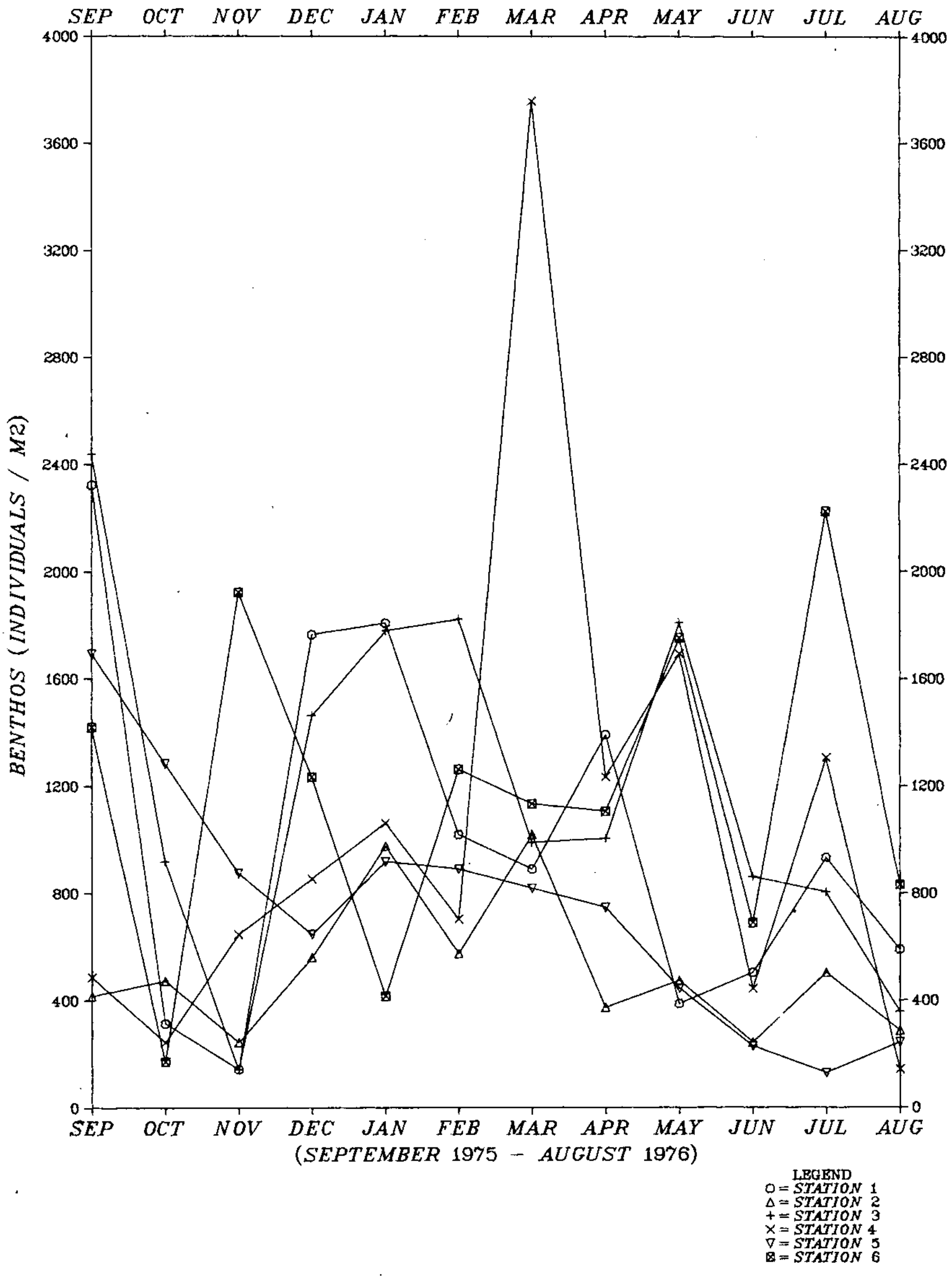


Figure 7-11. Mean Monthly Benthos Densities in Trinity Bay, September 1975-August 1976

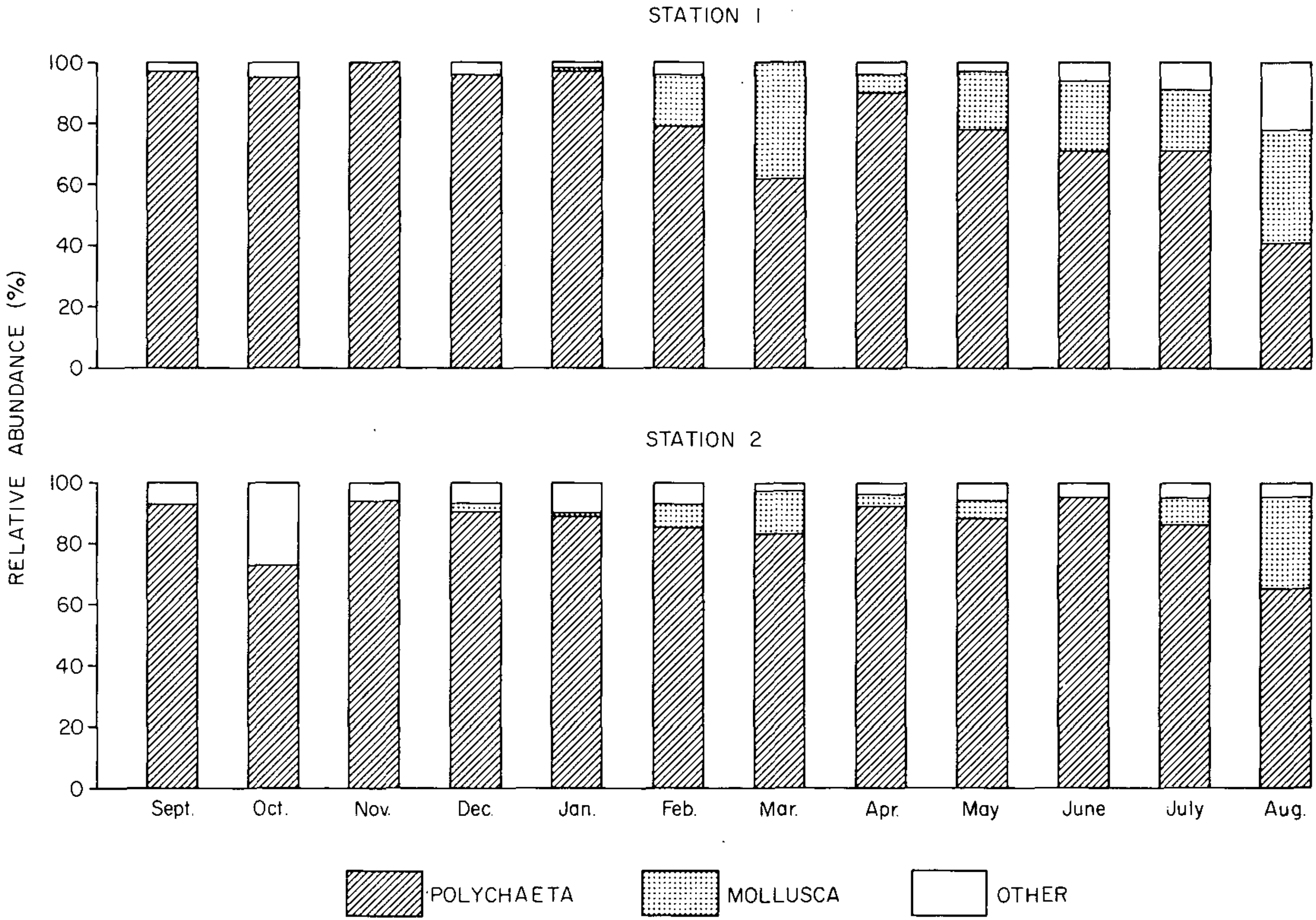


Figure 7-12. Relative Abundance of Major Benthic Groups in Trinity Bay, September 1975-August 1976

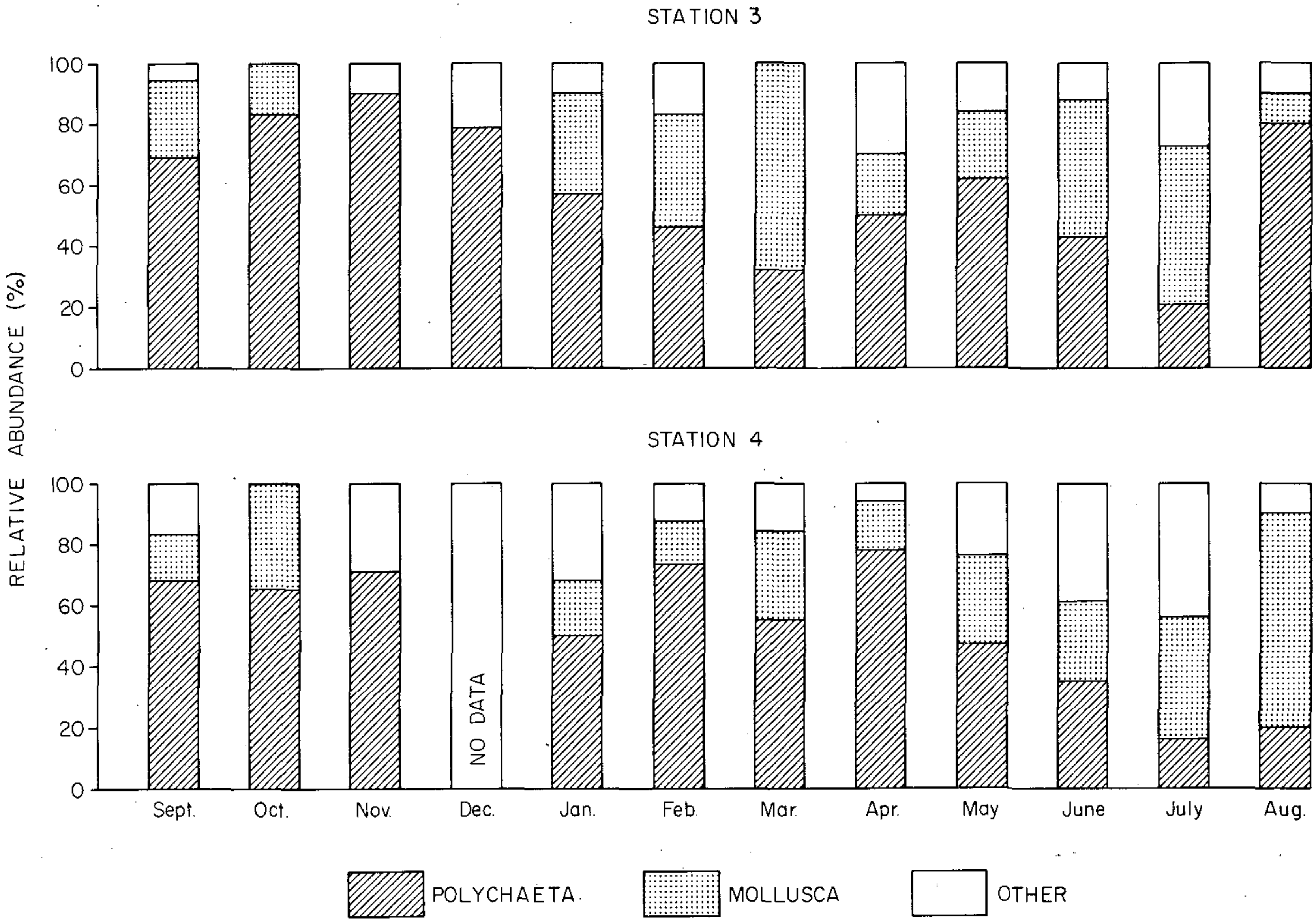


Figure 7-12 Cont.

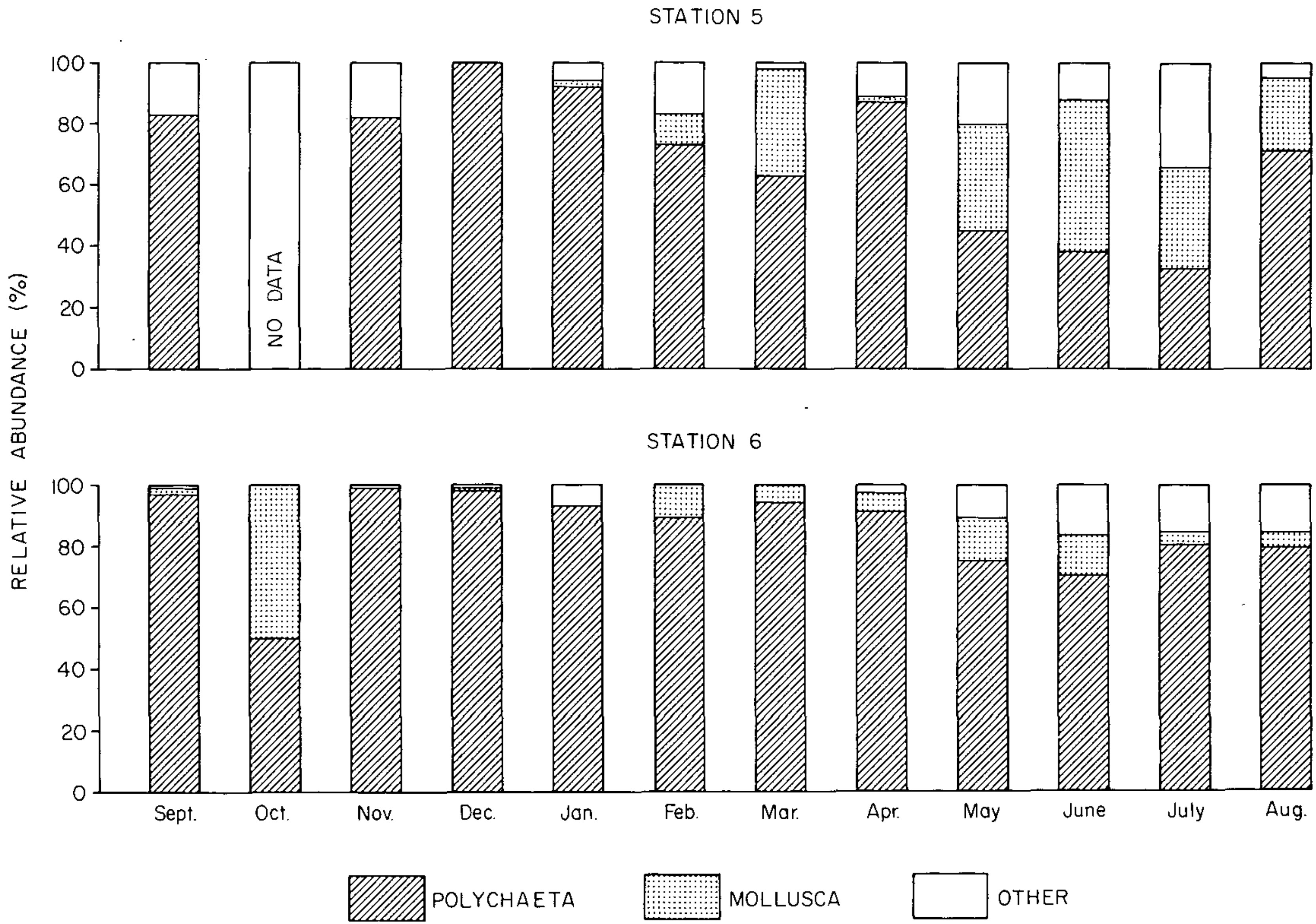


Figure 7-12 Cont.

The most abundant organisms in the benthos were an unidentified polychaete of the family Capitellidae and Mediomastus californiensis, also a capitellid polychaete. These two organisms were present at all stations often comprising a large percentage of the total numbers collected. The unidentified capitellid polychaete was most prominent in late fall and winter samples while Mediomastus californiensis was prevalent in spring and summer collections. Other organisms which constituted at least 30 percent of the standing crop of a particular collection are shown in Table 7-4. It is of interest to note that Amnicola, a freshwater gastropod, was dominant three months (September, October and November 1975) at station 3, near the mouth of the Trinity River.

Results of Analyses

Benthic organisms are generally considered to be intermediate in the estuarine food chain, functioning to transfer energy from primary trophic levels, including detritus and plankton, to higher consumers such as fish and shrimp. Since many benthic organisms are of limited mobility or even completely sedentary, biomass and diversity fluctuations are often investigated in order to demonstrate natural or man-made changes which can upset ecological balances. Further, it is known that the biomass of benthic fauna increases as the general productivity of an estuarine ecosystem increases (77).

Benthic diversity generally decreases with distance upstream in an estuary. From a minimum, at a salinity of 5.0 ppt, species numbers generally increase seaward to a maximum at about 35 ppt, the normal salinity of seawater, and decline once more with increasing salinity (111). This was found to be true in Lavaca and San Antonio Bays where benthic diversities declined from the high salinity lower bays to the low salinity upper bays and riverine areas. Diversities were highest during late winter and early spring when sustained freshwater inflows were low (291, 293). No such pattern was evident, however, in the benthic populations from the Trinity Bay study. Diversities were generally variable from month-to-month with no apparent seasonal trends.

Harper (245) studied the distribution of benthic organisms in undredged control areas of San Antonio Bay and found an almost logarithmic decrease in benthic populations with increased salinity. Holland et al. (325) also found this to be true in Nueces Bay where an inverse relationship was found between salinity and standing crop. In addition, Harper (245) found that increases in benthic populations, associated with decreased salinity, were attributed to increased flow of water-borne nutrients because benthic organisms like Rangia cuneata and Littoridina sphinctostoma are known to spawn in response to increased nutrients and rapid decreases in salinity. Gilmore et al. (293) reported that benthic populations in Lavaca Bay were not statistically related to freshwater inflows; significant relationships were discovered, however, with such hydrological parameters as bottom salinity, turbidity, total carbon, organic nitrogen, and nitrate. No significant statistical correlations ($\alpha > 0.05$) were discovered between Trinity Bay standing crop and river flow or bottom salinities. Benthic populations at stations 3, 4 and 5, under direct influence of the Trinity River, comprised 51 percent of the total standing crop during the study; stations 1, 2 and 6, exposed to tidal exchange or discharge of the Houston Ship Channel, comprised 49 percent (Figure 7-13).

Table 7-4. Number of Months in which Each Benthic Organism Constituted 30 Percent or More of the Total Standing Crop in Trinity Bay, September 1975 - August 1976

Station / Organism	1	2	3	4	5	6
Capitellidae	4	3	2	3	3	4
Mediomastus californiensis	7	8	2	3	5	7
Macoma (juvenile)	1		1		2	
Polychaete #3		3				
Amnicola			3			
Peloscolex				1	1	
Pelecypod (juvenile)			1			
Tanyplinidae				1		
Littoridina spinctostoma						1

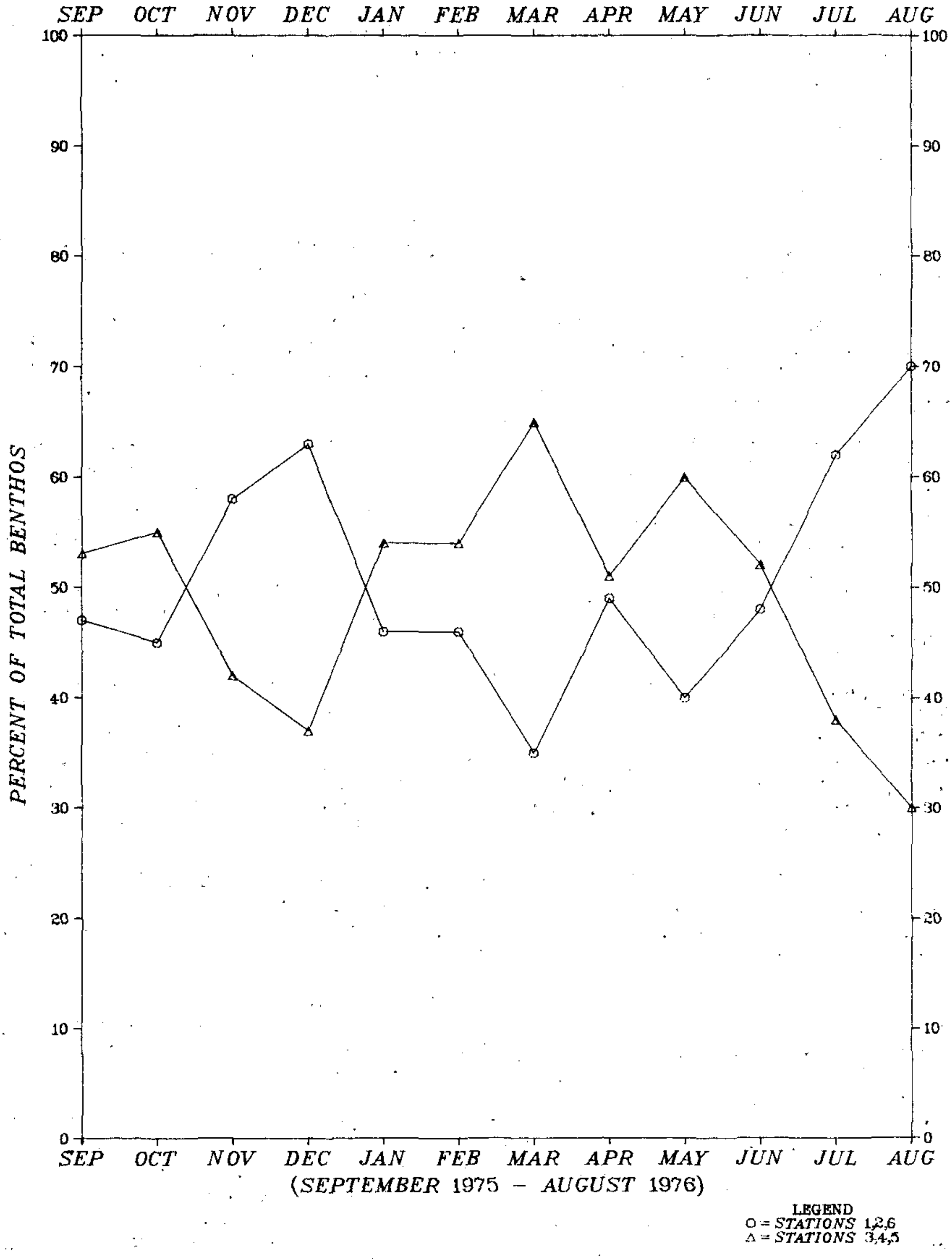


Figure 7-13. Percentage Representation of Benthos Standing Crops in Trinity Bay, September 1975-August 1976

Although not statistically correlated with inflows or salinity, it appears likely that the benthic community structure was influenced by these factors nevertheless. For example, low standing crops in October through November 1975 and June through August 1976 probably occurred in response to the low salinity regime resulting from greater river inflows (Figure 7-14).

Summary

The community composition, distribution, abundance, and seasonality of the phytoplankton, zooplankton, and benthic invertebrates of the Trinity-San Jacinto estuary were employed as "indicators" of primary productivity. The estuarine communities were typical in that they were composed of a mixture of endemic species (i.e., species restricted to the estuarine zone) and marine species plus several species with the osmoregulatory capabilities for penetrating from the freshwater environment.

The upper Texas bays have never been characterized by high plankton populations (253, 32). High plankton counts observed in South Texas bays are presumably influenced by higher salinities and shallow, clearer waters (23). Seven phytoplankton divisions represented by 132 taxa were collected from Trinity Bay. The diatoms were the most taxonomically dominant group, accounting for 41 percent of the total number of phytoplankton species collected. A clear distinction in community composition was discovered between stations 3, 4 and 5, directly influenced by the Trinity River, and the more saline stations 1, 2 and 6.

A total of 70 zooplankton species representing nine phyla were identified during the 12-month study. The Arthropoda accounted for 55 percent of the organisms identified. Regression analysis revealed no statistically significant correlations between zooplankton standing crops and freshwater inflows. However, these factors did exhibit a regulating influence on species composition, seasonal occurrence, and distribution of zooplankton in Trinity Bay as evidenced by comparing stations.

Six phyla represented by 72 benthic species were collected from Trinity Bay. The polychaetes, phylum Annelida, were the most prominent organisms collected. Although not statistically correlated with inflows or salinity, the benthic community appears to be influenced by these factors.

The phytoplankton, zooplankton, and benthic assemblages in any body of water respond to a combination of physical and chemical seasonal controlling factors. Thus, it is difficult to single out the influence of any one of these factors on the entire community. Most estuarine organisms can be classified by salinity tolerance as oligohaline, mesohaline, polyhaline, or euryhaline. That is, there is always an assemblage of species which will be capable of maintaining high standing crops, regardless of the salinity, as long as it is relatively stable, and provided that other physical and chemical requirements for that particular assemblage are met. If freshwater inflow is decreased, either partially or totally, the community composition will merely shift toward the neritic or marine (polyhaline and euryhaline) forms. The primary question, then, is how this shift affects the food chain and the environment of those economically important organisms which, during some stage of their life cycle, depend on freshwater inflow.

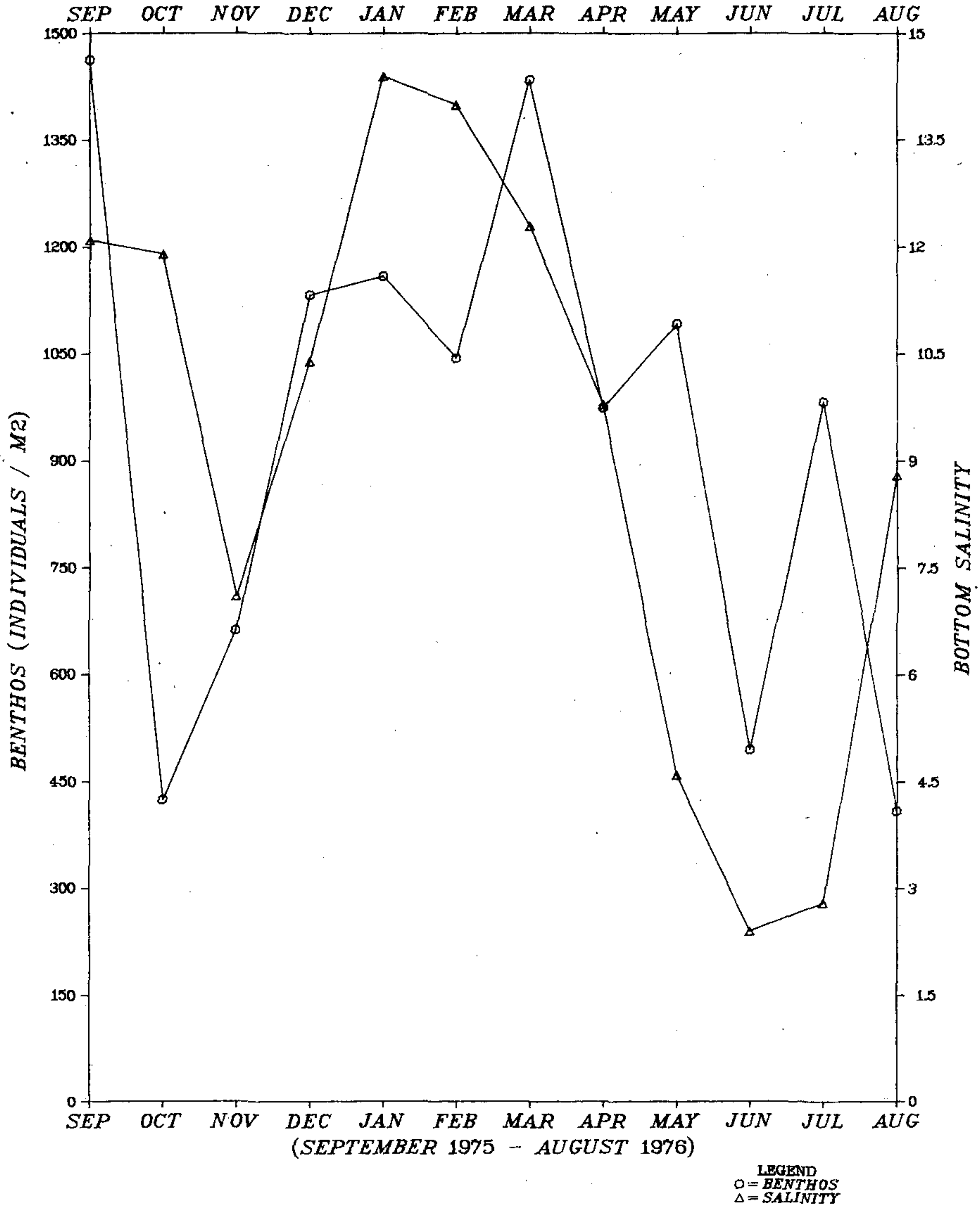


Figure 7-14. Mean Monthly Benthos Densities and Mean Monthly Bottom Salinities in Trinity Bay, September 1975-August 1976

CHAPTER VIII

FISHERIES

Introduction

Virtually all (97.5 percent) of the coastal fisheries species are considered estuarine-dependent (93). During the five year period, 1972 through 1976, commercial landings of finfish and shellfish in Texas averaged 97.3 million pounds (44.2 million kg) annually (475-479). Approximately 75 percent of the harvest was taken offshore in the Gulf of Mexico and the remainder was taken inshore in the bays and estuaries. Computed on the basis of two general fisheries components, the finfish harvest distribution was approximately 28 percent offshore and 72 percent inshore, while the shellfish harvest was of an opposite distribution with about 21 percent inshore and 79 percent offshore. Specifically, the offshore harvests accounted for about six percent of the total Texas red drum (redfish) landings, 17 percent of spotted seatrout landings, 60 percent of white shrimp landings, and 95 percent of brown and pink shrimp landings.

With respect to commercial Texas bay landings from 1972 to 1976, bays of the Trinity-San Jacinto estuary contributed an average 11.0 percent of finfish landings and 45.4 percent of shellfish landings made from Texas bays. The estuary is the largest of eight major Texas estuarine areas and ranks first in shellfish and fourth in finfish. Based on the five year inshore-offshore commercial landings distribution, the average contribution of the Trinity-San Jacinto estuary to total (bays and Gulf) Texas commercial landings is estimated at 827,700 pounds (375,440 kg) of fish and 40,792,500 pounds (18.5 million kg) of shellfish annually. In addition, the commercial fish harvest has been estimated to account for only about 14.1 percent of the total fish harvest in the estuary, with the remainder (85.9 percent) going to the sport or recreational catch (295). Thus, an additional 5,042,400 pounds (2.3 million kg) of sport catch can be computed which raises the estimated average annual fish harvest contribution from the estuary (both inshore and offshore) to 5,870,100 pounds (2.7 million kg). The average harvest contribution of all fisheries species (fish and shellfish) from the estuary is therefore estimated at 46.7 million pounds (21.2 million kg) annually.

Previous research has described the general ecology, utilization and management of the coastal fisheries (360, 180, 178, 88, 222, 218), and has provided information of Texas tidal waters (341, 346, 480, 202) and the relationship of freshwater inflow to estuarine productivity (501). Also, prior studies in the Trinity-San Jacinto estuary have covered a wide range of topics dealing with the estuary's fish (361, 352, 130, 299, 324, 209, 208, 350), shrimp (500, 21, 329), oysters (76, 300), and the effects of man-induced disturbances and pollution (334, 292, 161, 158, 335, 518, 288, 316, 184, 206, 241). For a more comprehensive listing of studies, the reader is referred to Christman, Kochman, and Lippencott's recent annotated bibliography of Galveston bay fish and wildlife resources (494) which contains over 1,600 scientific, engineering, and economic references to the estuary.

The fluctuating contributions of freshwater inflow and associated nutritive and sedimentary constituents from the Trinity River and Delta have been of continuing interest because of their physical, chemical, and biological effects on the estuary, particularly Trinity bay. In this regard, Diener (498) concludes that the optimum salinity range in the bay is 10-17 ppt and that an estimated 2,000 cubic feet per second (118,800 acre-feet per month) of Trinity River inflow during March through October is necessary to maintain the habitats. Copeland et al. (317) estimated that the upper Trinity Bay habitats were up to 72 percent dependent upon river-borne organic matter to support the observed high secondary productivity of the area. More specifically, Parker et al. (23) conclude that a minimum 1.3 million acre-feet (1.6 billion m^3) per year of Trinity River inflows may provide sufficient nutrients to sustain a low level of phytoplankton and marsh plant production in the Trinity Delta and Bay area. However, Soloman and Smith (25) suggest that while the bay is highly dependent upon the river inflows for salinity gradient maintenance, the bay may not be as dependent upon river-borne nutrients.

Although an inverse correlation has been reported between Trinity River flows and the bay's density of crustaceans (255), Cooper (31) notes that excessive retardation of freshwater flow acted as a stress which had synergistic effects with increased effluent loading. Using 1958 through 1968 commercial fisheries statistics, Parker and Blanton (24) hypothesize a reduction in seafood landings when average winter salinities exceed summer salinities as a result of high spring/summer freshwater inflows to the estuary. In another attempt to correlate fisheries with inflows, Armstrong and Hinson (336) report an analysis of 1959 through 1964 records indicates that Galveston Bay displacement rates exceeding twice per year apparently cause a decrease (i.e., negative correlation) in total commercial harvests. Recognizing this analysis as rather gross, they further suggest that the estuarine system would produce larger commercial catches with Galveston Bay water volume displacement rates less than 2.0 per year, estimating the maximum fisheries production to be near 0.5 per year or about 1.2 million acre-feet (1.5 billion m^3) annually. Powell (264) examined the seasonal distributions of freshwater inflow at Trinity Delta and found several dichotomies in seasonal inflow distributions associated with the "best" versus "worst" five harvest years in the 1962 to 1976 commercial fisheries records. Additionally, negative correlations were reported between oyster harvests and September-October inflow, and brown and pink shrimp harvests and March-May inflow (264). However, multivariate equational models of fisheries production from several important species as a function of the effects of seasonal freshwater inflows have not been previously constructed.

Data and Statistical Methods

Direct analysis of absolute fisheries biomass fluctuations as a function of freshwater inflow is not possible because accurate biomass estimation requires either considerable experimental calibration of current sampling methods (141) or the development and application of higher technologies such as the use of high resolution, computer interpreted, sonar soundings for estimation of absolute fish abundance (41). Therefore, some indirect or relative measure of the fisheries must be substituted in the analysis. In terms of measurement, precision is a major consideration of relative estimates, while accuracy is of paramount importance to absolute estimates of abundance (141).

Prior research has demonstrated that variations in rainfall and/or river discharge are associated with variations in the catch of estuarine-dependent fisheries, and can be used as an indicator for finfish and shellfish production (115, 96, 95, 423, 238, 237). Therefore, commercial harvest can be useful as a relative indicator of fisheries abundance, especially if the harvest is not critically limited below the production available for harvest on a long-term basis (i.e., the surplus production) by market conditions. Similarly, annual harvest variations can provide relative estimates of the fisheries biomass fluctuations occurring from year to year.

In Texas, commercial harvest data are available from the Texas Landings publications (481-487, 472-479) which report inshore harvests from the various bays and offshore harvests from the Gulf of Mexico. Since the offshore harvests reported in Texas Landings represent collective fisheries production from the western Gulf region's estuaries, it is the inshore harvests reported by estuarine area that provide fisheries data related to a particular estuary. In addition, the offshore shrimp fishery is partitioned into shrimp fishing grid zones in the Gulf Coast Shrimp Data publications (503-512, 519-526), which report the quantity and value of the commercial catch by species and the effort (number of fishing trips) in each area of capture at each trawling depth. Data from these offshore areas may also be useful in assessing the effects of seasonal freshwater inflows on inshore shrimp "nursery" habitats of geographically associated estuaries.

Commercial inshore harvests from bays of the Trinity-San Jacinto estuary are tabulated for several important fisheries components (Table 8-1). In addition, commercial offshore harvests of penaeid shrimp and fishing effort are tabulated for Gulf Area No. 18, the offshore fishing grid area associated with the Trinity-San Jacinto estuary (Table 8-2). By using inshore harvest data since 1962, data inconsistencies with earlier years and problems of rapidly increasing harvest effort as the commercial fisheries developed in Texas are avoided. For example, landings data for the penaeid shrimp fishery are better than for most of the fisheries components because of the high demand for this seafood. Nevertheless, landings data from the turn of the century to the late 1940's are incomplete and report only the white shrimp harvest. Exploitation of the brown shrimp began in 1947 with night trawling in offsfhore waters and rapidly increased throughout the 1950's; however, separation of the two species in the fisheries statistics was not begun until after 1957. Therefore, since reporting procedures were not fully standarized until the early 1960's, and since earlier harvest records are inconsistent, the inshore (bay) fisheries analysis utilizes the more reliable records available from 1962 to 1976. This 15-year interval includes both wet and dry climatic cycles and is sufficient in length to identify positive and negative fisheries responses to seasonal inflow, as well as quantify the seasonal freshwater inflow needs of the fisheries components. Analysis of the offshore shrimp fishery is slightly expanded to cover the 18-year interval from 1959 to 1976.

The finfish component of the fisheries harvest is specific for the combined harvests of croaker (mostly *Micropogon undulatus* Linnaeus), black drum (*Pogonis cromis* Linnaeus), red drum or redfish (*Sciaenops ocellata* Linnaeus), flounders (*Paralichthys* spp.; most *P. lethostigma* Jordan and Gilbert), sea catfish (*Arius felis* Linnaeus), spotted seatrout (*Cynoscion nebulosus* Cuvier), and sheepshead (*Archosargus probatocephalus* Walbaum). Similarly, the shellfish component refers to the blue crab (*Callinectes sapidus* Rathbun), American oyster (*Crassostrea virginica* Gmelin), white shrimp (*Penaeus setiferus*

Table 8-1. Commercial Fisheries Harvests in the Trinity-San Jacinto a/, 1962-1976 (462-469, 471-477)

Year	Commercial Fisheries Harvests (thousands of pounds)								
	Shellfish b/	White Shrimp	Brown & Pink Shrimp	Blue Crab	Bay Oyster	Finfish c/	Spotted Seatrout	Red Drum	Black Drum
1962	5,254.1	3,324.4	868.5	311.3	749.9	59.9	17.0	2.6	11.9
1963	6,736.8	3,027.2	600.8	977.5	2,131.3	159.0	142.9	1.3	7.9
1964	9,534.1	4,700.7	717.0	1,195.6	2,920.8	411.0	176.9	25.7	62.4
1965	10,599.6	3,066.2	1,132.2	1,817.9	4,583.3	413.4	277.0	32.2	23.9
1966	7,382.2	1,260.0	681.1	1,357.8	4,083.3	350.5	161.7	29.8	29.1
1967	6,227.8	1,038.8	1,148.5	1,047.9	2,992.6	635.1	280.4	45.0	124.9
1968	7,203.1	2,514.0	307.8	1,542.6	2,838.7	333.4	174.2	21.2	54.4
1969	9,438.0	3,809.6	475.5	1,705.7	3,447.2	278.1	55.7	38.1	44.6
1970	12,097.7	4,069.5	1,556.0	2,622.0	3,850.2	264.7	89.2	35.3	39.0
1971	11,196.4	2,963.8	2,050.1	2,160.8	4,021.7	155.3	75.9	18.1	25.2
1972	9,485.0	2,956.7	1,398.5	1,870.1	3,259.7	295.8	128.4	33.6	72.7
1973	9,184.4	4,063.4	951.6	2,040.0	2,129.4	498.6	232.8	49.6	93.0
1974	6,634.8	2,392.4	1,422.6	1,983.1	836.8	446.2	272.9	34.9	27.6
1975	7,855.9	3,927.2	828.4	1,863.5	1,236.8	452.9	221.0	79.5	46.4
1976	10,058.2	3,358.2	1,802.0	1,599.5	3,298.8	445.4	181.5	97.5	47.4
Mean	8,592.6	3,098.1	1,062.7	1,606.4	2,825.4	346.6	165.8	36.3	47.4
±S.E. d/	±516.1	±206.6	±129.4	±146.0	±306.6	±38.7	±21.3	±6.5	±8.1

a/ Estuary ranks first in shellfish and fourth in finfish commercial harvests of eight Major Texas estuarine areas
b/ Multi-species fisheries component includes blue crab, bay oyster, and white, brown, and pink shrimp harvests
c/ Multi-species fisheries component includes croaker, black drum, red drum, flounder, sea catfish, spotted seatrout, and sheepshead harvests
d/ Standard error of mean; two standard errors provide approximately 95 percent confidence limits about the mean

Table 8-2. Offshore Commercial Penaeid Shrimp Harvests in Gulf Area No. 18 a/, 1959-1976 (503-512, 519-526)

Year	White Shrimp b/		Brown and Pink Shrimp c/		All Penaeid Shrimp d/	
	Harvest e/	Effort f/	Harvest	Effort	Harvest	Effort
1959	2,279.1	4,209.9	8,222.7	4,520.7	10,502.7	4,520.7
1960	2,344.8	6,210.3	11,831.6	6,389.6	14,176.8	6,389.6
1961	1,372.6	3,929.1	4,022.2	4,192.4	5,403.9	4,192.4
1962	1,409.8	3,445.2	3,520.3	3,763.7	4,930.6	3,763.7
1963	1,988.2	3,595.1	5,655.3	3,933.2	7,684.2	3,933.2
1964	2,513.1	4,124.2	4,404.6	4,344.4	6,921.9	4,344.4
1965	1,851.8	4,176.7	6,630.0	4,410.7	8,484.7	4,410.7
1966	2,018.5	4,591.1	4,543.2	4,692.6	6,572.8	4,692.6
1967	2,049.8	6,992.7	17,740.1	7,294.4	19,790.1	7,294.4
1968	2,515.3	4,170.6	3,426.4	4,436.7	5,945.1	4,436.7
1969	3,445.7	5,049.9	3,716.3	5,399.7	7,162.0	5,399.7
1970	3,822.1	4,754.4	4,591.1	5,192.9	8,416.2	5,192.9
1971	3,851.0	7,009.6	11,637.2	7,355.9	15,492.7	7,355.9
1972	3,195.9	6,315.3	6,811.4	6,851.9	10,027.1	6,851.9
1973	4,064.7	5,613.2	2,988.0	6,191.9	7,059.6	6,191.9
1974	4,893.6	8,149.0	13,019.2	9,002.2	18,070.6	9,002.2
1975	3,287.5	6,238.4	6,482.9	6,660.2	9,776.1	6,660.2
1976	3,482.4	5,260.2	10,015.7	6,192.9	13,498.1	6,192.9
Mean	2,799.2	5,213.0	7,181.0	5,601.4	9,995.3	5,601.4
±S.E. g/	±234.0	±317.3	±970.0	±344.0	±1,042.4	±344.0

a/ Gulf shrimp fishing grid Area No. 18 lies directly offshore from the Trinity-San Jacinto estuary

b/ White shrimp harvest and fishing effort at depths ≤ 20 fathoms

c/ Brown and Pink shrimp harvest and fishing effort at all depths recorded

d/ White, Brown, and Pink shrimp harvest and fishing effort at all depths recorded

e/ Whole shrimp harvest weight in thousands of pounds estimated by tail weight X 1.54 (White shrimp), X 1.61 (Brown shrimp), and X 1.60 (Pink shrimp)

f/ Fishing effort in number of fishing trips by shrimp vessels

g/ Standard error of mean; two standard errors provide approximately 95 percent confidence limits about the mean

Linnaeus), and brown and pink shrimp (Penaeus aztecus Ives and P. duorarum Burkenroad; mostly P. aztecus). Other fisheries components are generally given as a single species or species group of interest.

Freshwater inflow to the estuary is discussed in Chapter IV and is tabulated here on the basis of three anayltical categories: (1) freshwater inflow at Trinity Delta (Table 8-3), (2) freshwater inflow from San Jacinto River basin (Table 8-4), and (3) combined freshwater inflow to Trinity-San Jacinto estuary from all contributing river and coastal drainage basins (Table 8-5). Each inflow category is thus specified by its historical record of seasonal inflow volumes.

The effects of freshwater inflow on an estuary and its fisheries production involve intricate and imperfectly understood physical, chemical, and biological pathways. Moreover, a complete hypothesis does not yet exist from which an accurate structural model can be constructed that represents the full spectrum of natural relationships. As a result, an alternative analytical procedure must be used which provides a functional model; that is, a procedure which permits estimation of harvest as a unique function of inflow. In this case, the aim is a mathematical description of relations among the variables as historically observed. Statistical regression procedures are most common and generally involve empirically fitting curves by a mathematical least squares criterion to an observed set of data, such as inflow and harvest records. Although functional model relationships do not necessarily have unambiguous, biologically interpretable meaning, they are useful when they adequately describe the relations among natural phenomena. Even after sufficient scientific knowledge is acquired to construct a preferable structural model, it may not actually be a markedly better predictor than a functional model. Thus, scientists often employ functional models to describe natural phenomena while recognizing that the relational equations may not or do not represent the true and as yet unclear workings of nature.

A time series analysis of the fisheries components from the Trinity-San Jacinto estuary was performed utilizing the University of Californis biomedical (BMD) computer program for the stepwise multiple regression procedure (16). This statistical procedure computes a sequence of multiple linear regression equations in a stepwise manner. At each step, the next variable which makes the greatest reduction in the sum of squares error term is added to the equation. Consequently, the best significant equation is developed as the equation of highest multiple correlation coefficient (r), greatest statistical significance (F value), and lowest error sum of squares. A typical form of the harvest regression equation can be given as follows:

$$H_t = a_0 + a_1 Q_{1,t-b_1} + \dots + a_n Q_{n,t-b_n} + E_t + e$$

where a_0 is the intercept harvest value, $a_1 \dots a_n$ are partial regression coefficients, and e is the normally distributed error term with a mean of zero. Regression variables used in the fisheries analysis are:

H_t = annual harvest of a fisheries component in thousands of pounds at year t;

E_t = annual fishing effort of offshore shrimp fishery in number of fishing trips at time t;

Table 8-3. Seasonal Freshwater Inflow Volumes from Trinity Delta Contributed to Trinity-San Jacinto Estuary, 1959-1976

Year	Seasonal Freshwater Inflow (thousands of acre-feet)				
	Winter Jan.-March	Spring April-June	Summer July-Aug.	Autumn Sept.-Oct.	Late Fall Nov.-Dec.
1959	1,020.0	2,240.1	756.0	655.0	950.0
1960	2,568.9	636.9	403.0	314.0	2,127.0
1961	4,050.9	1,118.1	432.0	837.0 a/	836.0
1962	821.1	848.1	321.0	871.0	737.0
1963	626.1	666.0	10.0	42.0 b/	111.0
1964	620.1	417.9	32.0	421.0	896.0
1965	1,628.1	2,310.9	50.0	113.0	618.0
1966	1,160.1	4,823.1	654.0	255.0	177.0
1967	185.1	677.1	84.0	278.0 c/	823.0
1968	2,211.9	4,977.9	491.0	164.0	512.0
1969	2,163.9	4,953.0	194.0	160.0	434.0
1970	1,982.1	1,025.1	108.0 d/	432.0	96.0
1971	107.1	173.1	64.0	116.0 e/	1,892.0
1972	1,686.0	569.1	99.0	120.0	484.0
1973	2,751.0	5,153.1	729.0	2,122.0 f/	1,842.0
1974	2,273.1	1,032.9	129.0	1,199.0	3,634.0
1975	3,186.0	3,476.1	653.0	169.0	251.0
1976	375.9	1,526.1	465.0	401.0	1,021.0
Mean	1,634.3	2,034.7	315.2	481.6	968.9
± S.E.	± 261.0	±425.1	±61.8	±121.8	±211.2

a/ Hurricane Carla, Sept. 8-14; near Port Lavaca
b/ Hurricane Cindy, Sept. 16-20; near Port Arthur
c/ Hurricane Beulah, Sept. 18-23; near Brownsville
d/ Hurricane Celia, Aug. 3-5; near Port Aransas
e/ Hurricane Fern, Sept. 9-13; near Port Aransas
f/ Hurricane Delia, Sept. 4-7; near Galveston
g/ Standard error of the mean; two standard errors provide approximately 95% confidence limits about the mean

Table 8-4. Seasonal Freshwater Inflow Volumes from San Jacinto River Contributed to Trinity-San Jacinto Estuary, 1959-1976

Year	Seasonal Freshwater Inflow (thousands of acre-feet) Winter Jan.-March	Spring April-June	Summer July-Aug.	Autumn Sept.-Oct.	Late Fall Nov.-Dec.
1959	525.9	1,212.9	669.0	264.0	285.0
1960	539.1	1,020.0	412.0	750.0	984.0
1961	1,475.1	833.1	647.0	791.0 a/	392.0
1962	195.0	267.0	140.0	99.0	318.0
1963	395.1	152.1	146.0	88.0 b/	101.0
1964	498.9	291.9	137.0	110.0	186.0
1965	359.1	243.0	140.0	110.0	296.0
1966	872.1	1,287.0	199.0	198.0	60.0
1967	107.1	180.9	195.0	181.0 c/	79.0
1968	480.0	2,106.9	304.0	212.0	279.0
1969	933.9	624.9	181.0	141.0	121.0
1970	324.0	788.1	198.0 d/	538.0	110.0
1971	95.1	156.9	247.0	293.0 e/	195.0
1972	428.1	1,131.9	228.0	185.0	390.0
1973	1,064.1	2,241.9	574.0	1,213.0 f/	461.0
1974	1,131.9	369.9	312.0	593.0	1,143.0
1975	567.9	1,167.9	270.0	146.0	91.0
1976	108.0	653.1	338.0	213.0	674.0
Mean	561.1	818.3	296.5	340.3	342.5
± S.E. g/	±91.6	±149.0	±40.5	±73.5	±72.6

a/ Hurricane Carla, Sept. 8-14; near Port Lavaca
b/ Hurricane Cindy, Sept. 16-20; near Port Arthur
c/ Hurricane Beulah, Sept. 18-23; near Brownsville
d/ Hurricane Celia, Aug. 3-5; near Port Aransas
e/ Hurricane Fern, Sept. 9-13; near Port Aransas
f/ Hurricane Delia, Sept. 4-7; near Galveston
g/ Standard error of the mean: two standard errors provide approximately 95% confidence limits about the mean

Table 8-5. Seasonal Voluimes of Combined Freshwater Inflow a/ Contributed to Trinity-San Jacinto Estuary, 1959-1976

Year	Seasonal Freshwater Inflow (thousands of acre-feet)				
	Winter Jan.-March	Spring April-June	Summer July-Aug.	Autumn Sept.-Oct.	Late Fall Nov.-Dec.
1959	2,285.1	3,942.9	2,300.0	1,130.0	1,402.0
1960	3,357.0	2,058.0	1,228.0	1,194.0	3,579.0
1961	5,988.9	2,553.0	1,459.0	2,203.0 b/	1,614.0
1962	1,041.0	1,314.0	556.0	1,022.0	1,409.0
1963	1,256.1	936.9	225.0	170.0 c/	270.0
1964	1,518.0	777.9	241.0	633.0	1,392.0
1965	2,079.0	2,691.0	269.0	308.0	1,278.0
1966	2,667.9	7,041.9	1,249.0	584.0	327.0
1967	366.0	1,151.1	411.0	552.0 d/	920.0
1968	3,183.0	8,441.1	929.0	557.0	863.0
1969	3,552.0	6,236.1	490.0	395.0	703.0
1970	2,664.0	2,387.1	403.0 e/	1,628.0	281.0
1971	240.9	471.0	450.0	747.0 f/	2,240.0
1972	2,337.0	2,388.9	443.0	565.0	1,166.0
1973	4,440.9	8,886.0	1,596.0	4,223.0 g/	2,309.0
1974	3,860.1	1,941.0	566.0	1,972.0	5,217.0
1975	3,909.0	5,384.1	1,251.0	568.0	451.0
1976	524.1	2,441.1	958.0	716.0	2,021.0
Mean	2,515.0	3,389.8	834.7	1,064.8	1,524.6
± S.E.h/	±364.2	±626.0	±135.5	±228.0	±295.2

a/ Includes inflow from all contributing river and coastal drainage basins
b/ Hurricane Carla, Sept. 8-14; near Port Lavaca
c/ Hurricane Cindy, Sept. 16-20; near Port Arthur
d/ Hurricane Beulah, Sept. 18-23; near Brownsville
e/ Hurricane Celia, Aug. 3-5; near Port Aransas
f/ Hurricane Fern, Sept. 9-13; near Port Aransas
g/ Hurricane Delia, Sept. 4-7; near Galveston
h/ Standard error of the mean; two standard errors provide approximately 95% confidence limits about the mean

$Q_{1,t-b_1}$ = winter season (January-March) mean monthly freshwater inflow in thousands of acre-feet at year $t-b_1$, where b_1 is a positive integer (Table 8-6);

$Q_{2,t-b_2}$ = spring season (April-June) mean monthly freshwater inflow in thousands of acre-feet at year $t-b_2$, where b_2 is a positive integer (Table 8-6);

$Q_{3,t-b_3}$ = summer season (July-August) mean monthly freshwater inflow in thousands of acre-feet at year $t-b_3$, where b_3 is a positive integer (Table 8-6);

$Q_{4,t-b_4}$ = autumn season (September-October) mean monthly freshwater inflow in thousands of acre-feet at year $t-b_4$, where b_4 is a positive integer (Table 8-6);

$Q_{5,t-b_5}$ = late fall season (November-December) mean monthly freshwater inflow in thousands of acre-feet at year $t-b_5$, where b_5 is a positive integer (Table 8-6);

MAX $Q_{n,t-b_n}$ = maximum monthly freshwater inflow during seasonal interval (Q_n) in thousands of acre-feet at year $t-b_n$, where b_n is a positive integer (Table 8-6).

In some cases the fisheries component harvests appear to relate curvilinearly to freshwater inflow. Therefore, in order to permit continued use of the stepwise multiple linear regression procedure it is necessary to transform the data variates to linearity. Natural log (ln) transformation of both dependent and independent variables improves the linear fit of many curves and a typical form of the double log transformed regression equation can be rewritten as follows:

$$\ln H_t = a_0 + a_1 (\ln Q_{1,t-b_1}) + \ldots + a_n (\ln Q_{n,t-b_n}) + e$$

where the variables are the same as defined above.

In practice, the time series for the dependent harvest variable (H) is the aforementioned inclusive period 1962 through 1976 for the inshore fisheries components and 1959 through 1976 for the offshore shrimp components, giving 15 and 18 annual harvest observations, respectively. In the multiple regression analyses, the independent variables (e.g.,$Q_1 \ldots Q_n$) each contain a number of observations equal to their associated dependent variable (H); however, the time series is not necessarily concomitant with that of harvest, varying because of consideration of species life history aspects involved in the analysis of different fisheries components. Depending upon the specific fishieries component being analyzed, the time factor (t-b) of the independent variables can be the same year as harvest (t-0), one-year antecedent to harvest (t-1), or a running average from three antecedent years before harvest

$$\left[\sum_{b=1}^{3} (t-b) \div 3 \right].$$

Table 8-6. Time Series Alignments of Dependent/Independent Data Variates for Fisheries Regression Analysis

H_t Fisheries Component	Q_1 (Jan.-Mar.)	Q_2 (Apr.-Jun.)	Q_3 (Jul.-Aug.)	Q_4 (Sep.-Oct.)	Q_5 (Nov.-Dec.)	Max Q_n
Shellfish a/ All Penaeid Shrimp White Shrimp Brown & Pink Shrimp (Inshore 1962-1976)	t-0 c/ and t-1 d/	t-0 and t-1	t-0 and t-1	t-0 and t-1	t-1	t-0 for Max Q_1 and Max Q_2; t-1 for Max Q_5
All Penaeid Shrimp White Shrimp Brown & Pink Shrimp (Offshore 1959-1976)	t-0	t-0	t-0	t-0	t-1	(not applied)
Blue Crab Bay Oyster (Inshore 1962-1976)	t-1	t-1	t-1	t-1	t-1	t-0 for Max Q_1 for Max Q_2; t-1 for Max Q_5
Finfish b/ Spotted Seatrout Red Drum Black Drum (Inshore 1962-1976)	$\frac{\sum_{b=1}^{3}(t-b)}{3}$ e/	$\frac{\sum_{b=1}^{3}(t-b)}{3}$	$\frac{\sum_{b=1}^{3}(t-b)}{3}$	$\frac{\sum_{b=1}^{3}(t-b)}{3}$	$\frac{\sum_{b=1}^{3}(t-b)}{3}$	(not applied)

a/ Multi-species component includes blue crab, bay oyster, and white, brown, and pink shrimp
b/ Multi-species component includes croaker,black drum, red drum, flounder,. sea catfish, spotted seatrout and sheepshead
c/ Inflow same year as harvest
d/ Inflow 1-year antecedent to harvest
e/ Running average inflow from three antecedent years before harvest

Thus, the data alignment between dependent/independent variates in the fisheries analysis is appropriately chosen to take into account the probable lagged effect, in time, of freshwater inflow upon production and subsequent harvest of a particular fisheries component (Table 8-6). This is a standard procedure since it has been long recognized that environmental factors affecting growth and survival of the young in critical developmental periods can show their effect some time later when the affected age-class matures and enters the commercially exploited adult population (84, 175). Early articulation of this idea was put forth by the Norwegian fishery scientist Johan Hjort in 1914 (117) and it is now generally known as "Hjort's critical period concept." This suggests that the ultimate population effect of freshwater inflow is somewhat delayed and can be potentially observed in annual harvest fluctuations of a fisheries component.

A major caveat to regression analysis is that significant correlation of the variables does not, by itself, establish cause and effect (216). Based on the equations alone, definite statements about the true ecological relationships among the variables cannot be made because of the inherent non-causal nature of statistical regression and correlation (84, 215). However, the hypothesis that freshwater inflow is a primary factor influencing the estuary and its production of estuarine-dependent fisheries is well-founded and reasonable considering the substantial volume of previous scientific research demonstrating inflow effects on nutrient cycling, salinity gradients, and the metabolic stresses and areal distributions of estuarine organisms.

Fisheries Analysis Results

Shellfish

Analysis of the shellfish fisheries component yields a significant regression equation that explains 87 percent of the observed variation in shellfish harvest from the estuary (Table 8-7). The equation is statistically significant (α = 2.5%) for correlation of shellfish harvests to spring (Q_2, Q_{-2}, and Max Q_2), summer (Q_3 and Q_{-3}), and late fall (Max Q_{-5}) season freshwater inflows from all contributing river and coastal drainage basins (FINC). Statistical information given for all reported regression equations includes: (1) level of statistical significance (α value); (2) multiple coefficient of determination (r^2 value); (3) standard error of the estimate for the dependent variable, fisheries harvest; (4) standard error of the regression coefficient associated with each independent variable, seasonal freshwater inflow; and (5) upper bounds, lower bounds, and means of the variables entering the equation.

The estimated effect of a correlating seasonal inflow on harvest is computed by holding all other correlating seasonal inflows in the best significant equation constant at their respective mean values, while varying the seasonal inflow of interest from its lower to upper observed bounds. Repeating this process for each correlating seasonal inflow in the best significant equation and plotting the results permits illustration of the effects of individual seasonal inflow variables on the estimate of harvest. For example, Panel A of Figure 8-1 shows the estimate of annual inshore shellfish harvest decreasing from about 11.0 million pounds to 4.2 million pounds as the inflow during the April-June (Q_2) interval increases from its observed lower bounds

Table 8-7. Equations of Statistical Significance Relating the Shellfish Fisheries Component to Freshwater Inflow Categories a/

Trinity-San Jacinto Estuary Shellfish Harvest = f (seasonal FINTD b/)
(no significant equation)

Trinity-San Jacinto Estuary Shellfish Harvest = f (seasonal FINSJ c/)
(no significant equation)

Trinity-San Jacinto Estuary Shellfish Harvest = f (seasonal FINC d/)
Significant Log Equation (α = 2.5%; r^2 = 87%; S.E.Est. = $\pm$ 1026.5)

$$H_{sf} = 8965.7 - \underset{(1.01)}{2.43} (Q_2) + \underset{(2.82)}{8.55} (Q_3) + \underset{(0.46)}{1.33} (Q_{-2}) - \underset{(2.04)}{12.16} (Q_{-3})$$

$$- \underset{(0.00014)}{0.00042} (Max\ Q_{-5})^2 + \underset{(1.34)}{4.19} (Max\ Q_2) - \underset{(0.00022)}{0.00092} (Max\ Q_2)^2$$

	H_{sf}	Q_2	Q_3	Q_{-2}	Q_{-3}	$(Max\ Q_{-5})^2$
upper bounds	12,097.7	2,962.0	798.0	2,962.0	798.0	10,349,089.0
upper bounds	5,254.1	157.0	112.5	157.0	112.5	36,481.0
mean	8,592.6	1,165.8	334.6	1,168.3	351.3	1,382,120.8

	Max Q_2	$(Max\ Q_2)^2$
upper bounds	4,567.0	20,857,489.0
lower bounds	198.0	39,204.0
mean	1,738.5	4,795,652.8

Where:

H_{sf} = Inshore commercial shellfish harvest, in thousands of pounds;

Q = mean monthly freshwater inflow, in thousands of acre-feet:

Q_1 = Jan.-Mar.	Q_4 = Sept.-Oct.
Q_2 = Apr.-Jun.	Q_5 = Nov.-Dec.
Q_3 = Jul.-Aug.	Q_{-n} = 1-yr. antecedent seasonal inflow

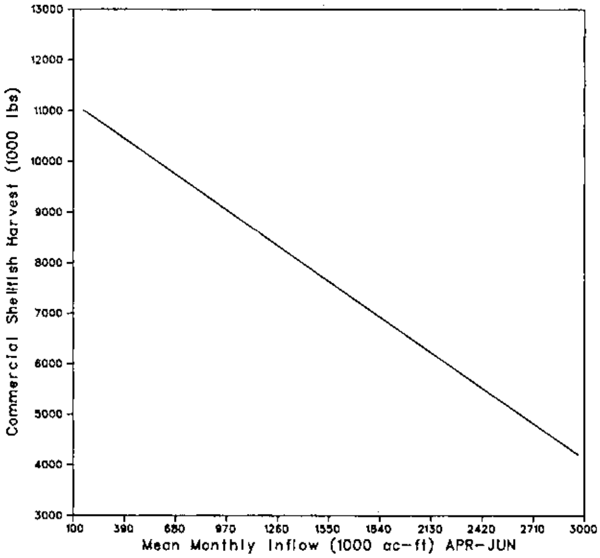
Max Q_n = maximum monthly freshwater inflow during seasonal interval (Q_n), in thousands of acre-feet.

a/ Standard error ($\pm$) of each regression coefficient is shown in parentheses beneath the coefficients of the regression equations

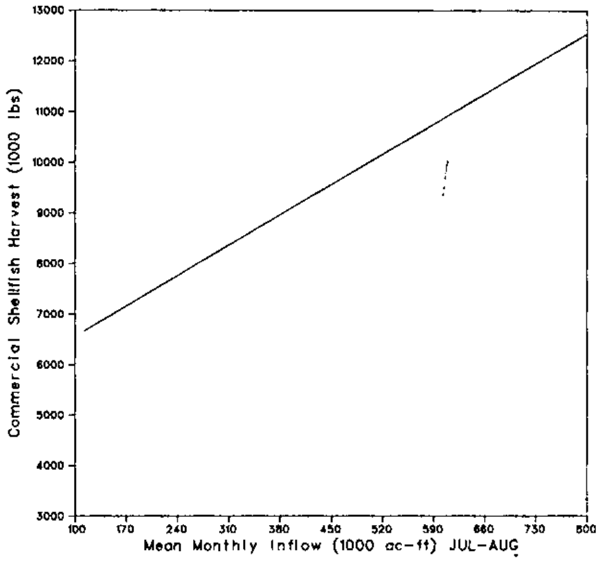
b/ FINTD = Freshwater inflow at Trinity Delta

c/ FINSJ = Freshwater inflow from San Jacinto River

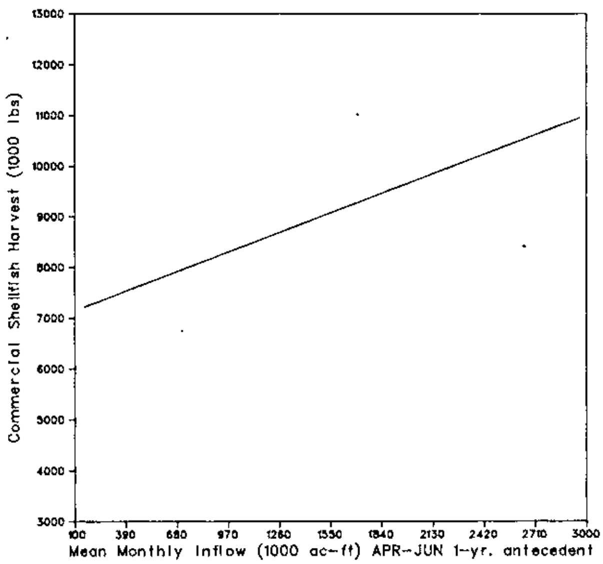
d/ FINC = Combined freshwater inflow to the estuary from all contributing river and coastal drainage basins



A. regression coefficient (slope) = -2.43,
standard error = ±1.01

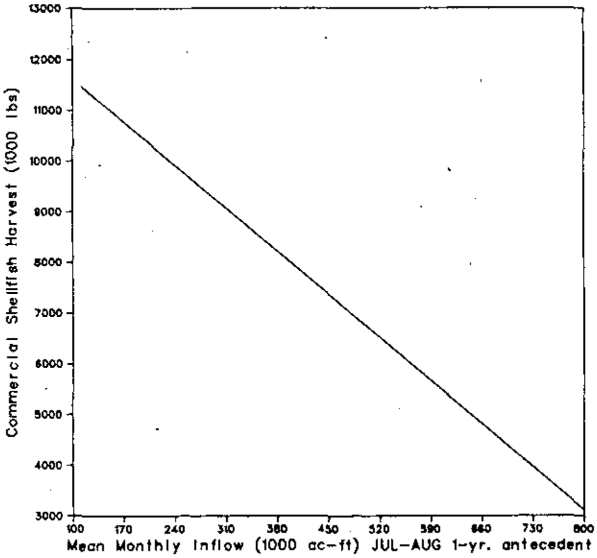


B. regression coefficient (slope) = +8.55,
standard error = ±2.82

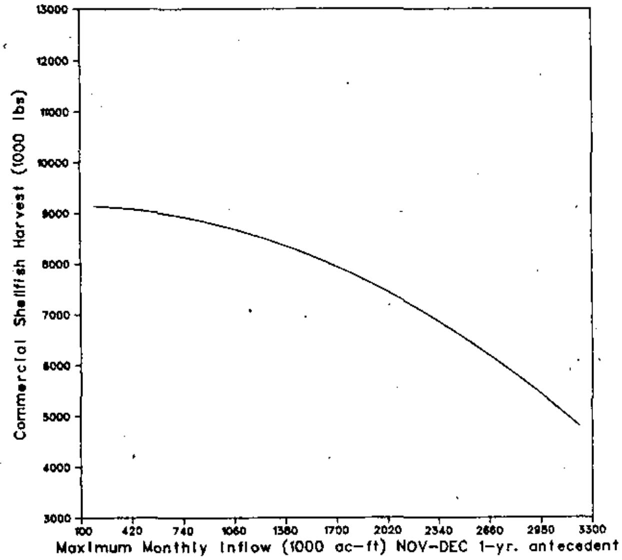


C. regression coefficient (slope) = +1.33,
standard error = ±0.46

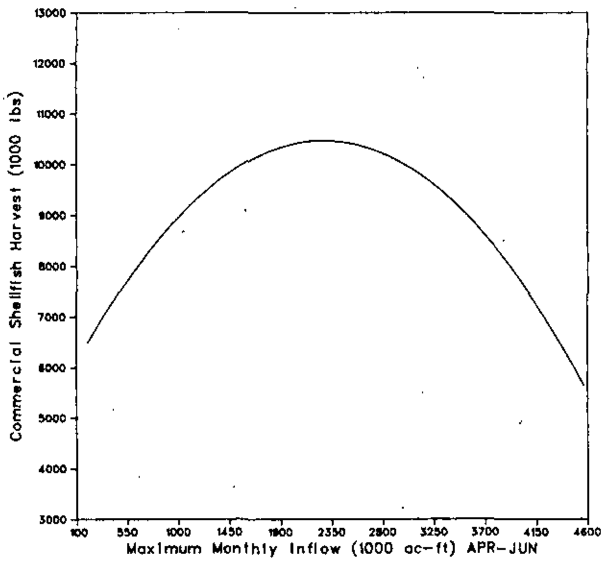
Figure 8-1. Inshore Commercial Shellfish Harvest as a Function of Each Seasonal Inflow From Combined River and Coastal Drainage Basins, Where all Other Seasonal Inflow in the Multiple Regression Equation are Held Constant at Their Mean Values



D. regression coefficient (slope) = -12.16,
standard error = ±2.04



E. See Table 8-7 for regression coefficient
and standard error



F. See Table 8-7 for regression coefficients
and standard errors

Figure 8-1. (Continued)

of 157.0 thousand acre-feet per month to its observed upper bounds of about 3.0 million acre-feet per month. Thus, the negative (-) sign on the regression coefficient (a_2) for the Q_2 inflow term in the equation is illustrated as a line of negative slope relating increasing spring season inflow to a decreasing estimate of annual harvest. It is noted that this line can be shifted upward or downward in a parallel manner from that which has been graphed by holding any of the other correlating seasonal inflow terms in the equation at specified levels of interest other than their mean observed values. For instance, if the positively correlating July-August (Q_3) inflow term is specified at some level lower than its mean of 334.6 thousand acre-feet per month while the other inflow terms in the equation remain at their mean observed values, then the estimated harvest response to April-June (Q_2) inflow would be similar to that shown in Panel A (Figure 8-1) and would have the identical negative slope; however, the computed line would be shifted downward and parallel to that which is graphed. Analogous circumstances exist for each of the harvest responses illustrated, but to facilitate comparisons only the seasonal inflow of interest in each panel graph is varied, while all others in the equation are held constant at their respective mean values.

Panel B (Figure 8-1) exhibits the positive response of shellfish harvest to summer season freshwater inflow from the same year as harvest. The estimate of harvest increases 1.9 times (from about 6.7 to 12.5 million pounds annually) as the July-August (Q_3) inflow increases from its observed lower bounds of 112.5 thousand acre-feet per month to its observed upper bounds of 798.0 thousand acre-feet per month.

Panel C (Figure 8-1) shows another positive harvest response to freshwater inflow. In this case, the estimate of shellfish harvest increases 1.5 times (from about 7.2 to 11.0 million pounds annually) as the 1-year antecedent April-June (Q_2) inflow increases from 157.0 thousand acre-feet per month to about 3.0 million acre-feet per month. Comparing Panel A to Panel C indicates that while spring season inflow from the same year as harvest are negatively related to shellfish harvest, spring season inflow from 1-year antecedent to harvest are positively related to shellfish harvest; however, the combined effect of both inflow terms in the equation is negative since the negative regression coefficient is larger than the positive one. The dichotomy in harvest response to spring season inflow is probably due to the content of the multi-species fisheries component for shellfish, since the component contains species that may be greater affected by inflows during the same year as harvest (e.g., brown shrimp) and species that may be greater affected by inflows 1-year antecedent to harvest (e.g., bay oyster).

Summer season inflow 1-year antecedent to harvest (Q_{-3}) exhibits a strong negative relationship to shellfish harvest and the harvest estimate declines 72.7 percent (from about 11.5 to 3.1 million pounds annually) as July-August inflow increases from 112.5 thousand acre-feet per month to 798.0 thousand acre-feet per month (Panel D, Figure 8-1). Similar to the previous example, a comparison of Panels B and D indicates differential responses of harvest to the timing of this season's inflow. Again, a probable explanation for the estimated positive harvest response to inflow in the same year, and negative response to 1-year antecedent inflow in the same season, may be found in the multi-species composition of the shellfish fisheries component where divergent species responses to inflow appear (also see Table 8-16).

A slight negative relationship of shellfish harvest to the square of the 1-year antecedent maximum monthly inflow in the late fall season (Max Q_{-5}) suggests a negative effect of high inflow events (i.e., floods) from this season on harvest. Panel E (Figure 8-1) illustrates this effect as a 47 percent decline in the estimate of harvest (from about 9.1 to 4.8 million pounds annually) as the maximum monthly inflow in the November-December seasonal interval increases from 191.0 thousand acre-feet to about 3.2 million acre-feet.

Panel F (Figure 8-1) displays the effect of the last two inflow terms (Max Q_2) and (Max Q_2)^2 in the shellfish harvest equation (Table 8-7). These are considered together because they both relate to the effect of maximum monthly inflow in the spring season on shellfish harvest. The effect is quadratic (i.e., the highest power of the variable is a square, thus (Max Q_2)^2 is a second degree term) and is illustrated as a convex curve with its maximum harvest estimate of about 10.5 million pounds annually occurring at a maximum monthly spring season inflow of about 2.3 million acre-feet. The computed relationship indicates that while moderate amounts of spring (April-June) inflow are beneficial, high inflows appear detrimental to shellfish component harvests.

All Penaeid Shrimp

Analysis of the inshore fisheries component for bay landings of all penaeid shrimp (i.e., white, brown, and pink shrimp) did not yield any significant relationships. However, analysis of the offshore penaeid shrimp harvest (Gulf Area No. 18) results in a highly significant (α = 1.0%) multiple regression equation (Table 8-8), where harvest is expressed as a function of the offshore fishing effort (E_o) and the seasonal freshwater inflows to Trinity San-Jacinto estuary from all contributing river and coastal drainage basins (FINC inflow category). The equation accounts for 87 percent of the observed harvest variation and includes regression variables for winter, spring, and summer inflow, as well as for offshore fishing effort.

The effect of each of the correlating terms in the highly significant equation is illustrated by using the previously discussed procedure of holding all other correlating terms in the equation constant at their respective mean values, while varying the term of interest over its observed range and computing the estimated harvest response (Figure 8-2). The estimate of offshore shrimp harvest is thus shown to decline 41.1 percent (from about 12.0 to 7.0 million pounds annually) as January-March (Q_1) inflow increases from its observed lower bounds of 80.3 thousand acre-feet per month to its observed upper bounds of about 2.0 million acre-feet per month (Panel A, Figure 8-2).

Panel B (Figure 8-2) exhibits the negative relationship of harvest to spring season inflow. In this case, the estimate of offshore shrimp harvest declines 34.9 percent (from about 11.4 to 7.4 million pounds annually) as April-June (Q_2) inflow increases from 157.0 thousand acre-feet per month to about 3.0 million acre-feet per month.

The positive effect of summer inflow is shown in Panel C (Figure 8-2), where the harvest estimate increases 1.4 times (from about 8.9 to 12.6 million pounds annually) as July-August (Q_3) inflow increases from 112.5 thousand acre-feet per month to about 1.2 million acre-feet per month.

Table 8-8. Equations of Statistical Significance Relating the All Penaeid Shrimp Fisheries Component to Freshwater Inflow Categories a/

Trinity-San Jacinto Estuary All Shrimp Harvest = f (seasonal FINTD b/)
(no significant equation)

Trinity-San Jacinto Estuary All Shrimp Harvest = f (seasonal FINSJ c/)
(no significant equation)

Trinity-San Jacinto All shrimp Harvest = f (seasonal FINC d/)
(no significant equation)

Trinity-San Jacinto Estuary Offshore All Shrimp Harvest = f (seasonal FINC $+E_O$)
Very Highly Significant Equation ($\alpha = 0.1\%$, $r^2 = 87\%$, S.E.Est. = $\pm 1,832.0$)

$$OH_{as} = -1,484.3 - \underset{(1.06)}{2.57} (Q_1) - \underset{(0.63)}{1.42} (Q_2) + \underset{(1.87)}{3.56} (Q_3) + \underset{(0.31)}{2.46} (E_o)$$

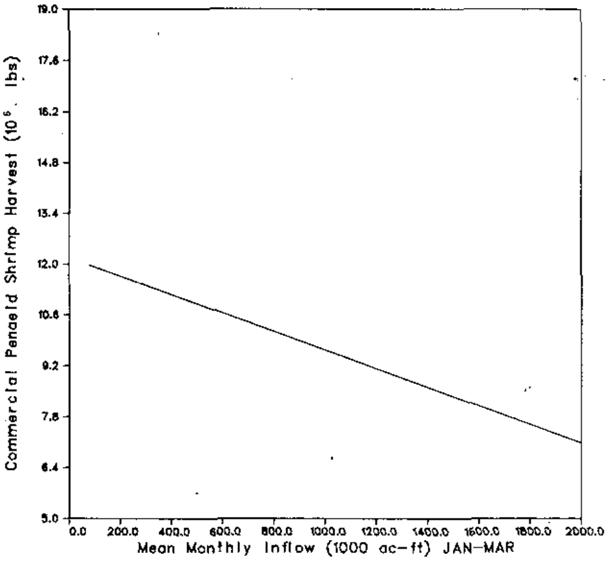
	OH_{as}	Q_1	Q_2	Q_3	E_o
upper bounds	19,790.1	1,996.3	2,962.0	1,150.0	9,002.2
lower bounds	4,930.6	80.3	157.0	112.5	3,763.7
mean	9,995.3	838.3	1,129.9	417.3	5,601.4

Where:

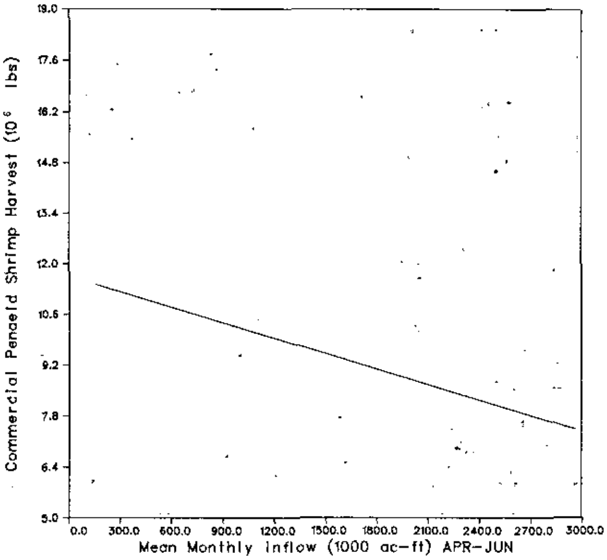
OH_{as} = offshore commercial penaeid shrimp harvest (Area #18), in thousands of pounds;
E_o = offshore harvest effort (Area #18), in number of fishing trips;
Q = mean monthly freshwater inflow, in thousands of acre-feet:

Q_1 = Jan.-Mar.
Q_2 = Apr.-Jun.
Q_3 = Jul.-Aug.
Q_4 = Sept.-Oct.
Q_5 = Nov. -Dec.

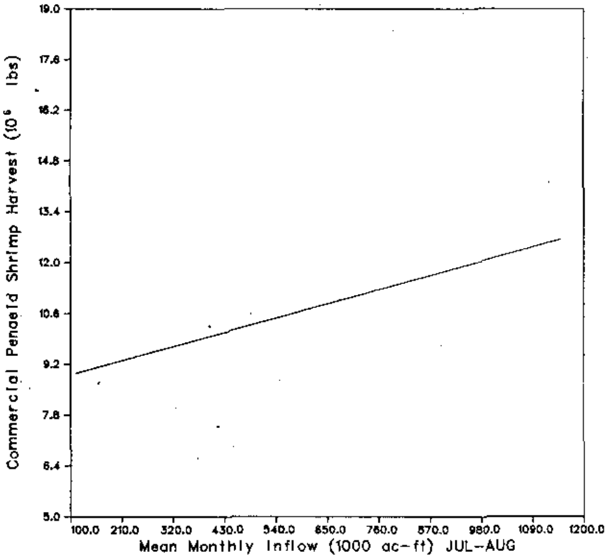
a/ Standard error ($\pm$) of each regression coefficient is shown in parentheses beneath the coefficients of the regression equations
b/ FINTD = Freshwater inflow at Trinity Delta
c/ FINSJ = Freshwater inflow from San Jacinto River
d/ FINC = Combined freshwater inflow to the estuary from all contributing river and coastal drainage basins



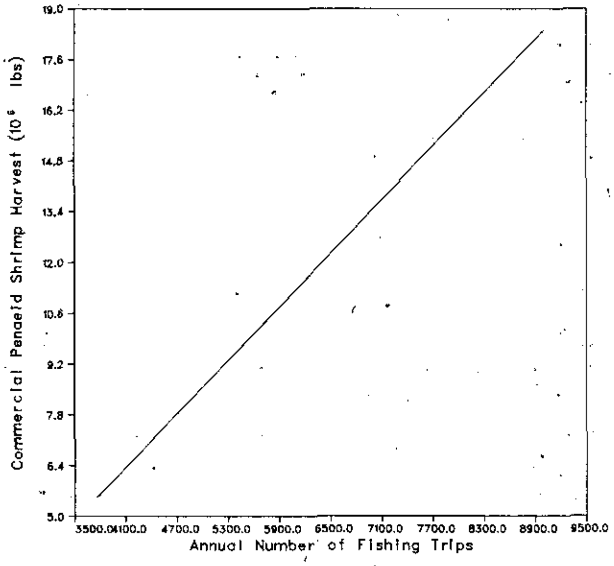
A. regression coefficient (slope) = -2.57,
standard error = ±1.06



B. regression coefficient (slope) = -1.42,
standard error = ±0.63



C. regression coefficient (slope) = +3.56,
standard error = ±1.87



D. regression coefficient (slope) = +2.46,
standard error = ±0.31

Figure 8-2. Offshore Commercial Penaeid Shrimp Harvest as a Function of Fishing Effort and Each Seasonal Inflow From Combined River and Coastal Drainage Basins, Where all Other Seasonal Inflows in the Multiple Regression Equation are Held Constant at Their Mean Values

As might be anticipated, fishing effort appears positively related to shrimp harvest (Panel D, Figure 8-2). Specifically, the estimate of harvest increases 3.3 times (from about 5.5 to 18.4 million pounds annually) as fishing effort increases from about 3.8 to 9.0 thousand fishing trips per year by shrimp vessels.

White Shrimp

Analysis of the inshore white shrimp component also did not yield any significant relationships. However, analysis of the offshore white shrimp harvest (Gulf Area No. 18; catch at $\leq$ 20 fathoms depth) gives a highly significant (α = 1.0%) equation (Table 8-9) that explains 61 percent of the observed harvest variation as a function of offshore fishing effort (E_o) and spring, summer, and autumn season freshwater inflows to the estuary from all contributing river and coastal drainage basins (FINC).

The effect of spring season inflow is computed to be positive and the estimate of offshore white shrimp harvest increases 1.4 times (from about 2.5 to 3.4 million pounds) as April-June (Q_2) inflow increases over its observed range (Panel A, Figure 8-3). On the other hand, Panel B (Figure 8-3) shows the harvest estimate declining 35.1 percent (from about 3.1 to 2.0 million pounds annually) as July-August (Q_3) inflow increases over its observed range. Another positive relationship of harvest to inflow is shown in Panel C (Figure 8-3), where the harvest estimate increases 1.5 times (from about 2.5 to 3.8 million pounds annually) as September-October (Q_4) inflow increases from 85.0 thousand acre-feet per month to about 2.1 million acre-feet per month. Again, fishing effort (E_o) is postivily related to harvest with the harvest estimate increasing 2.1 times (from about 2.0 to 4.2 million pounds annually) as effort increases from about 3.4 to 8.1 thousand fishing trips per year (Panel D, Figure 8-3).

Brown and Pink Shrimp

Analysis of the fisheries component for brown and pink shrimp results in four significant regression equations (Table 8-10). The best significant equation (fourth equation, Table 8-10) accounts for 80 percent of the observed variation in offshore harvest (Gulf Area No. 18) and is very highly significant (α = 0.1%) for correlation of harvest to fishing effort (E_o) and winter, spring, summer, and autumn season freshwater inflows to the estuary from all contributing river and coastal drainage basins (FINC).

The effects of each of the variables in the best significant equation are shown in Figure 8-4. A negative relationship of harvest to winter inflow is shown in Panel A (Figure 8-4), where the estimate of harvest declines 44 percent (from about 8.7 to 4.9 million pounds annually) as January-March (Q_1) inflow increases over its observed range. Panel B (Figure 8-4) also displays a negative relationship of harvest to spring season inflow. Here, the harvest estimate declines 56.4 percent (from about 8.9 to 3.9 million pounds annually) as April-June (Q_2) inflow increases over its observed range. On the other hand, the estimate of harvest increases 1.9 times (from about 5.6 to 10.9 million pounds annually) as July-August (Q_3) inflow increases over its observed range (Panel C, Figure 8-4). Another negative relationship, in this case with autumn season inflow, is illustrated in Panel D (Figure 8-4), where

Table 8-9. Equations of Statistical Significance Relating the White Shrimp Fisheries Component to Freshwater Inflow Categories a/

Trinity-San Jacinto Estuary White Shrimp Harvest = f (seasonal FINTD b/)
(no equation)

Trinity-San Jacinto Estuary White Shrimp Harvest = f (seasonal FINSJ c/)
(no equation)

Trinity-San Jacinto Estuary White Shrimp Harvest = f (seasonal FINC d/)
(no equation)

Trinity-San Jacinto Estuary Offshore White Shrimp Harvest = f (seasonal FINC $+E_O$)

Highly Significant Equation ($\alpha = 1.0\%$, $r^2 = 61\%$, S.E. Est. = $\pm$ 710.5)

$$OH_{WS} = 102.5 + \underset{(0.23)}{0.32}(Q_2) - \underset{(0.75)}{1.06}(Q_3) + \underset{(0.41)}{0.63}(Q_4) + \underset{(0.13)}{0.47}(E_O)$$

	OH_{WS}	Q_2	Q_3	Q_4	E_O
upper bounds	4,893.6	2,962.0	1,150.0	2,111.5	8,149.0
lower bounds	1,372.6	157.0	112.5	85.0	3,445.2
mean	2,799.2	1,129.9	417.3	532.4	5,213.0

Where:

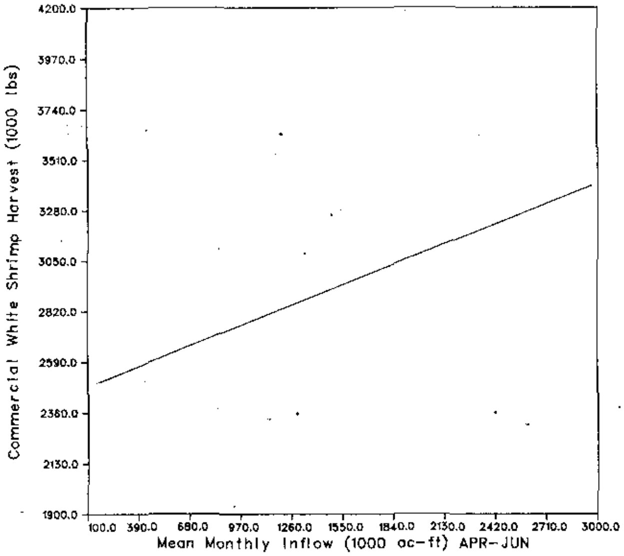
OH_{WS} = offshore commercial white shrimp harvest, ($\leq$ 20 fathoms, Area #18), in thousands of pounds;

E_O = offshore harvest effort ($\leq$ 20 fathoms, Area #18), in number of fishing trips;

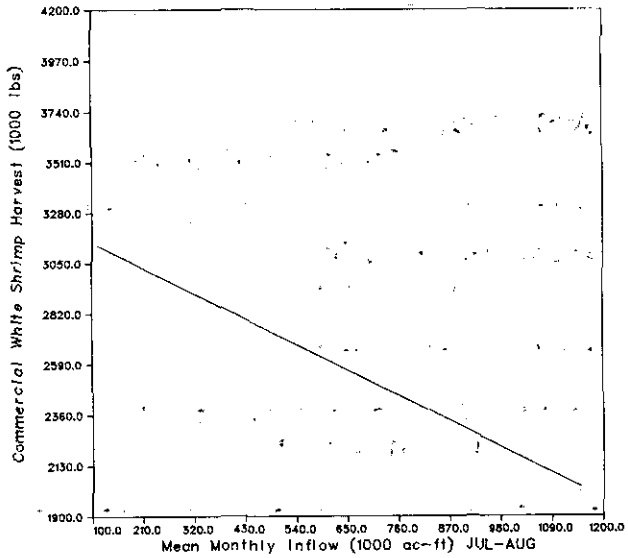
Q = mean monthly freshwater inflow, in thousands of acre-feet:

Q_1 = Jan.-Mar.
Q_2 = Apr.-Jun.
Q_3 = Jul.-Aug.
Q_4 = Sept.-Oct.
Q_5 = Nov. -Dec.

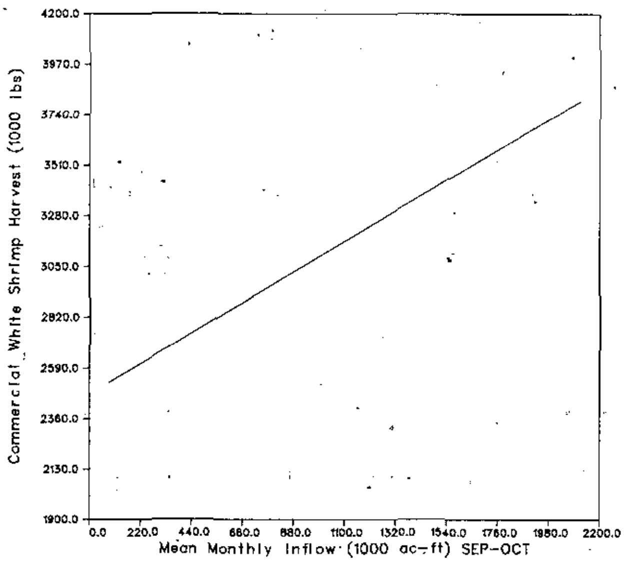
a/ Standard error ($\pm$) of each regression coefficient is shown in parentheses beneath the coefficients of the regression equations
b/ FINTD = Freshwater inflow at Trinity Delta
c/ FINSJ = Freshwater inflow from San Jacinto River
d/ FINC = Combined freshwater inflow to the estuary from all contributing river and coastal drainage basins



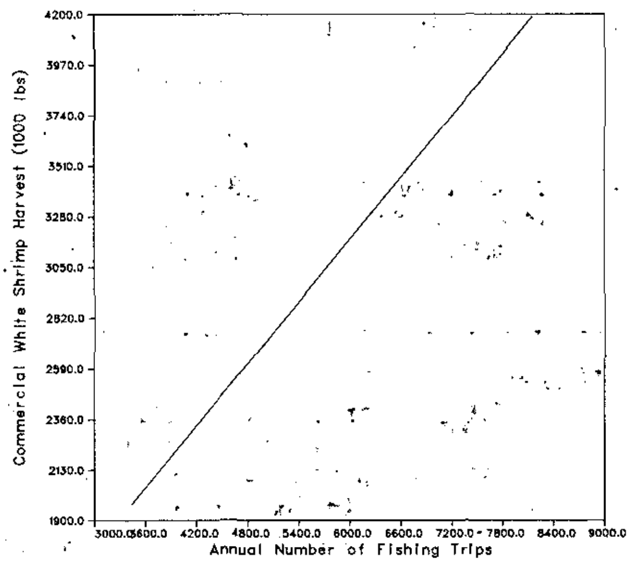
A. regression coefficient (slope) = +0.32, standard error = ±0.23



B. regression coefficient (slope) = -1.06, standard error = ±0.75



C. regression coefficient (slope) = +0.63, standard error = ±0.41



D. regression coefficient (slope) = +0.47, standard error = ±0.13

Figure 8-3. Offshore Commercial White Shrimp Harvest as a Function of Fishing Effort and Each Seasonal Inflow From Combined River and Coastal Drainage Basins, Where all Other Seasonal Inflows in the Multiple Regression Equation are Held Constant at Their Mean Values

Table 8-10. Equations of Statistical Significance Relating the Brown and Pink Shrimp Fisheries Component to Freshwater Inflow Categories a/

Trinity-San Jacinto Estuary Brown and Pink Shrimp Harvest = f (seasonal FINTDb/)
Significant Natural Log Equation (α= 5.0%; r^2 = 44%; S.E. Est. = ± 0.4225)

$$\ln H_{bps} = 8.6836 - \underset{(0.1461)}{0.4365} (\ln Q_2) + \underset{(0.1221)}{0.1953} (\ln Q)$$

	$\ln H_{bps}$	$\ln Q_2$	$\ln Q_3$
upper bounds	7.6256	7.4487	5.8985
lower bounds	5.7295	4.0553	1.6094
mean	6.8526	6.1312	4.3296

Trinity-San Jacinto Estuary Brown and Pink Shrimp Harvest = f (seasonal FINSJc/)
Significant Natural Log Equation (α= 2.5%, r = 64%, S.E. Est. = ± 0.3685

$$\ln H_{bps} = 7.9740 - \underset{(0.1552)}{0.5585} (\ln Q_1) - \underset{(0.4133)}{0.5740} (\ln Q_3) + \underset{(0.2311)}{0.6573} (\ln Q_4) + \underset{(0.1556)}{0.2653} (\ln Q_5)$$

	$\ln H_{bps}$	$\ln Q_1$	$\ln Q_3$	$\ln Q_4$	$\ln Q_5$
upper bounds	7.6256	5.9330	5.6595	6.4077	6.3483
lower bounds	5.7295	3.4563	4.2268	3.7842	3.4012
mean	6.8526	4.8498	4.7077	4.6592	4.6256

Trinity-San Jacinto Estuary Brown and Pink Shrimp Harvest = f (seasonal FINCd/)
Significant Natural Log Equation (α= 5.0%, r = 61%, S.E. Est = ± 0.3834)

$$\ln H_{bps} = 6.8224 - \underset{(0.1597)}{0.4977} (\ln Q_1) - \underset{(0.2060)}{0.2995} (\ln Q_3) + \underset{(0.1618)}{0.4955} (\ln Q_4) + \underset{(0.1749)}{0.3160} (\ln Q_5)$$

	$\ln H_{bps}$	$\ln Q_1$	$\ln Q_3$	$\ln Q_4$	$\ln Q_5$
upper bounds	7.6256	7.3000	6.6821	7.6552	7.8665
lower bounds	5.7295	4.3858	4.7230	4.4427	4.9053
mean	6.8526	6.3280	5.6339	5.8689	6.1993

(continued)

Table 8-10. Equations of Statistical Significance Relating the Brown and Pink Shrimp Fisheries Component to Freshwater Inflow Categories a/ (cont'd)

Trinity-San Jacinto Estuary Offshore Brown and Pink Shrimp Harvest = f (seasonal FINC + E_O)
Very Highly Significant Equation (α = 0.1%, r^2 = 80%, S.E. Est. = $\pm$2194.0)

$$OH_{bps} = -1836.6 - \underset{(1.40)}{1.99}\,(Q_1) - \underset{(0.75)}{1.79}\,(Q_2) + \underset{(2.33)}{5.03}\,(Q_3) - \underset{(1.43)}{1.67}\,(Q_4) + \underset{(0.38)}{2.05}\,(E_o)$$

	OH_{bps}	Q_1	Q_2	Q_3	Q_4	E_o
upper bounds	17,740.1	1996.3	2962.0	1150.0	2111.5	9002.2
lower bounds	2,988.0	80.3	157.0	112.5	85.0	3763.7
mean	7,181.0	838.3	1129.9	417.3	532.4	5601.4

Where:

- $\ln H_{bps}$ = natural log, inshore commercial brown and pink shrimp harvest, in thousands of pounds;
- OH_{bps} = offshore commercial brown and pink shrimp harvest (Area #18), in thousands of pounds;
- E_o = offshore harvest effort (Area #18), in number of fishing trips;
- Q = mean monthly freshwater inflow, in thousands of acre-feet;
- ln Q = natural log of Q:

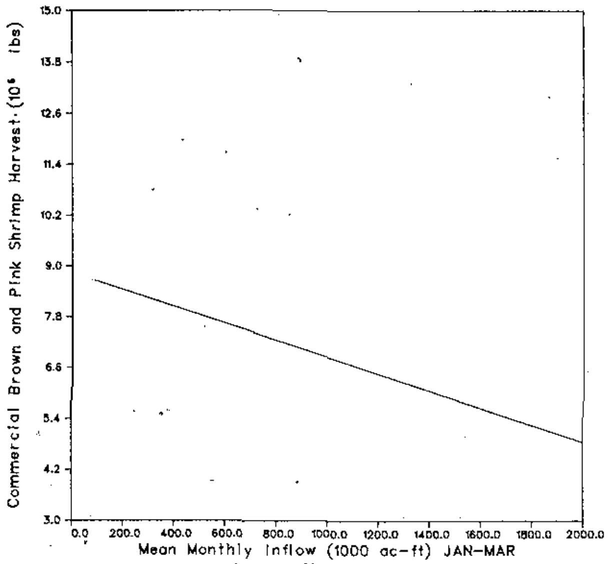
Q_1 = Jan.-Mar.	Q_4 = Sept.-Oct.
Q_2 = Apr.-Jun.	Q_5 = Nov. -Dec.
Q_3 = Jul.-Aug.	

a/ Standard error ($\pm$) of each regression coefficient is shown in parentheses beneath the coefficients of the regression equations

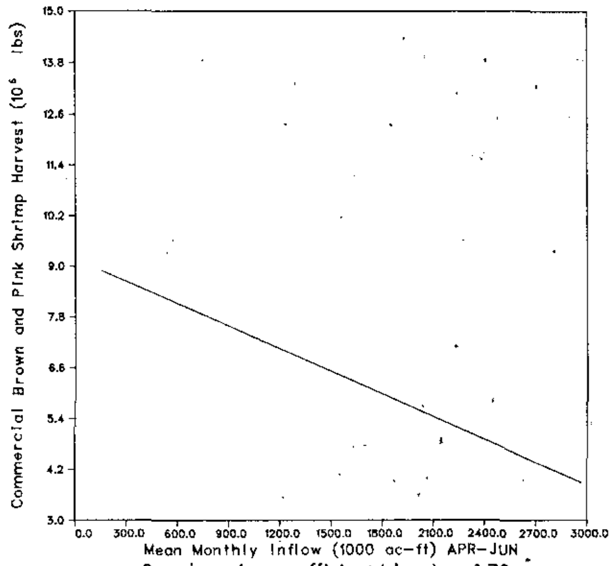
b/ FINTD = Freshwater inflow at Trinity Delta

c/ FINSJ = Freshwater inflow from San Jacinto River

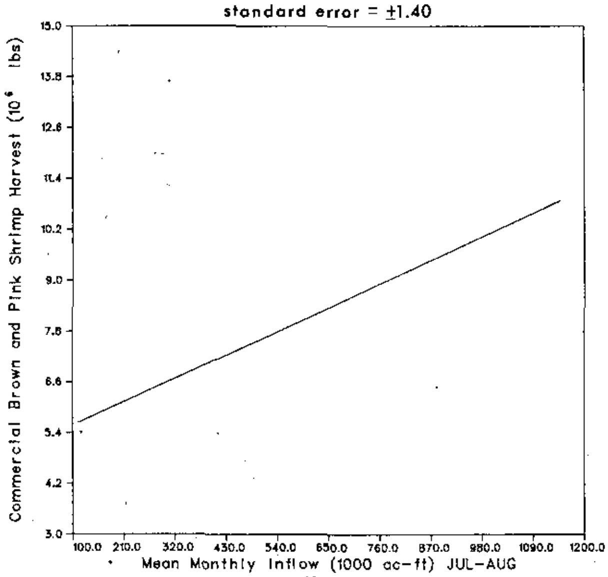
d/ FINC = Combined freshwater inflow to the estuary from all contributing river and coastal drainage basins



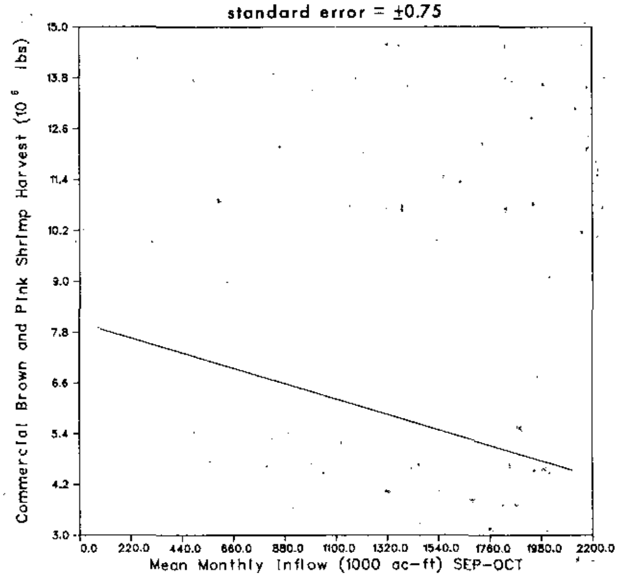
A. regression coefficient (slope) = -1.99, standard error = ±1.40



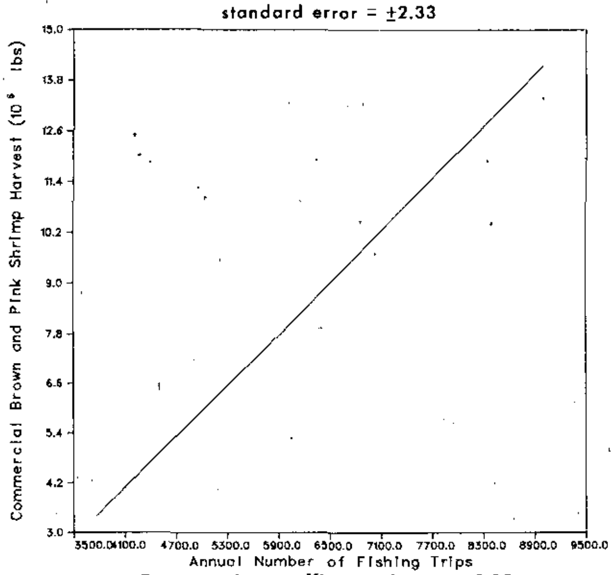
B. regression coefficient (slope) = -1.79, standard error = ±0.75



C. regression coefficient (slope) = +5.03, standard error = ±2.33



D. regression coefficient (slope) = -1.67, standard error = ±1.43



E. regression coefficient (slope) = +2.05, standard error = ±0.38

Figure 8-4. Offshore Commercial Brown & Pink Shrimp Harvest as a Function of Fishing Effort and Each Seasonal Inflow From Combined River and Coastal Drainage Basins, Where all Other Seasonal Inflows in the Multiple Regression Equation are Held Constant at Their Mean Values

the harvest estimate declines 42.8 percent (from about 7.9 to 4.5 million pounds annually) in response to increasing September-October (Q_4) inflow over its observed range. Similar to previous shrimp analyses, fishing effort (E_o) exhibits a strong positive relationship to harvest (Panel E, Figure 8-4). Specifically, the increase in effort from about 3.8 to 9.0 thousand fishing trips per year results in the estimate of annual harvest increasing 4.2 times (from about 3.4 to 14.1 million pounds).

Blue Crab

Analysis of the fisheries component for blue crab bay landings yields a significant equation (Table 8-11) for harvest as a function of seasonal freshwater inflows to the estuary from all contributing river and coastal drainage basins (FINC). The equation is statistically significant (α = 2.5%) for correlation of harvest to 1-year antecedent spring, summer, and autumn season inflows, and explains 58 percent of the observed harvest variation. The estimate of harvest is shown to increase 2.4 times (from about 1.1 to 2.5 million pounds annually) as April-June (Q_2) inflow increases over its observed range (Panel A, Figure 8-5). Panel B (Figure 8-5) displays a strong decline (87.8 percent) of the estimated annual harvest (from about 2.3 million pounds to 282.3 thousands pounds) as July-August (Q_3) inflow increases over its observed range. The positive relationship of harvest to autumn inflow results in the harvest estimate increasing 1.7 times (from about 1.4 to 2.4 million pounds annually) in response to increasing September-October (Q_4) inflow over its observed range (Panel C, Figure 8-5).

Bay Oyster

Analysis of the bay oyster fisheries component gives a significant equation for each of three inflow categories (Table 8-12). The best significant equation (second equation, Table 8-12) involves natural log (ln) transformation of the regression variables, accounts for 79 percent of the observed harvest variation, and is highly significant (α = 0.5%) for correlation of harvest to 1-year antecedent winter, spring, summer, and late fall season freshwater inflows to the estuary from San Jacinto River (FINSJ).

The responses of harvest to each of the inflow variables in the best significant equation are computed similar to previous examples; however, the results are graphed in non-transformed units to show the curvilinearity of harvest responses (Figure 8-6). A weak negative response to winter inflow is illustrated in Panel A (Figure 8-6), where the estimate of annual harvest declines 32 percent (from about 3.1 to 2.1 million pounds of oyster meat) as January-March (Q_1) inflow increases over its observed range. The estimate of annual harvest increases 1.7 times (from about 2.0 to 3.3 million pounds) in response to increasing April-June (Q_2) inflow over its observed range (Panel B, Figure 8-6). A strong negative response to increasing July-August (Q_3) inflow over its observed range results in a 75.9 percent decline in the harvest estimate (from about 4.0 to 1.0 million pounds annually) and is shown in Panel C (Figure 8-6). Another negative harvest response, in this case to late fall inflow, is exhibited in Panel D (Figure 8-6) where the estimated annual harvest declines 41 percent (from about 3.1 to 1.8 million pounds) as November-December (Q_5) inflow increases over its observed range.

Table 8-11. Equations of Statistical Significance Relating the Blue Crab Fisheries Component to Freshwater Inflow Categories a/

Trinity-San Jacinto Estuary Blue Crab Harvest = f (seasonal FINTD b/)
(no significant equation)

Trinity-San Jacinto Estuary Blue Crab Harvest = f (seasonal FINSJ c/)
(no significant equation)

Trinity-San Jacinto Estuary Blue Crab Harvest = f (seasonal FINC d/)
Significant Equation (α = 2.5%, r^2 = 58%, S.E. Est. = $\pm$ 416.0)

$$H_{bc} = 1773.4 + \underset{(0.16)}{0.52}\,(Q_2) - \underset{(0.80)}{2.96}\,(Q_3) + \underset{(0.27)}{0.49}\,(Q_4)$$

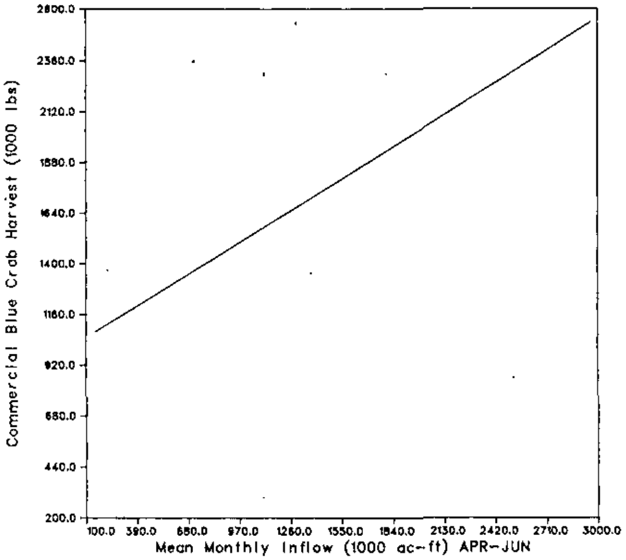
	H_{bc}	Q_2	Q_3	Q_4
upper bounds	2622.0	2962.0	798.0	2111.5
lower bounds	311.2	157.0	112.5	85.0
mean	1606.4	1168.3	351.3	537.6

---

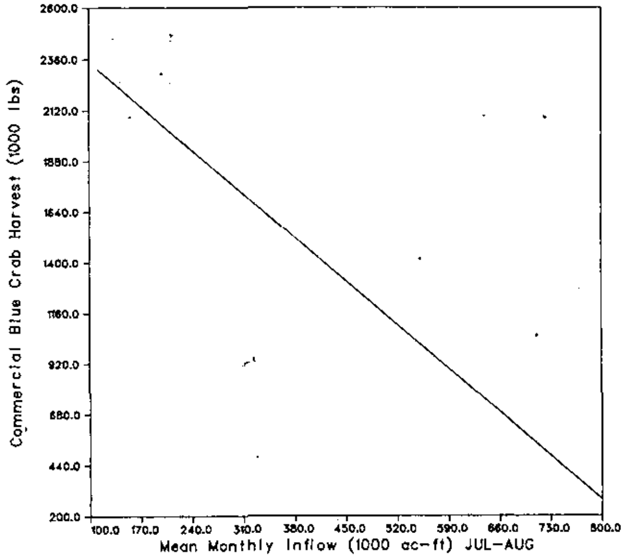
where
H_{bc} = inshore commercial blue crab harvest, in thousands of pounds;
Q = mean monthly freshwater inflow, in thousands of acre-feet:

Q_1 = Jan.-Mar.
Q_2 = Apr.-Jun.
Q_3 = Jul.-Aug.
Q_4 = Sept.-Oct.
Q_5 = Nov. -Dec.

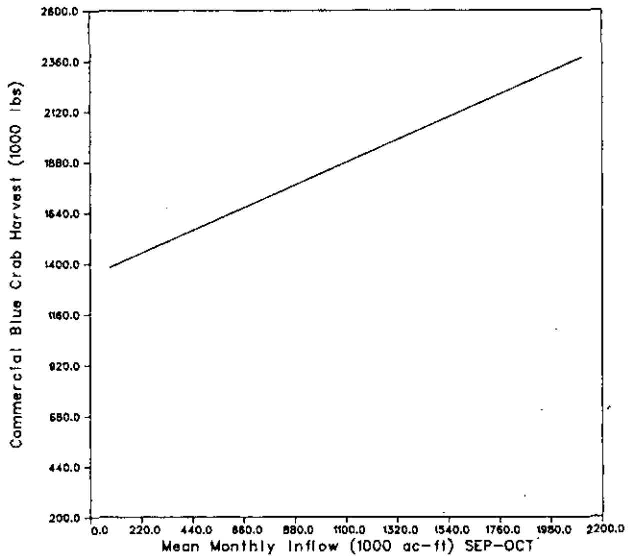
a/ Standard error ($\pm$) of each regression coefficient is shown in parentheses beneath the coefficients of the regression equations
b/ FINTD = Freshwater inflow at Trinity Delta
c/ FINSJ = Freshwater inflow from San Jacinto River
d/ FINC = Combined freshwater inflow to the estuary from all contributing river and coastal drainage basins



A. regression coefficient (slope) = +0.52,
standard error = ±0.16



B. regression coefficient (slope) = -2.96,
standard error = ±0.80



C. regression coefficient (slope) = +0.49,
standard error = ±0.27

Figure 8-5. Inshore Commercial Blue Crab Harvest as a Function of Each Seasonal Inflow From Combined River and Coastal Drainage Basins, Where all Other Seasonal Inflows in the Multiple Regression Equation are Held Constant at Their Mean Values

Table 8-12. Equations of Statistical Significance Relating the Bay Oyster Fisheries Component to Freshwater Inflow Categories a/

Trinity-San Jacinto Estuary Bay Oyster Harvest = f (seasonal FINTD b/)
Significant Equation (α = 2.5%, r^2 = 65%, S.E. Est. = $\pm$ 833.1)

$$H_{bo} = 3618.7 - \underset{(0.73)}{0.69}\,(Q_1) + \underset{(0.53)}{0.91}\,(Q_2) - \underset{(3.06)}{3.68}\,(Q_3) - \underset{(0.91)}{2.31}\,(Q_4)$$

	H_{bo}	Q_1	Q_2	Q_3	Q_4
upper bounds	4583.3	1350.3	1717.7	364.5	1061.0
lower bounds	749.9	35.7	57.7	5.0	21.0
mean	2825.4	565.6	716.0	135.0	243.3

Trinity-San Jacinto Estuary Bay Oyster Harvest = f (seasonal FINSJ c/)
Highly Significant Natural Log Equation (α = 0.5%, r^2 = 79%, S.E. Est. = $\pm$0.3093)

$$\ln H_{bo} = 12.7429 - \underset{(0.1355)}{0.1407}\,(\ln Q_1) + \underset{(0.1288)}{0.1873}\,(\ln Q_2) - \underset{(0.2434)}{0.9168}\,(\ln Q_3) - \underset{(0.1207)}{0.1792}\,(\ln Q_5)$$

	$\ln H_{bo}$	$\ln Q_1$	$\ln Q_2$	$\ln Q_3$	$\ln Q_5$
upper bounds	8.4302	6.1979	6.6165	5.7792	6.3483
lower bounds	6.6199	3.4563	3.9259	4.2268	3.4012
mean	7.8246	5.0241	5.1949	4.7510	4.6256

Trinity-San Jacinto Estuary Bay Oyster Harvest = F (seasonal FINC d/)
Significant Equation (α = 2.5%, r^2 = 69%, S.E. Est. = $\pm$ 776.2)

$$H_{bo} = 4205.8 + \underset{(0.31)}{0.47}\,(Q_2) - \underset{(1.51)}{3.41}\,(Q_3) - \underset{(0.60)}{0.58}\,(Q_4) - \underset{(0.42)}{0.62}\,(Q_5)$$

	H_{bo}	Q_2	Q_3	Q_4	Q_5
upper bounds	4583.3	2962.0	798.0	2111.5	2608.5
lower bounds	749.9	157.0	112.5	85.0	140.5
mean	2825.4	1168.3	351.3	537.6	681.3

(Continued)

Table 8-12. Equations of Statistical Significance Relating the Bay Oyster Fisheries Component to Freshwater Inflow Categories a/ (cont'd)

Where:

H_{bo} = commercial bay oyster harvest, in thousands of pounds;

$\ln H_{bo}$ = natural log of H_{bo};

Q = mean monthly freshwater inflow, in thousands of acre-feet;

$\ln Q$ = natural log of Q:

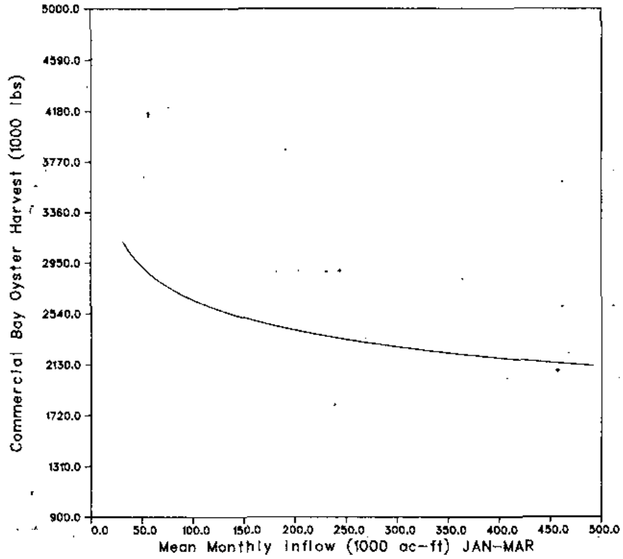
Q_1 = Jan.-Mar.
Q_2 = Apr.-Jun.
Q_3 = Jul.-Aug.
Q_4 = Sept.-Oct.
Q_5 = Nov. -Dec.

a/ Standard error ($\pm$) of each regression coefficient is shown in parentheses beneath the coefficients of the regression equations

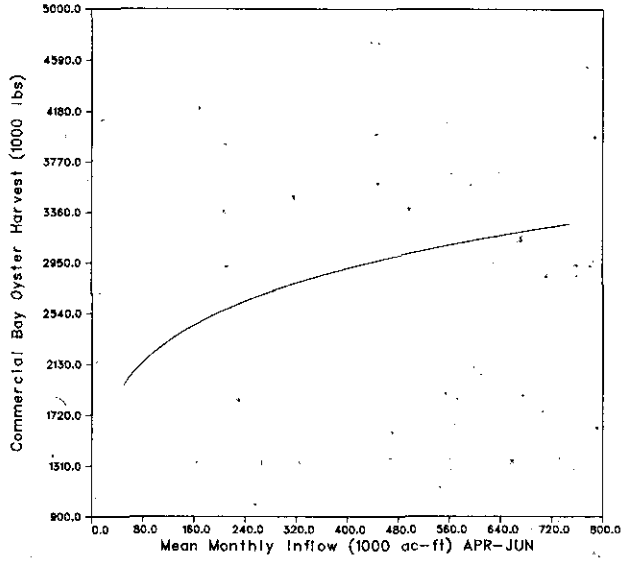
b/ FINTD = Freshwater inflow at Trinity Delta

c/ FINSJ = Freshwater inflow from San Jacinto River

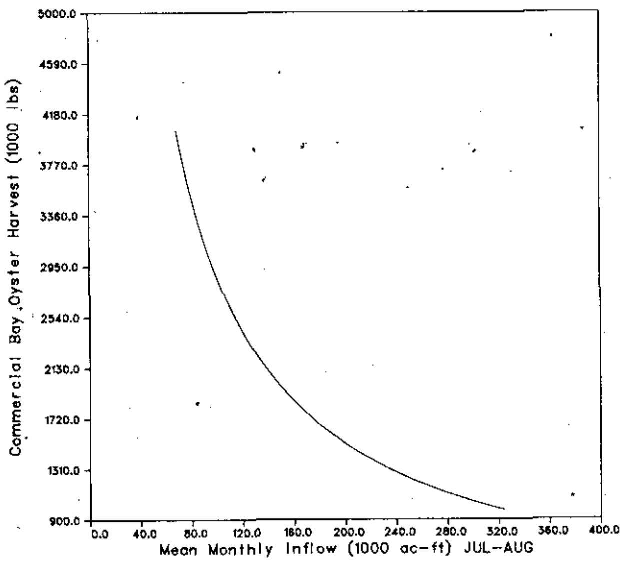
d/ FINC = Combined freshwater inflow to the estuary from all contributing river and coastal drainage basins



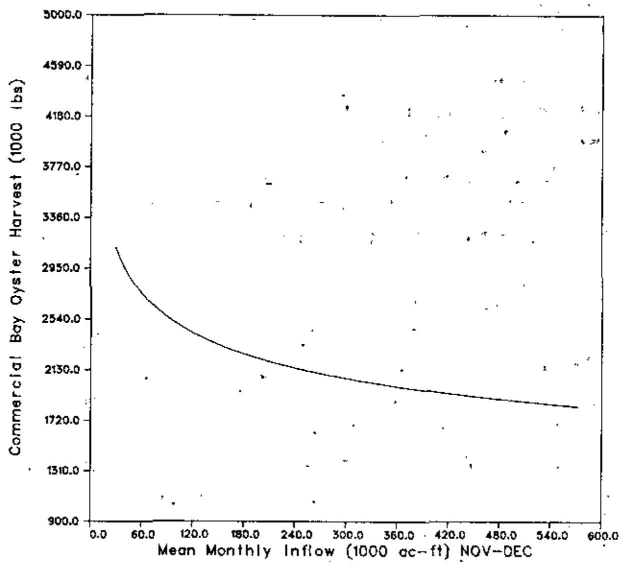
A. regression coefficient = -0.1407, standard error = ±0.1355



B. regression coefficient = +0.1873, standard error = ±0.1288



C. regression coefficient = -0.9168, standard error = ±0.2434



D. regression coefficient = -0.1792, standard error = ±0.1207

Figure 8-6. Commercial Oyster Harvest as a Function of Each Seasonal Inflow From the San Jacinto River, Where all Other Seasonal Inflows in the Natural Log Multiple Regression Equation are Held Constant at Their Mean Values

Finfish

Analysis of the multi-species fisheries component for bay landings of finfish results in two significant regression equations (Table 8-13). The best significant equation (second equation, Table 8-13) also involves logarithmic (ln) transformation of the regression variables, explains 51 percent of the observed harvest variation, and is significant (α = 5.0%) for correlation of harvest to 3-year average antecedent summer, autumn, and late fall season inflows to the estuary from San Jacinto River (FINSJ).

Again, the effects of each of the correlating seasonal inflows are graphed in non-transformed units to show the curvilinearity of the estimated harvest responses (Figure 8-7). The negative relationship between harvest and summer inflow is illustrated in Panel A (Figure 8-7), where the harvest estimate declines 97.3 percent (from about 1.4 million to 36.7 thousand pounds annually) as July-August (Q_3) inflow increases from its lower to upper observed bounds. On the other hand, the estimate of annual harvest increases 5.6 times (from 117.3 to 651.3 thousand pounds) as September-October (Q_4) inflow increases over its observed range (Panel B, Figure 8-7). Another positive harvest response, in this case to late fall inflow, is shown in Panel C (Figure 8-7), where the annual harvest estimate increases 2.2 times (from about 224.7 to 489.0 thousand pounds) as November-December (Q_5) inflow increases over its observed range.

Spotted Seatrout

Analysis of the spotted seatrout fisheries component yields a significant harvest equation for each of the three inflow categories (Table 8-14). The best significant equation (first equation, Table 8-14) accounts for 70 percent of the observed harvest variation and is highly significant (α = 0.5%) for correlation of the bay landings to 3-year average antecedent winter, summer, and autumn season inflows to the estuary at Trinity Delta (FINTD).

The effects of each of the seasonal inflows in the best significant equation on spotted seatrout harvest are shown in Figure 8-8. The response to winter inflow is negative and the estimate of annual harvest declines 74.2 percent (from about 257.6 to 66.5 thousand pounds) as January-March (Q_1) inflow increases over its observed range (Panel A, Figure 8-8). Also, the annual harvest is estimated to decline 54.5 percent (from about 229.3 to 104.3 thousand pounds) as July-August (Q_3) inflow increases over its observed range (Panel B, Figure 8-8). The positive response to autumn inflow results in the harvest estimate increasing 3.4 times (from about 97.9 to 335.9 thousand pounds annually) as September-October (Q_4) inflow increases over its observed range (Panel C, Figure 8-8).

Red Drum

Analysis of the red drum fisheries component also results in a significant harvest equation for each of the three inflow categories (Table 8-15). The best significant equation (first equation, Table 8-15) explains 69 percent of the observed harvest variation and is significant (α = 5.0%) for correlation of the bay landings to freshwater inflows at Trinity Delta (FINTD) from all seasonal intervals (Q_1 through Q_5).

Table 8-13. Equations of Statistical Significance Relating the Finfish Fisheries Component to Freshwater Inflow Categories a/

Trinity-San Jacinto Estuary Finfish Harvest = f (seasonal FINTD b/)
Significant Equation ($\alpha = 2.5\%$, $r^2 = 50\%$, S.E. Est. = $\pm$ 114.6)

$$H_{ff} = 540.1 - \underset{(0.20)}{0.67} (Q_1) + \underset{(0.25)}{0.71} (Q_4)$$

	H_{ff}	Q_1	Q_4
upper bounds	635.1	912.2	581.7
lower bounds	59.9	229.7	96.0
mean	346.6	547.2	240.5

Trinity-San Jacinto Estuary Finfish Harvest = f (seasonal FINSJ c/)
Significant Natural Log Equation ($\alpha = 5.0\%$, $r^2 = 51\%$, S.E. Est. = $\pm$ 0.4721)

$$\ln H_{ff} = 11.3076 - \underset{(0.8314)}{2.5766} (\ln Q_3) + \underset{(0.4877)}{0.9008} (\ln Q_4) + \underset{(0.3902)}{0.4976} (\ln Q_5)$$

	$\ln H_{ff}$	$\ln Q_3$	$\ln Q_4$	$\ln Q_5$
upper bounds	6.4538	5.6630	5.8046	5.8061
lower bounds	4.0927	4.2556	3.9020	4.2437
mean	5.7197	4.8412	4.9617	4.8561

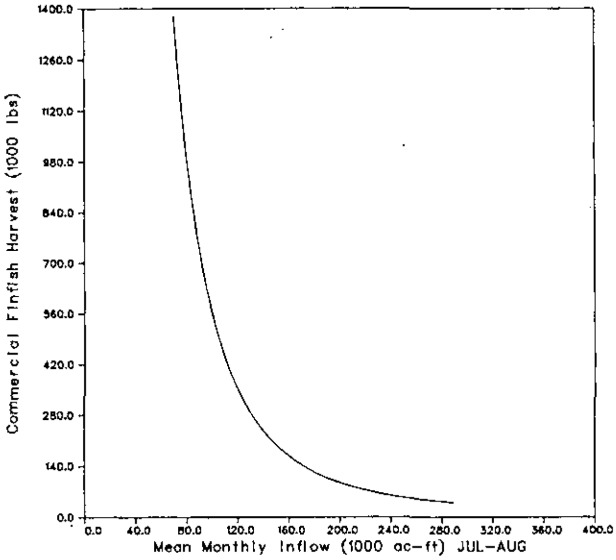
Trinity-San Jacinto Estuary Finfish Harvest = f (seasonal FINC d/)
(no significant equation)

Where:

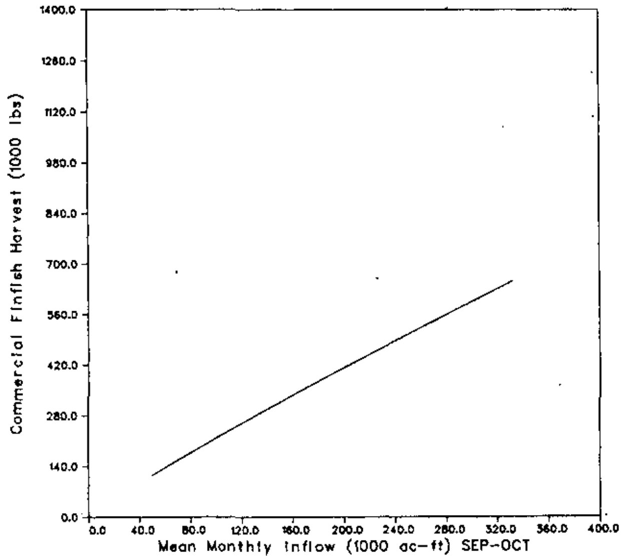
H_{ff} = inshore commercial finfish harvest, in thousands of pounds;
$\ln H_{ff}$ = natural log of H_{ff};
Q = mean monthly freshwater inflow, in thousands of acre-feet;
$\ln Q$ = natural log of Q:

Q_1 = Jan.-Mar.
Q_2 = Apr.-Jun.
Q_3 = Jul.-Aug.
Q_4 = Sept.-Oct.
Q_5 = Nov. -Dec.

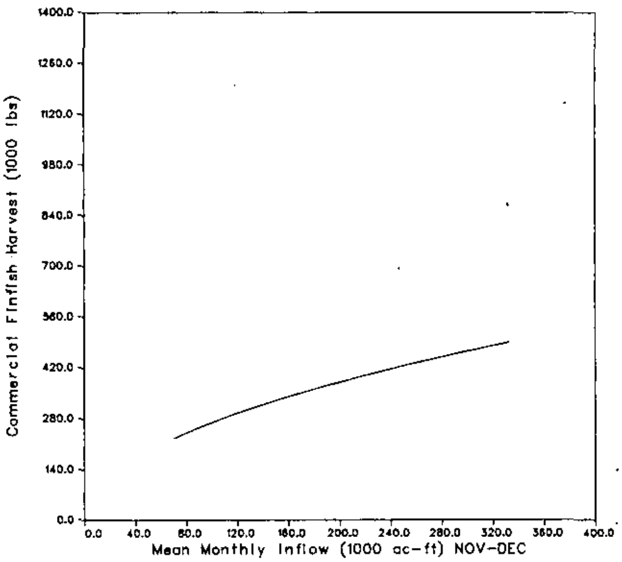
a/ Standard error ($\pm$) of each regression coefficient is shown in parentheses beneath the coefficients of the regression equations
b/ FINTD = Freshwater inflow at Trinity Delta
c/ FINSJ = Freshwater inflow from San Jacinto River
d/ FINC = Combined freshwater inflow to the estuary from all contributing river and coastal drainage basins



A. regression coefficient = -2.5766,
standard error = ±0.8314



B. regression coefficient = +0.9008,
standard error = ±0.4877



C. regression coefficient = +0.4976,
standard error = ±0.3902

Figure 8-7. Inshore Commercial Finfish Harvest as a Function of Each Seasonal Inflow From the San Jacinto River, Where all Other Seasonal Inflows in the Natural Log Multiple Regression Equation are Held Constant at Their Mean Values

Table 8-14. Equations of Statistical Significance Relating the Spotted Seatrout Fisheries Component to Freshwater Inflow Categories a/

Trinity-San Jacinto Estuary Seatrout Harvest = f (seasonal FINTD b/)
Highly Significant Equation ($\alpha = 0.5\%$, $r^2 = 70\%$, S.E. Est. = $\pm$ 51.1)

$$H_{ss} = 272.3 - \underset{(0.11)}{0.28}\,(Q_1) - \underset{(0.28)}{0.50}\,(Q_3) + \underset{(0.11)}{0.49}\,(Q_4)$$

	H_{ss}	Q_1	Q_3	Q_4
upper bounds	280.4	912.2	265.2	581.7
lower bounds	17.0	229.7	15.3	96.0
mean	165.8	547.2	136.4	240.5

Trinity-San Jacinto Estuary Seatrout Harvest = f (seasonal FINSJ c/)
Highly Significant Natural Log Equation Equation ($\alpha = 1.0\%$, $r^2 = 67\%$, S.E. Est. = $\pm$ 0.4886)

$$\ln H_{ss} = 12.0028 - \underset{(0.8606)}{3.8511}\,(\ln Q_3) + \underset{(0.5048)}{1.2948}\,(\ln Q_4) + \underset{(0.4039)}{1.0583}\,(\ln Q_5)$$

	$\ln H_{ss}$	$\ln Q_3$	$\ln Q_4$	$\ln Q_5$
upper bounds	5.6362	5.6630	5.8046	5.8061
lower bounds	2.8332	4.2556	3.9020	4.2437
mean	4.9221	4.8412	4.9617	4.8561

Trinity-San Jacinto Estuary Seatrout Harvest = f (seasonal FINC d/)
Significant Equation ($\alpha = 2.5\%$, $r^2 = 66\%$, S.E. Est. = $\pm$ 56.9)

$$H_{ss} = 281.2 - \underset{(0.11)}{0.23}\,(Q_1) - \underset{(0.15)}{0.21}\,(Q_3) + \underset{(0.14)}{0.15}\,(Q_4) + \underset{(0.11)}{0.11}\,(Q_5)$$

	H_{ss}	Q_1	Q_3	Q_4	Q_5
upper bounds	280.4	1356.7	831.2	1127.2	1148.7
lower bounds	17.0	423.9	122.5	185.2	307.8
mean	165.8	849.1	370.0	542.1	708.5

(Continued)

Table 8-14. Equations of Statistical Significance Relating the Spotted Seatrout Fisheries Component to Freshwater Inflow Categories a/ (Cont'd)

Where:

H_{ss} = inshore commercial spotted seatrout harvest, in thousands of pounds;

ln H_{ss} = natural log of H_{ss};

Q = mean monthly freshwater inflow, in thousands of acre-feet;

ln Q = natural log of Q:

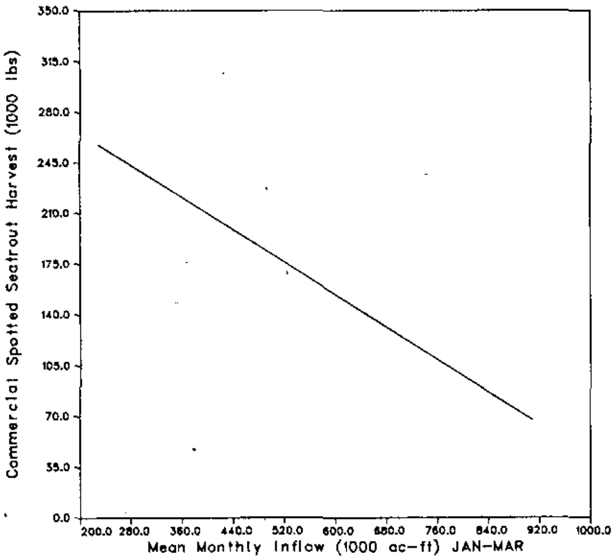
Q_1 = Jan.-Mar.
Q_2 = Apr.-Jun.
Q_3 = Jul.-Aug.
Q_4 = Sept.-Oct.
Q_5 = Nov. -Dec.

a/ Standard error (±) of each regression coefficient is shown in parentheses beneath the coefficients of the regression equations

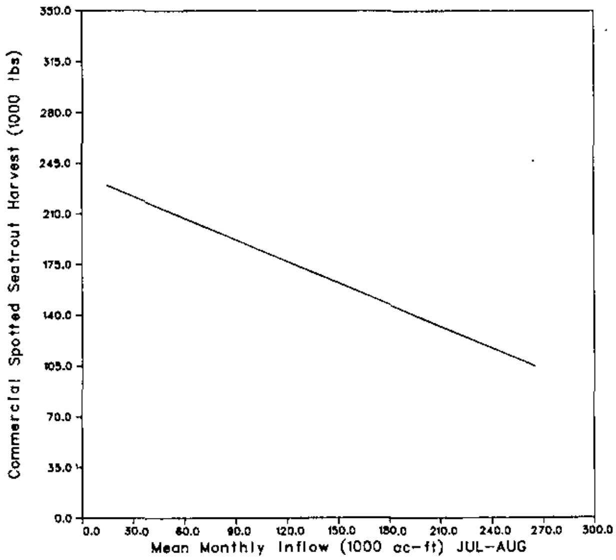
b/ FINTD = Freshwater inflow at Trinity Delta

c/ FINSJ = Freshwater inflow from San Jacinto River

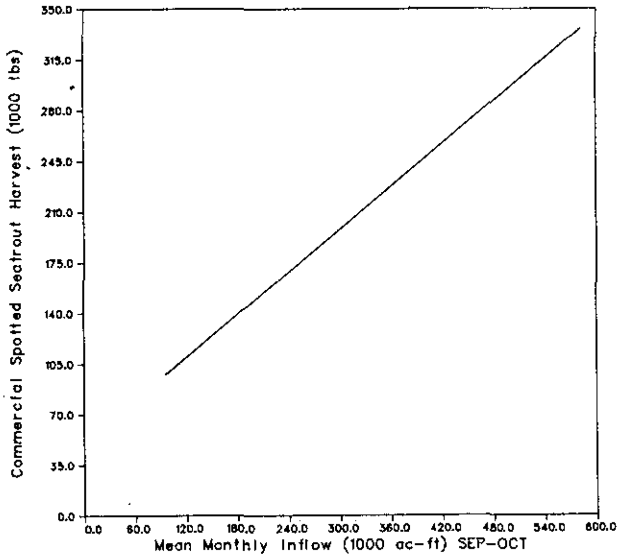
d/ FINC = Combined freshwater inflow to the estuary from all contributing river and coastal drainage basins



A. regression coefficient (slope) = -0.28,
standard error = ±0.11



B. regression coefficient (slope) = -0.50,
standard error = ±0.28



C. regression coefficient (slope) = +0.49,
standard error = ±0.11

Figure 8-8. Inshore Commercial Spotted Seatrout Harvest as a Function of Each Seasonal Inflow at Trinity Delta, Where all Other Seasonal Inflows in the Multiple Regression Equation are Held Constant at Their Mean Values

Table 8-15. Equations of Statistical Significance Relating the Red Drum Fisheries Component to Freshwater Inflow Categories a/

Trinity-San Jacinto Estuary Red Drum Harvest = f (seasonal FINTD b/)
Significant Equation (α = 5.0%, r^2 = 69%, S.E. Est. = $\pm$ 17.6)

$$H_{rd} = 10.6 - \underset{(0.04)}{0.04}\,(Q_1) + \underset{(0.01)}{0.04}\,(Q_2) - \underset{(0.11)}{0.18}\,(Q_3) + \underset{(0.07)}{0.10}\,(Q_4) + \underset{(0.05)}{0.05}\,(Q_5)$$

	H_{rd}	Q_1	Q_2	Q_3	Q_4	Q_5
upper bounds	97.5	912.2	1217.3	265.2	581.7	993.3
lower bounds	1.3	229.7	196.4	15.3	96.0	173.7
mean	36.3	547.2	682.9	136.4	240.5	456.6

Trinity-San Jacinto Estuary Red Drum Harvest = f (seasonal FINSJ c/)
Significant Equation (α = 5.0%, r^2 = 59%, S.E. Est. = $\pm$ 19.2)

$$H_{rd} = 38.5 + \underset{(0.06)}{0.09}\,(Q_2) - \underset{(0.18)}{0.58}\,(Q_3) + \underset{(0.15)}{0.15}\,(Q_4) + \underset{(0.14)}{0.19}\,(Q_5)$$

	H_{rd}	Q_2	Q_3	Q_4	Q_5
upper bounds	97.5	420.0	288.0	331.8	332.3
lower bounds	1.3	76.3	70.5	49.5	69.7
mean	36.3	267.2	137.7	173.0	151.0

Trinity-San Jacinto Estuary Red Drum Harvest = f (seasonal FINC d/)
Highly Significant Equation (α = 1.0%, r^2 = 65%, S.E. Est. = $\pm$ 17.0)

$$H_{rd} = 5.5 + \underset{(0.01)}{0.03}\,(Q_2) - \underset{(0.04)}{0.12}\,(Q_3) + \underset{(0.02)}{0.06}\,(Q_5)$$

	H_{rd}	Q_2	Q_3	Q_5
upper bounds	97.5	1896.0	831.2	1448.7
lower bounds	1.3	336.5	122.5	307.8
mean	36.3	1133.9	370.0	708.5

(Continued)

Table 8-15. Equations of Statistical Significance Relating the Red Drum Fisheries Component to Freshwater Inflow Categories a/. (cont'd)

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where:

H_{rd} = inshore commercial red drum harvest, in thousands of pounds;
Q = mean monthly freshwater inflow, in thousands of acre-feet:

Q_1 = Jan.-Mar.
Q_2 = Apr.-Jun.
Q_3 = Jul.-Aug.
Q_4 = Sept.-Oct.
Q_5 = Nov. -Dec.

a/ Standard error (±) of each regression coefficient is shown in parentheses beneath the coefficients of the regression equations
b/ FINTD = Freshwater inflow at Trinity Delta
c/ FINSJ = Freshwater inflow from San Jacinto River
d/ FINC = Combined freshwater inflow to the estuary from all contributing river and coastal drainage basins

Harvest responses to seasonal inflows in the best significant equation are illustrated in Figure 8-9. Panel A (Figure 8-9) shows the estimate of annual harvest declining 53.4 percent (from about 51.1 to 23.8 thousand pounds) as January-March (Q_1) inflow increases over its observed range. The positive response to spring season inflow results in the harvest estimate increasing 3.2 times (from about 18.9 to 59.7 thousand pounds annually) as April-June (Q_2) inflow increases over its observed range (Panel B, Figure 8-9). Panel C (Figure 8-9) shows a strong negative relationship of summer inflow to harvest and the estimate of harvest declines 74.8 percent (from about 60.2 to 15.2 thousand pounds annually) as July-August (Q_3) inflow increases over its observed range. The estimate of annual harvest increases 3.0 times (from about 23.9 to 72.5 thousand pounds) as September-October (Q_4) inflow increases over its observed range, indicating a positive response to autumn season inflow (Panel D, Figure 8-9). Panel E (Figure 8-9) exhibits another positive harvest response, in this case to late fall season inflow, and the estimate of harvest increases 2.7 times (from about 24.2 to 65.2 thousand pounds annually) as November-December (Q_5) inflow increases over its observed range.

Black Drum

Analysis of the fisheries component for black drum did not result in any significant regression equations for harvest as a function of seasonal freshwater inflows to the estuary.

Fisheries Component Summary

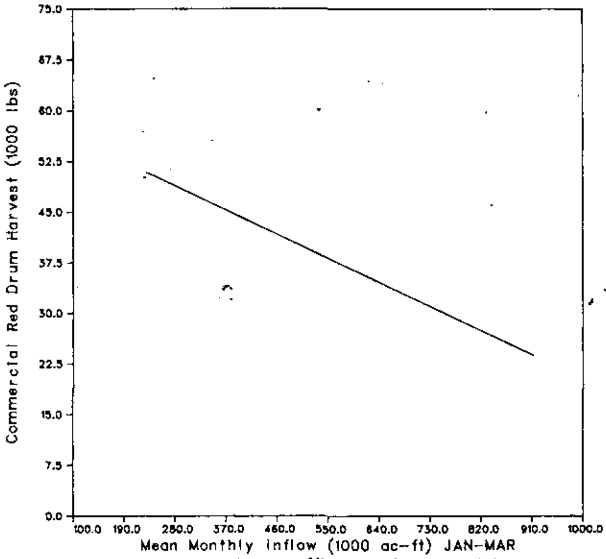
The fisheries analysis involves ten fisheries components and three freshwater inflow source categories in the analytical design, allowing a maximum 30 potentially significant equations. The analysis results in 19 equations of statistical significance. Although each of the three inflow categories can potentially produce ten significant equations, the analysis yields five equations with freshwater inflow at Trinity Delta (FINTD), five equations with freshwater inflow from San Jacinto River (FINSJ), and nine equations with combined freshwater inflow to Trinity-San Jacinto estuary from all contributing river and coastal drinage basins (FINC).

Seasonal inflow needs are similar for fisheries components when the signs (positive or negative) on the regression coefficients in the harvest equations are the same for a season of interest (Table 8-16). Therefore, the seasonal inflow needs of the fisheries components can reinforce each other. However, where seasonal inflow needs are of opposite signs, the fisheries components become competitive in terms of inflow management. Altogether, these results support the hypothesis that seasonal freshwater inflow has a significant impact on the estuary's fisheries, and by ecological implication, on the "health" of the ecosystem.

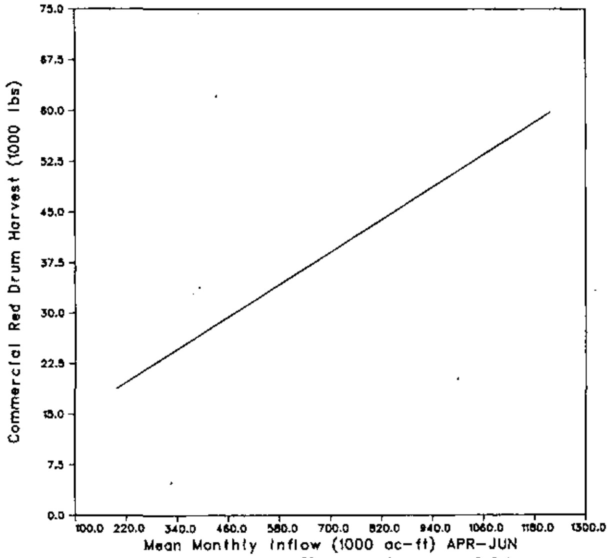
Freshwater Inflow Effects

Introduction

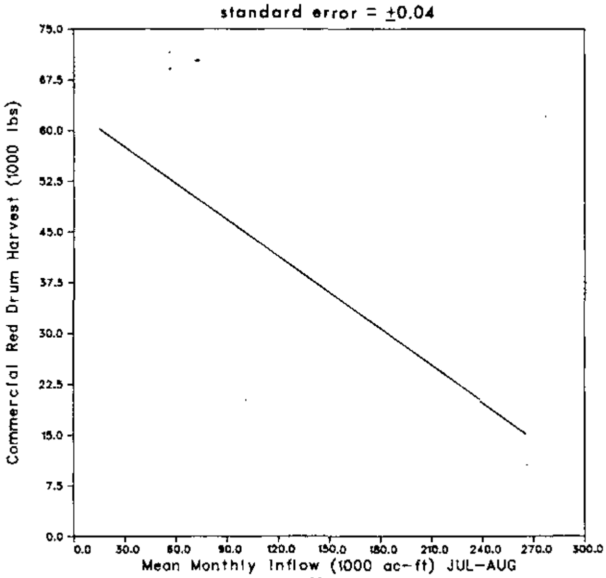
The hydrologic importance of both tidal inlets and freshwater inflow for ecological preservation of estuaries has been recognized (154,317). Since the



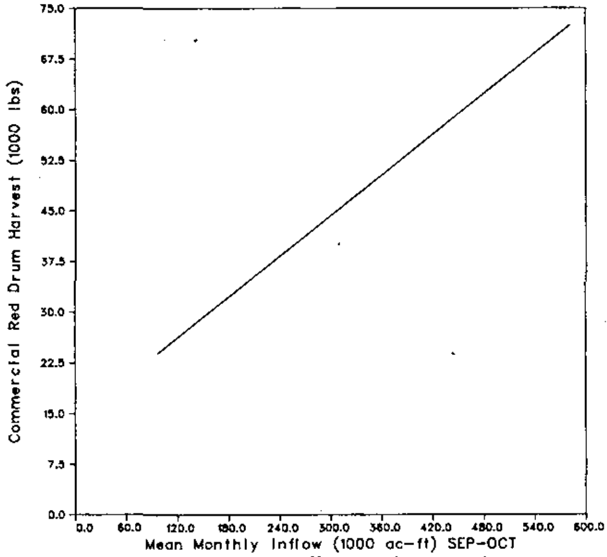
A. regression coefficient (slope) = -0.04,
standard error = ±0.04



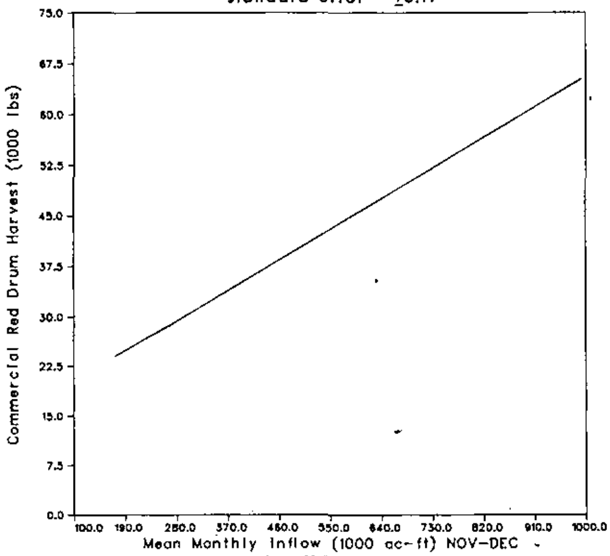
B. regression coefficient (slope) = +0.04,
standard error = ±0.01



C. regression coefficient (slope) = -0.18,
standard error = ±0.11



D. regression coefficient (slope) = +0.10,
standard error = ±0.07



E. regression coefficient (slope) = +0.05,
standard error = ±0.05

Figure 8-9. Inshore Commercial Red Drum Harvest as a Function of Each Seasonal Inflow at Trinity Delta, Where all Other Seasonal Inflows in the Multiple Regression Equation are Held Constant at Their Mean Values

Table 8-16. Positive (+) and Negative (-) Correlation of Fisheries Components to Seasonal Freshwater Inflow Categories

Fisheries Component	Winter Inflow Q_1 (Jan.-Mar.)	Spring Inflow (Apr.-Jun.) Q_2	Max Q_2	$(\text{Max } Q_2)^2$	Summer Inflow Q_3 (Jul.-Aug.)	Autumn Inflow Q_4 (Sept.-Oct.)	Late Fall Inflow (Nov.-Dec.) Q_5	Max Q_5	$(\text{Max } Q_5)^2$	Explained Variation r^2 (%)	Significance Level α (%)
Shellfish											
FINTD a/											
FINSJ b/											
FINC c/		-	+	-	-				-	87	2.5
Brown and Pink Shrimp											
FINTD		-			+					44	5.0
FINSJ		-			-	+	+			64	2.5
FINC		-			-	+	+			61	5.0
Blue Crab											
FINTD											
FINSJ											
FINC		+			-	+				58	2.5
Bay Oyster											
FINTD	-	+			-	-				65	2.5
FINSJ	-	+			-	-				79	0.5
FINC		+			-	-	-			69	2.5
Finfish											
FINTD	-					+				50	2.5
FINSJ					-	+	+			51	5.0
FINC											
Spotted Seatrout											
FINTD	-				-	+				70	0.5
FINSJ					-	+	+			67	1.0
FINC	-				-	+	+			66	2.5
Red Drum											
FINTD	-	+			-	+	+			69	5.0
FINSJ		+			-	+	+			59	5.0
FINC		+			-		+			65	1.0

(continued)

Table 8-16. Positive (+) and Negative (-) Correlation of Fisheries Components to Seasonal Freshwater Inflow Categories (cont'd)

Fisheries Component	Winter Inflow Q_1 (Jan.-Mar.)	Spring Inflow (Apr.-Jun.) Q_2	Max Q_2	$(\text{Max } Q_2)^2$	Summer Inflow Q_3 (Jul.-Aug.)	Autumn Inflow Q_4 (Sept.-Oct.)	Late Fall Inflow (Nov.-Dec.) Q_5	Max Q_5	$(\text{Max } Q_5)^2$	Explained Variation r^2 (%)	Significance Level α (%)
All Shrimp d/ FINC	-	-			+					87	0.1
White Shrimp e/ FINC		+			-	+				61	1.0
Brown and Pink Shrimp f/ FINC	-	-			+	-				80	0.1
Summary:											
FINTD	(+)=0 (-)=4	(+)=2 (-)=1	(+)=0 (-)=0	(+)=0 (-)=0	(+)=1 (-)=3	(+)=3 (-)=1	(+)=1 (-)=0	(+)=0 (-)=0	(+)=0 (-)=0		
FINSJ	(+)=0 (-)=1	(+)=2 (-)=1	(+)=0 (-)=0	(+)=0 (-)=0	(+)=0 (-)=5	(+)=4 (-)=1	(+)=4 (-)=0	(+)=0 (-)=0	(+)=0 (-)=0		
FINC	(+)=0 (-)=3	(+)=4 (-)=4	(+) 1 (-)=0	(+)=0 (-)=1	(+)=2 (-)=7	(+)=4 (-)=2	(+)=3 (-)=1	(+)=0 (-)=0	(+)=0 (-)=1		

a/ Freshwater inflow at Trinity Delta
b/ Freshwater inflow from San Jacinto River
c/ Combined freshwater inflow to estuary from all contributing river and coastal drainage basins
d/ Offshore penaeid shrimp harvest (Area #18)
e/ Offshore white shrimp harvest (≤ 20 fathoms; Area #18)
f/ Offshore brown and pink shrimp harvest (Area #18)

diminution of freshwater inflow to an estuary can decrease nutrient cycling and also result in unfavorable salinity conditions, many scientists have pointed to the deleterious effects of reduction and/or alteration of an estuary's freshwater inflow regime (34, 193, 161, 158, 195). Consequently, the addition of supplemental freshwater inflow for purposes of ecological maintenance and enhancing seafood production has been recommended for the Gulf estuaries of Texas (154, 373), Mississippi and Louisiana (65).

Perhaps the most direct and most apparent effects of freshwater inflow occur as a result of changes associated with estuarine salinity conditions. In addition, the concentration of salts can interact with other environmental factors to stimulate species-specific biotic responses (3) which may be reflected in physiological adaptation to the estuarine environment (138, 137, 535, 536), in species distribution patterns and community diversity (99, 94, 72, 101, 24, 143), and ultimately in species evolution (134). Previous research emphasizing Texas estuarine-dependent species has dealt with several aspects of the inflow/salinity relationship including environmental limits (358), tolerance to hypersaline waters (93, 111, 8), and rapid recovery of typical estuarine community species at the end of a severe drought (120). In addition, salinity changes resulting from man's development of an estuary and its contributing river and coastal drainage basins have been reviewed relevant to many Texas estuarine-dependent species (97, 427), and their diseases and symbionts (197).

While plants provide an estuary's primary production, most secondary production comes from the invertebrate bay fauna. For the invertebrates, inflow/ salinity effects have a demonstrated physiological basis (9, 388, 139, 148, 386) and are effective at modifying species distribution (326, 342, 199). The brackish water clam (Rangia cuneata) has been suggested as an indicator of ecological effects associated with salinity changes because of its sensitivity (243); however, the focus of invertebrate management is generally on the economically important mollusc (e.g., oyster) and crustacean (e.g., shrimp and crab) members of the invertebrate group (162).

Shrimp

The Gulf of Mexico shrimp fishery is the most valuable fishery in the United States (79) and the Gulf estuaries play a crucial role in the production of this renewable resource (83, 144). Commercial shrimp species are from the crustacean family Penaeidae. White shrimp (Penaeus setiferus Linnaeus, 1767) and brown shrimp (P. aztecus Ives, 1891) predominate in Texas harvests, although the pink shrimp (P. duorarum Burkenroad, 1939) also occurs in small numbers. Synopses of species life history and biological information are available for the white shrimp (151), brown shrimp (28), pink shrimp (36), and other species in the genus Penaeus (502). Additional information especially important for management of this fishery resource comes from research on shrimp spawning and early larval stages (433, 347, 367, 499), seasonal migration behavior (422, 33, 294, 356), utilization of estuarine nursery habitats (89), and major environmental factors influencing species population dynamics and production (246, 104, 168, 167, 38, 157). Species-specific responses to inflow/salinity conditions in the estuary are fundamentally physiological (4, 13, 256, 251, 146, 429), and therefore directly influence not only growth and survival of the postlarval shrimp (551, 552, 550, 534), but the distribution of the bay shrimp populations as well (354, 100, 329).

Results of the fisheries analysis (i.e., shellfish, all penaeid shrimp, white shrimp, and brown and pink shrimp fisheries components) support the importance of freshwater inflow to shrimp production and provide quantified data on the responses of inshore (bays of the Trinity-San Jacinto estuary) and offshore (Gulf Area No. 18) commercial shrimp harvests to seasonal freshwater inflow fluctuations. The equational harvest models indicate particularly notable seasonal dichotomies in the harvest responses of different shrimp species to spring, summer, and autumn season inflows (Table 8-16). Although offshore white shrimp harvests are positively related to spring inflow, negatively related to summer inflow, and positively related to autumn inflow, the offshore brown and pink shrimp harvests are related to each of these seasonal inflows in an opposite manner. In addition, offshore harvests of the all penaeid shrimp fisheries component and the brown and pink shrimp fisheries component are negatively related to winter inflow, while the offshore white shrimp fisheries component gives no significant correlation to this season's inflow. There are also differing responses between inshore and offshore brown and pink shrimp harvests to summer and autumn inflow. In this case, inshore harvests are negatively related to summer inflow and positively related to autumn inflow, while offshore harvests are just the reverse in their seasonal relationships to the combined freshwater inflow category (FINC). However, inshore brown and pink shrimp harvests also appear positively related to summer inflow at Trinity Delta (FINTD). Although the opposite responses to seasonal inflow between species are potentially explainable by divergent aspects of their life histories and ecology, such as the timing of migration into the estuary and the timing of recruitment of maturing shrimp to their respective adult populations, the differing responses of inshore and offshore harvests from the same species (i.e., brown and pink shrimp fisheries component) are more difficult to explain. It is possible, however, that an increase in a particular seasonal inflow may be locally detrimental to shrimp harvests in the bays, while being beneficial to offshore harvests, if the inflow results in the larger sub-adult and adult shrimp leaving the bays for the offshore waters where they may be subsequently caught. Thus, the total shrimp production may not necessarily have changed, but the inshore-offshore distribution of the catch may be altered by environmental factors such as freshwater inflow during later seasons of the annual growing cycle.

Blue Crab

Another major crustacean fishery species is the estuarine-dependent blue crab (*Callinectes sapidus* Rathbun, 1896). Previous research has described blue crab taxonomy (286, 327), life history (435, 285), migration behavior (333, 121, 294), and responses to environmental factors such as salinity (223, 37, 247, 145) and storm water runoff (150). Except for the strong negative relationship to summer inflow, the harvests responses are positive to inflows (FINC inflow category) during spring and autumn seasons (Table 8-16). Thus, high summer inflows and attendant low salinities appear detrimental to blue crab production in the estuary.

Bay Oyster

The American oyster (*Crassostrea virginica* Gmelin) is a molluscan shellfish species that has been harvested from Texas bay waters virtually since the aboriginal Indians arrived many thousands of years ago and it continues today as the only estuarine bivalve (a type of mollusc) of current commercial interest in the State. Because of man's historical interest in greater development and utilization of this fishery resource (e.g., raft farming, artificial reef formation, etc.), scientific information is available on the oyster's general ecology and life history (493, 539), as well as geographic variation of its populations (15, 226). The effects of inflow/salinity are particularly important and have stimulated considerable research covering a wide range of subjects including effects on oyster distribution (349, 166, 47), gametogenesis (development of viable eggs and sperm) and spawning (434, 14, 156, 217), eggs and larvae (5, 45, 495, 497, 113), respiration (359, 533), free amino acids which are protein building blocks (170), and the effects on oyster reef growth and mortality (91, 339), abundance of faunal associates (91, 76, 543) and reef diseases (254, 197).

Previous studies have described the Texas oyster fishery (296) and the State's major oyster producing areas (513, 300, 488). Numerous oyster reefs have been inventoried in the Trinity-San Jacinto estuary (480) with the most productive area, the Redfish Bar reef complex, located between Eagle Point and Smith Point in central Galveston Bay. However, extreme high inflows (e.g., flooding in the warmer seasons) can exert a controlling influence on the production of this and other oyster reef sites in the estuary. Indeed, the Texas Parks and Wildlife Commission closed the public reefs to oyster harvest at the beginning of the 1978 through 1979 oyster season and did not reopen the reefs until December 15, 1979 because of the scarcity of marketable oysters. Unfavorable salinity and temperature conditions for reproduction and survival in virtually all years between 1973 and 1979 (1978 is the exception with a good spat set) have resulted in low abundances of oyster larvae reaching the crucial setting stage, and consequently in the severe decline of production on the public reefs. Better conditions in 1980 suggest potentially improved production for the 1980 and 1981 oyster harvest seasons. In addition, classified "polluted areas" are also closed to harvest by the Texas Department of Health under authority of Section 76.202, Parks and Wildlife Code, until such time as sampling indicates a return of healthy estuarine conditions. Currently, the oyster areas closed include a substantial portion of the estuary except for central Galveston Bay (Redfish Bar reef), the western portion of East Bay (Hanna reef), and most of West Bay (Carancahua reef). However, private oyster leases are permitted in the estuary to translocate oysters from closed waters to open waters, and following depuration of pollutant and disease agents, the oysters can be sent to market.

Based on the equational harvest models, oyster harvest are positively related to spring season inflow and negatively related to summer and autumn season inflows from all three freshwater inflow categories (Table 8-16). In addition, inflow during the late fall season (FINC inflow category) appears negatively related to harvest, as does inflow during the winter season (FINTD and FINSJ inflow categories).

Finfish

Estuaries play a vital functional role in the life cycle and production of most coastal fish species (432, 131, 160, 290, 122). Environmental sensitivity of the estuarine-dependent fishes has allowed the use of species diversity indices as indicators of pollution (334). Although migration does occur across the boundary between riverine and estuarine habitats by both freshwater and estuarine-dependent marine fishes (192, 213), there is a predominance of young marine fishes found in this low salinity area (92).

In general, seasonal variations in estuarine fish abundance are related to life history and migrational behavior (98, 363, 362, 123, 333, 121, 294, 299, 221, 328, 548). The primary effects of inflow/salinity are physiological (119, 124, 149), and are particularly important for the survival of the early life stages (118) and the metabolism (i.e., metabolic stresses) of adult bay populations (353, 357, 365, 321, 538), and juvenile rates of adaptability (323, 322). Low temperature extremes can also interact physiologically with salinity stress to produce dramatic fish mortality (86, 87, 90).

Results from analysis of the multi-species finfish component indicates that harvests are negatively related to winter (FINTD) and summer (FINSJ) inflows, and positively related to autumn (FINTD and FINSJ) and late fall (FINSJ) inflows to the estuary (Table 8-16).

Spotted Seatrout

One of the most characteristic fish families of the bays, estuaries and neritic coastal waters between Chesapeake Bay and the Amazon River is the modern bony-fish (teleost) family Sciaenidae (432, 252, 122). The sciaenid genus *Cynoscion* contains four species in the Western Atlantic and Gulf of Mexico (three in Texas waters) with the most valued fishery species, the spotted seatrout (*Cynoscion nebulosus* Cuvier), also recognized as the most divergent of the four seatrout species (496). The greater restriction and estuarine-dependence of this species are reflected in its nearly exclusive utilization of estuarine habitats (82, 239, 73) and the increased genetic differences among populations in separate bays (542). Previous research has described spotted seatrout life history and seasonal abundance in Texas waters (436, 363, 280, 281, 362, 123, 121, 294), and the effects of inflow/salinity on metabolism (i.e., metabolic stresses) as salt concentration varies from an optimum condition of about 20 ppt salinity (320, 321, 351, 538, 323, 322).

Harvest responses to seasonal inflow are similar to those obtained in analysis of the multi-species finfish component. Thus, estimated harvest responses of the spotted seatrout component are negative to winter and summer inflow, and positive to autumn and late fall inflow (Table 8-16). The negative relationship to summer inflow and positive relationship to autumn inflow are uniform among all three inflow categories (FINTD, FINSJ, and FINC); however, the negative relationship to winter inflow only applies to FINTD and FINC inflow categories, while the positive relationship to late fall inflow only applies to FINSJ and FINC categories.

Red Drum

Another important sciaenid species is the red drum or redfish (*Sciaenops ocellata* Linnaeus). Prior studies have reported on the general biology, food items, and seasonal distribution of the red drum (436, 363, 280, 281, 172, 364, 362, 123, 549, 121, 294, 122, 196). In addition, the effects of inflow/salinity on the metabolism (i.e., metabolic stresses) of the species have been investigated as salt concentration varies from an optimum of about 25 ppt salinity (321, 538, 323, 322). Similar to results from the finfish and spotted seatrout fisheries components, analysis of the red drum component also shows negative harvest responses to winter and summer inflows, and positive responses to autumn and late fall inflows (Table 8-16). In addition, red drum harvests are also positively related to spring season inflows. The negative responses to summer inflow and the positive responses to spring and late fall inflows are uniform among all three inflow categories (FINTD, FINSJ, and FINC); however, the negative relationship to winter inflow is only significant for the FINTD inflow category, while the positive relationship to autumn inflow is significant for FINTD and FINSJ categories.

Black Drum

The black drum (Pogonias cromis Linnaeus) is also a sciaenid species of commercial and recreational interest. The general biology and life history aspects, including migrations and seasonal distributions, have been reported previously (363, 122, 294, 436, 364, 362, 432). In addition, the effects of inflow/salinity on the metabolism (i.e., metabolic stresses) of this broadly tolerant species have been investigated as salt concentration varies from an optimum of about 20-25 ppt salinity (321, 538). The sesonal importance of freshwater inflow to the species production and harvest was not demonstrated by the fisheries analysis and no significant harvest equations resulted; however, black drum harvests are included in the previously discussed seasonal inflow responses of the multi-species fisheries component for finfish. Further, the high degree of uniformity in seasonal responses to inflow among the finfish, spotted seatrout, and red drum fisheries components (Table 8-16) suggests that seasonal black drum inflow responses may be similar.

Harvest Responses to Long-and Short-Term Inflow

The analysis of inshore harvests spans the recent 1962 through 1976 short-term interval where more complete and compatible fisheries data exist. In addition, the offshore shrimp fisheries components are similarly limited to a slightly expanded 1959 through 1976 short-term interval. However, long-term inflow data are available for the estuary from 1941 to 1976 (See Chapter IV). Average (arithmetic and geometric mean) inflow conditions can be computed and a frequency analysis (i.e., Log-Pearson Type III) of the long-term inflow data can yield information about the exceedance frequencies of seasonal inflow to the estuary, including the frequency (percent) at which short-term average (arithmetic and geometric mean) inflow conditions were exceeded in the long-term record (Table 8-17). Exceedance frequencies of the short-term seasonal inflows for the three freshwater inflow categories (i.e., FINTD, FINSJ, and FINC) vary both above and below the 50 percent frequency level; however, only five of 45 seasonal inflows are equal to or above this level. Since lower exceedance frequencies indicate higher inflow, the short-term data bases are indicated as generally "wetter" than the long-term temporal median inflows.

Although the central seasonal tendencies of the short-term record are given as average (arithmetic and geometric mean) inflow conditions, the long-term central tendencies are expressed by both average (arithmetic and geometric mean) inflow conditions and the 50 percent exceedance frequency inflows which reflect the temporal median inflows to the estuary from the freshwater source categories (108). When short-term and long-term average inflow conditions, as well as the long-term 50 percent frequency inflow conditions, are used separately as input to the previously developed fisheries regression equations, predicted harvest responses can be computed for comparison (Table 8-18). It is noted that substitution of the long-term average inflows in the

Table 8-17. Comparison of Short-Term and Long-Term Seasonal Inflow Volumes, Including Inflow Exceedance Frequencies

Freshwater Inflow Category and Season	Short-Term Mean Seasonal Inflow a/ With Long-Term Exceedance Frequencies: D1 Inflow (EF%) c/	D2 Inflow (EF%)	D3 Inflow (EF%)	Long-Term Seasonal Inflow b/: Arithmetic Mean Inflow	Geometric Mean Inflow	10% EF Inflow	50% EF Inflow	90% EF Inflow
FINTD d/								
Q_1 (Jan. - March)	1,451.8 (49)	1,634.3 (44)	1,521.8 (47)	1,845	1,267	4,155	1,287	378
Q_2 (April - June)	2,175.3 (42)	2,034.7 (45)	1,731.2 (51)	2,478	1,693	5,691	1,707	498
Q_3 (July - Aug.)	272.2 (50)	315.2 (45)	224.2 (54)	400	175	1,002	238	28
Q_4 (Sept. - Oct.)	457.5 (39)	481.6 (37)	390.2 (44)	474	247	1,270	280	50
Q_5 (Nov. - Dec.)	889.5 (32)	968.9 (29)	794.4 (36)	828	511	2,004	512	128
Total	5,246.3	5,434.7	4,661.8	6,025	3,893	14,122	4,024	1,082
FINSJ e/								
Q_1 (Jan. - March)	504.0 (48)	561.1 (43)	550.7 (44)	609	454	1,320	459	156
Q_2 (April - June)	777.6 (35)	818.3 (33)	703.9 (39)	768	508	1,716	513	150
Q_3 (July - Aug.)	240.6 (41)	296.5 (31)	253.3 (39)	278	201	510	200	80
Q_4 (Sept. - Oct.)	288.0 (36)	340.3 (30)	285.7 (36)	326	186	708	184	48
Q_5 (Nov. - Dec.)	281.5 (39)	342.5 (33)	257.1 (42)	338	199	826	200	48
Total	2,091.7	2,358.7	2,050.7	2,319	1,548	5,080	1,556	482
FINC f/								
Q_1 (Jan. - March)	2,242.6 (51)	2,515.0 (46)	2,407.7 (48)	2,748	2,073	6,120	2,106	687
Q_2 (April - June)	3,497.5 (41)	3,389.8 (42)	2,993.4 (48)	3,696	2,722	8,034	2,739	915
Q_3 (July - Aug.)	669.1 (49)	834.7 (40)	663.8 (50)	898	659	1,882	658	230
Q_4 (Sept. - Oct.)	976.0 (38)	1,064.8 (35)	920.0 (40)	1,050	674	2,434	676	186
Q_5 (Nov. - Dec.)	1,362.7 (36)	1,524.6 (32)	1,257.7 (39)	1,372	891	3,236	898	242
Total	8,747.9	9,328.9	8,242.6	9,764	7,019	21,706	7,077	2,260

a/ Short-term inflow data bases, with seasonal volumes in thousands of acre-feet:
D_1 = inflow from November 1961 to October 1976 used in analysis of shellfish
D_2 = inflow from January 1959 to December 1976 used in analysis of offshore penaeid shrimp
D_3 = 3-year running average inflow, natural log transformed, from January 1959 to December 1975 used in analysis of finfish

b/ Selected exceedance frequencies (Log-Pearson Type III) and their respective seasonal inflow volumes, in thousands of acre-feet, from the long-term historical record (1941-1976)

c/ Long-term exceedance frequencies, in percent, of the short-term mean seasonal inflows

d/ Freshwater inflow at Trinity Delta

e/ Freshwater inflow from San Jacinto River

f/ Combined freshwater inflow from all contributing river and coastal drainage basins

Table 8-18. Estimated Average Harvest Responses from Fisheries Component Equations Using Short-Term Mean Inflow, Long-Term Mean Inflow and Long-Term 50-Percent Exceedance Frequency Inflow.

Fisheries Component	Trinity Delta Inflow FINTD a/					San Jacinto River Inflow FINSJ b/					Combined Estuary Inflow FINC c/				
	Short-Term: Mean Inflow: Harvest e/	Long-Term Mean-Inflow Harvest	(Shift) f/	Long-Term 50%EF d/ Inflow Harvest	(Shift)	Short-Term Mean Inflow: Harvest	Long-Term Mean Inflow Harvest	(Shift)	Long-Term 50% EF Inflow Harvest	(Shift)	Short-Term: Mean Inflow: Harvest	Long-Term Mean-Inflow Harvest	(shift)	Long-Term 50%EF Inflow Harvest	(Shift)
INSHORE:															
Brown and Pink Shrimp	946.3	890.0	(-5.9)	941.8	(- 0.5)	946.3	831.5	(-12.1)	824.7	(-12.9)	946.3	767.8	(-18.9)	764.9	(-19.2)
Blue Crab											1606.4	1342.3	(-16.4)	1439.9	(-10.4)
Bay Oyster	2825.4	2662.5	(-5.8)	3079.2	(+ 9.0)	2501.4	2822.0	(+12.8)	2838.0	(+13.5)	2825.4	2523.9	(-10.7)	3038.6	(+ 7.5)
Finfish	346.6	296.3	(-14.5)	352.1	(+ 1.6)	304.8	329.4	(+ 8.1)	332.5	(+9.1)					
Spotted Seatrout	165.8	116.2	(-29.9)	161.3	(- 2.7)	137.3	145.6	(+ 6.0)	147.9	(+ 7.7)	165.8	130.4	(-21.4)	150.7	(- 9.1)
Red Drum	36.3	27.4	(-24.5)	21.6	(-40.5)	36.3	37.5	(+3.3)	28.7	(-20.9)	36.3	29.7	(-18.2)	20.4	(-43.8)
OFFSHORE:															
White Shrimp											2799.2	2801.7	(+ 0.1)	2709.0	(- 3.2)
Brown and Pink Shrimp											7181.0	6999.9	(- 2.5)	7705.4	(+ 7.3)
All Shrimp											9995.3	9790.0	(- 2.1)	10,365.8	(+ 3.7)

a/ Freshwater inflow Trinity Delta
b/ Freshwater inflow from San Jacinto River
c/ Combined freshwater inflow from all contributing river and coastal drainage basins
d/ EF = exceedance frequency; 50% EF reflects the temporal median inflow to the estuary
e/ Average harvest, in thousands of pounds
f/ Shift in percent increase (+) or decrease (-) of harvest

fisheries equations involves using arithmetic mean seaonal inflows as input to the linear equations and geometric mean seasonal inflows as input to the natural log (ln) equations.

There are 13 positive and 23 negative shifts of the harvest estimates from exercise of the equational models. Long-term mean inflows are associated with five positive and 13 negative shifts of the harvest estimates, when compared to the fisheries harvest levels resulting from the observed short-term interval, and there are eight positive and ten negative harvest shifts in response to long-term 50 percent exceedance frequency (EF) inflows. The harvest shifts are variable among the fisheries components and range from an estimated +13.5 percent shift of oyster harvest in response to 50 EF inflows (FINSJ inflow category), to an estimated -43.8 percent shift of red drum harvest in response to 50 percent EF inflows (FINC). The results reflect not only differences in inflow quantity, but also differences in the seasonal distributions of inflow from the freshwater source categories. In addition, they suggest that fisheries harvests based on the long-term mean inflows would be lower overall because of the greater number of associated negative harvest shifts; however, long-term 50 percent EF inflows appear notably beneficial to inshore oyster and finfish components, and offshore all shrimp and brown and pink shrimp components.

While management policies could favor the specific seasonal inflow needs of preferred fisheries components, it is in reality difficult and in many cases impossible to maximize the harvests from more than one fisheries component at the same time because of competitive seasonal inflow needs among the species. Nevertheless, management scenarios for inflow can be developed that predict good harvest levels from several of the fisheries components simultaneously (see Chapter IX).

Summary

Virtually all of the Gulf fisheries species are estuarine-dependent. Commercial inshore harvests (1962-1976) from bays of the Trinity-San Jacinto estuary rank first in shellfish and fourth in finfish of eight major Texas estuarine areas. In addition, the sport or recreational finfish harvest has been estimated at six times larger than the commercial finfish harvest in the estuary. For the 1972 through 1976 interval, the average annual sport and commercial harvest of fish and shellfish dependent upon the estuary is estimated at 46.7 million pounds (21.2 million kg; 87 percent shellfish).

Although a large portion of the fisheries production from each Texas estuary is harvested offshore in collective association with fisheries production from other regional estuaries, inshore bay harvests are useful as relative indicators of the year to year variations in an estuary's surplus production (i.e., that portion available for harvest). These variations are affected by the seasonal quantities and sources of freshwater inflow to an estuary through ecological interactions involving salinity, nutrients, food (prey) production, and habitat availability. The effects of freshwater inflow on the Trinity-San Jacinto estuary are also reflected in the offshore harvests of the penaeid shrimp fishery. Therefore, the fisheries species can be viewed as integrators of their environment's conditions and their harvests used as relative ecological indicators, insofar as they reflect the general productivity and "health" of the estuarine ecosystem.

A time series analysis of the commercial bay fisheries landings (1962 through 1976) and the commercial offshore penaeid shrimp harvests (Gulf Area No. 18, 1959 through 1976) produces 19 statistical equations that estimate harvest as a function of seasonal freshwater inflows to the estuary. These equational models provide numerical estimates of the effects of variable seasonal inflows, contributed from the major freshwater sources, on the production of seafood organisms dependent on the estuarine ecosystem. The analysis also supports existing scientific information on the seasonal importance of freshwater inflow to the estuary.

All significant inshore and offshore harvest responses to winter (January-March) inflow are estimated to be negative for increased inflow in this season. With exception of the inshore brown and pink shrimp component's positive response to Trinity Delta summer inflow (FINTD inflow category), all other significant inshore harvest responses are estimated to relate negatively to increased summer (July-August) inflow. Offshore all shrimp and brown and pink shrimp fisheries components also relate positively to increased summer inflow, but negatively to increased spring (April-June) inflow. However, offshore white shrimp and inshore red drum, oyster and blue crab harvests relate positively to increased spring season inflow. Significant harvest responses to increased autumn (September-October) inflow are all positive, except for the negative responses of the oyster and offshore brown and pink shrimp fisheries components. Increased late fall (November-December) inflow relates positively to several fisheries components (e.g., finfish, spotted seatrout, and red drum), but again is negatively related to oyster harvest.

Where the estimated seasonal inflow needs of the fisheries components are similar, the components reinforce each other; however, where components are competitive by exhibiting opposite seasonal inflow needs, a management decision must be made to balance the divergent needs or to give preference to the needs of a particular fisheries component. A choice could be made on the basis of which species' production is more ecologically characteristic and/or economically important to the estuary. Whatever the decision, a freshwater inflow management regime can only provide an opportunity for the estuary to be viable and productive because there are no guarantees for estuarine productivity based on inflow alone, since many other biotic and abiotic factors are capable of influencing this production. However, most of these other factors are largely beyond human control, whereas freshwater inflows can be restricted by man's activities so that fish and wildlife resources are adversely affected.

CHAPTER IX

ESTIMATED FRESHWATER INFLOW NEEDS

Introduction

In previous chapters, the various physical, chemical and biological factors affecting the Trinity-San Jacinto estuary have been discussed. There has been a clear indication of the importance of the quality and quantity of freshwater inflows to the maintenance of a viable estuarine ecology. The purpose in Chapter IX is to integrate the elements previously described into a methodology for the purpose of establishing estimates of the estuary's freshwater inflow needs, based upon historical data.

Methodology for Estimating Selected Impacts of Freshwater Inflow Upon Estuarine Productivity

The response of an estuary to freshwater inflow is subject to a number of factors and a variety of interactions. These include changes in salinity due to mixing of fresh and saline water, fluctuations in biological productivity arising from variations in nutrient inflows, and many other phenomena.

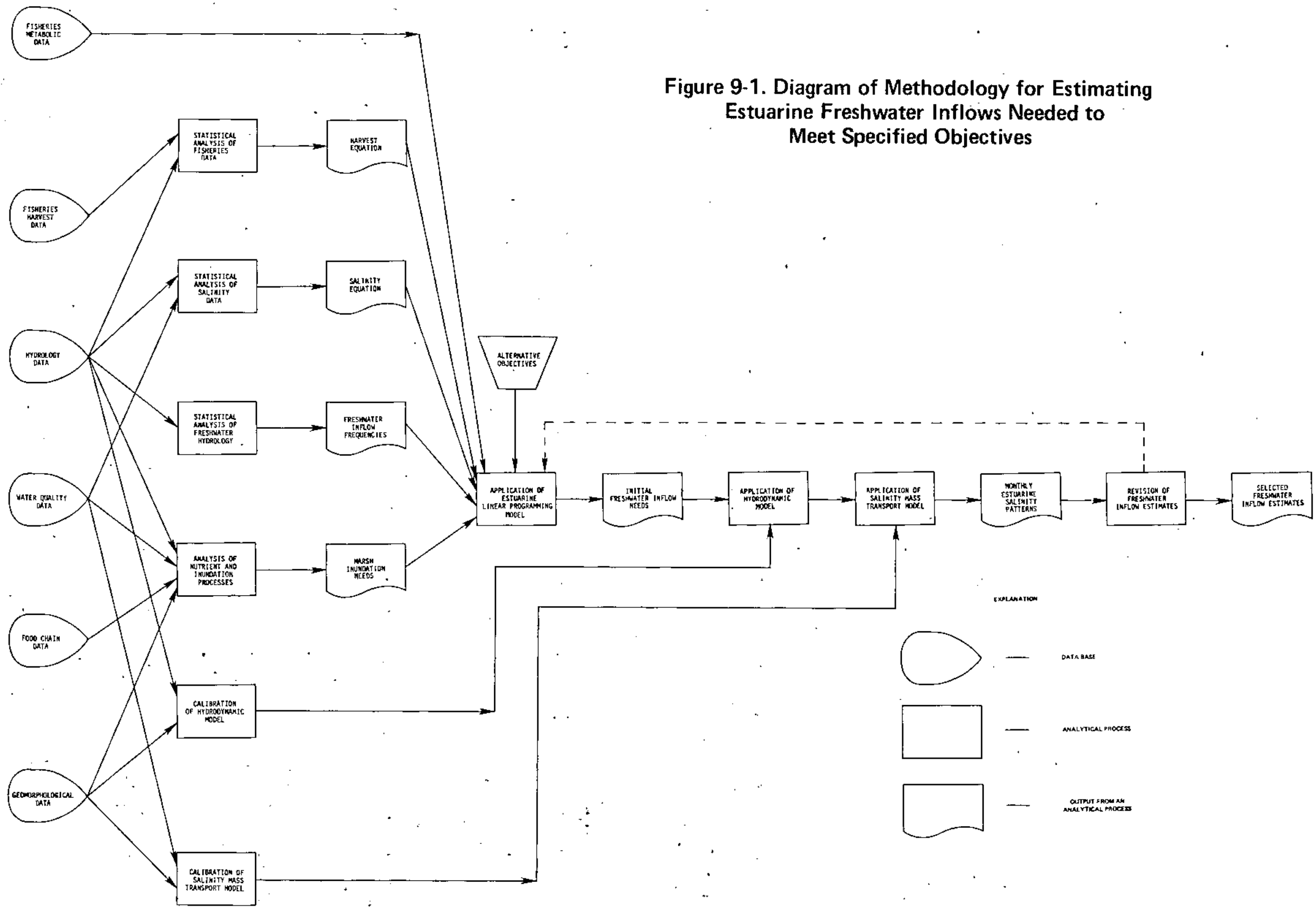
The methodology presented here incorporates major interacting elements described in previous chapters (Figure 9-1). The methodology includes the use of data bases and certain analytical processes described herein. Data for these analyses include six groups: (1) salinity data for finfish and shellfish, (2) commercial fisheries harvest data, (3) hydrologic data of freshwater and saline water, (4) water quality data, (5) aquatic food chain data, and (6) terrestrial and aquatic geomorphic data of the estuary and the surrounding coastal area.

In this section data and results of previous sections, including (1) statistical analysis of relationships among freshwater inflow, commercial fishery harvest, and estuarine salinity; (2) estimates of marsh freshwater inundation needs; (3) estimates of nutrient exchange; and (4) records of historical freshwater inflow, are used in an Estuarine Linear Programming (LP) Model to compute estimates of the monthly freshwater inflows needed to achieve specified objectives. The tidal hydrodynamic and salinity transport models are then applied to compute salinity levels and circulation patterns throughout the estuary for a set of computed freshwater inflow needs.

Application of the Methodology to Compute Estimates of Freshwater Inflow Levels Needed to Meet Selected Objectives

The schematic indicated in Figure 9-1 shows the sequence of steps utilized in computing the freshwater inflow needs to achieve specified objectives as expressed in terms of salinity, marsh inundation, and productivity. The six data bases developed for the Trinity-San Jacinto estuary provide the

Figure 9-1. Diagram of Methodology for Estimating Estuarine Freshwater Inflows Needed to Meet Specified Objectives



fundamental information of the system. These data were used in previous sections of these analyses. The relationships and results are incorporated into the Estuarine Linear Programming Model to compute estimates of effects of various levels of monthly freshwater inflows upon salinity, marsh inundation and fisheries harvests in the estuary. This model uses an optimization technique to select the optimal or "best" monthly inflows for the objective specified. The estimated monthly inflows are then used as data inputs in the tidal hydrodynamic and salinity transport models to simulate the effects of the inflows upon circulation and salinity patterns in the entire estuary. Should the computed salinity conditions in certain critical areas of the estuary be unsatisfactorily high or low, then the freshwater inflow estimates would require appropriate modification. This revision of the estimates (indicated by the dashed line in Figure 9-1) would necessitate a recomputation of the freshwater need by the Estuarine Linear Programming Model under a modified set of contraints.

The data bases and analytical processes utilized in this chapter have been described in detail in previous chapters. Only the procedures necessary to establish salinity bounds, estimate marsh inundation needs, and apply the Estuarine Linear Programming Model are presented in this chapter.

Salinity Bounds for Fish and Shellfish Species

The effects of salinity on estuarine-dependent fisheries organisms are fundamentally physiological, and influence growth, survival, distribution, and ecological relationships (see Chapter VIII).

Specific information on salinity limits, preferences and/or optima for selected fisheries species has been tabulated from the scientific literature and Texas Department of Water Resources research data (Table 9-1). The optimum condition for most of these species lies between 25 percent and 75 percent seawater (8.8-26.3 ppt). Young fish and shellfish commonly utilize estuarine "nursery" habitats that are below 50 percent seawater (less than 17.5 ppt), while adults seem to prefer salinities slightly higher than 50 percent seawater. In general, and within the tolerance limits, it is the season, not salinity *per se*, that is more important because of life cycle events such as spawning and migration. While the salinity limits for distribution of the species are ecologically informative, they are often physiologically too broad. Conditions encouraging good growth and production are commonly restricted to a substantially narrower range of salinity than are simple survival needs.

Data on salinity effects, combined with life cycle information, were utilized to provide seasonal bounds on estuarine salinity within which fish and shellfish can survive, grow, and maintain viable populations (Table 9-2). Since universal consensus is not evident for precise viability salinity limits, the monthly salinity bounds were established subjectively based upon the results available from scientific literature (Table 9-1). It is important to note that these limits are site specific and adjusted to two control points

Table 9-1. Salinity Limits, Preferences, and Optima for Selected Texas Estuarine-Dependent Species

Species	Limits Min. (ppt)	Limits Max. (ppt)	Preference or Optimum (ppt)	Remarks	Reference
Penaeus setiferus (white shrimp)					
	< 2	> 40		range at which 80% of 8-50 mm (postlarvae to juvenile) shrimp survive; 48 hr. acclimation	550
			5-15	increased growth at this range (and >25°C) more than two times tissue production of postlarvae at 25-35 ppt	550
			28.0	median salinity average of postlarval distribution (May-July) in laboratory gradient tanks	251
			21.0	median salinity average of postlarval distribution (Aug.-Nov.) in laboratory gradient tanks	251
		47.96		field collection of small white shrimp (23-76 mm) in Laguna Madre de Tamaulipas (Mexico)	114
	0.42			lower distribution limit in Grand and White Lakes (La.); young shrimp 140 times more abundant at 0.7-0.8ppt	101
			27.6-28.3	isosmotic salinity conditions for shrimp ≥ 100 mm length; osmoregulation below 27.6 ppt better than brown shrimp	177
	1	34	1-20	field distribution in Caminada Bay (La.) and range for 91.1% of juveniles collected	38
	2.1	36.6	10.0-14.9	field distribution in Copano and Aransas Bays (Tex.) and range of greater abundance; common at ≤ 4.9 ppt	354
	2.9	45.3		field distribution in Mesquite Bay (Tex.)	120
	2	45		field distribution in bays and lagoons of northwestern Gulf of Mexico (Tex.)	111
			< 10	preference based on population distributions	100
	0	38		optimum catch over entire salinity range with 20-38°C temperatures	358
Penaeus aztecus (brown shrimp)					
	2	40		range of equal postlarval growth over 23-25°C temperature; survival 90-100% in laboratory	551
	< 10			partial reduction in postlarval tolerance at low (7-15°C) temperatures to low (5 ppt) salinity	552
			15-35	range of increased postlarval growth at temperatures >25°C; decreased growth below 15 ppt	550
	< 5	> 40		range at which 80% of 10-15 mm postlarvae survive; 12 hr. acclimation	550
			> 15	appeared to enhance survival and growth of postlarvae in Barataria Bay (La.)	231
			> 15	commercial catches poor in years when postlarvae were present in Louisiana bays with < 15 ppt	169
			29.9	median salinity average of postlarval distribution (March-April) in laboratory gradient tank	251
			20.6	median salinity average of postlarval distribution (May-July) in laboratory gradient tank	251
			10.0-19.9	range at which juveniles were more abundant based on population distributions	100
	0.2	30	10-30	field distribution in Caminada Bay (La.) and range for 91.8% of juveniles collected	38
			< 17	preference of juvenile (70 mm) shrimp in laboratory at >20°C temperature	429
			15-25	optimal range for subadult (95 mm) shrimp in laboratory at <25°C temperature	429
			8.5-17	optimal range for juvenile growth on low (40%) protein diet in laboratory at 21-31°C temperatures; low salinity essential for fast postlarval growth from age 16 days and older	534
			27.6-28.3	isosmotic salinity conditions for shrimp > 100 mm length; osmoregulation above 28.3 ppt better than white shrimp	177
	2.1	36.6	15.0-19.9	field distribution in Copano and Aransas Bays (Tex.) and range of greater abundance	354
		69.0		field collection in Laguna Madre (Tex.)	331
	0.8			lower distribution limit in Grand and White Lakes (La.)	101
	0.22			field collection in St. Lucie Estuary (Fla.)	85
	5	70		field distribution in bays and lagoons of northwestern Gulf of Mexico (Tex.)	111
	0.1			field collection (North Carolina)	545
			5	acclimation at low (5 ppt) salinity provides near-optimum resistance to high temperatures and 5-25 ppt salinities in laboratory tests	544
	9	40		no optimum salinity established with 20-35°C temperatures	358
Callinectes sapidus (blue crab)					
	22.9	32.4	≥ 30.0	range for capture of egg-bearing females near Aransas Pass (Tex.)	354
			23-28	optimum range for hatching of eggs (Virginia)	223
			> 20	occurrence of spawning and early development	285
			< 1.9	peak abundance of juvenile blue crabs in Texas bays (1965)	285
	< 1.0		2-21	lethal limit at optimum (29°C) temperature and range of little effect on juvenile growth and survival	247
	0			observed freshwater populations in Louisiana	98
	2.0	37.2	10.0-20.0	field distribution in Copano and Aransas Bays (Tex.) and range of greater abundance	354
		117		field collection in Laguna Madre de Tamaulipas (Mexico); high salinity briefly tolerated	114
		45		blue crabs observed leaving upper Laguna Madre (Tex.) area as salinity increased	287
	2	60		field distribution in bays and lagoons of northwestern Gulf of Mexico (Tex.)	111
			24.2	salinity for widest thermal tolerance zone in adult blue crab	74
	0	40	0-27	optimum range with 10-35°C temperatures	358
			10-30	range of no effect on metabolic consumption of oxygen (respiration)	145
Crassostrea virginica (American bay oyster)					
	< 6			gametogenesis inhibited by prolonged low salinity exposure; up to 3-4 months required to regain normal gonadal activity after salinity increases towards the optimum	14
	5-7.5			normal gonadal development near 7.5 ppt; however, oysters with previously ripe gonads spawn when subjected to low (5 ppt) salinities	155
			20-21	larval spat setting requirement in Galveston Bay (Tex.)	434
	5-8		12.5-25	minimum tolerance of larvae 5-8 ppt; below 12.5 ppt adult reproduction is impaired while above 25 ppt predation and disease increase greatly, especially with high temperatures	139

Table 9-1. Salinity Limits, Preferences, and Optima for Selected Texas Estuarine-Dependent Species (cont'd.)

Species	Limits Min. (ppt)	Limits Max. (ppt)	Preference or Optimum (ppt)	Remarks	Reference
			19-30	maximum survival (80% contour plot) in lab of 2-day larvae at 19-30.5°C temperatures	497
			8-30.5	maximum survival (60% contour plot) in lab of 8-day larvae at temperatures > 21°C	497
			>33	maximum growth (100% contour plot) in lab of 8-day larvae at temperatures > 19°C	497
			18-35	optimum (80% contour plot) for both larval survival and growth at temperatures > 30°C	497
			15-22.5	optimum for juvenile growth and development	20
	1.5	39.0		early experimentally derived salinity limits	5
	0-2			oysters can survive freshwater (0ppt) for several days; increasing to about a month at 2 ppt salinity	354
			15-30	optimum range of salt content	296
	5	40	5-15	tolerance limits and optimum range for growth and survival; higher optimum (10-28 ppt) in cooler waters of northern latitudes (Chesapeake Bay)	493
		43.5-45		distribution limit in Redfish and Corpus Christi Bays (Tex.)	339
			15-20	ideal salinity conditions with lowest seasonal salinities in late summer and fall	1
	2-4	10-22	10.0-16.0	most productive reefs of Mississippi Sound subject to 10.0-16.0 ppt average conditions	47
	≤ 2			oysters can survive up to four weeks in low salinity at 20-27°C temperatures; mortality increases severely at higher temperatures in Galveston Bay (Tex.)	300
			15-30	best growth in reasonably stable salinity	197
	3			lower tolerance limit about 3 ppt	97
	8-10			lower limit of predator Thais haemastoma, a gastropod oyster drill or conch	97 354
	< 10			low incidence of infection with fungus, Dermocystidium marinum (presently known as the protozoan, Perkinsus marinus); infection increases above 10 ppt and mortality increases severely at both high salinities and high temperatures	348
Cynoscion nebulosus (spotted seatrout)					
	< 5		30-35	lower limit especially important when temperature is low (<10°C); peak spawning in estuaries and lagoons (Fla.) at 30-35 ppt; larval survival reduced if salinity low	239
			> 30	spawning occurs in estuarine areas of higher salinity (La.)	221
		≤ 60	< 45	"young" collected up to about 60 ppt in Laguna Madre (Tex.); no spawning if salinity > 45 ppt	331
		< 55	15-35	absent above 55 ppt in Baffin and Alazan Bays (Tex.); most abundant range 15-35 ppt	330
	2.3	34.9	5-20	field distribution in Copano and Aransas Bays (Tex.); over 80% collected in 5-20 ppt	363
	< 5	77		field distribution in bays and lagoons at northwestern Gulf of Mexico (Tex.)	111
	10	45	20	operational limits; optimum metabolic condition at 20-28°C temperatures	351

Species	Limits Min. (ppt)	Limits Max. (ppt)	Preference or Optimum (ppt)	Remarks	Reference
Sciaenops ocellata (red drum)					
	2.1	32.4	< 15	field distribution in Copano and Aransas Bays (Tex.); greater abundance below 15 ppt	363
	0	> 50	20-40	field distribution (Tex.); range of preference (most abundant in 30-35 ppt); young mature in 3-5 years	364
			< 50	populations in Laguna Madre (Tex.) severely limited by >50 ppt	331
	5-10	40-45	20-25	operational limits; range of optimum metabolic condition at 20-28°C temperatures	321
Pogonias cromis (black drum)					
	2.6	34.9	<15	field distribution in Copano and Aransas Bays (Tex.); most abundant range 10.0-15.0 ppt	363
	<5	77		field distribution in bays and lagoons of northwestern Gulf of Mexico (Tex.)	111
	0	80		field distribution (Tex.); usual range in Laguna Madre 25-50 ppt	364
	5	40-45	20-30	operational limits; range of optimum metabolic condition at 20-28 °C temperatures; maximum swimming performance at 28 °C and 20 ppt	321

Table 9-2. Salinity Characteristics of Upper Galveston Bay and Upper Trinity Bay

Month	Salinity in Upper Trinity Bay a/ (ppt)			Salinity in Upper Galveston Bay b/ (ppt)		
	Upper c/ Viability Limit	Lower c/ Viability Limit	Median Historic Salinity	Upper c/ Viability Limit	Lower c/ Viability Limit	Median Historic Salinity
January	20	10	5	30	10	13
February	20	10	4	30	10	13
March	20	10	4	25	10	14
April	15	5	4	20	5	14
May	15	1	4	20	5	12
June	15	1	3	20	5	13
July	20	10	5	25	10	17
August	20	10	11	25	10	16
September	15	5	13	20	5	17
October	15	5	12	20	5	18
November	20	10	11	30	10	21
December	20	10	7	30	10	15

a/ Represented by sampling site 8 on linesite 230 (Figure 3-9)
b/ Represented by statewide monitoring network station 1005.1, Morgan's Point (Figure 3-9)
c/ These values estimate the limits of long-term viable species activity at control points in the estuaries, and not individual organism survival limits (Table 9-1)

in the estuary below the "Null Zone" 1/: (1) in upper Galveston Bay at Morgan's Point, and (2) in upper Trinity Bay near the Trinity River delta. The limits are expressed as mean (average) monthly salinities for general limits of viability. From both locations, salinities generally increase towards the Gulf inlets (Bolivar Pass and San Luis Pass) and eventually attain seawater concentration (35 ppt). The salinity gradient in the estuary is thus steeper during seasons of higher inflow (e.g., the spring) and less distinct during seasonal low inflow (e.g., the summer). Moreover, the estuarine-dependent species have adapted their life cycles to the natural freshwater inflow regime and are today productively associated with local and State economies.

Although the fisheries species can generally tolerate salinities greater or less than the monthly specified viability range, foraging for food and production of body tissue (growth) becomes increasingly more difficult under extreme salinities, and may eventually cease altogether because body maintenance requirements consume an increasing amount of an organism's available energy under unfavorable conditions. High mortality and low production are expected during prolonged extremes of primary environmental factors such as salinity and temperature.

Monthly Salinity Conditions

The salinities within an estuarine system fluctuate with variations in freshwater inflow. During periods of flood or drought, salinity regimes may be so altered from normal conditions that motile species commonly residing in an estuary may migrate to other areas where the environmental conditions are more suitable. Generally, however, estuarine-dependent species will remain in the system during normal periodic salinity fluctuations. Should the normal salinity conditions be altered for prolonged periods due to natural or manmade causes, the diversity, distribution and productivity of species within an estuary will be depressed.

The median monthly salinity is a measure of the normal monthly salinity condition of the estuary. The median monthly salinity is that value for which one-half of the observed average monthly salinities exceed the value and one-half are less. The median monthly salinity thus reflects an "expected" salinity in the estuary and represents a numerical value exceeded 50 percent of the time. Median historic salinities have been computed for the two locations in upper Galveston and Trinity Bays (Table 9-2) for which the salinity regression equations were developed in Chapter V.

Marsh Inundation Needs

The periodic inundation of deltaic marshes serves to maintain shallow protected habitats for postlarval and juvenile stages of several important

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1/ Null Zone: The general area where the net landward flow creates the phenomenon of landward and seaward density currents being equal but opposite in effect. The nullification of net bottom flows in this area allows suspended materials to accumulate and has also been termed the entrapment zone, the critical area, the turbidity maxima, the nutrient trap, and the sediment trap (109, 7).

estuarine species, provides a suitable fluid medium for nutrient exchange processes, and acts as a transport mechanism to move detrital food materials from the deltaic marsh into the open estuary. The areal extent of deltaic marsh inundation is a function of the channel capacity, discharge rate and volume, wind direction, and tidal stage.

Historically, the discharge rates of Texas rivers have fluctuated on a seasonal basis. Monthly freshwater inflows usually peak in the spring and early fall, reflecting the increased rainfall and surface runoff that normally occur during these months. The cyclic periods of high and low freshwater discharge have influenced the life history of estuarine-dependent organisms, especially the early life stages which are dependent upon marsh inundation and nutrient processes for biological productivity.

Two river deltas of the Trinity-San Jacinto estuary (the San Jacinto and Trinity River deltas) are periodically inundated.1/ The Trinity delta is subject to periodic inundation by freshwater due to discharge from the Trinity River system. The areal extent of deltaic inundation is a function of wind, tide, and discharge rate and volume. If high tides are present, the area of delta inundated by a given peak flood discharge is greater than that occurring with normal or low tides. The San Jacinto River delta is much smaller in areal extent than the Trinity delta, and was not considered of sufficiently significant area to warrant extensive analysis of its inundation characteristics.

To formulate a water management program that incorporates deltaic inundation as an objective, it is necessary to determine both the frequency and magnitude of historical flood events for the Trinity delta. If what has happened naturally in the past has been sufficient to maintain the productivity of the estuary, incorporation of historical patterns into a management plan will most likely provide inundation sufficient to maintain productivity in the future.

Historical deltaic inundation was computed through the use of a hydrodynamic model for Trinity delta (62, 61). A series of peak discharges ranging from 10,000 to 35,000 ft^3/sec (283 to 991 m^3/sec) for low and high tidal regimes were used in the analysis and the areal extent of deltaic inundation was computed for each tide/discharge combination. With low tides (-0.9 feet to 0.8 feet above MSL), a peak discharge of 20,000 ft^3/sec (566 m^3/sec) would be sufficient to begin inundation of the delta. During high tides (range 0.6 feet to 2.4 feet above MSL), the model predicted that a 20,000 ft^3/sec (566 m^3/sec) peak discharge from the Trinity River would result in inundation of 44 percent of the delta. Since historical tide stages are unknown for a large portion of the period of record, a daily peak discharge of 20,000 ft^3/sec (566 m^3/sec) or greater was selected as a potential inundation event.

1/ Deltaic inundation is defined as submergence of a portion of the river delta by water to a depth of at least 0.5 feet for a period not less than 48 hours. These values are based upon TDWR supported research (310, 311). Studies indicate that maximum rates of nutrient release from the sediment of a discrete inundation event, following a prolonged period of emergence drying.

Daily gaged discharge data for the period of record (1924-1977) were examined to arrive at monthly and seasonal distributions of discharge events with daily peak flows of 20,000 ft^3/sec (566 m^3/sec) or greater (Table 9-3). It was apparent that more inundation events have occurred in the spring months of March, April, and May than during any other seasonal period. The data suggest that inundation events in the Trinity delta have occurred more often in the winter and spring than in the summer and fall. According to the biological evidence, spring inundation events are necessary for (1) adequate physical wetting of the marsh plant communities, (2) nutrient exchange and biogeochemical cycling of carbon, nitrogen and phosphorus, (3) transport of detrital food materials, and (4) reduction of salinity to suit the needs of juvenile, estuarine-dependent organisms utilizing the "nursery" habitats of the marsh and adjacent shallow water areas. In the tropical-storm dominated fall season, less frequent inundation events occur; however, maintenance benefits are still provided to the estuary and dependent species such as the redfish.

If historical inundation events (peak daily flows greater than 20,000 ft^3/sec or 566 m^3/sec) are grouped into those that occur in spring (March, April, and May), those that occur in the winter (December, January and February), and the total that occurs during the year, it is evident that an average of three inundation events have occurred per year in the Trinity delta over the period of record (Table 9-4). In order to maintain the historical inundation frequency, the Trinity River delta would need to receive three flood events per year with flows greater than 20,000 ft^3/sec (566 m^3/sec) in half of the years in any period.

Ideally, inundation events should occur at times which would provide the most benefit to estuarine organisms. The importance of at least one spring and one fall event has been discussed previously; therefore, flood events are specified for May and October. Since low salinities and shallow habitat (for protection of the young) are primary requisites during the spring, any inundation events occurring during this period will provide the greatest benefit to the organisms. Therefore, the third inundation event is specified for April and is expected to extend favorable habitat conditions for larval and juvenile stages of many estuarine-dependent organisms.

The median daily peak discharge for flood events (peak flows greater than 20,000 ft^3/sec) over the period of record has been 29,500 ft^3/sec (835 m^3/sec). The Trinity delta hydrodynamic model computed a delta inundation volume of 750,000 acre-feet (921 million m^3), for this peak discharge of 29,500 ft^3/sec. The percent of marsh inundated will vary with wind direction and tide stage. With a low tide (range -0.9 feet to 0.8 feet above MSL) and a peak discharge of the magnitude mentioned above, the model predicts that about 21 percent (Figure 5-46) of the delta area will be inundated to a depth of at least 0.5 feet for a minimum of 48 hours. Under a "high tide" (range 0.6 to 2.4 feet above MSL) similar peak discharges will result in inundation of 98 percent of the Trinity delta.

Estuarine Linear Programming Model Description

The combination of specified objectives and environmental and physical constraints relating the interactions of freshwater inflows with selected estuarine indicators is termed the Estuarine Linear Programming Model. The model relates the conditions of the estuary, in terms of a specified criteria,

Table 9-3. Peak Gaged Discharges for Discrete Flood Events Greater than 20,000 ft³/sec in the Trinity River at Romayor, 1924-1977

Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
					ft³/sec						
59,300	50,800	47,700	104,000	107,000	94,200	44,100	33,500	40,200	49,000	60,800	46,600
48,100	48,800	47,000	52,200	93,000	57,700	36,300	20,000	26,800	45,300	52,400	40,200
37,700	47,000	44,100	50,600	69,000	49,400	22,700		25,100	31,100	51,200	38,700
36,500	45,800	41,300	46,600	66,800	48,700				28,500	46,600	35,100
36,400	41,700	39,000	43,800	66,200	40,600				23,000	45,600	27,400
32,600	34,500	37,800	41,800	61,600	33,200					42,200	26,300
30,500	29,800	37,600	41,500	58,200	27,300					33,500	25,200
28,800	28,900	34,700	40,600	51,500	26,300					30,800	24,000
28,400	28,500	33,600	40,400	48,000	25,600					21,200	23,800
28,000	27,700	30,900	39,700	47,200	23,400						23,500
26,500	27,400	30,700	33,000	46,600	22,500						23,200
24,600	27,000	27,200	32,400	45,200							22,300
24,200	26,600	26,800	31,600	42,400							22,200
23,800	25,700	26,000	29,000	40,000							21,200
23,200	25,200	25,000	27,400	37,600							20,100
22,200	24,300	24,000	26,800	37,200							20,000
21,800	24,000	24,000	24,700	35,800							
20,800	22,500	23,800	21,700	35,100							
20,500	21,600	21,600	21,300	28,500							
20,100	21,600	21,300	20,200	26,400							
20,000	21,200	21,000	19,600	25,900							
	21,000	21,000		25,500							
		20,300		24,400							
				23,000							
				22,800							
				22,700							
				21,400							
				20,800							

Median peak flood discharge = 29,500 ft³/sec

Table 9-4. Frequency of Annual and Seasonal Flood Events with Peak Daily Gaged Flows Greater than 20,000 ft^3/sec in the Trinity River Delta, 1924-1977

Number of Events per Period	Number of Occurrences over Period of Record: Winter (December-February)		Spring (March-May)		Total Annual	
(x)	Freq.(f) a/	f*x b/	Freq.(f)	f*x	Freq.(f)	f*x
0	21	0	16	0	1	0
1	17	17	14	14	7	7
2	7	14	15	30	7	14
3	8	4	8	24	5	15
4	1	4	1	4	5	20
5					3	15
6					3	18
7					3	21
8					1	8
9					1	9
10					0	0
11					1	11
Σf^*x		59		72		164
Number of Years = 54						
Mean Number Inundation events per year		1.1		1.4		3.0
Median Number Inundation events per year		1		1		3

a/ Freq. (f) is the number of seasons or years in which the number of flood events greater than 20,000 ft^3/sec equaled x.

b/ f*x stands for f multiplied by x.

to the set of relevant variables, including monthly inflows from the San Jacinto and Trinity River Basins.1/ A Linear Programming (42) optimization procedure is used to compute the monthly freshwater inflows from the San Jacinto and Trinity River Basins needed to meet specified salinity, marsh inundation and commercial fisheries levels. The quantifications of salinity and commercial fisheries harvest as functions of seasonal freshwater inflow are represented by the statistical regression equations given in Chapters V and VIII, respectively. The harvest equation utilized for a given species or species group is the regression equation accounting for the most variance in the data (i.e., having the largest r^2 value) based upon the combined inflow to the estuary. In the case of total finfish harvest where such an equation was not derived, the finfish harvest was estimated by taking the average of the harvests predicted from equations using San Jacinto Basin inflows only and Trinity Basin inflows only.

Specification of Objectives. The criteria or objectives in this optimization formulation can be any desired estuarine condition. One objective of interest is to compute the least annual inflow to the estuary that meets the constraints on the salinity regime and marsh inundation. Another alternative could be to compute the estimated quantity of freshwater inflow to maximize the estimated commercial harvests in the estuary. This harvest could be either for an individual fisheries species, or a weighted sum of the harvests of a group of commercially important species (e.g., shellfish).

Computation Constraints for the Model. A set of constraints in the model relate freshwater inflow to various environmental and statistical limits specified as objectives. These constraints include:

(1) upper and lower limits for the seasonal inflows used in the regression equations which estimate annual commercial fisheries harvests,
(2) statistical regression equations relating mean monthly salinities to mean monthly freshwater inflows,
(3) upper and lower limits on the monthly flows used in computing the salinity regression relationships, and
(4) upper and lower vaiability limits on allowable monthly salinities (Table 9-2).

Alternative Estuarine Objectives

Three alternative objectives are considered as follows:

Alternative I, Subsistence
Objective: minimize annual combined inflow while meeting salinity viability limits and marsh inundation needs;

Alternative II, Maintenance of Fisheries Harvests
Objective: minimize annual combined inflow while providing freshwater inflows sufficient to provide predicted annual commercial harvests

1/ Additional freshwater inflows are contributed to the estuary from the Neches-Trinity, Trinity-San Jacinto and San Jacinto-Brazos Coastal Basins; however, the individual monthly inflows from these sources are taken to be fixed at their historical average monthly inflows over the period 1941 through 1976.

in the estuary of red drum, spotted seatrout, penaeid shrimp, and all shellfish combined at levels no less than their mean 1962 through 1976 historical values, satisfying marsh inundation needs, and meeting viability limits for salinity;

Alternative III, Shrimp Harvest Enhancement
Objective: maximize the total annual commercial harvest of shrimp in the offshore Gulf Area No. 18 adjacent to the estuary while meeting viability limits for salinity, satisfying marsh inundation needs, and utilizing an annual combined inflow to the estuary no greater than the combined individual average 1941 through 1976 annual historical inflows from the contributing river basins.

The objectives and constraints for the listed alternatives are indicated in Table 9-5. The three specified objectives are not the only possible options for the Trinity-San Jacinto estuary; however, they provide a range of alternatives: survival or subsistence (Alternative I), maintenance of estuarine harvest levels (Alternative II), and offshore shrimp harvest enhancement (Alternative III).

Alternative I: Subsistence. The objective of Alternative I (Subsistence) is to minimize total annual combined inflow while meeting specified bounds on salinity (Table 9-2) in upper Galveston and Trinity Bays and satisfying marsh inundation needs for the Trinity delta.[1/] The upper salinity bound for each month is the minimum of the upper salinity viability limit and the historic median salinity (Table 9-2).

The marsh inundation needs specified earlier in this chapter for the Trinity delta were found to be in conflict with the lower salinity limits established above during the month of April. From Table 9-2, the lower salinity limit in upper Trinity Bay for April is 5 parts per thousand (ppt); however, the inundation volume for the month gives a salinity level of 3 ppt. The lower limit on salinity during April in Trinity Bay was reduced to 3 ppt to accommodate the inundation event since it was judged that relatively little adverse impact would arise from the slightly reduced minimum salinity during that month. This revised lower bound for April was also applied in the evaluation of Alternatives II and III.

Optimal monthly inflows to the estuary needed to meet the objective were determined by the Estuarine Linear Programming Model. The estimated annual combined inflow need amounts to approximately 6.852 million acre-feet (8,418 million m^3) with 2.10 million acre-feet (2,589 million m^3) from the San Jacinto River Basin, 3.58 million acre-feet (4,414 million m^3) from the Trinity River Basin and 1.17 million acre-feet (1,443 million m^3) from the Neches-Trinity, Trinity-San Jacinto, and San Jacinto-Brazos Coastal Basins (Table 9-6).

Monthly freshwater inflow needs generated by the Estuarine Linear Programming Model for Alternative I provide salinities which closely approximate those for the required upper bounds during most months of the year (Figures 9-2 and 9-3). Trinity River Basin inflows during the months of April, May,

1/ Trinity delta inundation needs include two inundation events of 750,000 ac-ft for the period April through May (Trinity River peak daily discharge of 29,500 ft^3/sec at Romayor) and a single flood of 750,000 ac-ft (29,500 ft^3/sec at Romayor) in October.

Table 9-5. Criteria and System Performance Restrictions for the Selected Estuarine Alternatives

	Alternatives		
	I	II	III
Criteria:			
. Maximize Annual Combined Inshore and Offshore Harvest of Shrimp			x
. Least Possible Annual Combined Inflow to Estuary	x	x	
Constraints:			
. Annual Inflows from the San Jacinto and Trinity River Basins are each no greater than their Average Annual Historical Values (1941-1976)			x
. Predicted Annual Spotted Seatrout and Red Drum Commercial Harvests no less than their Average Annual Values (1962-1976)		x	
. Predicted Annual Shrimp, Blue Crab and Bay Oyster Commercial Harvests no less than their Average Annual Values (1962-1976)		x	
. Upper and Lower Limits on Seasonal Inflows to Insure Validity of Predictive Harvest Equations	x	x	x
. Upper and Lower Limits on Mean Monthly Salinity	x	x	x
. Upper and Lower Limits on Monthly Inflows to Insure Validity of Predictive Salinity Equations	x	x	x
. Lower Limits on Mean Monthly Trinity River Basin Inflows for Marsh Inundation of the Trinity Delta	x	x	x

Table 9-6. Freshwater Inflow Needs of the Trinity-San Jacinto Estuary under Alternative I a/

Month	San Jacinto River Basin: Total Inflow Needs	San Jacinto River Basin: Inflow Needs from Drainage Area of the Basin Upstream from the Last Downstream Stream Gage b/	Trinity River Basin: Total Inflow Needs	Trinity River Basin: Inflow Needs from Drainage Area of the Basin Upstream from the Last Downstream Stream Gage c/	Total Inflow From Coastal Basins d/	Combined Inflow e/
	Thousands of Acre-Feet					
January	249.4	181.5	135.9	96.1	103.0	488.3
February	215.1	153.0	136.9	97.1	128.0	480.0
March	164.2	110.6	115.8	81.4	85.0	365.0
April	217.0	154.5	750.0	691.2	109.0	1,076.0
May	268.0	197.0	750.0	702.2	144.0	1,162.0
June	180.5	124.1	450.7	429.9	129.0	760.2
July	134.1	85.4	49.2	56.5	54.0	237.3
August	132.8	84.4	62.7	59.0	60.0	255.5
September	149.2	98.0	86.5	70.2	97.0	332.7
October	99.9	57.0	750.0	670.2	89.0	938.9
November	95.0	52.9	133.5	94.8	76.0	304.5
December	198.3	139.0	159.6	119.1	94.0	451.9
Annual	2,103.5	1,437.4	3,580.8	3,167.7	1,168.0	6,852.3

a/ All inflows are mean monthly values

b/ These values computed using regression equations relating monthly river basin inflow to the estuary with monthly gaged inflows at USGS Stations #08074000, 08074500, 08075500, 08076000, and 08076500

c/ These values computed using regression equations relating monthly river basin inflow to the estuary with monthly gaged flows at USGS station at Romayor, with historic diversions between the stream gage and the estuary removed

d/ The coastal basins are the Neches-Trinity, Trinity-San Jacinto, and San Jacinto-Brazos

e/ Includes all freshwater inflow to the estuary except direct precipitation on the estuary's surface (see Chapter IV for definition)

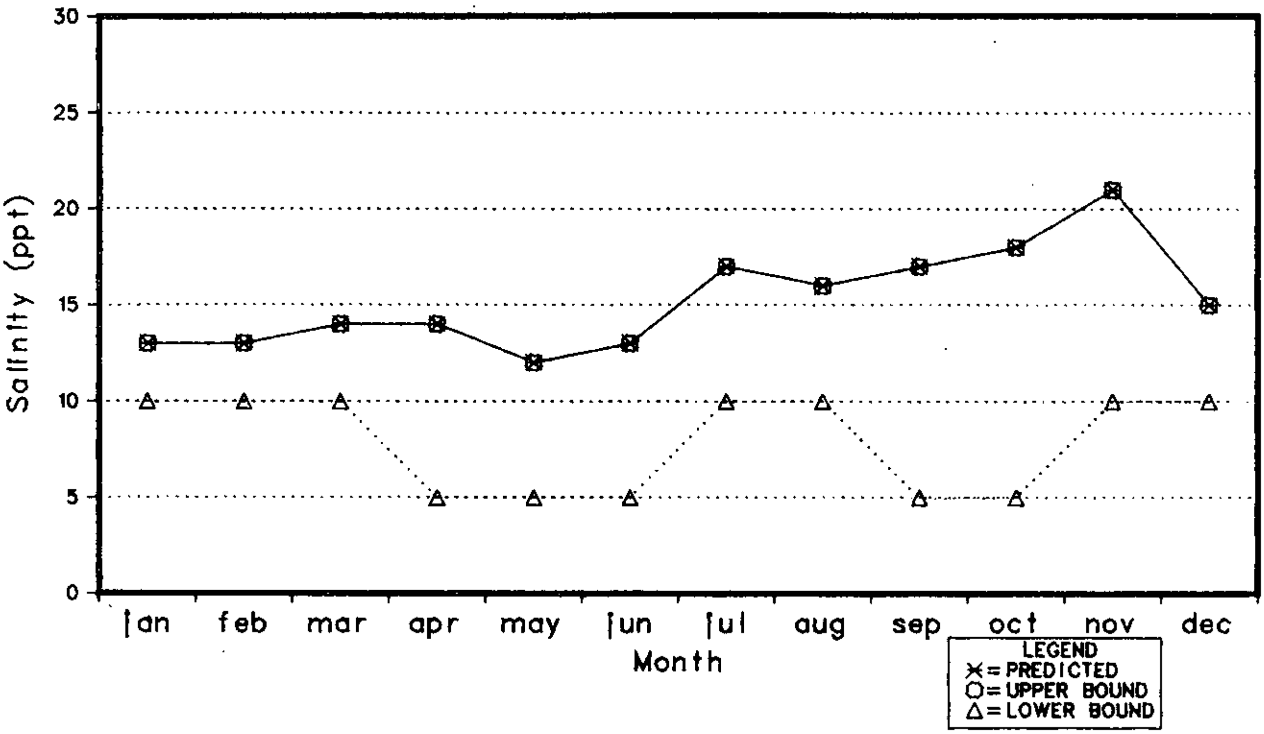

Figure 9-2. Average Monthly Salinities in Upper Galveston Bay Under Alternative I

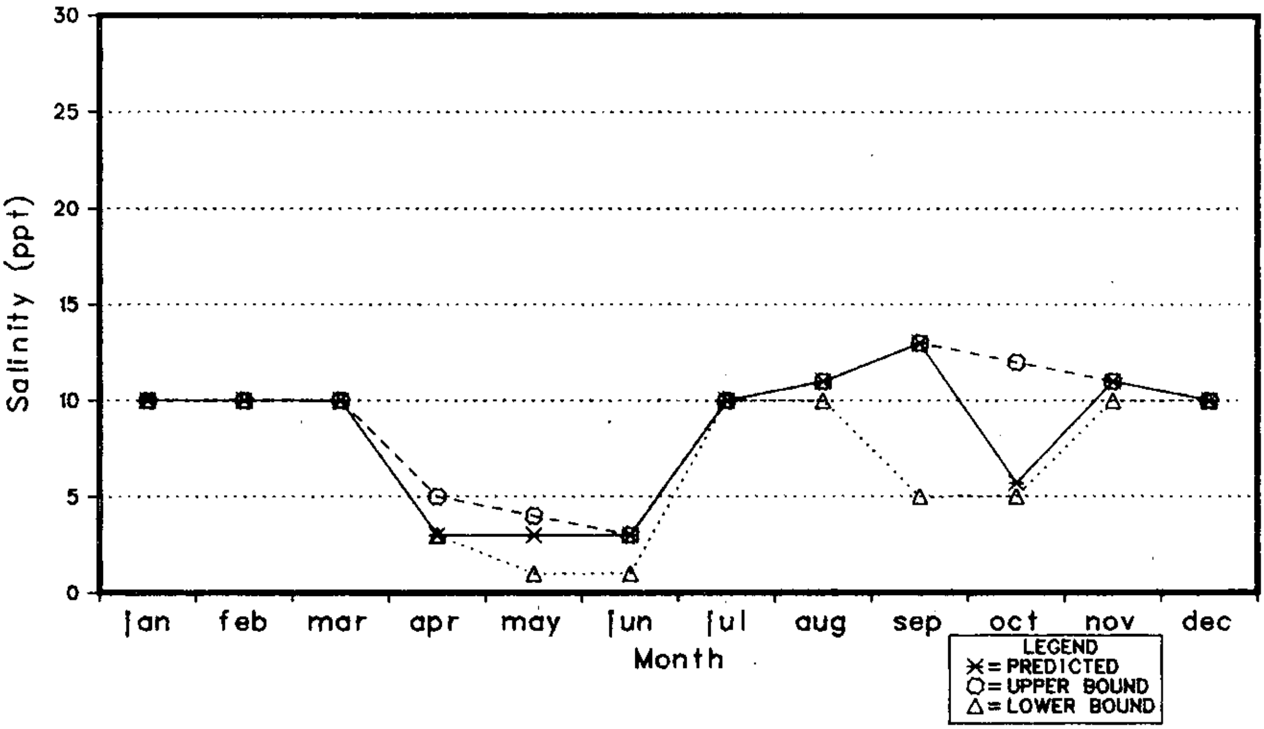

Figure 9-3. Average Monthly Salinities in Trinity Bay Under Alternative I

and October provide salinities lower than the upper limit as a consequence of meeting marsh inundation requirements for the Trinity delta. The upper and lower salinity limits are the same in Trinity Bay for the months of December through March and July since the median salinities were less than the lower viability limit.

Comparisons between the mean 1941 through 1976 historical combined inflows and the estimated freshwater inflow needs are made for each month (Figure 9-4 and 9-5), for the San Jacinto and Trinity River Basins. For the San Jacinto River Basin, the inflow needs are less than the mean monthly 1941 through 1976 inflows, with the exceptions of the months of January, March, August and December. For the Trinity River Basin, the mean 1941 through 1976 monthly inflows exceed the inflow need except for the months of April and September when marsh inundation events are scheduled. The distribution of the freshwater inflow needs between contributing basins is illustrated in Figure 9-6. The inflow from the three adjacent coastal basins is a significant contribution accounting for approximately 17 percent of the total annual inflow.

Implementation of Alternative I for the Trinity-San Jacinto estuary under the inflow regime indicated in Table 9-6 is projected to result in a general increase in commercial fisheries harvests from average historic levels (Figure 9-7). The finfish category is predicted to have an annual harvest of 500.8 thousand pounds (227 thousand kg), or a 44 percent increase above average; total shellfish harvest (including the harvest of shrimp from offshore Gulf Area No. 18), a 15 percent increase above average historic levels; and bay oyster, a predicted 14 percent above average historic levels. Only the bay harvest of red drum is predicted to be lower than the mean 1962 through 1976 mean historic harvest (26 thousand pounds or 12 thousand kg versus 36 thousand pounds or 16 thousand kg).

Alternative II: Maintenance of Fisheries Harvests. The objective of Alternative II (Maintenance of Fisheries Harvests) is to minimize combined inflow to the estuary while providing freshwater inflows sufficient to generate predicted annual commercial harvests of red drum, spotted seatrout, shrimp, blue crab, and bay oyster at levels no less than their mean 1962 through 1976 historical values, satisfying marsh inundation needs, and meeting bounds for salinity.

The optimal set of monthly freshwater inflow needs derived by the Estuarine Linear Programming Model for Alternative II (Table 9-7) amounts to 7.19 million acre-feet (8,865 million m^3) annually, of which 1.17 million acre-feet (1,443 million m^3) are contributed from the coastal basins. The computed annual contributions of the San Jacinto and Trinity River Basins are 2.42 thousand (2,984 million m^3) and 3.60 million acre-feet (4,439 million m^3), respectively. The yearly inflow volume from the San Jacinto River Basin is slightly greater (seven percent) than the average historical inflow, while the inflow specified from the Trinity River Basin is 40 percent less than the historical average annual inflow of 5.962 million acre-feet (7,351 million m^3) over the period 1941 through 1976.

Relatively little additional inflow (340 thousand acre-feet or 419 million m^3) above that required for Alternative I is needed to satisfy the constraints of this alternative since only one of the predicted species harvests (red drum), under Alternative I inflows, fails to be at least as great as its historical average harvest. The additional inflows occur in the months of November and December. All but approximately 20 thousand acre-feet (24 million m^3) of the 340 thousand acre-feet (419 million m^3) is required

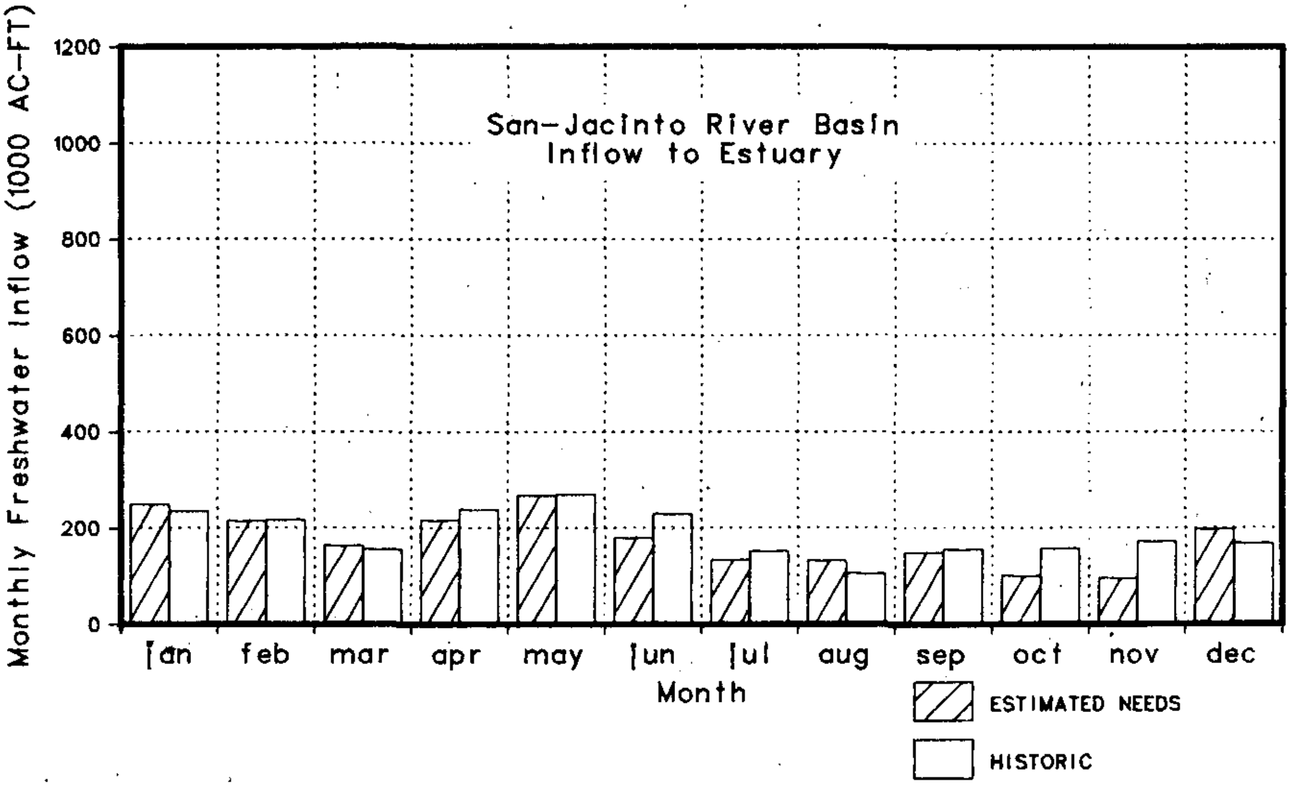

Figure 9-4. Comparison Between Mean Historical Freshwater Inflow and Inflow Needs Under Alternative I for the Trinity-San Jacinto Estuary From the San Jacinto River Basin

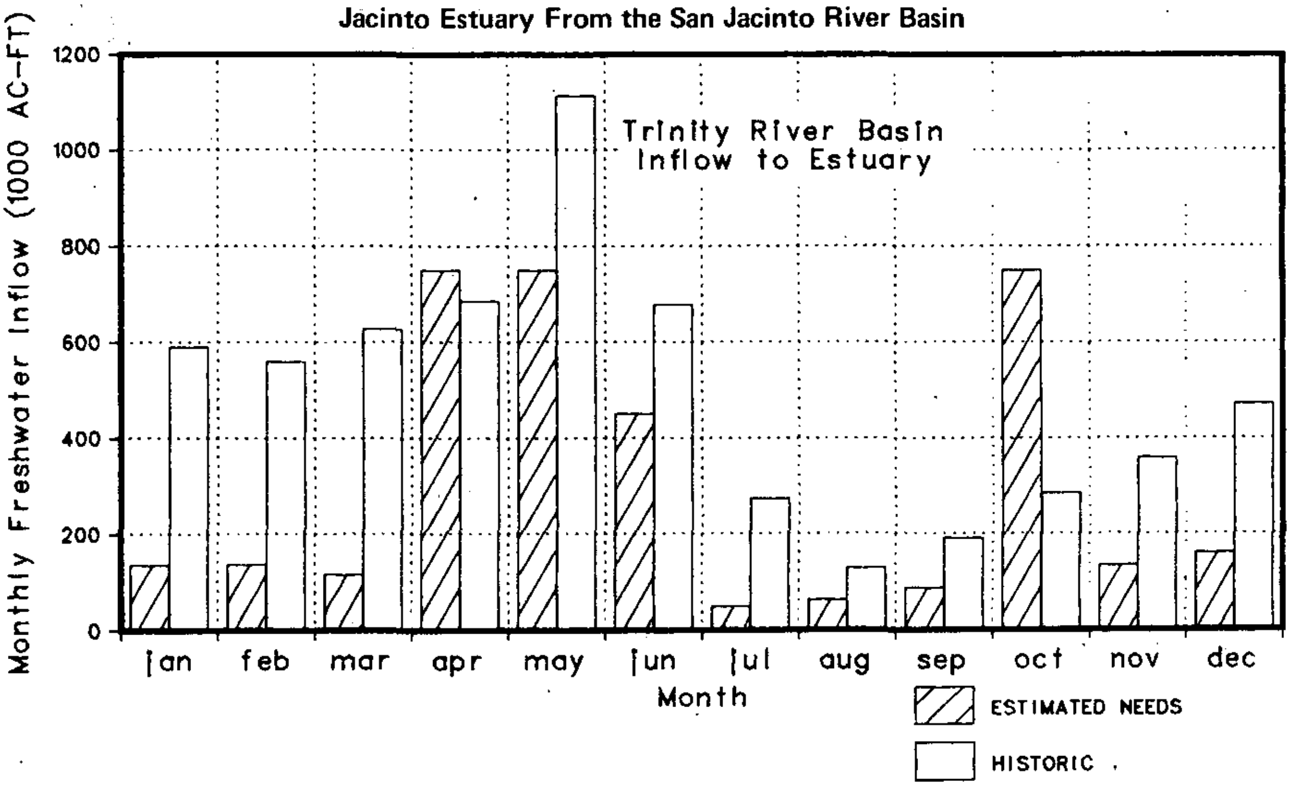

Figure 9-5. Comparison Between Mean Historical Freshwater Inflow and Inflow Needs Under Alternative I for the Trinity-San Jacinto Estuary From the Trinity River Basin

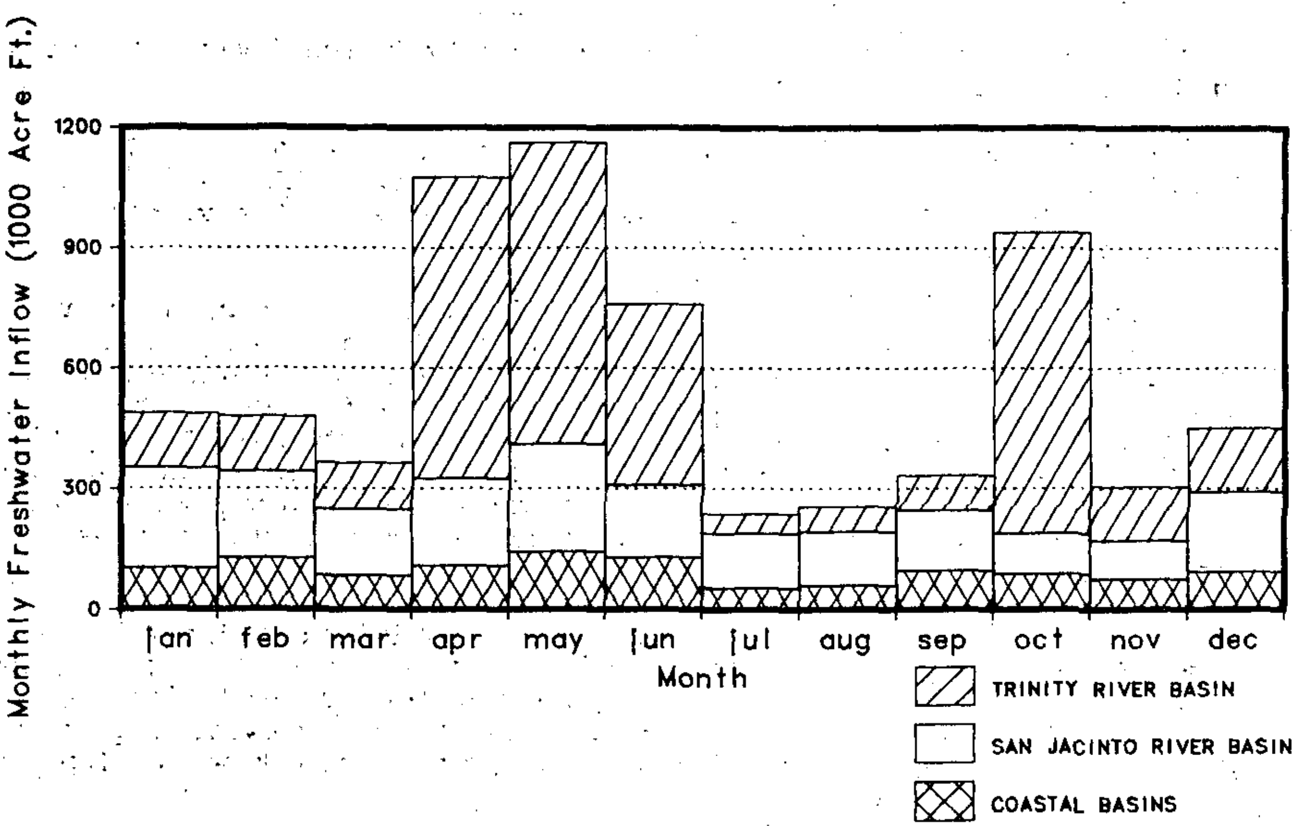

Figure 9-6. *Estimated Freshwater Inflow Needs for the Trinity-San Jacinto Estuary Under Alternative I*

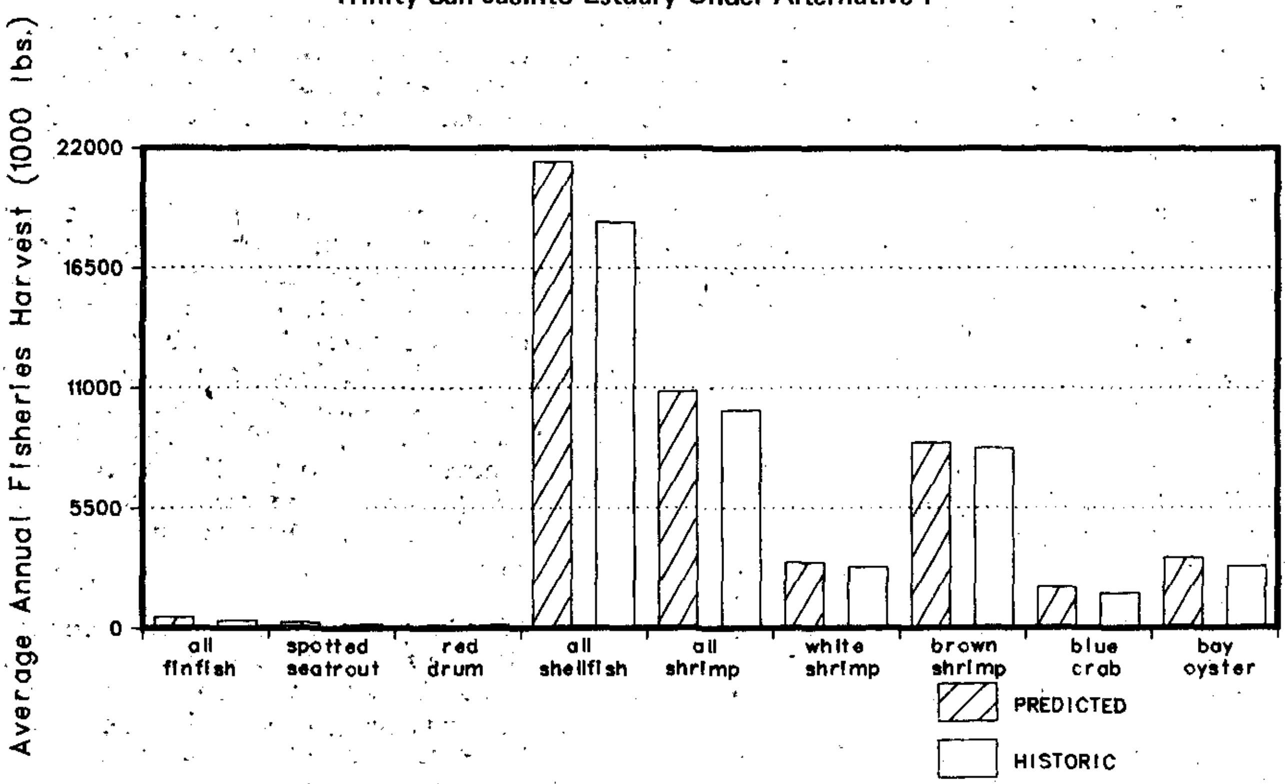

Figure 9-7. Comparison Between Trinity-San Jacinto Historical Fisheries Harvests and Predicted Harvests Under Alternative I

from the San Jacinto River Basin since salinity bounds limited additional inflow from the Trinity Basin.

Monthly freshwater inflow needs generated for Alternative II provide salinities which correspond to those under Alternative I (Figure 9-8), except for the months of November and December in upper Galveston Bay and November in upper Trinity Bay (Figure 9-9).

Comparisons between the mean historical combined inflows and estimated freshwater inflow needs are made for the San Jacinto and Trinity River Basins (Figures 9-10 and 9-11). The average 1941 through 1976 historical inflows from the San Jacinto River Basin are higher than the freshwater inflow needs under this alternative for about half of the months. From the Trinity River Basin, inflows larger than historical average values are needed only in April and October. The Estuarine Linear Programming Model distributes monthly inflows to achieve Alternative II (Maintenance of Fisheries Harvests) as indicated in Figure 9-12.

Implementation of Alternative II for the Trinity-San Jacinto estuary under the inflow regime indicated in Table 9-7 results in a projected increase in commercial fisheries harvests from average historical levels for all harvest groups except red drum (Figure 9-13). The red drum harvest is predicted to be equal to the 1962 through 1976 average historic harvest of 36.3 thousand pounds (16.4 thousand kg) annually.

Alternative III: Shrimp Harvest Enhancement. The objective of Alternative III (Shrimp Harvest Enhancement) is to maximize the annual offshore commercial harvest of shrimp in the offshore region adjacent to the estuary (Gulf Area No. 18) while observing salinity limits and marsh inundation needs, and utilizing annual San Jacinto and Trinity River Basin inflows no greater than there respective average historical annual inflows.

The Estuarine Linear Programming Model was utilized to determine an optimal set of monthly river basin inflows to meet the stated objective (Table 9-8). The annual combined inflow 1/ from freshwater sources needed to maximize the offshore shrimp harvest is estimated at 7.02 million acre-feet (8,656 million m^3). The total annual contribution from the Trinity River Basin is estimated at 3.59 million acre-feet (4,426 million m^3), while the corresponding San Jacinto River Basin contribution is limited to the historical average of 2.26 million acre-feet (2,787 million m^3). Additional inflow from the San Jacinto River Basin would have increased the predicted harvest without violating salinity limits. The remaining annual freshwater contribution of 1.17 million acre-feet (1,443 million m^3) is the historical average annual inflow from the contributing coastal basins.

Salinities in the upper Galveston Bay are the same under both Alternatives II and III, except in July, August, November, and December (Figure 9-14). Monthly freshwater inflow needs generated for Alternative III provide salinities which are lower than those under Alternative II only in the month of August in Trinity Bay (Figure 9-15). In November, however, upper Trinity Bay salinity is slightly higher than that under Alternative II.

1/ Combined inflow does not include direct precipitation on the estuary's surface (See Chapter IV for definition).

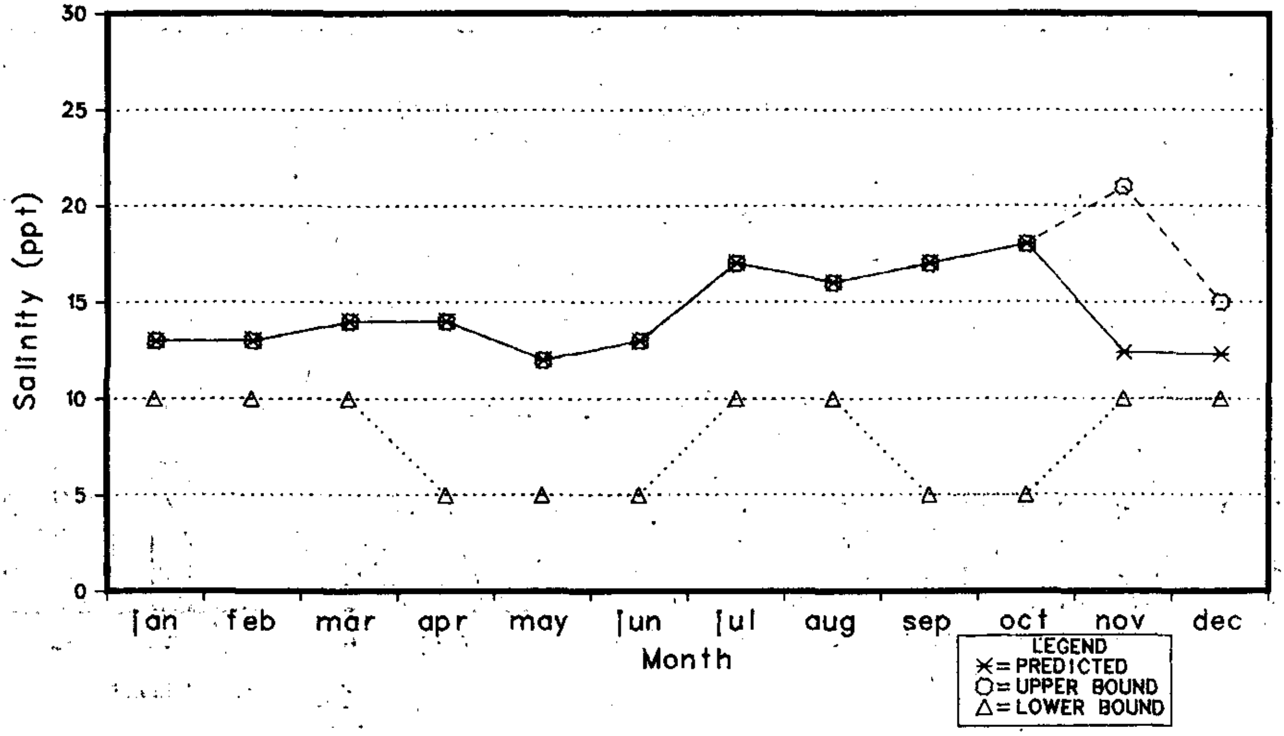

Figure 9-8. Average Monthly Salinities in Upper Galveston Bay Under Alternative II

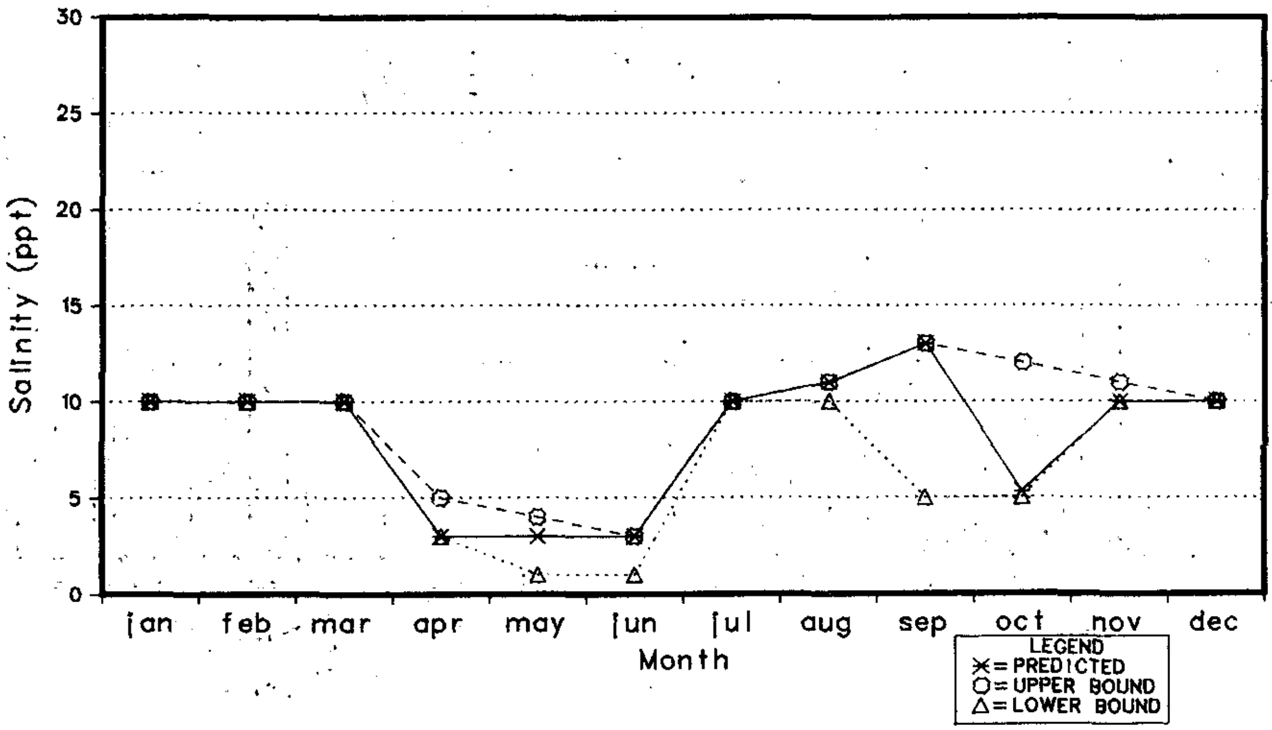

Figure 9-9. Average Monthly Salinities in Trinity Bay Under Alternative II

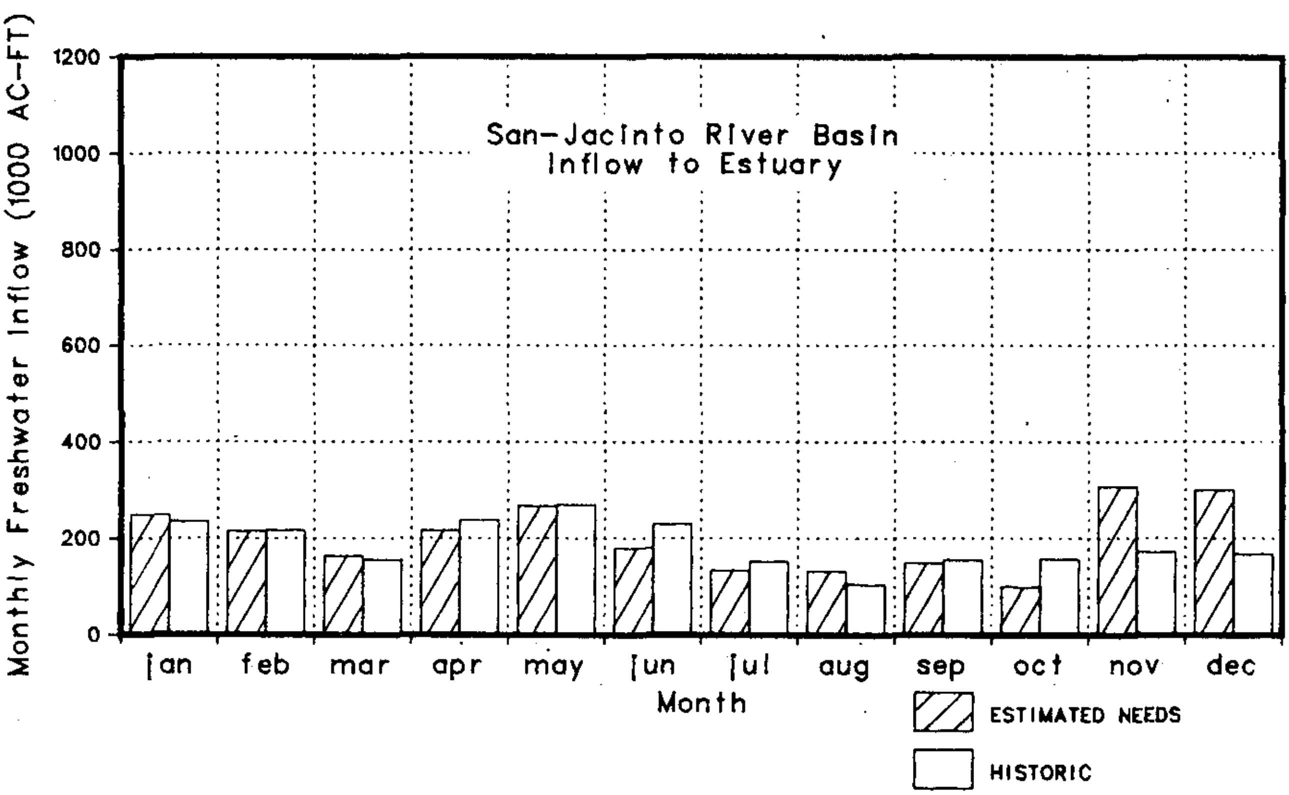

Figure 9-10. Comparison Between Mean Historical Freshwater Inflow and Inflow Needs Under Alternative II for the Trinity-San Jacinto Estuary From the San Jacinto River Basin

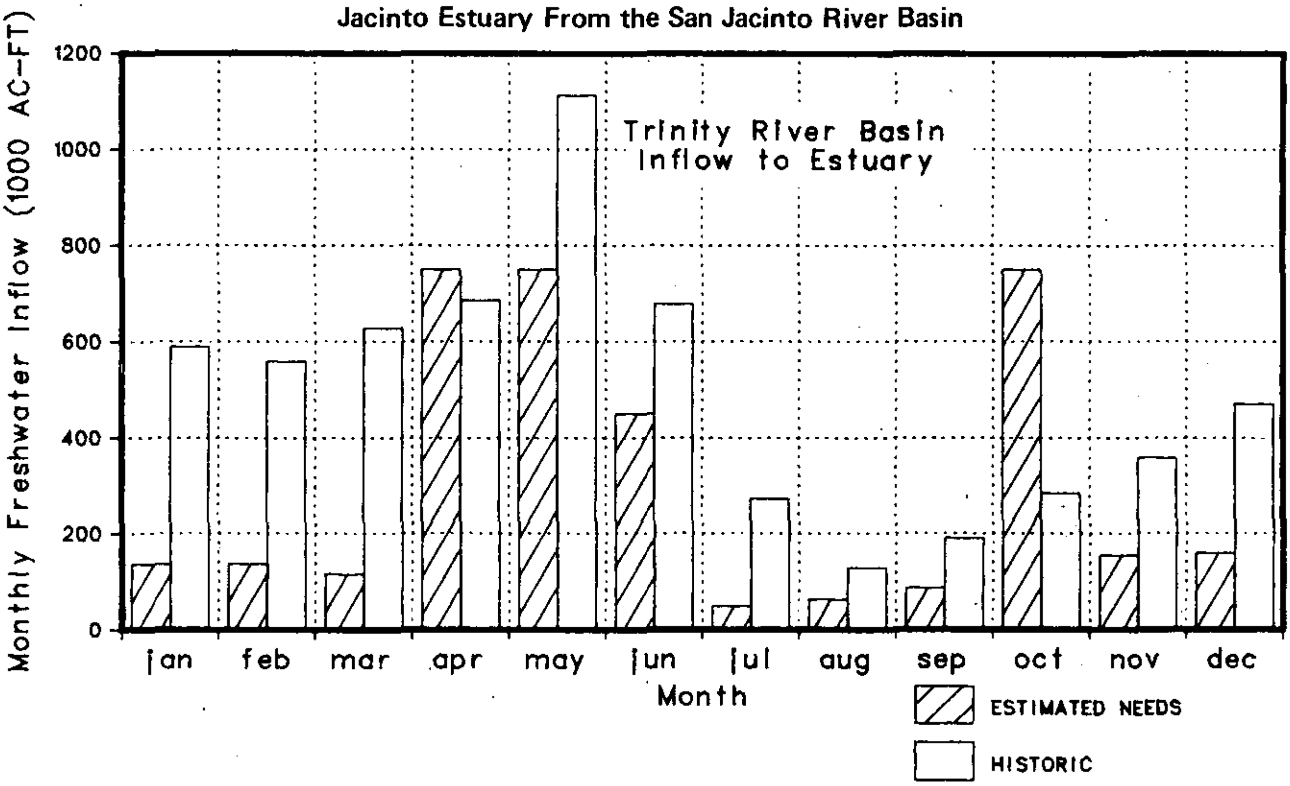

Figure 9-11. Comparison Between Mean Historical Freshwater Inflow and Inflow Needs Under Alternative II for the Trinity-San Jacinto Estuary From the Trinity River Basin

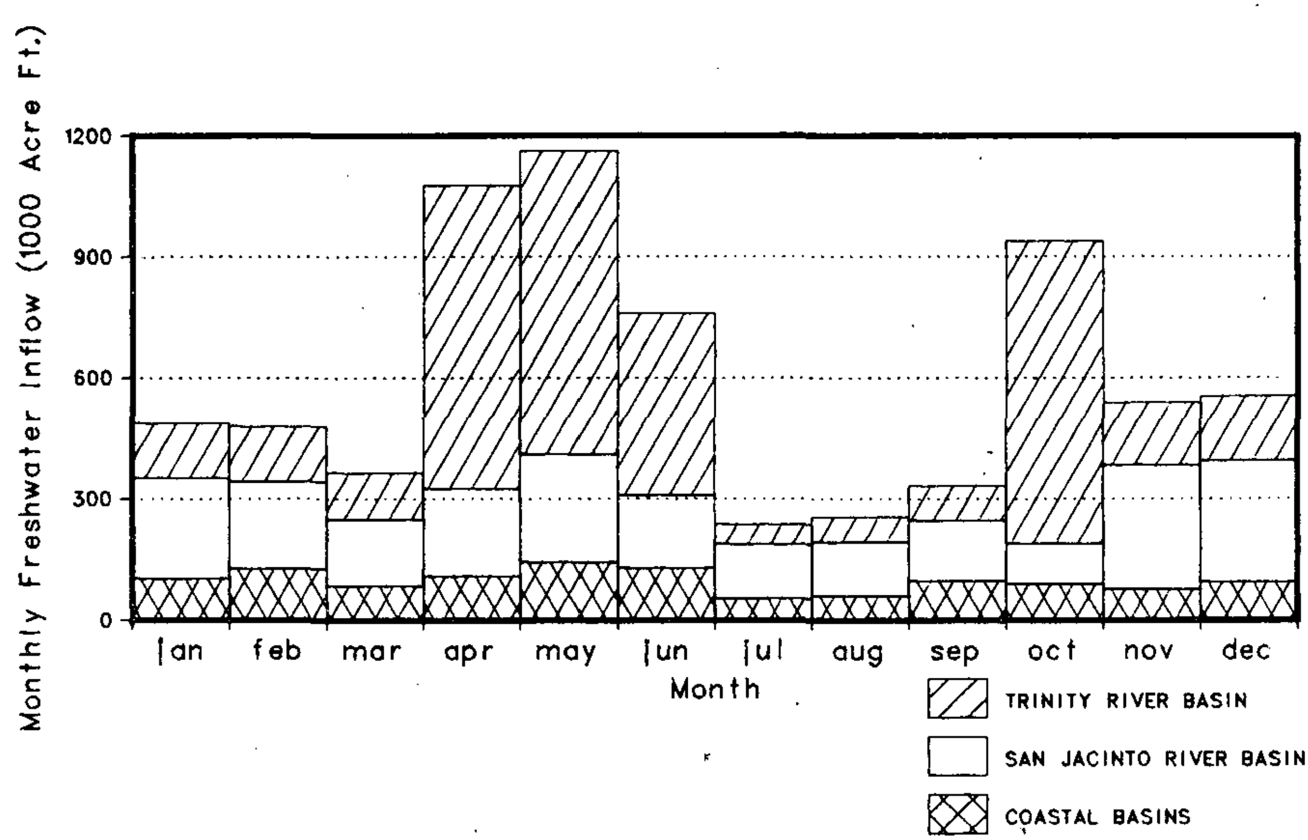

Figure 9-12. Estimated Freshwater Inflow Needs for the Trinity-San Jacinto Estuary Under Alternative II

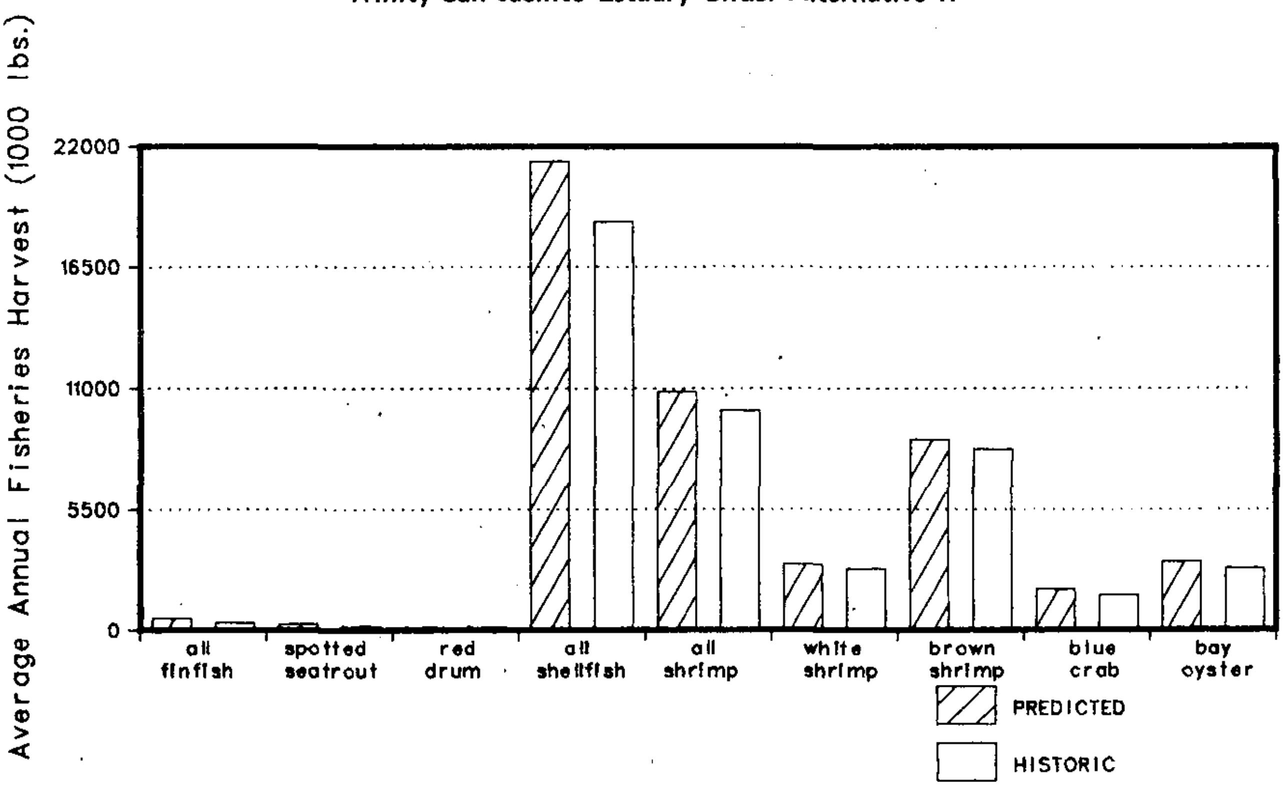

Figure 9-13. Comparison Between Trinity-San Jacinto Historical Fisheries Harvests and Predicted Harvests Under Alternative II

Table 9-7. Freshwater Inflow Needs of the Trinity-San Jacinto Estuary under Alternative II a/

Month	San Jacinto River Basin: Total Inflow Needs	San Jacinto River Basin: Inflow Needs from Drainage Area of the Basin Upstream from the Last Downstream Stream Gage b/	Trinity River Basin: Total Inflow Needs	Trinity River Basin: Inflow Needs from Drainage Area of the Basin Upstream from the Last Downstream Stream Gage c/	Total Inflow From Coastal Basins d/	Combined Inflow e/
	Thousands of Acre-Feet					
January	249.4	181.5	135.9	96.1	103.0	488.3
February	215.1	153.0	136.9	97.1	128.0	480.0
March	164.2	110.6	115.8	81.4	85.0	365.0
April	217.0	154.5	750.0	691.2	109.0	1,076.0
May	268.0	197.0	750.0	702.2	144.0	1,162.0
June	180.5	124.1	450.7	429.9	129.0	760.2
July	134.1	85.4	49.2	56.5	54.0	237.3
August	132.8	84.4	62.7	59.0	60.0	255.5
September	149.2	98.0	86.5	70.2	97.0	332.7
October	99.9	57.0	750.0	670.2	89.0	938.9
November	308.2 f/	230.5	154.4	114.2	76.0	538.5
December	300.9 f/	224.4	159.6	119.1	94.0	554.5
Annual	2,419.3	1,700.4	3,601.6	3,187.1	1,168.0	7,188.9

a/ All inflows are mean monthly values.

b/ These values computed using regression equations relating monthly river basin inflow to the estuary with monthly gaged inflows at USGS Stations #08074000, 08074500, 08075500, 08076000, and 08076500.

c/ These values computed using regression equations relating monthly river basin inflow to the estuary with monthly gaged flows at USGS station at Romayor, with historic diversions between the stream gage and the estuary removed.

d/ The coastal basins are the Neches-Trinity, Trinity-San Jacinto, and San Jacinto-Brazos.

e/ Includes freshwater inflow need from the basin distributed according to San Jacinto River Basin historical monthly freshwater inflow (1941-1976) in the season (November and December).

f/ Total seasonal freshwater inflow need from the basin distributed according to San Jacinto River Basin historical monthly freshwater inflow (1941-1976) in the season (November and December).

Table 9-8. Freshwater Inflow Needs of the Trinity-San Jacinto Estuary under Alternative III a/

Month	San Jacinto River Basin		Trinity River Basin		Total Inflow From Coastal Basins d/	Combined Inflow e/
	Total Inflow Needs	Inflow Needs from Drainage Area of the Basin Upstream from the Last Downstream Stream Gage b/	Total Inflow Needs	Inflow Needs from Drainage Area of the Basin Upstream from the Last Downstream Stream Gage c/		
	Thousands of Acre-Feet					
January	249.4	181.5	135.9	96.1	103.0	488.3
February	215.1	153.0	136.9	97.1	128.0	480.0
March	164.2	110.6	115.8	81.4	85.0	365.0
April	217.0	154.5	750.0	691.2	109.0	1,076.0
May	268.0	197.0	750.0	702.2	144.0	1,162.0
June	180.5	124.1	450.7	429.9	129.0	760.2
July	250.6f/	182.5	49.2	56.5	54.0	353.8
August	172.8f/	117.5	73.9	69.4	60.0	306.7
September	149.2	98.0	86.5	70.2	97.0	332.7
October	99.9	57.0	750.0	670.2	89.0	938.9
November	95.0	52.9	133.5	94.8	76.0	304.5
December	198.3	139.0	159.6	119.1	94.0	451.9
Annual	2,260.0	1,570.6	3,592.0	3,178.1	1,168.0	7,020.0

a/ All inflows are mean monthly values.

b/ These values computed using regression equations relating monthly river basin inflow to the estuary with monthly gaged inflows at USGS Stations #08074000, 08074500, 08075500, 08076000, and 08076500.

c/ These values computed using regression equations relating monthly river basin inflow to the estuary with monthly gaged flows at USGS station at Romayor with historic diversions between the stream gage and the estuary removed.

d/ The coastal basins are the Neches-Trinity, Trinity-San Jacinto, and San Jacinto-Brazos.

e/ Includes all freshwater inflow to the estuary except direct precipitation on the estuary's surface (see Chapter IV for definition).

f/ Total seasonal freshwater inflow need from the San Jacinto River Basin distributed August according to the river basin (1941-1976) average monthly inflow distribution in the season (July and August).

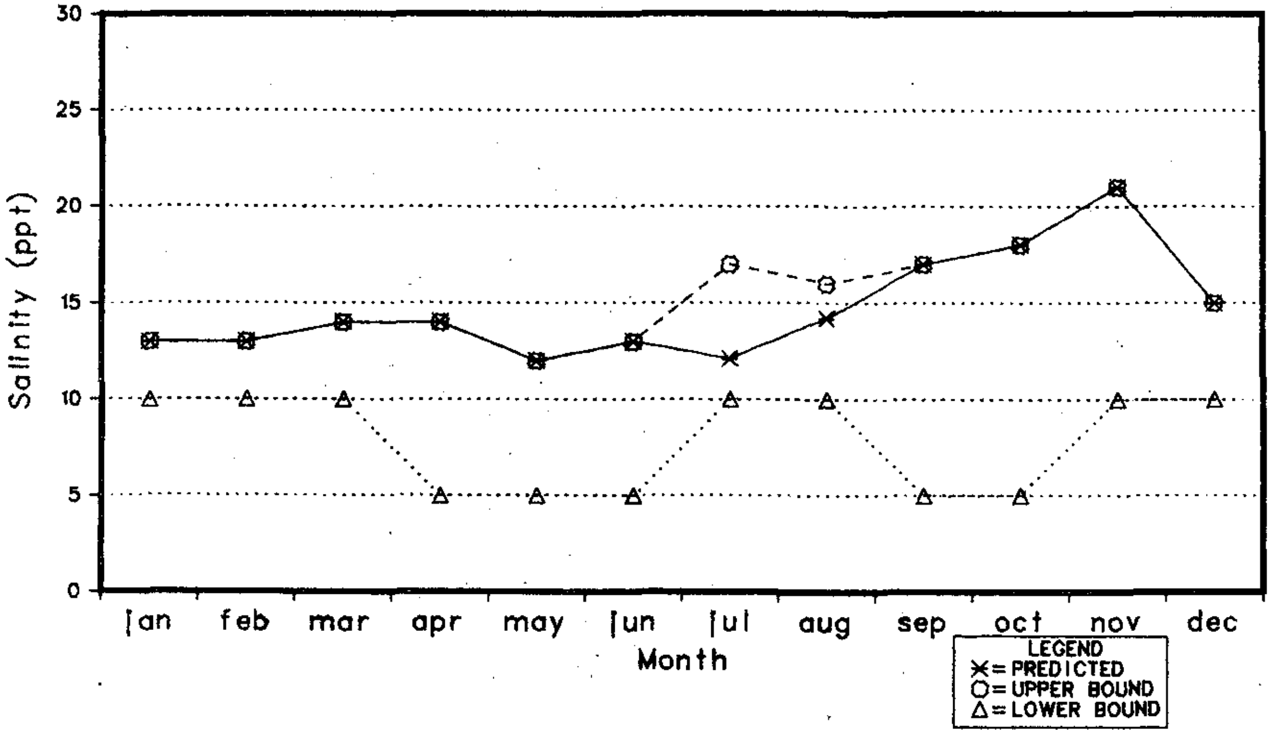

Figure 9-14. Average Monthly Salinities in Upper Galveston Bay Under Alternative III

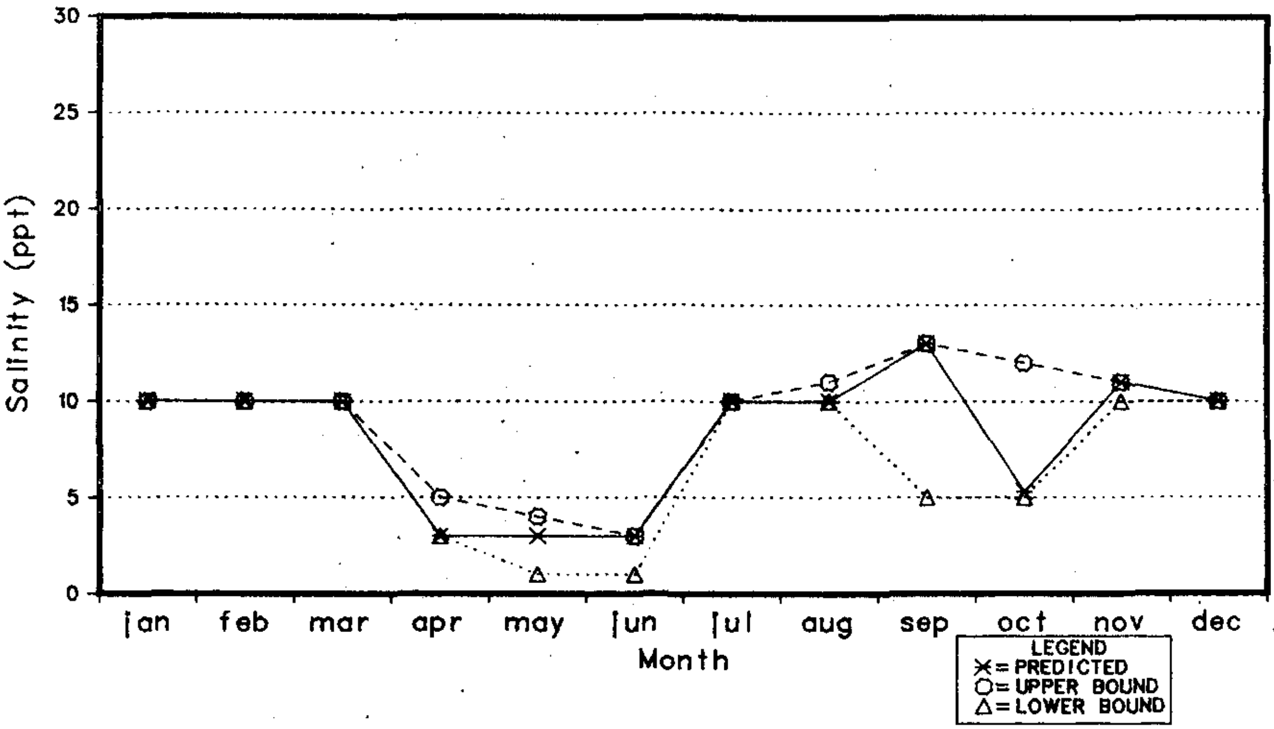

Figure 9-15. Average Monthly Salinities in Trinity Bay Under Alternative III

Comparisons between mean 1941 through 1976 historical combined inflows and estimated freshwater inflow needs under Alternative III have been made for the San Jacinto and Trinity River Basins (Figures 9-16 and 9-17). The average historical inflows from the San Jacinto River Basin are higher than the freshwater inflow needs under Alternative III for all months except January, March, July, August and December. Historical inflows from the Trinity River Basin are higher than the estimated needs under Alternative III for all months except April and October. The Estuarine Linear Programming Model distributes monthly inflows to achieve Alternative III (Shrimp Harvest Enhancement) as indicated in Figure 9-18.

According to this analysis, implementation of Alternative III for the Trinity-San Jacinto estuary under the inflow regime indicated in Table 9-8 would result in an estimated 12 percent increase in total offshore (Gulf Area No. 18) shrimp harvest above the 1962 through 1976 mean historical level (Figure 9-19). This increase occurs when the inflow level is equal to 100 percent of mean historical inflow from the San Jacinto River Basin and 60 percent of the mean historical inflow from the Trinity River Basin. Projected changes in individual harvest categories under Alternative III include a 15 percent increase in the overall shellfish harvest (including offshore shrimp), a very slight increase (0.5 percent) in blue crab harvest, a four percent increase in offshore white shrimp harvest, and a seven percent increase in offshore brown shrimp harvest. An increase in annual bay oyster harvest of four percent is also projected. In the finfish categories, projected changes from 1972 through 1976 historical harvests in the estuary include a 19 percent increase in the overall finfish harvest, a 49 percent increase in spotted seatrout harvest, and a 57 percent decrease in red drum harvest.

Application of Tidal Hydrodynamic and Salinity Transport Models

The determination of preliminary estimates of freshwater inflow needs, described above, must be followed by additional steps in the methodology in order to insure that the resulting salinity distribution throughout the estuary is satisfactory (Figure 9-1). The Estuarine Linear Programming Model considers salinities only at two points in the Trinity-San Jacinto estuary near the major sources of freshwater inflow. To determine circulation and salinity patterns throughout the estuary it is necessary to apply the tidal hydrodynamic and salinity mass transport models (described in Chapter V) using the estimates of monthly freshwater inflow needs obtained from the Estuarine Linear Programming Model. If the circulation patterns and salinity gradients predicted by the hydrodynamic and transport models are acceptable, then the tentative monthly freshwater inflow needs may be accepted. Should the estimated estuarine conditions not be satisfactory, then the constraints upon the Estuarine Linear Programming Model must be modified, and the model used again to compute new estimates.

Salinity patterns of the estuary are of primary importance for insuring that predicted salinity gradients provide a suitable environment for the estuarine organisms. For high productivity, it is estimated that mean monthly mid-bay salinities in Galveston Bay should not exceed 20 parts per thousand (ppt) in any month under the projected monthly freshwater inflow needs. The lowest annual inflow to the estuary from any of the three alternatives considered here is provided by Alternative I; thus, if the salinity conditions

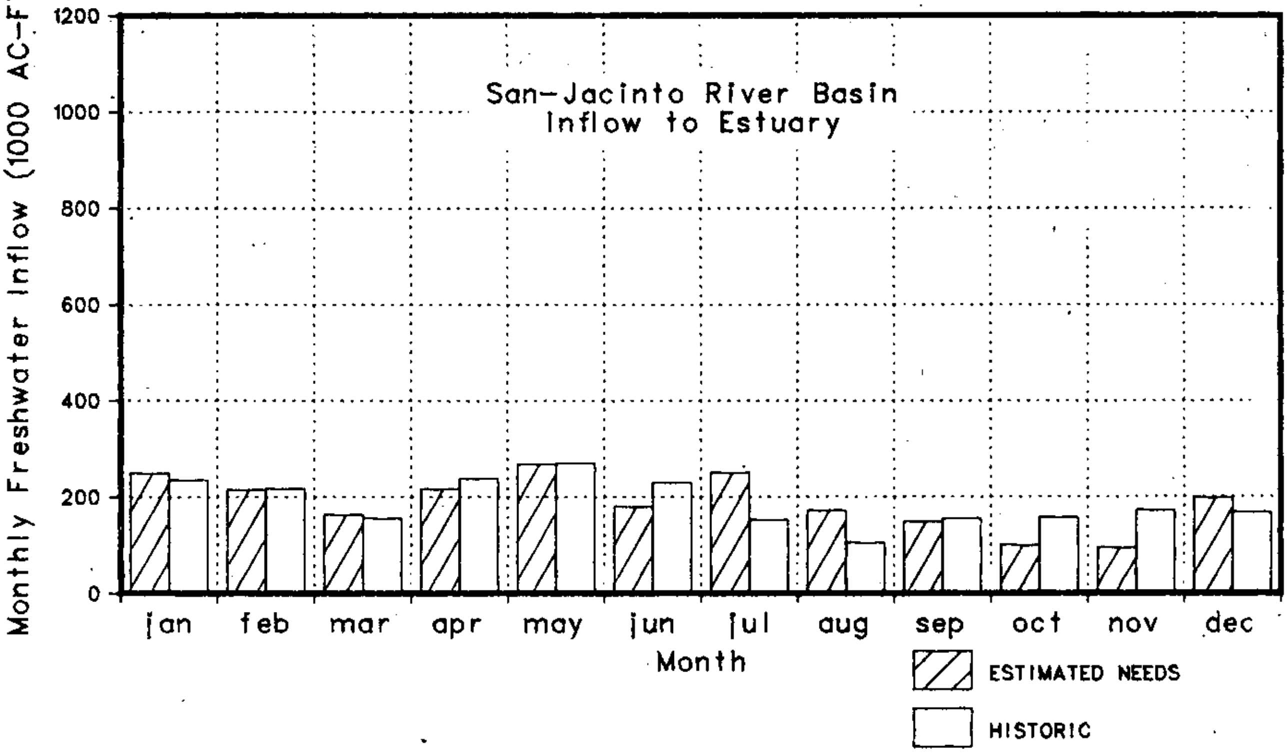

Figure 9-16. Comparison Between Mean Historical Freshwater Inflow and Inflow Needs Under Alternative III for the Trinity-San Jacinto Estuary From the San Jacinto River Basin

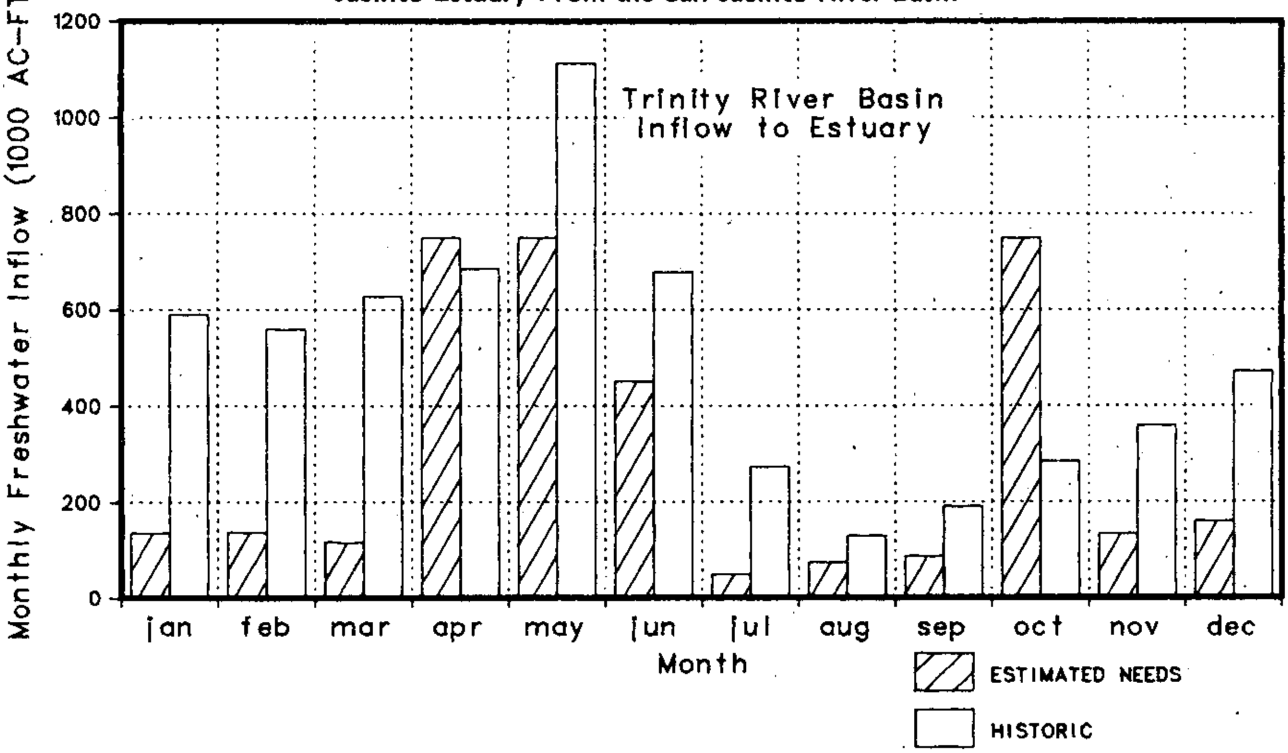

Figure 9-17. Comparison Between Mean Historical Freshwater Inflow and Inflow Needs Under Alternative III for the Trinity-San Jacinto Estuary From the Trinity River Basin

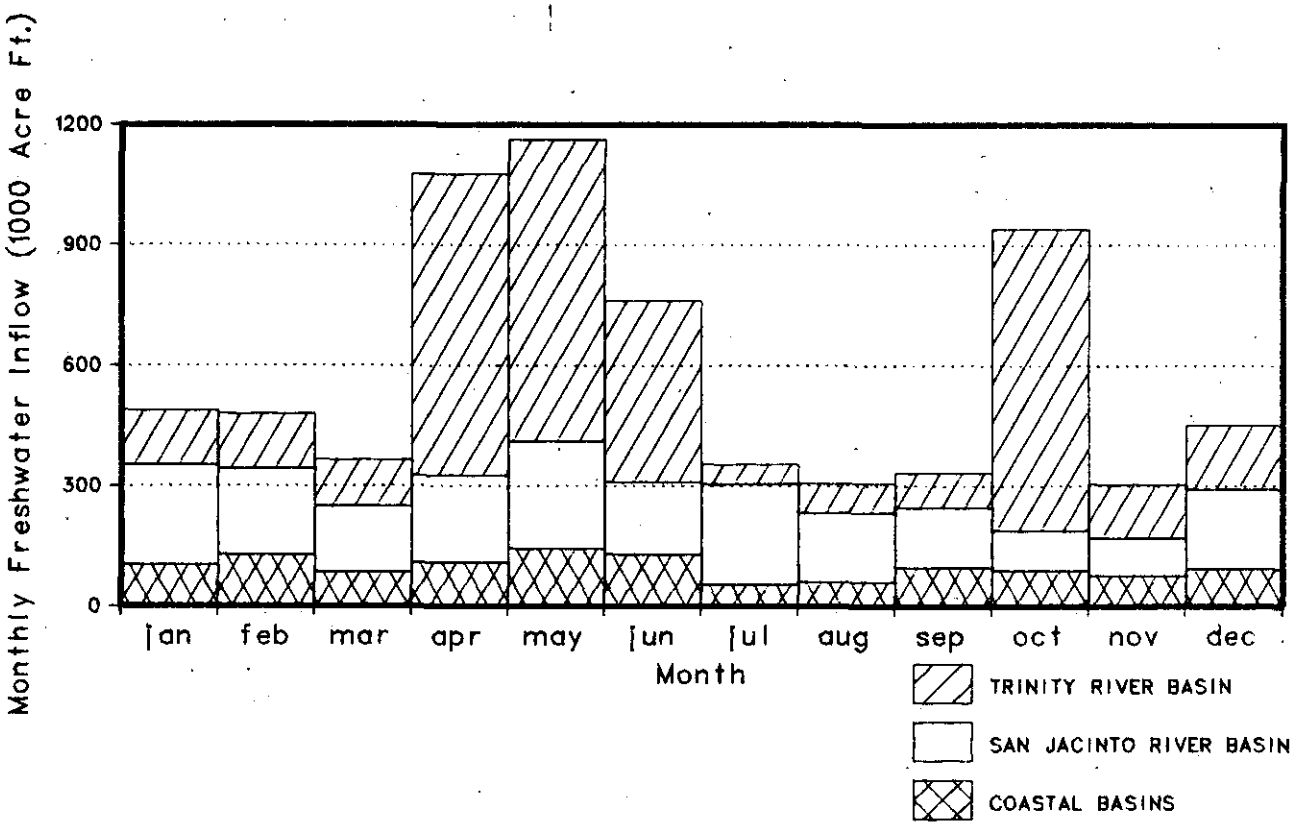

Figure 9-18. Estimated Freshwater Inflow Needs for the Trinity-San Jacinto Estuary Under Alternative III

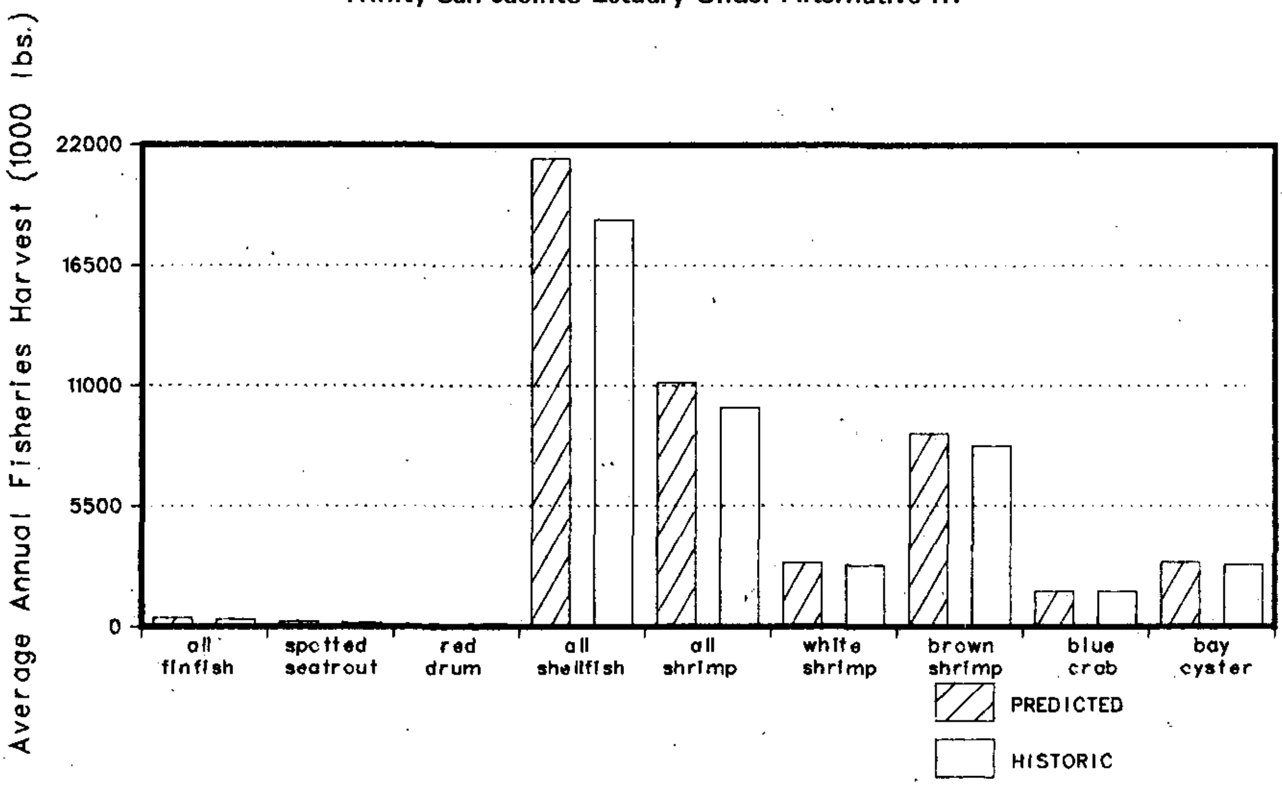

Figure 9-19. Comparison Between Trinity-San Jacinto Historical Fisheries Harvests and Predicted Harvests Under Alternative III

across the estuary meet the 20 ppt criteria under Alternative I, monthly freshwater inflows under the two other alternatives considered should also satisfy the condition (since they specify higher inflows). A lower limit on salinity in Galveston Bay is not evaluated since it was not anticipated that the monthly inflows under the three alternatives would give salinities lower than 10 ppt.

Simulation of Mean Monthly Circulation Patterns. The estimated monthly freshwater inflow needs of the Trinity-San Jacinto estuary under Alternative I are used as input conditions to the tidal hydrodynamics model, along with typical tidal and meteorological conditions for each month, to simulate average circulation patterns in the Trinity-San Jacinto estuary for each month of the year.

The output of the tidal hydrodynamics model consists of a set of tidal amplitudes and net flows computed for each cell in the 46 x 32 computational matrix representing the Trinity-San Jacinto estuary. The computed net flows are the average of the instantaneous flows calculated by the model over the tidal cycle. Thus, the circulation pattern represented by these net flows should not be interpreted as a set of currents that can be observed at any time during the tidal cycle, but rather as a representation of the net movement of water created by the combined action of the Gulf tides, freshwater inflow, and meteorological conditions during the tidal cycle.

The resultant circulation patterns can best be illustrated in the form of vector plots, wherein each vector (or arrow) represents the net flow through a computational cell. The orientation of the vector represents the direction of flow, and the length of the vector represents the magnitude of flow, with one inch corresponding to a flow rate of 11,000 ft^3/sec (310 m^3/sec).

The simulated monthly circulation (Figures 9-20 through 9-31) patterns in the estuary can be divided into two groupings based upon similarities: (1) March, June, August and October, and (2) all the remaining months. The flow characteristics exhibited by the numerical simulations in each of these cases are discussed below.

(1) Simulated March, June, August and October Circulation Patterns. The flow circulations in the Trinity-San Jacinto estuary are simulated for historical average meteorological conditions and estimated freshwater inflow needs for Alternative I for the months of March, June, August and October. The predominant wind speed and direction of 10.6 miles per hour (mph) (4.7 m/sec) from the south-southeast varies only slightly among these months. The most obvious circulation pattern evident in the estuary during the indicated months is a northwesterly-directed current in the Houston Ship Channel toward Morgan's Point. The magnitude of the net flow in the Ship Channel is exceeded only by the flow rate in the vicinity of Bolivar Pass. The dominant pattern in Trinity Bay is a clockwise circulation induced by prevailing winds. The current in West Bay is predominantly directed in a northeasterly direction from San Luis Pass to Galveston Bay. The movement of water in East Bay is generally in an easterly direction from Galveston Bay through Rollover Pass at the eastern end of Bolivar peninsula.

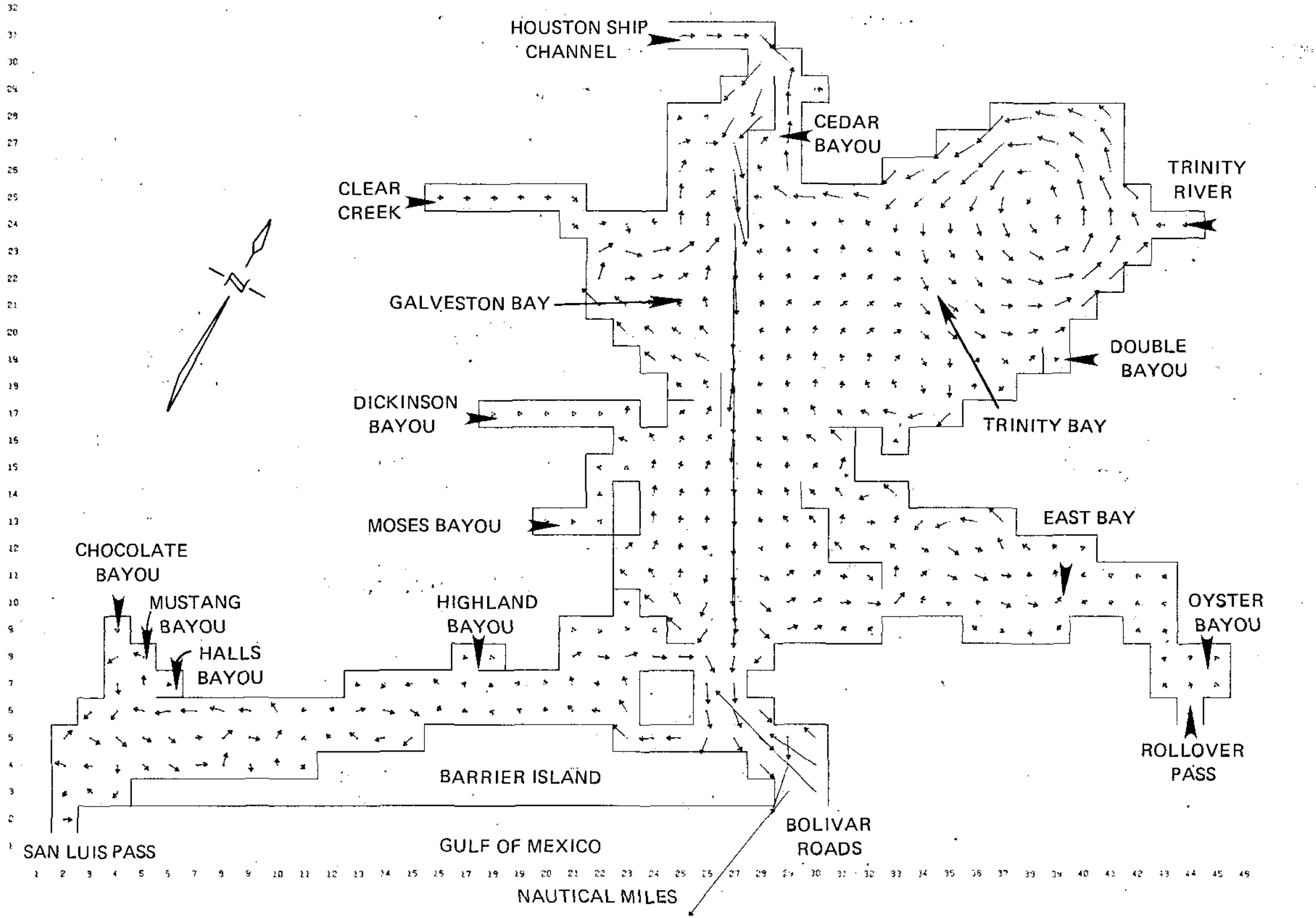

Figure 9-20. Simulated Net Steady-State Flows in the Trinity-San Jacinto Estuary Under January Freshwater Inflow Needs, Alternative I

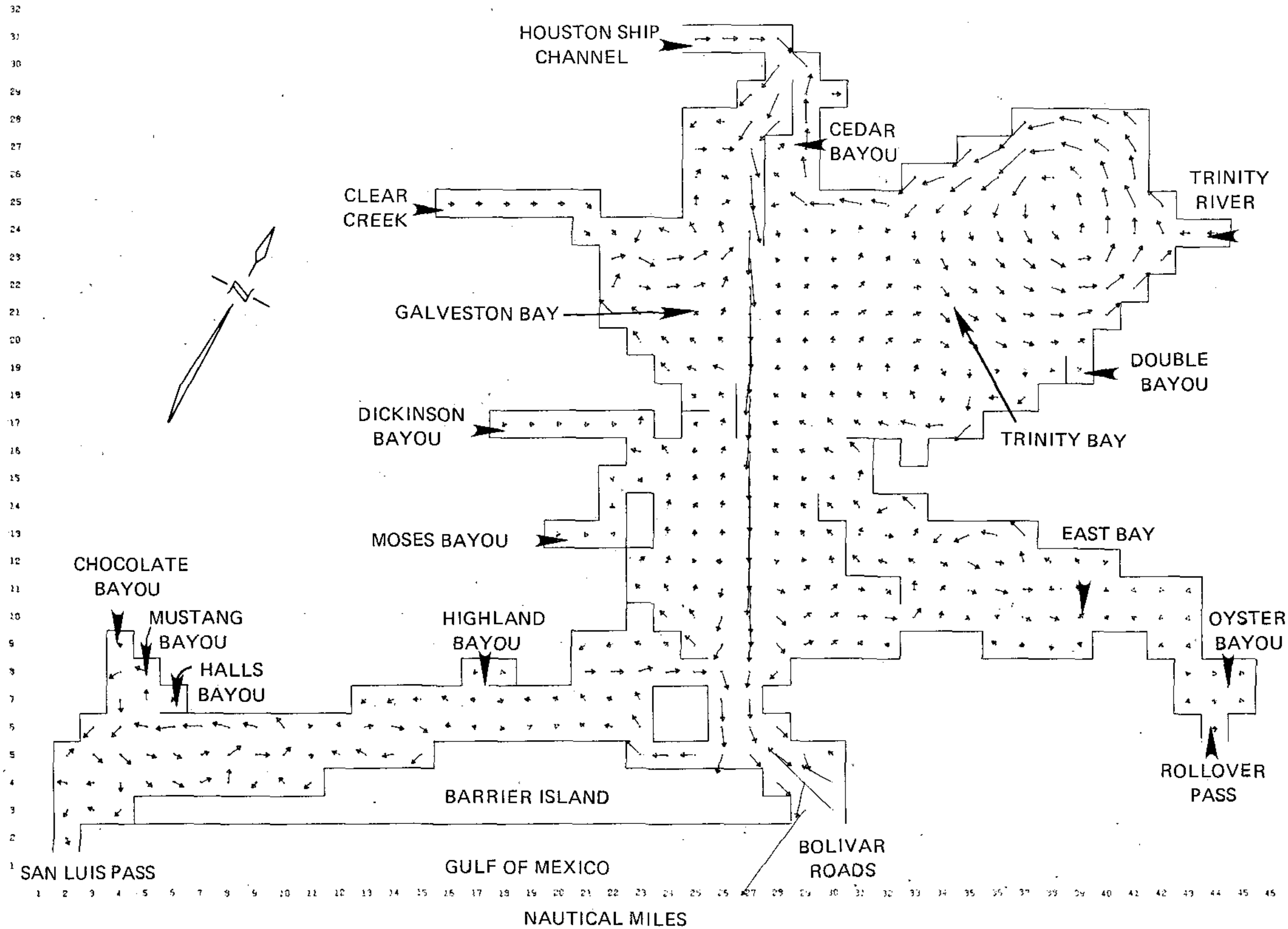

Figure 9-21. Simulated Net Steady-State Flows in the Trinity-San Jacinto Estuary Under February Freshwater Inflow Needs, Alternative I

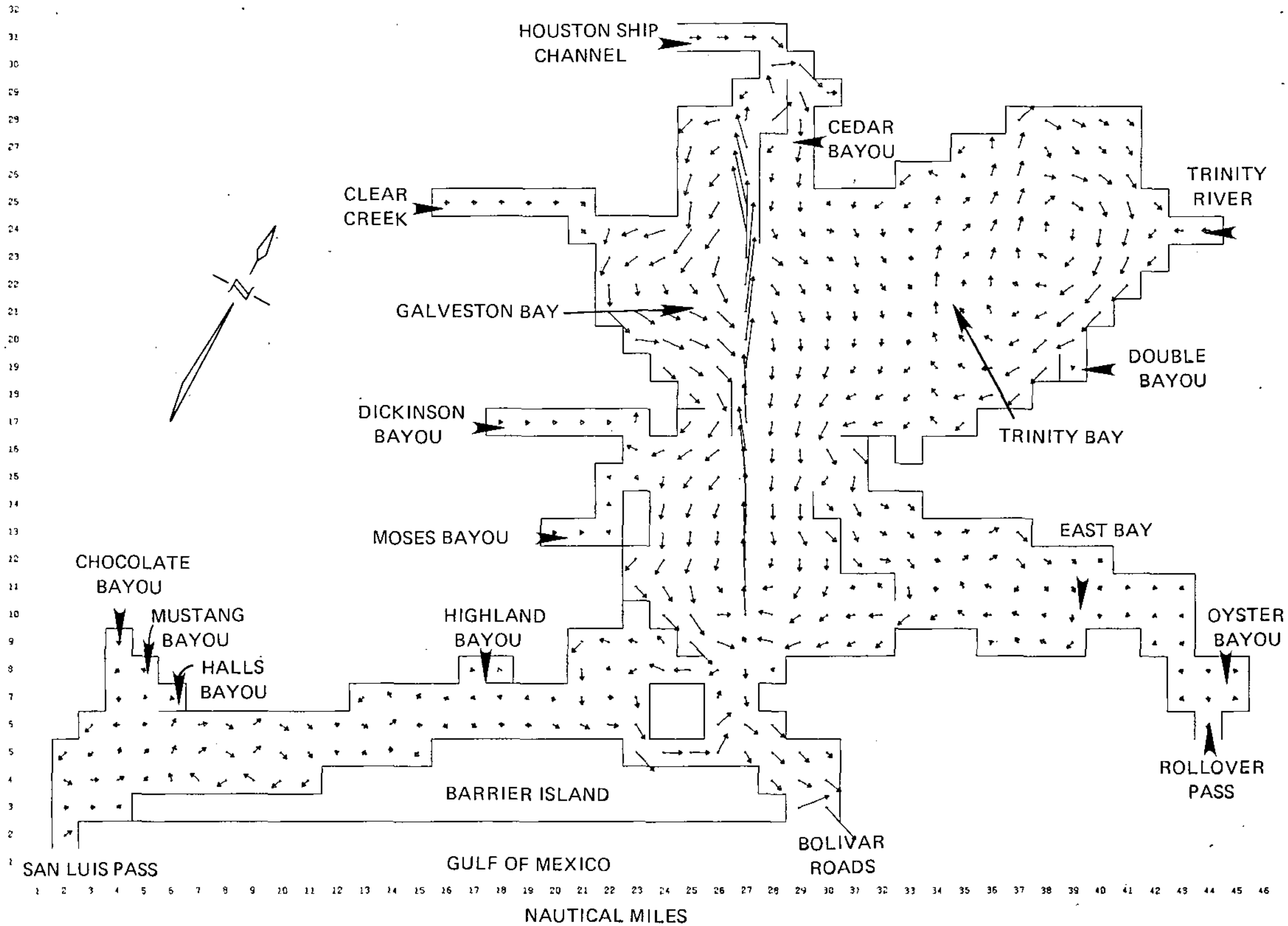

Figure 9-22. Simulated Net Steady-State Flows in the Trinity-San Jacinto Estuary Under March Freshwater Inflow Needs, Alternative I

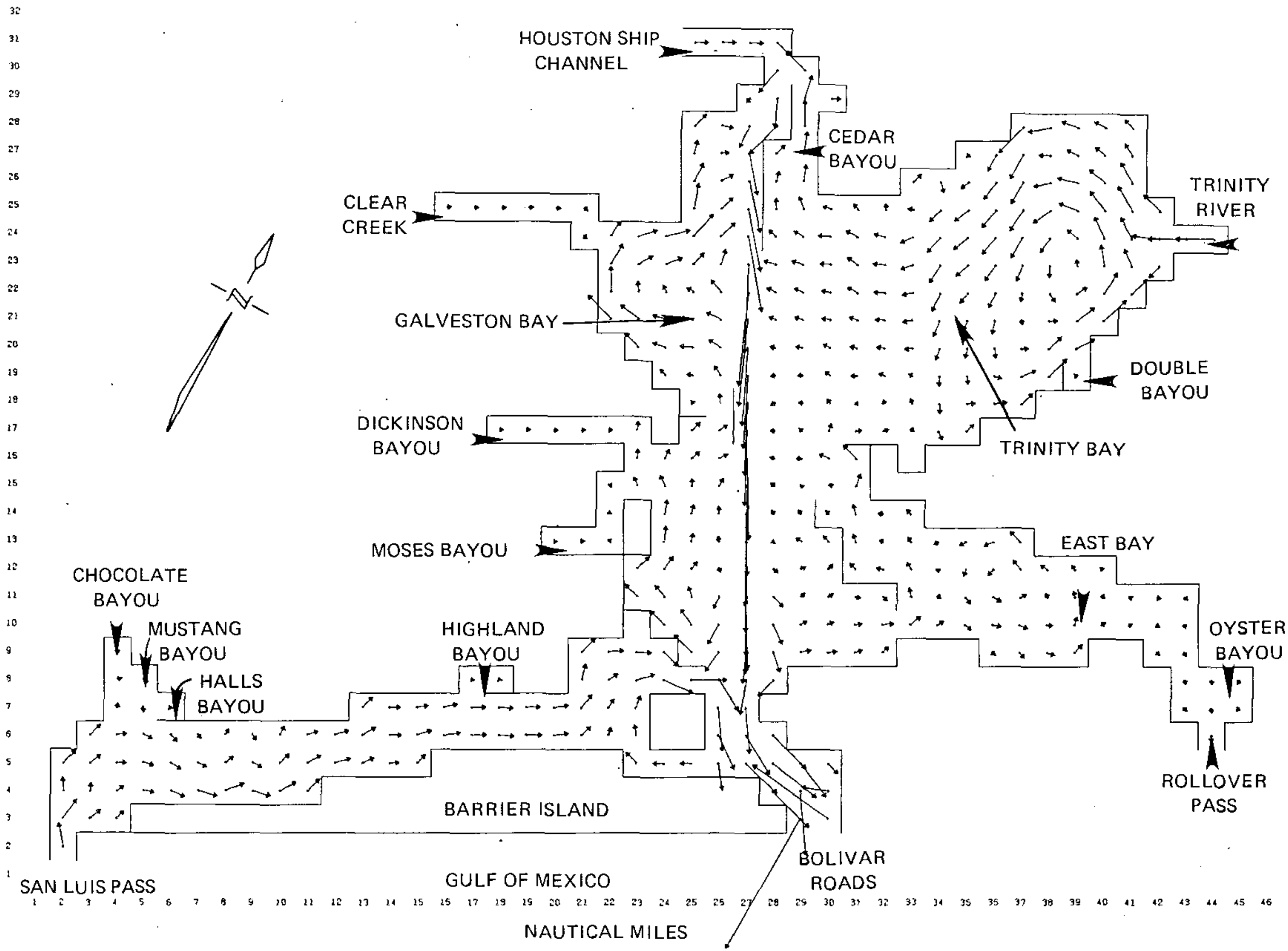

Figure 9-23. Simulated Net Steady-State Flows in the Trinity-San Jacinto Estuary Under April Freshwater Inflow Needs, Alternative I

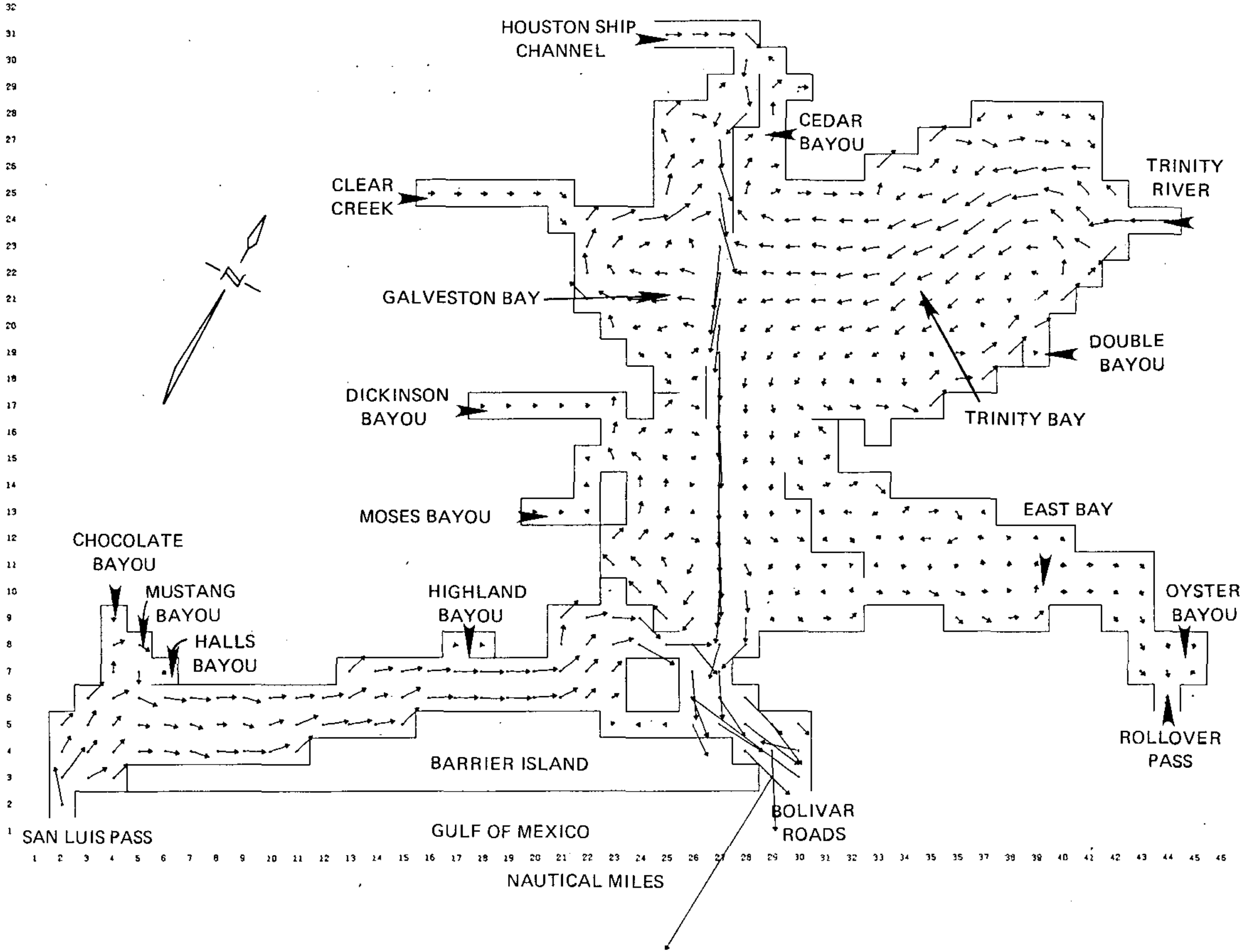

Figure 9-24. Simulated Net Steady-State Flows in the Trinity-San Jacinto Estuary Under May Freshwater Inflow Needs, Alternative I

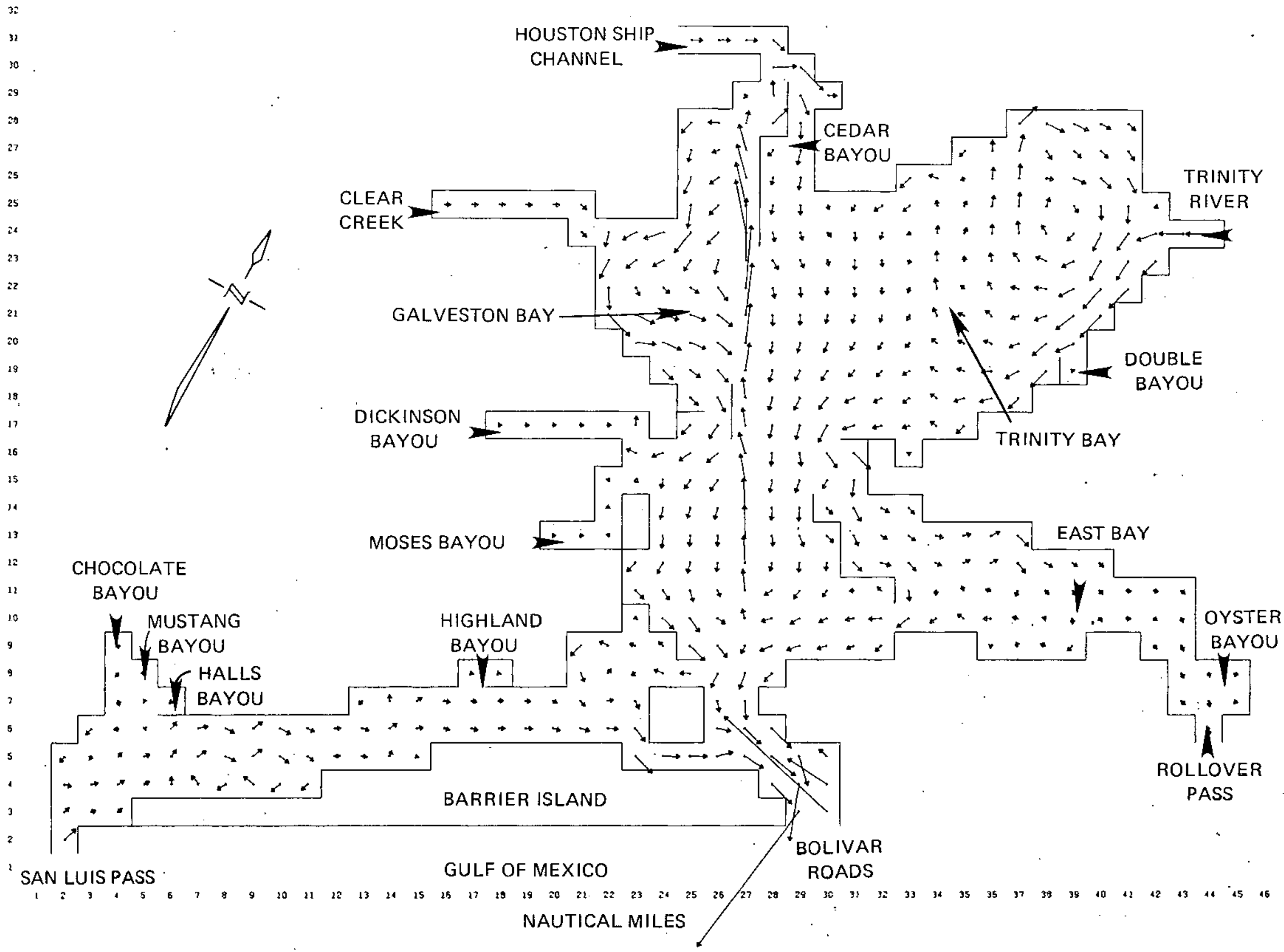

Figure 9-25. Simulated Net Steady-State Flows in the Trinity-San Jacinto Estuary Under June Freshwater Inflow Needs, Alternative I

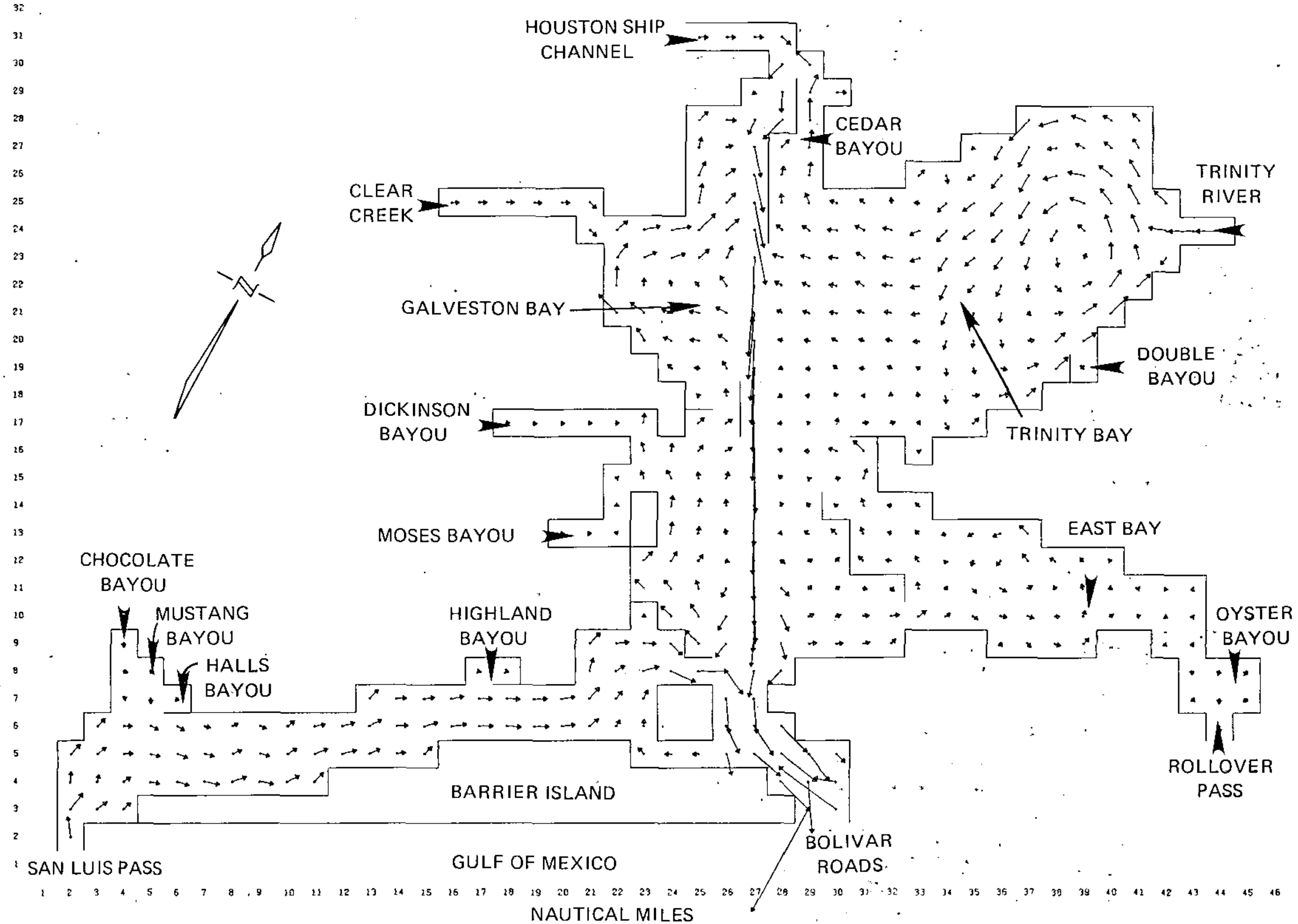

Figure 9-26. Simulated Net Steady-State Flows in the Trinity-San Jacinto Estuary Under July Freshwater Inflow Needs, Alternative I

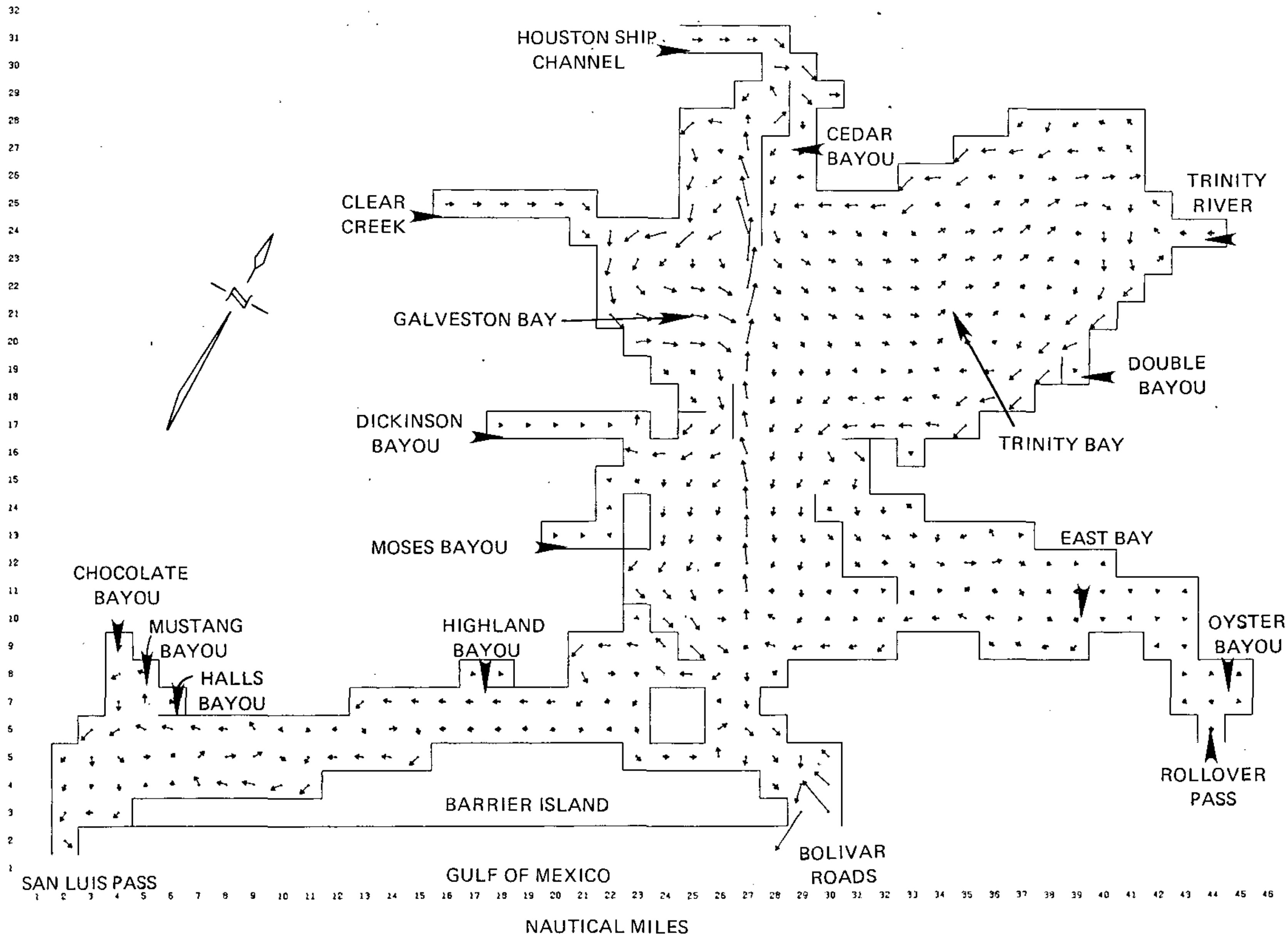

Figure 9-27. Simulated Net Steady-State Flows in the Trinity-San Jacinto Estuary Under August Freshwater Inflow Needs, Alternative I

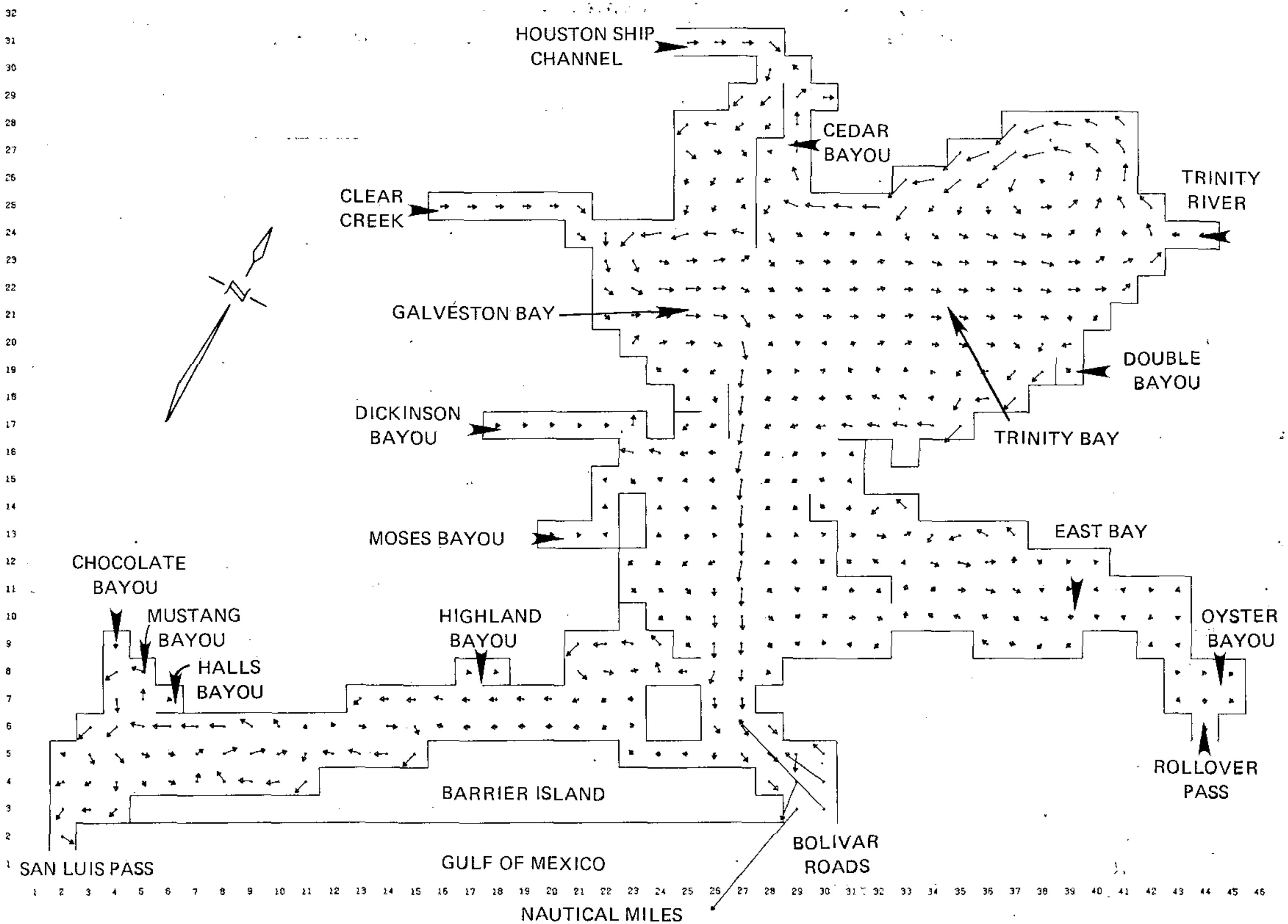

Figure 9-28. Simulated Net Steady-State Flows in the Trinity-San Jacinto Estuary Under September Freshwater Inflow Needs, Alternative I

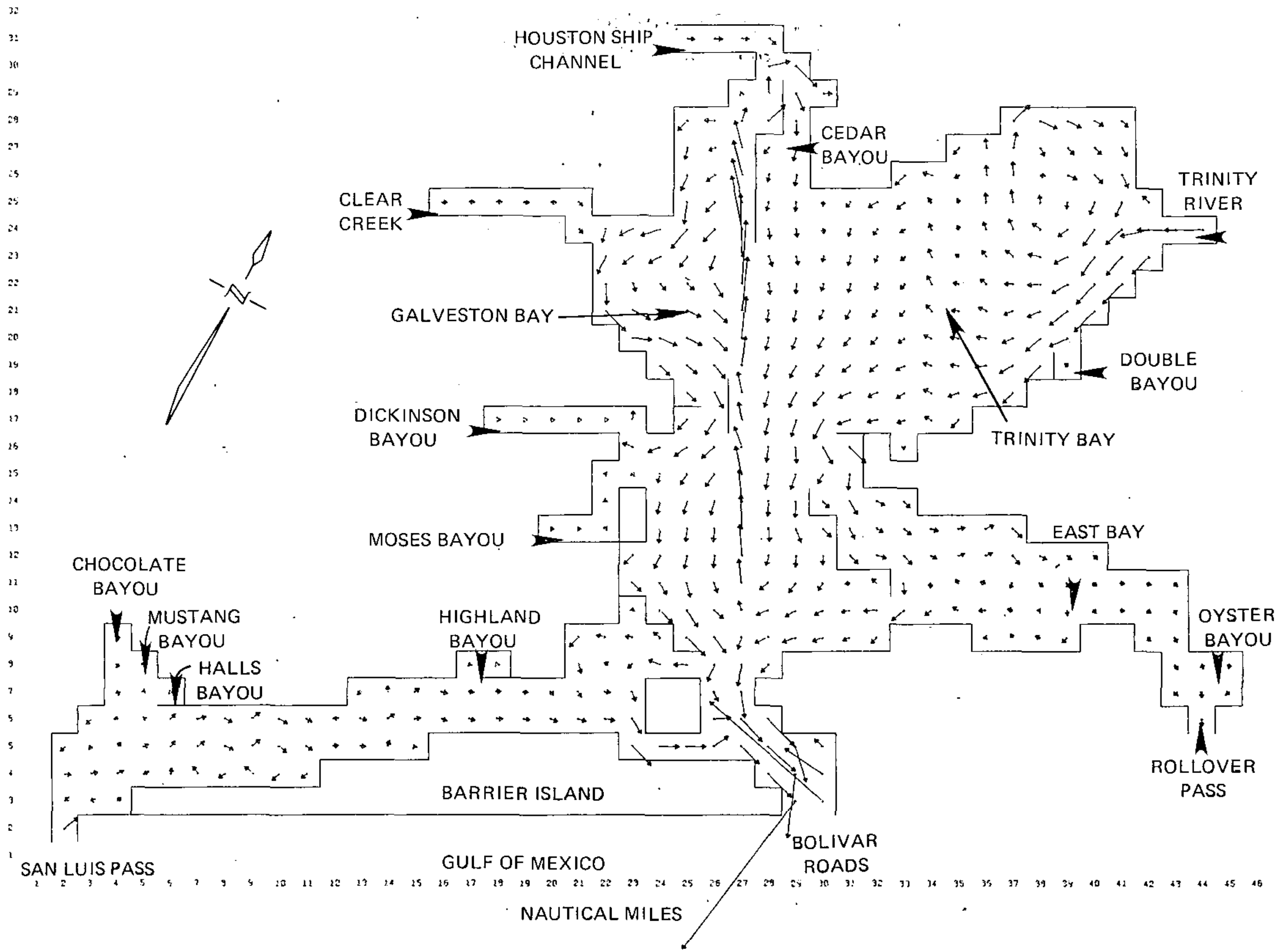

Figure 9-29. Simulated Net Steady-State Flows in the Trinity-San Jacinto Estuary Under October Freshwater Inflow Needs, Alternative I

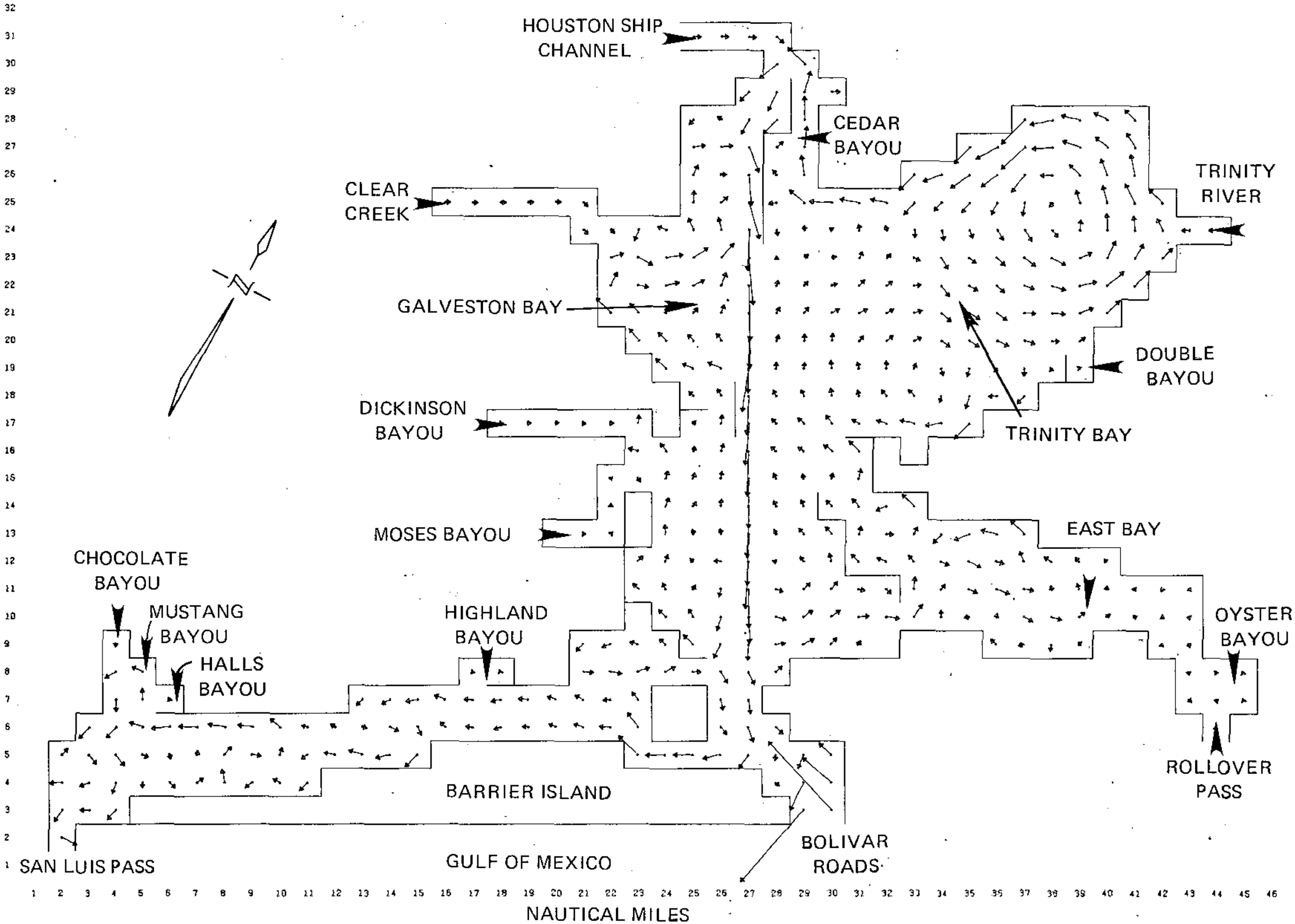

Figure 9-30. Simulated Net Steady-State Flows in the Trinity-San Jacinto Estuary Under November Freshwater Inflow Needs, Alternative I

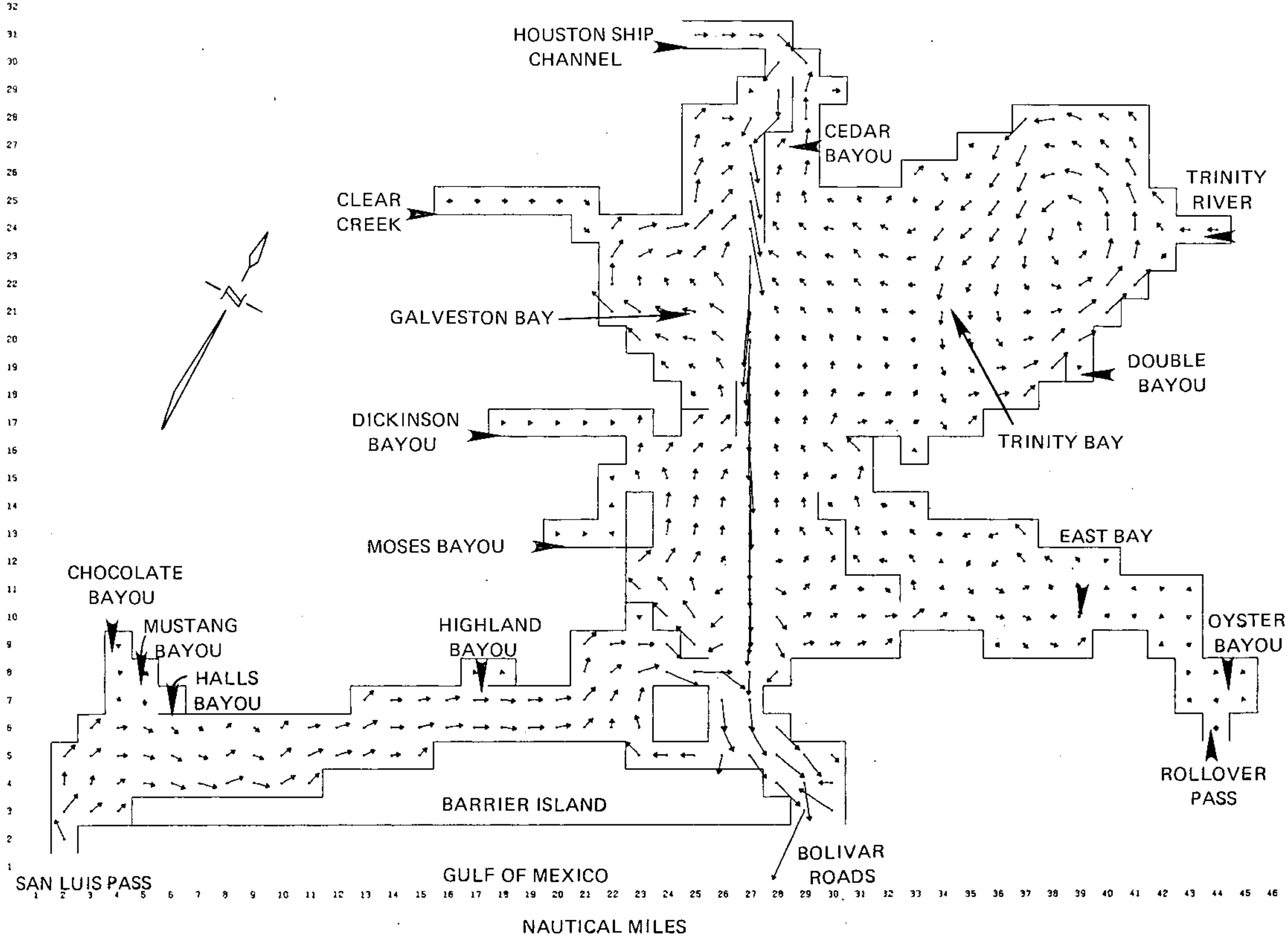

Figure 9-31. Simulated Net Steady-State Flows in the Trinity-San Jacinto Estuary Under December Freshwater Inflow Needs, Alternative I

The dominant flow pattern in Galveston Bay is a movement of water up the Houston Ship Channel toward Morgan's Point. This northwesterly movement of water along the Ship Channel induces return currents on either side of the Channel moving in the opposite direction; thus, there is a net southeasterly current along the western shore of Galveston Bay.

The simulated net circulation of water among the various bays is predominantly from Trinity Bay into Galveston Bay and from Galveston Bay into East Bay. Limited exchange occurs between Galveston Bay and West Bay. The net flow through Bolivar Pass during these months is out of the estuary into the Gulf.

(2) Simulated January, February, April, May, July, September, November and December Circulation Patterns. The flow circulations in the Trinity-San Jacinto estuary simulated under historical average meteorological and estimated freshwater inflow needs for Alternative I indicate similar flow patterns for the months of January, February, April, May, July, September, November and December (Figures 9-20, 9-21, 9-23, 9-24, 9-26, 9-28, 9-30 and 9-31). The average wind speed is 11.2 mph (5.01 m/sec) for the months, with the wind direction predominantly from the north and west.

The most evident circulation pattern in the estuary during these indicated months is a southeasterly-directed current in the Houston Ship Channel. The magnitude of the simulated current in the Ship Channel is generally exceeded only by the flow rates in the vicinity of Bolivar Pass. The dominant flow in Trinity Bay is a counter-clockwise rotating circulation in the upper bay. The circulation patterns in West Bay indicate that an internal current rotating counter-clockwise predominates in the upper end, with the net water movement from Galveston Bay near Bolivar Pass through the Galveston Ship Channel into West Bay, and from West Bay through San Luis Pass into the Gulf of Mexico. The simulated net flow of water in the western portion of East Bay is dominated by a northerly current from Galveston Bay into Trinity Bay. A secondary net flow in East Bay moves water from Galveston Bay through Rollover Pass at the eastern end of Bolivar peninsula.

The circulaion pattern for Galveston Bay shows a net movement of water down the Houston Ship Channel toward the Gulf. The movement of water along the Ship Channel induces return currents on either side moving in the opposite direction.

The circulation patterns simulated for the various bays in the estuarine system indicates, as with the months of March, June, August, and October, that the predominant net flow is from Trinity Bay into Galveston Bay and then into East Bay. Only limited net exchange occurs between Galveston Bay and West Bay. Also, the net flow through Bolivar Pass during these months is directed toward the estuary from the Gulf.

Simulated Mean Monthly Salinity Patterns. The tidal amplitudes and flows calculated by the tidal hydrodynamic model for the monthly inflows under Alternative I were utilized as input to operate the salinity transport model to simulate the salinity distributions in the Trinity-San Jacinto estuary for each month. The resultant salinity distributions are illustrated in the form of salinity contour plots wherein lines of uniform salinity are shown in increments of five parts per thousand (ppt). The evaluation of the simulated monthly salinities in the Trinity-San Jacinto estuary resulting from these model operations (Figures 9-32 through 9-43) revealed two distinct salinity distribution patterns: one evident during July and the high inflow months of April, May, June, and October; and the other during the remaining months of the year.

(1) Simulated April, May, June, July and October Salinity Patterns. The simulation of estuarine salinities under April, May, June, July and October inflow needs and average meteorological conditions results in salinities over the Trinity-San Jacinto estuary varying from less than five parts per thousand in Trinity Bay to slightly over 25 ppt near San Luis and Bolivar Passes (Figures 9-35 through 9-41). The salinity simulations for these months reveal that salinities in Trinity Bay are less than five parts per thousand over almost all of the bay. Salinities in Galveston Bay range from between five and ten parts per thousand in its upper portion to 25 ppt at the mouth of the bay near Bolivar Pass. The simulated salinities in West Bay range between 20 and 25 ppt. The simulated salinity distributions for East Bay during these months range between 10 and 15 ppt. The simulated salinities in the estuary are lowest for the spring month of May.

For the months during this period an intrusion of more highly saline water is evident along either side of the Houston Ship Channel. This simulated condition corresponded to observed variations in salinity. The intrusion of more saline water along the Houston Ship Channel is due to its 40-foot depth, compared to the adjacent shallow areas in Galveston Bay.

(2) Simulated November through March, August and September Salinity Patterns. Simulated salinity distributions in the Trinity-San Jacinto estuary for Alternative I inflows show relatively similar patterns for the remaining months of the year (Figures 9-42, 9-43, 9-32, 9-33, 9-34, 9-39, and 9-40). For Trinity Bay the simulated salinities are at a minimum near the Trinity River delta with concentrations lower than five parts per thousand during the seven remaining months. Maximum simulated salinities in Trinity Bay are between 10 and 15 ppt, except in the months of February, March and September when the maximum salinities are less than 10 ppt.

The simulated salinities for Galveston Bay range from less than ten parts per thousand in the upper portion of the bay near Morgan's Point to over 25 ppt near Bolivar Pass. Simulated concentrations for West Bay range from a maximum of over 25 ppt near Bolivar Pass to less than 20 ppt in the western end of the bay. East Bay salinities have a minimum value of less than 10 ppt near the eastern end of the bay and a maximum level of between 20 and 25 ppt at the boundary between East and Galveston Bays. Simulated salinities are greater than 10 ppt at Rollover Pass, the intermittent channel between East Bay and the Gulf of Mexico.

In all of the months, the salinities in the middle portion of Galveston Bay were simulated at under 20 ppt; thus, meeting the criterion given previously. Further refinement of the estimated monthly freshwater inflow needs for the three Alternatives is therefore not considered necessary at this time.

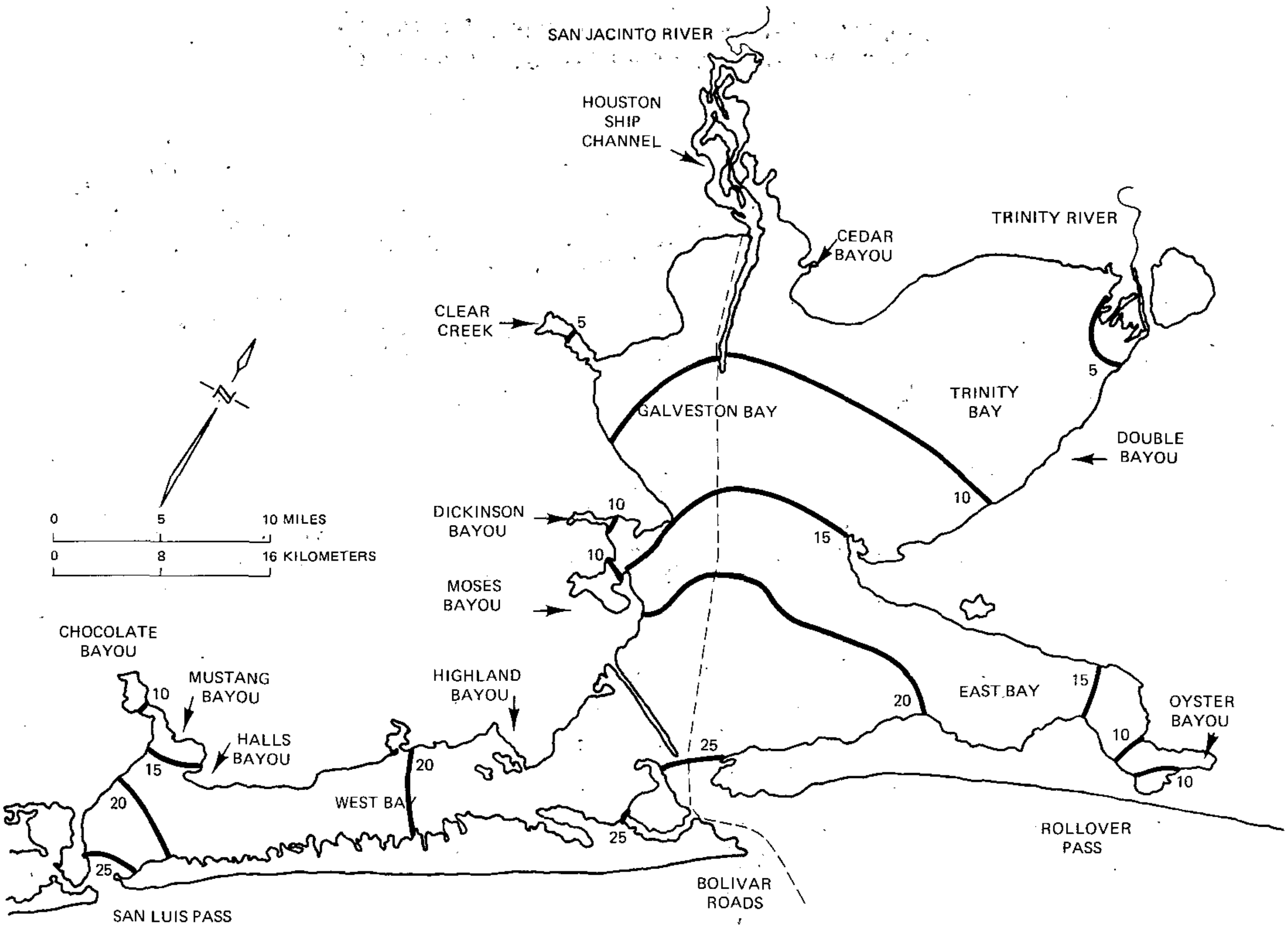

Figure 9-32. Simulated Salinities in the Trinity-San Jacinto Estuary Under January Freshwater Inflow Needs, Alternative I (ppt)

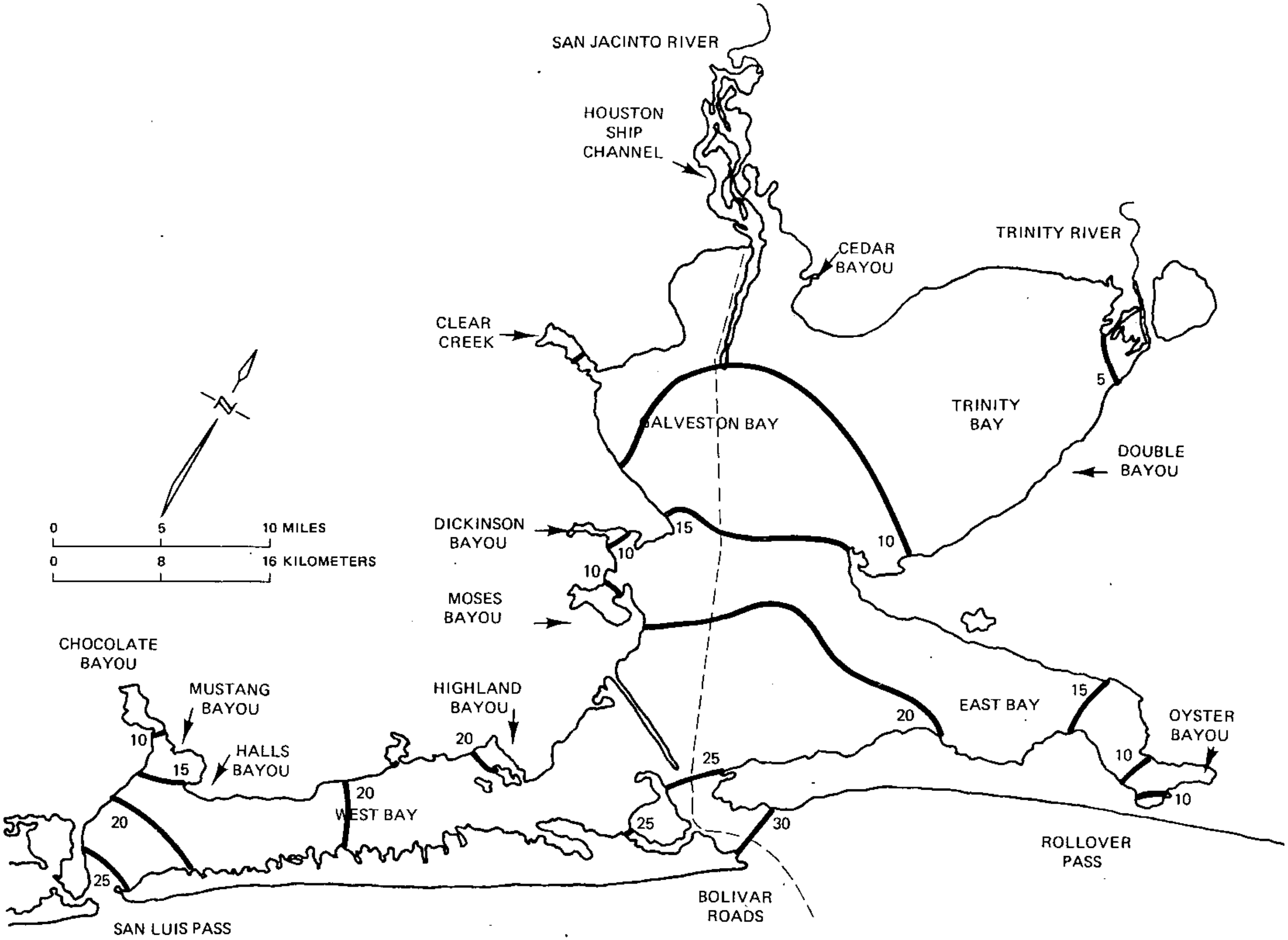

Figure 9-33. Simulated Salinities in the Trinity-San Jacinto Estuary Under February Freshwater Inflow Needs, Alternative I (ppt)

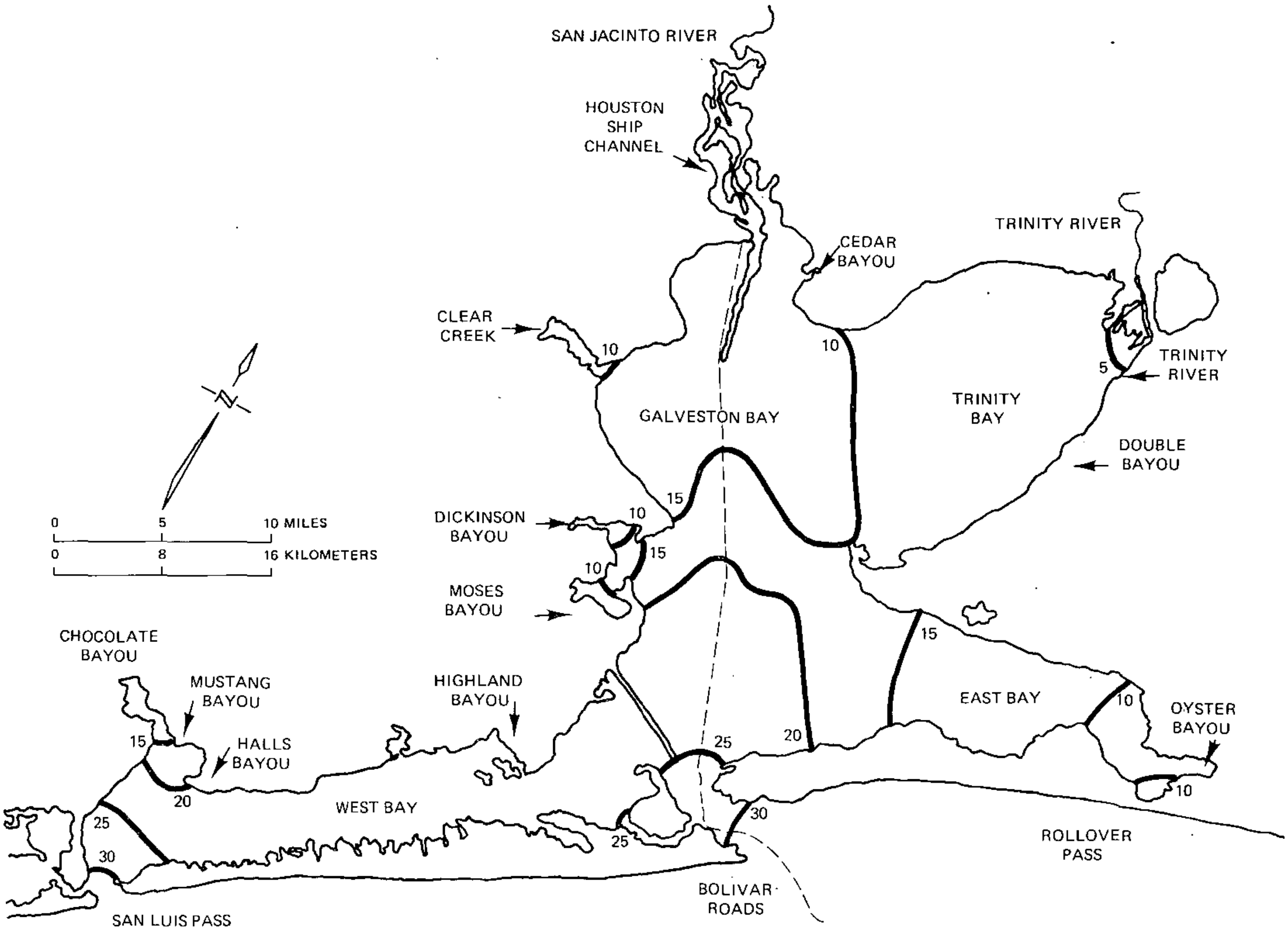

Figure 9-34. Simulated Salinities in the Trinity-San Jacinto Estuary Under March Freshwater Inflow Needs, Alternative I (ppt)

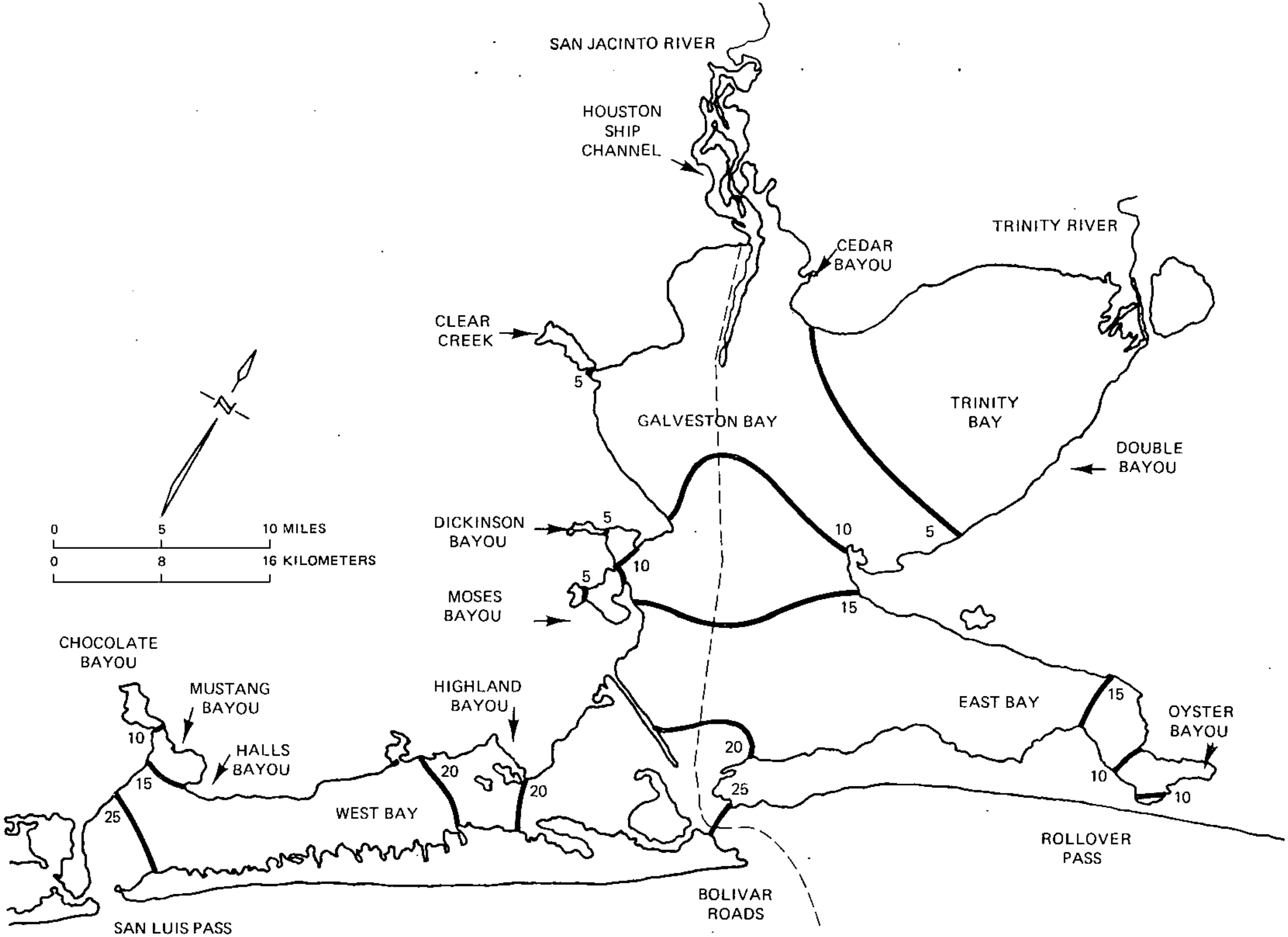

Figure 9-35. Simulated Salinities in the Trinity-San Jacinto Estuary Under April Freshwater Inflow Needs, Alternative I (ppt)

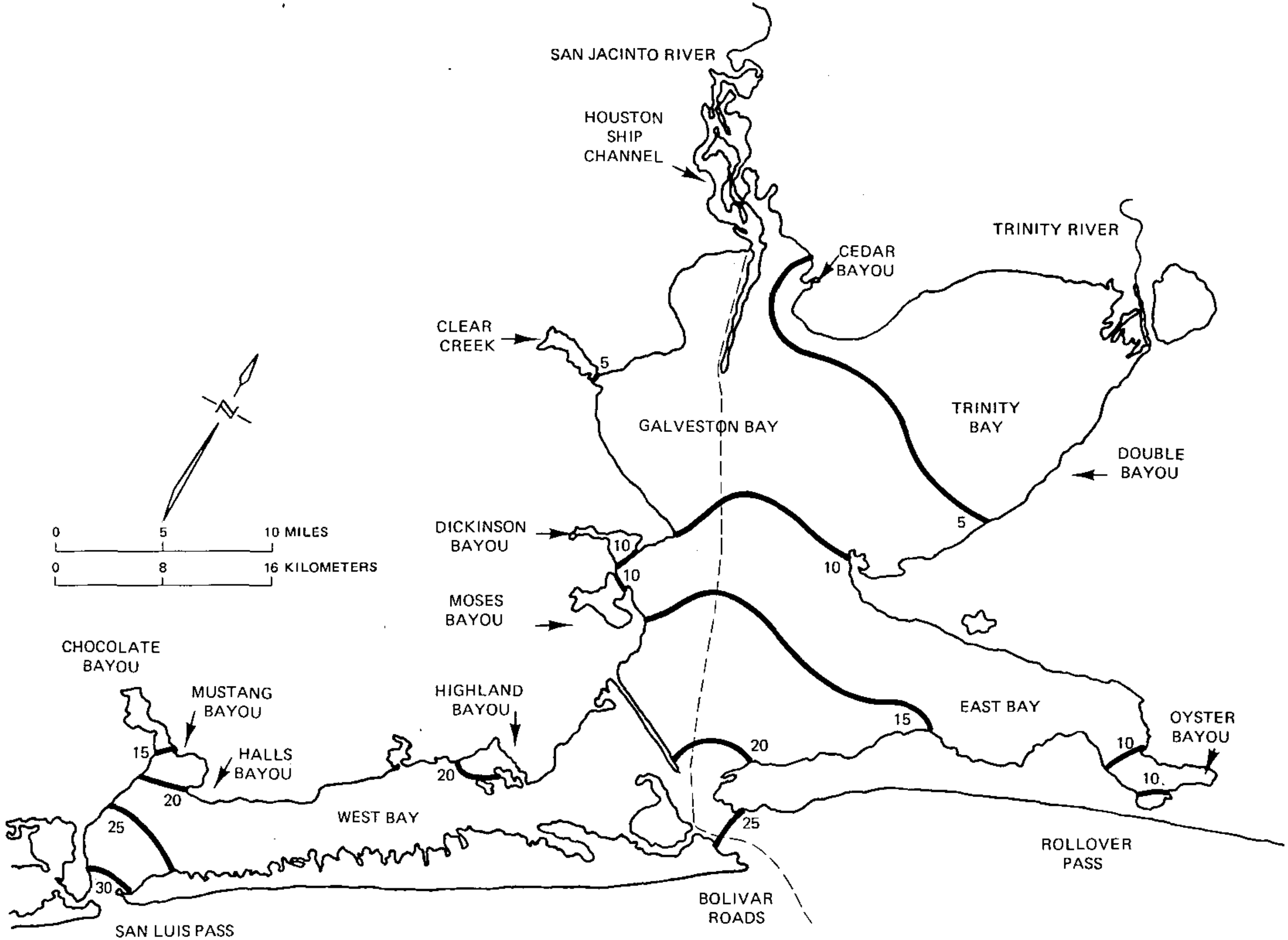

Figure 9-36. Simulated Salinities in the Trinity-San Jacinto Estuary Under May Freshwater Inflow Needs, Alternative I (ppt)

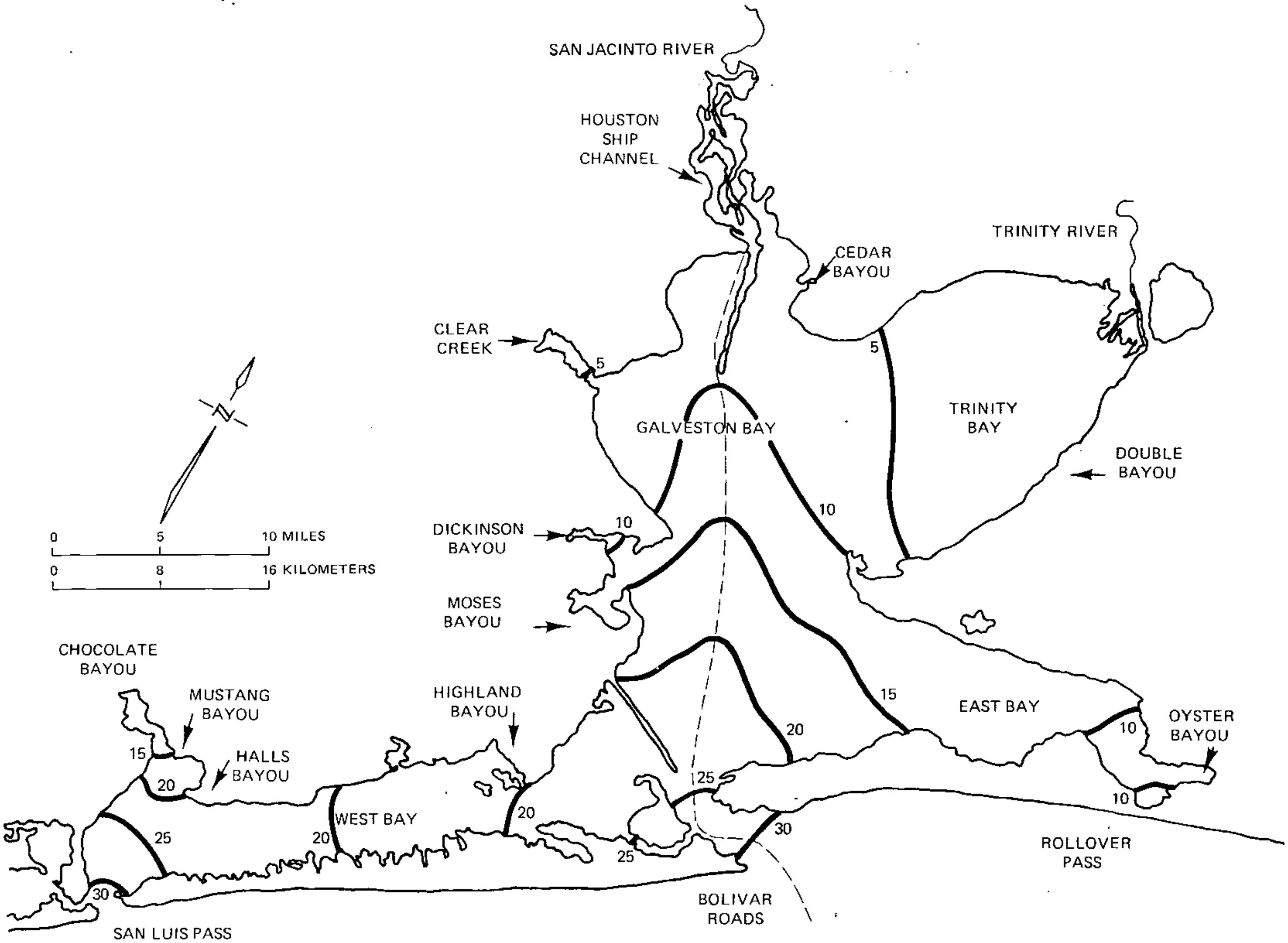

Figure 9-37. Simulated Salinities in the Trinity-San Jacinto Estuary Under June Freshwater Inflow Needs, Alternative I (ppt)

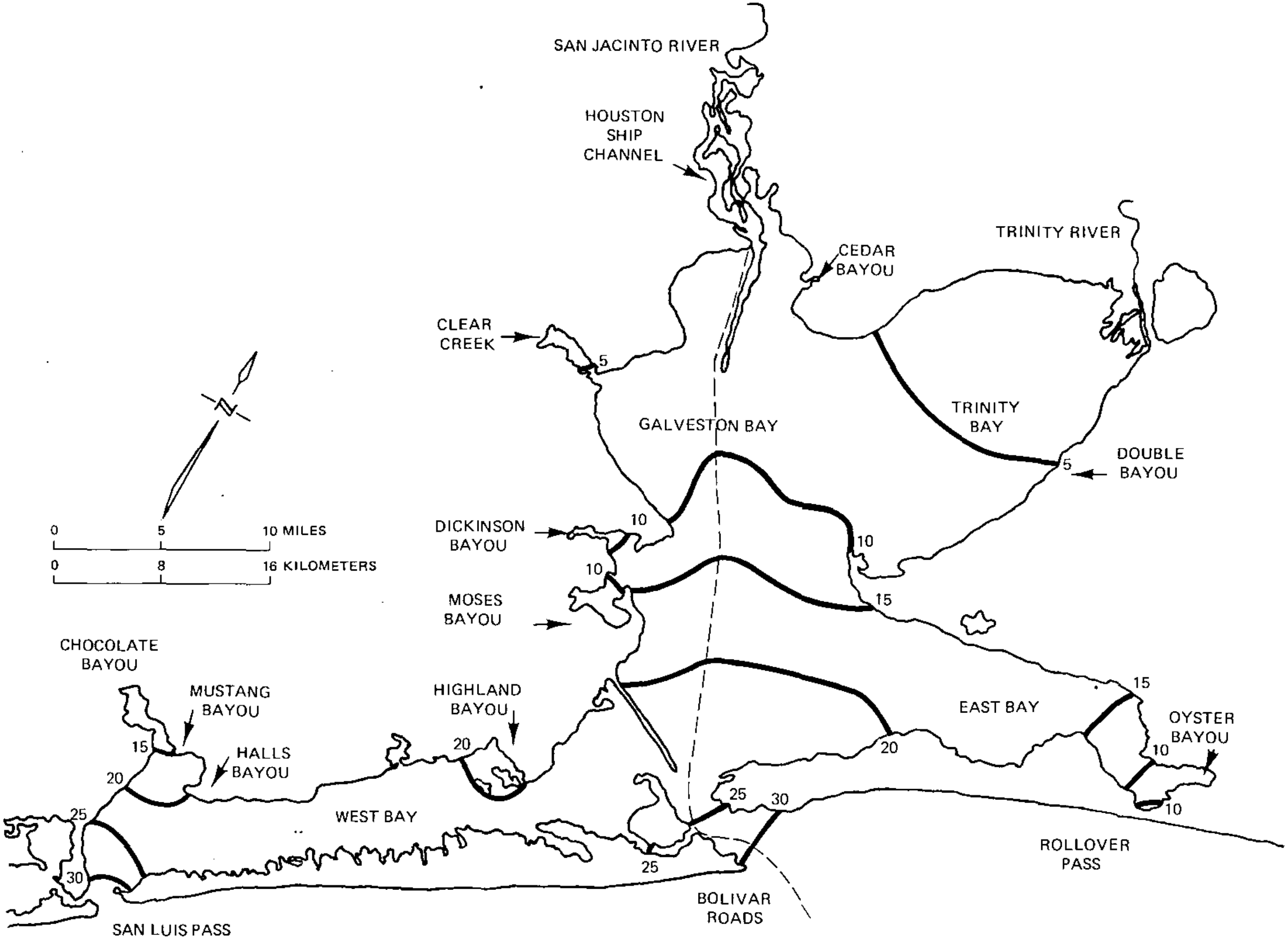

Figure 9-38. Simulated Salinities in the Trinity-San Jacinto Estuary Under July Freshwater Inflow Needs, Alternative I (ppt)

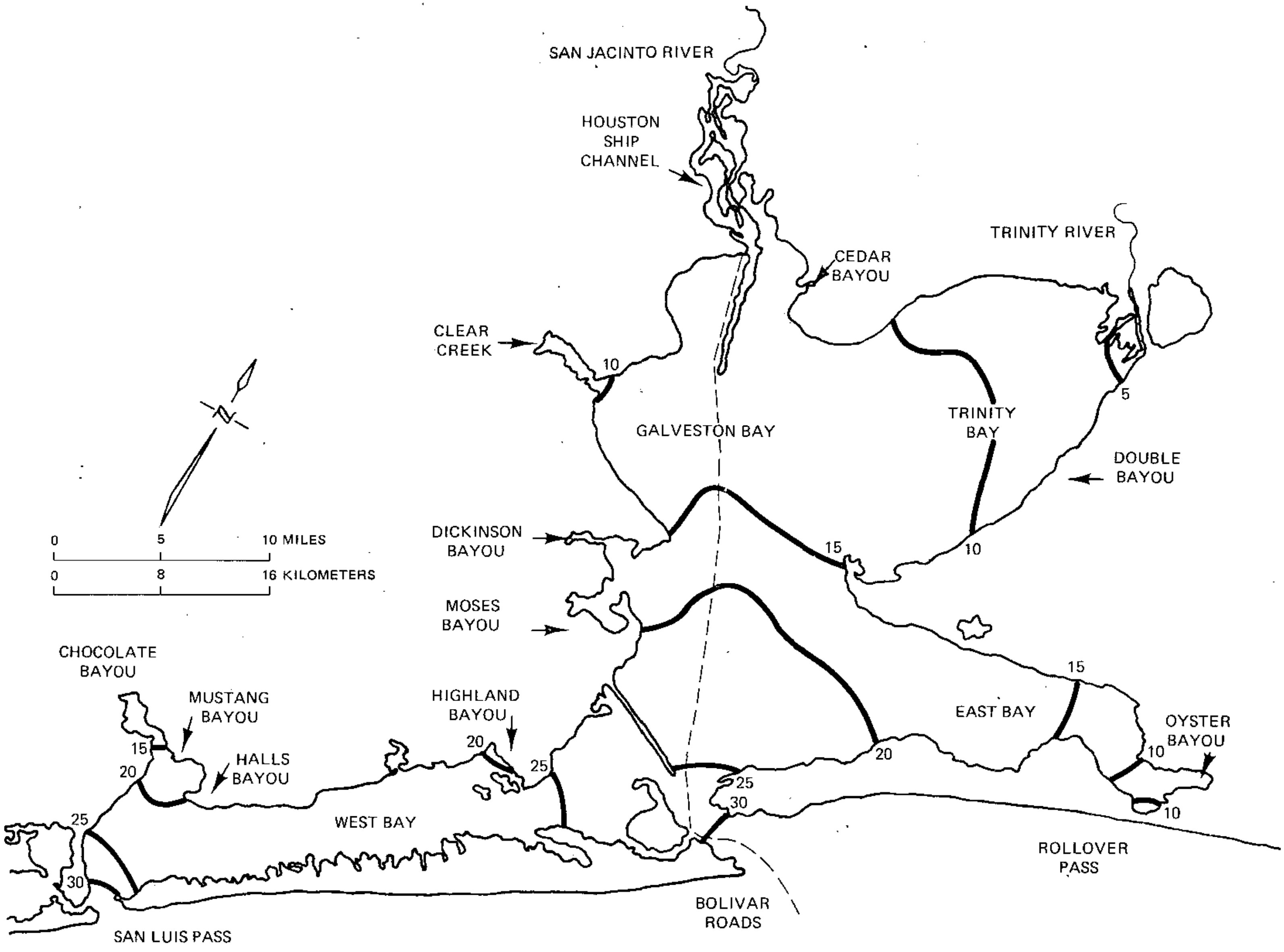

Figure 9-39. Simulated Salinities in the Trinity-San Jacinto Estuary Under August Freshwater Inflow Needs, Alternative I (ppt)

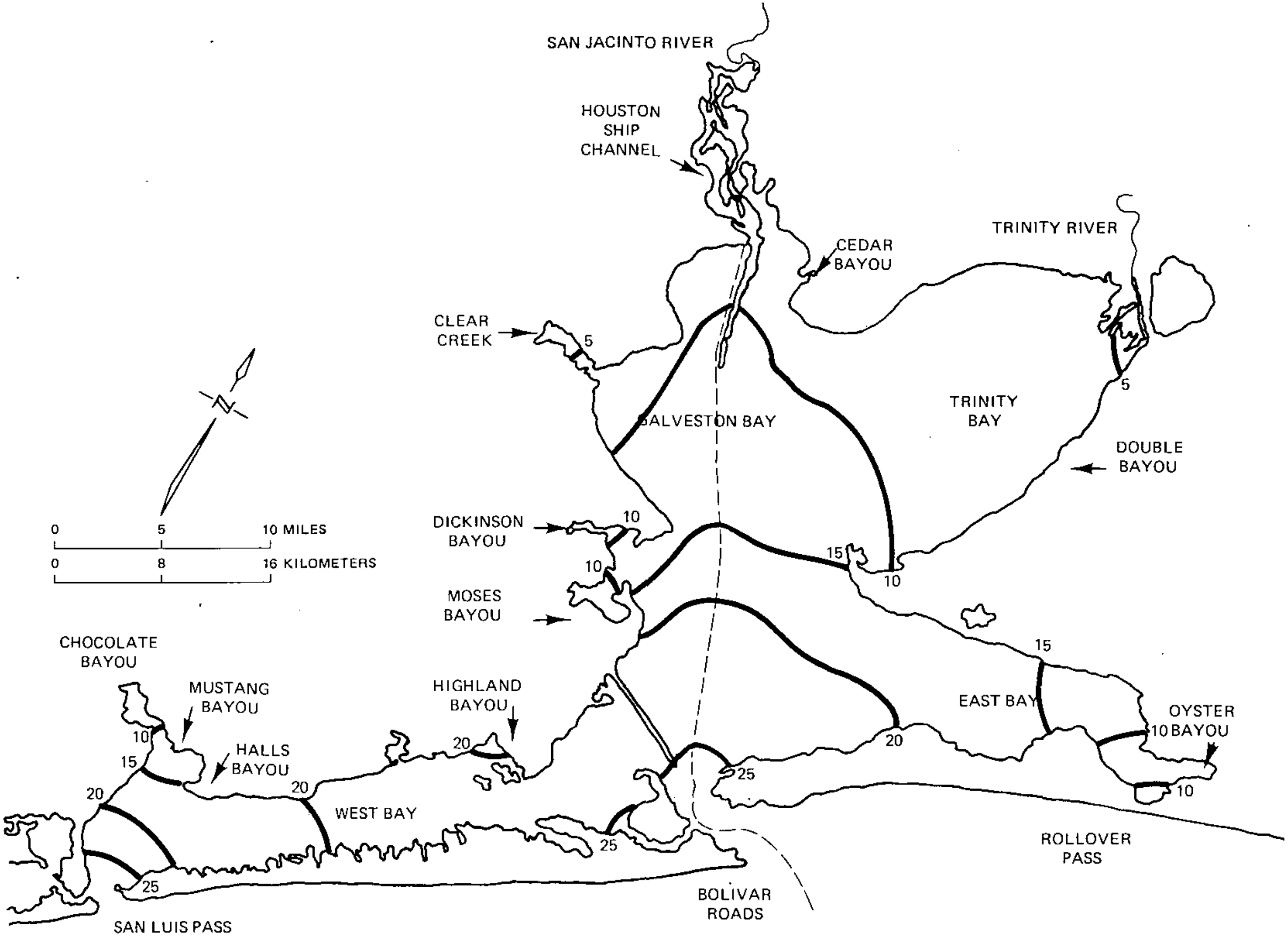

Figure 9-40. Simulated Salinities in the Trinity-San Jacinto Estuary Under September Freshwater Inflow Needs, Alternative I (ppt)

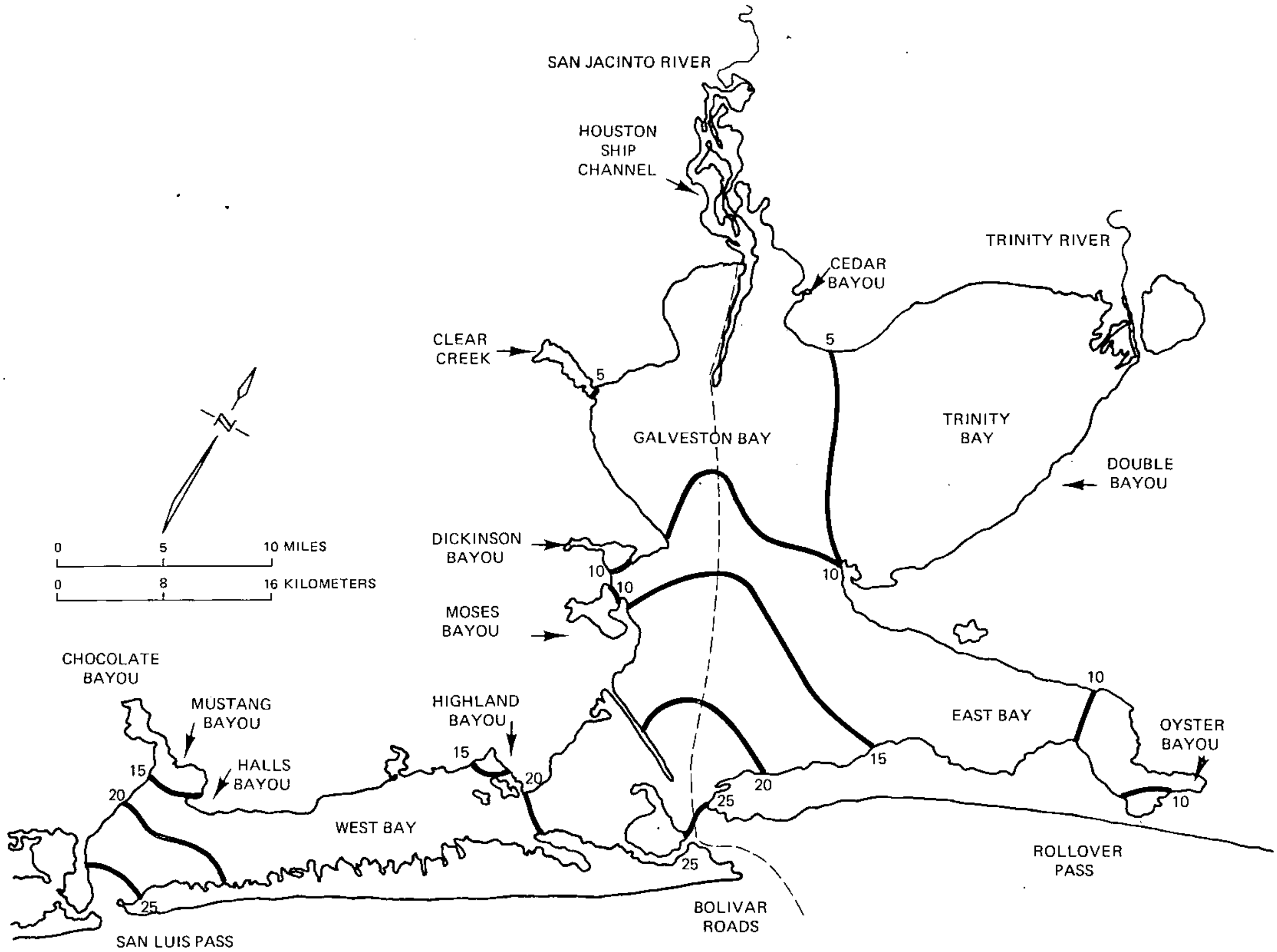

Figure 9-41. Simulated Salinities in the Trinity-San Jacinto Estuary Under October Freshwater Inflow Needs, Alternative I (ppt)

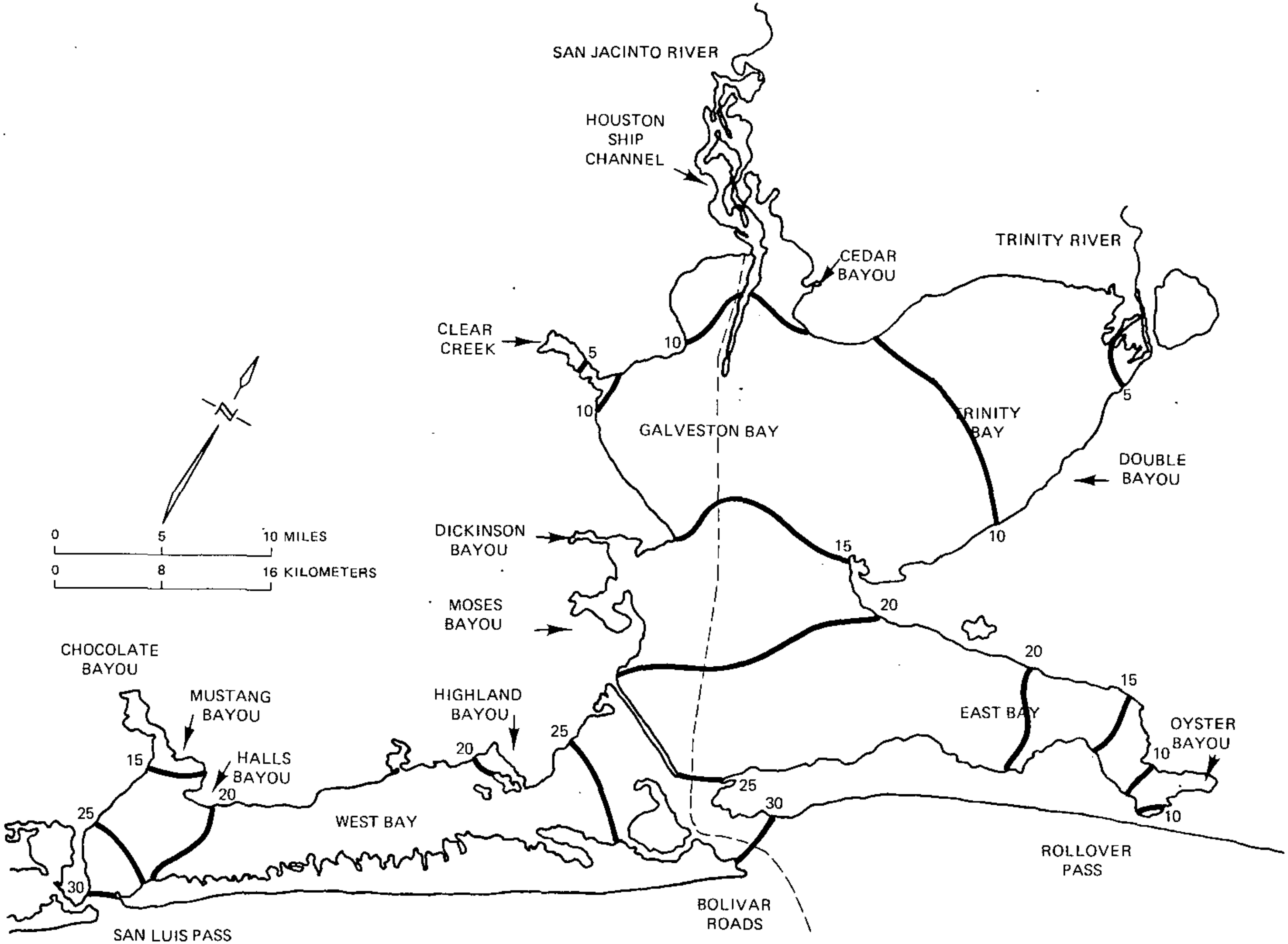

Figure 9-42. Simulated Salinities in the Trinity-San Jacinto Estuary Under November Freshwater Inflow Needs, Alternative I (ppt)

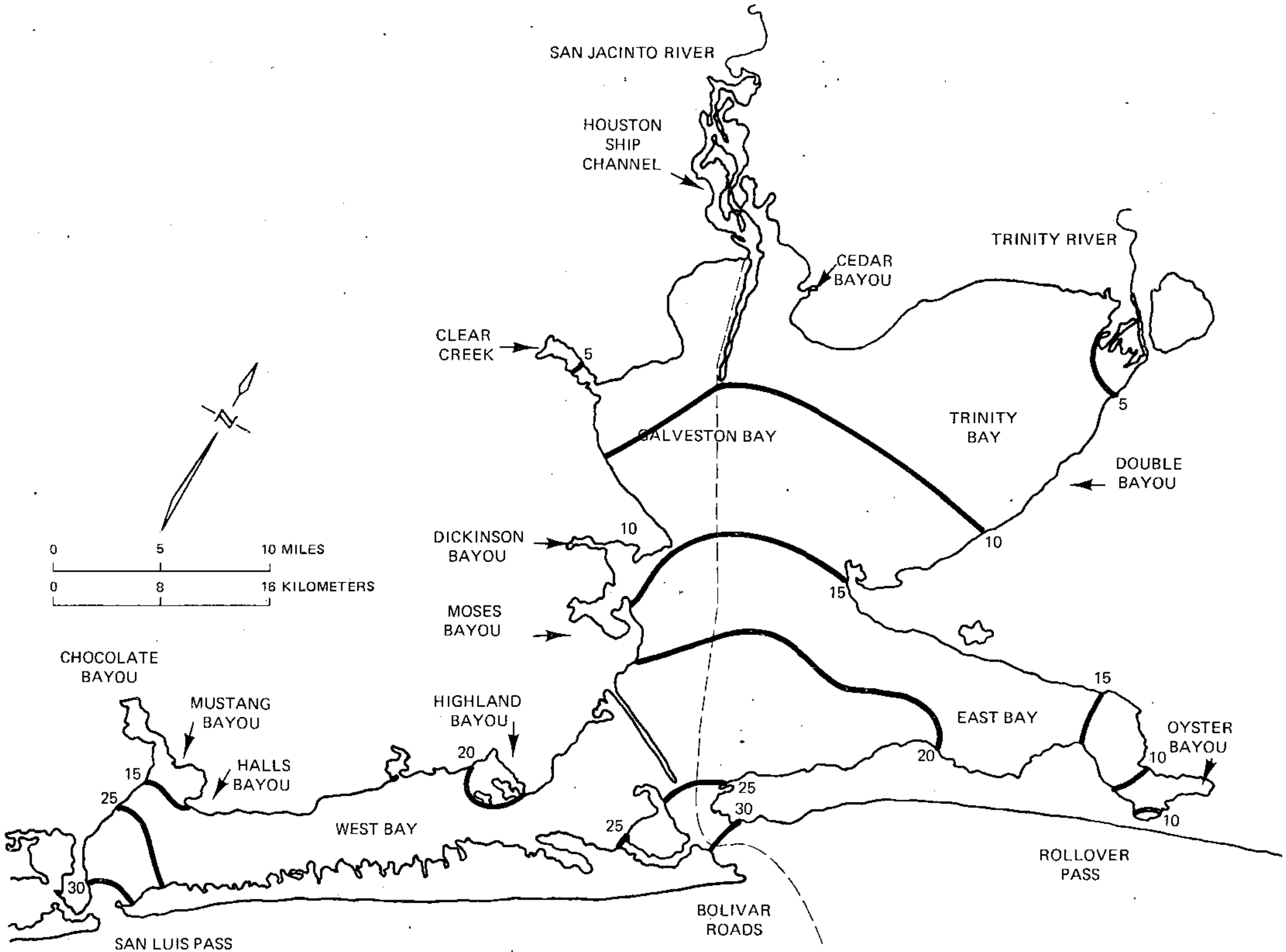

Figure 9-43. Simulated Salinities in the Trinity-San Jacinto Estuary Under December Freshwater Inflow Needs, Alternative I (ppt)

Interpretation of the Physical Significance of the Estimated Freshwater Inflow Needs

The monthly freshwater inflows, estimated in the Trinity-San Jacinto estuary report, from the San Jacinto and Trinity River Basins represent the best statistical estimates of monthly inflows needed to satisfy selected specified objectives for the major estuarine factors of marsh inundation, salinity distribution, and fisheries harvests. These estimates cover a range of potential factors and illustrate the complexity of the estuarine system.

Freshwater inflows approximately equal to the estimated needs may give estuarine responses which are indistinguishable, on a statistical basis, from the desired conditions. Confidence limits can be obtained for changes in estuarine conditions, such as salinity, using statistical techniques. It is not clear, however, as to the proper technique for determining confidence bounds on the actual monthly inflow estimates for those months where the individual confidence limits on the inflow needs for salinity, harvest and inundation must be combined into a single confidence interval.

A wide variability of freshwater inflow occurs in Texas estuaries from year to year, through drought and flood cycles. The monthly freshwater inflow levels received by the estuary fluctuate about the average inflow due to natural hydrologic variability. Such fluctuations are expected to continue to exist for practically any average level of inflow that might occur or that might be specified. It is not likely that sufficient control can be exerted to completely regulate the inflow extremes. In fact, to do so may be detrimental to the process of natural selection and other aspects of this vast living system. However, some provision may be needed to prevent an increase in the frequency of periods of low flows. Such a provision could specify minimum monthly inflows required to keep salinities below the upper viability limits given for the key estuarine-dependent species (Tables 9-1 and 9-2).

Summary

A methodology is presented which combines the analysis of the component physical, chemical and biological elements of the Trinity-San Jacinto estuary into a sequence of steps which results in estimates of the freshwater inflow needs for the estuary based upon specified salinity, marsh inundation and fishery harvest objectives.

Monthly mean salinity bounds are established at locations in the estuary near the inflow points of the San Jacinto and Trinity River Basins. These upper and lower limits on monthly salinity provide a salinity range within which viable metabolic and reproductive activity can be maintained and normal historical salinity conditions are observed.

Marsh inundation needs, for the flushing of nutrients from riverine marshes into the open bays, are computed and specified for the Trinity River delta. The San Jacinto River delta is limited in areal extent and far smaller than the Trinity delta. As a result, no inflow requirements for inundation of the San Jacinto River delta are specified from the San Jacinto River Basin. The Trinity River delta is frequently submerged by floods from the Trinity River. Based upon historical conditions and gaged streamflow records, freshwater inflow needs for marsh inundation are estimated and specified at 750

thousand acre-feet (924 million m^3) in each of the months April, May, and October. These volumes correspond to flood events with peak daily flow rates of 29,500 ft^3/sec (836 m^3/sec).

Estimates of the freshwater inflow needs for the Trinity-San Jacinto estuary are computed by representing the interactions among freshwater inflows, estuarine salinity and fisheries harvests within an Estuarine Linear Programming Model. The model computes the monthly freshwater inflows from the San Jacinto and Trinity River basins which best achieve a specified objective.

The monthly freshwater inflow needs for the Trinity-San Jacinto estuary were estimated for each of three alternatives:

Alternative I (Subsistence): minimization of annual combined inflow while meeting salinity viability limits and marsh inundation needs;

Alternative II (Maintenance of Fisheries Harvests): minimization of annual combined inflow while providing annual commercial harvests of red drum, seatrout, shrimp, blue crab, and bay oysters at levels no less than their mean 1962 through 1976 annual values, satisfying marsh inundation needs, and meeting viability limits for salinity; and

Alternative III (Shrimp Harvest Enhancement): maximization of the annual offshore commercial harvest of shrimp while meeting salinity limits, satisfying marsh inundation needs, and utilizing an annual inflow to the estuary at a level no greater than the combined individual average annual historical inflows from the contributing river basins.

Under Alternative I (Subsistence), the Trinity-San Jacinto system, which has functioned as both a commercial shellfish and finfish producing system in the past, can continue to be an important fisheries producing estuary with substantially less freshwater inflow. Freshwater inflows totalling 6.85 million acre-feet (8,446 million m^3) annually are predicted to satisfy the basic salinity gradient and marsh inundation needs, with resulting predicted increases in commercial finfish and shellfish harvests of 44 and 15 percent above average, respectively.

Under Alternative II (Maintenance of Fisheries Harvests), the predicted annual commercial harvests of red drum, spotted seatrout, shrimp, blue crab and bay oysters are required to be at least as great as historical 1962 through 1976 average levels. The marsh inundation needs and salinity limits must also be satisfied. To satisfy these criteria, an annual freshwater inflow of 7.19 million acre-feet (8,865 million m^3) is needed.

Under Alternative III (Shrimp Harvest Enhancement), the Trinity-San Jacinto estuary's annual freshwater inflow needs are estimated at 7.02 million acre-feet (8,656 million m^3) distributed in a seasonally unique manner, to achieve the objective of maximizing the annual predicted commercial offshore (Gulf Area No. 18) harvest of penaeid shrimp. Annual inflows from the San Jacinto River Basin are limited by the average annual 1941 though 1976 historical inflow from the basin. The objective of harvest enhancement is achieved with a predicted 15 percent increase in all shrimp harvested offshore in Gulf Area No. 18 and an estimated gain of 81 percent in total commercial bay finfish harvest (including a 57 percent decline in the commercial bay harvest of red drum).

The numerical tidal hydrodynamic and salinity mass transport models were applied to the Trinity-San Jacinto estuary to determine the effects of the estimated freshwater inflow needs for Alternative I1/ upon the average monthly net flow circulation and salinity characteristics of the estuarine system. The monthly simulations utilized typical tidal and meteorological conditions observed historically for each month simulated.

The net circulation patterns simulated by the tidal hydrodynamic model indicate that the dominant net current in Galveston Bay is a net water movement along the Houston Ship Channel. This dominant current influences circulation in the other areas of Galveston Bay. The simulated net water movements in Trinity, East, and West Bays were generally dominated by internal currents. The simulated monthly circulation patterns indicate that the currents in the Trinity-San Jacinto estuary are wind dominated.

The simulated salinities in the Trinity-San Jacinto estuary for the estimated monthly freshwater inflow needs under Alternative I vary over a wide range. Salinities throughout the estuary are lowest in the month of May, with average simulated salinities of less than 20 parts per thousand (ppt) over the entire estuary except near San Luis and Bolivar Passes. The highest levels of simulated salinities occur during the month of August, when salinities in Galveston Bay near Bolivar Pass exceed 30 ppt. The simulated salinities for Trinity Bay are generally less than 15 ppt throughout the year. The major portion of Galveston Bay has simulated salinities of between 15 and 20 ppt; however, during the high freshwater inflow months of April and May, the salinities in the bay are between 10 and 15 ppt. Since the middle portion of Galveston Bay has simulated salinities in all months below a target maximum allowable concentration of 20 ppt, the freshwater inflow needs established by the Estuarine Linear Programming Model would be adequate to sustain the salinity gradients specified, within the objectives, throughout the estuary.

The estimated monthly freshwater inflow needs derived in this report are the best statistical estimates of the monthly inflows satisfying specified objectives for fisheries harvest levels, marsh inundation and salinity regimes. These objectives cover a range of potential management policies.

A high level of variability of freshwater inflow occurs annually in Texas estuaries. Fluctuations in inflows are expected to continue for any average level of inflow into the estuary which may be specified. Some provision should be made, however, in any estuarine management program to prevent an increase (over historical levels) in the frequency of low inflows detrimental to the ecosystem and its resident aquatic organisms.

1/ The alternative having the lowest inflow level and thus the alternative that would impinge most heavily upon salinities.

BIBLIOGRAPHY

1. Abbott, W., C. E. Dawson, and C. H. Oppenheimer. "Physical, Chemical and Biological Characteristics of Estuaries." In: Water and Water Pollution Handbook, edited by L. L. Ciaccio. Vol. 1, pp. 51-140. Marcel Dekker, Inc., New York. 1971.

2. Alaska, University, Institute of Marine Science. "The Uptake and Utilization of Organic Substances by Marine Phytoplankton," by J. A. Hellebust. In: Symposium on Organic Matter in Nutrient Waters, edited by D. W. Hood. pp. 225-256. 1970.

3. Alderdice, D. F. "Factor Combination: Responses of Marine Poikilotherms to Environmental Factors Acting in Concert." In: Marine Ecology. edited by O. Kinne, Vol. 1, Part 2, pp. 1659-1722. Wiley-Interscience, New York. 1972.

4. Aldrich, D. V., et al. "An Ecological Interpretation of Low Temperature Responses in Penaeus aztecus and P. setiferus Postlarvae." Bull. Mar. Sci., Vol. 18, pp. 61-71. 1968.

5. Amemiya, I. "Notes on Experiments on the Early Developmental Stages of the Portuguese, American and English Native Oysters, with Special Reference to the Effect of Varying Salinity." J. Mar. Biol. Assoc. U. K., Vol. 14, pp. 161-175. 1926.

6. Armstrong, N. E. and M. O. Hinson. "Influence of Flooding and Tides on Nutrient Exchange from a Texas Marsh." In: Proceedings of the Fourth Biennial International Estuarine Research Conference. Estuarine Research Foundation. Mt. Pocono, Pennsylvania. 1977.

7. Arthur, J. F. and M. Ball. "Entrapment of Suspended Materials in the San Francisco Bay-Delta Estuary." U. S. Dept. Int., Bureau of Reclamation. Sacramento, California. GPO 789-115/78-5. 106 p. 1978.

8. Bayly, I. A. E. "Salinity Tolerance and Osmotic Behavior of Animals in Athalassic Saline and Marine Hypersaline Waters." Ann. Review Ecol. and Syst., Vol. 3, pp. 233-268. 1972.

9. Beadle, L. C. "The Effect of Salinity on the Water Content and Respiration of Marine Invertebrates." J. Exp. Biol., Vol.8, pp. 211-277. 1931.

10. Blum, U., et al. "Photosynthesis and Respiration of Spartina and Juncus Salt Marshes in North Carolina: Some Models." Estuaries, Vol. 1, pp. 228-238. 1978.

11. Brezonik, P. L. "Nitrogen: Sources and Transformations in Natural Waters." In: Nutrients in Natural Waters, edited by H. C. Allan and J. R. Kramer. pp. 1-50. John Wiley & Sons, New York. 1972.

12. Burrell, D. C., and J. R. Schubel. "Seagrass Ecosystem Oceanography." In: Seagrass Ecosystems, edited by C. P. McRoy and C. Helfferich. pp. 195-232. Marcel Dekker, Inc., New York. 1977.

13. Bursey, C. R. and C. E. Lane. "Osmoregulation in the Pink Shrimp Penaeus duroarum Burkenroad." Comp. Biochem. Physiol., Vol. 39 A, pp. 483-493, 1971.

14. Butler, P. A. "Gametogenesis in the Oyster under Conditions of Depressed Salinity." Biol. Bull., Vol. 96, pp. 263-269. 1949.

15. Butler, P. A. "Oyster Growth as Affected by Latitudinal Temperature Gradients." Comm. Fish. Rev., Vol. 15, pp. 7-12. 1953.

16. California, University of. "BMD Biomedical Computer Programs," edited by W. J. Dixon, Publications in Automatic Computation, No. 2. University of California at Berkley. 600 p. 1970.

17. California, Univ. Instit. of Marine Resources. "Coastal Zone Bibliography: Citations to Documents on Planning, Resources Management and Impact Assessment," by J. Sorensen et al. 133 p. in 2 Fiche. Their TR-43 Sea Grant Publication No. 8. Prepared for Office of Sea Grant. 1973.

18. California, Univ. Instit. of Marine Resources. "Coastal Zone Bibliography: Citations to Documents on Planning, Resources Management and Impact Assessment," by B. Jenks et al. 2nd ed. 161 p. Their IMR 76-8. 1976.

19. Central Power & Light Company. "Further Studies of the Effects of Power Plant Operation on Cox Bay, Texas," by F. N. Moseley et al. 1975.

20. Chanley, P. E. "Survival of Some Juvenile Bivalves in Water of Low Salinity." Proc. Natl. Shellfish Assoc., Vol. 48, pp. 52-65. 1957.

21. Chin, E. "The Bait Shrimp Fishery of Galveston Bay, Texas." Trans. Amer. Fish. Soc., Vol. 89, pp. 135-141. 1960.

22. Chu, S. P. "The Influence of the Mineral Composition of the Medium on the Growth of Planktonic Algae. Part I: Methods and Culture Media." J. Ecol., Vol. 30, pp. 284-325. 1942.

23. Coastal Ecosystems Management, Inc. "Environmental Assessment of the Trinity River Discharge on Productivity in Trinity Bay," by R. H. Parker, D. E. Solomon, and G. O. Smith. 162 p. Prepared for Fort Worth District, U. S. Corps of Engineers. 1972.

24. Coastal Ecosystems Management, Inc. "Environmental Factors Affecting Bay and Estuarine Ecosystems of the Texas Coast," by R. H. Parker and W. G. Blanton. Report to Humble Oil Co. 182 p. 1970.

25. Coastal Ecosystems Management, Inc. "Seasonal Assessment of the Relationships Between the Discharge on the Trinity River and the Trinity Bay Ecosystem," by D. E. Soloman and G. D. Smith. 147 p. Report to the U. S. Army Corps of Engineers, Fort Worth District. 1973.

26. Conner, J. and M. Truesdale, "Ecological Implications of a Freshwater Impoundment in a Low-Salinity Marsh." In: Proceedings of the Second Symposium of Coastal and Estuary Management, edited by R. H. Chabreck, pp. 259-276. 1972.

27. Conservation Foundation. "The Decline of Galveston Bay: A Profile of Government's Failure to Control Pollution in an Endangered American Estuary," by J. N. Smith. 127 p. 1972. [628.168/C765D]

28. Cook, H. L. and M. J. Lindner. "Synopsis of Biological Data on the Brown Shrimp Penaeus aztecus aztecus Ives, 1891." FAO Fish. Rept. 4, pp. 1471-1497. 1970.

29. Cooper, A. W. "Salt Marshes." In: Coastal Ecological Systems of the United States, Vol. 2, pp. 55-98. The Conservation Foundation, Washington, D. C. 1974.

30. Cooper, David Clayton. "Responses of Continuous-Series Estuarine Microecosystems to Point-Source Input Variations." 190 p. Thesis (Ph.D.), University of Texas at Austin. 1970. [574.5/C78RE]

31. Cooper, D. "River Input Studies Using Continuous-Series Microecosystems." Final Report, Galveston Bay Study Program, Texas Water Quality Board, Austin, Texas. 1970.

32. Copeland, B. J. and E. G. Fruh. "Ecological Studies of Galveston Bay, 1969." 482 p. Final Report to Texas Water Quality Board. 1970.

33. Copeland, B. J. and M. V. Truitt. "Fauna of the Aransas Pass Inlet, Texas. II. Penaeid Shrimp Postlarvae." Tex. J. Sci., Vol. 18, pp. 65-74. 1966.

34. Copeland, B. J. "Effects of Decreased River Flow on Estuarine Ecology." J. Water Pollution Control Fed., Vol. 38, pp. 1830-1839. 1966.

35. Copeland, B. J., et al. "Migrating Subsystems." In: Coastal Ecological Systems of the United States. Vol. III, pp. 422-453. The Conservation Foundation. Washington, D. C. 1974.

36. Costello, T. J. and D. M. Allen. "Synopsis of Biological Data on the Pink Shrimp Penaeus duorarum Burkenroad, 1939." FAO Fish. Rept. 4, pp. 1499-1537. 1970.

37. Costlow, J. D., Jr. "The Effect of Salinity and Temperature on Survival and Metamorphosis of Megalops of the Blue Crab, Callinectes sapidus." Helgolander wiss. Meeresunters, Vol. 15, pp. 84-97. 1967.

38. Crowe, A. L. "Population Dynamics of Two Species of Commercial Shrimp in Caminada Bay, Louisiana." Proc. Louisiana Acad. Sci., Vol. 38, pp. 86-91. 1975.

39. Cruz, A. A. de la. "Primary Production of Coastal Marshes in Mississippi." Gulf Res. Rept. 4, pp. 351-356. 1974.

40. Cruz, A. A., de la. "The Role of Tidal Marshes in the Productivity of Coastal Waters." Association Southeastern Biology Bulletin, Vol. 20, pp. 147-156. 1973.

41. Cushing, D. The Detection of Fish. Pergamon Press, New York. 200 p. 1973.

42. Dantzig, G. B., Linear Programming and Extensions, Princeton University Press, Princeton, New Jersey. 1963.

43. Darnell, R. M. "Organic Detritus in Relation to the Estuarine Ecosystem." In: Estuaries, edited by G. H. Lauff, Publ. No. 83, pp. 376-382. Am. Assoc. Advmt. Sci., Washington, D. C. 1967.

44. Darnell, R. M. "Trophic Spectrum of an Estuarine Community, based on Studies of Lake Pontchartrain, Louisiana." Ecology, Vol. 42, pp. 553-568. 1961.

45. Davis. H. C. "Survival and Growth of Clam and Oyster Larvae at Different Salinities." Biol. Bull. Mar. Biol. Lab., Woods Hole, Vol. 114, pp. 296-307. 1958.

46. de Sylva, D. P. "Nektonic Food Webs in Estuaries." In: Estuarine Research, edited by L. E. Cronin, Vol. 1, pp. 420-427. Academic Press, New York. 1975.

47. Eleuterius, C. K. "Location of the Mississippi Sound Oyster Reefs as Related to Salinity of Bottom Waters during 1973-1975." Gulf. Res. Repts., Vol. 6, pp. 17-23. 1977.

48. Espey, Huston and Associates, Inc. "Development and Application of a Hydrodynamic Model of the Lavaca and Guadalupe Deltaic Systems," by L. M. Hauck et al. Report to the Texas Water Development Board. EH&A 0163-01. 88 p. 1976.

49. Espey, Huston and Associates, Inc. "Ecological Studies in Sabine Lake, 1974-1975," by J. M. Wiersema et al. Technical Report to the Texas Water Development Board, EH&A Document No. 7644, 242 p. 1976.

50. Espey, Huston and Associates. "Galveston Bay Project; Addendum to Compilation of Water Quality Data Through August, 1972." R. J. Huston et al. Submitted to Texas Water Quality Board. 1973. [628.168/ES6GA]

51. Espey, Huston and Associates. "Galveston Bay Project; Statistical Summary of Water Quality Conditions in the Galveston Bay System," by R. J. Huston et al. 32 p. Their Document No. 7419, submitted to Texas Water Quality Board. 1974. [628.168/ES6GA]

52. Espey, Huston and Associates. "Hydrological and Biological Studies of the Trinity River Delta." Texas Department of Water Resources, LP-70. 1978.

53. Espey, Huston and Associates, Inc. "Marsh Biology and Nutrient Exchange in Three Texas Estuaries," by J. M. Wiersema et al. Report to the Texas Department of Water Resources. v.p. 1977.

54. Espey, Huston and Associates, Inc. "Marsh Plant Production and Potential Detritus in Lavaca, San Antonio and Nueces Bays," by D. B. Adams et al. v.p. and 3 maps in pocket. Their Document No. 7688. Prepared for Texas Water Development Board. 1977. [581.526/ES6M]

55. Espey, Huston and Associates, Inc. "Marsh Vegetation of the Colorado River Delta, Texas," by D. B. Adams and C. A. Tingley. Report to the Texas Department of Water Resources. 14 p. 1977.

56. Espey, Huston an Associates, Inc. "Phytoplankton Distribution and Community Structure in Trinity Bay, Texas," by B. M. Winsborough and G. H. Ward. Paper presented at First Winter meeting of the American Society of Limnology and Oceanography, Corpus Christi, Texas. January 2-5, 1979.

57. Espey, Huston and Associates, Inc. "A Study of the Hydrological and Nutrient Exchange Processes in the Trinity River Delta, Texas," by D. B. Adams and C. A. Tingley. 30 p. Submitted to the Texas Department of Water Resources. 1977.

58. Espey, Huston and Associates. "A Study of the Hydrology and Nutrient Exchange Processes in the Trinity River Delta, Texas Data Report," by M. M. Jennings. Prepared for Texas Department of Water Resources. 1978.

59. Espey, Huston and Associates, Inc. "A Study of the Hydrological and Nutrient Exchange Processes in the Trinity River Delta, Texas, Part I: An Investigation of Nutrient Exchange in the Trinity River Delta," by C. E. Belaire and P. T. Price. Prepared for Texas Department of Water Resources. 1977.

60. Espey, Huston and Associates, Inc. "A Study of the Hydrological and Nutrient Exchange Processes in the Trinity River Delta, Texas - Part II: Marsh Habitats and Primary Production in the Trinity River Delta," by D. B. Adams. Prepared for Texas Department of Water Resources. 1977.

61. Espey, Huston and Associates, Inc. "A Study of the Hydrological and Nutrient Exchange Processes in the Trinity River Delta, Texas, Part III: Development and Application of Hydrodynamic and Mass Transfer Models of the Trinity Deltaic System," by L. M. Hauck. Prepared for Texas Department of Water Resources. 1977.

62. Espey, Huston and Associates, Inc. "Trinity River Delta Inundation Study," L. M. Hauck and G. Ward. 22 p. Prepared for Texas Department of Water Resources. 1978. [551.45/ES6T]

63. Espey, Huston and Associates, Inc. Unpublished data, 1975-1976.

64. Espey, Huston and Associates, Inc. "User's Manual for Hydrodynamic - Mass Transfer Model of Deltaic Systems," by L. M. Hauck. Submitted to Texas Department of Water Resources. 142 p. and Appen. A-E. Austin. 1978.

65. Etzold, D. J. and D. C. Williams. "Data Relative to the Introduction of Supplemental Freshwater under Periodic Controlled Conditions for the Purpose of Enhancing Seafood Productivity in Mississippi and Louisiana Estuaries." Mississippi-Alabama Sea Grant Consortium, Ocean Springs, Miss. MASGP-74-18. 41 p. 1974.

66. Fiering, M. B. and B. B. Jackson. Synthetic Streamflows. Water Resources Monograph 1, American Geophysical Union. 1971.

67. Foerster, J. W. "The Fate of Freshwater Algae Entering an Estuary." In: Estuarine Microbial Ecology, edited by L. H. Stevenson and R. R. Colwell. University of South Carolina Press. 1973.

68. Fogg, G. E. Algal Cultures and Phytoplankton Ecology. University of Wisconsin Press. 1966.

69. Ford, Bacon and Davis. "Report on Water Supply for Galveston and the Texas City, Texas Industrial Area." 54 p. 1947. [628.11/F75GTC]

70. Fotheringham, N. and S. L. Brunemeister. "Common Marine Invertebrates of the Northwestern Gulf Coast." Gulf Publ. Co., Houston. 197 p. 1975.

71. Fruh, E. G. "Evaluation of Water Quality Data, March 1973-June 1976; Houston Lighting and Power Cedar Bayou Generating Station." 1976. [628.168/G95G]

72. Geological Society of America, Inc. "Salinity," by A. S. Pearse and G. Gunter. In: Treatise on Marine Ecology and Paleoecology, edited by J. W. Hedgpeth. Memoir No. 67, pp. 129-157. 1957.

73. Georgia Department of Natural Resources. "Seatrout of the Genus Cynoscion in Coastal Waters of Georgia," by R. K. Mahood. Contributing Series No. 26, 36 p. 1974.

74. Georgia Game & Fish Commission, Coastal Fish. Div. "A Report on the Co-operative Blue Crab Study--South Atlantic States," by R. Mahood et al. Contrib. Series No. 19, pp. 1-32. 1970.

75. Georgia, University, Marine Science Center. "Seasonal Measurements of Carbon, Nitrogen, Ash, Iron, Carbohydrates, and Pigments from Geographically Different Spartina alterniflora Marshes in the Southeast," by G. L. McIntire and W. M. Dunston. Technical Report No. 76-5. 1976.

76. Gillard, R. M. "An Ecological Study of Oyster Population, Including Selected Associated Organisms in West Bay, Galveston, Texas." M. S. Thesis. Texas A & M University, College Station, Texas. 136 p. 1969.

77. Green, J. "The Biologic of Estuarine Animals." University of Washington Press, Seattle. 401 p. 1968.

78. Gucinski, H. "A Note on the Relation of Size to Ecological Value of Some Wetlands." Estuaries, Vol. 1, pp. 151-156. 1978.

79. Gulf Coast Research Laboratories. "The Shrimp Fishery of the Gulf of Mexico United States: A Regional Management Plan," by J. Y. Christmas and D. J. Etzold, editors. Technical Reports Series No. 2, 128 p. 1977.

80. Gulf Coast Waste Disposal Authority. "Galveston Bay Project—Implementation of the Water Quality Management Plan of the Galveston Bay Project Water Quality Management Plan." 50 p. Report to Texas Water Quality Board. 1974. [628.168/G95G]

81. Gulf Coast Waste Disposal Authority. "A Report to the Texas Water Quality Board on Galveston Bay Project Problem Areas." 32 p. 1974. [628.168/G95R]

82. Gulf States Marine Fisheries Commission. "The Seatrout or Weakfishes (Genus Cynoscion) of the Gulf of Mexico," by W. C. Guest and G. Gunter. Technical Summary 1, pp. 1-40. 1958.

83. Gulf States Marine Fisheries Commission. "The Shrimp Fishery of the Gulf of Mexico: Biological Notes and Recommendations," by A. Collier et al. Information Series No. 2, 5 p. 1959.

84. Gulland, J. A. "Survival of the Youngest Stages of Fish, and its Relation to Year-Class Strength." ICNAF Special Publication 6, pp. 363-371. 1965.

85. Gunter, G. and G. E. Hall "Biological Investigations of the St. Lucie Estuary (Florida) in Connection with Lake Okeechobee Discharges through the St. Lucie Canal." Gulf Res. Rept., Vol. 1, pp. 189-307. 1963.

86. Gunter, G. "Death of Fishes Due to Cold on the Texas Coast, January, 1940." Ecology, Vol. 22, pp. 203-208. 1941.

87. Gunter, G. and H. H. Hildebrand. "Destruction of Fishes and Other Organisms on the South Texas Coast by the Cold Wave of January 28 - February 3, 1951." Ecology, Vol. 32, pp. 731-736. 1951.

88. Gunter, G. "Gulf Fisheries." In: The Encyclopedia of Marine Resources, edited by F. E. Firth. pp. 289-294. Van Nostrand Reinhold Co., New York. 1969.

89. Gunter, G. "Habitat of Juvenile Shrimp (family Penaeidae)." Ecology, Vol. 42, pp. 598-599. 1961.

90. Gunter, G. "The Importance of Catastrophic Mortalities for Marine Fisheries Along the Texas Coast." Journal of Wildlife Management, Vol. 16, pp. 63-69. 1952.

91. Gunter, G. "Mortality of Oysters and Abundance of Certain Associates as Related to Salinity." Ecology, Vol. 36, pp. 601-605. 1955.

92. Gunter, G. "Predominance of the Young among Marine Fishes found in Freshwater." Copeia, Vol. 1, pp. 13-16. 1957.

93. Gunter, G. "Some Relationships of Estuaries to the Fisheries of the Gulf of Mexico." In: Estuaries, edited by G. H. Lauff. Publ. No. 83, pp. 621-637. Am. Assoc. Advmt. Sci. 1967.

94. Gunter, G. "Some Relations of Estuarine Organisms to Salinity." Limnol. Oceanogr., Vol. 6, pp. 182-190. 1961.

95. Gunter, G. and J. C. Edwards. "The Relation of Rainfall and Freshwater Drainage to the Production of the Penaeid Shrimps (Penaeus fluviatilis Say and Penaeus aztecus Ives) in Texas and Louisiana Waters." FAO Fish. Rept. 57, pp. 875-892. 1969.

96. Gunter, G. and H. H. Hildebrand. "The Relation of Rainfall of the State and Catch of the Marine Shrimp (Penaeus setiferus) in Texas Waters." Bull. Mar. Sci., Gulf and Carib., Vol. 4, pp. 95-103. 1954.

97. Gunter, G., et al. "A Review of Salinity Problems of Organisms in United States Coastal Areas Subject to the Effects of Engineering Works." Gulf Res. Repts., Vol. 4, pp. 380-475. 1974.

98. Gunter, G. "Seasonal Variations in Abundance of Certain Estuarine and Marine Fishes in Louisiana, with Particular Reference to Life Histories." Ecol. Monogr., Vol. 8, pp. 313-346. 1938.

99. Gunter, G. "Some Relations of Faunal Distributions to Salinity in Estuarine Waters." Ecology, Vol. 37, pp. 616-619. 1956.

100. Gunter, G., et al. "Some Relations of Salinity to Population Distribution of Motile Estuarine Organisms with Special Reference to Penaeid Shrimp." Ecology, Vol. 45, pp. 181-185. 1964.

101. Gunter, G. and W. E. Shell. "A Study of an Estuarine Area with Water-Level Control in the Louisiana Marsh." Proc. Louisiana Acad. Sci., Vol. 21, pp. 5-34. 1958.

102. Guyton, W. F. & Associates. "Ground-Water Conditions in the Galveston Bay Area-Harris, Galveston, and Chambers Counties, Texas." 40 p. Prepared for Texas Water Quality Board. 1972. [551.49/G99G]

103. Hackney, C. T. and A. A. de La Cruz. "Changes in Interstitial Water Salinity of a Mississippi Tidal Marsh." Estuaries, Vol. 1, pp. 185-188. 1978.

104. Hackney, C. and O. Hackney. "The Effect of River Flow on the Production of White Shrimp (Penaeus setiferus) in a Georgia Estuary." Assoc. S. E. Biol. Bull., Vol. 19, 72 p. 1972.

105. Haines, E. B. "Nitrogen Pools in Georgia Coastal Waters." Estuaries, Vol. 2, pp. 33-39. 1979.

106. Haines, E. B. "On the Origin of Detritus in Georgia Salt Marsh Estuaries." Oikos, Vol. 29, pp. 254-260. 1977.

107. Hall, C. A. A. et al. "Material Exchange Between the Flax Pond Marsh Systems and Long Island Sound." In: Proceeding of the Third Biennial International Estuarine Research Conference. Galveston, Texas. 1976.

108. Hann, C. T. "Statistical Methods in Hydrology." 378 p. Iowa State University Press at Ames. 1977.

109. Hansen, D. V. "Currents and Mixing in the Columbia River Estuary." Ocean Sci. and Ocean Eng., Trans. Joint Conf. Marine Tech. Soc., Amer. Soc. Limnol. and Oceanogr., pp. 943-955. 1965.

110. Hayes, M. O. "Sedimentation on a Semiarid, Wave-Dominated Coast (South Texas) with Emphasis on Hurricane Effects." Ph. D. Dissertation. University of Texas at Austin. 350 p. Austin, Texas. 1965.

111. Hedgpeth, J. W. "Ecological Aspects of the Laguna Madre, a Hypersaline Estuary." In: Estuaries, edited by G. H. Lauff. Publ. No. 83, pp. 408-419. Am. Assoc. Advmt. Sci. 1967.

112. Heinle, D. R. et al. "Contribution of Tidal Marshes to Mid-Atlantic Estuarine Food Chains." In: Estuarine Processes, edited by M. Wiley, Vol. 2, pp. 309-320. Academic Press, New York. 1977.

113. Hidu, H. and H. H. Haskin. "Swimming Speeds of Oyster Larvae Crassostrea virginica in Different Salinities and Temperatures." Estuaries, Vol. 1, pp. 252-255. 1978.

114. Hildebrand, H. H. Estudios Biologicos Preliminares Sobre la Laguna Madre de Tamaulipas. Ciencia (Mexico), Vol. 17, pp. 151-173. 1958.

115. Hildebrand, H. H. and G. Gunter. "Correlation of Rainfall with Texas Catch of White Shrimp, Penaeus setiferus (Linnaeus)." Trans. Amer. Fish. Soc. Vol. 82, pp. 151-155. 1953.

116. Himmelblau, D. M. Applied Nonlinear Programming. McGraw-Hill, Inc., New York. 1972.

117. Hjort, J. "Fluctuations in the Great Fisheries of Northern Europe Viewed in the Light of Biological Research." Rapp. Proc. Verbaux, Vol. 20, pp. 1-228. 1914.

118. Holliday, F. G. T. "The Effects of Salinity on the Eggs and Larvae of Teleosts." In: Fish Physiology, edited by N. S. Hoar and D. J. Randall, Vol. 1, pp. 293-311. Academic Press, New York. 1969.

119. Holliday, F. G. T. "Salinity: Fishes." In: Marine Ecology, edited by O. Kinne, Vol. 1, Environmental Factors, Part 2 Salinity, pp. 997-1033. Wiley-Interscience, New York. 1971.

120. Hoese, H. D. "Biotic Changes in a Bay Associated with the End of a Drought." Limnol. Oceanogr., Vol. 5, pp. 326-336. 1960.

121. Hoese, H. D. et al. "Fauna of the Aransas Pass Inlet, Texas. III: Diel and Seasonal Variations in Trawlable Organisms of the Adjacent Area." Tex. J. Sci., Vol. 20, pp. 34-60. 1968.

122. Hoese, H. D. and R. H. Moore. " Fishes of the Gulf of Mexico, Texas, Louisiana and Adjacent Waters." Texas A & M University Press, College Station, Texas. 337 p. 1977.

123. Hoese, H. D. "Spawning of Marine Fishes in the Port Aransas, Texas Area as Determined by the Distribution of Young and Larvae." Ph. D. Dissertation, Univ. Tex., 144 p. 1965.

124. Hoss, D. E. and D. S. Peters. "Respiratory Adaptation: Fishes." In: Estuarine Processes, edited by M. Wiley, Vol. 1, pp. 335-346. Academic Press, New York. 1976.

125. Houston, University, Department of Civil Engineering. "Water Resources Planning for the Houston-Galveston Region." Seminar, January 18, 1971. [333.91/H81W]

126. Bernard Johnson Engineers, Inc. "Galveston Bay Project Alternative Corrective Measures." Prepared for Texas Water Quality Board. 3 Vols. 1974. [628.168/J62GA]

127. Bernard Johnson Engineers, Inc. "Galveston Bay Project: Regional Systems Task, Phase 1; Problem Definition, First Statement on Existing Waste Loads and General Effects on Major Receiving Waters." 61 p. 1971. [628.168/J62G]

128. Bernard Johnson Engineers, Inc. "Galveston Bay Project Water Quality Management Plan." Prepared for Texas Water Quality Board. 48 p. 1974. [628.168/J62GW]

129. Bernard Johnson Engineers, Inc. "Water Pollution Control Act of 1972, Regional Impact: Houston Ship Channel/Galveston Bay." Prepared for the National Commission on Water Quality. 3 Vols. in 10 Fiche. 1975. [FICHE/P8252/460]

130. Jordan, D. S. and C. H. Gilbert. "Notes on Fishes Observed about Pensacola, Florida and Galveston, Texas with Description of New Species." Proc. U. S. Nat. Mus., Vol. 5, pp. 241-307. 1882.

131. June, F. C. and L. Chamberlin. "The Role of an Estuary in the Life History of the Atlantic Menhaden." Proc. Gulf and Caribbean Fish. Inst., Eleventh Annual Session. pp. 41-45. 1959.

132. Kerr, P. C. et al. "The Carbon Cycle in Aquatic Ecosystem." In: Nutrients in Natural Waters, edited by H. Allen and J. R. Kramer, pp. 101-124. John Wiley & Sons, New York. 1972.

133. Ketchum, B. H. "Eutrophication of Estuaries." In: Eutrophication: Causes, Consequences, Corrections. National Academy of Sciences. Washington, D. C.. 1969.

134. Khlebovich, V. V. "Aspects of Animal Evolution Related to Critical Salinity and Internal State." Mar. Biol., Vol. 2, pp. 338-345. 1969.

135. Kjerfve, B. and J. E. Greer. "Hydrography of the Santee River during Moderate Discharge Conditions." Estuaries, Vol. 1, No. 2, pp. 111-119. 1978.

136. Kikuchi, T. and J. M. Peres. "Consumer Ecology of Seagrass Beds." In: Seagrass Ecosystems, edited by C. P. Mcroy and C. Helfferich. pp. 147-193. Marcel Dekker, Inc., New York. 1977.

137. Kinne, O. "Adaptation to Salinity Variations - Some Facts and Problems." In: Physiological Adaptation, edited by C. L. Prosser. pp. 92-106. Amer. Phys. Soc., Washington, D. C. 1958.

138. Kinne, O. "Physiology of Estuarine Organisms with Special References to Salinity and Tempeature." In: Estuaries, edited by G. H. Lauff. pp. 525-540. Am. Assoc. Advmt. Sci. Publ. No. 83. 1967.

139. Kinne, O. "Salinity: Invertebrates." In: Marine Ecology, edited by O. Kinne, Vol. 1, Environmental Factors, Part 2 Salinity, pp. 821-995. Wiley-Interscience, New York. 1971.

140. Kirby-Smith, W. W. "The Detritus Problem and the Feeding and Digestion of an Estuarine Organism." In: Estuarine Processes, edited by M. Wiley, Vol. 1, pp. 469-479. Academic Press, New York. 1976.

141. Kjelson, M. A. and D. R. Colby. "The Evaluation and Use of Gear Efficienices In the Estimation of Estuarine Fish Abundance." In: Estuarine Processes, edited by M. Wiley, Vol. 2, pp. 416-424. Academic Press, New York. 1977.

142. Kramer, James R. "Phosphorus: Analysis of Water, Biomass, and Sediment." In: Nutrients in Natural Waters, edited by Herbert Allen and James R. Kramer, pp. 51-100. John Wiley & Sons, New York. 1972.

143. Kushlan, J. A. "Environmental Stability and Fish Community Diversity." Ecology, Vol. 57, pp. 821-825. 1976.

144. Kutkuhn, J. H. "The Role of Estuaries in the Development and Perpetuation of Commercial Shrimp Resources." In: A Symposium on Estuarine Fisheries, edited by R. F. Smith, pp. 16-36. Amer. Fish. Soc., Spec. Publ. No. 3. 1966.

145. Laird, C. M. and P. A. Haefner, Jr. "The Effects of Intrinsic and Environmental Factors on the Oxygen Consumption of the Blue Crab, Callinectes sapidus Rathbun." J. Exp. Mar. Biol. Ecol., Vol. 22, pp. 171-178. 1976.

146. Lakshmi, G. J., et al. "Effects of Salinity and Photoperiod on the Burying Behavior of Brown Shrimp Penaeus aztecus Ives." Aquaculture, Vol. 8, pp. 327-336. 1976.

147. Lambert, W. P. and E. G. Fruh, "A Methodology for Investigating Freshwater Inflow Requirements for a Texas Estuary." In" Estuarine Interactions, edited by M. L. Wiley, pp. 403-413. Academic Press, New York. 1978.

148. Lange, R., et al. "The Effect of Salinity and Temperature on Solubility of Oxygen and Respiratory Rate in Oxygen-dependent Marine Invertebrates." J. Exp. Mar. Biol. Ecol., Vol. 9, pp. 217-229. 1972.

149. Lasserre, P. "Osmoregulatory Responses to Estuarine Conditions: Chronic Osmotic Stress and Competition." In: Estuarine Processes, edited by M. Wiley, Vol. 1, pp. 395-413. Academic Press, New York. 1976.

150. Laughlin, R. A., et al. "Field and Laboratory Avoidance Reactions by Blue Crabs (Callinectes sapidus) to Storm Water Runoff." Trans. Amer. Fish. Soc., Vol. 107, pp. 78-86. 1978.

151. Lindner, M. J. and H. L. Cook. "Synopsis of Biological Data on the White Shrimp Penaeus setiferus (Linnaeus) 1767." FAO Fish. Rept. 4, pp. 1439-1469. 1970.

152. Lockheed Eletronics Co., Inc. "An Assessment of the Accuracy of Areal Measurements of Water Bodies using ERISI MSS Data," by J. F. Paris. 13 p. 1973. [551.028/L81A]

153. Lockwood, Andrews and Newnam, Inc. "An Engineering Report on the Galveston Bay Shipping Study." 40 p. Prepared for Texas Water Quality Board and Harris County Houston Ship Channel Navigation District. 1970. [628.168/L81E]

154. Lockwood, M. G. and H. P. Carothers. "Tidal Inlets for Preservation of Estuaries." Amer. Soc. Civil Eng., Env. Eng. Conf., Dallas, Texas. pp. 1-15. 1967.

155. Loosanoff, V. L. "Behavior of Oysters in Water of Low Salinities." Proc. Natl. Shellfish Assoc., Vol. 135, 51 p. 1952.

156. Loosanoff, V. L. "Gonad Development and Discharge of Spawn in Oysters of Long Island Sound." Biol. Bull. Mar. Biol. Lab., Woods Hole, Vol. 129, pp. 546-561. 1965.

157. Louisiana Department of Wildlife and Fisheries. "1977 Environmental Conditions Relative to Shrimp Production in Coastal Louisiana along with

Shrimp Catch Data for the Gulf of Mexico," by B. B. Barrett and E. J. Ralph. Technical Bulletin No. 26. 16 p. 1977.

158. Louisiana State University. "Ecological Implications of a Freshwater Impoundment in a Low-salinity Marsh," by J. V. Conner and F. M. Truesdale. In: Proceedings, Second Symposium, Coastal Marsh and Estuary Management, edited by R. H. Chabreck, pp. 259-276. 1973.

159. Louisiana State University. "Nutrient Levels and Phytoplankton Productivity in the Estuary," by R. B. Williams. In: Proceedings of the Second Coastal Marsh and Estuary Management Symposium, edited by R. H. Chabreck, pp. 59-89. 1973.

160. Louisiana State University, Baton Rouge. "Finfish Productivity in Coastal Marshes and Estuaries," by M. L. Wiley et al. In: Proc., Second Symposium, Coastal Marsh and Estuary Management, edited by R. H. Chabreck, pp. 139-150. 1973.

161. Louisiana State University, Baton Rouge. "The Impact on Estuaries and Marshes of Modifying Tributary Runoff," by C. R. Chapman. In: Proceedings, Second Symposium, Coastal Marsh and Estuary Management, edited by R. H. Chabreck, pp. 235-258. 1973.

162. Louisiana State University, Baton Rouge. "Shellfish and Crustacean Productivity in Marshes and Estuaries," by L. S. St. Amant. In: Proceedings, Second Symposium, Coastal Marsh and Estuary Management, edited by R. H. Chabreck, pp. 151-161. 1973.

163. Louisiana State University, Baton Rouge. "The Importance of Vascular Plant Detritus to Estuaries," by W. E. Odum et al. In: Proc., Second Symposium, Coastal Marsh and Estuary Management, edited by R. H. Chabreck, pp. 91-114. 1973.

164. Louisiana State University, Baton Rouge. "Some Trophic Relationships of Marsh and Estuarine Area," by J. W. Day et al. In: Proc., Second Symposium, Coastal Marsh and Estuary Management, edited by R. H. Chabreck, pp. 115-135. 1973.

165. Louisiana Wildlife and Fisheries Commission. "Analysis and Treatment of Zooplankton of Estuarine Waters of Louisiana. Phase IV, Section II," by M. C. Gillespie. In: Cooperative Gulf of Mexico Estuarine Inventory and Study, pp. 107-175. 1971.

166. Louisiana Wildlife and Fisheries Commission. "Barataria Basin: Salinity Changes and Oyster Distribution," by V. R. Sickle et al. Technical Bulletin No. 20, 22 p. 1976.

167. Louisiana Wildlife and Fisheries Commission. "Effects of 1973 River Flood Waters on Brown Shrimp in Louisiana Estuaries," by C. T. White. Technical Bulletin No. 16, 24 p. 1975.

168. Louisiana Wildlife and Fisheries Commission. "Primary Factors which Influence Commercial Shrimp Production in Coastal Louisiana," by B. B. Barrett and M. C. Gillespie. 26 p. 1973.

169. Louisiana Wildlife and Fisheries Commission, Oysters, Water Bottoms, and Seafood Division. "Investigations of Commercially Important Penaeid Shrimp in Louisiana Estuaries," by W.J. Gaidry and C.J. White. Technical Bulletin No. 8, 154 p. 1973.

170. Lynch, M. P. and L. Wood. "Effects of Environmental Salinity on Free Amino Acids of Crassostrea virginica." Comp. Biochem. Physiol., Vol. 19, pp. 783-790. 1966.

171. Mackenzie, C. L., Jr. "Development of an Aquacultural Program for Rehabilitation of Damaged Oyster Reefs in Mississippii." Mar. Fish. Rev., Vol. 39, pp. 1-33. 1977.

172. Mansueti, R. J. "Restriction of Very Young Red Drum, Sciaenops ocellata, to Shallow Estuarine Water of Chesapeake Bay during Late Autumn." Chesapeake Sci., Vol. 1, pp. 207-210. 1960.

173. Masch, Frank D., and Associates. "Tidal Hydrodynamic and Salinity Models for San Antonio & Matagorda Bays, Texas." 130 p. Report to the Texas Water Development Board. 1971. [333.9/M37T]

174. Masch, Frank D., and Associates. "Tidal Hydrodynamic and Salinity Models for Coastal Bays, Evaporation Considerations," by R. J. Brandes and F. D. Masch. Report to the Texas Water Development Board. 40 p. Austin, Texas. 1972.

175. May, R. C. "Larval Mortality in Marine Fishes and the Critical Period Concept." In: The Early Life History of Fish, edited by J. H. S. Blaxter, pp. 3-19. Springer-Verlag, New York. 1974.

176. McCombie, A. M. "Factors Influencing the Growth of Phytoplankton." J. Fish. Res. Bd. Car., Vol. 10, pp. 253-282. 1953.

177. McFarland, W. N and B. D. Lee. "Osmotic and Ionic Concentrations of Penaeidean Shrimps of the Texas Coast." Bulletin Marine Science, Gulf Carib., Vol. 13, pp. 391-417. 1963.

178. McHugh, J. L. "Estuarine Fisheries: Are they doomed?" In: Estuarine Processes, edited by M. Wiley, Vol. 1, pp. 15-27. Academic Press, New York. 1976.

179. McHugh, J. L. "Estuarine Nekton." In: Estuaries. edited by G. H. Lauff, pp. 581-620. Amer. Assoc. Advmt. Sci., Publ. No. 83. Wash., D. C. 1967.

180. McHugh, J. L. "Management of Estuarine Fisheries." In: A Symposium on Estuarine Fisheries, edited by R. F. Smith, pp. 133-154. Amer. Fish. Soc., Special Publication No. 3. 1966.

181. McRoy, C. P. and C. McMillan. "Production Ecology and Physiology of Seagrasses." In: Seagrass Ecosystems, edited by C. P. McRoy and C. Hellferich, pp. 53-87. Marcel Dekker, Inc., New York. 1977.

182. Meinzer, O. E. Hydrology. Dover Publication, Inc., New York. 1942.

183. Moseley, F. N. and B. J. Copeland. "Brine Pollution System." In: Coastal Ecological System of the United States. Vol. III, pp. 342-352. The Conservation Foundation, Washington, D.C. 1974.

184. National Field Investigations Center. "Report on Pollution Affecting Shellfish Harvesting in Galveston Bay, Texas." 218 p. NFIC, Denver, Colorado. 1971.

185. Nestler, J. "Interstitial Salinity as a Cause of Ecophenic Variation in Spartina alterniflora." Estuarine and Coastal Marine Science, Vol. 5, pp. 707-714. 1977.

186. North Carolina State University, Pamlico Marine Lab. "Some Environmental Limits of Six Important Galveston Bay Species," by B. J. Copeland and T. J. Bechtel, 108 p. Their Contribution No. 20. Report to Galveston Bay Study Program, Texas Water Quality Board. 1971. [574.92/N81S]

187. Odum, E. P. "Fundamentals of Ecology" (3rd Edition). W. B. Saunders Co., Philadelphia. 574 p. 1971.

188. Odum, E. P. "Halophytes, Energetics and Ecosystems." In: Ecology of Halophytes, edited by R. J. Reimold and W. H. Queen, pp. 599-602. Academic Press, N. Y. 1974.

189. Odum, E. P. and A. A. de la Cruz. "Particulate Organic Detritus in a Georgia Salt Marsh-Estuarine Ecosystem." In: Estuaries, American Association for the Advancement of Science, Publication No. 83. Washington, D. C. 1967.

190. Odum, H. T. "Biological Circuits and the Marine Systems of Texas." In: Pollution and Marine Ecology, edited by T. A. Olson and F. J. Burgess, pp. 99-157. J. Wiley Interscience, New York. 1967.

191. Odum, H. T. Environment, Power, and Society. Wiley Interscience, New York. 1971.

192. Odum, H. T. "Factors Controlling Marine Invasion into Florida Freshwater." Bull. Mar. Sci. Gulf and Carribean, Vol. 3, pp. 134-156. 1953.

193. Odum, W. E. "Insidious Alteration of the Estuarine Environment." Trans. Amer. Fish. Soc., Vol. 99, pp. 836-847. 1970.

194. Oppenheimer, C. H. and B. Brogden. "The Ecology of a Texas Bay." In: Harvesting Polluted Waters, edited by O. Devik, pp. 237-279. Plenum Press, New York. 1974.

195. Orlob, G. T. "Impact of Upstream Storage and Diversions on Salinity Balance in Estuaries." In: Estuarine Processes, edited by M. Wiley. Vol. 2, pp. 3-17. Academic Press, New York. 1977.

196. Overstreet, R. M. and R. W. Heard. "Food of the Red Drum, Sciaenops ocellata, from Mississippi Sound." Gulf Res. Rep., Vol. 6, pp. 131-135. 1978.

197. Overstreet, R. M. "Marine Maladies: Worms, Germs, and other Symbionts from the Northern Gulf of Mexico." Mississippi-Alabama Sea Grant Consortium, MASGP-78-021. 140 p. 1978.

198. Palmisano, A. W. "The Effect of Salinity on the Germination and Growth of Plants Important to Wildlife in Gulf Coast Marshes." Proc. Southeast Assoc. Fish Game Comm., Vol. 25, pp. 215-228. 1972.

199. Parker, R. H. "Changes in the Invertebrate Fauna, Apparently Attributable to Salinity Changes, in the Bays of Central Texas." J. Paleont., Vol. 29, pp. 193-211. 1955.

200. Perkins, E. J. "The Biology of Estuaries and Coastal Waters." Academic Press, New York. 1974.

201. Peters, D. S. and M. A. Kjelson. "Consumption and Utilization of Food by Various Post Larval and Juvenile Fishes of North Carolina Estuaries." In: Estuarine Research, edited by L. E. Cronin, Vol. 1, pp. 448-472. Academic Press, New York, 738 p. 1975.

202. Pettitt, J. M. and R. H. Dutton. "Limnological Theses and Dissertations Concerning Texas Waters, 1897-1976." Tex. J. Sci., Vol. 28, pp. 295-338. 1977.

203. Phleger, C. F. "Effect of Salinity on Growth of Salt Marsh Grass." Ecology, Vol. 52, pp. 908-911. 1971.

204. Pomeroy, L. R., et al. "Nutrient Flux in Estuaries." In: Nutrients and E Eutrophication: The Limiting-Nutrient Controversy. Special Symposium, Vol. 1, pp. 274-291. American Society of Limnology and Oceanography. 1972.

205. Price, W. A. "Dynamic Environments: Reconnaissance Mapping, Geologic and Geomorphic of Continental Shelf of Gulf of Mexico." Gulf Coast Assoc. Geol. Socs. Trans., Vol. 4, pp. 75-107. 1954.

206. Reid, G. K., Jr. "Ecological Investigations in a Disturbed Texas Coastal Estuary." Texas. Jour. Sci., Vol. 8, pp. 296-327. 1956.

207. Reid, G. K. and R. D. Wood. "Ecology of Inland Waters and Estuaries." D. Van Nostrand Co., New York. 485 p. 1976.

208. Reid, G. K., et al. "Summer Foods of Some Fish Species in East Bay, Texas." Southwest Natl., Vol. 1, pp. 100-104. 1956

209. Reid, G. K., Jr. "A Summary Study of the Biology and Ecology of East Bay, Texas. Part II: The Fish Fauna of East Bay, the Gulf Beach and Summary." Tex. Jour. Sci., Vol. 7, pp. 420-453. 1955.

210. Reimold, R. J. "The Movement of Phosphorus through the Salt Marsh Cord Grass, Spartina alterniflora Loisel." Limnol. Oceanogr., Vol. 17, No. 4, pp. 606-611. 1972.

211. Reimold, R. J., et al. "Detritus Production in Coastal Georgia Salt Marshes." In: Estuarine Research, edited by L. E. Cronin, Vol. 1, pp. 217-228. Academic Press, New York, 738 p. 1975.

212. Remane, A. "Die Brackwasserfauna." Verh. dt. zool. Ges., Vol. 36, pp. 34-74. 1934.

213. Renfro, W. C. "Survival and Migration of Freshwater Fishes in Salt Water." Tex. J. Sci., Vol. 11, pp. 772-780. 1959.

214. Rice University, Rice Center for Community Design and Research. "Export of Food Materials from Marshes to Bays, Chambers County," by R. B. Borey, P. A. Harcombe and F. M. Fisher. In: Environmental Analysis for Development Planning, Chambers County, Texas. Technical Report Vol. 7, Environmental Analysis Case Study Applications and Selected Technical Papers. pp. 152-164. 1976.

215. Ricker, W. E. "Computation and Interpretation of Biological Statistics of Fish Populations." Fish. Res. Bd. Canada, Bulletin No. 191. 382 p. 1975.

216. Ricker, W. E. "Linear Regressions in Fishery Research." J. Fish. Res. Bd. Canada, Vol. 30, No. 3, pp. 409-434. 1973.

217. Rose, C. D. and E. Heath. "Viability of American oyster, Crassostrea virginica, Spermatozoa Exposed to Stress." Estuaries, Vol. 1, pp. 245-251. 1978.

218. Rounsefell, G. A. "Ecology, Utilization, and Management of Marine Fishes." The C. V. Mosby Co., St. Louis. 516 p. 1975.

219. Ryther, J. H. "The Measurement of Primary Production." Limnol. and Oceanogr., Vol. 1, pp. 72-84. 1956.

220. Ryther, J. H. and W. M. Dunstan. "Nitrogen, Phosphorus and Eutrophication in the Coastal Marine Environment. Science, Vol. 171, pp. 1008-1013. 1971.

221. Sabins, D. S. and F. M. Truesdale. "Diel and Seasonal Occurrence of Immature Fishes in a Louisiana Tidal Pass." In: Proc. 28th Ann. Conf. Southeastern Assoc. Game Fish Comm., pp. 161-171. 1974.

222. Saila, S. B. "Some Aspects of Fish Production and Cropping in Estuarine Systems." In: Estuarine Research, edited by L. E. Cronin, Vol. 1, pp. 473-493. 1975.

223. Sandoz, M. and R. Rogers. "The Effect of Environmental Factors on Hatching, Molting, and Survival of Zoea Lavae of Blue Crab, Callinectes sapidus Rathbun." Ecology, Vol. 25, pp. 216-218. 1944.

224. San Jacinto River Conservation & Reclamation District. "Proposal and Plan to Furnish Fresh Water to the Houston Ship Channel, Texas City & Galveston Areas." 14 p. [627./SA5P]

225. Settlemyer, J. L., et al. "A Field Study of Chemical Budgets for a Small Tidal Creek — Charleston Harbor, S.C." In: Marine Chemistry in the Coastal Environment. ACS Symposium Series No. 18. 1975.

226. Sheltema, R. S. "Relationship of Larval Dispersal, Gene-flow and Natural Selection to Geographic Variation of Benthic Invertebrates in Estuaries and Along Coastal Regions." In: Estuarine Research, edited by L. E. Cronin, Vol. 1, pp. 372-391. Academic Press, New York. 1975.

227. Shepard, F. P. "Submarine Geology." Harper and Row, New York. 517 p. 1973.

228. Smart, R. M. and J. W. Barko. "Influence of Sediment Salinity and Nutrients on the Physiological Ecology of Selected Salt Marsh Plants." Estuarine and Coastal Marine Science, Vol. 7, pp. 487-495. 1978.

229. Smith, R. V. and D. A. Stewart. "Statistical Models of River Loadings of Nitrogen and Phosphorus in the Lough Neagh System." Water Research, Vol. 11, No. 8, pp. 631-636. 1977.

230. Sport Fishing Institute. "Estuarine Productivity Source." Sport Fishing Institute Bulletin, Vol. 293, pp. 7-8. April 1978.

231. St. Amant, L. S., J. G. Broom and T. B. Ford. "Studies of the Brown Shrimp, Penaeus aztecus, in Barataria Bay, Louisiana, 1962-1965." Proc. Gulf Carib. Fish. Inst., 18th Ann. Sess., Nov. 1965, 17 p. 1966.

232. Steed, David Lewis. "Some Aspects of Organic Transport in Guadalupe - San Antonio Estuary." Ph. D. Dissertation, U. of Texas at Austin, 85 p. Austin, Texas. 1971. [574.92,ST3C]

233. Stein, J. E. and J. G. Denison. "Limitations of Indicator Organisms." In: Pollution and Marine Ecology, edited by T. A. Olson and F. J. Burgess, pp. 323-335. J. Wiley Interscience, New York. 1976.

234. Stevenson, L. H. and C. W. Erkenbrecker. "Activity of Bacteria in the Estuarine Environment. In: Estuarine Processes, edited by M. Wiley, Vol. 1, pp. 381-394. Academic Press, New York, 541 p. 1976.

235. Stevenson, J. C., et al. "Nutrient Exchange between Brackish Water and the Estuary." In: Proceedings of the Third Biennial International Estuarine Research Conference. Galveston, Texas. 1976.

236. Strickland, J. D. H. "Measuring the Production of Marine Phytoplankton." Fish. Res. Bd. of Canada. Bulletin No. 122, 172 p. 1960.

237. Sutcliffe, W. H., Jr. "Correlations Between Seasonal River Discharge and Local Landings of American Lobster (Homarus americanus) an Atlantic Halibut (Hippoglossus hippoglossus) in the Gulf of St. Lawrence." J. Fish. Res. Bd. Canada, Vol. 30, pp. 856-859. 1973.

238. Sutcliffe, W. H., Jr. "Some Relations of Land Drainage, Nutrients, Particulate Material, and Fish Catch in Two Eastern Canadian Bays." J. Fish. Res. Bd. Canada, Vol. 29, pp. 357-362. 1972.

239. Tabb, D. C. "The Estuary as a Habitat for Spotted Seatrout, Cynoscion nebulosus." In: A Symposium on Estuarine Fisheries, edited by R. F. Smith. Amer. Fish. Soc., Spec. Publ. No. 3, pp. 59-67. 1966.

240. Teal, J. M. "Energy Flow in the Salt Marsh Ecosystems in Georgia." Ecology, Vol. 43, pp. 614-624. 1962.

241. Tent, W. L., et al. "Waterfront Housing Developments: Their Effect on the Ecology of a Texas Estuarine Area." Marine Pollution and Sea Life, pp. 1-7. Dec. 1972.

242. Tett, P. and J. C. Cottrell. "Phosphorus Quota and the Chlorophyll: Carbon Ratio in Marine Phytoplankton." Limnology and Oceanography, Vol. 20, No. 4, pp. 587-603. 1975.

243. Texas A&M University. "The Brackish Water Clam Rangia cuneata as Indicator of Ecological Effects of Salinity Changes in Coastal Waters," by S. H. Hopkins et al. Research Foundation Contract Report H-73-1 to U. S. Army Engineer Waterways Experiment Station, Vicksburg. 250 p. 1973.

244. Texas A&M University. "Distribution of Aquatic Macro-Fauna in a Marsh on West Galveston Bay, Texas and Possible Effects Thereon Resulting from Impoundment for Shrimp Culture," by J. C. Parker et al, 32 p. Sea Grant Publ. 71-208. 1971. [333.916/T31C/71-208]

245. Texas A&M University. "The Distribution of Benthic and Nektonic Organisms in Undredged Control Areas of San Antonio Bay," by D. E. Harper, Jr. In: Environmental Impact Assessment of Shell Dredging in San Antonio Bay, Texas, Vol. 3, pp. 1-157. Res. Found. Rept. for U. S. Army Engineers District, Galveston, Texas. 1973.

246. Texas A&M University. "Ecological Aspects of Selected Crustacea of two Marsh Embayments of the Texas Coast," by F. S. Conte and J. C. Parker. Sea Grant Publ. 71-211, 184 p. 1971.

247. Texas A&M University. "Effect of Temperature and Salinity on Growth, Food Conversion, Survival, and Temperature Resistance of Juvenile Blue Crabs, Callinectes sapidus Rathbun," by J.S. Holland et al. Sea Grant Publ. 71-222, 166 p. 1971.

248. Texas A&M University. "Field Study of an Unconfined Spoil Disposal Area of the Gulf Intracoastal Waterways in Galveston Bay, Texas," by D. E. Bassi et al, 74 p. Sea Grant Publ. 74-208. Coastal and Ocean Engineering Report No. 174. 1974. [333.916/T31C/208]

249. Texas A&M University. "The Galveston Bay Work Plan." 2 Vols. For the Development of a Comprehensive Water Quality Management Program for Galveston Bay and Its Tributaries. 1966. [628.168/T31GA]

250. Texas A&M University. "Resource Evaluation Studies of the Matagorda Bay Area, Texas," by W. M. Ahr et al. Sea Grant Publ. 74-204. 1973.

251. Texas A&M University. "Salinity Preference of Post Larval Brown and White Shrimp (Penaeus aztecus and P. setiferus) in Gradient Tanks," by R. K. Keiser, Jr. and D. V. Aldrich. Sea Grant Publ. 75-208. 260 p. 1976.

252. Texas A&M University. "Sciaenid Stocks of the Western Central Atlantic Between Chesapeake Bay, Virginia and the Amazon River, Brazil," by E. J. Gutherz and P. A. Thompson, Jr. In: Proceedings Second Annual Tropical and Subtropical Fish. Tech. Conf. of the Americas. Sea Grant Publ. 78-101, pp. 1-13. 1977.

253. Texas A&M University. "A Study of the Effect of Oil Field Brine Effluent on Biotic Communities in Texas Estuaries," by J. G. Mackin. 73 p. TAMU Research Foundation Project 735. 1971.

254. Texas A&M University. "A Study of the Effect of Salinity Variation on Dermocystidium Infection in Oysters," by J. G. Mackin and T. L. Boswell. Res. Found. Tech. Rept. No. 5. 1953.

255. Texas A&M University. "A Study of Selected Chemical and Biological Conditions of the Lower Trinity River and Upper Trinity Bay," by R. J. Baldauf et al. 168 p. Tech. Rept. No. 26, Water Resources Institute. 1970.

256. Texas A&M University. "Thermal Resistance and Acclimation Rate in young White and Brown Shrimp, Penaeus setiferus Linn. and Penaeus aztecus Ives," by L. M. Wiesepape. Sea Grant Publ. 76-202, 196 p. 1975.

257. Texas A&M University, Environmental Engineering Division. "Sediment Analysis -- Galveston Bay," by R. W. Hann et al. Their Estuarine System Project Technical Report No. 24. Prepared for Galveston Bay Project, Texas Water Quality Board. 1972. [627.124/T31TR/24]

258. Texas A&M University, Remote Sensing Center. "Monitoring and Mapping of Texas Coastal Wetlands, Galveston Bay and Sabine Lake Areas, 1978 Growing Season," by A. R. Benton, Jr. et al. Technical Report to Texas Department of Water Resource. 1979.

259. Texas A&M University, Remote Sensing Center. "Monitoring of Texas Coastal Wetlands," by A.R. Benton, Jr. et al. Technical Report RSC-88, v.p. 1977.

260. Texas A&M University, Remote Sensing Center. "Monitoring of Texas Coastal Wetlands with Aerial Photograph: Phase I, Feasibility Study," by A. R. Benton, Jr. et al. Technical Report RSC-64, 34 p. and appendices. 1975.

261. Texas A&M University, Water Resources Institute. "A Study of Selected Chemical and Biological Conditions of the Lower Trinity River." 168 p. Their Report No. 26. 1970. [333.912/T31TR/26]

262. Texas Board of Water Engineers. "Inventory and Use of Sedimentation Data in Texas." Bull. 5912, 85 p. Austin, Texas. 1959.

263. Texas Department of Agriculture and the U.S. Department of Agriculture "1977 Texas County Statistics." Texas Crop and Livestock Report Service.

264. Texas Department of Water Resources. "Chapter V, Fisheries," by G. L. Powell. In: Hydrological and Biological Studies of the Trinity River Delta, Texas. LP-70, pp. V1-V29. 1978.

265. Texas Department of Water Resources. "Earnings Projections for Texas Counties (1960-2030)." Economics, Water Requirements and Uses Section, Economics Unit. December 1976.

266. Texas Department of Water Resources. "Employment Projections for Texas Counties (1960-2030)." Economics, Water Requirements and Uses Section, Economics Unit. December 1976.

267. Texas Department of Water Resources. "Hydrological and Biological Studies of the Colorado River Delta, Texas." LP-79, 73 p. Austin, Texas. 1978.

268. Texas Department of Water Resources. "Hydrological and Biological Studies of the Trinity River Delta, Texas." In cooperation with Espey, Huston & Associates, Inc. and Civil Engineering Department, University of Texas at Austin. LP-70. 1978. [551.45/T31H]

269. Texas Department of Water Resources. "Land Use/Land Cover Maps of Texas." LP-62, 47 p. 1977.

270. Texas Department of Water Resources. "Mathematical Simulation Capabilities in Water Resources Systems Analysis." LP-16, 62 p. Austin, Texas. 1978.

271. Texas Department of Water Resources. "Personal Income Projections for Texas Counties (1970-2030)." Economics, Water Requirements and Uses Section, Economic Unit. April 1979.

272. Texas Department of Water Resources. "Population Projections for Texas Counties (1975-2030)." Economics, Water Requirements and Uses Section, Economics Unit. December 1978.

273. Texas Department of Water Resources. "Suspended-Sediment Load of Texas Streams." Report 233, v.p. May 1979.

274. Texas Department of Water Resources. "Suspended-Sediment Load of Texas Streams, Compilation Report October 1965 - September 1971." Report 184. 1974.

275. Texas Department of Water Resources. "Techniques for Evaluating the Effects of Water Resources Development on Estuarine Environments." LP-75, 134 p. and appendices. Austin, Texas. 1978 (work completed August 1974).

276. Texas Department of Water Resources. "Texas Input-Output Model, 1972." Planning and Development Division. LP-24. February 1978.

277. Texas Department of Water Resources. Unpublished data, 1977-1979.

278. Texas Game and Fish Commission, Marine Fisheries Division. "Basic Ecological Survey of Area M-2: Check List of the Flora," by W. C. Renfro. Project M-2-R-1, Job Report No. C-2, 5 p. 1959.

279. Texas Game and Fish Commission, Marine Fisheries Division. "An Ecological Survey of Upper Galveston and Trinity Bays: A Study of the Marsh and Marine Plants," by E. J. Pullen. Project M-2-R-3, Job Report No. C-2, 6 p. 1962.

280. Texas Game, Fish and Oyster Commission. "The Life Histories of the Seatrout, Cynoscion nebulosus, and the Redfish, Sciaenops ocellata," by D. W. Miles. Ann. Rept. Mar. Lab., 1949-1950. 1950.

281. Texas Game, Fish and Oyster Commission. "The Life Histories of the Seatrout, Cynoscion nebulosus, and the Redfish, Sciaenops ocellata: Sexual Development," by D. W. Miles. Ann. Rept. Mar. Lab., 1950-1951. 1951.

282. Texas General Land Office. "Texas Coastal Management Program Social and Economic Component User's Manual. September 1978.

283. Texas Highway Department. "Texas Visitor Industry, 1975."

284. Texas Parks and Wildlife. "Coastal Fisheries Plan, 1977-1978." 31 p. 1977.

285. Texas Parks and Wildlife Department. "A Contribution to the Biology of the Blue Crab (Callinectes sapidus Rathbun) in Texas, with a Description of the Fishery," by W. R. More. Technical Series No. 1, 31 p. 1969.

286. Texas Parks and Wildlife Department. "The Crabs of Texas," by S. P. Leary. Bulletin No. 43 (revised 1964), 57 p. 1961.

287. Texas Parks and Wildlife Department. "A Study of Blue Crab Population of the Upper Laguna Madre," by W. Hawley. Coastal Fish. Proj. Repts. (mimeo), pp. 577-581. 1963.

288. Texas Parks and Wildlife Department. "Ecological Changes Associated with the Industrialization of Cedar Bayou and Trinity Bay, Texas," by R. B. Johnson. 79 p. Technical Series No. 16. 1974.

289. Texas Parks and Wildlife Department. "Inventory of Aquatic Vegetation," by R. L. West. Job No. 20, Progress Rept., Coastal Waterfowl Project. 6 p. 1972.

290. Texas Parks and Wildlife Department. "Life History Studies of Flounder in Aransas Bay," by G. M. Stokes. Annual Report, Coastal Fisheries Division, 18 p. 1974.

291. Texas Parks and Wildlife Department. "A Plankton and Benthos Survey of the San Antonio Bay System, March 1972 - July 1974," by G. A. Matthews et al. Technical Report to the Texas Water Development Board. 1975.

292. Texas Parks and Wildlife Department. "Shell Dredging Sedimentation in Galveston and San Antonio Bays, 1964-1969," by R. L. Benefield. Technical Series No. 19, 34 p. 1976.

293. Texas Parks and Wildlife Department. "A Study of the Effects of Freshwater on the Plankton, Benthos, and Nekton Assemblages of the Lavaca Bay System, Texas," by G. Gilmore et al. Report to the Texas Water Development Board. 113 p. 1976.

294. Texas Parks and Wildlife Department. "Study of Migratory Patterns of Fish and Shellfish through a Natural Pass," by B. D. King. Technical Series No. 9. 54 p. 1971.

295. Texas Parks and Wildlife Department. "Survey of Finfish Harvest in Selected Texas Bays," by T. L. Heffernan et al, 115 p. 1976.

296. Texas Parks and Wildlife Department. "The Texas Oyster Fishery," by R. P. Hofstetter. Bulletin No. 40 (revised 1964). 36 p. 1959.

297. Texas Parks and Wildlife Department. "Texas Trailways: A Feasibility Report on a System of Trails in Texas," by R. Josselet and B. Evans. 85 p. 1975.

298. Texas Parks and Wildlife Department. "Texas Waterways: A Feasibility Report on a System of Wild, Scenic, and Recreational Waterways in Texas," by H. J. Belisle and R. Josselet. 64 p. 1973.

299. Texas Parks and Wildlife Department. "Trends in Finfish Abundance in Texas Estuaries as Indicated by Gill Nets," by G. C. Matlock and J. E. Weaver. Coastal Fisheries Branch Report, 271 p. 1978.

300. Texas Parks and Wildlife Department. "Trends in Population Levels of the American Oyster Crassostrea virginica Gmelin on Public Reefs in Galveston Bay, Texas," by R. P. Hofstetter. Technical Series No. 24, 90 p. 1977.

301. Texas Railroad Commission, Oil and Gas Division. "Annual Report." 1977.

302. Texas, University at Austin, Bureau of Economic Geology. "Environmental Geologic Atlas of the Texas Coastal Zone," by L. F. Brown, Jr. v.p. 1972-1976.

303. Texas, University at Austin, Bureau of Economic Geology. "Land and Water Resources: Houston-Galveston Area Council," by A. E. St. Clair et al. Land Resources Laboratory Map Series, 25 p. 1975.

304. Texas, University at Austin, Bureau of Economic Geology. "Sand Resources of the Texas Gulf Coast," by L. E. Garner. Report of Investigations 60, 85 p. 1967.

305. Texas, University at Austin, Bureau of Economic Geology. "Shoreline Changes on Galveston Island (Bolivar Roads to San Luis Pass): An Analysis of Historical Changes of the Texas Gulf Shoreline," by R. A. Morton. Geological Circular No. 74-2, 34 p. 1974.

306. Texas, University at Austin, Center for Research in Water Resources. "Biogeochemical Cycling of Carbon, Nitrogen and Phosphorus in Saltwater Marshes in Lavaca Bay, Texas," by N. E. Armstrong et al. CRWR-121, v.p. 1975.

307. Texas, University at Austin, Center for Research in Water Resources." Establishment of Operational Guidelines for Texas Coastal Zone Management; Final Report: Water Needs and Residuals Management," by J. S. Sherman and J. F. Malina, Jr. CRWR-112, v.p. 1974.

308. Texas, University at Austin, Center for Research in Water Resources. "Exchange Rates for Carbon, Nitrogen and Phosphorus in Colorado River Delta Marshes," by N. E. Armstrong and N. Gordon. CRWR-153, v.p. 1977.

309. Texas, University at Austin, Center for Research in Water Resources. "Exchange Rates for Carbon, Nitrogen and Phosphorus in Nueces and San Antonio Bay Marshes," by N. E. Armstrong and N. V. Gordon. CRWR-152, EHE77-05, v.p. and appendix. 1977.

310. Texas, University at Austin, Center for Research in Water Resources. "Exchange of Carbon, Nitrogen and Phosphorus in Lavaca Bay, Texas Marshes: Volume I - The Role of Sediments in Nutrient Exchange in the Lavaca Bay Brackish Marsh System," by N. E. Armstrong and B. A. Brown. CRWR-147, v.p. 1976.

311. Texas, University at Austin, Center for Research in Water Resources. "Exchange of Carbon, Nitrogen, and Phosphorus in Lavaca Bay, Texas Marshes: Volume II. The Role of Plants in Nutrient Exchange in the Lavaca Bay Brackish Marsh System," by A. J. Dawson and N. E. Armstrong. CRWR-129, 115 p. 1975.

312. Texas, University at Austin, Center for Research in Water Resources. "Exchange Rates for Carbon, Nitrogen and Phosphorus in the Trinity River Delta Marshes," by N. E. Armstrong et al. CRWR-154, v.p. 1977.

313. Texas, University at Austin, Center for Research in Water Resources. "Galveston Bay Water Quality Study - Historical and Recent Data," by E. F. Gloyna and J. F. Malina. Report to Texas Water Pollution Control Board. CRWR-1, 120 p. and nine appendices. 1964. [333.9/T31CRWR/1]

314. Texas, University at Austin, Center for Research in Water Resources. "General Consideration Prerequisite to Further Galveston Bay Shell Removal," by Hill and Masch. CRWR-48, 50 p. Texas University Hydraulic Engineering Lab, TEC Report HYD 15-6901. 1969. [333.9/T31CRWR/48]

315. Texas, University at Austin, Center for Research in Water Resources. "Methodology to Evaluate Alternate Coastal Zone Management Policies: Application in the Texas Coastal Zone, Special Report III: A Methodology for Investigating Freshwater Inflow Requirements of a Texas Estuary," by W. P. Lambert and E. G. Fruh. Vol. I (Methodology) and Vol. II (Appendices), 999 p. 1975.

316. Texas, University at Austin, Center for Research in Water Resources. "Shell Dredging, A Factor in Sedimentation in Galveston Bay," by F. D. Masch and W. H. Espey, Jr. CRWR-7, 168 p. Prepared for Texas Parks and Wildlife Department. HYD 06-6702. 1967. [333.9/ T31CRWR/7]

317. Texas, University at Austin, Center for Research in Water Resources. "Water Quantity for Preservation of Estuarine Ecology," by B. J. Copeland et al. In: Conflicts in Water Resources Planning, E. F. Gloyna and W. S. Butcher editors. Water Research Symposium No. 5, pp. 107-126. 1972.

318. Texas, University, Division of Natural Resources and Environment. "Establishment of Operational Guidelines for Texas Coastal Zone Management. Final Report on Biological Uses Criteria," by C. H. Oppenheimer et al. v.p. Report to the National Science Foundation and the Division of Planning Coordination, Office of the Governor of Texas. 1974. [333.917/T31CES/6]

319. Texas, University, Division of Natural Resources and Environment. "Establishment of Operational Guidelines for Texas Coastal Zone Management. Final Report on Estuarine Modeling," by G. W. Murfee et al. v.p. Report to the National Science Foundation and Division of Planning Coordination, Office of the Governor of Texas. 1974. [333.917/ T31CES/4]

320. Texas, University at Austin, Marine Science Institute at Port Aransas. "Analysis of Freshwater Inflow Effects on Metabolic Stresses of Fish in Corpus Christi, San Antonio, and Matagorda Bays," by D. E. Wohlschlag. Final Report to Texas Department of Water Resources. 97 p. 1976.

321. Texas, University at Austin, Marine Science Institute at Port Aransas. "Analysis of Freshwater Inflow Effects on Metabolic Stresses of South Texas Bay and Estuarine Fishes: Continuation and Extension," by D. E. Wohlschlag. Final Report to Texas Department of Water Resources. 114 p. 1977.

322. Texas, University at Austin, Marine Science Institute. "Analysis of Freshwater Inflow Effects on Metabolic Stresses of South Texas Bay and Estuarine Fishes: Rates of Adaptability to Changing Salinity - Temperature Regimes," by D. E. Wohlschlag. Final Report to Texas Department of Water Resources. 89 p. 1980.

323. Texas, University at Austin, Marine Science Institute. "Analysis of Freshwater Inflow Effects on Metabolic Stresses of South Texas Bay and Estuarine Fishes: Studies on Small Fishes," by D. E. Wohlschlag. Final Report to Texas Department of Water Resources. 92 p. 1979.

324. Texas, University at Austin, Marine Science Institute. "An Annotated Checklist of the Fishes of the Galveston Bay System, Texas," by J. C. Parker. Contributions in Marine Science, Vol. 10, pp. 201-220. 1965.

325. Texas, University, Marine Science Institute, Port Aransas. "A Benthos and Plankton Study of Corpus Christi, Copano, and Aransas Bay Systems. III: Report on Data Collected During the Project Period July 1974 - May 1975 and Summary of the Three-year Project," by J. S. Holland et al. Technical Report to the Texas Water Development Board. 1975.

326. Texas, University at Austin, Marine Science Institute. "Brackish Water and Marine Assemblages of the Texas Coast, with Special Reference to Mollusks," by H. S. Ladd. Contributions in Marine Science, Vol. 2, pp. 125-164. 1951.

327. Texas, University at Austin, Marine Science Institute. "A Catalogue and Bibliography to the Crabs (Brachyura) of the Gulf of Mexico," by L. W. Powers. Contribution in Marine Science, Vol. 20 (supplement), pp. 1-190. 1977.

328. Texas, University at Austin, Marine Science Institute. "Community Structure of Fishes and Macrocrustaceans in Ponds of a Louisiana Tidal Marsh Influenced by Wiers," by J. E. Weaver and L. F. Holloway. Contributions in Marine Science, Vol. 18, pp. 57-69. 1974.

329. Texas, University at Austin, Marine Science Institute. "Distribution of Juvenile Brown Shrimp (Penaeus aztecus Ives) in Galveston Bay, Texas, as Related to Certain Hydrographic Features and Salinity," by J. C. Parker. Contributions in Marine Science, Vol. 15, pp. 1-12. 1970.

330. Texas, University at Austin, Marine Science Institute. "Ecological Survey of Baffin and Alazan Bays, Texas," by J, P. Breuer. Contributions to Marine Science, Vol. 4, pp. 134-155. 1957.

331. Texas, University at Austin, Marine Science Institute. "An Ecological Survey of the Upper Laguna Madre of Texas," by E. P. Simmons. Contributions to Marine Science, Vol. 4, pp. 156-200. 1957.

332. Texas, University at Austin, Marine Science Institute. "Effect of Higher than Normal Salinities on Salt Marshes," by H. D. Hoese. Contributions to Marine Science, Vol. 12, pp. 249-261. 1967.

333. Texas, University at Austin, Marine Science Institute. "Fauna of the Arkansas Pass Inlet, Texas: Emigration as shown by Tide Trap Collections," by B. J. Copeland. Contributions in Marine Science, Vol. 10, pp. 9-21. 1965.

334. Texas, University at Austin, Marine Science Institute. "Fish Species Diversity Indices as Indicators of Pollution in Galveston Bay, Texas," by T. J. Bechtel and B. J. Copeland. Contributions in Marine Science, Vol. 15, pp. 103-132. 1970.

335. Texas, University at Austin, Marine Science Institute. "Galveston Bay Benthic Community Structure as an Indicator of Water Quality," by J. S. Holland et al. Contributions in Marine Science, Vol. 17, pp. 169-188. 1973.

336. Texas, University at Austin, Marine Science Institute. "Galveston Bay Ecosystem Freshwater Requirements and Phytoplankton Productivity," by N. E. Armstrong and M. O. Hinson, Jr. In: Toxicity Studies of Galveston Bay Project. pp. II-1 to II-97. Final Report to Texas Water Quality Board. 1973.

337. Texas, University at Austin, Marine Science Institute. "Galveston Bay Project Environmental Limits for Galveston Bay." Submitted to Texas Water Quality Board. 1975. [628.168/T31GE]

338. Texas, University at Austin, Marine Science Institute. "Geographic Variations in Salt Marsh Macrophyte Production: A Review," by R. E. Turner. Contributions in Marine Science, Vol. 20, pp. 47-68. 1976.

339. Texas, University at Austin, Marine Science Institute. "Growth and Mortality of the American Oyster *Crassostrea virginica* in High Salinity Shallow Bays in Central Texas," by B. J. Copeland and H. D. Hoese. Contributions in Marine Science, Vol. 11, pp. 149-158. 1966.

340. Texas, University at Austin, Marine Science Institute. "Helicopter-Borne Purse Net for Population Sampling of Shallow Marine Bays," by R. S. Jones et al. Contributions in Marine Science. Vol. 9, pp. 1-6. 1963.

341. Texas, University at Austin, Marine Science Institute. "An Introduction to Tidal Waters of Texas," by A. Collier and J. W. Hedgpeth. Contributions in Marine Science, Vol. 1, pp. 125-194. 1950.

342. Texas, University at Austin, Marine Science Institute. "An Introduction to Zoogeography of the Northwestern Gulf of Mexico with Reference to the Invertebrate Fauna," by J. W. Hedgpeth. Contributions in Marine Science, Vol. 3, pp. 107-224. 1953.

343. Texas, University at Austin, Marine Science Institute. "Marsh Production: A Summary of the Literature," by C. S. Keefe. Contributions in Marine Science, Vol. 16, pp. 163-181. 1972.

344. Texas, University at Austin, Marine Science Institute at Port Aransas. "Nearshore Surface Currents, Southeastern Texas Gulf Coast," by R. L. Watson et al. Contributions in Marine Science, Vol. 15, pp. 133-143. 1970.

345. Texas, University at Austin, Marine Science Institute. "A Note on the Standing Crops of Spartina alterniflora in Texas and Florida," by R. E. Turner and J. G. Goesselink. Contributions in Marine Science, Vol. 19, pp. 113-119. 1975.

346. Texas, University at Austin, Marine Science Institute. "Observations on the Hydrology and Marine Organisms of the Tidal Colorado River and Adjacent Waters, Texas, February - June 1962," by R. A. Diener. Contributions in Marine Science, Vol. 17, pp. 99-110. 1973.

347. Texas, University at Austin, Marine Science Institute. "Observation on Spawning and Larval History of the Shrimp, Penaeus setiferus," by P. E. Heegaard. Contributions in Marine Science, Vol. 3, pp. 73-105. 1953.

348. Texas, University at Austin, Marine Science Institute. "Oyster Disease Caused by Dermocystidium marinum and other Microorganisms in Louisiana," by J. G. Mackin. Contributions to Marine Science, Vol. 7, 132 p. 1961.

349. Texas, University at Austin, Marine Science Institute. "The Relationship of the Bonnet Carre Spillway to Oyster Beds in Mississippi Sound and the 'Louisiana Marsh' with a Report on the 1950 Opening," by G. Gunter. Contributions in Marine Science, Vol. 3, No. 1, pp. 17-71. 1953.

350. Texas, University at Austin, Marine Science Institute. "Respiratory Metabolism of the Striped Mullet as an Assay of Low Level Stresses in Galveston Bay," by D. E. Wohlschlag. In: Toxicity Studies of Galveston Bay Project. pp. IV-1 to IV-37. Final report to Texas Water Quality Board. 1973.

351. Texas, University at Austin, Marine Science Institute. "Salinity Stresses, Metabolic Responses and Distribution of the Coastal Spotted Seatrout, Cynoscion nebulosus," by D. E. Wohlschlag and J. M. Wakeman. Contributions in Marine Science, Vol. 21, pp. 171-185. 1978.

352. Texas, University at Austin, Marine Science Institute. "Seasonal Abundance and Distribution of Marine Fishes at a Hot-water Discharge in Galveston Bay, Texas," by B. J. Gallaway and K. Strawn. Contributions in Marine Science. Vol. 18, pp. 71-137. 1974.

353. Texas, University at Austin, Marine Science Institute. "Seasonal Changes in the Respiratory Metabolism of the Pinfish (Lagodon rhomboides)," by

D. E. Wohlschlag et al. Contributions in Marine Science, Vol. 13, pp. 89-104. 1968.

354. Texas, University at Austin, Marine Science Institute. "Seasonal Population Changes and Distributions as Related to Salinity, of Certain Invertebrates of the Texas Coast, including the Commercial Shrimp," by G. Gunter. Contributions in Marine Science, Vol. 1, pp. 7-51. 1950.

355. Texas, University at Austin, Marine Science Institute. "Seasonality of Larger Animals in a Texas Turtle Grass Community," by H. D. Hoese and R. S. Jones. Contributions in Marine Science. Vol. 9, pp. 37-47. 1963.

356. Texas, University at Austin, Marine Science Institute. "Shrimp Landings and Production of the State of Texas for the Period 1956-1959, With a Comparison With Other Gulf States," by G. Gunter. Contributions in Marine Science, Vol. 8, pp. 216-226. 1962.

357. Texas, University at Austin, Marine Science Institute. "Size-related Metabolic Responses of the Pinfish, Lagodon rhomoboides, to Salinity Variations and Sublethal Petrochemical Pollution," by T. C. Kloth and D. E. Wohlschlag. Contributions in Marine Science, Vol. 16, pp. 126-137. 1972.

358. Texas, University at Austin, Marine Science Institute. "Some Environmental Limits of Six Gulf Coast Estuarine Organisms," by B. J. Copeland and T. J. Bechtel. Contributions in Marine Science, Vol. 18, pp. 169-204. 1974.

359. Texas, University at Austin, Marine Science Institute. "Some Observations on the Respiration of the American Oyster Crassostrea virginica (Gmelin)," by A. Collier. Contributions in Marine Science, Vol. 6, pp. 92-108. 1959.

360. Texas, University at Austin, Marine Science Institute. "Some Principles of Marine Fishery Biology," by D. Burkenroad. Contributions in Marine Science, Vol. 2, pp. 177-212. 1951.

361. Texas, University at Austin, Marine Science Institute. "Stomach Contents of Fishes from Clear Lake and Tributary Water, a Texas Estuarine Area," by R. A Diener et al. Contributions in Marine Science, Vol. 18, pp. 7-17. 1974.

362. Texas, University at Austin, Marine Science Institute. "Studies on the Hydrography and Fish Migration of Cedar Bayou, a Natural Tidal Inlet on the Central Texas Coast," by E. G. Simmons and H. D. Hoese. Contributions in Marine Science, Vol. 6, pp. 56-80. 1959.

363. Texas, University at Austin, Marine Science Institute. "Studies on Marine Fishes of Texas," by G. Gunter. Contributions in Marine Science, Vol. 1, pp. 1-190. 1945.

364. Texas, University at Austin, Marine Science Institute. "A Study of Red Fish, Sciaenops ocellata Linnaeus, and Black Drum, Pogonias cromis Linnaeus," by E. G. Simmons and J. P. Breuer. Contributions in Marine Science, Vol. 8, pp. 184-211. 1962.

365. Texas, University at Austin, Marine Science Institute. "Summer Growth Depression in the Stripped Mullet, Mugil cephalus," by J. J. Cech, Jr. and D. E. Wohlschlag. Contributions in Marine Science, Vol. 19, pp. 91-100. 1975.

366. Texas, University at Austin, Marine Science Institute. "Toxicity Studies of Galveston Bay Project. September 1, 1971 to December 1, 1972." Final Report to Texas Water Quality Board. 1973. [628.168/T31GT]

367. Texas, University at Austin, Marine Science Institute. "Vertical Distribution of the Planktonic Stage Shrimp in the Northwestern Gulf," by R. Temple and C. Fischer. Contributions in Marine Science, Vol. 10, pp. 59-67. 1965.

368. Texas, University at Houston, Institute of Environmental Health. "An Investigation of Tertiary Estuary Productivity and Nutrient Optimization in Texas Coastal Water," by E. M. Davis et al. IAC-71-73-909. Report to the Texas Water Development Board. 355 p. 1973.

369. Texas, University at Houston, Sc. of Public Health. "A Preliminary Investigation of the Nutrient Requirements of Four Texas Bay Systems," by G. F. Smith. In: Assessment of the Primary Ecological Interactions in Four Texas Estuarine Systems. Report to the Texas Water Development Board. Houston, Texas. 1973.

370. Texas Water Development Board. "Archeological Resources in the Texas Coastal Lowlands and Littoral," by A. K. Briggs. 46 p. 1971. [913/T31AC]

371. Texas Water Development Board. "Chemical and Physical Characteristics of Water in Estuaries of Texas, October 1969 - September 1970." TWDB Rept. 171, 123 p. 1973.

372. Texas Water Development Board. "Coastal Data System User Documentation; Vol. I - Storage Reference Manual; Vol. II - Retrieval Reference Manual." 1973 (revised 1977).

373. Texas Water Development Board. "Continuing Water Resources Planning and Development for Texas," 2 Vols. v.p. Austin, Texas. 1977.

374. Texas Water Development Board. "Estimated Monthly Runoff System WD8900: User Reference Manual." 104 p. Austin, Texas. 1976.

375. Texas Water Development Board. "Galveston Bay Inflow Study." Prepared for Texas Water Quality Board. 1973. [574.526/T318G]

376. Texas Water Development Board. "Inventories of Irrigation in Texas 1958, 1964, 1969 and 1974." Report 196, 265 p. Austin, Texas. 1975.

377. Texas Water Development Board. "Monthly Reservoir Evaporation Rates for Texas, 1940 through 1976." Report 64 (updated). 111 p. Austin, Texas. 1967.

378. Texas Water Development Board. "1975 National Water Assessment. Texas Gulf Region. Technical Memorandum Activity 2, Phase II." 234 p. 1977.

379. Texas Water Development Board. "Rice Irrigation Return-flow Study" 135 p. Austin, Texas 1974.

380. Texas Water Quality Board. "Comprehensive Water Pollution Control Planning for the Galveston Bay Study." Unpublished. 1970. [628.168/T31G]

381. Texas Water Quality Board. "Ecological Studies of Galveston Bay, 1969," by B. J. Copeland and E. G. Fruh. Final Report to Texas Water Quality Board. 482 p. 1970. [628.168/T31EC]

382. Texas Water Quality Board. "Galveston Bay Project Progress and Expenditures Report for First Project Year Ending December 13, 1971." Submitted to Environmental Protection Agency. 64 p. 1972. [628.168/T31GPR]

383. Texas Water Quality Board. "Galveston Bay Project, Summary Report," by J. J. Beal. 99 p. 1975. [628.168/T31GP]

384. Texas Water Quality Board. "Texas Water Quality Standards." 79 p. Austin, Texas: February 1976.

385. Texas Water Quality Board. "Water Quality Segment Report for Segment Nos. 2431, Moses Lake," by S. Warshaw. Report No. WQS-22. 33 p. 1976. [628.168/T31WQS/22]

386. Theede, H. "Aspects of Individual Adaptation to Salinity in Marine Invertebrates." In: Physiological Ecology of Estuarine Organisms, edited by F. J. Vernberg. pp. 213-225. Univ. South Carolina Press, Columbia. 1975.

387. Thiessen, A. H. "Precipitation for Large Areas." Monthly Weather Rev., Vol. 39, pp. 1082-1084. July 1911.

388. Thorson, G. "Reproduction and Larval Development of Marine Bottom Invertebrates." Biol. Rev., Vol. 25, pp. 1-45. 1950.

389. Tracor, Inc. "Data Management System User's Manual for Galveston Bay Project," by L. A. Hembree. 48 p. Submitted to Texas Water Quality Board. 1974. [628.168/T67GD]

390. Tracor, Inc. Appendices to Galveston Bay Project: Water Quality Modeling and Data Management; Phase II Technical Progress Report," by W. H. Espey et al. Submitted to Texas Water Quality Board. Rough draft. 1971. [628.168/T67GA/APP].

391. Tracor Inc. "Galveston Bay Project: Compilation of Water Quality data, July 1968 to September 1971," by R. J. Hudston. Submitted to Texas Water Quality Board. 1971. [628.168/T67GC]

392. Tracor Inc. "Galveston Bay Project Data Management System Preliminary User's Manual," by R. J. Huston. 20 p. Submitted to Texas Water Quality Board. 1972. [628.168/T67GD/PRE]

393. Tracor Inc. "Galveston Bay Project High Frequency Data Program." 1970. [628.168/T67GH]

394. Tracor Inc. "Galveston Bay Project Hydraulic Model User's Manual," by L. A. Hembree et al. 101 p. Submitted to Texas Water Quality Board. 1974. [628.168/T67GHY]

395. Tracor Inc. "Galveston Bay Project Monthly Sampling Program, July 1968-October 1970; Temporal Plots Chlorinity, Dissolved Oxygen, Phosphate, Water Temperature." 1971. [628.168/T67MC]

396. Tracor Inc. "Galveston Bay Project Monthly Sampling Program, July 1968-October 1970; Temporal Plots: Nitrogen Series, Coliform." Unp. 1971. [628.168/T67MN]

397. Tracor Inc. "Galveston Bay Project Water Quality, Modeling and Data Management; Phase II Progress Report Summary." 22 p. Submitted to Texas Water Quality Board. 1971. [628.168/T67GAP]

398. Tracor Inc. "Galveston Bay Project: Water Quality Modeling and Data Management; Phase II Technical Progress Report." by W. H. Espey et al. Submitted to Texas Water Quality Board. 1971. [628.168/T67GA]

399. Tracor Inc. "Galveston Bay Project Water Quality Modeling and Data Management; Phase II Technical Status Report." Submitted to Texas Water Quality Board. pp.1-73. 1971. [628.168/T67GAS]

400. Tracor, Inc. "Galveston Bay Study Phase I: Technical Report." 200 p. Submitted to Texas Water Quality Board. 1968. [628.168/T67GAF]

401. Tracor, Inc. "Galveston Bay Study: Phase I Technical Report Summary." 35 p. Submitted to Texas Water Quality Board. 1968. [628.168/T67G]

402. Tracor Inc. "Galveston Bay Study Phase I: Final Report." 2 Vols. in 1. Submitted to Texas Water Quality Board. 1968. [628.168/T67GAF]

403. Tracor, Inc. "Mathematical Modeling of Thermal Discharges into Shallow Estuaries." 114 p. Prepared for Texas Water Quality Board, Galveston Bay Project. 1971. [628.168/T67M]

404. Tracor, Inc. "Preliminary Galveston Bay Data Program." 21 p. Rough Draft. 1968. [628.168/T67P]

405. Tracor, Inc. "Preliminary User's Manual for the Galveston Bay Project BOD and DO Models (GBP Tasks IV.A.1 and 2)," by M. J. Cullender et al. 61 p. Submitted to Texas Water Quality Board. 1972. [628.168/T67PR]

406. Tracor, Inc. "Report on BOD and DO Modeling for the Galveston Bay System (GBP Tasks IV.A.1 and 2)," by M. J. Cullender et al. Submitted to Texas Water Quality Board. 1972. [628.168/T67RBD]

407. Tracor, Inc. "Report on BOD and DO Model Verification for the Galveston Bay System (GBP Tasks IV.A.1-2), by M. J. Cullender et al. Submitted to Texas Water Quality Board. 1972. [628.168/T67RB]

408. Tracor, Inc. "Report on Mathematical Modeling Investigations of the Clear Creek Basin." Presented to the Texas Water Quality Board. 1973. [551.483/T67R]

409. Tracor, Inc. "Report on Nitrogen Model Verification for the Galveston Bay System," by M. J. Cullender et al. 37 p. Submitted to Texas Water Quality Board. 1972. [628.168/T67RN]

410. Tracor, Inc. "The Status of Galveston Bay Temperature Study; Presentation to the Texas Water Quality Board." 1969. [628.168/T67S]

411. Tracor, Inc. "Suggestions for Proposed Galveston Bay Study." 16 p. Submitted to Texas Water Pollution Control Board. 1967. [628.168/T67SU]

412. Tracor, Inc. "Summary Report Outline, Task I." 26 p. Submitted to Texas Water Quality Board. 1968. [628.168/T67SUM]

413. Tracor, Inc. "Supporting Models User's Manual for the Galveston Bay Project," by Ron Taylor. 223 p. Submitted to Texas Water Quality Board. 1974. [628.168/T67GS]

414. Tracor, Inc. "User's Manual for the Clear Lake Mathematical Models." 102 p. November 1973. [628.168/T67UC/Final]

415. Tracor, Inc. "User's Manual for the Galveston Bay Project BOD and DO Models," by R. M. Chen. 148 p. Submitted to Texas Water Quality Board. 1974. [628.168/T67UB]

416. Tracor, Inc. "User's Manual for the Galveston Bay Project Clear Lake Model." 98 p. Submitted to Texas Water Quality Board. 1973. [628.168/T67UC]

417. Tracor, Inc. "User's Manual for the Nitrogen Model of the Galveston Bay System," by A. J. Hays. 124 p. Submitted to Texas Water Quality Board. 1974. [628.168/T67UN]

418. Tracor, Inc. "User's Manual for the Salinity Model of the Galveston Bay System," by R. M. Chen. 72 p. Submitted to Texas Water Quality Board. 1974. [628.168/T67US]

419. Tracor, Inc. "Waste Load Identification and Assessment Project for the Galveston Bay System; Final Report." 65 p. Submitted to Texas Water Quality Board. 1971. [628.168/T67W]

420. Tracor, Inc. "Waste Load Identification and Assessment Project for the Galveston Bay System; Inteirm Report," 28 p. Submitted to Texas Water Quality Board. 1971. [628.168/T67WI]

421. Tracor, Inc. "Zooplankton," by S. N. James. In: Sabine Ecological Project, Volume I, edited by J. W. Wiersema and R. P. Mitchell. Document No. T 73-AU-9507-U.

422. Trent, W. L. "Size of Brown Shrimp and Time of Emigration from the Galveston Bay System, Texas." Proc. Gulf. Carib. Fish. Inst., 19th Ann. Sess., pp. 7-16. 1966.

423. Turner, J. L. and H. K. Chadwick. "Distribution and Abundance of the Young Striped Bass Marone saxatilis in Relation to River Flow in the Sacremento - San Joaquin Estuary." Trans. Amer. Fish. Soc., Vol. 101, pp. 442-542. 1972.

424. Turner, R. E. "Intertidal Vegetation and Commercial Yields of Penaeid Shrimp." Trans. Amer. Fish. Soc., Vol. 106, pp. 411-416. 1977.

425. Turner, Collie & Braden, Inc. "Galveston Bay Project Stormwater Loading Study." 25 p. Prepared for the Texas Water Quality Board. 1973. [628.168/T85GA]

426. Turner, Collie & Braden, Inc. "Technical Assistance and Management Support for the Galveston Bay Study, A Proposal." Prepared for Texas Water Pollution Control Board. 1967. [628.168/T85G]

427. U. S. Army Engineer Waterways Experiment Station, Vicksburg. "Annotated Bibliography on Effects of Salinity and Salinity Changes on Life in Coastal Waters," by S. H. Hopkins. 411 p. 1973.

428. U. S. Army Engineer Waterways Experiment Station. "Common Marsh Plant Species of the Gulf Coast Area. Vol. II: Growth Dynamics," by J. G. Goesselink et al. Technical Report D-77-44, 57 p. 1977.

429. U. S. Army Engineer Waterways Experiment Station, Vicksburg. "Studies on the Time Course of Salinity and Temperature Adaptation in the Commercial Brown Shrimp Penaeus aztecus Ives," by A. Venkataramiah et al. 308 p. 1977.

430. U. S. Bureau of Commercial Fisheries. "Hydrological Conditions in Clear Lake Texas, 1958-66." 8 p. Contribution 270. U. S. Fish and Wildlife Service, Special Scientific Report--Fisheries-578. 1969. [551.48/UN3HC]

431. U. S. Bureau of Commercial Fisheries. "Hydrographic Observations from the Galveston Bay System, Texas, 1958-67." 152 p. In 3 Fiche. Bureau of Commercial Fisheries, Biological Laboratory, Galveston, Texas. Con-

tributions 280. U. S. Fish and Wildlife Service, Data Report 31. 1969. [Fiche/PB182/757]

432. U. S. Bureau of Fisheries. "Contributions to the Life Histories of Sciaenidae of the Eastern United States," by W. W. Welsh and C. M. Breder. Bulletin No. 39, pp. 141-201. 1924.

433. U. S. Bureau of Fisheries. "The Early Life Histories of Some American Penaeidae, Chiefly the Commercial Shrimp, Penaeus setiferus (Linn.)," by J. C. Pearson. Bulletin No. 49, pp. 1-73. 1939.

434. U. S. Bureau of Fisheries. "Factors Influencing the Spawning and Setting of Oysters in Galveston Bay, Texas," by A. E. Hopkins. Bulletin, Volume 42, pp. 57-84. 1931.

435. U. S. Bureau of Fisheries. "Life History of the Blue Crab," by E. P. Churchill. Bulletin No. 36, pp. 95-128. 1919.

436. U. S. Bureau of Fisheries. "Natural History and Conservation of the Redfish and Other Commercial Sciaenids on the Texas Coast," by J. C. Pearson. Bulletin No. 44, pp. 129-214. 1929.

437. U. S. Coastal Engineering Research Center. "Establishment of Vegetation for Shoreline Stablization in Galveston Bay," by J. D. Dodd. 67 p. Their Miscellaneous Paper No. 6-75. 1975. [627.58/UN3MP/6-75]

438. U. S. Coastal Engineering Research Center. "Vegetation Establishment and Shoreline Stabilization; Galveston Bay, Texas." 74 p. Their Technical Paper 76-13. 1976. [627.58/UN3TP/76-13]

439. U. S. 56th Congress, 1st Sess. 1900. "Examination and Survey of East Bay Bayou, Texas." 7 p. House Document No. 451. February 21, 1900. [DOC/56-1/HD451]

440. U. S. 76th Congress, 1st Sess. 1939. "Chocolate Bayou, Bastrop Bayou, and Oyster Creek, Texas." 18 p. House Document No. 337. June 12, 1939. [DOC/76-1/HD337]

441. U. S. 81st Congress, 1st Sess. 1949. "Galveston Harbor and Channel, Texas Sea-wall Extension." 30 p. Letter from the Secretary of the Army. House Document 173. 1949. [DOC/81-1/HD173]

442. U. S. 83d Congress, 1st Sess. 1953. "Gulf Shore of Galveston Island, Texas Beach Erosion Control Study." 48 p. Letter from the Secretary of the Army. House Document No. 218. 1953. [DOC/83-1/HD218]

443. U. S. 83d Congress, 2nd Sess. 1954. "Shore of Galveston Bay, Galveston County, Texas." 23 p. House Document No. 346. 1954. [DOC/83-2/HD346].

444. U. S. 85th Congress, 2nd Sess. 1958. "Galveston Harbor and Channel, Houston Ship Channel, and Texas City Channel, Texas." 62p. House Document No. 350. 1958. [DOC/85-2/HD350]

445. U. S. 86th Congress, 2nd Sess. 1960. "Texas City Channel, Texas. 63 p. House Document No. 427. 1960. [DOC/86-2/HD427]

446. U. S. 90th Congress, 1st Sess. 1967. "Texas City and Vincinity, Texas, La Marque-Hitchcock Extension." 120 p. House Document No. 187. 1967. [DOC/90-1/HD187]

447. U. S. 92nd Congress, 1st Sess. 1971. "Galveston Harbor and Channel, Texas. Galveston Channel 40-Foot Project." 79 p. House Document No. 92-121. 1971. [DOC/92-1/HD121]

448. U. S. 92nd Congress, 2nd Sess. 1972. "Texas City Channel, Texas (Industrial Canal). 78 p. House Document No. 92-199. 1972. [DOC/922/HD199]

449. U. S. Corps of Engineers. "Burnett, Crystal, and Scott Bays and Vicinity, Baytown, Texas: Feasibility Report for Flood Damage Reduction." 2 Vols. Vol. 1-Main Report; Vol. 2-Appendices. 1975. [USCE-G/B93]

450. U. S. Corps of Engineers. "Burnett, Crystal, and Scott Bays and Vicinity, Baytown, Texas." 49 p. Final Environmental Statement. 1976. [EIS/B93]

451. U. S. Corps of Engineers. "Channel From Galveston Harbor to Texas City, Texas, Texas City Dike," 27 p. 1949. [USCEG/T31]

452. U. S. Corps of Engineers. "Chocolate Bayou and Bastrop Bayou, Texas, Review of Reports." 34 p. 1947. [USCE-G/C45R]

453. U. S. Corps of Engineers. "Galveston Harbor and Channel, Texas; (Galveston Channel 40-Foot Project)." 33 p. Final Environmental Statement. 1973. [EIS/G13]

454. U. S. Corps of Engineers. "Galveston Harbor and Channel, Texas, (Galveston Channel) Maintenance Dredging." 75 p. Final Environmental Statement. 1975. [DIS/G13G]

455. U. S. Corps of Engineers. "Galveston Harbor and Channel, Texas, Review of Reports." 48 p. 1948. [USCEG/G13H/1948]

456. U. S. Corps of Engineers. "Gulf Intracoastal Waterway in South Galveston Bay, Texas, Review of Reports." 32 p. 1948. [USCE-G/G95GB]

457. U. S. Corps of Engineers. "Interim Report on Hurricane Survey of Freeport and Vicinity, Texas." Unpub. Contains Appendices I-VII. 1958. Rev. 1961. [USCE-G/H94F]

458. U. S. Corps of Engineers. "Maintenance Dredging Clear Creek and Clear Lake, Texas." 57 p. Final Environmental Statement. 1975. [EIS/C58]

459. U. S. Corps of Engineers. "Maintenance Dredging Galveston Harbor and Channel, Texas (Galveston Harbor Channels)." 62 p. Final Environmental Statement. 1975. [EIS/G13M]

460. U. S. Corps of Engineers. "Maintenance Dredging, Texas City Channel, Texas." 71 p. Final Environmental Statement. 1974. [EIS/T31]

461. U. S. Corps of Engineers Waterways Exper. Sta. "Model Study of Galveston Harbor Entrance, Texas, Hydraulic Model Investigation." 49 p. Their Technical Report No. H-69-2. 1969. [USCE-G/G13M]

462. U. S. Corps of Engineer. "The Ports of Galveston and Texas City, Texas." 121 p. Their Port Series No. 23. Rev. 1959. [USCE-PO/23/1959]

463. U. S. Corps of Engineers. "Preliminary Report on Barbour Cut at Morgan Point, Texas." 7 p. 1962. [USCE-G/H81B]

464. U. S. Corps of Engineers. "Review of Corps of Engineers Report on Texas City and Vicinity, Texas, La Marque-Hitchcock Extension." 1966. [USCE-G/L16HD]

465. U. S. Corps of Engineers. "Review of Reports on Chocolate Bayou, Texas." Unp. 1964. [USCE-G/C45]

466. U. S. Corps of Engineers. "Review of Reports on Galveston Harbor & Channel, Texas-Galveston Channel 40-Foot Project." 62. p. Galveston, Texas. 1970. [USCE-G/G13G]

467. U. S. Corps of Engineers. "Review of Reports on Texas City Channel, Texas-Industrial Canal." 37 p. Galveston, Texas. 1970. [USCE-G/T32R]

468. U. S. Corps of Engineers. "Review of Report on Texas City and Vicinity, Texas, La Marque-Hitchcock Extension Hurricane Flood Protection." v.p. 1965. [USCE-G/L16H]

469. U. S. Corps of Engineers. "The Shore of Galveston Bay, Texas Beach Erosion Control, Report on Preliminary Examination." 14 p. 1953.

470. U. S. Corps of Engineers. "Survey Report on Clear Creek, Texas Flood Control." Unpub. Appendices I-IV. 1967. [USCE-G/C58S]

471. U. S. Corps of Engineers. "Texas City and Vicinity, Texas, Storm Protection, Report on Survey of." 35 p. 1957. [USCE-G/T31T]

472. U. S. Department of Commerce, National Marine Fisheries Service, Texas Parks and Wildlife Department. "Texas Landings: Annual Summary, 1969," by O. H. Farley. Current Fisheries Statistics No. 5232. 1970.

473. U. S. Department of Commerce, National Marine Fisheries Service, Texas Parks and Wildlife Department. "Texas Landings: Annual Summary, 1970," by O. H. Farley. Current Fisheries Statistics No. 5616. 1971.

474. U. S. Department of Commerce, National Marine Fisheries Service, Texas Parks and Wildlife Department. "Texas Landings: Annual Summary, 1971," by O. H. Farley. Current Fisheries Statistics No. 5923. 1972.

475. U. S. Department of Commerce, National Marine Fisheries Service, Texas Parks and Wildlife Department. "Texas Landings: Annual Summary, 1972," by O. H. Farley. Current Fisheries Statistics No. 6124. 1973.

476. U. S. Department of Commerce, National Marine Fisheries Service, Texas Parks and Wildlife Department. "Texas Landings: Annual Summary, 1973," by O. H. Farley. Current Fisheries Statistics No. 6423. 1974.

477. U. S. Department of Commerce, National Marine Fisheries Service, Texas Parks and Wildlife Department. "Texas Landings: Annual Summary, 1974," by O. H. Farley. Current Fisheries Statistics No. 6723. 1975.

478. U. S. Department of Commerce, National Marine Fisheries Service, Texas Parks and Wildlife Department. "Texas Landings: Annual Summary, 1975," by O. H. Farley. Current Fisheries Statistics No. 6923. 1977.

479. U. S. Department of Commerce, National Marine Fisheries Service, Texas Parks and Wildlife Department. "Texas Landings: Annual Summary, 1976," by O. H. Farley. Current Fisheries Statistics No. 7223. 1978.

480. U. S. Department of Commerce, NOAA. "Cooperative Gulf of Mexico Estuarine Inventory and Study - Texas: Area Description," by R. A. Diener. National Marine Fisheries Service Circular 393. 129 p. 1975.

481. U. S. Department of Interior, Bureau of Commercial Fisheries, Texas Parks and Wildlife Department. "Texas Landings: Annual Summary, 1962," by O. H. Farley. Current Fisheries Statistics No. 3309. 1963.

482. U. S. Department of Interior, Bureau of Commercial Fisheries, Texas Parks and Wildlife Department. "Texas Landings: Annual Summary, 1963," by O. H. Farley. Current Fisheries Statistics No. 3627 (Revised). 1964.

483. U. S. Department of Interior, Bureau of Commercial Fisheries, Texas Parks and Wildlife Department. "Texas Landings: Annual Summary, 1964," by O. H. Farley. Current Fisheries Statistics No. 3901. 1965.

484. U. S. Department of Interior, Bureau of Commercial Fisheries, Texas Parks and Wildlife Department. "Texas Landings: Annual Summary, 1965," by O. H. Farley. Current Fisheries Statistics No. 4156. 1966.

485. U. S. Department of Interior, Bureau of Commercial Fisheries, Texas Parks and Wildlife Department. "Texas Landings: Annual Summary, 1966," by O. H. Farley. Current Fisheries Statistics No. 4529. 1967.

486. U. S. Department of Interior, Bureau of Commercial Fisheries, Texas Parks and Wildlife Department. "Texas Landings: Annual Summary, 1967," by O. H. Farley. Current Fisheries Statistics No. 4675. 1968.

487. U. S. Department of Interior, Bureau of Commercial Fisheries, Texas Parks and Wildlife Department. "Texas Landings: Annual Summary, 1968," by O. H. Farley. Current Fisheries Statistics No. 4962. 1969.

488. U. S. Environmental Protection Agency. "Report on Pollution Affecting Shellfish Harvesting in Galveston Bay, Texas." 1971. [628.168/UN3REP]

489. U. S. Environmental Protection Agency, Office of Water Planning & Standards. "Effects and Control of Nutrients in Estuarine Ecosystems," by J. E. Hobbie and B. J. Copeland. In: Estuarine Pollution Control and Assessment Proceedings of a Conference, Vol. 1, pp. 257-274. Washington, D. C. 1977.

490. U. S. Environmental Protection Agency, Office of Water Planning and Standards. "Nutrient Loading in the Nation's Estuaries," by M. A. Champ. In: Estuarine Pollution Control and Assessment Proceedings of a Conference. Vol. 1, pp. 237-255. Washington, D. C. 1977.

491. U. S. Environmental Protection Agency, The Texas Water Quality Board et al. Galveston Bay Enforcement Conference, Houston, Texas, June 7-12, 1971. Supplementary Report to Federal-State Technical Task Force; Working Paper Only. 1971. [628.168/G13/SUPP]

492. U. S. Federal Water Pollution Control Administration. "Public Hearing, October 8, 1968. Moody Center, Galveston, Texas." 353 p. 1971. [628.168/UN3PU]

493. U. S. Fish and Wildlife Service. "The American Oyster, Crassostrea virginica (Gmelin)," by P. S. Galtzoff. Fisheries Bulletin 6, 480 p. 1964.

494. U. S. Fish and Wildlife Service. "An Annotated Bibliography of the Fish and Wildlife Resources of Galveston Bay, Texas," by S. P. Christman et al. Biological Services Program, FWS/OBS-78-71. 2 Vols. 1978.

495. U. S. Fish and Wildlife Service. "Combined Effects of Temperature and Salinity on Development of Eggs and Growth of Larvae of M. Mercenaria and C. virginica," by H. C. Davis and A. Calabrese. Fisheries Bulletin, Vol. 63, pp. 643-655. 1964.

496. U. S. Fish and Wildlife Service. "Protein Taxonomy of the Gulf of Mexico and Atlantic Ocean Seatrouts, Genus Cynoscion," by M. P. Weinstein and R. W. Yerger. Fisheries Bulletin, Vol. 74, pp. 599-607. 1976.

497. U. S. Fish and Wildlife Service. "A Reevaluation of the Combined Effects of Temperature and Salinity on Survival and Growth of Bivalve Larvae using Response Surface Techniques," by R. G. Lough. Fisheries Bulletin, Vol. 73, pp. 86-94. 1975.

498. U. S. Fish and Wildlife Service. "Results of the Trinity Bay Study," by R. A. Diener. pp. 67-69. Service Circular 161. 1962.

499. U. S. Fish and Wildlife Service. "Seasonal Distribution and Relative Abundance of the Planktonic Stage Shrimp in the Northwestern Gulf," by R. Temple and C. Fischer. U. S. Fish and Wildlife Service Bulletin, Vol. 66, pp. 323-334. 1968.

500. U. S. Fish and Wildlife Service. "Seasonal Occurrence and Size Distribution of Post-larval Brown and White Shrimp near Galveston, Texas, with Notes on Species Identification," by K. N. Baxter and W. C. Renfro. Fisheries Bulletin, Vol. 66, pp. 148-158. 1966.

501. U. S. Fish and Wildlife Service. "Summary of Information: Relationship of Freshwater Inflow to Estuarine Productivity along the Texas Coast," by C. T. Hackney. Report FWS/OBS-78/73. 25 p. 1978.

502. U. S. Fish and Wildlife Service. "Western Atlantic Shrimps of the Genus Penaeus," by I. Perez-Farfante. Bulletin No. 67, pp. 461-591. 1969.

503. U. S. Fish and Wildlife Service, Bureau of Commercial Fisheries. "Gulf Coast Shrimp Data, Annual Summary 1959." 24 p. Prepared in cooperation with fishery agencies of Florida, Alabama, Mississippi, Louisiana, and Texas. U. S. Dept. Interior, Washington, D. C. 1960.

504. U. S. Fish and Wildlife Service, Bureau of Commercial Fisheries. "Gulf Coast Shrimp Data, Annual Summary 1960. 23 p. Prepared in cooperation with fishery agencies of Florida, Alabama, Mississippi, Louisiana, and Texas. U. S. Dept. Interior, Washington, D. C. 1961.

505. U. S. Fish and Wildlife Service, Bureau of Commercial Fisheries. "Gulf Coast Shrimp Data, Annual Summary 1961." 24 p. Prepared in cooperation with fishery agencies of Florida, Alabama, Mississippi, Louisiana, and Texas. U. S. Dept. Interior, Washington, D. C. 1962.

506. U. S. Fish and Wildlife Service, Bureau of Commercial Fisheries. "Gulf Coast Shrimp Data, Annual Summary 1962." 38 p. Current Fisheries Statistics No. 3358. Prepared in cooperation with fishery agencies of Florida, Alabama, Mississippi, Louisiana, and Texas. U. S. Dept. Interior, Washington, D. C. 1963.

507. U. S. Fish and Wildlife Service, Bureau of Commercial Fisheries. "Gulf Coast Shrimp Data, Annual Summary 1963." 53 p. Current Fisheries Statistics No. 3515. Prepared in cooperation with fishery agencies of Florida, Alabama, Mississippi, Louisiana, and Texas. U. S. Dept. Interior, Washington, D. C. 1964.

508. U. S. Fish and Wildlife Service, Bureau of Commercial Fisheries. "Gulf Coast Shrimp Data, Annual Summary 1964." 55 p. Current Fisheries Statistics No. 3784. Prepared in cooperation with fishery agencies of Interior, Washington, D. C. 1965.

509. U. S. Fish and Wildlife Service, Bureau of Commercial Fisheries. "Gulf Coast Shrimp Data, Annual Summary 1965." 36 p. Current Fisheries Statistics No. 4111. Prepared in cooperation with fishery agencies of Florida, Alabama, Mississippi, Louisiana, and Texas. U. S. Dept. Interior, Washington, D. C. 1966.

510. U. S. Fish and Wildlife Service, Bureau of Commercial Fisheries. "Gulf Coast Shrimp Data, Annual Summary 1966." 34 pp. Current Fisheries

Statistics No. 4411. Prepared in cooperation with fishery agencies of Florida, Alabama, Mississippi, Louisiana, and Texas. U. S. Dept. Interior, Washington, D. C. 1967.

511. U. S. Fish and Wildlife Service, Bureau of Commercial Fisheries. "Gulf Coast Shrimp Data, Annual Summary 1967." 39 p. Current Fisheries Statistics No. 4781. Prepared in cooperation with fishery agencies of Florida, Alabama, Mississippi, Louisiana, and Texas. U. S. Dept. Interior, Washington, D. C. 1968.

512. U. S. Fish and Wildlife Service, Bureau of Commercial Fisheries. "Gulf Coast Shrimp Data, Annual Summary 1968." 34 p. Current Fisheries Statistics No. 5107. Prepared in cooperation with fishery agencies of Florida, Alabama, Mississippi, Louisiana, and Texas. U. S. Dept. Interior, Washington, D. C. 1969.

513. U. S. Fisheries Commission. "Report on the Inquiry Respecting Food-Fishes and the Fishing Grounds," by R. Rathbun. Report 19, pp. 23-26. 1895.

514. U. S. Geological Survey. "Land Surface Subsidence in the Area of Moses Lake Near Texas City, Texas," by R. K. Gabrysch. 42 p. Their Water Resources Investigations 76-32. 1975. [333.9/UN3WRI/76-32]

515. U. S. Geological Survey. "Water Resources Data for Texas, 1966-1976." Austin, Texas. v.p.

516. U. S. Lyndon B. Johnson Space Center. "Comparison of Two Unsupervised Classification Algorithms for Delineation of Coastal Features of Galveston Island Texas," by Lockheed Electronics Co., Inc. 6 p. 1973. [550.28/UN3C]

517. U. S. National Marine Fisheries Service. "Economic Activity Associated with Marine Recreational Fisheries." 41 p. June 1977.

518. U. S. National Marine Fisheries Service. "An Evaluation of the Effects of Estuarine Engineering Projects," by R. B. Johnson, Jr. 141 p., Tech. Rept. NOAA-72091953. 1970.

519. U. S. National Marine Fisheries Service. "Gulf Coast Shrimp Data, Annual Summary 1969." 36 p. Current Fisheries Statistics No. 5412. Prepared in cooperation with fishery agencies of Alabama, Florida, Louisiana, Mississippi, and Texas. U. S. Dept. Commerce, Washington, D. C. 1970.

520. U. S. National Marine Fisheries Service. "Gulf Coast Shrimp Data, Annual Summary 1970." 30 p. Current Fisheries Statistics No. 5721. Prepared in cooperation with fishery agencies of Alabama, Florida, Louisiana, Mississippi, and Texas. U. S. Dept. Commerce, Washington, D. C. 1971.

521. U. S. National Marine Fisheries Service. "Gulf Coast Shrimp Data, Annual Summary 1971." 30 p. Current Fisheries Statistics No. 5925. Prepared in cooperation with fishery agencies of Alabama, Florida, Louisiana, Mississippi, and Texas. U. S. Dept. Commerce, Washington, D. C. 1973.

522. U. S. National Marine Fisheries Service. "Gulf Coast Shrimp Data, Annual Summary 1972." 30 p. Current Fisheries Statistics No. 6126. Prepared in cooperation with fishery agencies of Alabama, Florida, Louisiana, Mississippi, and Texas. U. S. Dept. Commerce, Washington, D. C. 1974.

523. U. S. National Marine Fisheries Service. "Gulf Coast Shrimp Data, Annual Summary 1973." 31 p. Current Fisheries Statistics No. 6425. Prepared in cooperation with fishery agencies of Alabama, Florida, Louisiana, Mississippi, and Texas. U. S. Dept. Commerce, Washington, D.C. 1974.

524. U. S. National Marine Fisheries Service. "Gulf Coast Shrimp Data, Annual Summary 1974." 33 p. Current Fisheries Statistics No. 6725. Prepared in cooperation with fishery agencies of Alabama, Florida, Louisiana, Mississippi, and Texas. U. S. Dept. Commerce, Washington, D. C. 1975.

525. U. S. National Marine Fisheries Service. "Gulf Coast Shrimp Data, Annual Summary 1975." 26 p. Current Fisheries Statistics No. 6925. Prepared in cooperation with fishery agencies of Alabama, Florida, Louisiana, Mississippi, and Texas. U. S. Dept. Commerce, Washington, D. C. 1976.

526. U. S. National Marine Fisheries Service. "Gulf Coast Shrimp Data, Annual Summary 1976." 13 p. Current Fisheries Statistics No. 7225. Prepared in cooperation with fishery agencies of Alabama, Florida, Louisiana, Mississippi, and Texas. U. S. Dept. Commerce, Washington, D. C. 1978.

527. U. S. National Marine Fisheries Service. "A Hydrographic Survey of the Galveston Bay System, Texas, 1963-66." 22 p. In 1 Fiche. NOAA Technical Report. NMFS SSRF-639. 1971. [FICHE/COM71/50604]

528. U. S. Soil Conservation Service. "Report of Drainage Survey of the Trinity Bay Soil Conservation District Texas." 18 p. Fort Worth, 1974. [627.54/H23TB]

529. U. S. Soil Conservation Service. "East Bay Bayou Erosion Control RC&D Measure Plan, Chambers and Jefferson Counties, Texas." 9 p. Southeast Texas RC&D Project. 1976. [631.45/UN3EBB]

530. Valiela, I. and J. M. Teal. "Nutrient Limitation in Salt Marsh Vegetation." In: Ecology of Halophytes. editors, R. J. Reimold and W. H. Queen, pp. 547-563. Academic Press, N. Y. 1974.

531. Valiela, I. et al. "Production and Dynamics of Salt Marsh Vegetation and the Effects of Experimental Treatment with Sewage Sludge." J. Applied Ecol., Vol. 12, pp. 973-981. 1975.

532. Van Roalte, C. D. et al. "Production of Epibenthic Salt Marsh Algae: Light and Nutrient Limitation." Limnology and Oceanography, Vol. 21, No. 6, pp. 862-872. 1976.

533. Van Winkle, W., Jr. "The Effects of Season, Temperature and Salinity on Oxygen Consumption of Bivalve Gill Tissue." Comp. Biochem. Physiol., Vol. 26, pp. 69-80. 1968.

534. Venkataramiah, A., et al. "A Review of the Effects of Some Environmental and Nutritional Factors on Brown Shrimp, Penaeus aztecus Ives in Laboratory Cultures." In: Proceedings of 10th European Symposium on Marine Biology (1975), Vol. 1, pp. 523-547. 1977.

535. Vernberg, F. J. and W. B. Vernberg. "Adaptations to Extreme Environments." In: Physiological Ecology of Estuarine Organisms, edited by F. J. Vernberg, pp. 165-180. Univ. South Carolina Press, Columbia. 1975.

536. Vernberg, W. B. and F. J. Vernberg. "Environmental Physiology of Marine Animals." Springer-Verlag, New York. 346 p. 1972.

537. Waisel, Y. "Biology of the Halophytes." Academic Press, New York. 395 p. 1972.

538. Wakeman, J. M. "Environmental Effects on Metabolic Scope and Swimming Performance of Some Estuarine Fishes." Ph. D. Dissertation, Univ. Tex., 146 p. 1978.

539. Wallace, D. H. "Oysters in the Estuarine Environment." In: A Symposium on Estuarine Fisheries, edited by R. F. Smith, Amer. Fish. Soc., Spec. Publ. No. 3, pp. 68-73. 1966.

540. Water Resources Engineers, Inc. "An Aquatic Ecologic Model for Texas Bays and Estuaries," by R. J. Brandes. Report to Texas Water Development Board, Austin, Texas. August 1976.

541. Water Resources Engineers, Inc. "RIVTID, Simulation of Flood-Flow Hydrodynamics in River/Tidal Systems: Program Documentation and User's Manual," by R. J. Brandes and R. B. Wise. v.p. Austin, Texas. 1973.

542. Weinstein, M. P. and R. W. Yerger. "Electrophoretic Investigaion of Subpopulations of the Spotted Seatrout, Cynoscion nebulosus (Cuvier), in the Gulf of Mexico and Atlantic Coast of Florida." Comp. Biochem. Physiol., Vol. 54, pp. 97-102. 1976.

543. Wells, H. W. "The Fauna of Oyster Beds, with Special Reference to the Salinity Factor." Ecol. Monitor, Vol. 31, pp. 239-266. 1961.

544. Wiesepape, L. M., D. V. Aldrich, and K. Strawn. "Effects of Temperature and Salinity on Thermal Death in Postlarval Brown Shrimp, Penaeus aztecus." Physio. Zoo. Vol. 45, pp. 22-33. 1972.

545. Williams, A. B. and E. E. Deubler. "A Ten Year Study of Meroplankton in North Carolina Estuaries: Assessment of Environmental Factors and Sampling Success among Bothid Flounders and Penaeid Shrimps." Ches. Sci., Vol. 9, pp. 27-41. 1968.

546. Williams, R. B. and M. B. Murdoch. "The Potential Importance of Spartina alterniflora in Conveying Zinc, Manganese, and Iron into Estuarine Food Chains." In: Proc. of the Second National Symposium on Radioecology, edited by D. J. Nelson and F. C. Evans, pp. 431-439. USAEC, Conf. - 670503. 1969.

547. Wohlschlag, D. E. and B. J. Copeland. "Fragile Estuarine Systems — Ecological Considerations." Water Res. Bull., Vol. 6, pp. 94-105. 1970.

548. Yakupzack, P. M., et al. "Emigration of Juvenile Atlantic Croakers, Micropogon undulatus, from a Semi-impounded Marsh in Southwestern Louisiana." Trans. Amer. Fish. Soc., Vol. 106, pp. 538-544. 1977.

549. Yokel, B. J. "A Contribution to the Biology and Distribution of the Red Drum, Sciaenops ocellata." M. S. Thesis, Univ. Miami, Coral Gables, Florida. 1966.

550. Zein-Eldin, Z. P. and G. W. Griffith. "An Appraisal of the Effects of Salinity and Temperature on Growth and Survival of Postlarval Penaeids," FAO Fish. Rept., Vol. 3, pp. 1015-1026. 1969.

551. Zein-Eldin, Z. P. "Effect of Salinity on Growth of Postlarval Penaeid Shrimp." Biol. Bull., Vol. 125, pp. 188-196. 1963.

552. Zein-Eldin, Z. P. and D. V. Aldrich. "Growth and Survival of Postlarval Penaeus aztecus under Controlled Conditions of Temperature and Salinity." Biol. Bull., Vol. 129, pp. 199-216. 1965.

APPENDIX

List of Persons Receiving the Draft Report

Name	Agency
Bob Armstrong*	General Land Office Texas, Austin
Charles D. Travis	Texas Parks & Wildlife Department, Austin
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Jimmie Schindewolf	Houston Department of Public Works, Houston
Bill Clayton	Speaker, Texas House of Representatives, Austin
William P. Hobby	Lt. Governor of Texas, Austin
Emmett Gloyna	U.S. Water and Power Resources Service, Austin
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* Indicates a letter was received from the named individual--or his (her) respective agency--in reply to the TDWR's request for comments on the draft report.