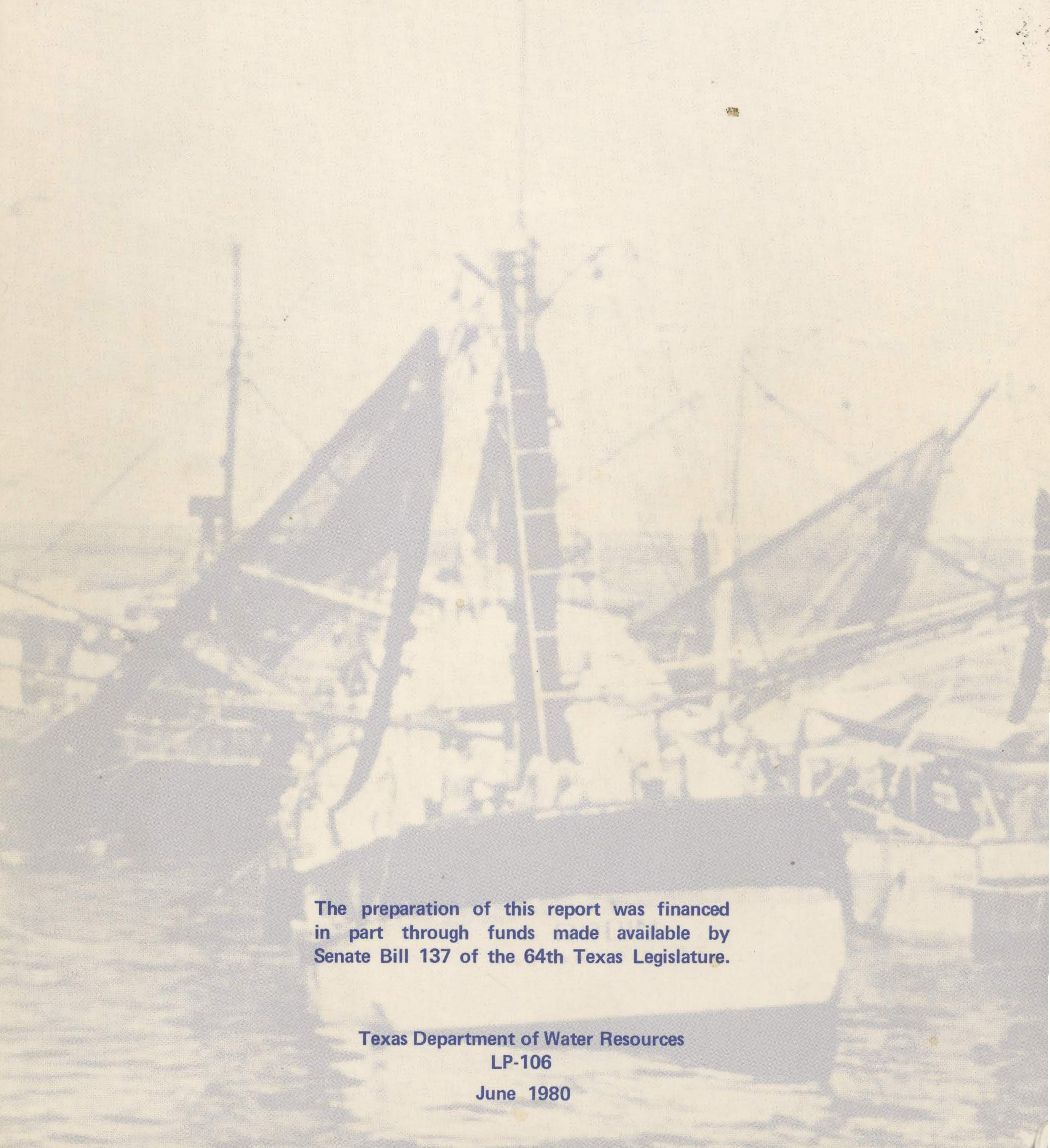
LAVACA-TRES PALACIOS ESTUARY:

A Study of the Influence of Freshwater Inflows



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Texas Department of Water Resources
LP-106
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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 inflow and estuarine productivity for the Lavaca-Tres Palacios estuary of Texas, and establishes the seasonal and monthly freshwater inflow needs for a range of alternative management policies.

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. Indicator species are generally chosen on the basis of their wide distribution thoughout 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 inflow.

Description of the Estuary and the Surrounding Area

The Lavaca-Tres Palacios estuary includes Matagorda Bay, Lavaca Bay, Cox Bay, Keller Bay, Carancahua Bay, Tres Palacios Bay, and several other bays. About 44,040 square miles (114,600 km^2) of Texas contribute runoff to the estuary, including the Colorado and Lavaca Basins, and the Colorado-Lavaca and Lavaca-Guadalupe Coastal Basins.

Major marsh areas of the Lavaca-Tres Palacios estuary are associated with river deltas. Active delta plains, such as the Lavaca delta, are covered with salt, brackish, and freshwater marshes. The Lavaca delta is being eroded along its perimeter. In fact, most of the shorelines associated with the Lavaca-Tres Palacios estuary are eroding, indicating that the sediment volume supplied to Gulf and bay shorelines is insufficient to balance the amount of sediment removed by waves and longshore drift. Mainland beaches are made up predominately of shell and rock fragments, indicating that very little sand is currently being supplied to these beaches by the rivers.

Groundwater resources of the area occur in a thick sedimentary sequence of interbedded gravel, sand, silt and clay. Near the Lavaca-Tres Palacios estuary the fresh to slightly saline portion of the aquifer (up to 3,000 mg/l total dissolved solids) extends to a maximum depth of about 1,600 feet (488 m). The most productive part of the aquifer is from 200 to 600 feet (61 - 183 m) thick.

Land use in the area is dominated by agricultural and ranching activities, with rice being the principal irrigated crop. Crops such as grain sorghum, corn, soybeans, and cotton are dryland crops produced in the area.

The estuary is a significant resource of the commercial fishing industry in Texas. Since 1962, the average annual commercial inshore catch (all species) in this estuarine system has exceeded 3.3 million pounds (1.5 million kg), second in Texas–only to the Trinity-San Jacinto estuary. Shellfish, particularly shrimp, constitute the major portion of the commercial landings, accounting for more than 90 percent of the total harvest weight. The fishing resources of the estuary include many fish species preferred by sport fisherman. Studies by the Texas Parks and Wildlife Department of the sport catch in the estuary indicate that an estimated 970,000 pounds (440,000 kg) of fish (all species) were caught during the one year period from September 1975 through August 1976. Species composition of the sport harvest are predominantly seatrout (32.6 percent), gafftop-sail (19.4 percent), and flounder (18.2 percent). The total contribution of this estuary to the sport and commercial harvests of estuarine-dependent fisheries species during the 1972 through 1976 interval is estimated at 18.1 million pounds (8.2 million kg) annually for combined inshore and offshore areas.

Hydrology

Sources of freshwater inflow to the Lavaca-Tres Palacios 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. Measurement of freshwater inflow adds to the understanding of inflow timing and volumes and their influence on bay productivity. To compute accurate inflow estimates, 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 inflow, in terms of annual and monthly average values over the 1941 to 1976 period, varied widely as a result of recurrent drought and flood conditions. On the average, the total freshwater inflow to the estuary (1941-1976) consisted of: (1) gaged contributions from the Lavaca Basin (16 percent), (2) a portion of gaged inflow from the Colorado Basin (34 percent), (3) runoff from ungaged areas (25 percent), (4) return flows from ungaged areas (2 percent), and (5) direct precipitation on the estuary (23 percent).

In general, the quality of gaged inflows to the Lavaca-Tres Palacios estuary has been good. None of the streams contributing to the estuary have been in violation of existing State/Federal stream standards. Detailed studies of past water quality problems in and around the estuary have pinpointed heavy metals as a significant concern near the major industrial sites. Locally, bottom sediment samples have exceeded EPA dredge criteria (1974) for metals in sediments for arsenic, cadmium, mercury and zinc. Bottom sediments collected and analyzed for herbicides and pesticides showed DDD, DDE, DDT, and dieldrin occurring in local areas in concentrations equal to or greater than the analytical detection limit during the period 1969 to 1974.

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 more fully evaluate the tidal hydrodynamic and salinity transport characteristics of estuarine systems, the Texas Department of Water Resources developed digital mathematical models representing the important mixing and physical exchange processes of the estuaries. These models were 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 was 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 was developed to simulate the passage of water and nutrients through a deltaic system. The computations were based upon use of a finite difference approximation to the equations which describes the governing physical relationships.

The marsh inundation model has been applied separately to both the Lavaca and Colorado River deltas. Each 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 Colorado River delta includes the section of the Gulf of Mexico and Matagorda Bay adjacent to the delta and the Colorado River Channel up to Bay City, Texas. The representation of the Lavaca River delta includes the non-tidally influenced floodplain of the Lavaca and Navidad Rivers from the stream gages near Edna and Ganado downstream to Lavaca Bay.

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 have been applied to the Lavaca-Tres Palacios estuary, with the model representation of the system including Lavaca Bay, Matagorda Bay, and a portion of the Gulf of Mexico adjacent to Matagorda Peninsula. The hydrodynamic and mass transport models were calibrated and verified for the estuary.

The extent of marsh inundation in the Lavaca and Colorado River deltas was investigated utilizing the verified inundation models for these systems. The submerged surface area of the Lavaca delta was determined for six typical flood hydrographs under low, high and average tidal amplitudes. Flooding of the Colorado River delta has been due principally to tidal inundation, since extensive levees prevent stream bank overtopping except under extreme flooding conditions.

Statistical analyses were undertaken to quantify the relationship between freshwater inflows from the Lavaca and Colorado River and salinities in upper Lavaca Bay and the eastern end of Matagorda Bay. Utilizing gaged daily river flows in the Lavaca and Colorado Rivers and observed salinities, a set of monthly predictive salinity equations was derived utilizing regression analyses for the two indicated areas of the estuary. These equations predict the mean monthly salinity as a function of the mean monthly freshwater inflow rate.

Nutrient Processes

Freshwater inundation of the Colorado River delta marshes from river overbanking is a rare event. Marshes in this delta probably function much like those along the east coast of the United States; that is, export of nutrients, both dissolved and particulate, occur as a function of regular periodic tidal activity. High tides in Matagorda Bay and/or strong southeasterly winds are the major driving forces causing inundation of these intertidal marsh areas.

By contrast, the marshes of the Lavaca River delta are subject to periodic inundation during periods of high river flows as well as tidal inundation. During inundation events, high rates of organic carbon and organic nitrogen export (both particulate and dissolved) occur initially. After the initial flush of material, steady-state exchange rates in the Lavaca River delta are similar to those that have been observed in the Colorado River delta marshes. Pulses of high freshwater discharge and the resulting deltaic inundation are thus important mechanisms contributing to increased nutrient transport from the Lavaca River delta marshes to the estuary.

Aerial photographic studies of the Lavaca River delta, lower Colorado River, and Pass Cavallo area have provided an insight into on-going wetland processes. For the most part, the Lavaca River delta marshes appear to be the most altered by man (agricultural and cattle-raising activities and oil production); the marshes of the Pass Cavallo area appear least impacted. The long-range condition of the wetland environment will be considerably impacted 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.

Primary and Secondary Bay Production

The community composition, distribution of abundance and seasonality of the phytoplankton, zooplankton, and benthic invertebrates of the Lavaca-Tres Palacios estuary have been employed by Texas Parks and Wildlife Department (244) as "indicators" of primary and secondary productivity. The estuarine communities identified are typical in that they are composed of freshwater, marine, and a mixture of endemic species (i.e., species restricted to the estuarine zone).

A total of 156 phytoplankton taxa representing seven divisions were identified. Phytoplankton taxa diversities were generally related to freshwater inflows. Minimum densities were found to occur when river inflow was greater than 2,000 ft^3/sec (56 m^3/sec), while maximum standing crops were associated with blooms of microflagellates and diatoms as the bay salinity stabilized after high inflows.

A total of 201 zooplankton taxa representing 14 phyla have been identified. Over 80 percent of the total zooplankton standing crop was composed of populations of barnacle nauplii, *Acartia tonsa*, and *Oithona* spp. Salinity and water temperature were the two most important factors governing the species composition during the study (244). No significant statistical correlations were found between zooplankton standing crops or taxa diversity and freshwater inflows.

A total of 169 benthos taxa representing nine phyla have been identified. Diversities have been generally greater in the lower bay where high salinities prevail. Standing crops were not found to be significantly correlated to freshwater inflow.

Fisheries

Virtually all of the Gulf fisheries species are estuarine-dependent. Commercial inshore harvests from bays of the Lavaca-Tres Palacios estuary rank second in shellfish and fifth in finfish of eight major Texas estuarine areas. In addition, the estuary's sport or recreational finfish harvest is estimated to be about five and one-half times larger than the commercial finfish harvest.

Although a large portion of each Texas estuary's fisheries production is harvested offshore in collective association with fisheries production from other regional Texas 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. 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 1962 through 1976 commercial bay fisheries landings was successful for 70 percent of the correlations attempted between the harvests and the seasonal freshwater inflows to the Lavaca-Tres Palacios estuary. The analysis of harvest as a function of the seasonal inflows resulted in 19 statistically significant regression equations. These equational models provide numerical estimates of the effects of variable seasonal inflows, contributed from the major freshwater sources, on the inshore commercial harvest of seafood organisms from the estuary. The statistical analysis supports existing scientific information on the seasonal importance of freshwater inflow to the estuary. Except for the blue crab fisheries component, all harvest responses are estimated to be positive for increased spring season (April-June) inflow and negative for increased summer (July-August) inflow. In addition, the estimated harvest responses are all positive to autumn inflow (the tropical storm dominated September-October interval), except for the slight negative responses of the finfish and spotted seatrout components to increased autumn inflow at Colorado delta. Although penaeid shrimp harvests relate negatively to both late fall (November-December) and winter (January-March) season inflows, the blue crab, bay oyster, finfish, and red drum fisheries components are estimated to respond positively to late fall inflow, especially when it occurs at Lavaca delta. Only blue crab, bay oyster, and finfish components relate positively to winter inflow.

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's 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.

Estimated Freshwater Inflow Needs

A methodology is presented in Chapter IX which combines the analysis of the component physical, chemical and biological elements of the Lavaca-Tres Palacios estuary into a sequence of steps which results in estimates of the freshwater inflow needed to achieve selected salinity, marsh inundation and fishery harvest objectives.

Monthly mean salinity bounds are specified for selected locations in the estuary near the inflow points of the Colorado and Lavaca River Basins. These upper and lower limits on monthly salinity were selected to provide a salinity range which will not exceed bounds for viable metabolic and reproductive activity, and also which will not exceed median monthly historical salinity conditions.

Marsh inundation needs, for the flushing of nutrients from riverine marshes into the open bays, are computed and specified for the Lavaca and Colorado River deltas. Inundation of the marshes in the Colorado River delta is rarely the result of freshwater discharge from the Colorado River, but is normally due to tidal action. As a result, no inflow requirements for inundation of the Colorado River delta are specified from the Colorado River Basin.

The Lavaca River delta, however, is frequently submerged by floods from the Lavaca and Navidad Rivers. Based upon historical gaged streamflow records and mathematical analyses, freshwater inflows for marsh inundation needed to sustain historical inundation magnitude and frequency are estimated at 70.0 thousand acre-feet (86 million m^3) in each of the months April and May, and 60.0 thousand acre-feet (74 million m^3) in October. These volumes correspond to flood events with peak flow rates of 11,320 ft^3/sec (321 m^3/sec) and 10,370 ft^3/sec (294 m^3/sec), respectively.

Evaluation of Estuarine Alternatives

Estimates of the freshwater inflow needs for the Lavaca-Tres Palacios 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 Colorado and Lavaca River Basins which best achieve a specified objective.

The monthly freshwater inflow needs for the Lavaca-Tres Palacios estuary were estimated for each of three selected alternatives.

Alternative I (Subsistence): minimization of annual combined inflow while meeting salinity bounds and marsh inundation needs;

Alternative II (Maintenance of Fisheries Harvests): minimization of annual combined inflow while providing annual commercial harvests of red drum, seatrout, all shrimp, blue crab, and bay oysters at levels no less than their mean 1962 through 1976 historical values, satisfying marsh inundation needs, and meeting metabolic bounds for salinity; and

Alternative III (Shellfish Harvest Enhancement): maximization of the total annual commercial estuarine harvest of shellfish (represented by the sum of all shrimp, blue crab, and bay oyster harvests) while meeting bounds for salinity, satisfying marsh inundation needs, providing commercial harvests of bay oysters at no less than mean 1962 through 1976 historical values and utilizing an annual combined inflow no greater than the average 1941 through 1976 historical combined inflow.

Under Alternative I (Subsistence), the Lavaca-Tres Palacios 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, with slightly reduced estimated harvests. Freshwater inflows totalling 2.1 million acre-feet (2.6 billion m^3) annually are predicted to satisfy the basic salinity gradient and marsh inundation needs, but would result in slight decreases in commercial finfish and shellfish harvests of five percent from average values for the period 1962 through 1976 (Figure 1-1).

Under Alternative II (Maintenance of Fisheries Harvests), the predicted annual commercial harvests of red drum, spotted seatrout, all shrimp, blue crab and bay oysters are required to be at least as great as historical average levels. To satisfy these criteria, it is estimated that an annual freshwater inflow of about 2.8 million acre-feet (3.5 billion m^3) is needed (Figure 1-1).

Under Alternative III (Shellfish Harvest Enhancement), the Lavaca-Tres Palacios estuary annually needs an estimated 2.81 million acre-feet (3.5 billion m^3)[1/], distributed in a seasonally unique manner (Figure 1-1). This is necessary to achieve the objective of maximizing the total annual predicted commercial harvest of shrimp, blue crab and bay oysters, with the condition that the predicted commercial harvest of bay oysters is at least as great as the 1962 through 1976 historical average. Alternative III is achieved with a 22 percent increase in shellfish harvest, at an estimated loss of five percent in total commercial finfish harvest.

[1/] Freshwater inflow supplied to the estuary under Alternative III was not allowed to exceed the historical "combined inflow" (1941 through 1976) as defined in Chapter IV.

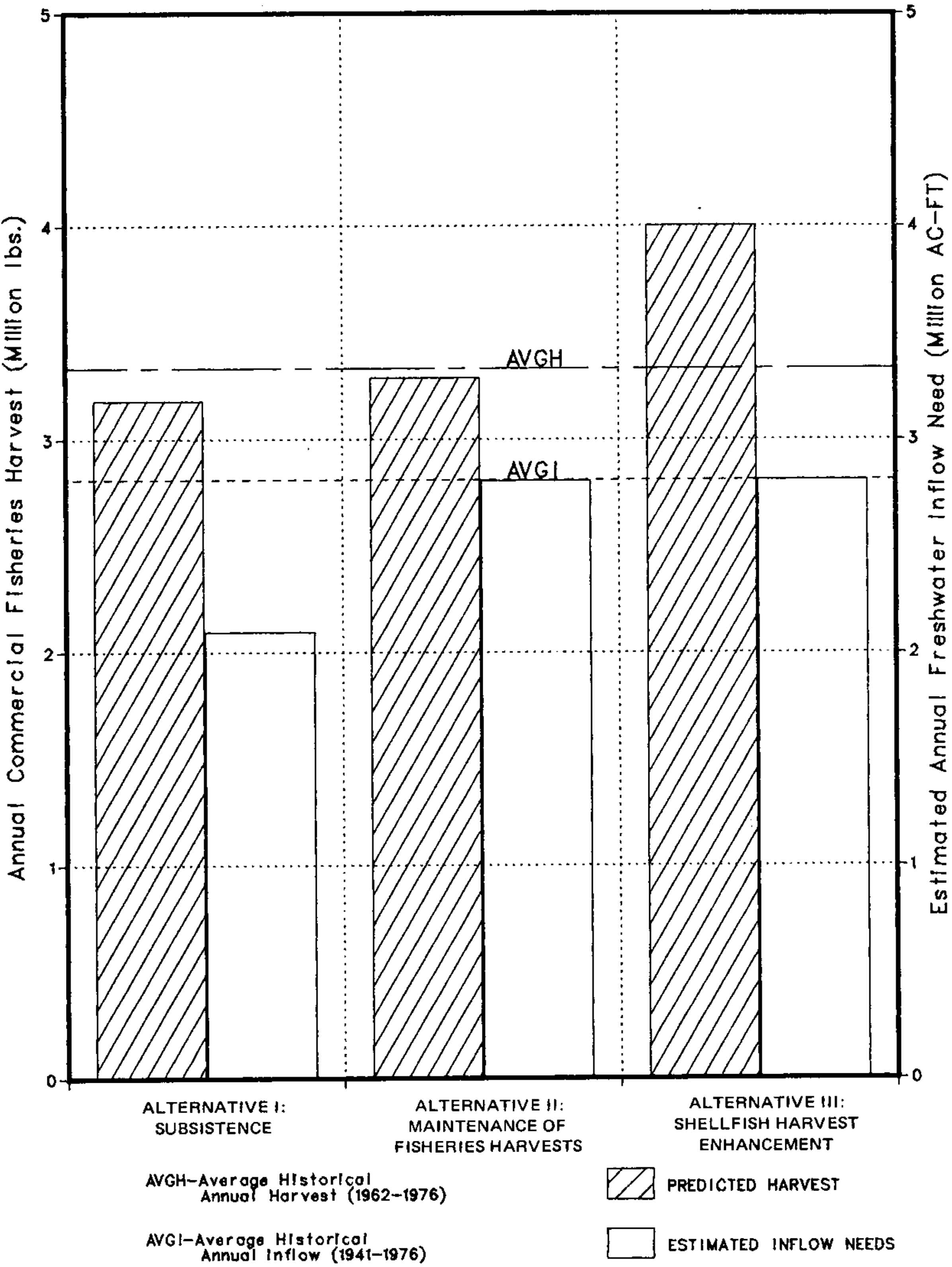

Figure 1-1. Predicted Annual Commercial Fisheries Harvest and Estimated Inflow Needs under Three Alternatives for the Lavaca-Tres Palacios Estuary

The monthly distribution of the inflows for each of the Alternatives and the average historical monthly 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 Lavaca-Tres Palacios 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 internal circulation currents dominate the water movements of the Lavaca-Tres Palacios estuary. Depending upon the month simulated, the net circulation in Matagorda Bay reveals up to three individual currents, each moving in a circular pattern within the boundaries of the bay. Water in Matagorda Bay is readily mixed among these circulation currents; however, relatively little net flow of water, except during high freshwater inflow periods, takes place among Matagorda, Lavaca, and Carancahua Bays.

The simulated salinities in the Lavaca-Tres Palacios estuary for the estimated monthly freshwater inflow needs vary over a wide range. Salinities throughout the estuary are lowest in the month of June, with average simulated salinities of less than 20 parts per thousand (ppt) over the entire estuary. The highest levels of simulated salinities occur during the month of August, when salinities in Matagorda Bay near Pass Cavallo exceed 30 ppt. The simulated salinities for Lavaca Bay are generally less than 15 ppt throughout the year. The major portion of Matagorda Bay has simulated salinities of between 20 and 25 ppt; however, during the high freshwater inflow months of May and June, the salinities in the bay are between 10 and 20 ppt.

Since the middle portion of Matagorda Bay has simulated salinities in all months below a target maximum allowable concentration of 25 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. The Alternatives considered 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 resident aquatic organisms.

[1/] The alternative having the lowest inflow level and thus the alternative that would impinge most heavily upon salinity levels.

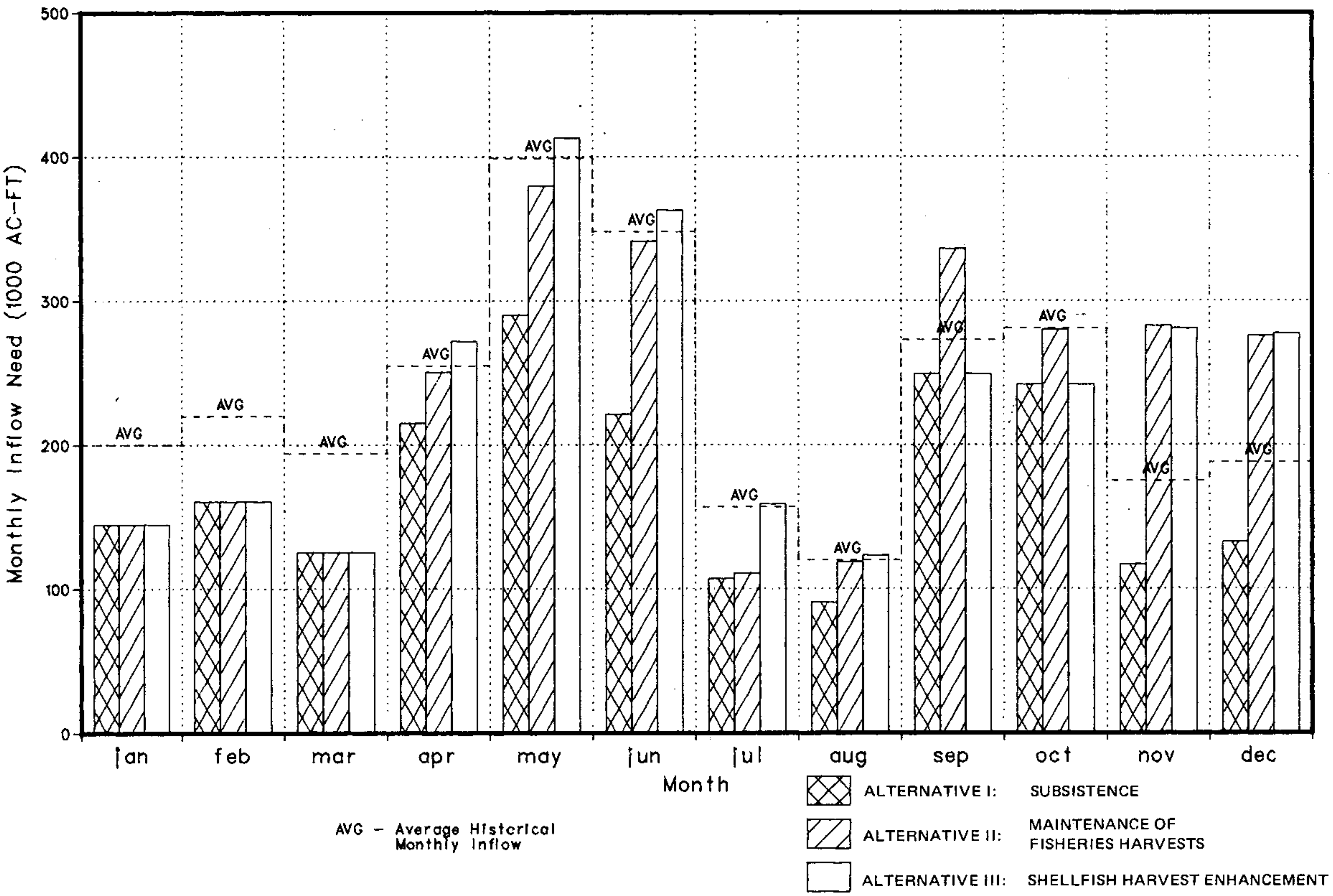

Figure 1-2. Estimated Monthly Freshwater Inflow Needs for the Lavaca-Tres Palacios Estuary under Alternatives I, II, III

CHAPTER II

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

Scope of Study

Senate 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 Lavaca-Tres Palacios 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 (168). 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 Lavaca-Tres Palacios 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 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) and include many shallow bays behind the barrier islands (325). Physical characteristics of the Lavaca-Tres Palacios 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 Lavaca-Tres Palacios 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

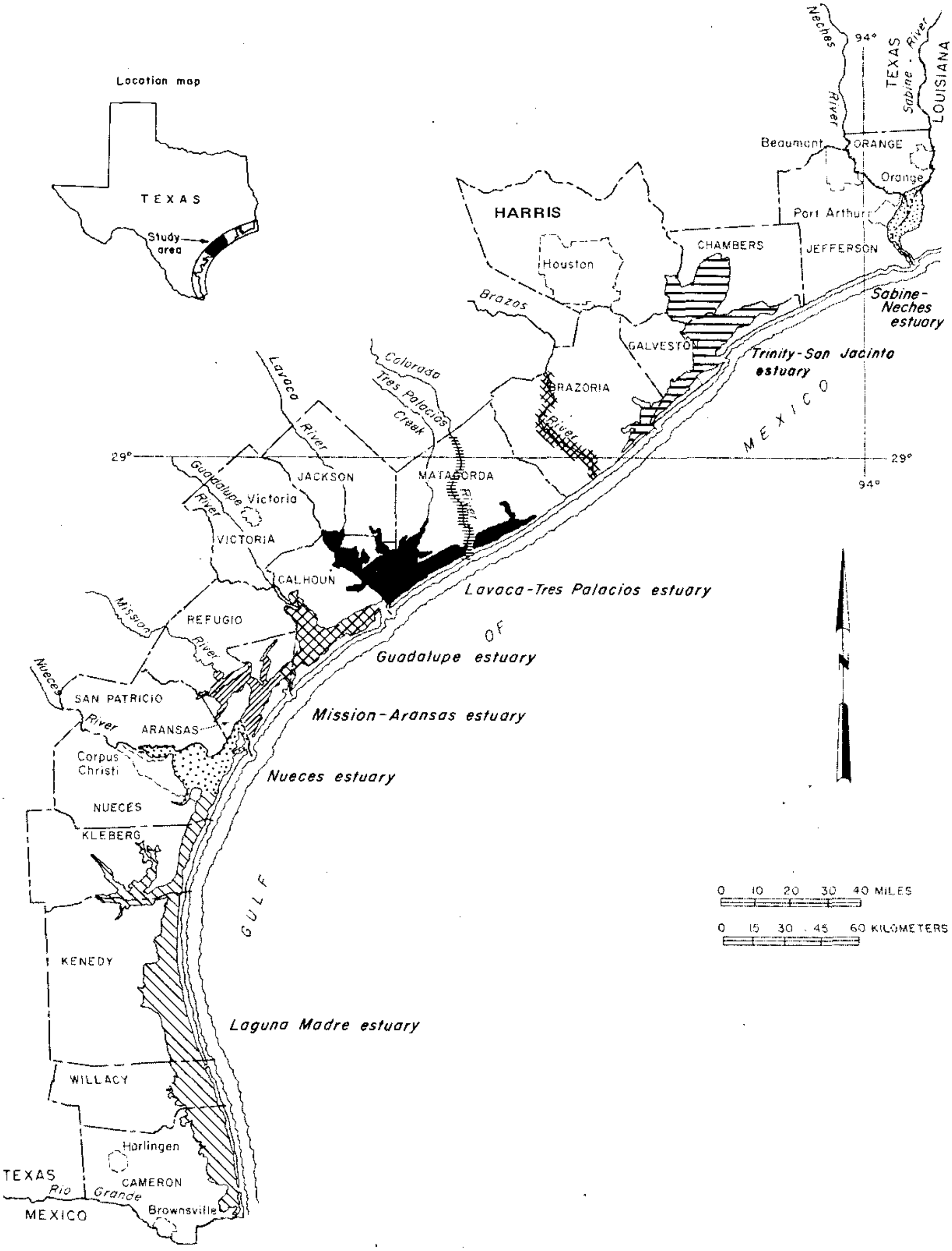

Figure 2-1. Locations of Texas Estuaries

Base from Official State Highway Map of Texas, 1971 nutrients, such as nitrogen and phosphorus; the basic cellular building block, 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, shellfish, and finfish.

Salinity, temperature, and 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 species fluctuate with the seasons and with hydrologic cycles (177, 63, 175). 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 Lavaca-Tres Palacios 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 (37, 137, 40, 94, 158, 205). The aquatic ecosystem can be conceptualized as comprising four major components, all interrelated through various life processes (Figure 2-2):

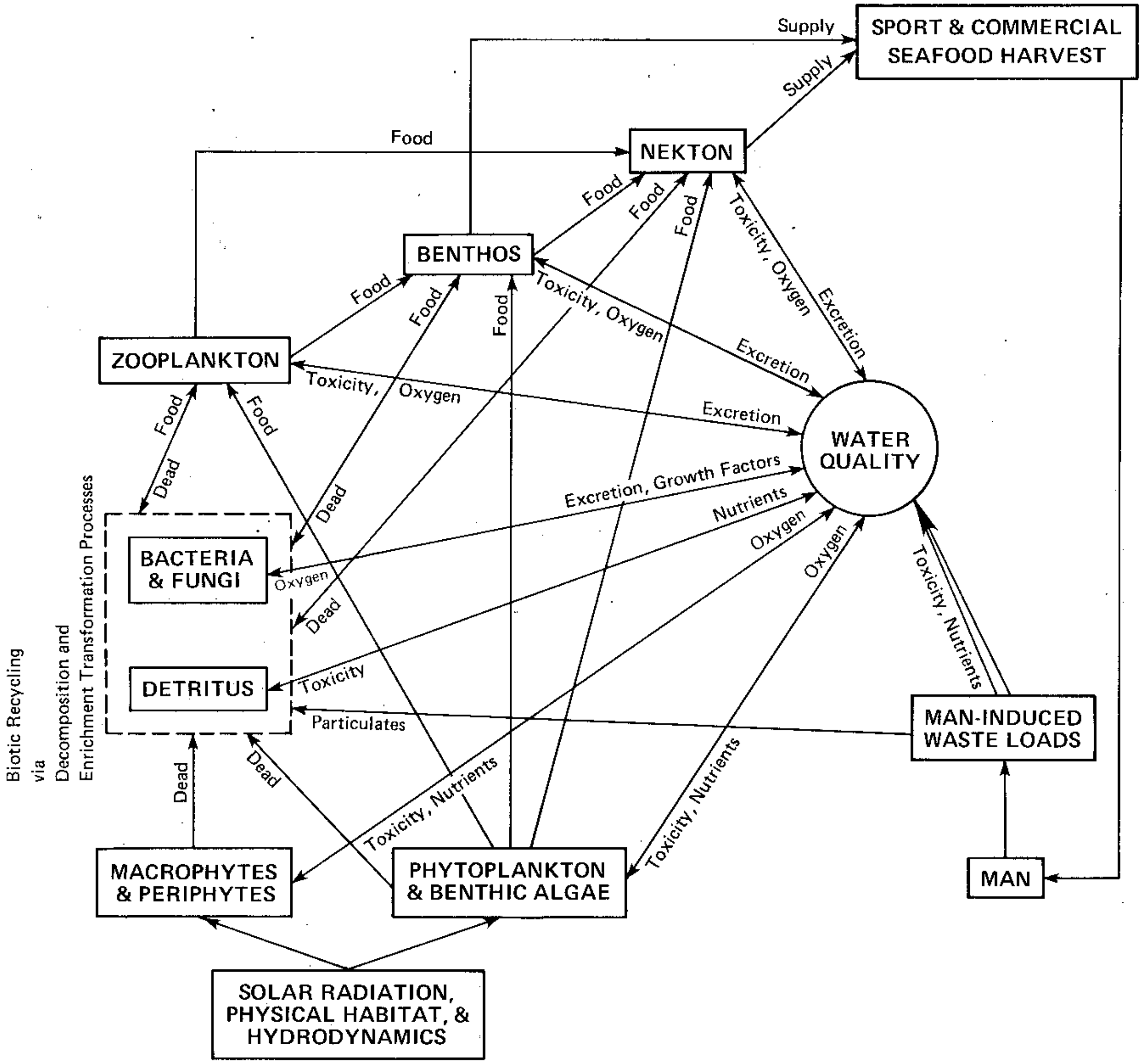

Figure 2-2. Component Schematic Diagram of a Generalized Texas Estuarine Ecosystem.

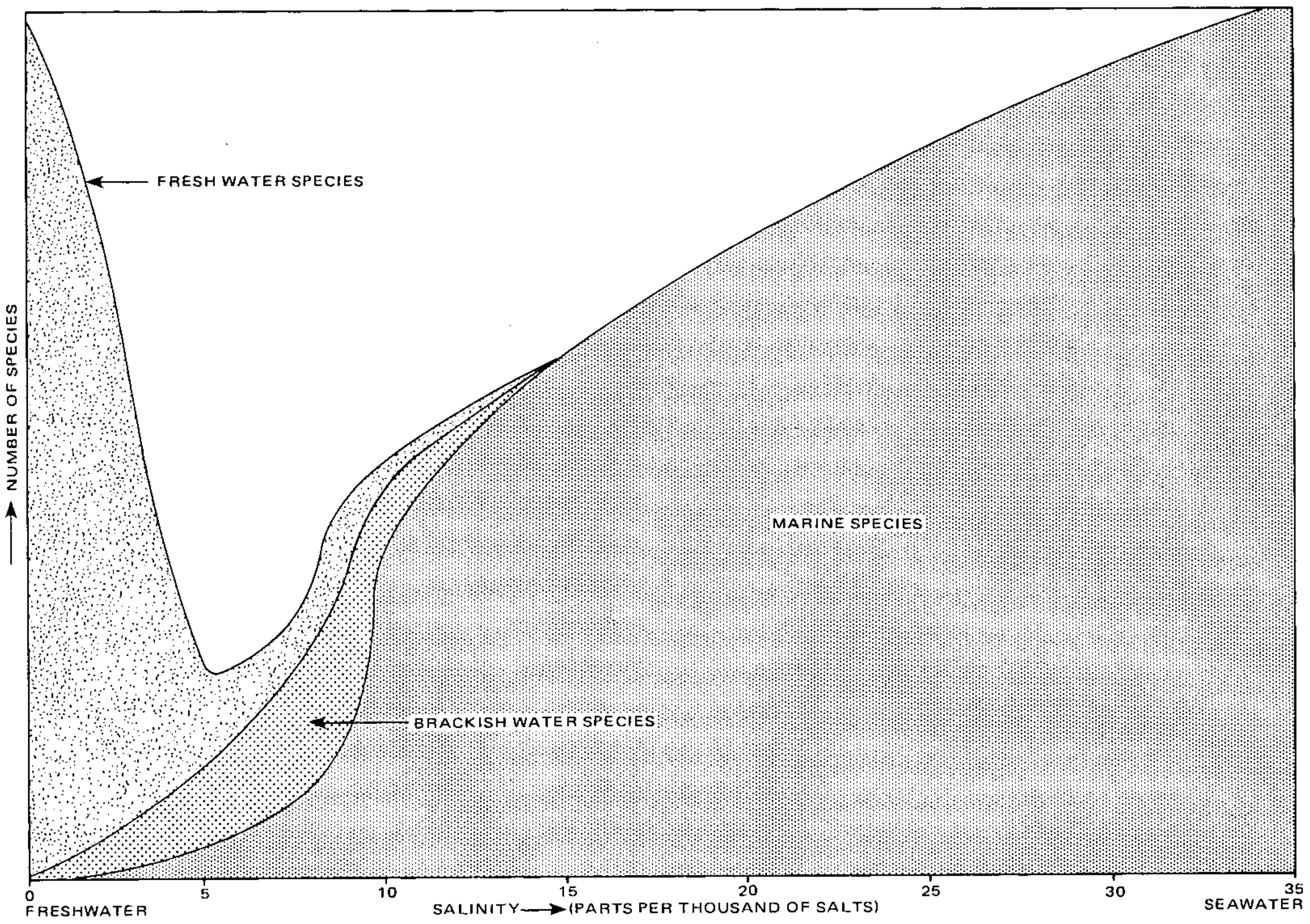

Figure 2-3. Species Composition of Estuarine Environments (177).

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 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 (182). 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 (114, 384), and/or for protection against predators and parasites (119, 166). Juvenile forms use the shallow "nursery" areas during early growth (76), migrating back to the Gulf of Mexico in their adult or subadult life stage.

For high ecosystem 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 (397).

Virtually all (97.5%) of the Gulf fisheries species are considered estuarine-dependent (77); however, the seasonal aspects of their life cycles

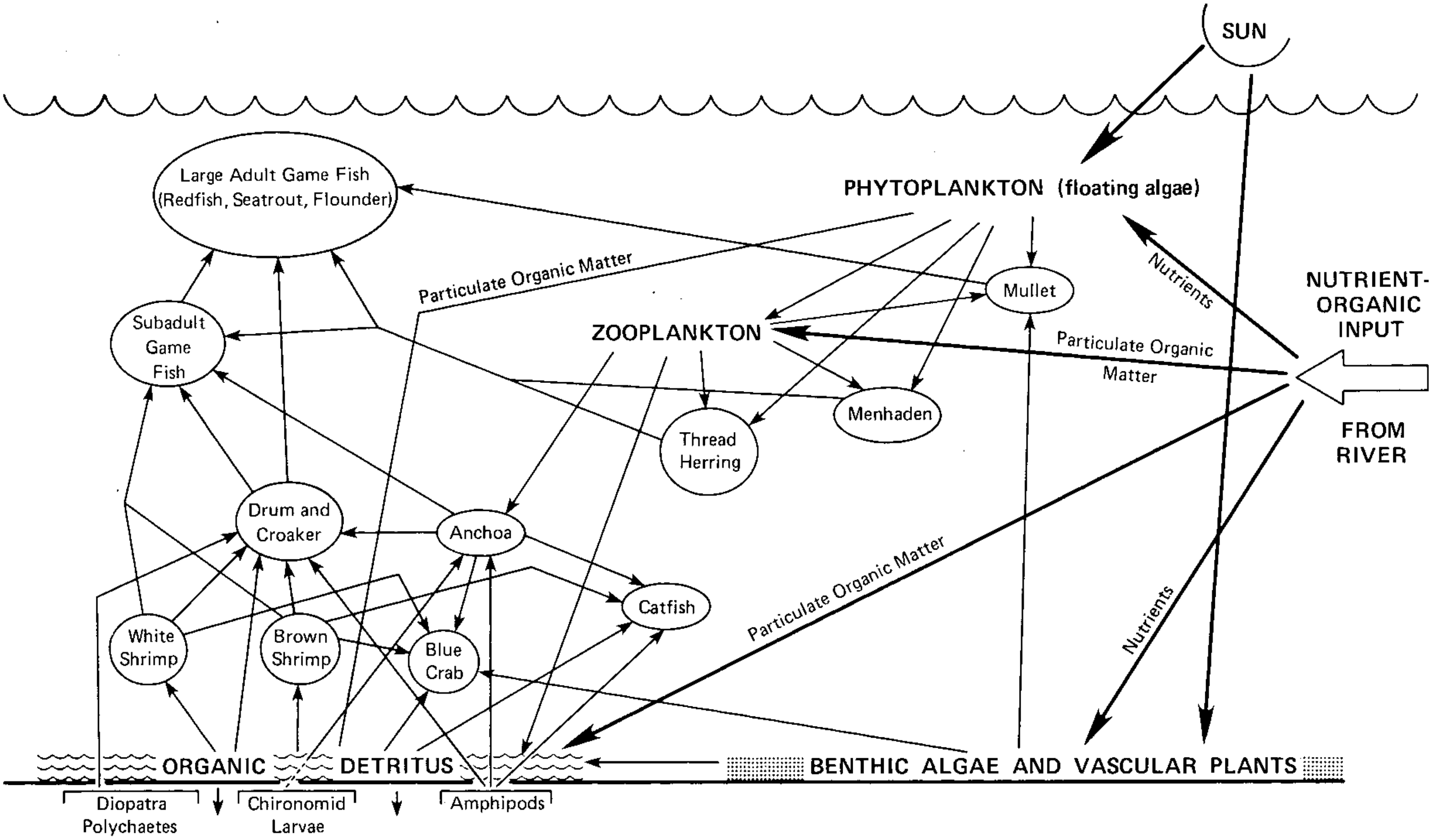

Figure 2-4. Simplified Trophic Relationships in a Texas Estuary [after WRE (390)].

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 "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 (153).

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 (49). Throughout the world, only tropical rain forests, coral reefs, and some algal beds produce more abundantly per unit of area (158, 290).

Marsh production has been shown to be a major source of organic material supporting the estuarine food web in coastal areas from New England and the South Atlantic, to the Gulf of Mexico (32, 94, 136). Because of high plant productivities an estuarine marsh can assimilate, if necessary, substantial volumes of nutrient-rich municipal and industrial wastes (380, 381) 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 provide 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. Hundreds of thousands of acres of adjacent marshes 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 induce physiological 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. Finfish and shellfish species, in particular, 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 the estuarine-dependent species.

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 relationships 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 statements approximating 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 algorithms, 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 Lavaca-Tres Palacios 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

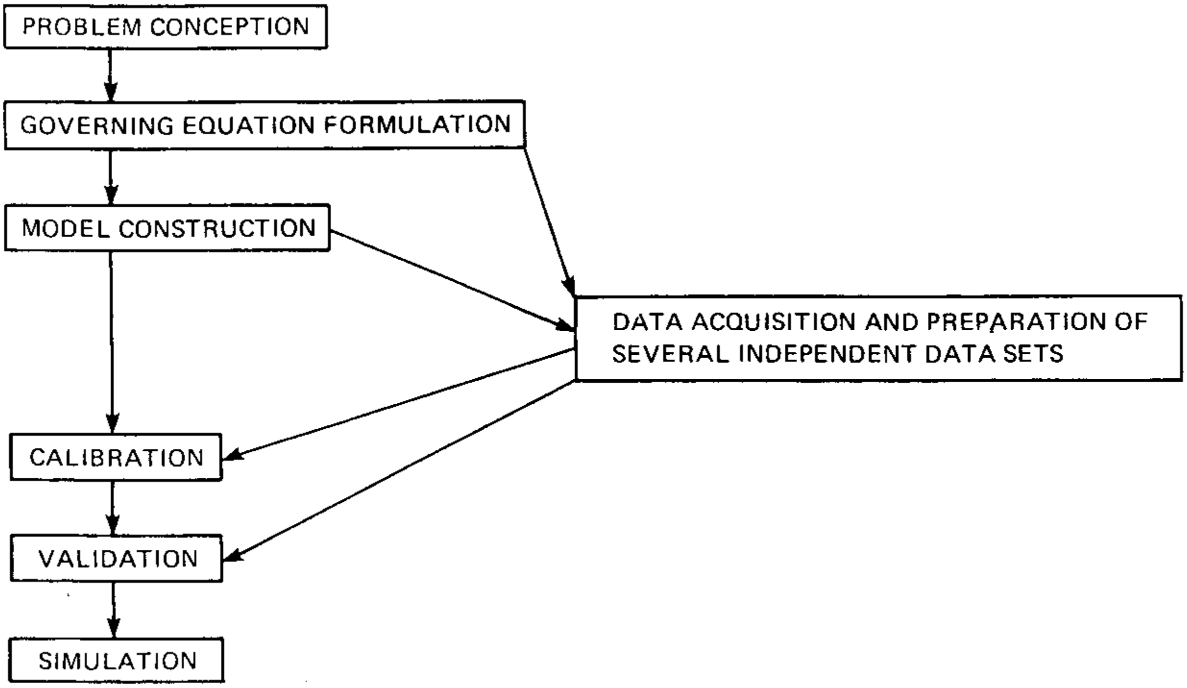

Figure 2-5. Flow Diagram of Model Development

identifiable biological populations can be used, however, as "key indicators" to understand and demonstrate the response of higher food chain organisms, such as shellfish and finfish, to major changes in the ecosystem (199, 158). Physical and chemical constituents of prime importance to the estuarine ecosystem include freshwater inflows, 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 overlying water column. The subsidence of the flood waters and the subsequent dewatering of the marshes results in the movement of organic nutrients from the marsh into the nearby tertiary and secondary bays. On the other hand, large volumes of freshwater inflow can also be detrimental and may act to flush even the primary bays of an estuarine system. Flood events may resuspend and transport sediments, increase turbidity, and cause a rapid decrease in the standing crop of phytoplankton, zooplankton, benthos and nekton 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 (93, 140). 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 resource 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 (146). 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 the estuary is vital to the understanding of environmental conditions within the system. To better assess the variations in salinities, a salinity transport mathematical model has been developed (146, 147) 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; evaporation 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 also 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 (32, 136). 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 and water depths in a river delta (44). This model applies in cases of both low-flow and flood conditions. The effects of freshwater inflow 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

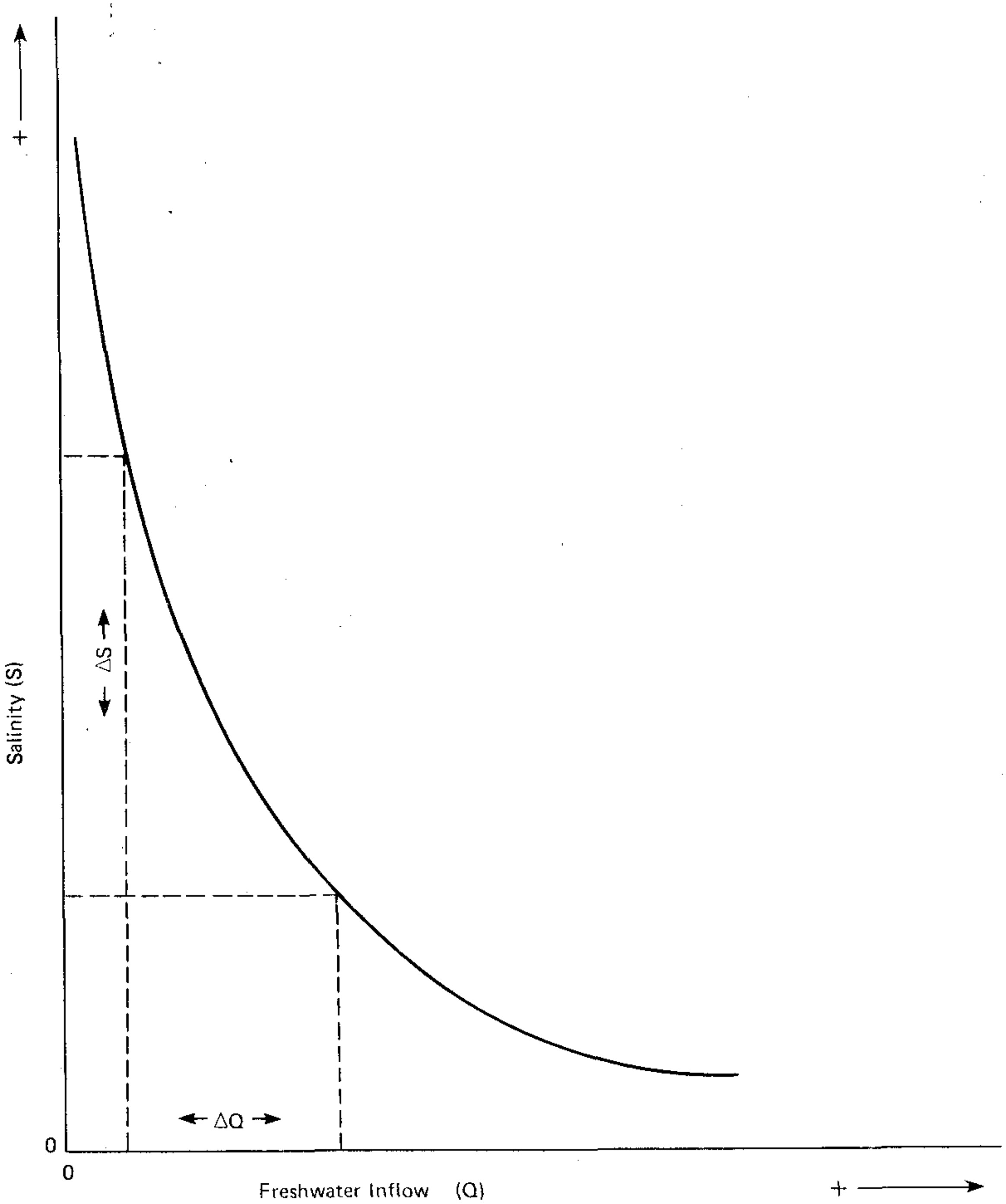

Figure 2-6. Typical Variation of Freshwater Inflow Versus Salinity in a Texas Estuary

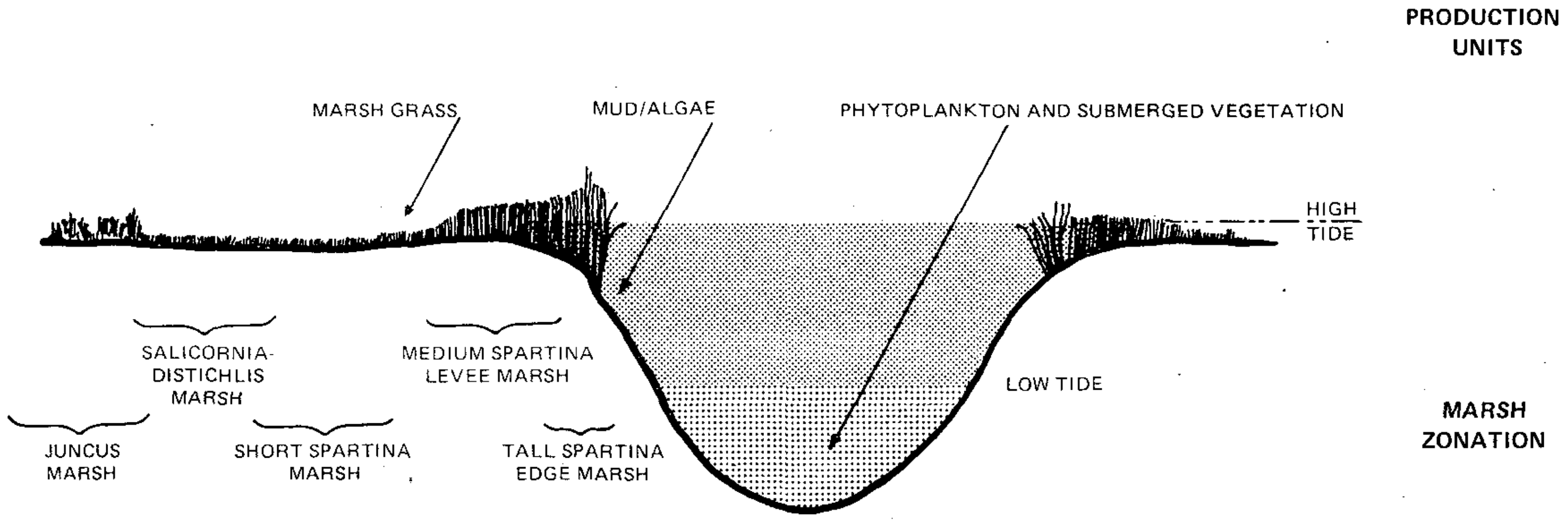

Figure 2-7. Zonation of a Salt Marsh in a Texas Estuary (230).

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 a short enough life cycle to permit observation of changes in organism densities and productivity in association with observations of environmental change.

Dr. Eugene Odum has remarked that "ecologists constantly employ such organisms as indicators in exploring new situations or evaluating large areas" (158). 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 the 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 (230). 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 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 are not yet available to accurately calibrate the estuarine ecologic model for simulation periods in excess of one year. 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, white shrimp, brown and pink shrimp, blue crab, and bay oysters 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 freshwater inflows. However, there are variations in the historical harvest data which were 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 much needed data does not exist, so the mathematical representations required to describe such phenomena have not been adequately defined. Therefore, regression techniques are being 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 (271, 272) and Wakeman (388) have reported on the stress of salinity changes upon the metabolic activities of several Texas estuarine fish species. Wakeman (388) 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. 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 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 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 (35) 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 fish harvested, but also the predicted harvest levels and salinities resulting from the 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 the salinity, metabolic stress, 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 fish 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 Lavaca-Tres Palacios estuary is discussed in Chapter IX.

Techniques for Meeting Freshwater Inflow Needs. The freshwater inflow 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 most likely 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 most likely 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 ultimately, the possible 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 highly 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 69 percent complete. Although the adjudication program is being accelerated, several years will be required to complete the remaining unadjudicated 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 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 for estuarine inflow 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 Lavaca-Tres Palacios 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 the 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 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. 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 inflow.

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 Lavaca-Tres Palacios estuary covers about 352 square miles (910 square kilometers) and includes Matagorda Bay, Lavaca Bay, Cox Bay, Keller Bay, Carancahua Bay, Tres Palacios Bay, and several smaller bays (Figure 3-1). Water depth at mean low water varies from six feet (1.8 meters) in the Colorado River Channel to 13 feet (4.0 meters) or less in Matagorda Bay, except in parts of the Matagorda Ship Channel, where the depth is 36 feet (11.0 meters).

This study area lies in the Upper Coast climatological division of Texas in the warm temperate zone. Its climatic type is classified as subtropical (humid and warm summers). The climate is also predominantly marine because of the proximity of the Gulf of Mexico. Prevailing winds are southeasterly to south-southeasterly throughout the year. Day-to-day weather during the summer offers little variation except for the occasional occurrence of thunderstorms. The sea breeze allows warmer daytime temperatures during winter and prevents the summer daytime temperatures from becoming as high as those observed further inland. Winters are mild and the moderate polar air masses which push rapidly southward out into the Gulf bring cool, cloudy, and rainy weather for brief periods.

Some of the heavier rainfall occurrences during late summer and early fall are associated with tropical disturbances which move in with the easterly waves. Snow is a rare occurrence.

The annual net lake surface evaporation rate in the area is about 20 inches (50.8 cm). Seasonal variation in relative humidity is small as a result of the influence of the Gulf and the direction of the prevailing wind.

Influence of Contributory Basins

Drainage areas within the State of Texas contributing totally or in part to the Lavaca-Tres Palacios estuary include approximately 44,040 square miles (114,600 km^2), divided among the Colorado River Basin, the Lavaca River Basin, the Colorado-Lavaca Coastal Basin, and the Lavaca-Guadalupe Coastal Basin (Figure 3-2). This vast area includes various climatic zones with a wide variation in precipitation and evaporation across the region, east and west.

The Colorado River Basin includes approximately 41,800 square miles (108,800 km^2) in Texas and New Mexico, of which only 1,900 square miles (4,940 km^2) are in New Mexico. Approximately 12,880 square miles (343,514

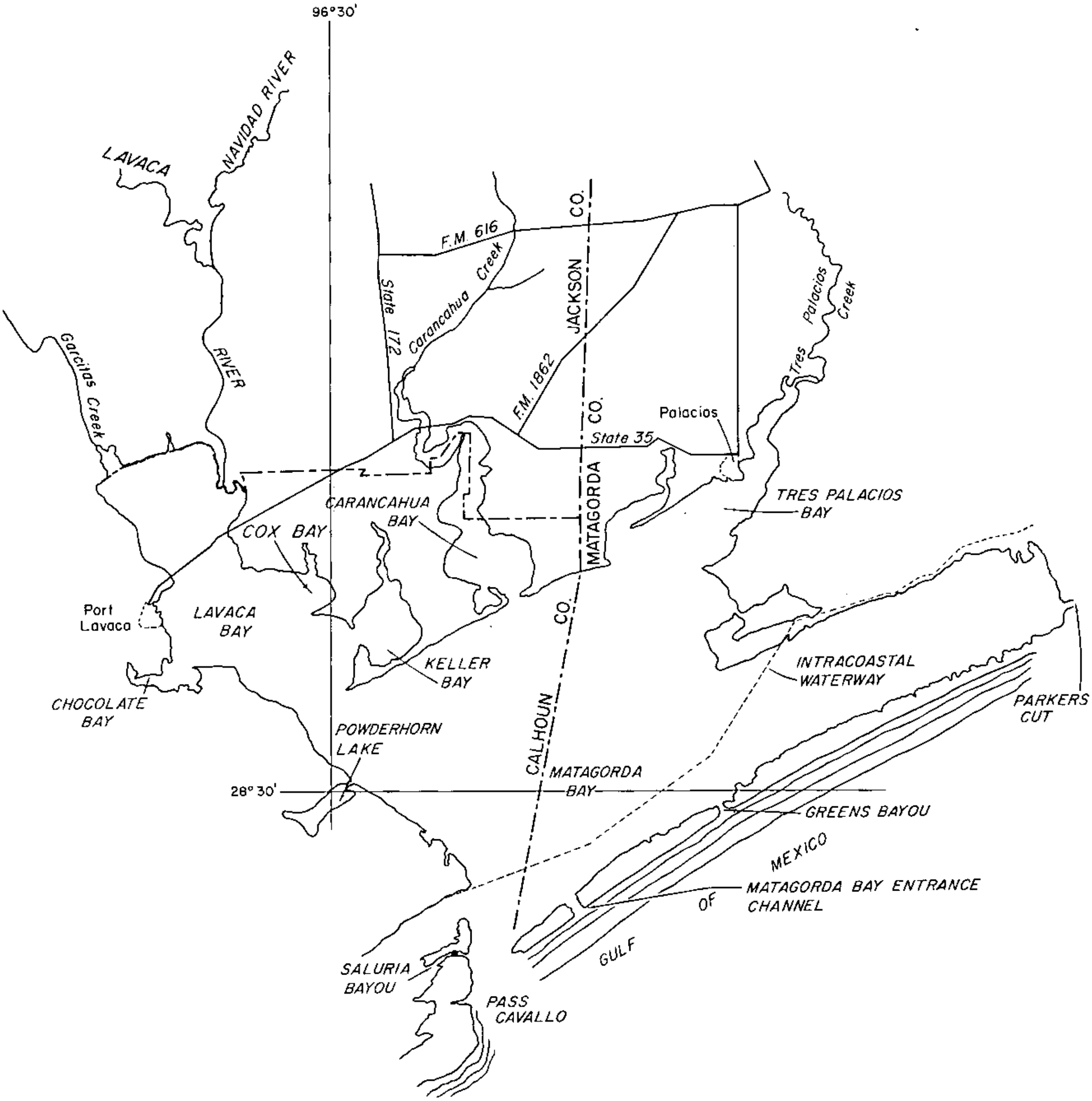

Figure 3-1. Lavaca-Tres Palacios Estuary.

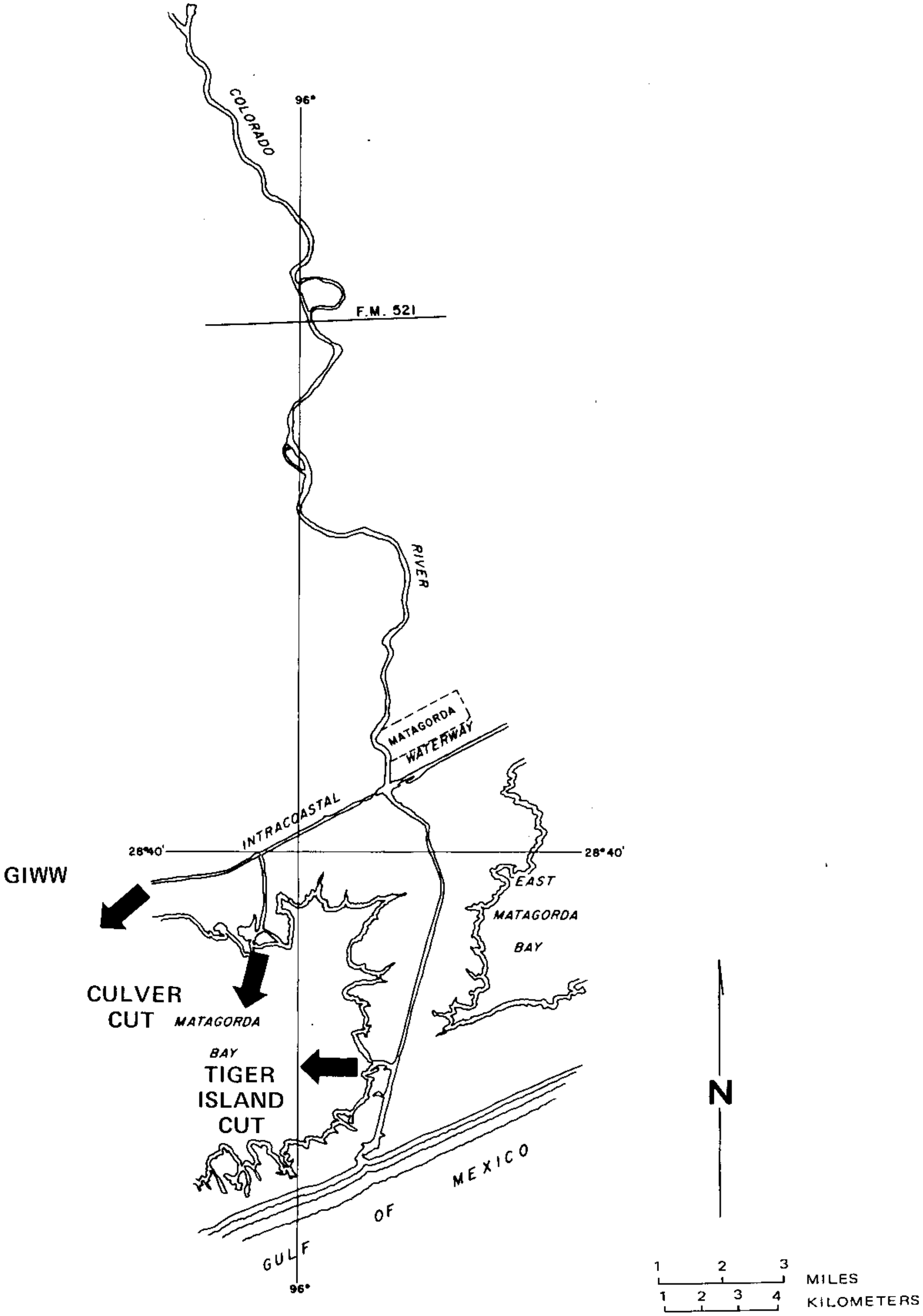

Figure 3-2. Colorado Basin Inflow to Matagorda Bay.

km^2) of the western portion of the basin are probably noncontributory. Average annual runoff in the basin ranges from a maximum of about 350 ac-ft/sq. mi. (1,670 m^3/ha) near the mouth of the Colorado River to less than 50 ac-ft/sq. mi. (240 m^3/ha) in the contributing area of the basin west of San Angelo. Major Colorado River tributaries include the Concho River, Pecan Bayou, the San Saba River, the Llano River, and the Pedernales River. A portion of the flow of the Colorado River enters the Lavaca-Tres Palacios estuary through Tiger Island Cut and the Intracoastal Waterway (Figure 3-2).

There are 24 major reservoirs either existing or under construction in the Colorado River Basin (Figure 3-3). Almost all of these impoundments are used for water supply and recreation; a few also provide for hydroelectric power generation and/or flood control (Table 3-1).

The Lavaca River Basin is made up of approximately 2,310 square miles (6,010 km^2) in the Gulf Coastal Plains. Average annual runoff in the basin varies from about 235 ac-ft/sq. mi. (1,119 m^3/ha) in the western portion to 335 ac-ft/sq. mi. (1,596 m^3/ha) in the east. A major tributary to the Lavaca River is the Navidad River. Lake Texana, which is presently under construction on the Navidad River, is the only major reservoir in the Lavaca River Basin.

The Lavaca-Guadalupe Coastal Basin drains approximately 1,000 square miles (2,600 km^2), with about 890 square miles (2,320 km^2) contributing to Lavaca Bay. Average annual runoff in the basin is approximately 200 ac-ft/sq. mi. (953 m^3/ha). Major streams of this coastal basin include Garcitas Creek, Coleto Creek and Chocolate Bayou.

The Colorado-Lavaca Coastal Basin has a drainage area of approximately 940 square miles (2,450 km^2). The average annual runoff in the basin is estimated to be about 300 ac-ft/sq. mi. (1,429 m^3/ha). All of this coastal basin drains into Lavaca-Tres Palacios estuary. Major streams in the basin include Cox Creek, Kellers Creek, Carancahua Creek and Tres Palacios Creek.

Geological Resources

Sedimentation and Erosion. The Navidad River carries an estimated average annual sediment volume of 1.04 acre-foot per square mile (4.95 m^3/ha) of drainage area as it enters the Fayette Prairie physiographic province. Much of the sediment load is deposited in the floodplains of this area due to the decreased gradient of the stream. By the time the Navidad River reaches its confluence with the Lavaca River, the average annual sediment production rate decreases to an estimated 0.24 acre-foot per square mile (1.1 m^3/ha). These figures have been developed by the U. S. Soil Conservation Service (220) and include both bedload and suspended-sediment load.

The mainland shore is characterized by near vertical bluffs cut into Pleistocene fluvial and deltaic sand, silt, and mud (Figure 3-4). Erosion of these bluffs furnish sediment to the adjacent lakes, marshes, and bays. The type of sediment deposited on the delta plain depends on whether the adjacent bluff is composed of predominantly sand or mud. Pleistocene overbank and bay muds have a high shrink-swell ratio causing desiccation cracks to form. Aided by the desiccation cracks, breaking waves cut into the base of these slopes.

Figure 3-3. Basins Contributing to the Lavaca-Tres Palacios Estuary.

Table 3-1. Reservoirs of Contributing Basins, Lavaca-Tres Palacios 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
Lavaca River Basin							
Lake Texana d/	W.S.,R	—	11,600	44.0	192.0		192.0
Colorado River Basin							
Lake J. B. Thomas	W.S.,R	1952	7,820	2,258.0	203.6		203.6
Lake Colorado City	W.S.,R	1949	1,612	2,070.2	31.8		31.8
Champion Creek Reservoir	W.S.,R	1959	1,560	2,083.0	42.5		42.5
E. V. Spence Reservoir	W.S.,R	1969	14,950	1,898.0	488.8		488.8
Oak Creek Reservoir	W.S.,R	1952	2,375	2,000.0	39.4		39.4
O. C. Fisher Reservoir	W.S.,R, F.C.	1951	5,440	1,908.0	119.2	277.2	396.4
Twin Buttes Reservoir	W.S.,R, F.C.	1963	9,080	1,940.2	186.2	454.4	640.6
Lake Nasworthy	W.S.,R	1930	1,596	1,872.2	12.4		12.4
Lake Clyde	W.S.,R	1970	449	1,872.0	5.7		5.7
Hords Creek Reservoir	W.S.,R, F.C.	1948	510	1,900.0	8.6	16.7	25.3
Lake Coleman	W.S.,R	1966	2,000	1,717.5	40.0		40.0
Brownwood Reservoir	W.S.,R	1933	7,300	1,424.6	143.4		143.4
Brady Creek Reservoir	W.S.,R	1963	2,020	1,743.0	30.4		30.4
Lake Buchanan	W.S.,R., H.E.	1938	23,060	1,020.5	992.0		992.0
Inks Lake	W.S.,R, H.E.	1938	803	888.5	17.5		17.5
Lake LBJ	W.S.,R, H.E.	1951	6,375	825.0	138.5		138.5
Marble Falls Lake	W.S.,R, H.E.	1951	780	738.0	8.8		8.8
Lake Travis	W.S.,R, H.E.,F.C.	1942	18,930	681.1	1,172.6	781.4	1,954.0
Lake Austin	W.S.,R, H.E.	1939	1,830	492.8	21.0		21.0
Lake Walter E. Long e/	W.S.,R	1967	1,269	555.0	33.9		33.9
Lake Bastrop e/	W.S.,R	1964	906	450.0	16.6		16.6
Cedar Creek Reservoir e/	W.S.,R	1978	2,434	390.0	71.4		71.4
Eagle Lake e/	Ir.	1900	1,200	170.0	9.6		9.6
South Texas Project e/	W.S.,R	1979	7,000	49.0	187.0		187.0
Lavaca-Guadalupe Coastal Basin							
None							
Colorado-Lavaca Coastal Basin							
None							

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a/ W.S. - water supply (May include municipal, manufacturing, irrigation, steam electric power and/or mining uses)
R. - Recreation
H.E. - Hydro-electric power generation
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

Figure 3-4. 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)

The process effectively removes slope support and the cliff fails by slumping. Energy levels (erosional capacity) in the Lavaca-Tres Palacios estuary are dominated by wind action, since the range of astronomical tides is only about 0.5 foot (0.15 m). Winds blowing across the bay generate waves (or wind tides) and cause a change in water level at the shoreline.

Where the Lavaca River enters Lavaca Bay, flow velocities decrease and the transport capability is reduced; thus, sediment is deposited near the headwaters, forming a bay-head delta. Due to the type of minerals comprising the transported sediment and the chemical character of Lavaca Bay, clay size particles entering the bay flocculate and settle to the bottom. The active delta forming at the mouth of the Lavaca River is classified as a high constructive elongate type delta exhibiting typical distributary mouth bars (254). These deltas develop under conditions of high sediment inflow into a relatively quiescent body of water (i.e., Lavaca Bay).

The marsh areas in the Lavaca-Tres Palacios estuary system are associated with deltas. Delta plains of active deltas, such as the Lavaca-Navidad, are covered with salt, brackish, and freshwater 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 sediment deposition, the plants drown and erosion by waves and currents deepen the marsh to form lakes or enlarged bay areas.

The Lavaca-Navidad delta is being eroded along its perimeter except in the immediate area of the mouth of the Lavaca River. The active delta has prograded about 2.7 miles (4.4 km) into Lavaca Bay, with rates near the river mouth of 4 feet per year (1.2 m) for the period 1957 through 1972 (254).

At the present, marsh surface-water level relationships of Garcitas, Lavaca, and Colorado deltas are reported to be stable (257). Sedimentation rates and subsidence apparently have a constant relationship. 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.

Shoreline and vegetation changes within the Lavaca-Tres Palacios estuary and in other areas of the Texas Gulf Coast are the result of natural processes (257, 258). Erosion produces a net loss of land; accretion, a net gain of land; and equilibrium conditions, no net change in land area. Shorelines are either in a state of erosion or accretion, or have been stabilized either naturally or artificially.

Most of the shorelines associated with the Lavaca-Tres Palacios estuary system are eroding (Figures 3-5), which indicates that the sediment volume supplied to Gulf and bay shorelines is insufficient to balance the amount of sediment removed by waves and longshore drift (254). The nature of beaches is

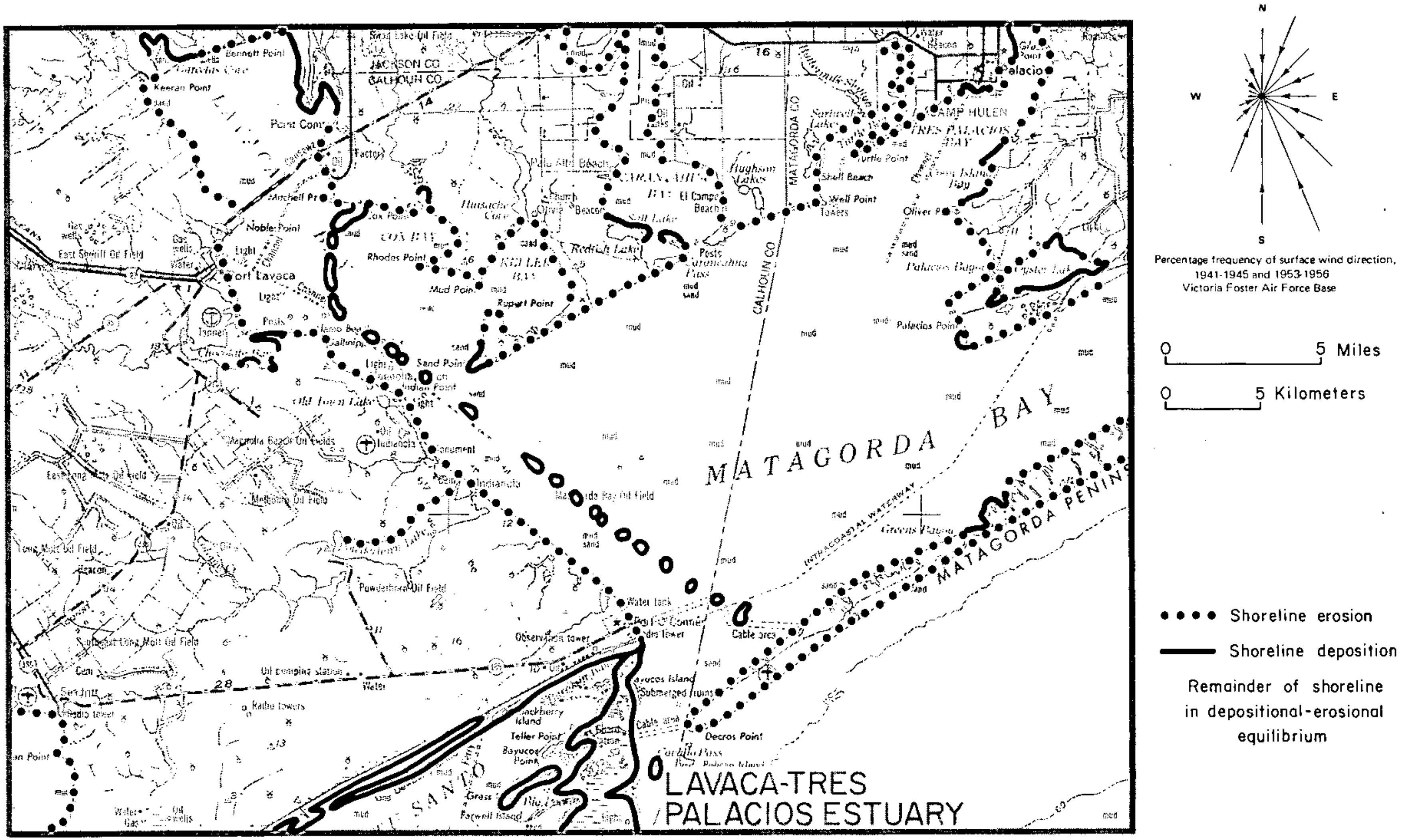


Figure 3-5. Shoreline Physical Processes, Lavaca-Tres Palacios Estuary (254).

an indicator of the condition of shoreline stability. Sediments of the mainland beaches are a mixture of sand, shell, and rock fragments, with shell and rock fragments being the most common constituents. This is an indication that very little sand is currently being supplied to these beaches by the rivers.

Processes that are responsible for the construction of shorelines and that are presently modifying shorelines in the Lavaca-Tres Palacios 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 bay to a maximum of about 2 feet (0.61 m) along the Gulf shorelines. Wind is a major factor in influencing coastal processes; it can either raise or lower water levels along the Gulf and/or mainland shore according to the direction it is blowing. Wind also generates waves and longshore currents (179, 92, 291).

The seasonal threat of wind and water damage associated with tropical cyclones entering 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 (190). Storm surge flooding and attendant breaking waves may erode Gulf shorelines tens or hundreds of feet. Surge heights may range up to 15 feet in some areas (254, 255). 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 correspond either with spring thunderstorms or with the summer hurricane season. Rivers generally flood as a result of regional rainfall, but flooding along smaller streams may be activated by local thunderstorms (254). Some effects of flooding include: (1) overbank flooding into marsh areas of the floodplain and onto delta plains; (2) building of bay-head 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 3-6), which serve not only for fuel but also provide raw material for many petrochemical processes. In addition, the coastal zone contains important resources of chemical raw materials, such as sulfur, salt and shell for lime. The great abundance of these chemical and petroleum raw materials and their occurrence in a zone with ocean access helps to make this area one of the major petrochemical and petroleum-refining centers of the world.

The production of oil, natural gas, and natural gas liquids plays a prominent role in the economy of the Lavaca-Tres Palacios estuary. 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 from the Texas coastal zone are natural aggregates and bulk construction materials (e.g., gravel and stone for crushing). At the

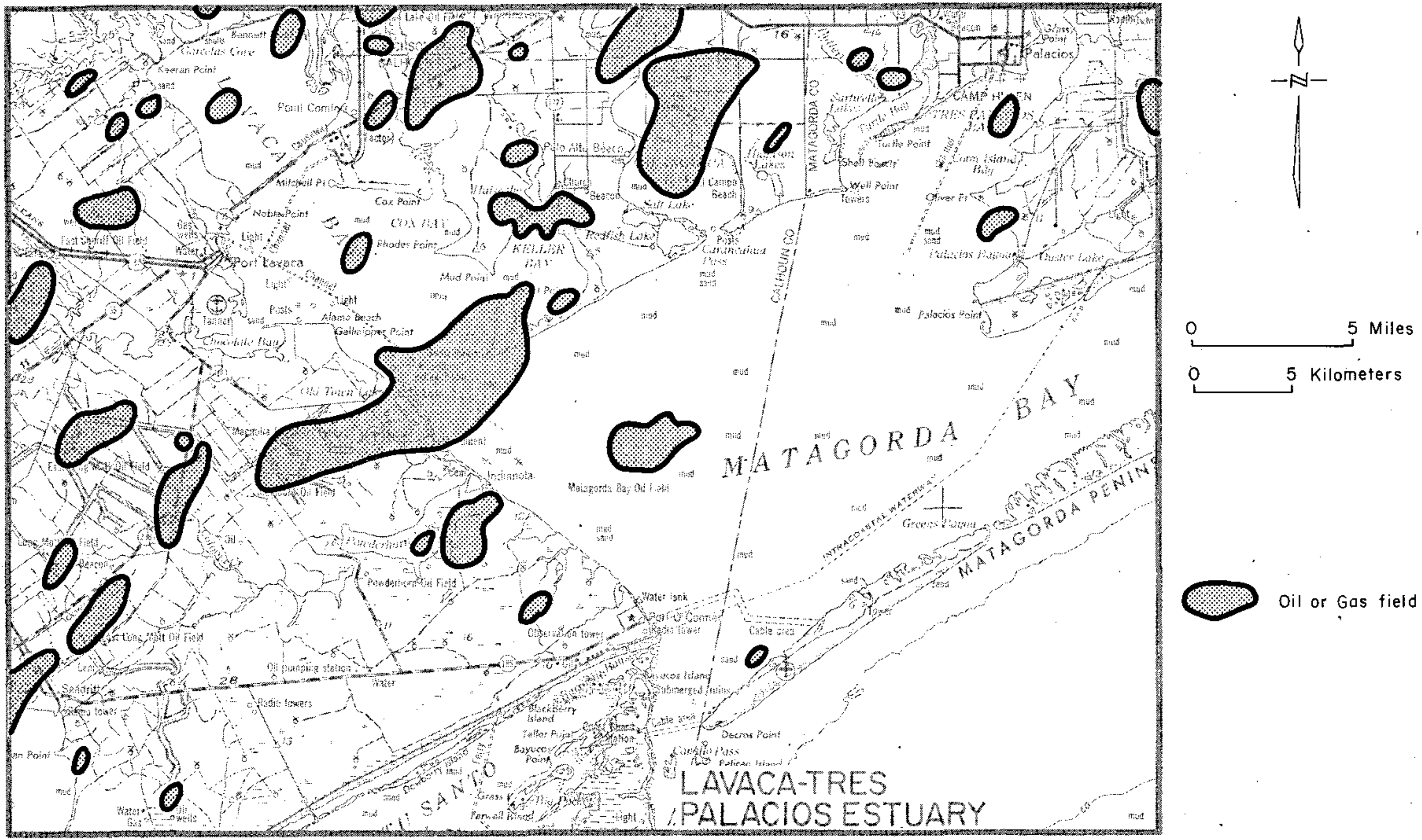


Figure 3-6. Oil and Gas Fields, Lavaca-Tres Palacios Estuary (254).

same time, however, 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.

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 150 miles (240 km) from the nearest Central Texas source. Shell resources are finite, and at present rates of consumption in the coastal zone 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 Lavaca-Tres Palacios 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 Age; and the Willis, Lissie, and Beaumont Formations of Quaternary Age. These ancient sedimentary units are not uniform in composition and thickness; they 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 are hydrologically connected laterally and vertically. Because of this interconnection, groundwater can move from one bed to another and from one formation to another. Thus the entire sequence of sediment, with the exception of the Jackson Group, functions as a single aquifer referred to as the Gulf Coast Aquifer.

Near the Lavaca-Tres Palacios estuary the 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 1,600 feet (488 m). The most productive part of the aquifer is from 200 to 600 feet (61 to 183 m) thick (232).

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

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 (257, 258).

The Lavaca-Tres Palacios estuary lies in the Coastal Prairie land resource area (319). The native vegetation consists of coarse grasses with a narrow fringe of trees along the streams. Much of the surrounding area is now covered by improved pasture grasses and cultivated crops. Marshes are confined to narrow strips along the coast and are composed of saltgrass, cordgrass, and spikesedge. Soils vary from light, acid sands to darker, loamy clays.

Land use in the area is dominated by agricultural and ranching activities (Figure 3-7), with rice being the principal irrigated crop (227, 321). Results of studies on irrigation return-flow quantities (324) show that 30 to 40 percent of the water applied for rice irrigation returns as surface flow to the drainage system. Crops such as grain sorghum, corn, soybeans, and cotton are dryland crops produced in the area. Improved pastures have been created from brushland. Forested areas, primarily oak, are prevalent.

The only state-owned recreational facility in the immediate vicinity of the Lavaca-Tres Palacios estuary is the Port Lavaca Causeway, a lighted fishing pier. Archeological sites within the area indicate aboriginal utilization of the region from the Paleo-Indian through the Neo-American periods (294). Important historic sites (Figure 3-8) include the Townsite of Indianola, a 19th century seaport in Calhoun County, the Nuestra Senora del Refugio Mission (possible location), and Fort St. Louis (established in 1685 by Rene Robert Cavelier, Sieur de la Salle, on Garcitas Creek) (248, 249, 323).

The Lavaca-Tres Palacios estuary system is a significant resource of the commercial fishing industry in Texas. Since 1962, the average annual commercial catch (all species) from this bay system has exceeded 3.3 million pounds (1.5 million kilograms), second in Texas only to Galveston Bay. Shellfish, particularly shrimp, comprise the major portion of the commercial landings, accounting for more than 90 percent of the total harvest weight. The remaining portion of the annual commercial catch is distributed among the finfish species, with seatrout, red drum, black drum, and flounder being the major commercial species.

Natural resources of the bay system and adjoining inland areas provide a wide variety of recreational opportunities for the people of Texas, as well as visitors from other states. Water-oriented recreational activities such as fishing and boating, skiing, and swimming are amply available to the recreationists, with approximately 240,000 surface acres (97,000 hectares) of bay waters available for recreational use. The fishing resources of the Lavaca-Tres Palacios estuary system include many fish species preferred by sport fishermen. Sport creel studies conducted by the Texas Parks and Wildlife Department (347) indicate that an estimated 970,000 pounds (440,000 kilograms) of fish (all species) were harvested by sport fishermen in this estuary during the year 1975 through 1976. Species composition of the sport harvest was predominantly seatrout (32.6 percent), gafftop-sail (19.4 percent), and flounder (18.2 percent). Other preferred species include red drum, black drum, croaker, sand trout, and sheepshead.

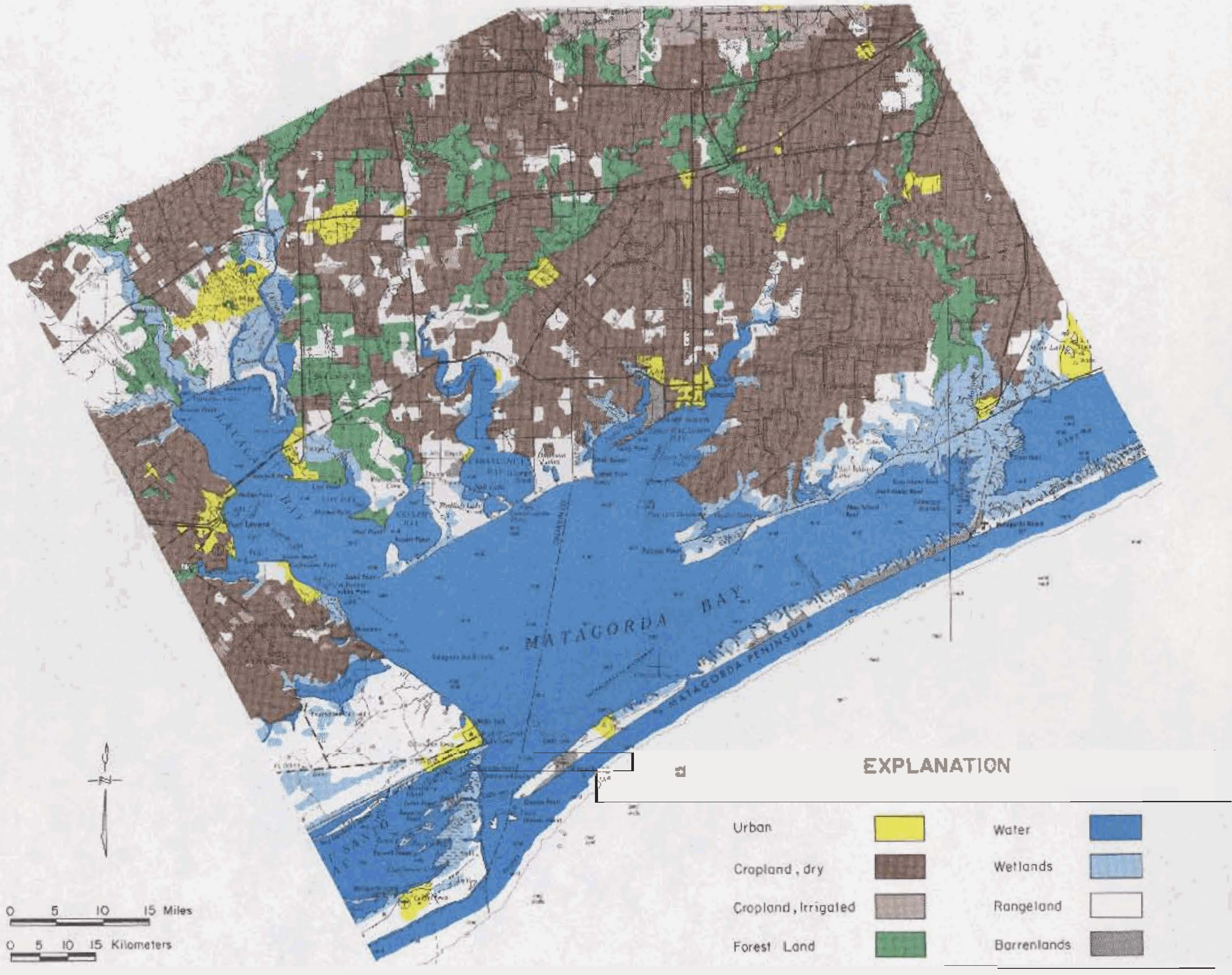


Figure 3-7. Land Use/Land Cover, Lavaca-Tres Palacios Estuary (227).

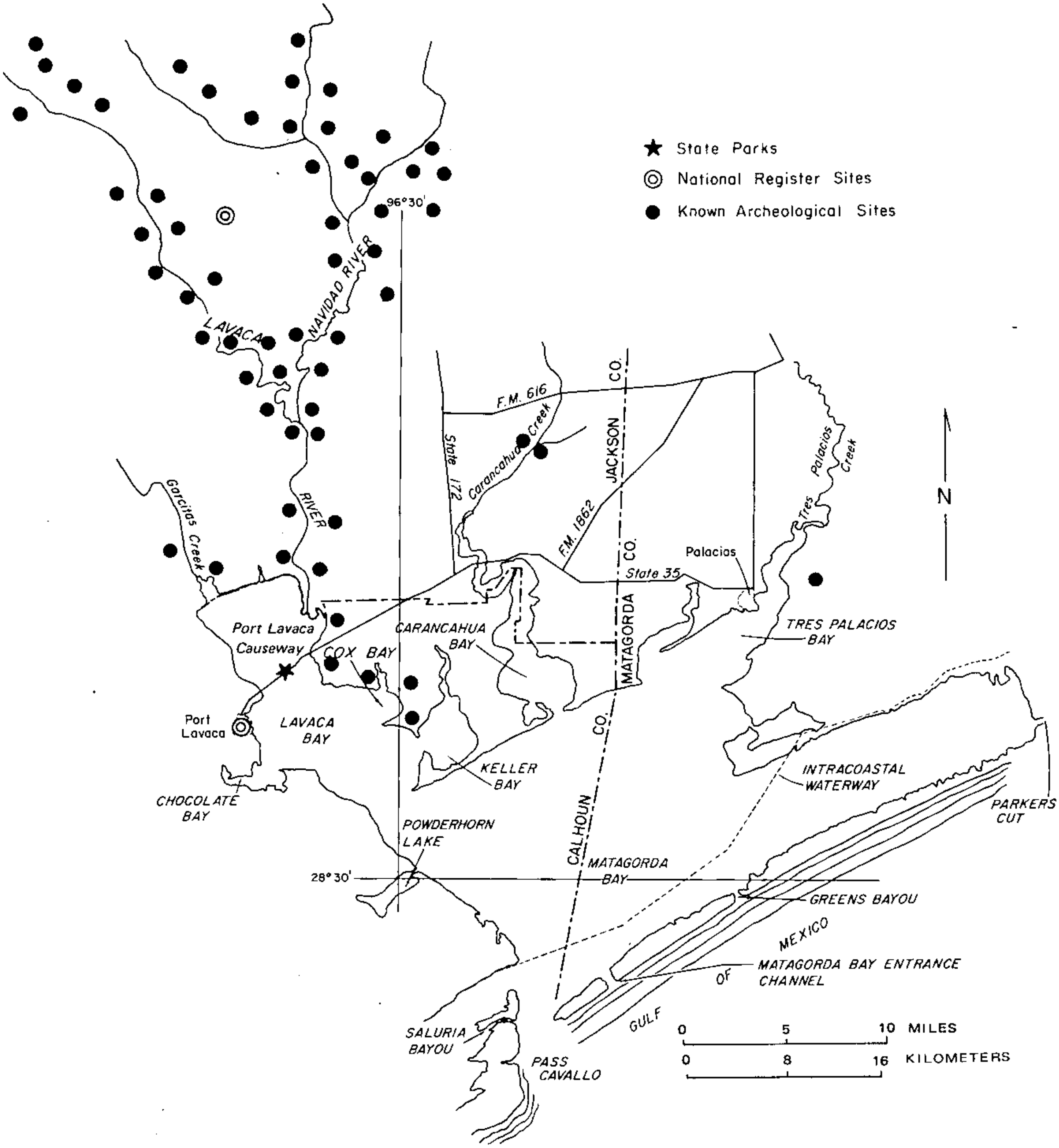


Figure 3-8. Natural Resources, Lavaca-Tres Palacios Estuary (323).

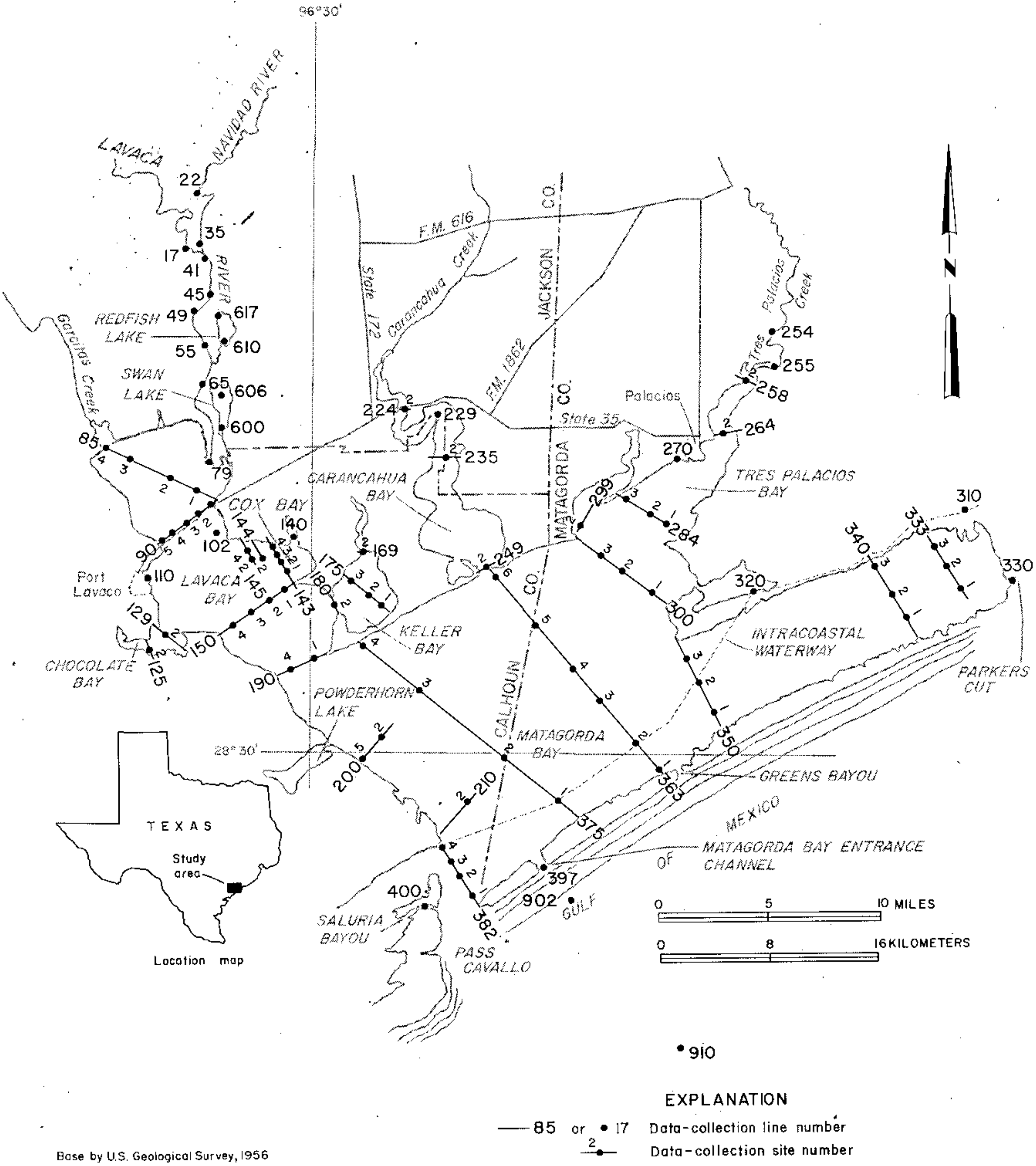
Inland areas and marshes contiguous to the Lavaca-Tres Palacios estuary provide terrestrial and aquatic habitat for many species of wildlife including the endangered American alligator, the whooping crane, the Atlantic Ridley turtle, and brown pelican, and the leatherback turtle. Wildlife resources of the area enhance the recreational opportunities, including sightseeing, nature studies and esthetic benefits accruing to naturalists and environmentalists alike. In addition, approximately 35,000 acres (14,000 hectares) of marshland are available to outdoor sportsmen for hunting opportunities. These marsh areas support large populations of migratory game birds, such as geese and ducks.

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, very little data were available on the estuaries of Texas. Several limited research programs were underway; however, these were largely independent of 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 quality 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 the 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 Lavaca-Tres Palacios estuary during October 4-5, 1971 and October 16-19, 1972. Tidal amplitudes were measured simultaneously at numerous locations throughout the estuary (Figure 3-10). Tidal flow measurements were made at several different bay cross-sections (A, B, C, D, E, F, G, H and I of Figure 3-10). In addition, conductivity data were collected at many of the sampling stations shown in Figure 3-9. Studies of past and present freshwater inflows to Texas' estuaries have used all available sources



Base by U.S. Geological Survey, 1956

Figure 3-9. Data Collection Sites in the Lavaca-Tres Palacios Estuary.

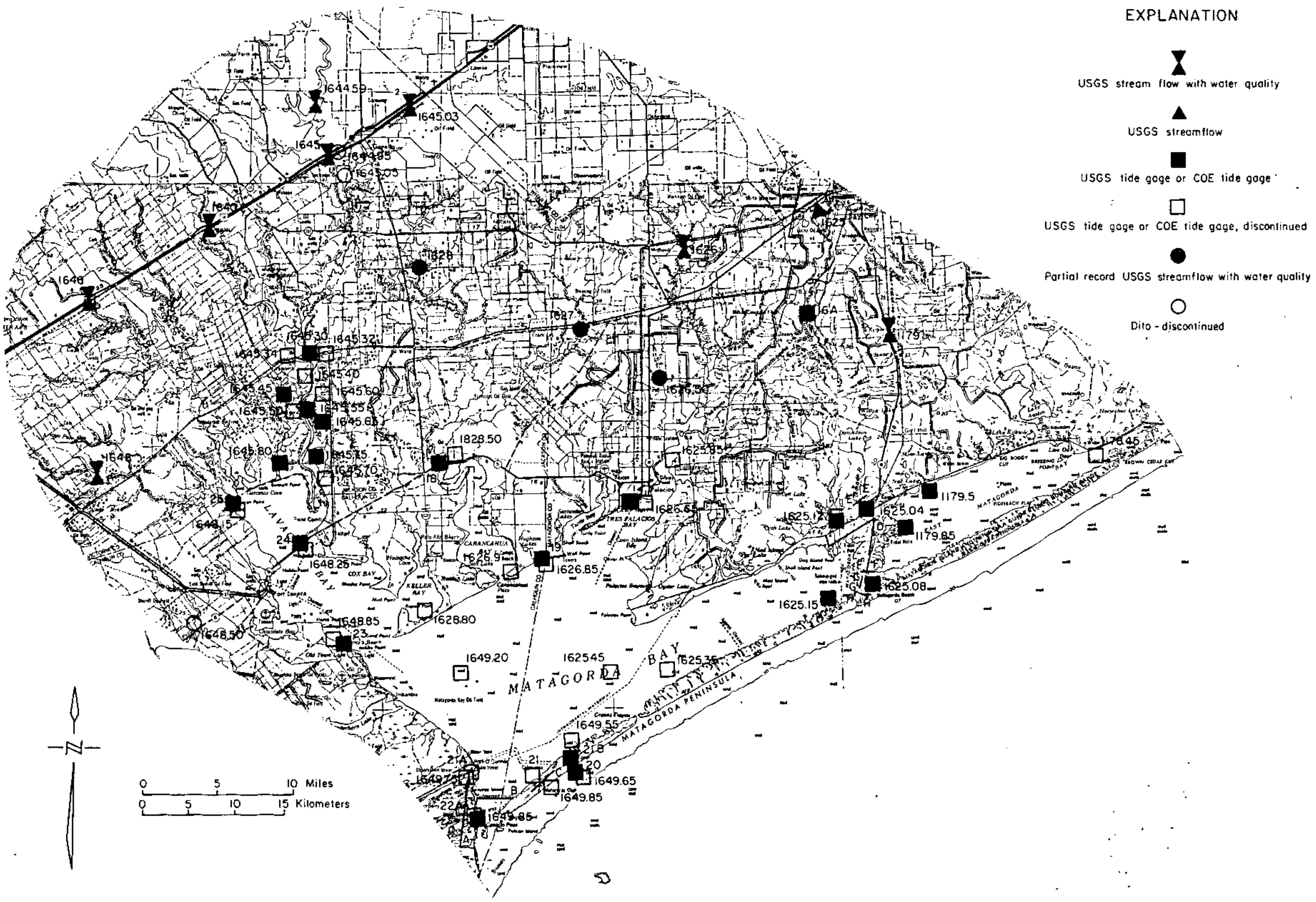


Figure 3-10. Locations of Gaging Stations, Lavaca-Tres Palacios Estuary.

Table 3-2. U. S. Geological Survey (USGS) or Corps of Engineers (COE) Gages, Lavaca-Tres Palacios Estuary

Station Number	Station Description	Period of Record	Operating Entity	Type of Record
	Tide Gages			
16A	Colorado River nr. Wadsworth, Celenese Dock	1975-	COE	Continuous Recording
17	Tres Palacios Bay at Palacios, Sh. Bt. basin	1967-	COE	Continuous Recording
18	Carancahua Bay at Hwy. 35 bridge	1968-	COE	Continuous Recording
19	Piper Lakes, Fish & Wildlife	1968-	COE	Continuous Recording
20	Entrance, Matagorda Ship Channel	1963-	COE	Continuous Recording
21	Matagorda Bay, Range, Tr., Entrance Cut	1963-74	COE	Continuous Recording
21A	Matagorda Bay, GIWW, Air Force Dock	1970-71	COE	Continuous Recording
21B	Matagorda Bay, N. Dike, Entr. Channel	1975-	COE	Continuous Recording
22A	Saluria Bayou, Old Coast Guard Sta.	1964-69	COE	Continuous Recording
23	Lavaca Bay, Mag. Beach, Humble Oil	1968-	COE	Continuous Recording
24	Lavaca Bay, Hwy. 35 bridge	1964-	COE	Continuous Recording
25	Lavaca Bay, Six Mile Rd. Co. Park	1976-	COE	Continuous Recording
1178.45	East Matagorda Bay nr. Sargent	1973-75	USGS	Continuous Recording
1179.50	Intracoastal Waterway nr. Matagorda	1977-	USGS	Continuous Recording

(continued)

Table 3-2. U. S. Geological Survey (USGS) or Corps of Engineers (COE) Gages, Lavaca-Tres Palacios Estuary (cont'd.)

Station Number	Station Description	Period of Record	Operating Entity	Type of Record
1179.85	East Matagorda Bay nr. Matagorda	1973-	USGS	Continuous Recording
1625.04	Colorado River at Matagorda	1977-	USGS	Continuous Recording
1625.08	Colorado River nr. Tiger Island Cut	1977-	USGS	Continuous Recording
1625.12	Culver Cut nr. Matagorda	1977-	USGS	Continuous Recording
1625.15	Matagorda Bay nr. Matagorda	1972-	USGS	Continuous Recording
1625.35	Matagorda Bay nr. Palacios Point	1971-72	USGS	Continuous Recording
1625.45	Matagorda Bay nr. Half Moon Reef	1972-75	USGS	Continuous Recording
1625.85	Tres Palacios Bay nr. Collegeport	1973-75	USGS	Continuous Recording
1626.65	Tres Palacios Bay at Palacios	1967-76	USGS	Continuous Recording
1626.85	Matagorda Bay nr. Palacios	1968-76	USGS	Continuous Recording
1626.9[illegible]	Carancahua Bay nr. Palacios	1968-76	USGS	Continuous Recording
1628.50	Carancahua Bay nr. Point Comfort	1968-76	USGS	Continuous Recording
1628.80	Keller Bay nr. Point Comfort	1973-75	USGS	Continuous Recording
1646.30	Lavaca River nr. Lolita	1973-	USGS	Continuous Recording
1645.32	Lavaca River nr. Lolita, east overflow	1974-76	USGS	Continuous Recording
1645.34	Lavaca River nr. Lolita, west overflow	1974-76	USGS	Continuous Recording

(continued)

Table 3-2. U. S. Geological Survey (USGS) or Corps of Engineers (COE) Gages, Lavaca-Tres Palacios Estuary (cont'd.)

Station Number	Station Description	Period of Record	Operating Entity	Type of Record
1645.40	Menefee Lake, No. 1, nr. Vanderbilt	1974-76	USGS	Continuous Recording
1645.45	Menefee Lake, No. 2, nr. Vanderbilt	1974-	USGS	Continuous Recording
1645.50	Menefee Bayou nr. Vanderbilt	1974-76	USGS	Continuous Recording
1645.55	Lavaca River nr. Vanderbilt	1974-	USGS	Continuous Recording
1645.60	Redfish Lake nr. Lolita (CSG)	1974-76	USGS	Continuous Recording
1645.65	Redfish Lake nr. Lolita	1976-	USGS	Continuous Recording
1645.70	Swan Lake No. 2 nr. Point Comfort	1974-76	USGS	Continuous Recording
1645.75	Swan Lake No. 1 nr. Point Comfort	1974-	USGS	Continuous Recording
1645.80	Venado Lake nr. Vanderbilt	1974-	USGS	Continuous Recording
1648.15	Lavaca Bay at Six Mile Rd. Co. Park	1968-76	USGS	Continuous Recording
1648.25	Lavaca Bay nr. Point Comfort	1963-76	USGS	Continuous Recording
1648.85	Lavaca Bay, Magnolia Beach nr. Pt. Lavaca	1968-76	USGS	Continuous Recording
1649.20	Matagorda Bay, Sandy Point, nr. Indianola	1971-77	USGS	Continuous Recording
1649.55	Matagorda Bay, Range Tower nr. Port O'Connor	1963-76	USGS	Continuous Recording
1649.65	Matagorda Bay, Entrance Channel, Port O'Connor	1963-76	USGS	Continuous Recording
1649.75	Intracoastal Waterway at Port O'Connor	1970-71	USGS	Continuous Recording

(continued)

Table 3-2. U. S. Geological Survey (USGS) or Corps of Engineers (COE) Gages, Lavaca-Tres Palacios Estuary (cont'd.)

Station Number	Station Description	Period of Record	Operating Entity	Type of Record
1649.85	Saluria Bayou nr. Port O'Connor	1971-	USGS	Continuous Recording
	Stream Gages			
1179.00	Big Boggy Cr. nr. Wadsworth	1970-77	USGS	Continuous Recording
1625.00	Colorado River at Bay City	1948-	USGS	Continuous Recording
1626.00	Tres Palacios Creek nr. Midfield	1970-	USGS	Continuous Recording
1640.00	Lavaca River nr. Edna	1938-	USGS	Continuous Recording
1644.50	Sandy Creek nr. Louise	1978-	USGS	Continuous Recording
1645.00	Navidad River nr. Ganado	1939-	USGS	Continuous Recording
1645.03	West Mustang Creek nr. Ganado	1978-	USGS	Continuous Recording
1646.00	Garcitas Creek nr. Inez	1969-	USGS	Continuous Recording
1648.00	Placedo Creek nr. Placedo	1970-	USGS	Continuous Recording
	Partial Record Stream Gages			
1626.50	Cashs Creek nr. Blessing	1969-	USGS	Limited Data
1627.00	East Carancahua Creek nr. Blessing	1967-68 1970-	USGS	Limited Data
1628.00	West Carancahua Creek nr. La Ward	1967-68 1970-	USGS	Limited Data
1644.95	Sandy Creek nr. Ganado	1975-77	USGS	Limited Data
1645.05	Mustang Creek below Ganado	1975-77	USGS	Limited Data
1648.50	Chocolate Bayou nr. Port Lavaca	1967-68 1970-	USGS	Limited Data

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 Lavaca-Tres Palacios estuary is reflected in the direct and indirect linkages of the bay-supported resources to the economies of Calhoun, Jackson, Matagorda and Victoria Counties. Trends in population, employment, 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 4.1 percent between 1970 and 1975. Calhoun and Jackson County populations showed insignificant changes of -0.2 percent and +0.2 percent, respectively, while Matagorda County population grew 2.1 percent. Only one county, Victoria, grew significantly (7.5 percent), but its increase was still below statewide population growth (8.8 percent) for the same period.

In 1975, the population of the four county area was 117,100. Victoria and Matagorda Counties accounted for 49 percent and 24 percent of the total, respectively. Population forecasts for the period 1975 to 2030 indicate that the population of the study area can be expected to increase 110 percent by the year 2030. Victoria County is projected not only to remain the most populated, but also to remain the fastest growing, with an annual rate of growth (1.6 percent) twice that of any other county in the study area (Table 3-3).

Income. Along with the growth in population, the four county study area is expected to experience increases in personal income through the year 2030. Regional personal income is projected to more than double in the period 1970 to 2000, and by 2030 to exceed 10 times the 1970 amount. However, regional personal income is projected to increase at a slower rate than state income.

Employment. In 1970, an estimated 39,400 persons were employed in the study area, and almost half of these (19,306) worked in Victoria County. Jackson County had the lowest employment, only 11 percent of the regional total.

The four county area employment is projected to increase 112 percent from 1970 to 2030, bringing total employment to 83,575. However, during this time, the region's share of total state employment should fall from 0.95 percent to 0.65 percent.

Eighty-one 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.

Table 3-3. Population Estimates and Projections, Area Surrounding Lavaca-Tres Palacios Estuary, 1970-2030 (229)

	1970	1975	1980	1990	2000	2010	2020	2030	Percent Change 1970 to 2030	Compound Growth %	
										Annual	Decadal
Calhoun	17,831	17,800	18,100	18,800	19,800	21,600	24,700	29,900	+67.7	.87	9.0
Jackson	12,975	13,000	13,200	13,500	14,000	15,100	16,900	20,000	+54.1	.72	7.48
Matagorda	27,913	28,500	29,200	30,500	32,400	35,000	39,300	45,900	+64.0	.83	8.64
Victoria	53,766	57,800	63,200	74,400	86,400	100,000	117,700	140,200	+161.0	1.61	17.32
Total	112,485	117,100	123,700	137,200	152,600	171,700	198,600	236,000	+110.0	1.24	13.15
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	+172.0	1.68	18.15

Industry. The "basic" industries in the area (i.e., those which produce output largely for export) are manufacturing, agriculture-forestry-fisheries, and mining (Table 3-4). These sectors account for over 30 percent of all employment in the study area. In addition to the basic sectors are the service sectors: wholesale and retail trade, professional services, civilian government, and amusement and recreation. These employ 41 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, is manufacturing (Table 3-5). Most of the manufacturing activity is concentrated in the production of primary metals, chemicals and allied products.

The mineral wealth of the area is also an important factor in its economy. The four counties annually produce $212.9 million of oil, gas, stone, sand, salt, shell and gravel. These mineral products supply raw materials for the manufacturing, petroleum refining and petrochemical industries.

The area surrounding the Lavaca-Tres Palacios estuary produces a significant portion of the coastal region's agricultural output, with average annual receipts of $98.6 million. Jackson and Matagorda Counties are rice producers; other major regional crops are cotton, sorghum, soybeans, and corn. Sixty percent of farm income in Victoria County originates from livestock and poultry. In addition, the bay-supported commercial fishing industry provides such as 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, employment, 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, fishing, and oil and gas mining are able to coexist in the bay environment.

The economic outlook for the study area is somewhat uncertain due to the limited growth potential of the agricultural, oil and gas, and commercial fisheries industries which currently play such an important role in the economy. In view of this situation, water-oriented outdoor recreational potential may have an impact on the economic progress of the area and may provide a vehicle for boosting income levels and job opportunities.

Economic Importance of Sport and Commercial Fishing

Introduction. Concurrent with the biological and hydrological studies of the Lavaca-Tres Palacios 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

Table 3-4. Employment by Industrial Sector, Area Surrounding Lavaca-Tres Palacios Estuary, 1970 (224)

Sector	1970					
	Calhoun	Jackson	Matagorda	Victoria	Total	Percent of Total Employment of Study Area
Wholesale and Retail Trade	1,020	802	2,001	4,466	8,289	21.0
Manufacturing	1,589	392	1,297	3,196	6,474	16.4
Professional Services	877	674	1,505	3,251	6,307	16.0
Construction	758	484	1,006	1,567	3,815	9.7
Agriculture, Forestry, and Fisheries	521	715	1,168	863	3,267	8.3
Mining	80	595	599	980	2,254	5.7
Civilian Government	198	132	303	604	1,237	3.1
Amusement and Recreation	31	4	35	169	239	0.6
All Other	761	731	1,765	4,260	7,517	19.1
Total	5,835	4,529	9,679	19,356	39,399	100.0

Table 3-5. Earnings (1967 Dollars) by Industrial Sector, Area Surrounding Lavaca-Tres Palacios Estuary, 1970 (223)

Sector	1970					
	Calhoun	Jackson	Matagorda	Victoria	Total	Percent of Total Employment of Study Area
Wholesale and Retail Trade	5,450	3,525	9,012	22,836	40,823	18.22
Manufacturing	17,918	3,410	8,688	26,962	56,978	25.43
Professional Services	3,012	1,904	4,504	10,686	20,106	8.98
Construction	4,109	2,158	5,573	8,129	19,969	8.91
Agriculture, Forestry, and Fisheries	4,030	4,550	4,222	6,390	19,192	8.57
Mining	558	3,414	5,278	6,543	15,793	7.05
Civilian Government	2,826	1,550	4,591	8,251	17,218	7.69
Amusement and Recreation	96	10	116	502	724	0.32
All Other	3,780	2,700	6,832	19,923	33,235	14.83
Area Total	41,779	23,221	48,816	110,222	224,038	100.00
State Total					26,328,041	

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 Lavaca-Tres Palacios estuary. The surveys included: (1) personal interviews; (2) roving counts; and (3) motor vehicle license plate counts (347). Personal interviews of a sample of sport fishing parties on a randomly selected sample of weekend days and weekdays were conducted at major access points to the Lavaca-Tres Palacios 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 sample survey, counts of sport fishermen and boat trailers were made at a statistically randomized sample of boat ramps, wade-bank areas, and commercial piers to estimate the number of sport fishing parties in the bay area. Data from the personal interview sample and fishermen counts conducted during the period September 1, 1975 through August 31, 1976 were used in this analysis. A motor vehicle license plate sample 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 sample survey and the fishermen and boat trailer counts from the roving count sample survey. The fishing party was selected as the measurement unit because expenditures were made 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, fishing strata (boats, wade-bank, or pier) and day type (weekend or weekday).

The roving count sample survey consisted of boat trailer counts at each of the designated boat ramps and the number of individuals observed fishing at each of the designated wade-bank and pier areas 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 Lavaca-Tres Palacios estuary for the study period is stated as follows:

$$T = Z + W + P$$

where:

T = Estimated total annual fishing parties,
Z = Estimated number of boat fishing parties,
W = Estimated number of wade-bank fishing parties, and
P = Estimated number of pier 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, 1975

where:

Z = Estimated number of boat parties fishing in Lavaca-Tres Palacios estuary for the period September 1, 1975 through August 31, 1976.

z_k = Estimated number of boat parties fishing in Lavaca-Tres Palacios estuary during the kth calendar quarter of the study period.

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

where:

W = Estimated number of wade-bank parties fishing in Lavaca-Tres Palacios estuary for the period September 1, 1975 through August 31, 1976.

w_k = Estimated number of wade-bank parties fishing in Lavaca-Tres Palacios estuary during the kth calendar quarter of the study period.

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

where:

P = Estimated number of pier parties fishing in Lavaca-Tres Palacios estuary for the period September 1, 1975 through August 31, 1976.

p_k = Estimated number of pier parties fishing in Lavaca-Tres Palacios 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 weekdays. An identical definition pertains to weekend days and is not repeated here. 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 weekdays in quarter k,

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

H_k = Number of hours subject to being surveyed per weekday 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 = Sample boat sites within the study area (25 boat sites for the Lavaca-Tres Palacios estuary),

D_k = Weekdays in quarter k ($m = 64$ in fall, spring, and winter, $m = 67$ in summer),

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

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

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

For wade-bank fishing:

$$w_k = \frac{H_k \cdot D_k \cdot \sum_{i=1}^{r} \sum_{j=1}^{m} \frac{x_{ij}}{N_{ik}}}{\overline{A}_k}$$

where:

w_k = Estimated number of wade-bank fishing parties on weekdays in quarter k,

r = Sample wade-bank sites within the study area (23 wade-bank sites for the Lavaca-Tres Palacios estuary),

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

$\overline{A}_w$ = Average number of hours fished per wade bank party on weekdays in quarter k,

H_k, D_k, and N_{ik} are as defined above for boat parties.

For commercial pier fishing:

$$p_k = \frac{H_k \cdot D_k \cdot \sum_{i=1}^{r} \sum_{j=1}^{m} \frac{x_{ij}}{N_{jk}}}{\overline{A}_k}$$

where:

p_k = Estimated number of pier fishing parties on weekdays in quarter k,

r = Sample pier sites within the study area (three pier sites for the Lavaca-Tres Palacios estuary),

$\overline{A}_k$ = Average number of hours fished per pier party on weekdays in quarter k,

H_k, D_k, and N_{ik} are as defined above for boat parties and x_{ij} is as defined above for wade-bank parties.

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 more than 161 thousand fishing parties visited the Lavaca-Tres Palacios estuary during the period September 1, 1975 through August 31, 1976 (Table 3-6). Seasonal visitation as a percentage of annual visitation ranged from a high of more than 46 percent for the summer quarter to a low of approximately 14 percent during the winter quarter. The distribution of fishing parties by strata indicates that wade-bank fishing accounted for about 64 percent of annual visitation followed by boat fishing with approximately 31 percent and pier fishing with approximately five 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 (618 in all) was too small to estimate a general visitation pattern to the estuary system. Thus, an intensive sample 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 about 60 percent of fishermen at Lavaca-Tres Palacios estuary came from the following ten counties — Harris (12.5 percent of the summer 1977 visitation), Victoria (11.8 percent), Calhoun (6.9 percent), Travis (6.7 percent), Bexar (6.2 percent), Wharton (4.1 percent), DeWitt (2.7 percent), Dallas (3.0 percent), Brazoria (2.1 percent), and Tarrant (1.9 percent). A more general visitation pattern distinction of "local", "nonlocal" and "out-of-state" was also made. "Local", for the purposes of this study, includes counties within approximately 60 miles of the estuary area. For the Lavaca-Tres Palacios estuary, these counties are Aransas, Calhoun, Jackson, Matagorda, Refugio, Victoria, and Wharton. "Nonlocal" comprises all other Texas counties.

Since it is expected that the proportions of local, nonlocal and out-of-state 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

Table 3-6. Estimated Seasonal Sport Fishing Visitation to Lavaca-Tres Palacios Estuary, 1975-1976 a/

Season b/	Boat	Wade-Bank	Pier	Total - All Strata
		thousands of parties		
Fall	12.0 (2.34)	19.5 (2.23)	2.2 (2.34)	33.7 (2.26)
Winter	10.0 (2.38)	11.6 (2.17)	1.0 (1.77)	22.6 (2.22)
Spring	5.1 (2.97)	24.1 (2.17)	1.4 (1.97)	30.6 (2.32)
Summer	23.0 (2.90)	47.8 (2.69)	3.5 (2.47)	74.3 (2.60)
Total All Seasons	50.1 (2.61)	103.0 (2.27)	8.1 (2.27)	161.2 (2.37)

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a/ The figures in parentheses 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

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 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) and strata (boat, wade-bank, or pier). 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). Nearly 44 percent of estimated $6.7 million expenditures were made during the summer and 22 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 transportation 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, the expenditures for transportation, food, lodging, equipment, 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 Lavaca-Tres Palacios 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 sales of equipment, supplies, and services to 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 (231) and regional input-output tables derived from the state model (235).[1/]

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

Table 3-7. Estimated Seasonal Sport Fishing Visitation Patterns at Lavaca-Tres Palacios Estuary, 1975-1976

Visitation	Fall	Winter	Spring	Summer	Total-Annual
			thousands of parties		
Local	11.1	4.0	10.1	19.0	44.2
Nonlocal	22.4	16.0	19.2	52.9	110.5
Out-of-State	0.2	2.6	1.3	2.4	6.5
Total Visitation	33.7	22.6	30.6	74.3	161.2

Table 3-8. Estimated Average Cost per Sport Fishing Party by Type and Origin, Lavaca-Tres Palacios Estuary, 1975-1976

Average Cost per Party	Boat	Wade-Bank	Pier	Weighted Average
		1975 dollars		
Local	21.63	10.91	15.67	14.38
Nonlocal a/	49.85	47.66	54.82	48.71

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a/ Out-of-state costs per party, for the estimated 6,500 parties, was computed at $426.83. However, it is not clear that total costs of out-of-state trips should be attributed to fishing.

The expenditure data collected by personal interviews of a sample of fishing parties at the Lavaca-Tres Palacios estuary (Table 3-9) indicated only the magnitude of variable expenditures by sport fishermen. To estimate the sectoral distribution of all expenditures, the interview data were supplemented with data from estimated retail sales in 1975 by marine sport fishing related industries in the West Gulf of Mexico region (Mississippi delta to Mexican border) (378). 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 and pier parties; nonlocal and out-of-state wade-bank and pier parties; and nonlocal and out-of-state 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 Lavaca-Tres Palacios estuary were over $5.94 million. In addition, there was an estimated $755.8 thousand spent outside the region, within Texas (Table 3-10). Most of the expenditure impact, over 89 percent, accrues to the region. However, when the total impacts are calculated, the regional gross impact of over $10 million accounts for less than half (46 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 35 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 $3.1 million from the sport fishing business in the area (Table 3-11). Statewide, the income impact amounted to over $6.1 million, annually.

The input-output analysis estimated a total of 357 full time job equivalents directly related to sport fishing in the Lavaca-Tres Palacios estuary region in 1975 through 1976. Statewide, an additional 65 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 718 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 over $221 thousand, with $78 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 $166 thousand resulted from direct, indirect and induced sport fishing expenditures (Table 3-11). In addition, local governments outside the Lavaca-Tres Palacios region collected an estimated $172 thousand in taxes on travel expenditures by fishing parties in 1975 through 1976.

The data show that sport fishing in the Lavaca-Tres Palacios region results in a larger economic impact in areas outside the region than within

Table 3-9. Estimated Sport Fishing Expenditures by Season and Fishing Party Type, Lavaca-Tres Palacios Estuary, 1975-1976

Season a/	Boat	Wade-Bank	Pier	Total	Percent
	thousands of 1976 dollars				
Fall	514.2	732.9	93.0	1346.0	20.07
Winter	476.3	503.9	49.3	1029.6	15.36
Spring	219.2	907.3	64.0	1190.5	17.76
Summer	1036.9	1934.1	166.9	3137.9	46.81
Total	2246.6	4078.2	379.2	6704.0	100.00

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

Table 3-10. Estimated Sport Fishing Variable Expenditures by Sector, Lavaca-Tres Palacios Estuary, 1975-1976

	Bait	Travel	Food	Lodging	Recreation a/	Total
	thousands of 1976 dollars					
Total	1,739.4	1,670.7	1,862.9	566.5	864.5	6,704.0 b/

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a/ Marinas, boat fuel, and boat rental.
b/ Adjusted for travel expenditures outside the study area 6,704.0 - 755.8. Expenditures in the region = $5,948.2 thousand.

Table 3-11. Direct and Total[a] Economic Impact from Sport Fishing Expenditures, Lavaca-Tres Palacios Estuary, 1975-1976 [b]

	Direct [c]		Total	
	Regional	State	Regional	State [d]
Output (thousands)	$5,948.2	$6,704.0	$10,059.7	$21,640.3
Employment (Man-Years)	357	422	451	718
Income (thousands)	2,093.5	2,470.1	3,150.9	6,139.6
State Tax Revenues (thousands)	e/	51.3	78.1	221.2
Local Tax Revenues (thousands)	e/	73.3	166.4	339.2

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[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.

the region, except for regional local tax revenues. However, data necessary to analyze the effects of sport fishing equipment business were not available. Thus, the annual statewide gross output impact of over $21 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.

Economic Impact of Commercial Fishing. The analysis of the commercial fishing industry in the Lavaca-Tres Palacios estuary was somewhat limited by the availability of estuary-specific data. Estimates were made of the inshore-offshore catch associated with the estuary. However, the specific markets into which the fish catch 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 338,900 pounds (154,045 kg) of finfish and 15,892,900 pounds (7,224,045 kg) of shellfish for the period 1972 through 1976. Using 1976 dockside finfish and shellfish prices ($.357 per pound of fish and $1.456 per pound of shellfish), the direct commercial value of fish attributed to the estuary was estimated at $23.26 million (1976 dollars) (354). Shrimp, blue crab, and oysters constituted approximately 95 percent of this value.

The Texas economy-wide total business resulting from commercial fish catch attributed to the Lavaca-Tres Palacios estuary was estimated using the 1972 Texas Input-Output Model fisheries sector multipliers. Total value of the catch was $23.26 million, direct employment in the fisheries sector was 847, and direct salaries to fisheries employees was $7.77 million (Table 3-12).

Gross Texas business resulting from fishing, processing, and marketing the catch attributed to the estuary in 1976 was estimated at $72.4 million. Indirect supporting and marketing activities provided 510 full time job equivalents and an additional 847 full time job equivalents associated with the direct fishing activity statewide. Gross personal income in Texas attributed to the estuarine fishing and supporting sectors was estimated at $19.92 million, state taxes at $658 thousand, and taxes paid to local units of governments throughout Texas, as a result of this fishery business, at $914.2 thousand in 1976 (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

Table 3-12. Direct and Total a/ Economic Impact of Commercial Fishing in the Lavaca-Tres Palacios Estuary, 1976

	Fishing Sector	Total	
		Regional	State
Output (1000's 1975 $)	23,261.1	38,962.3	72,458.2
Employment (Man-Years)	847	1,357	1,800
Income (1000's 1975 $)	7,771.5	13,405.8	19,926.1
State Tax Revenues (1000's 1975 $)	88.4	311.7	658.3
Local Tax Revenues (1000's 1975 $)	104.7	628.0	914.2

a/ Total = direct, indirect and induced.

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 $5.94 million. In addition, there were an estimated $755.8 million spent outside the region, within Texas.

Over 35 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 $6.7 million, annually. In addition, the total employment impact to the State economy was 718 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 $221 thousand. Except for regional local tax revenues, sport fishing resulted in a larger economic impact in areas outside the region than locally.

Estimates were made of the inshore-offshore commercial fisheries catch associated with the Lavaca-Tres Palacios estuary. The average annual commercial fisheries contribution was estimated at 16,231,800 pounds of finfish and shellfish for the period 1972 through 1976. The total value of the catch was $23.26 million, direct employment in the commercial fisheries sector was 847, and direct salaries to employees was $7.77 million.

CHAPTER IV

HYDROLOGY

Introduction

Detailed studies of the hydrology of areas draining to the Lavaca-Tres Palacios estuary were necessary to estimate historical freshwater inflows from contributory areas, only a portion of which are gaged. Two major river basins contribute to the Lavaca-Tres Palacios estuary, the Lavaca and Colorado Basins. Additionally, small coastal basins, including a portion of the Lavaca-Guadalupe Coastal Basin and the Colorado-Lavaca Coastal Basin, contribute to the estuary. An earlier section of this report (Chapter III, "Influence of Contributory Basins") describes upstream reservoirs in the major basins. This chapter deals with aspects of the quality and quantity of freshwater inflow from a historical perspective.

Freshwater Inflows

Freshwater inflow contributions to the Lavaca-Tres Palacios estuary consist of (1) gaged inflow from the Lavaca and Colorado River Basins; (2) ungaged runoff; (3) return flows from municipal, industrial and agricultural sources in ungaged areas; and (4) 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 in order to arrive at a freshwater inflow balance.

Gaged Inflows from the Lavaca Basin

The Lavaca Basin has a total gaged drainage area of 1,879 square miles (4,889 km^2). This inflow enters the estuary through the Lavaca delta at the northwestern edge of Lavaca Bay. Gaged contributions of the Lavaca River Basin to the estuary have averaged 614,000 acre-feet/year (754 million m^3/yr) over the period 1941 through 1976 (Table 4-1). Gaged yield from the Lavaca Basin (1941-1976) has averaged 327 acre-feet per square mile (1,557 m^3/ha). Gaged Lavaca Basin flows accounted for 21 percent of the combined inflow[1/] and 16 percent of the total freshwater inflow[2/] to the Lavaca-Tres Palacios estuary (Table 4-2) over the 1941 through 1976 period.

Gaged Inflows from the Colorado Basin

The total gaged drainage area of the Colorado Basin is 41,650 square miles (108,373 km^2), of which 12,880 square miles (33,514 km^2) are

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[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, Lavaca-Tres Palacios Estuary (1941-1976) a/

MONTH	GAGED LAVACA INFLOW	TOTAL COLO. INFLOW	TOTAL GAGED INFLOW	UNGAGED INFLOW	RETURN FLOWS	DIVERSIONS	COMBINED INFLOW	PRECIPITATION ON BAY	TOTAL FRESHWATER INFLOW	BAY EVAPORATION LOSSES	FRESHWATER INFLOW BALANCE
AVERAGE OVER ALL YEARS							thousands of acre-feet				
JANUARY	44	104	149	55	0	0	205	53	258	51	207
FEBRUARY	47	110	157	68	0	0	226	57	283	51	232
MARCH	36	105	144	53	0	0	197	39	236	68	167
APRIL	64	116	181	76	0	0	257	60	318	81	237
MAY	98	165	264	140	0	0	404	83	488	106	382
JUNE	89	137	227	123	0	0	351	77	429	129	299
JULY	26	83	110	48	37	0	196	61	257	154	103
AUGUST	21	59	80	49	0	0	129	94	223	157	66
SEPTEMBER	62	85	147	131	20	0	298	130	428	125	303
OCTOBER	54	104	158	127	16	0	302	84	387	106	280
NOVEMBER	35	106	141	39	0	0	181	58	239	79	160
DECEMBER	36	99	136	58	0	0	194	62	257	60	197
TOTALS	614	1273	1894	967	73	0	2940	858	3803	1167	2633
MONTHLY AVERAGE	51	106	158	81	6	0	245	71	317	97	219

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

Table 4-2. Annual Freshwater Inflow[a], Lavaca-Tres Palacios Estuary, 1941-1976[b]

YEAR	GAGED LAVACA INFLOW	TOTAL COLO. INFLOW	TOTAL GAGED INFLOW	UNGAGED INFLOW	RETURN FLOWS	DIVERSIONS	COMBINED INFLOW	PRECIPITATION ON BAY	TOTAL FRESHWATER INFLOW	BAY EVAPORATION LOSSES	FRESHWATER INFLOW BALANCE
1941	1426	3270	4696	2131	69	0	6896	1160	8056	939	7117
1942	446	1327	1773	820	69	0	2662	826	3488	961	2527
1943	251	1139	1390	324	69	0	1783	690	2473	1043	1430
1944	738	1567	2305	1552	69	0	3926	925	4851	1002	3849
1945	365	1760	2125	926	69	0	3120	798	3918	1001	2917
1946	1003	1943	2946	1654	69	0	4669	1150	5819	981	4838
1947	321	1226	1547	410	69	0	2026	734	2760	1001	1759
1948	256	678	934	350	69	0	1353	581	1934	1022	912
1949	534	1070	1604	1470	69	0	3143	1212	4355	983	3372
1950	170	846	1016	222	69	0	1307	465	1772	1105	667
1951	129	424	553	207	69	0	829	748	1577	1148	429
1952	407	447	854	446	69	0	1369	823	2192	1107	1085
1953	288	735	1023	784	69	0	1876	900	2776	1147	1629
1954	23	300	323	42	69	0	434	428	862	1189	-327
1955	223	770	993	143	69	0	1205	620	1825	1399	426
1956	14	329	343	27	69	0	439	489	928	1379	-451
1957	1053	3209	4262	1454	69	0	5785	1026	6811	1232	5579
1958	496	2073	2569	931	69	0	3569	890	4459	1252	3207
1959	787	1782	2569	1427	69	0	4065	1023	5088	1170	3918
1960	1253	2007	3260	2655	69	0	5984	1255	7239	1149	6090
1961	1311	2336	3647	1994	69	0	5710	1075	6785	1129	5656
1962	228	560	788	137	69	0	994	620	1614	1252	362
1963	126	369	495	57	69	0	621	513	1134	1275	-141
1964	165	345	510	478	69	0	1057	775	1832	1192	640
1965	764	1265	2029	341	80	0	2450	742	3192	1272	1920
1966	460	818	1278	1084	80	0	2442	886	3328	1107	2221
1967	511	433	944	1159	80	0	2183	1032	3215	1252	1963
1968	1078	2218	3288	1849	80	0	5217	1072	6289	1272	5017
1969	840	1187	2027	998	80	0	3105	826	3931	1376	2555
1970	631	1599	2230	1610	84	0	3924	944	4868	1275	3593
1971	487	748	1235	1030	84	0	2349	943	3292	1374	1918
1972	761	643	1404	1170	84	0	2658	1024	3682	1246	2436
1973	2019	1679	3698	2234	96	0	6028	1148	7176	1222	5954
1974	1041	1764	2805	1289	96	0	4190	1066	5256	1220	4036
1975	671	1900	2571	576	96	0	3243	700	3943	1183	2760
1976	821	1291	2112	836	96	0	3044	993	4037	1290	2747
TOTAL	22089	46057	68146	34817	2692	0	105655	31102	136757	42147	94610
AVERAGE	614	1279	1893	967	75	0	2935	864	3799	1171	2628
MEDIAN	503	1206	1688	928	69	0	2660	888	3585	1186	2481
PERCENT	16 +	34 =	50 +	25 +	2 -	0 =	77 +	23 =	100 :	30	
PERCENT	21 +	43 =	64 +	33 +	3 -	0 =	100 :	29			

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a/ Units are thousands of acre-feet.

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

probably noncontributing in west Texas. The total contributing drainage area is 28,770 square miles (74,860 m^2) at the Bay City gage (USGS #08162500). Only a portion of the flow passing the Bay City gage is directed into the Lavaca-Tres Palacios estuary. Inflow points include Tiger Island (Parkers) Cut and the Gulf Intracoastal Waterway (GIWW) (Figure 4-1).

The magnitude of Colorado River flow passing into the estuary is a function of several variables. Among them are the rate of flow in the Colorado River; relative tidal alignments in East Matagorda Bay and the Gulf of Mexico; local wind velocity; the condition of the mouth of the Colorado River (from scoured open to silted-closed); and the operation of the locks on the GIWW. To determine the portion of the Colorado River flow that enters the estuary through the delta, an algorithm was developed (see Chapter V, "Colorado River Delta"). Over the period 1941 through 1976, average annual inflow to the estuary from the Colorado River was 1,279,000 acre-feet (1.58 billion m^3) (Table 4-2). Gaged Colorado Basin inflows accounted for 43 percent of the combined inflow and 34 percent of the total freshwater inflow over the 1941 through 1976 period.

Ungaged Runoff Contributions

Ungaged drainage areas contributory to the Lavaca-Tres Palacios estuary include some 2,242[1/] square miles (5,834 km^2) in the Colorado-Lavaca Coastal Basin, the Lavaca-Guadalupe Coastal Basin, the Lavaca River Basin, and the Colorado River Basin. To facilitate the study of inflow contributions, the ungaged drainage area immediately contributing to the Lavaca- Tres Palacios estuary was divided into 15 subbasins (Figure 4-2). Using a Thiessen network (328), the weighted daily precipitation was determined for each subbasin (Table 4-3). A water yield model which uses daily precipitation, Soil Conservation Service's average curve numbers, and soil depletion index (Beta) to predict runoff from small watersheds was calibrated with the seven gaged subbasins located within the contributing drainage area (320). Statistical correlations between annual and monthly gaged and simulated on 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).

During the period 1941 through 1976, ungaged runoff averaged[2/] 967,000 acre-feet/year (1.19 billion m^3/yr) and runoff yield averaged 431 acre-feet/mi^2 (2,053 m^3/ha). Ungaged runoff accounted for 33 percent of the combined inflow and 25 percent of the total freshwater inflow to the Lavaca-Tres Palacios estuary (Table 4-2) over the 1941 through 1976 period.

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

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[1/] With the installation of three coastal gages in 1970, the ungaged drainage area decreased to 1,940 sq. mi. (5,048 km^2).

[2/] Ungaged drainage area held constant at 2,242 sq. mi. (5,834 km^2).

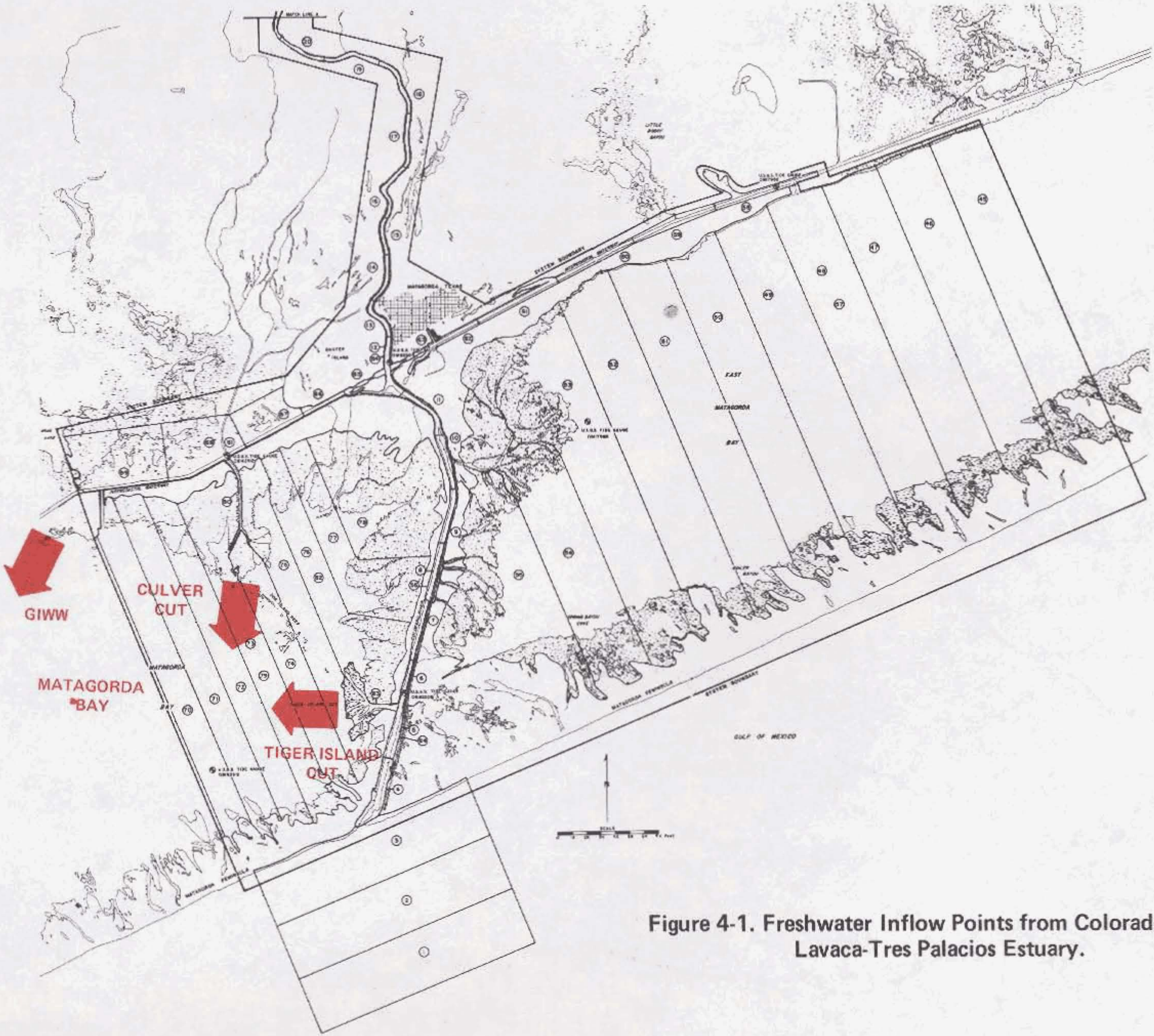


Figure 4-1. Freshwater Inflow Points from Colorado Basin, Lavaca-Tres Palacios Estuary.

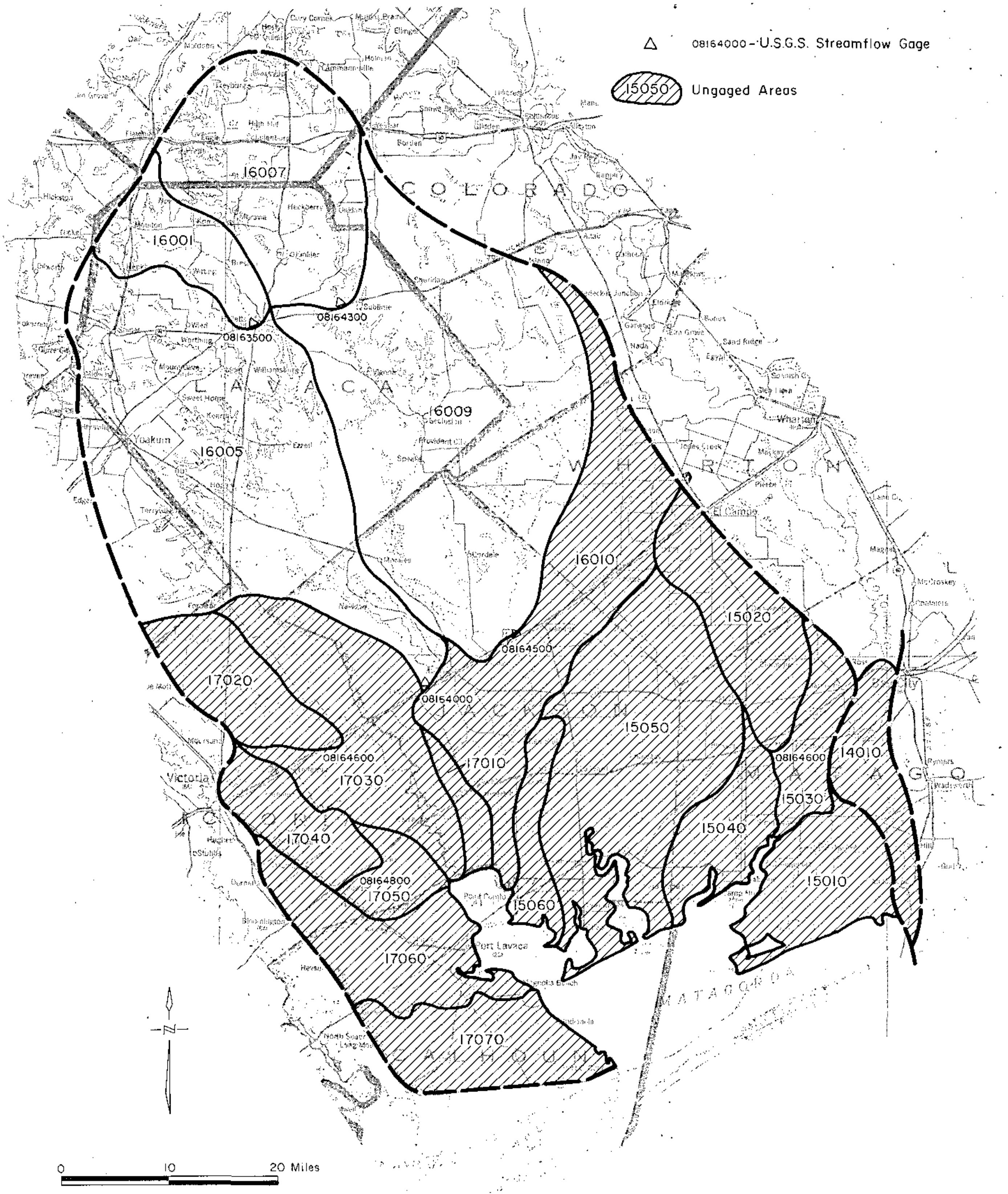


Figure 4-2. Ungaged Areas Contributing to Lavaca-Tres Palacios Estuary.

Table 4-3. Runoff from Ungaged Areas, Lavaca-Tres Palacios Estuary

Subbasin Description	Drainage Area (mi^2)	Weighted Precipitation		Average Runoff (1941-1976) ac-ft/mi^2	Average Curve Number c/ / Beta x10^{-6} d/	Explained Variation (%)		Gaged	
		NWS a/ Station No.	Weight Factor b/			Annual r^2	Monthly r^2	USGS Station No.	Period of Record mth/yr
14010 Bay City gage (081625) to salt water	61.0	0569 5659	.43 .57	485	77/74.5	—	—	——	——
15010 Colorado R. Basin to Tres Palacios basin	151.6	5659 6750	.64 .36	472	75/77.5	—	—	——	——
15020 Tres Palacios (gaged)	145.0	2266 6286	.74 .26	559	86/64.3	99	91	081626	6/70-
15030 Tres Palacios (ungaged)	136.0	0569 2266 6750	.24 .34 .42	521	79/69.2	—	—	——	——
15040 Turtle Creek	94.4	6750	1.00	503	75/77.4	—	—	——	——
15050 Carancahua and Keller Creeks	398.5	2266 2768 6750 7182	.16 .52 .22 .10	475	78/70.4	—	—	——	——
15060 Cox Creek	51.6	2768 7182	.36 .64	405	73/90.6	—	—	——	——
16001 Lavaca River above Hallettsville	108.0	3183 3873	.47 .53	321	75/79.5	56	82	081635	7/39-
16005 Lavaca River above Edna	817.0	2595 2768 3873 9952	.09 .15 .29 .47	277	77/74.0	83	86	081640	8/38-

(continued)

See page IV-9 for footnotes.

Table 4-3. Runoff from Ungaged Areas, Lavaca-Tres Palacios Estuary (cont'd.)

Subbasin Description	Drainage Area (mi^2)	Weighted Precipitation		Average Runoff (1941-1976) ac-ft/mi^2	Average Curve Number c/ / Beta $x10^{-6}$ d/	Explained Variation (%)		Gaged	
		NWS a/ Station No.	Weight Factor b/			Annual r^2	Monthly r^2	USGS Station No.	Period of Record mth/yr
16007 Navidad River above Hallettsville	332.0	3183 3873 8126	.17 .18 .65	347	73/81.5	57	79	081643	10/61-
16009 Navidad River above Ganado	1062.0	2768 3878 8519	.12 .20 .68	381	85/55.7	68	76	081645	5/39-
16010 Lavaca River below Edna and Ganado gages	385.0	2768 6286 2768	.22 .51 .27	337	75/79.9	—	—	----	----
17010 Lavaca-Garcitas coastal	40.9	2768 7182	.48 .52	276	72/87.3	—	—	----	----
17020 Above Garcitas gage	91.7	2173 9364	.15 .85	349	76/64.5	58	86	081646	6/70-
17030 Below Garcitas gage	262.5	2768 9364	.52 .48	416	80/61.2	—	—	----	----
17040 Above Placedo gage	66.1	9364	1.00	595	85/43.9	94	83	081648	6/70-
17050 Below Placedo gage	54.5	7182 9364	.82 .18	519	80/61.5	—	—	----	----
17060 Chocolate Bayou	117.7	7182 9364	.78 .22	369	75/74.6	—	—	----	----
17070 Chocolate Bayou to Port O'Connor coastal	185.9	0305 7182 7186	.17 .40 .43	360	75/75.3	—	—	----	----

a/ National Weather Service

b/ Percentage of area of influence expressed as a factor (328).

c/ An assigned parameter for a particular hydrologic soil-cover complex (320).

d/ Soil moisture depletion coefficient (320).

flow studies (321, 324). Average return flows over the 1941 through 1976 period were approximately 75,000 acre-feet per year (92.6 million m^3). Estimated ungaged return flows accounted for three percent of the combined inflow and two percent of the total freshwater inflow to the Lavaca-Tres Palacios estuary (Table 4-2) over the 1941 through 1976 period.

Combined Inflow

A category of combined inflow is obtained by aggregating gaged Colorado River and Lavaca River contributions, ungaged runoff, and estimated ungaged return flows. Over the period 1941 through 1976, combined inflows have averaged 2,935,000 acre-feet per year (3.62 billion m^3/yr) (Table 4-2). Combined inflow accounts for 77 percent of the total freshwater inflow to the Lavaca-Tres Palacios estuary over the 1941 through 1976 period. Average monthly distributions of combined inflow are shown in Figure 4-3. Wide variations in monthly combined inflow have occurred throughout the period of record (Figure 4-4).

Precipitation on the Estuary

Direct precipitation on the 250,485 acre (101,368 hectare) surface area (356) of Lavaca-Tres Palacios estuary was calculated using Thiessen-weighted precipitation techniques (328). Over the 1941 through 1976 period, annual mean precipitation amounted to 864,000 acre-feet per year (1.07 billion m^3/yr). Direct precipitation accounted for 23 percent of the total freshwater inflow to the Lavaca-Tres Palacios estuary (Table 4-2) over the period 1941 through 1976.

Total Freshwater Inflow

Total freshwater inflow includes gaged Lavaca and Colorado River contributions, ungaged runoff, return flows from ungaged areas and direct precipitation on the estuary. For the 1941 through 1976 period, average annual freshwater inflow amounted to 3,799,000 acre-feet (4.69 billion cubic meters). Average monthly distributions of total freshwater inflow are shown in Figure 4-5.

Bay Evaporation Losses

Gross surface evaporation rates for the estuary were calculated from Texas Department of Water Resources pan evaporation data (322). 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 neglected. The estimation of evaporation over the 250,485 acre (101,368 hectare) estuary surface averaged 1,171,000 acre-feet per year (1.45 billion m^3/yr). When compared to total freshwater inflow, evaporation on the estuary's surface was about 30 percent of total inflow over the 1941 through 1976 period.

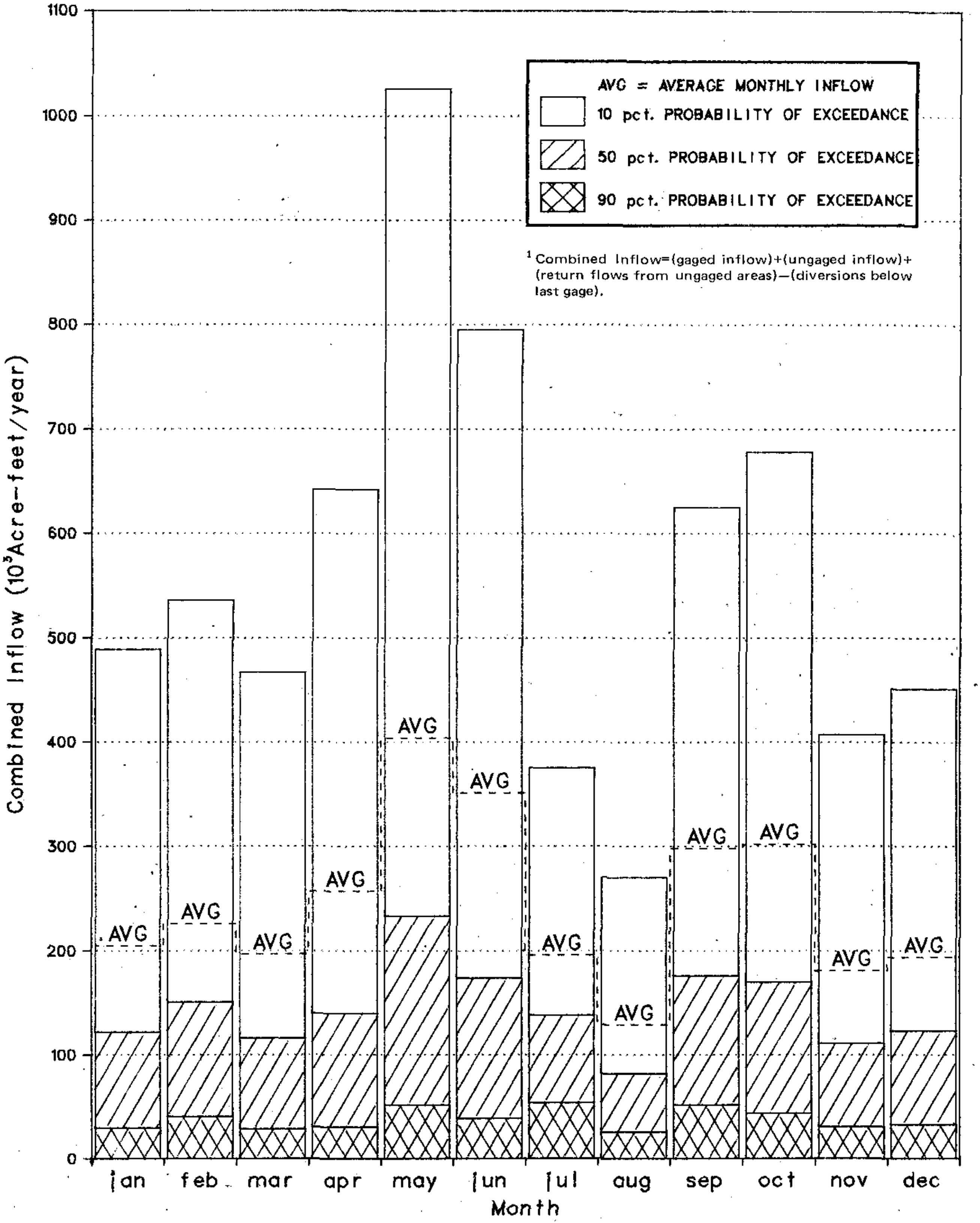


Figure 4-3. Monthly Distribution of Combined Inflow¹, Lavaca-Tres Palacios Estuary, 1941-1976.

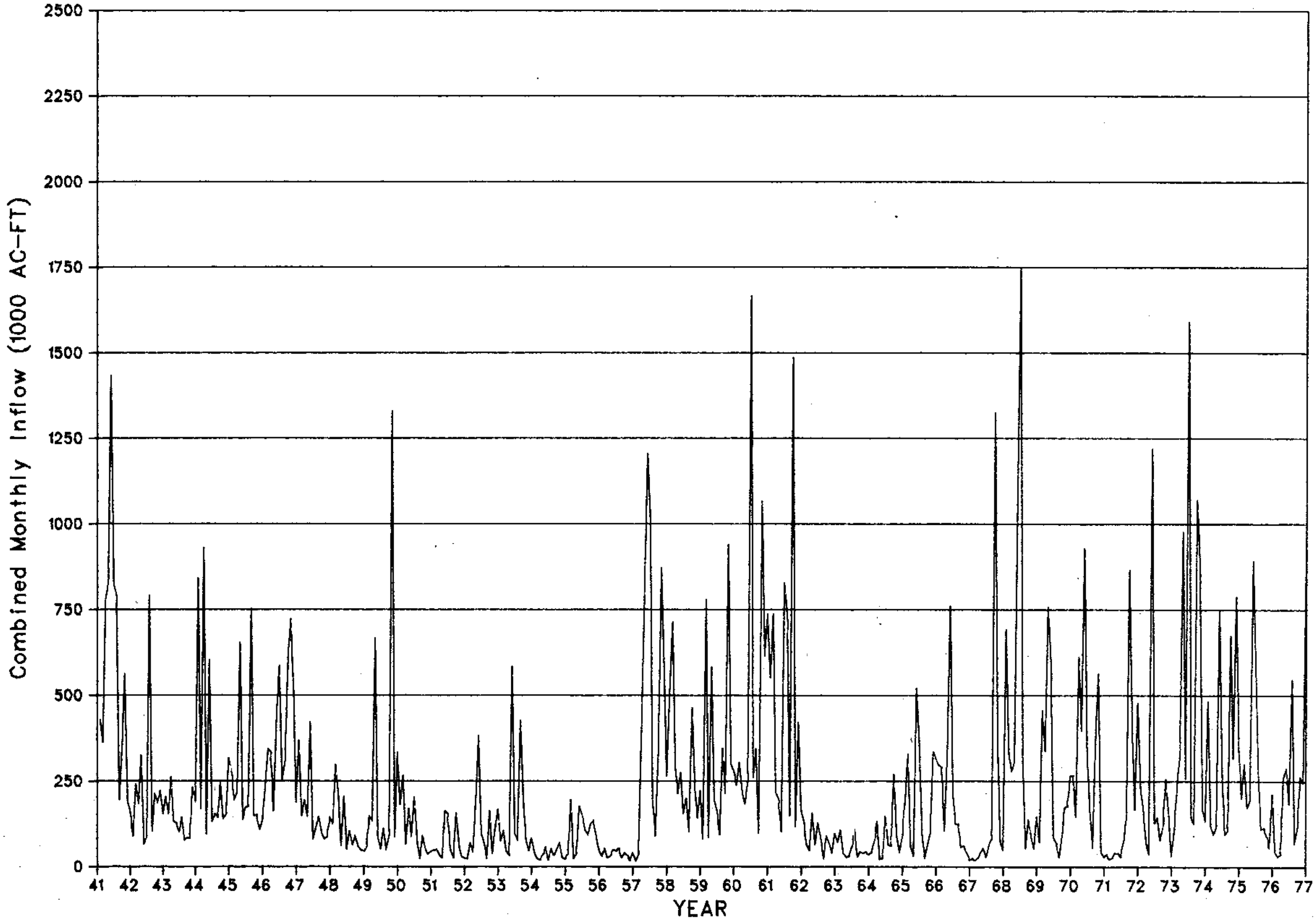
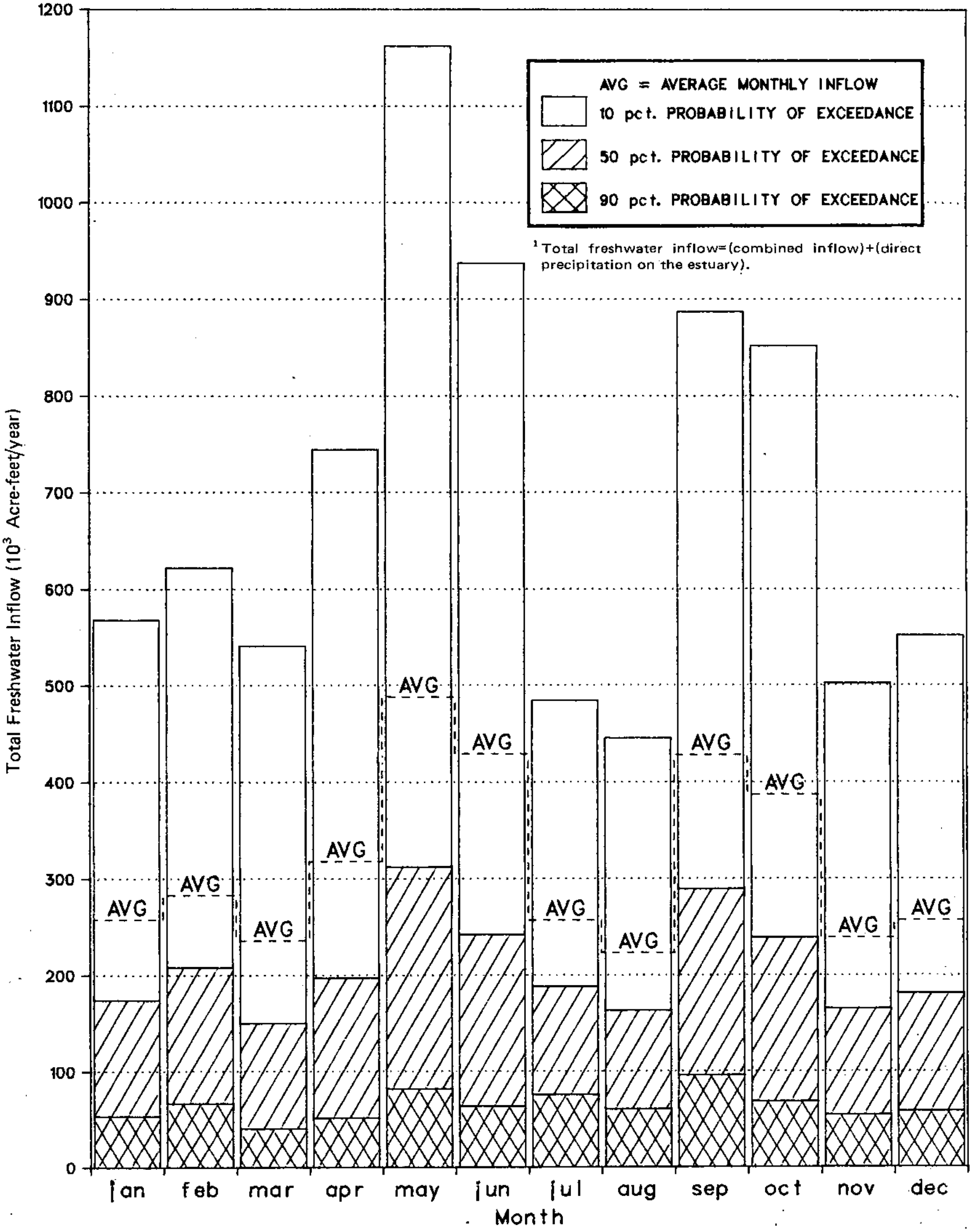


Figure 4-4. Combined Monthly Inflow to the Lavaca-Tres Palacios Estuary, 1941-1976.



[1] Total freshwater inflow=(combined inflow)+(direct precipitation on the estuary).

Figure 4-5. Monthly Distribution of Total Freshwater Inflow[1], Lavaca-Tres Palacios Estuary, 1941-1976.

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 2,628,000 acre-feet per year (3.24 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 represent 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 4-5 for combined inflow and total freshwater inflow, respectively.

Quality of Gaged Inflows

Two USGS gaging stations monitor the quality of inflows to the Lavaca-Tres Palacios estuary: Station No. 08162000 (Colorado River at Wharton) and Station No. 08164500 (Navidad River near Ganado). The range of water quality parameters that were experienced in the 1976 water year are tabulated in Figure 4-6. During the period, 12 samples were available for most parameters.

Student's t-tests were performed on the data to determine if any statistical differences (two-tailed test) were evident between the sample means for the two gaging stations. It was found that for many parameters the difference between the mean values recorded was not statistically significant. However, highly significant statistical differences ($\alpha = 0.01$) between the individual parameter means from the two stations were found for silica, magnesium, sodium, and sulfate.

Statistically significant differences between individual parameter means ($\alpha = 0.05$) were found for chloride and nitrate nitrogen (as N). As a result, concentrations of magnesium, sulfate, chloride and nitrate nitrogen (as N) flowing to the bay from the Colorado Basin are generally higher than are found in Navidad River inflows. On the other hand, silica and sodium concentrations in the Navidad River tend to be higher than are found in the Colorado River flows.

In general, the water quality of flows draining to the Matagorda-Lavaca Bay is very good. No parameters have been in violation of Texas water quality standards, although fecal coliform concentrations in the Navidad River occasionally reach elevated levels during flood events.

Table 4-4. Monthly Inflows to the Lavaca-Tres Palacios Estuary for Corresponding Exceedance Frequencies a/, b/

Month	Gaged Lavaca Basin Inflow			Colorado Basin 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%
January	137	17	1	226	78	26	178	10	0	489	122	30	114	40	14	568	174	54	66	50	38
February	128	22	3	242	84	28	216	22	0	536	151	41	114	43	12	622	208	67	65	51	40
March	97	15	2	230	74	24	163	9	0	467	116	29	91	26	7	541	150	41	84	68	55
April	170	23	3	266	80	24	218	15	0	642	140	31	134	45	15	744	197	52	99	81	65
May	312	43	4	363	108	32	532	33	0	1026	233	52	184	63	21	1162	312	82	128	105	86
June	224	32	3	304	84	24	301	30	0	795	174	39	162	55	17	937	242	64	164	127	98
July	66	13	2	181	58	19	113	4	0	375	138	54	146	39	10	484	188	76	193	153	118
August	54	10	2	114	48	20	140	6	0	270	82	26	193	73	27	445	163	61	194	155	124
September	137	25	5	167	66	26	369	29	0	625	176	52	285	99	33	887	289	96	151	124	101
October	143	14	1	212	76	27	418	21	0	678	170	44	215	57	12	852	239	69	129	107	86
November	95	11	0	225	75	25	123	10	0	407	111	31	132	42	13	502	165	55	97	78	63
December	103	14	1	211	75	26	119	10	0	451	123	33	128	50	17	552	181	59	75	59	46

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.

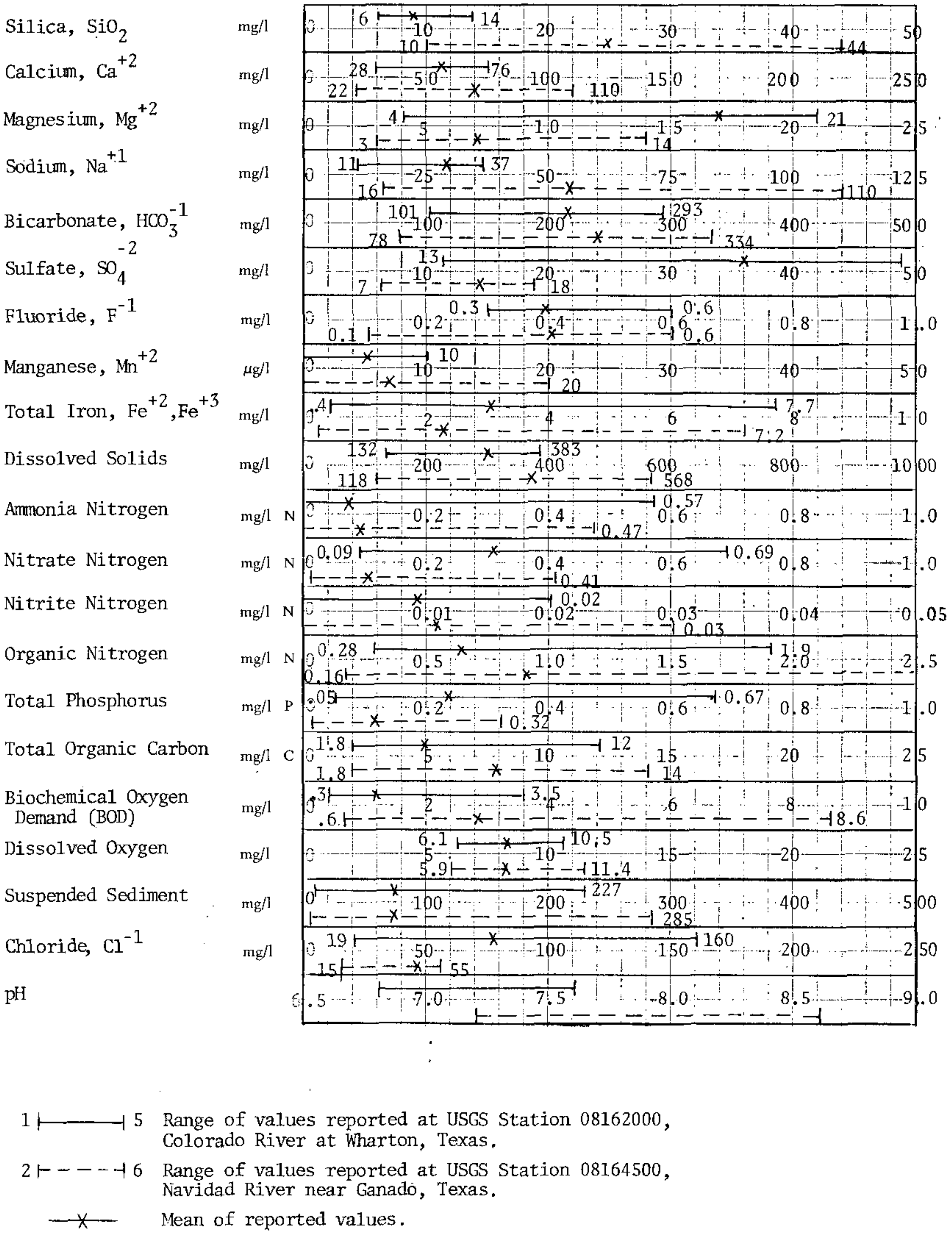


Figure 4-6. Range of Values for Water Quality Parameters, Gaged Inflow to Lavaca-Tres Palacios Estuary, October 1975-September 1976 (377).

Quality of Estuarine Waters

Nutrient Concentrations in the Lavaca-Tres Palacios 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 the lack of sufficient data precludes a determination of seasonal nutrient concentrations in the estuary, available data can be used to determine general 1968 through 1976 concentrations of carbon, nitrogen, and phosphorus (CNP) in the Lavaca-Tres Palacios estuary.

The estuary was considered as three major distinct sections for the analysis: (1) Lavaca Bay, (2) the east arm of Matagorda Bay, and (3) the rest of Matagorda Bay (excluding the upper portion of Tres Palacios Bay, termed "open bay" in the analysis). Only those sampling locations located away from major population or industrial centers in open bay waters were considered, since nutrient concentrations near these locales would bias the resultant concentrations in open waters.

Freshwater discharges from the major rivers, the Lavaca and Colorado, and contributions of deltaic marshes of the Lavaca delta were expected to be the major source of nutrient input to the system. The carbon-nitrogen-phosphorus (CNP) concentrations in Lavaca Bay and the east arm of Matagorda Bay would thus be expected to be greater than those in the open water of Matagorda Bay in proximity of the Gulf of Mexico. The CNP data for each of the three distinct portions of the estuary were tabulated, averaged, and finally 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.

Ammonia nitrogen and nitrate-nitrogen concentrations were summed for each sample to arrive at total available nitrogen concentrations. Nitrite-nitrogen data were infrequent; thus, nitrite-nitrogen concentrations were assumed to be zero in this analysis.

Frequency histogram plots of grouped nitrogen and phosphorus data (Figures 4-7 and 4-8) indicate strongly skewed frequency distributions in all three study areas. The bulk of the observed nitrogen and phosphorus concentrations were less than 0.10 mg/l. Concentrations of nitrogen and phosphorus in Lavaca Bay and the eastern arm of Matagorda Bay were considerably higher than concentrations of the same parameters in the open waters of Matagorda Bay.

Organic carbon concentrations ranged from near zero to about 20 mg/l (Figure 4-9). Concentrations in Lavaca Bay were considerably higher than those in either the east arm of Matagorda Bay or in the open bay itself.

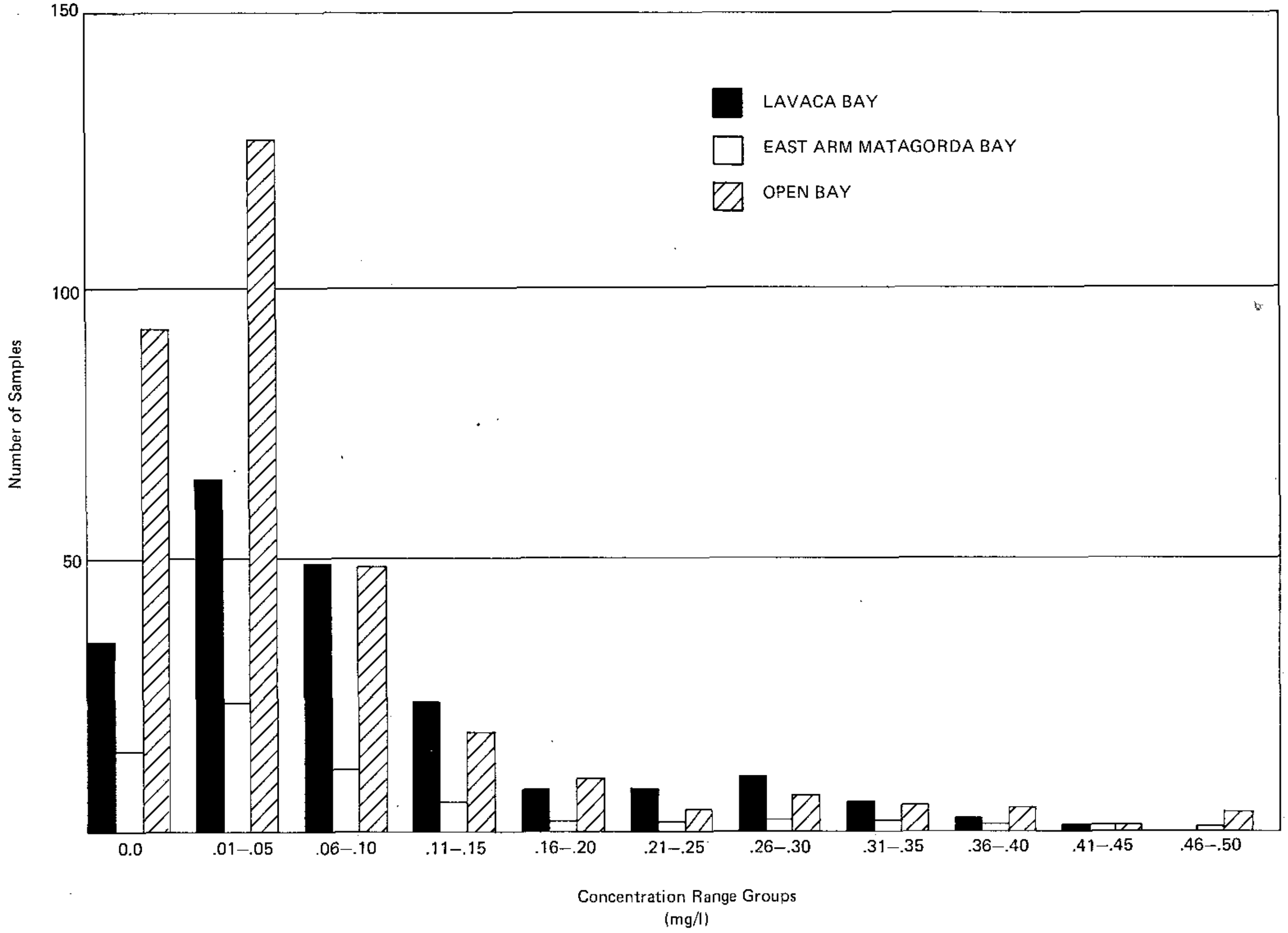


Figure 4-7. Distribution of Total Nitrogen (as N) Concentrations Occurring in the Lavaca-Tres Palacios Estuary, 1968-1977.

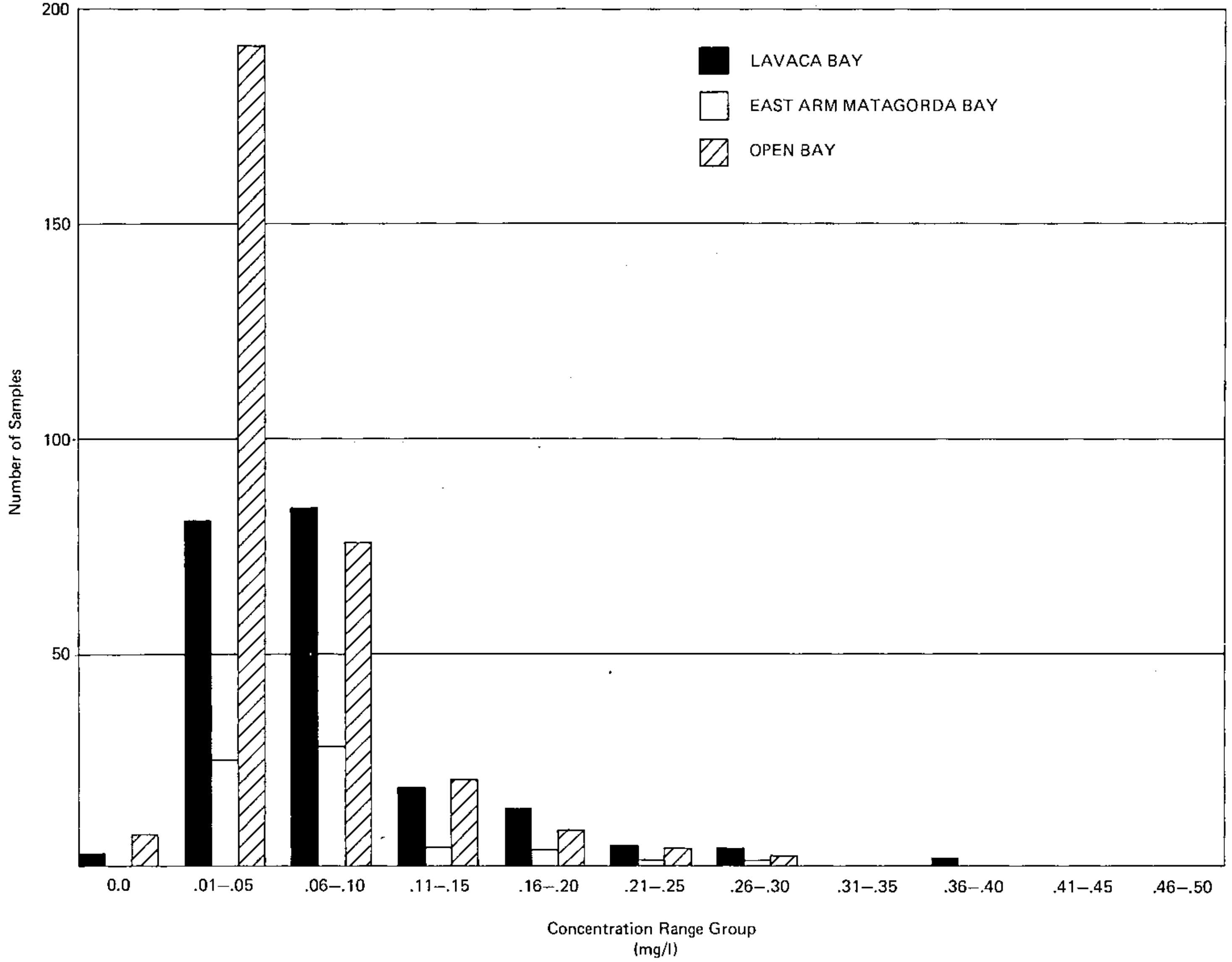


Figure 4-8. Distribution of Total Phosphorus (as P) Concentrations Occurring in the Lavaca-Tres Palacios Estuary, 1968-1977.

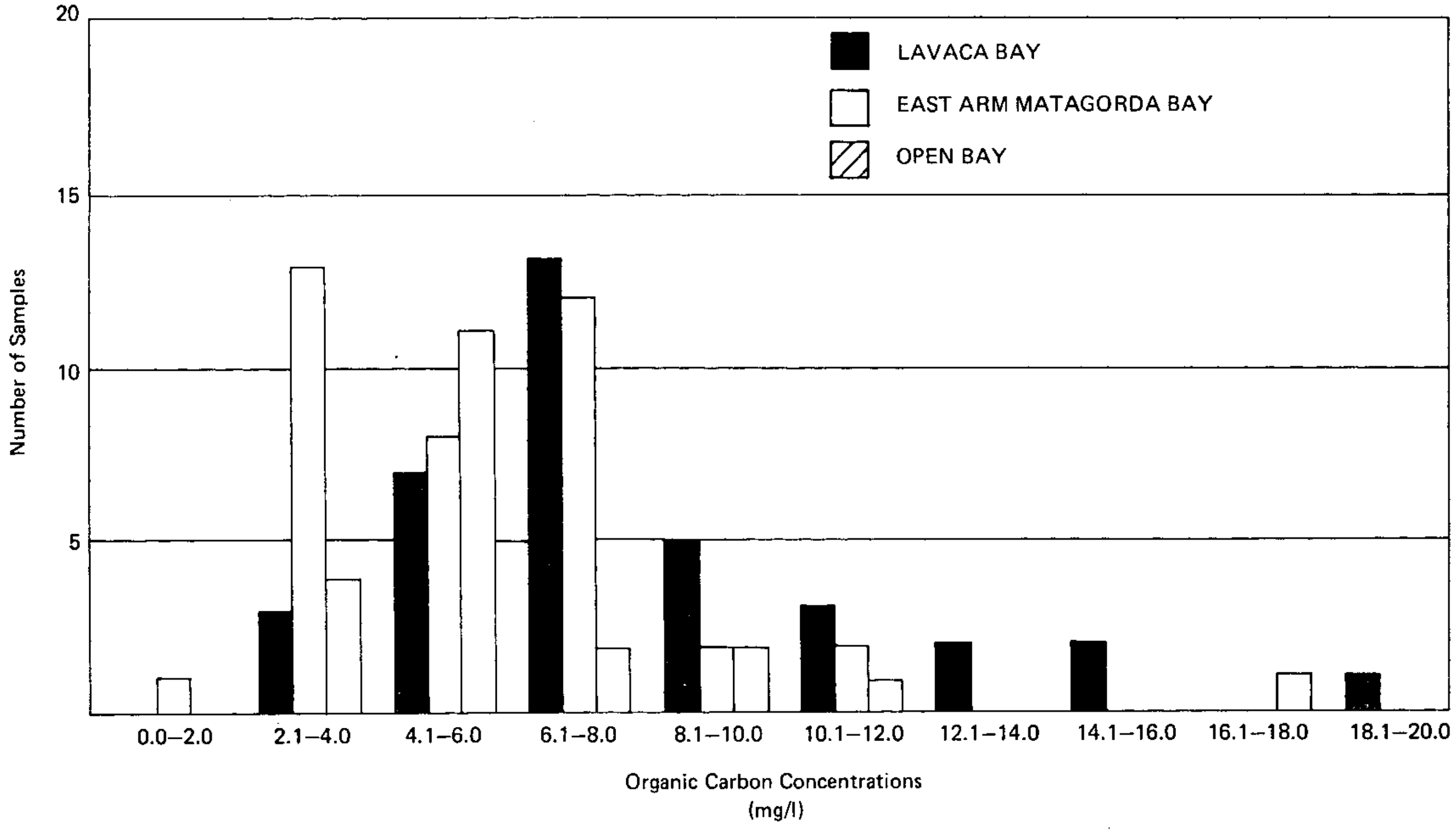


Figure 4-9. Distribution of Organic Carbon (as C) Concentrations Occurring in the Lavaca-Tres Palacios Estuary, 1968-1977.

At present, a limited data base prevents a correlation of changes in CNP concentrations in the open bay waters with varying freshwater inflow regimes. The evidence suggests, however, that freshwater inflow is one mechanism for transporting nutrients to open bay areas.

Heavy Metals

From time to time detailed studies of water quality problems in and around the Lavaca-Tres Palacios estuary have pinpointed heavy metals as a significant concern near major industrial plant sites (226). The present section is not intended to be a comprehensive analysis of the sources from which heavy metals originate in the area. The purpose here is to summarize the available data on heavy metals and give the range of values that have been found in recent sampling efforts. The detection of heavy metals in water is relatively unlikely, except in heavily polluted areas, so that bottom sediments are often analyzed for heavy metals which have been absorbed onto the sediment particles from the water column.

Samples of bottom sediments in the Lavaca-Tres Palacios estuary were available for the period 1972 to 1978 at sampling sites shown in Figure 3-9. Sampling efforts were carried out by the USGS and the Texas Department of Water Resources in cooperation with other interested agencies. From the 19 data collection sites heavy metals detected included arsenic (As), boron (B), barium (Ba), cadmium (Cd), chromium (Cr), cobalt (Co), copper (Cu), iron (Fe), lead (Pb), manganese (Mn), nickel (Ni), silver (Ag), and zinc (Zn). Statistical analyses were not carried out due to the limited number of samples during the test period from 1972 through 1978. The range of values for heavy metals is shown in Table 4-5, for Matagorda Bay, Tres Palacios Bay, Lavaca Bay, Cox Bay and Keller Bay.

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 edible shellfish such as oysters and crabs as these organisms generally concentrate certain metals in their bodies when feeding in polluted areas. Reduction in 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. Areas of the Lavaca-Tres Palacios estuary may exceed U. S. EPA criteria for metals in the sediment (prior to dredging) for the following constituents (Table 4-5): arsenic, cadmium, mercury, and zinc.

Herbicides and Pesticides

Samples of the bottom sediments in the Lavaca-Tres Palacios estuary were collected through the USGS-TDWR cooperative program and analyzed for herbicide

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

Station Location b/ & USGS Station Number: / Parameter	Lavaca Bay 2453.02 & 2453.03	Matagorda Bay 2451.01	Tres Palacios Bay 2452.01	Cox Bay 2454.01	Keller Bay 2455.01	Dredge Criteria
	Units are mg/kg					
Arsenic	<1.0-5.8*	<1.0-4.5	<1.0	<1.0-4.4	<1.0-2.3	5
Boron	0.45-18	0.41-26	0.63-13	—	—	—
Barium	5-50	5-80	4.5-38	16-58	15-50	—
Cadmium	<0.1-7*	0.2-3*	0.1-11*	<0.1-7*	—	2
Chromium	2.9-40	2-30	1.4-31	1.4-24	0.2-14	100
Copper	0.54-16	0.5-17	0.7-12	1.6-17	0.4-14	50
Lead	<1.1-17	3.6-28	3.0-16	1.1-17	1.1-14	50
Manganese	7.1-980	12.5-725	2.7-660	140-610	10.4-400	—
Mercury	<0.002-3.8*	—	—	0.003-2.5*	—	1
Nickel	1.5-25	1.5-24	1.5-2.3	2.7-23	1.6-12	50
Silver	<1.0-1.4	<1.0-2.2	<1.0	<1.0-50	<1.0-1.5	—
Zinc	4-96*	7.2-73	10.4-175*	2.7-60	1.3-33	75

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a/ Includes data from ref. (232).
b/ See Figure 3-9 for location of sample sites.
* Denotes at least one sample in violation of EPA's dredge spoil criteria.

Table 4-6. Range of Pesticide Concentrations in Sediment, Lavaca-Tres Palacios Estuary, 1969-1974 (377)

Sampling Station a/ / Parameter	Navidad River	Lavaca River	Near Mouth of Garcitas Creek	Lavaca Bay	Matagorda Bay	Carancahua Bay	Tres Palacios Bay
	17	22	85.3	90.3 110	333.1 375.1	224 235	258 264 284.2
	Units are µg/kg						
DDD	<0.2- 9.2	<0.2- 2.8	<0.2- 7.1	<0.2- 34.0	<0.2- 2.2	<0.2- 1.2	<0.2- 21.0
DDE	1.5- 27.0	1.3- 20.0	1.2- 11.0	<0.2- 24.0	<0.2- 3.7	0.2- 6.4	0.6- 52.0
DDT	—	<0.2- 4.4	—	<0.2 16.0	—	—	<0.2- 33.0
Dieldrin	—	<0.2- 0.34	—	4.4	—	<0.2- 4.8	<0.2- 1.2

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a/ See Figure 3-9 for location of sample sites.

and pesticide concentrations (Table 4-6). From the 19 data collection sites, parameters detected included aldrin; DDD; DDE; DDT; dieldrin; endrin; heptachlor; heptachlor expoxide; 2,4-D; 2,4,5-T; and silvex. Of these, only the pesticides DDD, DDE, DDT, and dieldrin, were found at levels above or equal to the detection limit of 0.2 µg/kg during the sampling periods from 1969 to 1974. Only 12 stations had data for these pesticides at levels above or equal to the detection limit. Statistical analyses were not possible due to the limited number of samples available.

Summary

Sources of freshwater inflow to the Lavaca-Tres Palacios 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. Measurement of freshwater inflow adds to the understanding of inflow timing and volumes and their influence on bay productivity. To compute accurate inflow estimates, gaged stream flows required adjustment to reflect any withdrawals or return flows downstream from gage locations. Ungaged runoff was estimated by computerized mathematical models that were developed, calibrated, and verified using field data. Rainfall was estimated as a distance-weighted average of the daily precipitation recorded at weather stations surrounding the estuary.

Freshwater inflow, in terms of annual and monthly average values over the 1941 through 1976 period, varied widely from the mean as a result of recurrent drought and flood conditions. On the average, the total freshwater inflow to the estuary (1941-1976) consisted of: (1) gaged contributions from the Lavaca Basin (16 percent), (2) a portion of the gaged inflow from the Colorado Basin (34 percent), (3) runoff from ungaged areas (25 percent), (4) return flows from ungaged areas (2 percent), and (5) direct precipitation on the estuary (23 percent).

In general, the quality of gaged inflows to the Lavaca-Tres Palacios estuary is good. None of the streams contributing to the estuary are in violation of existing State/Federal stream standards. Detailed studies of past water quality problems in and around the estuary have pinpointed heavy metals as a significant concern near the major industrial sites. Locally, bottom sediment samples have exceeded EPA dredge criteria (1974) for metals in sediments for arsenic, cadmium, mercury and zinc. Bottom sediments collected and analyzed for herbicides and pesticides showed DDD, DDE, DDT, and dieldrin occurring in local areas in concentrations equal to or greater than the analytical detection limit during the period 1969 to 1974.

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 Lavaca-Tres Palacios 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 accurately reproduce 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 numerical methods 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.

Numerical 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 capacity 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 constraints 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

The mathematical tidal hydrodynamic and conservative transport models for the Lavaca-Tres Palacios estuary have been developed by Masch (146). 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 flow. These are then used as input to the conservative transport model to compute vertically averaged salinities (or any 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 transport model ordinarily cannot be operated unless the tidally generated convective inputs are available.

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

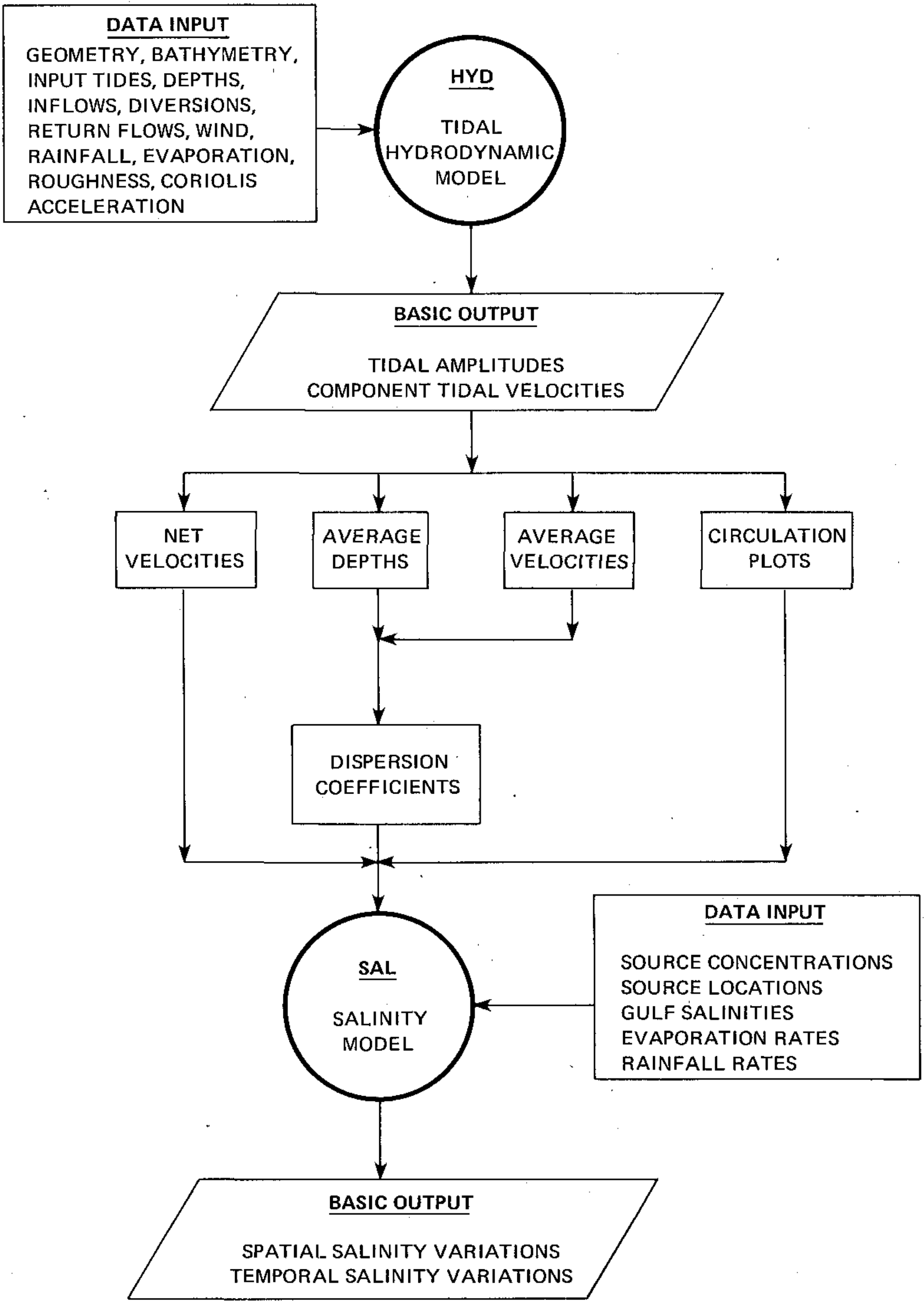

Figure 5-1. Relationship Between Tidal Hydrodynamic and Salinity Models (146).

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 = 28.5° for the Lavaca-Tres Palacios estuary
r = rainfall intensity
e = evaporation rate.

The numerical solution utilized in the hydrodynamic model of the Lavaca-Tres Palacios 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} is the maximum water depth encountered in the computational matrix. The numerical solutions of the basic equations and the programming techniques have been described previously (146).

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

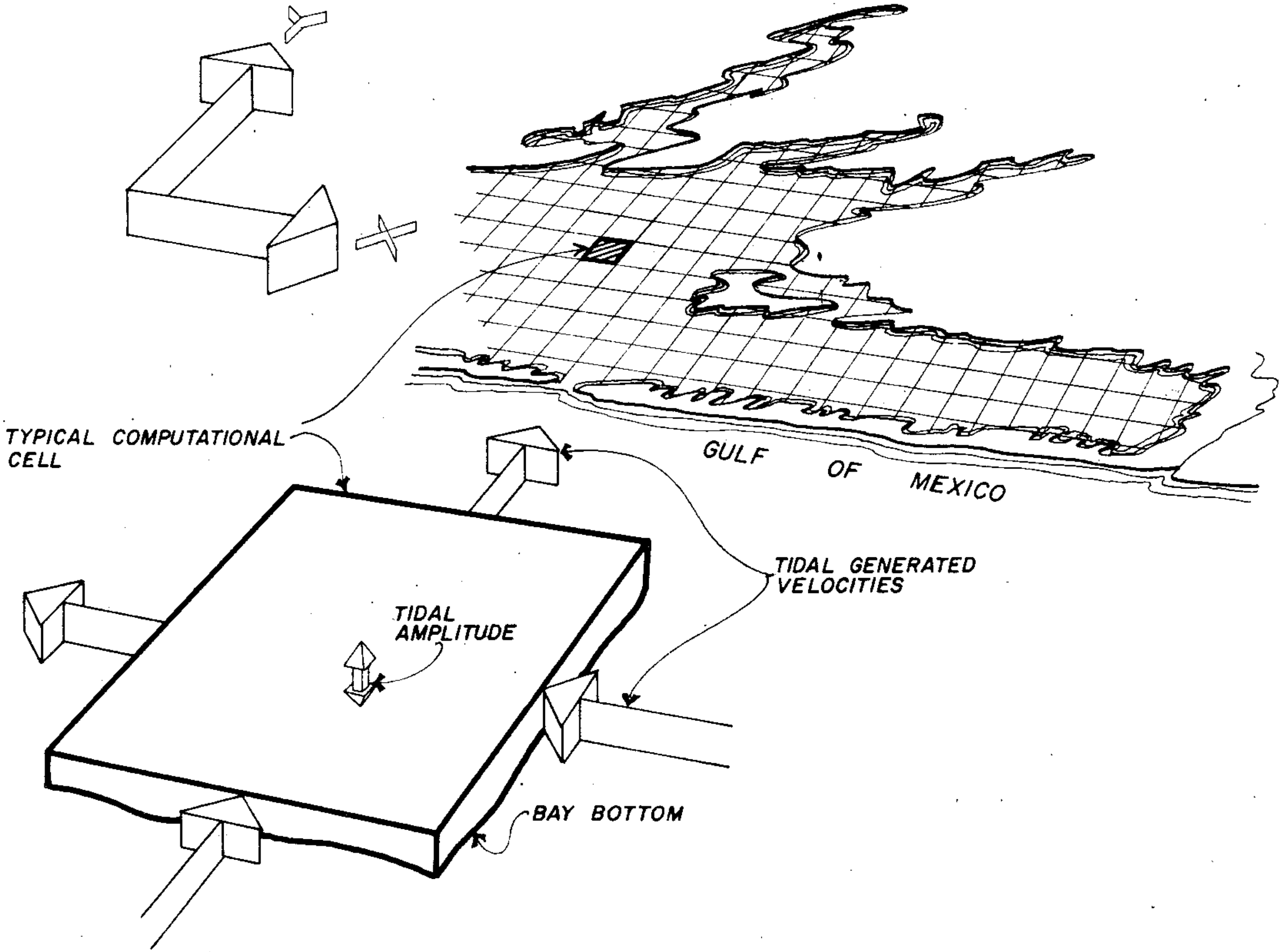

Figure 5-2. Conceptual Illustration of Discretization of a Bay (146).

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 (146). The primary difference in the form of Equation [4] given above and that reported previously (146), 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 $\Delta t/\Delta\bar{s}^2 \leqslant 1/2$ was always maintained throughout this work. Details of the numerical solution of Equation [4] and programming techniques have also been previously described by Masch (146).

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 low-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 floodplain 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]

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

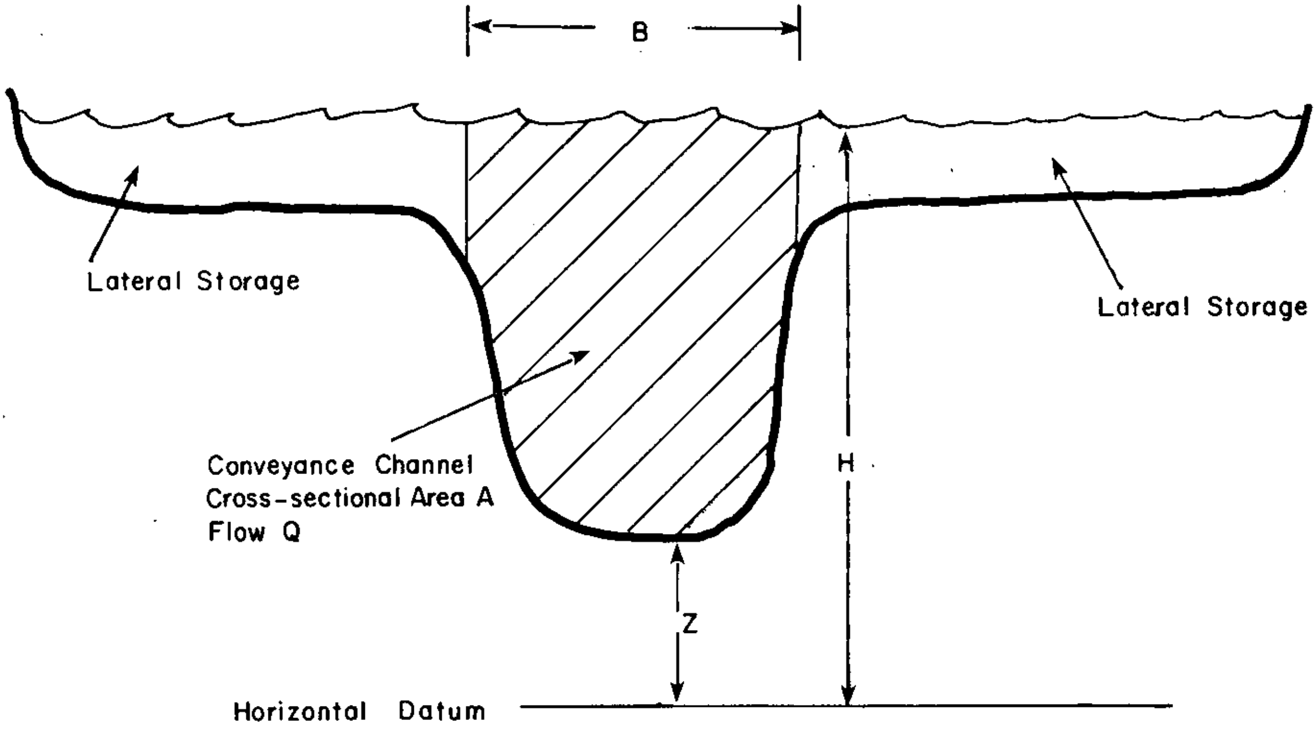


Figure 5-3. Definition of Variables in Cross Section (44).

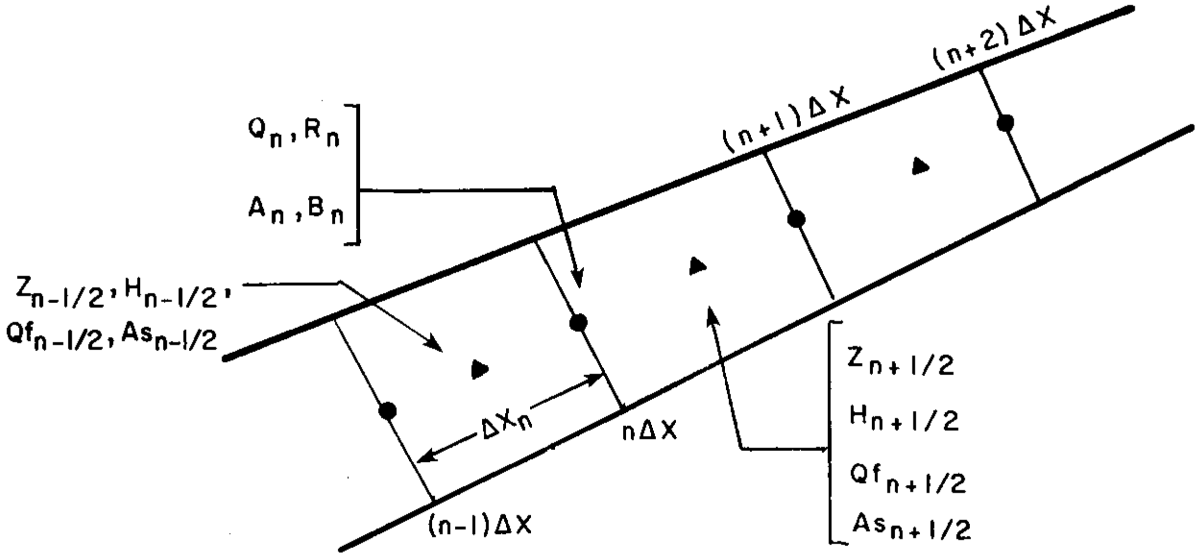


Figure 5-4. Definition of Finite-Difference Segmentation for Hydrodynamic Model (44).

(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:

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

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 both the Lavaca and Colorado River deltas by Hauck, Ward, and Huston (44) and Sullivan and Hauck (45). Only the Colorado delta possessed characteristics which prohibited a straightforward application and analysis of results.

Lavaca River Delta. The system boundaries and segmentation schematic utilized for the Lavaca delta are presented in Figure 5-5. The upstream and downstream system boundaries are selected in accordance with model specifications, the availability of tide records for Lavaca Bay, and availability of flow data for the Lavaca and Navidad Rivers. Tidal records are supplied by a continuous recording tide gage near Point Comfort (081661825), while the freshwater inflows are derived from two U. S. Geological Survey (USGS) streamflow gages, the Lavaca River gage near Edna (08164000) and the Navidad River gage near Ganado (08164500). Additional data have been obtained from two USGS continuous recording tide gages located in the delta area, one near Vanderbilt (08164555) and one near Lolita (08164530).

An initial series of low-flow calibration simulations were performed applying tide and flow data for the period February 25 through March 10, 1975 (see example result, Figure 5-6). These simulations demonstrated the model's ability to satisfactorily reproduce water surface elevations at the two independent tide gages (not used as input data) for conditions of constant freshwater inflow and normal tide ranges.

Three flood cases encompassing both normal and high driving tides, as well as the daily tidal fluctuations, were simulated utilizing data from June and November 1974, and May and June 1975. HYDELT was able to adequately reproduce, in all but one case, both phase and amplitude variations at the Vanderbilt and Lolita gages throughout the simulation periods (44).

Colorado River Delta. The mouth of the Colorado River and Tiger Island Cut are constantly being modified through geomorphological forces, including freshwater inflows, tides, sedimentation/erosion, and long-shore

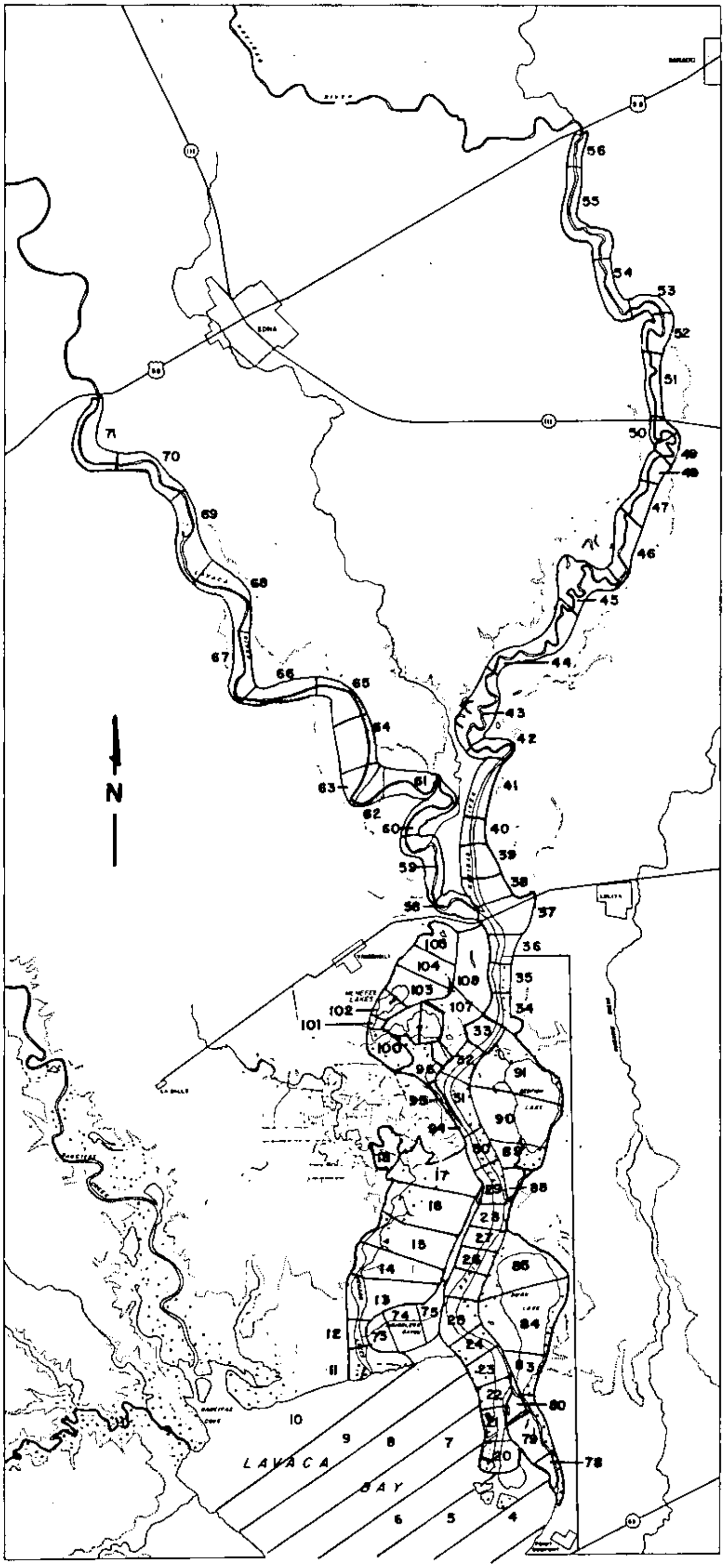


Figure 5-5. Deltaic Systems Boundaries of the Lavaca Delta (44).

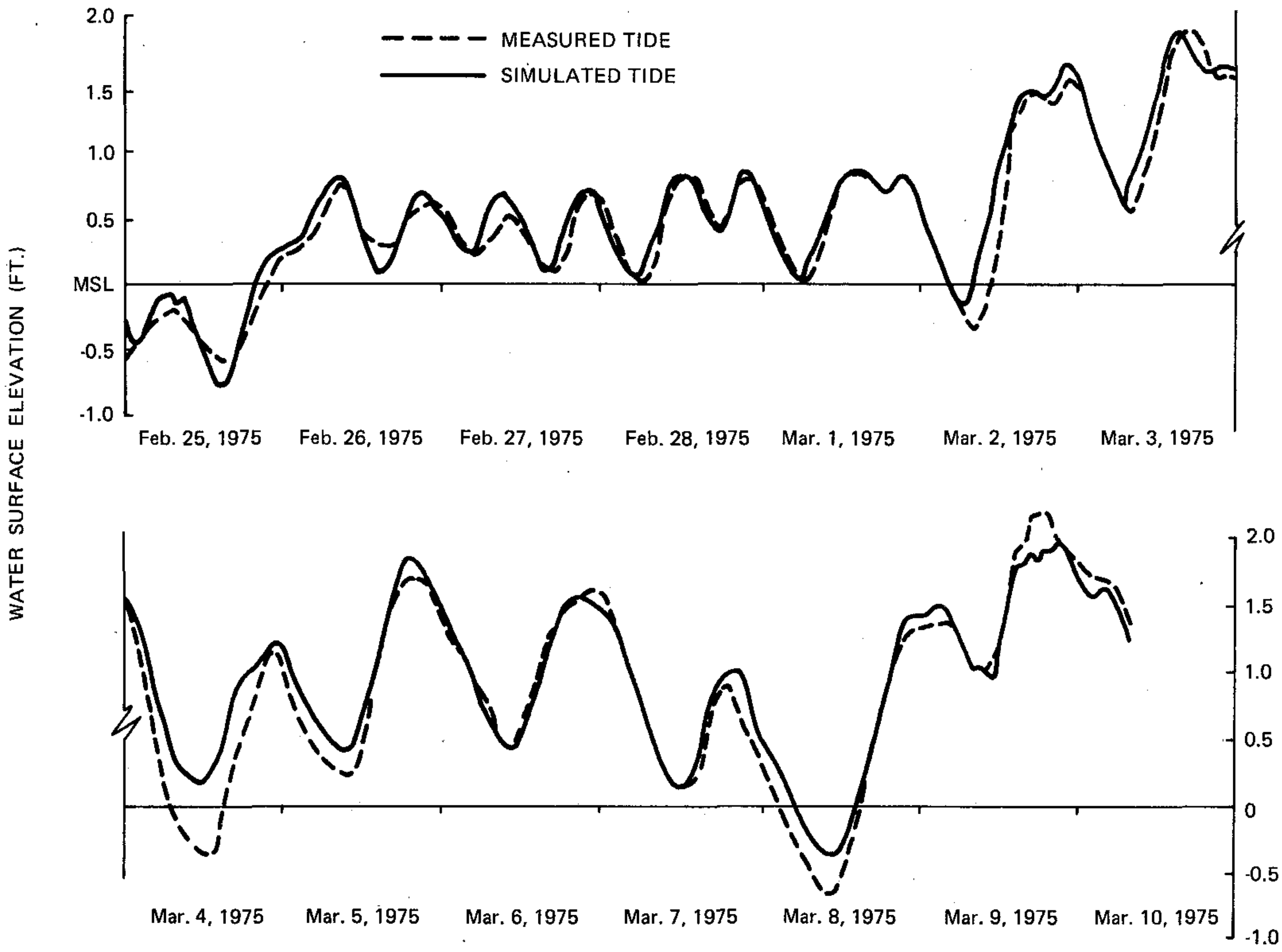


Figure 5-6. Comparison of Measured and Simulated Tidal Elevations at Section 31, Vanderbilt Tide Gage (45).

drift. Such a system does not lend itself to a generalized modeling approach, thus requiring special consideration.

A map of the Colorado River delta showing system boundaries selected for modeling purposes is presented in Figure 5-7. The modeling system is driven by three separate tides, two of which are related through simple phase and amplitude variations. HYDELT required the addition of a new subroutine to accommodate the third driving tide, East Matagorda Bay, which is unrelated to the Matagorda Bay and Gulf of Mexico tides.

Two inflow cases were selected to calibrate and validate HYDELT for the Colorado River delta. Calibration periods selected were May 18-26, 1977 and July 20-28, 1977, differing principally in the magnitude of Colorado River flow. The average flow recorded in May 1977 was 5,510 ft^3/sec (156 m^3/sec) while that recorded in July 1977 was 1,400 ft^3/sec (40 m^3/sec). Comparison of simulated and observed water surface elevations throughout the delta were in close agreement for both calibration cases (Figures 5-8 and 5-9). Comparison of simulated and observed flows at Tiger Island Cut over these periods showed considerable variance. Inspection of the observed flow profiles suggested the presence of bidirectional flow, whereas HYDELT is predicated upon the assumption of unidirectional flow. Comparison of the simulated and observed (time-averaged) net flow through the cut yielded very good agreement, so that HYDELT can be considered calibrated for water surface elevations and time-averaged net flows (Figures 5-10 and 5-11) in the Colorado River delta.

A single flood event on the Colorado River was selected for validation simulations with HYDELT for a flow peak of 49,100 ft^3/sec (1,375 m^3/sec) and a duration of 18 days. The driving tides in Matagorda Bay and the Gulf of Mexico appeared semidiurnal early in the simulation period, changing to diurnal during the remainder of the period. Comparison of simulated and observed water surface elevations at Matagorda (Figure 5-12) and above Tiger Island Cut (Figure 5-13) demonstrated good correlation of both phase and amplitude. The simulated surface profiles at Matagorda were only slightly under the observed; whereas, the predicted profiles above Tiger Island Cut were in near perfect agreement. Therefore, HYDELT can be considered adequately validated with respect to water surface elevations as well as net flow.

Application of Mathematical Models, Lavaca-Tres Palacios Estuary

Hydrodynamic and Mass Transport Models

The computational grid network used to describe the Lavaca-Tres Palacios estuary is illustrated in Figure 5-14. 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

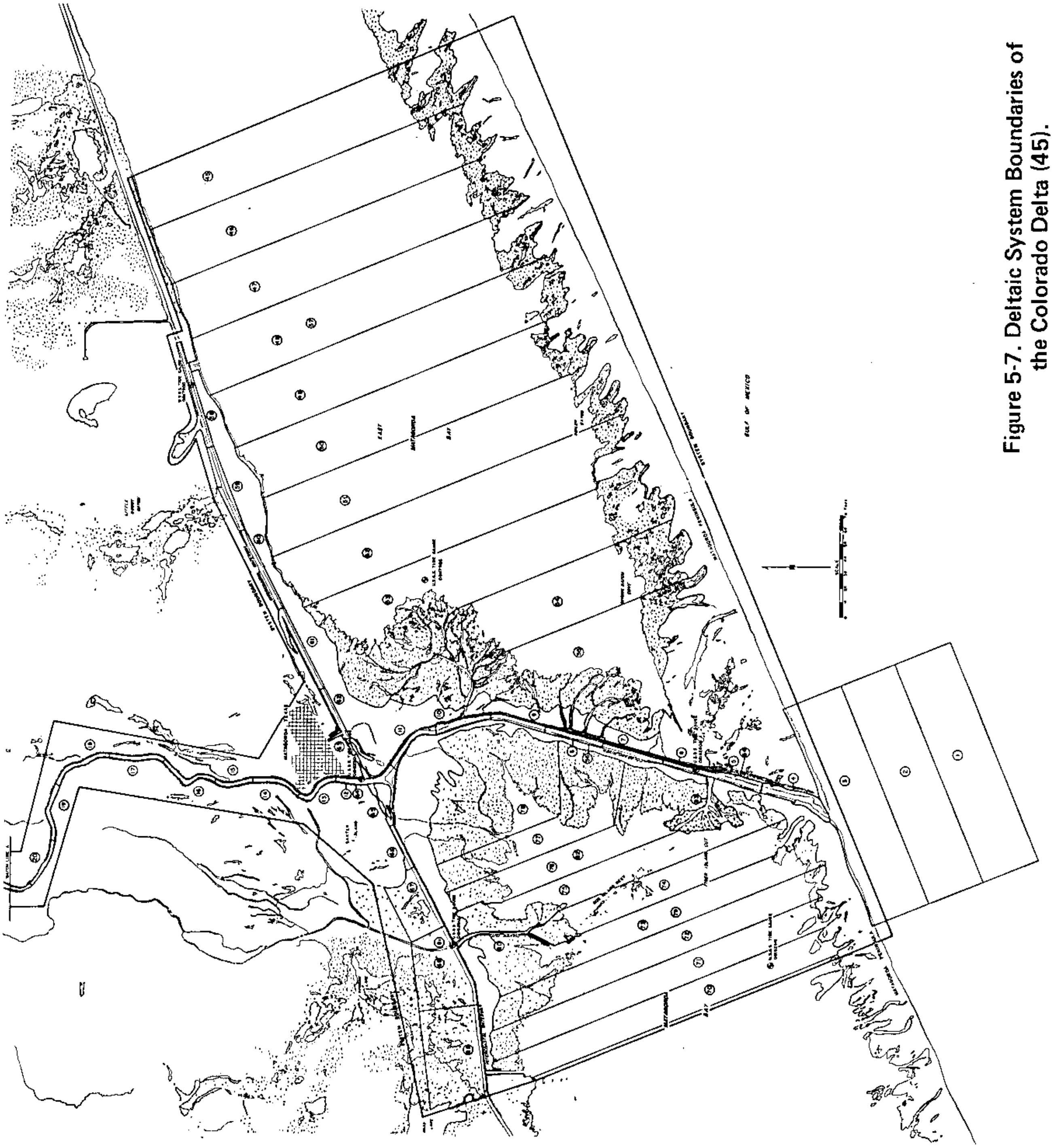


Figure 5-7. Deltaic System Boundaries of the Colorado Delta (45).

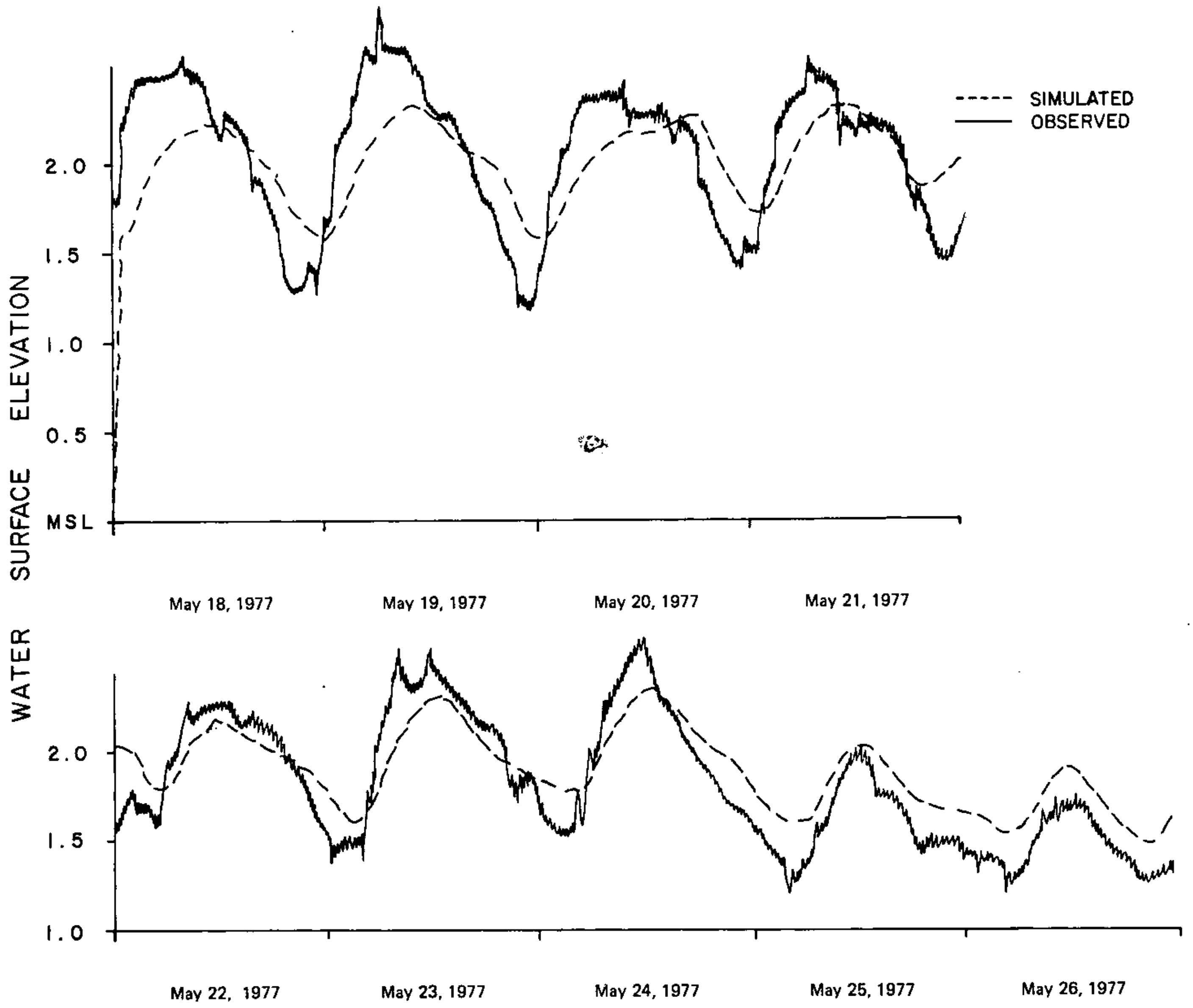


Figure 5-8. Comparison of Observed and Simulated Tidal Elevations above Tiger Island Cut, May 18-26, 1977 (45).

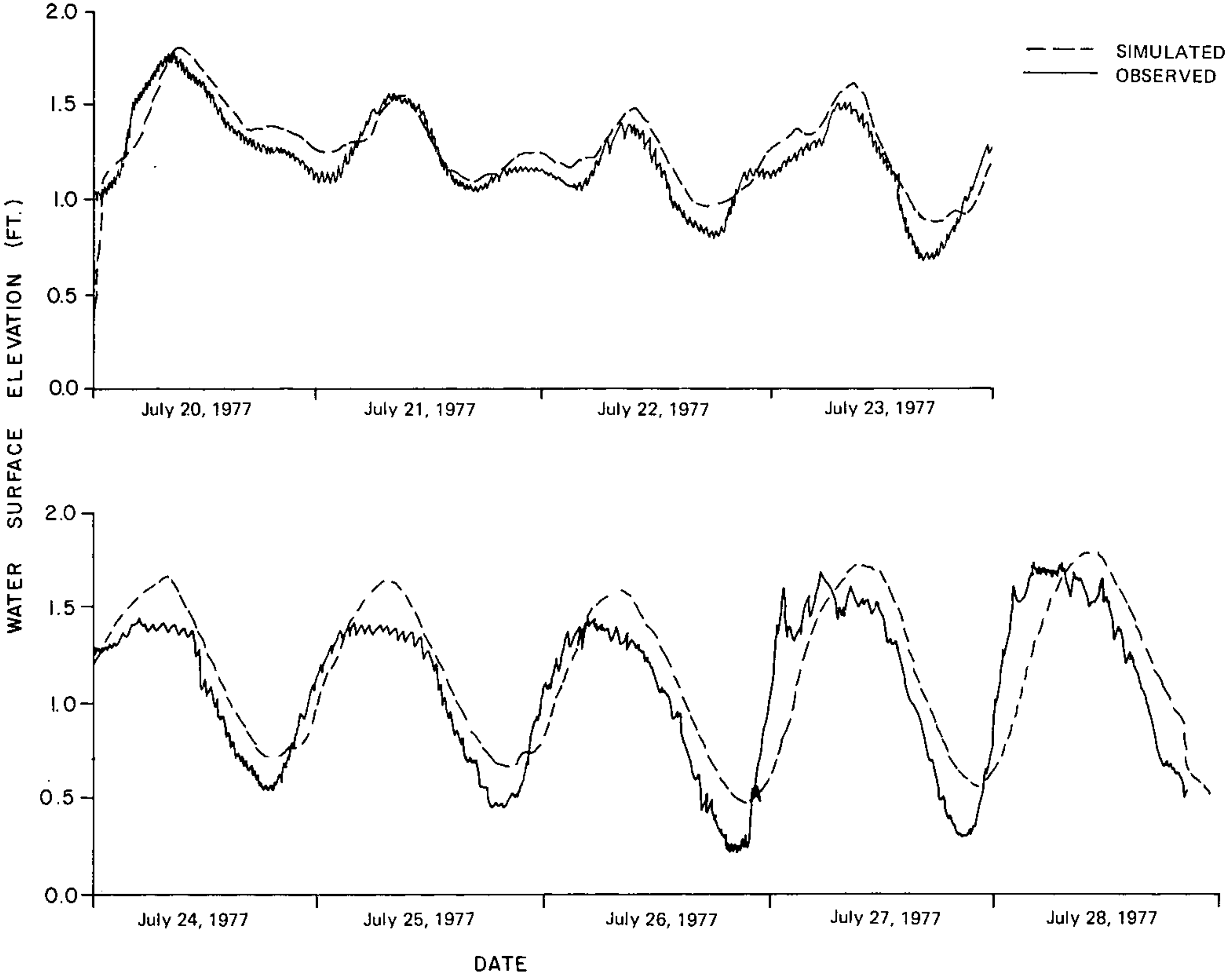


Figure 5-9. Comparison of Observed and Simulated Tidal Elevations above Tiger Island Cut, July 20-28, 1977 (45).

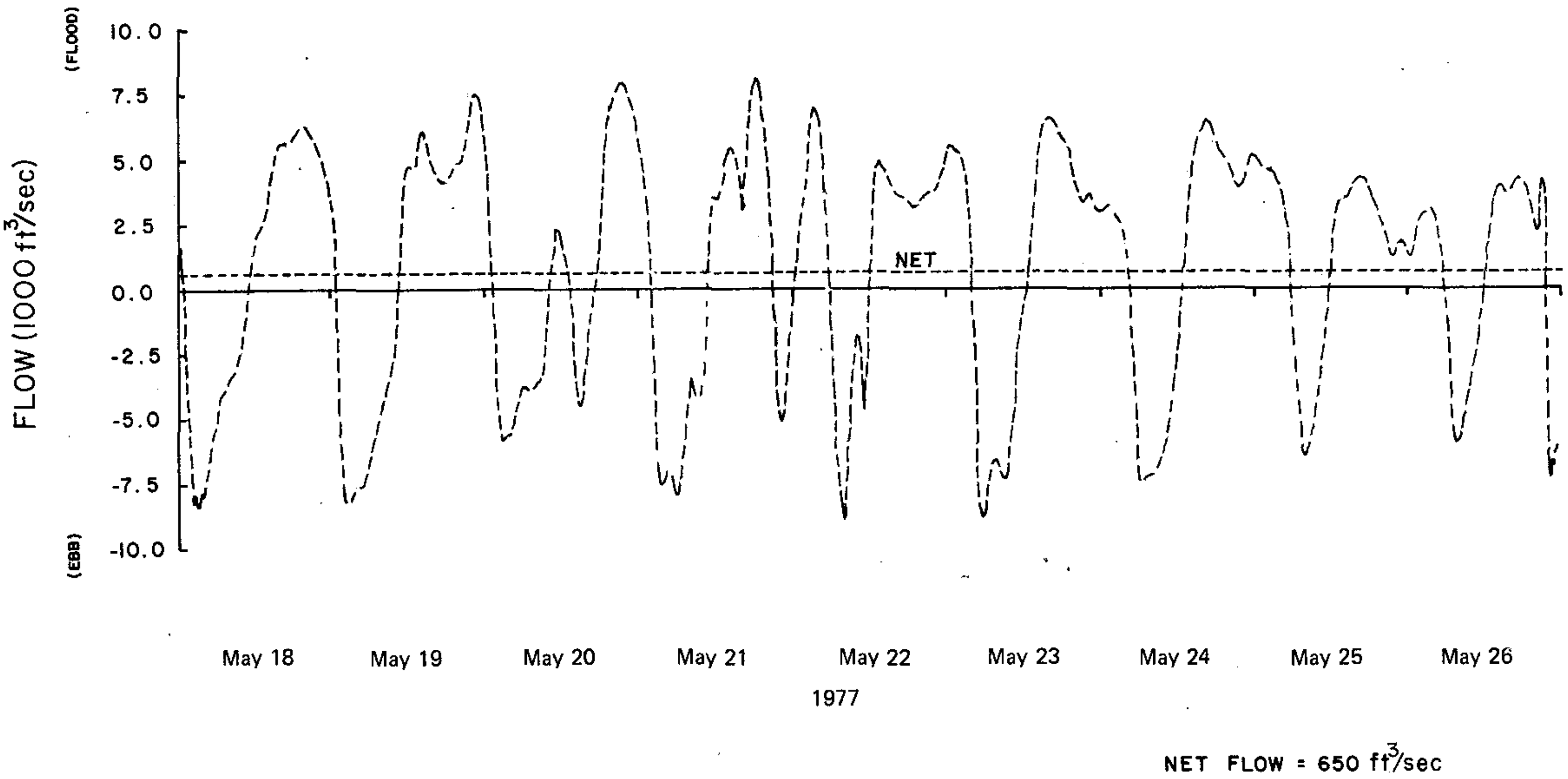
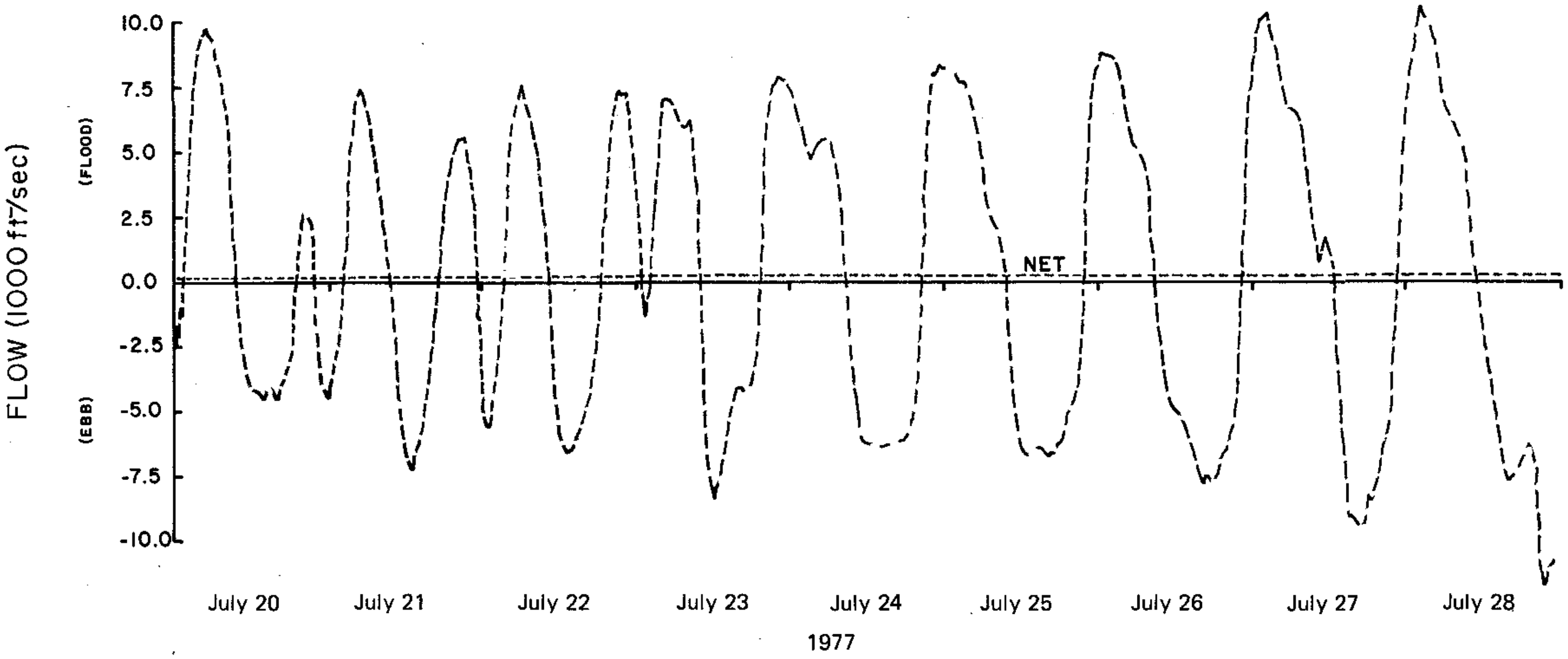


Figure 5-10. Simulated Flow at Tiger Island Cut, May 18-26, 1977 (45).



NET FLOW = 170 ft^3/sec

Figure 5-11. Simulated Flow at Tiger Island Cut, July 20-28, 1977 (45).

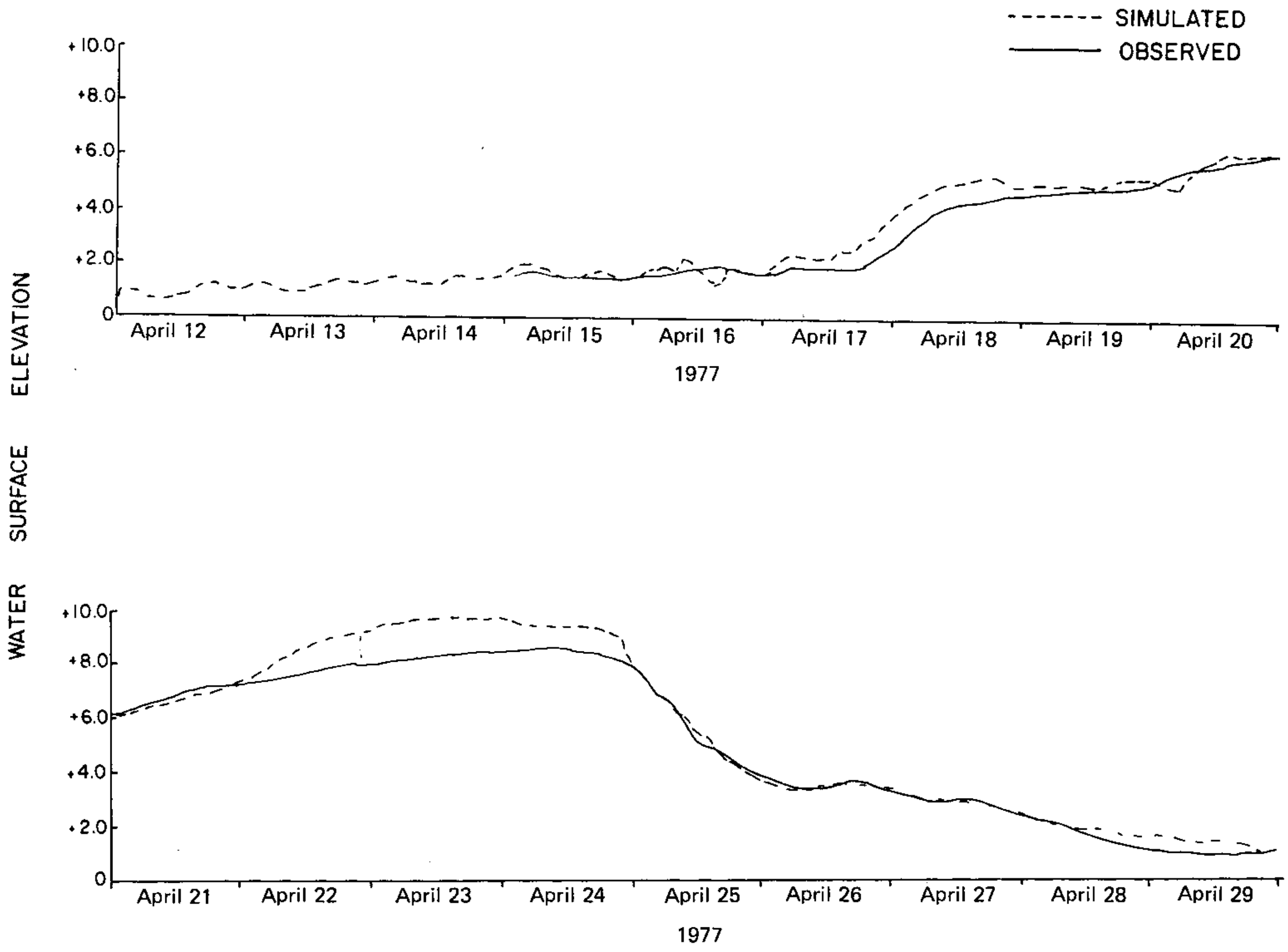


Figure 5-12. Comparison of Observed and Simulated Tidal Elevations at Matagorda, Texas, April 12-29, 1977 (45).

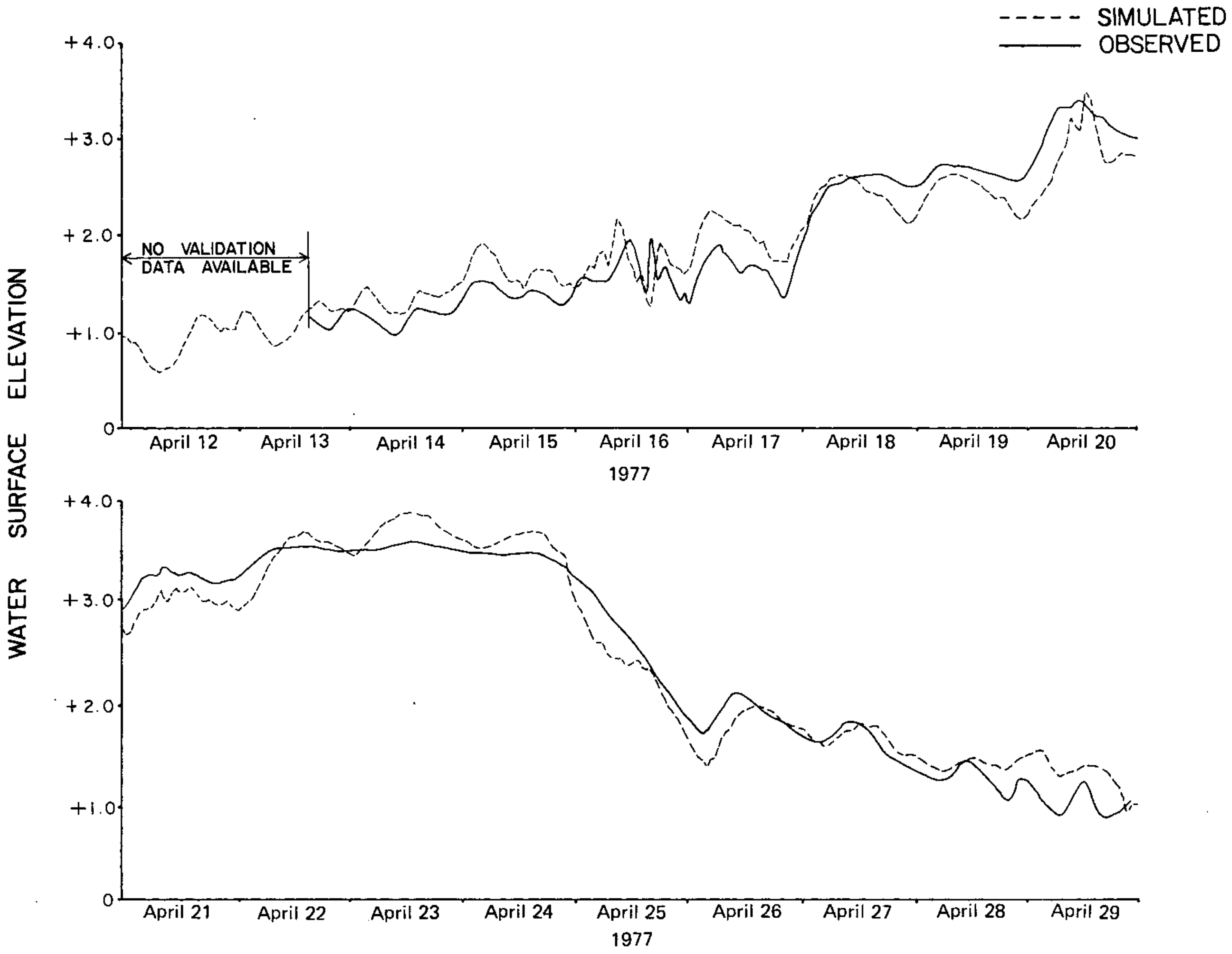


Figure 5-13. Comparison of Observed and Simulated Tidal Elevations above Tiger Island Cut, April 12-29, 1977 (45).

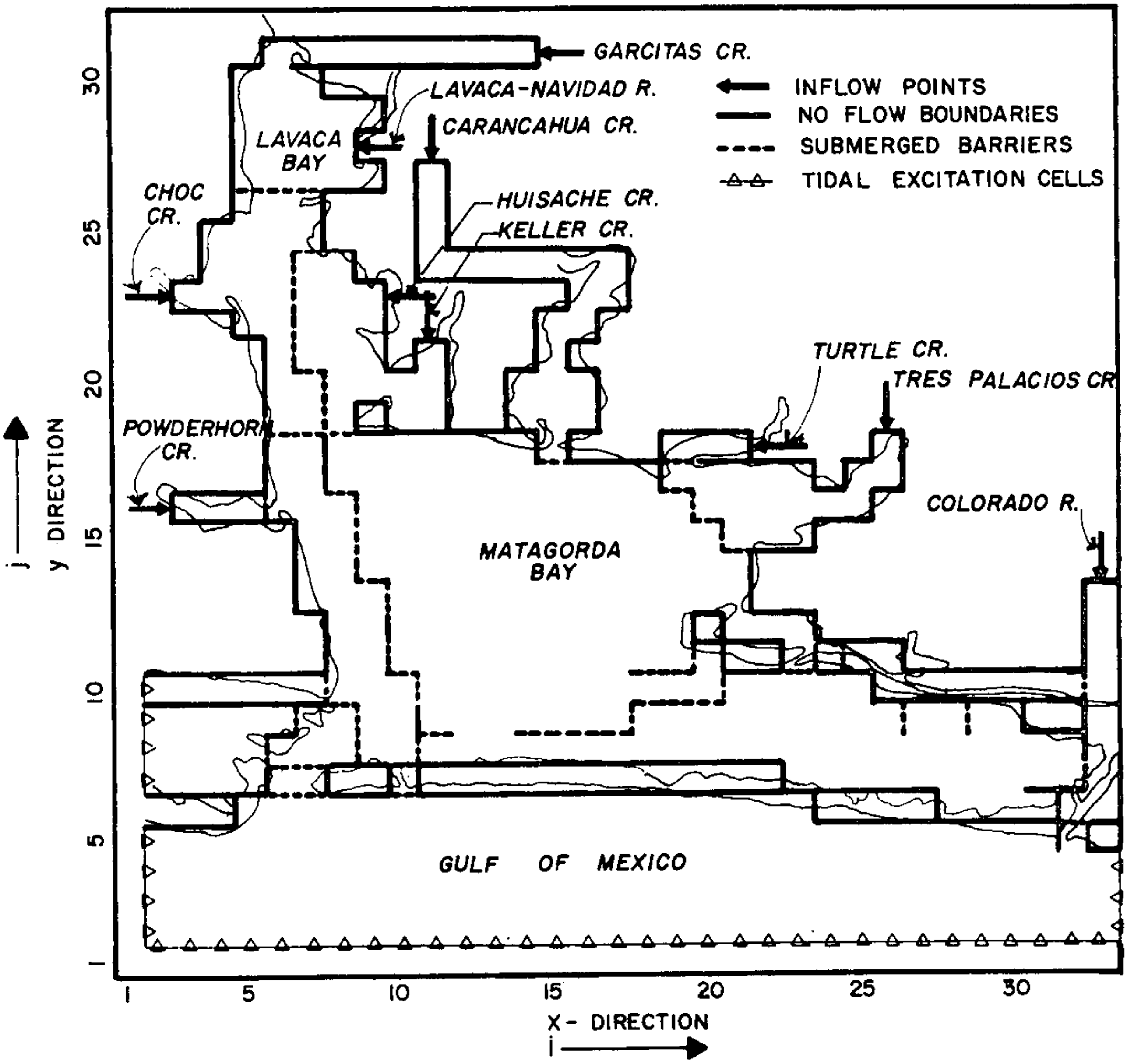


Figure 5-14. Schematic Computational Grid, Lavaca-Tres Palacios Estuary (146).

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 5-14, cells are numbered with the indices $1 < i < IMAX = 33$ and $1 < j < JMAX = 32$. With this arrangement, all model parameters such as water depths, 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 are the two comprehensive data collection efforts conducted in the estuary during March 1971 and October 1972.

The initial calibration and verificaton of the Lavaca-Tres Palacios estuary models is reported by Masch (146). A representative sample of the results of the final calibration of the models using data obtained during the October 1972 field study are presented in Figures 5-15 to 5-17 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 1971 through 1974. The four-year period was divided into 37 consecutive hydrologic sequences1/. 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 5-18 to 5-23). 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 Lavaca and Colorado River deltas in an effort to delineate flow distribution patterns and establish areas that would be

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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.

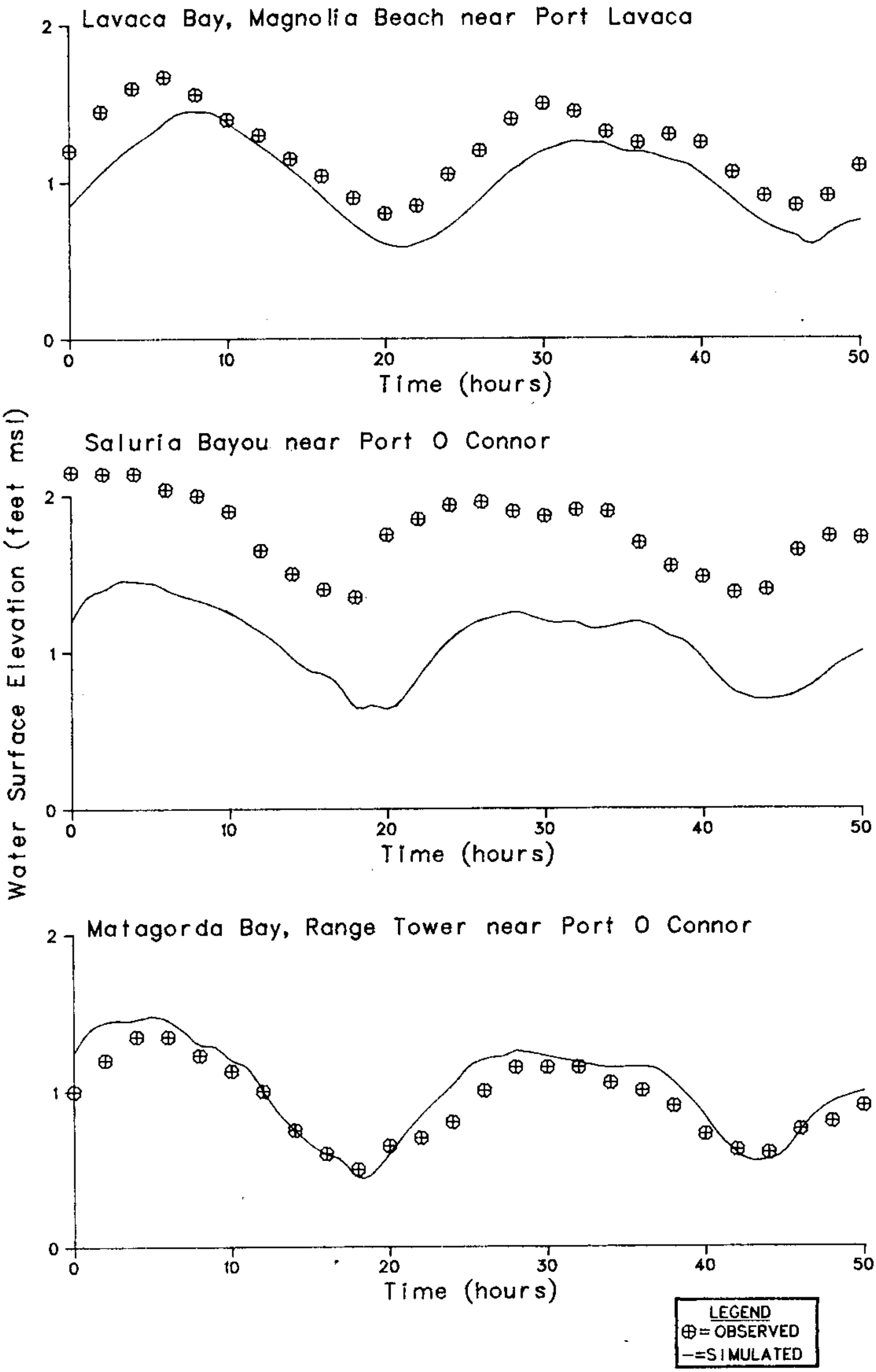

Figure 5-15. Comparison of Observed and Simulated Tidal Elevations, Lavaca-Tres Palacios Estuary, October 17-18, 1972

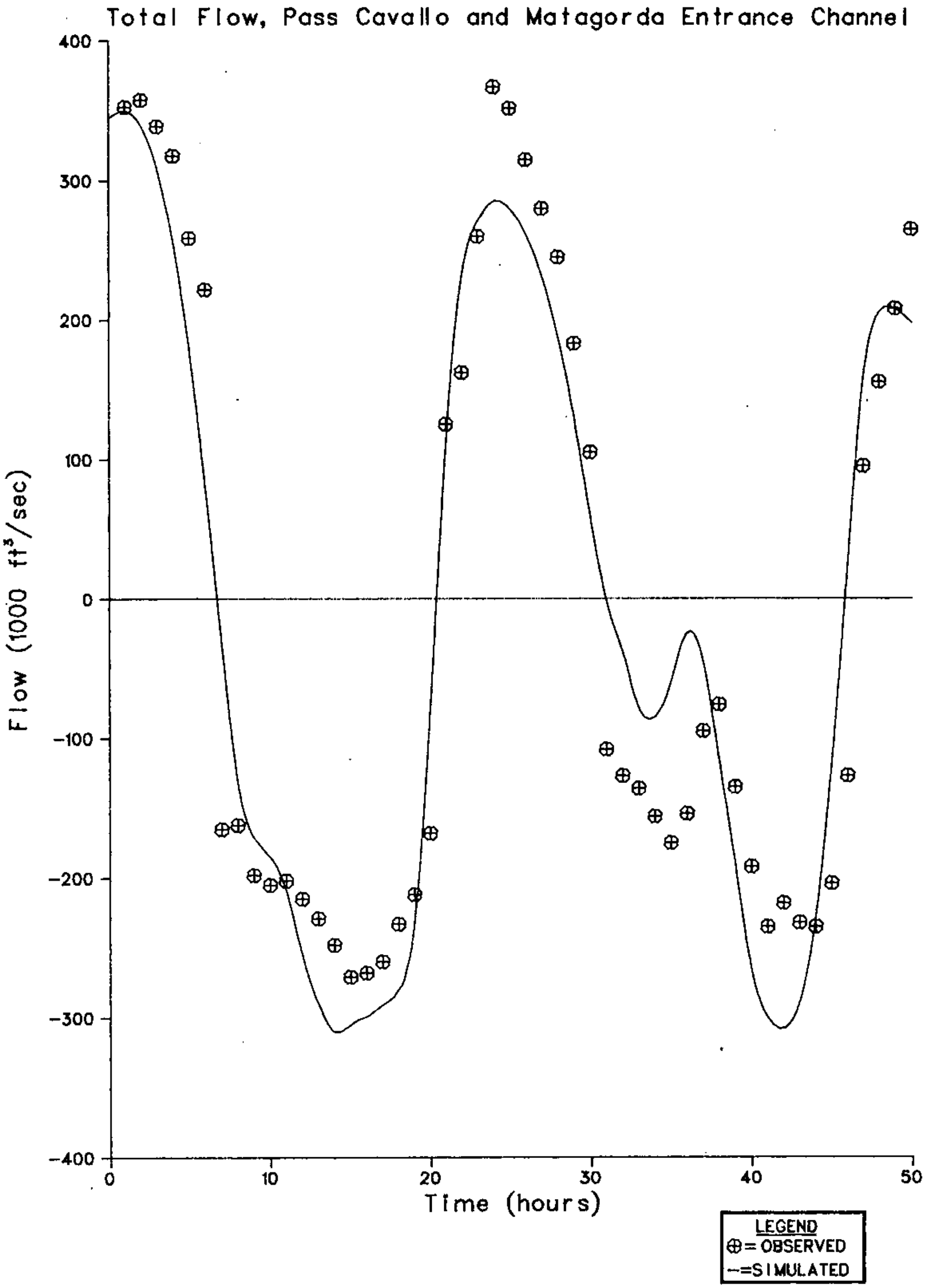

Figure 5-16. Comparison of Observed and Simulated Flows, Lavaca-Tres Palacios Estuary, October 17-18, 1972—Continued

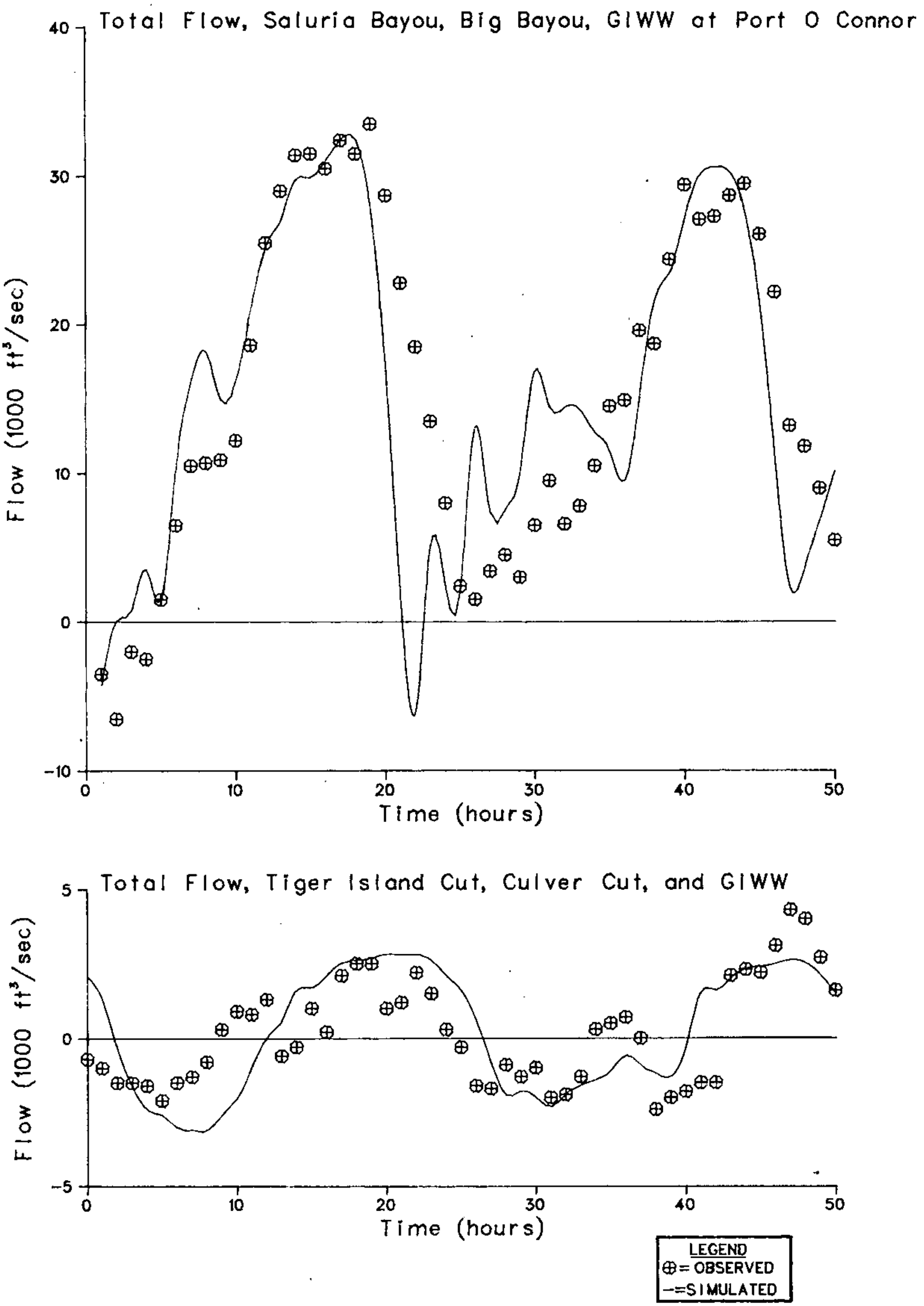

Figure 5-16. Comparison of Observed and Simulated Flows, Lavaca-Tres Palacios Estuary, October 17-18, 1972.

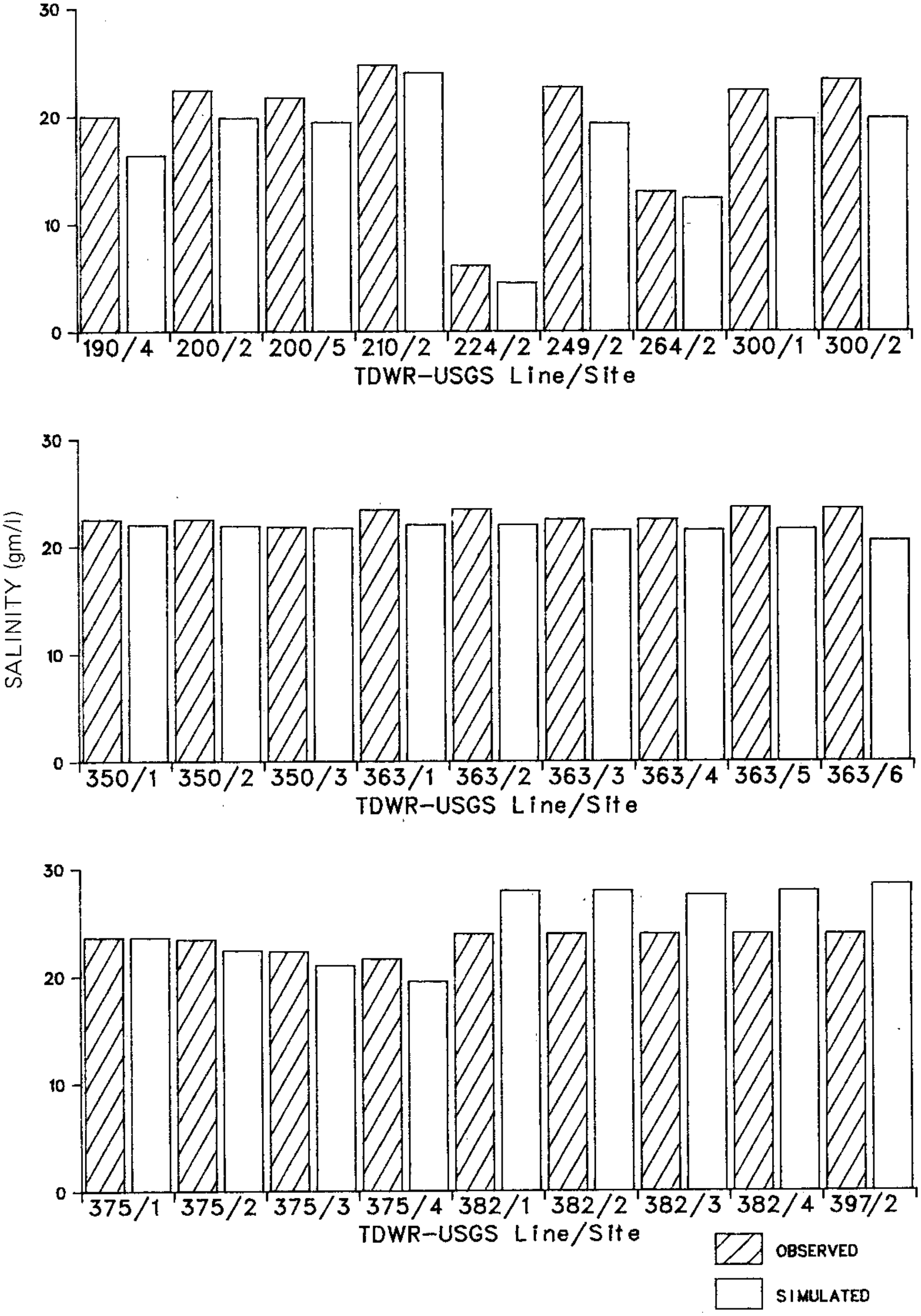

Figure 5-17. Comparison of Observed and Simulated Salinities, Lavaca-Tres Palacios Estuary, October 17-18, 1972

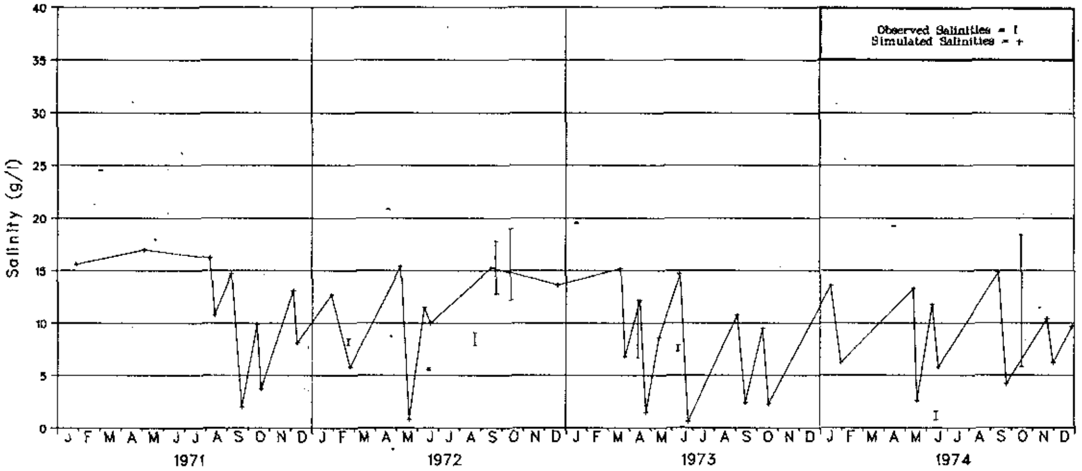

Figure 5-18. Comparison of Observed and Simulated Salinities, Lavaca-Tres Palacios Estuary, Line 090 Site 03.

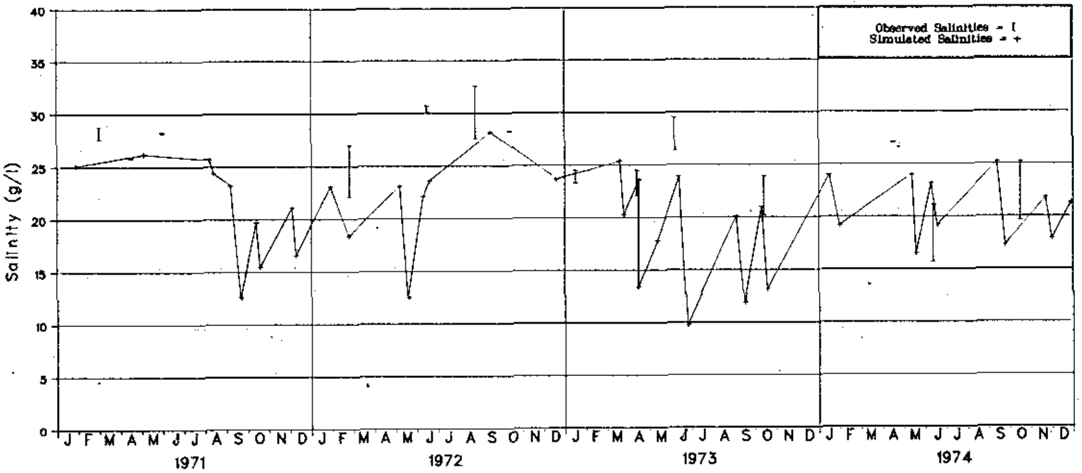

Figure 5-19. Comparison of Observed and Simulated Salinities Lavaca-Tres Palacios Estuary, Line 210 Site 02.

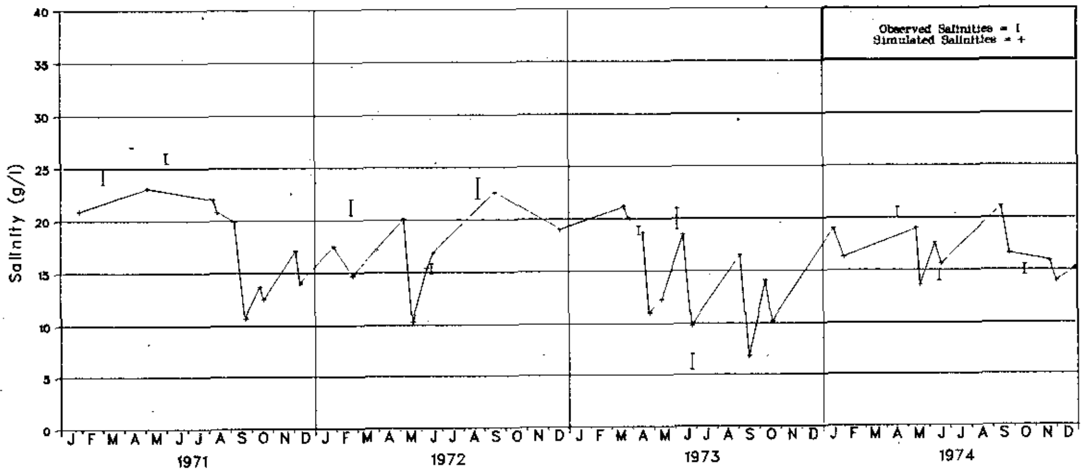

Figure 5-20. Comparison of Observed and Simulated Salinities, Lavaca-Tres Palacios Estuary, Line 284 Site 02.

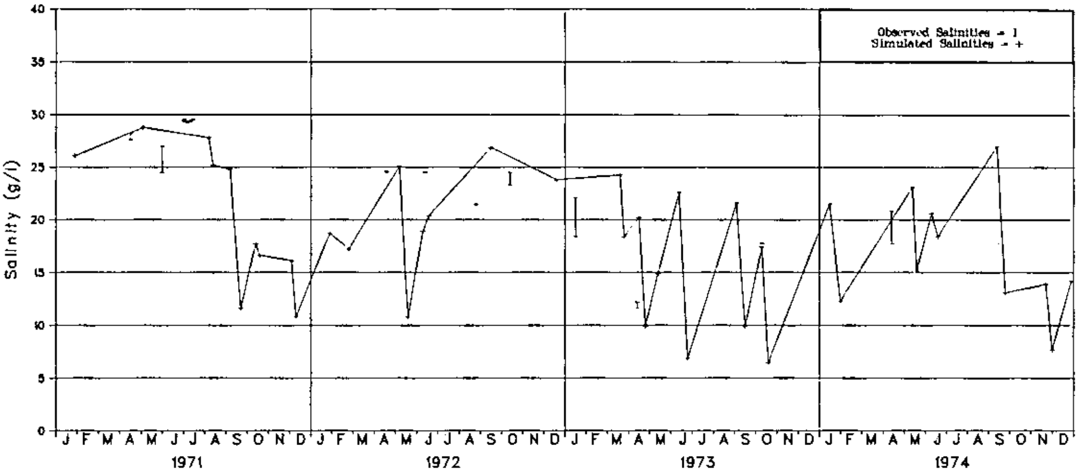

Figure 5-21. Comparison of Observed and Simulated Salinities, Lavaca-Tres Palacios Estuary, Line 333 Site 02.

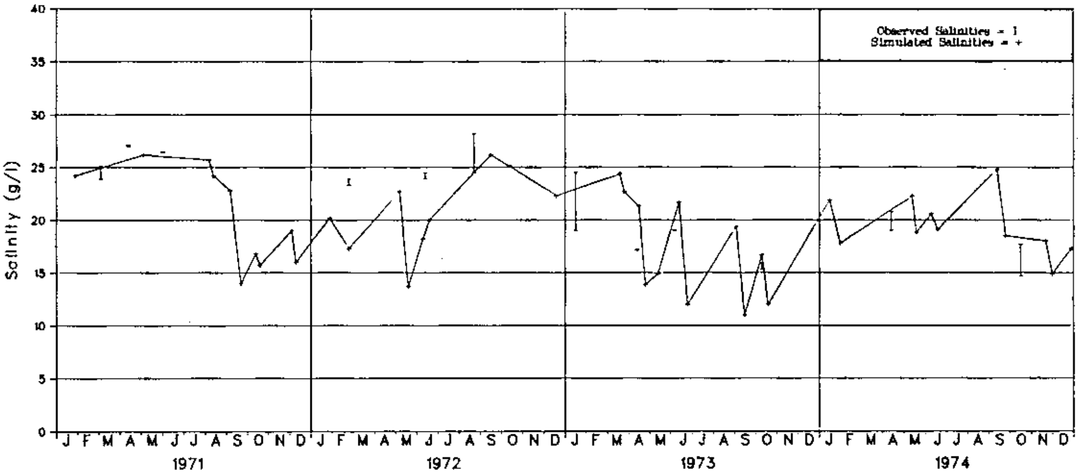

Figure 5-22. Comparison of Observed and Simulated Salinities, Lavaca-Tres Palacios Estuary, Line 350 Site 03.

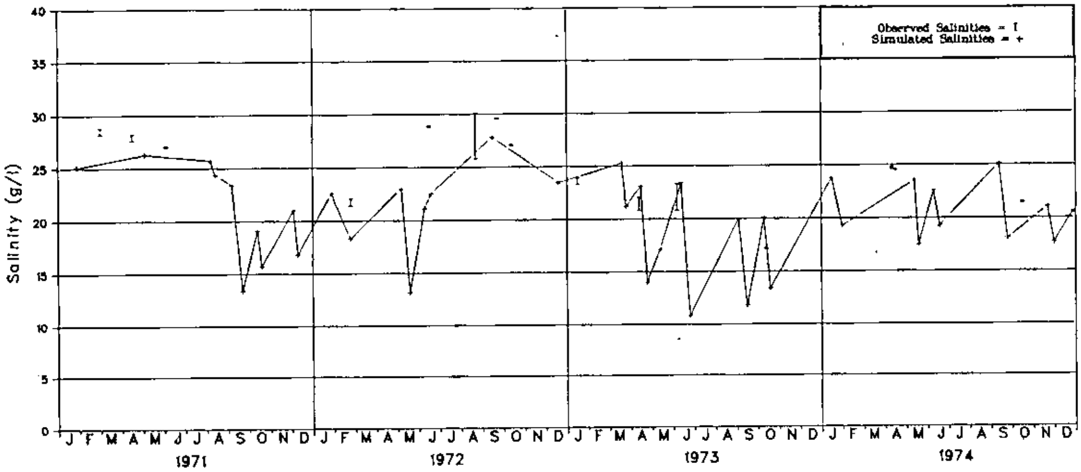

Figure 5-23. Comparison of Observed and Simulated Salinities, Lavaca-Tres Palacios Estuary, Line 375 Site 02.

subject to the previously defined inundation criterion of 0.5 feet (0.15 m) of depth for 48 consecutive hours.

Lavaca River Delta. In the Lavaca 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. Six Lavaca River flood events of varying magnitude and duration were selected from historical records obtained at the USGS Ganado (08164500) and Edna (08164000) flow gages (Table 5-1). In addition, two independent tide records from the USGS Lavaca Bay gage (08164825) were selected which corresponded to average or normal tides. Each of the six flood cases were simulated with both a high and normal driving tide in an effort to differentiate portions of the delta that would be inundated as a result of high flows, and to differentiate areas which would be inundated as a result of the interaction of high freshwater inflows and high tidal activity.

Driven by normal tides, studies indicate that inundation of the Lavaca River delta below the confluence of the Lavaca River and Navidad Rivers did not occur for flows of 13,000 ft^3/sec (364 m^3/sec) or below. Inundation does not occur anywhere in the delta for flows of 6,430 ft^3/sec (180 m^3/sec) or less. For high tides, simulations predict inundation in the Menefee Lake, Redfish Lake, and Swan Lake areas, as well as a larger portion of the lower delta for each of the flood peaks simulated. Inundation in the area of Venado Lake appears to be tide dominated; during an extreme flood event, the area was not flooded by normal tides, while during low freshwater inflows and higher tides, inundation did occur (Figure 5-24). As a result of these studies, curves are developed relating the percentage of marsh area inundated to a function of flow, for both normal and high tides. These results are presented in Figure 5-25.

Colorado River Delta. Management of the complex system of variables which describe the flow patterns within the Colorado delta is expedited through the utilization of specific scenarios and simplifying assumptions. The simulated results obtained from the application of such assumptions and system simplifications are less precise than those obtainable if each variable is investigated separately; however, it appears that overall trends of such an analysis are discernable and the absolute values generated are of sufficient resolution to result in an adequate analysis.

The first assumption is that the configuration and related cross-sectional area of the mouth of the Colorado River vary with the freshwater inflow. It is assumed to decrease in cross-sectional area over extended low flow periods and degenerate to almost total closure with increased siltation from Gulf tides and low freshwater flow velocities. Inspection of historical cross-section data assembled by the U. S. Army Corps of Engineers, supports this assumption; however, the rate of closure due to the sediment deposition and the rate of sediment scour at elevated flows are unknown.

The second assumption concerns the status of the navigation locks located on the Gulf Intracoastal Waterway (GIWW) east and west of the Colordo River at Matagorda (open or closed). The locks are generally closed when river velocities reach approximately 3-4 ft/sec (1 m/sec). For the cross-sectional

Table 5-1. Hydrograph Peaks for DELTA Simulation Model

USGS, 08164000 Lavaca River Maximum ft^3/sec	USGS, 08164500 Navidad River Maximum ft^3/sec	Total ft^3/sec	Date of Occurrence
1,060	1,810	2,870	April 6-14, 1973
3,260	3,170	6,430	July 6-14, 1973
5,700	3,820	9,130	May 7-14, 1975
4,060	9,040	13,100	May 8-27, 1974
14,000	10,700	24,700	October 10-30, 1973
31,800	12,700	44,500	September 11-21, 1974

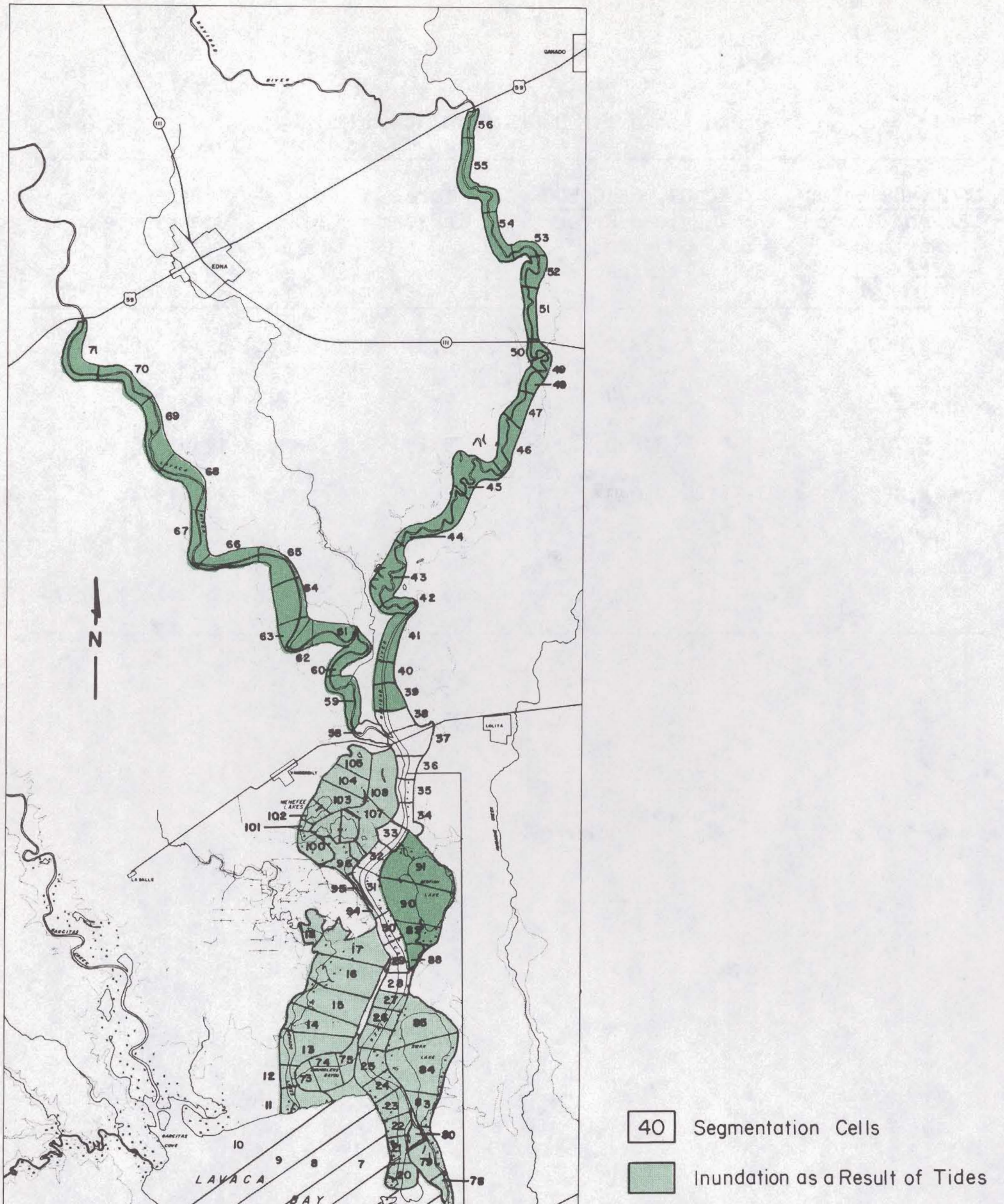

Figure 5-24. Lavaca Delta System Showing Inundation Areas [base adapted from Espey Huston & Assoc. Inc. (44)].

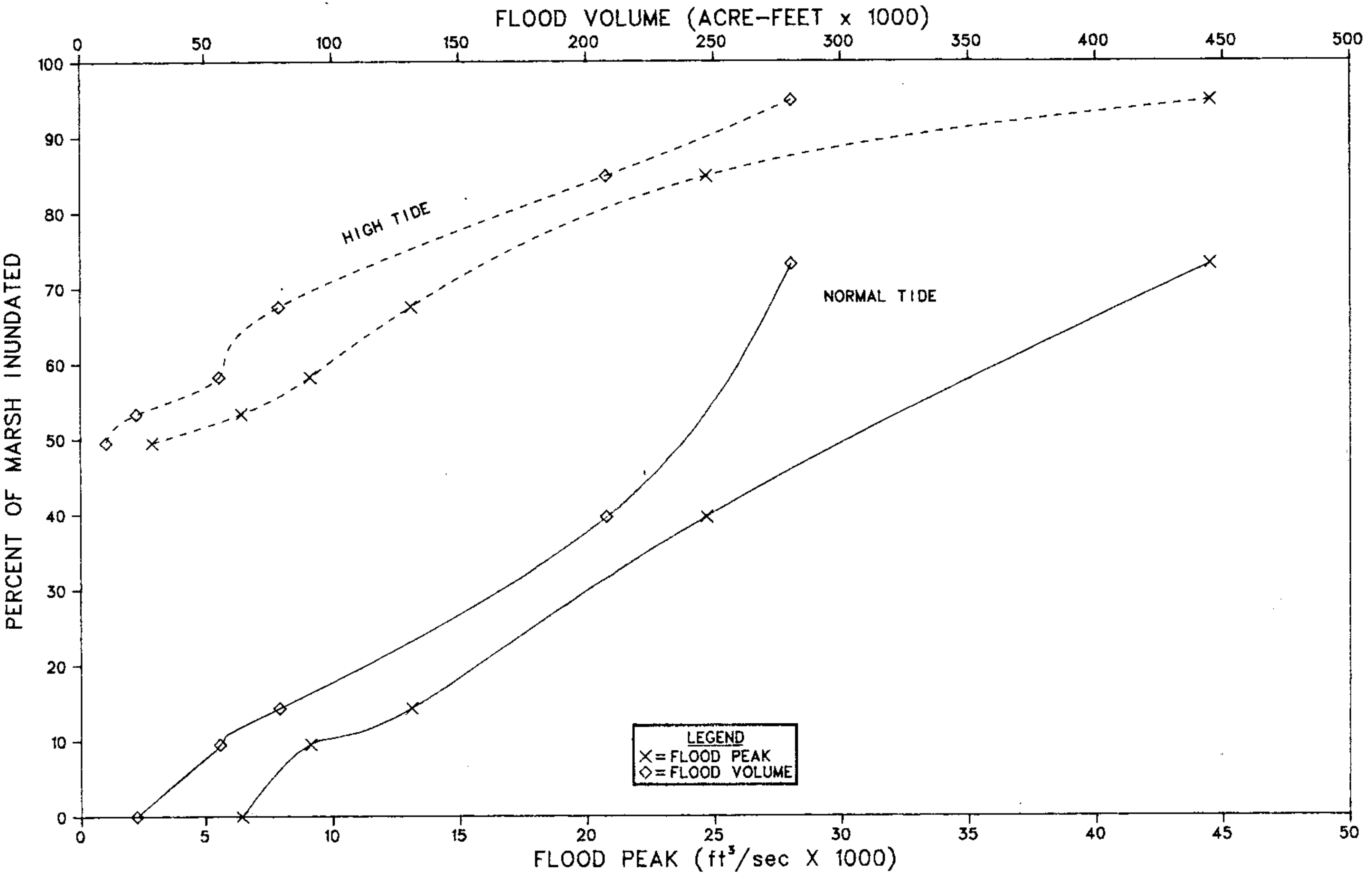

Figure 5-25. Simulated Lavaca Delta Marsh Inundation, High and Normal Tides

configuration used in this modeling effort, such velocities will occur at a flow of roughly 5,000 ft^3/sec (140 m^3/sec); therefore, it is assumed that the navigation locks were closed for all Colorado River flows greater than or equal to 5,000 ft^3/sec. The lock configuration at Matagorda strongly influences water surface elevations and net flows at Tiger Island Cut.

Given the assumptions stated above, three scenarios should represent the deltaic flow patterns under all anticipated Colorado River mouth and navigation lock conditions.

The three scenarios are:

Scenario 1. Colorado River flows range from 250 to 1,000 ft^3/sec (7 to 28 m^3/sec); low flow conditions have persisted for some time, and the mouth of the Colorado River is silted closed with respect to mean tidal elevations, but becomes periodically inundated on the flood tide; the average bed elevation is +0.3 ft. (+0.1 m) MSL and the average channel width is 100 ft. (30 m).

Scenario 2. Colorado River flows range from 1,100 to 4,900 ft^3/sec (31 to 137 m^3/sec); the mouth of the river has been maintained partially open by the downstream momentum; the average bed elevation is -0.3 ft. (-0.1 m) MSL and the average channel width is 250 ft. (75 m); the navigation locks at Matagorda are open.

Scenario 3. Colorado River flows vary from 5,100 to 10,000 ft^3/sec (143 to 2,800 m^3/sec); the river mouth is completely open; average bed elevation is -4.5 ft. MSL (-1.3 m) and average channel width is 450 ft. (135 m); the navigation locks at Matagorda are closed.

Reliable flow verification data were available for portions of the first scenario, but were not available for Scenarios 2 and 3. The driving tides for each of the above scenarios remained the same and were constructed from observed tide gage data obtained from tide gages located in Matagorda Bay and East Matagorda Bay during the period October 13-19, 1972. The tides were consistent with the typical tidal elevations observed at these locations for the season. The 1972 tide was selected to coincide with available flow data collected during the same period at Tiger Island Cut. The 1977 data for East Matagorda Bay were utilized because recorded data for 1972 were unavailable for that location.

The results of the flow relationships within the Colorado delta are presented in three parts: (1) flow trifurcation at the junction of the Colorado River and GIWW, (2) flow diverted through Tiger Island Cut, and (3) flow through Culver Cut. The sensitivity analyses performed with this model demonstrate the strong influence of the Matagorda Bay and East Matagorda Bay tidal alignments on flow patterns throughout the delta (45). Since the tides of Matagorda Bay and East Matagorda Bay appear to be unrelated, the modeling results must be viewed as indicative of this tidal alignment only. The results are not absolute and may vary slightly for differing tidal alignments.

The interaction of the Colorado River and the GIWW at Matagorda for Scenarios 1 and 2 is demonstrated in Figure 5-26. At low river flows, with river mouth constrictions (Scenario 1), the flows in the Colorado River indicate that from 10 to 100 percent of this increase can be directly attributed to circulation patterns removing water from East Matagorda Bay, depending on the magnitude of river flow. Moderate river flows, with their accompanying increased river mouth cross-sectional area (Scenario 2), tend to contribute water to the GIWW at rates up to 40 percent of the river flow; the greater the Colorado River flow, the greater the diversion at the GIWW. Throughout Scenario 3 the exchange between the Colorado River and the GIWW will be negligible because the navigation locks were closed.

At Tiger Island Cut the interactions of river mouth geomorphology, recirculation patterns, and navigation lock positioning are not so easily discernable. In attempting to develop a relationship between flow through Tiger Island Cut and flow in the Colorado River above Tiger Island Cut, the three simulation scenarios have yielded three distinct curves. As flow increased for each scenario, the percentage diverted through Tiger Island Cut increases. With the increased flow, however, the average percent of flow diverted decreases from Scenario 1 to Scenario 2 and from Scenario 2 to Scenario 3. This appears to be incongruous, but under the assumptions, the river mouth cross-sectional area was constant for each scenario, when in fact, the cross-sectional area is known to increase gradually with increased flow and accompanying increased downstream momentum. Utilizing an exponential regression, a curve of "best fit" was computed for the simulated data. A correlation coefficient (r) of 0.78 was obtained for the fitted curve indicating a reasonably close fit with the simulated data. The percentage of river flow diverted through Tiger Island Cut as a function of river flow above the cut (accounting for the continuously variable nature of the river mouth) is displayed in Figure 5-27. Under conditions of low flow and a constricted river mouth as much as 95 percent of the river flow is diverted into Matagorda Bay through Tiger Island Cut. When Colorado River flows are 6,000 ft^3/sec (170 m^3/sec) or greater, the percentage of flow diverted through Tiger Island Cut is reduced to approximately 62 percent.

For cases simulated utilizing the October 1972 data, 12-15 percent of the simulated Colorado River inflow was directed through Culver Cut into Matagorda Bay. At low to moderate flow, less than 2,000 ft^3/sec (57 m^3/sec), simulation indicated that the Colordo River flow below the GIWW was augmented with flow derived from the GIWW. Inspection of the simulated flow indicated that under the October tidal alignment, nearly all of the additional water was derived from East Matagorda Bay. Under different tidal conditions, river flow augmentation may be derived from Matagorda Bay.

Inundation analyses indicate that flooding of marsh areas within the Colorado River delta is largely the result of tidal activity, or a combination of high bay and Gulf tides and southerly winds (Figure 5-28).

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

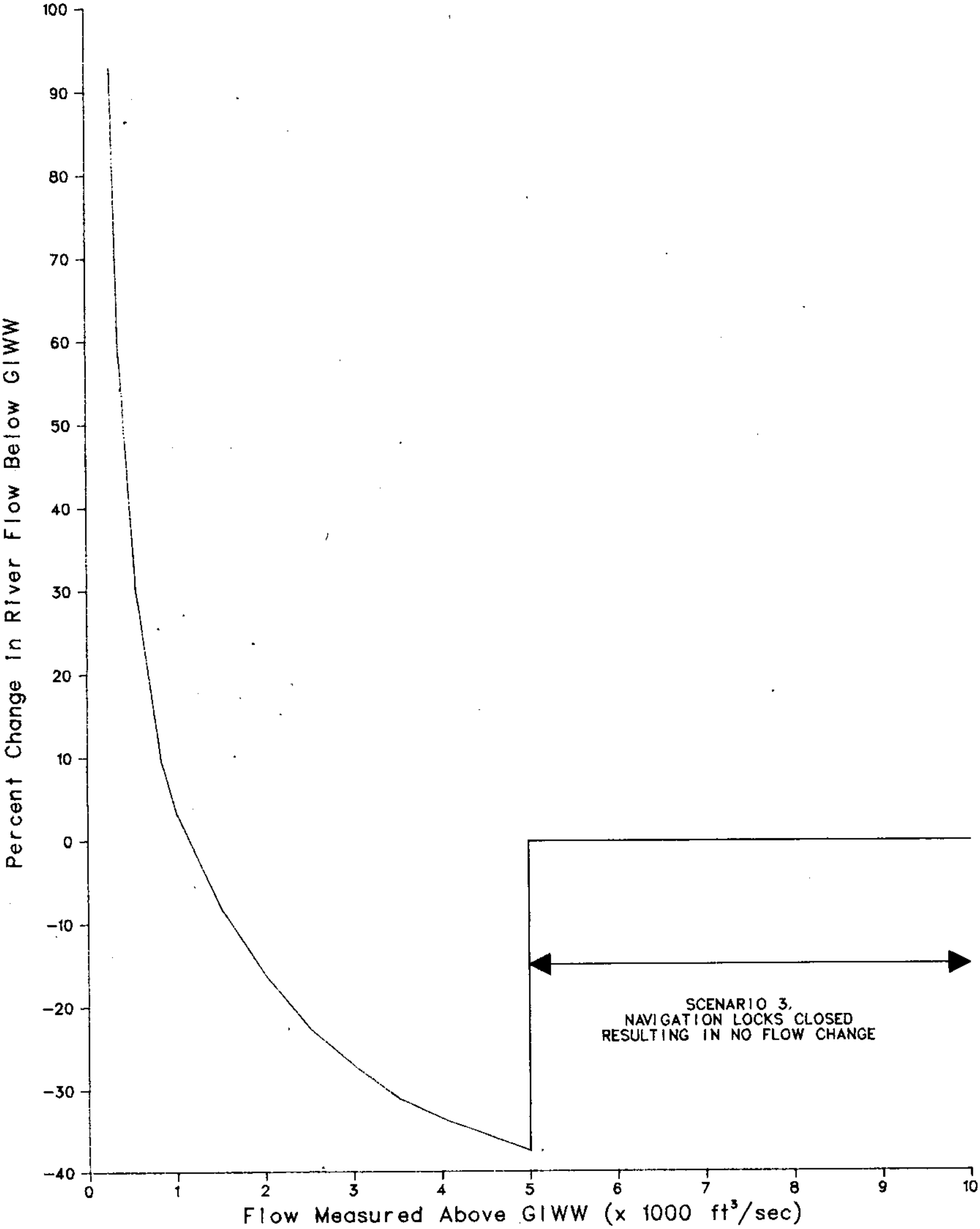

Figure 5-26. Percent Change in River Flow below GIWW as a Function of River Flow above GIWW (225).

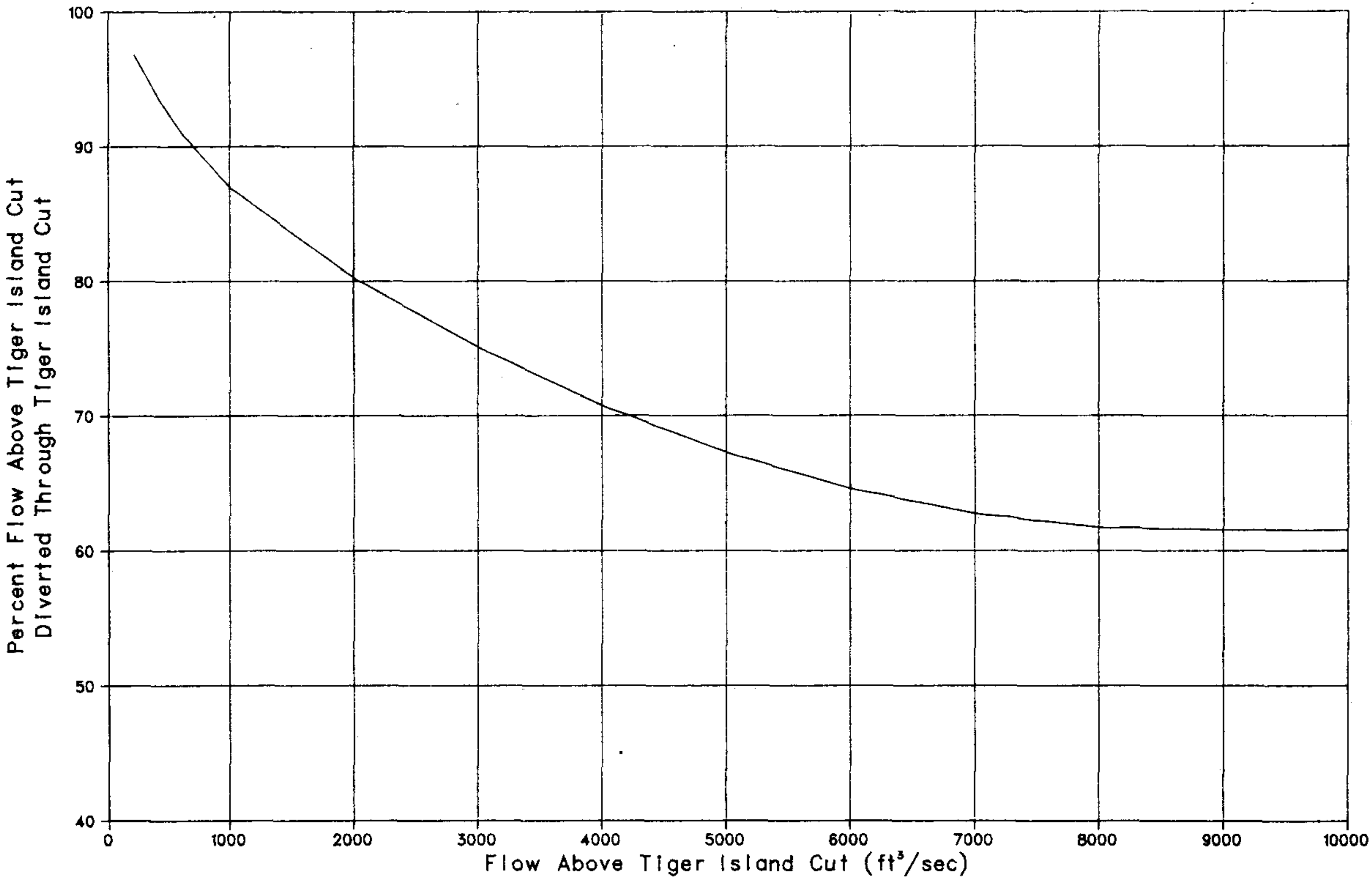

Figure 5-27. Percent Flow through Tiger Island Cut as a Function of Colorado River Flow (225).

Figure 5-28. Inundation of Deltaic Segments of the Colorado Delta [base adapted from Espey Huston & Assoc., Inc. (225)].

the absence of sources of highly saline inflow and neglecting wind effects, the magnitudes of antecedent inflows and the influence of 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 have been carried out to verify and quantify such a relationship. Salinity data from Lavaca Bay and the eastern end of Matagorda Bay are correlated with gaged streamflows from the Lavaca and Colorado Rivers, respectively.

The average daily salinities are assumed to be related to gaged streamflow 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 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 are determined using a step-wise multiple regression procedure (13).

The regression equations developed for Lavaca Bay use salinities obtained by the Department of Water Resources and Texas Parks and Wildlife Department cooperative data collection programs at line 85, sites 1, 2, 3 and line 150, site 4 (Figure 3-9) and the sum of the gaged streamflows recorded for the Lavaca River near Edna and the Navidad River near Ganado (Table 5-2). The average of the salinities at line 85, sites 1, 2 and 3 is related to gaged streamflow by the equation

$$S_t = 2{,}613.1 \; Q_{t-7}^{-0.266} \left(\sum_{i=1}^{29} Q_{t-i} \right)^{-0.440} \qquad [3]$$

The units of S_t and Q_t in [3] are ppt and ft^3/sec, respectively. With a correlation coefficient (r) of 0.81 and an explained variation (r^2) of 66 percent, the regression is tested to be highly significant ($\alpha = .01$).

Average monthly salinity-inflow relationships are derived using equation [3] to generate daily salinities for the period of streamflow record, 1940 through 1976. The computed daily salinity values are averaged monthly over the study period, and the averages are related to the average monthly flows by the geometric equation

Table 5-2. Description of Data for Regression Analyses

Bay	Salinity		Inflow		No. of Obs. for Regression
	Station	Period	USGS Station	Period of Record	
Lavaca	Avg. of 85-1 85-2 & 85-3	Feb. 1968 Aug. 1976	Lavaca River near Edna & Navidad near Ganado (Sum)	Jan. 1940 to Sep. 1976	87
Lavaca	150-4	Jun. 1968 to Aug. 1975	—	—	—
East Arm Matagorda	A (avg. of 330-2, 333-1,3 & 340-2,3	Jul. 1967 to Feb. 1977	Colorado River near Bay City	Jan. 1949 to Sep. 1976	26
East Arm Matagorda	350-2	Apr. 1969 to Jun. 1977	—	—	—

$$S_M = C_0 \ (Q_M)^{C_1} \ \exp(ts_e) \qquad [4]$$

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 exp (ts_e) is a random component (56), in which 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). The inclusion of the random component takes into account the spread of the points about the regression line. Resulting correlation coefficients (r) for the twelve months ranged from 0.68 to 0.89 (Table 5-3), which are highly significant ($\alpha = 0.01$).

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

$$S_Y = 182.16 \ Q_Y^{-0.457} \qquad [5]$$

where S_Y and Q_Y are average monthly 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 5-29. The other statistics of Equation [5] are listed in Table 5-3.

The spatial distribution of salinities was evaluated by correlating the average salinities (ppt) measured at line 85 with measurements (ppt) obtained at line 150 site 4. Assuming a geometric relation, the analysis yielded

$$S_{150} = 3.883 \ S_{85}^{0.73} \qquad [6]$$

with $r^2 = 0.69$. The relation is highly significant ($\alpha = 0.01$).

The analysis for the eastern arm of Matagorda Bay uses salinity measurements obtained at line 330 site 2, line 333 sites 1, 2, 3, line 340 sites 2, 3, and line 350 site 2, and gaged streamflow for the Colorado River near Bay City (Table 5-4). Using the averages of salinities measured at line 330 site 2, line 333 sites 1, 2, 3; and line 340 sites 2, 3, the analysis yields the relationship

$$S_t = 9.42 + 37.79_{t-4}^{-0.5} + 1{,}584.7 \ \Big(\sum_{i=1}^{29} Q_{t-i}\Big)^{-0.5} \qquad [7]$$

with the correlation coefficient (r) of 0.79. The correlation is high significant ($\alpha = 0.01$). The unit of S_t and Q_t [7] are ppt and ft^3/sec, respectively.

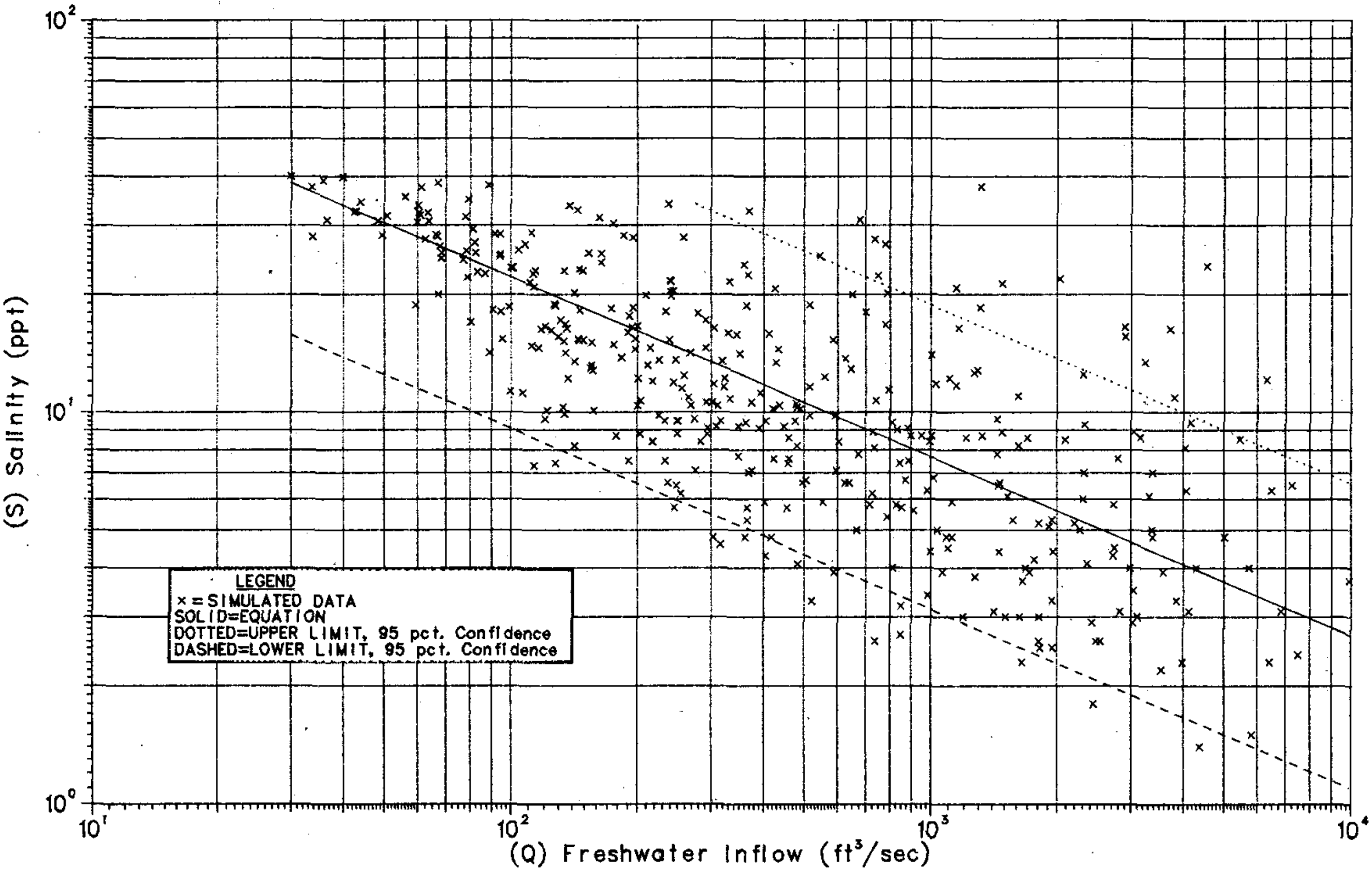

Figure 5-29. Average Monthly Salinity versus Average Monthly Gaged Inflow, Lavaca Bay, 1940-1976.

Table 5-3. Results of Salinity Regression Analyses, Lavaca Bay

Station a/	Class	Regression Equation (S_t in ppt and Q_t in cfs)	Correlation Coefficient r	Explained Variation r^2	Standard Error of Estimate s_e	F-test
85-1∿3	Daily	$S_t = 2613.1\, Q_{t-7}^{-0.266} \left(\sum_{i=1}^{29} Q_{t-i} \right)^{-0.440}$	0.81	0.66	—	**
	Jan.	$S = 200.14\, Q^{-0.464} e^{0.462t}$, $30 \leq Q \leq 3{,}700$	0.82	0.67	0.462	**
	Feb.	$S = 249.76\, Q^{-0.498} e^{0.572t}$, $40 \leq Q \leq 4{,}100$	0.75	0.56	0.572	**
	Mar.	$S = 151.76\, Q^{-0.450} e^{0.439t}$, $30 \leq Q \leq 4{,}100$	0.81	0.65	0.439	**
	Apr.	$S = 157.37\, Q^{-0.412} e^{0.436t}$, $30 \leq Q \leq 6{,}400$	0.81	0.65	0.436	**
	May	$S = 150.41\, Q^{-0.416} e^{0.673t}$, $30 \leq Q \leq 7{,}300$	0.68	0.46	0.673	**
	Jun.	$S = 108.70\, Q^{-0.397} e^{0.631t}$, $25 \leq Q \leq 14{,}300$	0.70	0.49	0.631	**
	Jul.	$S = 280.58\, Q^{-0.583} e^{0.362}$ $30 \leq Q \leq 7{,}500$	0.89	0.80	0.362	**
	Aug.	$S = 159.42\, Q^{-0.435} e^{0.501t}$, $30 \leq Q \leq 2{,}000$	0.68	0.47	0.501	**
	Sep.	$S = 159.42\, Q^{-0.418} e^{0.443t}$, $40 \leq Q \leq 6{,}500$	0.77	0.59	0.443	**
	Oct.	$S = 157.44\, Q^{-0.437} e^{0.476t}$, $25 \leq Q \leq 6{,}300$	0.83	0.69	0.476	**
	Nov.	$S = 206.21\, Q^{-0.487} e^{0.582t}$, $30 \leq Q \leq 9{,}900$	0.79	0.63	0.582	**

(continued)

Table 5-3. Results of Salinity Regression Analyses, Lavaca Bay (cont'd.)

Station a/	Class	Regression Equation (S_t in ppt and Q_t in cfs)	Correlation Coefficient r	Explained Variation r^2	Standard Error of Estimate s_e	F-test
85-1∿3	Dec.	$S = 413.74\ Q^{-0.597}\ e^{0.467t}$, $50 \leq Q \leq 4{,}400$	0.86	0.75	0.476	**
85-1∿3	All Months	$S = 182.16\ Q^{-0.451}$, $25 \leq Q \leq 14{,}300$	0.78	0.61	0.533	**
85-1∿3 vs 150-4	Spatial	$S_{150} = 3.883\ S_{85}^{0.73}$	0.83	0.69	—	**

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

a/ See Figure 3-9.

Table 5-4. Results of Salinity Regression Analyses, East Arm of Matagorda Bay

Station a/	Class	Regression Equation (S_t in ppt and Q_t in cfs)	Correlation Coefficient r	Explained Variation r^2	Standard Error of Estimate s_e	F-test
A	Daily	$S_t = 9.42 + 37.79\ Q_{t-4}^{-0.5} + 1584.7\ (\sum_{i=1}^{29} Q_{t-1})^{-0.5}$	0.79	0.62	—	**
	Jan.	$S = 84.67\ Q^{-0.205}\ e^{0.112t}$, $250 \le Q \le 8{,}250$	0.88	0.77	0.112	**
	Feb.	$S = 87.94\ Q^{-0.207}\ e^{0.095t}$, $245 \le Q \le 9{,}900$	0.92	0.84	0.095	**
	Mar.	$S = 98.37\ Q^{-0.231}\ e^{0.123t}$, $260 \le Q \le 7{,}500$	0.89	0.80	0.123	**
	Apr.	$S = 132.14\ Q^{-0.254}\ e^{0.125t}$, $125 \le Q \le 7{,}600$	0.93	0.86	0.125	**
	May	$S = 129.98\ Q^{-0.248}\ e^{0.193t}$, $340 \le Q \le 27{,}800$	0.85	0.71	0.193	**
	Jun.	$S = 98.03\ Q^{-0.220}\ e^{0.197t}$, $180 \le Q \le 24{,}560$	0.84	0.70	0.197	**
	Jul.	$S = 214.47\ Q^{-0.342}\ e^{0.138}$ $130 \le Q \le 7{,}700$	0.97	0.95	0.138	**
	Aug.	$S = 397.34\ Q^{-0.419}\ e^{0.433t}$, $200 \le Q \le 2{,}900$	0.64	0.42	0.433	**
	Sep.	$S = 122.27\ Q^{-0.232}\ e^{0.338t}$, $120 \le Q \le 11{,}200$	0.58	0.33	0.338	**
	Oct.	$S = 77.06\ Q^{-0.184}\ e^{0.213t}$, $290 \le Q \le 12{,}800$	0.67	0.45	0.213	**

(continued)

Table 5-4. Results of Salinity Regression Analyses, East Arm of Matagorda Bay (cont'd.)

Station a/	Class	Regression Equation (S_t in ppt and Q_t in cfs)	Correlation Coefficient r	Explained Variation r^2	Standard Error of Estimate s_e	F-test
A	Nov.	$S = 89.03\, Q^{-0.215} e^{0.062t}$, $225 \leq Q \leq 13{,}500$	0.97	0.94	0.245	**
A	Dec.	$S = 111.52\, Q^{-0.245} e^{0.062t}$, $300 \leq Q \leq 6{,}200$	0.97	0.94	0.245	**
A	All Months	$S = 128.02\, Q^{-0.256}$ $120 \leq Q \leq 27{,}800$	0.81	0.65	0.227	**
350-2 vs. A	Spatial	$S_{350} = 11.58\, A + 0.58\, A$	0.79	0.62	—	**

** Indicates a statistical significance, level of $\alpha = 0.01$, i.e., highly significant.

a/ Station A is the average of Stations 330, 333 and 340 (Figure 3-9).

Using equation [7] to generate mean daily salinities for the period of streamflow record, 1949 through 1976, relationships between coupled mean monthly salinities and mean monthly recorded streamflow are determined (Table 5-4). The average condition of the monthly relationships is shown in Figure 5-30, and is fitted to the equation

$$S_Y = 128.02\ Q_Y^{-0.256} \qquad [8]$$

where S_Y and Q_Y are defined in [5]. The statistics of equation [8] are listed in Table 5-4.

The regression of daily salinity data at location A (average of lines 330, 333, and 340) on line 350 site 2 yields the equation

$$S_{350} = 11.58 + 0.58\ S_A \qquad [9]$$

where S_A and S_{350} are daily average salinities in ppt at location A and line 350 site 2, respectively. The regression is highly significant (α = .01), with $r^2 = 0.62$ (62 percent of variation explained).

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 impacts 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 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.

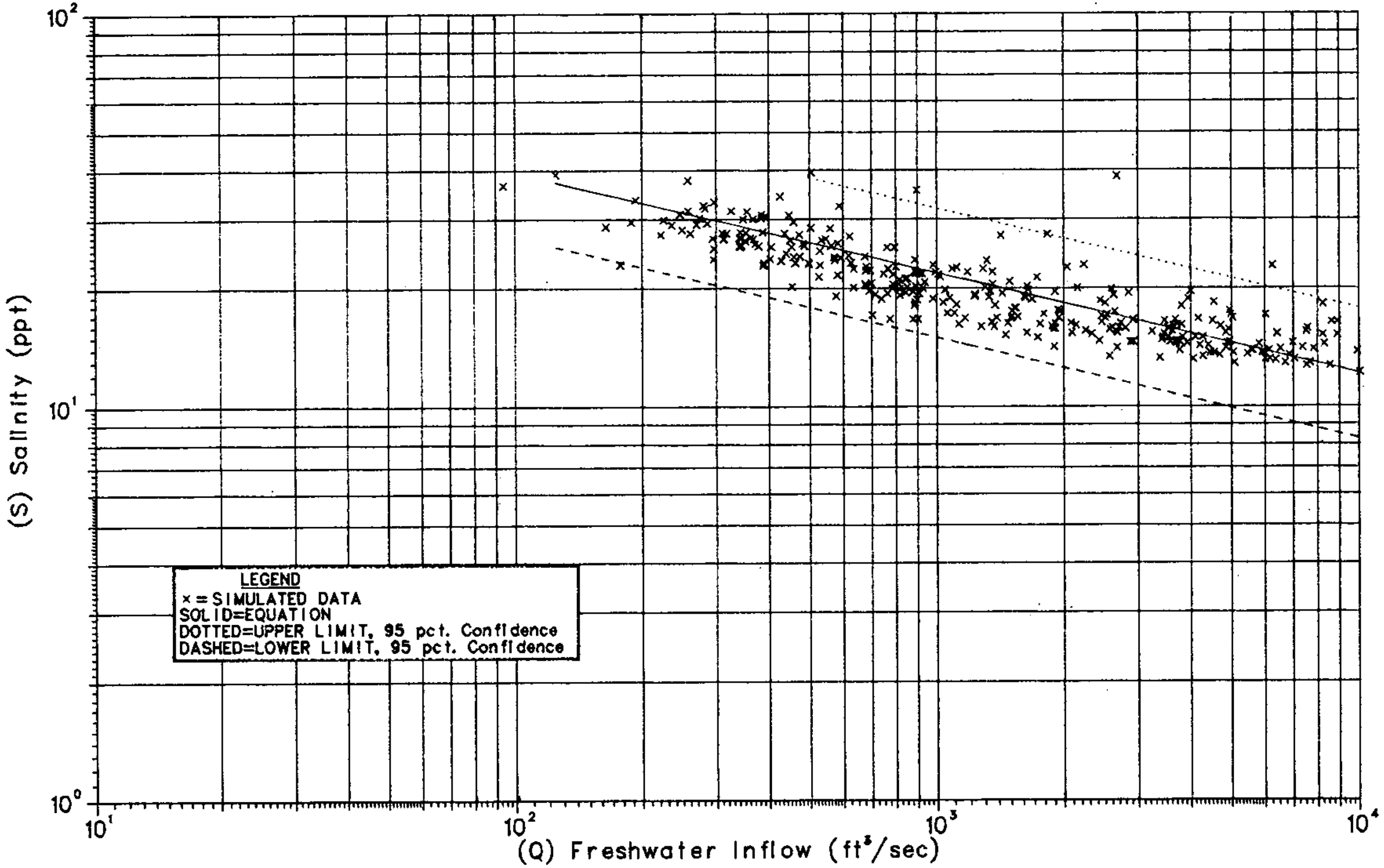

Figure 5-30. Average Monthly Salinity versus Average Monthly Gaged Inflow, East Arm Matagorda Bay, 1949-1976.

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 Lavaca-Tres Palacios deltaic system. The computations are based upon use of a finite difference approximation to the equations which describe the governing physical relationships.

The marsh inundaton model is applied separately to both the Lavaca and Colorado River deltas. Each 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 Colorado River delta includes the section of the Gulf of Mexico and Matagorda Bay adjacent to the delta and the Colorado River Channel up to Bay City, Texas. The representation of the Lavaca River delta includes the non-tidally influenced flood plain of the Lavaca and Navidad Rivers from the stream gages near Edna and Ganada downstream to Lavaca Bay.

The correct model coefficients for calibration of the hydrodynamic model, reflecting each delta's hydraulic characteristic, were determined by simulating the flow conditions and water inundation depths in each 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 Lavaca-Tres Palacios estuary, with the model representation of the system including Lavaca Bay, Matagorda Bay, and a portion of the Gulf of Mexico adjacent to Matagorda Peninsula. The hydrodynamic and mass transport models were calibrated and verified for the estuary.

The extent of marsh inundation in the Lavaca and Colorado River deltas was investigated utilizing the verified inundation models for these systems. The surface area of the Lavaca delta flooded was determined for six typical flood hydrographs under low, high and average tidal amplitudes. Application of the Colorado River delta inundation model indicated that the flooding of the marsh areas in the delta has been due principally to tidal inundation, since extensive levees prevent stream bank overtopping except under extreme flooding conditions.

Statistical analyses were undertaken to quantify the relationship between freshwater inflows from the Lavaca and Colorado River and salinities in upper Lavaca Bay and the eastern end of Matagorda Bay. Utilizing gaged daily river flows in the Lavaca and Colorado Rivers and observed salinities, a set of monthly predictive salinity equations was derived utilizing regression analyses for the two 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 to drive the biological processes. In addition, readily available supplies of nutrient materials are essential, the most obvious being carbon, nitrogen, and phosphorus (CNP). No less important, but required in smaller amounts are silicon, sodium, calcium, potassium, manganese, chlorine and sulfate ions. Other essential trace elements are required in minute 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 ratios (carbon to nitrogen to phosphorus) vary from organism to organism. Generally, oceanic species have a reported CNP ratio of 106:16:1 (117). Nitrogen to phosphorus ratios for a variety of phytoplankton species are usually in the range of 10-12:1 (117). Carbon is normally required in the greatest quantity, followed by nitrogen and phosphorus. Carbon is rarely if ever limiting, however, due to the readily available supply of atmospheric CO_2 and the ability of autotrophic organisms to use it in this form; therefore, nitrogen and phosphorus can be considered to be the two "critical" nutrients in most aquatic ecosystems.

The amount of nitrogen required in an aquatic ecosystem is generally greater than phosphorus, thus biological productivity is most likely to be nitrogen limited. This has been reported to be the case in a number of estuaries (382, 132, 184, 188, 109) including those in Texas (314, 313).

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 effluent, 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 an induced current 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 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, 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.

Nutrient Loading

Attempts to determine the amount of nutrient loading from a riverine source to an estuary have been conducted by Smith and Stewart (194). 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.

The Colorado River contributes freshwater and nutrients to the northern arm of the estuary near Matagorda, Texas, through exchange passes at Tiger Island (Parker) and Culver Cuts. The contributions from the Lavaca-Navidad River system enter the southwest extremity of the estuary at the Lavaca River delta near Port Lavaca, Texas. U. S. Geological Survey discharge records for the Colorado River have been kept continuously since 1948 at Bay City, Texas. Water quality data, however, are absent until October 1974 when the USGS began chemical and biochemical analyses. Water quality data are available beginning in 1968 from an upstream site at Wharton. USGS discharge data for the Lavaca and Navidad Rivers are available for the period of record since 1940. Water quality data have been collected since 1960 at two sites (Lavaca River near Edna and Navidad River near Ganado).

Nutrient data usually are limited to one sample per month, or one sample every other month. Using such a sparse data base to determine nutrient loadings to the bay can present several problems. An attempt has been made to reduce these problems by determining maximum and minimum monthly discharges over the period of record, and mean monthly concentrations for CNP where possible. Such an approach has the effect of reducing potential error due to seasonal variation of biological activity and flow. Using the maximum and minimum observed monthly discharges over the period of record, a range of "expected" values can be calculated that represent a "potential" monthly loading.

Field studies have been conducted under contract to the Department of Water Resources in order to gain insight into nutrient contributions of the Lavaca and Colorado River delta marshes (50, 265, 232). These studies include seasonal field sampling done over one or two day periods. The data reveal the general magnitude of nutrient contributions from major sources.

Water quality samples taken by the U. S. Geological Survey at the river gaging locations at Wharton and Bay City have been analyzed for concentrations of various chemical species (377). Total nitrogen concentrations range from 0.15 mg/l to 2.34 mg/l, total phosphorus ranges from 0.03 mg/l to 0.76 mg/l, and total organic carbon (TOC) concentrations range from 1.0 mg/l to 19.0 mg/l. Monthly (maximum and minimum) nutrient concentrations are combined with appropriate estimates of freshwater inflow (Chapter IV) to obtain a range of nutrient loading values that might be expected to occur during a "normal" year (Table 6-1). With few exceptions, highest nutrient loadings in Matagorda Bay occur in May and June during the period of greatest freshwater inflow.

Nutrient loading ranges for the Navidad and Lavaca Rivers (kilograms/day) are also calculated (Tables 6-2 and 6-3). The total Lavaca Basin nutrient contribution to the Lavaca-Tres Palacios estuary (Table 6-4) is a summation of the respective parameters in Tables 6-2 and 6-3. Since the USGS takes biochemical data bimonthly in the Lavaca River, a total expected contribution range is not computed for months where data are lacking. A field study of the Lavaca delta (48) found CNP concentrations generally within the ranges reported in the USGS water quality data. River discharges during the study were substantially less than the mean discharges reported in the USGS data, and therefore the resulting nutrient loadings were somewhat less than minimum values as reported in Tables 6-2 and 6-3. A third major source of riverine nutrients to the Lavaca-Tres Palacios estuary is Tres Palacios Creek, discharging into Tres Palacios Bay. The USGS has taken discharge measurements along with monthly water quality data since 1971 at a site near Midfield, Texas (Table 6-5).

A comparison of average monthly nutrient concentrations for streams contributing to the Lavaca-Tres Palacios estuary reveals that, in general, Tres Palacios Creek often contains the highest concentration of nutrients measured (Figures 6-1, 6-2, 6-3 and 6-4). In Tres Palacios Creek, organic nitrogen levels exhibit a major peak in concentration between March and June (Figure 6-1). A second, but slightly lower peak, is observed between September and November. Inorganic nitrogen concentration levels peak in the bays between December and May (Figure 6-2). All four rivers have the lowest inorganic nutrient concentrations between July and September. Total phosphorus levels are generally low, consistently between 0.1 and 0.3 mg/l year-round (Figure 6-3). The exception is Tres Palacios Creek, which exhibits a dramatic increase in total phosphorus during the fall-winter period, gradually diminishing to a yearly low in early summer. Total organic carbon concentrations exhibit no clear-cut seasonal pattern (Figure 6-4).

In general, high nutrient concentrations correlate with periods of high freshwater inflow, while low nutrient concentrations correlate with periods of low freshwater inflow. For this reason, freshwater inflow contributions appear to be a dominant factor in determining the nutrient loading of the Lavaca-Tres Palacios estuary.

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 basic food source for the estuary, (2) "nursery" habitats for the young of economically important estuarine-dependent fisheries species, (3) maintenance of water

Table 6-1. Range of Expected Carbon, Nitrogen, and Phosphorus Loading into Matagorda Bay, based on Mean Monthly Gaged Colorado River Discharges (kg/day).

		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Monthly Mean Gaged flows at Bay City P.O.R. 1947-76 (cfs)		2,100	2,835	2,035	2,556	4,206	3,741	1,525	912	1,963	2,549	2,506	1,979
Total Nitrogen Range (kg/d)	high	5,750	6,570	5,265	7,028	12,613	9,503	2,760	4,549	4,502	8,427	8,237	6,051
	low	1,268	3,883	4,738	2,179	11,702	3,300	2,388	292	2,193	2,046	4,789	1,280
Total Phosphorus Range (kg/d)	high	1,132	4,181	2,413	2,179	1,752	3,630	2,016	1,166	769	4,902	1,916	2,909
	low	680	597	439	545	0	660	465	0	385	980	958	194
Total Organic Carbon Range (kg/d)	high	27,166	113,490	57,037	43,585	70,072	98,987	24,809	19,439	34,627	107,165	28,734	31,031
	low	4,528	5,970	30,712	21,792	56,058	32,996	15,505	11,664	11,542	9,742	14,367	7,758

Table 6-2. Range of Expected Carbon, Nitrogen and Phosphorus Loading into Lavaca Bay, based on Mean Monthly Gaged Navidad River Discharges (kg/day).

		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Mean Gaged Flows Near Ganado (cfs)		480	581	403	672	951.	1,003	298	232	728	509	375	300
Total Nitrogen Range (kg/d)	high	1,858	1,060	2,063	3,227	3,844	2,703	767	1,609	2,925	1,322	1,654	390
	low	388	305	266	1,613	606	1,843	387	352	571	710	275	80
Total Phosphorus Range (kg/d)	high	588	358	148	527	349	319	131	148	466	175	147	125
	low	35	13	49	165	186	172	58	57	285	112	37	29
Total Organic Carbon (kg/d)	high	23,520	7,290	21,721	23,050	39,609	17,692	6,498	3,865	53,508	9,727	26,644	15,435
	low	5,174	5,302	4,542	9,384	10,951	14,744	5,111	1,421	21,403	8,355	0	7,350

Table 6-3. Range of Expected Carbon, Nitrogen, and Phosphorus Loading into Lavaca Bay, based on Mean Monthly Gaged Lavaca River Discharges (kg/day).

		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Mean Gaged Flows Nead Edna (cfs)		246	304	227	417	652	507	137	109	323	352	207	147
Total Nitrogen Range (kg/d)	high	1,036	*	884	*	3,163	*	427	*	1,218	*	543	*
	low	132	*	383	*	208	*	137	*	222	*	124	*
Total Phosphorus Range (kg/d)	high	127	*	117	*	447	*	50	*	182	*	107	*
	low	24	*	17	*	160	*	34	*	111	*	51	*
Total Organic Carbon Range kg/d)	high	*	*	*	*	*	*	*	*	*	*	*	*
	low	*	*	*	*	*	*	*	*	*	*	*	*

* No available data.

Table 6-4. Range of Expected Carbon, Nitrogen, and Phosphorus Loading from the Lavaca-Navidad Rivers to Lavaca Bay, based on Mean Monthly River Discharge (kg/day).

		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Total Mean Gaged Flows		726	*	630	*	1,803	*	435	*	1,051	*	582	*
Total Nitrogen Range (kg/d)	high	2,894	*	2,947	*	7,007	*	1,194	*	4,143	*	2,197	*
	low	520	*	649	*	814	*	524	*	793	*	399	*
Total Phosphorus Range (kg/d)	high	715	*	265	*	796	*	181	*	628	*	254	*
	low	59	*	66	*	346	*	92	*	396	*	88	*
Total Organic Carbon Range (kg/d)	high	*	*	*	*	*	*	*	*	*	*	*	*
	low	*	*	*	*	*	*	*	*	*	*	*	*

* Data unavailable or incomplete.

Table 6-5. Range of Expected Carbon, Nitrogen and Phosphorus Loading into Tres-Palacios Bay, based on Mean Monthly Gaged Tres-Palacios Creek Discharges (kg/day).

		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Mean Gaged Flows at Midfield (cfs)		144	233	195	93	80	329	227	139	144	59	53	35
Total Nitrogen Range (kg/d)	high	1,104	2,169	1,916	513	468	1,491	590	388	752	228	445	152
	low	194	405	459	175	302	274	111	146	191	82	42	14
Total Phosphorus Range (kg/d)	high	353	360	358	80	90	202	167	109	159	54	100	76
	low	81	177	124	55	33	97	50	55	60	19	31	17
Total Organic Carbon Range (kg/d)	high	5,645	17,126	12,422	2,506	3,136	16,927	6,674	5,789	7,762	3,036	3,246	1,372
	low	1,482	2,854	2,007	1,481	1.372	7,013	3,837	4,427	4,586	752	701	515

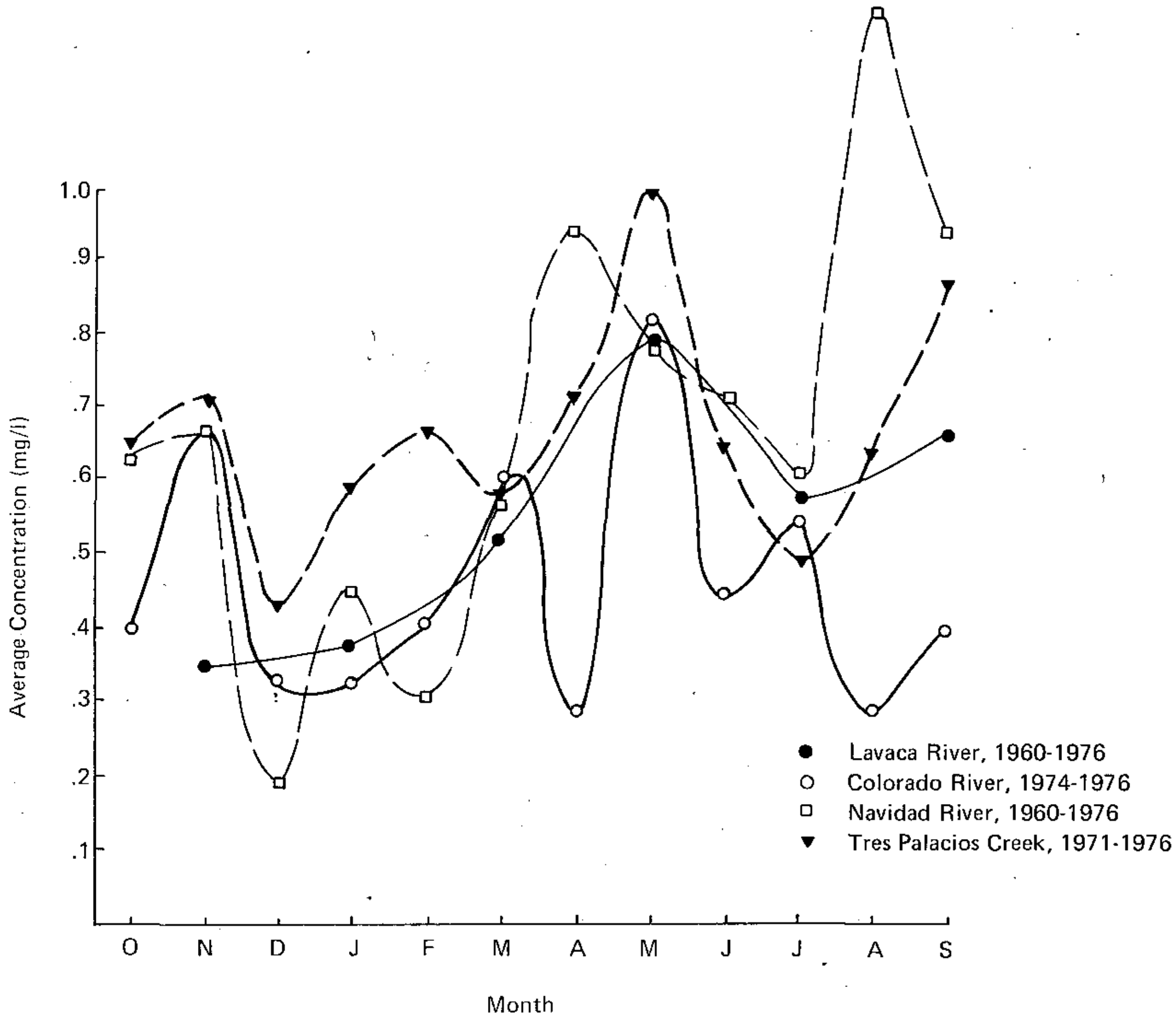

Figure 6-1. Mean Monthly Organic Nitrogen Concentrations in Rivers Contributing to the Lavaca-Tres Palacios Estuary

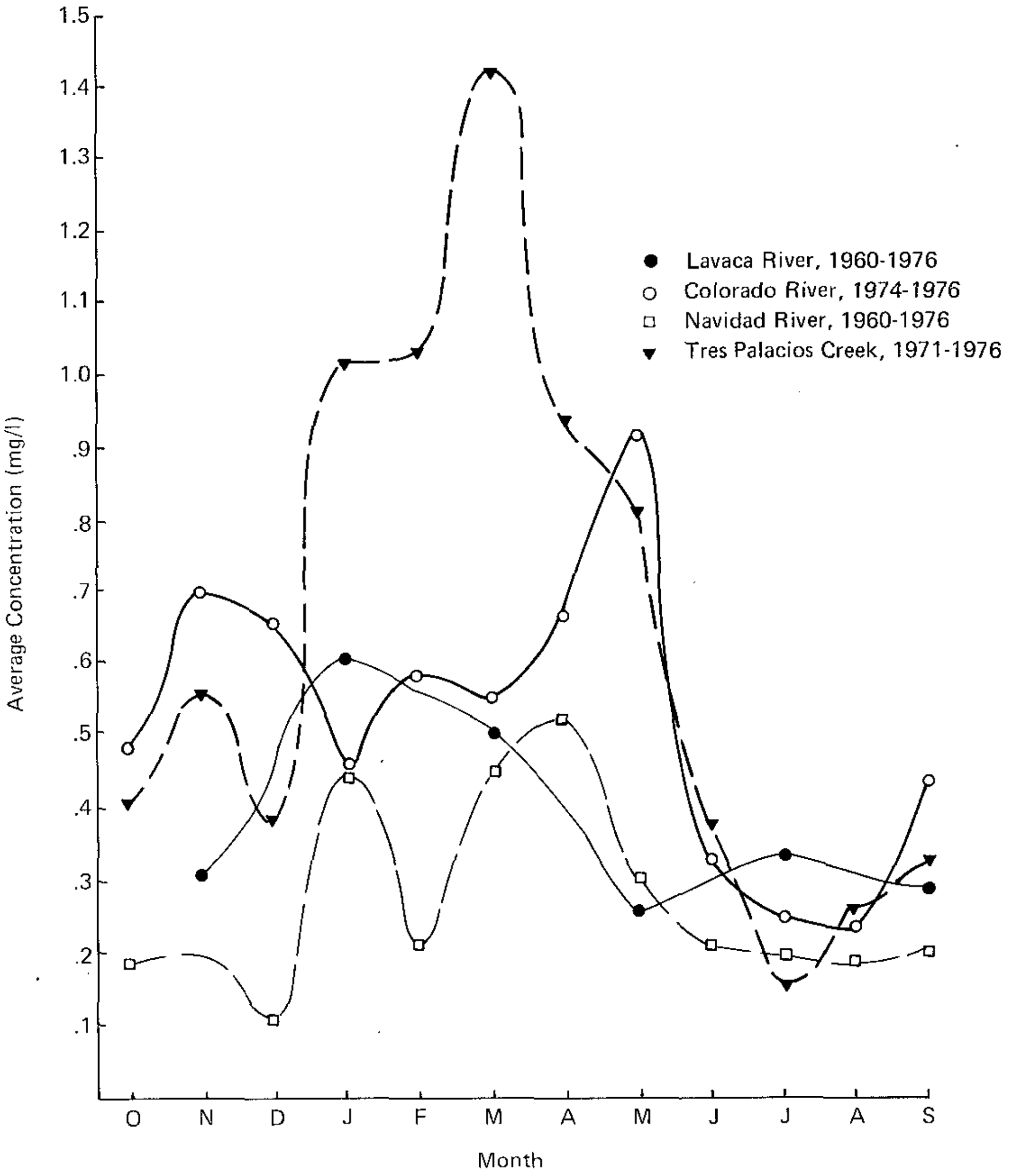

Figure 6-2. Mean Monthly Inorganic Nitrogen Concentrations in Rivers Contributing to the Lavaca-Tres Palacios Estuary

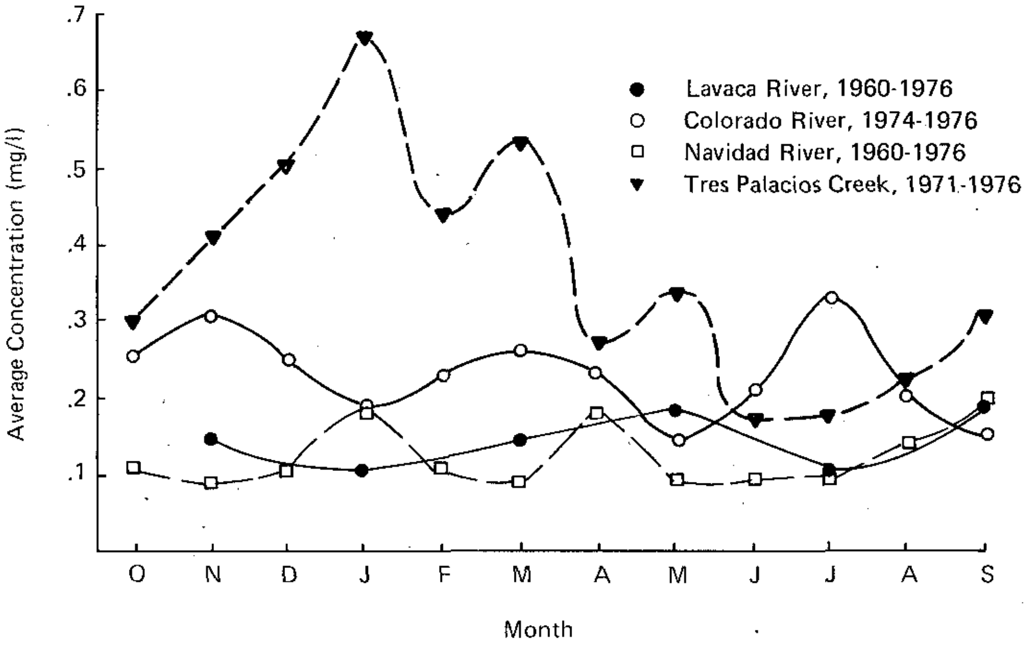

Figure 6-3. Mean Monthly Total Phosphorus Concentrations in Rivers Contributing to the Lavaca-Tres Palacios Estuary

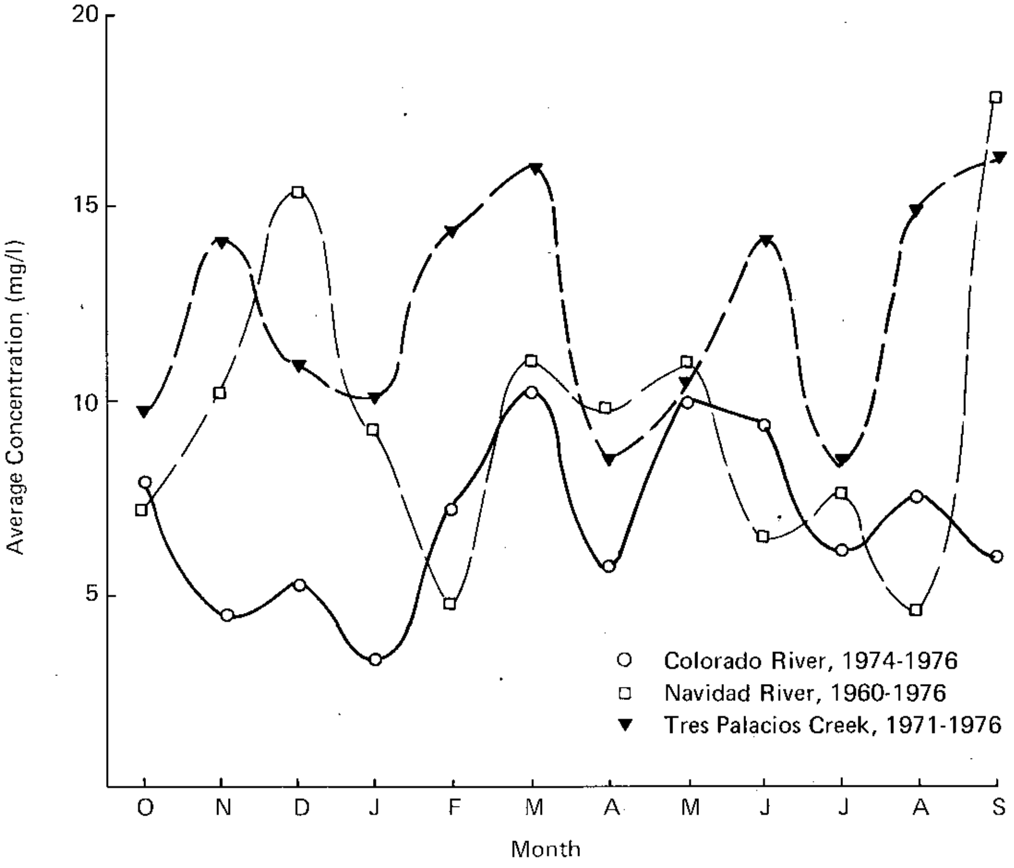

Figure 6-4. Mean Monthly Total Organic Carbon Concentrations in Rivers Contributing to the Lavaca-Tres Palacios Estuary

quality by filtering upland runoff and tidal waters, and (4) shoreline stabilization and other buffer functions.

The most striking characteristic 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 (158). United States estuarine marshes of the Atlantic and Gulf coasts are no exception, since the inhabiting rooted vascular plants have adapted advantageously to the environment and are known to exhibit high biomass production (290, 387, 31, 176, 292, 286, 336). As a result, the marshes are large-scale contributors to estuarine productivity, providing a major source of particulate (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 (36, 37, 205, 160, 137, 136, 32, 171, 40, 115, 200, 88, 94). Recent research has demonstrated a correlation between the area of salt marsh vegetation and the commercial harvests of penaeid shrimp (333). For Texas estuaries, the statistical relationship indicates at least 30.0 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 (64). 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 aquatic and wetland 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. The direct effects of freshwater inflow/salinity fluctuations are primarily physiological in this case, 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 (282, 173, 167, 157, 86).

Major contributing marshes to the Lavaca-Tres Palacios estuary include wetland areas of both the Lavaca and Colorado River deltas. The Lavaca delta has been delineated into five hydrological units with a combined area of 8,431 acres (3,412 hectares) (49). Dominant marsh plants include the vascular macrophytes <u>Scirpus maritimus</u>, <u>Distichlis spicata</u>, <u>Spartina spartinae</u>, <u>S. patens</u>, and <u>Juncus roemerianus</u>. Above-ground net production (ash-free dry weight) is estimated at 99.2 million lbs/yr (45,013 metric tons/yr) and annual net productivity (also ash-free dry weight) averages 11,770 lbs per acre (1,319 g/m^2). Approximately 68 percent of the annual production occurs during the spring and summer quarters and about 69 percent of the annual loss of detritus occurs during the summer and fall quarters. In addition, inundated areas of the Lavaca delta exhibit net production (ash-free dry weight) from periphytes (organisms attached to surfaces of plants and other objects) that range from 2.10 lb/ac/day (0.235 g/m^2/day) in December to 2.68 lb/ac/day (0.300 g/m^2/day) in early April, with an overall average of 2.60 lb/ac/day (0.292 g/m^2/day) (48).

The Colorado delta has been delineated into twelve marsh vegetation zones with a combined area of 19,912 acres (8,017.5 hectares) (50). In terms of areal extent, dominant macrophytes include Spartina spartinae, S. patens, S. alterniflora, Batis maritima, and Salicornia spp. (mostly S. virginica). Above-ground net production (ash-free dry weight) is estimated at 161.5 million lbs/yr (72,243 metric tons/yr) and averages 8,150 lbs/ac (913.6 g/m^2).

Although the high productivity of these deltaic marshes results in large amounts of detritus for potential transport to the estuary's aquatic habitats, actual detrital transport is dependent upon the episodic nature of the marsh inundation/dewatering process. The vast majority of primary production in the higher, irregularly-flooded vegetative zones may go into peat production and not be exported out of the marsh (25). It has been estimated, however, that in the lower, frequently-flushed vegetative zone characterized by Spartina alterniflora about 45 percent of the net production is exported to estuarine waters (205).

Marsh Nutrient Cycling

Functions of Delta Marshes in Nutrient Processes

Brackish delta marshes are common features of river-estuary interfaces, which are formed as decreasing stream velocity allows the suspended sediment load carried by the moving water to drop out of suspension. Wind and tidal action along with variable river discharges combine to alternately inundate and dewater these areas, thereby creating suitable habitat for salt tolerant macrophytic species. The delta marsh habitat performs the following functions: (1) shoreline stabilization, (2) nursery habitat for the young of estuarine and gulf species, (3) a natural system for cleaning and restoring water quality, (4) a food source for open water organisms, and (5) a sediment nutrient trap and location for recycling mechanisms. These functions are highly interdependent.

Marshes on the Texas coast provide nutrients to the estuary in both dissolved and particulate forms. Biogeochemical cycling of nutrients occurs in the deltaic sediments, as organic and inorganic particulates are trapped in the sediment. Bacteria, algae, rooted vegetation, and benthic organisms act to convert the inorganics to organics. Bacteria and detritivores break down complex organic molecules to simple forms capable of incorporation into plant biomass by the rooted vegetation.

Studies by Armstrong et al. (261), Dawson and Armstrong (265), Armstrong and Brown (264), Armstrong and Gordon (262, 263), and Armstrong, Harris and Gordon (266) have been conducted under contract to the Department of Water Resources to determine the role of plants and deltaic sediments in the nutrient exchange processes occurring in Texas' coastal marshes. In most cases these roles seem similar in magnitude among the marshes along the entire Texas coast. For the most part inorganic nitrogen and phosphorus are taken up in the system while organic carbon is generally exported. In the Colorado delta, total suspended solids (TSS) and total organic carbon (TOC) are consistently exported while the inorganic nitrogen and phosphorus species are absorbed, as evidenced by nutrient exchange rates in Table 6-6.

Table 6-6. Summary of Nutrient Exchange Rates for Macrophytes in the Colorado River Delta System a/

Analysis	Spartina alterniflora	Sporobolis virginicus
Total Suspended Solids b/	-6.77	-14.12
Volatile Suspended Solids	-0.57	0.94
Biochemical Oxygen Demand b/ (5 Day)	-0.02	0.00
Total Organic Carbon	-0.41	-0.52
Total Kjeldahl - Nitrogen b/	-0.01	0.00
Total Kjeldahl - Nitrogen	-0.01	0.00
Organic Nitrogen	-0.01	0.00
Ammonia - Nitrogen	0.01	0.01
Nitrite - Nitrogen	0.00	0.00
Nitrate - Nitrogen	0.10	0.13
Total Phosphorus b/	-0.01	0.00
Total Phosphorus	0.01	0.01
Ortho Phosphorus	0.02	0.02

a/ Units are kilograms per hectare per day (kg/ha/d).
b/ Unfiltered samples; all others filtered.

Texas' deltaic marshes act as nutrient sinks for dissolved and particulate materials throughout much of the year (48). During a given inundation event, both particulate and dissolved organic material are exported from the marshes in large quantities. Particulate organic material occurs mainly in the form of dead or decayed plant material and associated bacteria. Studies by Dawson and Armstrong (265) have indicated that dissolved material, particularly dissolved organic carbon (DOC) is exported from the marsh at particularly high rates immediately after initiation of inundation. The rate of export tapers off rapidly, a lower rate persisting throughout the duration of the inundation event. A time period of 12-24 hours seems to be required for the export rate to approach a lower steady-state equilibrium.

Under normal conditions, detrital particles derived from marsh vegetation rarely reach the open estuarine waters, remaining at high concentrations near their sources. The evidence suggests that Texas marshes thus function between inundation events in the manner suggested by Haines (196) for marshes of the Southeastern United States. Marsh vegetation is acted upon by benthic organisms and bacteria, converted to biomass by grazing migratory organisms, and the biomass is transported from the marsh. Only during major inundation events, when flood waters scour the marshes, does export of particulate detrital material occur to any significant degree.

Nutrient Contributions of the Colorado River Delta Marshes

The marshes in the Colorado River delta are subject to periodic inundation by tide and wind driving forces. Mathematical modeling studies indicate that freshwater inundation of the marshes in Matagorda Bay is unlikely to occur as a direct result of Colorado River overbanking during a flood event (45). Field observations from one such event during April 1977 verify this prediction. Bank elevations on the south bank of the river are sufficiently high to restrict the river flow to the channel until it can be diverted through Tiger Island Cut or discharged directly into the Gulf of Mexico.

Assuming a range of dissolved organic carbon (DOC) export from an inundated marsh in this delta to be between 0.4 to 0.5 kg/ha/day, periods of inundation of the intertidal marsh of Matagorda Bay in the vicinity of the Colorado River may be expected to contribute 2,450-3,070 kg/day (5,401-6,768 lb/day) DOC. Since inorganic nitrogen and phosphorus are constantly being taken up, their contribution to the estuary will occur during future inundation events when marsh detritus from senesced or decayed macrophytes would be flushed into the bay.

Nutrient Contributions of the Lavaca River Delta Marshes

In contrast to the Colorado River delta, the marshes in the Lavaca delta are subject to periodic inundation and dewatering. Inundation is here defined as a layer of water at least 0.5 feet (0.15 m) deep remaining for a period of at least 48 consecutive hours. The duration of such a state is a function of river discharge, wind and tides.

Studies were conducted using a mathematical model of the Lavaca River delta developed by Hauck et al. (44). Given a normal tide range of 0.7-1.83

ft. above mean sea level (or 0.2-0.56 m) (Table 6-7), the model predicted no overbanking of the river channels would occur until flows reached 9,000 ft^3/sec (255 m^3/sec). Discharges up to 13,000 ft^3/sec (368 m^3/sec) resulted in overbanking only in the Lavaca and Navidad River channels above Farm to Market Road 616. Inundation of the lower delta was predicted to occur at combined river discharges of 25,000 ft^3/sec (700 m^3/sec), and a major portion of the delta (73.1 percent) would be inundated as discharges approached 45,000 ft^3/sec (1,270 m^3/sec).

During higher than normal tides, 1.8-3.24 ft. above mean sea level (0.55-1.0 m) (Table 6-8), deltaic inundation ranges from 49 percent coverage at flows of 2,870 ft^3/sec (81 m^3/sec) to 95 percent inundation at discharges of 45,000 ft^3/sec (1,270 m^3/sec).

Results of nutrient exchange studies conducted in the Lavaca River delta by Armstrong et al. (261) demonstrate that dissolved organic carbon (DOC) is consistently exported from Lavaca delta marshes at rates varying from 0.94 to 12.6 kg/ha/day. The lower figure occurs during steady state periods of small net water discharge. It is well within the order of magnitude of discharge rates for DOC reported in various laboratory studies for vegetation and sediment on the Texas coast (266). The higher figure is an export rate measured during an actual deltaic flood and inundation event.

Calculations have been made to determine the contribution of DOC from the Lavaca River delta that might be expected during flood events of various magnitudes and durations as predicted by the Lavaca delta inundation model (Table 6-7 and 6-8). To arrive at these figures three assumptions are made. The first is that the highest rates of DOC release (12.6 kg/ha/day) occur simultaneously with the occurrence of the inundation event. The second is that a 24-hour period is required for these rates to decline from an initial high value to a lower steady-state condition (0.94 kg/ha/day) as described by Dawson and Armstrong (265). The third is that the decrease in this rate occurs as a linear algebraic function. After the initial 24 hours of the inundation event, the DOC export rate is considered to be relatively constant throughout the remainder of the event.

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

Table 6-7. Export of Dissolved Organic Carbon (DOC) from the Lavaca River Delta during Flood Events and Normal Tides a/

Lavaca-Navidad (cfs) River Discharges		9,130	13,100	24,700	44,500
Area of Delta Inundation (ha)		602	907	2,510	6,436
Inundation Hour No.	DOC Exchange Rate (kg/ha/d)	kg DOC			
1	12.5	314	472	1,307	3,352
2	12.0	301	454	1,255	3,218
3	11.5	289	435	1,203	3,084
4	11.0	276	416	1,150	2,950
5	10.5	263	404	1,098	2,816
6	10.0	251	377	1,046	2,682
7	9.5	238	359	994	2,548
8	9.0	226	340	941	2,414
9	8.5	213	321	889	2,279
10	8.0	201	302	837	2,145
11	7.5	188	283	784	2,011
12	7.0	176	265	732	1,877
13	6.5	163	246	680	1,743
14	6.0	151	227	628	1,609
15	5.5	138	208	575	1,475
16	5.0	125	189	523	1,341
17	4.5	113	170	471	1,206
18	4.0	100	151	418	1,073
19	3.5	88	132	366	939
20	3.0	75	113	314	805
21	2.5	63	95	262	670
22	2.0	50	76	209	536
23	1.5	38	57	157	402
24	1.0	25	38	105	268
		Total DOC Exported During 1st day (kg)			
		4,065	6,130	16,944	43,443
		Range of DOC Exported Following 1st day (kg/day)			
25- ∞	.5-1.0	300-600	450-910	1,250-2,510	3,220-6,440

a/ Range 0.7 - 1.83 Feet above Mean Sea Level

Table 6-8. Export of Dissolved Organic Carbon (DOC) from the Lavaca River Delta during Flood Events and above Normal Tides a/

Lavaca-Navidad (cfs) River Discharge		2,870	6,430	9,130	13,100	24,700	44,500
Area of Delta Inundation (ha)		3,142	3,380	3,694	4,286	5,383	8,017
Inundation Hour No.	DOC Exchange Rate (kg/ha/d)	kg DOC					
1	12.5	1,637	1,760	1,924	2,223	2,804	4,176
2	12.0	1,571	1,690	1,847	2,143	2,694	4,009
3	11.5	1,506	1,620	1,770	2,054	2,579	3,841
4	11.0	1,440	1,549	1,693	1,964	2,467	3,674
5	10.5	1,375	1,479	1,616	1,875	2,355	3,507
6	10.0	1,309	1,408	1,539	1,786	2,243	3,340
7	9.5	1,244	1,338	1,462	1,697	2,131	3,173
8	9.0	1,179	1,268	1,385	1,607	2,019	3,006
9	8.5	1,113	1,197	1,308	1,518	1,906	2,839
10	8.0	1,048	1,127	1,231	1,429	1,794	2,672
11	7.5	982	1,056	1,154	1,339	1,682	2,505
12	7.0	917	986	1,077	1,250	1,570	2,338
13	6.5	851	915	1,000	1,161	1,458	2,171
14	6.0	786	845	924	1,072	1,346	2,004
15	5.5	720	775	847	982	1,234	1,837
16	5.0	655	704	770	893	1,121	1,670
17	4.5	589	634	693	804	1,009	1,503
18	4.0	524	563	616	714	897	1,336
19	3.5	458	493	539	625	785	1,169
20	3.0	393	423	462	536	673	1,002
21	2.5	328	352	385	446	561	835
22	2.0	262	282	309	357	449	668
23	1.5	197	211	231	268	336	501
24	1.0	131	141	154	179	224	334
		Total DOC Exported during 1st day (kg)					
		21,215	22,816	24,936	28,931	36,337	54,110
		Range of DOC Exported Following 1st day (kg/day)					
25- ∞	.5-1.0	3,140- 1,570	3,380- 1,690	1,850- 3,900	2,140- 4,290	2,690- 5,380	4,010- 8,020

a/ Range 1.8 - 3.24 Feet above Mean Sea Level following description of the Lavaca River delta, the lower Colorado River, and the Pass Cavallo area is a by-product of seasonal aerial photographic studies conducted during the 1976 growing season (217).

The Lavaca River delta has been significantly altered from its natural state and supports heavy agricultural and pastoral use, with a great deal of grazing activity occurring even in the wetland meadows. Ongoing dredging and oil production operations are also contributing to this alteration. Much of the wetlands, especially those lying west of the Lavaca River, have been crisscrossed by shell roads, pipelines, and dragline channels. The river, on the other hand, has been diked with spoil deposits, severely limiting flood overflow into the adjacent wetlands.

The shift of the Colorado River delta southward across Matagorda Bay and the process of channelization have significantly altered the wetlands of this area. The older marshes, north of the Intracoastal Waterway, have slowly changed to become transitional meadows, supporting a great deal of grazing activity. At the same time, new potential wetland areas are being created to the west of the river in Matagorda Bay while, to the east, freshwater flows through the old dendritic passages to the marsh areas of East Matagorda Bay are practically negligible.

The Pass Cavallo area is dominated by the strong tidal mixing through the channels running between Pass Cavallo and Espiritu Santo Bay. A large number of healthy, seemingly productive marsh areas indicate relatively little man-caused environmental degradation.

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 the most productive areas on earth. Therefore, the direct and indirect impacts of water development, power development, navigational development, oil and gas production, and expansion of agricultural and cattle-raising activities in the coastal zone should be of consuming interest.

Summary

Freshwater inundation of the Colorado River delta marshes from river overbanking is a rare event. Marshes in this delta probably function much like those along the east coast of the United States; that is, export of nutrients, both dissolved and particulate, occurs as a function of regular periodic tidal activity. High tides in Matagorda Bay and/or strong southeasterly winds are the major driving forces causing inundation of these intertidal marsh areas.

By contrast, the marshes of the Lavaca River delta are subject to periodic inundation during periods of high river flows as well as tidal inundation. During inundation events, high rates of carbon and organic nitrogen export (both particulate and dissolved) occur initially. After the initial flush of material, steady-state exchange rates in the Lavaca River delta are similar to those that have been observed in the Colorado River delta marshes. Pulses of high freshwater discharge and the resulting deltaic inundation are thus important mechanisms contributing to increased nutrient transport from the Lavaca River delta marshes to the estuary.

Aerial photographic studies of the Lavaca River delta, lower Colorado River, and Pass Cavallo area have provided an insight into on-going wetland processes. For the most part, the Lavaca River delta marshes appear to be the most altered by man (agricultural and cattle-raising activities and oil production); the marshes of the Pass Cavallo area appear least impacted. The long-range condition of the wetland environment will be considerably impacted 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 factors interact to govern the overall biological productivity in a river fed, embayment-type system such as the Lavaca-Tres Palacios 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 period sufficiently long to establish seasonality, distribution of production, and community composition. Ecological variables which were studied and are discussed herein include the density (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 have a diversity of phytoplankton and thereby experience 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, and seasonality of the following important ecological groups: phytoplankton, zooplankton, and benthic invertebrates.

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

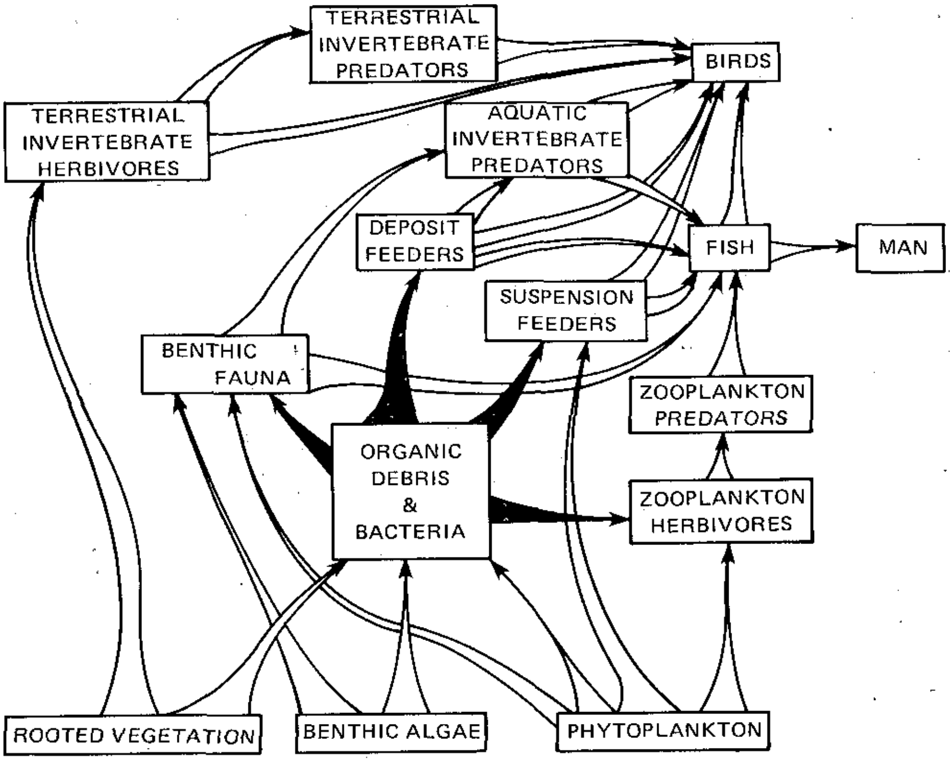

Figure 7-1. Estuarine Food-Web Relationships Between Important Ecological Groups (63).

a Texas Parks and Wildlife Study (244) conducted under interagency contract with the Texas Department of Water Resources. The objectives of the study were: (1) to determine standing crops and species composition of the phytoplankton, zooplankton, benthos, and nekton assemblages of the Lavaca Bay system; and (2) to determine how freshwater inflow and water quality of the Lavaca Bay system affect these assemblages.

Hydrologic parameters were monitored on a monthly basis at 21 bay sites and five river sites (Figures 7-2 and 7-3) from January through September 1973. Starting in October, parameters were monitored at all sites toward the end of each month and at nine sites (600-2, 617-2, 65-2, 85-2, 90-1, 115-1, 143-2, 150-2, and 190-2) during the middle of the month. Salinity, dissolved oxygen, water temperature, turbidity, and pH were determined for each sample. Surface water samples were analyzed for nitrate nitrogen, nitrite nitrogen, ammonia, organic nitrogen, and ortho- and total phosphorus. Sediment samples were analyzed for percent composition of sedimentary particle sizes.

Phytoplankton and zooplankton samples were collected at nine sites at semi-monthly intervals from September 1973 through June 1975. Chlorophyll a measurements were determined on a semi-monthly basis for each of the nine phytoplankton count sites and on a monthly basis for the additional 17 sites. Monthly benthos samples were collected at 20 sites in Lavaca Bay and five sites in the lower Lavaca River for the 30-month study period.

For convenience in data handling, the study area was divided into three regions (Figures 7-2 and 7-3). Sites 65-2, 600-2, 610-2, and 617-2 in the lower Lavaca River, Redfish Lake, and Swan Lake comprised Region I. Region II, the upper portion of Lavaca Bay above the Highway 35 Causeway, included sites 83-2, 93-5, 84-2, 85-2, 85-4, 90-1, 90-3, and 90-5. The southern or lower portion of Lavaca Bay comprised Region III and included sites 115-1, 115-3, 115-4, 129-2, 140-2, 143-2, 143-4, 150-2, 150-5, 180-2, 190-2, 190-4 and 190-5.

Phytoplankton

Data Collection

According to Gilmore et al. (244), seven taxonomic divisions represented by a total of 155 phytoplankton species were collected from the Lavaca Bay system: Bacillariophyta - diatoms [78], Chlorophyta - green algae [28], Pyrrophyta - dinoflagellates [24], Cyanophyta - blue-green algae [13], Euglenophyta - euglenoids [7], Cryptophyta [4], and Chrysophyta - golden-brown algae [1]. The Cryptophytes (e.g., phytoflagellates and *Chroomonas* sp.) were the major species in the river areas, while Lavaca Bay was dominated by the Cryptophyta and Bacillariophyta (e.g., *Navicula*, *Nitzschia*, and *Skeletonema*) (Figures 7-4, 7-5 and 7-6). Many of the species collected, especially the Chlorophyta, were considered to be freshwater forms.

Phytoplankton concentrations in a single sample from the Lavaca Bay study ranged from 50,000 cells/l at sites 90-1 (October 1973) and 85-2 (September 1974) to 24,260,000 cells/l at site 115-1 (May 1974). The overall mean density for all stations was 3,700,000 cells/l for the 22-month study period. The highest mean standing crop for the study was 6,050,000 cells/l which

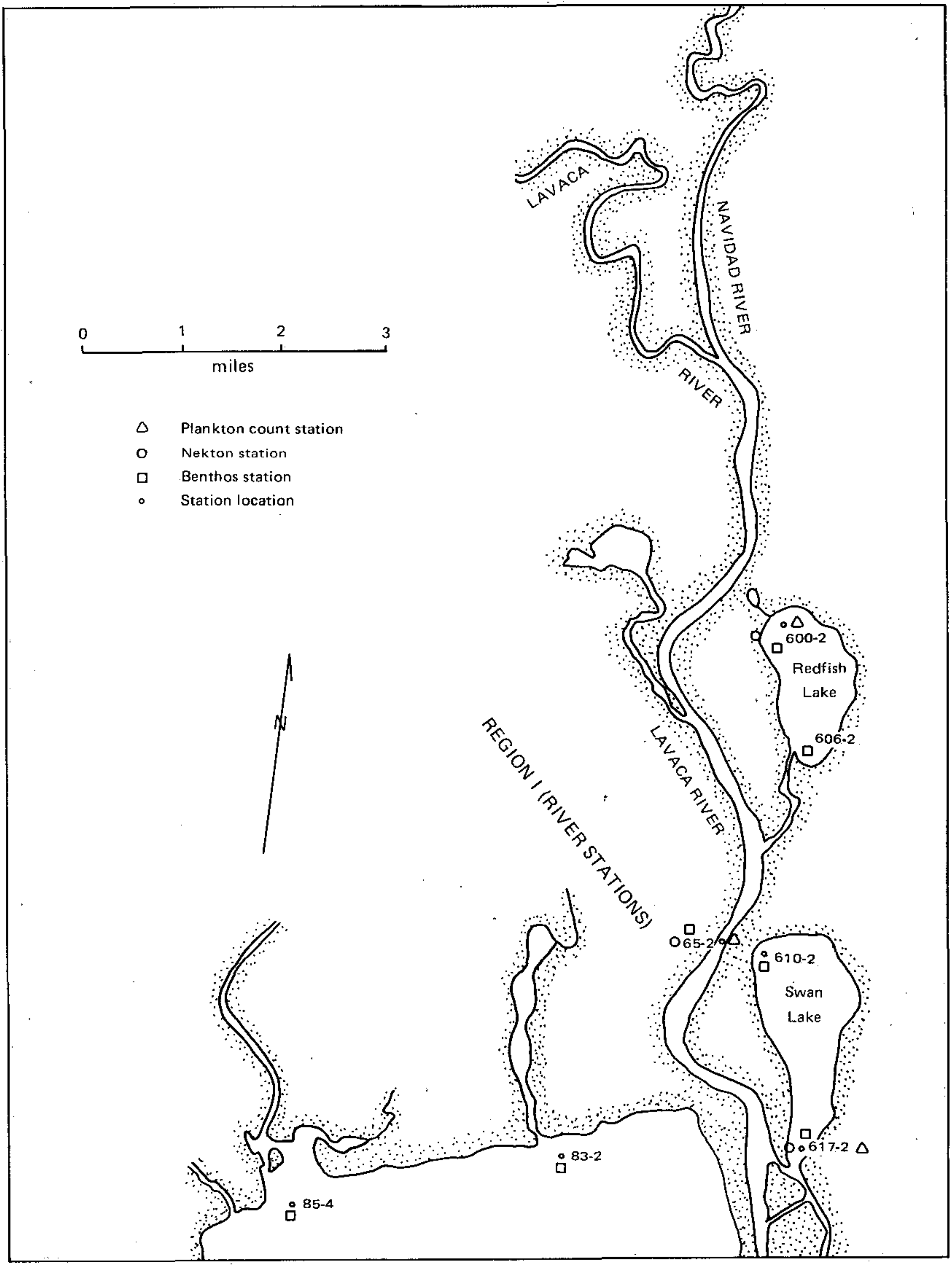

Figure 7-2. Lavaca River Sample Sites (244).

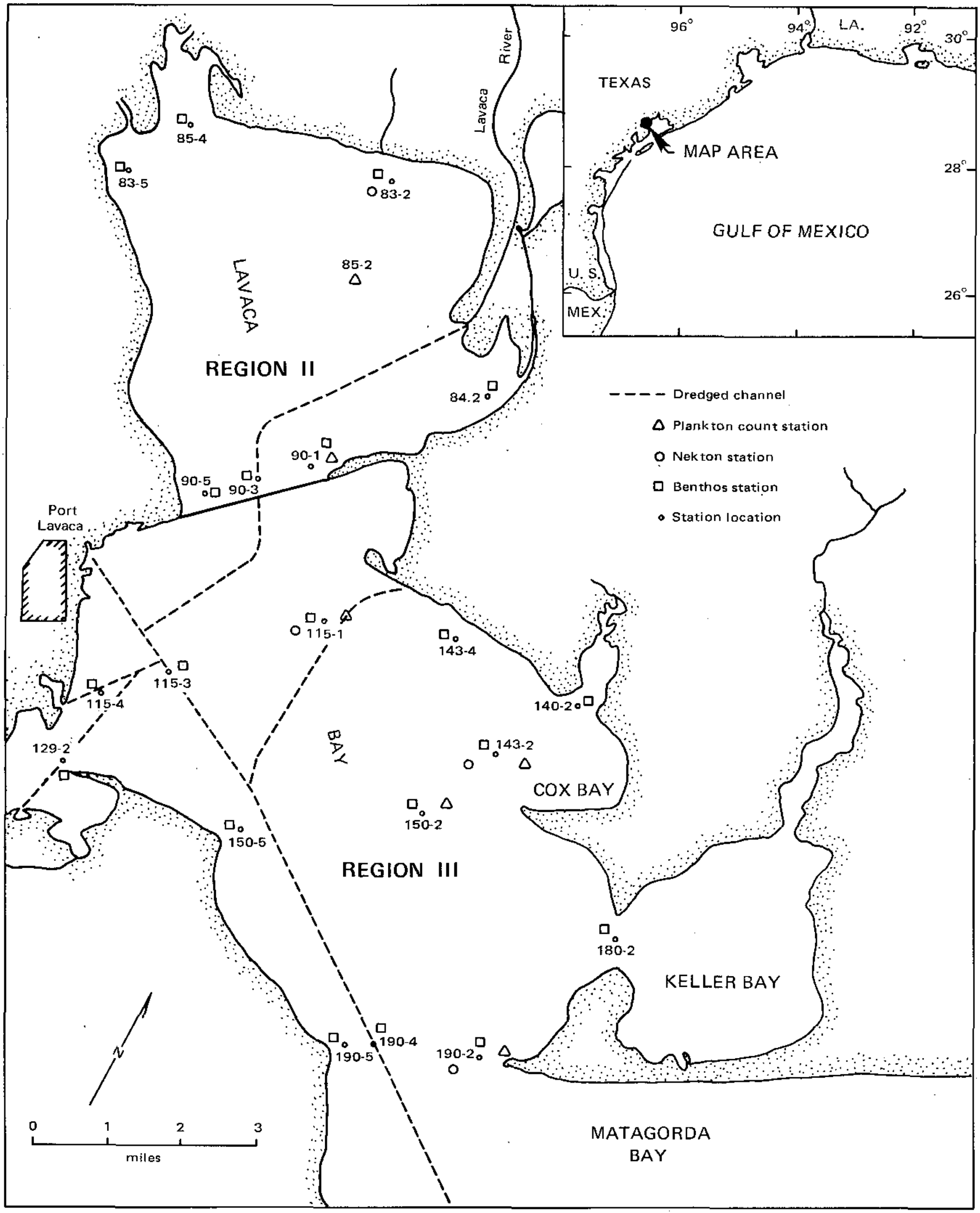

Figure 7-3. Lavaca Bay Sample Sites and Regional Divisions (244).

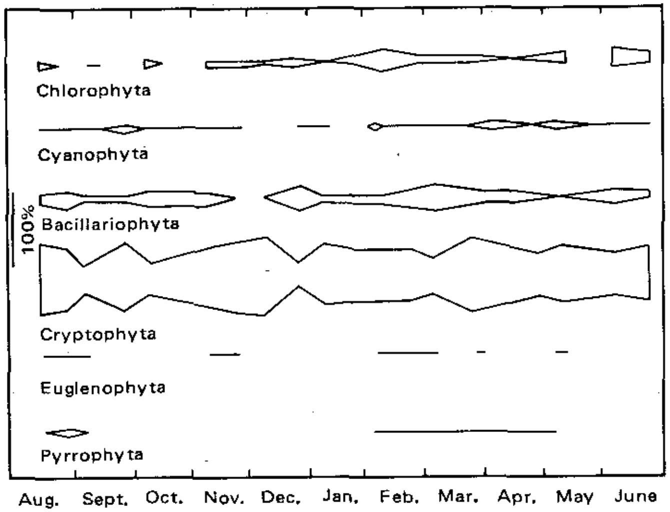

Figure 7-4.—Redfish and Swan Lakes

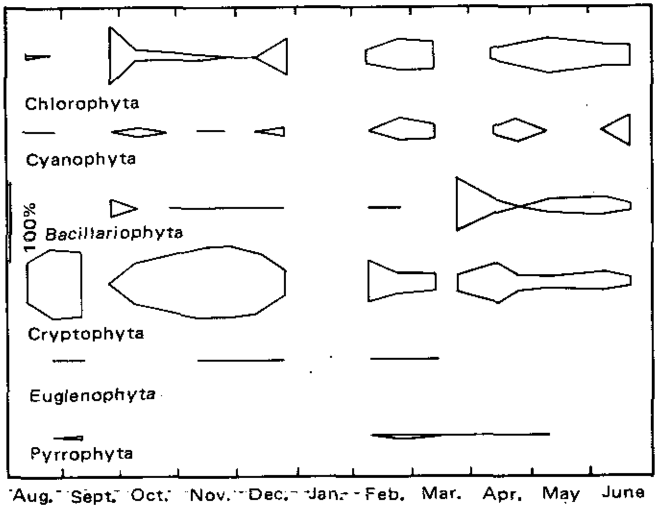

Figure 7-5.—Lavaca River

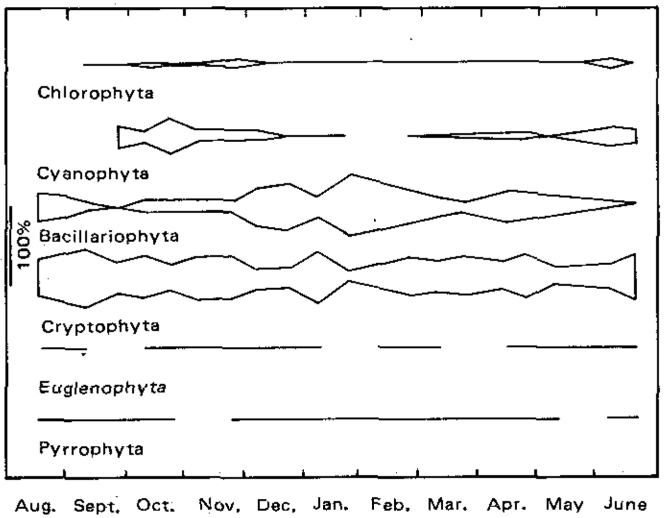

Figure 7-6.—Lavaca Bay

Percentage Composition of Six Phytoplankton Divisions Present in Semi-monthly Samples, 1974-1975 (224).

occurred at riverine site 65-2 in Region I; the lowest mean standing crop was 2,950,000 cells/l occurring at the bay-mouth site 190-2 (Region III). According to Gilmore et al. (244), numbers of taxa ranged from 1 at site 65-1 (June 1974) to 35 at site 85-2 (April 1975).

Spring and summer months of 1974 (March through August) produced consistently higher phytoplankton densities (Figure 7-7). Average regional densities ranged from 198,000 cells/l in September 1973 in Region III to 15,980,00 cells/l in February 1975 in Region I.

The TPWD study indicated that the phytoplankton standing crop was composed of cryptomonads, green algae, blue-green algae, diatoms, and others (e.g., Euglenophyta, Pyrrophyta) (Table 7-1). In addition, group proportions in the three regions were not markedly different.

The group of unidentified cryptomonad phytoflagellates was ubiquitous throughout the study period in all regions (Table 7-2). The second most abundant species, <u>Chroomonas</u> sp., maintained relatively high populations throughout the study period but reached maximum densities in late winter. Populations of this species were most prominent in Region I. Among the green algae, <u>Westella botryoides</u>, <u>Ankistrodesmus falcatus</u>, and <u>Chlorella</u> sp. were dominant in late winter and early spring. <u>Navicula</u> sp., a freshwater diatom, was prominent in all regions from September 1973 through April 1974. A "bloom" of <u>Navicula</u> sp. occurred in Region III in August 1974 when it constituted 43.29 percent of the regional phytoplankton community.

Results of Analyses

Lavaca Bay phytoplankton densities observed during the TPWD study were high in comparison to other marine areas and estuaries of Texas. Mean standing crop for the study period was 3,700,000 cells/l of which 2,390,000 were microflagellates, 520,000 were diatoms, and 360,000 were green algae (exclusive of <u>Chlamydomonas</u> and <u>Pyramimonas</u>). Moseley et al. (18) found phytoplankton densities of 730,000 cells/l in Cox Bay, Texas, while Espey, Huston and Associates (46) reported densities of 133,000 cells/l from Sabine Lake.

Seasonally, phytoplankton densities and chlorophyll <u>a</u> measurements appeared to fluctuate independently of one another. Peaks in mean monthly phytoplankton standing crops occurred in March, May, and August 1974 and February 1975; lowest numbers were collected in November 1974. Highest mean monthly chlorophyll <u>a</u> measurements were recorded in April and May 1974, while lowest values occurred in January, April and June 1975.

The green and blue-green algae collected were representative of typical forms found in freshwater reservoirs in the southwestern United States. Diatoms and dinoflagellates were a mixture of freshwater forms, plus brackish and marine species which are frequently found in coastal areas of the Gulf of Mexico. Although euglenoids are generally regarded as freshwater organisms, species such <u>Euglena</u>, <u>Eutreptia</u>, and <u>Trachelomonas</u> are frequently tolerant of salinity. Leedale (125) reports that <u>Eutreptia</u> is sometimes considered a marine form.

Correlation analysis of river inflow versus phytoplankton counts per liter was not statistically significant ($\alpha > 0.05$). Freshwater inflows from

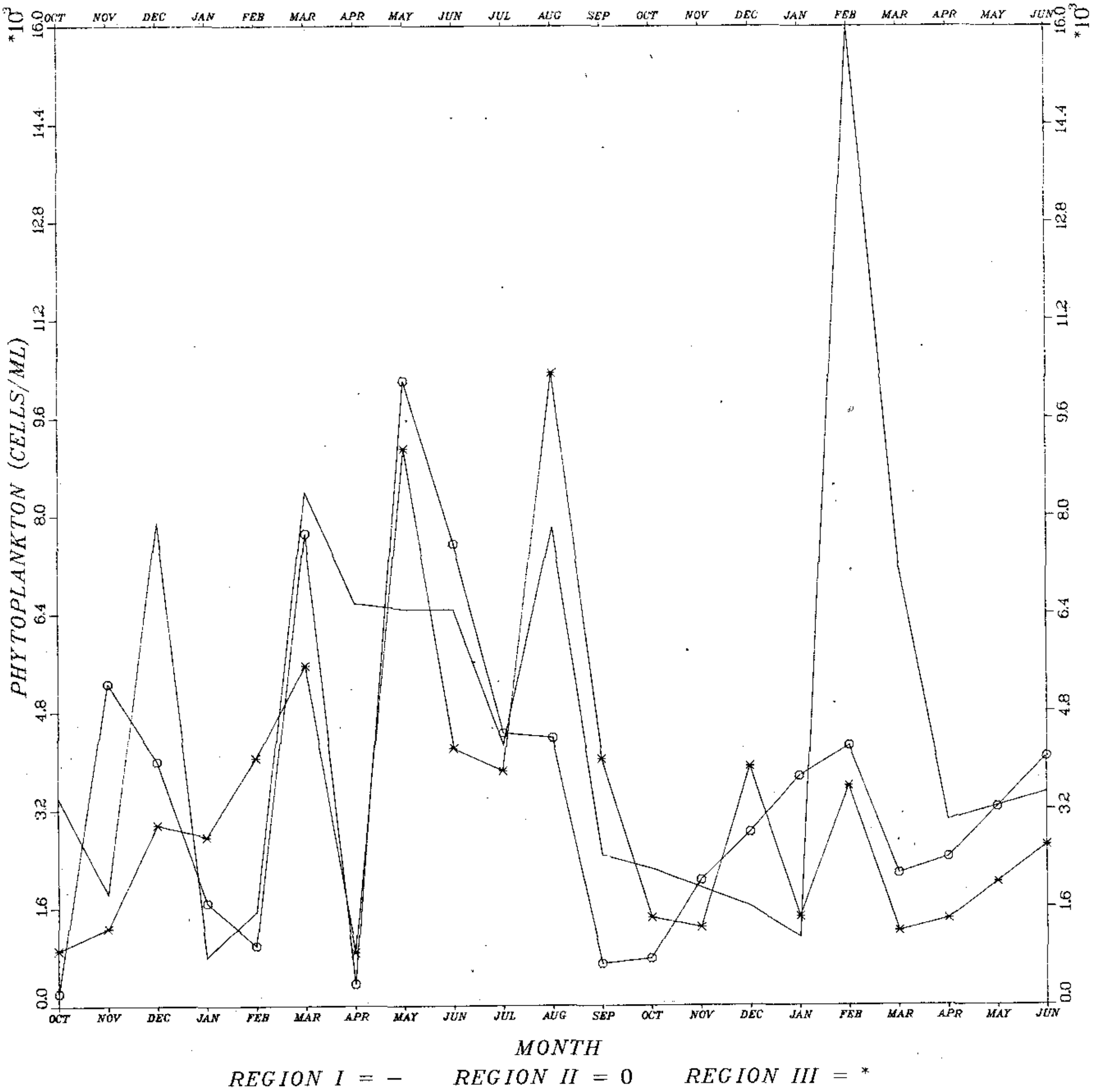

Figure 7-7. Mean Monthly Phytoplankton Densities in Lavaca Bay, October 1973-June 1975.

Table 7-1. Mean Percentage Representation by Biomass of Phytoplankton in the Lavaca Bay System (September 1973 - June 1975)

Phytoplankton	Region I a/	Region II	Region III
		(percent)	
Unidentified cryptomonad phytoflagellates	43.0	61.3	46.0
Cryptomonads	23.5	16.3	16.2
Green algae	15.4	10.4	5.0
Blue-green algae	7.8	5.1	12.0
Diatoms	7.4	6.0	20.0
Others	2.9	0.9	0.8
Total Phytoplankton Biomass	100.0	100.0	100.0

a/ Refer to Figures 7-2 and 7-3 for location of Regions I, II, and III.

Table 7-2. Percent Composition by Biomass of Dominant Phytoplankton Species in the Lavaca Bay System (September 1973 - June 1975)

Region a/	Species	Percent Composition b/
Region I	Unidentified phytoflagellates	43.0
	Chroomonas sp.	23.5
	Westella botryoides	4.6
	Navicula sp.	3.0
	Ankistrodesmus falcata	2.5
	Chlorella sp.	2.8
		79.4
Region II	Unidentified phytoflagellates	61.3
	Chroomonas sp.	16.3
	Westella botryoides	6.3
	Merismopedia sp.	3.6
	Navicula sp.	2.4
	Chlorella sp.	1.6
		91.5
Region III	Unidentified phytoflagellates	45.6
	Chroomonas sp.	16.2
	Navicula sp.	10.5
	Coccoid (Blue-green algae)	5.6
	Westella botryoides	3.9
	Anabaena sp.	3.3
		85.1
All Regions	Unidentified phytoflagellates	48.0
	Chroomonas sp.	18.9
	Navicula sp.	6.0
	Westella botryoides	4.7
	Merismopedia sp.	2.7
	Coccoid (Blue-green algae)	2.4
		82.7

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a/ Refer to Figures 7-2 and 7-3 for location of Regions I, II, and III.

b/ Total Phytoplankton Biomass = 100 percent in each regional category.

river sources import freshwater phytoplankton species into the estuarine system. This input may be substantial as evidenced by the high average phytoplankton densities for Region I, the river areas, as compared to Regions II and III. Although river inflows 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 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 the high turbidities, salinity changes, and flushing out of indigenous populations may depress phytoplankton abundance and productivity. Gilmore et al. (244) state that minimum phytoplankton density in Lavaca Bay was associated with river inflows above 2,000 cfs (56 m^3/sec) while maximum standing crops occurred with blooms of microflagellates and diatoms as the bay salinity began to stabilize after high inflow (Figure 7-8).

Phytoplankton species vary markedly in ability to withstand changes in salinity. Accurate halobion classification of most species found in Lavaca Bay is impossible due to insufficient culture experimentation on salinity optima and tolerances. Chu (20) notes that although cell division can continue in freshwater for most estuarine species, most freshwater species cannot grow in salinities exceeding 2.0 ppt. Foerster (57) finds, however, that many freshwater species can resume growth after exposure to seawater if placed in a freshwater medium.

Estuarine plankton are divided by Perkins (170) 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 Lavaca Bay system supports a phytoplankton population derived from this entire range. The permanent autochthonous populations are represented by such brackish-water species as *Cryptomonas* spp. and *Katodinium rotundatum*. Temporary autochthonous species include diatoms, e.g., *Skeletonema costatum* and *Chaetoceros* spp., and dinoflagellates, e.g., *Peridinium trochoideum* and *Prorocentrum micans*. The allochthonous element is difficult to define but is probably represented by diatoms and green algae derived from fresh and marine environments.

The seasonal changes in average temperature in the Lavaca Bay study correlated only weakly with average phytoplankton density; changes in surface salinities exhibited no correlation with phytoplankton standing crops (244). This implies, perhaps, that there are a combination of primary seasonal controlling factors of Lavaca Bay phytoplankton. Although typical phytoplankton populations appear to be primarily influenced by temperature, salinity and availability of nutrients, each species' presence and density is governed by physical, chemical, and biological parameters operating simultaneously.

Zooplankton

Data Collection

According to Gilmore et al. (244) a total of 4,499,745 organisms representing 201 taxa in 14 phyla were identified from 360 samples collected during

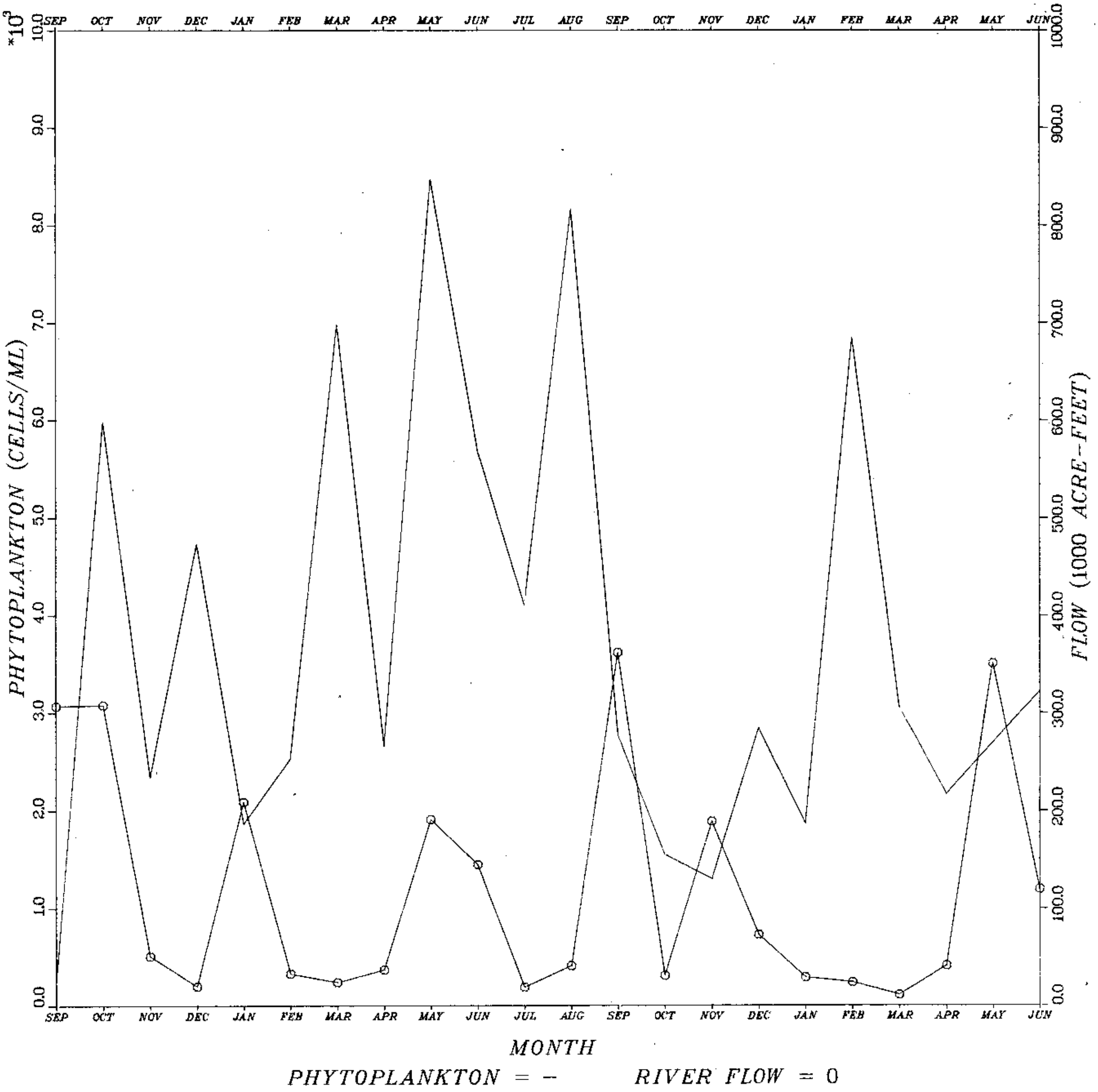

Figure 7-8. Mean Monthly Phytoplankton Densities versus Combined River inflow in Lavaca Bay, September 1973-June 1975.

the 22-month zooplankton study. The most prominent phylum was the Arthropoda which accounted for 63 percent (127 taxa) of the species identified. The chordates accounted for 10 percent (19 taxa), rotifers for seven percent (14 taxa), cnidarians for four percent (9 taxa), and protozoans for three percent (6 taxa). The remaining 13 percent (26 taxa) were distributed among the nine additional phyla. The freshwater zooplankton assemblages included such organisms as cyclopoid copepods of the genus *Cyclops* and cladoceran water fleas of the genus *Daphnia*. The brackish or estuarine species were commonly represented by calanoid copepods *Acartia tonsa*, *Paracalanus crassirostris*, and *Pseudodiaptomus coronatus*, or the cyclopoid copepod *Oithona brevicornis*. Marine species from the neritic Gulf waters were represented by calanoid copepods *Centropages hamatus* and *Labidocera aestiva*, the bioluminescent dinoflagellate *Noctiluca scintillans*, and the chordate larvacean genus *Oikopleura*.

Standing crops ranged from 127,381 individuals/m^3 at site 150-2 in Region III (April 1975) to six individuals/m^3 in Region I, site 600-2, in November 1974. The overall annual mean density for the Lavaca Bay system was 12,449 individuals/m^3 (244).

Zooplankton populations illustrated greater seasonal fluctuations than phytoplankton. Populations were generally high during late winter and spring and low during summer and early fall (Figure 7-9). The mean monthly density for all stations ranged from 28,611 individuals/m^3 in March 1974 to 2,160 individuals/m^3 in August 1974. Zooplankton taxa diversities were generally greater at lower bay sites in Region III.

The zooplankton community of the Lavaca Bay system can be summarized as follows:

1. Immature barnacles - barnacle nauplii and barnacle cyprids.
2. Acartice - calanoid copepods of the genus *Acartia*. In this study, *Acartia tonsa* was the dominant species.
3. Other copepods - all Copepoda with the exception of *Acartia* spp., such as *Cyclops* sp., *Oithona* sp., and *Paracalanus* spp.
4. Immature copepods - naupliar larvae and copepodites.
5. Rotifers - almost entirely freshwater forms, such as *Asplancha* sp., *Brachionus* spp., and *Keratella* spp.
6. Microcrustaceans - all other crustaceans not included above, such as ostracods, cladocerans, etc.
7. Protozoans - primarily *Noctiluca scintillans*.
8. Others - annelid larvae, immature gastropods, insect and fish larvae, etc.

The overall mean percentage composition by biomass for these groups in the Lavaca Bay system is shown in Table 7-3. The immature barnacles, including the naupliar and cypris forms, were prominent in the late winter and early spring months of the study which corresponds to the period of greatest spawning activity of the barnacle. *Acartia* spp., especially *Acartia tonsa*, were prominent on all sampling dates but reached peak densities in the summer and early fall months of the study. Immature copepods and other copepods were most abundant in October and November 1973 and April through August 1974.

The dominance of the barnacle nauplii and the copepod, *Acartia tonsa*, was evident in all three regions (Table 7-4). These two groups constituted over

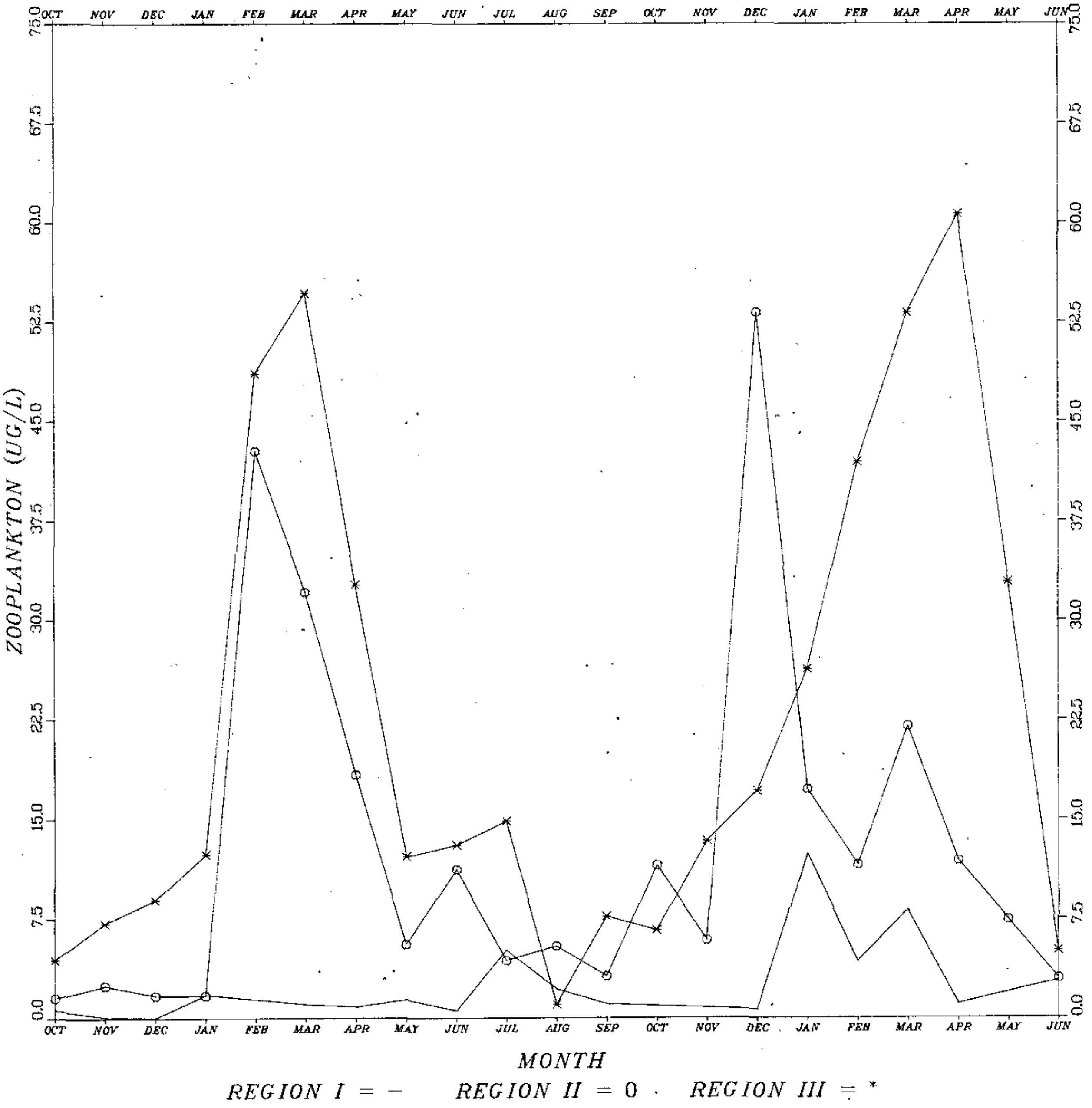

Figure 7-9. Mean Monthly Zooplankton Densities in Lavaca Bay, October 1973-June 1975.

Table 7-3. Mean Percentage Representation by Biomass of Zooplankton in the Lavaca Bay System (September 1973 - June 1975)

Zooplankton	Region I a/	Region II	Region III
		(percent)	
Immature barnacles	53.7	58.4	49.8
Acartice	28.5	22.2	29.8
Other Copepods	3.4	2.8	9.3
Immature copepods	5.7	1.3	2.1
Rotifers	5.0	0.2	0.1
Macrocrustaceans	1.8	0.2	0.1
Protozoans	0.0	13.9	6.8
Others	1.9	1.0	2.0
Total Zooplankton Biomass	100.0	100.0	100.0

a/ Refer to Figures 7-2 and 7-3 for location of Regions I, II, and III.

Table 7-4. Percent of Composition by Biomass of Dominant Zooplankton Species in the Lavaca Bay System (September 1973 - June 1975)

Region a/	Species	Percent Composition b/
Region I	Barnacle nauplii	53.3
	Acartia tonsa	28.5
	Copepod nauplii	2.6
	Cyclopoid	2.5
	Diaptomus sp.	1.8
	Brachionus quadridentata	1.4
		90.1
Region II	Barnacle nauplii	57.3
	Acartia tonsa	22.2
	Noctiluca scintillans	13.9
	Oithona sp.	2.0
	Barnacle cypris	1.1
	Copepod nauplii	1.0
		97.5
Region III	Barnacle nauplii	49.0
	Acartia tonsa	29.8
	Noctiluca scintillans	6.8
	Oithona sp.	6.2
	Barnacle cypris	2.1
	Paracalanus crassirostris	1.8
		95.7
All Regions	Barnacle nauplii	51.0
	Acartia tonsa	28.1
	Noctiluca scintillans	8.1
	Oithona sp..	5.0
	Barnacle cypris	1.8
	Paracalanus crassirostris	1.4
		95.4

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a/ Refer to Figures 7-2 and 7-3 for location of Regions I, II, and III.
b/ Total Zooplankton Biomass = 100 percent.

75 percent of the biomass of each region for the entire study period. The marine protozoan, Noctiluca scintillans, was more abundant in the lower regions farthest from the freshwater inflow effects. Populations of the cyclopoid copepod Oithona sp., reached maximum densities also in Regions II and III during the latter months of the year (i.e., June through December). The rotifer, Brachionus quadridentata, and the copepod, Diaptomus sp., showed the reverse in their preference for the fresher waters of Region I.

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 the Lavaca estuarine system are widely distributed along the coasts of the United States, while others may even have a worldwide distribution. For example, Green (63) reports that Acartia tonsa may be found in the Central Baltic Sea area; Centropages hamatus has been collected in British waters and in the Gulf of Bothnia in the Baltic Sea; and Brachionus quadridentata is also known from points as distant as the Aral Sea of Russia.

Other zooplankton studies conducted in estuaries and bays along the Gulf of Mexico have produced similar results to the TPWD Lavaca Bay study. James (330) has reported that naupliar larvae and calanoid copepods are the dominant zooplankton forms in the estuarine marsh areas of Old River Cove near Sabine Lake. This study is in agreement with zooplankton studies in Sabine Lake (46) and in Nueces, Corpus Christi, Copano, and Aransas Bays (275). Maximum and minimum total mean monthly densities in Lavaca Bay were also similar to results from the studies mentioned above (Table 7-5).

Zooplankton densities in Lavaca Bay are compared with combined (gaged and ungaged) river inflow in Figure 7-10. High flow rates in September through October 1973, May through June 1974, and September 1974 are accompanied by low zooplankton standing crops. Conversely, zooplankton blooms in February through April 1974 and December through April 1975 occur during periods of low flow. However, no statistical correlations were discovered between these parameters.

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 overall zooplankton populations. Perkins (170) reports that the primary factor influencing the composition and abundance of estuarine zooplankton is development rate versus flushing time. For example, Holland et al. (275) found a decrease of brackish water-marine zooplankton and an increase in

Table 7-5. Range of Mean Monthly Zooplankton Densities in Texas Estuaries (Individuals/m^3)

System	Minimum	Maximum
Nueces Bay (275)	832 (Oct. 1973)	8,027,855 (Feb. 1974)
Corpus Christi Bay (275)	1,722 (Dec. 1972)	53,657,037 (Mar. 1973)
Copano Bay (275)	1,296 (Sept. 1974)	53,536 (Feb. 1973)
Aransas Bay (275)	2,497 (Dec. 1972)	3,008,679 (Feb. 1974)
Sabine Lake (46)	381 (Apr. 1975)	20,042 (Oct. 1974)
Lavaca Bay (244)	1,980 (Oct. 1973)	27,846 (Feb. 1974)
San Antonio Bay (242)	820 (June 1973)	46,296 (Feb. 1973)

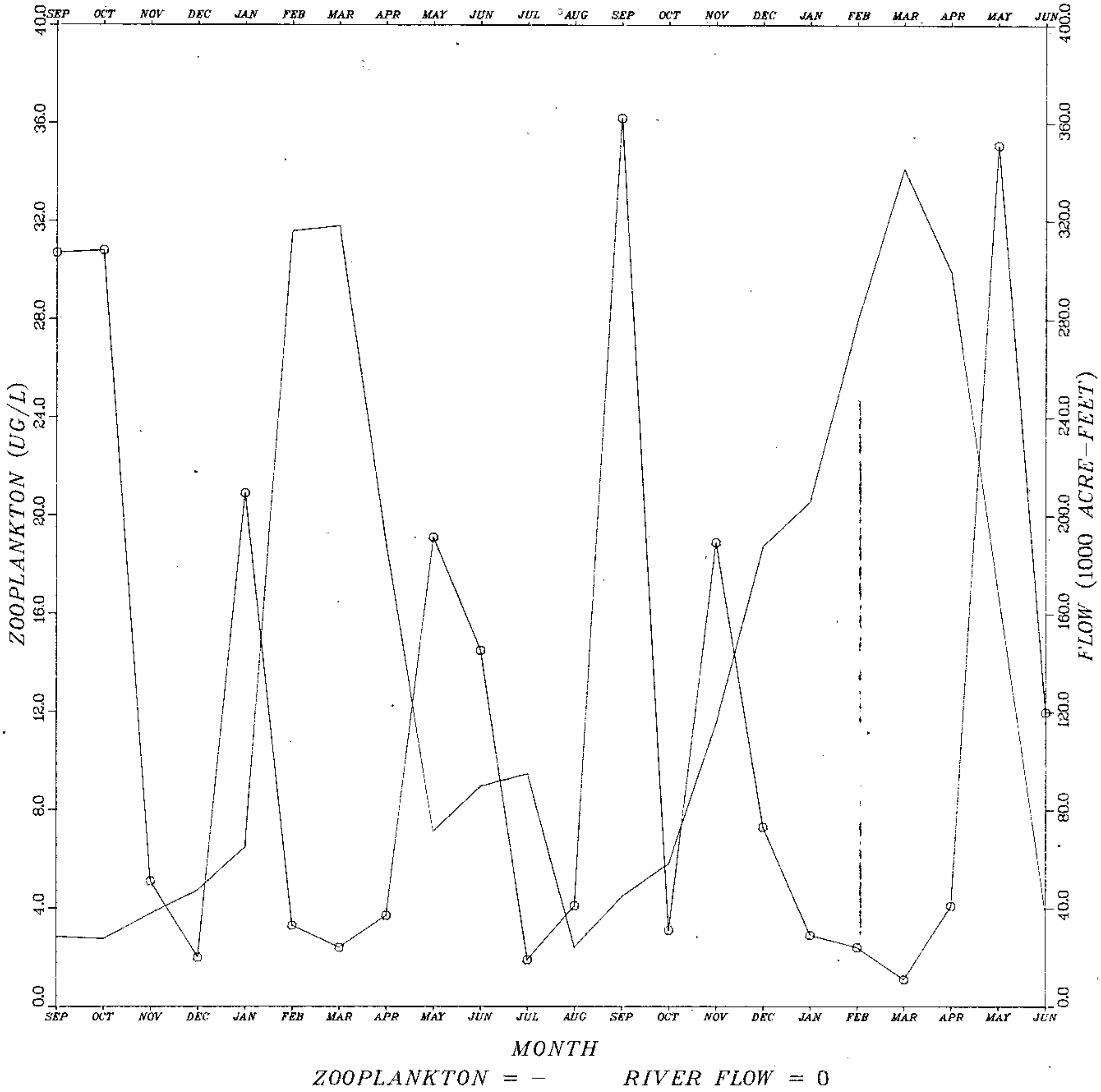

Figure 7-10. Mean Monthly Zooplankton Densities versus Combined River Inflow in Lavaca Bay September 1973-June 1975.

freshwater zooplankton whenever inflows were great and salinities declined. 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.

According to Gilmore et al. (244), zooplankton standings crops were inversely related to water temperature and directly related to salinity. This relationship is in agreement with Matthews et al. (242) and Holland et al. (275), who reported that temperature and salinity are the two most important factors regulating community species composition and spatial and temporal distribution of zooplankton in the San Antonio and Corpus Christi Bay systems, respectively. Greatest densities of the dominant zooplankton of the system, the meroplanktonic barnacle nauplii, occurred in the cool, higher salinity waters of the winter, which corresponds to the period of peak spawning activity of the barnacle (Table 7-6). The second most abundant zooplankton, Acartia tonsa, was nearly ubiquitous throughout the temperature/salinity ranges. The lowest catches occurred under extreme conditions such as low salinity/low temperature and high salinity/high temerpature (Table 7-7).

Benthos

Data Collection

A total of 132,079 animals representing 169 taxa in nine phyla were identified from the 730 benthic samples collected during the 30-month Texas Parks and Wildlife Department (TPWD) study in the Lavaca Bay system (244). The most prominent phyla was the Annelida which accounted for 34 percent (56 taxa) of the species identified, followed closely by the Arthropoda with 31 percent (51 taxa), and Mollusca with 28 percent (48 taxa). The Chordates accounted for five percent (8 taxa), nemertines for one percent (2 taxa), and echinoderms for one percent (1 taxon).

Standing crops ranged from 2,568 individuals/0.1 m^2 at site 85-4 (Region II) in July 1973 to zero at site 65-2 (Region I) in April 1973. The overall mean density was 181 individuals/0.1 m^2 for the entire study (229). The mean monthly density for all stations ranged from 62.49 organisms/m^2 in January 1973 to 303.24 organisms/m^2 in April 1974.

Benthic populations were observed to vary seasonally with high spring/summer and low fall/winter standing crops indicated (Figure 7-11). The largest number of species occurred in the lower, more saline reaches of the system and the smallest number in the upper, low salinity areas of Region I.

Annelid biomass tended to decrease in the low salinity waters of the upper bay areas, while the opposite relationship was apparent for the molluscan bivalves. Biomass for other groups was similar from region to region (Table 7-8).

It is apparent that the molluscan gastropod Littoridina sphinctostoma was most abundant and nearly ubiquitous through the system, followed by the polychaete worm Mediomastus californiensis and the molluscan pelecypod Rangia cuneata (Table 7-9). Certain species like Littoridina sphinctostoma, Rangia cuneata, Hypaniola gunneri floridus, and chironomid fly larvae had their

Table 7-6. Distribution of Barnacle Nauplii by Salinity and Temperature Ranges, Lavaca Bay System (January 1974–June 1975)

Salinity (ppt)		Water Temperature (Degrees Centigrade)											
		0.– 3.	3.– 6.	6.– 9.	9.– 12.	12.– 15.	15.– 18.	18.– 21.	21.– 24.	24.– 27.	27.– 30.	30.– 33.	33.– 36.
0.–4.	Samples				1	7	8	7	10	11	15	10	1
	Occurrences				1	5	5	6	8	6	10	6	1
	Avg. Catch a/				267	55	487	1055	421	237	215	276	0
4.–8.	Samples				1		1	5	6	9	5	5	
	Occurrences				1		1	4	6	6	4	3	
	Avg. Catch				552		8850	459	371	850	1137	747	
8.–12.	Samples					3	2	4	5	6	5	7	
	Occurrences					3	2	4	5	6	4	6	
	Avg. Catch					7398	1855	16502	1227	4293	1193	1422	
12.–16.	Samples				5	1	7	3	5	7	2	1	1
	Occurrences				5	1	7	3	5	6	2	1	1
	Avg. Catch				13953	20390	21084	720	16062	3052	7129	274	1715
16.–20.	Samples			1		6	10	5	6	2	6	2	
	Occurrences			1		5	10	5	6	2	6	1	
	Avg. Catch			28020		11067	8783	18114	14946	1708	3085	434	
20.–24.	Samples				2	2	12	10	19	3	8	2	
	Occurrences				2	2	11	9	18	3	8	0	
	Avg. Catch				23760	7895	15939	24904	17156	25512	2992	0	
24.–28	Samples						1				2	1	
	Occurrences						1				2	0	
	Avg. Catch						632				8	0	

a/ Average catch is expressed in individuals/m^3.

Table 7-7. Distribution of Acartia Tonsa by Salinity and Temperature Ranges, Lavaca Bay System (January 1974–June 1975)

Salinity (ppt)		Water Temperature (Degrees Centigrade)											
		0.– 3.	3.– 6.	6.– 9.	9.– 12.	12.– 15.	15.– 18.	18.– 21.	21.– 24.	24.– 27.	27.– 30.	30.– 33.	33.– 36.
0.–4.	Samples				1	7	8	7	10	11	15	20	1
	Occurrences				1	3	6	7	8	8	14	6	1
	Avg. Catch a/				36	15	132	2536	545	85	1390	1471	0
4.–8.	Samples				1		1	5	6	9	5	5	
	Occurrences				1		1	4	6	6	4	3	
	Avg. Catch				518		2535	2493	5549	1584	3881	1744	
8.–12.	Samples					3	2	4	5	6	5	7	
	Occurrences					3	2	4	5	6	4	6	
	Avg. Catch					2027	985	1927	8624	2010	3575	997	
12.–16.	Samples				5	1	7	3	5	7	2	1	1
	Occurrences				5	1	7	3	5	6	2	1	1
	Avg. Catch				4401	6000	2701	942	4491	2556	14314	532	3360
16.–20.	Samples			1		6	10	5	6	2	6	2	
	Occurrences			1		5	10	5	6	2	6	1	
	Avg. Catch			738		3344	2753	663	3544	2019	6456	673	
20.–24.	Samples				2	2	12	10	19	3	8	2	
	Occurrences				2	2	11	9	19	3	8	0	
	Avg. Catch				288	6266	3843	6891	12832	19426	7330	0	
24.–28.	Samples						1				2	1	
	Occurrences						1				2	0	
	Avg. Catch						659				387	0	

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a/ Average catch is expressed in individuals/m^3.

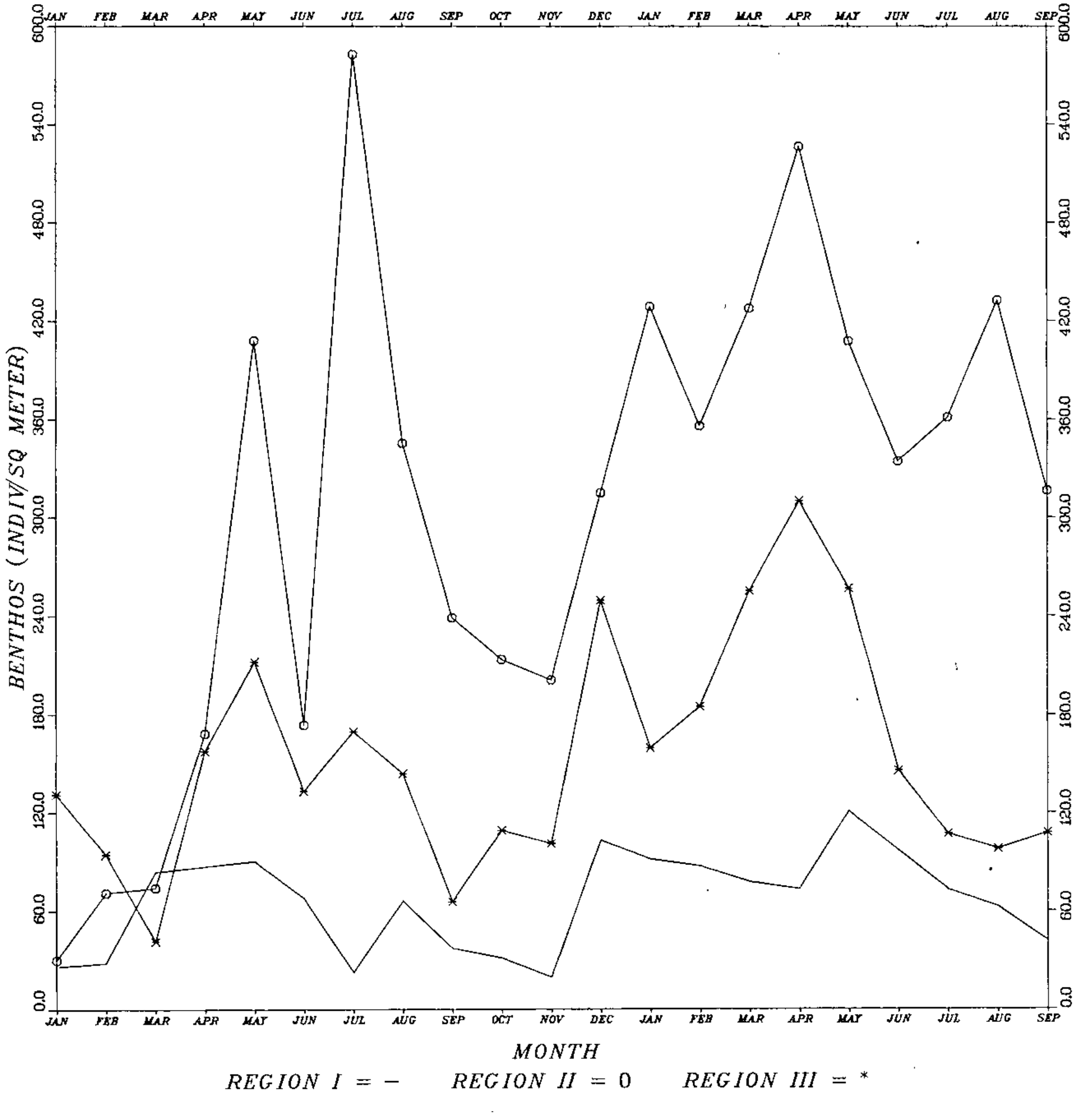

Figure 7-11. Mean Monthly Benthos Densities in Lavaca Bay, January 1973-September 1974.

Table 7-8. Mean Percentage Representation by Biomass of Benthic Organisms in the Lavaca Bay System (January 1973 - June 1975)

Group	Region I a/	Region II	Region III
		(percent)	
Molluscan bivalves	49.6	30.5	21.1
Molluscan gastropods	8.4	46.1	0.2
Annelids (polychaetes and oligochaetes	28.6	22.1	70.8
Arthropod crustaceans	4.6	0.3	4.6
Nemertines	1.2	0.7	3.0
Insect larvae	7.4	0.2	0.1
Others	0.2	0.1	0.2
Total Benthic Biomass	100.0	100.0	100.0

a/ See Figures 7-2 and 7-3 for location of Regions I, II, and III.

Table 7-9. Percent Composition by Biomass of Dominant Benthic Species in the Lavaca Bay System (January 1973 - June 1975)

Region a/	Species	Percent Composition b/
Region I	*Rangia cuneata*	23.7
	Tellina tampaensis	23.4
	Hypaniola gunneri	14.7
	Chironomid larvae	7.4
	Mediomastus californiensis	6.6
	Littoridina sphinctostoma	5.6
		81.4
Region II	*Littoridina sphinctostoma*	46.0
	Rangia cuneata	20.7
	Mediomastus californiensis	12.2
	Mulina lateralis	7.6
	Streblospio benedicti	4.4
	Macoma mitchelli	1.7
		92.6
Region III	*Mediomastus californiensis*	40.0
	Mulina lateralis	17.6
	Streblospio benedicti	14.5
	Cossura delta	5.8
	Prionspio pinnata	3.6
	Amphipod A	2.4
		83.9
All Regions	*Littoridina sphinctostoma*	25.0
	Mediomastus californiensis	22.7
	Rangia cuneata	12.7
	Mulina lateralis	11.1
	Streblospio benedicti	8.3
	Cossura delta	2.3
		82.1

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a/ See Figures 7-2 and 7-3 for locations of Regions I, II, and III.
b/ Total Benthic Biomass = 100 percent.

highest numbers in the upper, low-salinity regions, while species such as Mediomastus californiensis and Streblospio benedicti seemed to prefer the higher salinity waters of the lower bay. Although the lowest number of species were taken from Regions I and II (Figures 7-2 and 7-3), these lower salinity areas clearly had the largest benthic biomass.

Three samples sites (90-3, 115-3, and 190-4) in Lavaca Bay were located in dredged or dredge influenced areas. Standing crops and species diversities at these locations were generally lower than nearby non-dredged sites.

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 (63).

Benthos diversity generally decreases with distance moved upstream in an estuary. From a minimum, at a salinity of 5.0 ppt, species numbers increase seaward to a maximum at about 35 ppt, the normal salinity of sea water, and decline once more with increasing salinity. Taxa diversity in Lavaca Bay declined from the high salinity lower bay to the low salinity upper bay and riverine areas (244). Diversities were highest during the winter and early spring when sustained freshwater inflows were low. Although low inflows were generally associated with high salinity, low turbidity, and low nutrient concentrations, Gilmore et al. (244) found no statistical correlation between benthic populations and freshwater inflows. Benthic standing crops were generally variable from month to month at all stations.

In contrast, Harper, (208) in studying the distribution of benthic organisms in undredged control areas of San Antonio Bay, found an almost logarithmic decrease in benthic populations with increasing salinity. Increases in benthic populations, associated with decreased salinity, are attributed to increased inflow 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.

Summary

The community composition, distribution, density, and seasonality of the phytoplankton, zooplankton, and benthic invertebrates of the Lavaca-Tres Palacios estuary have been used by the Texas Parks and Wildlife Department (244) as "indicators" of primary and secondary productivity. The estuarine communities identified are typical in that they are composed of freshwater, marine, and a mixture of endemic species (i.e., species restricted to the estuarine zone).

A total of 156 phytoplankton taxa representing seven divisions were identified. Phytoplankton taxa diversities were generally related to freshwater inflows. Minimum densities occurred when river inflow was greater than 2,000 ft^3/sec (56 m^3/sec), while maximum standing crops were associated with blooms of microflagellates and diatoms as the bay salinity began to stabilize after high inflows.

A total of 201 zooplankton taxa representing 14 phyla were identified. Over 80 percent of the total zooplankton standing crop was composed of populations of barnacle nauplii, *Acartia tonsa*, and *Oithona* spp. Salinity and water temperature were the two most important factors regulating the species composition. No significant statistical correlations were found between zooplankton standing crops or taxa diversity and freshwater inflow.

A total of 169 benthos taxa representing nine phyla were identified. Diversities were generally greater in the lower bay where high salinities prevailed. Standing crops were not significantly correlated to freshwater inflow.

CHAPTER VIII

FISHERIES

Introduction

During the five year period, 1972 through 1976, commercial Texas landings of finfish and shellfish averaged 97.3 million pounds (44.2 million kg) annually (351-355). 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 the 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.

Virtually all (97.5 percent) of the coastal fisheries species are considered estuarine-dependent (77). The Lavaca-Tres Palacios estuary is the second largest estuarine ecosystem on the Texas coast and ranks second overall of eight Texas estuarine areas for inshore commercial harvest of seafood organisms.

Since most of an estuary's fisheries production is taken offshore in collective association with the production from other regional estuaries, the inshore bay harvests may be useful as a relative indicator of the estuary's fisheries contribution. With reference to the commercial Texas bay landings during the 1972 through 1976 period, bays of the Lavaca-Tres Palacios estuary contributed an average 4.6 percent of finfish landings and 17.7 percent of shellfish landings. By comparison the largest Texas estuary, the Trinity-San Jacinto estuary, contributed an average 11.0 percent of finfish and 45.4 percent of shellfish bay landings during the same period (222).

Based on the five year inshore-offshore commercial landings distribution, the average contribution of the Lavaca-Tres Palacios estuary to total Texas commercial landings is estimated at 338,900 pounds (153,700 kg) of finfish and 15,892,900 pounds (7.2 million kg) of shellfish annually. In addition, the commercial fish harvest has been estimated to account for only about 15.4 percent of the total fish harvest in the estuary, with the remainder (84.6 percent) going to the sport or recreational catch (347). An additional 1,861,700 pounds (844,500 kg) of sport harvest can be computed which raises the estimated average annual finfish harvest contribution from the estuary (both inshore and offshore) to 2,200,600 pounds (998,200 kg). The average annual harvest contribution of all fisheries species (finfish and shellfish) from the estuary is therefore estimated at 18.1 million pounds (8.2 million kg).

Previous research has described the general ecology, utilization, and management of the coastal fisheries (304, 250, 154, 152, 72, 186, 182), and has provided information on Texas tidal waters (288, 293, 356, 172) and the relationship of freshwater inflow to estuarine productivity (374). However, a specific analysis of the effects of seasonal freshwater inflow on the fisheries production components of the Lavaca-Tres Palacios estuary has not been previously performed.

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 (116) or the development and application of better technologies such as the use of high resolution, computer interpreted, sonar soundings for estimation of absolute fish abundance (33). 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 (116).

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 (96, 80, 79, 332, 203, 202). 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 fluctuations can provide relative estimates of the fisheries biomass fluctuations occurring from year to year. In Texas, commercial harvest data are available from the <u>Texas Landings</u> publications (357-363, 348-355) which report inshore harvests from the various bays and offshore harvests from the Gulf of Mexico. Since the offshore harvest represents collective fisheries production from the region's estuaries, it is the inshore harvest reported by estuarine area that provides fisheries data related to a particular estuary.

Commercial inshore harvests from bays of the Lavaca-Tres Palacios estuary are tabulated for several important fisheries components (Table 8-1). By using 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 offshore 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 standardized until the early 1960's, and since earlier harvest records are inconsistent, the fisheries analysis utilizes the better 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.

Table 8-1. Commercial Fisheries Harvests in the Lavaca-Tres Palacios Estuary a/, 1962-1976 (357-363, 348-355)

Year	Commercial Fisheries Harvests (thousands of pounds)							
	Shellfish b/	White Shrimp	Brown & Pink Shrimp	Blue Crab	Bay Oyster	Finfish c/	Spotted Seatrout	Red Drum
1962	3,843.7	1,405.1	277.3	2,006.8	154.5	232.0	105.6	60.3
1963	2,635.1	1,601.5	169.3	728.4	135.9	174.0	76.2	41.8
1964	3,001.0	2,435.6	199.0	225.9	140.5	116.4	43.5	22.6
1965	2,889.6	1,290.3	1,074.4	401.3	123.6	209.5	80.0	50.7
1966	2,928.9	1,643.0	319.4	477.2	489.3	554.9	274.7	106.8
1967	1,930.0	1,056.0	210.8	360.8	302.4	322.7	138.4	69.0
1968	3,668.5	2,364.5	82.1	933.3	288.6	533.1	267.9	121.2
1969	2,536.2	1,319.1	108.7	891.0	217.4	410.3	168.6	109.0
1970	3,259.0	1,823.0	174.5	782.0	479.5	446.9	173.8	128.7
1971	1,976.1	1,070.0	217.2	394.3	294.6	280.8	140.5	65.5
1972	2,629.3	1,294.3	238.1	882.0	214.9	298.8	123.0	76.9
1973	5,013.3	2,934.2	875.8	1,129.6	73.7	284.4	133.4	70.5
1974	3,044.9	1,418.7	469.8	959.3	197.1	226.9	130.1	52.5
1975	2,978.5	920.5	785.6	897.7	374.7	236.4	94.8	72.1
1976	3,180.5	1,313.5	934.0	651.7	281.2	172.2	65.3	47.9
Mean	3,034.3	1,592.6	409.1	781.4	251.2	300.0	134.4	73.0
±S.E. d/	± 195.1	± 147.6	±86.4	±111.4	±32.3	±34.0	±17.2	±7.9

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a/ Estuary ranks second in shellfish and fifth in finfish commercial harvests of eight Texas estuarine areas

b/ Includes blue crab, bay oyster, and white, brown, and pink shrimp

c/ Includes croaker, black drum, red drum, flounder, sea catfish, spotted seatrout, and sheepshead

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

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), flounder (*Paralichthys* spp.; mostly *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* Linnaeus), and brown and pink shrimp (*Penaeus aztecus* Ives and *P. duorarum* Burkenroad; mostly P. *aztecus*). Other fisheries components are 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 analytical categories: (1) freshwater inflow at Lavaca delta (FINLD) contributed to the estuary (Table 8-2), (2) freshwater inflow at Colorado delta (FINCD) contributed to the estuary (Table 8-3), and (3) combined freshwater inflow (FINC) from all river and coastal drainage basins contributed to the estuary (Table 8-4). 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 Lavaca-Tres Palacios estuary fisheries components was performed utilizing the University of California biomedical (BMD) computer program for the stepwise multiple regression procedure (13). 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:

$$H_t = a_0 + a_1 Q_{1,t-b_1} + a_2 Q_{2,t-b_2} + a_3 Q_{3,t-b_3} + a_4 Q_{4,t-b_4} + a_5 Q_{5,t-b_5} + e$$

Table 8-2. Seasonal Freshwater Inflow Volumes at Lavaca Delta Contributed to Lavaca-Tres Palacios Estuary, 1959-1976

	Seasonal Freshwater Inflow (thousands of acre-feet)				
Year	Winter (Jan.-March)	Spring (April-June)	Summer (July-Aug.)	Autumn (Sept.-Oct.)	Late Fall (Nov.-Dec.)
1959	300.9	378.0	52.0	179.0	119.0
1960	116.1	501.9	202.0	470.0	342.0
1961	474.9	321.0	145.0	519.0[a]	160.0
1962	30.9	135.9	22.0	30.0	15.0
1963	59.1	11.1	29.0	5.0[b]	21.0
1964	53.3	66.0	16.0	70.0	5.0
1965	188.1	351.9	19.0	30.0	192.0
1966	141.9	360.9	51.0	18.0	3.0
1967	6.9	21.9	33.0	552.0[c]	12.0
1968	297.0	848.1	66.0	45.0	53.0
1969	351.0	534.0	14.0	44.0	61.0
1970	185.1	378.0	26.0[d]	261.0	8.0
1971	9.9	17.1	89.0	371.0[e]	107.0
1972	174.9	584.1	48.0	24.0	14.0
1973	233.1	1,476.9	89.0	479.0[f]	57.0
1974	237.9	303.9	41.0	368.0	207.0
1975	62.1	540.0	90.0	37.0	55.0
1976	15.0	237.0	56.0	111.0	423.0
Mean	163.3	392.7	60.4	200.7	103.0
± S.E.[g]	±31.5	±83.0	±11.5	±47.8	±28.6

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[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 8-3. Seasonal Freshwater Inflow Volumes at Colorado Delta Contributed to Lavaca-Tres Palacios 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	270.0	455.1	160.0	481.0	416.0
1960	528.9	627.9	209.0	239.0	402.0
1961	665.1	509.1	403.0	419.0a/	340.0
1962	207.9	111.0	51.0	87.0	103.0
1963	152.1	75.9	57.0	46.0b/	38.0
1964	87.0	69.9	34.0	87.0	67.0
1965	297.9	489.0	84.0	81.0	313.0
1966	245.1	404.1	59.0	49.0	61.0
1967	54.0	81.9	42.0	157.0c/	98.0
1968	762.0	1,008.9	185.0	124.0	138.0
1969	341.1	431.1	45.0	97.0	273.0
1970	537.9	641.1	146.0d/	211.0	63.0
1971	71.1	81.9	64.0	185.0e/	346.0
1972	195.9	234.9	71.0	68.0	73.0
1973	339.9	567.9	117.0	424.0f/	230.0
1974	384.0	189.0	86.0	455.0	650.0
1975	578.1	885.0	251.0	89.0	97.0
1976	92.1	408.0	237.0	174.0	380.0
Mean	322.8	404.0	127.8	192.9	227.0
± S.E.g/	±50.5	±66.2	±23.1	±35.1	±40.5

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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 Volumes of Combined Freshwater Inflow a/ Contributed to Lavaca-Tres Palacios Estuary, 1959-1976

	Seasonal Freshwater Inflow (thousands of acre-feet)				
Year	Winter (Jan.-March)	Spring (April-June)	Summer (July-Aug.)	Autumn (Sept.-Oct.)	Late Fall (Nov.-Dec.)
1959	942.9	948.9	440.0	1,153.0	580.0
1960	765.9	2,096.1	604.0	1,164.0	1,354.0
1961	1,508.1	1,128.0	878.0	1,603.0b/	593.0
1962	243.0	348.9	110.0	156.0	136.0
1963	215.1	110.1	134.0	84.0c/	78.0
1964	243.9	195.0	123.0	368.0	127.0
1965	584.1	911.1	144.0	158.0	653.0
1966	692.1	1,320.9	248.0	117.0	64.0
1967	68.1	123.9	145.0	1,723.0d/	123.0
1968	1,311.0	3,105.0	371.0	231.0	199.0
1969	864.9	1,443.0	100.0	254.0	443.0
1970	1,025.1	1,667.1	224.0e/	936.0	72.0
1971	81.9	110.1	216.0	1,295.0f/	646.0
1972	483.9	1,386.0	224.0	373.0	191.0
1973	669.0	2,828.1	270.0	1,953.0g/	308.0
1974	696.9	1,155.9	200.0	994.0	1,143.0
1975	672.9	1,683.9	409.0	207.0	270.0
1976	111.0	734.1	615.0	376.0	1,208.0
Mean	621.1	1,183.1	303.1	730.3	454.9
± S.E.h/	±98.2	±208.3	±50.4	±147.1	±97.5

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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

where a_0 is the intercept harvest value, $a_1 \ldots a_5$ are partial regression coefficients, e is the normally distributed error term with a mean of zero, and the regression variables are:

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

$Q_{1,t-b_1}$ = 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 8-5),

$Q_{2,t-b_2}$ = 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 8-5),

$Q_{3,t-b_3}$ = 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 8-5),

$Q_{4,t-b_4}$ = 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 8-5),

$Q_{5,t-b_5}$ = 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 8-5).

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 data variates to linearity. Natural log (ln) transformation of both dependent and independent variables improves the linear fit of the curves and the double log transformed regression equation is rewritten as follows:

$$\ln H_t = a_0 + a_1 (\ln Q_{1,t-b_1}) + \ldots + a_5 (\ln Q_{5,t-b_5}) + e$$

where the variables are the same as defined above.

In practice, the time series for the dependent variable (H) is the aforementioned inclusive period 1962 through 1976, giving 15 annual harvest observations for the regression analysis. The independent variables ($Q_1 \ldots Q_5$) also result in 15 observations each; however, the time series is not necessarily concomitant with that of harvest and varies because of consideration of species life history aspects involved in the analysis of each fisheries component. Thus, the data alignment between dependent/independent variates in the fisheries analysis is appropriately chosen to take into account the

Table 8-5. Time Series Alignments of Dependent/Independent Data Variates for Fisheries Regression Analysis

H_t Fisheries Component	$Q_{1,t-b_1}$ (Jan.-March)	$Q_{2,t-b_2}$ (April-June)	$Q_{3,t-b_3}$ (July-Aug.)	$Q_{4,t-b_4}$ (Sept.-Oct.)	$Q_{5,t-b_5}$ (Nov.-Dec.)
Shellfish a/ All Penaeid Shrimp White, Brown & Pink Shrimp	inflow same year as harvest	inflow same year as harvest	inflow same year as harvest	inflow same year as harvest	inflow 1-year antecedent to harvest
(1962-1976)	(1962-1976)	(1962-1976)	(1962-1976)	(1962-1976)	(1961-1975)
Blue Crab Bay Oyster	inflow 1-year antecedent to harvest	inflow 1-year antecedent to harvest	inflow 1-year antecedent to harvest	inflow 1-year antecedent to harvest	inflow 1-year antecedent to harvest
(1962-1976)	(1961-1975)	(1961-1975)	(1961-1975)	(1961-1975)	(1961-1975)
Finfish b/ Spotted Seatrout Red Drum	running average inflow from 3 antecedent years before harvest	running average inflow from 3 antecedent years before harvest	running average inflow from 3 antecedent years before harvest	running average inflow from 3 antecedent years before harvest	running average inflow from 3 antecedent years before harvest
(1962-1976)	(1959-1975)	(1959-1975)	(1959-1975)	(1959-1975)	(1959-1975)

a/ includes blue crab, bay oyster, and white, brown, and pink shrimp
b/ includes croaker, black drum, red drum, flounder, sea catfish, spotted seatrout, and sheepshead

probable lagged effect, in time, of freshwater inflow upon production and subsequent harvest of a particular fisheries component (Table 8-5). This is a standard procedure since it has been long recognized that environmental factors affecting growth and survivial 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 (68, 149). Early articulation of this idea was put forth by the Norwegian fishery scientist Johan Hjort in 1914 (99) 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 (180). 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 (68, 179). 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 results in two significant equations (Table 8-6). Statistical information given for each regression equation 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, inshore 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 equations.

The best significant equation (first equation of Table 8-6) accounts for 68 percent of the observed variation in inshore harvest and is highly significant (α = 0.5%) for correlation of shellfish inshore harvests to winter (Q_1), spring (Q_2), and summer (Q_3) seasonal freshwater inflows at Lavaca delta (FINLD). 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 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 individual seasonal inflow effects on the estimate of inshore commercial shellfish harvest (Figure 8-1). For example, Panel A of Figure 8-1 shows that the annual harvest is estimated to decrease from about 3.5 million pounds to 2.2 million pounds as mean monthly inflow at Lavaca delta during the January-March (Q_1) seasonal interval increases from its observed lower bounds of 2.3 thousand acre-feet per month to its observed upper bounds of 117.0 thousand acre-feet per month. Thus, the negative sign on the regression coefficient (a_1) for the correlat-

Table 8-6. Equations of Statistical Significance Relating the Shellfish Fisheries Component to Freshwater Inflow Categories a/

Shellfish Harvest = f (Seasonal FINLD b/)
Highly Significant Equation ($\alpha = 0.5\%$; $r^2 = 68\%$; S.E. Est. = ± 482.8)

$$H_{sf} = 3107.9 - \underset{(5.7)}{11.3}\,Q_1 + \underset{(1.8)}{7.7}\,Q_2 - \underset{(13.5)}{24.2}\,Q_3$$

	H_{sf}	Q_1	Q_2	Q_3
upper bounds	5013.3	117.0	492.3	45.0
lower bounds	1930.0	2.3	3.7	7.0
mean	3034.3	45.5	130.4	23.0

Shellfish Harvest = f (Seasonal FINCD c/)
(no significant equation)

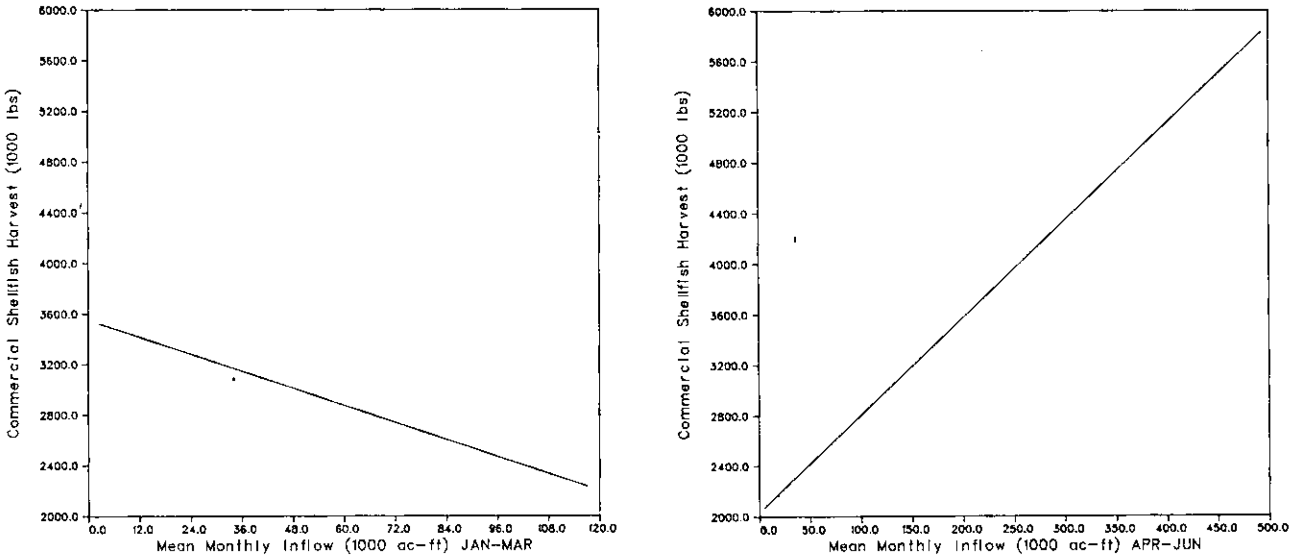
Shellfish Harvest = f (Seasonal FINC d/)
Significant Equation ($\alpha = 2.5\%$; $r^2 = 50\%$; S.E. Est. = ± 575.8)

$$H_{sf} = 2614.9 - \underset{(2.4)}{3.5}\,Q_1 + \underset{(0.9)}{2.7}\,Q_2$$

	H_{sf}	Q_1	Q_2
upper bounds	5013.3	437.0	1035.0
lower bounds	1930.0	22.7	36.7
mean	3034.3	177.0	380.5

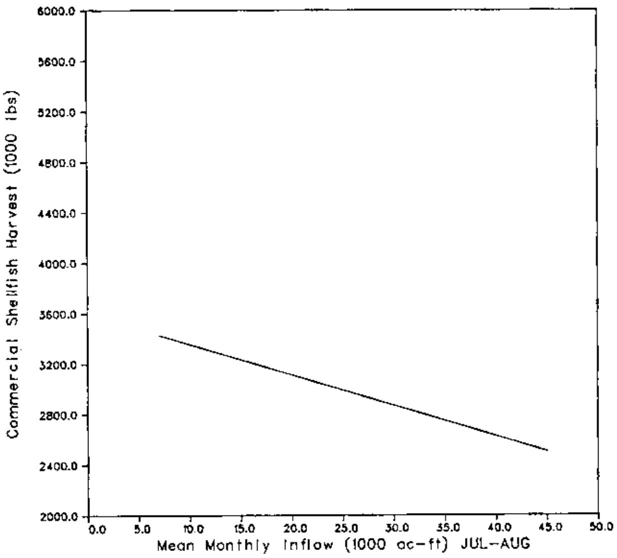
where: H_{sf} = commercial inshore harvest of shellfish in Lavaca-Tres Palacios Estuary, in thousands of pounds;
Q = mean monthly freshwater inflow, in thousands of acre-feet:
Q_1 = January-March
Q_2 = April-June
Q_3 = July-August
Q_4 = September-October
Q_5 = November-December

a/ Standard error of each regression coefficient is shown in parentheses beneath the coefficients of the regression equations
b/ FINLD = freshwater inflow at Lavaca Delta
c/ FINCD = freshwater inflow at Colorado Delta
d/ FINC = combined inflow to estuary from all contributing river and coastal drainage basins



A. regression coefficient (slope) = -11.3, standard error = ±5.7

B. regression coefficient (slope) = +7.7, standard error = ±1.8



C. regression coefficient (slope) = -24.2, standard error = ±13.5

Figure 8-1. Inshore Commercial Shellfish Harvest as a Function of Each Seasonal Inflow at Lavaca Delta, where all other Seasonal Inflows in the Multiple Regression Equation are held Constant at their Mean Values ing Q_1 inflow term in the best significant equation (Table 8-6) is illustrated as a line of negative slope relating increasing winter season inflow at Lavaca delta to a decreasing estimate of annual shellfish harvest (Panel A, Figure 8-1). It is noted that this line can be shifted upward or downward in a parallel manner from that which has been graphed by holding the other correlating seasonal inflows (i.e., Q_2 and Q_3) in the best significant equation at specified levels of interest other than their mean values. For instance, if the positively correlating April-June (Q_2) inflow is specified at some level higher than its mean while the July-August (Q_3) inflow continues to be held at its mean, then the estimated harvest response to January-March (Q_1) inflow would be similar and have the identical negative slope; however, the computed line would be shifted upward and parallel to that graphed in Panel A. Analogous circumstances exist for each of the harvest responses graphed in Figure 8-1, but to facilitate comparisons only the seasonal inflow of interest in each panel is varied while all others in the best significant equation are held constant at their respective mean values.

Panel B (Figure 8-1) exhibits the positive response of shellfish harvest to spring season freshwater inflow at Lavaca delta. The estimate of harvest increases about 2.8 times (2.1 to 5.8 million pounds annually) as the July-August (Q_2) inflow increases from its observed lower bounds of 3.7 thousand acre-feet per month to its observed upper bounds of 492.3 thousand acre-feet per month.

Similar to Panel A, Panel C (Figure 8-1) also displays a negative harvest response to summer inflow at Lavaca delta. The estimate of annual harvest decreases from 3.4 to 2.5 million pounds as July-August (Q_3) inflow increases over the observed range of 7.0 to 45.0 thousand acre-feet per month.

Considered together, Panels A, B and C in Figure 8-1 illustrate a strong positive statistical response of inshore commercial shellfish harvest to spring season (Q_2) inflow and weaker negative statistical responses to winter (Q_1) and summer (Q_3) inflow over the observed ranges of these seasonal inflows at Lavaca delta (FINLD). Based on the statistical regression model described by the best significant equation, maximization of shellfish harvest can be achieved by diminishing winter and summer inflow, and increasing spring season inflow at Lavaca delta.

All Penaeid Shrimp

Analysis of the fisheries component for all penaeid shrimp (i.e., white, brown, and pink shrimp) yields a significant equation for each of the three freshwater inflow categories (Table 8-7). The best significant equation (first equation of Table 8-7) explains 75 percent of the observed variation in harvest and is highly significant (α = 0.5%) for correlation of inshore penaeid shrimp harvests to winter (Q_1), spring (Q_2), summer (Q_3), and late fall (Q_5) seasonal freshwater inflows at Lavaca delta (FINLD).

The effect of each of the correlating seasonal inflows in the best significant equation is illustrated by using the previously discussed procedure of holding all other correlating inflows in the equation constant at their respective mean values while varying the seasonal inflow of interest over its observed range and computing the estimated harvest response (Figure 8-2). The

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

All Shrimp Harvest = f (Seasonal FINLD b/)
Highly Significant Equation ($\alpha = 0.5\%$; $r^2 = 75\%$; S.E. Est. = ± 374.2)

$$H_{as} = 1874.0 - \underset{(4.4)}{7.5\ Q_1} + \underset{(1.4)}{5.8\ Q_2} - \underset{(10.5)}{10.0\ Q_3} - \underset{(2.9)}{4.0\ Q_5}$$

	H_{as}	Q_1	Q_2	Q_3	Q_5
upper bounds	3810.0	117.0	492.3	45.0	103.5
lower bounds	1266.8	2.3	3.7	7.0	1.5
mean	1935.1	45.5	130.4	23.0	32.2

All Shrimp Harvest = f (Seasonal FINCD c/)
Significant Equation ($\alpha = 5.0\%$; $r^2 = 62\%$; S.E. Est. = ± 459.9)

$$H_{as} = 1358.1 - \underset{(4.3)}{8.4\ Q_1} + \underset{(3.8)}{9.9\ Q_2} - \underset{(5.9)}{7.3\ Q_3} + \underset{(2.1)}{6.5\ Q_4}$$

	H_{as}	Q_1	Q_2	Q_3	Q_4
upper bounds	3810.0	254.0	336.3	125.5	227.5
lower bounds	1266.8	18.0	23.3	17.0	23.0
mean	1935.1	96.6	126.2	51.0	77.8

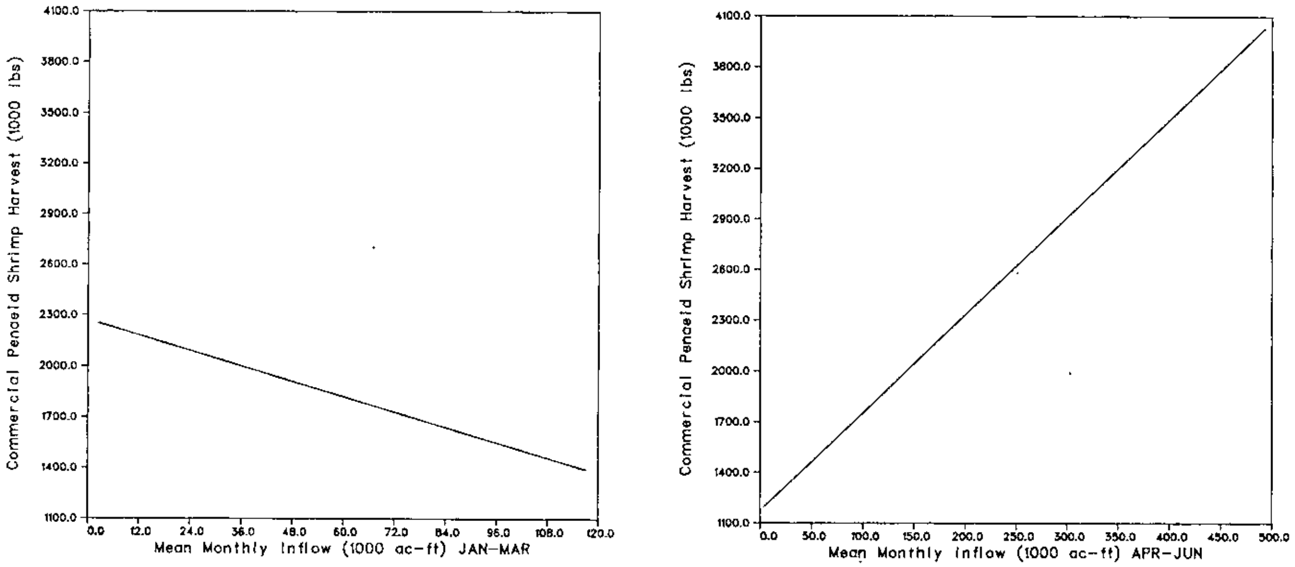
All Shrimp Harvest = f (Seasonal FINC d/)
Highly Significant Equation ($\alpha = 1.0\%$; $r^2 = 67\%$; S.E.Est. = ± 412.0)

$$H_{as}\ 1735.8 - \underset{(1.7)}{3.7\ Q_1} + \underset{(0.7)}{2.7\ Q_2} - \underset{(0.7)}{1.0\ Q_5}$$

	H_{as}	Q_1	Q_2	Q_5
upper bounds	3810.0	437.0	1035.0	571.5
lower bounds	1266.8	22.7	36.7	32.0
mean	1935.1	177.0	380.5	168.2

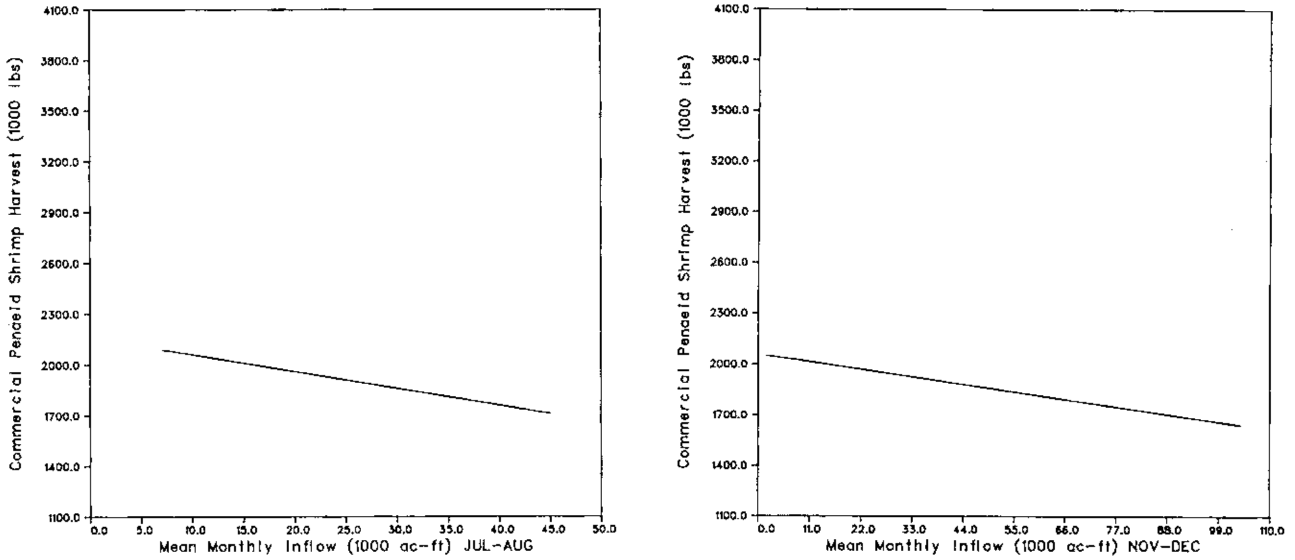
where: H_{as} = commercial inshore harvest of all penaeid shrimp species in Lavaca-Tres Palacios Estuary, in thousands of pounds;
Q = mean monthly freshwater inflow, in thousands of acre-feet:
Q_1 = January-March
Q_2 = April-June
Q_3 = July-August
Q_4 = September-October
Q_5 = November-December

a/ Standard error of each regression coefficient is shown in parentheses beneath the coefficients of the regression equations
b/ FINLD = freshwater inflow at Lavaca Delta
c/ FINCD = freshwater inflow at Colorado Delta
d/ FINC = combined inflow to estuary from all contributing river and coastal drainage basins



A. regression coefficient (slope) = −7.5, standard error = ±4.4

B. regression coefficient (slope) = +5.8, standard error = ±1.4



C. regression coefficient (slope) = −10.0,
standard error = ±10.5

D. regression coefficient (slope) = −4.0,
standard error = ±2.9

Figure 8-2. Inshore Commercial Penaeid Shrimp Harvest as a Function of Each Seasonal Inflow at Lavaca Delta, where all Other Seasonal Inflows in the Multiple Regression Equation are held Constant at their Mean Values estimate of harvest decreases from about 2.3 to 1.4 million pounds annually as January-March (Q_1) inflow increases from the observed lower bounds of 2.3 thousand acre-feet per month to the observed upper bounds of 117.0 thousand per month (Panel A, Figure 8-2). Thus, the penaeid shrimp fisheries component is also shown to have a negative relationship with winter season inflow. A strong positive shrimp response to spring inflow results in the estimate of harvest increasing about 3.3 times (1.2 to 4.0 million pounds annually) as April-June (Q_2) inflow increases over the observed range of 3.7 to 492.3 thousand acre-feet per month (Panel B, Figure 8-2). The estimate of harvest decreases from 2.1 to 1.7 million pounds annually as July-August (Q_3) inflow increases from 7.0 to 45.0 thousand acre-feet per month (Panel C, Figure 8-2), indicating a slight negative relationship of harvest to summer inflow. There is a similar negative response to late fall inflow (Panel D, Figure 8-2), with the estimate of harvest decreasing from 2.1 to 1.6 million pounds annually as November-December (Q_5) inflow increases from 1.5 to 103.5 thousand acre-feet per month. Maximization of shrimp harvest is therefore statistically related to increasing spring season inflow (Q_2) while diminishing winter (Q_1), summer (Q_3), and late fall (Q_5) inflows at Lavaca delta.

White Shrimp

Analysis of the white shrimp component results in two significant equations. The best equation (second equation, Table 8-8) is significant ($\alpha = 2.5\%$) for correlation of inshore white shrimp harvests to spring (Q_2) and late fall (Q_5) seasonal freshwater inflows from all contributing river and coastal drainage basins (FINC), but explains only 48 percent of the observed harvest variation.

The estimated harvest response to each of the correlating seasonal inflows is illustrated in Figure 8-3. The results support information from analysis of the previous fisheries components, with inshore commercial white shrimp harvest increasing as April-June (Q_2) inflow increases (Panel A, Figure 8-3) and decreasing as November-December (Q_5) inflow increases (Panel B, Figure 8-3). Consequently, maximization of white shrimp harvest is statistically related to increasing spring inflow and decreasing late fall inflow.

Brown and Pink Shrimp

No statistically significant equations were obtained from analysis of the brown and pink shrimp fisheries component.

Blue Crab

Analysis of the blue crab component gives three significant equations. Although two of the equations are highly significant ($\alpha = 0.5\%$) and explain 72 percent of the observed harvest variation, the most general equation (third equation, Table 8-9) estimates inshore commercial blue crab harvest as a function of summer (Q_3), autumn (Q_4), and late fall (Q_5) seasonal freshwater inflows from all contributing river and coastal drainage basins (FINC). The effects of increasing each of the correlating seasonal inflows from this combined inflow category are positive (Figure 8-4). In the strongest correlat-

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

White Shrimp Harvest = f (Seasonal FINLD b/)
Significant Equation (α = 2.5%; r^2 = 46%; S.E. Est. = ± 454.0)

$$H_{ws} = 1419.0 + \underset{(0.9)}{2.6}\,Q_2 - \underset{(3.5)}{5.3}\,Q_5$$

	H_{ws}	Q_2	Q_5
upper bounds	2934.2	492.3	103.5
lower bounds	920.5	3.7	1.5
mean	1592.6	130.4	32.3

White Shrimp Harvest = f (seasonal FINCD c/)
(no significant equation)

White Shrimp Harvest = f (Seasonal FINC d/)
Significant Equation (α= 2.5%; r^2 = 48%; S.E.Est. = ± 444.7)

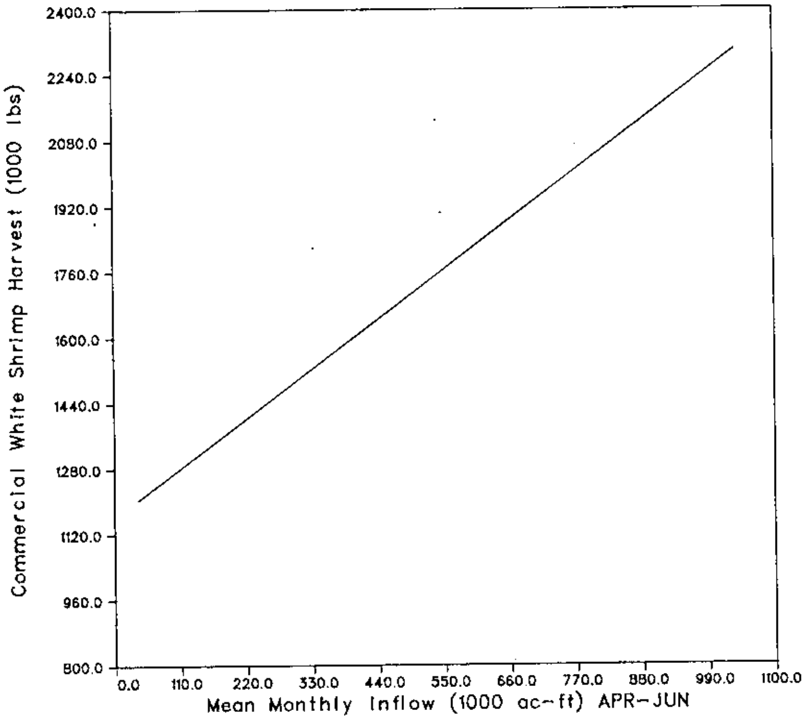
$$H_{ws} = 1447.1 + \underset{(0.4)}{1.1}\,Q_2 - \underset{(0.8)}{1.7}\,Q_5$$

	H_{ws}	Q_2	Q_5
upper bounds	2934.2	1035.0	571.5
lower bounds	920.5	36.7	32.0
mean	1592.6	380.5	168.2

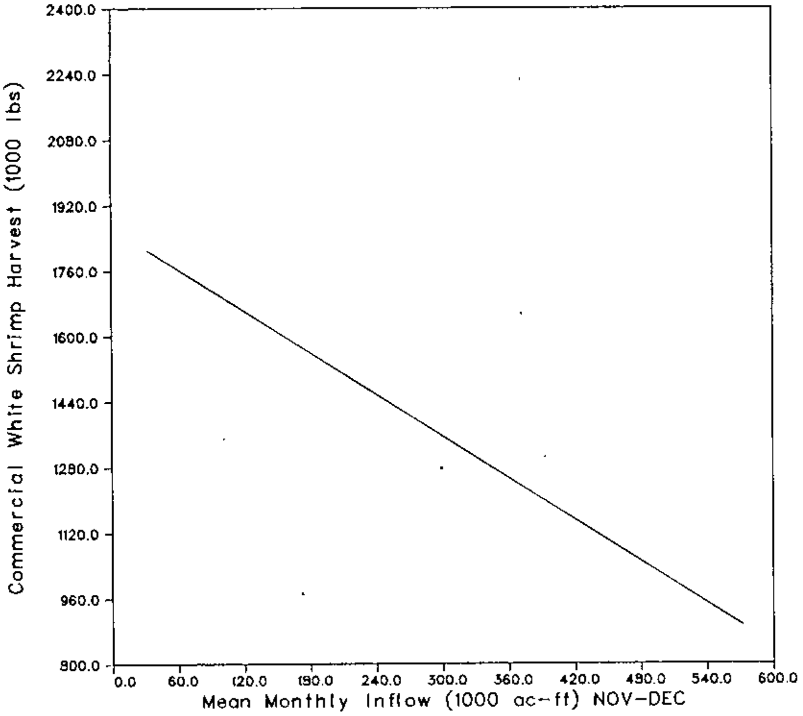
---

where: H_{ws} = commercial inshore harvest of white shrimp in Lavaca-Tres Palacios Estuary, in thousands of pounds;
Q = mean monthly freshwater inflow, in thousands of acre-feet:
Q_1 = January-March
Q_2 = April-June
Q_3 = July-August
Q_4 = September-October
Q_5 = November-December

a/ Standard error of each regression coefficient is shown in parentheses beneath the coefficients of the regression equations
b/ FINLD = freshwater inflow at Lavaca Delta
c/ FINCD = freshwater inflow at Colorado Delta
d/ FINC = combined inflow to estuary from all contributing river and coastal drainage basins



A. regression coefficient (slope) = +1.1, standard error = ±0.4



B. regression coefficient (slope) = -1.7, standard error = ±0.8

Figure 8-3. Inshore Commercial White Shrimp 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 8-9. Equations of Statistical Significance Relating the Blue Crab Fisheries Component to Freshwater Inflow Categories a/

Blue Crab Harvest = f (Seasonal FINLD b/)
Highly Significant Equation ($\alpha = 0.5\%$; $r^2 = 72\%$; S.E. Est. = ± 258.2)

$$H_{bc} = 205.5 + \underset{(1.6)}{3.6\,Q_1} + \underset{(4.6)}{9.9\,Q_3} + \underset{(0.8)}{1.3\,Q_4}$$

	H_{bc}	Q_1	Q_3	Q_4
upper bounds	2006.8	158.3	72.5	276.0
lower bounds	255.9	3.3	7.0	2.5
mean	781.4	55.7	25.9	95.1

Blue Crab Harvest = f (Seasonal FINCD c/)
Significant Equation ($\alpha = 2.5\%$; $r^2 = 62\%$; S.E. Est. = ± 298.1)

$$H_{bc} = 465.4 - \underset{(1.0)}{1.6\,Q_2} + \underset{(2.3)}{6.4\,Q_3} + \underset{(1.3)}{1.8\,Q_4}$$

	H_{bc}	Q_2	Q_3	Q_4
upper bounds	2006.8	336.3	201.5	227.5
lower bounds	255.9	23.3	17.0	23.0
mean	781.4	128.5	56.5	86.0

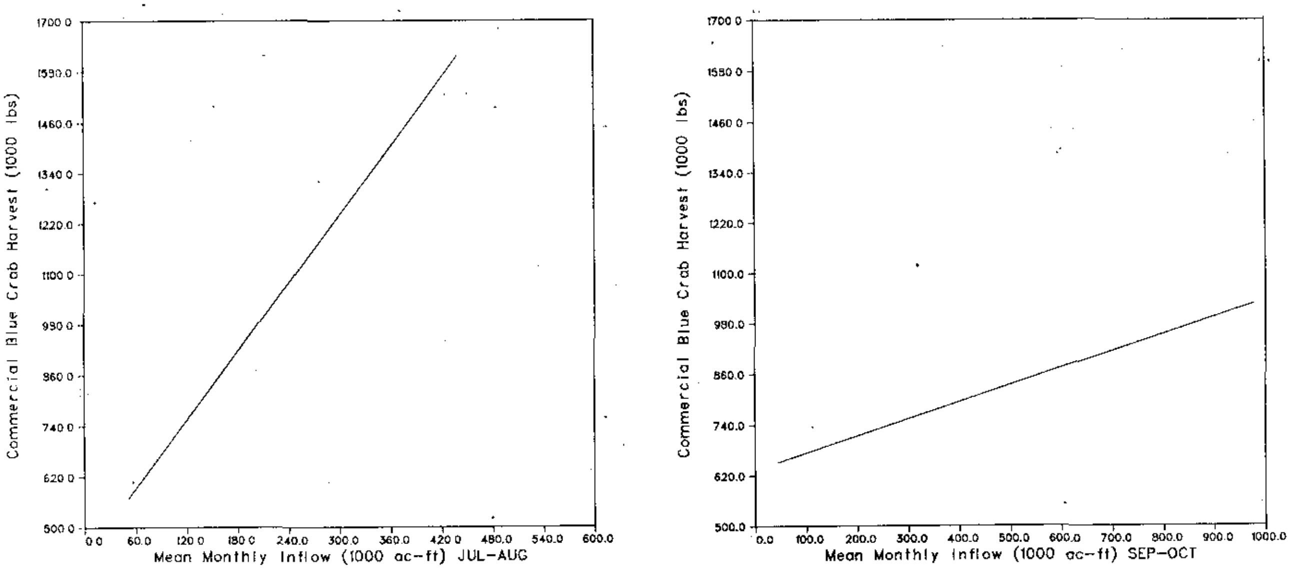
Blue Crab Harvest = f (Seasonal FINC d/)
Highly Significant Equation ($\alpha = 0.5\%$; $r^2 = 72\%$; S.E.Est. = ± 259.5)

$$H_{bc} = 208.3 + \underset{(0.8)}{2.7\,Q_3} + \underset{(0.2)}{0.4\,Q_4} + \underset{(0.5)}{0.5\,Q_5}$$

	H_{bc}	Q_3	Q_4	Q_5
upper bounds	2006.8	439.0	976.5	571.5
lower bounds	255.9	50.0	42.0	32.0
mean	781.4	126.5	348.4	168.2

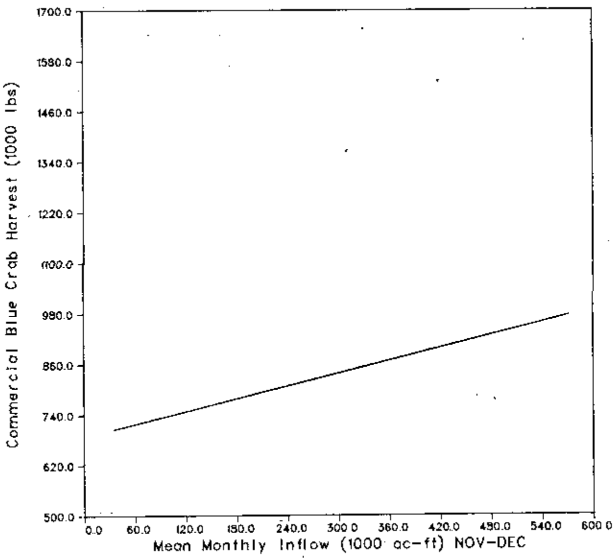
where: H_{bc} = commercial inshore harvest of blue crab in Lavaca-Tres Palacios Estuary, in thousands of pounds;
Q = mean monthly freshwater inflow, in thousands of acre-feet:
Q_1 = January-March
Q_2 = April-June
Q_3 = July-August
Q_4 = September-October
Q_5 = November-December

a/ Standard error of each regression coefficient is shown in parentheses beneath the coefficients of the regression equations
b/ FINLD = freshwater inflow at Lavaca Delta
c/ FINCD = freshwater inflow at Colorado Delta
d/ FINC = combined inflow to estuary from all contributing river and coastal drainage basins



A. regression coefficient (slope) = +2.7, standard error = ±0.8

B. regression coefficient (slope) = +0.4, standard error = ±0.2



C. regression coefficient (slope) = +0.5, standard error = ±0.5

Figure 8-4. 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 ing season (Panel A, Figure 8-4), the estimate of harvest increases approximately 2.9 times its minimum value as July-August (Q_3) inflow increases over its observed range. Increasing September-October (Q_4) and November-December (Q_5) inflows only increases the harvest estimates about 1.6 and 1.4 times their minimum values, respectively. Maximization of blue crab harvest by increasing summer through late fall inflows appears in conflict with maximization of penaeid shrimp harvest which generally shows negative responses to increased inflow in summer and late fall.

Bay Oyster

Analysis of the bay oyster component results in two significant equations (Table 8-10). The best equation (second equation, Table 8-10) explains 51 percent of the observed harvest variation and is significant (α = 5.0%) for correlation of oyster harvests to winter (Q_1), summer (Q_3), and late fall (Q_5) seasonal freshwater inflows from all contributing river and coastal drainage basins (FINC). The effects on harvest of each of the correlating seasonal inflows from this combined inflow category are strongly negative for increasing July-August (Q_3) inflow (Panel B, Figure 8-5), and positive for increasing January-March (Q_1) and November-December (Q_5) inflows (Panels A and C, Figure 8-5). Therefore, maximization of oyster harvest is statistically related to decreased summer inflow and increased late fall and winter inflows.

Finfish

Analysis of the finfish component involves logarithmic transformation of the regression variables to natural logarithms (ln) and results in three significant regression equations (Table 8-11). The best significant equation (second equation, Table 8-11) explains 73 percent of the observed harvest variation and is highly significant (α = 0.5%) for correlation of natural log transformed inshore finfish harvests to natural log transformed winter (Q_1), spring (Q_2), and autumn (Q_4) seasonal freshwater inflows at Colorado delta (FINCD).

The effects of each of the correlating seasonal inflows on the estimate of harvest are computed similar to previous examples by varying a correlating season's inflow over its observed range, while holding all other correlating seasonal inflows in the best significant equation at their respective mean values. However, illustrations of the seasonal effects are graphed in non-transformed units to show the curvilinearity of harvest responses. The estimate of annual harvest decreases from 514.1 thousand pounds to 160.8 thousand pounds as January-March (Q_1) inflow at Colorado delta increases from 49.7 to 182.3 thousand acre-feet (Panel A, Figure 8-6). A strongly positive, near-linear response to spring season inflow again supports this season's importance to estuarine productivity. The estimate of harvest increases about 6.8 times (76.8 to 522.2 thousand pounds annually) as April-June (Q_2) inflow increases from 28.5 to 231.2 thousand acre-feet per month (Panel B, Figure 8-6). A weak, negative curvilinear response to autumn inflow results in the estimate of harvest declining from 389.7 to 183.5 thousand pounds annually as September-October (Q_4) inflow increases from 35.7 to 189.8 thousand acre-feet per month (Panel C, Figure 8-6). Therefore, maximization of inshore commercial finfish harvest is statistically related to increased spring season inflow and

Table 8-10. Equations of Statistical Significance Relating the Bay Oyster Fisheries Component to Freshwater Inflow Categories a/

Bay Oyster Harvest = f (Seasonal FINLD b/)
Significant Equation ($\alpha = 5.0\%$; $r^2 = 44\%$; S.E. Est. = ± 100.9)

$$H_{bo} = 266.7 - \underset{(1.5)}{3.4}\, Q_3 + \underset{(0.8)}{2.2}\, Q_5$$

	H_{bo}	Q_3	Q_5
upper bounds	489.3	72.5	103.5
lower bounds	73.7	7.0	1.5
mean	251.2	25.9	32.3

Bay Oyster Harvest = f (Seasonal FINCD c/)
(no significant equation)

Bay Oyster = f (Seasonal FINC d/)
Significant Equation ($\alpha = 5.0\%$; $r^2 = 51\%$; S.E. Est. = ± 99.2)

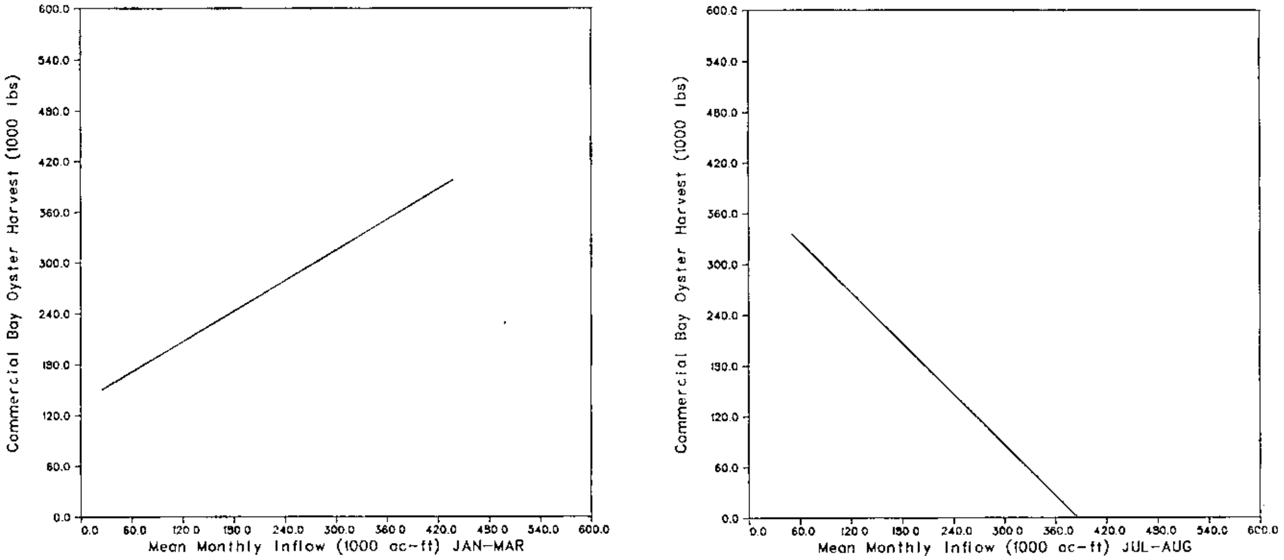
$$H_{bo} = 194.7 + \underset{(0.3)}{0.6}\, Q_1 - \underset{(0.4)}{1.0}\, Q_3 + \underset{(0.2)}{0.4}\, Q_5$$

	H_{bo}	Q_1	Q_3	Q_5
upper bounds	489.3	502.7	439.0	571.5
lower bounds	73.7	22.7	50.0	32.0
mean	251.2	208.0	126.5	168.2

---

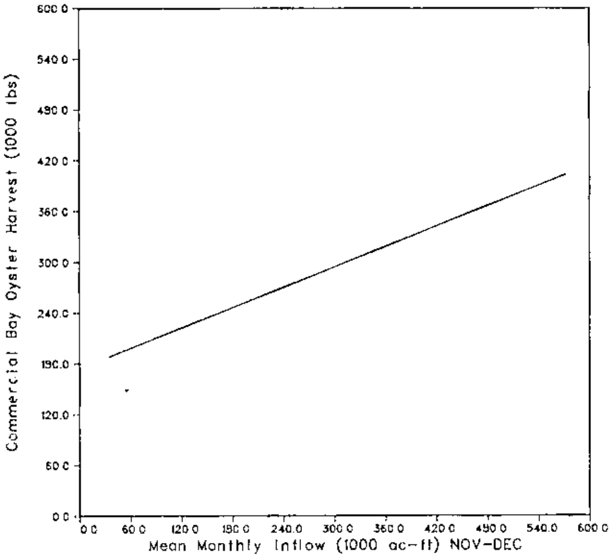
where: H_{bo} = commercial harvest of bay oyster in Lavaca-Tres Palacios Estuary, in thousands of pounds;
Q = mean monthly freshwater inflow, in thousands of acre-feet:
Q_1 = January-March
Q_2 = April-June
Q_3 = July-August
Q_4 = September-October
Q_5 = November-December

a/ Standard error of each regression coefficient is shown in parentheses beneath the coefficients of the regression equations
b/ FINLD = freshwater inflow at Lavaca Delta
c/ FINCD = freshwater inflow at Colorado Delta
d/ FINC = combined inflow to estuary from all contributing river and coastal drainage basins



A. regression coefficient (slope) = +0.6, standard error = ±0.3

B. regression coefficient (slope) = -1.0, standard error= ±0.4



C. regression coefficient (slope) = +0.4, standard error = ±0.2

Figure 8-5. Inshore Commercial Bay Oyster 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 8-11. Equations of Statistical Significance Relating the Finfish Fisheries Component to Freshwater Inflow Categories a/

Finfish Harvest = f (Seasonal FINLD b/)
Significant Natural Log Equation (α = 5.0%; r^2 = 53%; S.E. Est. = ± 0.3395)

$$\ln H_{ff} = 6.8150 - \underset{(0.3697)}{1.1615\ (\ln Q_3)} + \underset{(0.2099)}{0.3928\ (\ln Q_4)} + \underset{(0.1797)}{0.2333\ (\ln Q_5)}$$

	$\ln H_{ff}$	$\ln Q_3$	$\ln Q_4$	$\ln Q_5$
upper bounds	6.3188	4.1972	5.2713	4.6396
lower bounds	4.7570	2.3671	2.8622	1.9218
mean	5.6152	3.2070	4.3985	3.4183

Finfish Harvest = f (Seasonal FINCD c/)
Highly Significant Natural Log Equation (α = 0.5%; r^2 = 73%; S.E. Est. = ± 0.2592)

$$\ln H_{ff} = 7.3470 - \underset{(0.3517)}{0.8936\ (\ln Q_1)} + \underset{(0.2413)}{0.9163\ (\ln Q_2)} - \underset{(0.1644)}{0.4503\ (\ln Q_4)}$$

	$\ln H_{ff}$	$\ln Q_1$	$\ln Q_2$	$\ln Q_4$
upper bounds	6.3188	5.2058	5.4434	5.2461
lower bounds	4.7570	3.9053	3.3511	3.5742
mean	5.6152	4.6073	4.7417	4.3518

Finfish Harvest = f (Seasonal FINC d/)
Highly Significant Natural Log Equation (α = 5.0%; r^2 = 40%; S.E.Est. = ± 0.3657)

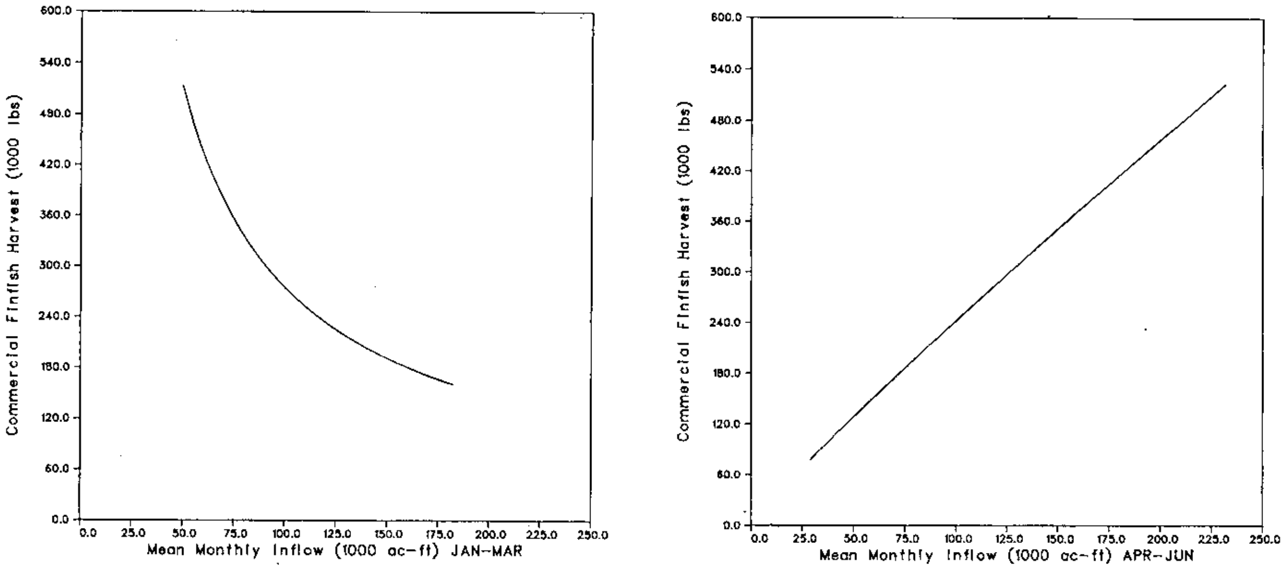
$$\ln H_{ff} = 7.0605 + \underset{(0.3556)}{0.5045\ (\ln Q_1)} - \underset{(0.3165)}{0.8586\ (\ln Q_3)}$$

	$\ln H_{ff}$	$\ln Q_1$	$\ln Q_3$
upper bounds	6.3188	5.8789	5.7694
lower bounds	4.7570	4.3567	4.1136
mean	5.6152	5.2807	4.7861

---

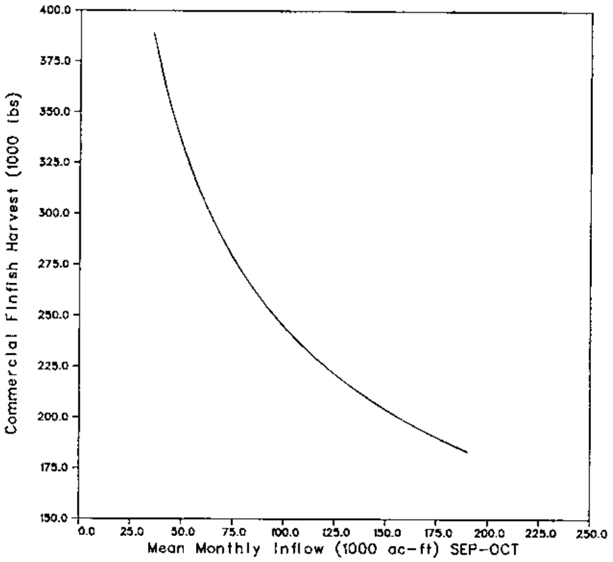
where: $\ln H_{ff}$ = natural log, commercial inshore harvest of finfish in Lavaca-Tres Palacios Estuary, in thousands of pounds;
$\ln Q$ = natural log mean monthly freshwater inflow, in thousands of acre-feet:
Q_1 = January-March
Q_2 = April-June
Q_3 = July-August
Q_4 = September-October
Q_5 = November-December

a/ Standard error of each regression coefficient is shown in parentheses beneath the coefficients of the regression equations
b/ FINLD = freshwater inflow at Lavaca Delta
c/ FINCD = freshwater inflow at Colorado Delta
d/ FINC = combined inflow to estuary from all contributing river and coastal drainage basins



A. regression coefficient = -0.8936, standard error = ±0.3517

B. regression coefficient = +0.9163, standard error = ±0.2413



C. regression coefficient = -0.4503, standard error = ±0.1644

Figure 8-6. Inshore Commercial Finfish Harvest as a Function of Each Seasonal Inflow at Colorado Delta, where all other Seasonal Inflows in the Natural Log Multiple Regression Equation are held Constant at their Mean Values decreased winter and autumn inflows at Colorado delta contributed to the estuary.

Spotted Seatrout

Analysis of the spotted seatrout fisheries component also involves logarithmic transformation of the regression variables and gives a highly significant ($\alpha = 0.5\%$) equation for correlation of the inshore spotted seatrout harvests to winter (Q_1), spring (Q_2), and autumn (Q_4) seasonal freshwater inflows at Colorado delta (FINCD) which explains 73 percent of the observed harvest variation (Table 8-12). The curvilinear effects of each of the correlating seasonal inflows on harvest are strongly negative for increasing January-March (Q_1) inflow (Panel A, Figure 8-7), strongly positive for increasing April-June (Q_2) inflow (Panel B, Figure 8-7), and negative for increasing September-October (Q_4) inflow (Panel C, Figure 8-7). In particular, the estimate of annual harvest increases about 11.1 times (24.2 to 269.6 thousand pounds) as spring season inflow increases over its observed range of 28.5 to 231.2 thousand acre-feet per month. Maximization of inshore commercial spotted seatrout harvest is thus statistically related to increasing spring season inflow while diminishing winter and autumn inflows at Colorado delta.

Red Drum

Analysis of the red drum fisheries component yields three significant equations (Table 8-13) following natural log transformation of the regression variables. The best significant equation (second equation, Table 8-13) explains 65 percent of the observed harvest variation and is highly significant ($\alpha = 0.5\%$) for correlation of inshore red drum harvests to spring (Q_2) and summer (Q_3) seasonal freshwater inflows at Colorado delta (FINCD). The curvilinear effects of each of the correlating seasonal inflows in the best significant equation are positive for increasing April-June (Q_2) inflow (Panel A, Figure 8-8) and negative for increasing July-August (Q_3) inflow (Panel B, Figure 8-8). Therefore, maximization of inshore commercial red drum harvest is statistically related to increased spring season inflow and decreased summer inflow at Colorado delta.

Fisheries Component Summary

The fisheries analysis involves nine fisheries components and three freshwater inflow source categories in the analytical design, allowing a maximum 27 potentially significant equations. The analysis results in 19 regression equations of statistical significance and is therefore successful for 70 percent of the correlations attempted. Although each of the inflow categories can potentially produce nine significant equations, the analysis yields seven equations with freshwater inflow at Lavaca delta (FINLD), five equations with inflow at Colorado delta (FINCD), and seven equations with combined inflow (FINC) to the estuary from all contributing river and coastal drainage basins. 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 8-14). Therefore, the seasonal

Table 8-12. Equations of Statistical Significance Relating the Spotted Seatrout Fisheries Component to Freshwater Inflow Categories a/

Spotted Seatrout Harvest = f (Seasonal FINLD b/)
(no significant equation)

Spotted Seatrout Harvest = f (Seasonal FINCD c/)
Highly Significant Natural Log Equation ($\alpha = 0.5\%$; $r^2 = 73\%$; S.E. Est. = $\pm$ 0.2901)

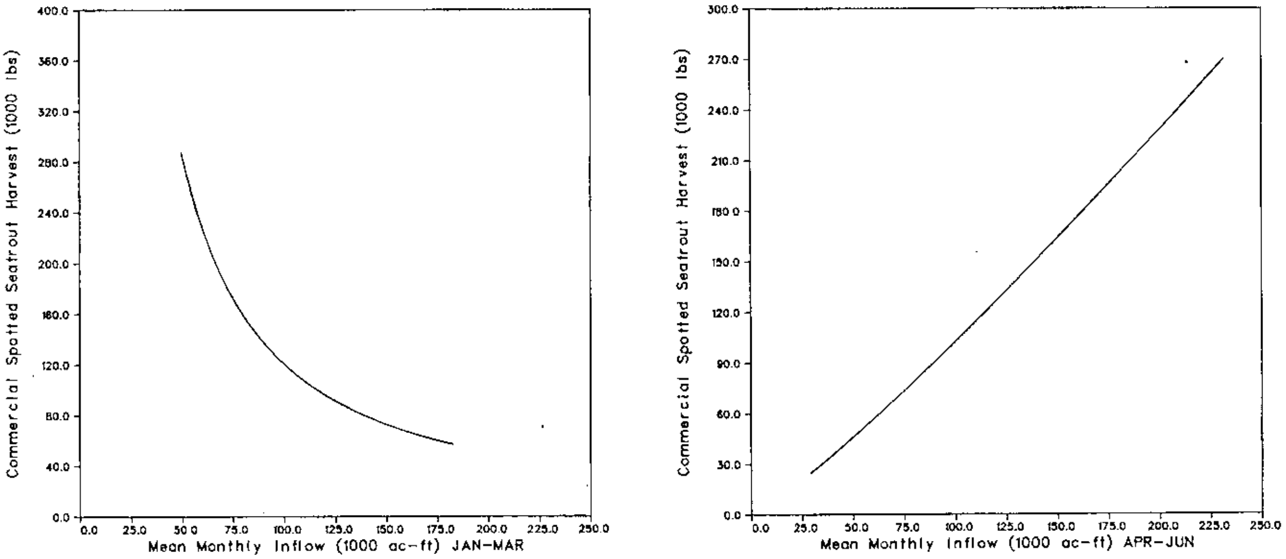
$$\ln H_{ss} = 6.8264 - \underset{(0.3937)}{1.2473} (\ln Q_1) + \underset{(0.2702)}{1.1526} (\ln Q_2) - \underset{(0.1840)}{0.4037} (\ln Q_4)$$

	$\ln H_{ss}$	$\ln Q_1$	$\ln Q_2$	$\ln Q_4$
upper bounds	5.6157	5.2058	5.4434	5.2461
lower bounds	3.7728	3.9053	3.3511	3.5742
mean	4.7880	4.6073	4.7417	4.3518

Spotted Seatrout Harvest = f (Seasonal FINC d/)
(no significant equation)

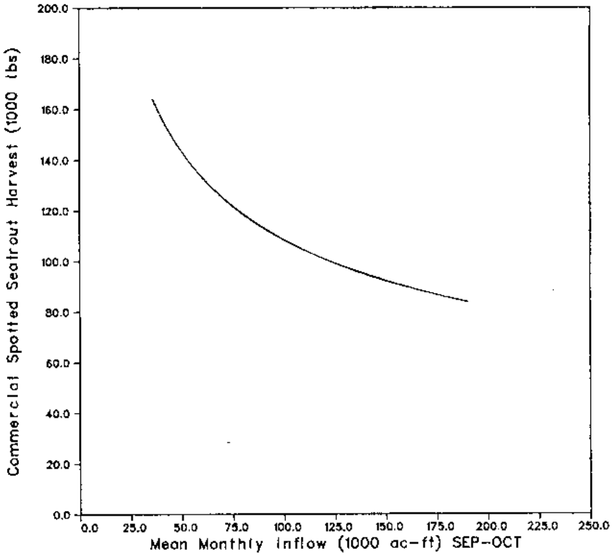
where: $\ln H_{ss}$ = natural log, commercial inshore harvest of spotted seatrout in Lavaca-Tres Palacios estuary, in thousands of pounds;
$\ln Q$ = natural log, mean monthly freshwater inflow, in thousands of acre-feet:
Q_1 = January-March
Q_2 = April-June
Q_3 = July-August
Q_4 = September-October
Q_5 = November-December

a/ Standard error of each regression coefficient is shown in parentheses beneath the coefficients of the regression equations
b/ FINLD = freshwater inflow at Lavaca Delta
c/ FINCD = freshwater inflow at Colorado Delta
d/ FINC = combined inflow to estuary from all contributing river and coastal drainage basins



A. regression coefficient = -1.2473,
standard error = ±0.3937

B. regression coefficient = +1526,
standard error = ±0.2702



C. regression coefficient =-0.4037,
standard error = ±0.1840

Figure 8-7. Inshore Commercial Spotted Seatrout Harvest as a Function of Each Seasonal Inflow at Colorado Delta, where all other Seasonal Inflows in the Natural Log Multiple Regression Equation are held Constant at their Mean Values

Table 8-13. Equations of Statistical Significance Relating the Red Drum Fisheries Component to Freshwater Inflow Categories a/

Red Drum Harvest = f (Seasonal FINLD b/)
Significant Natural Log Equation ($\alpha = 5.0\%$; $r^2 = 50\%$; S.E. Est. = $\pm$ 0.3664)

$$\ln H_{rd} = 5.1382 - \underset{(0.3989)}{1.2391} (\ln Q_3) + \underset{(0.2265)}{0.5430} (\ln Q_4) + \underset{(0.1939)}{0.1896} (\ln Q_5)$$

	$\ln H_{rd}$	$\ln Q_3$	$\ln Q_4$	$\ln Q_5$
upper bounds	4.8575	4.1972	5.2713	4.6396
lower bounds	3.1179	2.3671	2.8622	1.9218
mean	4.2010	3.2070	4.3985	3.4183

Red Drum Harvest = f (Seasonal FINCD c/)
Highly Significant Natural Log Equation ($\alpha = 0.5\%$; $r^2 = 65\%$; S.E. Est. = $\pm$ 0.2900)

$$\ln H_{rd} = 4.3204 + \underset{(0.1868)}{0.6937} (\ln Q_2) - \underset{(0.1901)}{0.8718} (\ln Q_3)$$

	$\ln H_{rd}$	$\ln Q_2$	$\ln Q_3$
upper bounds	4.8575	5.4434	4.8572
lower bounds	3.1179	3.3511	3.1641
mean	4.2010	4.7417	3.9103

Red Drum Harvest = f (Seasonal FINC d/)
Significant Natural Log Equation ($\alpha = 5.0\%$; $r^2 = 42\%$; S.E.Est. = $\pm$ 0.3753)

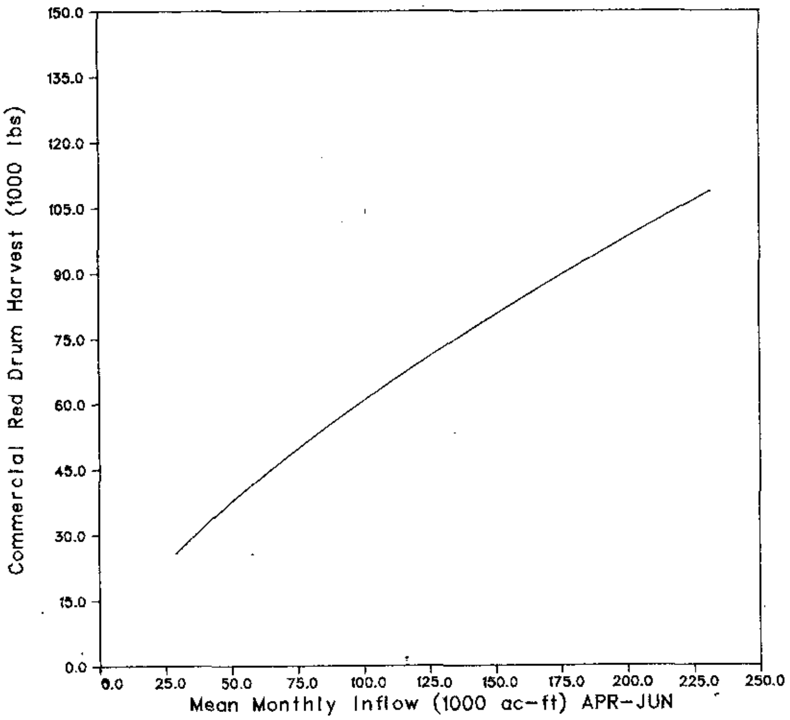
$$\ln H_{rd} = 5.5033 + \underset{(0.1798)}{0.3578} (\ln Q_2) - \underset{(0.2471)}{0.7078} (\ln Q_3)$$

	$\ln H_{rd}$	$\ln Q_2$	$\ln Q_3$
upper bounds	4.8575	6.5375	5.7694
lower bounds	3.1179	4.2859	4.1136
mean	4.2010	5.8281	4.7861

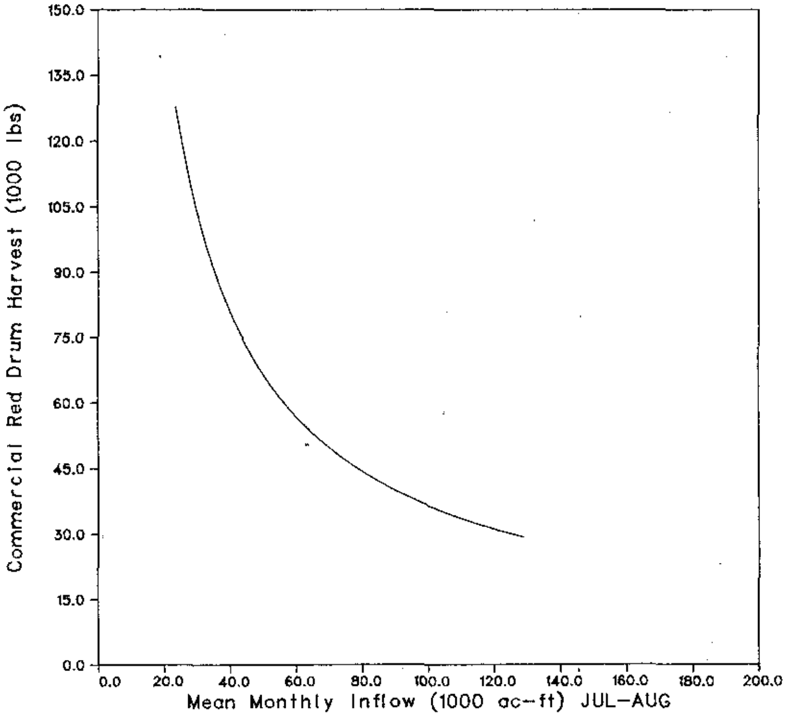
---

where: $\ln H_{rd}$ = natural log, commercial inshore harvest of red drum in Lavaca-Tres Palacios estuary, in thousands of pounds;
$\ln Q$ = natural log, mean monthly freshwater inflow, in thousands of acre-feet:
Q_1 = January-March
Q_2 = April-June
Q_3 = July-August
Q_4 = September-October
Q_5 = November-December

a/ Standard error of each regression coefficient is shown in parentheses beneath the coefficients of the regression equations
b/ FINLD = freshwater inflow at Lavaca Delta
c/ FINCD = freshwater inflow at Colorado Delta
d/ FINC = combined inflow to estuary from all contributing river and coastal drainage basins



A. regression coefficient = +0.6937, standard error = ±0.1868



B. regression coefficient = -0.8718, standard error = ±0.1901

Figure 8-8. Inshore Commercial Red Drum Harvest as a Function of Each Seasonal Inflow at Colorado Delta, where all other Seasonal Inflows in the Natural Log Multiple Regression Equation are held Constant at their Mean Values

Table 8-14. Positive (+) and Negative (-) Correlation of Fisheries Components to Seasonal Freshwater Inflow Categories

Fisheries Component	Winter Inflow Q_1 (Jan.-Mar.)	Spring Inflow Q_2 (Apr.-Jun.)	Summer Inflow Q_3 (Jul.-Aug.)	Autumn Inflow Q_4 (Sept.-Oct.)	Late Fall Inflow Q_5 (Nov.-Dec.)	Explained Variation r^2 (%)	Significance Level α (%)
Shellfish							
FINLD a/	-	+	-			68	0.5
FINCD b/							
FINC c/	-	+				50	2.5
All Shrimp							
FINLD	-	+	-		-	75	0.5
FINCD	-	+	-	+	-	62	5.0
FINC	-	+			-	67	1.0
White Shrimp							
FINLD		+			-	46	2.5
FINCD							
FINC		+			-	48	2.5
Blue Crab							
FINLD	+		+	+		72	0.5
FINCD		-	+	+		62	2.5
FINC			+	+	+	72	0.5
Bay Oyster							
FINLD			-		+	44	5.0
FINCD							
FINC	+		-		+	51	5.0
Finfish							
FINLD			-	+	+	53	5.0
FINCD	-	+		-		73	0.5
FINC	+		-			40	5.0
Spotted Seatrout							
FINLD							
FINCD	-	+		-		73	0.5
FINC							
Red Drum							
FINLD			-	+	+	50	5.0
FINCD		+	-			65	0.5
FINC		+	-			42	5.0
Summary							
FINLD	(+)=1	(+)=3	(+)=1	(+)=3	(+)=3		
	(-)=2	(-)=0	(-)=5	(-)=0	(-)=2		
FINCD	(+)=0	(+)=4	(+)=1	(+)=2	(+)=0		
	(-)=3	(-)=1	(-)=2	(-)=2	(-)=0		
FINC	(+)=2	(+)=4	(+)=1	(+)=1	(+)=2		
	(-)=2	(-)=0	(-)=3	(-)=0	(-)=2		

a/ FINLD = freshwater inflow at Lavaca Delta
b/ FINCD = freshwater inflow at Colorado Delta
c/ FINC = combined inflow to estuary from all contributing river and coastal drainage basins

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 have been recognized for ecological preservation of estuaries (127, 268). Since the 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 (26, 163, 134, 131, 164). Consequently, the addition of supplemental freshwater inflow for purposes of ecological maintenance or enhancing seafood production has been recommended for the Gulf estuaries of Texas (127, 319), Mississippi, and Louisiana (55).

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 (112, 113, 385, 386), in species distribution patterns and community diversity (83, 73, 59, 85, 22, 118), and ultimately in species evolution (110). Previous research emphasizing Texas estuarine-dependent species has dealt with several aspects of the inflow/salinity relationship including environmental limits (302), tolerance to hypersaline water (77, 93, 6), and rapid recovery of typical estuarine community species at the end of a severe drought (102). In addition, salinity changes resulting from man's development of the estuary and its contributing river and coastal drainage basins have been reviewed relevant to many Texas estuarine-dependent species (81, 335), and their diseases and symbionts (166).

While plants provide the estuary's primary production, most secondary production comes from the invertebrate bay fauna. For the invertebrates, inflow/salinity effects have a demonstrated physiological basis (7, 329, 114, 122, 327) and are effective at modifying species distribution (276, 289, 168). The brackish water clam (*Rangia cuneata*) has been suggested as an indicator of ecological effects associated with salinity changes because of its sensitivity (207); 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 (135).

Shrimp

The Gulf of Mexico shrimp fishery is the most valuable fishery in the United States (65) and the Gulf estuaries play a crucial role in the production of this renewable resource (67, 119). 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 (126), brown shrimp (24), pink shrimp (28), and for all species in the genus Penaeus (375). Other information especially important for management of this fisheries resource comes from research on shrimp spawning and early larval stages (340, 294, 310, 373), seasonal migration behavior (331, 27, 245), utilization of estuarine nursery habitats (73), and major environmental factors influencing species population dynamics and production (209, 87, 141, 140, 30, 130). Species-specific response to inflow/ salinity conditions in the estuary are fundamentally physiological (4, 10, 216, 213, 121, 337), and therefore directly influence not only growth and survival of the postlarval shrimp (401, 402, 400, 384), but the distribution of the bay shrimp populations as well (300, 84, 279).

Results of the fisheries analysis (i.e., shellfish, all penaeid shrimp, and white shrimp fisheries components) support the importance of freshwater inflow to shrimp production and provide quantified data on the responses of commercial inshore harvests from the Lavaca-Tres Palacios estuary to seasonal fluctuations of the three analyzed inflow categories (i.e., FINLD, FINCD, and FINC). In general, the associated harvest responses are negative for winter (January-March), summer (July-August) and late fall (November-December) freshwater inflow, and strongly positive for inflow during the spring (April-June).

Blue Crab

Another major crustacean fishery species is the estuarine-dependent blue crab (Callinectes sapidus Rathbun, 1896). Previous research has described blue crab taxomony (239, 277), life history (342, 238), migration behavior (284, 103, 245) and responses to environmental factors such as salinity (187, 29, 210, 120) and storm water runoff (124).

Results of the fisheries analysis (i.e., blue crab component) also support the importance of freshwater inflow, particularly summer (July-August) and autumn (September-October) seasonal inflow, to the production and harvest of the blue crab. All three of the significant regression equations developed for the blue crab indicate positive harvest responses to increasing summer and autumn inflow. In addition, each equation contains a correlating season not found in the others; that is, the regression models for blue crab harvest as a function of freshwater inflow also include a positive correlation to winter (January-March) inflow at Lavaca delta, a negative correlation to spring (April-June) inflow at Colorado delta, and a positive correlation to late fall (November-December) inflow from all contributing rivers and coastal drainage basins.

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 (eg., raft farming, artificial reef formation, etc.), scientific information is available on the oyster's general ecology and life history (368, 389), as well as geographic variation of its populations (189). The effects of inflow/salinity are particularly important and have stimulated considerable research covering a wide range of subjects including effects on oyster distribution (296, 139, 42), gametogenesis (development of viable eggs and sperm) and spawning (341, 11, 129, 181), eggs and larvae (5, 39, 369, 372, 95), respiration (303, 383), free amino acids which are protein building blocks (143), the effects on oyster reef growth and mortality (75, 287), abundance of faunal associates (75, 393) and reef diseases (215, 166).

Previous studies have described the Texas oyster fishery (247) and the State's major oyster producing areas (376, 251). Oyster production in lower Matagorda Bay was surveyed by Moore (344) during the 1904 through 1905 oyster season at an estimated 445,900 barrels, which is more than 6.2 million pounds (2.8 million kg) of oyster meats. Although numerous oyster reefs have been recently inventoried throughout the secondary bays of the estuarine system (356), most are currently in classified "polluted areas" which are closed 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. These areas include mid to upper Tres Palacios Bay, all of Turtle Bay, mid to upper Carancahua Bay, all of Chocolate Bay, and northern Lavaca Bay near Port Comfort, Texas.

Analysis of the bay oyster harvest in the estuary indicates a negative response to summer (July-August) inflow and a positive response to late fall (November-December) inflow at Lavaca delta. In addition, the best significant equation also includes a positive harvest response to winter (January-March) inflow from all contributing river and coastal drainage basins.

Finfish

Estuaries play a vital functional role in the life cycle and production of most coastal fish species (339, 107, 133, 241, 104). Environmental sensitivity of the estuarine-dependent fishes has allowed the use of species diversity indices as indicators of pollution (285). Although migration does occur across the boundary between riverine and estuarine habitats by both freshwater and estuarine-dependent marine fishes (162, 178), there is a predominance of young marine fishes found in this low salinity area (76).

In general, seasonal variations in estuarine fish abundance are related to life history and migrational behavior (82, 306, 305, 105, 284, 103, 245, 250, 185, 278, 398). The primary effects of inflow/salinity are physiological (101, 106, 123), and are particularly important for the survival of the early life stages (100) and the metabolism (i.e., metabolic stresses) of adult bay populations (299, 301, 308, 272, 388) and juvenile rates of adaptability (274, 273). Low temperature extremes can also interact physiologically to produce dramatic fish mortality (70, 71, 74).

The importance of freshwater inflow to finfish of the Lavaca-Tres Palacios estuary is supported by the fisheries analysis. The best significant equation indicates that commercial inshore finfish harvests relate positively to spring

(April-June) inflow and negatively to winter (January-March) and autumn (September-October) inflow at Colorado delta. In addition, a weaker regression equation developed for inflow at Lavaca delta indicates a negative harvest response to summer (July-August) inflow and positive responses to autumn and late fall (November-December) inflow. It is apparent from the analytical results that the harvest responses to seasonal freshwater inflow at Colorado and Lavaca deltas differs considerably. This may be due to differential utilization of the respective habitat areas by members of this multispecies fisheries component (34, 148, 191).

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 (339, 214, 104). The sciaenid genus Cynoscion contains four species in the Western Atlantic and the 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 (371). The greater restriction and estuarine-dependence of this species are reflected in its nearly exclusive utilization of estuarine habitats (66, 204, 60) and the increased genetic differences among populations in separate bays (392). Previous research has described spotted seatrout life history and seasonal abundance in Texas waters (343, 306, 233, 234, 305, 105, 103, 245), 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 (271, 272, 297, 274, 388, 273).

Analysis of the spotted seatrout fisheries component additionally supports the importance of seasonal freshwater inflow, particularly inflow at Colorado delta, to annual harvests in the Lavaca-Tres Palacios estuary. Similar to results of the finfish component analysis, this component also indicates that commercial inshore harvests are positively related to spring (April-June) inflow and negatively related to winter (January-March) and autumn (SeptemberOctober) inflows at Colorado delta.

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 (343, 306, 233, 234, 145, 307, 305, 105, 399, 103, 245, 104, 165). 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 (272, 388, 273, 274).

Results of the fisheries analysis further support the importance of seasonal freshwater inflow to the annual red drum harvest from the estuary. All three of the significant regression equations indicate a negative harvest response to increased summer (July-August) inflow. However, inflow at Lavaca delta also correlates positively for autumn (September-October) and late fall (November-December) seasons, while inflow at Colorado delta and from the combined inflow category additionally correlates to the spring (April-June) season with a positive harvest response. Although both deltas are vitally important to the estuary's production, the Lavaca delta and bay area may provide preferred habitat to the red drum, while the oyster reefs and seagrass beds of West Matagorda Bay nearer the Colorado delta may provide better habitat for the spotted seatrout (34).

Harvest Response to Long and Short Term Inflow

The fisheries analysis spans the recent 1962 through 1976 short-term interval where more complete and compatible fisheries data exist; however, long-term inflow data are available for the estuary from 1941 to 1976 (see Chapter IV). Average (arithmetic and geometric mean) inflow conditions are computed and a frequency analysis (i.e., Log-Pearson Type III) of the long-term inflow data yields 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 8-15). The short-term average inflow data were exceeded at frequencies varying from 56 percent (summer, FINCD) to 23 percent (autumn, FINLD); however, most were below the 50 percent frequency level. Since lower exceedance frequencies indicate higher inflow, the short-term inflows are indicated as comparatively "wetter" than the long-term temporal median inflows.

Although the central seasonal tendencies of the short-term data bases 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 (90). 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 8-16). It is noted that substitution of the long-term average inflows in the fisheries equations involves using arithmetic mean seasonal inflows in the linear equations and geometric mean seasonal inflows in the natural log (ln) equations.

There are 11 positive and 27 negative shifts in the harvest estimates from exercise of the equational fisheries models, when compared to fisheries harvest levels related to the more recent short-term interval and its mean seasonal inflows. Long-term inflows are associated with six positive and 13 negative harvest shifts, while long-term 50 percent frequency inflows are associated with five positive and 14 negative harvest shifts. Results are variable among the fisheries components and range from an estimated +12.6 percent shift of blue crab harvest in response to long-term mean inflow (FINLD inflow category), to an estimated -37.1 percent shift of blue crab harvest in response to long-term 50 percent frequency inflow (FINLD). The results reflect not only differences in inflow quantity, but also differences in the seasonal distributions of inflow from the freshwater source categories, and suggest that long-term harvests would be somewhat lower overall than those resulting from the "wetter" 15-year experience of the recent short-term record unless management policies favored the specific seasonal inflow needs of preferred fisheries components. In actuality, it is 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

Table 8-15. Comparison of Short-Term and Long-Term Seasonal Inflow, Including Inflow Exceedance Frequencies

Freshwater Inflow Category and Season	Short-Term Mean Seasonal Inflow a/ With Long-Term Exceedance Frequencies: D_s Inflow (EF%) c/	D_{s-1} Inflow (EF%)	D_f Inflow (EF%)	Long-Term Seasonal Inflow b/: Arithmetic Mean Inflow	Geometric Mean Inflow	10% EF Inflow	50% EF Inflow	90% EF Inflow
FINLD, Lavaca Delta Inflow								
Q_1 (Jan. - March)	136.5 (41)	167.1 (35)	156.9 (38)	154	82	462	84	15
Q_2 (April - June)	391.1 (31)	396.7 (31)	330.7 (38)	304	169	918	174	30
Q_3 (July - Aug.)	45.9 (42)	51.9 (39)	49.4 (40)	79	31	154	30	6
Q_4 (Sept. - Oct.)	163.0 (29)	190.2 (23)	162.7 (29)	145	57	402	56	8
Q_5 (Nov. - Dec.)	64.7 (40)	64.7 (40)	61.0 (42)	82	31	254	34	2
Total	801.2	870.6	760.7	764	370	2,190	378	61
FINCD, Colorado Delta Inflow								
Q_1 (Jan. - March)	289.7 (44)	327.9 (40)	300.6 (43)	319	246	666	249	90
Q_2 (April - June)	378.6 (42)	385.4 (42)	343.9 (45)	418	298	891	297	99
Q_3 (July - Aug.)	101.9 (55)	113.0 (49)	99.8 (56)	142	111	286	110	42
Q_4 (Sept. - Oct.)	155.6 (48)	171.9 (44)	155.2 (48)	189	148	372	148	58
Q_5 (Nov. - Dec.)	192.7 (42)	192.7 (42)	182.7 (44)	205	154	430	154	54
Total	1,118.54	1,190.9	1,082.2	1,273	957	2,645	958	343
FINC, Combined Inflow								
Q_1 (Jan. - March)	530.9 (45)	624.0 (40)	589.5 (42)	628	442	1,440	447	135
Q_2 (April - June)	1,141.5 (34)	1,167.8 (33)	1,109.1 (38)	1,012	673	2,388	681	189
Q_3 (July - Aug.)	235.5 (52)	253.1 (39)	239.7 (51)	325	245	642	244	94
Q_4 (Sept. - Oct.)	615.0 (34)	696.8 (31)	635.7 (35)	600	389	1,342	388	114
Q_5 (Nov. - Dec.)	336.4 (41)	336.4 (41)	323.4 (43)	375	249	850	248	72
Total	2,859.3	3,078.1	2,807.4	2,940	1,998	6,662	2,008	604

a/ Short-term inflow data bases, with seasonal volumes in thousands of acre-feet:

D_s = inflow (Nov., 1961 - Oct., 1976) used in analysis of Shellfish, All Shrimp, White Shrimp, and Brown and Pink Shrimp fisheries components

D_{s-1} = 1-year antecedent inflow (Jan., 1961 - Dec., 1975) used in analysis of Blue Crab and Bay Oyster fisheries components

D_f = 3-year average antecedent inflow (Jan., 1959 - Dec., 1975) natural log transformed and used in analysis of Finfish, Spotted Seatrout, and Red Drum fisheries components

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.

Table 8-16. Estimated Average Inshore 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	Lavaca Delta Inflow FINLD					Colorado Delta Inflow FINCD					Combined Inflow a/ FINC				
	Short-Term Mean Inflow	Long-Term Mean-Inflow		Long-Term 50%EF d/ Inflow		Short-Term Mean Inflow	Long-Term Mean Inflow		Long-Term 50% EF Inflow		Short-Term Mean Inflow	Long-Term Mean Inflow		Long-Term 50% EF Inflow	
	Harvest b/	Harvest	(Shift) c/	Harvest	(Shift)	Harvest	Harvest	(Shift)	Harvest	(Shift)	Harvest	Harvest	(Shift)	Harvest	(Shift)
Shellfish	3,034.3	2,341.3	(-22.8)	2,875.1	(-5.2)						3,034.3	2,793.3	(-7.9)	2,706.3	(-10.8)
All Shrimp	1,935.1	1,513.3	(-21.8)	1,782.4	(-7.9)	1,935.1	1,943.0	(+0.4)	1,720.5	(-11.1)	1,935.1	1,684.1	(-13.0)	1,673.4	(-13.5)
White Shrimp	1,592.6	1,464.3	(-8.1)	1,479.7	(-7.1)						1,592.6	1,498.2	(-5.9)	1,486.0	(-6.7)
Blue Crab	781.4	880.0	(+12.6)	491.2	(-37.1)	781.4	868.4	(+11.1)	792.2	(+1.4)	781.4	862.4	(+10.4)	677.3	(-13.3)
Bay Oyster	251.2	220.9	(-12.1)	253.1	(+0.8)						251.2	232.3	(-7.5)	211.7	(-25.7)
Finfish	274.6	266.9	(-2.8)	281.3	(+2.4)	274.6	293.4	(+6.9)	290.2	(+5.7)	274.6	231.9	(-15.5)	235.2	(-14.3)
Spotted Seatrout						120.1	132.8	(+10.6)	130.8	(+8.9)					
Red Drum	66.8	59.2	(-11.3)	62.1	(-7.0)	66.8	54.2	(-18.3)	55.4	(-17.1)	66.8	56.5	(-15.4)	57.1	(-14.5)

a/ Inflow from all contributing river and coastal drainage basins
b/ Average harvest, in thousands of pounds
c/ Shift in percent increase (+) or decrease (-) of harvest
d/ EF = exceedance frequency

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 from bays of the Lavaca-Tres Palacios estuary rank second in shellfish and fifth in finfish of eight major Texas estuarine areas. In addition, the estuary's sport or recreational finfish harvest is estimated to be about five and one-half times larger than the commercial finfish harvest.

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 (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. 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 1962 through 1976 commercial bay fisheries landings was successful for 70 percent of the correlations attempted between the harvests and the seasonal freshwater inflows to the Lavaca-Tres Palacios estuary. The analysis of harvest as a function of the seasonal inflows resulted in 19 statistically significant regression equations. These equational models provide numerical estimates of the effects of variable seasonal inflows, contributed from the major freshwater sources, on the inshore commercial harvest of seafood organisms from the estuary. The analysis also supports existing scientific information on the seasonal importance of freshwater inflow to the estuary. Except for the blue crab fisheries component, all harvest responses are estimated to be positive for increased spring season (April-June) inflow and negative for increased summer (July-August) inflow. In addition, the estimated harvest responses are all positive to autumn inflow (the tropical storm dominated September-October interval), except for the slight negative responses of the finfish and spotted seatrout components to increased autumn inflow at Colorado delta. Although penaeid shrimp harvests relate negatively to both late fall (November-December) and winter (January-March) inflows, the blue crab, bay oyster, finfish, and red drum fisheries components are estimated to respond positively to late fall inflow, especially when it occurs at Lavaca delta. Only blue crab, bay oyster, and finfish components relate positively to winter inflow.

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's 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. Most of these other factors are largely beyond human control, whereas man's activities can restrict freshwater inflows to the detriment of fish and wildlife resources.

CHAPTER IX

ESTIMATED FRESHWATER INFLOW NEEDS

Introduction

In previous chapters, the various physical, chemical and biological factors affecting the Lavaca-Tres Palacios 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.

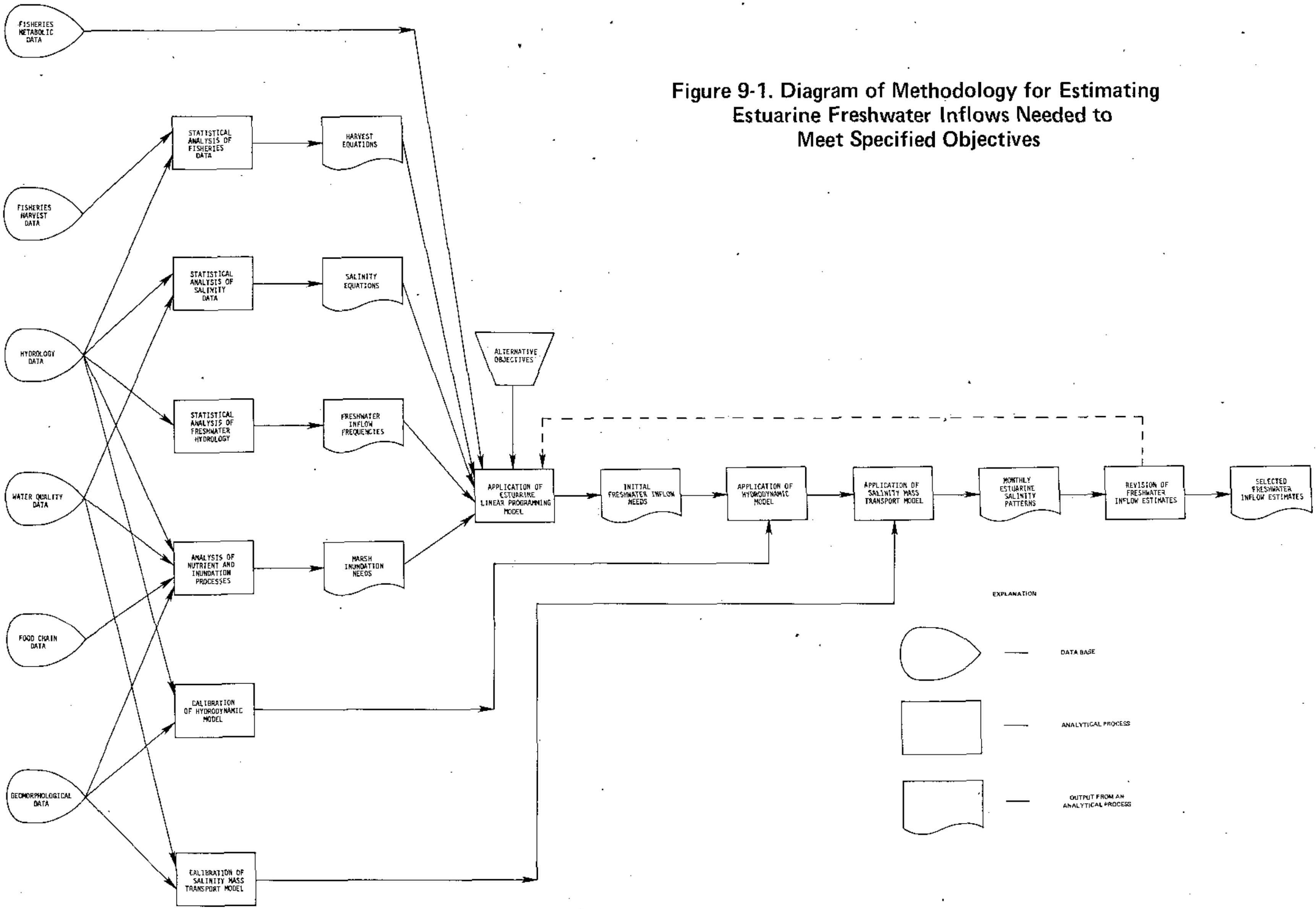
The methodology presented here incorporates major interacting elements described in previous chapters (Figure 9-1). The methodology includes the use of data bases and certain analytical processes described herein. Data for these analyses include six groups: (1) metabolic data for finfish and shellfish, (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 physical geomorphologic 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 monthly freshwater inflows.

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 Lavaca-Tres Palacios estuary provide the fundamental information of the system. These data were used in previous sections of these analyses. The relationships and results are incorporated into the

Figure 9-1. Diagram of Methodology for Estimating Estuarine Freshwater Inflows Needed to Meet Specified Objectives



Estuarine Linear Programming Model to compute estimates of effects of various levels of monthly freshwater inflows upon near-shore salinities, 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 revision of the Estuarine Linear Programming Model.

The data bases and analytical processes utilized in this chapter have been described in detail in previous chapters (Figure 9-1). 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 reproduction are commonly restricted to a substantially narrower range of salinity than are simple survival needs. The salinity regime thus becomes an important ecological factor in the estuary's freshwater inflow needs.

Data on salinity effects, when 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 salinity viability limits, the seasonal 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 in the estuary: (1) an area below the estuary's "null zone"1/ in upper Lavaca

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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 (91, 364).

Table 9-1. Salinity Limits, Preferences, and Optima for Selected Texas Estuaries-Dependent Species

Species	Limits		Preference or Optimum (ppt)	Remarks	Reference
	Min. (ppt)	Max. (ppt)			
Penaeus setiferus (white shrimp)	< 2	> 40		range at which 80% of 8-50 mm (postlarvae to juvenile) shrimp survive; 48 hr. acclimation	401
			5-15	increased growth at this range (and >25°C) more than two times tissue production of postlarvae at 25-35 ppt	400
			28.0	median salinity average of postlarval distribution (May-July) in laboratory gradient tanks	213
			21.0	median salinity average of postlarval distribution (Aug.-Nov.) in laboratory gradient tanks	213
		47.96		field collection of small white shrimp (23-76 mm) in Laguna Madre de Tamaulipas (Mexico)	97
	0.42			lower distribution limit in Grand and White Lakes (La.); young shrimp 140 more abundant at 0.7-0.8 ppt	85
			27.6-28.3	isosmotic salinity conditions for shrimp ≥ 100 mm length; osmoregulation below 27.6 ppt better than brown shrimp	151
	1	34	1-20	field distribution in Caminada Bay (La.) and range for 91.1% of juveniles collected	30
	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	300
	2.9	45.3		field distribution in Mesquite Bay (Tex.)	102
	2	45		field distribution in bays and lagoons of northwestern Gulf of Mexico (Tex.)	93
			< 10	preference based on population distributions	84
	0	38		optimum catch over entire salinity range with 20-38°C temperatures	302
Penaeus aztecus (brown shrimp)	2	40		range of equal postlarval growth over 23-25°C temperature; survival 90-100% in laboratory	401
	< 10			marked reduction in postlarval tolerance at low (7-15°C) temperatures to low (5 ppt) salinity	402
			15-35	range of increased postlarval growth at temperatures >25°C; decreased growth below 15 ppt	400
	< 5	> 40		range at which 80% of 10-15 mm postlarvae survive; 12 hr. acclimation	400
			> 15	appeared to enhance survival and growth of postlarvae in Barataria Bay (La.)	197
			> 15	commercial catches poor in years when postlarvae were present in Louisiana bays with < 15 ppt	142
			29.9	median salinity average of postlarval distribution (March-April) in laboratory gradient tank	213
			20.6	median salinity average of postlarval distribution (May-July) in laboratory gradient tank	213
			10.0-19.9	range at which juveniles were more abundant based on population distributions	84
	0.2	30	10-30	field distribution in Caminada Bay (La.) and range for 91.8% of juveniles collected	30
			< 17	preference of juvenile (70 mm) shrimp in laboratory at >26°C temperature	337
			15-25	optimal range for subadult (95 mm) shrimp in laboratory at <25°C temperature	337
			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	384
			27.6-28.3	isosmotic salinity conditions for shrimp ≥ 100 mm length; osmoregulation above 28.3 ppt better than white shrimp	151
	2.1	36.6	15.0-19.9	field distribution in Copano and Aransas Bays (Tex.) and range of greater abundance	300
		69.0		field collection in Laguna Madre (Tex.)	281
	0.8			lower distribution limit in Grand and White Lakes (La.)	85
	0.22			field collection in St. Lucie Estuary (Fla.)	69
	5	70		field distribution in bays and lagoons of northwestern Gulf of Mexico (Tex.)	93
	0.1			field collection (North Carolina)	396
			5	acclimation at low (5 ppt) salinity provides near-optimum resistance to high temperatures and 5-25 ppt salinities in laboratory tests	394
	9	40		no optimum salinity established with 20-35°C temperatures	302
Callinectes sapidus (blue crab)	22.9	32.4	≥ 30.0	range for capture of egg-bearing females near Aransas Pass (Tex.)	300
			23-28	optimum range for hatching of eggs (Virginia)	187
			> 20	occurrence of spawning and early development	238
			< 1.9	peak abundance of juvenile blue crabs in Texas bays (1965)	238
	< 1.0		2-21	lethal limit at optimum (29°C) temperature and range of little effect on juvenile growth and survival	210
	0			observed freshwater populations in Louisiana	82
	2.0	37.2	10.0-20.0	field distribution in Copano and Aransas Bays (Tex.) and range of greater abundance	300
		117		field collection in Laguna Madre de Tamaulipas (Mexico); high salinity briefly tolerated	97
		45		blue crabs observed leaving upper Laguna Madre (Tex.) area as salinity increased	243
	2	60		field distribution in bays and lagoons of northwestern Gulf of Mexico (Tex.)	93
			24.2	salinity for widest thermal tolerance zone in adult blue crab	61
	0	40	0-27	optimum range with 10-35°C temperatures	302
			10-30	range of no effect on metabolic consumption of oxygen (respiration)	120
Crasostrea 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	11
	5-7.5			normal gonadal development near 7.5 ppt; however, oysters with previously ripe gonads spawn when subjected to low (5 ppt) salinities	128
			20-21	larval spat setting requirement in Galveston Bay (Tex.)	341
	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	114

Table 9-1. Salinity Limits, Preferences, and Optima for Selected Texas Estuaries-Dependent Species (cont'd.)

Species	Limits		Preference or Optimum (ppt)	Remarks	Reference
	Min. (ppt)	Max. (ppt)			
			19-30	maximum survival (80% contour plot) in lab of 2-day larvae at 19-30.5°C temperatures	372
			8-30.5	maximum survival (60% contour plot) in lab of 8-day larvae at temperatures > 21°C	372
			>33	maximum growth (100% contour plot) in lab of 8-day larvae at temperatures > 19°C	372
			18-35	optimum (80% contour plot) for both larval survival and growth at temperatures > 30°C	372
			15-22.5	optimum for juvenile growth and development	19
	1.5	39.0		early experimentally derived salinity limits	5
	0-2			oysters can survive freshwater (oppt) for several days; increasing to about a month at 2 ppt salinity	300
			15-30	optimum range of salt content	247
	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)	368
		43.5-45		distribution limit in Redfish and Corpus Christi Bays (Tex.)	287
			15-20	ideal salinity conditions with lowest seasonal salinities in late summer and fall	1
	2-4	18-22	10.0-16.0	most productive reefs of Mississippi sound subject to 10.0-16.0 ppt average conditions	42
	≤ 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.)	251
			15-30	best growth in reasonably stable salinity	166
	3			lower tolerance limit about 3 ppt	81
	8-10			lower limit of predator Thais haemastoma, a gastropod oyster drill or conch	81 300
	< 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	295
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	204
			> 30	spawning occurs in estuarine areas of higher salinity (La.)	185
		≤ 60	< 45	"young" collected up to about 60 ppt in Laguna Madre (Tex.); no spawning if salinity > 45 ppt	281
		< 55	15-35	absent above 55 ppt in Baffin and Alazan Bays (Tex.); most abundant range 15-35 ppt	280
	2.3	34.9	5-20	field distribution in Copano and Aransas Bays (Tex.); over 80% collected in 5-20 ppt	306
	< 5	77		field distribution in bays and lagoons at northwestern Gulf of Mexico (Tex.)	93
	10	45	20	operational limits; optimum metabolic condition at 20-28°C temperatures	297
Sciaenops ocellata (red drum)					
	2.1	32.4	< 15	field distribution in Copano and Aransas Bays (Tex.); greater abundance below 15 ppt	306
	0	> 50	20-40	field distribution (Tex.); range of preference (most abundant in 30-35 ppt); young mature in 3-5 years	307
			< 50	populations in Laguna Madre (Tex.) severely limited by >50 ppt	281
	5-10	40-45	20-25	operational limits; range of optimum metabolic condition at 20-28°C temperatures	272

Bay near the Lavaca River delta, and (2) an area of Matagorda Bay near the Colorado River delta. The limits are expressed as mean (average) monthly salinities for general limits of viability. From both locations, salinities generally increase towards the major Gulf inlets (Pass Cavallo and the mouth of the Colorado River) 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 cycle to the natural freshwater inflow regime of this estuary.

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 species commonly residing in an estuary may migrate to other estuarine or Gulf areas where the environmental conditions are more suitable. Generally, however, estuarine-dependent species remain in the system during normal periodic salinity fluctuations. Should the normal salinity conditions be altered for prolonged periods due to natural or man-made causes, the diversity, distribution and productivity of species within an estuary will be depressed.

The median monthly salinity (Table 9-2) 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 the "expected" salinity in the estuary and represents a value exceeded one-half of the time. Comparative median historic salinities have been computed for the two locations in upper Lavaca Bay and Matagorda Bay for which the salinity regression equations were developed (Table 9-2).

Marsh Inundation Needs

The periodic inundation of deltaic marshes serves to maintain shallow protected habitats for postlarval and juvenile stages of several important estuarine species, provides a suitable fluid medium for nutrient exchange processes, and acts as a transport mechanism to move detrital materials (food) 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

Table 9-2. Salinity Characteristics of Upper Lavaca Bay and Eastern Arm of Matagorda Bay

Month	Salinity in Upper Lavaca Bay a/ (ppt)			Salinity in Eastern End of Matagorda 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	13	30	10	19
February	20	10	12	30	10	19
March	20	10	12	25	10	19
April	15	5	13	20	5	21
May	15	1	10	20	5	19
June	15	1	9	20	5	19
July	20	10	11	25	10	21
August	20	10	17	25	10	24
September	15	5	13	20	5	23
October	15	5	13	20	5	20
November	20	10	13	30	10	19
December	20	10	14	30	10	19

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a/ Represented by the average of sampling sites 1, 2, & 3 on linesite 85 (Figure 3-9)

b/ Represented by the average of sampling sites 1, 2, & 3 on linesite 333, site 330, and sites 1, 2, & 3 on linesite 340 (Figure 3-9)

c/ These values estimate the limits of long-term viable species activity at control points in the system, and not individual organism survival limits (Table 9-1).

occurs 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 food production.

Two river deltas of the Lavaca-Tres Palacios estuary (the Lavaca and Colorado River deltas) are periodically inundated.1/ The Lavaca delta is subject to periodic inundation by freshwater due to discharge from the Lavaca-Navidad 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; however, results of field observations and modeling studies suggest that the Colorado delta marshes are rarely, if ever submerged by freshwater discharge from the river. Leveed river banks act to contain high flows which are then discharged into the Gulf of Mexico or shunted directly into Matagorda Bay through Tiger Island Cut. Wind and tide setups are thus the primary mechanisms of marsh inundation in the Colorado River delta. The physical nature of the delta and the existing inundation mechanisms preclude (at least presently) upstream water management techniques (i.e., freshwater releases from storage) as a feasible method for regulating either timing or areal extent of inundation of the Colorado delta.

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 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 Lavaca delta (44). A series of peak discharges ranging from 2,000 to 45,000 ft^3/sec (57 to 1,274 m^3/sec) for normal and high tidal regimes were used in the analysis and the areal extent of deltaic inundation was computed for each tide/discharge combination. With normal tides (0.70 feet to 1.83 feet above MSL), a peak discharge of less than 2,900 ft^3/sec (82 m^3/sec) would be insufficient to inundate the delta. During high tides (range 1.80 feet to 3.24 feet above MSL), the model predicted that a 2,900 ft^3/sec (82 m^3/sec) peak discharge from the Lavaca River would result in inundation of 50 percent of the delta.

For normal tides, the model predicted inundation of the delta with peak discharge floods of above 9,000 ft^3/sec (255 m^3/sec). Since historical tide stages are unknown for a large portion of the period of record, a daily peak discharge of 5,000 ft^3/sec (142 m^3/sec) or greater was selected as one potential inundation event. This rate of discharge was selected because it fell approximately half-way between the 2,000 and 9,000 ft^3/sec (57 to

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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 (264, 265). Studies indicate that maximum rates of nutrient release from the sediment to the overlying water column occur and diminish within the first 48 hours of a discrete inundation event, following a prolonged period of emergence drying.

255 m^3/sec) discharge rates for which inundation occurred under high and normal tides, respectively.

Daily gaged data for the period of record (1941-1976) were examined to arrive at monthly and seasonal distributions of discharge events with peak flows of 5,000 ft^3/sec (142 m^3/sec) or greater (Table 9-3). It was apparent that more inundation events have occurred in the spring months of April, May, and June than during any other seasonal period. The data suggest that inundation events in the Lavaca delta have occurred more often in the spring and fall than in winter and summer. 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 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.

If historical inundation events (peak daily flows greater than 5,000 ft^3/sec or 142 m^3/sec) are grouped into those that occur in spring (April, May, and June), those that occur in the later fall and early winter (October, November, December, and January), and the total that occur during the year, it is evident that an average of three inundation events have occurred per year in the Lavaca delta over the period of record (Table 9-4). In order to maintain the historical inundation frequency, the Lavaca River delta would need to receive three flood events per year with flows greater than 5,000 ft^3/sec (142 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. 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. An inundation event in April and a subsequent event in May would be expected to extend favorable habitat conditions for larvae and juvenile stages of estuarine dependent organisms. The April-June median daily peak discharge over the period of record has been 11,320 ft^3/sec (321 m^3/sec), while that of the period October through January has been 10,370 ft^3/sec (294 m^3/sec).

The typical flood hydrographs for the contributing basins associate flood volumes of 70,000 and 60,000 acre-feet (86 to 74 million m^3) with the peak discharges of 11,320 and 10,370 ft^3/sec (321 and 294 m^3/sec), respectively. The percent of marsh inundated, as computed by the delta hydrodynamic model, will vary with wind direction and tide stage. With a normal tide (range 0.70 feet to 1.83 feet above MSL) and peak discharges of the magnitudes mentioned above, the model predicts that about 10 to 12 percent of the delta area will be inundated. Under a "high tide" (range 1.80 to 3.24 feet above MSL) similar peak discharges will result in inundation of 62 to 67 percent of the Lavaca delta.

Table 9-3. Peak Gaged Discharges for Discrete Flood Events Greater than 5000 ft^3/sec in the Lavaca River Basin, 1941-1976

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
					ft^3/sec						
26,720	21,260	22,900	31,260	35,000	70,300	22,300	22,710	45,800	44,400	17,400	20,420
14,750	17,470	20,480	23,870	30,000	41,080	9,830	12,930	45,700	35,900	16,450	13,300
13,250	16,880	15,510	22,960	28,200	29,300	9,024	11,890	44,500	23,360	11,780	13,000
11,570	14,520	13,770	22,900	21,360	16,330	5,740	9,760	21,790	18,650	11,570	12,370
11,260	14,050	8,950	20,220	21,300	11,800		7,560	8,430	17,450	11,520	8,910
11,100	13,800	8,110	13,650	20,180	11,600		5,070	7,230	16,480	10,880	8,320
10,550	13,530	5,290	13,510	15,540	10,510			5,000	10,370	9,600	8,170
9,540	11,830	5,250	12,700	13,920	9,860				10,270	9,520	6,330
8,510	8,050	5,150	11,320	13,890	9,550				7,880	7,370	5,880
7,780	7,010		11,100	13,880	8,980				7,160	7,290	5,860
7,320	6,790		10,100	13,100	8,870				5,900	6,560	
6,140	6,560		8,710	12,460	8,420					6,310	
5,490	6,540		8,590	11,220	8,110					6,122	
5,250			8,120	9,130	7,200						
			7,990	7,680	7,160						
			6,160	5,970	6,210						
			5,440	5,111	5,790						
				5,050							

Median peak flood discharge
April - June = 11,320 ft^3/sec
October - January = 10,370 ft^3/sec

Table 9-4. Frequency of Annual and Seasonal Flood Events with Peak Daily Gaged Flows Greater than 5,000 ft^3/sec in the Lavaca River Basin, 1941-1976

Number of Events per Period	Number of Occurrences over Period of Record Spring		Fall		Total Annual	
(x)	Freq.(f) a/	f*x b/	Freq.(f)	f*x	Freq.(f)	f*x
0	9	0	14	0	1	0
1	12	12	8	8	7	7
2	11	22	9	18	7	14
3	3	9	2	6	5	15
4	2	8	4	16	5	20
5					3	15
6					3	18
7					3	21
8					1	8
9					1	9
10					0	0
11					1	11
Σ f*x		51		48		138
Number of Years = 37						
Mean Number Inundation events per year		1.4		1.3		3.7
Median Number Inundation events per year		1		1		3

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a/ Freq. (f) is the number of seasons or years in which the number of flood events greater than 5,000 ft^3/sec equaled x.

b/ f*x stands for f multiplied by x.

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, to the set of relevant variables, including monthly inflows from the Lavaca and Colorado River Basins.[1/] A Linear Programming optimization procedure (35) is used to compute the monthly freshwater inflows from the Colorado and Lavaca River Basins needed to meet specified salinity, marsh inundation and commercial harvest levels. The quantification of salinity and commercial fisheries harvest as functions of seasonal freshwater inflow are represented by the statistical regression equations given in Chapter V and VIII, respectively. The harvest equation utilized for a given fisheries component is the best significant regression equation accounting for the most variance in the data (i.e., having the largest r^2 value) and having the smallest standard error term.

Specification of Objectives. The criteria or objectives in this optimization formulation can be any desired estuarine condition. One objective for which there may be interest is to compute the least annual inflow to the estuary while meeting the constraints on salinity regimes 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 species of aquatic organism, a weighted sum of the harvests of any or all of the commercially important species, or other combinations.

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 inflows used in computing the salinity regression relationships, and
(4) upper and lower 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;

[1/] Additional freshwater inflows are contributed to the estuary from the Colorado-Lavaca and Lavaca-Guadalupe 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.

Alternative II, Maintenance of Fisheries Harvests
Objective: minimize annual combined inflow while providing freshwater inflows sufficient to provide predicted annual commercial harvests in the estuary of red drum, seatrout, shrimp, and all shellfish combined at levels no less than their mean historical values over the period 1962 through 1976, satisfying marsh inundation needs and meeting viability limits for salinity;

Alternative III, Shellfish Harvest Enhancement
Objective: maximize the total annual commercial harvest of shellfish (represented by the sum of the harvests for all shrimp, blue crab, and bay oysters) in the estuary while meeting viability limits for salinity, satisfying marsh inundation needs, and utilizing an annual combined inflow no greater than the average annual historical combined inflow for the period 1941 through 1976.

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 Lavaca-Tres Palacios estuary; however, they provide a range of alternatives: survival or subsistence (Alternative I), maintenance of harvest levels (Alternative II), and shellfish harvest enhancement (Alternative III). Attempts to include offshore fishery harvests in the analysis were unsuccessful because of the inability to determine statistical relationships between Gulf harvests and Guadalupe seasonal inflows.

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 Lavaca and Matagorda Bays and satisfying marsh inundation needs for the Lavaca delta.[1] The upper salinity bound for each month at each of these two key locations is taken as the minimum of the upper salinity viability limit and the historic median salinity (Table 9-2). Optimal monthly inflows to the estuary needed to meet the objective are determined by the Estuarine Linear Programming Model. The estimated annual combined inflow need amounts to approximately 2.1 million acre-feet (2,587 million m^3) with 882.3 thousand acre-feet (1,088 million m^3) from the Colorado River Basin, 418.8 thousand acre-feet (517 million m^3) from the Lavaca River Basin and 796.0 thousand acre-feet (982 million m^3) from the Colorado-Lavaca and Lavaca-Guadalupe Coastal Basins (Table 9-6).

Monthly freshwater inflow needs generated by the Estuarine Linear Programing Model for Alternative I provide salinities which closely approximate those for the required upper bounds during most months of the year (Figure 9-2 and 9-3). Lavaca River Basin inflows during the months of April, May, and October provide lower salinities as a consequence of meeting marsh inundation requirements.

Comparisons between the mean historical combined inflows and the estimate freshwater inflow needs are made for each month (Figure 9-4 and 9-5), for the

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[1] Lavaca delta inundation needs include inundation volumes of 70,000 ac-ft for the period April through June (peak daily discharge of 11,320 ft^3/sec at Lavaca delta) and 60,000 ac-ft for October-January (10,370 ft^3/sec at Lavaca delta), as well as a median inundation frequency of three events per year.

Table 9-5. Criteria and System Performance Restrictions for the Selected Estuarine Alternatives

	Alternatives		
	I	II	III
Criteria:			
. Maximize Annual Combined Harvest of Shrimp, Blue Crab and Bay Oysters			x
. Least Possible Annual Combined Inflow	x	x	
Constraints:			
. Annual Inflow from the Colorado and Lavaca 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 Bay Oyster Commercial Harvest no less than the average Bay Oyster Harvest (1962-1976)			x
. Predicted Annual Shrimp, Blue Crab and Bay Oyster Commercial Harvests are each no less than their Average Harvests (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 Lavaca River Basin Inflows for Marsh Inundation of the Lavaca Delta	x	x	x

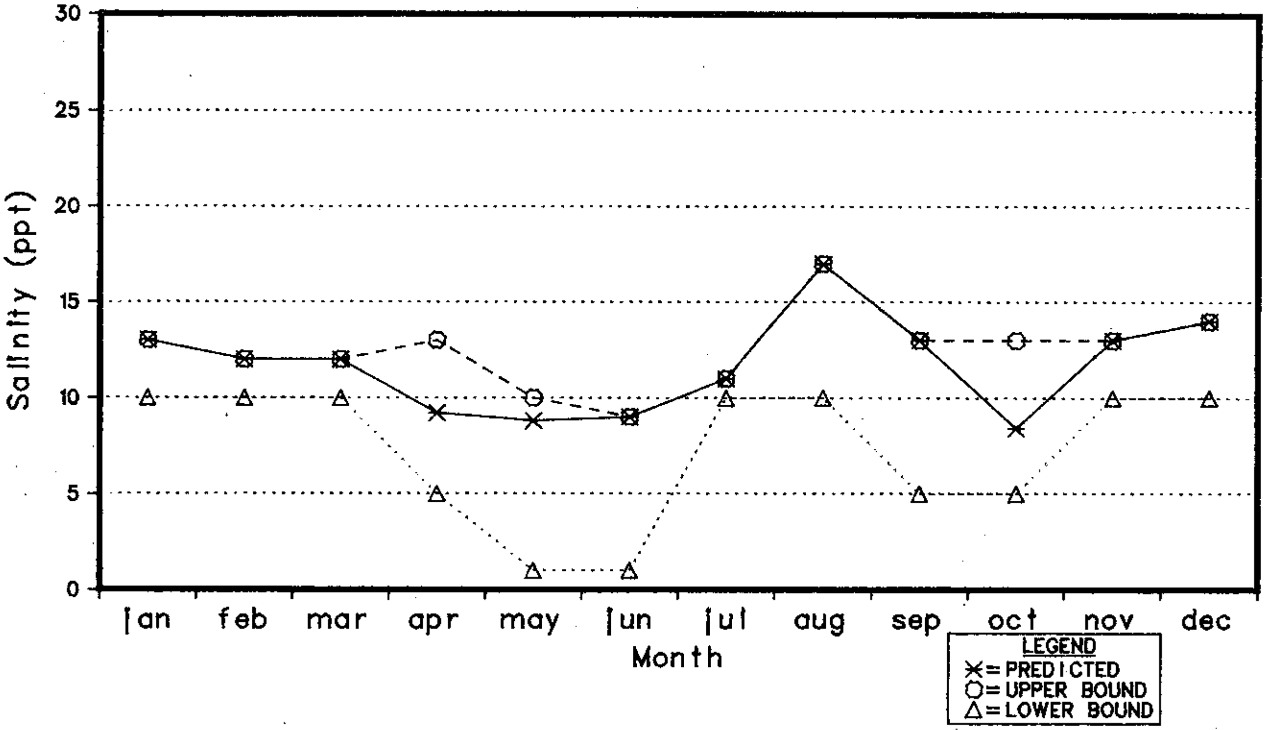

Figure 9-2. Average Monthly Salinities in Upper Lavaca Bay under Alternative I

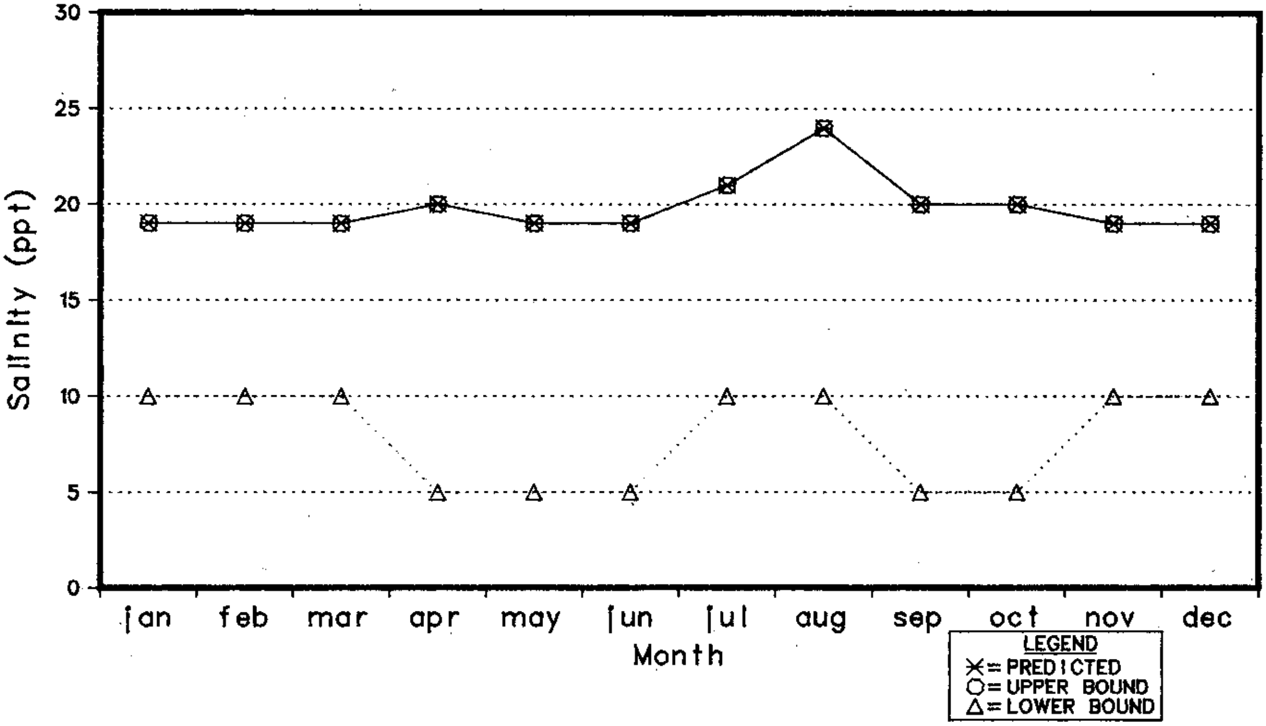

Figure 9-3. Average Monthly Salinities in Eastern Arm of Matagorda Bay under Alternative I

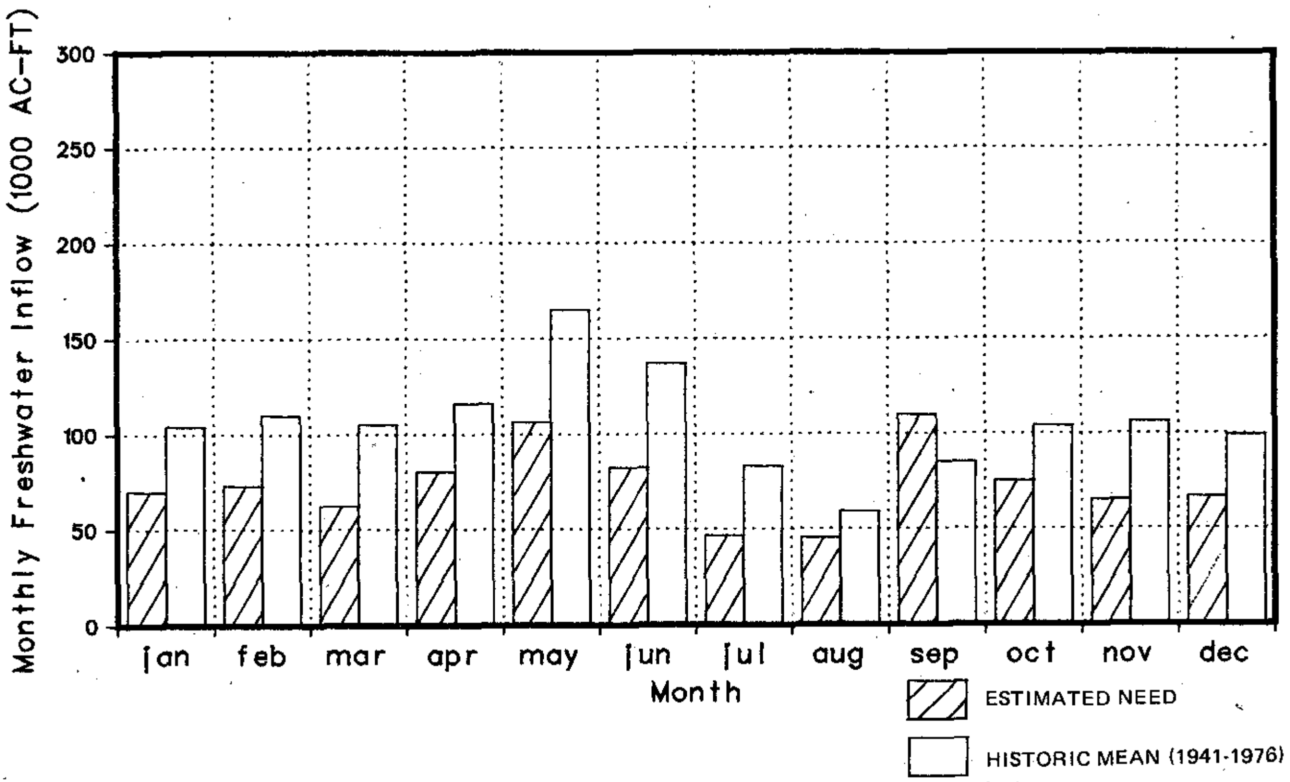

Figure 9-4. Comparison between Mean Historical Freshwater Inflow and Inflow Needs under Alternative I for the Lavaca-Tres Palacios Estuary from the Colorado River Basin

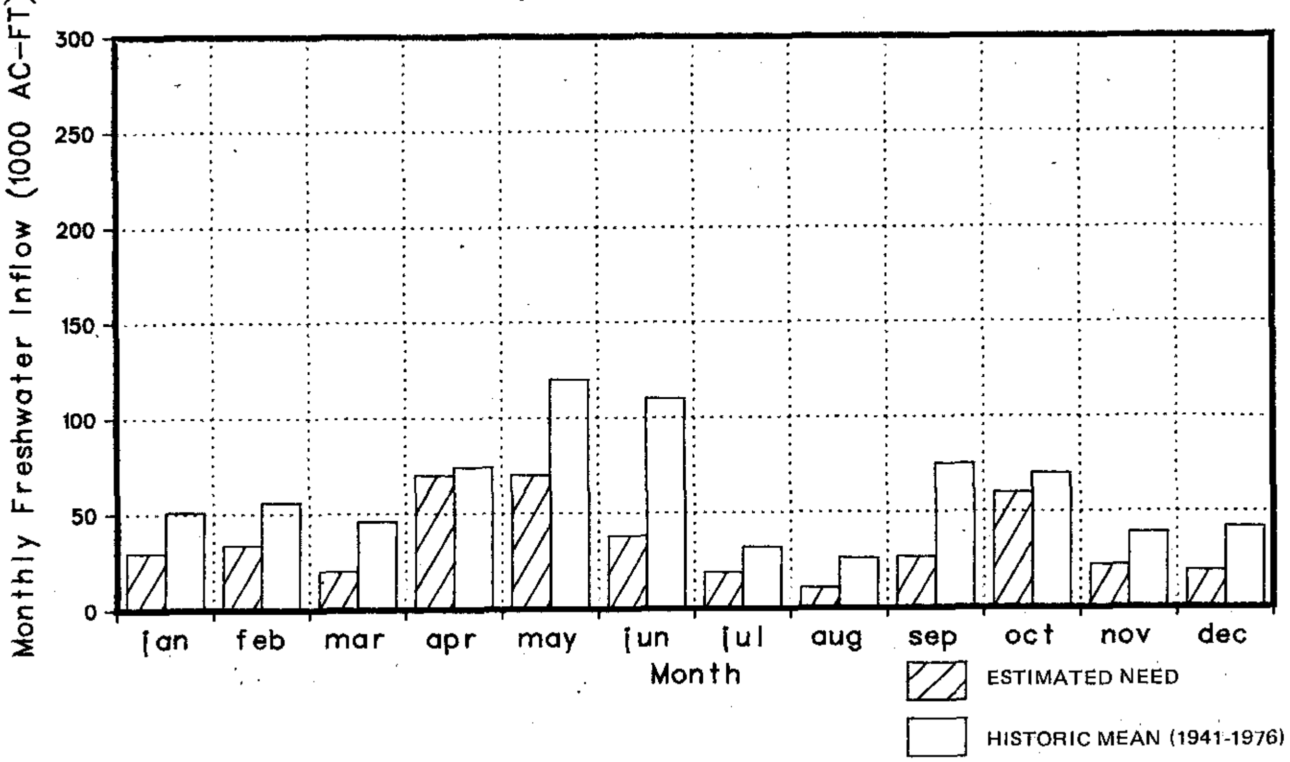

Figure 9-5. Comparison between Mean Historical Freshwater Inflow and Inflow Needs under Alternative I for the Lavaca-Tres Palacios Estuary from the Lavaca River Basin

Colorado and Lavaca River Basins. The estimated monthly freshwater inflow needs are less than the mean 1941 through 1976 historical inflows except for the month of September in the Colorado River Basin.[1/] The distribution of the freshwater inflow needs between basins is illustrated in Figure 9-6. The ungaged inflow from the Colorado-Lavaca and Lavaca-Guadalupe coastal basins is of major significance, since it is more than 30 percent of total inflow in most months.

Implementation of Alternative I for the Lavaca-Tres Palacios estuary under the inflow regime indicated in Table 9-6 is projected to result in a slight decrease in commercial fisheries harvests from average historical levels over the 1962 through 1976 period (Figure 9-7). The finfish category is predicted to have an annual harvest of 284.8 thousand pounds (129 thousand kg), or a five percent decrease from the average; total shellfish harvest, a 4.6 percent reduction from mean historical levels; and blue crab harvest, a predicted 19 percent decline from historical levels.

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, 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 2.81 million acre-feet (3,458 million m^3) annually, of which 796.0 thousand acre-feet (981 million m^3) are contributed from the coastal basins. The computed annual contributions of the Lavaca and Colorado River Basins would be 737.9 thousand (910 million m^3) and 1.27 million acre-feet (1,566 million m^3), respectively. These yearly volumes are only slightly less (0.1 percent) than the average 1941 through 1976 historical inflows from the respective river basins.

The Estuarine LP Model does not specify unique monthly inflows from the Lavaca River Basin in the spring (April, May, and June), summer (July and August), and early fall (September and October) seasons, or from the Colorado River Basin in the spring (April, May, and June) and early winter (November and December) seasons. The inflows in these seasons greater than that needed in the individual months for salinity maintenance and marsh inundation (Table 9-6) could be distributed on a monthly basis in any desired manner, consistent with the minimum inflow needed in each month, since the inflow variables in the fisheries equations represent only seasonal inflows. It was decided to distribute the inflows for the above seasons to individual months based upon the historical (1941-1976) inflow distribution (see Chapter III), while observing monthly salinity and inundation needs.

Monthly freshwater inflow needs generated for Alternative II (Figure 9-8) provide salinities which are considerably lower in upper Lavaca Bay than those under Alternative I, but which continue to closely approximate the upper salinity bound in the eastern arm of Matagorda Bay (Figure 9-9). Pre-

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[1/] This greater inflow need arises since the upper salinity limit in September is less than the median salinity for sample sites in Matagorda Bay where the salinity was evaluated (Table 9-2).

Table 9-6. Freshwater Inflow Needs of the Lavaca-Tres Palacios Estuary under Alternative I a/

Month	Lavaca River Basin		Colorado River Basin b/		Total Inflow From Coastal Basins	Combined Inflow e/
	Total Inflow Needs	Inflow Need from Gaged Portion of the Basin c/	Total Inflow Needs	Flow Need from Gaged Portion of the Basin d/		
			Thousands of Acre-Feet			
January	29.7	21.8	70.0	88.1	45.0	144.7
February	33.7	26.8	73.0	99.2	54.0	160.7
March	20.1	17.0	62.3	76.4	43.0	125.4
April	70.0	59.0	80.3	101.1	65.0	215.3
May	70.0	56.1	106.3	139.7	114.0	290.3
June	38.1	32.0	82.3	105.4	101.0	221.4
July	18.8	15.6	45.5	53.4	42.0	107.3
August	10.6	10.4	45.2	49.1	35.0	90.8
September	26.6	24.2	109.8	147.7	113.0	249.4
October	60.0	48.8	75.0	91.6	107.0	242.0
November	22.1	17.6	65.0	79.5	30.0	117.1
December	19.1	17.5	66.6	82.2	47.0	132.7
Annual	418.8	346.8	882.3	1,113.4	796.0	2,097.1

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a/ All inflows are mean monthly values.

b/ Some of the water passing the most downstream gage goes directly into the Gulf.

c/ These values computed using regression equations relating monthly river basin inflow to the estuary with the sum of the monthly gaged inflows at the USGS Stations at Ganado and Edna.

d/ These values computed using regression equations relating monthly river basin inflow to the estuary with monthly gaged inflows at the USGS Station at Bay City.

e/ Includes all freshwater inflow to the estuary except direct precipitation on the estuary's surface (see Chapter IV for definition).

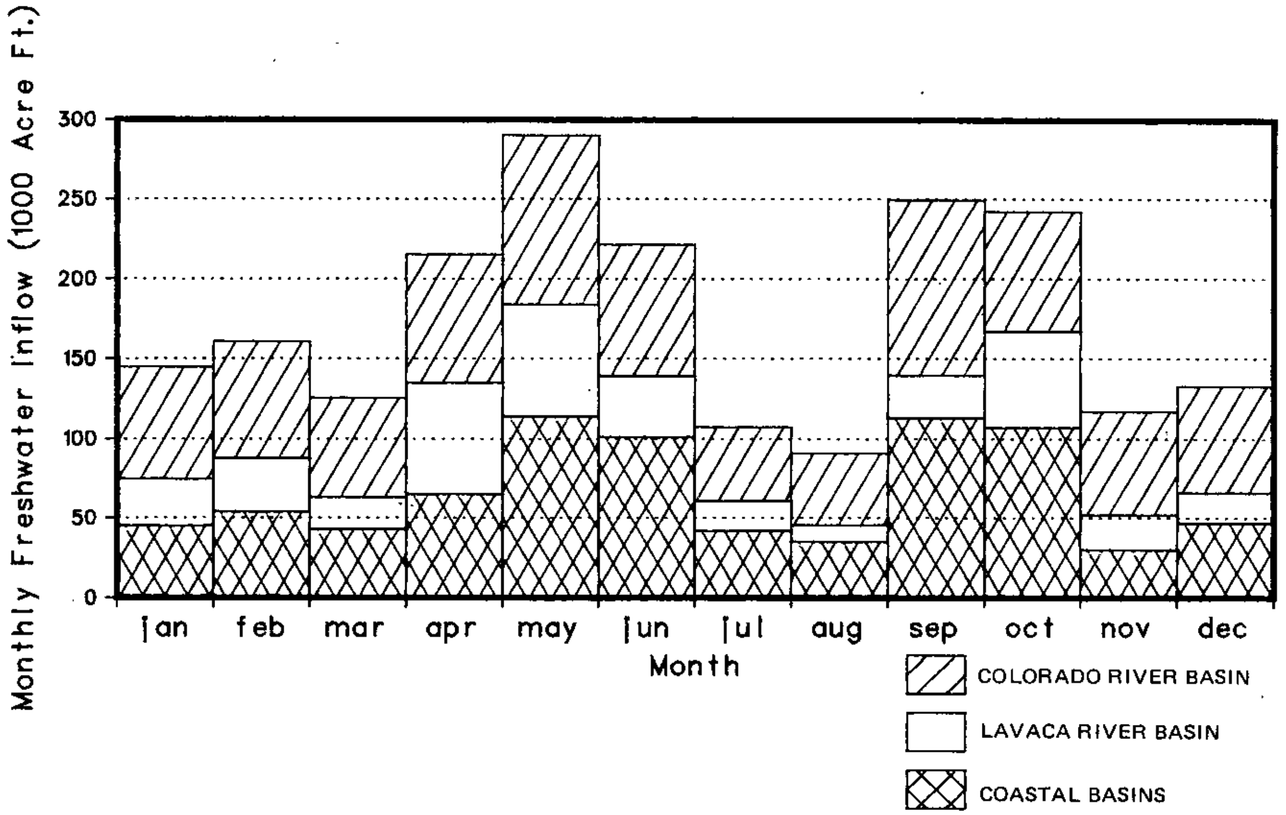

Figure 9-6. Estimated Freshwater Inflow Needs for the Lavaca-Tres Palacios Estuary under Alternative I

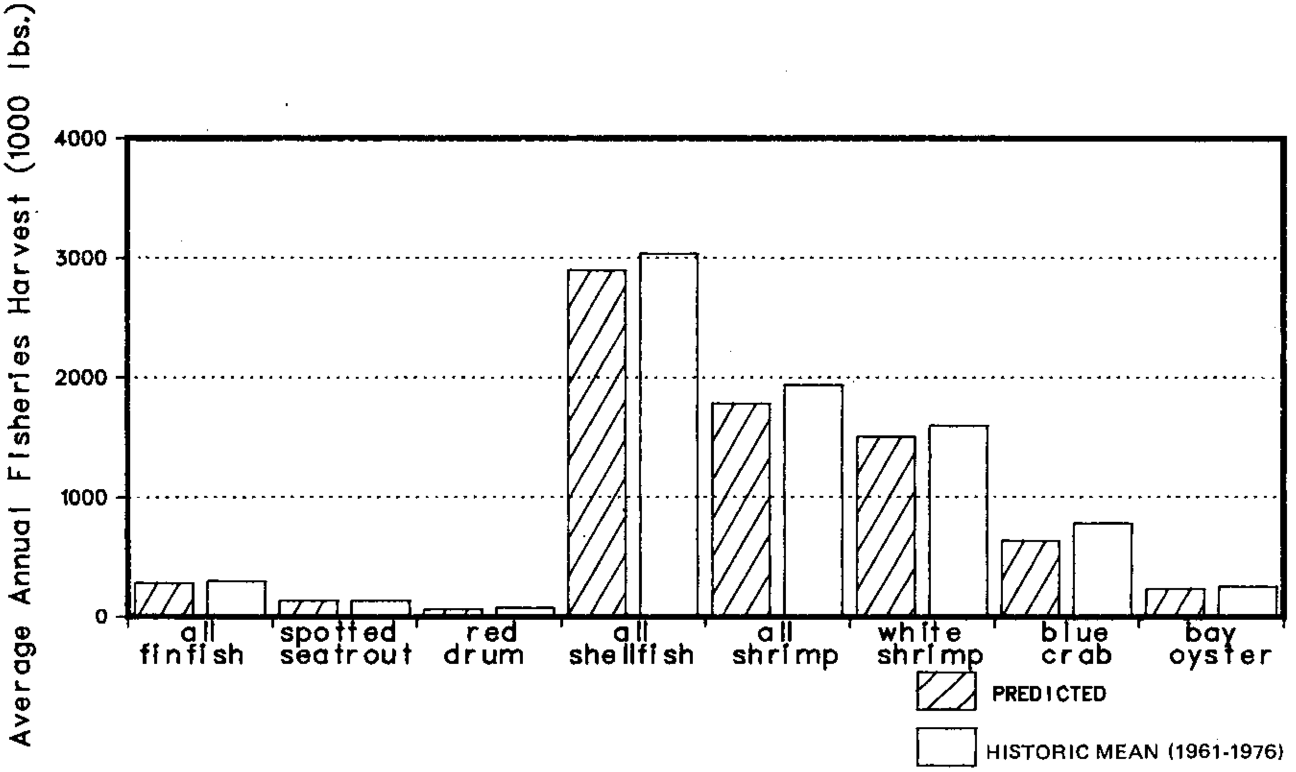

Figure 9-7. Comparison between Lavaca-Tres Palacios Historical Fisheries Harvests and Predicted Harvests under Alternative I

Table 9-7. Freshwater Inflow Needs of the Lavaca-Tres Palacios Estuary under Alternative II a/

Month	Lavaca River Basin		Colorado River Basin b/		Total Inflow From Coastal Basins	Combined Inflow e/
	Total Inflow Needs	Inflow Need from Gaged Portion of the Basin c/	Total Inflow Needs	Flow Need from Gaged Portion of the Basin d/		
	Thousands of Acre-Feet					
January	29.7	21.8	70.0	88.1	45.0	144.7
February	33.7	26.8	73.0	99.2	54.0	160.7
March	20.1	17.0	62.3	76.4	43.0	125.4
April	85.1 f/	71.7	100.5 i/	133.2	65.0	250.6
May	130.8 f/	104.8	135.0 i/	188.0	114.0	379.8
June	124.5 f/	106.4	116.1 i/	160.8	101.0	341.5
July	22.4 g/	18.4	46.5	53.4	42.0	110.9
August	38.8 g/	35.1	45.2	49.1	35.0	119.0
September	113.4 h/	97.1	109.8	147.7	113.0	336.2
October	98.2 h/	77.8	75.0	91.6	107.0	280.2
November	22.1	17.6	230.7 j/	387.7	30.0	282.8
December	19.1	17.6	209.6 j/	322.3	47.0	275.7
Annual	737.9	612.1	1,273.6	1,797.5	796.0	2,807.5

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a/ All inflows are mean monthly values.

b/ Some of the water passing the most downstream gage goes directly into the Gulf.

c/ These values computed using regression equations relating monthly river basin inflow to the estuary with the sum of the monthly gaged inflows at the USGS Stations at Ganado and Edna.

d/ These values computed using regression equations relating monthly river basin inflow to the estuary with monthly gaged inflows at the USGS Station at Bay City.

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 distributed according to the Lavaca River Basin historical (1941-1976) monthly freshwater inflow in the season (April, May, June).

g/ Total seasonal freshwater inflow need distributed according to the Lavaca River Basin historical (1941-1976) monthly freshwater inflow in the season (July, August).

h/ Total seasonal freshwater inflow need distributed according to the Lavaca River Basin historical (1941-1976) monthly freshwater inflow in the season (September, October).

i/ Total seasonal freshwater inflow need distributed according to the Colorado River Basin historical (1941-1976) monthly freshwater inflow in the season (April, May, June).

j/ Total seasonal freshwater inflow need distributed according to the Colorado River Basin historical (1941-1976) monthly freshwater inflow in the season (November, December).

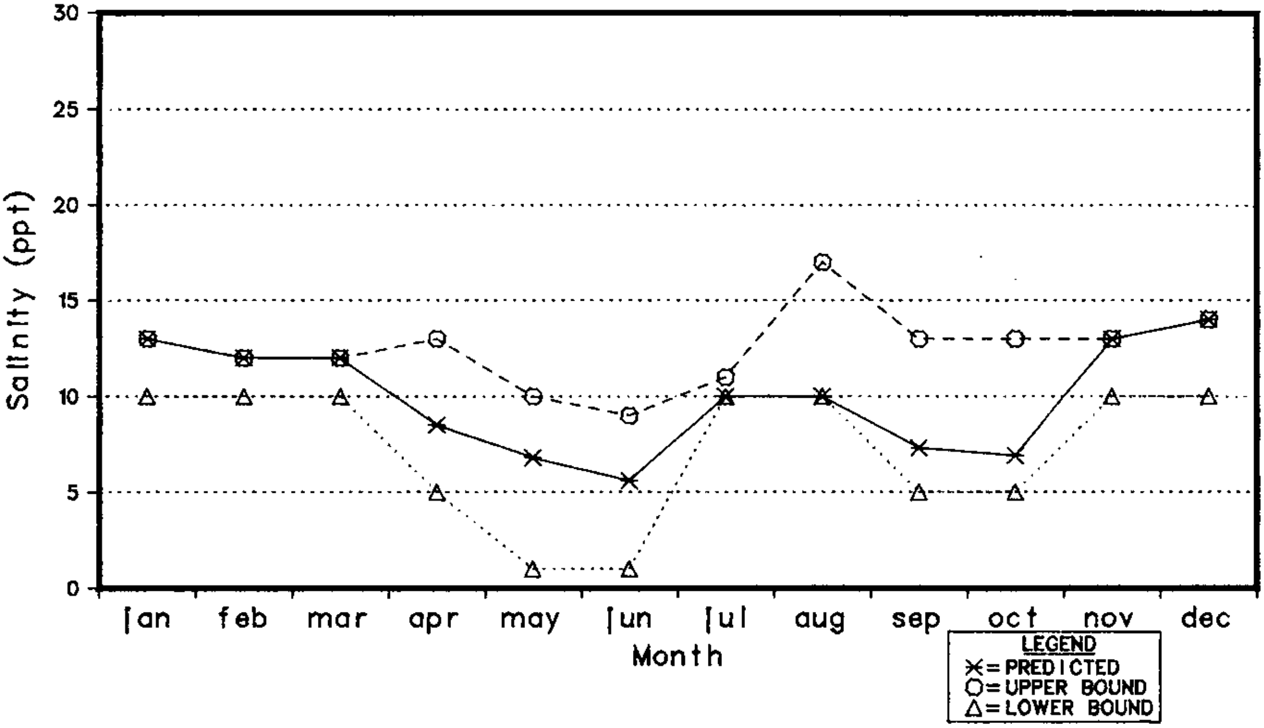

Figure 9-8. Average Monthly Salinities in Upper Lavaca Bay under Alternative II

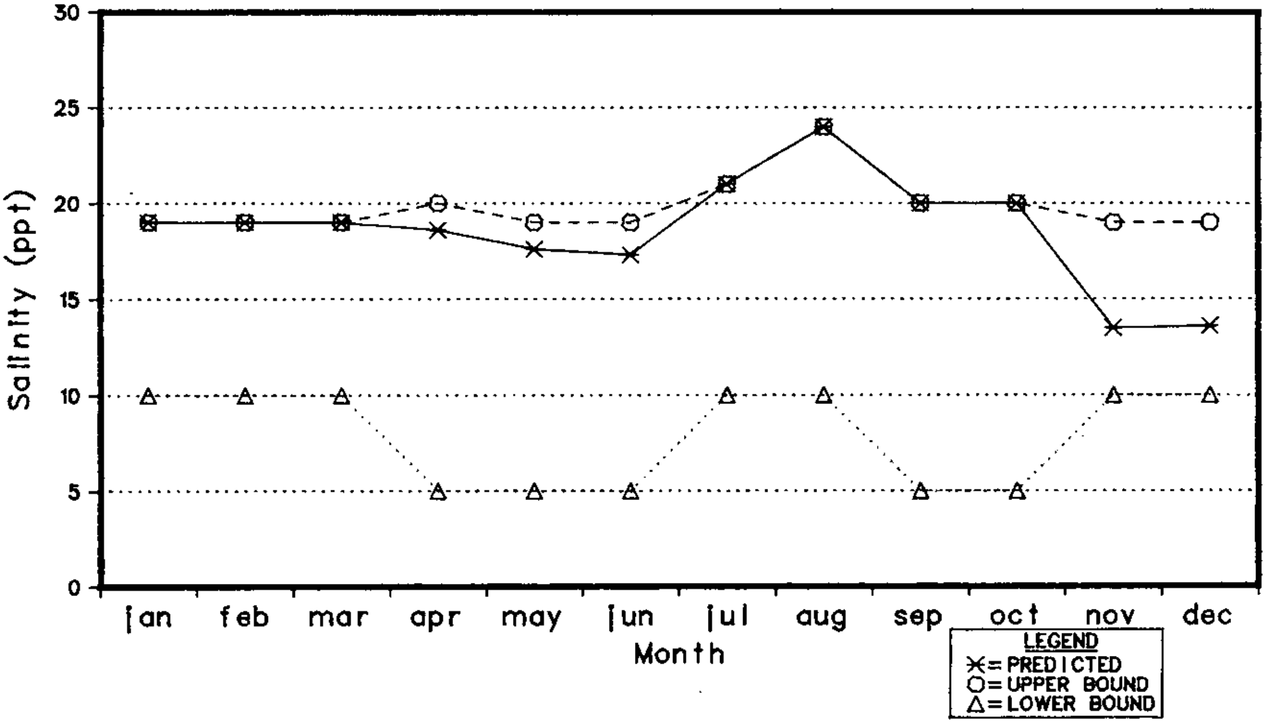

Figure 9-9. Average Monthly Salinities in Eastern Arm of Matagorda Bay under Alternative II

dicted salinities are lower for this alternative than those for Alternative I during critical months of fisheries productivity, as additional inflow is supplied to increase fisheries harvests under Alternative II.

Comparisons between the mean historical combined inflows and estimated freshwater inflow needs for Alternative II were made for the Colorado and Lavaca Basins (Figures 9-10 and 9-11). The average historical inflows for the Colorado Basin are generally greater for each month than the freshwater inflow needs under this Alternative. Notable exceptions are the months of September, November, and December.[1/] From the Lavaca Basin, larger inflows are needed in the spring season (April, May, and June) to increase the shrimp harvest. Inflow needs in the winter (January through March) and fall (November and December) seasons are near minimum values necessary to satisfy the upper bounds for salinity. 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 Lavaca-Tres Palacios estuary under the inflow regime indicated in Table 9-7 results in a projected increase in commercial fisheries harvests from average historical levels over the 1962 through 1976 period for all harvest groups except total shellfish and white shrimp (Figure 9-13). Total shellfish harvest is projected to be slightly (3.5 percent) less than the historical average, while estimated white shrimp harvest would decrease by 16.5 percent.

Alternative III: Shellfish Harvest Enhancement. The objective of Alternative III (Shellfish Harvest Enhancement) is to maximize the annual commercial harvest of shellfish, as represented by the sum of the shrimp, blue crab, and bay oyster estuarine harvests, while observing salinity limits and marsh inundation needs, utilizing annual Lavaca and Colorado River Basin inflows no greater than their respective 1941 through 1976 average historical annual inflows, and not allowing the estimated blue crab and bay oyster harvests to be below their 1962 through 1976 historical averages.

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 [2/] from freshwater sources needed to maximize the shellfish harvest was estimated at 2.811 million acre-feet (3,45 million m^3). The total annual contribution from the Colorado River Basin was estimated at 1.27 million acre-feet (1,566 million m^3), while the corresponding Lavaca River Basin contribution was 740 thousand acre-feet (913 million m^3). The remaining annual freshwater contribution of 796 thousand acre-feet (981 million m^3) was the 1941 through 1976

[1/] A result of the distribution of monthly inflows needed to achieve the desired management objectives is that if the November and December inflows were set closer to average historical levels while the other monthly inflows remain unchanged, then it would be impossible to simultaneously provide predicted harvests of blue crab and bay oysters at levels as great as their historical 1962 through 1976 averages. Normally, greater than average harvests of bay oyster and blue crab have not occurred in the same year.

[2/] Combined inflow does not include direct precipitation on the estuary's surface (See Chapter IV for definition).

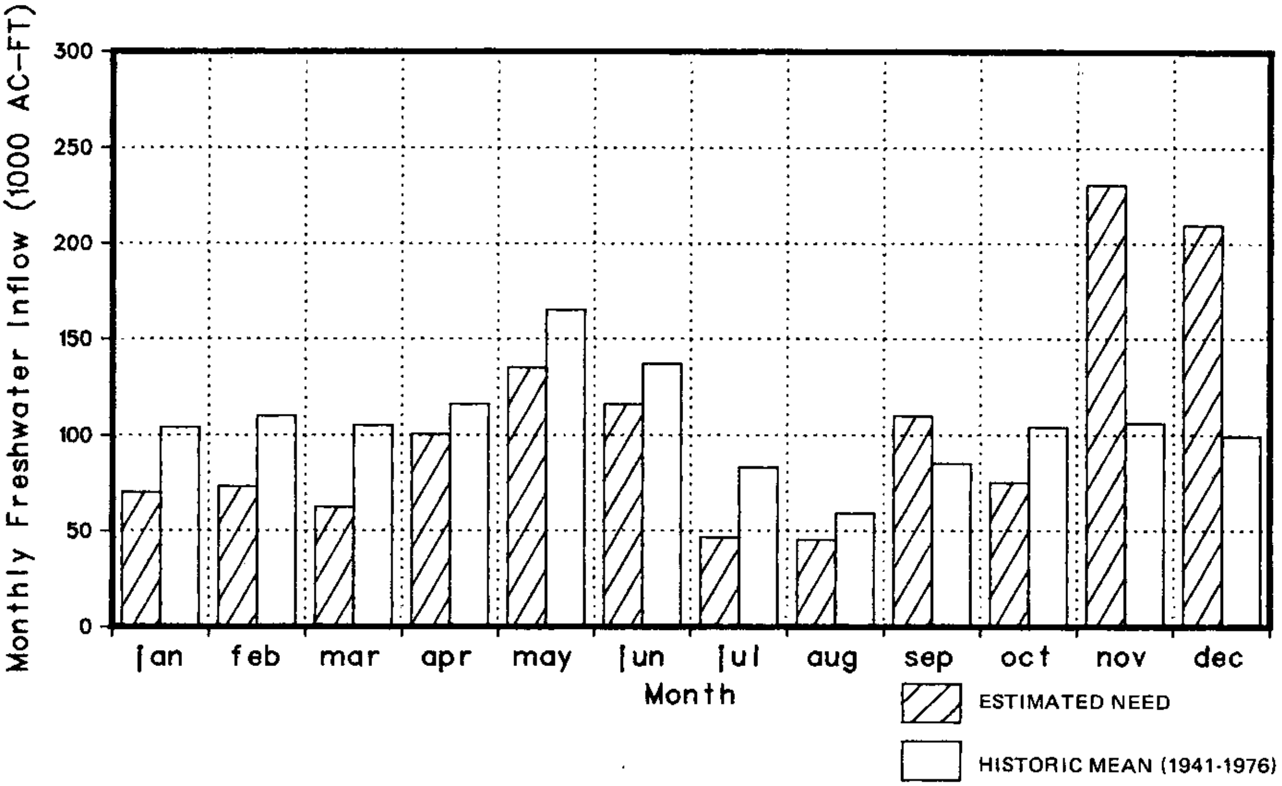

Figure 9-10. Comparison between Mean Historical Freshwater Inflow and Inflow Needs under Alternative II for the Lavaca-Tres Palacios Estuary from the Colorado River Basin

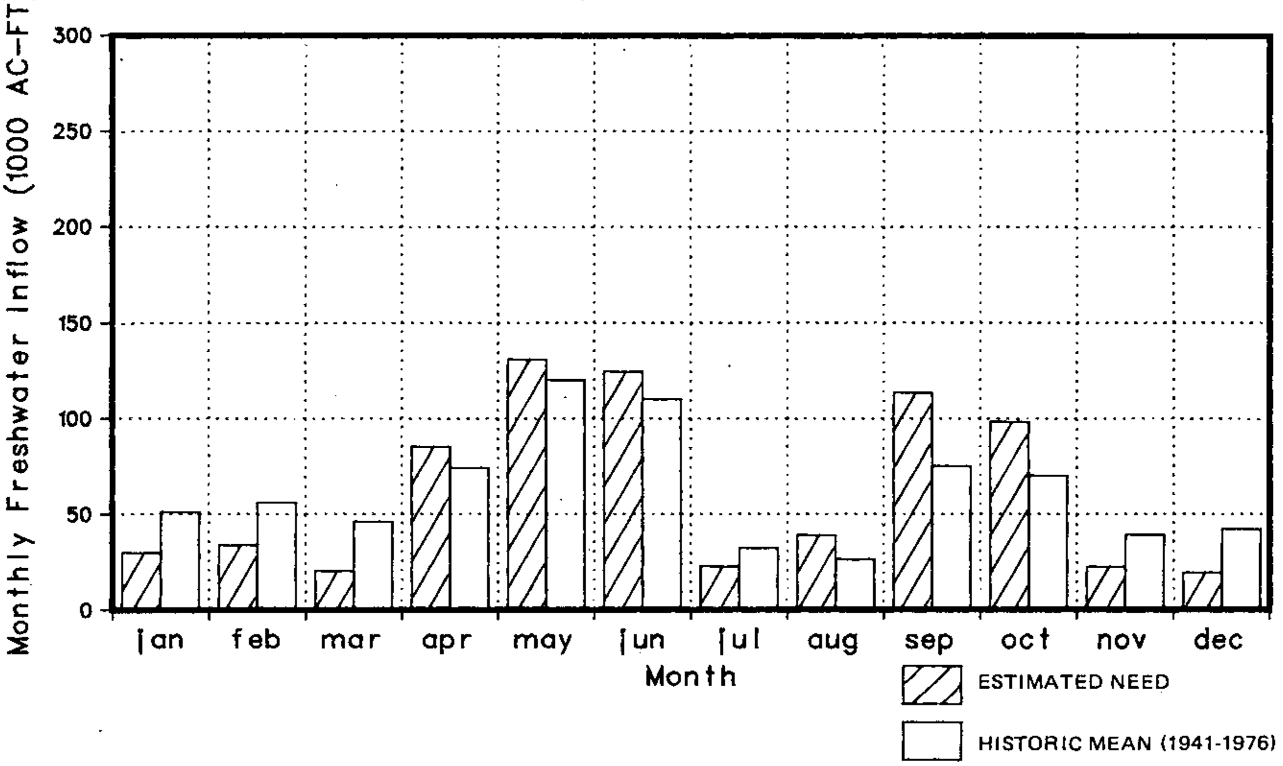

Figure 9-11. Comparison between Mean Historical Freshwater Inflow and Inflow Needs under Alternative II for the Lavaca-Tres Palacios Estuary from the Lavaca River Basin

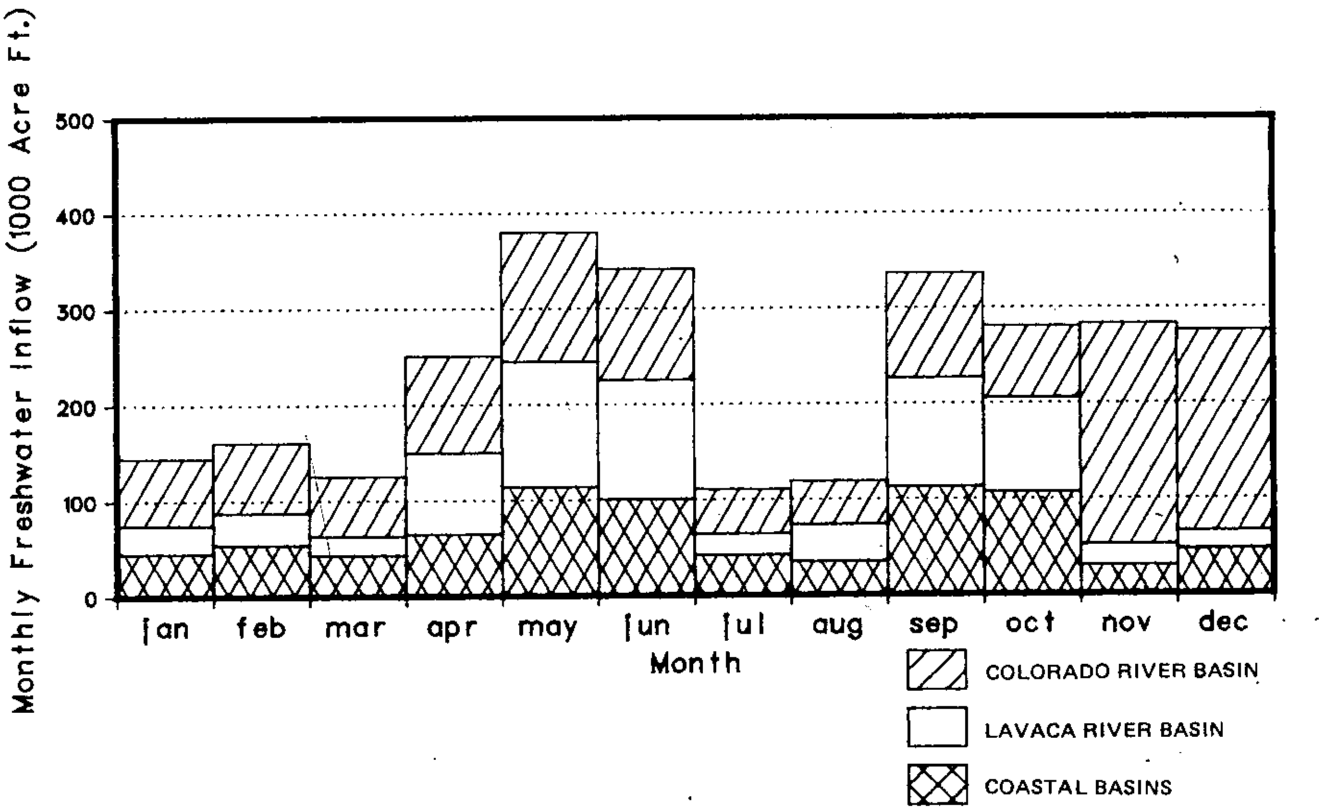

Figure 9-12. Estimated Freshwater Inflow Needs for the Lavaca-Tres Palacios Estuary under Alternative II

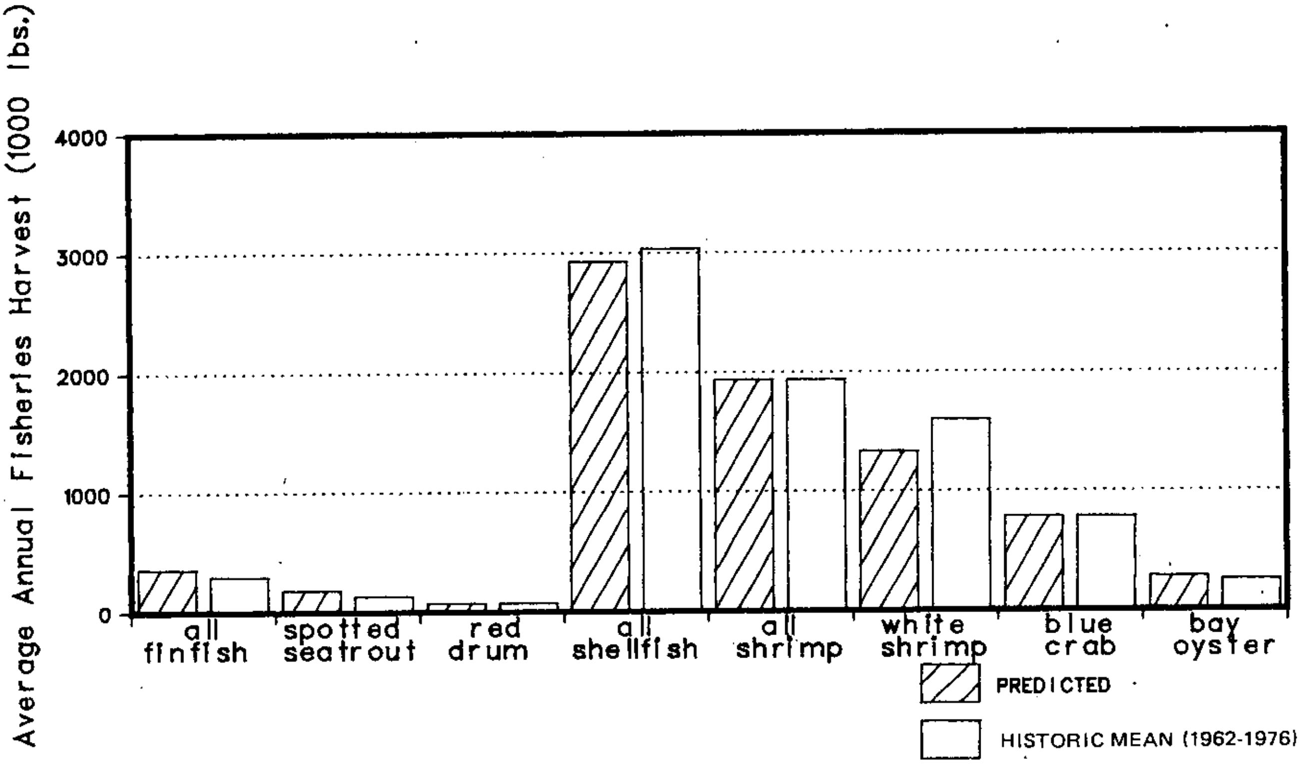

Figure 9-13. Comparison between Lavaca-Tres Palacios Historical Fisheries Harvests and Predicted Harvests under Alternative II

Table 9-8. Freshwater Inflow Needs of the Lavaca-Tres Palacios Estuary under Alternative III a/

Month	Lavaca River Basin		Colorado River Basin b/		Total Inflow From Coastal Basins	Combined Inflow e/
	Total Inflow Needs	Inflow Need from Gaged Portion of the Basin c/	Total Inflow Needs	Flow Need from Gaged Portion of the Basin d/		
	Thousands of Acre-Feet					
January	29.7	21.8	70.0	88.1	45.0	144.7
February	33.7	26.8	73.0	99.2	54.0	160.7
March	20.1	17.0	62.3	76.4	43.0	125.4
April	126.8f/	106.4	80.3	101.1	65.0	272.1
May	192.7f/	154.3	106.3	139.7	114.0	413.0
June	179.7f/	153.8	82.3	105.4	101.0	363.0
July	18.8	15.6	98.4g/	162.5	42.0	159.2
August	10.6	10.4	77.8g/	109.7	35.0	123.4
September	26.6	24.2	109.8	147.7	113.0	249.4
October	60.0	48.8	75.0	91.6	107.0	242.0
November	22.1	17.6	228.7h/	383.7	30.0	280.8
December	19.1	17.5	211.1h/	325.1	47.0	277.2
Annual	739.9	614.2	1,275.0	1,830.2	796.0	2,810.9

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a/ All inflows are mean monthly values.

b/ Some of the water passing the most downstream gage goes directly into the Gulf.

c/ These values computed using regression equations relating monthly river basin inflow to the estuary with the sum of the monthly gaged inflows at the USGS Stations at Ganado and Edna.

d/ These values computed using regression equations relating monthly river basin inflow to the estuary with monthly gaged inflows at the USGS Station at Bay City.

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 distributed according to the Lavaca River Basin historical (1941-1976) monthly freshwater inflow in the season (April, May, June).

g/ Total seasonal freshwater inflow need distributed according to the Lavaca River Basin historical (1941-1976) monthly freshwater inflow in the season (July, August).

h/ Total seasonal freshwater inflow need distributed according to the Lavaca River Basin historical (1941-1976) monthly freshwater inflow in the season (September, October).

estimated historical average annual inflow from the Colorado-Lavaca and Lavaca-Guadalupe Coastal Basins. As with Alternative II, some seasonal inflows were distributed monthly on the basis of historical inflows as indicated in Table 9-8.

Monthly freshwater inflow needs generated for Alternative III (Figure 9-14) provide salinities which are slightly lower in spring months for Lavaca Bay than those under Alternative II. In the summer and fall months; however, Lavaca Bay salinities are about the same as those under Alternative I. Salinity in the eastern arm of Matagorda Bay is markedly lower under Alternative III (Figure 9-15) in the summer months, where inflows are required for shellfish harvest enhancement.

Comparisons between mean historical combined inflows and estimated freshwater inflow needs under Alternative III have been made for the Colorado and Lavaca Basins (Figures 9-16 and 9-17). The average historical inflows for the Colorado Basin are higher than freshwater inflow needs under Alternative III for winter and spring months, slightly lower than estimated needs in the summer, and much lower than the needs for shellfish enhancement in late fall (November and December). Historical inflows from the Lavaca Basin are higher than the estimated needs under Alternative III for all months except in the spring, when freshwater inflow needs for shrimp harvest enhancement are substantial. The Estuarine Linear Programming Model distributes monthly inflows to achieve Alternative III (Shellfish Harvest Enhancement) as indicated in Figure 9-18.

According to this analysis, implementation of Alternative III for the Lavaca-Tres Palacios estuary under the inflow regime indicated in Table 9-8 would result in an estimated 22 percent increase in total shellfish harvest above the mean historical level (Figure 9-19), while the inflow level is equal to the mean 1941 through 1976 historical inflow. Projected changes in individual shellfish categories under Alternative III include a 26 percent increase in all shrimp harvested, a six percent increase in blue crab harvested, and a 14 percent decrease in white shrimp harvested. No change is projected in bay oyster harvests. In the finfish categories, projected changes from historic conditions include a five percent decrease in all finfish harvested, a one percent increase in spotted seatrout harvested, and a 46 percent decrease in red drum harvested.

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 Lavaca-Tres Palacios 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

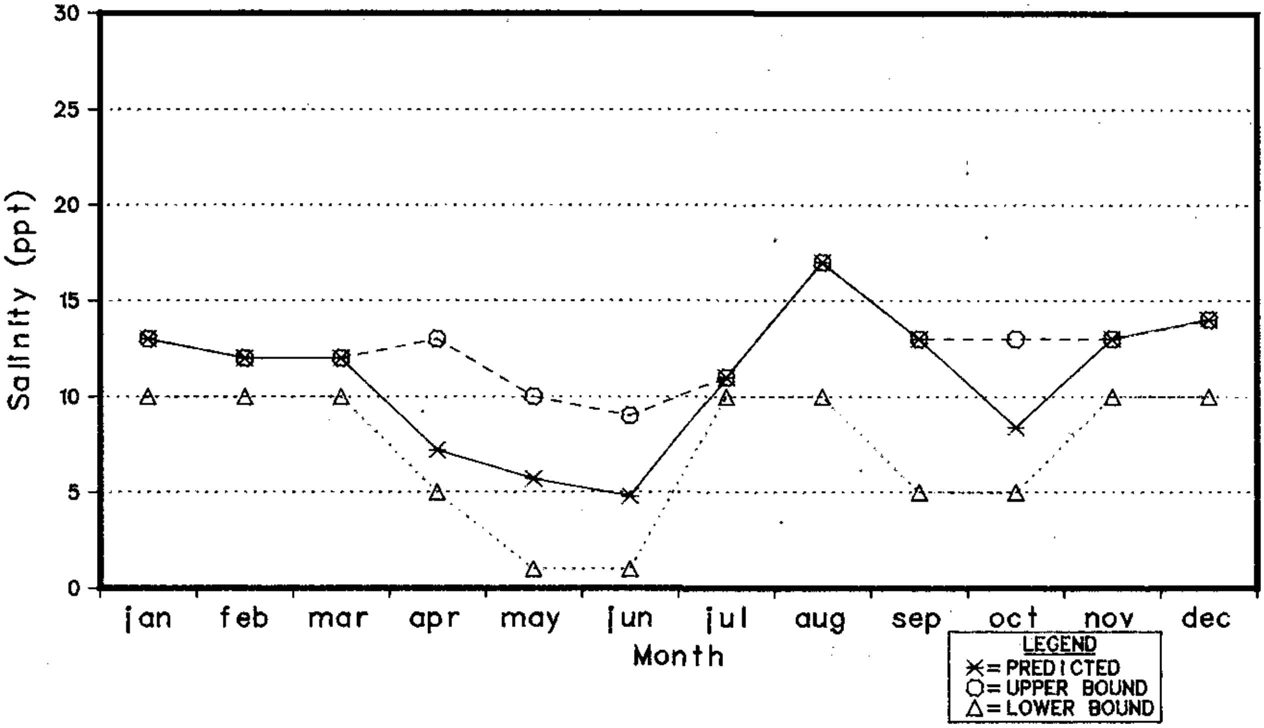

Figure 9-14. Average Monthly Salinities in Upper Lavaca Bay under Alternative III

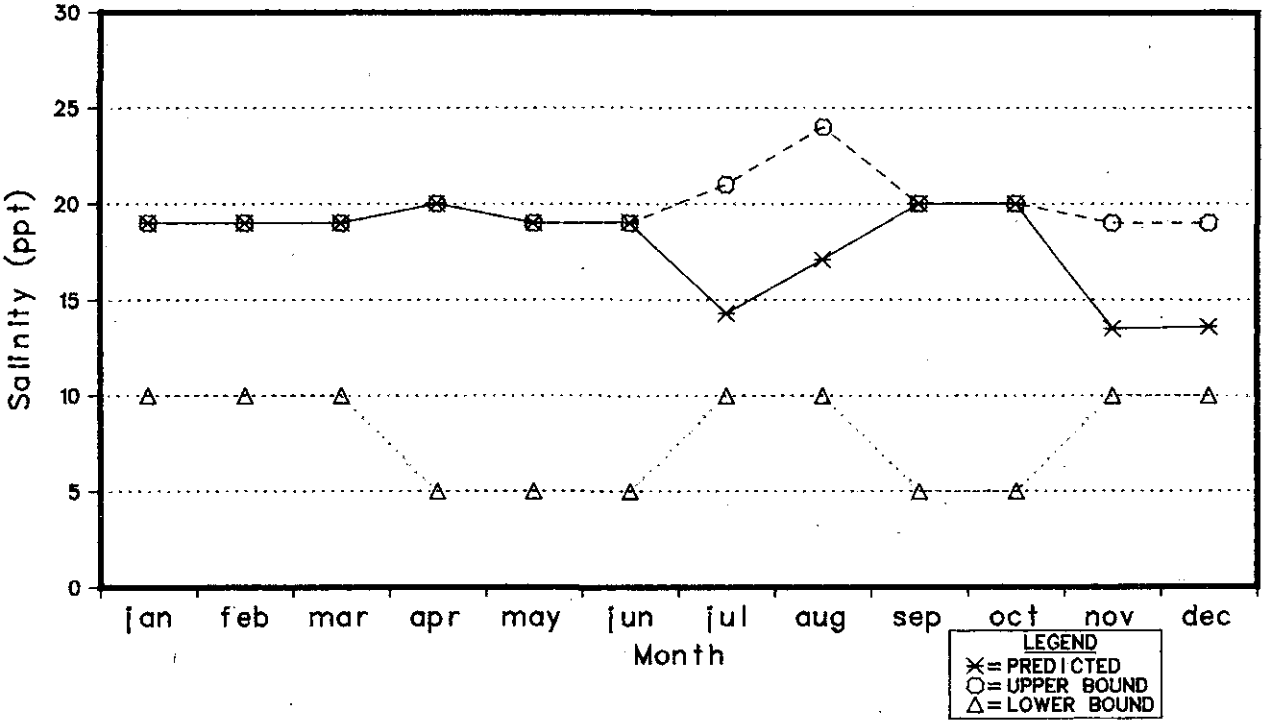

Figure 9-15. Average Monthly Salinities in Eastern Arm of Matagorda Bay under Alternative III

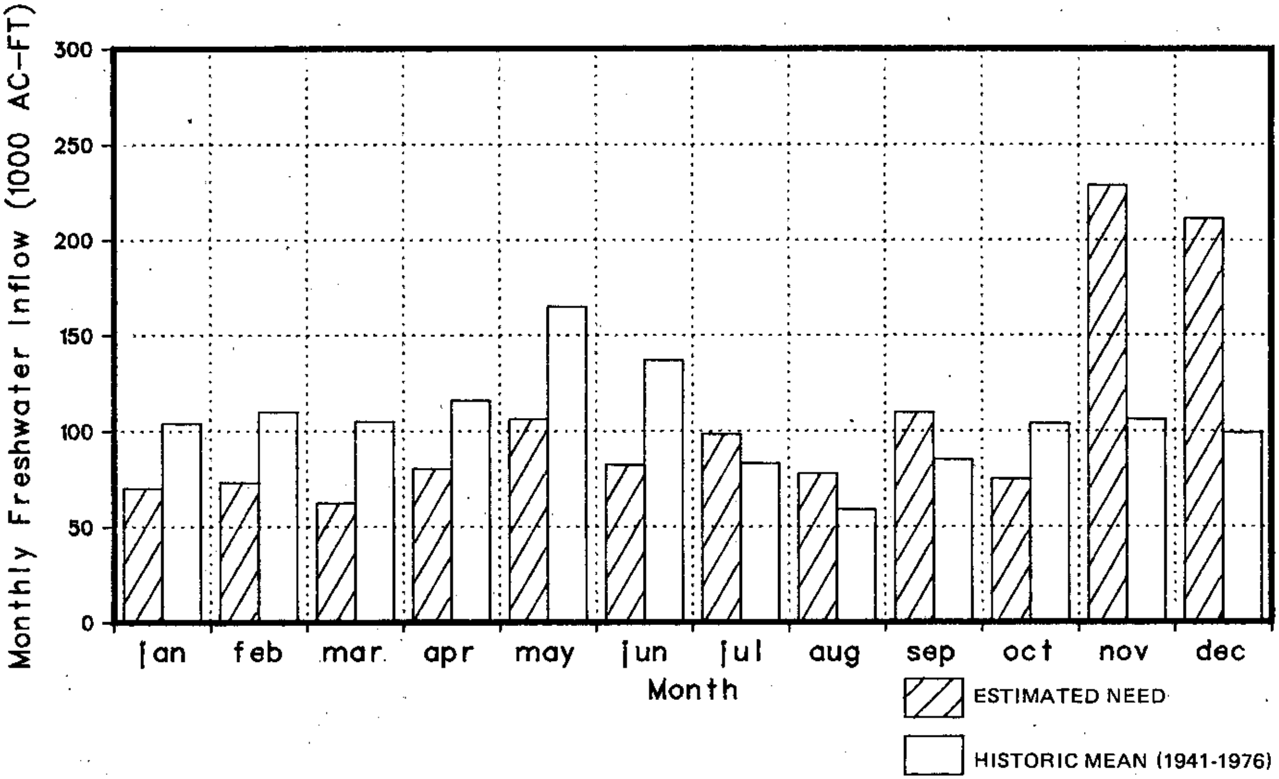

Figure 9-16. Comparison between Mean Historical Freshwater Inflow and Inflow Needs under Alternative III for the Lavaca-Tres Palacios Estuary from the Colorado River Basin

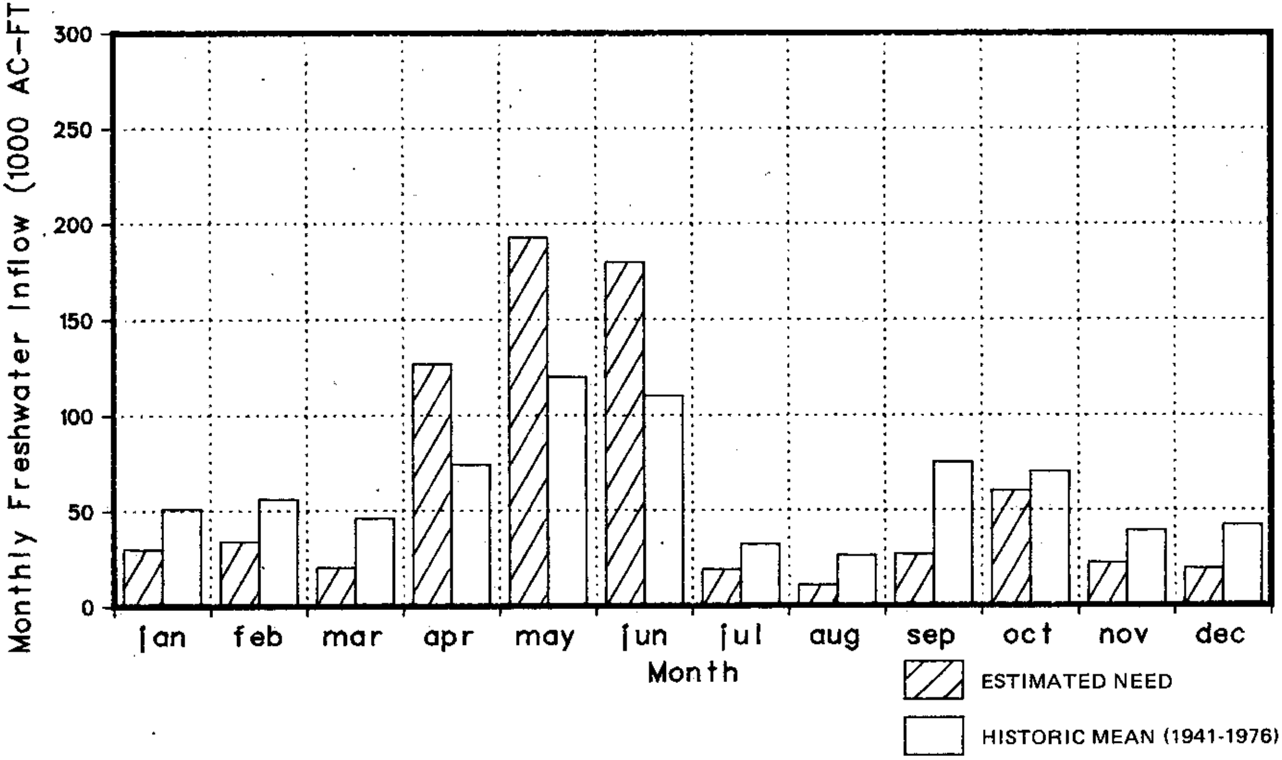

Figure 9-17. Comparison between Mean Historical Freshwater Inflow and Inflow Needs under Alternative III for the Lavaca-Tres Palacios Estuary from the Lavaca River Basin

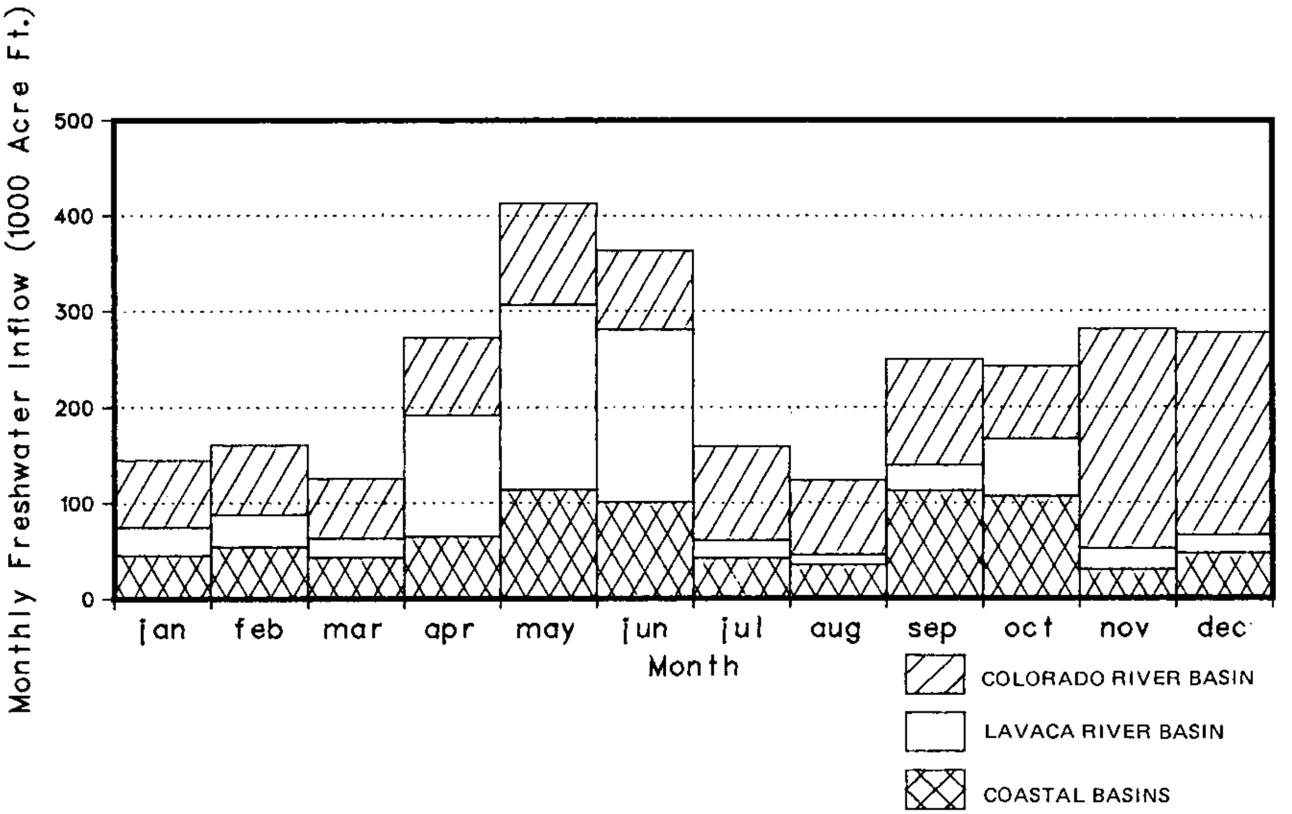

Figure 9-18. Estimated Freshwater Inflow Needs for the Lavaca-Tres Palacios Estuary under Alternative III

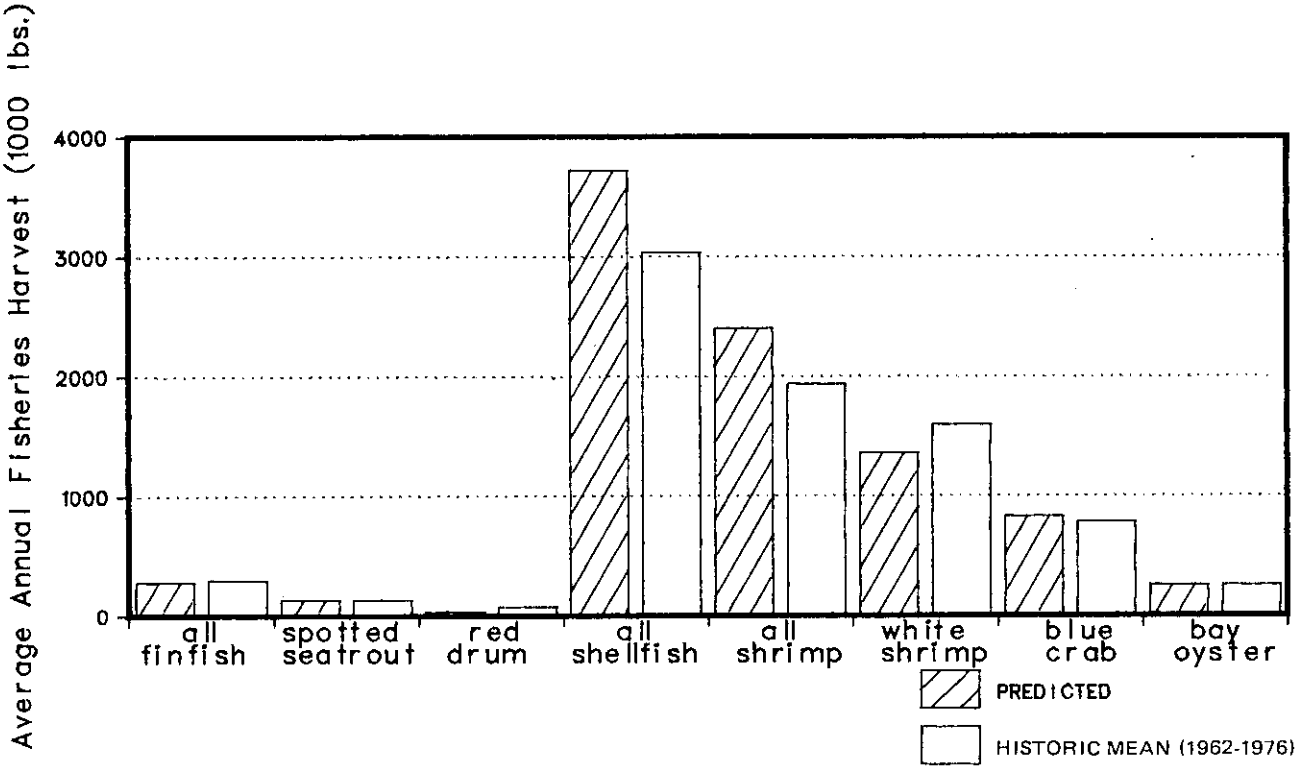

Figure 9-19. Comparison between Lavaca-Tres Palacios Historical Fisheries Harvests and Predicted Harvests under Alternative III

the estimated estuarine conditions not be satisfactory, then the constraints upon the Estuarine Linear Programming Model must be modified, and the model again used 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 Matagorda Bay should not exceed 25 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 across the estuary meet the 25 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 Matagorda Bay is not evaluated since it was not anticipated that the monthly inflows under the three alternatives would give salinities lower than 10 ppt.

<u>Simulation of Mean Monthly Circulation and Salinity Patterns</u>. The estimated monthly freshwater inflow needs to the Lavaca-Tres Palacios 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 Lavaca-Tres Palacios 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 33 x 32 computational matrix representing the Lavaca-Tres Palacios 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.

The tidal amplitudes and flows calculated by the tidal hydrodynamics model are used as input to operate the salinity transport model to simulate the salinity distributions in the Lavaca-Tres Palacios estuary for each of the mean monthly periods. 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 simulated monthly circulation (Figures 9-20 through 9-31) and salinity (Figures 9-32 through 9-43) patterns in the estuary can be divided into five groupings based upon similarities: (1) November, December and January; (2) February, March and April; (3) May and June; (4) July and August; and (5) September and October. The flow and salinity characteristics exhibited by the numerical simulations in each of the five cases are discussed below.

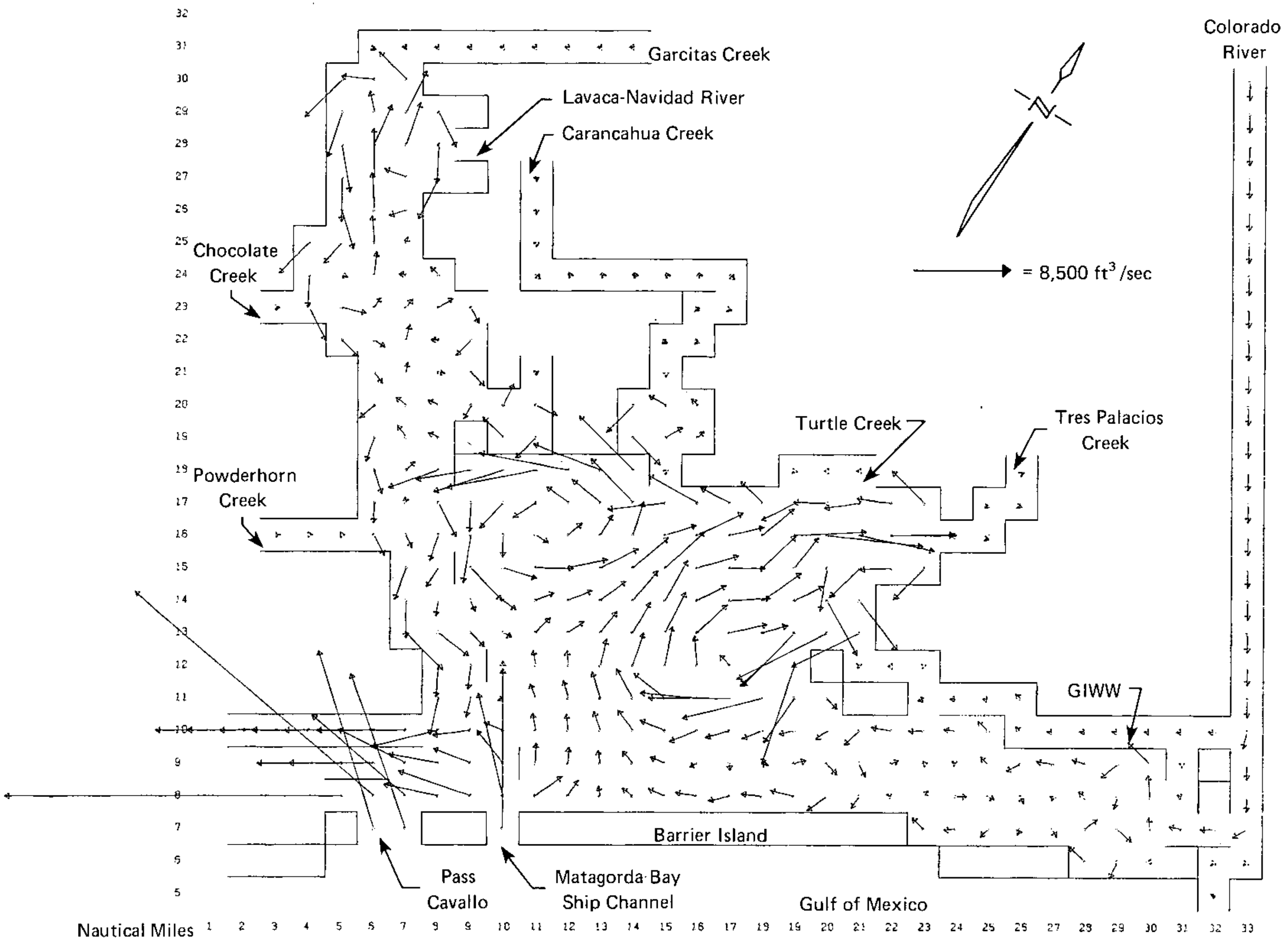

Figure 9-20. Simulated Net Steady-State Flows in the Lavaca-Tres Palacios Estuary under January Freshwater Inflow Needs, Alternative I

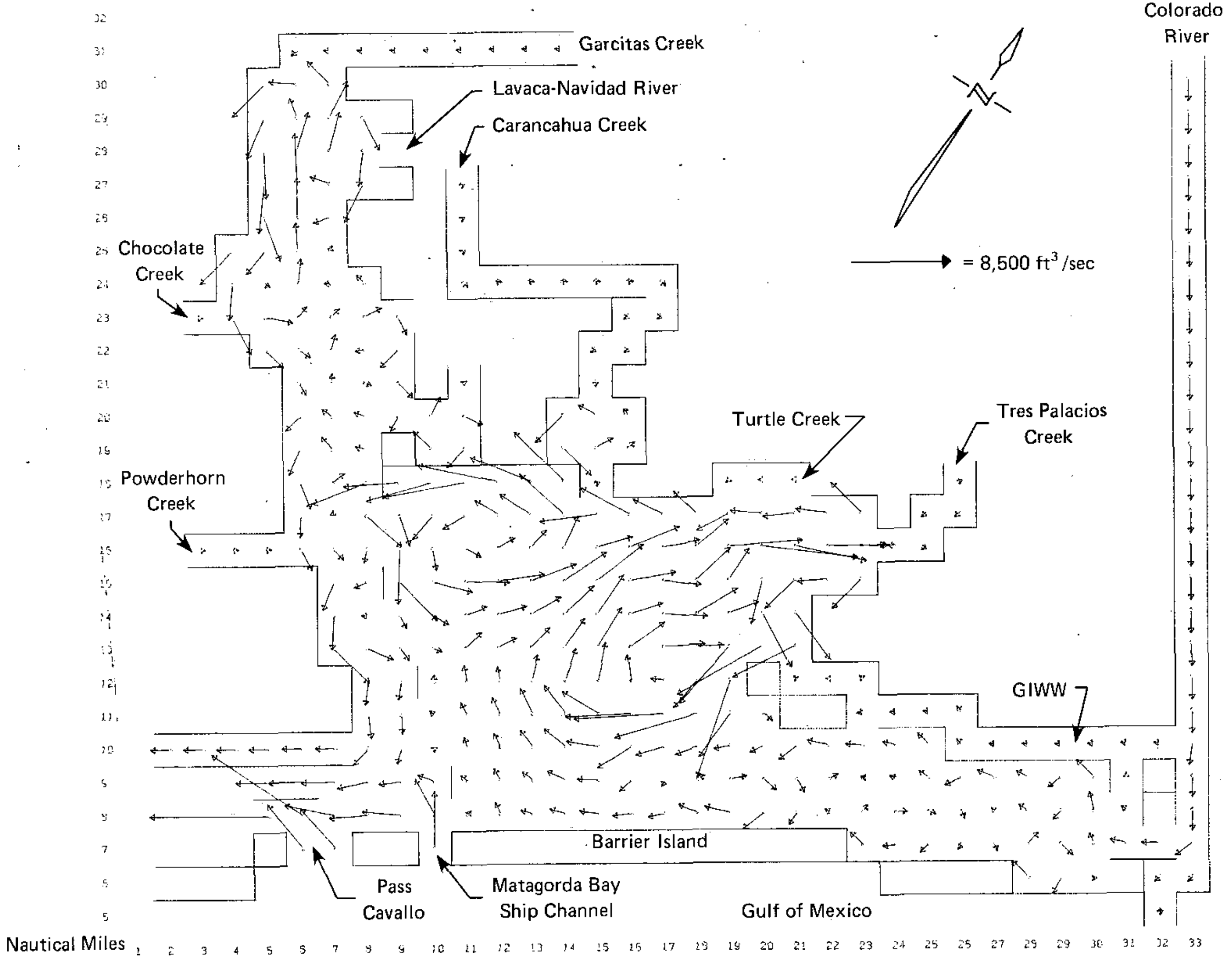

Figure 9-21. Simulated Net Steady-State Flows in the Lavaca-Tres Palacios Estuary under February Freshwater Inflow Needs, Alternative I

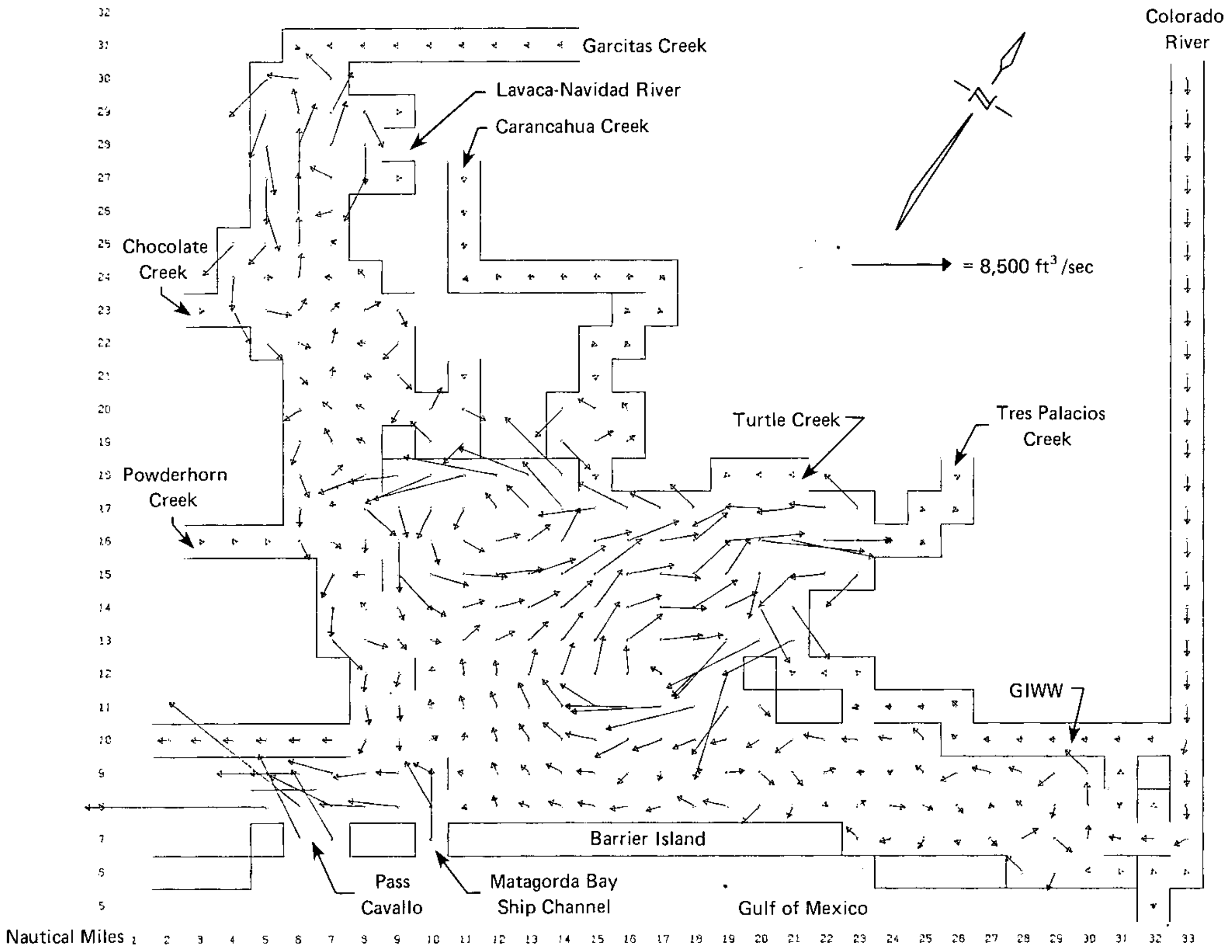

Figure 9-22. Simulated Net Steady-State Flows in the Lavaca-Tres Palacios Estuary under March Freshwater Inflow Needs, Alternative I

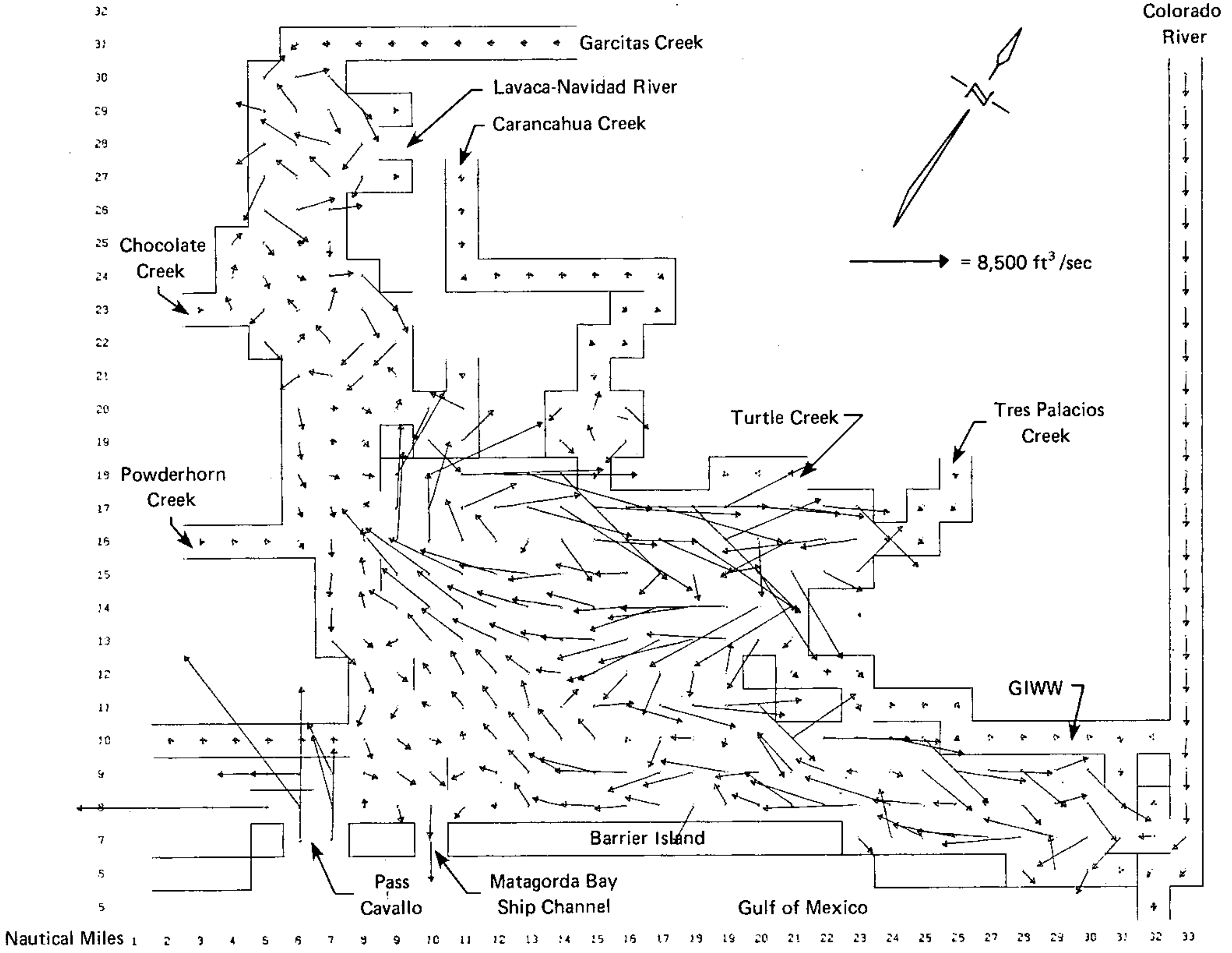

Figure 9-23. Simulated Net Steady-State Flows in the Lavaca-Tres Palacios Estuary under April Freshwater Inflow Needs, Alternative I

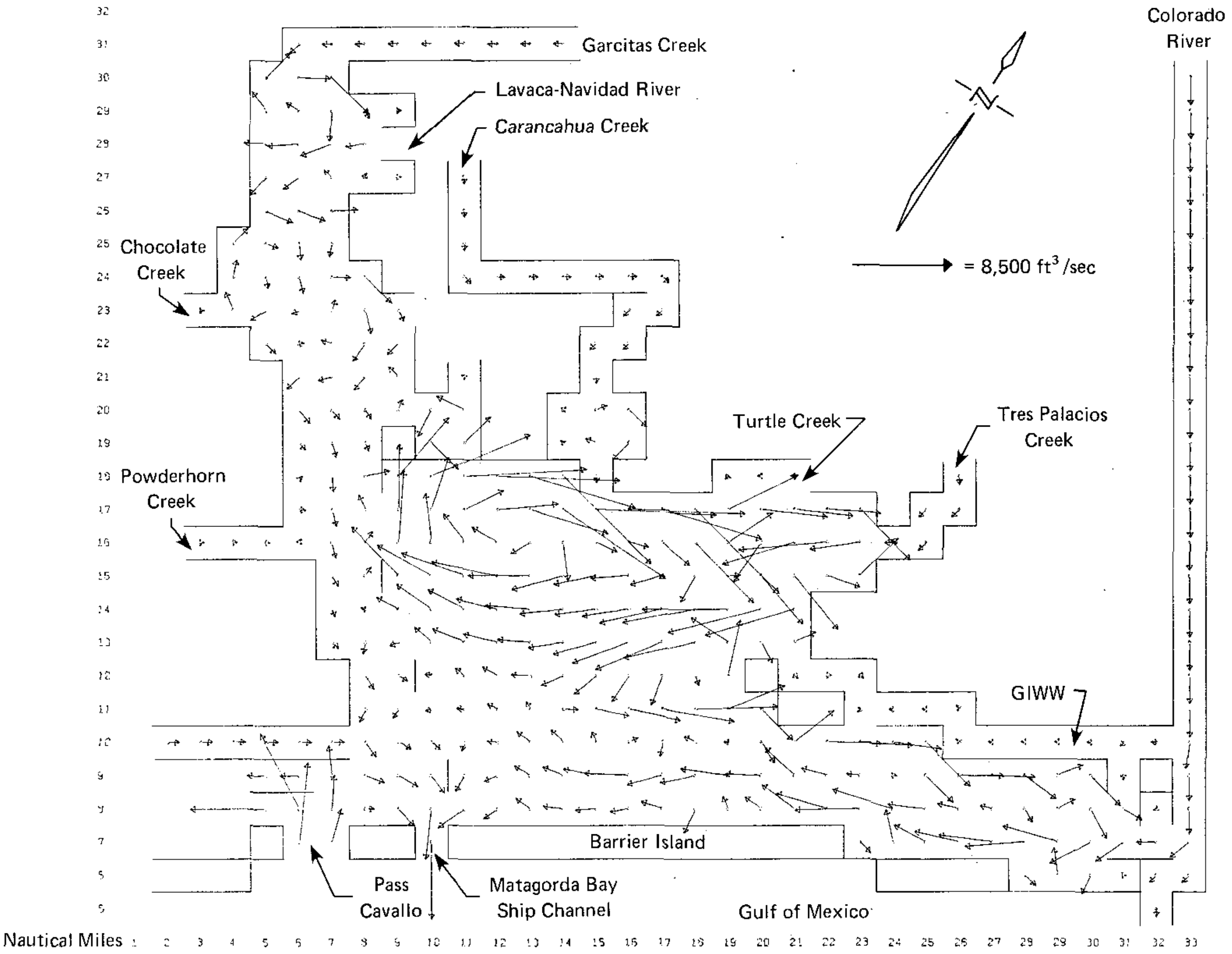

Figure 9-24. Simulated Net Steady-State Flows in the Lavaca-Tres Palacios Estuary under May Freshwater Inflow Needs, Alternative I

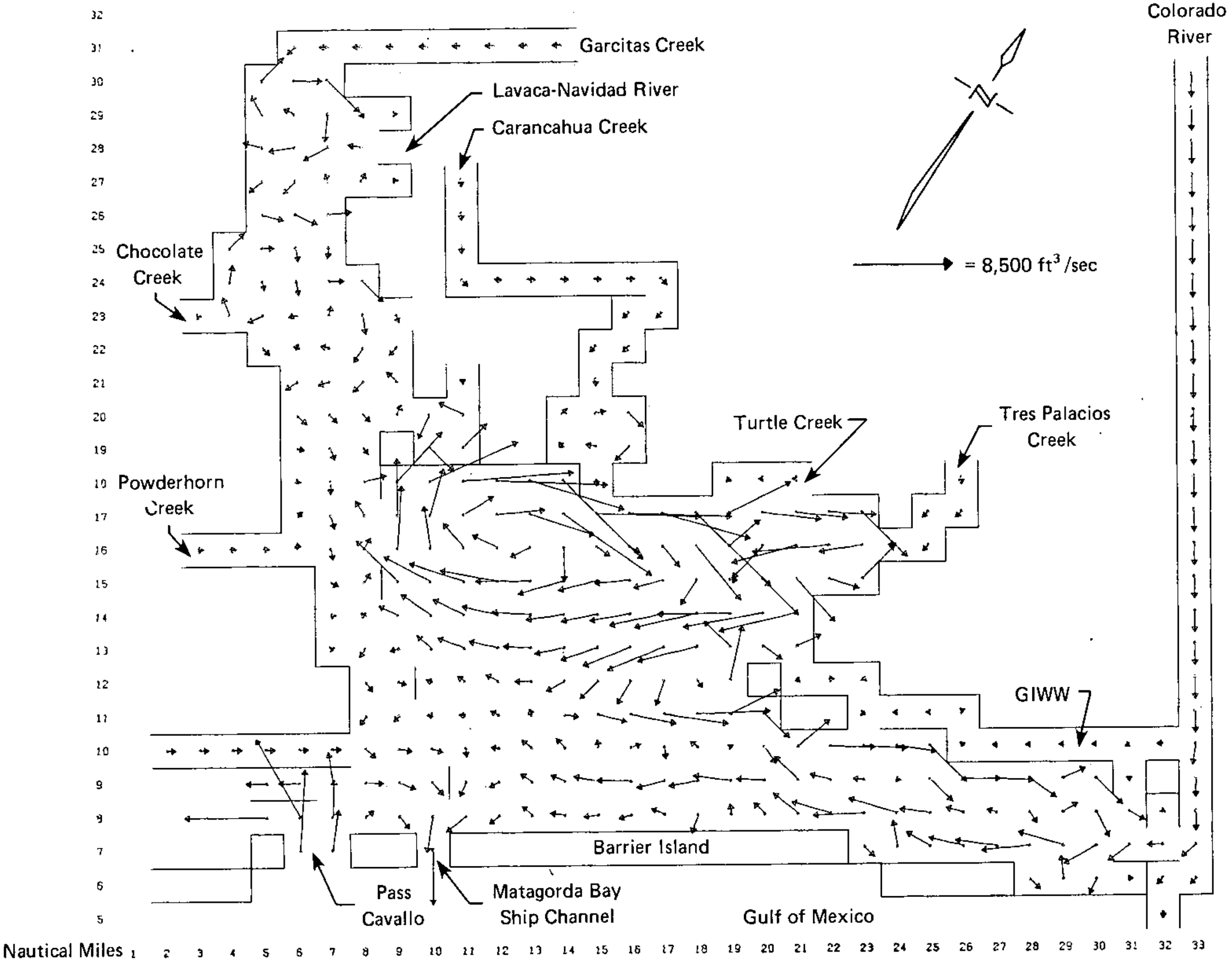

Figure 9-25. Simulated Net Steady-State Flows in the Lavaca-Tres Palacios Estuary under June Freshwater Inflow Needs, Alternative I

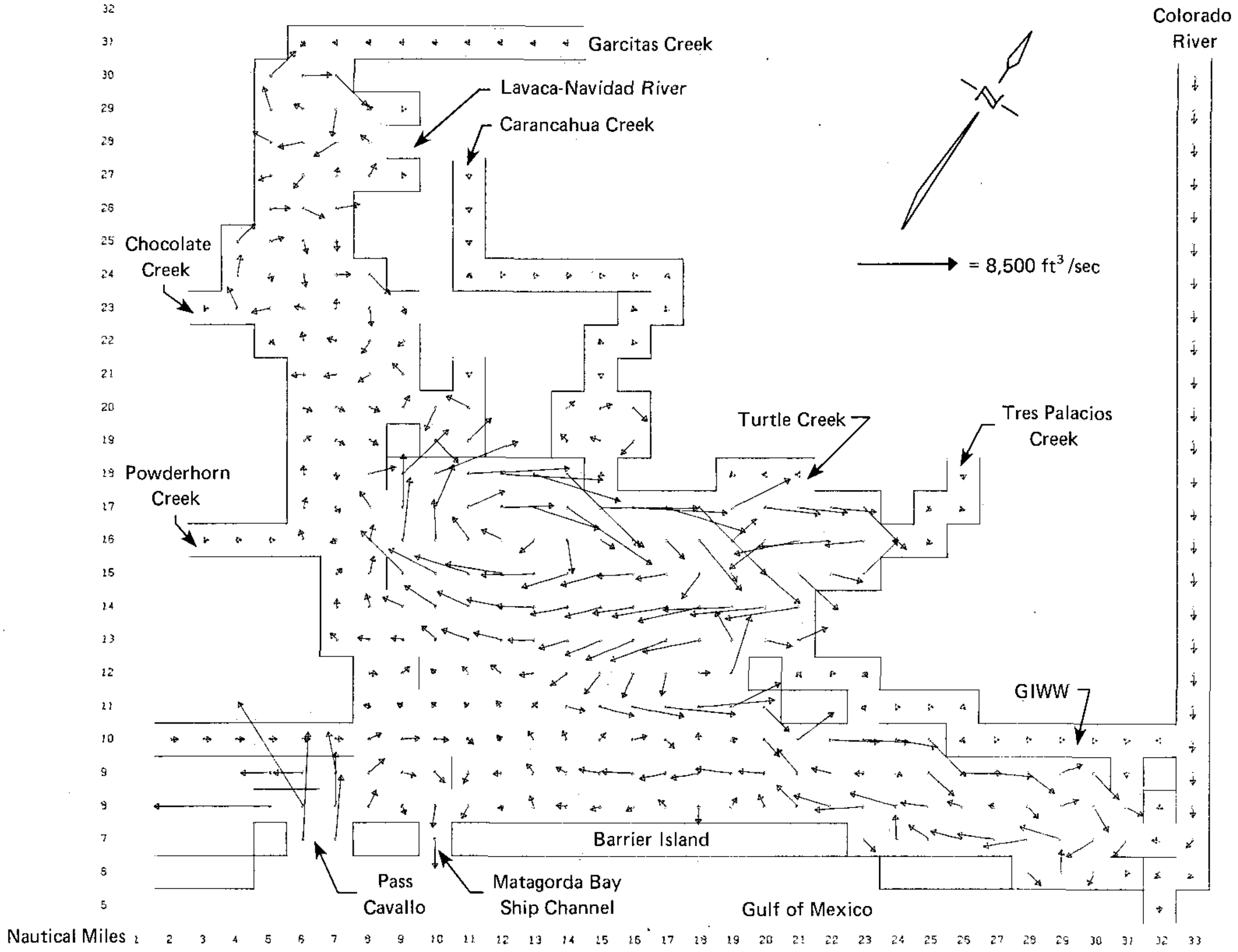

Figure 9-26. Simulated Net Steady-State Flows in the Lavaca-Tres Palacios Estuary under July Freshwater Inflow Needs, Alternative I

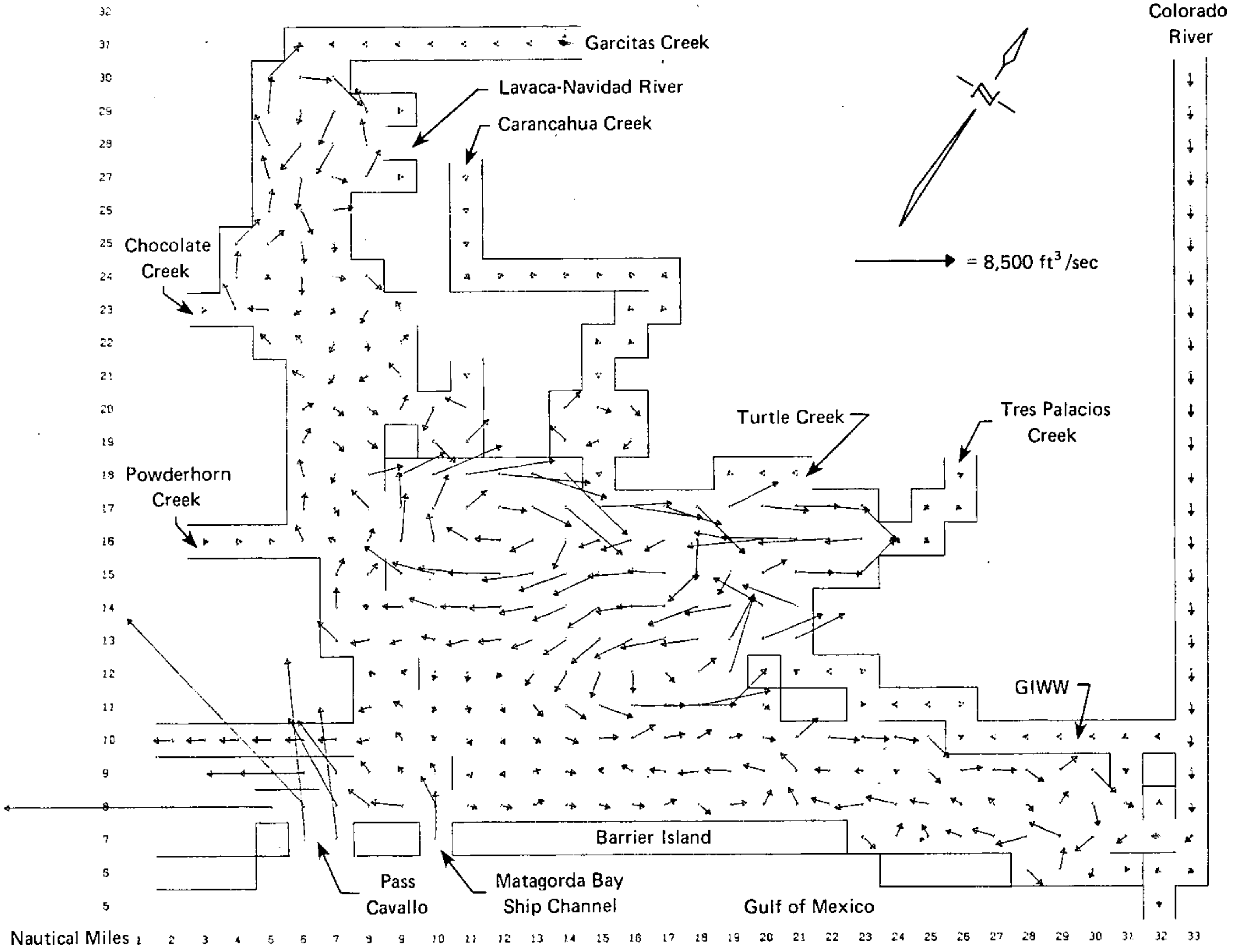

Figure 9-27. Simulated Net Steady-State Flows in the Lavaca-Tres Palacios Estuary under August Freshwater Inflow Needs, Alternative I

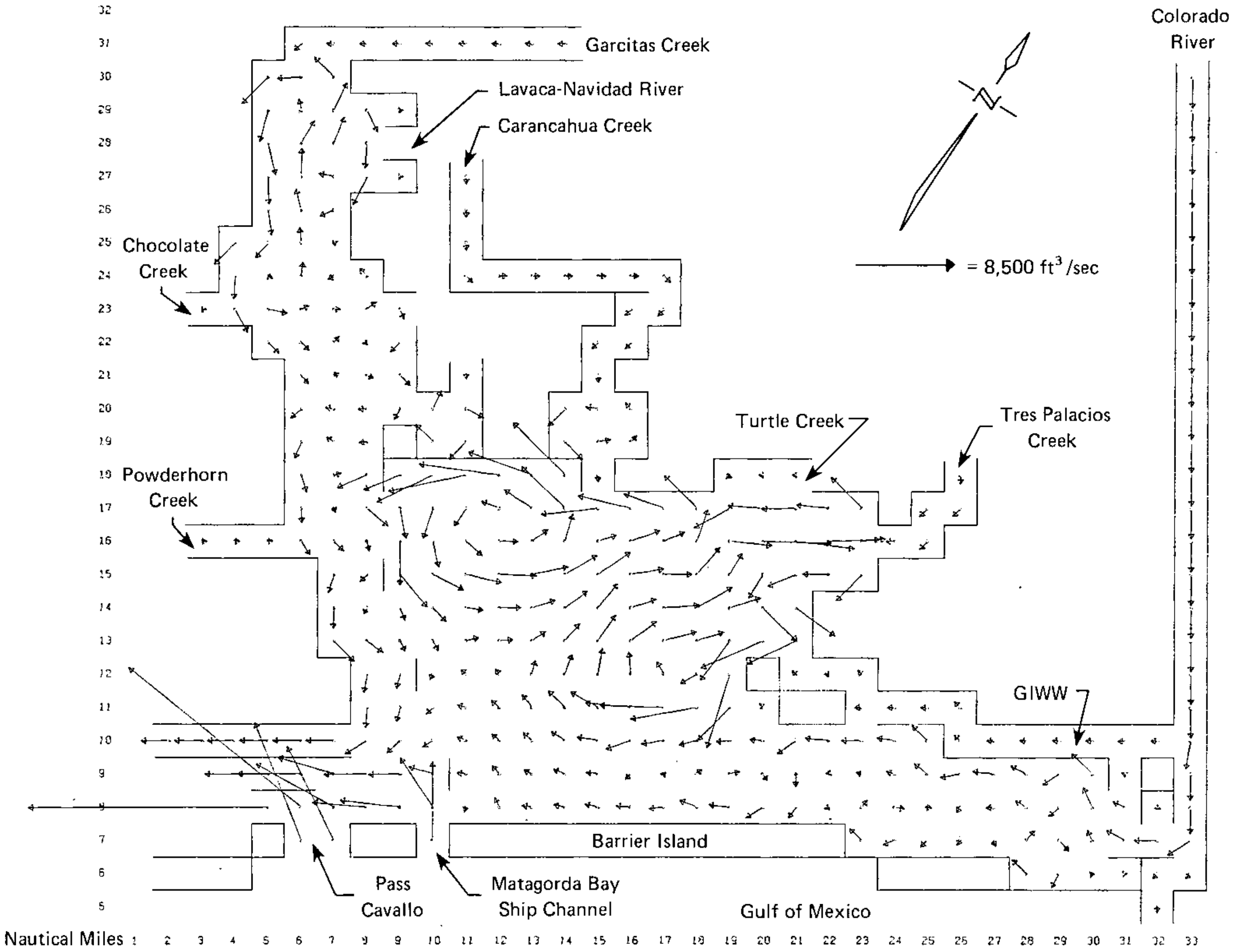

Figure 9-28. Simulated Net Steady-State Flows in the Lavaca-Tres Palacios Estuary under September Freshwater Inflow Needs, Alternative I

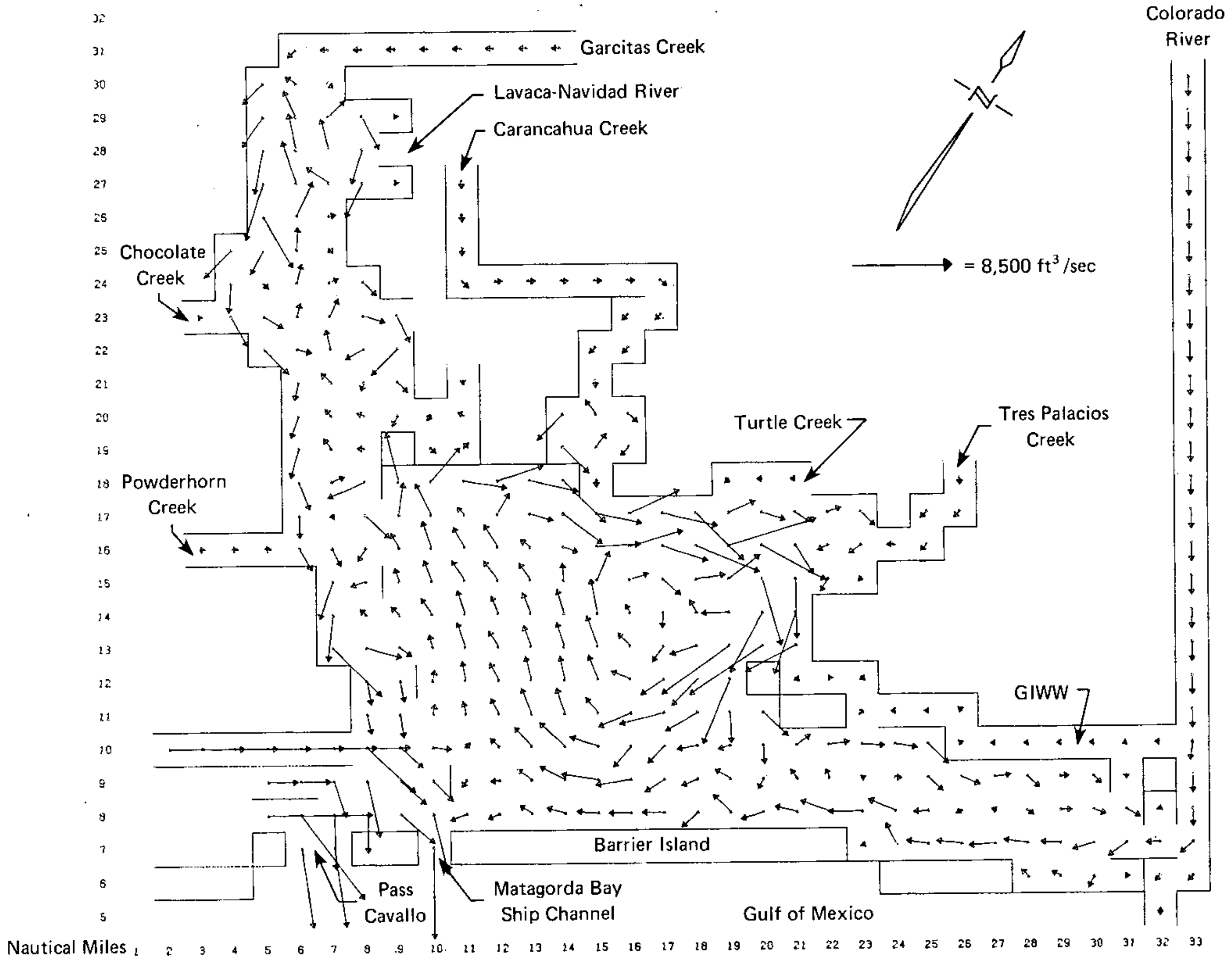

Figure 9-29. Simulated Net Steady-State Flows in the Lavaca-Tres Palacios Estuary under October Freshwater Inflow Needs, Alternative I

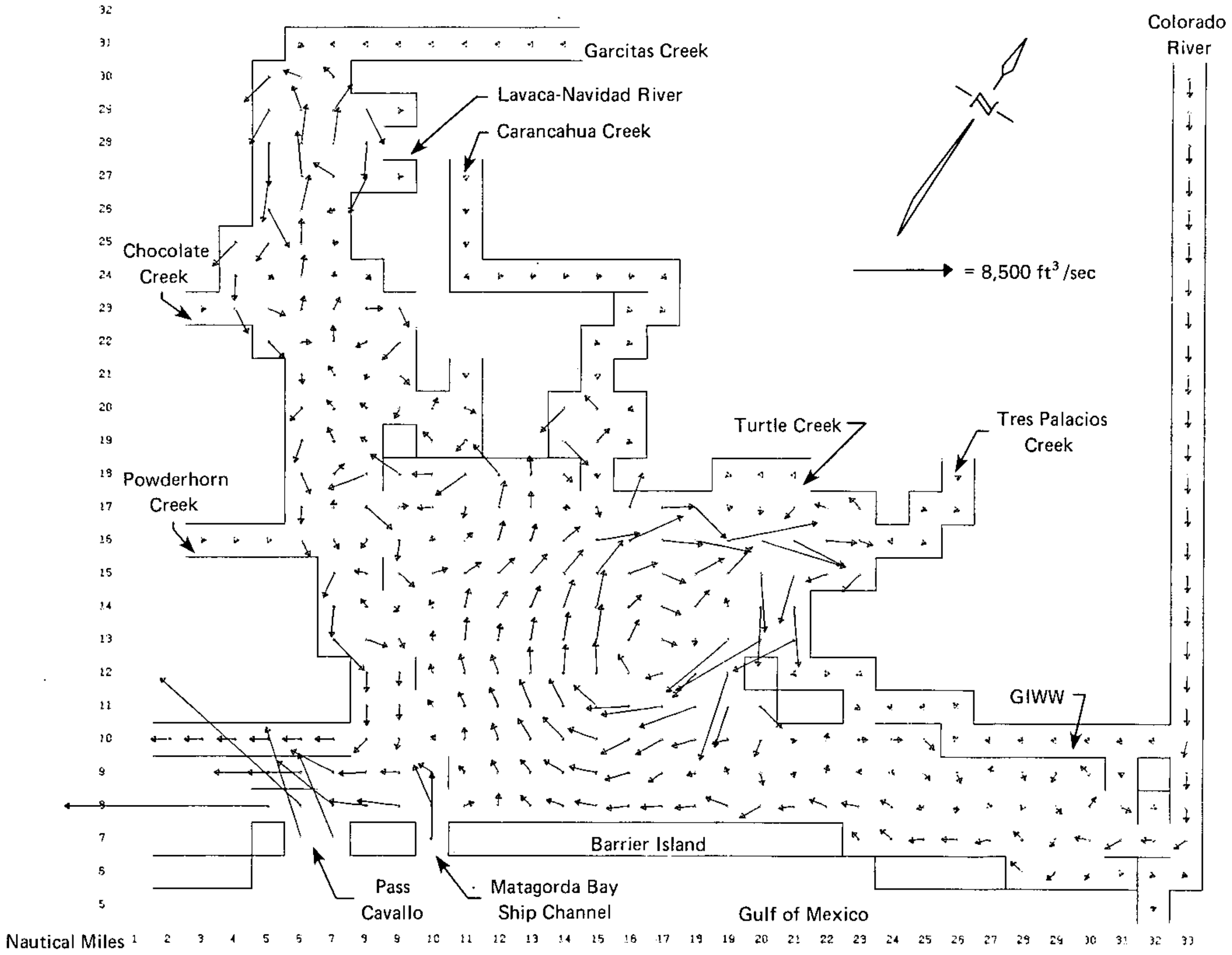

Figure 9-30. Simulated Net Steady-State Flows in the Lavaca-Tres Palacios Estuary under November Freshwater Inflow Needs, Alternative I

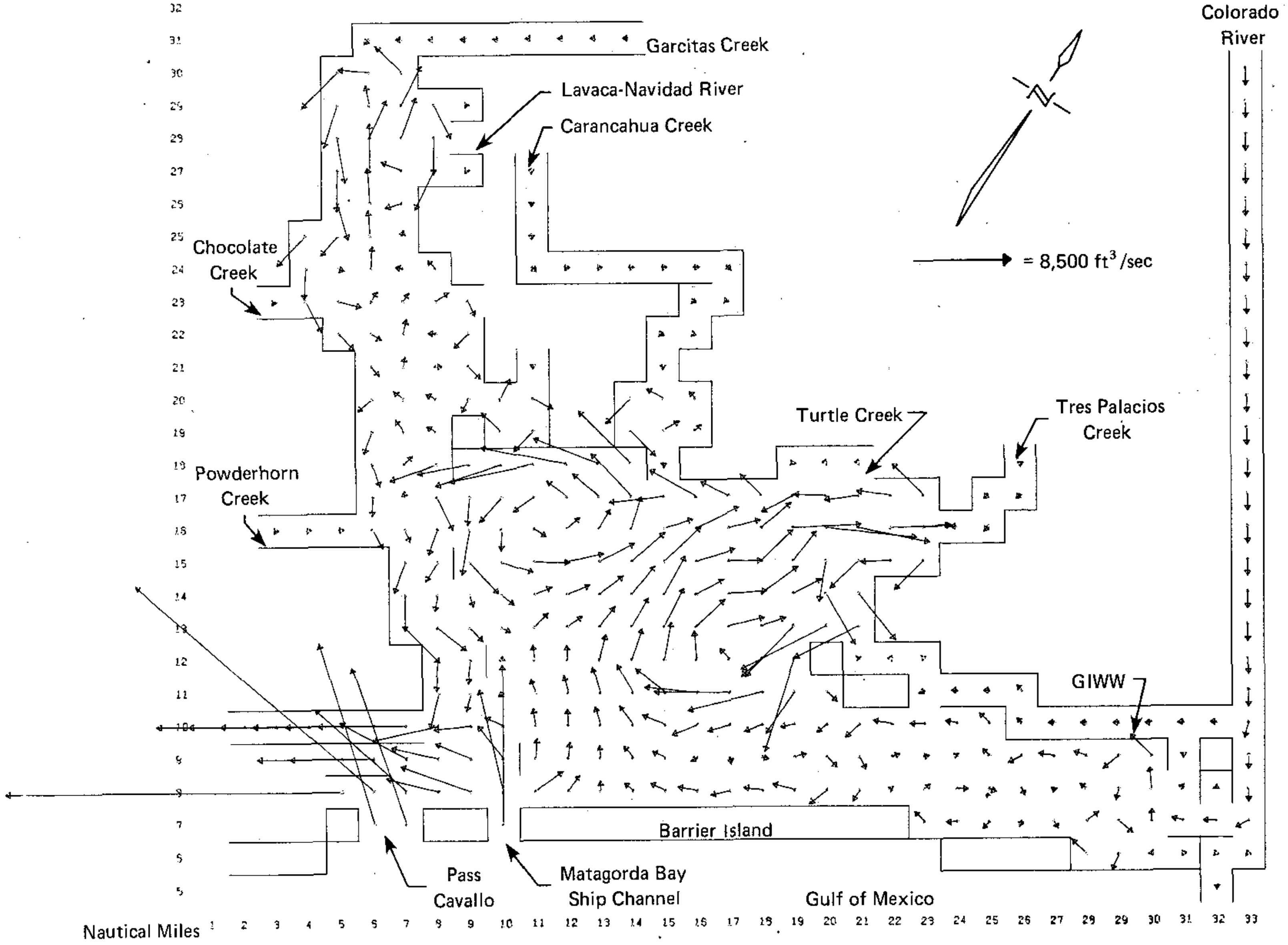

Figure 9-31. Simulated Net Steady-State Flows in the Lavaca-Tres Palacios Estuary under December Freshwater Inflow Needs, Alternative I

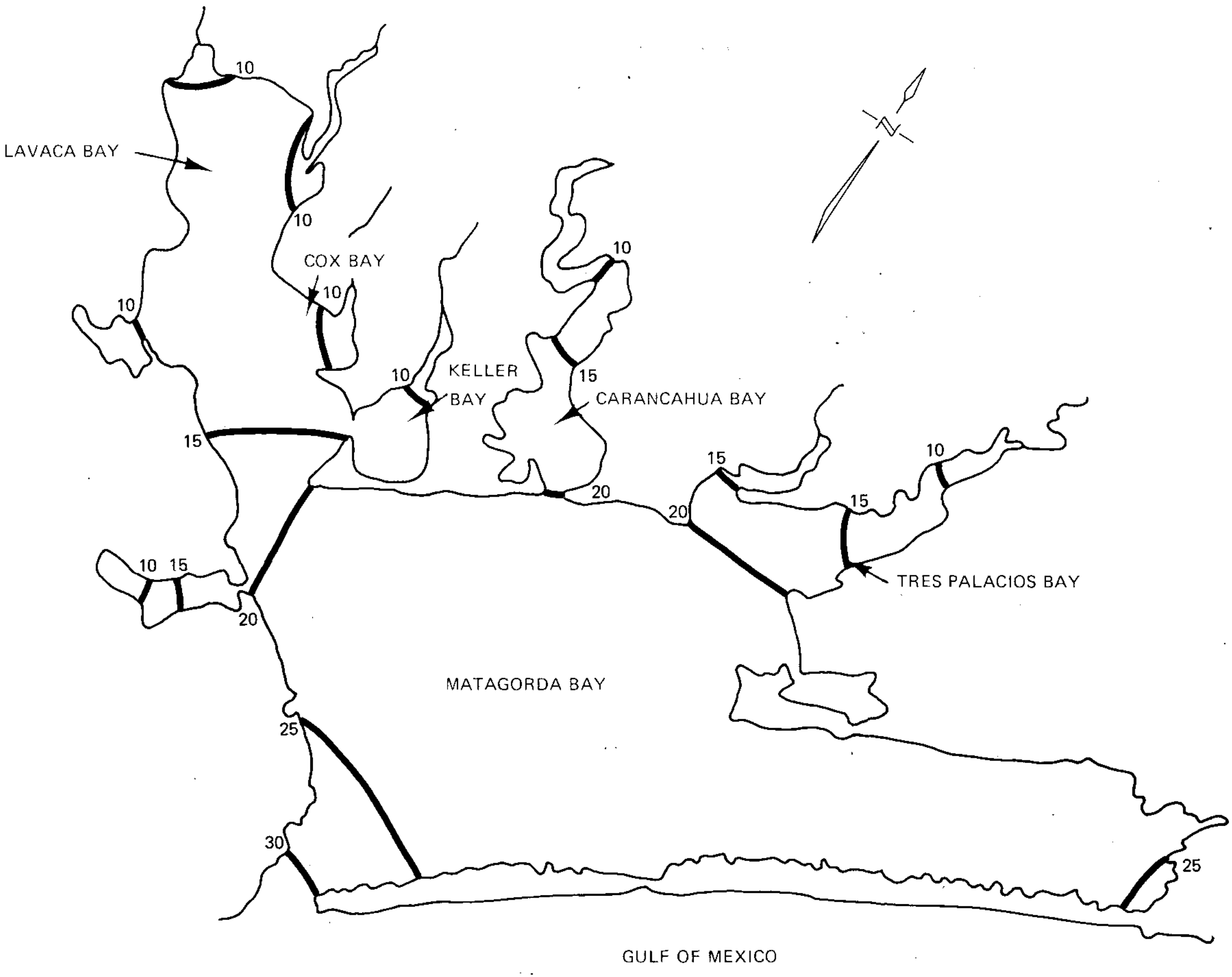

Figure 9-32. Simulated Salinities in the Lavaca-Tres Palacios Estuary under January Freshwater Inflow Needs, Alternative I (ppt)

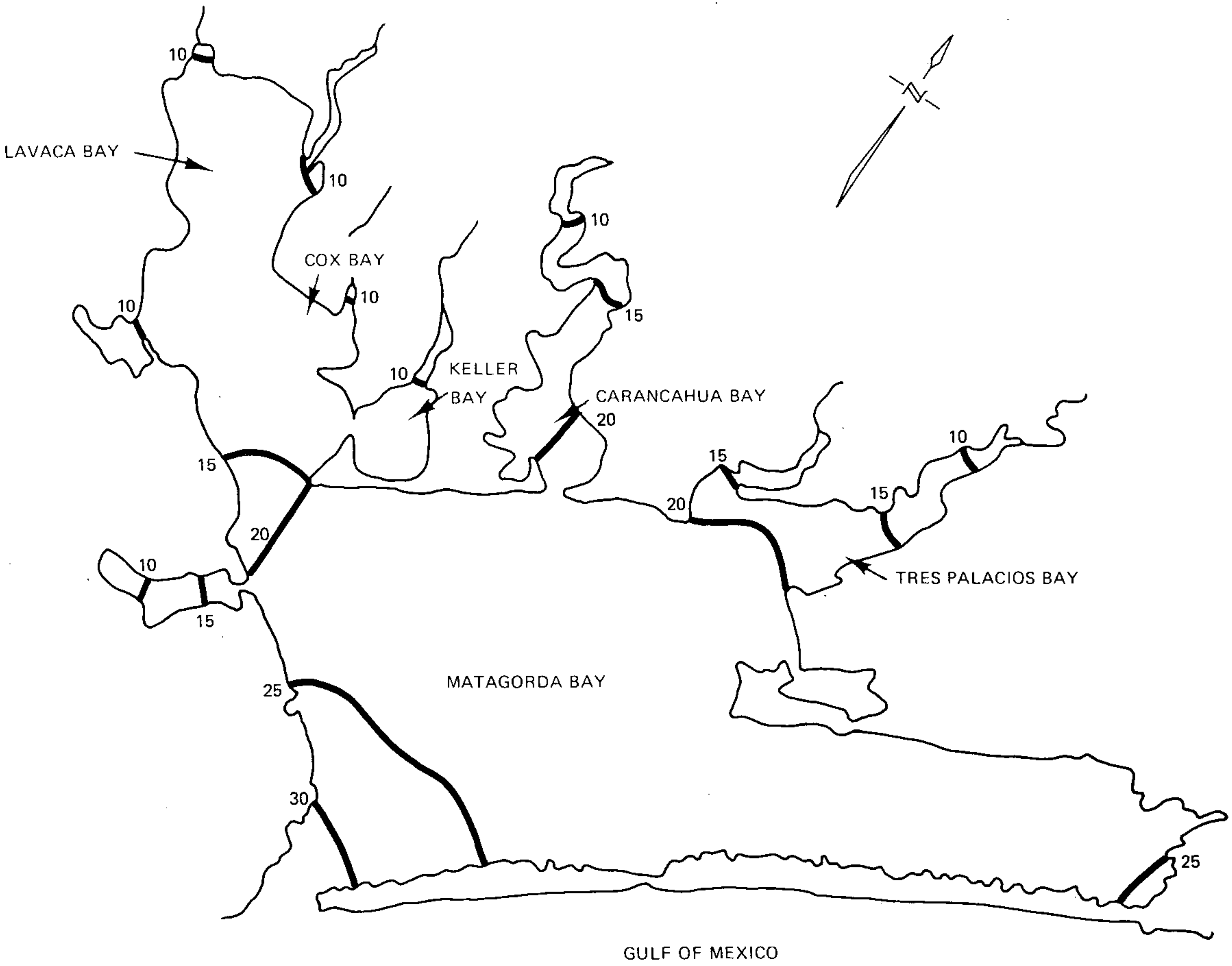

Figure 9-33. Simulated Salinities in the Lavaca-Tres Palacios Estuary under February Freshwater Inflow Needs, Alternative I (ppt)

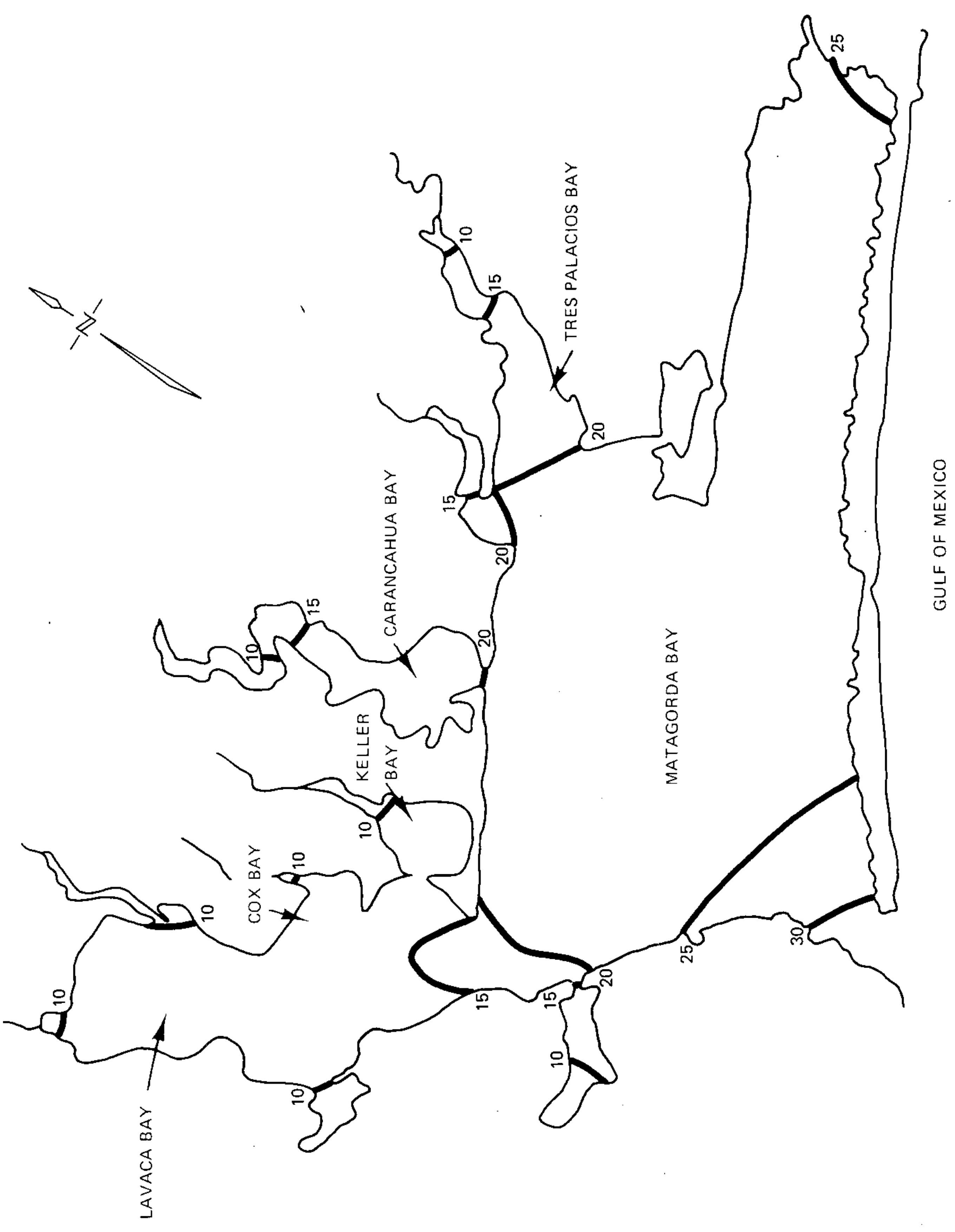

Figure 9-34. Simulated Salinities in the Lavaca-Tres Palacios Estuary under March Freshwater Inflow Needs, Alternative I (ppt)

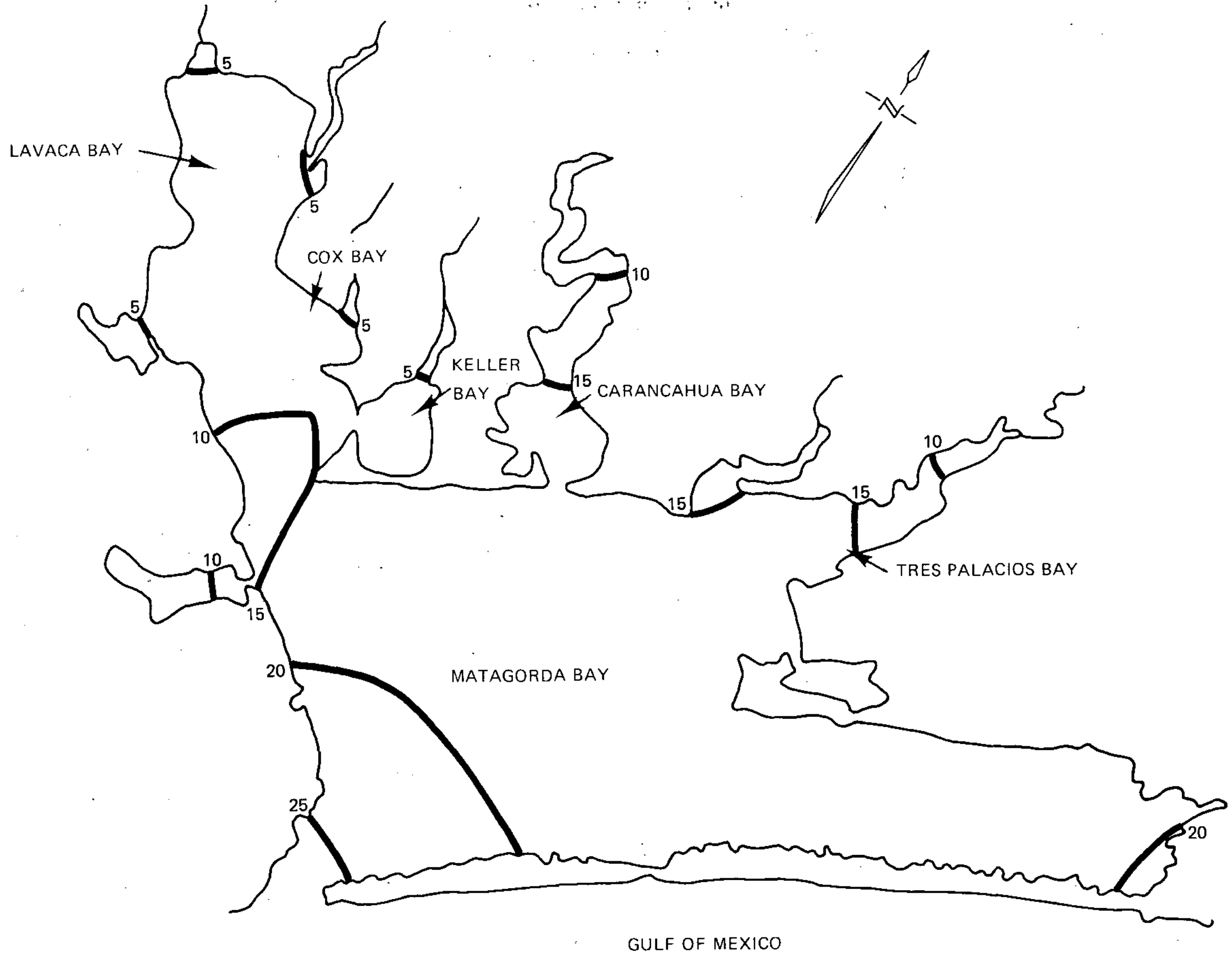

Figure 9-35. Simulated Salinities in the Lavaca-Tres Palacios Estuary under April Freshwater Inflow Needs, Alternative I (ppt)

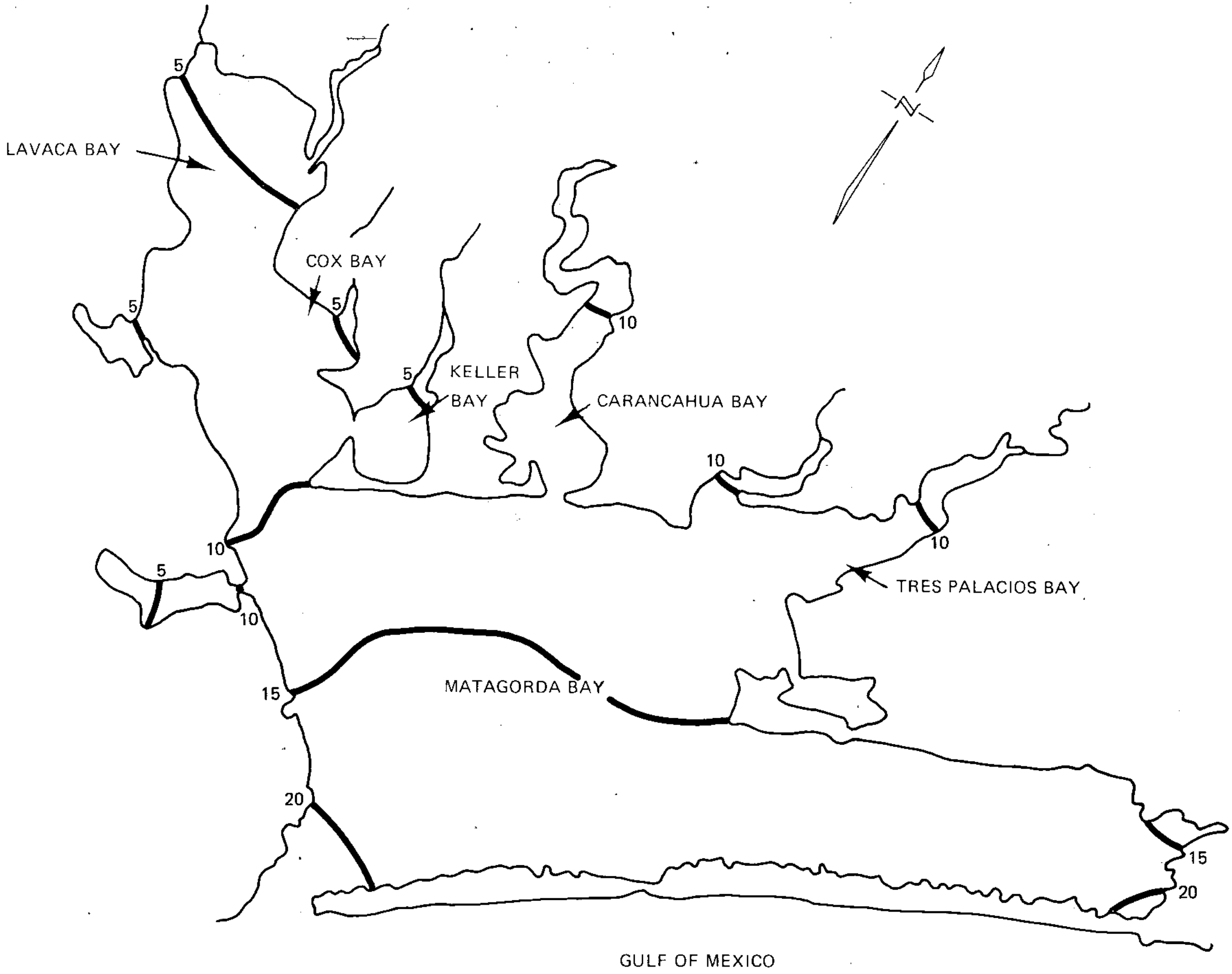

Figure 9-36. Simulated Salinities in the Lavaca-Tres Palacios Estuary under May Freshwater Inflow Needs, Alternative I (ppt)

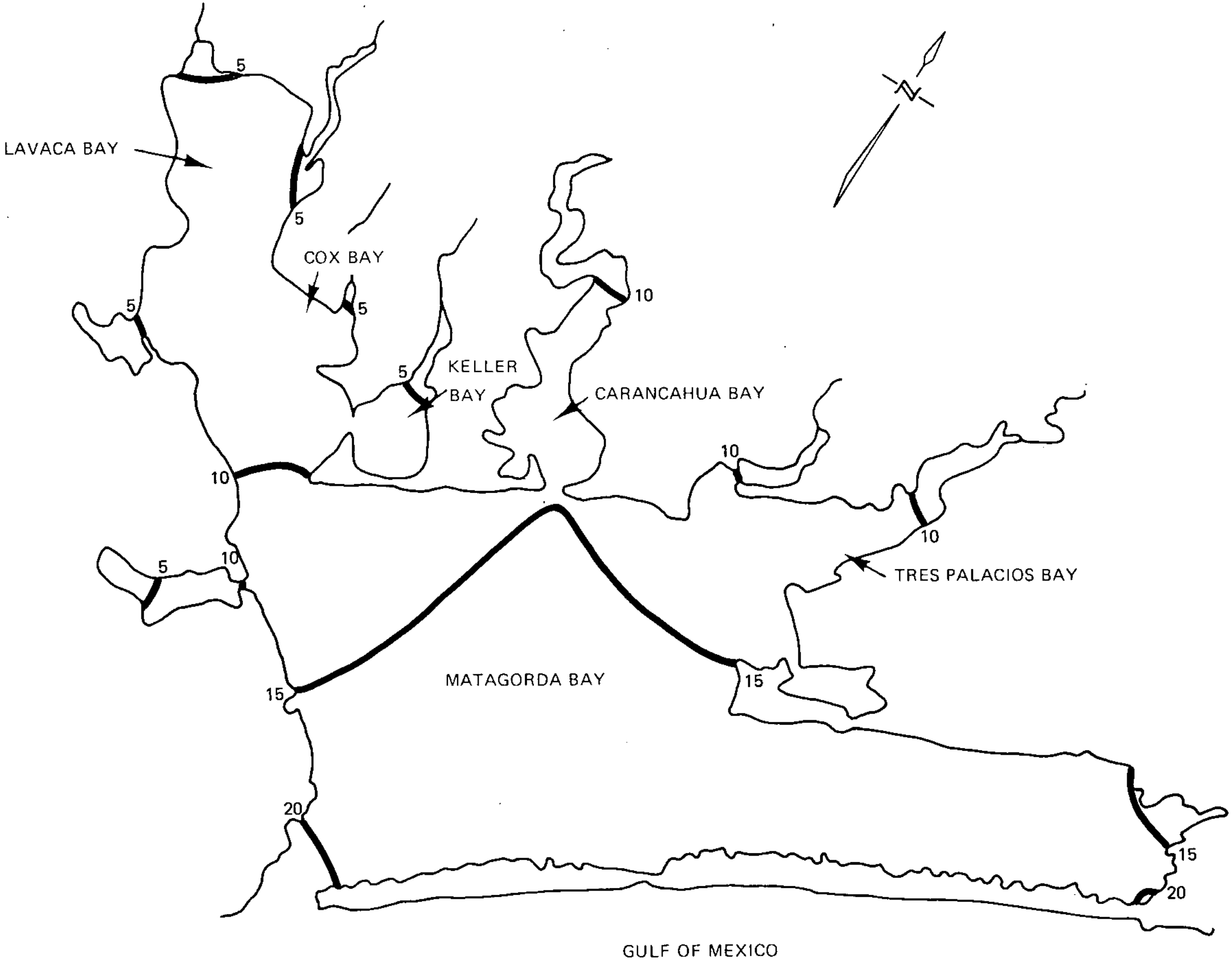

Figure 9-37. Simulated Salinities in the Lavaca-Tres Palacios Estuary under June Freshwater Inflow Needs, Alternative I (ppt)

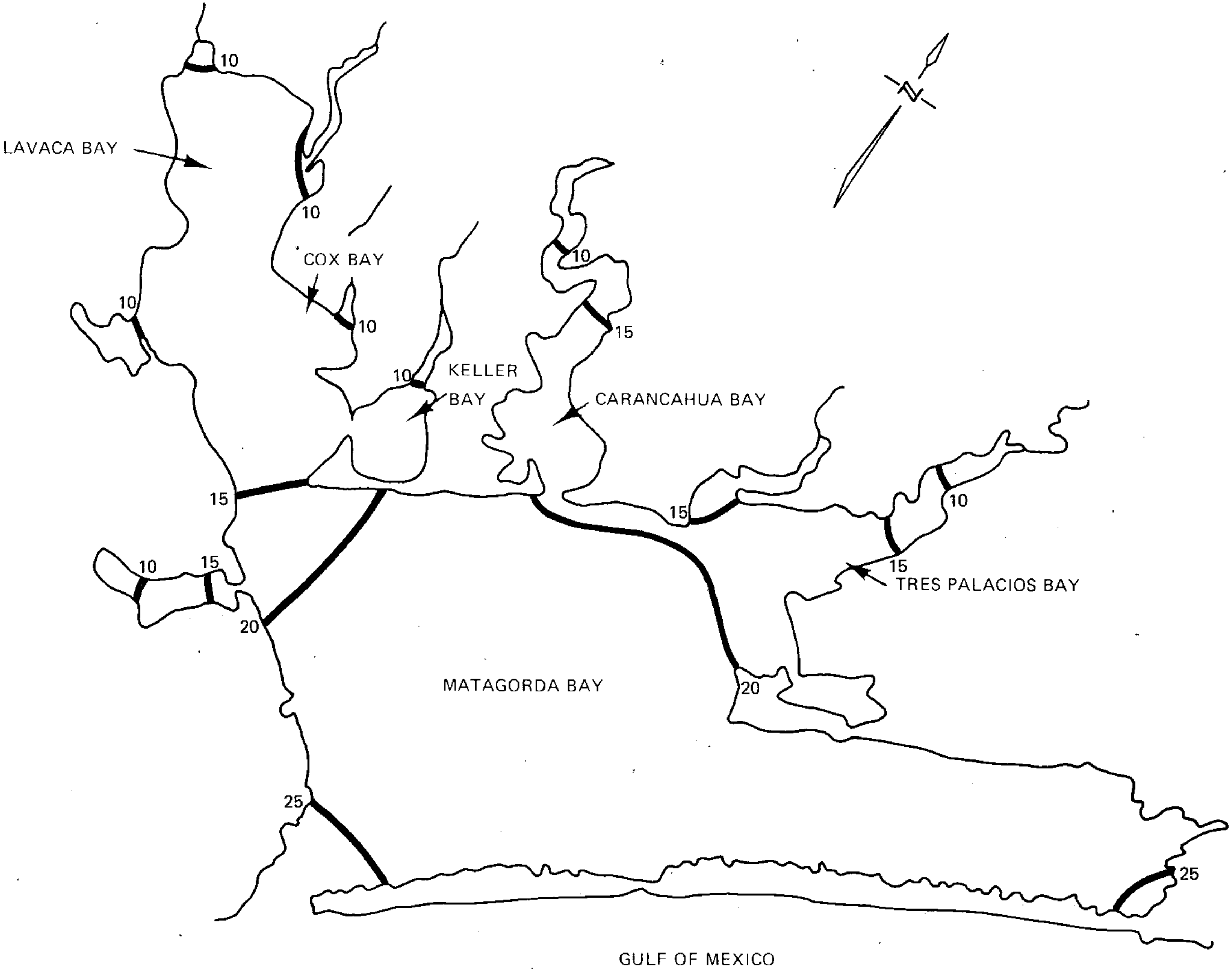

Figure 9-38. Simulated Salinities in the Lavaca-Tres Palacios Estuary under July Freshwater Inflow Needs, Alternative I (ppt)

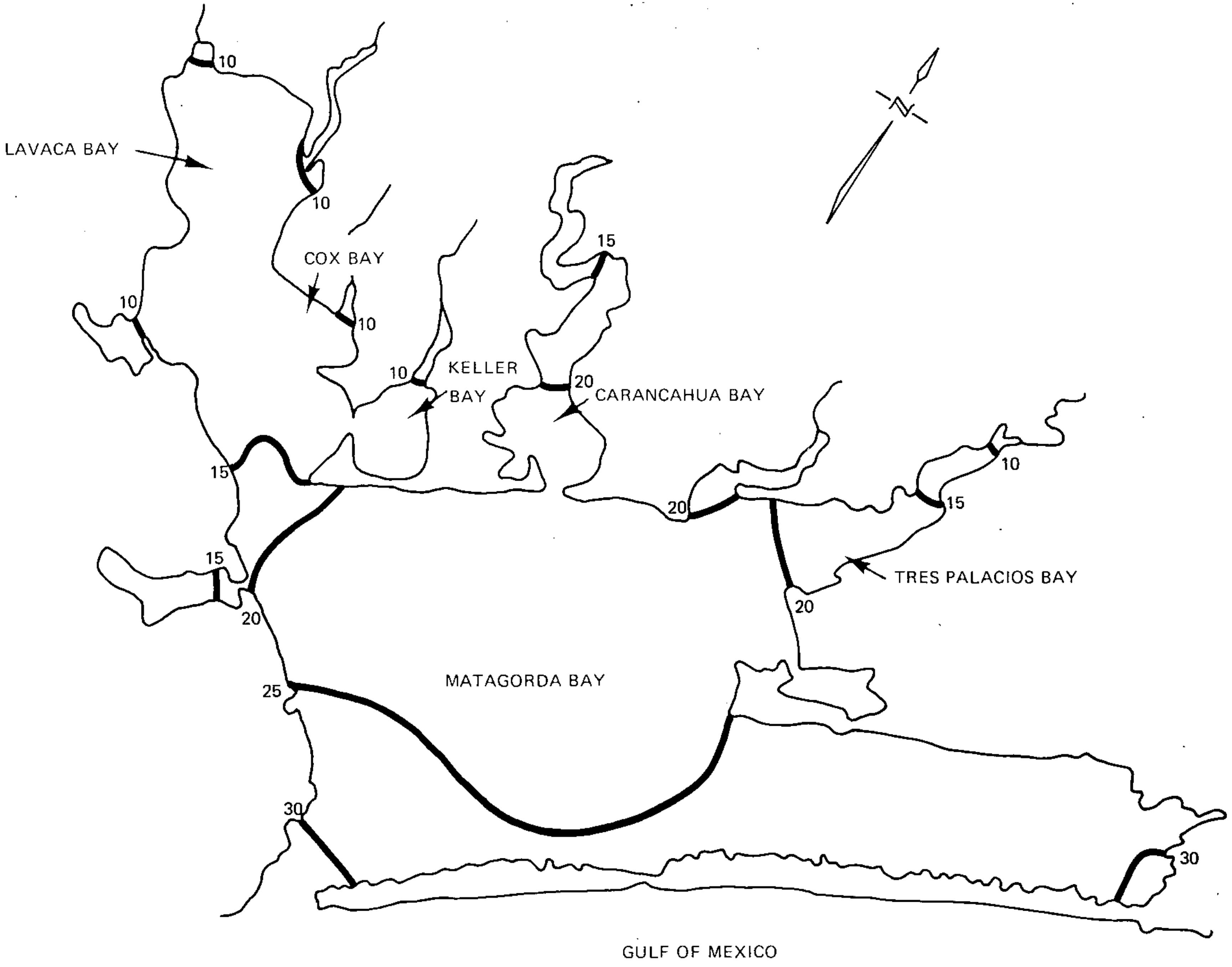

Figure 9-39. Simulated Salinities in the Lavaca-Tres Palacios Estuary under August Freshwater Inflow Needs, Alternative I (ppt)

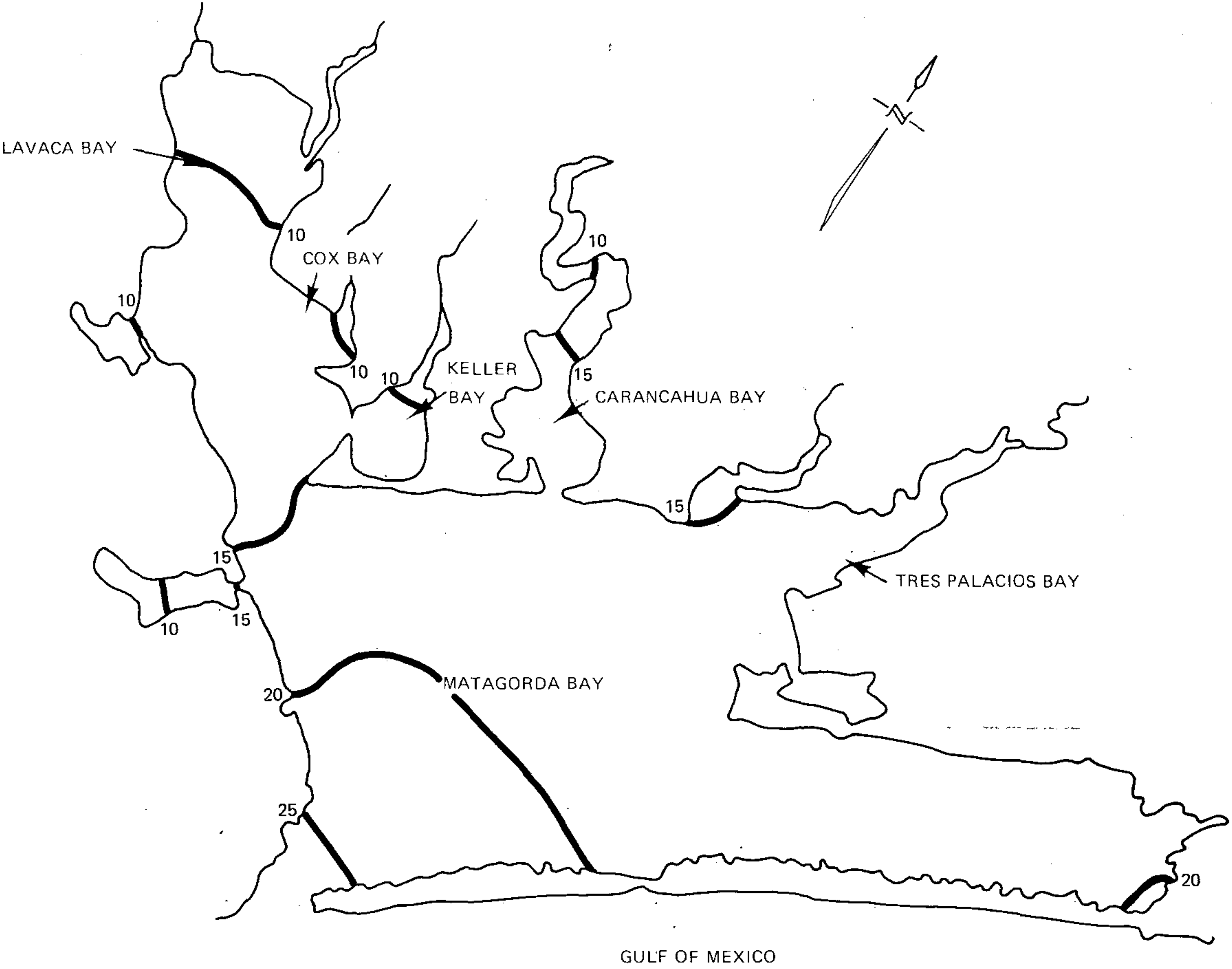

Figure 9-40. Simulated Salinities in the Lavaca-Tres Palacios Estuary under September Freshwater Inflow Needs, Alternative I (ppt)

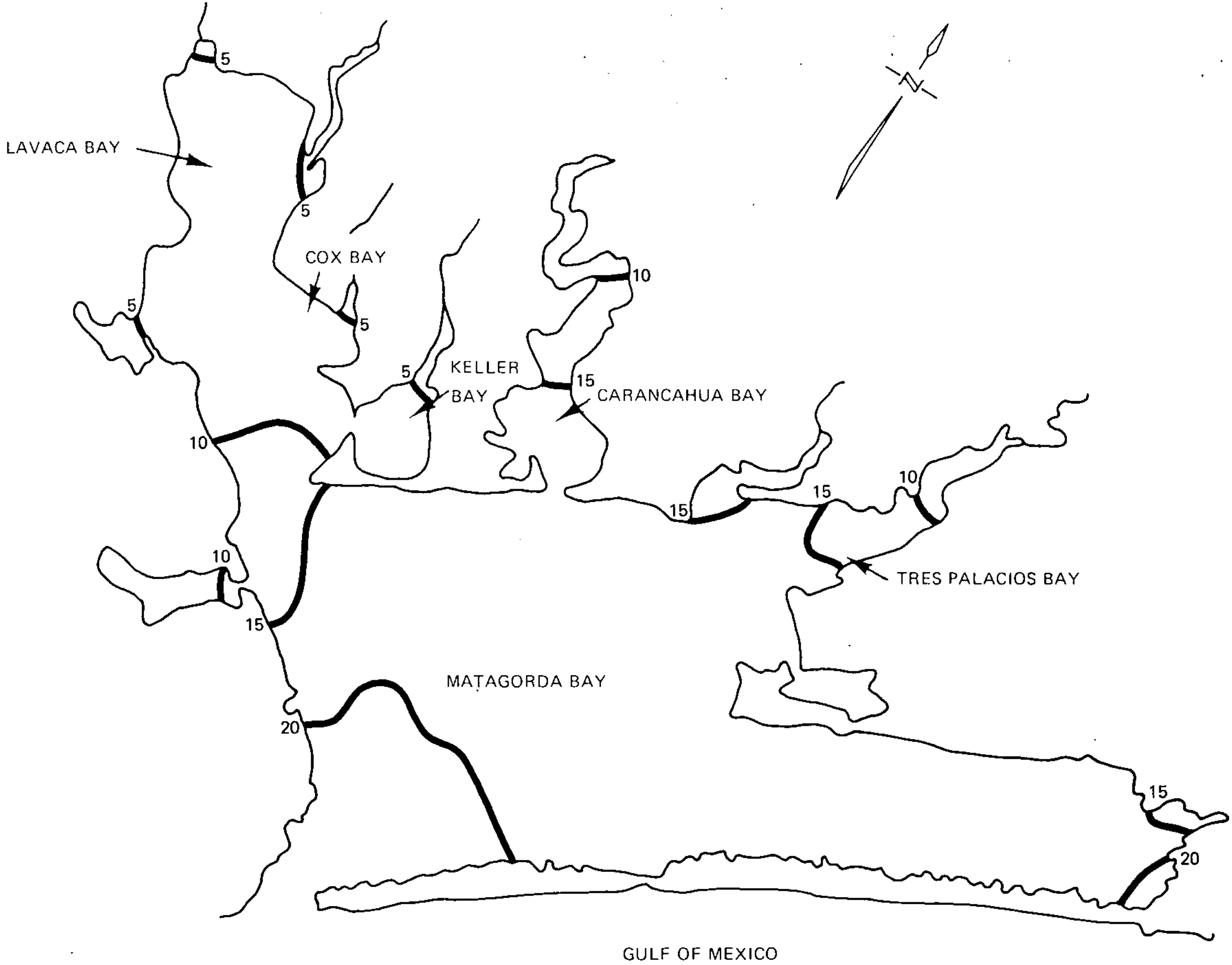

Figure 9-41. Simulated Salinities in the Lavaca-Tres Palacios Estuary under October Freshwater Inflow Needs, Alternative I (ppt)

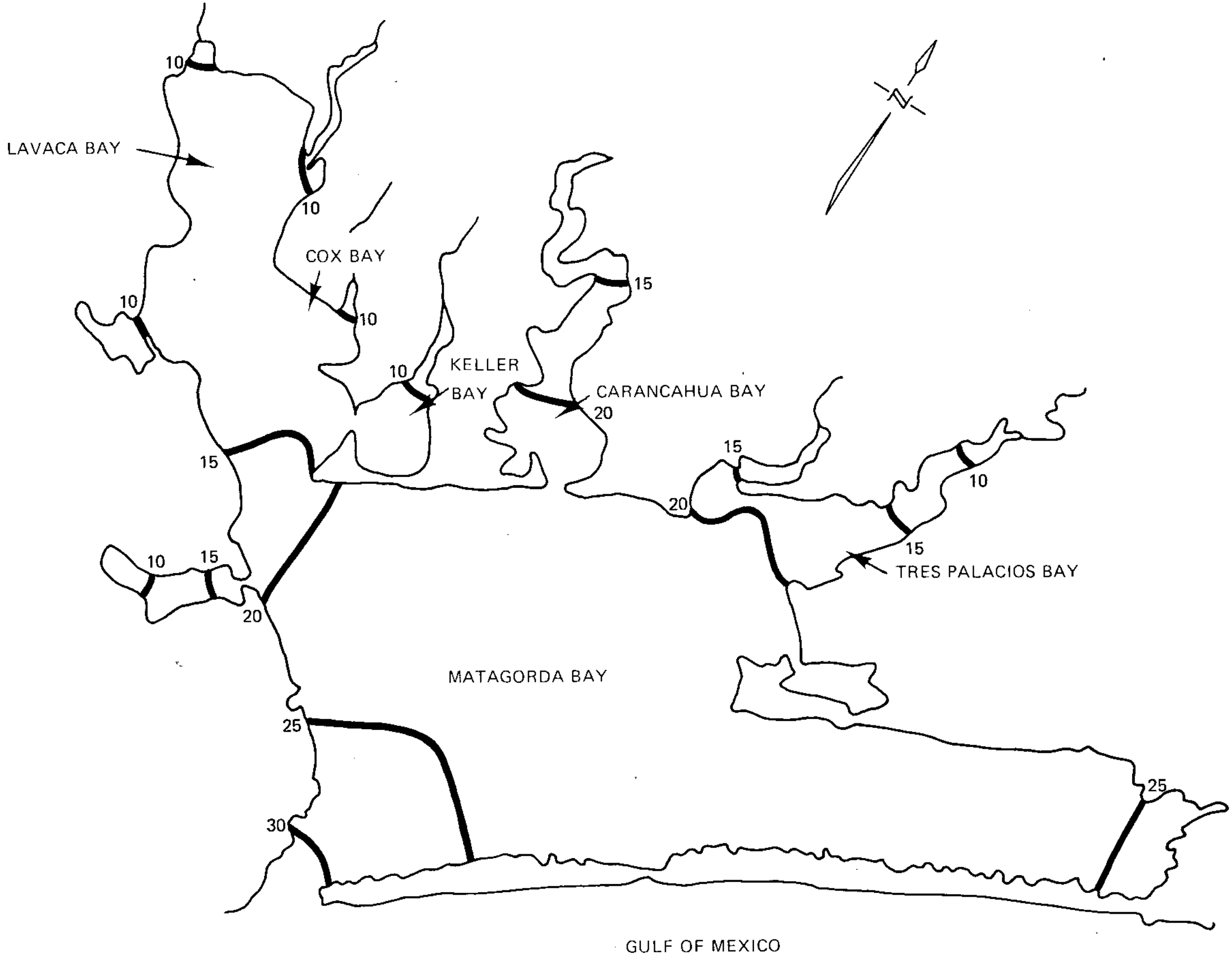

Figure 9-42. Simulated Salinities in the Lavaca-Tres Palacios Estuary under November Freshwater Inflow Needs, Alternative I (ppt)

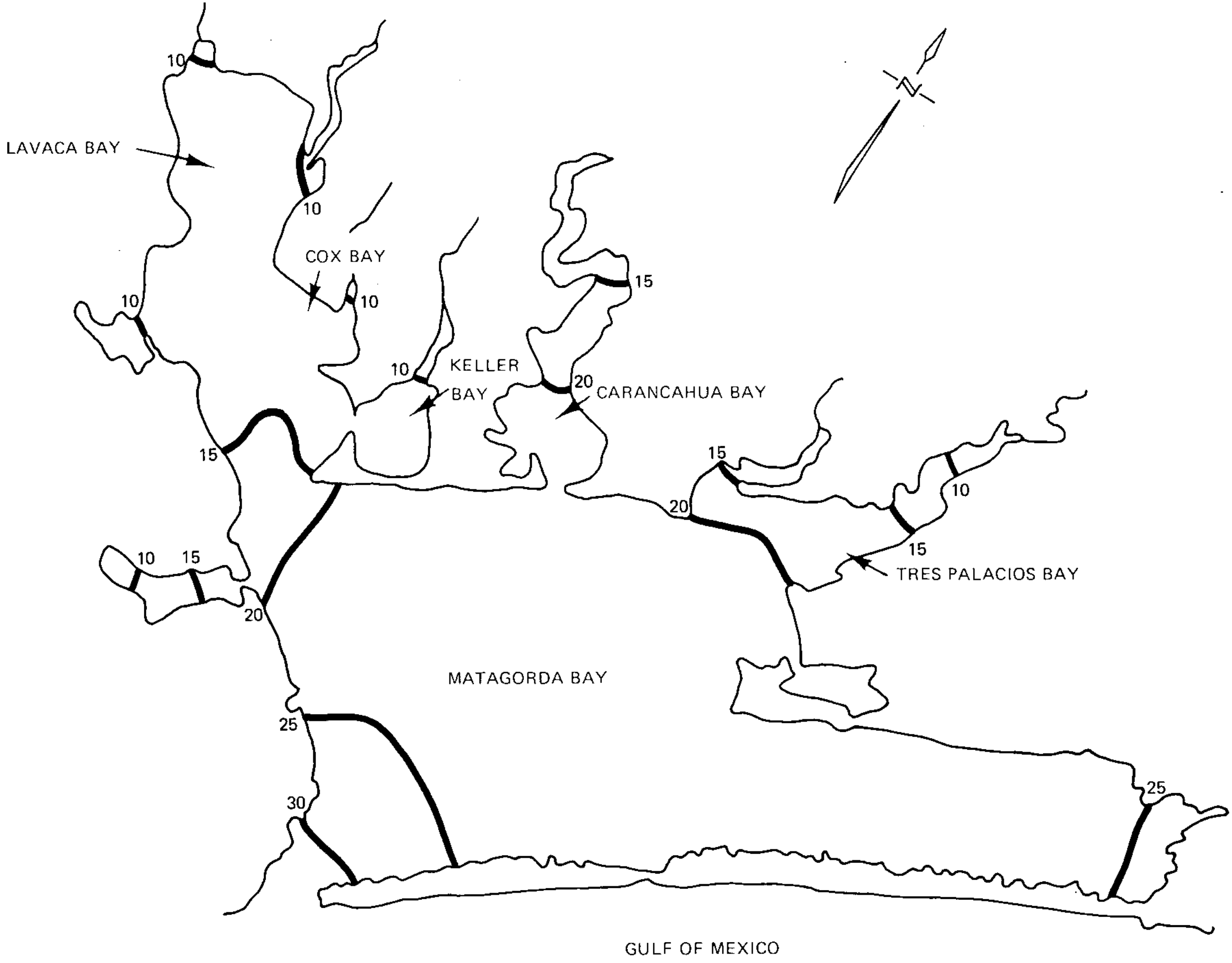

Figure 9-43. Simulated Salinities in the Lavaca-Tres Palacios Estuary under December Freshwater Inflow Needs, Alternative I (ppt)

Simulated November, December and January Circulation and Salinity Patterns. The flow circulations and salinities in the Lavaca-Tres Palacios estuary were simulated for historical average meteorological conditions and estimated freshwater inflow needs for Alternative I for the months of November, December and January. The predominant wind speed and direction of 10 miles per hour (mph) (or 4.5 m/sec) from the northeast varies only slightly among these late fall and winter months. The most obvious circulation pattern evident in the estuary for the indicated months is a clockwise current in the central and northeastern portions of Matagorda Bay (Figures 9-30, 9-31 and 9-20). Smaller counterclockwise flow circulation patterns are evident in upper Lavaca Bay and the northwestern portion of Matagorda Bay. Water enters the Guadalupe estuary to the southwest from the Gulf of Mexico via Pass Cavallo, the Matagorda Bay Entrance Channel, and Matagorda Bay. Little net flow is directed into the main body of Matagorda Bay from the Gulf of Mexico through Pass Cavallo. Flow from the Colorado River passes through the eastern portion of Matagorda Bay along the northern coast of Matagorda Peninsula and joins in the major circulation pattern in the middle of Matagorda Bay. Some flow occurs between Lavaca and Matagorda Bays, but not of as great a magnitude as the flows in the circulation patterns in Lavaca Bay.

The simulation of estuarine salinities under November, December and January inflow needs and average meteorological conditions results in the greatest areal portion of Matagorda Bay having salinities between 20 and 25 ppt (Figures 9-42, 9-43 and 9-32). Lavaca Bay has simulated salinities of less than 15 ppt in its upper half and concentrations of 15-20 ppt in its lower portion. Salinities in excess of 25 ppt are predicted to occur near Pass Cavallo, the Matagorda Bay Entrance Channel, and Tiger Island Cut.

Simulated February, March and April Circulation and Salinity Patterns. Average meteorological conditions and estimated freshwater inflow needs for Alternative I were used to drive the simulation model computing the flow circulation patterns for the months of February, March and April (Figures 9-21, 9-22 and 9-23). The net circulation patterns evident in the estimates for the months of November through January are again predominant, with the main circulation being a clockwise vortex of flow in the middle of Matagorda Bay. The average wind speeds for the months of February, March and April are 11.1, 11.8 and 12.2 mph (or 5, 5.3 and 5.5 m/sec), respectively. The predominant wind direction shifts from northeast in February and March to southeast in April.

The simulated net flow through Pass Cavallo moves into the Guadalupe estuary and not into Matagorda Bay, whereas the flow through the Matagorda Bay Entrance Channel is directed into the Lavaca-Tres Palacios estuary from the Gulf of Mexico during the months of February and March, but out of the estuary during April.

Noticeable increases in flow rates can be observed in the vector plots of April over those of February and March. This reflects a more turbulent condition in the estuary system due to tidal action and wind effects.

The simulation of salinity conditions over these later winter and early spring months (Figures 9-33, 9-34 and 9-35) indicates that Matagorda Bay has 20-25 ppt salinities in February and March, and 15-20 ppt salinities in April.

The salinities in Lavaca Bay are simulated to be less than 15 ppt and 15-20 ppt in the upper and lower portions, respectively, for February and March, and less than 10 ppt in April. Salinities in excess of 25 ppt are simulated near Pass Cavallo.

Simulated May and June Circulation and Salinity Patterns. The average flow circulation patterns in Lavaca-Tres Palacios estuary for May and June reflect the influence of two of the months of greatest estimated freshwater inflow need. The mean historical wind speed and direction for May and June are, respectively, 10.8 mph (4.9 m/sec) and 9.8 mph (3.4 m/sec) from the southeast.

The simulated net circulation pattern dominant in the estuary during these months is a clockwise-rotating current in the northern and central portions of Matagorda Bay. An additional circulation pattern is evident in the northeastern and eastern sections of the bay. This latter pattern causes flow from the central portion of Matagorda Bay to move toward Tiger Island Cut near the mouth of the Colorado River along the northern banks of eastern Matagorda Bay. Near Tiger Island Cut, water from Matagorda Bay is mixed with water from the Colorado River and the Gulf of Mexico and moved along the northern shore of Matagorda Peninsula which separates the estuary from the Gulf of Mexico. Flow through Pass Cavallo moves almost directly into Espiritu Santo Bay of the Guadalupe estuary and does not enter into the main body of Matagorda Bay. Inflow from the Lavaca River in May and June results in a significant net flow from Lavaca Bay into Matagorda Bay. No predominant current is evident in Lavaca Bay (probably the result of high inflow predominating over tidal action).

The salinity simulations for the months of May and June reveal the effects of significant freshwater inflows upon the salinity in the estuary (Figures 9-36 and 9-37). The only areas of the estuary exceeding 20 ppt simulated salinity are small areas adjacent to Pass Cavallo and Tiger Island Cut. All of Lavaca Bay has simulated salinities of less than 10 ppt, with Matagorda Bay having salinity levels of between 10 and 20 ppt.

Simulated July and August Circulation and Salinity Patterns. The months of July and August have the lowest estimated monthly freshwater inflow needs under Alternative I for the Lavaca-Tres Palacios estuary. The mean historical wind speeds and directions during these months are 8.9 mph (4 m/sec) and 8.4 mph (3.8 m/sec) from the southeast and south for July and August, respectively.

The simulated net circulation patterns for July and August (Figures 9-26 and 9-27) indicate that the circulation in Matagorda Bay is governed by three patterns: a counterclockwise rotating current in the central portion of the bay, a clockwise moving current in the upper part of the bay, and a clockwise circulation vortex in the eastern part. Some net exchange of water from Matagorda Bay into Lavaca Bay appears evident; however, several clockwise-rotating net currents entirely within Lavaca Bay dominate net circulation in that bay.

Little net flow exchange is evident between Matagorda Bay and the area in the vicinity of Pass Cavallo and the Matagorda Bay Entrance Channel. Water passes through Pass Cavallo from the Gulf; however, this inflow is directed into Espiritu Santo Bay of the Guadalupe estuary.

The simulated salinity patterns in the estuary (Figures 9-38 and 9-39) indicate levels of salinity within almost all of Matagorda Bay in excess of 20 ppt. Lavaca Bay has simulated salinities of 10-15 ppt. The salinities in excess of 25 ppt in July and 30 ppt in August are simulated over the extreme eastern and western ends of Matagorda Bay near the major flow exchange points with the Gulf of Mexico. The central portion of Matagorda Bay has simulated salinities less than 25 ppt in August.

Simulated September and October Circulation and Salinity Patterns. The hydrodynamic model simulations for the Lavaca-Tres Palacios estuary for the months of September and October indicates similar steady-state net flow circulation patterns throughout the period under Alternative I freshwater inflow needs and meteorological conditions (Figures 9-28 and 9-29). The average historical wind speed for these months is approximately 8.7 mph (3.9 m/sec) (September, 8.6 mph; and October, 8.8 mph). The mean wind direction is northerly for September and northeasterly for October.

The most prominant net circulation pattern in these simulations is a clockwise rotating current in the central and northern portions of Matagorda Bay. During September an additional current rotating in a counterclockwise direction is also evident in upper Matagorda Bay. During the month of October, a clockwise circulation is simulated in the eastern portion of Matagorda Bay. Internal circulation patterns predominate in Lavaca Bay during these months with both September and October showing contributions of net flow from Lavaca Bay to Matagorda Bay.

Simulated net flows at the exchange points for the Lavaca-Tres Palacios estuary, the Gulf of Mexico and the Guadalupe estuary during these months show little net contribution to Matagorda Bay except in Tiger Island Cut. At Pass Cavallo, the flows during September pass directly into the Guadalupe estuary. During October, water moves from Espiritu Santo Bay out into the Gulf without entering Matagorda Bay. At the Matagorda Bay Entrance Channel, water passes to the Gulf from Matagorda Bay in October, while flow moves into Espiritu Santo Bay from the Gulf in September.

The simulation of salinity conditions under the freshwater inflow needs for Alternative I during September and October (Figure 9-40 and 9-41) indicates average salinities of 20-25 ppt should occur over approximately one-fifth of Matagorda Bay with the remaining area experiencing concentrations of 15-20 ppt. Salinities in the vicinity of Pass Cavallo and Tiger Island Cut are approximately 25 ppt and 20 ppt, respectively.

In all months, the salinities in the middle portion of Matagorda Bay were simulated at under 25 ppt; thus, further refinement of the estimated monthly freshwater inflow needs for the three Alternatives was not considered necessary.

Interpretation of the Physical Significance of the Estimated Freshwater Inflow

The monthly freshwater inflows estimated in this report for the Lavaca-Tres Palacios estuary from the Lavaca and Colorado 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. 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 variability limits indicated for the key species of the estuary (Table 9-1).

Summary

A methodology is presented which combines the analysis of the component physical, chemical and biological elements of the Lavaca-Tres Palacios 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 Colorado and Lavaca River Basins. These upper and lower limits on monthly salinity were selected to provide a salinity range which will not exceed bounds for viable metabolic and reproductive activity, and also which will not exceed median monthly historical salinity conditions.

Marsh inundation needs, for the flushing of nutrients from riverine marshes into the open bays, are computed and specified for the Lavaca and Colorado River deltas. Inundation of the marshes in the Colorado River delta is rarely the result of freshwater discharge from the Colorado River, but is normally due to tidal action. As a result, no inflow requirements for inundation of the Colorado River delta are specified from the Colorado River Basin. The Lavaca River delta, however, is frequently submerged by floods from the Lavaca and Navidad Rivers. Based upon historical conditions and gaged streamflow records, freshwater inflow needs for marsh inundation are estimated and specified at 70.0 thousand acre-feet (86 million m^3) in April and May, and 60.0 thousand acre-feet (74 million m^3) in October. These volumes correspond to flood events with peak flow rates of 11,320 ft^3/sec (321 m^3/sec) and 10,370 ft^3/sec (294 m^3/sec), respectively.

Estimates of the freshwater inflow needs for the Lavaca-Tres Palacios 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 Colorado and Lavaca River Basins which best achieve a specified objective.

The monthly freshwater inflow needs for the Lavaca-Tres Palacios estuary were estimated for each of three alternatives.

Alternative I (Subsistence): minimization of annual combined inflow while meeting salinity bounds and marsh inundation needs;
Alternative II (Maintenance of Fisheries Harvests): minimization of annual combined inflow while providing annual commercial harvests of red drum, seatrout, all shrimp, blue crab, and bay oysters at levels no less than their mean 1962 through 1976 historical values, satisfying marsh inundation needs, and meeting metabolic bounds for salinity; and
Alternative III (Shellfish Harvest Enhancement): maximization of the total annual commercial estuarine harvest of shellfish (represented by the sum of all shrimp, blue crab, and bay oyster harvests) while meeting bounds for salinity, satisfying marsh inundation needs, 1962 through 1976 historical values, and utilizing an annual combined inflow no greater than the average 1941 through 1976 historical combined inflow.

Under Alternative I (Subsistence), the Lavaca-Tres Palacios 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, but with slightly reduced harvests. Freshwater inflows totalling 2.1 million acre-feet (2,587 million m^3) annually are predicted to satisfy the basic salinity gradient and marsh inundation needs, but would resulting in slight decreases in commercial finfish and shellfish harvests of five percent, from average values for the period 1962 through 1976 (Figure 1-1).

Under Alternative II (Maintenance of Fisheries Harvests), the predicted annual commercial harvests of red drum, spotted seatrout, all shrimp, blue crab and bay oysters are required to be at least as great as historical 1962 through 1976 average levels. To satisfy these criteria, an annual freshwater inflow of 2.8 million acre-feet (3,458 million m^3) is needed (Figure 1-1).

Under Alternative III (Shellfish Harvest Enhancement), the Lavaca-Tres Palacios estuary annually needs an estimated 2.81 million acre-feet (3,459 million m^3)1/, distributed in a seasonally unique manner (Figure 1-1). This is necessary to achieve the objective of maximizing the total annual predicted commercial harvest of shrimp, blue crab and bay oysters, with the condition that the predicted commercial harvest of bay oysters is at least as great as the 1962 through 1976 historical average. Alternative III is achieved with a 22 percent increase in shellfish harvest, at an estimated

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1/ Freshwater inflow supplied to the estuary under Alternative III was not allowed to exceed the historical "combined inflow" (1941 through 1976) as defined in Chapter IV.

loss of five percent in total commercial finfish harvest (including a 46 percent decline in the commercial harvest of red drum).

The numerical tidal hydrodynamic and salinity mass transport models were applied to the Lavaca-Tres Palacios 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 internal circulation currents dominate the water movements of the Lavaca-Tres Palacios estuary. Depending upon the month simulated, the net circulation in Matagorda Bay reveals up to three individual currents, each moving in a circular pattern within the boundaries of the bay. Water in Matagorda Bay is readily mixed among these circulation currents; however, relatively little net flow of water, except during high freshwater inflow periods, takes place among Matagorda, Lavaca, and Carancahua Bays.

The simulated salinities in the Lavaca-Tres Palacios estuary for the estimated monthly freshwater inflow needs vary over a wide range. Salinities throughout the estuary are lowest in the month of June, with average simulated salinities of less than 20 parts per thousand (ppt) over the entire estuary. The highest levels of simulated salinities occur during the month of August, when salinities in Matagorda Bay near Pass Cavallo exceed 30 ppt. The simulated salinities for Lavaca Bay are generally less than 15 ppt throughout the year. The major portion of Matagorda Bay has simulated salinities of between 20 and 25 ppt; however, during the high freshwater inflow months of May and June, the salinities in the bay are between 10 and 20 ppt. Since the middle portion of Matagorda Bay has simulated salinities in all months below a target maximum allowable concentration of 25 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. The Alternatives considered 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 resident aquatic organisms.

[1/] The alternative having the lowest inflow level and thus the alternative that would impinge most heavily upon maximum 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, ed. 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. 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.

7. 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.

8. 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.

9. 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.

10. Bursey, C. R. and C. E. Lane. "Osmoregulation in the Pink Penaeus duroarum Burkenroad." Comp. Biochem. Physiol. Vol. 39 A, pp. 484-493, 1971.

11. Butler, P. A. "Gametogenesis in the Oyster under Conditions of Depressed Salinity." Biol. Bull. Vol. 96, pp. 263-269. 1949.

12. California, State Water Pollution Control Board. "General Features of Algal Growth in Sewage Oxidation Ponds," by M. B. Allen. Publication 13. 1955.

BIBLIOGRAPHY (cont'd)

13. 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.

14. 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. [Fiche/COM73/11567]

15. 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. [33.916/C125I/76-8]

16. Central Power & Light. "Ecology of Cox Bay, Texas, First Annual Report, 1969-1970," by F. N. Mosely and B. J. Copeland. 243 p. 1970.

17. Central Power & Light. "Ecology of Cox Bay, Texas, Interim Report, 1969-1972," by F. N Moseley and B. J. Copeland. 90 p. and appendices. 1973.

18. Central Power & Light Company. "Further Studies of the Effects of Power Plant Operation on Cox Bay, Texas," by F. N. Moseley, et al. 1975.

19. Chanley, P. E. "Survival of Some Juvenile Bivalves in Water of Low Salinity." Roc. Natl. Shellfish Assoc., Vol. 48. pp. 52-65. 1957.

20. 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.

21. Cleveland State University, College of Business Administration. "GRG2 User's Guide," by L. S. Lasdon, et al. 1978.

22. Coastal Ecosystems Management, Inc. "Environmental Factors affecting Bay and Estuarine Ecosystems of the Texas Coast," by R. H. Parker and W. G. Blankton. Report to Humble Oil Co. 182 p. 1970.

23. 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.

24. 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.

25. 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.

26. Copeland, B. J. "Effects of Decreased River Flow on Estuarine Ecology." J. Water Pollution Control Fed., Vol. 38, pp. 1830-1839. 1966.

27. 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.

28. 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.

29. 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.

30. 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.

31. Cruz, A. A. de la. "Primary Production of Coastal Marshes in Mississippi." Gulf Res. Rept. 4, pp. 351-356. 1974.

32. 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.

33. Cushing, D. The Detection of Fish. Pergamon Press, New York. 200 p. 1973.

34. Dailey, J. A. (personal communication). Tex. Parks Wildl. Dept., Marine Fish. Res. Station, Palacios, Texas. 1979.

35. Dantzig, G. B., Linear Programming and Extensions, Princeton University Press, Princeton, New Jersey. 1963.

36. 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.

37. Darnell, R. M. "Trophic Spectrum of an Estuarine Community, based on Studies of Lake Pontchartrain, Louisiana." Ecology, Vol. 42, pp. 553-568. 1961.

38. Davis, E. M. "Development of Methodology for Evaluation and Prediction of the Limnological Aspects of Matagorda and San Antonio Bays." 202 p. Report to the TWDB. 1971. [551.36/D29D]

39. 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.

40. 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.

41. Donaldson, A. C., et al. "Holocene Guadalupe Delta of Texas Gulf Coast." In: Deltaic Sedimentation Modern and Ancient. Society of Economic Paleontologists and Mineralogists Special Publication Vol. 15, pp. 107-137. 1970.

42. 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.

43. Environment Monitors. "The Ecological Impact of Mercury Discharge on an Enclosed Secondary Bay," by W. G. Blanton et al. 231 p. 1972.

44. Espey, Huston and Associates, Inc. "Development and Application of a Hydrodynamic Model fo the Lavaca and Guadalupe Deltaic Systems," by L. M. Hauck et al. Report to the Texas Water Development Board. EH&A 0163-01. 1976.

45. Espey, Huston and Associates, Inc. "Development and Application of a Hydrodynamic Model of the Colorado River Delta," by M. P. Sullivan and L. M. Hauck, EH&A 0216. 1978.

46. Espey, Huston and Associates, Inc. "Ecological Studies in Sabine Lake, 1974-1975." Technical Report to the Texas Water Development Board, EH&A Document No. 7644. 1976.

47. Espey, Huston and Associates, Inc. "Fish Studies and Mathematical Modeling of the Joslin Station Discharge in Cox Bay," by G. H. Ward, et al. Report to F. N. Moseley, Central Power and Light Co., 1975.

48. 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.

49. 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]

50. 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.

51. 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. 1977.

BIBLIOGRAPHY (cont'd)

52. Espey, Huston and Associates, Inc. "A Study of the Hydrological and Nutrient Exchange Processes in the Trinity River Delta, Texas, Part II: March Habitats and Primary Production in the Trinity River Delta," by D. B. Adams. Austin, Texas. 1977.

53. Espey, Huston and Associates, Inc "A Study of the Placement of Materials Dredged from Texas Ports and Waterways." 3 Vol. (V. 3 - Executive Summary) Prepared for General Land Office of Texas. 1976. [627.73/ ES6S]

54. Espey, Huston and Associates, Inc. "Test Verification, Lavaca Estuary," by L. M. Hauck et al. Interim Report to the Texas Water Development Board. 18 p. 1976.

55. 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, MASGP-74-18. 41 p. 1974.

56. Fiering, M. B. and B. B. Jackson. <u>Synthetic Streamflows</u>. Water Resources Monograph 1, American Geophysical Union. 1971.

57. Foerster, J. W. "The Fate of Freshwater Algae Entering an Estuary." In: <u>Estuarine Microbial Ecology</u>, edited by L. H. Stevenson and R. R. Colwell. University of South Carolina Press. 1973.

58. Fotheringham, N. and S. L. Brunemeister. "Common Marine Invertebrates of the Northwestern Gulf Coast." Gulf Publ. Co., Houston. 197 p. 1975.

59. Geological Society of America, Inc. "Salinity," by A. S. Pearse and G. Gunter. In: <u>Treatise on Marine Ecology and Paleoecology</u>, edited by J. W. Hedgpeth. Memoir No. 67. pp. 129-157. 1957.

60. Georgia Department of Natural Resources. "Seatrout of the Genus <u>Cynoscion</u> in Coastal Waters of Georgia," by R. K. Mahood. Contributing Series No. 26. 36 p. 1974.

61. Georgia Game & Fish Commission, Coastal Fish. Div. "A Report on the Cooperative Blue Crab Study — South Atlantic States," by R. Mahood et al. <u>Contrib. Series</u>, No. 19. pp. 1-32. 1970.

62. Georgia, University, Marine Science Center. "Seasonal Measurements of Carbon, Nitrogen, Ash, Iron, Carbohydrates, and Pigments from Geographically Different <u>Spartina alterniflora</u> Marshes in the Southwest," by G. L. McIntire and W. M. Dunston. Technical Report No. 76-5. 1976.

63. Green, J. "<u>The Biology of Estuarine Animals</u>." University of Washington Press, Seattle. 401 p. 1968.

64. Gucinski, H. "A Note on the Relation of Size to Ecological Value of Some Wetlands." Estuaries, Vol. 1, pp. 151-156. 1978.

65. 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 Report Series No. 2 128 p. 1977.

66. 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.

67. 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.

68. 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.

69. 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. Rep., Vol. 1. pp. 189-307. 1963.

70. Gunter, G. "Death of Fishes Due to Cold on the Texas Coast, January, 1940." Ecology, Vol. 22, pp. 203-208. 1941.

71. 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.

72. Gunter, G. "Gulf Fisheries." In: The Encyclopedia of Marine Resources, ed. F. E. Firth. pp. 289-294. Van Nostrand Reinhold Col., New York. 1969.

73. Gunter, G. "Habitat of Juvenile Shrimp (family Penaeidae)." Ecology, Vol. 42, pp. 598-599. 1961.

74. Gunter, G. "The Importance of Catastrophic Mortalities for Marine Fisheries Along the Texas Coast." Journal of Wildlife Management, Vol. 16, pp. 63-69. 1952.

75. Gunter, G. "Mortality of Oysters and Abundance of Certain Associates as Related to Salinity." Ecology, Vol. 36, pp. 601-605. 1955.

76. Gunter, G. "Predominance of the Young among Marine Fishes found in Freshwater." Copeia, Vol. 1, pp. 13-16. 1957.

77. 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.

BIBLIOGRAPHY (cont'd)

78. Gunter, G. "Some Relations of Estuarine Organisms to Salinity." *Limnol. Oceanogr.*, Vol. 6, pp. 182-190. 1961.

79. 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.

80. 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.

81. 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.

82. Gunter, G. "Seasonal Variations in Abundance of Certain Estuarine and Marine Fishes in Louisiana, with particular reference of Life Histories." *Ecol. Monogr*. Vol. 8, pp. 313-346. 1938.

83. Gunter, G. "Some Relations of Faunal Distributions to Salinity in Estuarine Waters." *Ecology*, Vol. 37, pp. 616-619. 1956.

84. 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.

85. 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.

86. Hackney, C. T. and de la Cruz, A. A. "Changes in Interstitial Water Salinity of a Mississippi Tidal Marsh." *Estuaries*, Vol. 1, pp. 185-188. 1978.

87. 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.

88. Haines, E. B. "On the Origin of Detritus in Georgia Salt Marsh Estuaries." *Oikos*, Vol. 29, pp. 254-260. 1977.

89. Haines, E. B. "Nitrogen Pools in Georgia Coastal Waters." *Estuaries*, Vol. 2. pp. 33-39. 1979.

90. Hann, C. T. *Statistical Methods in Hydrology*. Iowa State University Press at Ames. 378 p. 1977.

91. 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.

BIBLIOGRAPHY (cont'd)

92. 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.

93. 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.

94. Heinle, D. R., et al. "Contributation 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.

95. 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.

96. 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.

97. Hildebrand, H. H. "Estudio Biologicos Prelliminares Sobre la Laguna Madre de Tamaulipas." Ciencia (Mexico). Vol. 17. pp. 151-173. 1958.

98. Himmelblau, D. M. Applied Nonlinear Programming. McGraw-Hill, Inc., New York. 1972.

99. 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.

100. Holliday, F. G. T. "The Effects of Salinity on the Eggs and Larvae of Teleosts." In: Fish Physiology, ed. N. S. Hoar and D. J. Randall, Vol. 1. Academic Press, New York. pp. 293-311. 1969.

101. Holliday, F. G. T. "Salinity: Fishes." In: Marine Ecology, ed. O. Kinne, Vol. 1 Environmental Factors, Part 2 Salinity. pp. 997-1033. Wiley-Interscience, New York. 1971.

102. Hoese, H. D. "Biotic Changes in a Bay Associated with the End of a Drought." Limnol. Oceanogr., Vol. 5, pp. 326-336. 1960.

103. 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.

104. Hoese, H. D. and R. H. Moore. Fishes of the Gulf of Mexico, Texas, Louisiana, and Adjacent Waters. Texas A&M University Press, 337 p. College Station, Texas. 1977.

105. 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.

106. Hoss, D. E. and D. S. Peters. "Respiratory Adaptation: Fishes." In: Estuarine Processes, ed. M. Wiley, Vol. 1, pp. 335-346. Academic Press, New York. 1976.

107. 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.

108. 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.

109. Ketchum, B. H. "Eutrophication of Estuaries." In: Eutrophication: Causes, Consequences, Corrections. National Academy of Sciences. Washington, D. C.: 1969.

110. Khlebovich, V. V. "Aspects of Animal Evolution Related to Critical Salinity and Internal State." Mar. Biol., Vol. 2, pp. 338-345. 1969.

111. Kjerfve, B. and J. E. Greer. "Hydrography of the Santee River during Moderate Discharge Conditions." Estuaries, Vol. 1, No. 2, pp. 111-119. 1978.

112. Kinne, O. "Adaptation to Salinity Variations - Some Facts and Problems." In: Physiological Adaptation, ed. C. L. Prosser. pp. 92-106. Amer. Physiol. Soc., Washington, D. C. 1958.

113. Kinne, O. "Physiology of Estuarine Organisms with Special References to Salinity and Tempeature." In: Estuaries, edited by G. H. Lauff. Publ. No. 83. pp. 525-540. Am. Assoc. Advmt. Sci. 1967.

114. Kinne, O. "Salinity: Invertebrates." In: Marine Ecology, ed. O. Kinne, Vol. 1. Environmental Factors, Part 2 Salinity, pp. 821-995. Wiley-Interscience, New York. 1971.

115. 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.

116. Kjelson, M. A. and D. R. Colby. "The Evaluation and Use of Gear Efficiencies In the Estimation of Estuarine Fish Abundance." In: Estuarine Processes, ed. M. Wiley, Vol. 2, pp. 416-424. Academic Press, New York. 1977.

117. Kramer, J. R. "Phosphorus: Analysis of Water, Biomass, and Sediment." In: Nutrients in Natural Waters, H. Allen and J. R. Kramer, editors. John Wiley & Sons. pp. 51-100. New York. 1972.

118. Kushlan, J. A. "Environmental Stability and Fish Community Diversity." Ecology, Vol. 57, pp. 821-825. 1976.

119. Kutkuhn, J. H. "The Role of Estuaries in the Development and Perpetuation of Commercial Shrimp Resources." In: A Symposium on Estuarine Fisheries, ed. R. F. Smith. pp. 16-36. Amer. Fish. Soc., Spec. Publ. No. 3, 1966.

120. 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.

121. 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.

122. 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.

123. Lasserre, P. "Osmoregulatory Responses to Estuarine Conditions; Chronic Osmotic Stress and Competition." In: Estuarine Processes, ed. M. Wiley, Vol. 1, pp. 395-413. Academic Press, New York. 1976.

124. 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.

125. Leedale, G. F. Euglenoid Flagellates. Prentice-Hall, Inc., Englewood Cliffs, New Jersey. 1967.

126. 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.

127. 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.

128. Loosanoff, V. L. "Behavior of Oysters in Water of Low Salinities." Proc. Natl. Shellfish Assoc., Vol. 135. 51 p. 1952.

129. 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.

130. 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.

131. 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.

132. 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.

133. 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.

134. Louisiana State University, Baton Rouge. "The Impact of 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.

135. 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.

136. 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.

137. 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.

138. 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.

139. Louisiana Wildlife and Fisheries Commissionn. "Barataria Basin: Salinity Changes and Oyster Distribution," by V. R. Sickle et al. Technical Bulletin No. 20. 22 p. 1976.

140. 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.

141. 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.

142. 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.

143. 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.

144. Mackenzie, C. L., Jr. "Development of an Aquacultural Program for Rehabilitation of Damaged Oyster Reefs in Mississippi." Mar. Fish. Rev., Vol. 39. pp. 1-33. 1977.

145. 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.

146. Masch, F. 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]

147. Masch, F. 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.

148. Matlock, G. C. (personal communication) Tex. Parks & Wild. Dept., Fish. Div., Austin, Texas. 1979.

149. 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.

150. McCaffrey, K. M. et al. "Project Description: Upland Detention/Retention Demonstration Project." Coordinating Council on the Restoration of the Kissimmee River Valley and Taylor Creek-Nubbin Slouth Basin. 1977.

151. 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.

152. 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.

153. McHugh, J. L. "Estuarine Nekton." In: Estuaries. ed. G. H. Lauff. pp. 581-620. Amer. Assoc. Advmt. Sci., Publ. No. 83. Wash., D.C. 1967.

154. 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.

155. Meinzer, O. E. Hydrology. Dover Publication, Inc., New York. 1942.

156. Moore, R. H. "Variations in the Diversity of Summer Estuarine Fish Populations in Aransas Bay, Texas, 1966-1973." Estuarine and Coastal Marine Science, Vol. 6. pp. 495-501. 1978.

157. Nestler, J. "Interstitial Salinity as a Cause of Ecophenic Variation in Spartina alterniflora." Estuarine and Coastal Marine Science, Vol. 5. pp. 707-714. 1977.

158. Odum, E. P. Fundamentals of Ecology (3rd Edition). W. B. Saunders Co., Philadelphia. 574 p. 1971.

159. Odum, E. P. "Halophytes, Energetics and Ecosystems." In: Ecology of Halophytes, eds. R. J. Reimold and W. H. Queen. Academic Press, N.Y. 1974.

160. 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.

161. Odum, H. T. Environment, Power, and Society. Wiley Interscience, New York. 1971.

162. Odum, H. T. "Factors Controlling Marine Invasion into Florida Freshwater." Bull. Mar. Sci. Gulf and Carribean, Vol. 3. pp. 134-156. 1953.

163. Odum, W. E. "Insidious Alteration of the Estuarine Environment." Trans. Amer. Fish. Soc., Vol. 99. pp. 836-847. 1970.

164. 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.

165. 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.

166. 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.

167. 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.

168. 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.

169. Pearce, J. and N. G. Carr. "The Metabolism of Acetate by the Blue-grass Algae; Anabaena variabilis and Anagcysotis nidulans." J. Gen. Microbiology. Vol. 49, pp. 301-313. 1967.

170. Perkins, E. J. The Biology of Estuaries and Coastal Waters. Academic Press, New York. 1974.

171. 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. 1975.

172. Pettitt, J. M. and R. H. Dutton. "Limnological Theses and Dissertations concerning Texas Waters, 1897-1976." Tex. J. Sci., Vol. 28. pp. 285-338. 1977.

173. Phleger, C. F. "Effect of Salinity on Growth of Salt Marsh Grass." Ecology, Vol. 52. pp. 908-911. 1971.

174. 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.

175. Reid, G. K. and R. D. Wood. Ecology of Inland Waters and Estuaries. D. Van Nostrand Co., New York. 485 p. 1976.

176. 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. 1975.

177. Remane, A. "Die Brackwasserfauna." Verh. dt. zool. Ges. Vol. 36. pp. 34-74. 1934.

178. Renfro, W. C. "Survival and Migration of Freshwater Fishes in Salt Water." Tex. J. Sci., Vol. 11. pp. 772-780. 1959.

179. Ricker, W. E. "Computation and Interpretation of Biological Statistics of Fish Populations." Fish. Res. Bd. Canada, Bulletin No. 191. 382 p. 1975.

180. Ricker, W. E. "Linear Regressions in Fishery Research." J. Fish. Res. Bd. Canada, Vol. 30, No. 3. pp. 409-434. 1973.

181. Rose, C. D. and E. Heath. "Viability of American oyster, Crassostrea virginica, Spermatozoa Exposed to Stress." Estuaries, Vol. 1. pp. 245-251. 1978.

182. Rounsefell, G. A. Ecology, Utilization, and Management of Marine Fishes. The C. V. Mosby Co., St. Louis. 516 p. 1975.

183. Ryther, J. H. "The Measurement of Primary Production." Limnol. and Oceanogr., Vol. 1. pp. 72-84. 1956.

184. Ryther, J. H. and W. M. Dunstan. "Nitrogen, Phosphorus and Eutrophication in the Coastal Marine Environment: Science, Vol. 171 (3875). pp. 1008-1013. 1971.

185. 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.

186. 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.

187. 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.

188. Scripps Institute of Oceanography. Institute of Marine Resources. "Eutrophication in Coastal Waters: Nitrogen as a Controlling Factor," by R. W. Eppley. Report to the Environmental Protection Agency. University of California, San Diego. 1971.

189. 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.

190. Shepard, F. P. Submarine Geology. Harper and Row, New York. 517 p. 1973.

191. Simmons, E. G. (personal communication) Tex. Parks Wildl. Dept., Fish. Div., Austin, Texas. 1979.

192. 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.

193. Smith, A. J., et al. "Biochemical Basis of Obligate Autotrophy in Blue-green Algae and *Thiobacilli*." J. Bact., Vol. 94. pp. 972-983. 1967.

194. 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.

195. Smith, R. V. "Domestic and Agricultural Contributions to the Inputs of Phosphorus and Nitrogen to Lough Neagh." Water Research, Vol. 11, No. 5. pp. 453-459. 1977.

196. Sport Fishing Institute. "Estuarine Productivity Source." Sport Fishing Institute Bulletin. Vol. 293. pp. 7-8. April 1978.

197. 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.

198. 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]

199. Stein, J. E. and J. G. Denison. "Limitations of Indicator Organisms." In: Pollution and Marine Ecology, eds. T. A. Olson and F. J. Burgess, pp. 323-335. J. Wiley Interscience, New York. 1976.

200. 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. 1976.

201. Strickland, J. D. H. "Measuring the Production of Marine Phytoplankton Fish. Res. Bd. of Canada. Bulletin No. 122. 172 p. 1960.

202. Sutcliffe, W. H., Jr. "Correlations between Seasonal River Discharge and Local Landings of American Lobster (Homarus americanus) and Atlantic Halibut (Hippoglossus hippoglossus) in the Gulf of St. Lawrence." J. Fish. Res. Bd. Canada, Vol. 30. pp. 856-859. 1973.

203. 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.

204. 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.

205. Teal, J. M. "Energy Flow in the Salt Marsh Ecosystems in Georgia." Ecology, Vol. 43. pp. 614-624. 1962.

206. 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.

207. 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.

208. 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.

209. 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.

210. 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.

BIBLIOGRAPHY (cont'd)

211. Texas A&M University. "A Quantitative Analysis of Shoreline Change, Sargent, Texas," by J. E. Sealy. Sea Grant Publ. 75-209. 1975. [333.916/T31C/75-209]

212. 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.

213. 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.

214. Texas A&M University. "Sciaenid Stocks of the Western Central Atlantic Between Chesapeak 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*, pp. 1-13. Sea Grant Publication 78-101. 1977.

215. 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.

216. 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.

217. 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.

218. 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.

219. Texas A&M University, Remote Sensing Center. "Vegetative Community Maps: Lavaca River Delta, Pass Cavallo Area, Colorado River Delta South, and Colorado River Delta North." 1976.

220. Texas Board of Water Engineers. "Inventory and Use of Sedimentation Data in Texas." Bull. 5912. 85p. Austin, Texas. 1959.

221. Texas Department of Water Resources. "Biogeochemical Cycling of Carbon, Nitrogen and Phosphorus Nutrients in River Delta Marshes of Lavaca Bay, Texas." (LP-39) v.p. Originally published by the Center for Research in Water Resources as Technical Reports CRWR-121, January 24, 1975; CRWR-129, August 21, 1975; and CRWR-147, December 31, 1976. 1978.

222. 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.

BIBLIOGRAPHY (cont'd)

223. Texas Department of Water Resources. "Earnings Projections for Texas Counties (1960-2030)." Economics, Water Requirements and Uses Section, Economics Unit. December 1976.

224. Texas Department of Water Resources. "Employment Projections for Texas Counties (1960-2030)." Economics, Water Requirements and Uses Section, Economics Unit. December 1976.

225. Texas Department of Water Resources. "Hydrological and Biological Studies of the Colorado River Delta, Texas." LP-79. 73 p. Austin, Texas. 1978.

226. Texas Department of Water Resources. "Intensive Surface Water Monitoring Survey for Segment No. 2453, Lavaca Bay." Report IMS-70. 59 p. 1978.

227. Texas Department of Water Resources. "Land Use/Land Cover Maps of Texas." LP-62. 47 p. 1977.

228. Texas Department of Water Resources. "Mathematical Simulation Capabilities in Water Resources Systems Analysis." LP-16. 62 p. Austin, Texas. 1978.

229. Texas Department of Water Resources. "Population Projections for Texas Counties (1975-2030)." Economics, Water Requirements and Uses Section, Economics Unit. December 1978.

230. 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).

231. Texas Department of Water Resources. "Texas Input-Output Model, 1972." Planning and Development Division. LP-24. February 1978.

232. Texas Department of Water Resources. Unpublished data, 1977-1979.

233. 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.

234. 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.

235. Texas General Land Office. Texas Coastal Management Program Social and Econnomic Component User's Manual. September 1978.

236. Texas Highway Department. "Texas Visitor Industry, 1975."

237. Texas Parks and Wildlife. "Coastal Fisheries Plan, 1977-1978." 31 p. 1977.

238. 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.

239. Texas Parks and Wildlife Department. "The Crabs of Texas," by S. P. Leary. Bulletin No. 43 (revised 1964). 57 p. 1961.

240. Texas Parks and Wildlife Department. "The Effects of Freshwater Inflows on Hydrological and Biological Parameters in the San Antonio Bay System, Texas," by R. Childress et al., 190 p. Austin, Texas. 1975. [574.526/T31E]

241. 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.

242. 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.

243. Texas Parks and Wildlife Department. "A Study of the Blue Crab Population of the upper Laguna Madre," by W. Hawley. Coastal Fish. Proj. Rpts. (mimeo) pp. 577-581. 1963.

244. 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.

245. 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.

246. Texas Parks and Wildlife Department, Coastal Fisheries Branch. "Survey of Finfish Harvest in Selected Texas Bays," by T. L. Heffernan et al. pp. 5-8. 1977.

247. Texas Parks and Wildlife Department. "The Texas Oyster Fishery," by R. P. Hofstetter. Bulletin No. 40 (revised 1964). 36 p. 1959.

248. 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.

249. 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.

250. 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.

251. 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.

252. 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.

253. Texas, University at Austin, Bureau of Economic Geology. "Environmental Geologic Atlas of the Texas Coastal Zone - Port Lavaca Area," by J. H. McGowen et al. 107 p. 1976.

254. Texas, University at Austin, Bureau of Economic Geology. "Historical Changes and Related Coastal Processes, Gulf and Mainland Shorelines, Matagorda Bay Area, Texas," by J. H. McGowen et al. 72 p. 1975. 2V. [551.36/T31H]

255. 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.

256. 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.

257. Texas, University at Austin, Bureau of Economic Geology. "Shoreline Changes on Matagorda Peninsula (Brown Cedar Cut to Pass Cavallo), An Analysis of Historical Changes of the Texas Gulf Shoreline," by R. A. Morton et al. Geological Circular 76-6. 37 p. plus appendices. 1976.

258. Texas, University at Austin, Bureau of Economic Geology. "Shoreline Changes on Matagorda Island and San Jose Island (Pass Cavallo to Aransas Pass), An Analysis of Historical Changes of the Texas Gulf Shoreline," by R. A. Morton et al. Geological Circular 76-4. 42 p. 1976. [557.64/T31G/776-4]

259. Texas, University at Austin, Bureau of Economic Geology. "Shoreline Changes in the Vicinity of the Brazos River Delta (San Luis Pass to Brown Cedar Cut), An Analysis of Historical Changes of the Texas Gulf Shoreline," by R. A. Morton and M. J. Pieper. Geological Circular 75-4. 47 p. 1975.

260. Texas, University at Austin, Bureau of Economic Geology. "Shoreline Changes Between Sabine Pass and Bolivar Roads, An Analysis of Historical Changes of the Texas Gulf Shoreline," by R. A. Morton. Geological Circular 75-6. 43 p. 1975.

261. 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. v.p. CRWR-121 [333.9/T31CRWR/121]

262. 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. v.p. CRWR 153. 1977. [333.9/T31CRWR/153]

263. 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. v.p. and appendix. Technical Report CRWR-152, EHE77-05. 1977. [333.9/T31CRWR/152]

264. 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. Report CRWR-147. v.p. 1976. [333.9/T31CRWR/147]

265. 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. Report to the Texas Water Development Board (IAC-74/74-1217). 115 p. 1975. [333.9/T31CRWR/129]

266. 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. 1977.

267. Texas, University at Austin, Center for Research in Water Resources. "The Role of Sediments in Nutrient Exchange in the Lavaca Bay Brackish Marsh System," by N. E. Armstrong and B. A. Brown. CRWR-147. 1976.

268. 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. pp. 107-126. Water Research Symposium No. 5. 1972.

269. 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]

270. 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]

271. Texas, University at Austin, Marine Science Institute. "Analysis of Freshwater Inflow Effects on Metabolic Stresses of Fish in Corpus Christi, San Antonio, and Matagorda Bays," by D. E. Wohlschlag. IAC-76/77-0632. 97 p. 1976.

272. Texas, University at Austin, Marine Science Institute. "Analysis of Freshwater Inflow Effects on Metabolic Stresses of South Texas Bay and Estuarine Fishes: Continuation and Extension," by D. E. Wohlschlag. IAC-76/77-1690. 114 p. 1977.

273. 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 the Texas Department of Water Resources. 89 p. 1980.

274. 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.

275. Texas, University at Austin, Marine Science Institute. "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.

276. 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.

277. 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.

278. 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.

279. 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.

280. 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.

281. 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.

282. 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.

283. Texas, University at Austin, Marine Science Institute. "Environmental Effects on Metabolic Scope and Swimming Performance of Some Estuarine Fishes," by J. M. Wakeman. Ph.D. Dissertation, 147 p. 1978.

284. 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.

285. Texas, University at Austin, Marine Science Institute. "Fish Species Diversity Indices s 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.

286. 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.

287. 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.

288. 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.

289. 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.

290. 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.

291. Texas, University at Austin, Marine Science Institute. "Nearshore Surface Currents, Southeastern Texas Gulf Coast," by R. L. Watson et al. Contributions in Marine Science, Vol. 15, pp. 133-143. 1970.

292. 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.

293. 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.

294. Texas, University at Austin, Marine Science Institute. "Observations on Spawning and Larval History of the Shrimp, *Penaeus setiferus*," by P. E. Heegaard. *Contributions in Marine Science*, Vol. 3. pp. 73-105. 1953.

295. 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.

296. 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.

297. 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.

298. Texas, University at Austin, Marine Science Institute. "Salinity Stress and Swimming Performance of Spotted Seatrout," by J. M. Wakeman and D. E. Wohlschlag. 15 p. 1977. (in press)

299. Texas, University at Austin, Marine Science Institute. "Seasonal Changes in the Respiratory Metabolism of the Finfish (*Lagodon rhomboides*)," by D. E. Wohlschlag et al. *Contributions in Marine Science*, Vol. 13. pp. 89-104. 1968.

300. 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.

301. Texas, University at Austin, Marine Science Institute. "Size-related Metabolic Responses of the Finfish, *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.

BIBLIOGRAPHY (cont'd)

302. 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.

303. 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.

304. 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.

305. 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.

306. 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.

307. 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.

308. 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.

309. Texas, University at Austin, Marine Science Institute. "Vertebrates in Hypersaline Waters," by G. Gunter. Contributions in Marine Science, Vol. 12. pp. 230-241. 1967.

310. 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.

311. Texas, University at Houston, Institute of Environmental Health. "Development of Methodology for Evaluation and Prediction of the Limnological Aspects of Matagorda and San Antonio Bays," by E. M. Davis. Report to the Texas Water Development Board IAC-70-71-467. 202 p. 1971.

312. 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. 1973.

BIBLIOGRAPHY (cont'd)

313. Texas, University at Houston, Sc. of Public Health. "An Investigation of Tertiary Estuary Productivity and Nutrient Optimization in Texas Coastal Waters," by E. M. Davis. Report to the Texas Water Development Board. 355 p. Houston, Texas. 1973. [574.526/T314I]

314. 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.

315. Texas, University at Houston, Sc. of Public Health. "Primary Productivity and Nutrient Budget of San Antonio Bay - A Texas Estuary," by W. C. Langdon et al. 83 p. 1972. [551.46/T31P]

316. Texas Water Development Board. "Archeological Resources in the Texas Coastal Lowlands and Littoral," by A. K. Briggs. 46 p. 1971. [913/T31AC]

317. Texas Water Development Board. "Chemical and Physical Characteristics of Water in Estuaries of Texas, October 1969 - September 1970." TWDB Rept. 171. 123 p. 1973.

318. Texas Water Development Board. "Coastal Data System User Documentation; Vol. I - Storage Reference Manual; Vol. II - Retrieval Reference Manual." 1973 (revised 1977).

319. Texas Water Development Board. "Continuing Water Resources Planning and Development for Texas," 2 Vol. v.p. Austin, Texas. 1977.

320. Texas Water Development Board. "Estimated Monthly Runoff System WD8900: User Reference Manual." 104 p. Austin, Texas. 1976.

321. Texas Water Development Board. "Inventories of Irrigation in Texas 1958, 1964, 1969, and 1974." Report 196. 265 p. Austin, Texas. 1975.

322. Texas Water Development Board. "Monthly Reservoir Evaporation Rates for Texas, 1940 through 1976." Report 64 (updated). 111 p. Austin, Texas. 1967.

323. Texas Water Development Board. "1975 National Water Assessment. Texas Gulf Region. Technical Memorandum Activity 2, Phase II." 234 p. 1977.

324. Texas Water Development Board. "Rice Irrigation Return-flow Study" 135 p. Austin, Texas. 1974.

325. Texas Water Quality Board. "Texas Water Quality Standards." 79 p. Austin Texas: February 1976.

326. Texas Water Quality Board. "Water Quality Segment Report for Segment Nos. 2453 and 2454, Lavaca and Cox Bays," by S. Holman (WQS-2). 49 p. August 1977.

BIBLIOGRAPHY (cont'd)

327. Theede, H. "Aspects of Individual Adaptation to Salinity in Marine Invertebrates." In: Physiological Ecology of Estuarine Organisms, ed. F. J. Vernberg. pp. 213-225. Univ. South Carolina Press, Columbia, 1975.

328. Thiessen, A. H. "Precipitation for Large Areas." Monthly Weather Rev., Vol. 39, pp. 1082-1084. July 1911.

329. Thorson, G. "Reproduction and Larval Development of Marine Bottom Invertebrates." Biol. Rev., Vol. 25. pp. 1-45. 1950.

330. 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. 1973.

331. 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.

332. 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.

333. Turner, R. E. "Intertidal Vegetation and Commercial Yields of Penaeid Shrimp." Trans. Amer. Fish. Soc., Vol. 106. pp. 411-416. 1977.

334. URS/Forrest and Cotton, Inc. "Tidal Hydrodynamic and Salinity Models of Matagorda Bay for El Paso LNG Terminal Co." 2V. 1977. [532.5/UR7T]

335. U. S. Army Engineer Waterways Experiment Station, Vicksburg. "Annotated Bibliography on Effects on Salinity and Salinity Changes on Life in Coastal Waters," by S. H. Hopkins. 411 p. 1973.

336. 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.

337. 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.

338. U. S. Army Corps of Engineers. "Wallisville Environmental Impact Statement Vegetation Transects." Unpublished data.

339. 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.

BIBLIOGRAPHY (cont'd)

353. 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.

354. 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.

355. 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.

356. 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.

357. 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.

358. 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.

359. 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.

360. 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.

361. 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.

362. 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.

363. 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.

364. U. S. Department of Interior, Bureau of Reclamation. "Entrapment of Suspended Materials in the San Francisco Bay-Delta Estuary," by J. F. Arthur and M. Ball. 106 p. GPO 789-115/78-5. Sacramento, Calif. 1978.

353. 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.

354. 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.

355. 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.

356. 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.

357. 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.

358. 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.

359. 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.

360. 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.

361. 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.

362. 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.

363. 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.

364. U. S. Department of Interior, Bureau of Reclamation. "Entrapment of Suspended Materials in the San Francisco Bay-Delta Estuary," by J. F. Arthur and M. Ball. 106 p. GPO 789-115/78-5. Sacramento, Calif. 1978.

BIBLIOGRAPHY (cont'd)

365. 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.

366. 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.

367. U. S. Federal Power Commission. "Matagorda Bay Project," 2 V. Final Environmental Impact Statement. V. 2 - Attachments and Appendices. 1977. [EIS/M41]

368. U. S. Fish and Wildlife Service. "The American Oyster, *Crassostrea virginica* (Gmelin)," by P. S. Galtzoff. *Fisheries Bulletin* 6. 480 p. 1964.

369. 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.

370. U. S. Fish and Wildlife Service. "Environmental Assessment of Proposed BLHP Projects, Anahuac National Wildlife Refuge, Texas." 1978.

371. 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 a.

372. 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.

373. 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.

374. 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.

375. U. S. Fish and Wildlife Service. "Western Atlantic Shrimps of the Genus *Penaeus*," by I. Perez-Farfante. Bulletin No. 67. pp. 461-591. 1969.

376. U. S. Fisheries Commission. "Report on the Inquiry Respecting Food-Fishes and the Fishing Grounds," by R. Rathbun. Report 19. pp. 23-26. 1895.

BIBLIOGRAPHY (cont'd)

377. U. S. Geological Survey. "Water Resources Data for Texas, 1966-1976." Austin, Texas. v.p.

378. U. S. National Marine Fisheries Service. Economic Activity Associated with Marine Recreational Fisheries. p. 41. June 1977.

379. U. S. National Oceanic and Atmospheric Administration. "Cooperative Gulf of Mexico Estuarine Inventory and Study - Texas: Area Description," by R. A. Diener. 129 p. NOAA Technical Report NMFS CIRC-393. Seattle, Washington. 1975.

380. 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.

381. 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.

382. 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.

383. Van Winkle, W., Jr. "The Effects of Season, Temperature and Salinity on Oxygen Consumption of Bivalve Gill Tissue." Comp. Biochem. Physiol., Vol. 26. p. 69-80. 1968.

384. 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.

385. Vernberg, F. J. and W. B. Vernberg. "Adaptations to Extreme Environments." In: Physiological Ecology of Estuarine Organisms, ed. F. J. Vernberg. pp. 165-180. Univ. South Carolina Press, Columbia. 1975.

386. Vernberg, W. B. and F. J. Vernberg. Environmental Physiology of Marine Animals. Springer-Verlag, New York, 346 p. 1972.

387. Waisel, Y. Biology of the Halophytes. Academic Press, New York. 395 p. 1972.

388. Wakeman, J. M. "Environmental Effects on Metabolic Scope and Swimming Performance of Some Estuarine Fishes." Ph. D. Dissertation, Univ. Tex., 146 p. 1978.

389. Wallace, D. H. "Oysters in the Estuarine Environment." In: A Symposium on Estuarine Fisheries, ed. R. F. Smith. Amer. Fish. Soc., Spec. Publ. No. 3, pp. 68-73. 1966.

390. 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.

391. 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.

392. Weinstein, M. P. and R. W. Yerger. "Electrophoretic Investigation of Sub-populations 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.

393. Wells, H. W. "The Fauna of Oyster Beds, with Special Reference to the Salinity Factor." Ecol. Monitor, Vol. 31. pp. 239-266. 1961.

394. 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.

395. 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, eds. D. J. Nelson and F. C. Evans. pp. 431-439. USAEC, Conf. - 670503. 1969.

396. 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.

397. Wohlschlag, D. E. and B. J. Copeland. "Fragile Estuarine Systems—Ecological Considerations." Water Res. Bull. Vol. 6. pp. 94-105. 1970.

398. Yakupzack, P. M., et al. "Emigration of Juvenile Atlantic Croakers, Micropogon undalatus, from a Semi-impounded Marsh in Southwestern Louisiana." Trans. Amer. Fish. Soc., Vol. 106. pp. 538-544. 1977.

399. 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.

400. 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.

401. Zein-Eldin, Z. P. "Effect of Salinity on Growth of Postlarval Penaeid Shrimp." Biol. Bull., Vol. 125. pp. 188-196. 1963.

402. 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

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Charles D. Travis	Texas Parks & Wildlife Department, Austin
Executive Director	Texas Coastal & Marine Council, Austin
Robert Bernstein*	Texas Department of Health, Austin
John Poerner	Railroad Commission of Texas, Austin
Edward Vetter	Texas Energy & Natural Resources Council, Austin
Mark White	Attorney General of Texas, Austin
Mit Spears	Governor's Budget & Planning Office, Austin
A.R. Schwartz	Texas Senate, Galveston
John Sharp	Texas House of Representatives, Victoria
W.N. Patman	Texas Senate, Ganado
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
James C. Donovan	U.S. Army Corps of Engineers, Dallas
Donald J. Palladino	U.S. Army Corps of Engineers, Fort Worth
James M. Sigler	U.S. Army Corps of Engineers, Galveston
Bill Waddle	Texas Water Conservation Association, Austin
John Specht	Guadalupe-Blanco River Authority, Seguin

List of Persons Receiving the Draft Report (Cont'd.)

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Charles F. Herring	Lower Colorado River Authority, Austin
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Dale Yost	U.S. Geological Survey, Austin
Clark Hubbs	University of Texas at Austin
N.E. Armstrong	University of Texas at Austin
G.A. Rohlich	University of Texas at Austin
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Ralph Rayburn	Texas Shrimp Commission, Austin
Catherine Perrine	League of Women Voters, Dallas
Paul Fore	U.S. Fish & Wildlife Service, Albuquerque
Sharron Stewart	Texas Environmental Coalition, Lake Jackson
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Jack Runkles*	Texas A&M University, College Station
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Vito Blomo	Gulf of Mexico Fishery Management Council, Tampa, FLA

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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.