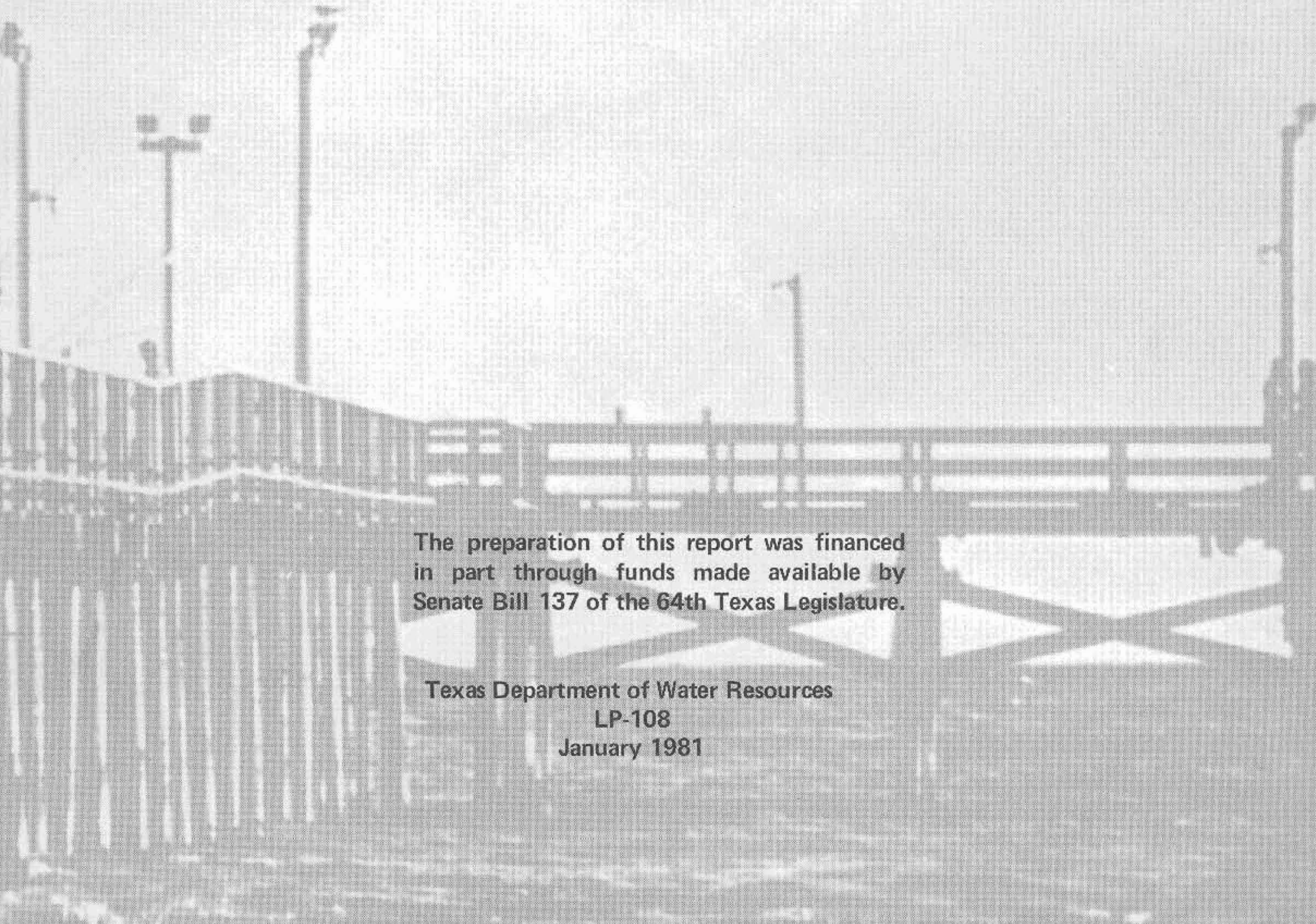
NUECES AND MISSION-ARANSAS ESTUARIES:
A Study of the Influence of Freshwater Inflows



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Texas Department of Water Resources
LP-108
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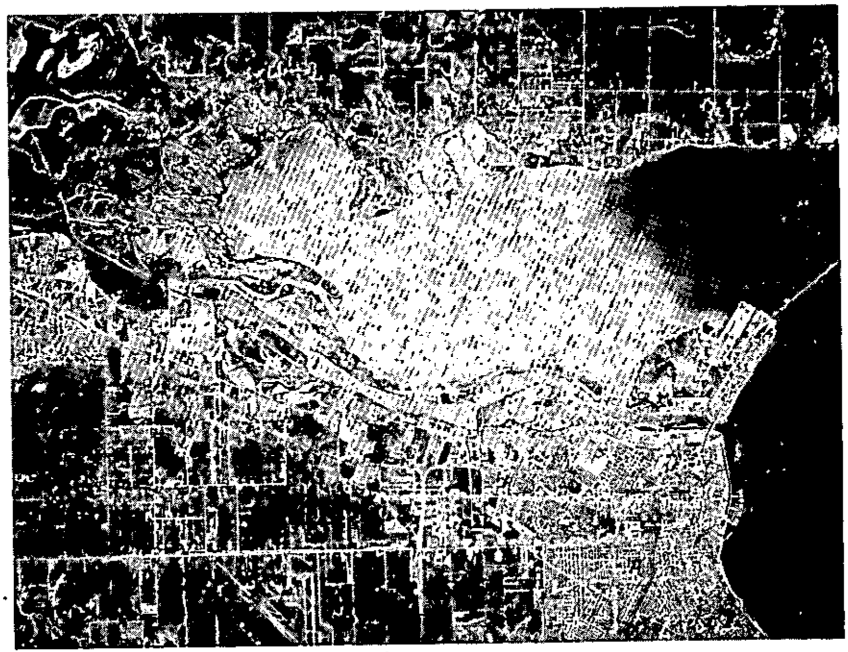

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TEXAS DEPARTMENT OF WATER RESOURCES

Harvey Davis, Executive Director

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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 Nueces and Mission-Aransas estuaries 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 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.

Description of the Estuary and the Surrounding Area

The Nueces and Mission-Aransas estuaries include Copano Bay, Aransas Bay, Nueces Bay, Corpus Christi Bay, and several smaller bays. About 19,497 square miles (50,497 km^2) of Texas contribute inflow to these estuaries, including the entire Nueces Basin and parts of the San Antonio-Nueces and the Nueces-Rio Grande Coastal Basins.

Major marsh areas of the Nueces and Mission-Aransas estuaries are associated with river deltas. Active deltaic plains are covered with salt, brackish and freshwater marshes. Most of the shoreline along the south side of Corpus Christi and Nueces Bays is stabilized. Erosion is occurring along the Ingleside and Portland shorelines. The mainland shoreline of Copano and Aransas Bays is mostly in a state of erosion; whereas the barrier island shoreline of both Corpus Christi and Aransas Bay is generally either in a state of equilibrium or accretion.

Land use in the area is dominated by agricultural and ranching activities. Grain sorghum, corn and cotton are dryland crops produced in the area.

The Nueces and Mission-Aransas estuaries support a significant portion of the commercial fishing industry in Texas. The annual commercial bay harvest of fish and shellfish in these estuarine systems has averaged 3.1 million pounds (1.4 million kg) during the 1962 to 1976 interval. Shellfish, particularly shrimp, constitute the majority of these commercial bay landings, accounting for 72 percent of the total harvest weight. However, a large part of each estuary's production of fish and shellfish is caught offshore by commercial and sport fishermen. When these harvests are considered, the total contribution of both estuaries to the Texas coastal fisheries (all species) is estimated at 19.6 million pounds (8.9 million kg; 81 percent shellfish) annually for a recent five year period (1972-1976).

The fishing resources of the Nueces and Mission-Aransas estuaries included many of the fish species preferred by sport fishermen. The method of input-output analysis was used to calculate the economic impact of sport fisheries activities. The results showed that sport fishing expenditures (excluding fishing tackle and equipment) in the local area exceed $17.02 million per year. In addition, there was an estimated $2.31 million per year spent outside the region, but within Texas, as a result of the sport fishing activity around these estuaries.

Hydrology

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

Freshwater inflows in terms of annual and monthly average values over the 1941 through 1976 period varied widely from the mean as a result of recurrent drought and flood conditions. On the average, the total freshwater inflow (excluding direct precipitation) to the Nueces estuary (1941-1976) consisted of 680 thousand acre-feet (840 million m^3) annually, of which an estimated 570 thousand acre-feet (704 million m^3) was contributed from gaged drainage areas. For the Mission-Aransas estuary, the average freshwater inflow (excluding direct precipitation) over the period 1941 through 1976 amounted to 380 thousand acre-feet (470 million m^3), with approximately 570 thousand acre-feet (704 million m^3) contributed from gaged drainage areas.

In general, the water quality of gaged inflows to these estuaries has been good. No parameters were found in violation of existing Texas stream standards.[1/] Studies of past water quality in and around these estuaries have pinpointed the occurrence of heavy metals in sediment samples as a significant concern. Locally, bottom sediment samples have exceeded the U. S. Environmental Protection Agency criteria for metals in sediments (prior to dredging) for arsenic, cadmium, lead, mickel, mercury and zinc. Bottom sediments collected and analyzed during the period 1971 through 1975 for herbicides and pesticides showed DDD; DDT; 2,4-D; 2,4,5-T; and silvex occurring

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[1/] No Texas stream standards currently exist for Oso Creek or Chiltipin Creek.

in some local areas in concentrations equal to or greater than the analytical detection limit.

Circulation and Salinity

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

To fully evaluate the tidal hydrodynamic and salinity transport characteristics of estuarine systems using field data, the Texas Department of Water Resources developed digital mathematical models representing the important mixing and physical exchange processes of the estuaries. These models are designed to simulate the tidal circulation patterns and salinity distributions in shallow, irregular, non-stratified estuaries. Physical data collected in these estuaries was utilized to calibrate and verify the models for the Nueces and Mission-Aransas estuaries.

In testing the salinity transport model's abilities to simulate the salinity response of the estuary over an extended time period, it was determined that lower salinities were being predicted in Nueces and Corpus Christi Bays than have been actually observed in recent years. Several additional input sources were included in the models to more adequately represent the numerous permitted brine discharges located in and near Nueces and Corpus Christi Bays. This led to some improvement in the simulated results, but additional effort will be necessary to further improve the simulated results during low-inflow periods.

Statistical analyses were also undertaken to quantify the relationship between freshwater inflows from the Nueces and Mission-Aransas Rivers and salinities at selected points in Nueces and Copano Bays. Utilizing gaged daily river flows and observed salinities, a set of monthly predictive salinity equations were derived utilizing regression analyses for two areas of these estuaries: (1) an area near the Nueces River delta, and (2) an area near the mouth of the Mission River. These equations enable the prediction of the mean monthly salinity as a function of the mean monthly freshwater inflow rate.

Nutrient Processes

The marshes of the Nueces and Mission-Aransas deltas are subject to periodic inundation during periods of increased river flows. High rates of nutrient (organic carbon and nitrogen) export (both particulate and dissolved) occur during the initial stages of these flood periods. After this initial pulse of material is flushed out, nutrient release rates decrease rapidly until they reach seasonal equilibrium. Pulses of increased freshwater discharge (i.e., flooding) and the resulting deltaic inundation appear to be important mechanisms contributing to increased nutrient transport from deltaic marshes to the estuary.

Aerial photographic studies of key coastal wetlands in the Nueces and Mission-Aransas estuaries provided baseline characterization of the marsh vegetative communities and insight into on-going wetland processes. For the most part, the Nueces River delta appears to be most affected by the forces of urbanization and industrialization. Scars from oil drilling and production activities are particularly noticeable at the eastern edge of the Rincon Bayou area. The long-term condition of the wetlands environment is highly sensitive to man's activities.

Primary and Secondary Bay Production

The community composition, distribution, density, and seasonality of the phytoplankton, zooplankton, and benthic invertebrates of the Nueces and Mission-Aransas estuaries were employed 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).

Five phytoplankton divisions represented by 248 taxa were collected from the Nueces and Mission-Aransas estuaries. Salinity increases and zooplankton predation decreases exerted the most obvious influences toward increasing phytoplankton populations. Salinity regimes in each bay system resulted in distinctly different populations.

A total of 319 zooplankton taxa representing 16 phyla were identified. Temperature and salinity were found to be the two most important factors regulating the species composition, seasonal occurrence, and distribution of zooplankton populations.

Fourteen phyla represented by 395 benthic species were collected from the Nueces and Mission-Aransas estuaries. In general, the density of the standing benthic crops were found to be inversely related to salinity.

In Texas estuaries, there is always present a collection of species which are capable of maintaining high standing crops, regardless of the salinity, as long as it is relatively stable, and provided that other physical-chemical requirements for that particular collection are met. If freshwater inflow is decreased, either partially or totally, the most dominant group in the community will merely shift toward the more marine forms.

Fisheries

Virtually all of the Gulf fisheries species are estuarine-dependent. Commercial inshore harvests (1962-1976) from bays of the Mission-Aransas estuary rank fourth in shellfish and third in finfish, while bays of the Nueces estuary rank sixth in shellfish and seventh in finfish of eight major Texas estuarine areas. In addition, the sport or recreational finfish harvest is approximately equal to the commercial finfish harvest in the estuaries. For the 1972 through 1976 interval, the average annual sport and commercial harvest of fish and shellfish dependent upon the Nueces and Mission-Aransas estuaries is estimated at 19.6 million pounds (8.9 million kg; 81 percent shellfish).

Although a large portion of each Texas estuary's fisheries production is harvested offshore in collective association with fisheries production from other regional estuaries, inshore bay harvests are useful as relative indicators of the year-to-year variations in an estuary's fisheries production. These variations are affected by the seasonal quantities and sources of fresh water 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, regression analysis of the 1962 through 1976 commercial bay fisheries landings was undertaken for the annual commercial harvests and the seasonal freshwater inflows to the Nueces and Mission-Aransas estuaries. The analysis of harvest as a function of the seasonal inflows resulted in 52 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 commercial harvests of seafood organisms from these estuaries. The analysis also supports existing scientific information on the seasonal importance of freshwater inflow to these estuaries. Virtually all harvest responses to spring (April-June) and late fall (November-December) inflows are estimated to be positive for increased inflow in these seasons. In addition, most estimated harvest responses to increased summer (July-August) inflow are also positive. Although several shellfish organisms (i.e., white shrimp, blue crab, and oyster) are estimated to relate positively to winter (January-March) inflow, all fisheries components containing fish species (i.e., spotted seatrout, redfish, and black drum) are estimated to relate negatively to this season's inflow. Harvest responses to autumn (September-October) inflow are more variable than responses to other seasons, possibly because the season is tropical-storm dominated. In general, most shellfish organisms relate positively to autumn season inflow while fish species relate negatively. Exceptions occur with the positive relationships of spotted seatrout and red drum harvests to Mission-Aransas estuary inflow during the autumn season.

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

Estimated Freshwater Inflow Needs

A methodology is presented which combines the analyses of the component physical, chemical and biological elements of the Nueces and Mission-Aransas estuaries 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 were specified for two selected locations in these estuaries near the major freshwater inflow points of the Nueces and Mission 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 not exceed median monthly 1941 through 1976 historical salinity conditions.

Marsh inundation needs, for the flushing of nutrients from riverine marshes into the open bays, were computed and specified for the Nueces River delta. Based upon historical gaged streamflow records, freshwater inflows from the Nueces Basin for marsh inundation needed to sustain historical inundation magnitude and frequency were estimated at 79.0 thousand acre-feet (97 million m^3) in the month of May and 139.0 acre-feet (171 million m^3) in September. These volumes correspond to flood events with peak flow rates of 8,500 ft^3/sec (241 m^3/sec) and 11,000 ft^3/sec (312 m^3/sec), respectively.

Evaluation of Estuarine Alternatives

Estimates of the freshwater inflow needs for the Nueces and Mission-Aransas Estuaries were 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 Nueces and Mission-Aransas River Basins which best achieves a specified objective.

The monthly freshwater inflow needs for the Nueces and Mission-Aransas estuaries were estimated for each of three selected alternatives. These alternatives are intended to demonstrate the method of estimating freshwater inflows.

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

Alternative II (Maintenance of Fisheries Harvests): minimization of annual combined inflow to both estuaries while providing freshwater inflows sufficient to supply predicted combined annual commercial bay harvests from both estuaries of red drum, seatrout, white shrimp, and blue crab at levels no less than their 1962 through 1976 mean historical values, satisfying marsh inundation needs, and meeting viability limits for salinity; and

Alternative III (Finfish Harvest Enhancement): maximization of the total annual commercial bay harvest of all finfish from both estuaries while observing salinity limits, satisfying marsh inundation needs, and utilizing an annual combined freshwater inflow to each estuary no greater than their individual average 1941 through 1976 historical freshwater inflows.

Under Alternative I (Subsistence), the Nueces and Mission-Aransas estuarine 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 annual freshwater inflow.

Freshwater inflows totaling 0.69 million acre-feet (850 billion m^3) annually (of which 46 percent is estimated from ungaged areas) are predicted to satisfy the basic salinity gradient and marsh inundation needs, and with a resulting increase in combined commercial finfish and shellfish bay harvests of 21 percent, from average values for the period 1962 through 1976 (Figure 1-1). This annual inflow is approximately 69 percent of the 1941 through 1976 historical average inflow.

Under the inflows for this Alternative, the commercial bay fisheries harvest in both estuaries is estimated to be greater than the mean 1962 through 1976 historical value, even though the annual inflow is significantly less than the 1941 through 1976 historical average. The monthly freshwater inflow needs are significantly lower than 1941 through 1976 mean inflows, however, they are significantly greater than the median (50 percent frequency) monthly inflows. The median inflows are more influencial upon the historical mean harvests in these estuaries than the average freshwater inflows, thus the estimated freshwater inflow needs generally give greater than average harvest estimates. Thus, decreasing September through October inflows results in an increase, or at least no decrease, in the predicted fisheries harvests, based upon the commercial harvest equations developed in this report.

Under Alternative II (Maintenance of Fisheries Harvests), the predicted annual commercial bay harvests of red drum, spotted seatrout, white shrimp, and blue crabs are each required to be at least as great as their 1962 through 1976 historical average levels. Salinity limits and marsh inundation needs are also to be observed. To satisfy these criteria, it is estimated that an annual freshwater inflow of 0.75 million acre-feet (920 billion m^3) (with 44 percent from ungaged areas) is needed (Figure 1-1). This annual inflow volume is 75 percent of the average inflow (1941-1976). The combined predicted annual total finfish and shellfish commercial bay harvest for these estuaries is 4.23 million pounds (1.93 million kg), or approximately 35 percent higher than the 1962 through 1976 average.

Under Alternative III (Finfish Harvest Enhancement), the Nueces and Mission-Aransas estuaries have an annual estimated freshwater need of approximately 1.0 million acre-feet (1,243 billion m^3; 41 percent from ungaged areas), distributed in a seasonally unique manner, to achieve the objective of maximizing the total annual predicted commercial bay harvest of finfish from both estuaries (Figure 1-1). The water supplied to these estuaries equals the arbitrary maximum annual inflow set at the 1941 through 1976 average level. This inflow regime is predicted to give a 43 percent increase in the allshrimp harvest category and an estimated gain of 91 percent in the commercial finfish harvest. The total predicted commercial bay fisheries harvest is 71 percent greater than the 1962 through 1976 average.

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

To establish that the freshwater inflow needs specified above provide desired salinity gradients throughout the estuary, the numerical tidal hydrodynamic and salinity mass transport models were applied to the Nueces and

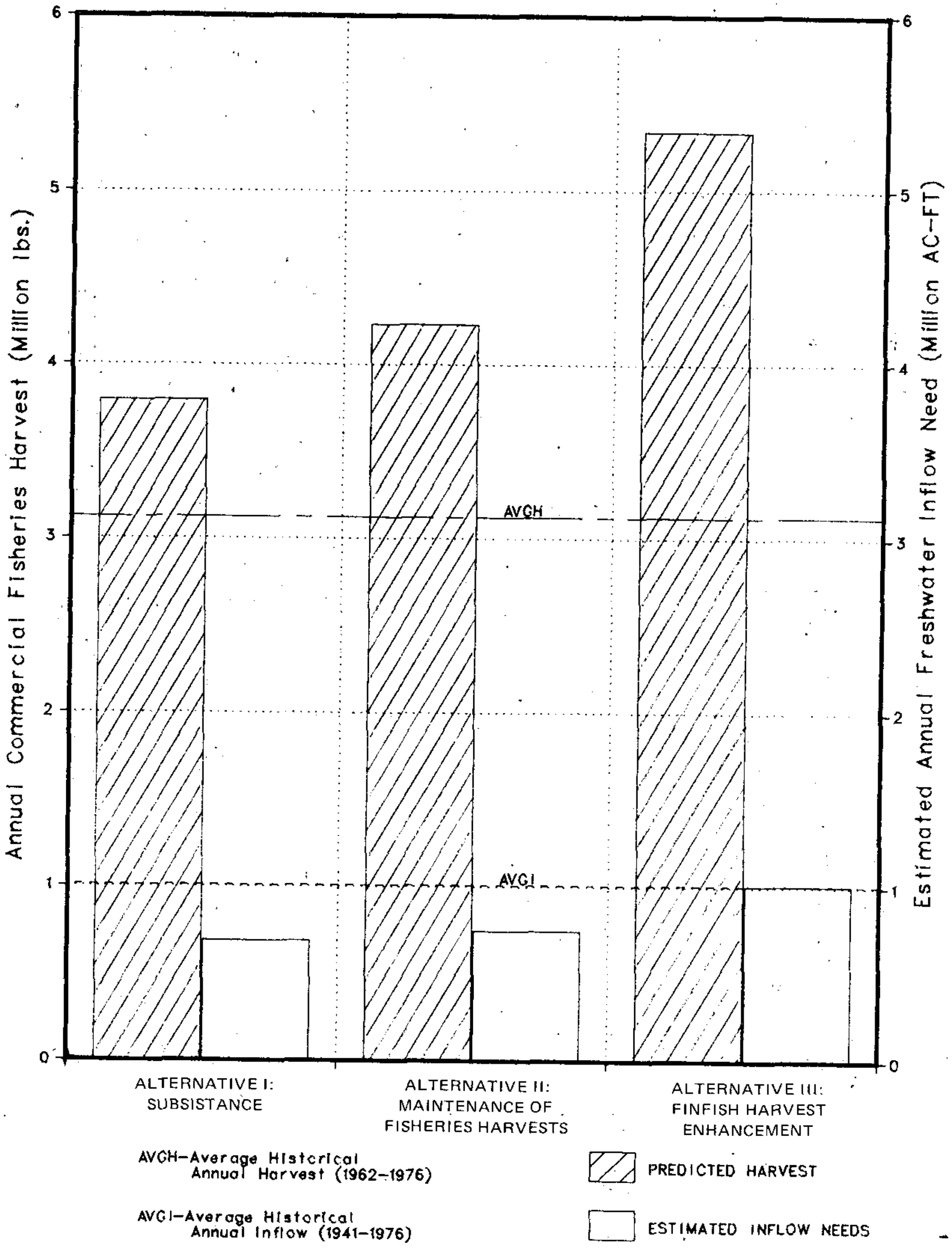

Figure 1-1. Predicted Annual Commercial Fisheries Harvest and Estimated Inflow Needs Under Three Alternatives for the Nueces and Mission-Aransas Estuaries

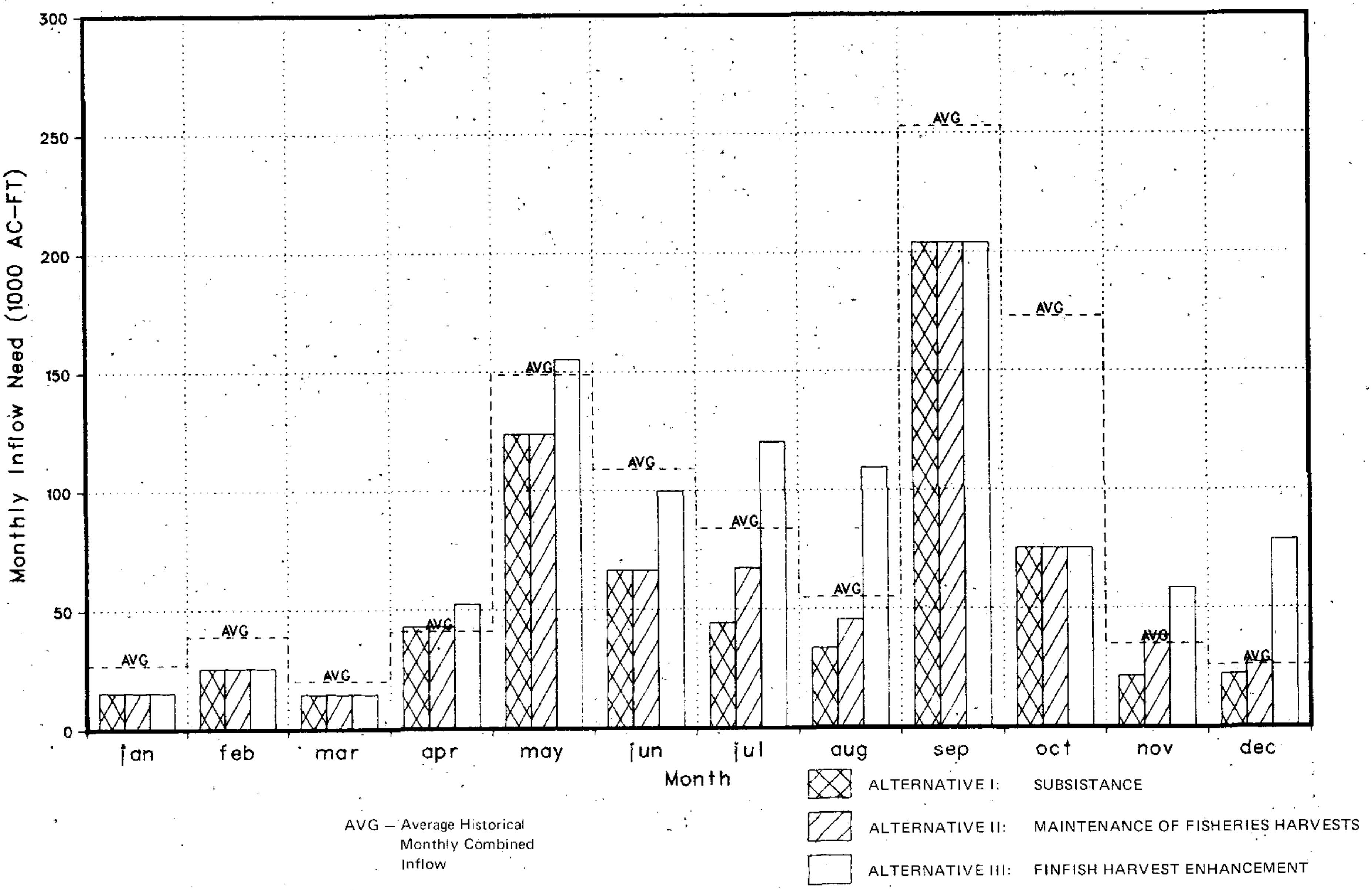

Figure 1-2. Estimated Monthly Freshwater Inflow Needs for the Nueces and Mission-Aransas Estuaries Under Alternatives I, II, III

Mission-Aransas estuaries. Their application determines the effects of the estimated freshwater inflow needs for Alternative I[1/] upon the average monthly net flow circulation and salinity characteristics of the estuarine system. The monthly simulations utilized typical tidal and meteorological conditions observed historically for each month simulated.

The net circulation patterns simulated by the tidal hydrodynamic model indicate that the dominant circulation pattern in the Nueces and Mission-Aransas estuaries is a net movement of water from Laguna Madre through Corpus Christi, Redfish, Aransas and Copano Bays and into the Guadalupe estuary. Simulated net flows in Copano and Nueces Bays are governed by internal circulation currents rather than by circulation patterns in adjacent bay systems.

Simulated steady-state, monthly salinities for the set of monthly inflows specified under Alternative I indicate similar patterns in these estuaries over all months. Average simulated salinities in Corpus Christi Bay are less than 25 parts per thousand (ppt) except near the entrance to Laguna Madre and Aransas Pass. The simulated mean salinities for Saint Charles and Copano Bays are less than 10 ppt. Salinities simulated for Nueces Bay are under 20 ppt, with salinities near 15 ppt in the middle portion of the bay. In Redfish and Aransas Bays, simulated salinities average over 20 ppt in the former and between 10 and 15 ppt in the latter bay.

Since the middle portion of Corpus Christi Bay has simulated salinities in all months below a target maximum allowable concentration of 25 ppt, the freshwater inflow needs established for Alternative I are adequate to sustain the desired salinity gradients specified 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 bay 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 estuarine-dependent organisms.

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

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 Nueces and Mission-Aransas estuaries. 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 (176). 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 Nueces and Mission-Aransas estuaries.

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., individual 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 has open waters 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 primary bay areas, and are thus removed from direct flow exchange with the Gulf. In secondary bays, the salinities are usually lower than the primary bay. In terms of energy input to the estuarine systems, the most productive and dynamic of estuarine habitats are the tertiary bays. Tertiary bays are generally shallow, brackish to freshwater areas where sunlight can effectively penetrate the water column to support phytoplankton, benthic algae, and other submerged vegetation. Substantial chemical energy is produced in these areas through photosynthetic processes. These nutritive biostimulants are distributed throughout the estuarine system by inflow, tides, and circulation.

Texas has about 373 miles (600 kilometers) of open-ocean or Gulf shoreline and 1,419 miles (2,290 kilometers) of bay shoreline, along which are located seven major estuarine systems and three smaller estuaries (Figure 2-1). Eleven major river basins, ten with headwaters originating within the boundaries of the state, have estuaries of major or secondary importance. These estuarine systems have a total open-water surface area of more than 1.5 million acres (607,000 hectares) with more than 1.1 million acres (445,000 hectares) of adjacent marshlands and tidal flats (378). Physical characteristics of the Nueces and Mission-Aransas estuaries 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 Nueces and Mission-Aransas estuaries 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

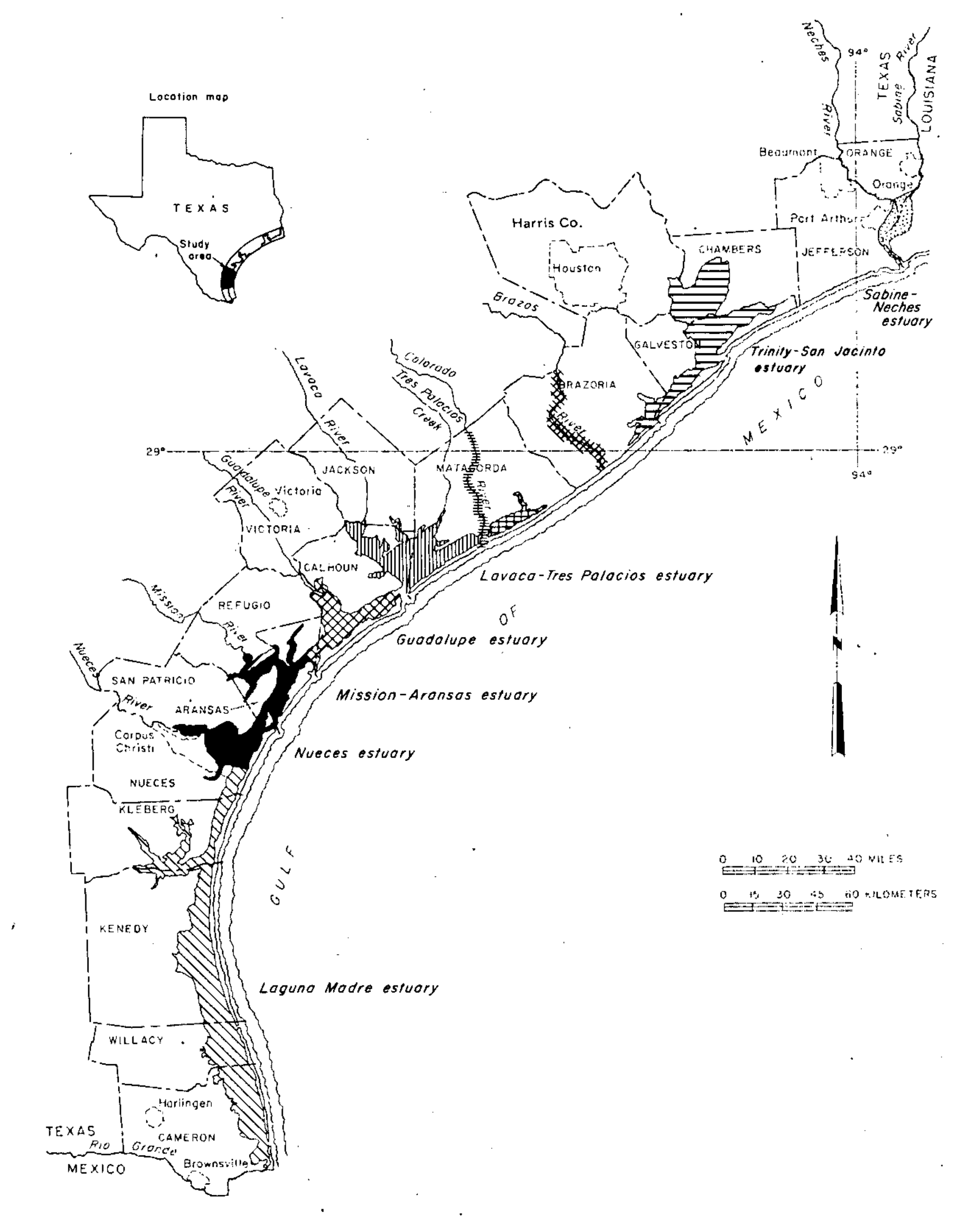

Figure 2-1. Locations of Texas Estuaries

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 depending 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, benthos (infauna), 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 single species may be high, fluctuating with the seasons and with hydrologic cycles (185, 62, 183). 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 Nueces and Mission-Aransas estuaries 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, 140, 40, 94, 165, 213). The aquatic ecosystem can be conceptualized as comprising four major components, all interrelated through various life processes (Figure 2-2):

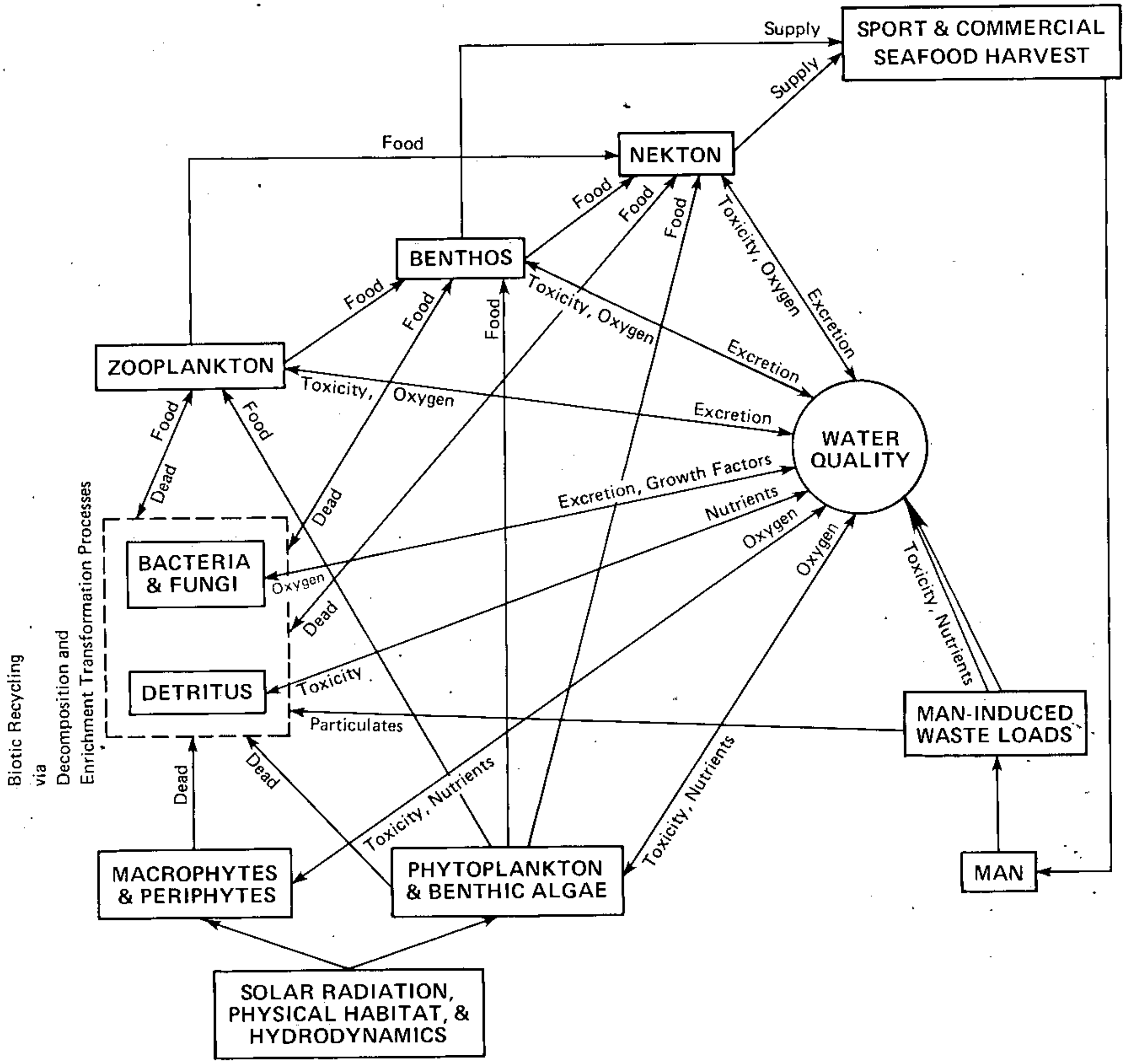

Figure 2-2. Component Schematic Diagram of a Generalized Texas Estuarine Ecosystem.

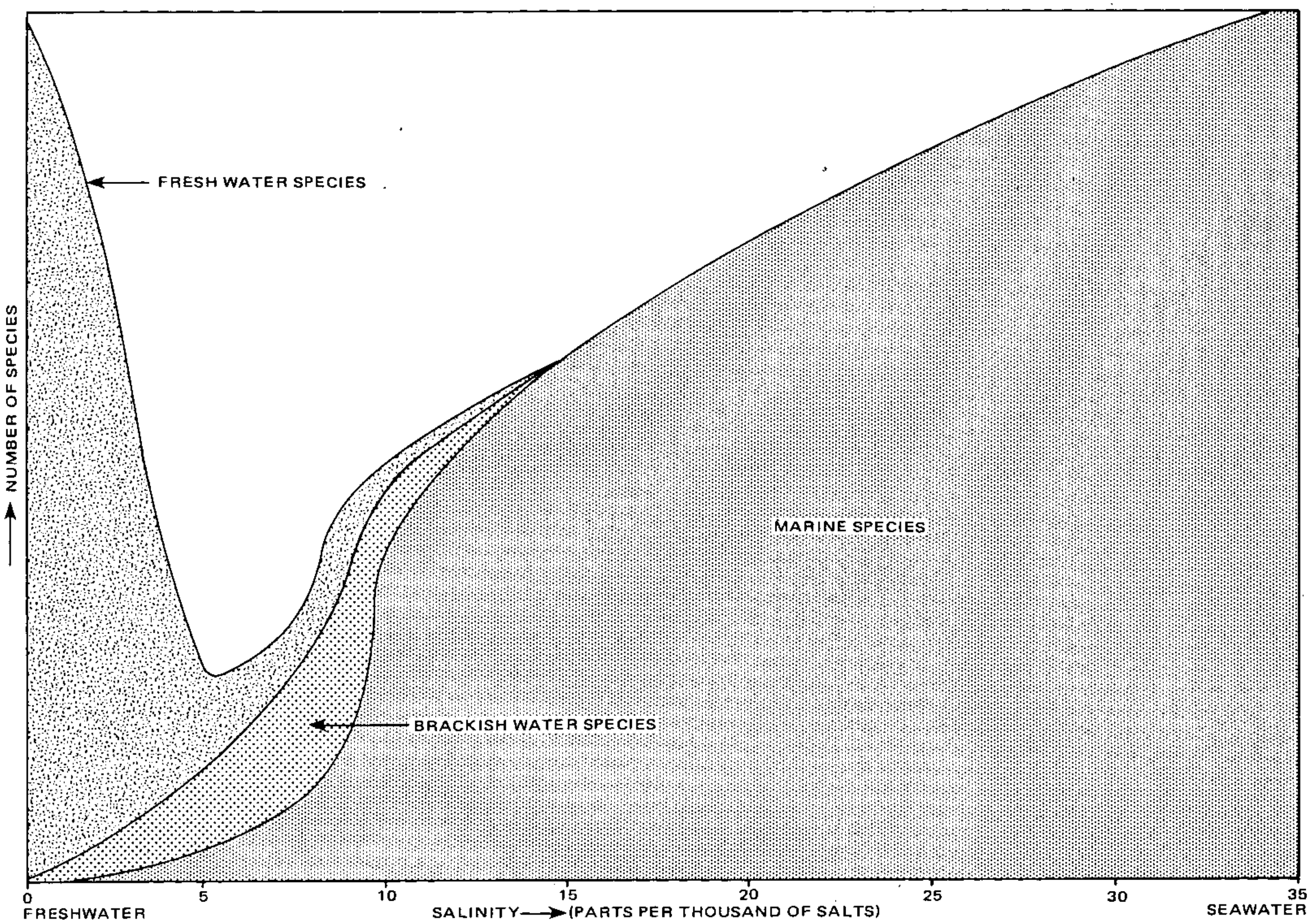

Figure 2-3. Species Composition of Estuarine Environments (185)

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 (189). 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 (116, 404), and/or for protection against predators and parasites (121, 174). Juvenile forms use the shallow "nursery" areas during early growth (75), 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 environment. These species have adapted their life cycles to the natural schedule of seasonal events in the ecosystem, which increases survival and reduces 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 (417).

Virtually all (97.5 percent) of the Gulf fisheries species are considered estuarine-dependent (76); however, the seasonal aspects of their life cycles are quite different. Some species, such as the redfish, spawn in the fall and the young are particularly dependent on migration to and utilization of the

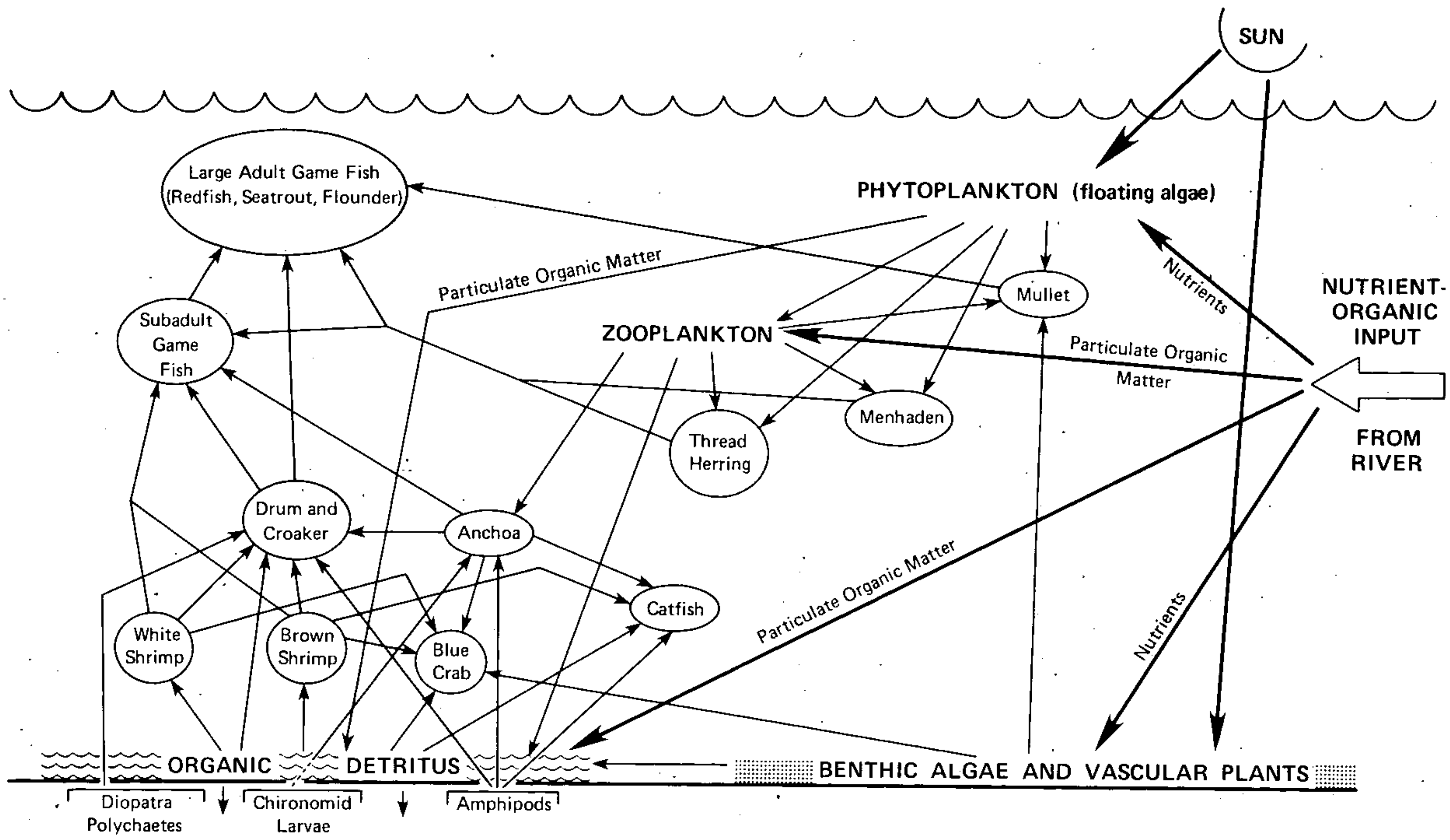

Figure 2-4. Simplified Trophic Relationships in a Texas Estuary [After WRE (410)]

"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 (157).

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 (48). Throughout the world, only tropical rain forests, coral reefs, and some algal beds produce more abundantly per unit of area (165, 303).

Marsh production has been shown to be a major source of organic material supporting the estuarine food web in coastal areas from New England to the Gulf of Mexico (30, 83, 130). Because of high plant productivities an estuarine marsh can assimilate, if necessary, substantial volumes of nutrient-rich municipal and industrial wastes (400, 401) and incorporate them into the yield of organic material which supports higher trophic level production, such as fisheries 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 waterfowl 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) with more than 1.1 million acres (445,000 hectares) of adjacent marshlands and tidal flats. The 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 (metabolic) stresses that can inhibit reproduction and growth, and may have long-lasting effects on the estuary.

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

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

Estuarine wetlands and river deltas are the most important habitat areas for juvenile forms of many aquatic species. These marsh systems contribute nutrients to the estuaries while providing nursery habitats for 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 interrelationships among physical, chemical, and biological parameters that govern the productivity within these systems.

Mathematical Modeling

The concept of mathematical modeling is fundamental to understanding the techniques utilized in this study for evaluation of freshwater inflow effects upon an estuary. In general, a mathematical model is a specific set of mathematical 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 algorithmus, data input and output requirements are determined, and the necessary computer files are created.

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

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

Once a model has been satisfactorily calibrated, an independent set of input values (not previously used in the calibration process) should be used to simulate a new set of response values. A comparison of the simulated responses with the observed data should yield close agreement. Close agreement within predetermined tolerance levels indicates model "validation". It is then possible to simulate conditions for which comparative repsonse 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 Nueces and Mission-Aransas estuaries 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

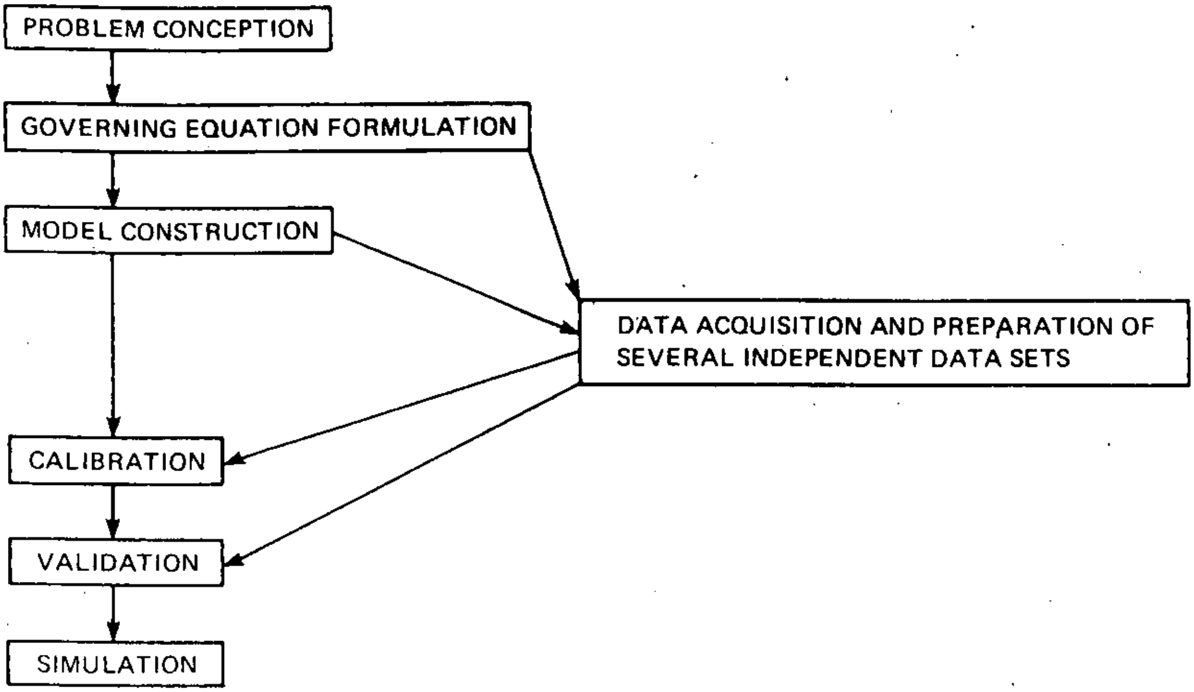

Figure 2-5. Flow Diagram of Model Development

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 (207, 165). 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 overylying water column. The subsidence of the floodwaters and the subsequent dewatering of the marshes results in the movement of organic nutrients from the marsh into the nearby tertiary and secondary bays. Large volumes of freshwater inflow can also be detrimental by depressing biological production and flushing even the primary bay 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, 143). 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 (100, 152), and the transport of sediment and nutritive substrate materials (especially detritus) to the estuary.

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

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

(3) Circulation. The movement of waters within an estuary largely determines the distribution of biotic and abiotic constituents in the system. To study the movement of estuarine waters under varying conditions, tidal hydrodynamic mathematical models have been developed and applied to individual Texas estuaries (149, 150). 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 salinity, a salinity transport mathematical model has been developed (149, 151) to simulate the salinity changes in response to dispersion, molecular diffusion and tidal hydrodynamics. This model is a companion model to the hydrodynamic model described previously.

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

In this study, relationships between inflow and salinity were established using the statistical technique of regression analysis. Regression analysis is a method of estimating the functional relationship among variables. The relative accuracy of such a predictive model, commonly measured in terms of the correlation coefficient, is dependent upon the correlation of salinities to inflow volumes. The statistical relationship between salinity and inflow can generally be represented as a 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 (33, 139). 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 species are chosen on the basis of their wide distribution throughout the system of interest (e.g., an estuary), a sensitivity to change in the system (or to a single variable, like freshwater inflow), and an appropriate life-cycle to permit observation of changes in organism densities and productivity in association with observations of environmental change.

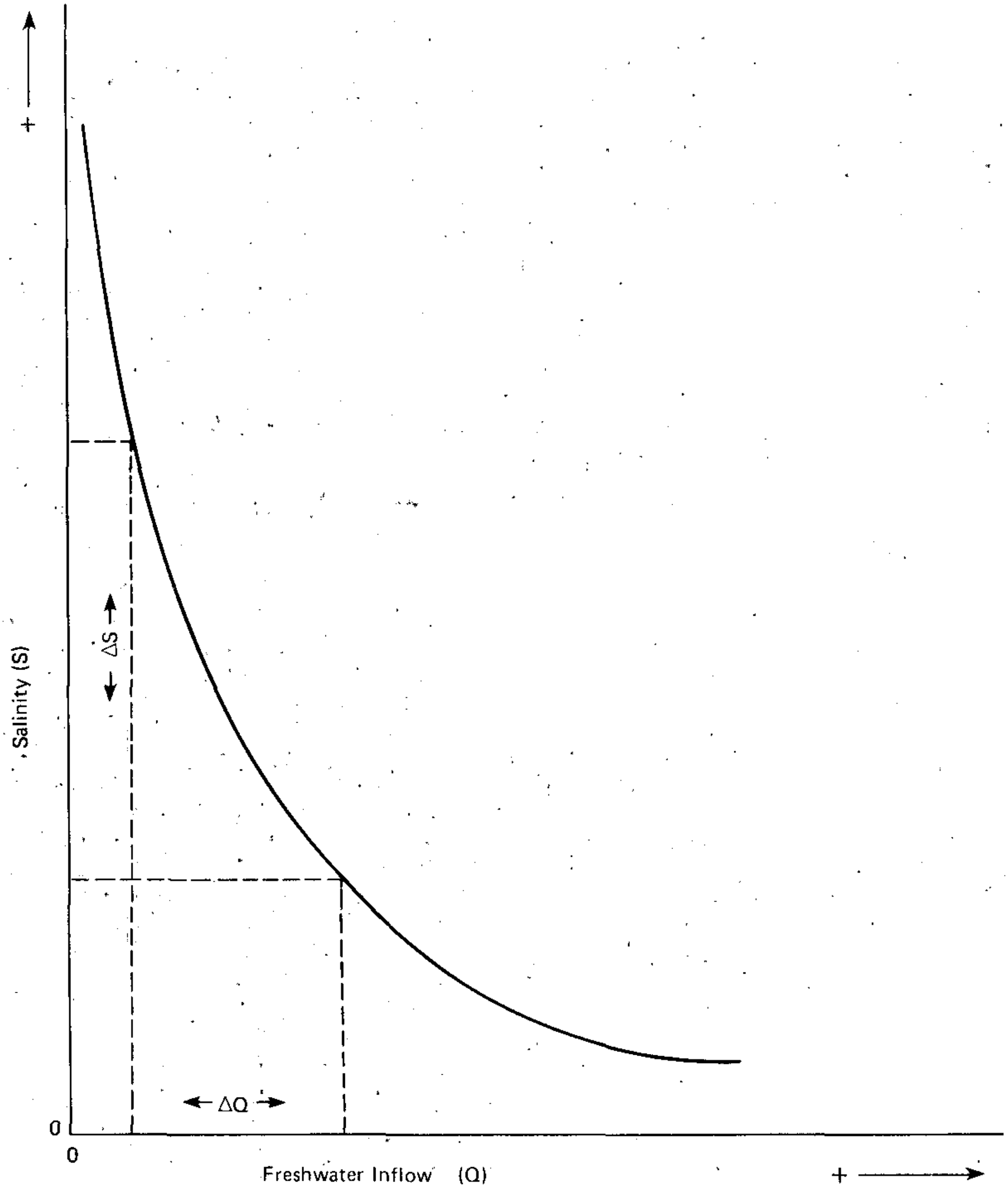

Figure 2-6. Typical Variation of Freshwater Inflow Versus Salinity in a Texas Estuary

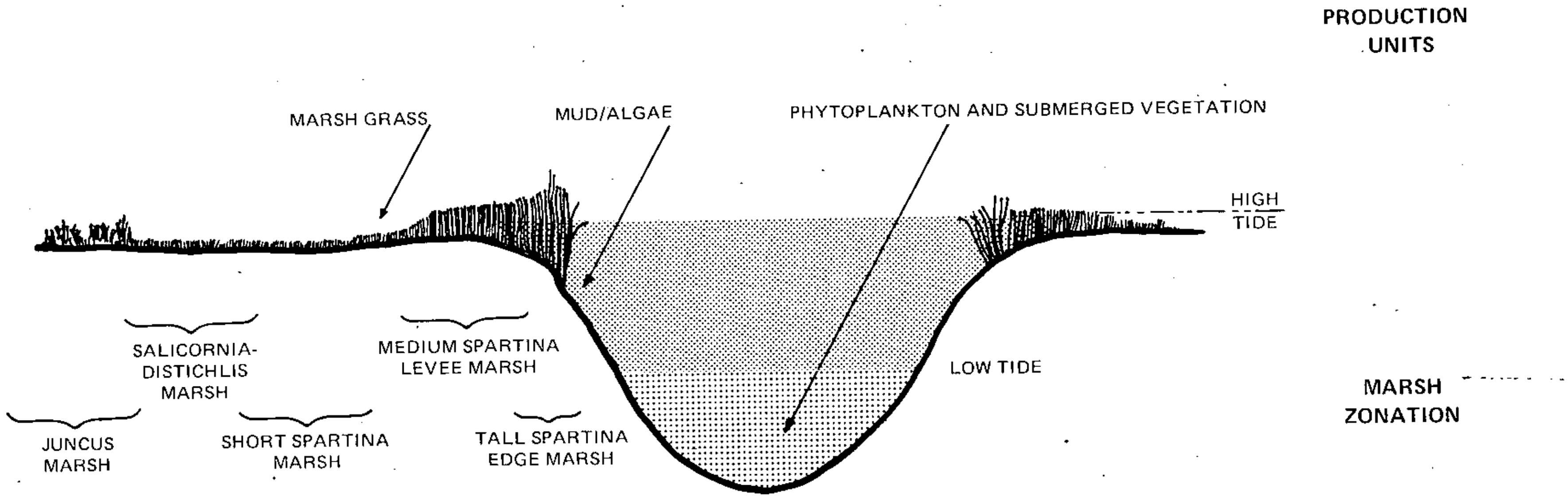

Figure 2-7. Zonation of a Salt Marsh in a Texas Estuary (241)

Dr. Eugene Odum has remarked that "ecologists constantly employ such organisms as indicators in exploring new situations or evaluating large areas" (165). 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 (241). 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 to accurately calibrate the estuarine ecologic model for simulation periods in excess of one year are not yet available. Further refinement of the model is anticipated as these data become available.

At present, the most serious deficiency of the estuarine ecological model is its inability to accurately describe and predict the standing biomass of commercially important fish and shellfish which spend all or 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 harvests of finfish and shellfish. The specific regression equations for estimating harvest of spotted seatrout, red drum, black drum, white shrimp, brown and pink shrimp, blue crab, and bay oyster as a function of seasonal freshwater inflow are computed using data from each estuarine system (Chapter VIII). These regression equations can be used to compute estimates of the estuarine productivity, in terms of harvested fisheries biomass, as a function of seasonal freshwater inflow. However, there are variations in the historical harvest data which 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 (283, 284, 285, 286) and Wakeman (408) have reported on the stress of salinity changes upon the metabolic activities of several Texas estuarine fish species. For example, Wakeman measured the maximum sustained swimming speeds of four estuarine fish species (i.e., spotted seatrout, sheepshead, and black and red drum) at 28 degrees Celsius over a range of salinities (10-40 parts per thousand, ppt) normally encountered in the estuary to determine their optima. All of these species are of commercial and recreational importance; therefore, results of these metabolic research studies are valuable in the planning and management of the Texas estuarine systems and their production of renewable fish resources. Salinity ranges and 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 continually being developed and used for assessment of alternative projects and programs.

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

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

Determination of Freshwater Inflow Needs. (1) Estuarine Inflow Model. In order to establish an estimate of the freshwater inflow needs for an estuary, mathematical techniques are applied to integrate the large number of relationships and contraints, 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 fisheries harvest, but also the predicted harvest levels and salinities resulting from the model's freshwater inflow regime. The harvests that are predicted under such a regime of freshwater inflows can be compared with the average historical harvests to estimate changes in productivity.

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

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

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

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

Water Rights Allocation. Adjudication of surface-water rights in Texas is an extremely important factor in addressing the issue of allocation, and 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 adjudication for the remaining basins. Final judgments have been rendered by the appropriate District Courts and certificates of adjudication have been issued in portions of the Rio Grande, Colorado, San Antonio and Guadalupe Basins.

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

Operations of Upstream Reservoirs in Contributing Basins. The control of surface-waters through impoundment and release from large storage reservoirs is a potential source of supplementary waters for the Texas estuaries. The Texas Water Plan specified 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 no 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. The 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 Nueces and Mission-Aransas estuaries, 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 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 estuarine-dependent 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 other 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 fisheries harvest (production) objectives subject to the maintenance of salinity viability 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 Nueces and Mission-Aransas estuaries cover about 360 square miles (932 km^2) and include Copano Bay, Aransas Bay, Nueces Bay, Corpus Christi Bay, and several smaller bays (Figure 3-1). Water depth at mean low water varies from less than two feet (0.6 m) in Mission Bay to 13 feet (4 m) in Corpus Christi Bay, except for navigation channels where it may be deeper.

This study area lies in the warm, temperate zone of the South Central climatological division of Texas. Its climatic type is classified as subtropical (humid and hot summers with mild, dry winters). The climate is also predominantly marine influenced because of the area's proximity to 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 occasional thunderstorms. Some of the heavier rainfall occurrences during late summer and early fall are associated with tropical disturbances. Warm, tropical air from the Gulf of Mexico is responsible for mild winter temperatures and hot, humid summer weather.

The annual net lake surface evaporation rate in the area is about 27 inches (68.6 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 contributing inflow to the Nueces and Mission-Aransas estuaries include the entire Nueces River Basin and parts of the San Antonio-Nueces and the Nueces-Rio Grande Coastal Basins (Figure 3-2).

Total drainage area of the Nueces River Basin is 16,660 square miles (43,150 km^2). Runoff in the upper reaches of the basin in the Edwards Plateau area averages about 118 acre-feet per square mile (562 m^3/ha). A substantial part of the flow originating in the upper area of the Nueces River Basin is intercepted by the fractured and cavernous limestone formations exposed in the Balcones Fault Zone resulting in loss of surface flows. Runoff rates in the lower part of the basin average about 90 acre-feet per square mile (429 m^3/ha). Major tributaries of the Nueces River Basin include the Frio, Sabinal, and Atascosa Rivers.

Total drainage area of the San Antonio-Nueces Coastal Basin which contributes runoff is 2,613 square miles (6,800 km^2). Major tributaries include the Mission and Aransas Rivers. Average annual runoff within the basin is about 111 acre-feet per square mile (528 m^3/ha).

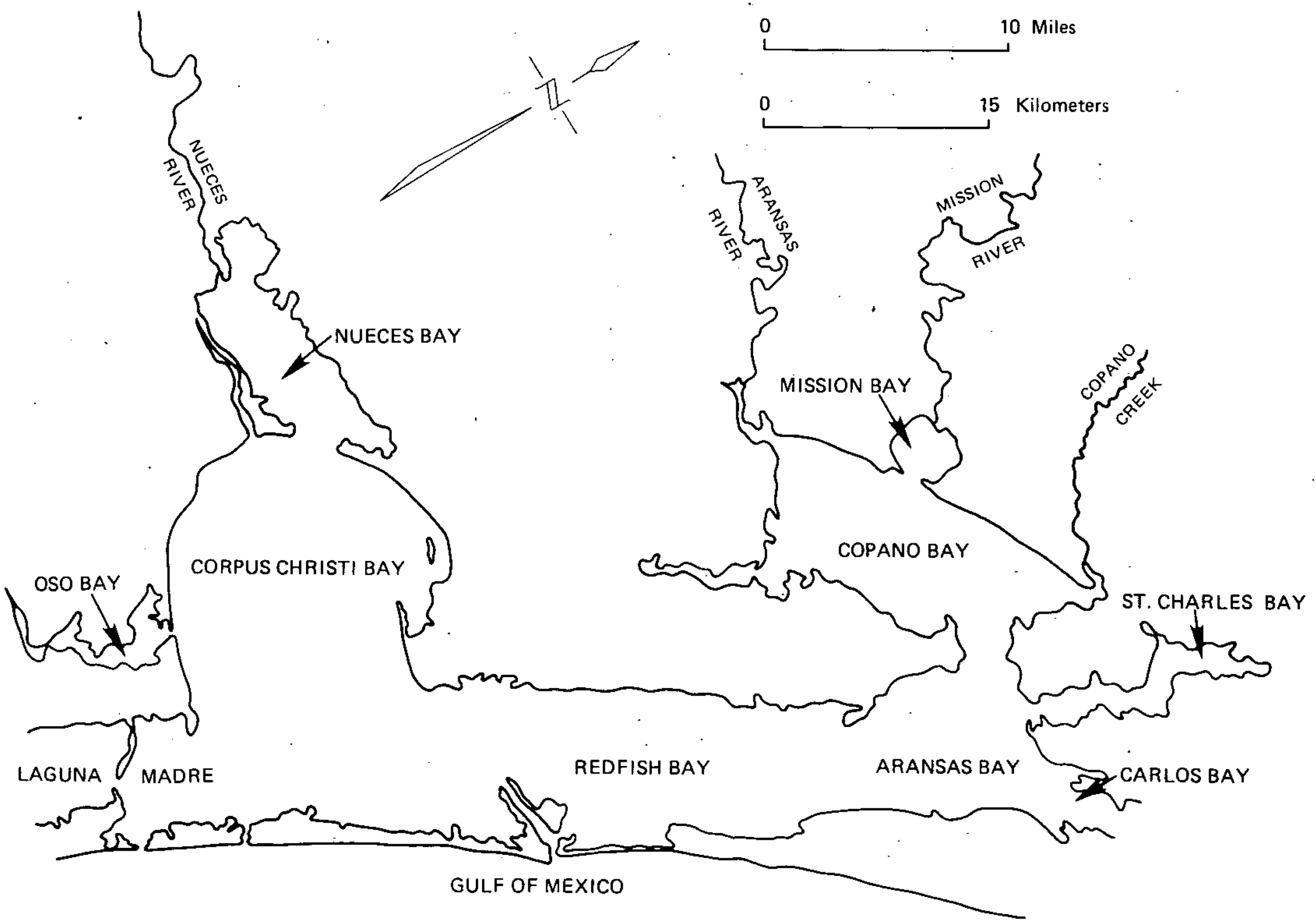

Figure 3-1. Nueces and Mission-Aransas Estuaries

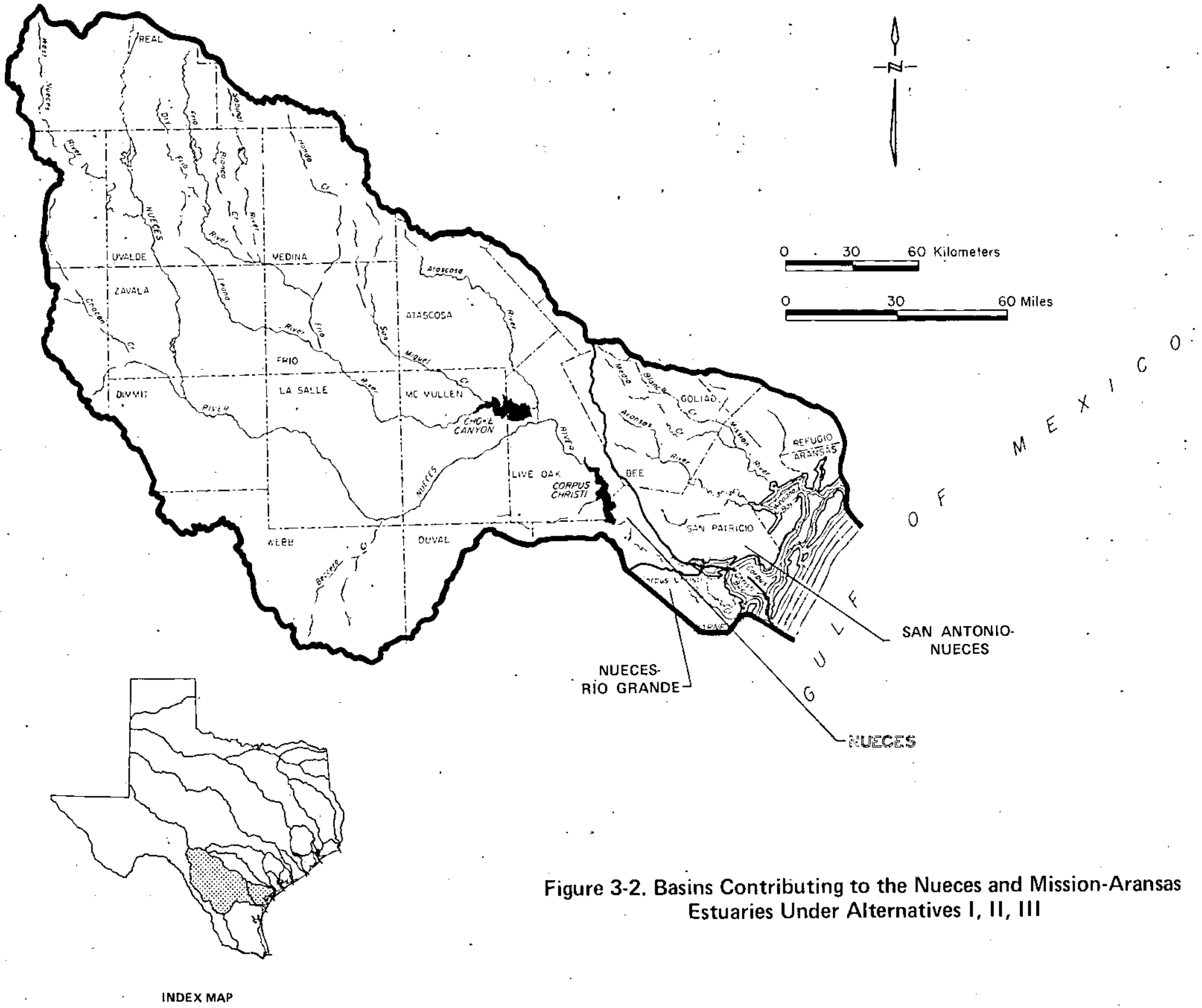

Figure 3-2. Basins Contributing to the Nueces and Mission-Aransas Estuaries Under Alternatives I, II, III

Total drainage area of the Nueces-Rio Grande Coastal Basin contributing runoff to the Nueces estuary is 274 square miles (710 km^2). This area includes the Corpus Christi urban area and the Oso Creek drainage.

Reservoir development within the contributing area began as early as 1929 with the completion of Mathis Dam creating Lake Corpus Christi on the Nueces River. The Mathis Dam was inundated in 1958 by the present Lake Corpus Christi created by Wesley E. Seale Dam. The Choke Canyon Reservoir site is currently being developed (Table 3-1).

Geological Resources

Sedimentation and Erosion. The Nueces estuary's main source of sediment is the Nueces River system. This system heads in the Edwards Plateau and flows southeasterly through the Rio Grande Prairie. Sediment reaching the Mission-Aransas estuary comes from the Rio Grande Prairie primarily by the Mission and Aransas Rivers.

Annual sediment production rates in the Edwards Plateau are low, ranging from 0.052 to 0.055 acre-feet per square mile (25 to 26 m^3/km^2) of drainage area. As the rivers flow over the Rio Grande Prairie the average annual sediment production rates reach a high of 0.18 acre-feet per square mile (86 m^3/km^2) of drainage area (229, 240). Annual sediment production rates for the Mission and Aransas Rivers are 0.17 acre-feet per square mile (81 m^3/km^2) and 0.18 acre-feet per square mile (86 m^3/km^2), respectively.

Where a stream enters a bay, flow velocities decrease and the sediment transport capability is reduced; thus, sediment is deposited near the headwaters, forming a bay-head delta. The delta which formed at the mouth of the Nueces River is of a type which develops under conditions of high sediment inflow into a relatively quiescent body of water.

The major marsh areas in the Nueces and Mission-Aransas estuaries are associated with deltas. Delta plains are covered with fresh, brackish, and saline marshes. In order for marshes to propagate there must be a balance between sediment deposition and compactional subsidence. If there is excessive vertical accretion, marsh vegetation is replaced by mainland grasses, shrubs, and trees. Where subsidence is more rapid than deposition, the plants drown and erosion by waves and currents deepen the marsh to form tertiary lakes or enlarge the secondary bay area.

The mainland shore of these estuaries is characterized by near vertical bluffs cut into Pleistocene sand, silt, and mud (Figure 3-3). Erosion of these bluffs furnishes sediment to the adjacent lakes, marshes and bays. The type of sediment deposited depends on whether the adjacent bluff is composed of predominantly sand or mud. Pleistocene overbank and bay muds have a high shrink-swell ratio, causing dessication cracks to form. Breaking waves, aided by the dessication cracks, cut into the base of the bluffs along the shoreline. This process effectively removes slope support and the bluff fails by slumping. Energy levels (erosional capacity) in the Nueces and Mission-Aransas estuaries are dominated by wind action since the range of astronomical tides is only about 0.5 foot (0.15 m). Winds blowing across Corpus Christi, Aransas, and Copano Bays generate waves which cause erosion along the shoreline.

Table 3-1. Reservoirs of Contributing Basins, Nueces and Mission-Aransas Estuaries

Reservoir Name	Type of Use(s) a/	Year Dam Completed	Surface Area Acres	Conservation Pool Elevation ft (msl)	Conservation Pool Storage thousand ac-ft	Flood Control Storage thousand ac-ft	Total Storage thousand ac-ft
Lake Corpus Christi	W.S., R.	1958	19,576	94.3	278.2	—	278.2
Choke Canyon b/	W.S., R.	—	26,000	220.5	700.0	—	700.0

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a/ W.S. (May include municipal, manufacturing, irrigation, steam-electric power and/or mining uses).
R. (Recreation)

b/ Under construction.

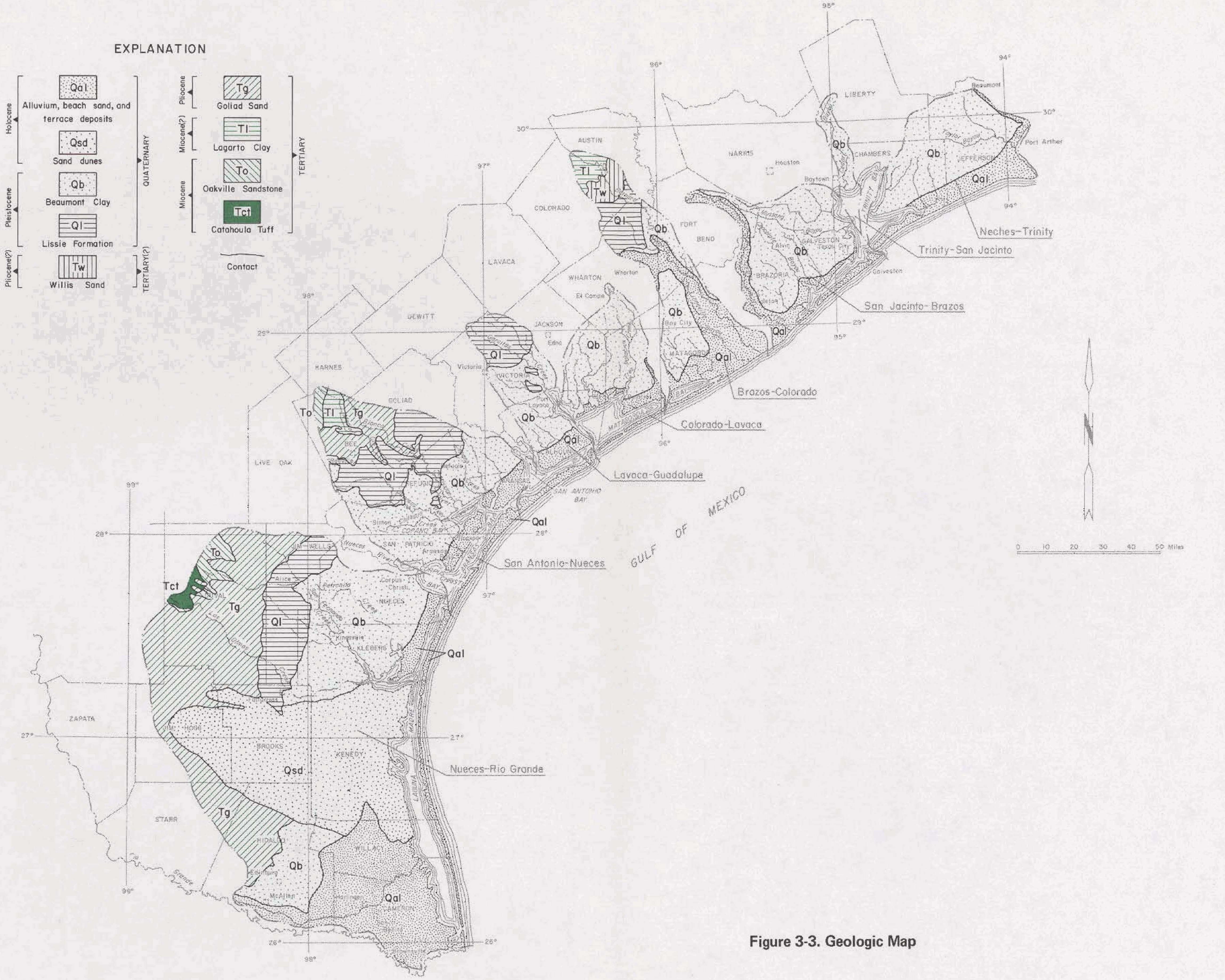

Figure 3-3. Geologic Map

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

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

Shoreline and vegetation changes within the estuaries and in other areas of the Texas Gulf Coast are the result of natural processes (268, 271). Shorelines are either in a state of erosion, accretion, or are stabilized either naturally or artificially. Erosion produces a net loss in land, accretion produces a net gain in land, and equilibrium conditions produce no net change in land area.

Most of the shoreline along the south side of Corpus Christi and Nueces Bays is stabilized. A state of erosion exists along the Ingleside and Portland shoreline. The mainland shoreline of Copano and Aransas Bays is mostly in a state of erosion, whereas the barrier island shoreline of both Corpus Christi and Aransas Bays is generally either in a state of equilibrium or accretion (Figures 3-4 and 3-5). Gulfward of the barrier island the shoreline is mostly in a state of equilibrium (267). This is an indication that the sediment volume being supplied is sufficient to balance the amount of sediment removed by waves and longshore drift.

Processes that are responsible for the present shoreline configuration and that are continually modifying shorelines in the Nueces and Mission-Aransas estuaries include astronomical and wind tides, longshore currents, normal wind and waves, hurricanes, river flooding, and slumping along cliffed shorelines. Astronomical tides are low, ranging from about 0.5 foot (0.15 m) in the bays to a maximum of about two feet (0.6 m) along the Gulf shorelines. Wind is a major factor in influencing coastal processes. It can raise or lower the water level along the Gulf and/or mainland shore according to the direction it is blowing. Wind can also generate waves and longshore currents (182, 91, 306).

The seasonal threat of wind and water damage associated with tropical cyclones occurring in the Gulf of Mexico exists each year from June through October. Wind damage from hurricanes and associated tornadoes can be costly, but the most severe losses occur from the flooding brought by heavy rains and high storm tides along the coast. Gulf and mainland shorelines may be drastically altered during the approach, landfall, and inland passage of hurricanes (91, 198). Storm surge flooding and attendant breaking waves erode Gulf shorelines from a few tens to a few hundreds of feet. Washovers along the barrier islands and peninsulas are common, and saltwater flooding may be extensive along the mainland shorelines.

Flooding of rivers and small streams normally corresponds 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 (268). Some effects of flooding include: (1) overbank flooding into marsh areas of the floodplain and onto delta plains; (2) progradation of bayhead and oceanic deltas; (3) flushing of bays and estuaries; and (4) reduction of salinities.

Mineral and Energy Resources. Resources of the Texas coastal zone include oil and natural gas (Figures 3-6 and 3-7), which serve not only for fuel but also provide raw material for many petrochemical processes. In addition, the coastal zone contains important sources 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

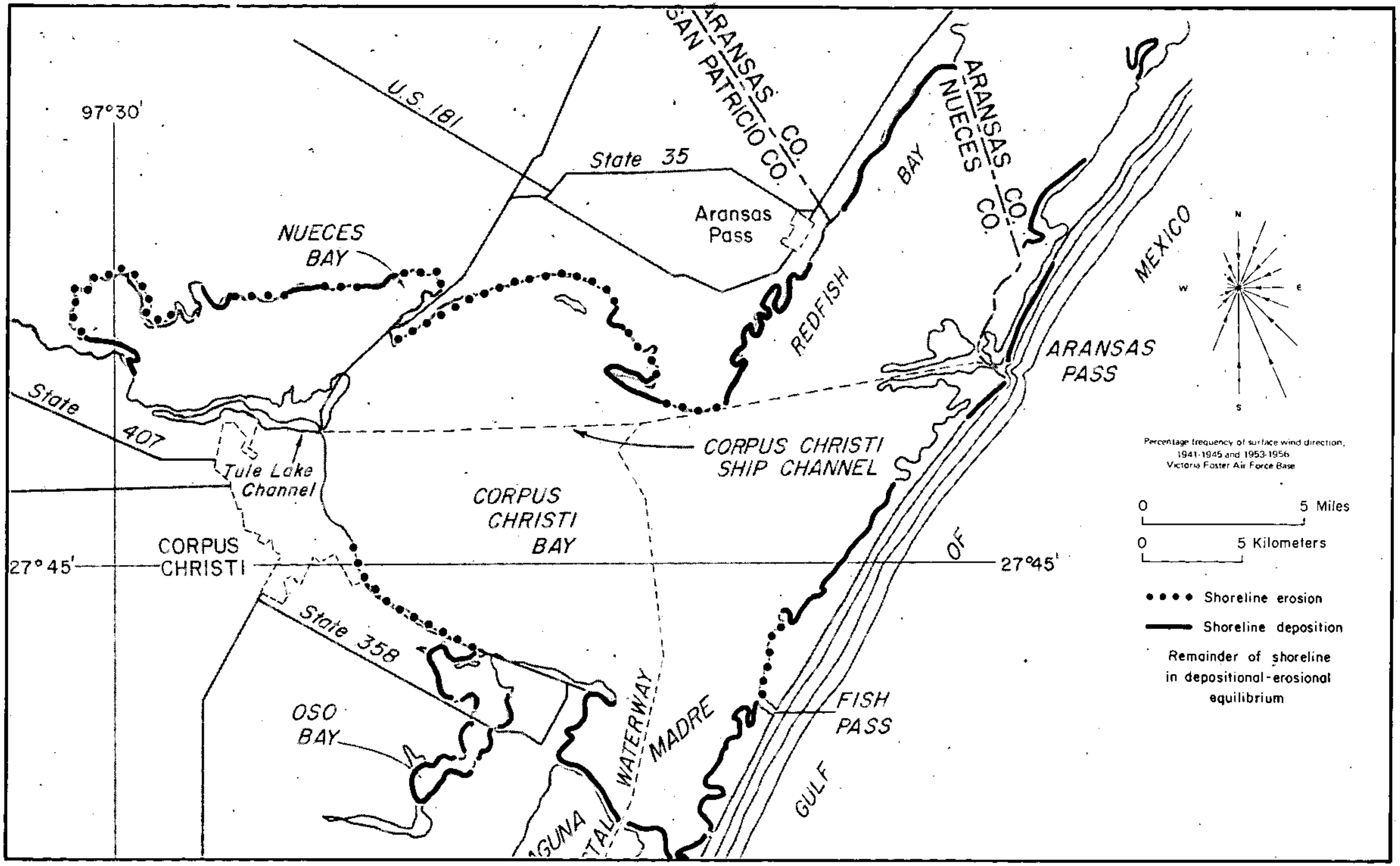

Figure 3-4. Shoreline Physical Processes, Nueces Estuary (267)

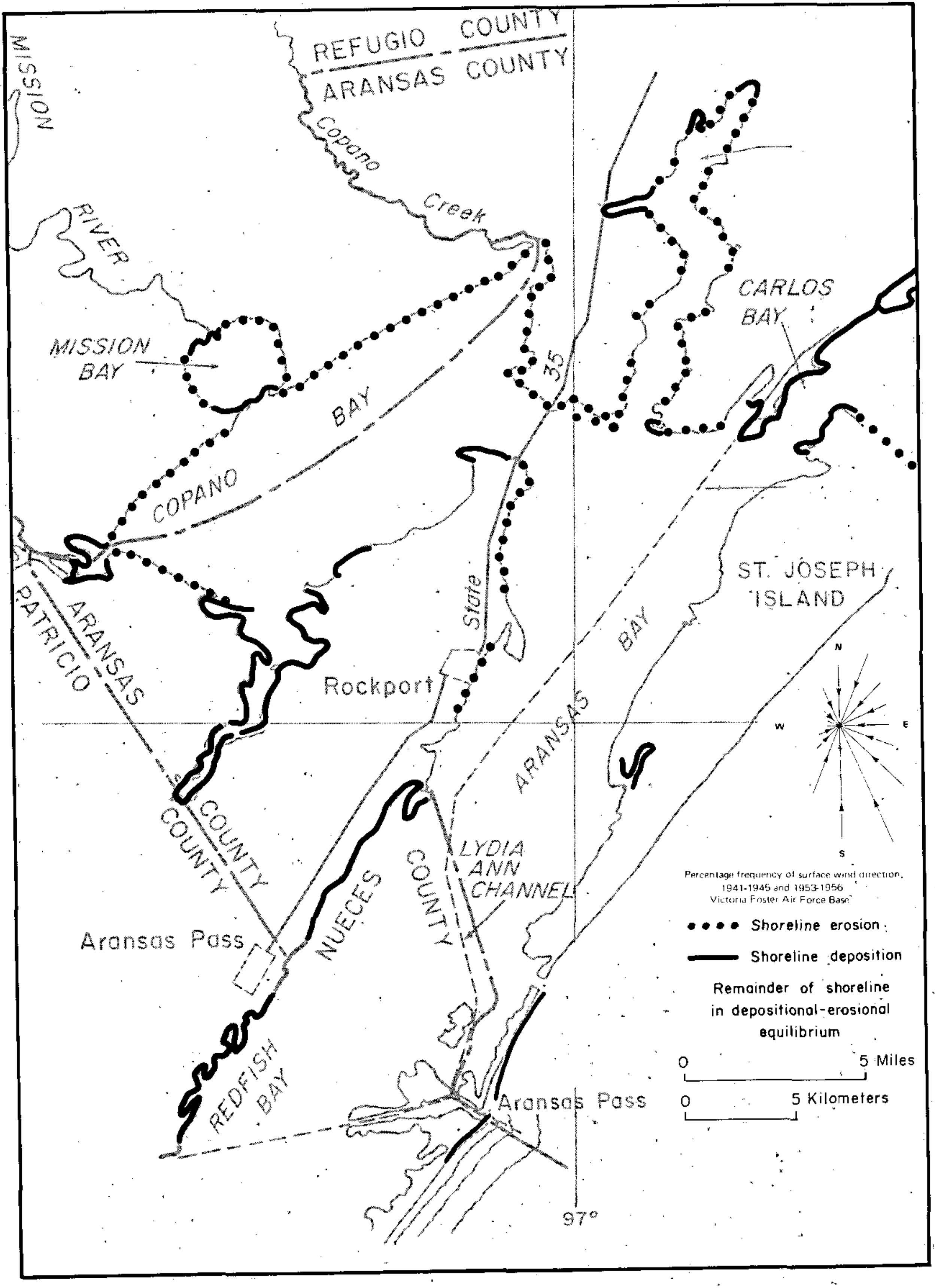

Figure 3-5. Shoreline Physical Processes, Mission-Aransas Estuary (267)

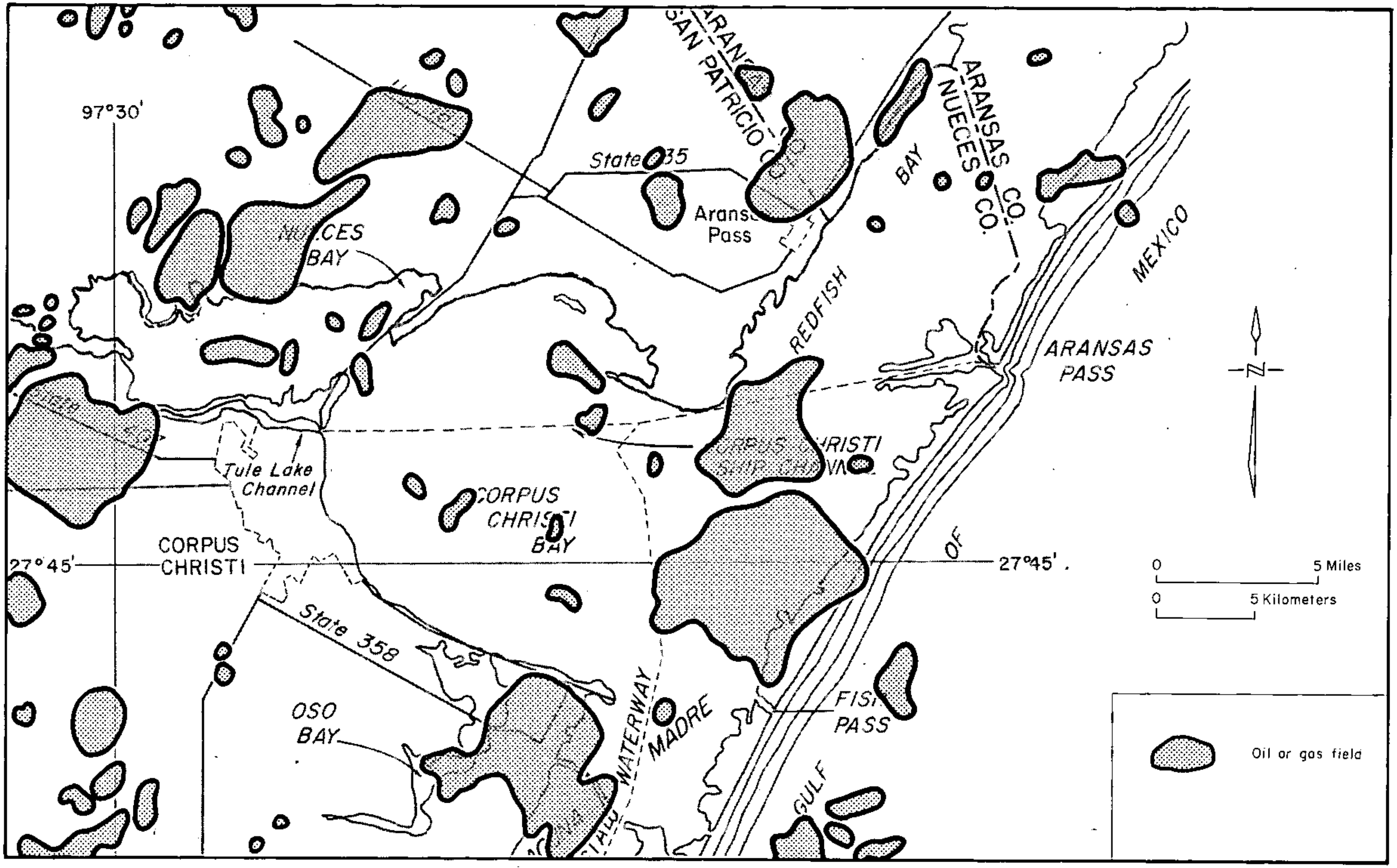

Figure 3-6. Oil and Gas Fields, Nueces Estuary (267)

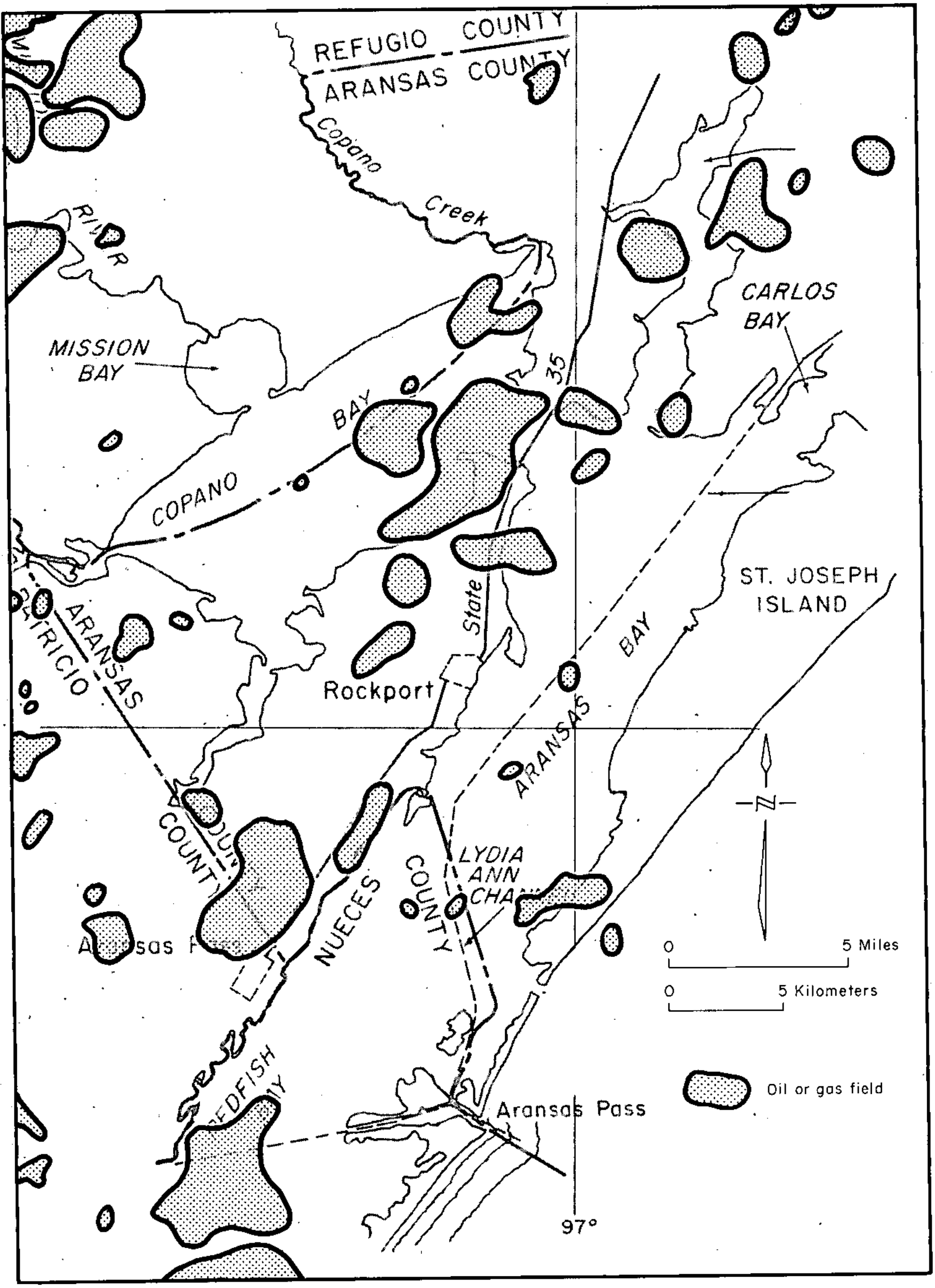

Figure 3-7. Oil and Gas Fields, Mission-Aransas Estuary (267)

to make this area one of the major petrochemical and petroleum-refining centers of the world.

There are several oil and gas fields within the area surrounding Nueces and Mission-Aransas estuaries, both onshore and offshore. The production of oil, natural gas, and natural gas liquids plays a prominent role in the total economy of the area. In addition to the direct value of these minerals, oil and gas production supports major industries within the area and elsewhere in the coastal zone by providing readily available fuels and raw materials.

Notably absent in the Texas coastal zone are natural aggregates and bulk construction materials (e.g., gravel and stone for crushing). At the same time the demand for these materials is high in the heavily populated and industrialized areas of the coastal zone; therefore, a large portion of these 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. The total resources of shell are finite, and at present rates of consumption 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 Nueces and Mission-Aransas estuaries occur in a thick sedimentary sequence of interbedded gravel, sand, silt, and clay. The stratigraphic units included in this sequence are the Oakville, Lagarto, and Goliad Formations of Tertiary Age; and the Lissie and Beaumont Formations of Quaternary Age. These ancient sedimentary units are variable in composition and thickness and were deposited by the same natural processes that are now active in shaping the coastline. Thick layers of sand and gravel representing ancient river channel deposits grade laterally into silt and clay beds which were deposited by the overbank flooding of ancient rivers. Individual beds of predominantly sand and clay interfinger with each other and generally are hydrologically connected laterally and vertically. Because of this interconnection, groundwater can move from one bed to another and from one formation to another. The entire sequence of sediment functions as a single aquifer, which is referred to as the Gulf Coast Aquifer.

Near the Nueces and Mission-Aransas estuaries this fresh (up to 1,000 mg/l total dissolved solids) to slightly saline (1,000 to 3,000 mg/l total dissolved solids) portion of the aquifer extends to a maximum depth of about 1,800 feet (550 m). The most productive part of the aquifer is from 200 to 500 feet (60 to 150 m) thick (243).

Excessive pumping of groundwater can cause land surface subsidence and saltwater encroachment, which are both irreversible. Locally, the shallow aquifer may contain saltwater; whereas, the deeper aquifer sands may have freshwater. Excessive pumping of freshwater will allow saline waters to encroach into the freshwater zone, contaminating wells and degrading the general groundwater quality. Re-leveling of some survey lines by the National Geodetic Survey in 1959 indicates subsidence of three feet (1 m) since 1942 over the area of the Saxet oil and gas field (Figure 3-8). Total subsidence over the Saxet field is approximately six feet (2 m) (267). The principal effects of subsidence are activation of surface faults, loss of ground elevation in critical low-lying areas already prone to flooding, and alteration of natural slopes and drainage patterns.

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 (268).

The Nueces and Mission-Aransas estuaries occur in the Coastal Prairie land resource area (335). The native vegetation consists of coarse grasses with narrow fringes of trees along the streams. Much of the area is now covered by improved pasture grasses and cultivated crops. Marshes are confined to narrow fringes along the coast and are composed of saltgrass, cordgrass, and spikesedge (341). Soils vary from light, acidic sands to darker, loamy clays.

Land use in the area is dominated by agricultural and ranching activities (Figure 3-9), with only minor amounts of irrigated crops (339, 236). Irrigation return flow quantities (342) are insignificant in this area. Grain sorghum, corn, small grains and cotton are dryland crops produced in the region. Improved pastures have been created from brushland. Forested areas are primarily oak.

The Aransas National Wildlife Refuge, managed by the U. S. Fish and Wildlife Service, and the locally managed Welder Wildlife Refuge occur in the immediate vicinity of the Nueces and Mission-Aransas estuaries (Figure 3-10) (341). More than 140 known archeological sites and four National Register sites occur in the area. The Johnson site, a type archeological site located along the shore, indicates the presence of nomadic aboriginal food collectors, hunters and fishermen (333). In addition, there are six state parks of recreational, historic, and scenic significance in the area (262, 263).

The Nueces and Mission-Aransas estuaries support a significant portion of the commercial fishing industry in Texas. The annual commercial bay harvest of fish and shellfish in these estuarine systems has averaged 3.1 million pounds (1.4 million kg) during the 1962 to 1976 interval. Shellfish, particularly shrimp, constitute the majority of these commercial bay landings, accounting for 72 percent of the total harvest weight. However, a large part of each estuary's production of fish and shellfish is caught offshore by commercial and sport fishermen. When these harvests are considered, the total contribution of both estuaries to the Texas coastal fisheries (all species) is estimated at 19.6 million pounds (8.9 million kg; 81 percent shellfish) annually for a recent five year period (1972-1976).

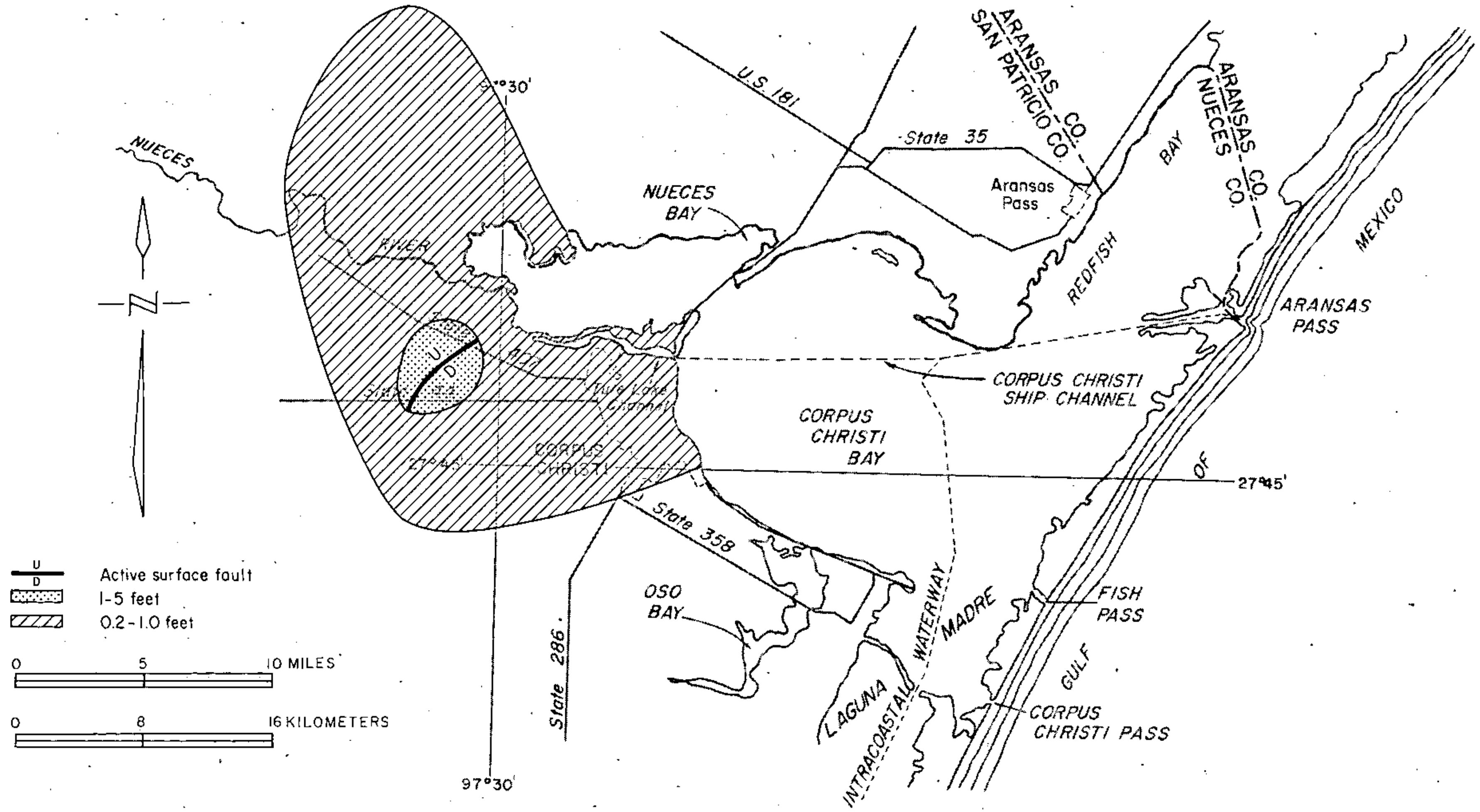

Figure 3-8. Land-Surface Subsidence, Nueces Estuary (267)

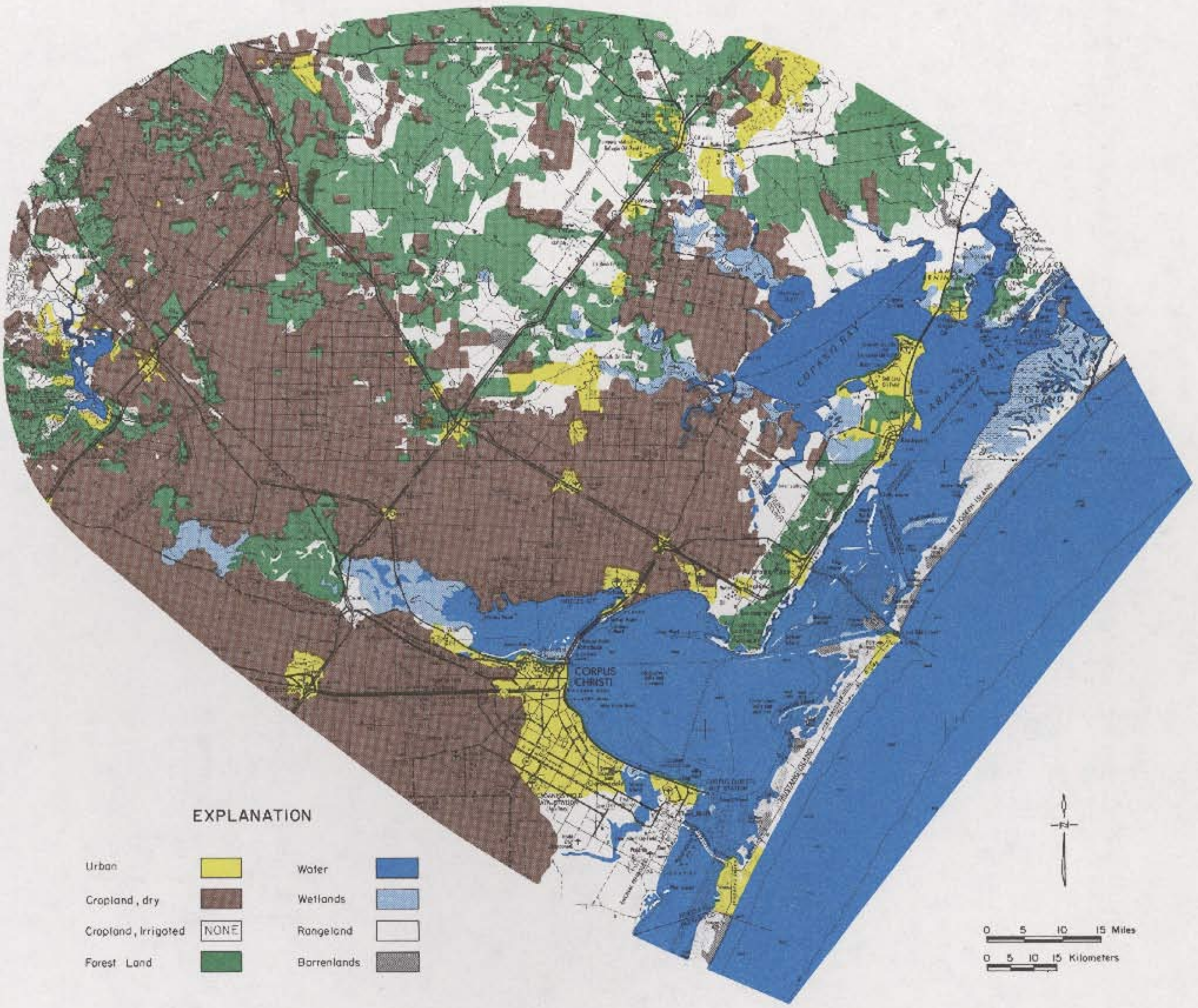

Figure 3-9. Land Use/Land Cover, Nueces and Mission-Aransas Estuaries (236)

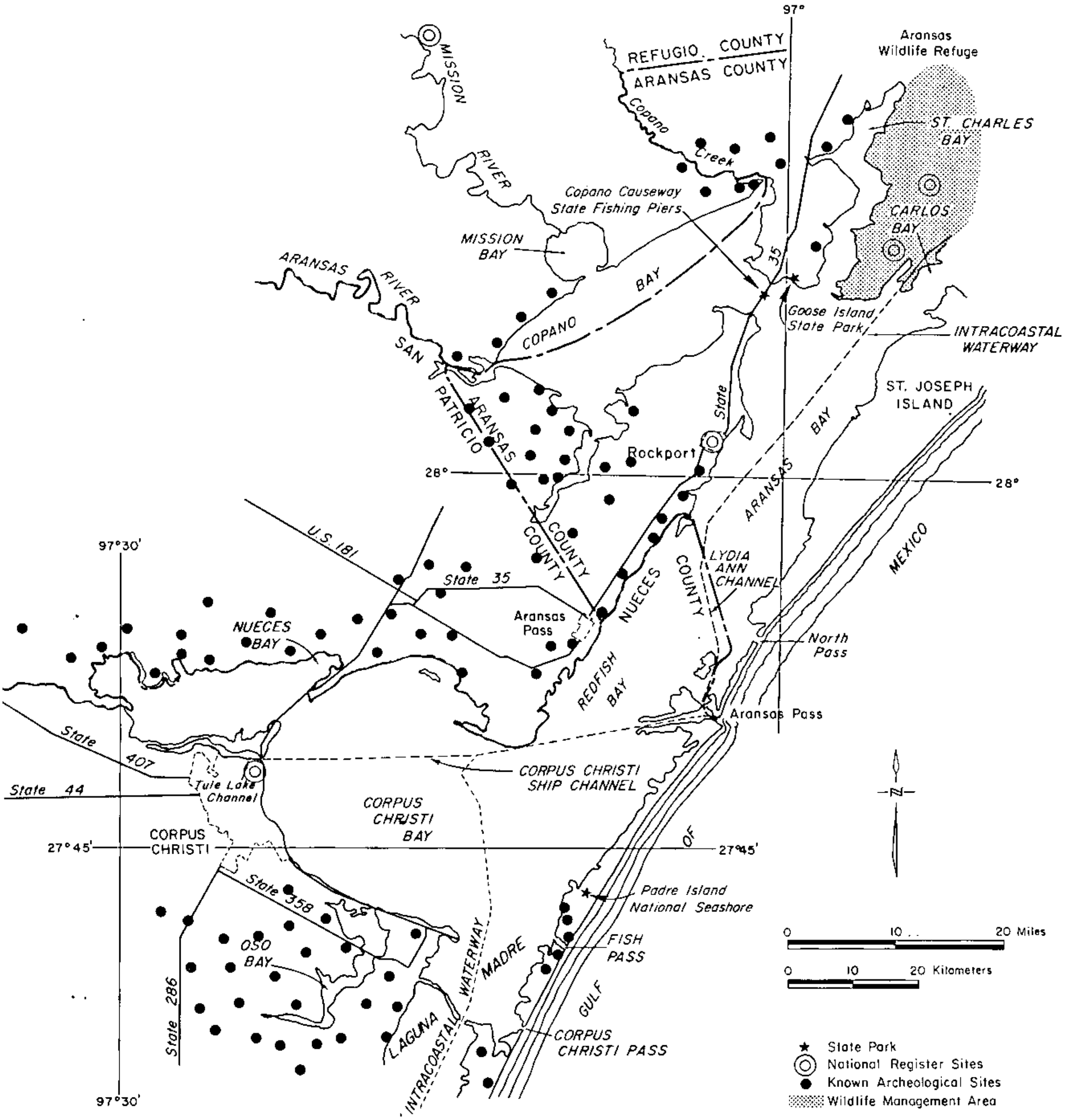

Figure 3-10. Natural Resources, Nueces and Mission-Aransas Estuaries (341)

Natural resources of the bay system and adjoining inland areas provide a wide variety of recreation opportunities for the people of Texas as well as for visitors from other states. Water-oriented recreation activities such as fishing, boating, skiing, and swimming are available to the recreationists with approximately 130 thousand surface acres (526 million m^2) of bay waters for recreational use. There are 106 miles (170 km) of bay frontage accessible to the public.

The fishing resources of the Nueces and Mission-Aransas estuaries include many of the fish species preferred by sport fishermen. Sport creel studies conducted by the Texas Parks and Wildlife Department indicate that an estimated 590.1 thousand pounds (267.7 thousand kg) of fish (all species) were harvested by sport fishermen in the Nueces estuary during a 12-month interval from 1975 through 1976 (260). Species composition of the sport harvest was predominantly spotted seatrout (31.3 percent), black drum (18.8 percent) and sand seatrout (18.4 percent). Other preferred species included croaker, red drum, and gafftopsail catfish. Similarly, the sport fish harvest in the Mission-Aransas estuary has been estimated at 518.6 thousand pounds (235.2 thousand kg) during a 12-month interval from 1974 to 1975 (259). Species composition of the harvest was 49.6 percent spotted seatrout, 13.4 percent red drum, 10.2 percent sheepshead, and 6.7 percent sand seatrout. Other preferred species included gafftopsail catfish, southern flounder, black drum, and others.

Inland areas and marshes adjacent to the estuaries provide terrestrial and aquatic habitat for many species of wildlife including the endangered American alligator, whooping crane, brown pelican, leatherback turtle, and the Atlantic Ridley sea turtle. Wildlife resources of the area enhance the recreation opportunities for sightseeing and nature studies, with esthetic benefits accruing to both naturalists and environmentalists. In addition, outdoor sportsmen can take advantage of 8,300 acres (34 million m^2) of salt-water marsh for hunting opportunities. The 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, limited 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 all estuarine systems of the Texas Coast (Figures 3-11 and 3-12, 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 Nueces and Mission-Aransas estuaries on June 3-6, 1974. Tidal amplitudes were measured simultaneously at numerous locations throughout the estuaries (Figure 3-13). Tidal flow measurements were made at several different bay cross-sections. In addition, conductivity data were collected at many of the sampling stations shown in Figures 3-11 and 3-12. Studies of past and present freshwater inflows to Texas' estuaries have used all available sources of information on the physical, chemical, and biological characteristics of these estuarine systems in an effort to define the relationship between freshwater and nutrient inflows and estuarine environments.

Economic Characteristics

Socioeconomic Assessment of Adjacent Counties

The economic significance of the natural and man-made resources associated with the Nueces and Mission-Aransas estuaries is reflected in the direct and indirect linkages of bay-supported resources to the economies of Aransas, Nueces, Refugio, and San Patricio Counties. Trends in population, earnings, and personal income levels are presented for the four counties (Aransas and Refugio Counties were also discussed in the study of the Guadalupe Estuary).

Population. The population of the four-county study area experienced an annual growth of 0.9 percent between 1970 and 1975, which is well below the statewide figure of 1.7 percent for the same period. Only Aransas County had an annual growth rate (3.4 percent) higher than the statewide average, while Nueces and Refugio Counties had slight annual changes (+.82 and -.84 percent, respectively). San Patricio County population grew in this period (1.2 percent annually), but at a slower rate than the statewide average.

In 1975, the population of the four-county area was 317,300. Nueces County, which includes the City of Corpus Christi, accounted for 78 percent of the total. Population forecasts for the period 1975 to 2030 indicate that the population of the study area can be expected to increase 1.4 percent per annum to the year 2030. Nueces County is projected to remain the most populated, growing to 83 percent of the study area population in 2030. Aransas County,

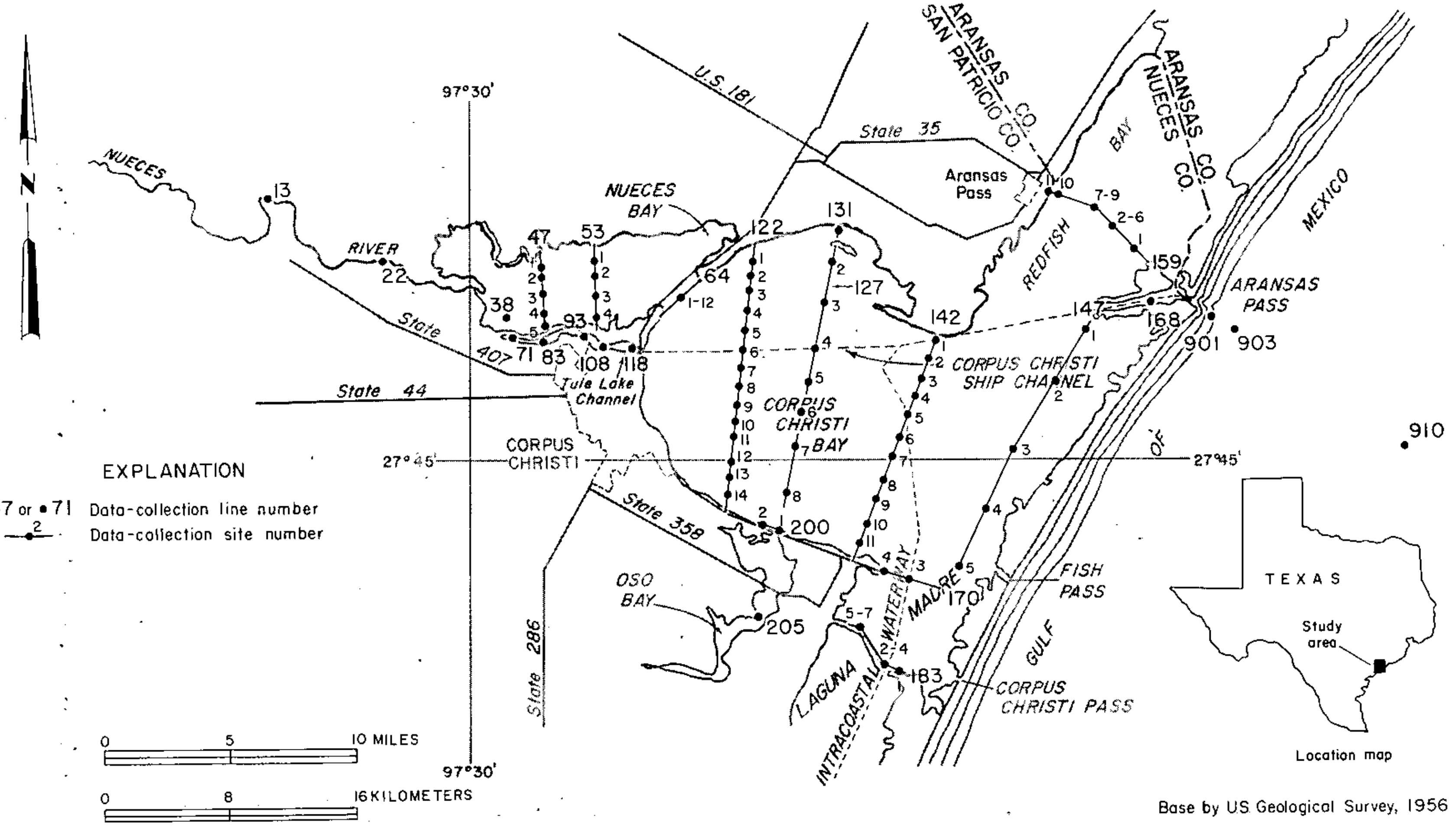

Figure 3-11. Data Collection Sites in the Nueces Estuary

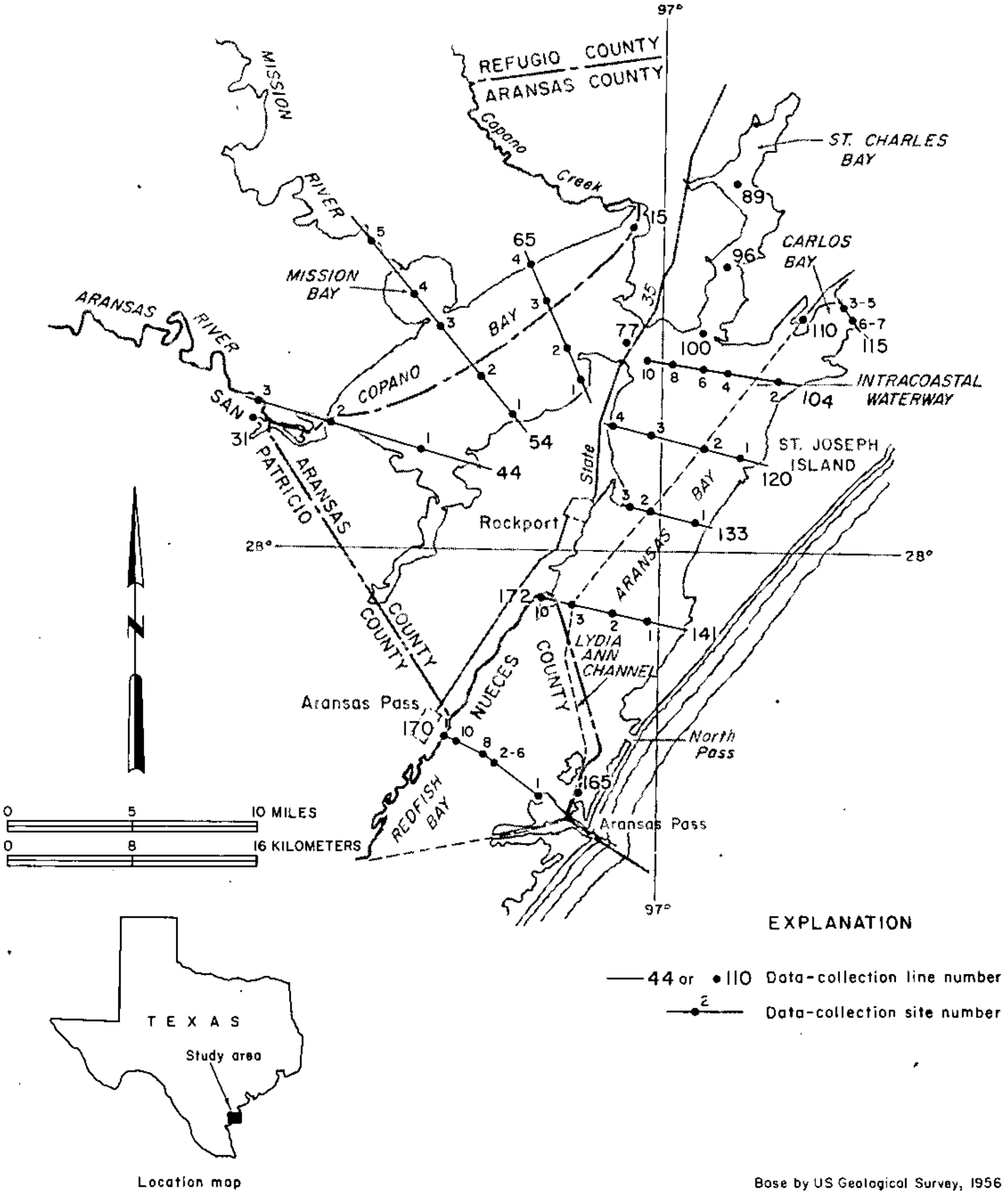

Figure 3-12. Data Collection Sites in the Mission-Aransas Estuary

Table 3-2. U. S. Geological Survey (USGS) or Corps of Engineers (COE) Gages, Nueces and Mission-Aransas Estuaries

Station Number	Station Description	Period of Record	Operating Entity	Type of Record
	Tide Gages			
28	St. Charles Bay, Indian Head Point	1977-	COE	Continuous Recording
29	Copano Bay, Hwy. 35 bridge	1968-	COE	Continuous Recording
30	Copano Bay, Bayside, Cities Service Pump Sta.	1966-	COE	Continuous Recording
31	Aransas Bay, Nine Mile Point Light	1971-75	COE	Continuous Recording
31A	Aransas Bay, Rockport Harbor, Texas P & WL	1971-	COE	Continuous Recording
32	Redfish Bay, Aransas Pass Channel, Hwy. 361	1973-	COE	Continuous Recording
32A	Redfish Bay, Aransas Pass Channel MKR #12	1971-73	COE	Continuous Recording
33	Aransas Pass, Port Aransas, South Jetty	1968-	COE	Continuous Recording
34	Nueces Bay, Arco Well #10 (Wht. Pt.)	1971-75	COE	Continuous Recording
34A	Nueces Bay, White Point-Phillips 66	1969-71	COE	Continuous Recording
34B	Nueces Bay, Phillips Well #5 (Wht. Pt.)	1975-	COE	Continuous Recording
35	Nueces Bay, Hwy. 181 Causeway	1971-	COE	Continuous Recording
35A	Corpus Christi Bay, Turning Basin, Pier 9	1968-69	COE	Continuous Recording
36	Corpus Christi Bay, COE Area Office	1969-	COE	Continuous Recording

(continued)

Table 3-2. U. S. Geological Survey (USGS) or Corps of Engineers (COE) Gages, Nueces and Mission-Aransas Estuaries (cont'd.)

Station Number	Station Description	Period of Record	Operating Entity	Type of Record
37	Corpus Christi Bay, Naval Air Station	1966–	COE	Continuous Recording
38	Corpus Christi Bay, Ingleside, Sun P. L. Dock	1969–	COE	Continuous Recording
39	Corpus Christi Bay, 4600 Bayshore Drive	1969–75	COE	Continuous Recording
40	North Laguna Madre, GIWW Marker #21	1971–75	COE	Continuous Recording
1890.80	Aransas Bay (Dun. Pt.) nr. Fulton	1971–	USGS	Continuous Recording
1890.85	Saint Charles Bay nr. Fulton	1971–76	USGS	Continuous Recording
1895.55	Copano Bay nr. Bayside	1966–76	USGS	Continuous Recording
1898.24	Aransas Bay at Rockport	1975–76	USGS	Continuous Recording
1898.25	Aransas Bay nr. Rockport	1971–75	USGS	Continuous Recording
1898.85	Aransas Bay (Mud Isle) nr. Port Aransas	1971–75	USGS	Continuous Recording
1898.95	Redfish Bay (SH 361) nr. Aransas Pass	1971–76	USGS	Continuous Recording
1899.45	Corpus Christi Ship Channel nr. Ingleside	1969–76	USGS	Continuous Recording
1899.65	Nueces Bay (Wh. Pt.) nr. Corpus Christi	1969–76	USGS	Continuous Recording
1899.67	Nueces Bay nr. Whites Point nr. Corpus Christi	1974–	USGS	Continuous Recording
2115.05	Nueces Bay (U.S. 181) nr. Corpus Christi	1971–76	USGS	Continuous Recording
2115.30	Laguna Madre (ICWW) nr. Corpus Christi	1976–	USGS	Continuous Recording

(continued)

Table 3-2. U. S. Geological Survey (USGS) or Corps of Engineers (COE) Gages, Nueces and Mission-Aransas Estuaries (cont'd.)

Station Number	Station Description	Period of Record	Operating Entity	Type of Record
	Stream Gages			
1892	Copano Creek nr. Refugio	1970-	USGS	Continuous Recording
1895	Mission River at Refugio	1939-	USGS	Continuous Recording
1897	Aransas River nr. Skidmore	1964-	USGS	Continuous Recording
1898	Chiltipin Creek at Sinton	1970-	USGS	Continuous Recording
2112	Nueces River nr. Mathis	1939-	USGS	Continuous Recording
2115	Nueces River nr. Calallen	1966-67	USGS	Continuous Recording
2115.2	Oso Creek at Corpus Christi	1972-	USGS	Continuous Recording
	Partial Record Stream Gages			
1891.00	Salt Creek nr. Refugio	1967-77	USGS	Limited Data

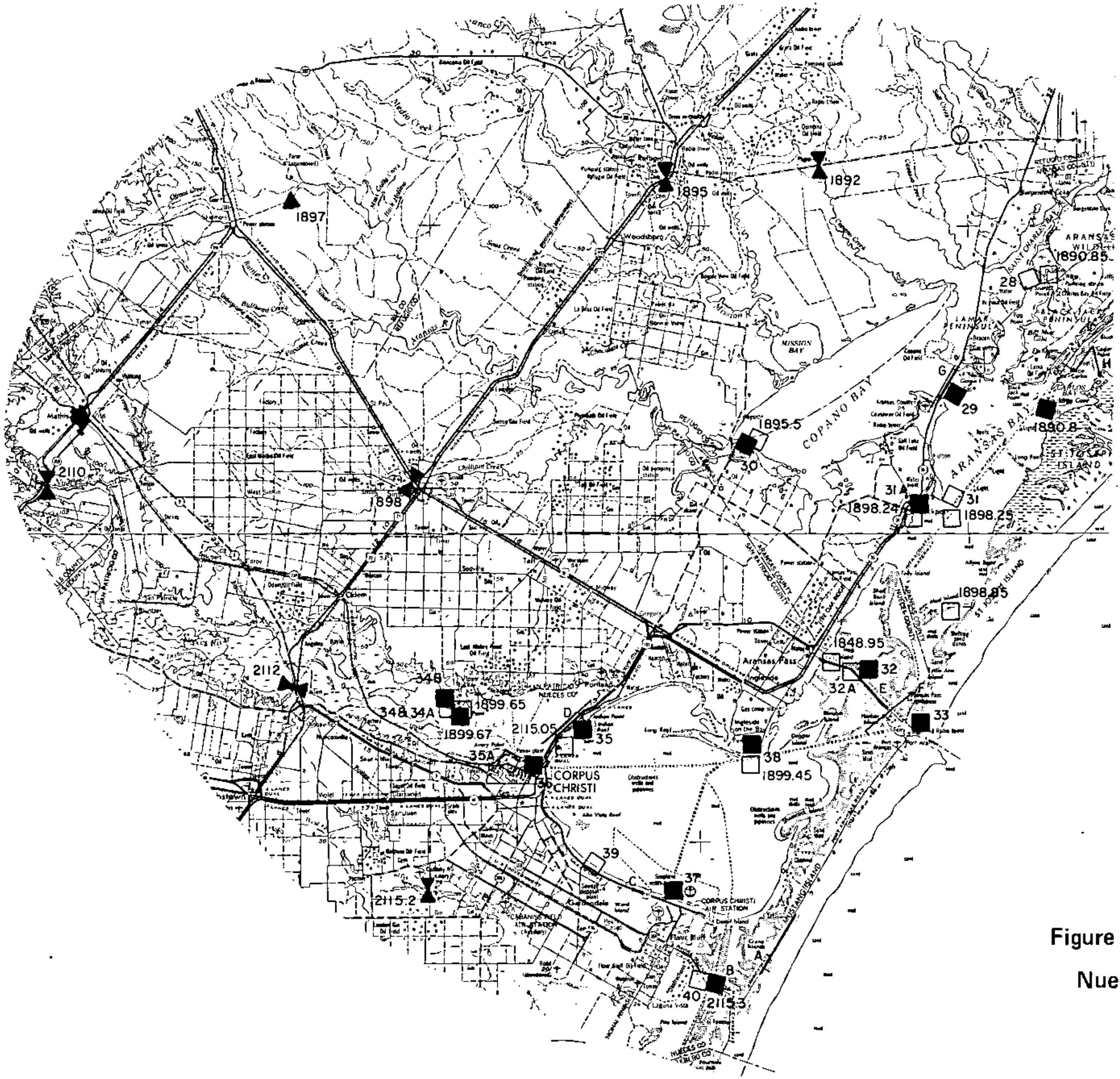

Figure 3-13. Locations of Gaging Stations, Nueces and Mission-Aransas Estuaries

however, has the highest projected growth rate, growing by 2.6 percent per annum from 1970 (2.9 percent of the study area population) to 2030 (6.1 percent of the study area population). Details of future population estimates for the four-county area are presented in Table 3-3.

Income. Real personal income for the four county region comprised approximately 2 percent or $874.3 million of the state's estimated personal income in 1970. Nueces County accounted for more than 80 percent of the regional estimate followed by San Patricio (14 percent), Aransas (3 percent) and Refugio (3 percent).

Employment. In 1970, an estimated 102,568 persons were employed in the study area, and over 79 percent of these worked in Nueces County. Aransas County had the lowest study area employment in 1970 (2.8 percent of the regional total), followed by Refugio County (3.4 percent).

The study area employment accounted for approximately 2.5 percent of the total statewide employment in 1970.

Over three-fourths of the region's employed labor force is distributed among eight major industrial sectors (Table 3-4). Workers employed by wholesale and retail trade establishments, the largest employment sector, account for almost 23 percent of the area's labor force.

Industry. The "basic" industries in the area are manufacturing, agriculture-forestry-fisheries, and mining. These sectors account for 20 percent of all employment in the study area. In addition to the basic sectors are the service sectors: wholesale and retail trade, professional services, construction, civilian government, and amusement and recreation. These employ over 57 percent of the region's workers. The service sectors provide goods and services to the basic industries as well as the general public and are, in varying degrees, dependent upon them.

The most significant basic sector, in terms of total earnings, is manufacturing (Table 3-5). The major portion of manufacturing activity is centered in the Corpus Christi metropolitan area and is concentrated in the production of primary metals (mainly aluminum), chemicals, and petroleum refining.

The Port of Corpus Christi is another important factor in the regional economy. In 1970, it was the thirteenth largest port in the United States and the second largest in Texas (92). It functions as a maritime harbor as well as an inland harbor with access via the Intracoastal Canal to ports on the Mississippi River. In addition to providing basic low-cost transportation for raw materials and finished products, it is also an important source of direct and indirect employment in the area.

The mineral wealth of the area is also an important factor in its economy. Crude oil production in 1977 exceeded 43 million barrels, or approximately 4 percent of the state total. Eighty-three percent of regional crude oil production came from Refugio County alone. Regional natural gas

Table 3-3. Population Estimates and Projections, Area Surrounding Nueces and Mission-Aransas Estuaries, 1970-2030 (239)

County	1970	1975	1980	1990	2000	2010	2020	2030	1970-2000 Annual % Change	1970-2030 Annual % Change
Aransas	8,902	10,500	12,400	16,200	20,600	26,000	33,000	42,200	2.8	2.6
Annual % Change	3.4	3.4	2.7	2.4	2.4	2.4	2.5			
Nueces	237,544	247,400	261,300	288,400	322,400	374,300	453,800	576,300	1.0	1.5
Annual % Change	.82	1.1	.99	1.1	1.5	1.9	2.4			
Refugio	9,494	9,100	8,900	8,300	7,900	7,600	7,500	7,500	-.61	-.39
Annual % Change	-.84	-.44	-.70	-.49	-.39	-.13	0.0			
San Patricio	47,288	50,300	53,100	56,600	59,000	61,600	64,600	67,600	.74	.60
Annual % Change	1.2	1.1	.64	.42	.43	.48	.45			
Area Total	303,228	317,300	335,700	369,500	409,900	469,500	558,900	693,600	1.0	1.4
Annual % Change	.91	1.1	.96	1.0	1.4	1.8	2.2			
State Total	11,198,655	12,193,200	13,393,100	15,593,700	18,270,700	21,540,600	25,548,400	30,464,900	1.6	1.7
Annual % Change	1.7	1.9	1.5	1.6	1.7	1.7	1.8			

Table 3-4. Employment by Industrial Sector, Area Surrounding Nueces and Mission-Aransas Estuaries, 1970 (234)

Sector	1970					
	Aransas	Nueces	Refugio	San Patricio	Total	Percent of Total Employment of Study Area
Wholesale and Retail Trade	721	18,850	815	3,139	23,525	22.9
Manufacturing	295	8,973	198	1,818	11,284	11.0
Professional Services	305	14,050	490	2,236	17,081	16.7
Construction	273	7,175	257	1,536	9,241	9.0
Agriculture, Forestry, and Fisheries	217	2,171	369	1,731	4,488	4.4
Mining	129	3,253	441	959	4,782	4.7
Civilian Government	132	7,414	124	675	8,345	8.1
Amusement and Recreation	55	602	7	85	729	.7
All Other	738	18,817	770	2,768	23,093	22.5
Total	2,845	81,305	3,471	14,947	102,568	100.0

Table 3-5. Earnings by Industrial Sector, Area Surrounding Nueces and Mission-Aransas Estuaries, 1970 (233)

Sector	1970					
	Aransas	Nueces	Refugio	San Patricio	Area Total	Percent of Total Earnings in Study Area
	(Thousands of 1967 Dollars)					
Wholesale and Retail Trade	3,761	115,193	3,002	13,923	135,879	19.4
Manufacturing	2,250	83,488	1,053	11,643	98,439	14.1
Professional Services	933	50,352	1,058	5,816	58,159	8.3
Construction	1,431	44,042	951	6,843	53,267	6.6
Agriculture, Forestry, and Fisheries	1,898	22,249	2,279	12,876	39,302	5.6
Mining	1,015	29,996	2,451	6,419	39,881	5.7
Civilian Government	2,078	136,724	1,378	9,035	149,215	21.3
Amusement and Recreation	118	2,371	17	243	2,749	.39
All Other	2,953	105,857	2,316	17,063	122,379	17.5
County Totals	16,437	590,272	14,505	78,046	699,260	100.0

production (gas well and casinghead gas) in 1977 was over 330 billion cubic feet, or 4.5 percent of the state total (266).

Agriculture. The four-county area had over $92 million in receipts from crop production in 1977. Major regional crops are cotton, corn, and grain sorghum. Livestock and livestock product receipts in 1977 were over $17 million, for a total regional agricultural output of over $110 million in that year. In addition, the bay-supported commercial fishing industry provides fish and shellfish seafoods to local and regional markets.

Summary. The four county area possesses natural and man-made resources. Examination of projected trends in population, industrial composition and earnings, and personal income provides a clearer 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 well-being of the regional economy 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 reflective of the continued growth of the area's basic industries, i.e., manufacturing, agriculture, and mining. Industries involved in the production of primary metals, chemicals, and petroleum refining is expected to continue to provide the impetus for the area's employment and earnings potential. Additional business generated by the Port of Corpus Christi should continue to enhance the economic development potential of the area, thus providing additional employment opportunities for the populus of Nueces and surrounding counties. The future economic situation of the study area appears to be bright and progressive due to the strength of the area's basic industries and the diversity of its industrial structure.

Economic Importance of Sport and Commercial Fishing

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

Sport Fishing Data Base. In cooperation with the Texas Parks and Wildlife Department three types of sample surveys were conducted for the purpose of obtaining the data necessary for these studies of sport fishing in the Nueces and Mission-Aransas estuaries. The surveys included: (1) personal interviews, (2) roving counts, and (3) motor vehicle license plate counts. Personal interviews of a sample of sport fishing parties on a randomly selected sample of weekend days were conducted at major access points to the estuaries 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 and wade-bank areas to estimate the number of sport fishing parties in the bay area. Data for the personal interview sample and fishermen counts conducted during the period September 1, 1976 through August 31, 1977 were used in this analysis. A motor vehicle license plate 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 and fishing strata (boats, wade-bank, or pier).

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 areas within the study area (estuary systems). An adjustment of the boat trailer count was made to correct for those boats which were not fishing in these estuary systems. Sample data from the boat party personal interview survey were used to estimate the proportion of boat parties that were fishing in the study area.

The estimated number of fishing parties at the Nueces and Mission-Aransas estuaries 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 of the year beginning with September 1, 1976.

where:

Z = Estimated number of boat parties fishing in the Nueces and Mission-Aransas estuaries for the period September 1, 1976 through August 31, 1977.

z_k = Estimated number of boat parties fishing in the Nueces and Mission-Aransas estuaries 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 the Nueces and Mission-Aransas estuaries for the period September 1, 1976 through August 31, 1977.

w_k = Estimated number of wade-bank parties fishing in the Nueces and Mission-Aransas estuaries during the kth calendar quarter of the study period.

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

where;

P = Estimated number of pier parties fishing in the Nueces and Mission-Aransas estuaries for the period September 1, 1976 through August 31, 1977.

P_k = Estimated number of pier parties fishing in the Nueces and Mission-Aransas estuaries during the kth calendar quarter of the study.

The equations 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 computation methods are stated and defined below for the general case, for weekends. Since roving count, and interview data were not collected on weekdays in this study period, weekday analyses were based on the weekday/weekend visitation distribution as observed in the motor vehicle license plate survey. The results for weekdays and weekend days were summed to obtain estimates for the entire quarter.

For boat fishing:

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

where:

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

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

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

r = Sample boat sites within the study area (10 boat sites for the Nueces and Mission-Aransas estuaries),

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

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

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

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

No data were collected for wade-bank and pier fishing in this study period; therefore, the estimate of wade-bank and pier parties was based on the relation of wade-bank and pier fishing to boat fishing as observed in the year-long studies of Corpus Christi and Aransas Bays (259, 260).

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 319 thousand fishing parties annually visit the Nueces and Mission-Aransas estuaries (Table 3-6). Seasonal visitation as a percentage of annual visitation ranged from a high of more than 33 percent for the fall quarter to a low of approximately eight percent during the winter quarter. The distribution of fishing parties by strata indicates that wade-bank fishing accounted for about 55 percent of annual visitation followed by boat fishing with approximately 28 percent (Table 3-7).

Sport Fishing Visitation Patterns. Although the personal interview information included the county of residence of the interviewee, the number of interviews (423 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 over 60 percent of fishermen at the Nueces and Mission-Aransas estuaries came from the following six counties — Nueces (19.4 percent of the summer 1977 visitation), Bexar (18.8 percent), San Patricio (7.8 percent), Harris (6.9 percent), Dallas (3.8 percent), and Travis (3.7 percent). A more general visitation pattern distinction of "local" and "nonlocal" was also made. "Local," for the purposes of this study, includes counties within approximately 60 miles of the estuary area. For the Nueces

Table 3-6. Estimated Seasonal Sport Fishing Visitation to Nueces and Mission-Aransas Estuaries, 1976-1977 a/

Season b/	Boat	Wade-Bank c/	Pier d/	Total - All Strata
	thousands of parties			
Fall	31.3 (2.80)	61.4 (1.85)	15.3 (1.97)	107.9
Winter	8.7 (2.42)	15.3 (1.73)	1.7 (2.15)	25.7
Spring	20.3 (2.73)	58.4 (2.17)	13.6 (2.49)	92.3
Summer	28.4 (2.64)	40.7 (2.22)	24.9 (2.58)	94.0
Total All Seasons	88.7 (2.71)	175.8 (1.97)	55.4 (2.23)	319.9

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

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

c/ Wade-bank fishermen/party data obtained from (259, 260)

d/ Pier fishermen/party (259, 260)

Table 3-7. Estimated Seasonal Sport Fishing Visitation Patterns at Nueces and Mission-Aransas Estuaries, 1976-1977

Visitation	Fall	Winter	Spring	Summer	Total-Annual
			thousands of parties		
Local	36.8	9.0	35.5	28.6	109.9
Nonlocal	71.1	16.7	56.8	65.4	210.0
Total Visitation	107.9	25.5	92.3	94.0	319.9

Table 3-8. Estimated Average Cost per Sport Fishing Party by Type and Origin, Nueces and Mission-Aransas Estuaries, 1976-1977

Average Cost per Party	Boat	Wade-Bank	Pier	Weighted Average
		1976 dollars		
Local	13.52	6.47	6.33	8.39
Nonlocal	99.16	92.18	55.99	87.73

and Mission-Aransas estuaries, these counties are Aransas, Bee, Goliad, Jim Wells, Refugio, Nueces, and San Patricio. "Non-local" comprises all other Texas counties and out-of-state visitors.

Since it is expected that the proportions of local and nonlocal bay sport fishermen vary from season to season, an attempt was made to estimate this pattern for seasons other than the summer period. The only information available on visitation patterns for all seasons was the sample of personal interview data which, in addition to the small number of observations, was felt to be biased toward local parties. Thus, the summer license survey visitation pattern was compared to the summer interview pattern, for the purpose of computing an adjustment factor. This was applied to the remaining quarters of 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). As previously mentioned, no data were collected for wade-bank and pier parties during this study period; therefore, the relationship between average cost per boat party and wade-bank and pier parties from the 1975 through 1976 study of Corpus Christi Bay (260) was used to estimate average cost per party for the two strata. The average cost per party for the various fishing types and origins (Table 3-8) was applied to the adjusted visitation distribution estimates (Table 3-7) and visitation estimation by type (Table 3-6) to obtain an estimate of total sport fishing expenditures (Table 3-9). More than 34 percent of the estimated $19.34 million expenditures were made during the fall and 30.0 percent was made during the summer 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 expenditure information for boat insurance, boats, motors, trailers, and fishing tackle is not available. Thus, this analysis is an understatement of the total business associated with sport fishing in the Nueces and Mission-Aransas estuaries.

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

Table 3-9. Estimated Sport Fishing Expenditures by Season and Fishing Party Type, Nueces and Mission-Aransas Estuaries, 1976-1977

Season a/	Boat	Wade-Bank	Pier	Total	Percent
		thousands of 1976 dollars			
Fall	2,215.4	3,933.3	600.1	6,748.8	34.9
Winter	589.2	925.2	64.5	1,578.9	8.2
Spring	1,323.1	3,394.5	494.5	5,212.1	26.9
Summer	2,073.2	2,697.9	1,034.1	5,805.2	30.0
Total	6,200.9	10,950.9	2,193.2	19,345.0	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

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 (242) and regional input-output tables derived from the state model (246).[1/]

The expenditure data collected by personal interviews of a sample of fishing parties at the Nueces and Mission-Aransas estuaries (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) (399). To account for different origins and types of fishing parties, variable expenditures were analyzed for each of the four types of fishing parties: local boat parties; local wade-bank parties; nonlocal wade-bank parties; and nonlocal boat parties. Variable expenditures, except for travel, were classified as having been made within the local region, since that is the site at which the service is produced. For the travel sector, it was assumed that one-half of the expenditures occurred within the local area and one-half occurred elsewhere in the state en route to the study area.

The results of the survey show that variable sport fishing expenditures in the local area of the Nueces and Mission-Aransas estuaries were over $17.02 million. In addition, there was an estimated $2.31 million spent outside the region, within Texas (Table 3-10). Most of the expenditure impact, over 88 percent, accrues to the region. However, when the total impacts are calculated, the regional gross impact of over $36.12 million accounts for a little more than half (57.8%) 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.

Approximately 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 $10.63 million from the sport fishing business in the area (Table 3-11). Statewide, the income impact amounted to over $17.7 million, annually.

The input-output analysis estimated a total of 1,017 full time job equivalents directly related to sport fishing in the Nueces and Mission-Aransas estuaries region in 1976 through 1977. Statewide, an additional 203 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 2,075 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 $637.6 thousand, with $377.3 thousand collected in the local region.

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

Table 3-10. Estimated Sport Fishing Variable Expenditures by Sector, Nueces and Mission-Aransas, Estuaries, 1976-1977

	Bait	Travel	Food	Lodging	Recreation a/	Total
	thousands of 1976 dollars					
Total	5,051.6	4,851.9	5,410.2	1,645.2	2,386.1	19,345.0 b/

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a/ Marinas, boat fuel, and boat rental.
b/ Adjusted for travel expenditures outside the study area 19,345.0 - (2,315.8). Expenditures in the region = $17,029.2 thousand.

Table 3-11. Direct and Total[a/] Economic Impact from Sport Fishing Expenditures, Nueces and Mission-Aransas Estuaries, 1976-1977 b/

	Direct c/		Total	
	Regional	State	Regional	State d/
Output (thousands)	$17,029.2	$19,345.0	$36,121.8	$62,434.8
Employment (Man-Years)	1,017	1,220	1,441	2,075
Income (thousands)	5,969.3	7,124.7	10,635.8	17,708.5
State Tax Revenues (thousands)	e/	147.0	377.3	637.6
Local Tax Revenues (thousands)	e/	209.4	638.7	976.8

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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

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 $638.7 thousand resulted from direct, indirect and induced sport fishing expenditures (Table 3-11). In addition, local governments outside the Nueces and Mission-Aransas estuaries region collected an estimated $338 thousand in taxes on travel expenditures by fishing parties in 1976 through 1977.

The data shows that sport fishing in the Nueces and Mission-Aransas estuaries region results in a larger economic impact in areas outside the region than within the region. However, data necessary to analyze the effects of the sport fishing equipment business were not available. Thus, the annual statewide gross output impact of over $62.43 million represents a contribution to the State's economy from only the variable expenditures by sport fishermen in the estuarine 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 Nueces and Mission-Aransas estuaries was somewhat limited by the availability of estuary-specific data. Estimates made of each estuary's total contribution to commercial fisheries harvests were based on the fisheries inshore-offshore harvest distributions. 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 estuaries was estimated at 1,910,500 pounds (866,600 kg) of finfish and 15,833,500 pounds (7.2 million kg) of shellfish for the period 1972 through 1976. Using 1976 dockside finfish and shellfish prices ($.357 per lb. and $1.456 per lb., respectively), the direct commercial value of fish attributed to the estuaries was estimated at $23.73 million (1976 dollars) (377). Shrimp, blue crab, and oysters constituted approximately 89 percent of this value.

The Texas economy-wide total business resulting from commercial fish catch attributed to the Nueces and Mission-Aransas estuaries was estimated using the 1972 Texas Input-Output Model fisheries sector multipliers. Total value of the catch was $23.7 million, direct employment in the fisheries sector was 864, and direct salaries to fisheries employees was $7.93 million (Table 3-12).

Gross Texas business resulting from fishing, processing, and marketing the catch attributed to the estuaries in 1976 was estimated at $73.93 million. Indirect supporting and marketing activities provided an additional 864 full time job equivalents regionally and an additional 676 full time job equivalents statewide. Gross personal income in Texas attributed to the estuarine fishing and supporting sectors was estimated at $20.33 million, state taxes at $671.7 thousand, and taxes paid to local units of governments throughout Texas, as a result of this fishery business, at $932.8 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 com-

Table 3-12. Direct and Total a/ Economic Impact of Commercial Fishing in the Nueces and Mission-Aransas Estuaries, 1976

	Fishing Sector	Total	
		Regional	State
Output (1000's 1976 $)	23,735.6	49,631.5	73,936.5
Employment (Man-Years)	864	1,540	1,837
Income (1000's 1976 $)	7,930.1	16,423.8	20,332.8
State Tax Revenues (1000's 1976 $)	90.2	519.8	671.7
Local Tax Revenues (1000's 1976 $)	106.8	802.3	932.8

a/ Total = direct, indirect and induced

mercial fishing and the economic impact of these fisheries upon the local and state economies.

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

The method of input-output analysis, using both the Texas Input-Output Model and regional tables derived from the state model, was used to calculate the total impact. The results showed that variable sport fishing expenditures in the local area were greater than $17.02 million. In addition, there was an estimated $2.31 million spent outside the region, within Texas.

Approximate 35 percent of the direct expenditures by sport fishermen in the region surrounding the Nueces and Mission-Aransas estuaries resulted in increased personal incomes for regional households directly affected by the sport fishing industry. Statewide, the income impact amounted to over $17.70 million, annually. In addition, the total employment impact to the State economy was 2,075 full-time job equivalents.

Revenues to State and local government (including schools) were postively impacted by the increased business activity and gross dollar flows from the sport fishing industry in both estuaries. The total statewide State tax revenues amounted to over $637.6 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 total (inshore and offshore) commercial fisheries harvest dependent upon the Nueces and Mission-Aransas estuaries. The average annual commercial fisheries contribution was estimated at 17.7 million pounds of finfish (11 percent) and shellfish (89 percent) for the period 1972 through 1976. The total value of the catch was $23.7 million (1976 dollars), direct employment in the commercial fisheries sector was 864, and direct salaries to employees was $7.93 million.

CHAPTER IV

HYDROLOGY

Introduction

Detailed studies of the hydrology of areas draining to the Nueces and Mission-Aransas estuaries were necessary to estimate historical freshwater inflows from contributory areas, only a portion of which are gaged. Freshwater inflow contributions to the Nueces estuary come from the Nueces Basin and several small coastal basins, including portions of the San Antonio-Nueces Coastal Basin and the Nueces-Rio Grande Coastal Basin. Contributions of freshwater to the Mission-Aransas estuary come in large part from the Mission and Aransas Rivers. Their watersheds comprise the major portion of the San Antonio-Nueces Coastal Basin. An earlier section of this report (Chapter III, "Influence of Contributory Basins") describes upstream reservoirs in the major basins. The present section deals with aspects of the quality and quantity of freshwater inflow from a historical perspective.

Freshwater Inflows

Freshwater inflow contributions to the Nueces and Mission-Aransas estuaries consist of (1) gaged inflow from the Nueces Basin and San Antonio-Nueces Coastal Basin; (2) ungaged runoff; (3) return flows from municipal, industrial and agricultural sources in ungaged areas; and (4) precipitation on the estuary. The following paragraphs consider each of these individually. In addition to freshwater inflow, evaporation from the bay surface is considered to arrive at a freshwater inflow balance.

Gaged Inflow, Nueces Estuary

Utilizing the most downstream gage, the Nueces River near Mathis (USGS Gage #08211000), the Nueces River Basin has a total gaged drainage area of 16,660 square miles (43,150 km^2). Gaged flow at the Mathis gage on the Nueces River has averaged 628,000 acre-feet/year (771 million m^3/yr) over the period 1941 through 1976 (Table 4-1). Gaged yield from the Nueces Basin (1941 through 1976) has averaged 40 acre-feet per square mile (190 m^3/ha). A major diversion of the Nueces River occurs a short distance upstream from the river mouth in Calallen pool. Calallen pool is formed behind an uncontrolled rock-rubble salt-water barrier, and all water supplies for the region are diverted from this pool. Nueces River inflow enters the estuary through the Nueces delta at the western edge of Nueces Bay. Utilizing reported diversion records of the Texas Department of Water Resources (TDWR) Water Usage System, gaged Nueces River inflows have averaged 575,000 acre-feet/year (706 million m^3/yr) over the period 1941 through 1976.1/ Nueces River inflow accounted for 84 percent of the combined inflow2/ and 60 percent

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1/ Gaged Nueces Inflow = (gaged Nueces flow) - (diversions); see Table 4-2.

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

Table 4-1. Monthly Freshwater Inflow, Nueces Estuary, 1941-1976 a/

Month	Gaged Nueces Flow	Gaged Nueces Inflow	Total Gaged Inflow	Ungaged Inflow	Return Flows	Diversions	Combined Inflow	Precipitation on Bay	Total Freshwater Inflow	Bay Evaporation Losses	Freshwater Inflow Balance
					Thousands of Acre-Feet						
Average over all Years											
January	21	18	18	2	1	3	22	13	36	24	12
February	20	16	16	3	1	3	22	16	38	24	14
March	20	16	16	0	2	4	19	10	29	32	-2
April	21	17	17	4	2	4	24	18	42	37	5
May	91	86	86	9	2	5	98	30	128	46	81
June	71	66	66	6	2	5	76	26	102	57	45
July	54	48	48	7	3	5	59	20	79	71	8
August	32	27	27	7	2	5	37	29	67	73	-5
September	136	131	131	21	2	4	155	48	203	58	145
October	112	108	108	11	2	4	121	27	149	49	100
November	31	27	27	1	2	4	30	14	45	37	8
December	12	8	8	2	2	4	13	13	27	28	0
Totals	621	568	568	73	23	50	676	264	945	536	411
Monthly Average	52	47	47	6	2	4	56	22	79	45	34

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a/ Rounding errors may result in small differences between Tables 4-1 and 4-2 of the total freshwater inflow[1] to the Nueces estuary (Table 4-2) over the 1941 through 1976 period.

Gaged Inflows, Mission-Aransas Estuary

Utilizing the two most downstream gages, (1) Mission River at Refugio (USGS Gage #08189500) and (2) Aransas River near Skidmore (USGS Gage #08189700), the San Antonio-Nueces Coastal Basin has a total gaged drainage area of 937 square miles (2,438 km^2). Gaged contributions of the San Antonio-Nueces Coastal Basin to the estuary have averaged 104,000 acre-feet/year (128 million m^3/yr) over the period 1941 through 1976. A breakdown of average monthly inflows over the period is shown in Table 4-3. Gaged yield from the San Antonio-Nueces Coastal Basin (1941-1976) has averaged 111 acre-feet per square mile (528 m^3/ha). Gaged San Antonio-Nueces Coastal Basin inflows accounted for 27 percent of the combined inflow and 14 percent of the total freshwater inflow to the Mission-Aransas estuary (Table 4-4) over the 1941 through 1976 period.

Ungaged Runoff Contributions

Ungaged drainage areas contributory to the Nueces estuary include 697 square miles (1,813 km^2)[2] in the Nueces River Basin, the San Antonio-Nueces Coastal Basin, and the Nueces-Rio Grande Coastal Basin. Ungaged drainage areas contributory to the Mission-Aransas estuary include 1,676 square miles (4,362 km^2)[3] in the San Antonio-Nueces Coastal Basin. To facilitate the study of inflow contributions, the ungaged drainage area immediately contributing to the Nueces estuary was divided into seven subbasins (Figure 4-1) and the ungaged drainage area immediately contributing to the Mission-Aransas estuary was divided into 16 subbasins (Figure 4-2). Using a Thiessen network (348), the weighted daily precipitation was determined for each subbasin (Table 4-5). A water yield model which uses daily precipitation, Soil Conservation Service average curve numbers, and soil depletion index (Beta) to predict runoff from small watersheds was calibrated with two gaged subbasins located within the contributing drainage area and adjacent drainage areas (338). Statistical correlations between annual and monthly gaged and simulated runoff were used to determine the "goodness of fit" of the calibration procedure. The calibrated model was then applied to the ungaged runoff (Table 4-5 and Table 4-6).

During the period 1941 through 1976, ungaged runoff to the Nueces estuary averaged[4] 78,000 acre-feet/year (96 million m^3/yr) and runoff yield averaged 112 acre-feet/mi^2 (534 m^3/ha). Ungaged inflow accounted for 11 percent of the combined inflow and eight percent of the total freshwater inflow to the Nueces estuary (Table 4-2) over the 1941 through 1976 period. During the same period, ungaged runoff to the Mission-Aransas estuary

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

[2] With the installation of one coastal gage in 1972, the ungaged drainage area decreased to 607 square miles (1,580 km^2)

[3] With the installation of two coastal gages in 1970, the ungaged drainage area decreased to 1,460 square miles (3,799 km^2)

[4] Ungaged drainage area held constant at 697 sq. mi. (1,813 km^2)

Table 4-2. Annual Freshwater Inflow a/, Nueces Estuary, 1941-1976 b/

Year	Gaged Nueces Flow c/	Gaged Nueces Inflow c/	Total Gaged Inflow	Ungaged Inflow	Return Flows	Diversions c/	Combined Inflow	Precipitation	Total Freshwater Inflow	Bay Evaporation Losses	Freshwater Inflow Balance
1941	1338	1322	1322	321	9	16	1652	420	2072	431	1641
1942	1275	1261	1261	99	10	14	1370	301	1671	438	1233
1943	204	189	189	21	10	15	220	252	472	512	-40
1944	742	722	722	29	12	20	763	243	1006	448	558
1945	488	462	462	40	14	26	516	247	763	512	251
1946	1306	1282	1282	87	14	24	1383	305	1688	449	1239
1947	323	294	294	106	15	29	415	306	721	469	252
1948	138	111	111	140	14	28	265	206	471	512	-41
1949	906	876	876	61	15	30	952	277	1229	447	782
1950	204	168	168	115	17	36	300	142	442	521	-79
1951	428	391	391	80	18	38	489	247	736	540	196
1952	161	121	121	52	19	40	192	194	386	521	-135
1953	637	592	592	139	22	47	753	221	974	513	461
1954	243	193	193	10	23	51	226	146	372	540	-168
1955	129	79	79	43	25	50	147	200	347	715	-368
1956	136	83	83	74	27	54	184	199	383	649	-266
1957	1546	1493	1493	9	27	53	1529	256	1785	587	1198
1958	1412	1358	1358	116	26	54	1500	389	1889	557	1332
1959	418	365	365	30	26	53	421	352	773	521	252
1960	455	400	400	128	27	55	555	406	961	512	449
1961	319	263	263	53	27	56	343	243	586	484	102
1962	76	10	10	0	32	66	42	142	184	588	-404
1963	82	12	12	0	33	70	45	134	179	577	-398
1964	277	208	208	1	32	70	241	199	440	560	-120
1965	369	303	303	1	33	66	337	230	567	567	0
1966	331	265	265	41	44	66	350	274	624	494	130
1967	1802	1729	1729	304	46	73	2079	351	2430	605	1825
1968	672	602	602	82	43	70	727	380	1107	593	514
1969	249	166	166	25	51	83	242	215	457	604	-147
1970	359	281	281	64	47	84	392	361	753	557	196
1971	2537	2455	2455	238	51	82	2744	337	3081	604	2477
1972	298	215	215	33	52	83	300	333	633	558	75
1973	1043	960	960	155	50	85	1165	398	1563	543	1020
1974	391	302	302	8	53	89	342	228	570	574	-4
1975	373	295	295	30	53	87	378	230	608	559	49
1976	927	856	856	80	52	85	988	359	1347	553	794
TOTAL	22594	20684	20684	2815	1069	1948	24547	9723	34270	19414	14856
AVERAGE	628	575	575	78	30	54	682	270	952	539	413
MEDIAN	382	302	302	57	30	54	403	249	728	541	196
PERCENT	66.0	: 60.4	= 60.4	+ 8.2	+ 3.0	(5.7)	= 71.6	+ 28.4	= 100.0	: 56.6	
PERCENT	92.1	: 84.3	= 84.3	+ 11.4	+ 4.3	(8.0)	= 100.0	: 39.6			

a/ Units are thousands of acre-feet

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

c/ Nueces Inflow = (Gaged Nueces Flow) - (Diversions)

Table 4-3. Monthly Freshwater Inflow, Mission-Aransas Estuary, 1941-1976 a/

Month	Gaged Mission Flow	Gaged Aransas Inflow	Total Gaged Inflow	Ungaged Inflow	Return Flows	Diversions	Combined Inflow	Precipitation on Bay	Total Freshwater Inflow	Bay Evaporation Losses	Freshwater Inflow Balance
					Thousands of Acre-Feet						
Average over all Years											
January	1	0	2	5	0	0	8	18	26	26	0
February	4	1	6	14	0	0	21	21	42	26	16
March	1	0	2	2	0	0	4	14	19	33	-14
April	4	1	5	15	0	0	21	23	45	38	6
May	12	3	15	39	0	0	55	34	89	48	41
June	7	1	9	28	0	0	39	31	70	59	11
July	6	2	8	21	0	0	31	21	53	71	-17
August	3	0	4	17	0	0	23	37	60	75	-14
September	23	8	31	70	0	0	102	54	156	60	96
October	11	1	12	41	0	0	54	35	89	52	37
November	1	0	2	5	0	0	7	20	27	40	-12
December	3	0	3	12	0	0	16	20	36	31	5
Totals	76	17	99	269	0	0	381	328	712	559	155
Monthly Average	6	1	8	22	0	0	32	27	59	47	13

a/ Rounding errors may result in small differences between Tables 4-3 and 4-4.

Table 4-4. Annual Freshwater Inflow a/, Mission-Aransas Estuary, 1941-1976b/

YEAR	GAGED MISSIO. INFLOW	GAGED ARANSA. INFLOW	TOTAL GAGED INFLOW	UNGAGED INFLOW	RETURN FLOWS	DIVERSIONS	COMBINED INFLOW	PRECIPITATION ON BAY	TOTAL FRESHWATER INFLOW	BAY EVAPORATION LOSSES	FRESHWATER INFLOW BALANCE
1941	161	60	221	633	0	0	854	472	1326	457	869
1942	206	59	265	501	0	0	766	406	1172	448	724
1943	31	4	35	42	0	0	77	265	342	543	-201
1944	45	3	48	88	0	0	136	346	482	476	6
1945	34	0	34	156	0	0	190	337	527	533	-6
1946	73	8	81	345	0	0	426	450	876	487	389
1947	47	12	59	49	0	0	108	292	400	506	-106
1948	4	0	4	59	0	0	63	285	348	534	-186
1949	24	8	32	148	0	0	180	389	569	503	66
1950	0	0	0	5	0	0	5	156	161	571	-410
1951	28	0	28	105	0	0	133	297	430	581	-151
1952	73	29	102	185	0	0	287	278	565	580	-15
1953	40	0	40	217	0	0	257	317	574	553	21
1954	1	0	1	82	0	0	83	205	288	628	-340
1955	1	0	1	53	0	0	54	225	279	742	-463
1956	7	0	7	15	7	0	29	212	241	705	-464
1957	74	35	109	252	7	0	368	376	744	600	144
1958	118	26	144	480	7	0	631	433	1064	467	597
1959	44	3	47	230	9	0	286	432	718	599	119
1960	145	14	159	823	9	0	991	559	1550	582	968
1961	45	11	56	256	9	0	321	348	669	542	127
1962	30	3	33	15	9	0	57	264	321	667	-346
1963	3	0	3	2	11	0	16	199	215	627	-412
1964	8	0	8	84	11	0	103	265	368	600	-232
1965	37	9	46	55	11	0	112	308	420	560	-140
1966	86	20	106	328	11	0	445	325	770	515	255
1967	375	149	524	1005	11	0	1540	481	2021	609	1412
1968	107	15	122	579	13	0	714	488	1202	506	696
1969	60	11	71	174	13	0	258	373	631	630	1
1970	54	11	65	293	14	0	372	409	781	591	190
1971	306	92	398	740	14	0	1152	422	1574	603	971
1972	144	27	171	363	14	0	548	407	955	524	431
1973	287	56	343	711	14	0	1068	495	1563	530	1033
1974	88	40	128	389	14	0	531	443	974	582	392
1975	30	1	31	35	11	0	77	0	77	565	-488
1976	204	24	228	424	13	0	665	0	665	554	111
TOTAL	3620	730	3750	9921	232	0	13903	11959	25862	20300	5562
AVERAGE	84	20	104	276	6	0	386	332	718	564	154
MEDIAN	46	10	57	201	8	0	272	341	602	562	43
PERCENT	11.7	+ 2.8	= 14.5	+ 38.5	+ .9	- .0	= 53.8	+ 46.3	= 100.0	: 78.6	
PERCENT	21.8	+ 5.2	= 27.0	+ 71.6	+ 1.6	- .0	= 100.0	: 86.1			

a/ Units are thousands of acre-feet.

b/ Rounding erros may result in small differences between Tables 4-3 and 4-4.

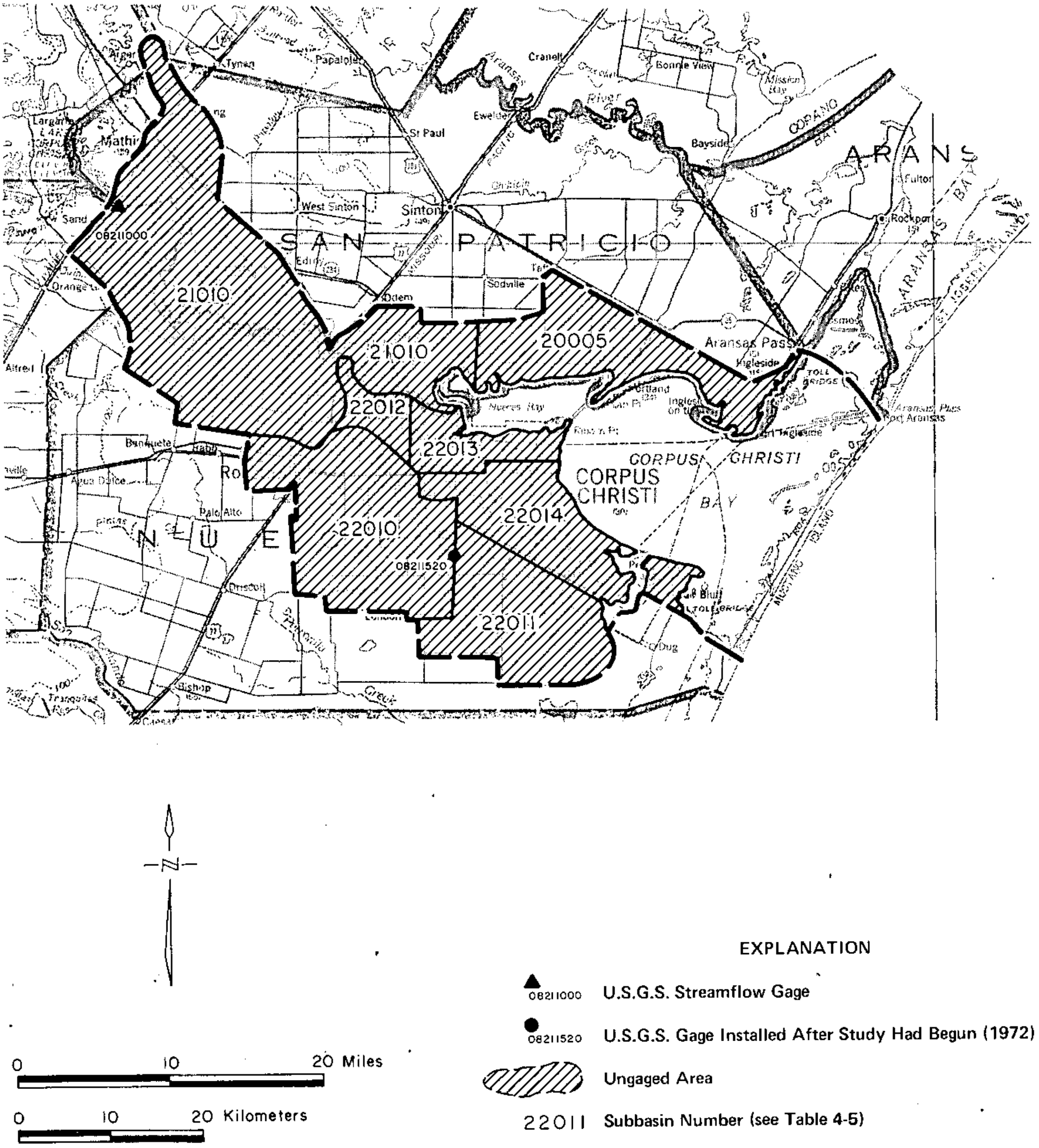

Figure 4-1. Ungaged Areas Contributing to Nueces Estuary

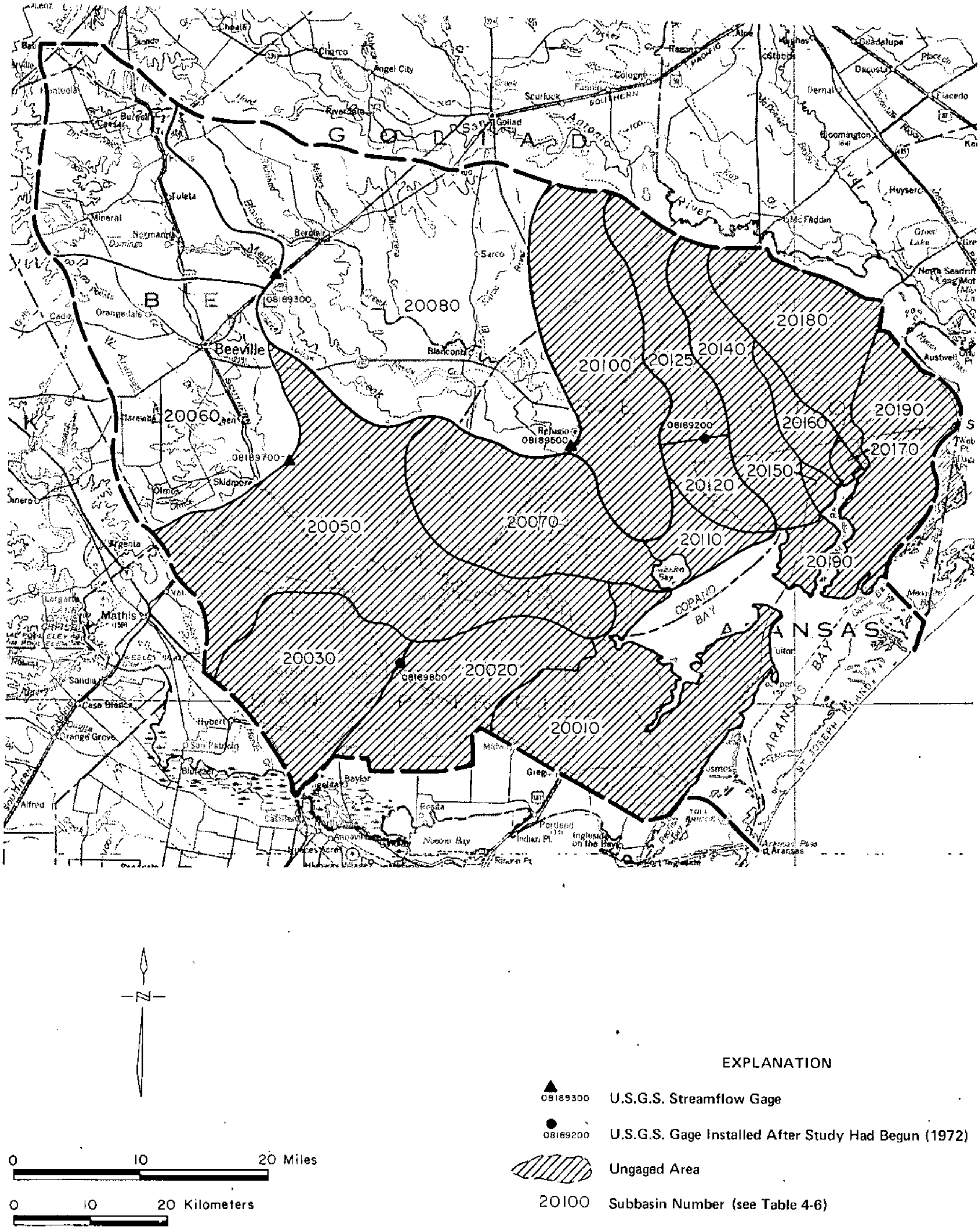

Figure 4-2. Ungaged Areas Contributing to Mission-Aransas Estuary

Table 4-5. Runoff from Ungaged Areas, Nueces Estuary

Subbasin Description		Drainage Area (mi^2)	Weighted Precipitation		Average Runoff ac-ft/mi^2 (1941-1976) e/	Average Curve Number c/ / Beta x10^{-6} d/	Explained Variation (%)		Gaged	
			NWS a/ Station No.	Weight b/ Factor			Annual r^2	Monthly r^2	USGS Station No.	Period of Record
20005	Portland	133	0302 2015	.25 .75	67	56/121.1	—	—	—	—
21010	Calallen	290	0144 2015 7677 8354	.06 .03 .53 .38	74	55/126.3	—	—	—	—
22010	Oso Above FM 763	90.3	2015 7677 1651	.60 .35 .05	183	72.9/60.5	.99	.93	08211520	9/72-
22011	Oso Below FM 763	100	1651 2015	.84 .16	76	56/117.1	—	—	—	—
22012	Nueces River Urban 1941-1951	24.5	2015 7677	.80 .20	143	70/64.1	—	—	—	—
22012	Nueces River Urban 1951-1960	24.5	2015 7677	.80 .20	216	71/56.8	—	—	—	—
22012	Nueces River Urban 1961-1976	24.5	2015 7677	.80 .20	286	72.5/55.8	—	—	—	—
22013	Tule Lake Urban 1941-1950	5.9	2015	1.00	186	71/59.3	—	—	—	—
22013	Tule Lake Urban 1951-1960	5.9	2015	1.00	322	75/47.0	—	—	—	—

See next page for footnotes

Table 4-5. Runoff from Ungaged Areas, Nueces Estuary (cont'd)

Subbasin Description		Drainage Area (mi^2)	Weighted Precipitation		Average Runoff ac-ft/mi^2 (1941-1976) e/	Average Curve Number c/ / Beta x10^{-6} d/	Explained Variation (%)		Gaged	
			NWS a/ Station No.	Weight b/ Factor			Annual r^2	Monthly r^2	USGS Station No.	Period of Record
22013	Tule Lake Urban 1961-1976	5.9	2015	1.00	390	78/44.9	—	—	—	—
22014	Cayo Del Oso Urban 1941-1950	53.1	2015	1.00	183	71/60.7	—	—	—	—
22014	Cayo Del Oso Urban 1951-1960	53.1	2015	1.00	326	75/47.0	—	—	—	—
22014	Cayo Del Oso Urban 1961-1976	53.1	2015	1.00	371	76.5/47.7	—	—	—	—

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a/ National Weather Service

b/ Percentage of area of influence expressed as a factor (348)

c/ An assigned parameter for a particular hydrologic soil-cover complex (338)

d/ Soil moisture depletion coefficient (338)

e/ Unless otherwise noted

Table 4-6. Runoff from Ungaged Areas, Mission-Aransas Estuary

Subbasin Description	Drainage Area (mi^2)	Weighted Precipitation		Average Runoff ac-ft/mi^2 (1941-1976)	Average Curve Numberc/ / Beta x10^{-6}d/	Explained Variation (%)		Gaged	
		NWS a/ Station No.	Weight b/ Factor			Annual r^2	Monthly r^2	USGS Station No.	Period of Record
20010 Intervening Coastal Area	165	9559 7704 0302	.10 .45 .45	187	64/89.7	--	--	--	--
20020 Chiltipin Creek Below Sinton	108	9559	1.00	263	56/125.4	--	--	--	--
20030 Chiltipin Creek Above Sinton	128	5661 9559 7677	.38 .47 .15	187	69/79.3	.93	.92	08189800	7/70-
20040 Intervening Coastal Area	24	9559	1.00		64/84.4	--	--	--	--
20050 Aransas River Below Skidmore	372	0639 5661 9559 7529	.22 .33 .39 .06	92	59/104.9	--	--	--	--
20060 Aransas River Above Skidmore	247	0639 5661	.80 .20	81	60/106.0	.90	.89	08189700	3/64-
20070 Mission River Below Refugio	169	7529 9559	.66 .34	157	63/96.6	--	--	--	--
20080 Mission River Above Refugio	386	3618 7529 0639	.30 .31 .39	142	73/74.8	.92	.95	08189500	7/39-
20090 Medio Creek Near Beeville	204	0639	1.00	90	58/104.1	.55	.57	08189300	3/62-

See next page for footnotes.

(continued)

Table 4-6. Runoff from Ungaged Areas, Mission-Aransas Estuary (cont'd)

Subbasin Description	Drainage Area (mi^2)	Weighted Precipitation		Average Runoff ac-ft/mi^2 (1941-1976)	Average Curve Numberc/ / Beta x10^{-6}d/	Explained Variation (%)		Gaged	
		NWS a/ Station No.	Weight b/ Factor			Annual r^2	Monthly r^2	USGS Station No.	Period of Record
20100 Melon Creek	156	3618 7529	.24 .76	260	70/75.8	—	—	—	—
20110 Intervening Coastal Area	37	7704 7529	.62 .38	168	64/93.0	—	—	—	—
20120 Copano Creek Below Refugio	48.2	7529 7704 3618	.87 .02 .11	156	62/103.7	—	—	—	—
20125 Copano Creek Above Refugio	87.8	3618 7529	.45 .55	385	73/77.7	.50	.74	08189200	6/70-P
20130 Intervening Coastal Area	23.4	7704	1.00	171	62/99.5	—	—	—	—
20140 Cavasso Creek	34.7	0437 7529 7704	.41 .39 .20	170	64/97.2	—	—	—	—
20150 Intervening Coastal Area	10.8	0437	1.00	194	62/107.0	—	—	—	—
20160 Salt Creek	54.1	0437 7529	.35 .65	305	72/71.4	—	—	—	—
20170 Intervening Coastal Area	1.97	0437	1.00	152	62/107.0	—	—	—	—
20180 Artesian Creek	80.2	0437 7529	.83 .17	197	64/97.8	—	—	—	—
20190 Burgentine Creek	176.1	0437	1.00	223	64/98.0	—	—	—	—

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a/ National Weather Service
b/ Percentage of area of influence expressed as a factor (348)
c/ An assigned parameter for a particular hydrologic soil-cover complex (338)
d/ Soil moisture depletion coefficient (338)

averaged[1] 276,000 acre-feet/year (330 million m^3/yr) and runoff yield averaged 165 acre-feet/mi^2 (786 m^3/ha). Ungaged inflow accounted for 72 percent of the combined inflow and 38 percent of the total freshwater inflow to the Mission-Aransas estuary (Table 4-4) 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 flow studies (339, 342). Average return flows over the 1941 through 1976 period were approximately 29,000 acre-feet per year (313 million m^3) for the Nueces estuary and 6,800 acre-feet per year (8.4 million m^3) for the Mission-Aransas estuary. Estimated ungaged return flows accounted for four percent of the combined inflow and three percent of the total freshwater inflow to the Nueces estuary (Table 4-2) over the 1941 through 1976 period and 1.6 percent of the combined inflow and 0.9 percent of the total freshwater inflow to the Mission-Aransas estuary (Table 4-4).

Combined Inflow

A category called combined inflow was obtained by aggregating gaged estuary inflow contributions, ungaged runoff, and estimated ungaged return flows. Over the period 1941 through 1976 combined inflows averaged 682,000 acre-feet per year (840 milion m^3/yr) for the Nueces estuary (Table 4-2) and 386,000 acre-feet per year (480 million m^3/yr) for the Mission-Aransas estuary (Table 4-4). Combined inflow accounted for 72 percent of the total freshwater inflow to the Nueces estuary over the 1941 through 1976 period and 54 percent to the Mission-Aransas estuary. Combined inflows for the Nueces and Mission-Aransas estuaries during this period are illustrated in Figures 4-3 and 4-4. Average monthly distributions of combined inflow are shown for the Nueces and Mission-Aransas estuaries in Figure 4-5 and Figure 4-6, respectively.

Precipitation on the Estuary

Direct precipitation on the 109,795 acre (44,451 ha) surface area of Nueces estuary and 114,310 acres (46,279 ha) surface area of the Mission-Aransas estuary was calculated using Thiessen-weighted precipitation techniques (378, 348). Over the 1941 through 1976 period, annual mean precipitation amounted to 270,000 acre-feet per year (330 million m^3/yr) for the Nueces estuary and 332,000 acre-feet (410 million m^3/yr) for the Mission-Aransas estuary. Direct precipitation accounted for 28 percent of the total freshwater inflow to the Nueces estuary (Table 4-2) and 46 percent of the total freshwater inflow to the Mission-Aransas estuary (Table 4-4).

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[1] Ungaged drainage area held constant at 1,676 sq. mi. (4,362 km^2)

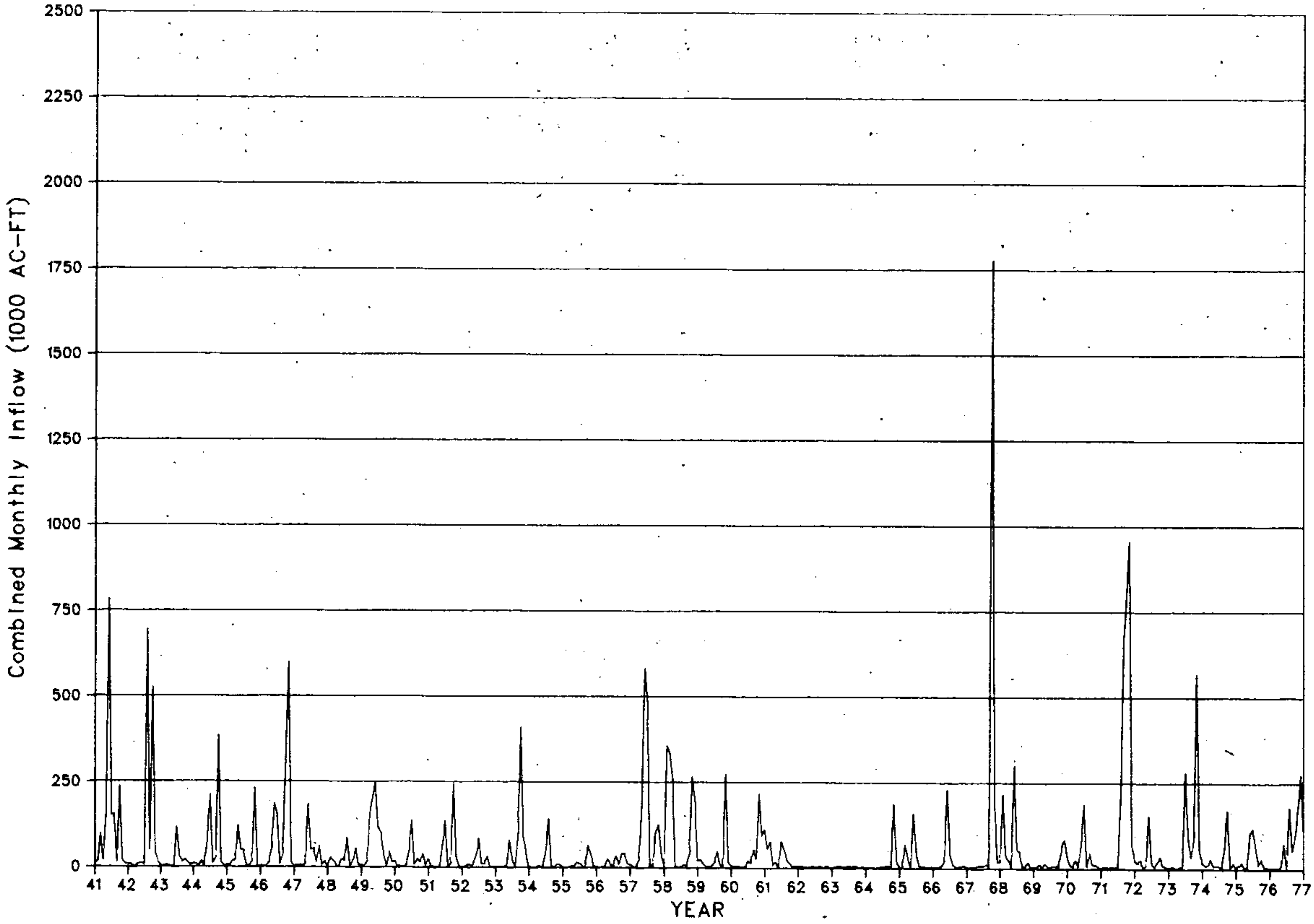


Figure 4-3. Combined Monthly Inflow to the Nueces Estuary, 1941-1976

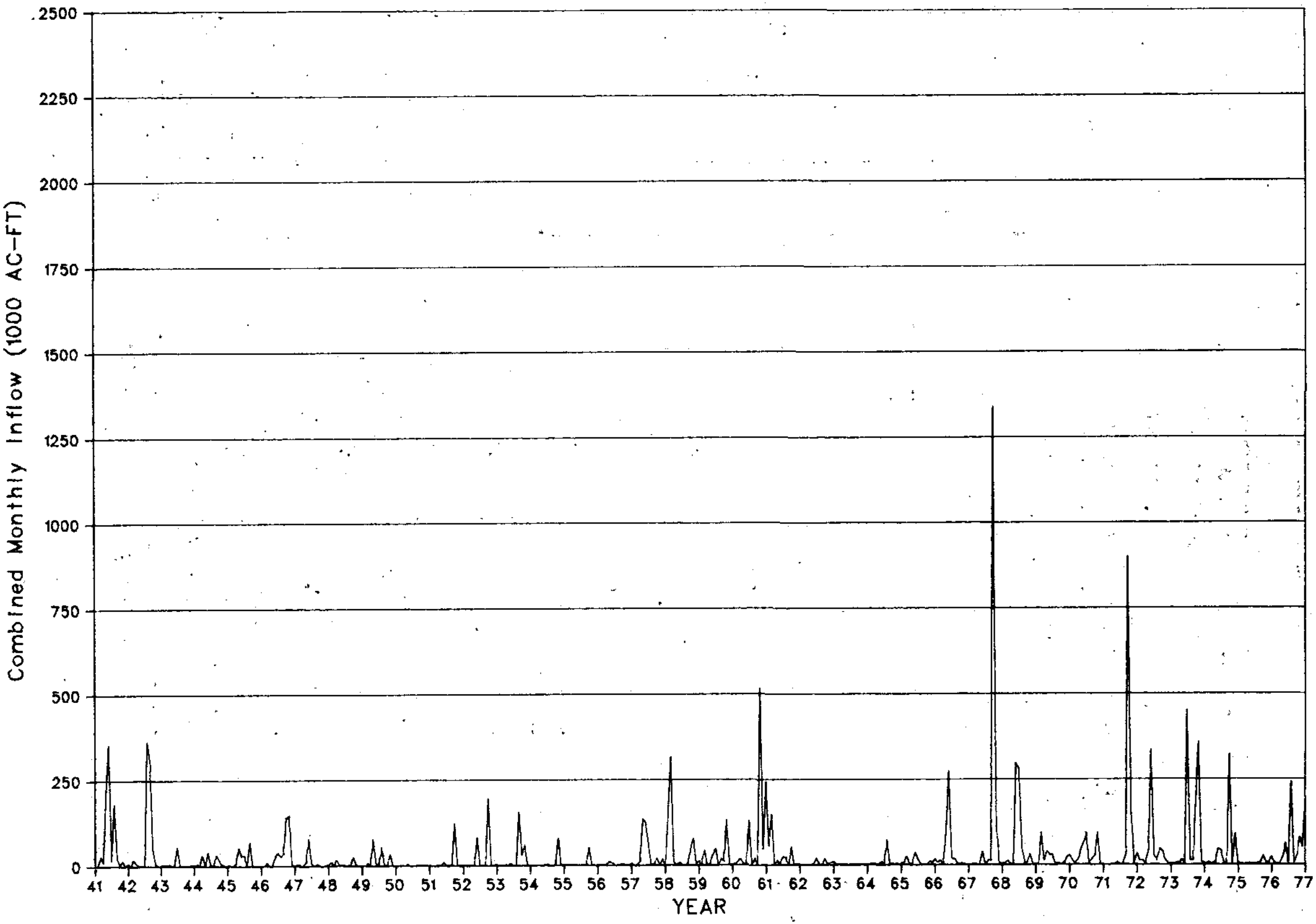


Figure 4-4. Combined Monthly Inflow to the Mission-Aransas, Estuary, 1941-1976

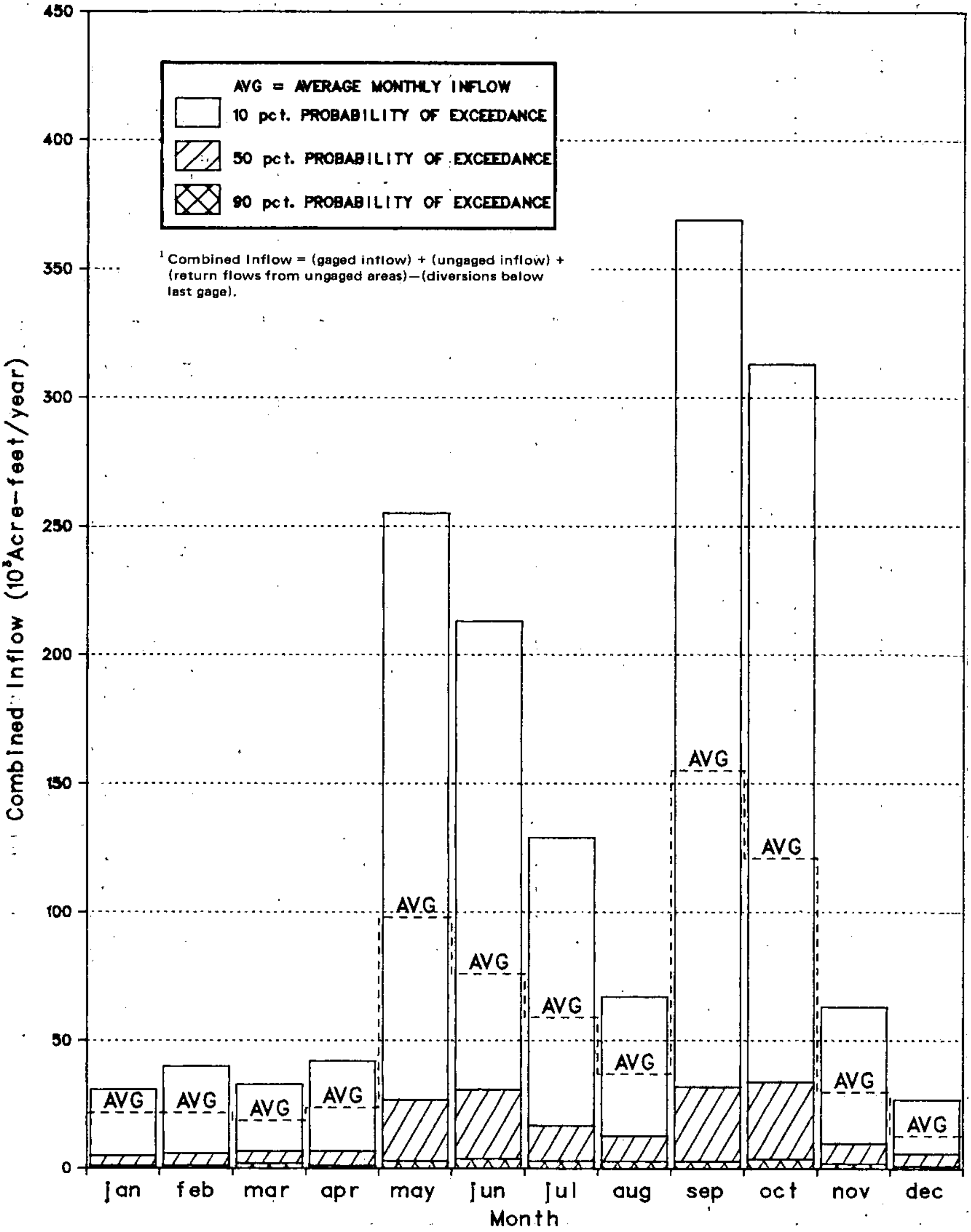
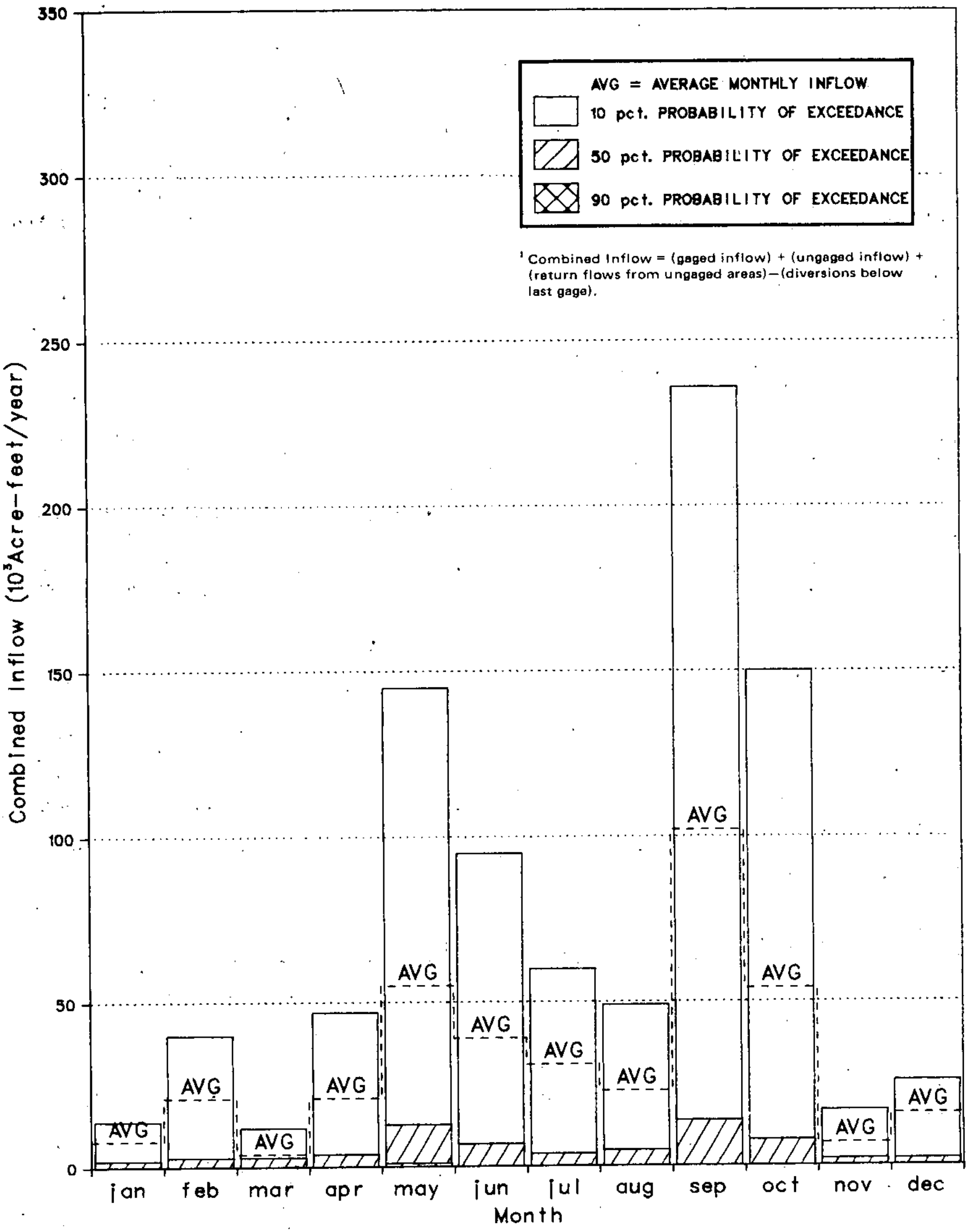


Figure 4-5. Monthly Distribution of Combined Inflow,[1] Nueces Estuary, 1941-1976



[1] Combined Inflow = (gaged inflow) + (ungaged inflow) + (return flows from ungaged areas) – (diversions below last gage).

Figure 4-6. Monthly Distribution of Combined Inflow,[1] Mission-Aransas Estuary, 1941-1976

Total Freshwater Inflow

Total freshwater inflow includes gaged estuary inflow 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 952,000 acre-feet (1,170 million m^3) for the Nueces estuary and 718,000 acre-feet (890 million m^3) for the Mission-Aransas estuary. Average monthly distributions of total freshwater inflow are shown in Figure 4-7 and Figure 4-8.

Bay Evaporation Losses

Gross surface evaporation rates for the estuary were calculated from Texas Department of Water Resources pan evaporation data (340). 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 in the estimation of evaporation rates. Over the period 1941 through 1976, mean evaporation over the 109,795 acres Nueces estuary surface averaged 539,000 acre-feet per year (670 million m^3/yr) and over the 114,310 acre Mission-Aransas estuary surface averaged 564,000 acre-feet per year (700 million m^3/yr). When compared to total freshwater inflow, surface evaporation for the Nueces estuary was about 57 percent of total inflow over the 1941 through 1976 period and 79 percent for the Mission-Aransas estuary.

Freshwater Inflow Balance

A freshwater inflow balance for the period 1941 through 1976 is shown in Table 4-2 and Table 4-4. 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 413,000 acre-feet per year (510 million m^3/yr) for the Nueces estuary and 154,000 acre-feet per year (190 million m^3/yr) for the Mission-Aransas estuary.

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 component near limit probabilities are shown in Table 4-7 and Table 4-8. The "50%" column for each component inflow represents a 50 percent probability of exceedance value for that component. These values can be compared to average values given in Table 4-1 and Table 4-3. 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 4-7 and 4-8 for combined inflow and total freshwater inflow, respectively.

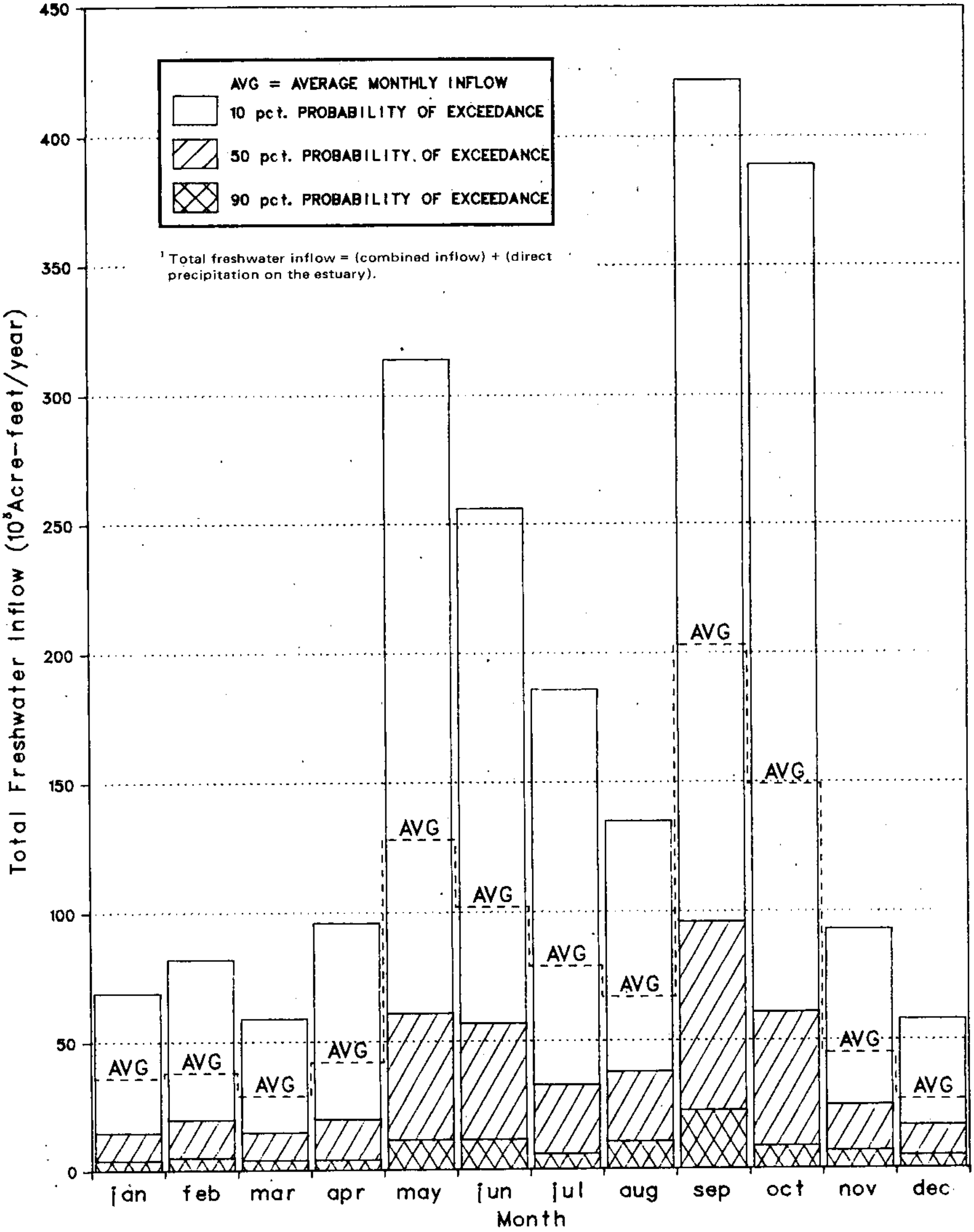


Figure 4-7. Monthly Distribution of Total Freshwater Inflow,[1] Nueces Estuary, 1941-1976

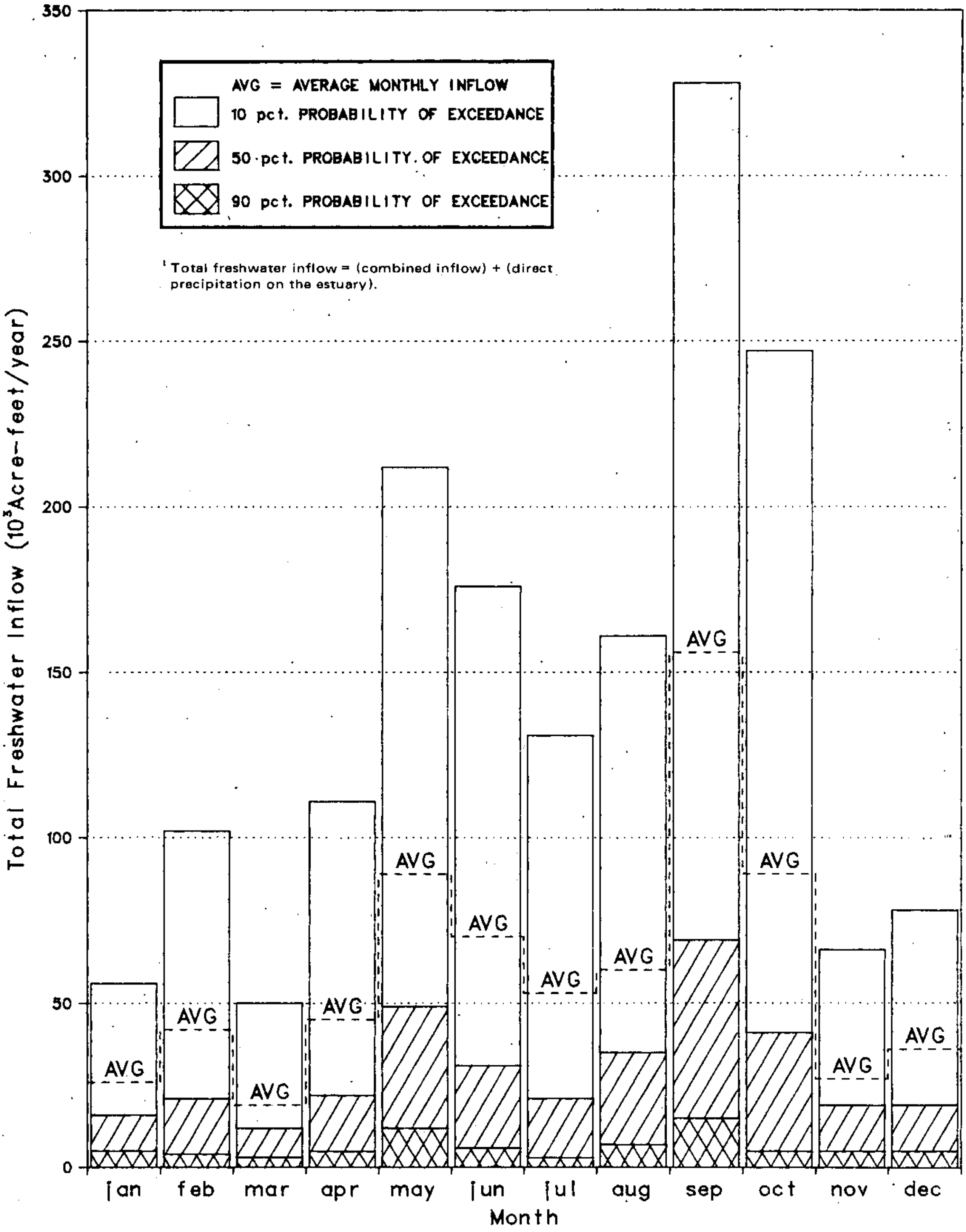


Figure 4-8. Monthly Distribution of Total Freshwater Inflow,[1] Mission-Aransas, 1941-1976

Table 4-7. Monthly Inflows to the Nueces Estuary for Corresponding Exceedance Frequencies a, b/

Month	Gaged Nueces Basin Inflow			Gaged Nueces Inflow			Total Gaged Inflow			Ungaged Inflow			Combined Inflow			Precipitation on Bay			Total Freshwater Inflow			Bay Evaporation Losses		
	10%	50%	90%	10%	50%	90%	10%	50%	90%	10%	50%	90%	10%	50%	90%	10%	50%	90%	10%	50%	90%	10%	50%	90%
January	30	6	2	27	1	0	27	1	0	5	0	0	31	5	1	35	8	2	69	15	4	32	23	17
February	34	7	1	35	1	0	35	1	0	12	0	0	40	6	1	44	11	1	82	20	5	32	24	18
March	35	8	2	36	2	0	36	2	0	2	0	0	33	7	2	26	6	1	59	15	4	40	32	25
April	36	8	2	31	1	0	31	1	0	11	0	0	42	7	1	54	10	2	96	20	4	45	37	30
May	230	28	3	329	12	0	329	12	0	22	2	0	255	27	3	74	21	5	314	61	12	57	46	38
June	186	30	5	250	17	0	250	17	0	20	2	0	213	31	4	69	15	3	256	57	12	71	56	44
July	108	20	4	128	8	0	128	8	0	23	0	0	129	17	3	56	11	0	186	33	6	89	70	55
August	49	12	3	45	4	0	45	4	0	21	1	0	67	13	3	82	18	4	135	38	11	90	72	58
September	286	28	3	369	14	0	369	14	0	52	4	0	369	32	3	103	35	12	422	96	23	70	58	47
October	267	33	4	330	21	0	330	21	0	32	2	0	313	34	4	73	18	2	389	61	9	62	50	38
November	61	12	3	65	6	0	65	6	0	4	0	0	63	10	2	37	9	2	93	25	7	48	36	28
December	24	7	2	23	2	0	23	2	0	6	0	0	27	6	1	38	8	1	58	17	5	37	27	20

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

Table 4-8. Monthly Inflows to the Mission-Aransas Estuary for Corresponding Exceedance Frequencies a, b/

Month	Gaged Mission Basin Inflow			Gaged Aransas c/ Basin Inflow			Total Gaged Inflow			Ungaged Inflow			Combined Inflow			Precipitation on Bay			Total Freshwater Inflow			Bay Evaporation Losses		
	10%	50%	90%	10%	50%	90%	10%	50%	90%	10%	50%	90%	10%	50%	90%	10%	50%	90%	10%	50%	90%	10%	50%	90%
January	4	1	0	0	0	0	5	1	0	10	0	0	14	2	0	41	14	4	56	16	5	33	26	20
February	11	1	0	3	0	0	12	1	0	30	1	0	40	3	0	60	15	3	102	21	4	33	25	20
March	5	1	0	0	0	0	5	1	0	8	0	0	12	3	0	36	9	2	50	12	3	43	33	26
April	14	1	0	4	0	0	16	1	0	41	0	0	47	4	0	60	16	4	111	22	5	48	38	30
May	32	4	0	10	0	0	41	4	0	115	8	0	145	13	1	78	29	10	212	49	12	60	48	38
June	19	2	0	4	0	0	22	2	0	82	4	0	95	7	0	83	21	5	176	31	6	73	58	47
July	13	0	0	4	0	0	16	0	0	53	0	0	60	4	0	67	15	3	131	21	3	88	71	55
August	8	1	0	2	0	0	10	1	0	41	2	0	49	5	0	91	29	8	161	35	7	93	74	59
September	45	2	0	15	0	0	57	3	0	179	9	0	236	14	0	119	44	16	328	69	15	74	60	48
October	31	0	0	5	0	0	34	1	0	130	5	0	150	8	0	85	28	7	247	41	5	65	53	41
November	5	1	0	0	0	0	5	1	0	12	0	0	17	2	0	49	16	5	66	19	5	52	40	30
December	7	1	0	0	0	0	7	1	0	22	0	0	26	2	0	50	15	5	78	19	5	40	31	23

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

c/ Aransas Basin Gaged (247 sq. mi.) 1965-1976
Aransas Basin Simulated (247 sq. mi.) 1941-1964

Quality of Gaged Inflows, Nueces Estuary

Two USGS gaging stations monitor the quality of inflows to the Nueces estuary: Station No. 08211000 (Nueces River near Mathis) and Station No. 08211520 (Oso Creek at Corpus Christi). The range of water quality parameters that were experienced in the 1977 water year are tabulated in Figure 4-9. During the period, seven to nine samples were available for most parameters, although nutrient data were lacking at the Nueces River station.

Student's t-tests were performed on the data to determine if any statistical difference was evident between the sample means for the two gaging stations. The difference between the mean values for each parameter are not statistically significant; however, highly significant statistical differences between the individual parameter means ($\alpha = 0.01$) occur for calcium, magnesium, sodium, sulfate, dissolved solids, and chloride. As a result, concentrations of calcium, magnesium, sodium, sulfate, dissolved solids, and chloride flowing to the bay from Oso Creek are shown to be higher than those found in the Nueces River inflows. Nutrient concentration in Oso Creek, particularly nitrate nitrogen and total phosphorus, are high compared to coastal streams in the Mission-Aransas estuary. These high concentrations may be the result of agricultural runoff and/or effluent from the Robstown wastewater treatment plant, a major source of flow in Oso Creek.

In general, the water quality of flows draining to the Nueces estuary has been good, except for some apparent problems in Oso Creek. No parameters were found in violation of Texas stream standards.1/

Quality of Gaged Inflows, Mission-Aransas Estuary

Three USGS gaging stations monitor the quality of inflows to the Mission-Aransas estuary: Station No. 08189200 (Copano Creek near Refugio), Station No. 08189500 (Mission River at Refugio), and Station No. 08189800 (Chiltipin Creek at Sinton). The range of water quality parameters that were experienced in the 1977 water year are tabulated in Figure 4-10. During the period, five to nine samples were available for most parameters.

Student's t-tests were performed on the data to determine if any statistical difference (two-tailed test) was evident among the sample means for the three gaging stations. The differences between the mean values were not statistically significant; however, sample means from the Mission River station at Refugio were significantly higher than the other two stations for dissolved silica and bicarbonate, and lower for total phosphorus. No statistically significant finding was made, but the Chiltipin Creek station at Sinton occasionally experienced very high salt concentrations as evidenced from chloride samples that ranged up to 11,000 mg/l, sodium samples up to 5,600 mg/l and dissolved solids up to 18,200 mg/l. Although the cause is undocumented, oil field operations in the drainage basin may be at fault.

In general, the water quality of flows draining to the Mission-Aransas estuary has been good except for the problems noted in Chiltipin Creek. No parameters were found in violation of Texas stream standards.2/

1/ No Texas stream standards exist for Oso Creek at present.

2/ No Texas stream standards exist for Chiltipin Creek at present.

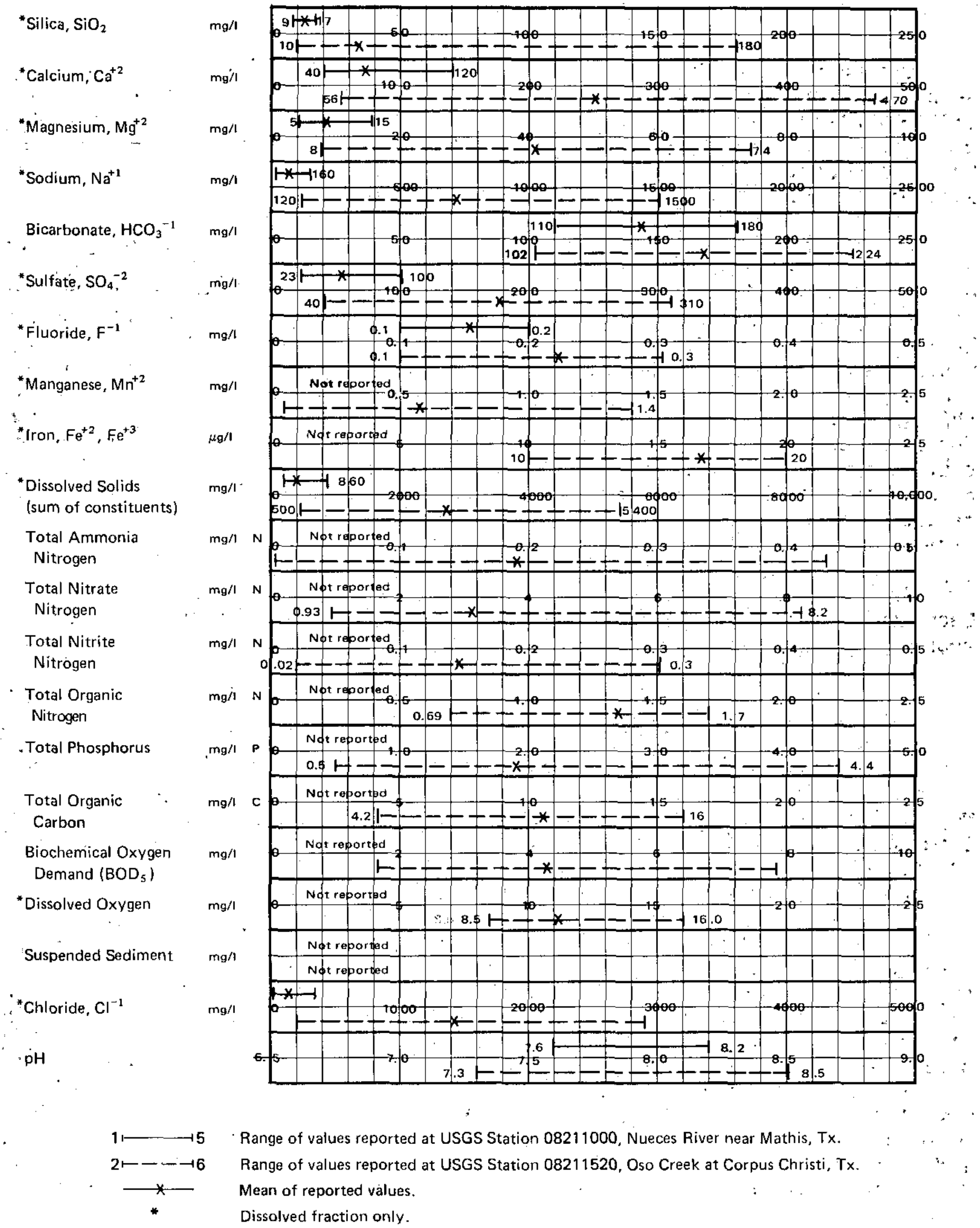


Figure 4-9. Range of Values for Water Quality Parameters, Gaged Inflow to Nueces Estuary, October 1976-September 1977 (398)

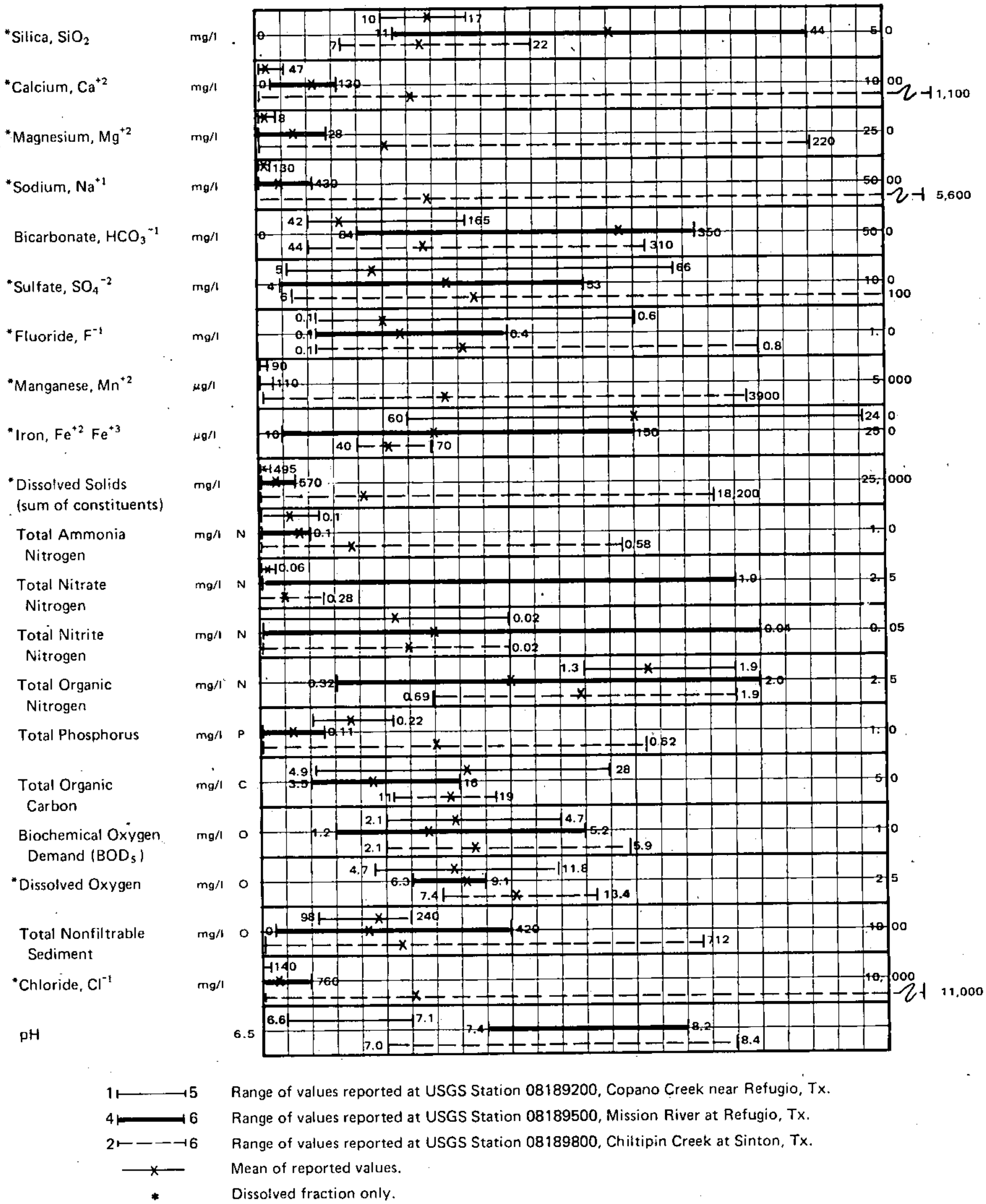


Figure 4-10. Range of Values for Water Quality Parameters, Gaged Inflow to Mission-Aransas Estuary, October 1976-September 1977 (398)

Quality of Estuarine Waters

Nutrient Concentrations in the Nueces and Mission-Aransas Estuaries

Historical concentrations of carbon, nitrogen, and phosphorus in Texas estuarine systems are largely unknown. Until 1968, water quality parameters in the open bays has 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.

Available data can be used to determine general 1968 through 1977 concentrations of carbon, nitrogen, and phosphorus (CNP) in the Nueces and Mission-Aransas estuaries. These estuarine systems were divided into five major subregions for analysis: (1) Nueces Bay, (2) Corpus Christi Bay, (3) Copano Bay, (4) Aransas Bay, and (5) Redfish Bay (Figures 4-11 and 4-12). Oso Bay and St. Charles Bay were omitted in the analysis due to insufficient data. Likewise, 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 from open waters.

Freshwater discharges from the Nueces River and contributions from the deltaic marshes of the Nueces delta were the major source of nutrients for the Nueces and Mission-Aransas estuaries. The Nueces River accounts for 73 percent of the mean annual total discharges into the Nueces and Mission-Aransas estuaries. The Aransas River, Mission River, Copano Creek, Chiltipin Creek and Oso Creek account for 4.4 percent, 10 percent, 4.4 percent, 4.7 percent and 3.1 percent of the mean annual total discharge into the estuaries, respectively. The CNP concentrations in Nueces Bay would therefore be expected to be greater than the remaining sections of the estuary and to exhibit a decreasing gradient from the Nueces delta outward into Nueces and Corpus Christi Bays. The CNP data for each of the five subregions were tabulated, averaged, and subjected to standard statistical analysis for comparison of the means (student's t-test) to determine which subregions, if any, consistently exhibited CNP concentrations significantly different from others. In addition, the total nitrogen and total phosphorus data were summed and averaged, respectively, for each of the following seasons: 1) Winter (December, January and February); 2) Spring (March, April and May); 3) Summer (June, July and August) and 4) Fall (September, October and November) to arrive at seasonal averages for the year, 1968 through 1977 (Figures 4-13 through 4-20).

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

Total Kjeldahl nitrogen concentrations ranged from near zero to 2.2 mg/l. Student's t-test analysis revealed that concentrations in Nueces Bay were significantly higher (95 percent confidence level) than those in the remaining subregions of the estuaries.

Base - North Arrow - Scale - Base Note
Border - Location Map

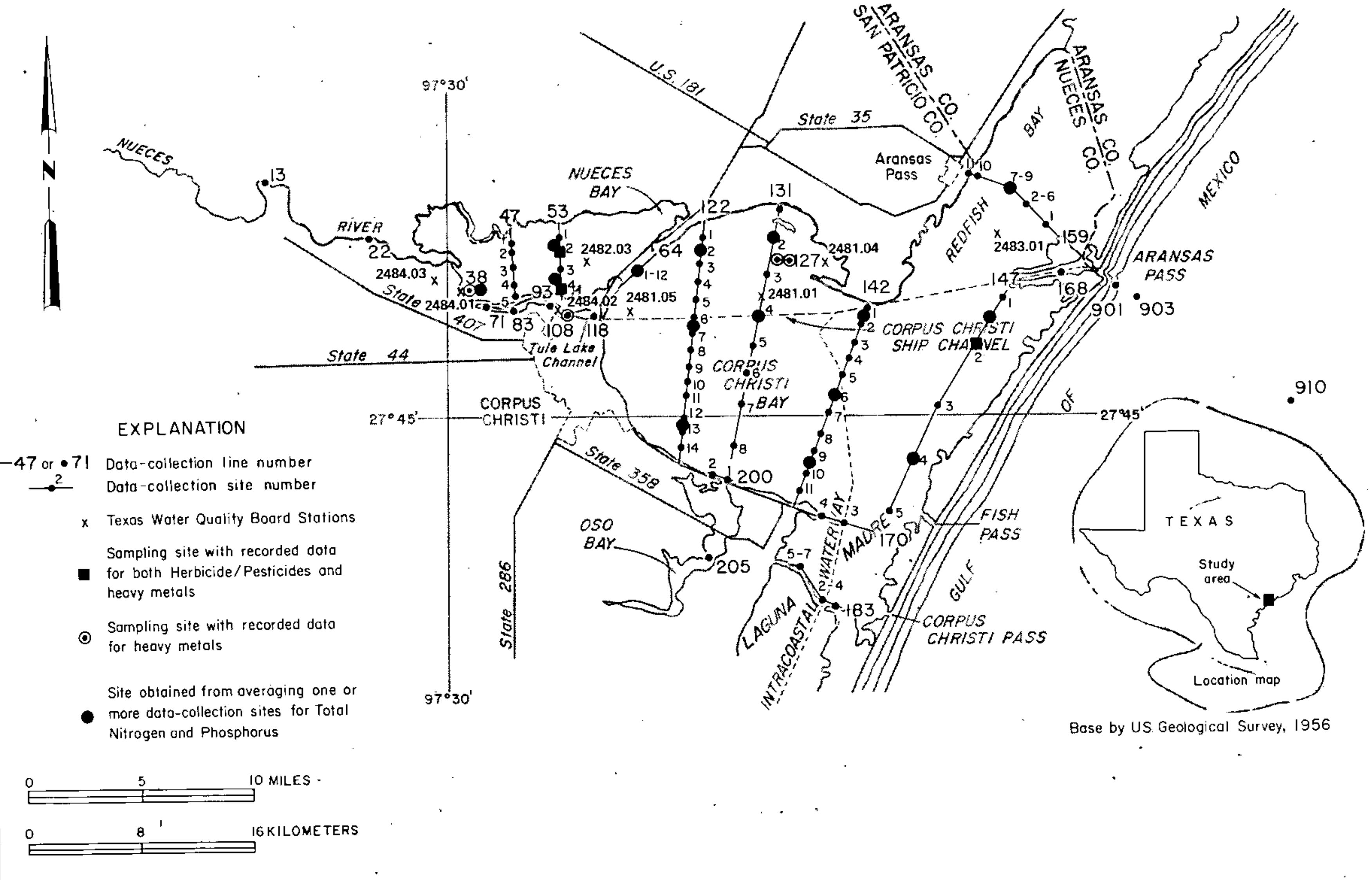


Figure 4-11. Data Collection Sites in the Nueces Estuary

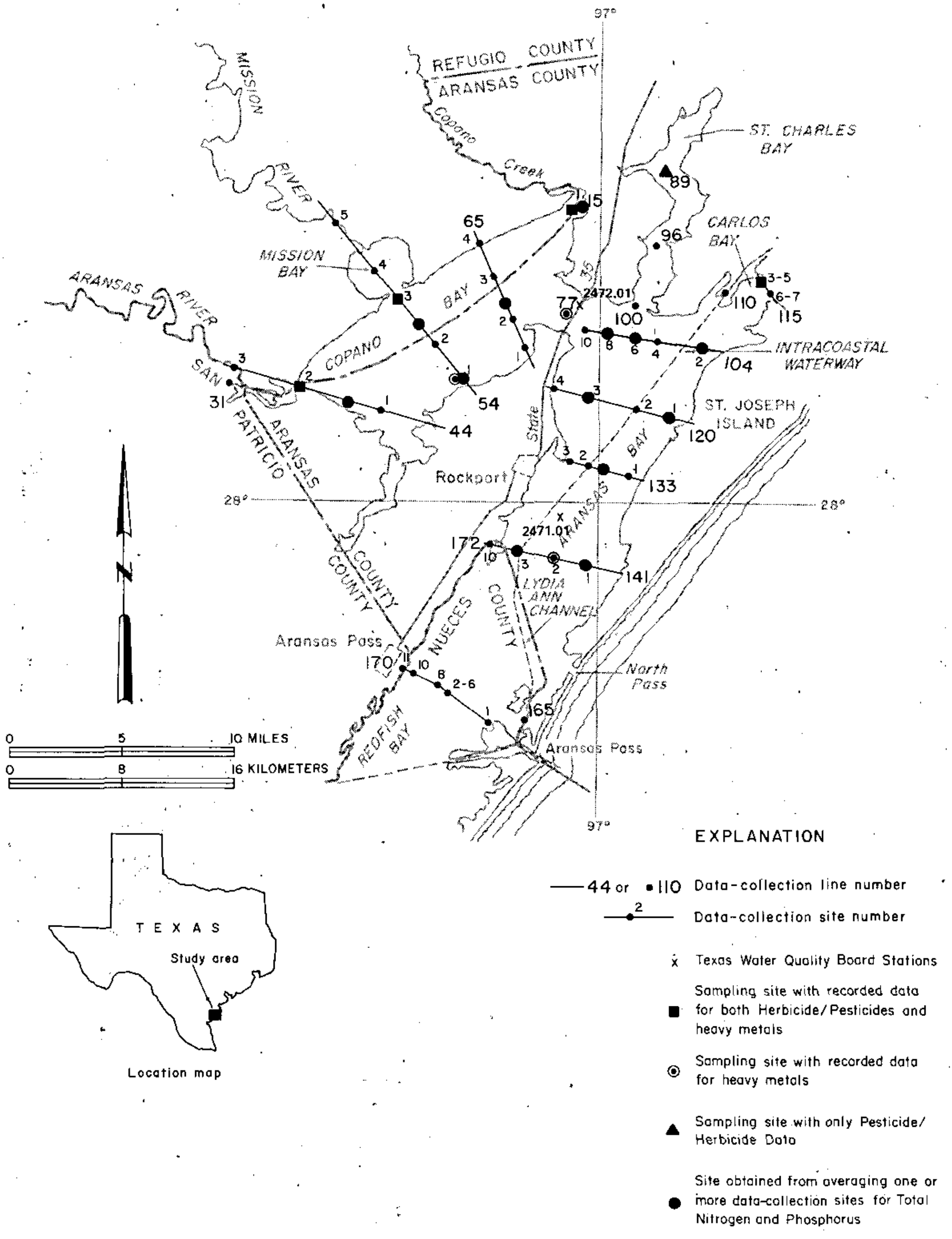


Figure 4-12. Data Collection Sites in the Mission-Aransas Estuary

Base by U.S. Geological Survey, 1956

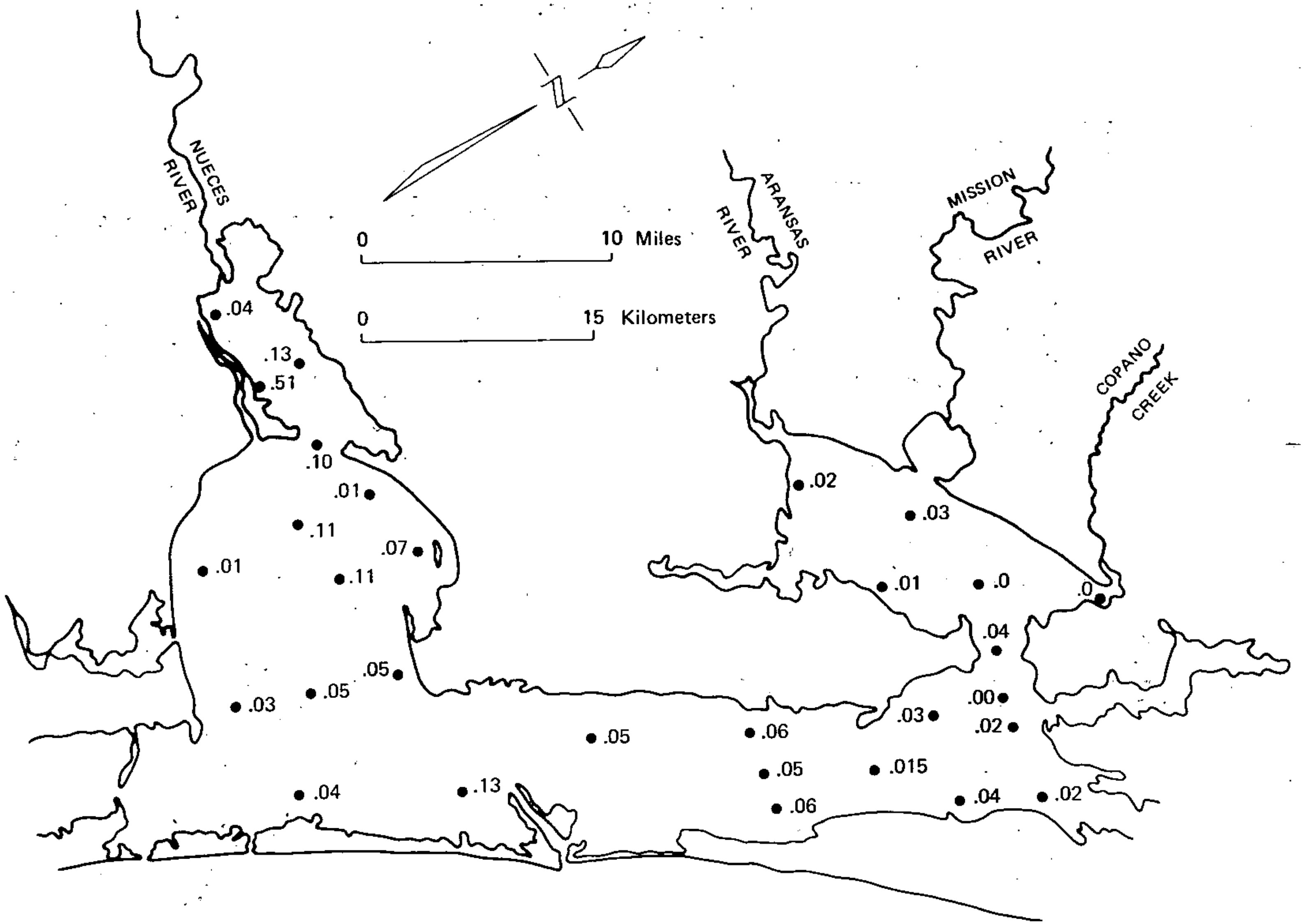
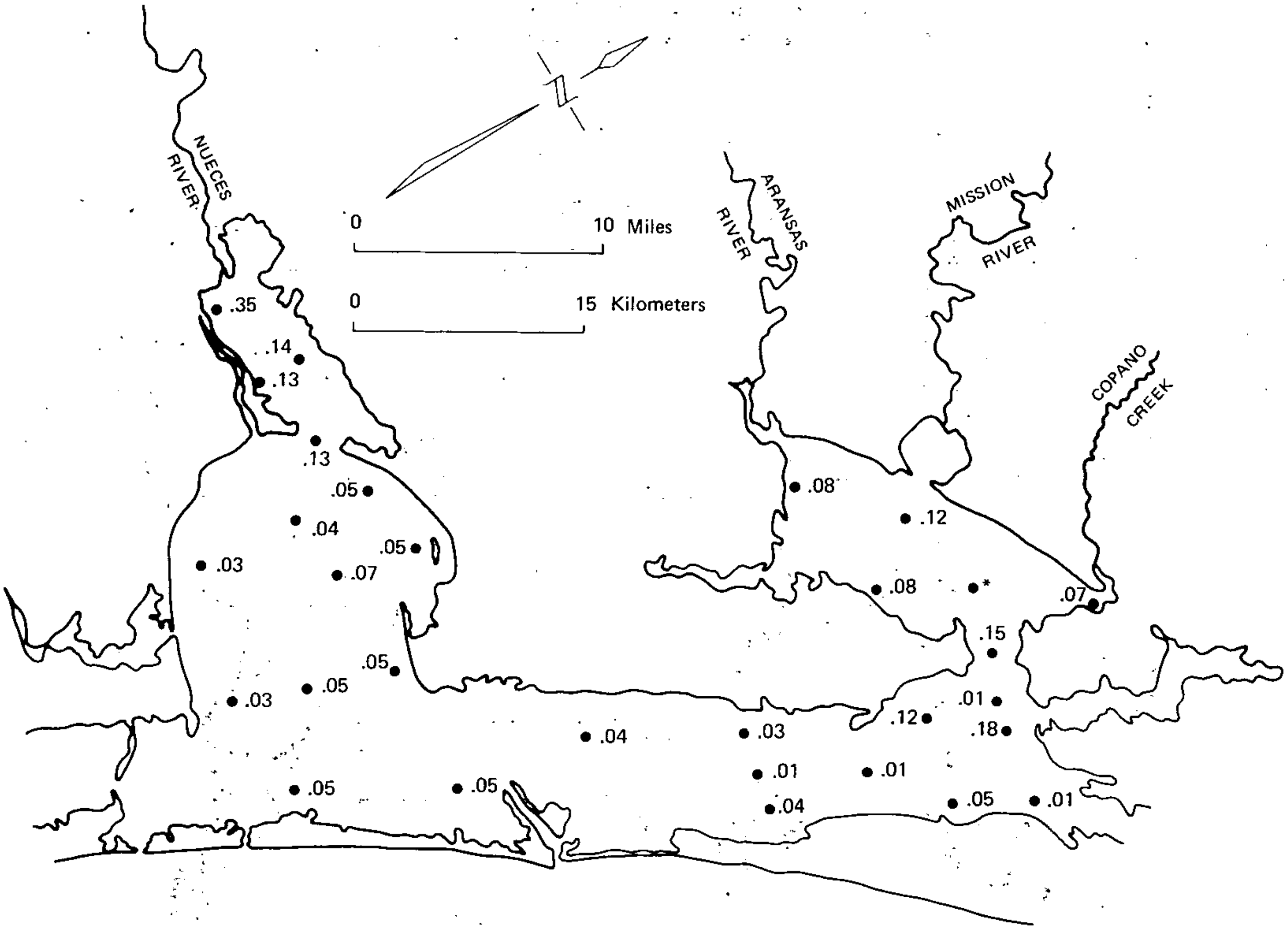


Figure 4-13. Average Seasonal Concentrations (mg/l) of Total Nitrogen (December, January, February)



*Data unavailable

Figure 4-14. Average Seasonal Concentrations (mg/l) of Total Nitrogen (March, April, May)

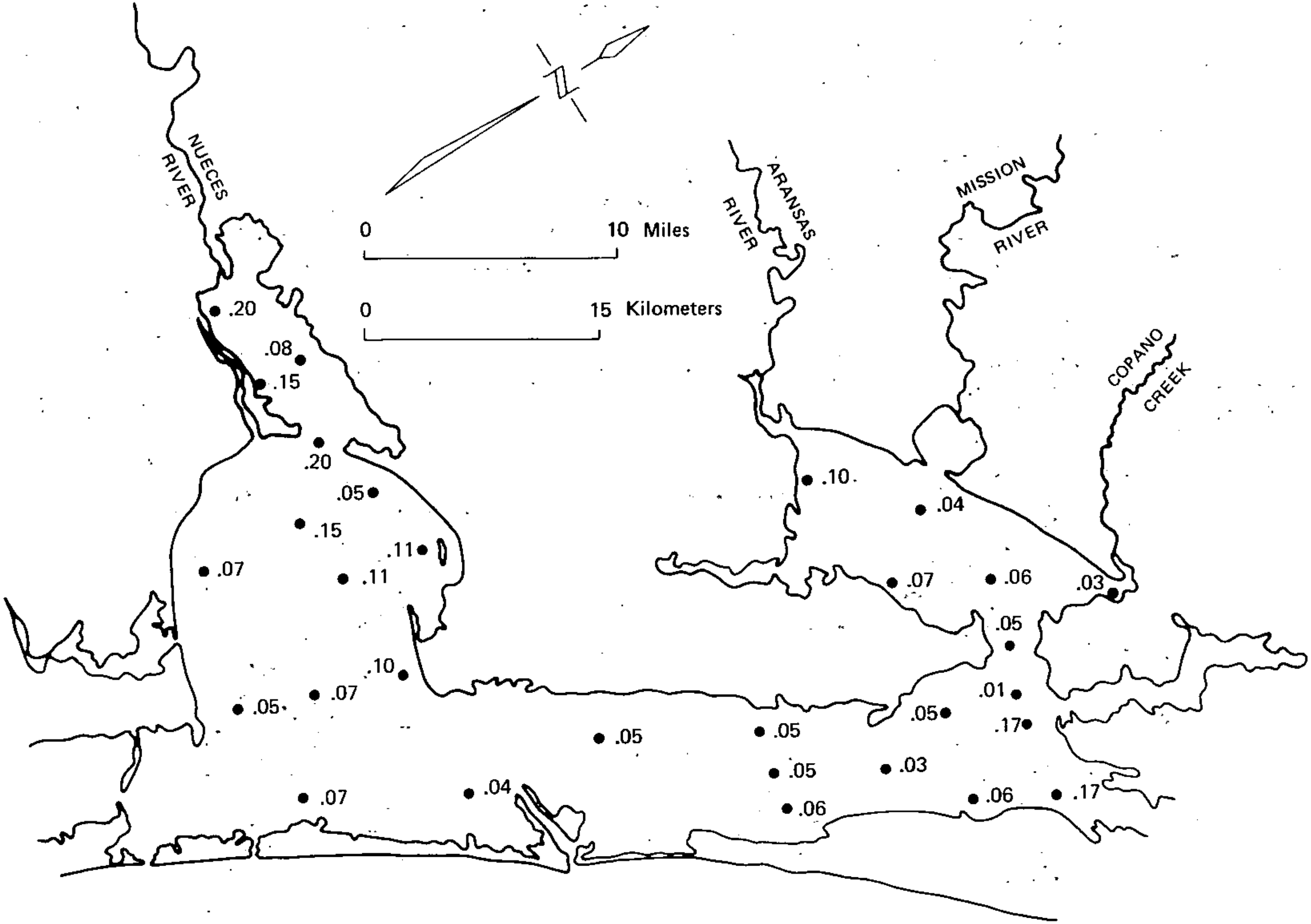
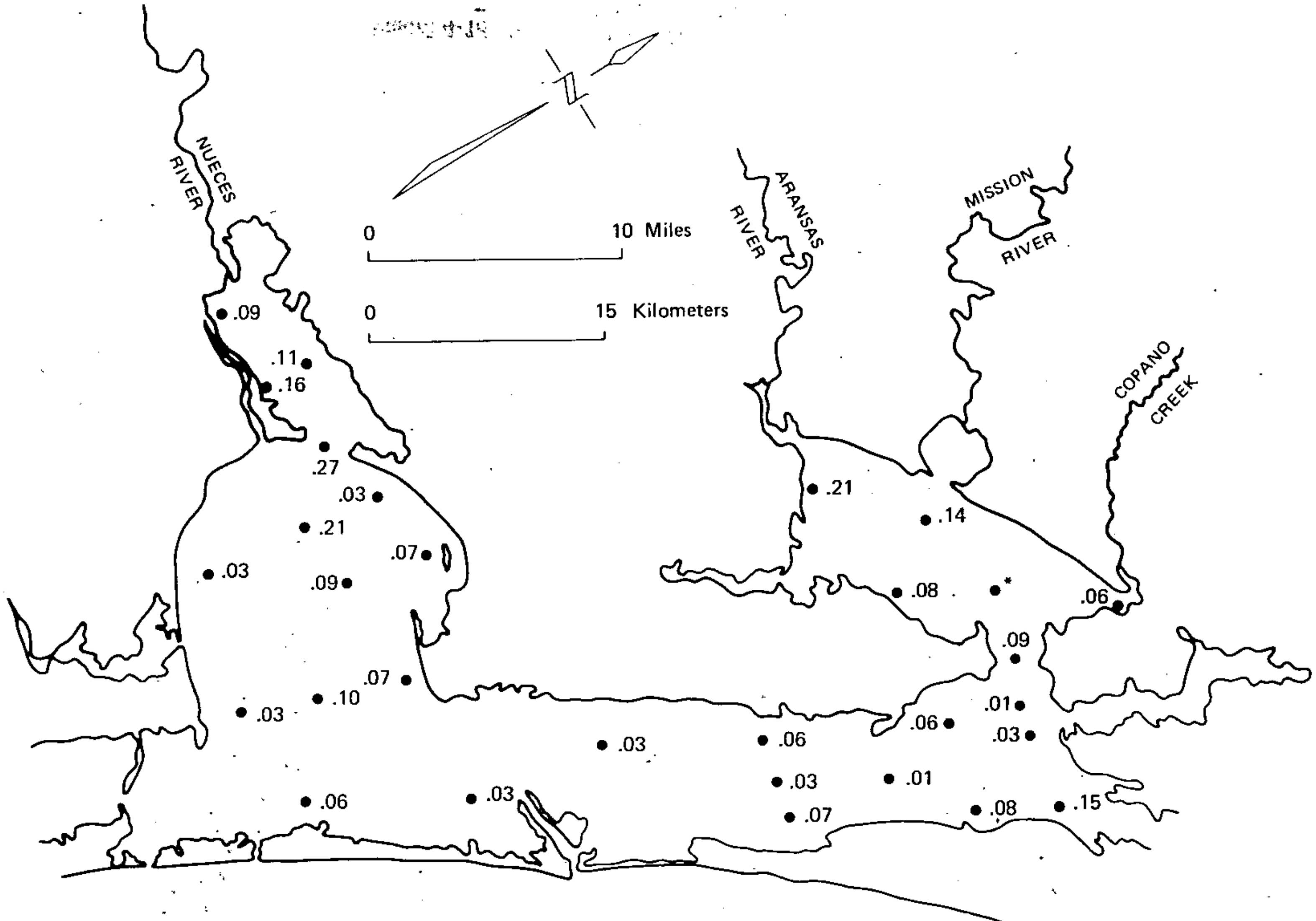


Figure 4-15. Average Seasonal Concentrations (mg/l) of Total Nitrogen (June, July, August)



*Data unavailable

Figure 4-16. Average Seasonal Concentrations (mg/l) of Total Nitrogen (September, October, November)

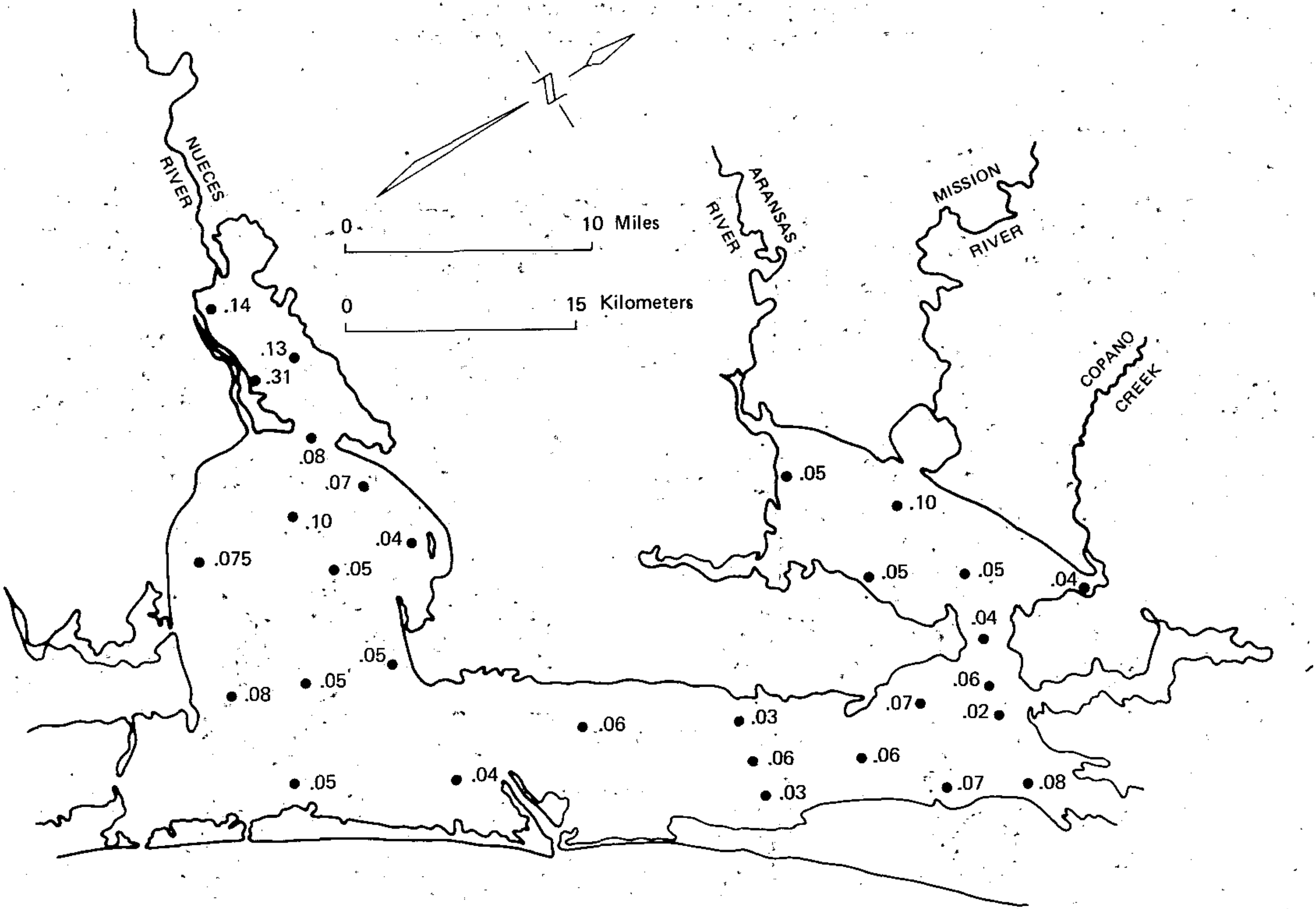


Figure 4-17. Average Seasonal Concentrations (mg/l) of Total Phosphorus (December, January, February)

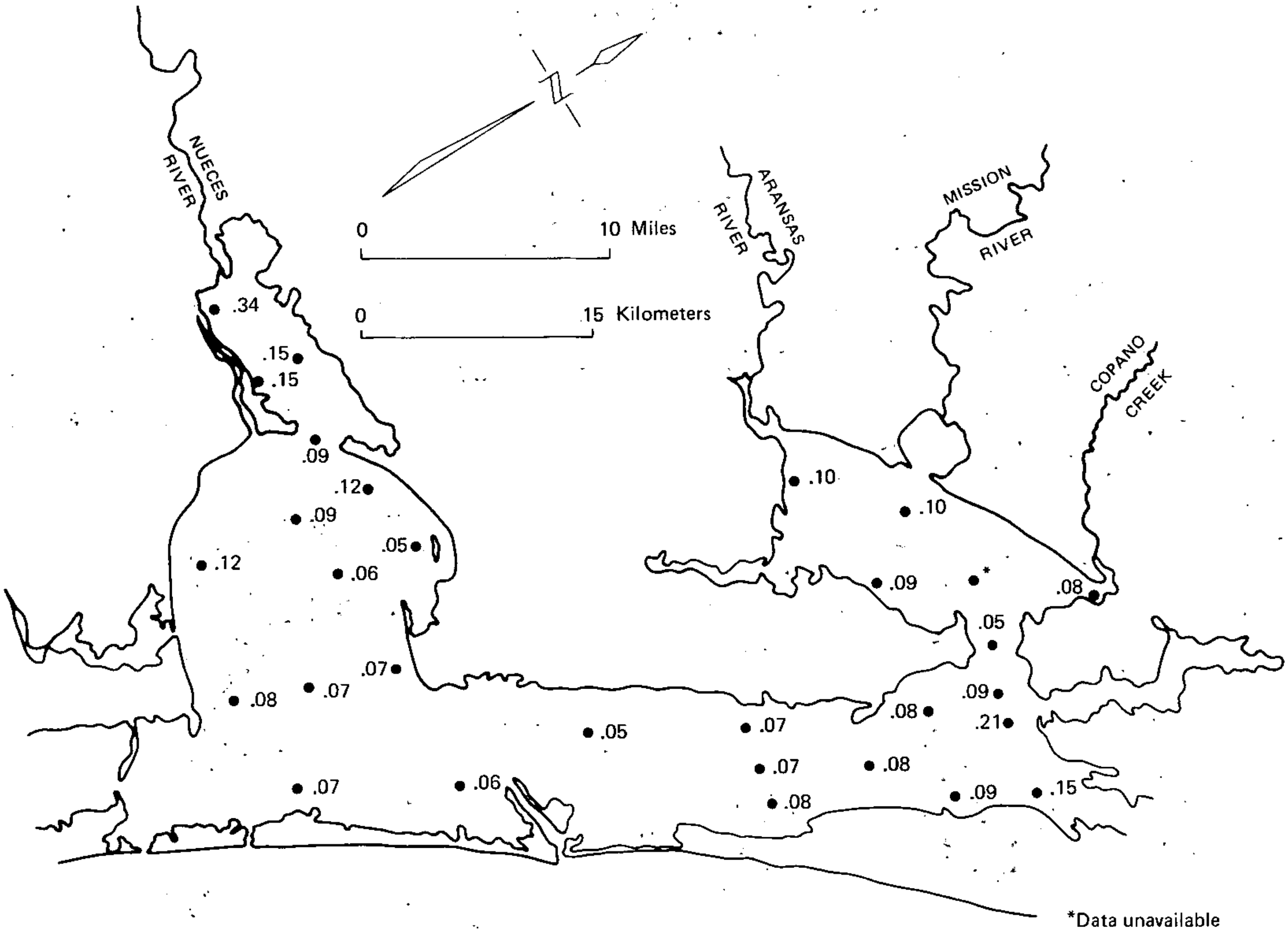


Figure 4-18. Average Seasonal Concentrations (mg/l) of Total Phosphorus (March, April, May)

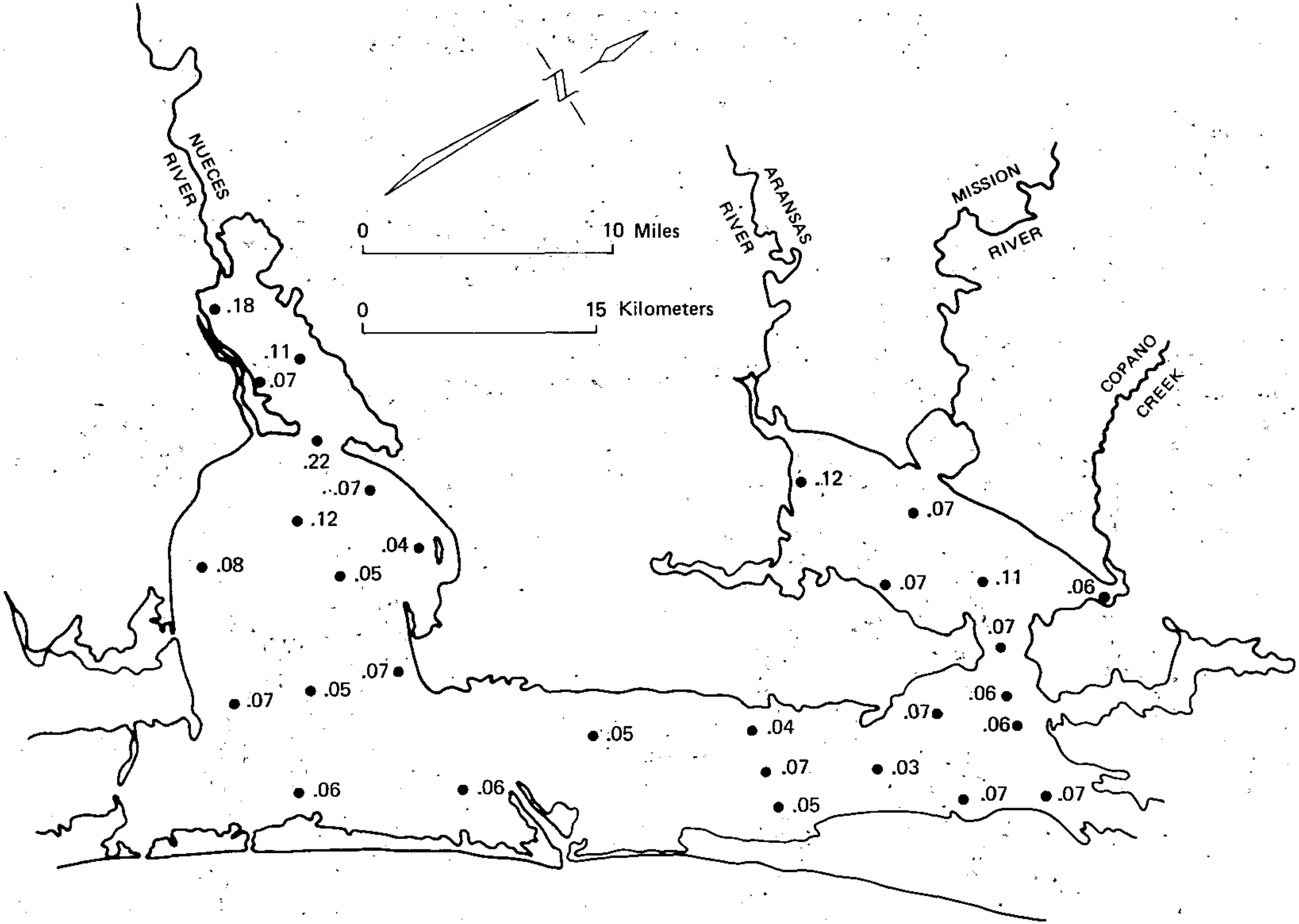
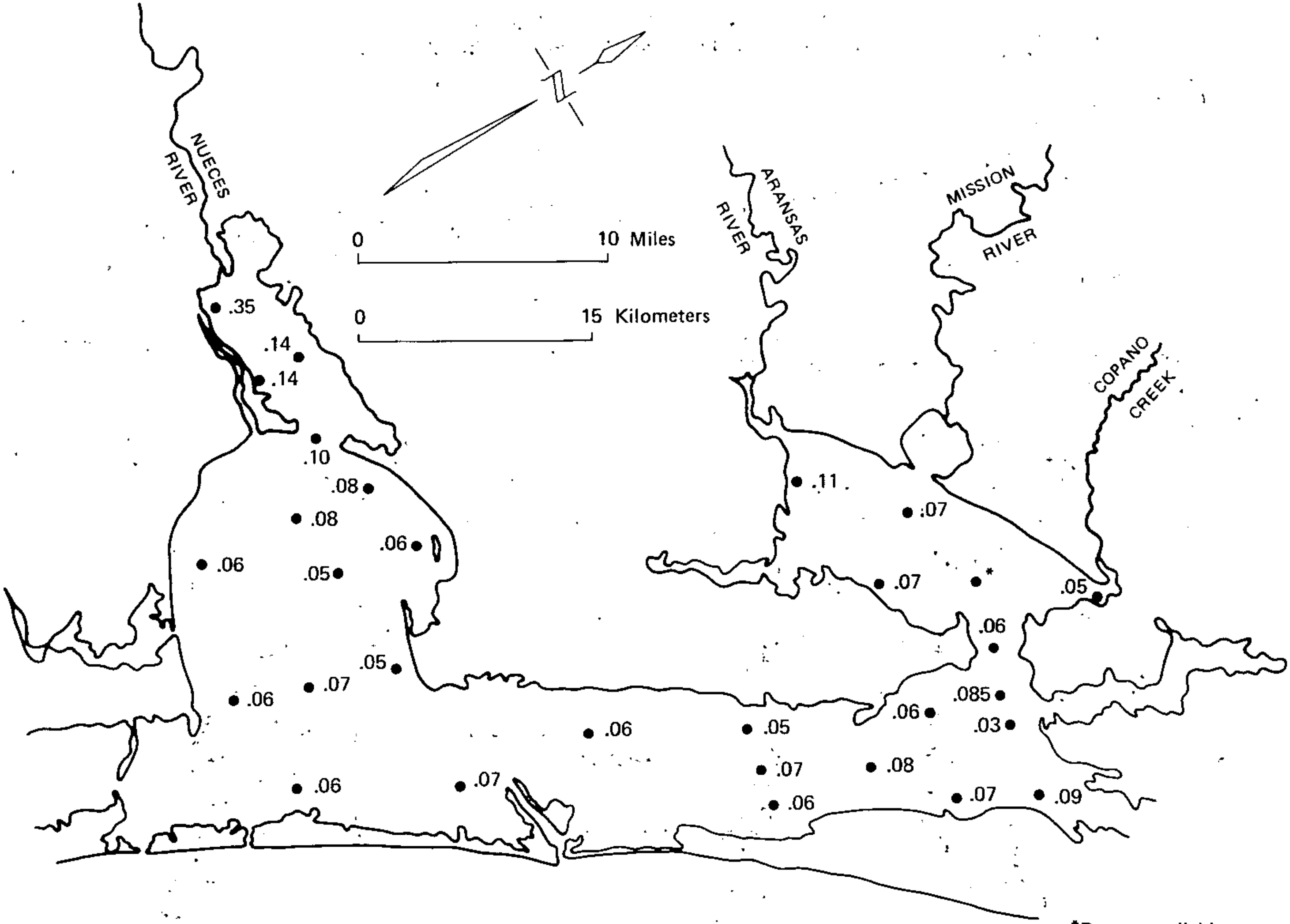


Figure 4-19. Average Seasonal Concentrations (mg/l) of Total Phosphorus (June, July, August)



*Data unavailable

Figure 4-20. Average Seasonal Concentrations (mg/l) of Total Phosphorus (September, October, November)

Organic carbon concentrations ranged from near zero to 32.0 mg/l. Student's t-test analysis revealed that concentrations in Copano Bay were significantly higher (95 percent confidence level) than those in Aransas Bay.

Total nitrogen concentrations ranged from zero to 1.0 mg/l; whereas, total phosphorus concentrations ranged from 0.0 to 0.65 mg/l. The average seasonal concentrations of nitrogen and phosphorus in Nueces Bay have been greater than those concentrations experienced in Corpus Christi Bay (generally less than 0.1 mg/l), resulting in a seasonal concentration gradient between the two bays (Figures 4-13 through 4-20). The average seasonal concentrations of nitrogen in Copano Bay were greater than those concentrations in Aransas Bay only in the fall and spring. In both Copano and Aransas Bays, the average seasonal phosphorus concentrations were relatively uniform throughout the year. Student's t-test analysis indicated that concentrations of both nitrogen and phosphorus in Nueces Bay were significantly higher (95 percent confidence level) than those in the remaining subregions of the Nueces and Mission-Aransas estuaries.

Heavy Metals

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

Samples of the bottom sediments in the Nueces and Mission-Aransas estuaries were collected at 23 data collection sites shown in Figures 4-11 and 4-12 for the period of record from 1969 to 1978. Sampling was conducted by the USGS and the Texas Department of Water Resources in cooperation with other interested agencies. The heavy metals detected included arsenic (As), cadmium (Cd), cobalt (Co), chromium (Cr), copper (Cu), lead (Pb), manganese (Mn), nickel (Ni), zinc (Zn), silver (Ag), mercury (Hg), and iron (Fe).

Statistical analyses were not possible due to the limited number of samples for the test period from 1969 to 1978. The range of values for heavy metals detected in the Copano, Aransas, Redfish, Corpus Christi, and Nueces Bays are listed in Table 4-9.

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 these bodies when feeding in polluted areas. Reduction of productivity in the area may be the result of toxic effects of heavy metals upon organisms, and may have an ultimate effect on man if he is exposed to heavy metals through edible fish and shellfish. Areas of the bottom sediments in the Nueces and Mission-Aransas estuaries may exceed the

Table 4-9. Ranges of Concentrations for Metals in Sediment Compared to USEPA (1974) Dredge Criteria a/

Station Location b/ & USGS Station Number / Parameter	Corpus Christi Bay				Nueces Bay					Redfish Bay	Dredge Criteria
	147.2	127.2 127.6 & 2481.04	2481.01	2481.05	38.2 & 2484.01	108.2 & 2484.02	53.4	53.2 & 2482.03	2484.03	2483.01	
	units are mg/kg										
Arsenic	3.0	0.6-5.2*	0.07-5.8*	3.5-9.0*	1.0-60.0*	0.06.8.5*	5.1*	1.0-52.0*	1.0-7.5*	0.74-7.7*	5
Cadmium	<10.0*	0.5-25.0*	0.5-9.5*	0.6-0.94	0.06-108*	25-66*	0.4	0.4-22.0*	0.06-36.0*	0.70-14.0*	2
Chromium	—	7.5-25.0	6.0-63.0	26.0-53.0	9.7-91.0	9.3-94.0	—	1.0-19.0	7.7-36.0	1.6-22.0	100
Cobalt	<10.0	<10.0	—	—	<10.0	<10.0	1.8	2.2-<10.0	—	—	—
Copper	<10.0	<10.0	—	—	<10.0	<10.0	7.0	2.8-<10.0	—	—	50
Iron	—	—	—	—	—	—	20,000	3600-16000	—	—	—
Lead	<10.0	1.3-16.0	1.3-23.0	19.0-32.0	0.6-103.3*	<10.0-340*	3.5	<0.6-29.0	<0.6-86.8*	6.0-16.0	50
Manganese	220	100-470	250-770	550-610	180.6-490	65.3-360	230	38-290	100.4-250	98-620	—
Mercury	0.26	0.05-0.23	0.02-0.190	0.20-0.21	0.42-4.0*	0.62-8.5*	—	0.05-1.5*	0.1-1.5*	0.03-0.110	1
Nickel	—	6.0-26	3.0-24.0	19-21	0.2-80.0*	1.5-13.0	—	1.0-13.0	0.2-12.0	2.0-18.0	50
Silver	—	0.2-3.3	0.2-5.0	0.9-1.8	0.2-7.0	0.2-4.5	—	<0.3-3.0	0.2-1.2	0.2-1.0	—
Zinc	100*	25-74	4.3-170*	170-190*	80.0-1600*	290-4900*	150*	33-240*	34-2600*	28.0-75.0*	75

a/ Includes data from ref. (243)
b/ See Figure 4-11 for station locations
* Denotes at least one sample in violation of EPA's dredge spoil criteria

(continued)

Table 4-9. Ranges of Concentrations for Metals in Sediment Compared to USEPA (1974) Dredge Criteria a/ (cont'd)

Station Location b/ & USGS Station Number: / Parameter	Copano Bay				Aransas Bay		Dredge Criteria
	44.2	54.1	77.2 & 2472.01	15	141.2 & 2471.01	115.5	
	units are mg/kg						
Arsenic	0-6.0*	7.0*	1.6-6.0*	1.3-3.0	1.0-5.0*	5.0*	5
Cadmium	0-<10.0*	<10.0*	1.0-<10.0*	0-<10.0*	0.1-48.0*	<10.0*	2
Chromium	—	—	2.0-19.0	—	2.7-19.0	—	100
Cobalt	2.5-<10.0	<10.0	<10.0	2.4-<10.0	<10.0	<10.0	—
Copper	4.8-<10.0	<10.0	<10.0	3.8-<10.0	<10.0	<10.0	50
Iron	7400-15000	—	—	8000-8300	—	—	—
Lead	7.5-18.0	<10.0	<10.0-35.0	3.8-<10.0	1.3-19.0	<10.0	50
Manganese	160-270	310	210-380	90-280	120-430	270	—
Mercury	0.10-0.20	0.20	0.02-0.10	0-0.21	0.07-0.28	0.18	1
Nickel	—	—	5.5-15.0	—	3.5-2.7	—	50
Silver	—	—	0.5-<3.0	—	<0.3-1.3	—	—
Zinc	28-42	20	13-65.0	18-23	12.2-91.0*	20.0	75

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a/ Includes data from ref. (243)
b/ See Figure 4-12 for station locations
* Denotes at least one sample in violation of EPA's dredge spoil criteria

U.S. EPA criteria for metals in the sediments (prior to dredging) for the following constitutents (Table 4-9): arsenic, cadmium, lead, nickel, zinc, and mercury.

Pesticides and Herbicides

Samples of the bottom sediments in the Nueces and Mission-Aransas estuaries were collected at seven data collection sites shown in Figures 4-11 and 4-12 for the period from 1971 to 1975 through the USGS-TDWR cooperative program. The data were analyzed for pesticides and herbicides concentrations. (Table 4-10). The parameters detected included aldrin; lindane; DDD; DDE; DDT; dieldrin; endrin; heptachlor; heptachlor expoxide; 2,4-D; 2,4,5-T; and silvex. Only the pesticides DDD and DDT; and the herbicides 2,4-D; 2,4,5-T; and silvex were detected at levels above or equal to the detection limit of 0.2 g/kg. Statistical analyses were not possible due to the limited number of samples available.

Summary

Sources of freshwater inflow to the Nueces and Mission-Aransas estuaries 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 sources of freshwater inflow adds to the understanding of inflow timing and volumes and their influence on bay productivity. To acquire accurate inflow measurements, gaged stream flows require adjustment to reflect any withdrawals or return flows downstream from gage locations. Ungaged runoff is estimated by computerized mathematical models using field data for calibration and verification. Rainfall is estimated as a distance-weighted average of the daily precipitation recorded at weather stations surrounding the estuary.

Freshwater inflows in terms of annual and monthly average values over the 1941 to 1976 period varied widely from the mean as a result of recurrent drought and flood conditions. The total average freshwater inflow to the Nueces and Mission-Aransas estuaries (1941-1976) consisted of gaged contributions, runoff from ungaged areas, return flows from ungaged areas, and direct precipitation on the estuary.

In general, the water quality of gaged inflows to the estuaries was good. No samples were found in violation of Texas stream standards.[1/] Detailed studies of past water quality problems in and around the estuary have pinpointed heavy metals as a significant concern. Locally, bottom sediment samples have exceeded EPA criteria for metals in sediments (prior to dredging) for arsenic, cadmium, lead, nickel, mercury and zinc. Bottom sediments collected and analyzed showed the pesticides DDD and DDT; and the herbicides 2,4-D; 2,4,5-T; and silvex occurring in concentrations equal to or greater than the detection limit during the period of 1971 to 1975.

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

[1/] No Texas stream standards exist for Oso Creek or Chiltipin Creek at present.

Table 4-10. Range of Pesticide/Herbicide Concentrations in Sediment, Nueces and Mission-Aransas Estuaries, 1971-1975 (398)

Sampling a/ Station / Parameter	Copano Bay		Aransas Bay		Nueces Bay	
	44.2	34.3	115.5	89.2	53.2	53.4
	Units are µg/kg					
DDD	0.2-7.6	3.4	—	—	—	—
DDE	2.0-19.0	12.0	—	—	0.0-9.4	2.0
2,4-D	—	—	<2.6	<2.7	—	—
2,4,5-T	—	—	<0.7	<0.8	—	—
Silvex	—	—	<0.7	<0.8	—	—

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a/ See Figures 4-11 and 4-12 for station locations

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 and mass transport models used to evaluate the circulation and salinity patterns of the Nueces and Mission-Aransas estuaries.

Description of the Estuarine Mathematical Models

Description of Modeling Process

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

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

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

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

Mathematical Model Development

The mathematical tidal hydrodynamic and conservative transport models for the Nueces and Mission-Aransas estuaries have been developed by Masch (150). These models are designed to simulate the tidal and circulation patterns and salinity distributions in a shallow, irregular, non-stratified estuary. The two models are sequential (Figure 5-1) in that the tidal hydrodynamic model computes temporal histories of tidal amplitudes and flows. These are then used as input to the conservative 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 motion and the unsteady continuity equation. In summary, the equations of

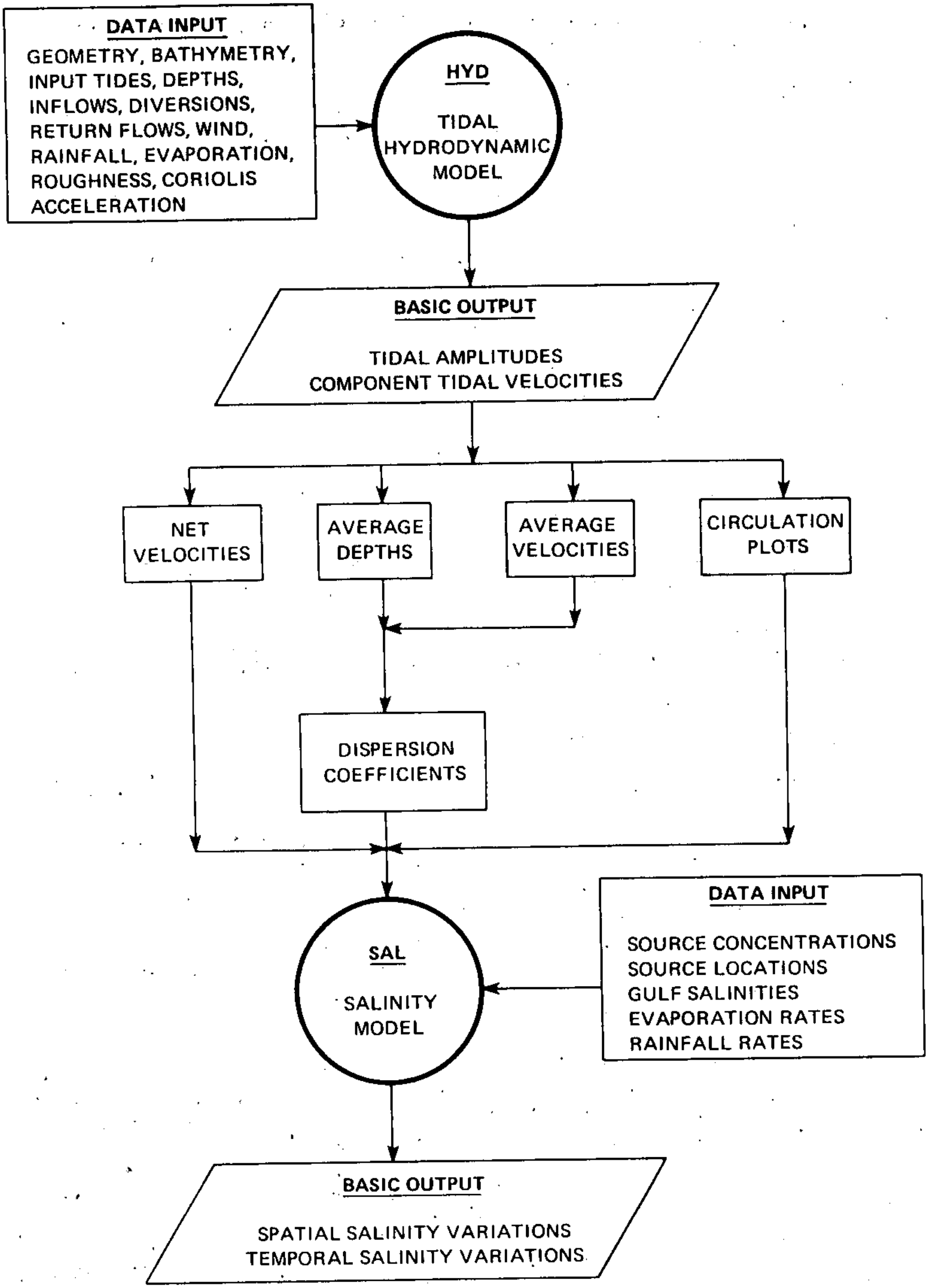

Figure 5-1. Relationship Between Tidal Hydrodynamic and Salinity Models (150)

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 = 27.8° for the Nueces and Mission-Aransas estuaries
r = rainfall intensity
e = evaporation rate

The numerical solution utilized in the hydrodynamic model of the Nueces and Mission-Aransas estuaries 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 the 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 (150).

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

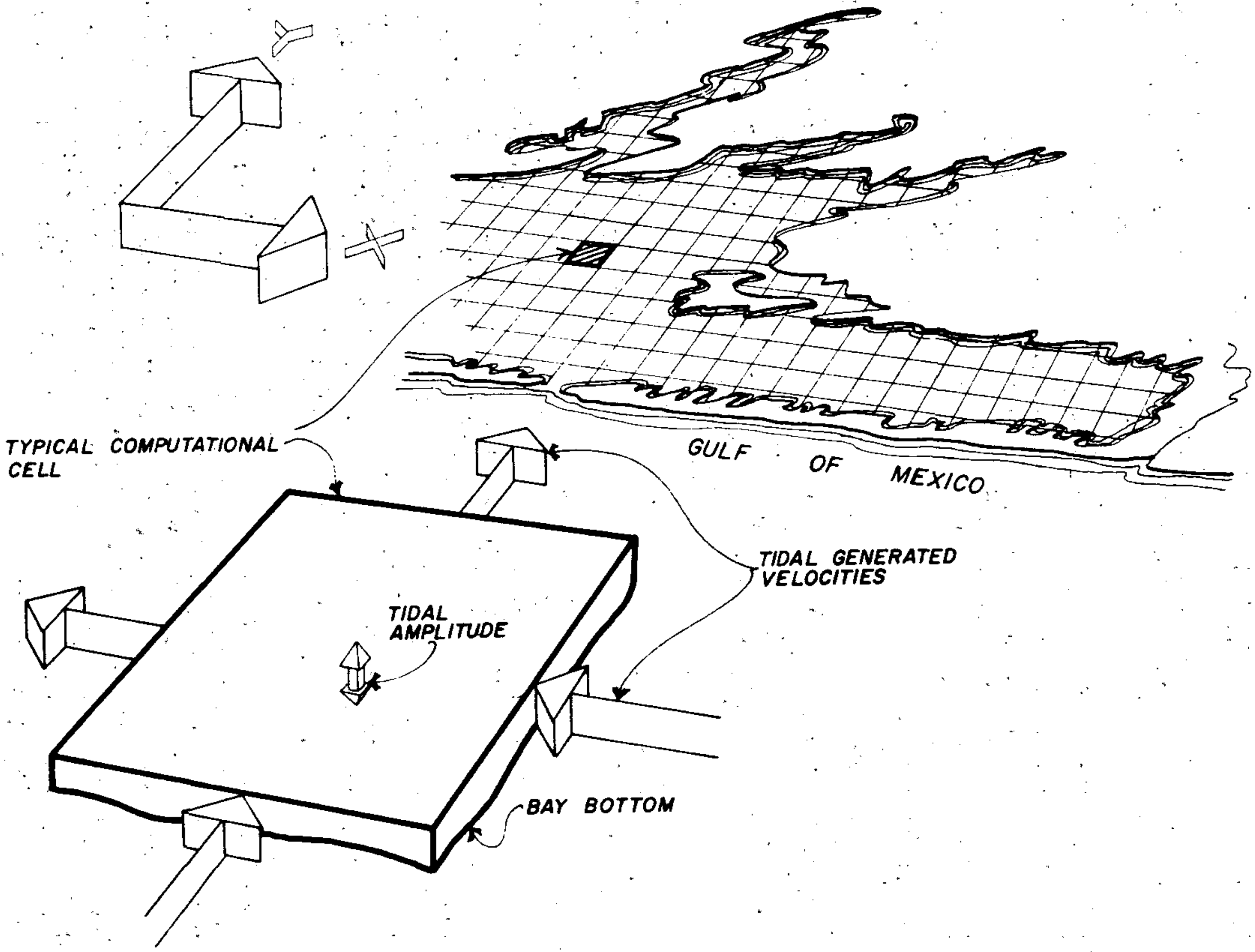

Figure 5-2. Conceptual Illustration of Discretization of a Bay (150)

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 (150). The primary difference in the form of Equation [4] given above and that reported previously (150), 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 (150).

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.

Application of Mathematical Models, Nueces and Mission-Aransas Estuaries

Hydrodynamic and Mass Transport Models

The computational grid network used to describe the Nueces and Mission-Aransas estuaries is illustrated in Figure 5-3. The grid is superimposed on a map showing the general outline of the estuary. Included in the grid network are the locations of islands (solid lines), submerged reefs (dash lines), inflow points, and tidal excitation cells. The x-axis of the grid system is aligned approximately parallel to the coastline, and the y-axis extends far enough landward to cover the lower reaches of all freshwater sources to the bay. The cell size (one square nautical mile) is based on (1) the largest possible dimension that would provide sufficient accuracy, (2) the density of available field data, and (3) computer storage requirements and computational time. Similar reasoning is used in selection of the computational time step except that the maximum possible time step in the hydrodynamic model is constrained by the criterion for mathematical stability. In the indexing scheme shown in Figure 5-3, cells are numbers with the indices $1 < i < IMAX = 41$ and $1 < j < JMAX = 28$. 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 meaurements 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 November 1971 and June 1974.

The initial calibration and verificaton of the Nueces and Mission-Aransas estuary models is reported by Masch (150). A representative sample of the results of the final calibration of the models using data obtained during the June 1972 field study are presented in Figures 5-4 to 5-8 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 24 consecutive hydrologic sequences[1/]. The minimum time period used as a hydrologic sequence was seven days.

[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.

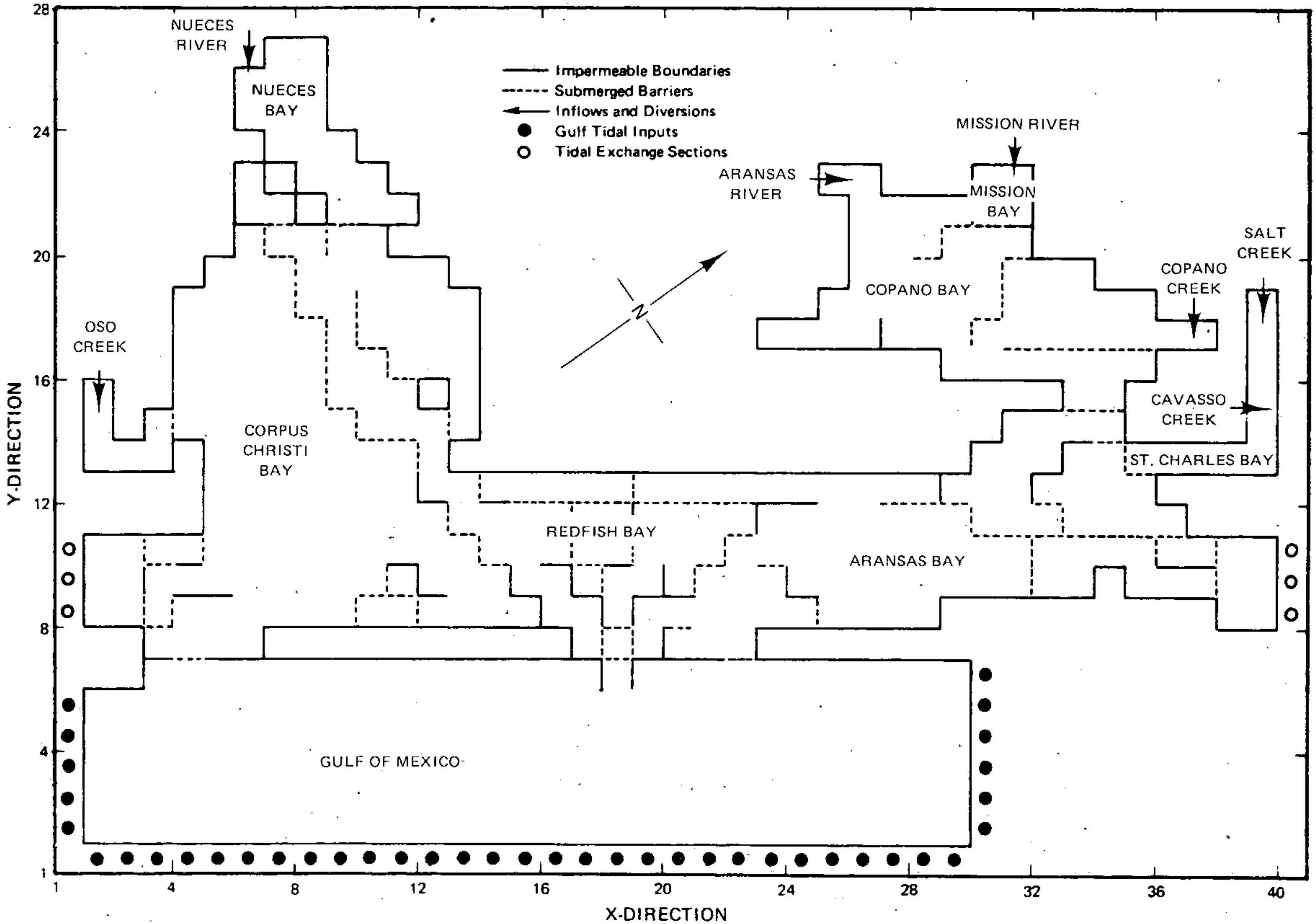

Figure 5-3. Schematic Computational Grid, Nueces and Mission-Aransas Estuaries (150)

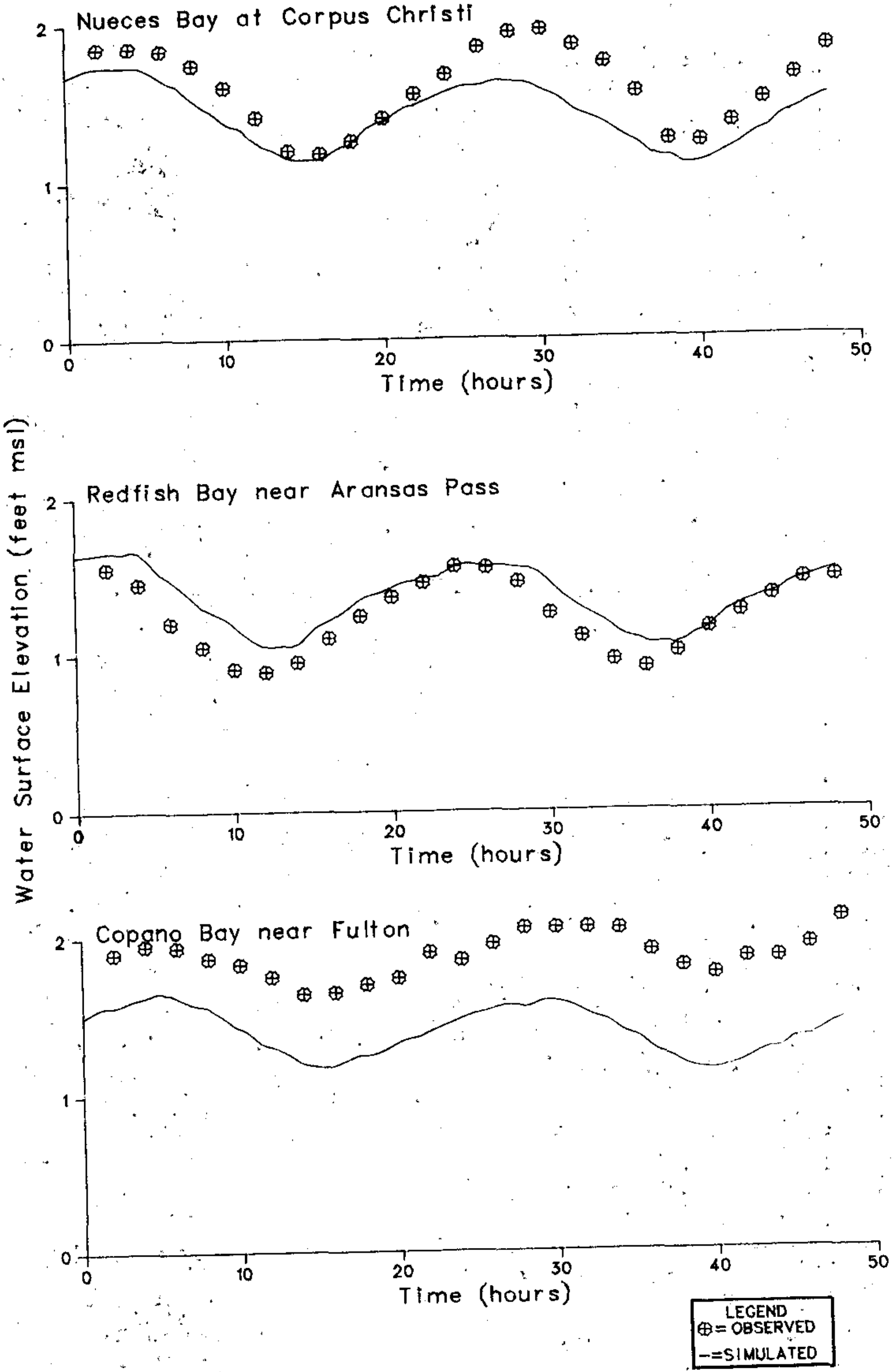

Figure 5-4. Comparison of Observed and Simulated Tidal Elevations, Nueces and Mission-Aransas Estuaries, June 4-6, 1974

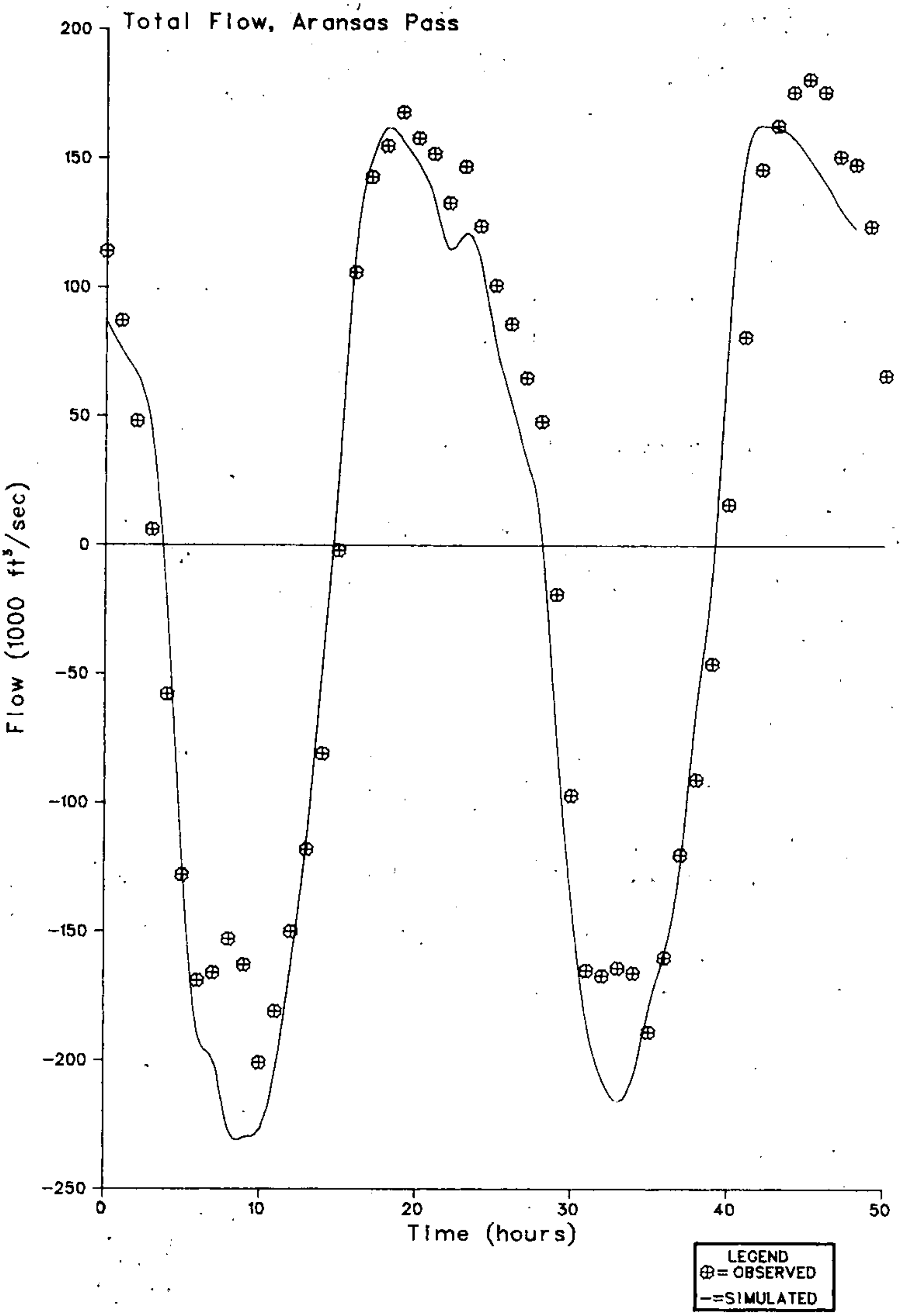

Figure 5-5. Comparison of Observed and Simulated Flows, Aransas Pass, June 4-6, 1974

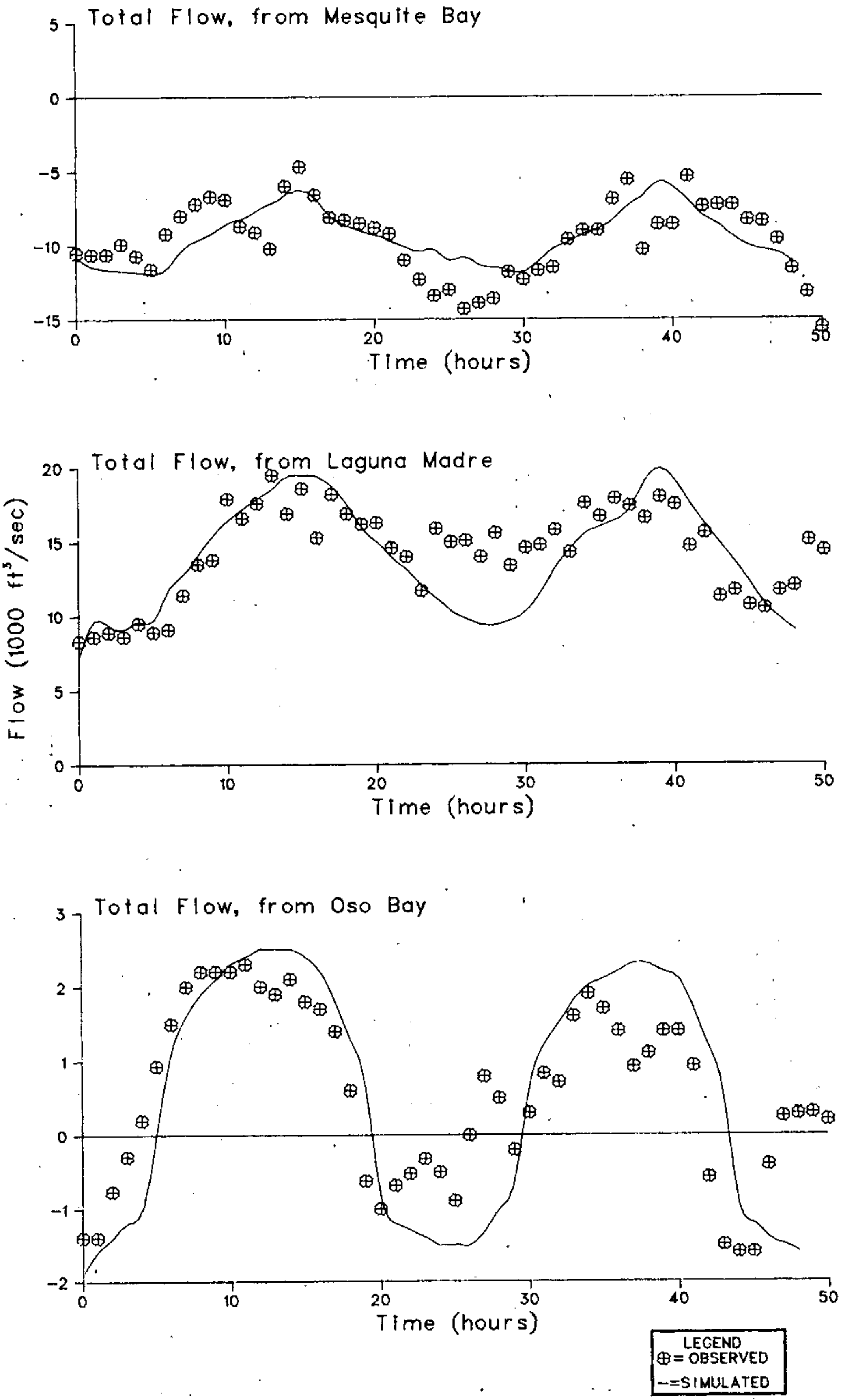

Figure 5-6. Comparison of Observed and Simulated Flows, Nueces and Mission-Aransas Estuaries, June 4-6, 1974

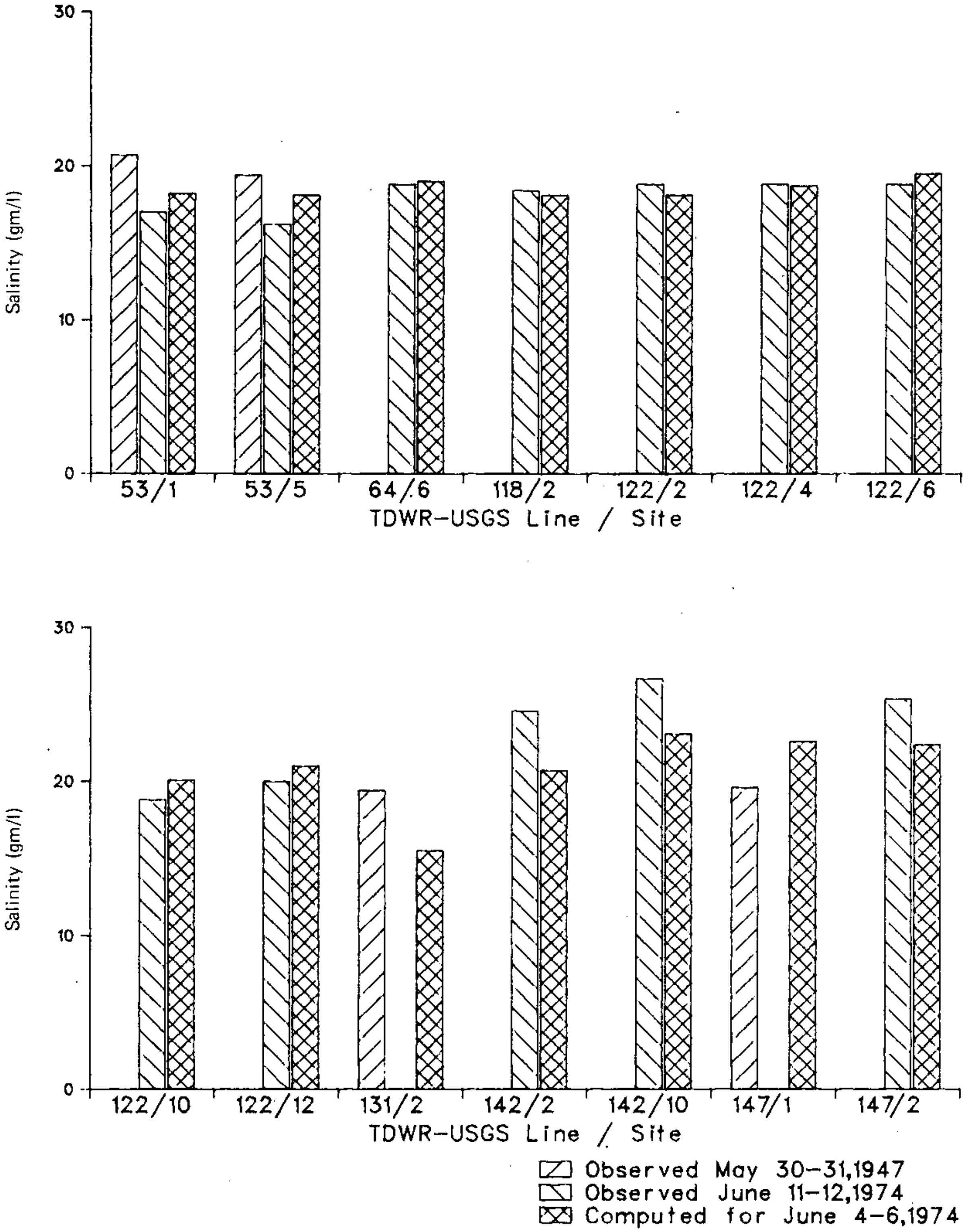

Figure 5-7. Comparison of Observed and Simulated Salinities, Nueces Estuary, May 30-June 12, 1974

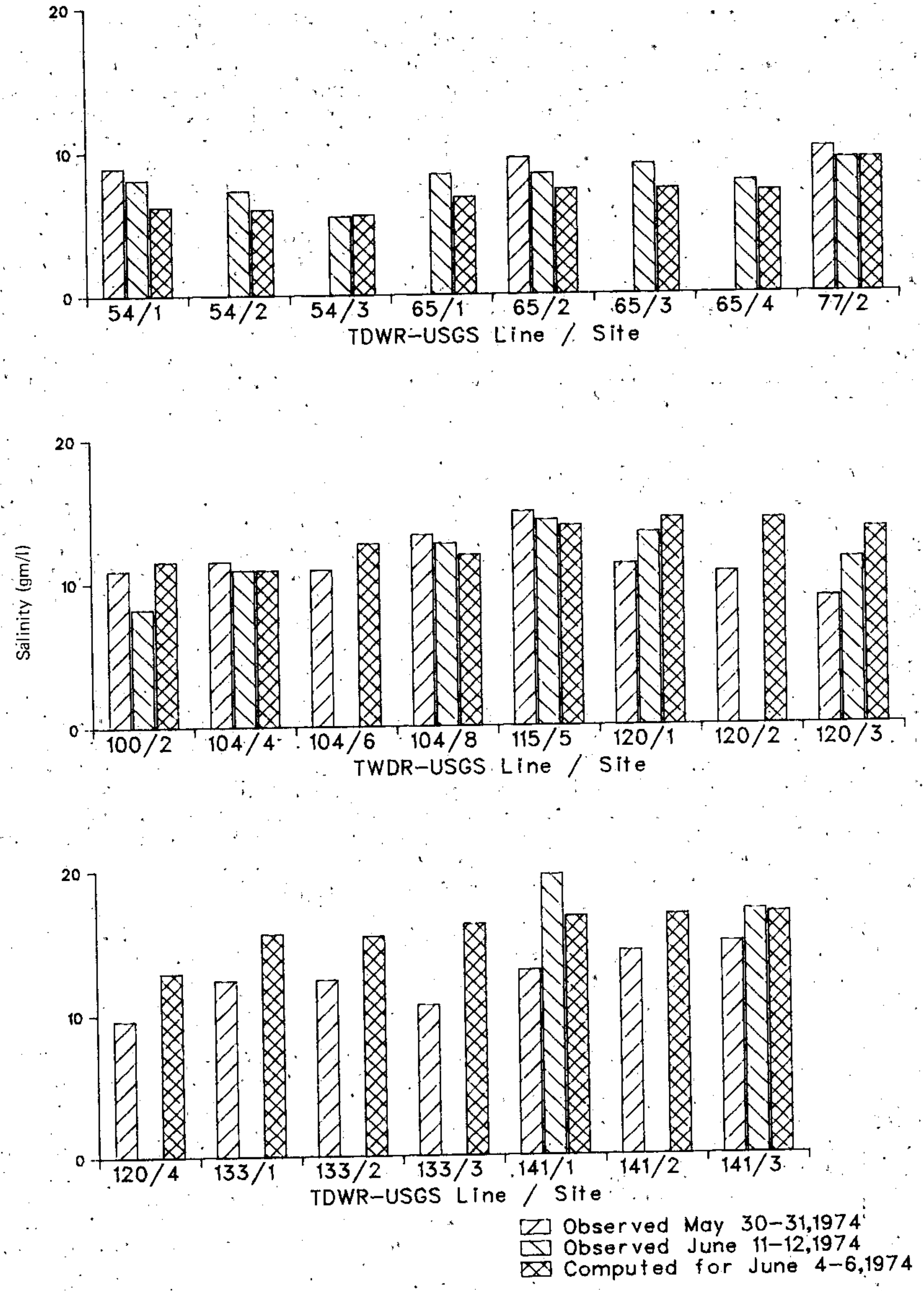

Figure 5-8. Comparison of Observed and Simulated Salinities, Mission-Aransas Estuary, May 30-June 12, 1974

Seasonal averages were used for the meteorological and tidal inputs. After comparing the simulated to the observed salinities for this period, it was determined that the simulated salinities in Redfish, Aransas, and Copano Bays generally agreed with the observed data throughout. During extended low inflow periods the model consistently underestimated the observed salinities in Nueces and Corpus Christi Bays. An investigation of observed data for 1968 through 1977 revealed that during low inflow periods, the Nueces estuary did did not demonstrate a salinity gradient typical of Texas Gulf Coast estuaries (i.e., low salinities in the vicinity of the river mouth, gradually increasing in the direction of the Gulf Pass). This type of salinity gradient generally occurred in the Nueces estuary only during periods of high flow and for a length of time thereafter that is dependent on the volume of inflow. Other wise, the salinities consistently remained 20 to 30 parts per thousand (ppt) throughout Nueces and Corpus Christi Bays with little appreciable gradient toward the Gulf. The results of the model simulations predicted the occurrence of a salinity gradient at all times, with the gradient's severity increasing during low inflow periods and decreasing during high inflow periods.

The presence of additional sources of influent water containing high total dissolved solids (TDS) concentrations unaccounted for by the models was suspected as the cause for observed salinities being consistently higher than those simulated by the models in Nueces and Corpus Christi Bays. An investigation determined that all major industrial return flows had been input to the models. However, Sherman (274) reported that, based on information obtained from U.S. Army Corps of Engineers and the Texas Railroad Commission permit files in 1970, there were a total of 71 individual points of brine discharge from oil and gas operations located around the Nueces estuarine system which were not included in the models. In general, individual discharges were small, with an average of about 30,000 gallons per day and totaled approximately 2.2 million gallons per day. An update of these data from Texas Railroad Commission files determined that by 1978 the total number of locations of brine discharge had increased to 183 for the Nueces estuary and 276 for the combined Nueces and Mission-Aransas estuaries and totaled approximately 3.3 and 3.7 million gallons per day of discharge, respectively. Little data are available on the quality of individual discharges, however, total dissolved solids concentrations can range as high as over 100 ppt (281, 284).

Based on this information, additional source inputs were added to the models and the 24 hydrologic sequences were rerun. The resulting simulated salinities demonstrate a better comparison with the observed salinities (Figures 5-9 through 5-17).

Perfect agreement can not be expected since the simulated results represent average salinity conditions for the time period covered by the hydrologic sequence while the measured data represent an instananeous response of the estuary to the specific tidal, freshwater inflow, and meteorological conditions present at the time of the measurement. With the exception of Nueces Bay (line 53, site 3, Figure 5-9), the simulated salinities are generally within 5 ppt of the observed salinities. However, during low inflow periods the simulated salinities particularly in the Nueces estuary are still consistently lower than the observed salinities. In the extreme, the simulated salinities for Nueces Bay (line 53, site 3) never rise above 16 to 18 ppt while the observed salinities in Nueces Bay during the low inflow periods are consistently above 20 ppt and at times exceed 30 ppt. Further investigation

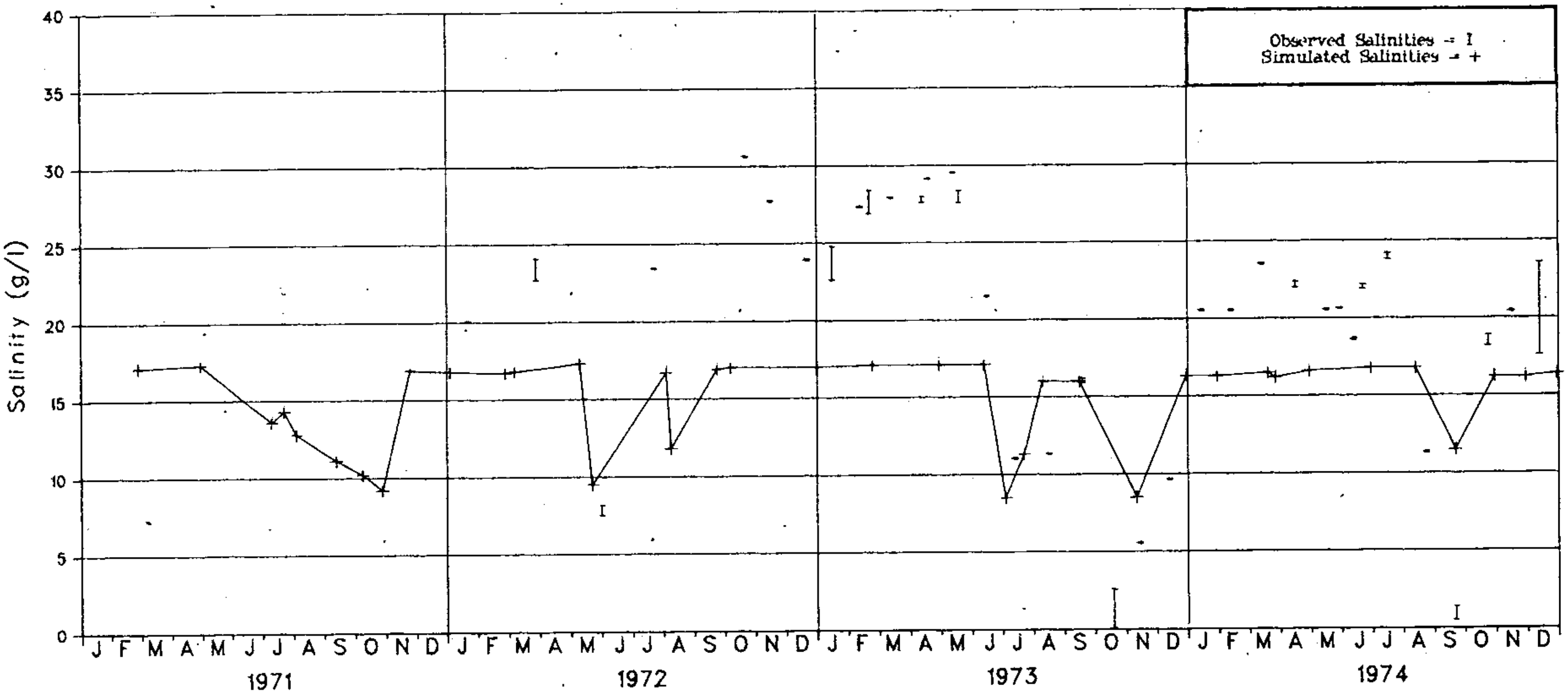

Figure 5-9. Comparison of Observed and Simulated Salinities, Nueces Estuary, Line 53 Site 9

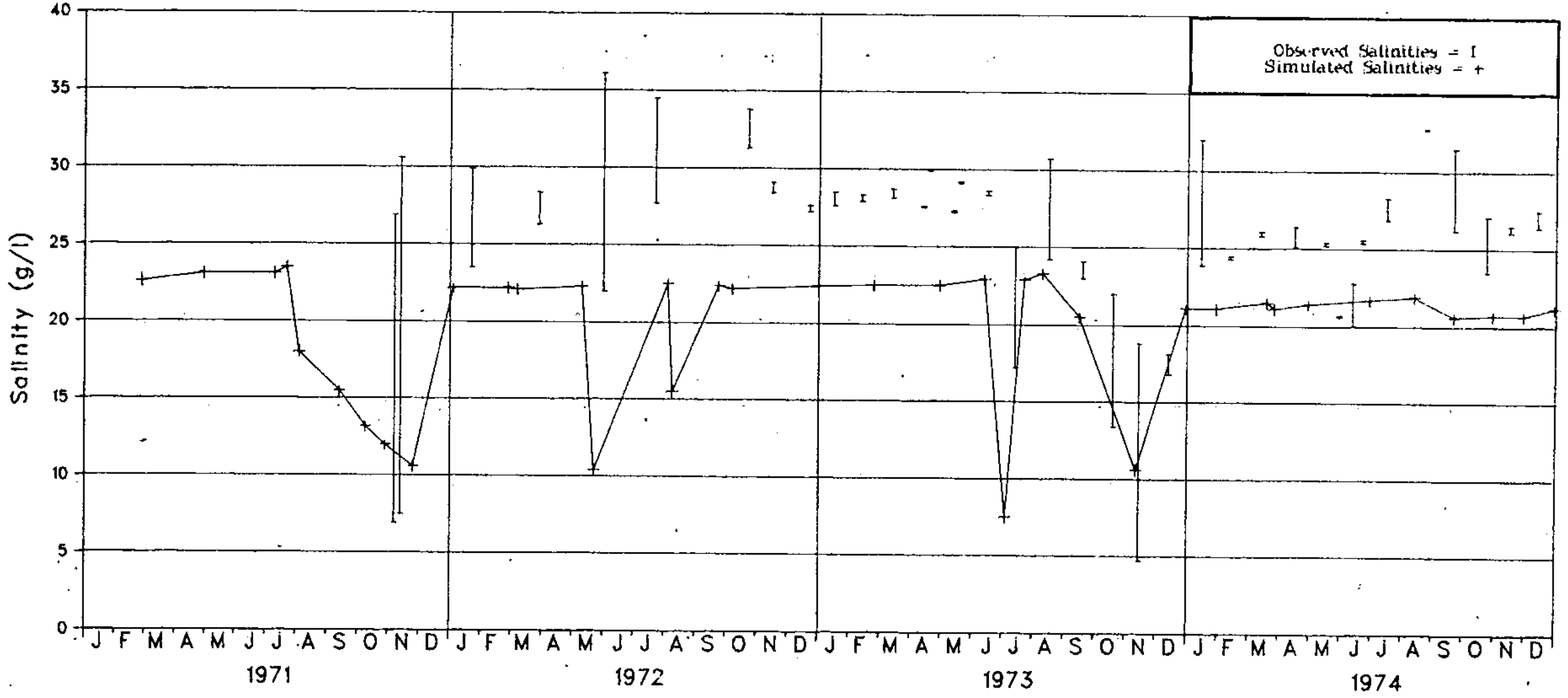

Figure 5-10. Comparison of Observed and Simulated Salinities
Nueces Estuary, Line 122 Site 6

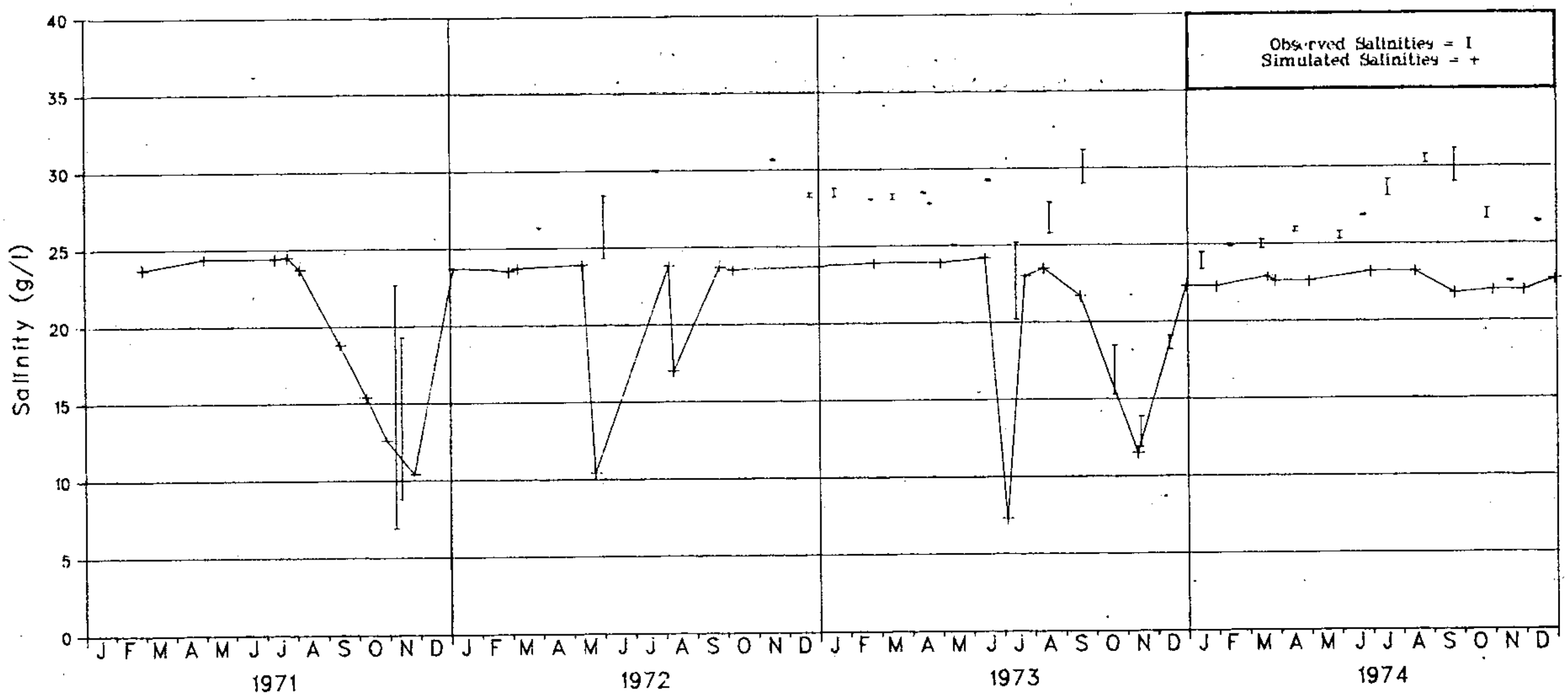

Figure 5-11. Comparison of Observed and Simulated Salinities, Nueces Estuary, Line 127 Site 6

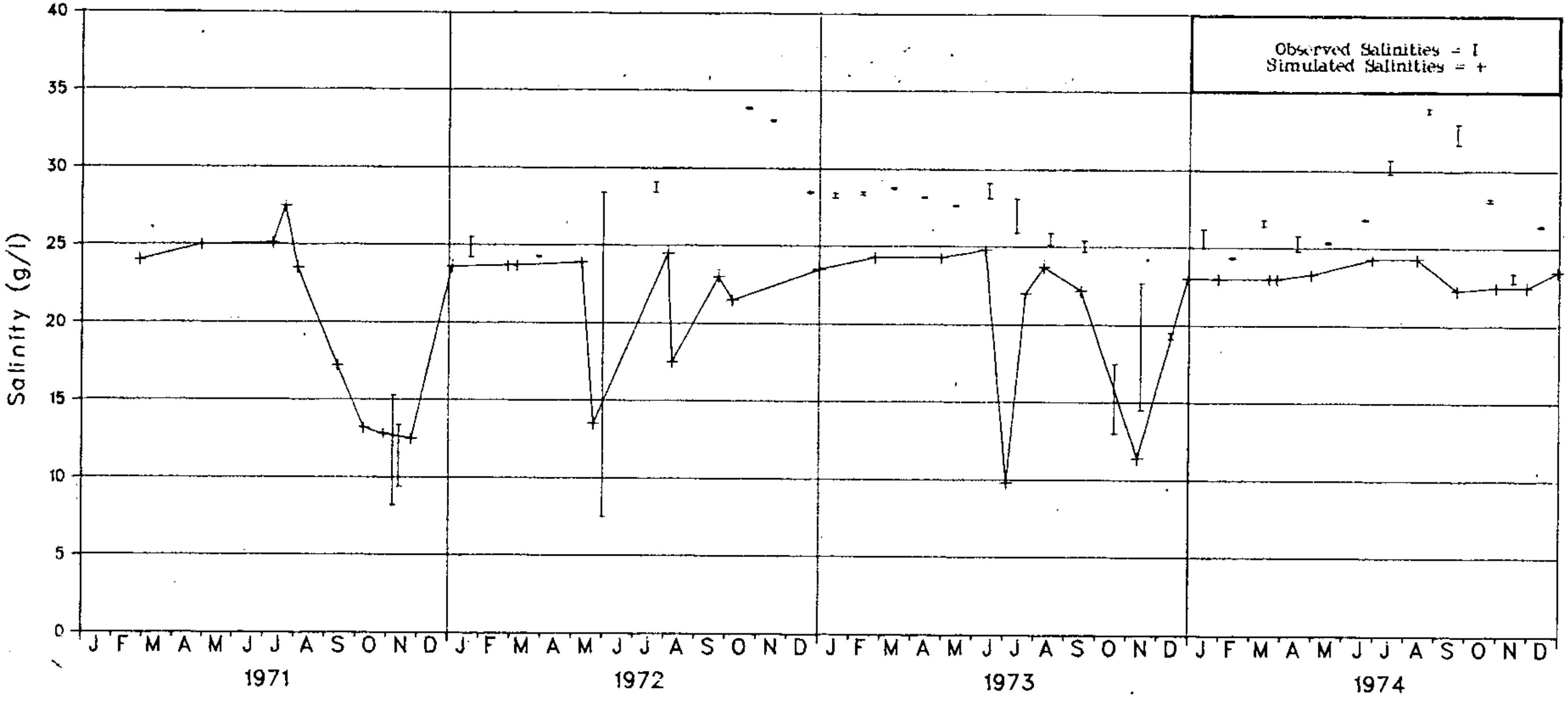

Figure 5-12. Comparison of Observed and Simulated Salinities, Nueces Estuary, Line 142 Site 6

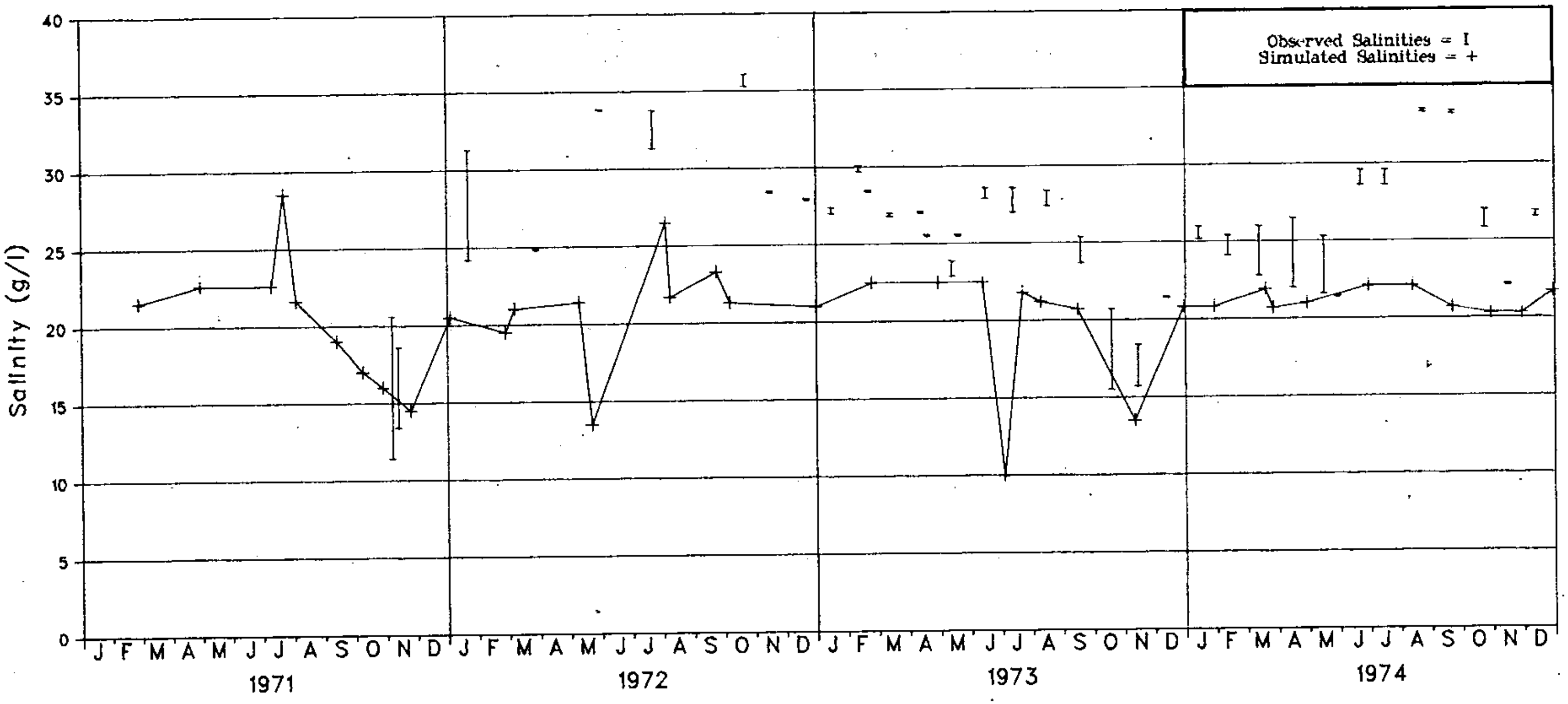

Figure 5-13. Comparison of Observed and Simulated Salinities, Nueces Estuary, Line 147 Site 1

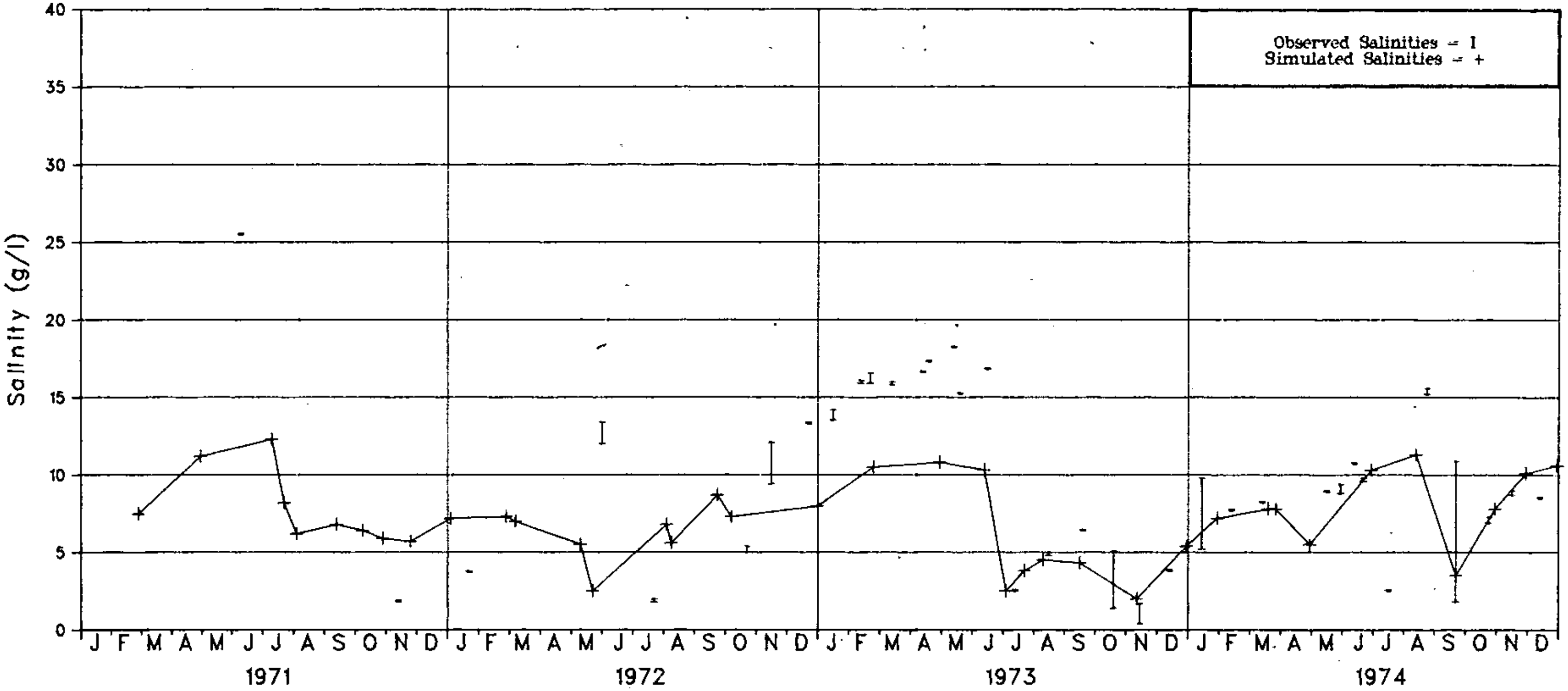

Figure 5-14. Comparison of Observed and Simulated Salinities
Mission-Aransas Estuary, Line 54 Site 1

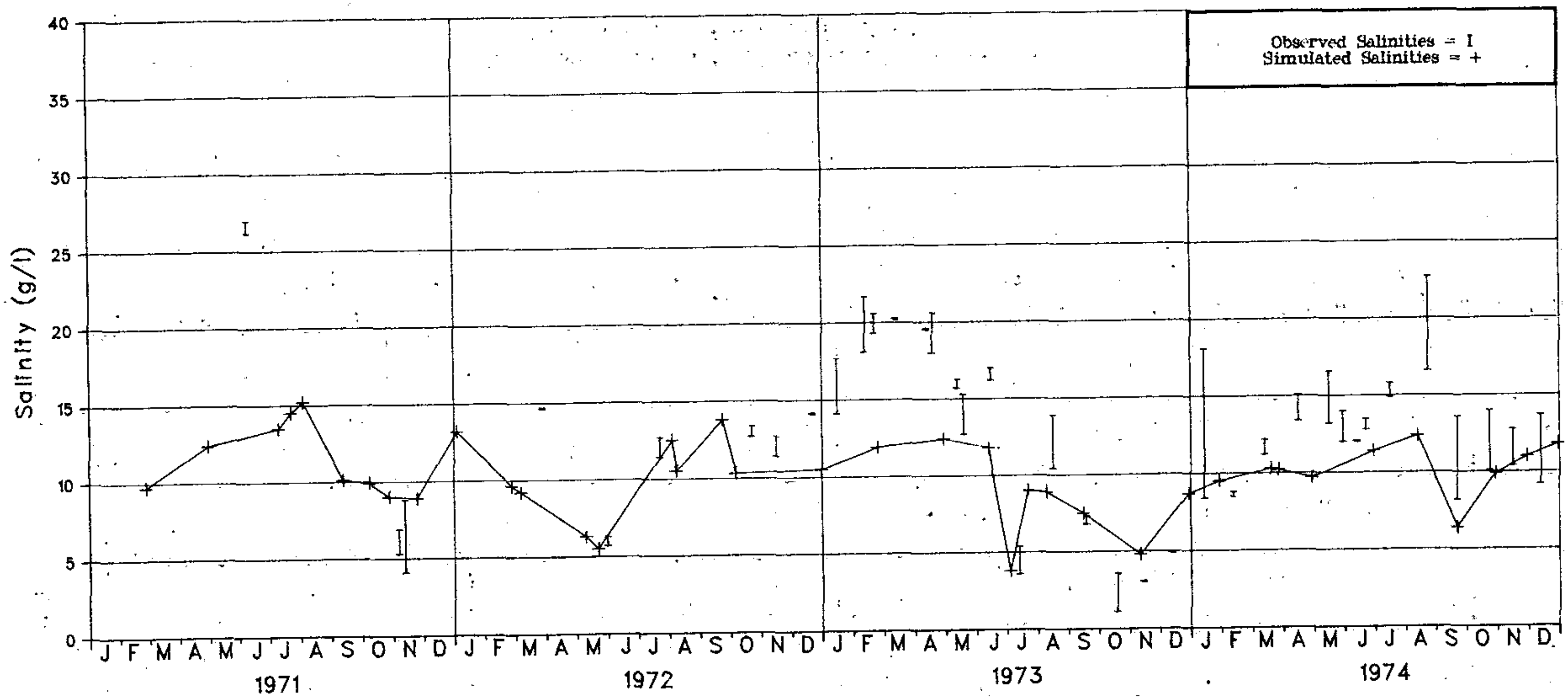

Figure 5-15. Comparison of Observed and Simulated Salinities, Mission-Aransas Estuary, Line 77 Site 2

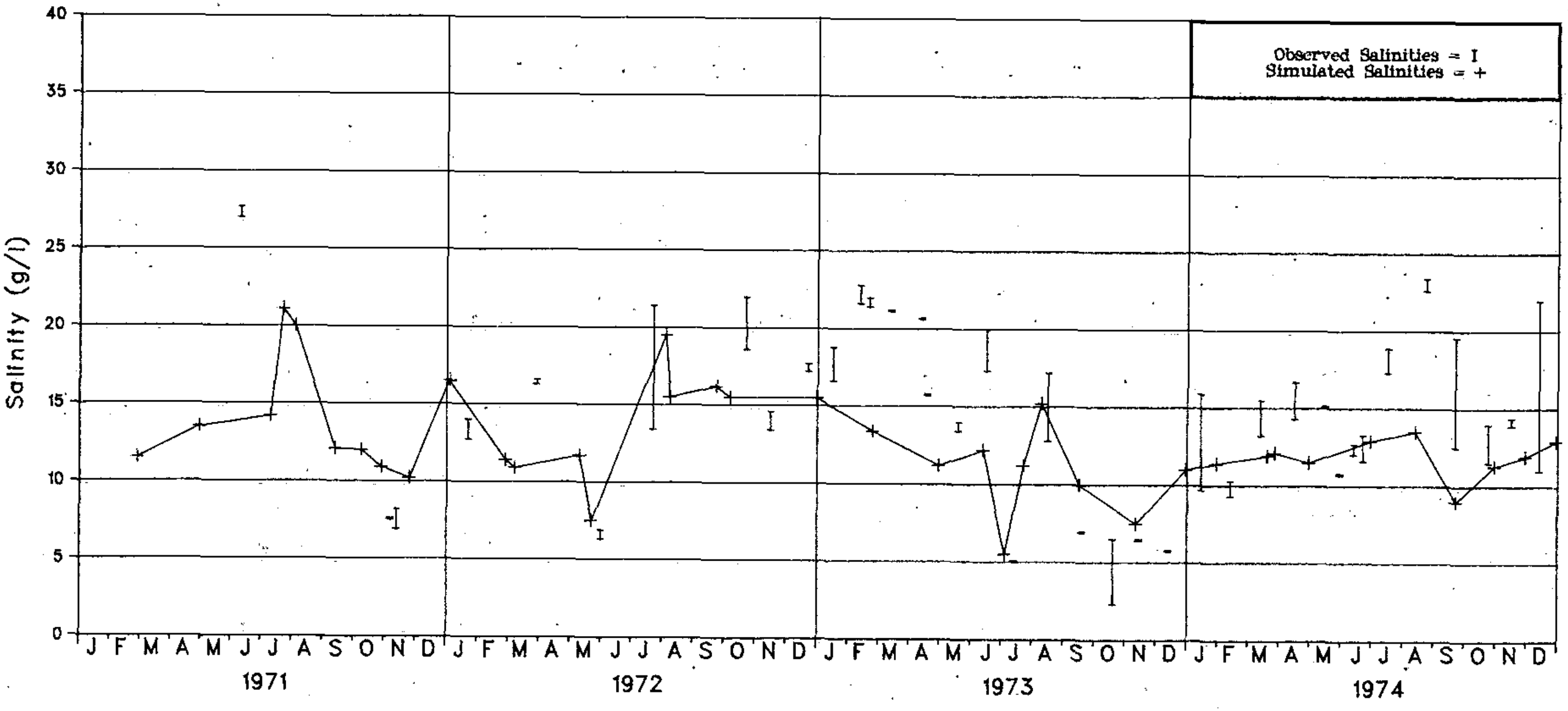

Figure 5-16. Comparison of Observed and Simulated Salinities, Mission-Aransas Estuary, Line 120 Site 3

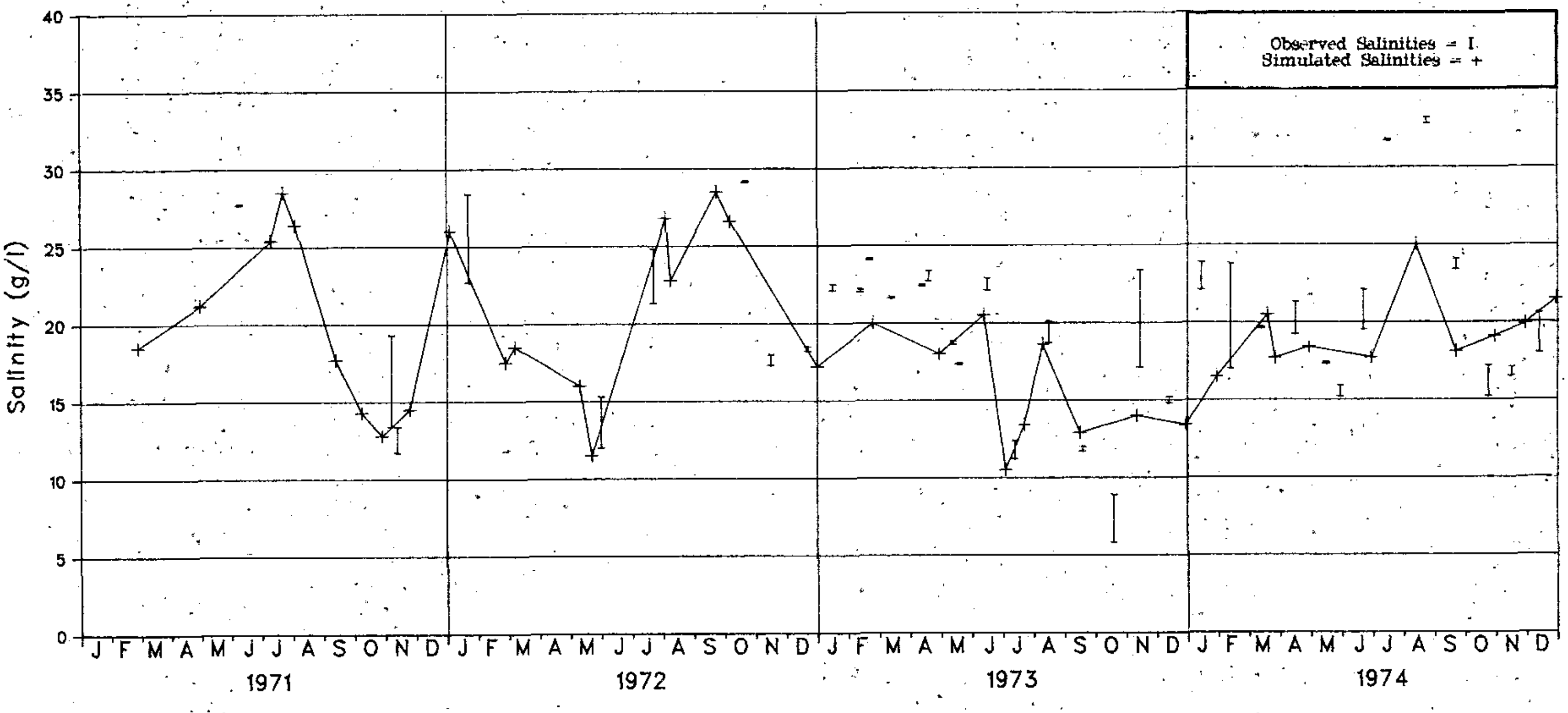

Figure 5-17. Comparison of Observed and Simulated Salinities, Mission-Aransas Estuary, Line 141 Site 1

is necessary to better define the location, quantity and quality of all discharges of high total dissolved solids concentration in the Nueces estuary and also to determine if any hydraulic anomalies exist in the Nueces estuary during low inflow periods which could exacerbate the salinity conditions in upper Corpus Christi Bay and Nueces Bay.

Freshwater Inflow/Salinity Regression Analysis

Changes in estuarine salinity patterns are a function of several variables, including the magnitude of freshwater inflow, tidal mixing, density currents, wind induced mixing, evaporation and salinity of source inflows. In the absence of highly saline inflow and neglecting wind effects, the volume of antecedent inflow and 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 were carried out to verify and quantify such a relationship.

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 $\sum_{i=1}^{n} Q_{t-i}$ in equations [1] and [2] represents the antecedent inflow conditions, while Q_{t-k} represents the conditions making into consideration streamflow time lag between the gage and the inflow estuary. The regression coefficients were determined using a step-wise multiple regression procedure (15).

The regression equations developed for Nueces Bay use the salinities obtained by the Department of Water Resources and United States Geological Survey cooperative data collection programs at line 53, site 2 and the gaged streamflows recorded for the Nueces River near Mathis (Table 5-1). The daily average salinity is related to the daily gaged streamflow by the equation

$$S_t = 0.88 + 85.6\, Q_{t-3}^{-0.5} + 893.7 \left(\sum_{i=1}^{29} Q_{t-i} \right)^{-0.5} \qquad [3]$$

Table 5-1. Description of Data for Regression Analysis

Bay	Salinity		Inflow		Number of Observations for Regression
	Station Line-Site	Period of Record	USGS Station	Period of Record	
Nueces	TDWR-USGS 53-2	Dec. 1967 to Jun. 1977	Nueces River near Mathis	Jan. 1941 to Jun. 1977	33
Copano	TDWR-USGS 44-1, 44-2 54-2, 54-3	Mar. 1968 to Jun. 1977	Mission River at Refugio	Jan. 1941 to Jun. 1977	29

where S_t and Q_{t-i} are salinity and streamflow in ppt and ft^3/sec, respectively. With a correlation coefficient (r) of 0.94 and an explained variation (r^2) of 89 percent, the regression is tested to be highly significant ($\alpha = .01$).

Monthly salinity-inflow relationships were derived using equation [3] to generate daily salinities for the period of streamflow record, 1941 through 1976. The computed daily salinity values were averaged monthly over the study period, and the averages were related to the monthly average flows by the geometric equation

$$S_m = c_0 \ (Q_m)^{C_1} \exp \ (ts_e) \qquad [4]$$

where S_m and Q_m are monthly average salinity and gaged flow in ppt and ft^3/sec, respectively, c_0 and c_1 are regression coefficients, and (ts_e) is a random component. The frequency analyses for Nueces and Mission-Aransas estuaries indicate that both monthly salinities and monthly gaged streamflows are approximately log-normal distributed. Therefore, the random component has a normal distribution and can be expressed by ts_e (54), where t is a standard normal deviate with zero mean and unit variance, and s_e is the standard error of estimate of $\ln (S_m)$ on $\ln (Q_m)$. Resulting correlation coefficients of equation [4] for Nueces Bay (Table 5-2) for the twelve months (r) ranged from 0.61 to 0.9, which are highly significant ($\alpha = .01$).

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

$$S_y = 112.6 \ Q_y^{-0.318} \qquad [5]$$

where S_y nd Q_y are mean monthly average salinity, and gaged flow, respectively. The equation and the 95 percent confidence limits of S_y versus Q_y are plotted in Figure 5-18. The other statistics of equation [5] are listed in Table 5-2.

The analysis for Copano Bay uses salinities obtained by the Texas Department of Water Resources and U. S. Geological Survey cooperative data collection programs at line 44, sites 1, 2 and line 54, sites 2, 3, and the gaged streamflows recorded for the Mission River at Refugio (Table 5-1). Using the averages of salinities measured at the four line sites, the analysis yields the relationship

$$S_t = 113.5 \ Q^{-0.2796} \ \Big(\sum_{i=1}^{26} Q_{t-i} \Big)^{-0.2314} \qquad [6]$$

with highly significant correlation coefficients of 0.87.

Using equation [6] to generate mean daily salinity for the period of streamflow record, 1941 through 1976, the relationships between computed mean monthly salinities and mean monthly streamflows are determined (Table 5-3). The average condition of the relationships can be fitted to the equation

Table 5-2. Results of Salinity Regression Analysis, Nueces Bay

Station a/	Class	Regression Equation (S in ppt and Q in ft^3/sec)	Correlation Coefficient r	Explained Variation r²	Standard Error of Estimate s_e	F-test
	Daily	$S = 0.88 + 85.59\, Q_{t-3}^{-0.5} + 893.7 \left(\sum_{i=1}^{29} Q_{t-i} \right)^{-0.5}$	0.94	0.89	---	**
53-2	Jan.	$S = 109.7\ Q^{-0.300}$, $50 \le Q \le 5{,}000$	0.90	0.81	0.163	**
	Feb.	$S = 139.8\ Q^{-0.352}$, $50 \le Q \le 5{,}200$	0.91	0.83	0.195	**
	Mar.	$S = 169.5\ Q^{-0.393}$, $50 \le Q \le 4{,}400$	0.94	0.87	0.158	**
	Apr.	$S = 82.9\ Q^{-0.242}$, $50 \le Q \le 3{,}400$	0.83	0.69	0.193	**
	May	$S = 116.7\ Q^{-0.300}$, $50 \le Q \le 10{,}500$	0.83	0.69	0.325	**
	Jun.	$S = 123.0\ Q^{-0.349}$, $50 \le Q \le 8{,}150$	0.87	0.76	0.273	**
	Jul.	$S = 71.3\ Q^{-0.258}$, $50 \le Q \le 10{,}500$	0.86	0.74	0.205	**
	Aug.	$S = 114.8\ Q^{-0.329}$, $50 \le Q \le 10{,}500$	0.83	0.69	0.262	**
	Sep.	$S = 76.7\ Q^{-0.240}$, $50 \le Q \le 25{,}000$	0.78	0.61	0.335	**
	Oct.	$S = 117.4\ Q^{-0.330}$, $50 \le Q \le 14{,}900$	0.84	0.71	0.330	**
	Nov.	$S = 176.3\ Q^{-0.437}$, $50 \le Q \le 3{,}380$	0.94	0.89	0.175	**
	Dec.	$S = 183.7\ Q^{-0.430}$, $50 \le Q \le 1{,}000$	0.95	0.90	0.122	**
	All Months	$S = 112.6\ Q^{-0.318}$, $50 \le Q \le 25{,}000$	0.87	0.75	0.268	**

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a/ See Figure 3-11.
** Indicates a statistical significance level of $\alpha = 0.01$ (highly significant).

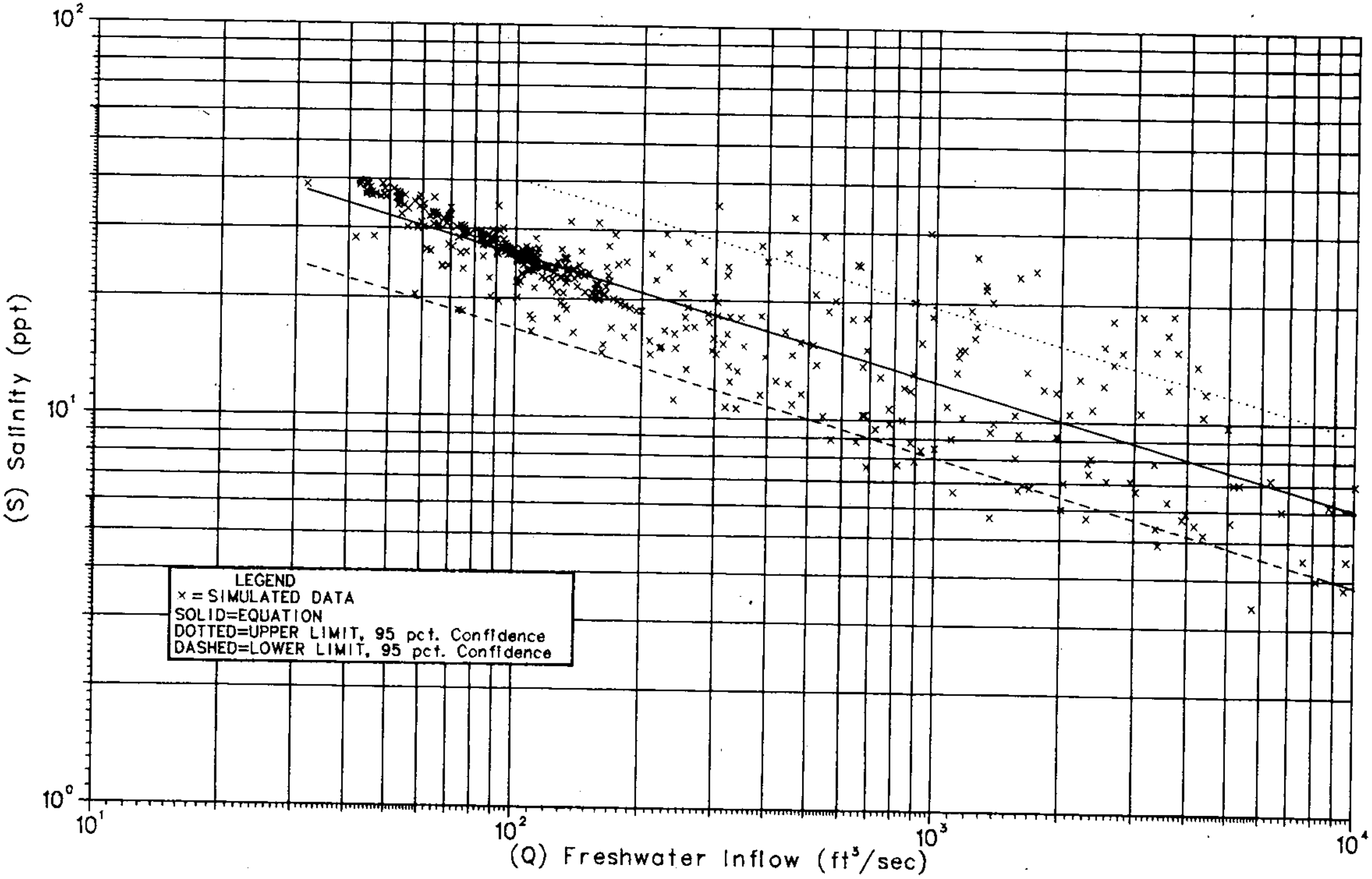

Figure 5-18. Average Monthly Salinity Versus Average Monthly Gaged Inflow, Nueces Estuary, 1940-1976

Table 5-3. Results of Salinity Regression Analysis, Copano Bay

Station a/	Class	Regression Equation (S in ppt and Q in ft^3/sec)	Correlation Coefficient r	Explained Variation r^2	Standard Error of Estimate s_e	F-test
Average of Stations	Daily	$S_t = 113.47\, Q_{t-3}^{-0.2796} \left(\sum_{i=1}^{26} Q_{t-i} \right)^{-0.2314}$	0.87	0.76	0.175	**
44-1, 44-2 54-2, 54-3	Jan.	$S = 41.11\, Q^{-0.38}$, $4 \leq Q \leq 390$	0.89	0.79	0.227	**
	Feb.	$S = 32.38\, Q^{-0.260}$, $4 \leq Q \leq 1{,}200$	0.85	0.71	0.254	**
	Mar.	$S = 30.25\, Q^{-0.264}$, $4 \leq Q \leq 260$	0.69	0.48	0.327	**
	Apr.	$S = 27.00\, Q^{-0.185}$, $4 \leq Q \leq 240$	0.68	0.47	0.331	**
	May	$S = 41.77\, Q^{-0.321}$, $4 \leq Q \leq 540$	0.82	0.67	0.406	**
	Jun.	$S = 28.83\, Q^{-0.286}$, $4 \leq Q \leq 1{,}120$	0.81	0.65	0.288	**
	Jul.	$S = 32.47\, Q^{-0.306}$, $3 \leq Q \leq 1{,}850$	0.86	0.74	0.328	**
	Aug.	$S = 34.22\, Q^{-0.245}$, $3 \leq Q \leq 1{,}080$	0.75	0.56	0.349	**
	Sep.	$S = 29.53\, Q^{-0.217}$, $3 \leq Q \leq 3{,}900$	0.78	0.61	0.383	**
	Oct.	$S = 35.12\, Q^{-0.329}$, $3 \leq Q \leq 4{,}140$	0.87	0.75	0.386	**
	Nov.	$S = 46.32\, Q^{-0.446}$, $3 \leq Q \leq 400$	0.85	0.72	0.358	**
	Dec.	$S = 37.72\, Q^{-0.342}$, $4 \leq Q \leq 250$	0.85	0.72	0.288	**
	All Months	$S = 32.9\, Q^{-0.282}$, $3 \leq Q \leq 4{,}140$	0.80	0.64	0.368	**

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a/ See Figure 3-12.
** Indicates a statistical significance level of $\alpha = 0.01$ (highly significant).

$$S_y = 32.9\ Q_y^{-0.282} \qquad [6]$$

where S_y and Q_y are mean monthly average salinity and gaged flow, respectively. The equation and the 95 percent confidence limits of S_y versus Q_y are plotted in Figure 5-19. The other statistics of equation [6] are listed in Table 5-3.

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 concentration 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 has participated in the development of 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.

The numerical tidal hydrodynamic and salinity mass transport models were applied to the Nueces and Mission-Aransas estuaries, with the model representation of the system including Nueces Bay, Corpus Christi Bay, Redfish Bay, Aransas Bay, Copano Bay, Mission Bay, and a portion of the Gulf of Mexico adjacent to Mustang and St. Joseph Islands. The hydrodynamic and mass transport models were calibrated and verified for the estuary. In testing the model's abilities to simulate the salinity response of the estuary over an extended time period, it was determined that lower salinities were being predicted in Nueces and Corpus Christi Bays than have been actually observed in recent years. Several additional input sources were included in the models to more adequately represent the numerous permitted brine discharges located in and near Nueces and Corpus Christi Bays. This lead to some improvement in

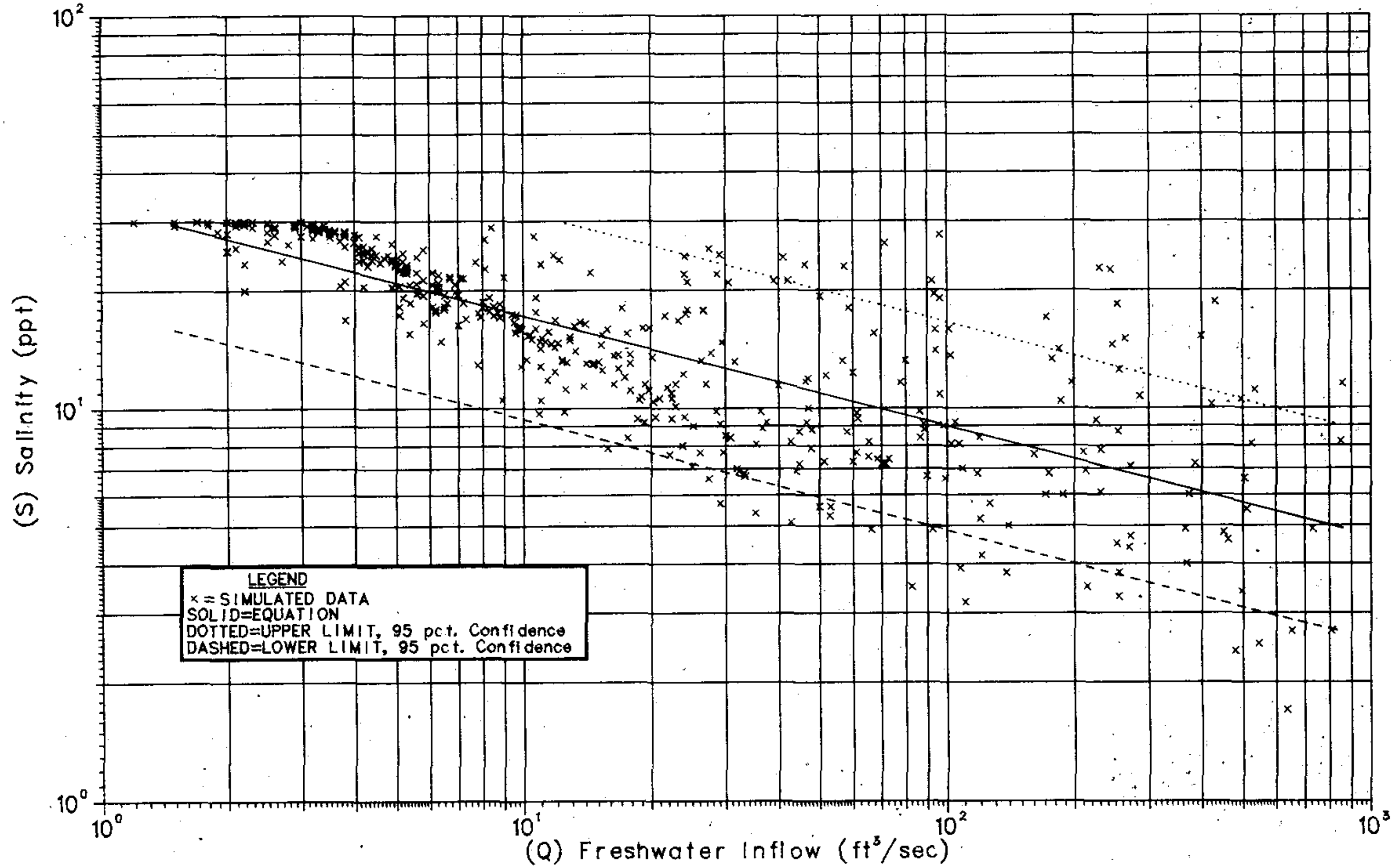


Figure 5-19. Average Monthly Salinity Versus Average Monthly Gaged Inflow, Mission-Aransas Estuary, 1941-1976

the simulated results, but additional effort will be necessary to further improve the simulated results during low inflow periods.

Statistical analyses were undertaken to quantify the relationship between freshwater inflows from the Nueces and Mission Rivers and salinities in Nueces and Copano Bays. Utilizing gaged daily river flows in the Nueces and Mission Rivers and observed salinities, a set of monthly predictive salinity equations were 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 (e.g., sun light and tides) to drive the biological processes. In addition, readily available supplies of inorganic materials are essential, the most obvious being carbon, nitrogen, and phosphorus. 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.

Carbon to nitrogen to phosphorus (CNP) ratios vary from organism to organism. Carbon is normally required in the greatest quantity followed by nitrogen and phosphorus. Generally, oceanic species have a reported value of 106:16:1 (119). Nitrogen to phosphorus ratios for a variety of phytoplankton species are usually in the range of 10-12:1 (119). These two elements are considered to be the "critical" nutrients in aquatic ecosystems since carbon is rarely, if ever, limiting due to the readily available supply of atmospheric CO_2 and the ability of autotrophic organisms to use this form.

The amount of nitrogen required in an aquatic ecosystem is generally greater than phosphorus, thus biological productivity is most likely to be nitrogen-limited. This has been reported to be the case in a number of estuaries (400, 402, 135, 192, 110, 196) including those in Texas (331, 330).

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

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

Nutrient Loading

Attempts to determine the amount of nutrient loading from a riverine source to an estuary have been conducted by Smith and Stewart (202). 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 systematically collected for these rivers only since the late 1960's.

The major contributory channels of freshwater inflow to the Mission-Aransas estuary are Copano Creek, Chiltipin Creek, Mission River, and the Aransas River which empty into Copano Bay. Contributions of nutrients from the Aransas River may be intermittent as an earthen dam about one mile upstream from the confluence with Copano Bay probably prohibits inflows to the bay during low flow periods. The major sources of freshwater inflow and the associated nutrient load to the Nueces estuary are the Nueces River and Oso Creek.

The mean annual total discharge measured at the closest non-tidally influenced gage for the six major freshwater inflow sources to the Nueces and Mission-Aransas estuaries is about 800,000 acre-feet (986 million m^3). About 73.2 percent of this inflow (586,000 acre-feet or 723 million m^3) is contributed by the Nueces River. Contributions from the remaining sources are as follows: Oso Creek, 3.1 percent (25,000 acre-feet or 31 million m^3); Chiltipin Creek, 4.7 percent (37,900 acre-feet or 47 million m^3); Aransas River, 4.4 percent (35,400 acre-feet or 44 million m^3); Mission River, 10.1 percent (80,600 acre-feet or 99 million m^3); and Copano Creek, 4.4 percent (35,200 acre-feet or 43 million m^3).

U. S. Geological Survey discharge and water quality data over the period of record (1970-1977) were used to calculate the potential nutrient loading contribution from Copano Creek, Mission River, and Chiltipin Creek. The U. S. Geological Survey has not collected water quality data for the lower reaches of the Aransas River; however, some data from the Texas Department of Water Resources statewide water quality monitoring network (1967-1977) were available. U. S. Geological Survey data were available for Oso Creek (1972-1977), while Texas Department of Water Resources monitoring network data were available for the lower Nueces River above Calallen Dam (1972-1977).

Nutrient data 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. By 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, involving seasonal intensive field sampling efforts over a one or two day period, have been conducted in the Nueces River delta in order to gain insight into nutrient contributions from this brackish intertidal marsh to the Nueces estuary. As is the case with riverine water quality, an analysis of the deltaic marsh contribution is inadequate based upon data collected over one or two years on a seasonal basis. More data are needed, particularly for extreme events such as floods, hurricanes, and droughts, in order to refine these analyses.

Water quality data collected by the U. S. Geological Survey indicated organic nitrogen concentrations in Copano Creek near Refugio, Texas, to range from 0.06 mg/l to 5.7 mg/l. Organic nitrogen concentrations from other sources were recorded as follows: Mission River (0.0 - 2.0 mg/l), Chiltipin Creek (0.0 - 9.0 mg/l), and Oso Creek (0.0 - 3.1 mg/l). Monthly water quality analyses performed by Wiersema et al. (47) indicated organic nitrogen concentrations in the Nueces River ranging from 0.2 to 1.3 mg/l. No USGS organic nitrogen data were available for either the Nueces or Aransas Rivers.

Texas statewide monitoring network data indicated that inorganic nitrogen concentrations ranged from 0.06 mg/l to 0.92 mg/l in the Nueces River and from 0.4 mg/l to 2.65 mg/l in the Aransas River. Other sources revealed inorganic nitrogen concentrations of 0.01 - 0.92 mg/l in Copano Creek, 0.0 - 5.72 mg/l in the Mission River, 0.0 - 5.5 mg/l in Chiltipin Creek, and 0.18 - 16.77 mg/l in Oso Creek. Inorganic nitrogen concentrations reported by Wiersema et al. (47) in the lower Nueces River ranged from less than 0.14 mg/l to 0.22 mg/l.

Total phosphorus concentrations reported by the U. S. Geological Survey were similar in almost all of the contributing streams (generally 0.01 - 0.6 mg/l). Oso Creek was an exception, with total phosphorus concentrations generally two to ten times higher than those recorded elsewhere. Concentrations in the Aransas River were consistently higher than in the majority of contributing streams during the spring season.

Total organic carbon (TOC) concentrations reported in the Texas water quality monitoring network and by Wiersema et al. (47) for the Nueces River were generally less than 10 mg/l. In each of the other contributing streams TOC concentrations were significantly higher. The upper limit of TOC extremes ranged from about 30-35 mg/l, with the exception of one value (80 mg/l) reported from the Aransas River.

Mean monthly organic nitrogen concentrations exhibited no definite seasonal patterns (Figure 6-1). In general, concentrations in the Mission River were roughly half those of other streams. Mean monthly inorganic nitrogen concentrations recorded from Oso and Chiltipin Creeks were, as a rule, greater than those concentrations in the remaining streams (Figure 6-2). Concentrations in Oso Creek were particularly high. Oso Creek is the only stream that exhibited a definite seasonal pattern for mean monthly inorganic nitrogen concentrations, ranging from a low point in late summer to highest values occurring from December through February.

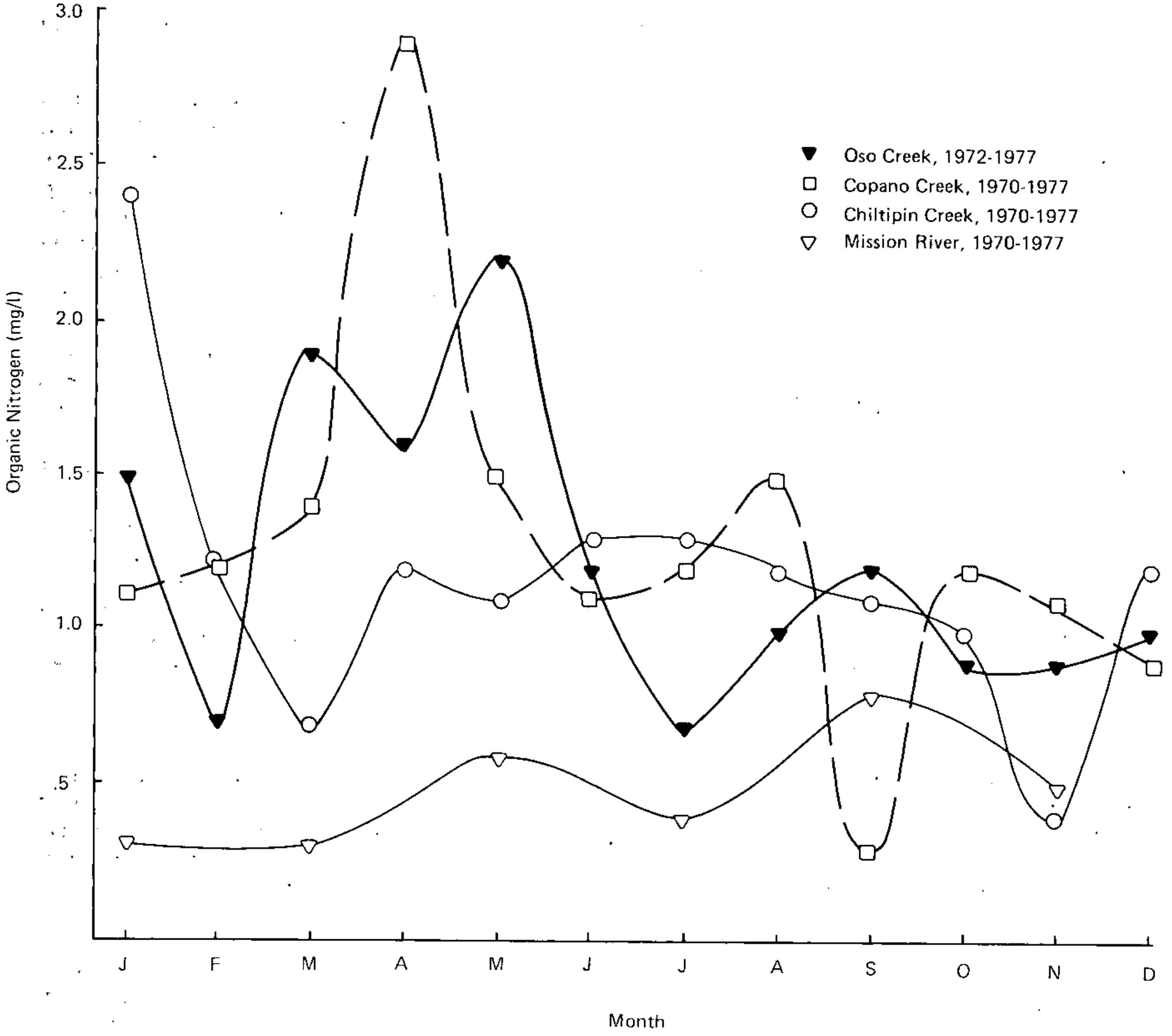


Figure 6-1. Mean Monthly Organic Nitrogen Concentrations of Streams Contributory to the Nueces and Mission-Aransas Estuary

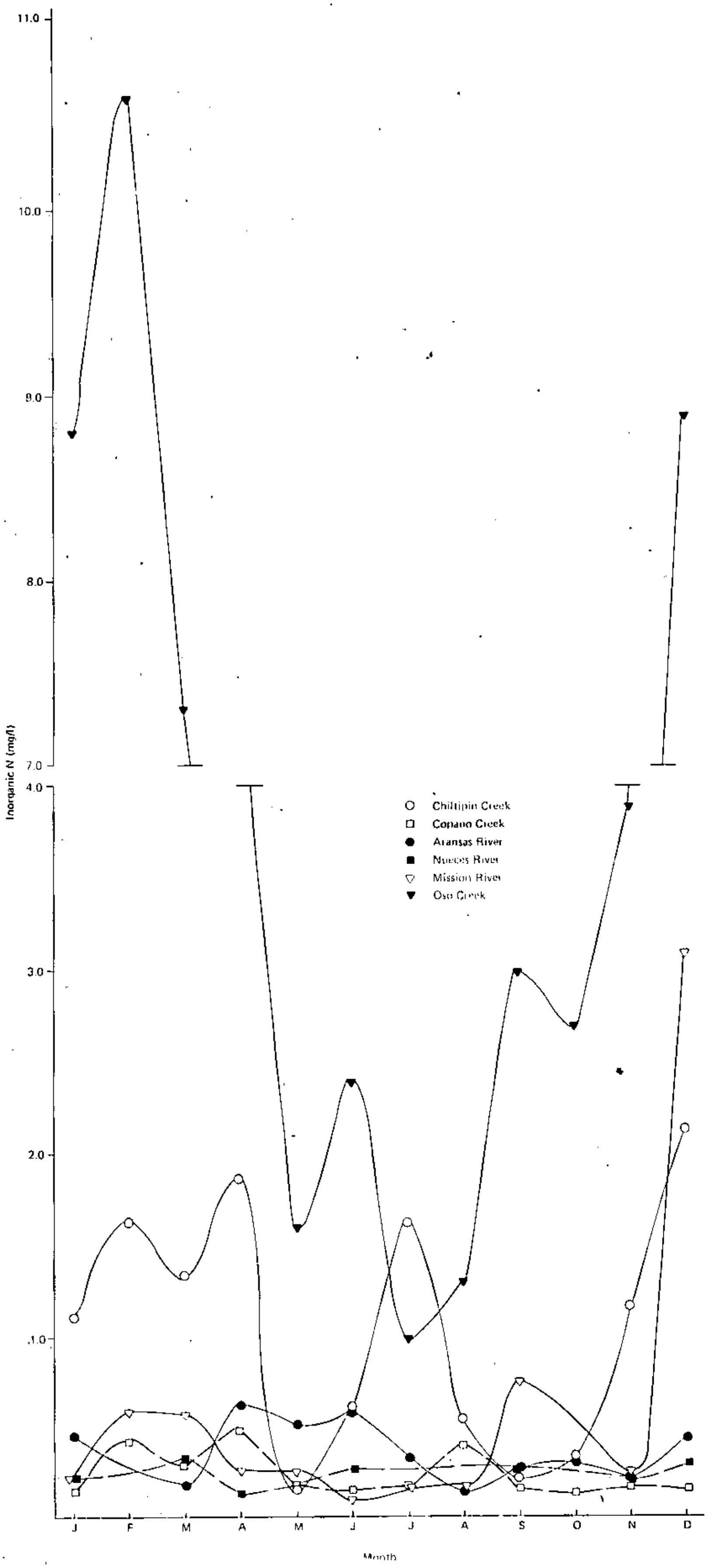


Figure 6-2. Mean Monthly Inorganic Nitrogen Concentrations of Streams Contributory to the Nueces and Mission-Aransas Estuaries

Total phosphorus concentrations exhibited patterns similar to those of inorganic nitrogen (Figure 6-3). With the exception of consistently high values (2 to 10 times greater) for Oso Creek and consistently low values for the Mission River, there appeared to be no readily observable differences in phosphorus concentrations among contributory streams. Mean total phosphorus concentrations in Oso Creek appeared to follow a seasonal trend similar to that shown by inorganic nitrogen. Mean monthly total organic carbon concentrations were highest in Copano Creek and lowest in the Mission River (Figure 6-4). The lack of sufficient data for the Aransas and Nueces Rivers precluded an evaluation of seasonal TOC concentration trends in those streams.

The range of potential nutrient loadings (kg/day) to the Nueces and Mission-Aransas estuaries (from the six major contributing streams) was calculated using the maximum and minimum concentrations observed for each nutrient species (in each of the twelve months, for the entire period of record) and the mean monthly discharge measured at the first non-tidally influenced gaging station (Tables 6-1 through 6-4). Potential Aransas and Nueces River nutrient loadings were calculated by a slightly altered procedure. Since few data points existed for individual months, observed maximum and minimum concentrations over the period of record for each species were used rather than monthly maximum/minimum as was done for the other four streams.

Even though individual concentrations of various nutrient species are higher in the other streams, the total nutrient contribution from the Nueces River dominates those from other major freshwater inflow sources. This demonstrates the importance of freshwater inflow as the dominant factor in estimating nutrient loading. In comparison with the other sources, contributions from Oso Creek are unusually high in proportion to the percent of flow contribution to the estuary, particularly for total phosphorus and inorganic nitrogen. The cause for these high concentrations is uncertain but may result from agricultural runoff and/or effluent from the Robstown and Corpus Christi Westside wastewater treatment plants which are the major sources of flow in Oso Creek.

Marsh Vegetative Production

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

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 (166, 165). 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 (305, 407, 32, 184, 307, 300, 355, 9). As a result, the marshes are large-scale contributors to estuarine productivity, poviding a major source of particulate (detrital) substrate and nutrients to the microbial transformation processes

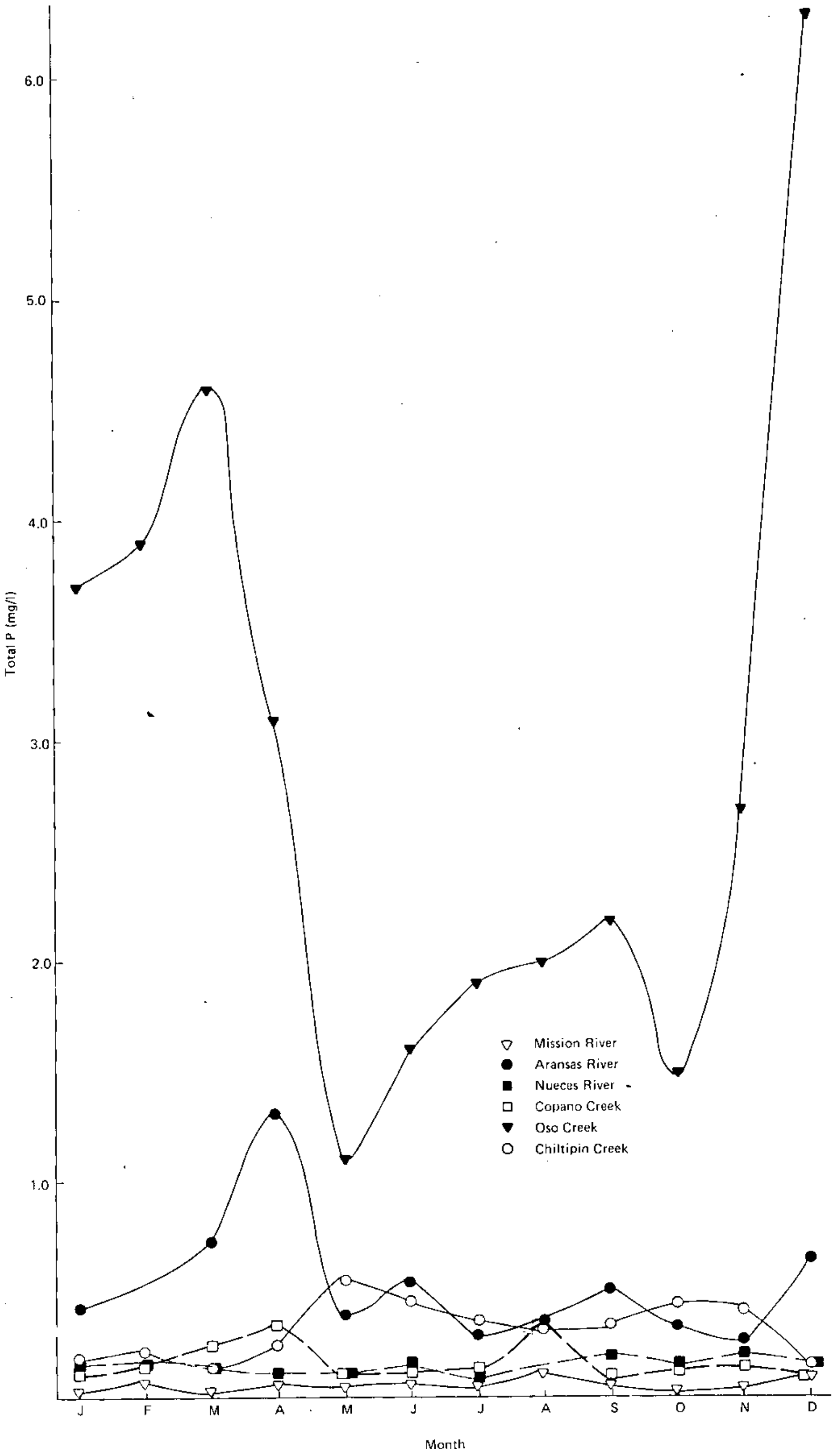


Figure 6-3. Mean Monthly Total Phosphorus Concentrations of Streams Contributory to the Nueces and Mission-Aransas Estuaries

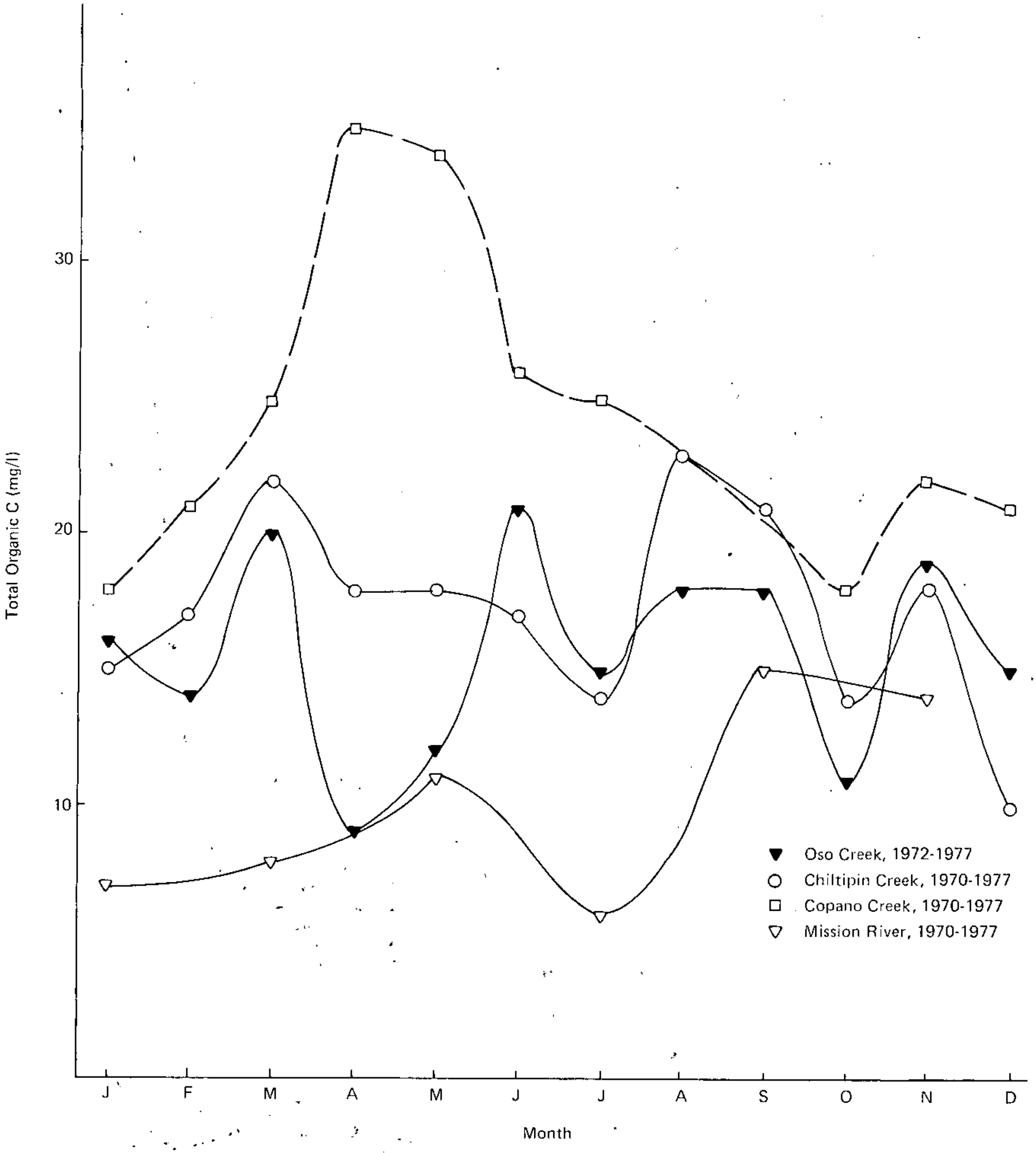


Figure 6-4. Mean Monthly Total Organic Carbon Concentrations of Streams Contributory to the Nueces and Mission-Aransas Estuaries

Table 6-1. Range of Potential Inorganic Nitrogen from Sources Influent to the Nueces and Mission-Aransas Estuaries (kg/day)

Year			Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
1970-1977	Mission R.	High	27	137	118	79	224	34	39	27	2662	*	27	538
		Low	13	135	8	3	62	30	6	0	224	*	8	48
1970-1977	Copano Cr.	High	4	7	1	74	68	65	38	6	120	119	10	3
		Low	1	0	0	14	24	12	5	3	50	3	2	1
1972-1977	Oso Cr.	High	92	66	330	68	109	1155	472	43	1957	1199	152	90
		Low	11	15	52	6	33	152	70	10	41	98	18	15
1970-1977	Chiltipin Cr.	High	13	17	12	35	32	854	815	109	330	155	79	13
		Low	0	0	0	0	10	10	4	1	49	13	2	0
1967-1977	Aransas R.	High	97	58	17	42	260	193	53	33	1188	148	11	15
		Low	3	2	1	1	7	6	2	1	34	4	0	0
1972-1977	Nueces R.	High	899	809	807	690	2978	2531	1388	1346	4605	4364	1028	390
		Low	127	114	114	98	421	358	196	190	651	617	145	55

*No available data

Table 6-2. Range of Potential Organic Nitrogen from Sources Influent to the Nueces and Mission-Aransas Estuaries (kg/day)

Year	:		Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
1970-1977	Mission R.	High	78	*	41	*	668	*	158	*	1704	*	141	*
		Low	2	*	2	*	0	*	4	*	96	*	3	*
1970-1977	Copano Cr.	High	28	15	6	458	419	513	160	21	359	670	32	15
		Low	6	5	2	96	130	67	64	12	30	98	11	5
1972-1977	Oso Cr.	High	13	6	81	14	131	432	277	31	389	388	27	5
		Low	5	0	32	8	64	0	2	0	213	91	0	5
1970-1977	Chiltipin Cr.	High	24	14	5	13	208	595	528	116	1221	362	22	11
		Low	0	1	0	2	70	124	0	0	226	111	0	0

*No available data

Table 6-3. Range of Potential Total Phosphorus from Sources Influent to the Nueces and Mission-Aransas Estuaries (kg/day)

Year			Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
1970-1977	Mission R.	High	4	28	3	14	38	34	10	17	96	20	8	198
		Low	2	7	1	6	5	13	1	3	43	10	0	12
1970-1977	Copano Cr.	High	2	2	1	39	46	42	26	5	85	49	4	2
		Low	1	1	0	20	7	18	7	3	30	18	3	1
1972-1977	Oso Cr.	High	29	28	218	36	50	452	918	65	1006	891	68	44
		Low	17	6	37	3	50	226	117	18	155	139	8	29
1970-1977	Chiltipin Cr.	High	1	2	1	4	106	336	176	35	366	220	17	1
		Low	0	0	0	0	56	18	7	2	92	49	2	0
1967-1977	Aransas R.	High	38	189	53	135	842	627	170	108	3853	481	37	48
		Low	1	2	1	2	10	8	2	1	48	6	1	1
1972-1977	Nueces R.	High	899	809	807	690	2978	2531	1385	1346	4605	4364	1028	390
		Low	127	114	114	98	421	358	196	190	651	617	145	55

Table 6-4. Range of Potential Total Organic Carbon from Sources Influent to the Nueces and Mission-Aransas Estuaries (kg/day)

Year			Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
1970-1977	Mission R.	High	1,345	*	933	*	7,155	*	1,720	*	31,943	*	1,969	*
		Low	0	*	192	*	2,337	*	287	*	0	*	295	*
1970-1977	Copano Cr.	High	348	250	92	3,938	8,609	7,504	3,599	*	*	7,217	866	265
		Low	261	108	43	1,607	6,181	2,765	1,599	*	*	2,113	478	207
1972-1977	Oso Cr.	High	115	102	839	93	725	10,689	3,628	529	5,468	3,882	550	86
		Low	89	38	262	13	363	1,809	2,988	224	2,286	959	167	75
1970-1977	Chiltipin Cr.	High	51	94	96	153	*	5,951	4,064	2,234	15,264	4,398	563	29
		Low	27	51	65	45	*	3,105	1,478	372	8,548	2,846	241	20
1967-1977	Aransas R.	High	666	3,332	941	2,372	14,837	11,035	2,999	1,901	67,855	8,467	647	843
		Low	50	250	71	178	1,113	828	225	143	5,089	635	49	63
1972-1977	Nueces R.	High	13,686	12,314	12,279	10,496	45,310	38,519	21,129	20,477	70,075	66,405	15,641	5,934
		Low	1,955	1,759	1,754	1,499	6,473	5,503	3,018	2,925	10,011	9,486	2,234	848

*No available data

at the base of the food-web which enrich the protein levels and food value for consuming organisms (36, 37, 213, 167, 415, 140, 139, 33, 179, 40, 117, 208, 87, 88, 94). Recent research has demonstrated a correlation between the area of salt marsh vegetation and the commercial harvests of penaeid shrimp (353). 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 (63). 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 marsh habitats. Deltaic marshes at the headwaters of an estuary generally exhibit a dendritic pattern of drainage channels and are especially important because they form a vital link between an inflowing river and its resulting estuary. The direct effects of freshwater inflow/salinity fluctuations are primarily physiological, affecting both seed germination and plant growth, and are ultimately reflected in the competitive balance among plant species and the presence of vegetative "zones" in the marsh (296, 181, 175, 163, 85, 199).

The Nueces and Mission-Aransas estuaries receive major hydrologic input from the Nueces River and the marshes of the Nueces delta. Adams et al. (48) delineated eight hydrological units in the Nueces delta and estimated above ground net primary production of the rooted vascular plants (macrophytes) at 92.4 million dry weight pounds per year (42,000 metric tons/year) over the 13,220 acre (5,350 ha) study area. Annual net productivity (ANP) averaged approximately 7,000 dry weight pounds per acre (785 g/m^2) over the entire study area, with maximum ANP in Spartina spartinae habitats estimated at 15,120 dry weight pounds per acre (1,695 g/m^2).

In addition, Wiersema et al. (47) estimated net periphyton production to range from a minimum of 1.07 dry weight pounds per acre per day (0.120 $g/m^2/d$) in December to a maximum of 5.12 dry weight pounds per acre per day (0.574 $g/m^2/d$) in April. Assuming that an average 25 percent of the study area was inundated, the periphyton ANP can be estimated at approximately 3.31 million dry weight pounds (1,500 metric tons).

Specific estimates of the above ground net primary production of rooted vascular plants (macrophytes) are not available for the deltaic and intertidal marshes of the Mission-Aransas estuary; however, such values are expected to be intermediate to those of nearby marshes where the macrophyte production values have been measured. In this regard, the Nueces delta marshes to the west have an estimated ANP average of 7,000 dry weight pounds per acre (785 g/m^2), while those of the Guadalupe delta to the east have an estimated ANP average of 10,800 dry weight pounds per acre (1,211 g/m^2). Maximum macrophyte production under favorable conditions may exceed 15,120 dry weight pounds per acre (1,695 g/m^2) in this Texas coastal region.

Although the high productivity of these deltaic marsh habitats makes available large amounts of detritus for potential transport to the estuary's aquatic habitats, actual detrital transport is dependent on the episodic nature of the marsh inundation/dewatering process. The vast majority of the primary production in the higher, irregularly-flooded vegetative zones may go into peat production and is not exported (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 the estuarine waters (213).

In many coastal areas the production and nutritive contibution of emergent vascular plants to the estuarine ecosystems is supplemented or even largely replaced by vast submerged seagrass beds. This is particularly true for estuarine areas on the South Texas coast (e.g., Laguna Madre). An established seagrass community is highly productive, provides valuable habitat (food and cover) to economically important estuarine-dependent fish and shellfish, and stabilizes the bottom of the estuary (159, 113, 11).

In the Nueces and Mission-Aransas estuaries, areal extent of submerged vegetation has been estimated by Diener (378) at 16,875 acres (6,828 ha). Dominant species in the Mission-Aransas estuary, particularly Redfish Bay, were Halodule beaudettei, Ruppia maritima, and Thalassia testudinum. R. maritima was the dominant seagrass in Corpus Christi Bay. Henley and Rauschuber (95) have also reported on seagrasses of both estuaries where R. maritima, Halodule beaudettei, and T. testudinum were found to be community dominants in two study areas (Areas 12 and 14) with a total of 17,069 acres (6,906 ha). Syringodium filiforme and Halophila engelmanni were found to be lesser community species in these areas. Transects through seagrass beds near Harbor Island (west side) and Pelone Island (south of Corpus Christi ship channel) were sampled from October 1978 to June 1979 (95). Estimates of the ANP (measured as sum of live biomass losses) in Harbor Island quadrats ranged from 2,900 to 4,440 dry weight pounds per acre (325 to 498 g/m^2) and averaged about 3,600 dry weight pounds per acre (404 g/m^2). Similarly, the ANP of Pelone Island quadrat was estimated at 2,775 dry weight pounds per acre (311 g/m^2). McMillan and Moseley (423) compared the growth and survival of five seagrasses from Redfish Bay in terms of their salinity tolerances and found that Halodule is broadly tolerant (growth to 72 ppt), followed in order of decreasing tolerance by Thalassia, Ruppia, and Syringodium (growth to 40 ppt). The salinity tolerance of Halophila was intermediate but could not be determined by the study. It is noted that the distributional patterns of the seagrasses in the area appear at least partially related to the species-specific salinity tolerances.

Marsh Nutrient Cycling

Deltaic and other brackish and salt marshes are known to be sites of high biological productivity. Emergent macrophytes and blue-green algal mats serve to trap nutrients and sediment as flow velocities decrease. These nutrients are incorporated into the plant biomass during growth periods and are sloughed off and exported to the bay as detrital material during seasons of plant senescence and/or periods of inundation and increased flows into the open bay. The periphery of the Nueces and Mission-Aransas estuaries is primarily sand, mud flats, and intertidal marsh. One extensive deltaic marsh system exists at the point where the Nueces River enters Nueces Bay. Predominant marsh and wetland macrophyte species reported in the Nueces delta are Batis maritima, Borrichia frutescens, Monanthochloe littoralis, Salicornia virginica, Spartina alterniflora, and Spartina spartinae (226, 48).

Studies by Armstrong et al. (273), Dawson and Armstrong (278), Armstrong and Brown (277), and Armstrong and Gordon (275, 276) have been conducted to determine the role of the plants and deltaic sediments in nutrient exchange processes. In most cases these patterns seem to be similar from species to species. The rates of nutrient exchange for marsh macrophytic species and associated sediment in the Nueces delta was found to be similar in magnitude to exchange rates in other Texas coastal marsh systems. Seasonal exchange rates measured under controlled laboratory conditions are presented in Figures 6-5 through 6-10. Total organic carbon is released by each of the subject species. Unfiltered total Kjeldahl nitrogen measurements also reflect the occurrence of a release process. Ammonia nitrogen is taken up, particularly as the growing season progresses. With the exception of the Salicornia reactors, the same pattern appears to hold for nitrate nitrogen uptake. The aberrance of this one species may be due to the low volume of the experimental reactor which precluded the growth of the algal mats; such mats are apparently responsible for a significant amount of nitrogen uptake. Nitrite nitrogen exchange rates are practically zero; the low concentrations indicate that nitrite is being converted to nitrate almost as quickly as it is formed.

Export of total phosphorus and orthophosphate indicates that plant growth in the Nueces delta is not phosphorus limited. Coupled with the evidence of inorganic nitrogen uptake, this would indicate that nitrogen is probably the limiting nutrient in the system. Based on the above data, average seasonal exchange rates have been calculated for six nutrient parameters (Table 6-5).

The areal extent of the Nueces delta composed of algae covered mud flats and emergent marsh vegetation has been determined to be about 4,990 hectares (12,330 acres) (226). Assuming that the exchange rates presented in Table 6-5 are consistent throughout a finite period of inundation, the Nueces delta marsh could export as much as 36,900 kg per day (kg/d) (or 16,773 lbs/d) total organic carbon, 1,550 kg/d (or 705 lbs/d) Kjeldahl nitrogen (largely as organic nitrogen), and 1,250 kg/d (or 568 lbs/d) total phosphorus to the Nueces estuary. This would be in addition to the nutrients delivered to the estuary in the form of large clumps (branches, grass stems, etc.) or as particulate detrital materials from senesced or decayed macrophytes flushed out of the delta during an inundation event.

Wiersema et al. (47) indicated that the Nueces River deltaic marsh was acting as a nutrient sink. It should be noted, however, that the delta was never inundated due to low flow regimes during the study. The study also indicated that large amounts of plant detritus and animal biomass were produced in the marsh.

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..."

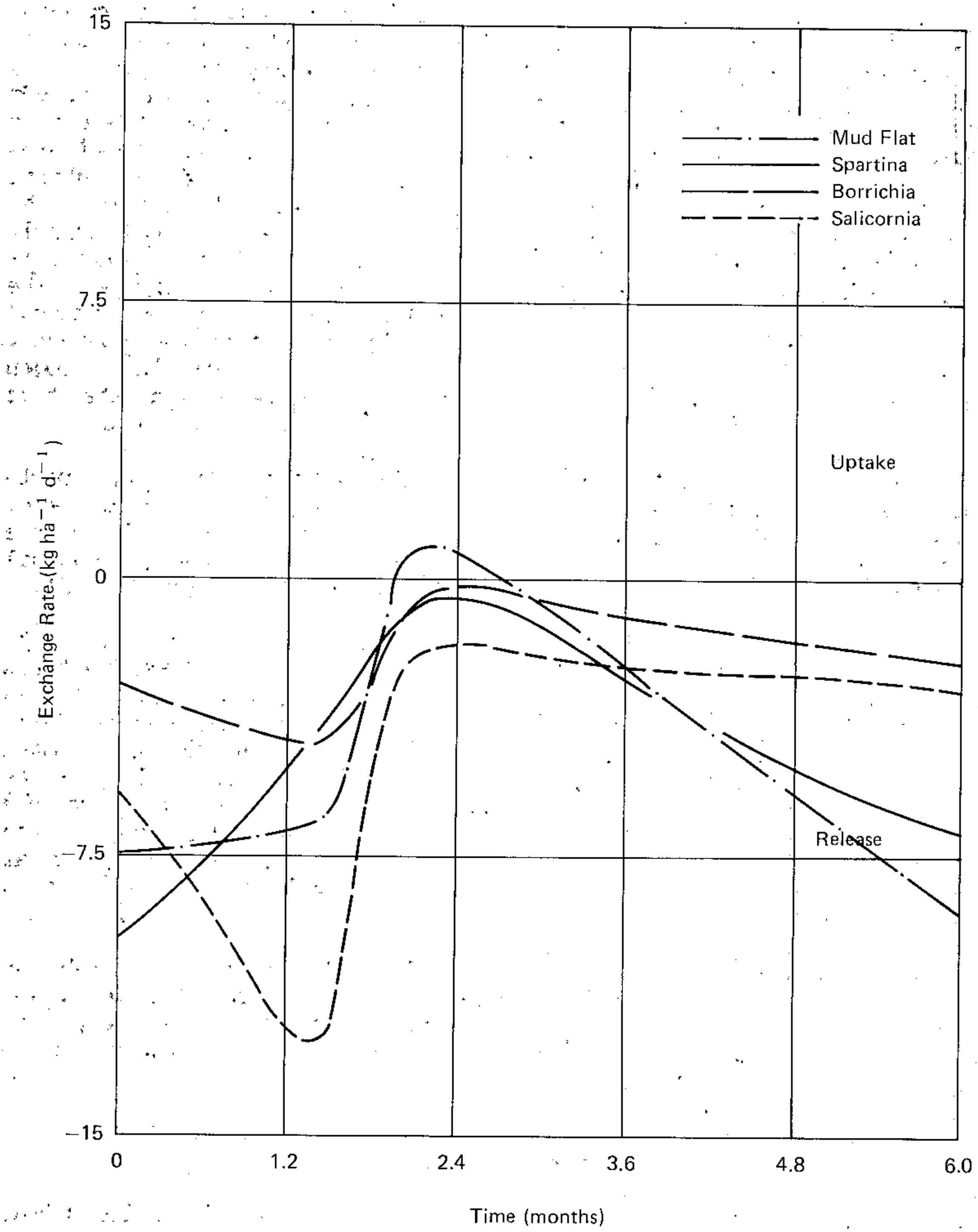


Figure 6-5. Exchange Rates for Total Organic Carbon in Nueces River Delta (276)

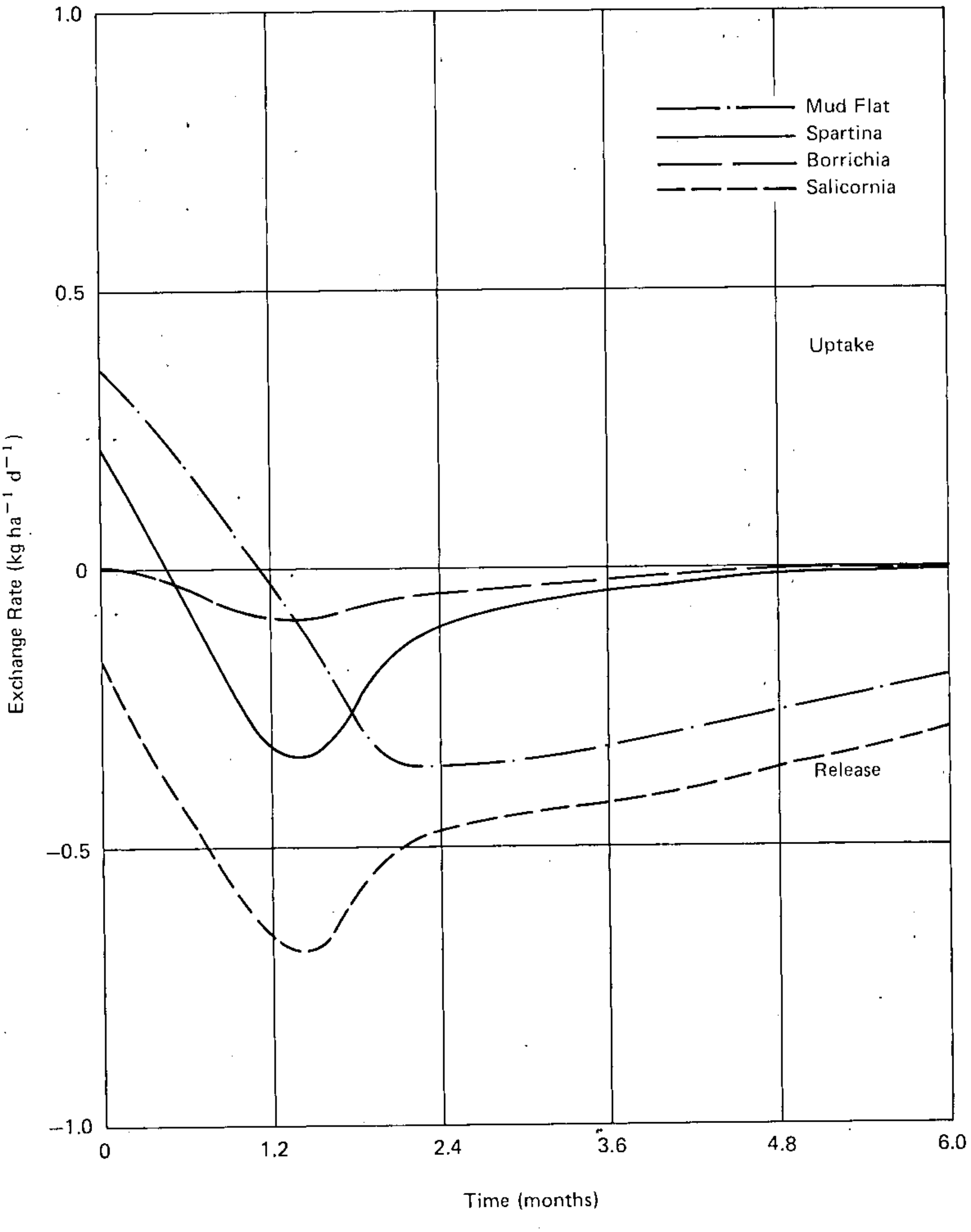


Figure 6-6. Exchange Rates for Unfiltered Total Kjeldahl Nitrogen in Nueces River Delta (276)

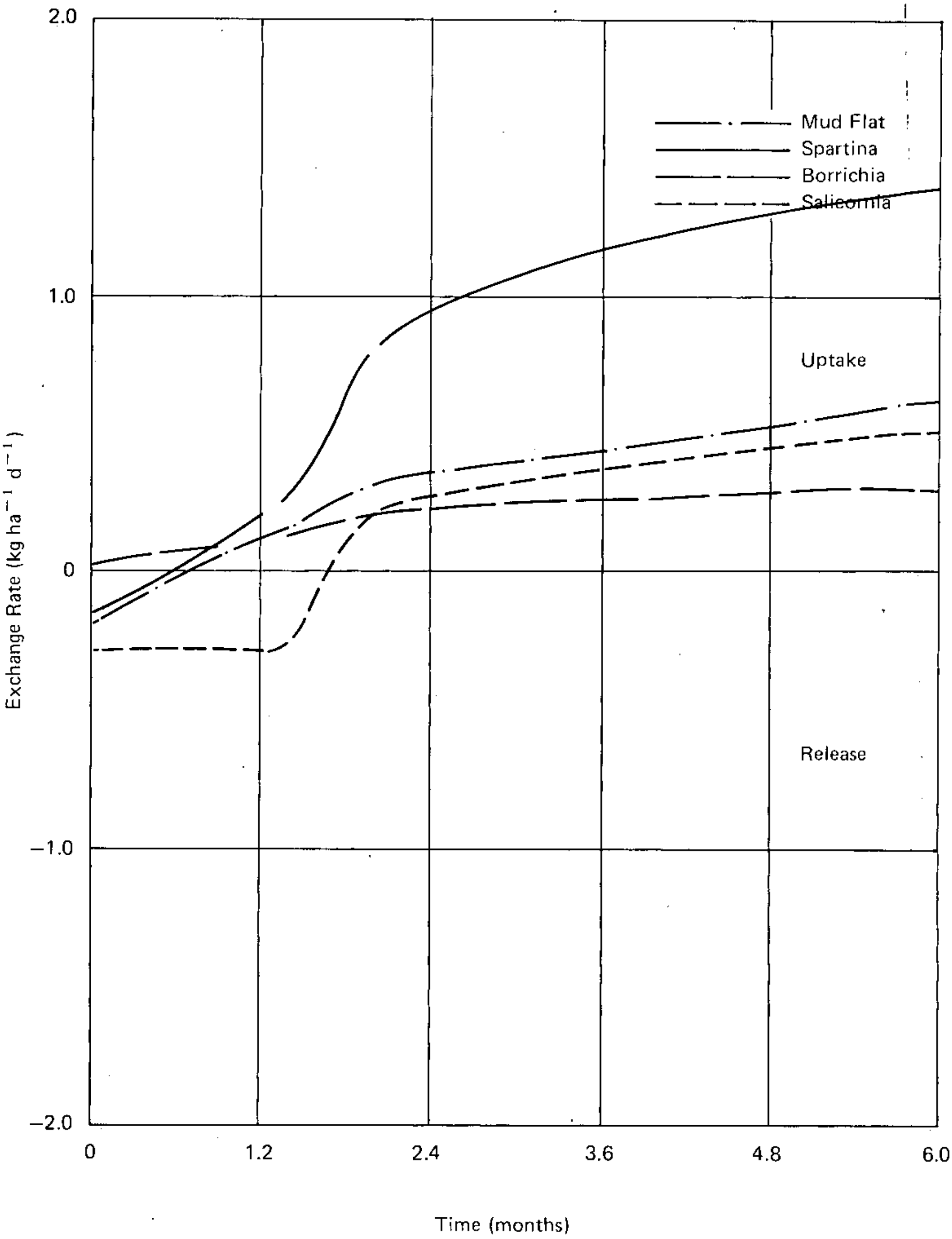


Figure 6-7. Exchange Rates for Ammonia Nitrogen in Nueces River Delta (276)

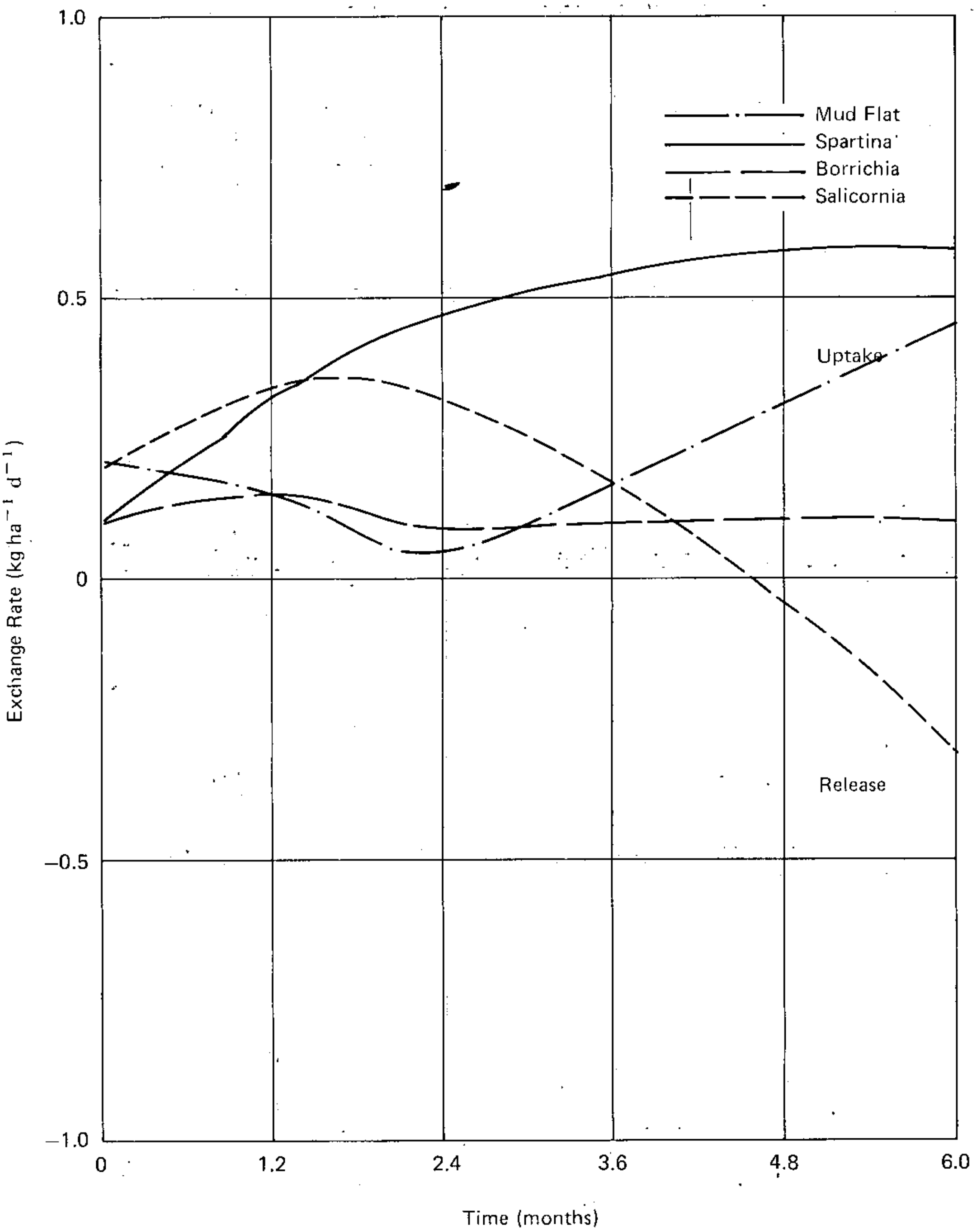


Figure 6-8. Exchange Rates for Nitrate Nitrogen in Nueces River Delta (276)

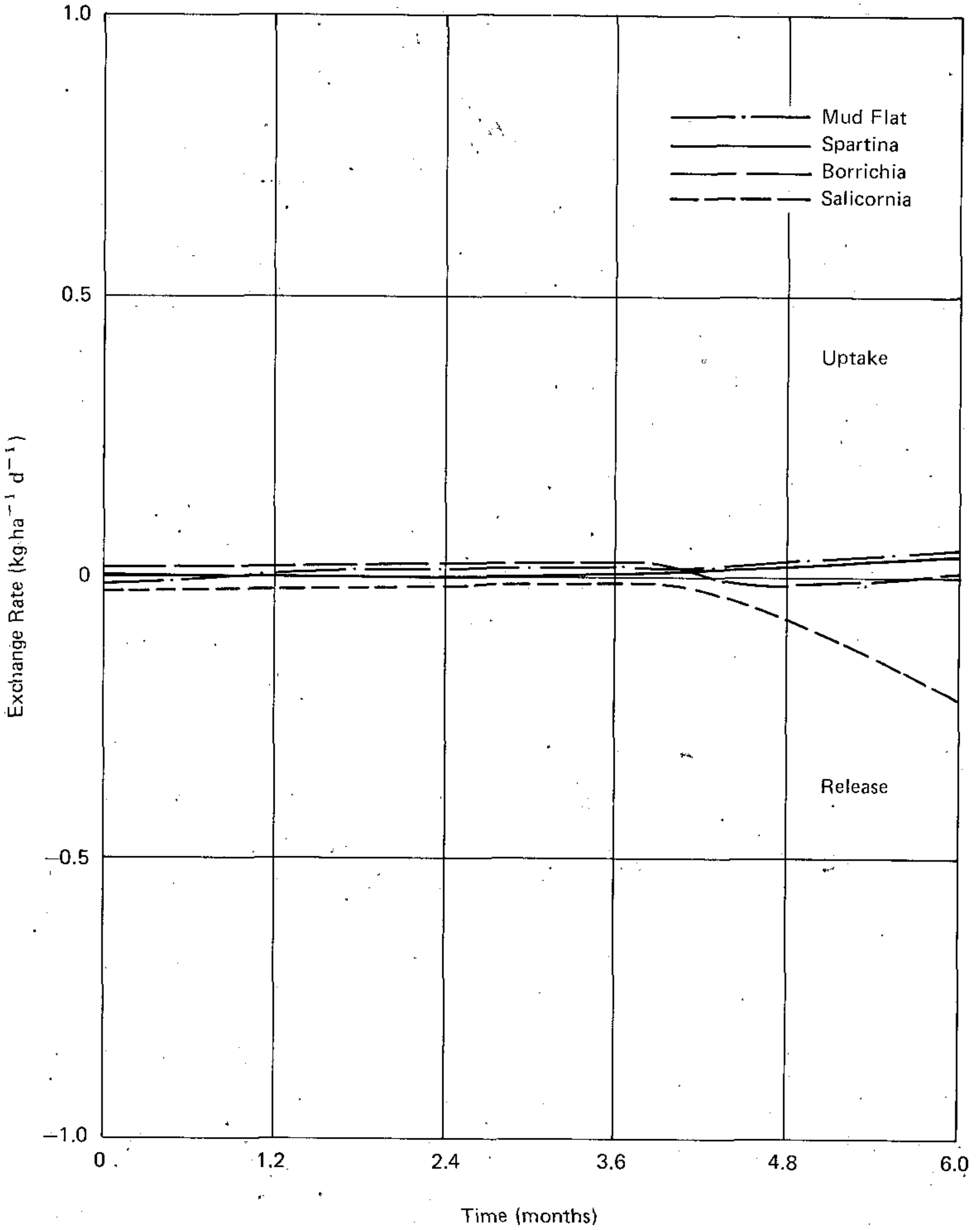


Figure 6-9. Exchange Rates for Nitrite Nitrogen in Nueces River Delta (276)

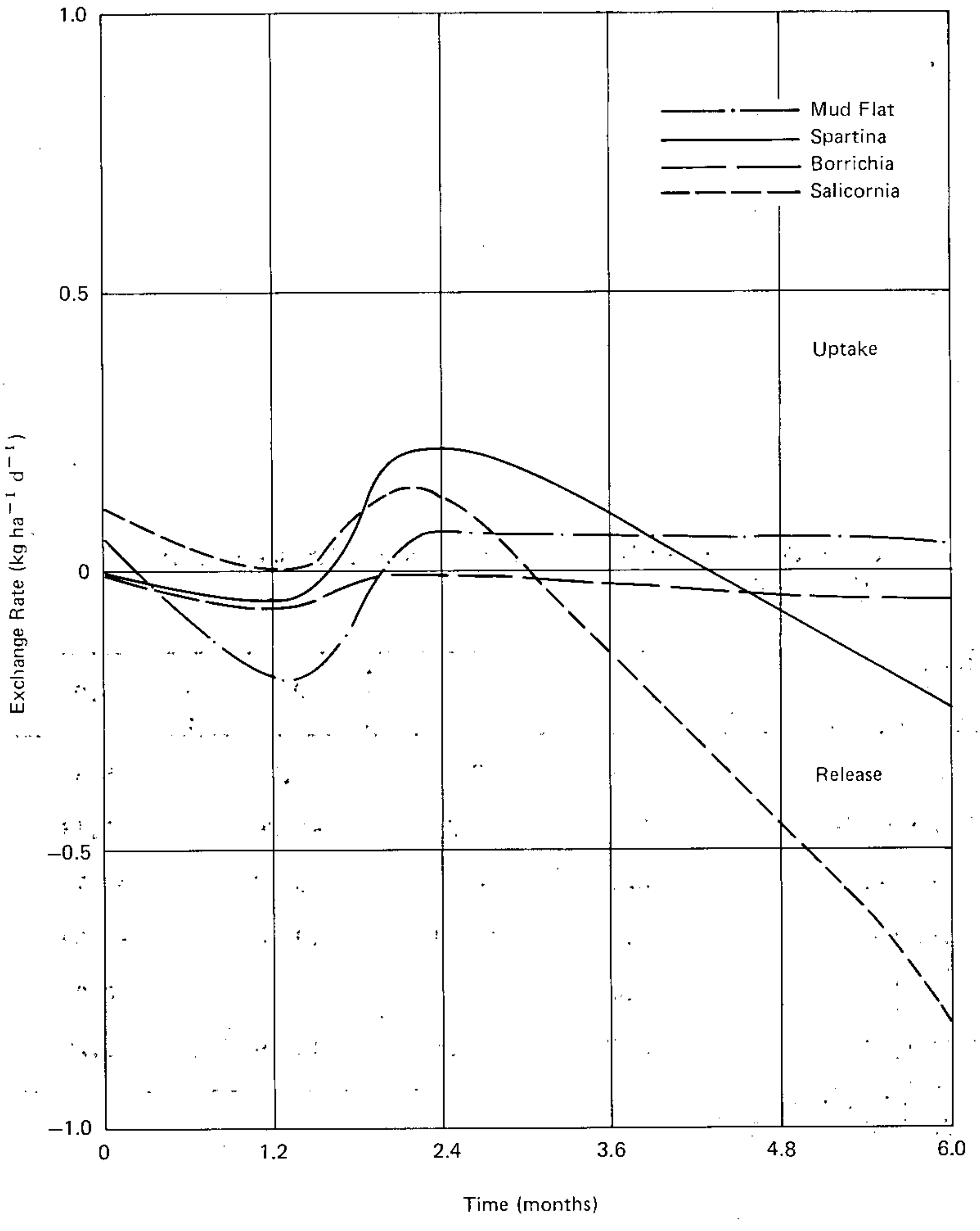


Figure 6-10. Exchange Rates for Unfiltered Total Phosphorus in Nueces River Delta (276)

Table 6-5. Average Seasonal Exchange Rates for Nutrient Species in the Nueces River Delta (kg/ha/d)(276)

Months from beginning of year (Jan. 1)	0	1.3	2.0	6.0
Total Organic Carbon	-6.6	-7.4	-0.7	-5.3
Total Kjeldahl Nitrogen	-0.06	-0.31	-0.26	-0.18
Ammonia Nitrogen	-0.19	+0.01	+0.38	+0.71
Nitrate Nitrogen	+0.15	+0.24	+0.24	-0.39
Nitrite Nitrogen	+0.01	0.0	0.0	0.0
Total Phosphorus	+0.05	-0.06	+0.09	-0.25

\- values indicate release
\+ values indicate uptake

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 following description of the Rincon Bayou area is a by-product of seasonal aerial photographic studies conducted during the 1976 growing season (226).

The Rincon Bayou area, the lower deltaic marsh of the Nueces River, lies in a broad valley, flanked by bluffs on each side. The Nueces River lies along the south side of the marsh and a natural floodway passes through the middle of the marsh, apparently along the old river bed. Rincon Bayou is crossed in a few places by shell roads and once by the right-of-way of the Missouri Pacific Railroad. Scars from drilling and production activities are particularly noticeable at the east end of the Rincon Bayou area where a few old dredged channels and shell roads remain. There appears to be suprisingly little damage from the building of shell-surface roads or even from railroad rights-of-way. The area is bounded on the south by residential, commercial, and industrial (oil storage) development. The bayou is bounded on the north by a considerable level of agricultural and pastoral activity. Although it might be expected that fertilizer runoff might increase the productivity of the adjacent wetlands, this appears not to be the case in the Rincon Bayou area. For the most part, the Nueces delta appears to be most affected by the forces of urbanization and industrialization.

Another item of significant interest is the introduction of the water hyacinth (Eichhornia crassipes) into the western side of Rincon Bayou, brought in, no doubt, by the floods of October 1976. Successful expansion of this exotic species could lead to competition with other native wetland species.

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 and navigational development, oil and gas production, and expansion of agricultural and cattle-raising activities in the coastal zone should be of consuming interest.

Summary

The deltaic marshes are important sources of nutrients for the estuarine system. Periodic inundation events are natural and necessary in order for the marshes of the Nueces and Mission-Aransas estuaries to deliver their potential nutrient stores to the open waters of the bays. This will occur as the slug of freshwater moving across the delta sweeps decayed macrophyte and dried algal mat material out of the system. Dawson and Armstrong (278) found that a sudden inundation event over the delta marshes, following a period of emersion, results in a short period of high nutrient release from the established vegetation and sediments. This period may last one or two days and is followed by a period in which release rates decrease rapidly until they approach the seasonal equilibrium. During periods of high river discharge and/or extremely high tides that immediately follow prolonged dry periods, the contribution of carbon, phosphorus, and nitrogen from the deltaic marshes to the estuarine system can be expected to increase dramatically.

Aerial photographic studies of the Rincon Bayou area have also provided an insight into on-going wetland processes. For the most part, the Nueces River delta appears to be most affected by the forces of urbanization and industrialization. Scars from drilling and production activities are particularly noticeable at the eastern edge of the Rincon Bayou area. 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.

CHAPTER VII

PRIMARY AND SECONDARY BAY PRODUCTION

Introduction

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

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

The phytoplankton (free-floating plant cells) form a portion of the base of this trophic structure as primary producers. Estuaries 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 other suspension feeders; 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 of abundance, and seasonality of the following important ecological groups: phytoplankton, zooplankton, and benthic invertebrates.

Data presented in this report for each of the three lower food chain categories (i.e., phytoplankton, zooplankton, and benthos) were obtained from a 30-month study (October 1972 - March 1975) conducted by the University of

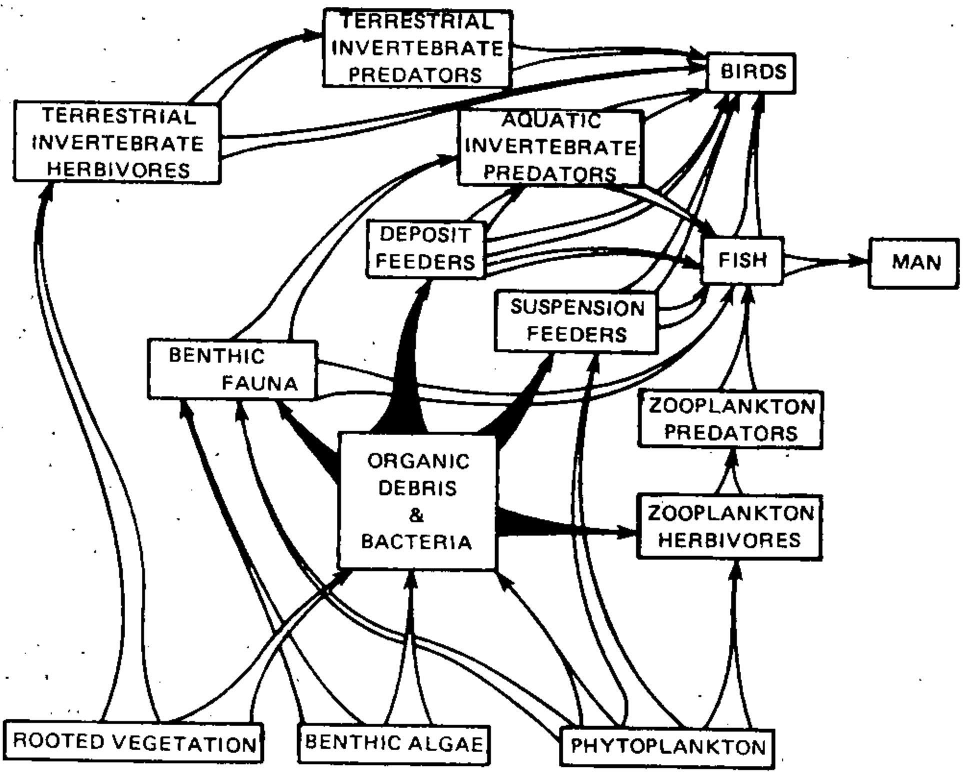


Figure 7-1. Estuarine Food-Web Relationships Between Important Ecological Groups (62)

Texas Marine Science Institute at Port Aransas under interagency contract with the Texas Department of Water Resources (289). The objectives of the study were:

(1) to survey the benthic and planktonic communities and their seasonal fluctuations in the Nueces and Mission-Aransas estuaries;

(2) to determine the nutrient budget of these systems using data collected under the USGS cooperative program;

(3) to define the primary biological productivity of the systems for the project period; and

(4) to correlate nutrient supplies and primary productivity of the estuarine system with seasonal freshwater inflows.

Monthly data collected during the study included hydrographic, benthic, and planktonic information from 30 sites in the Nueces and Mission-Aransas estuaries (Figures 7-2 and 7-3). Hydrographic parameters measured in this study included total water depth, water temperature, conductivity, dissolved oxygen, nutrients, turbidity, and pH. Nutrients included organic nitrogen, nitrate, nitrite, ammonia, total phosphate, orthophosphate, inorganic and organic carbon.

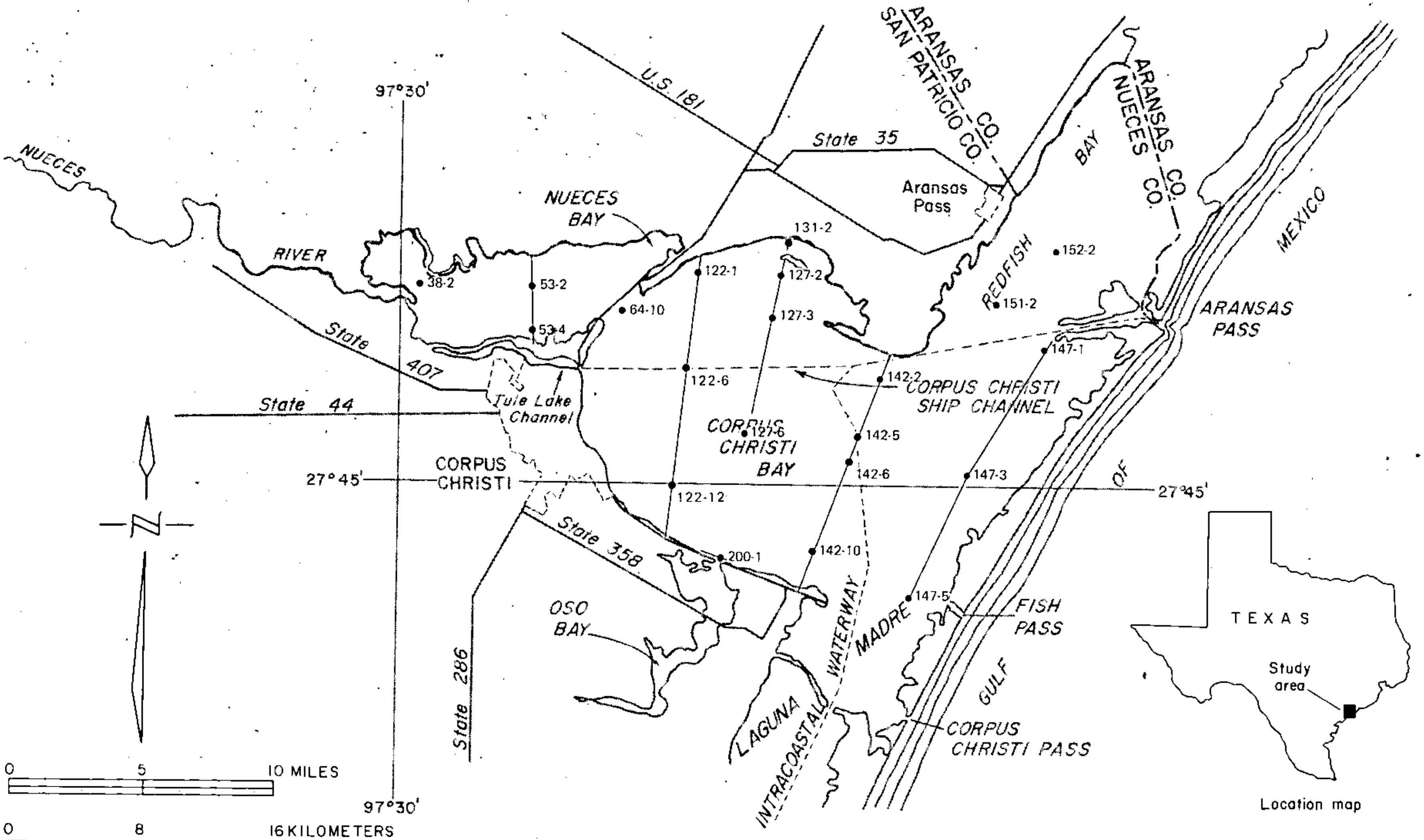
Phytoplankton

Data Collection

According to Holland et al. (289), five taxonomic divisions represented by 248 taxa were collected in the Nueces and Mission-Aransas estuaries from October 1972 through March 1975: Chrysophyta - golden-brown algae [157]; Pyrrophyta - dinoflagellates [45]; Chlorophyta - green algae [27]; Cyanophyta-blue-green algae [15]; and Euglenophyta - euglenoids [4]. The dominant class was the Chrysophyta, the diatoms, which accounted for 62 percent of the total number of phytoplankton species collected. The least abundant division, the Euglenophyta, is predominantly a freshwater group.

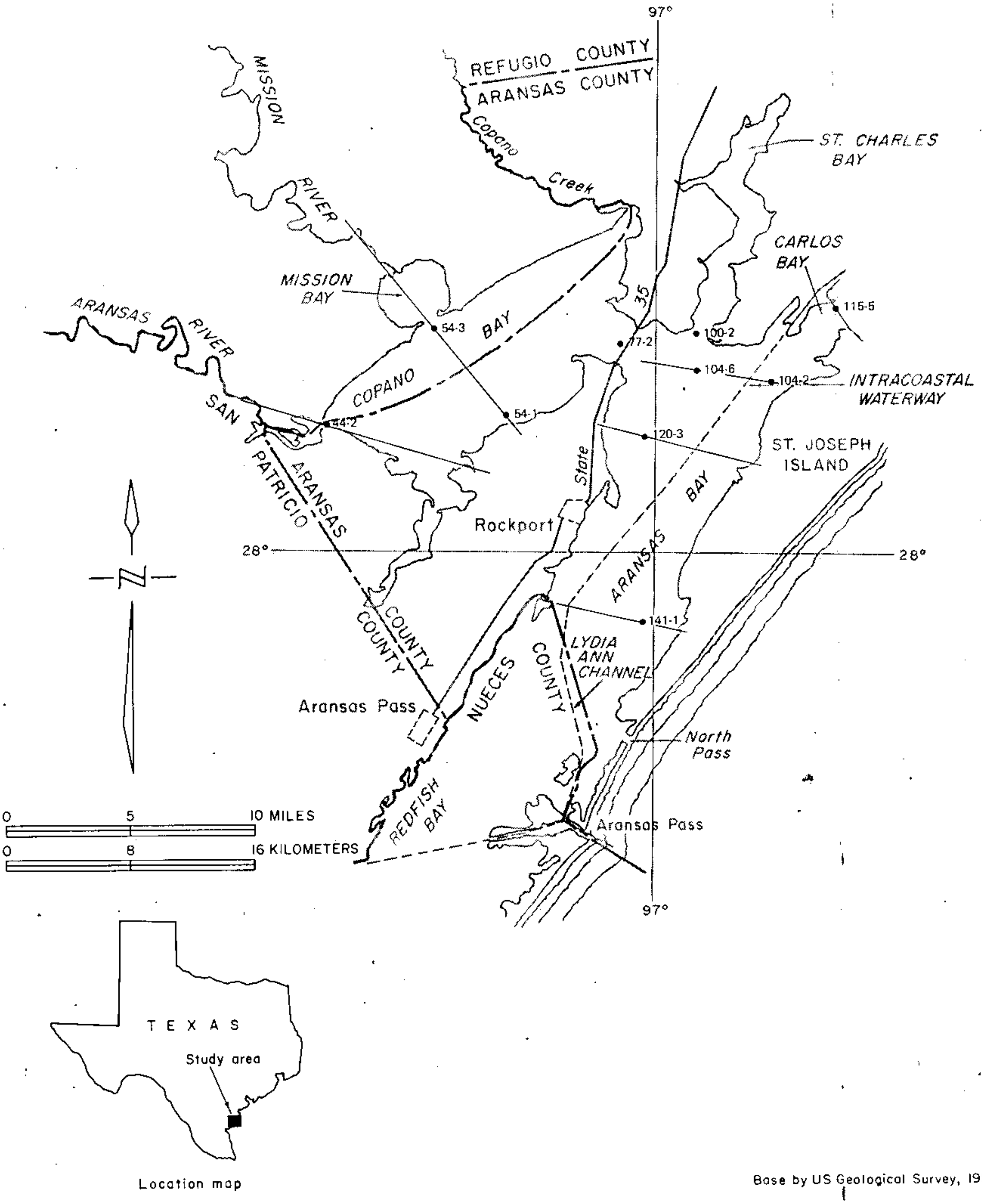
Phytoplankton concentrations in a single sample from the Nueces and Mission-Aransas estuarine study ranged from 81,141,000 cells/l at site 64-10 in Nueces Bay in October 1972 to 150 cells/l at site 53-2 also in Nueces Bay in September 1973. The highest mean monthly standing crop for the study was 20,308,300 cells/l which occurred in Nueces Bay in October 1972; the lowest mean monthly standing crop, 1,700 cells/l, occurred in Copano Bay in November 1972. Species diversity values exhibited a great deal of variability. For example, a diversity value of 4.04 was calculated for the May 1974 sample at site 147-5 in Corpus Christi Bay; the following month the diversity value decreased to only 0.13. No blooming populations were observed in the May sample while an extremely large bloom (2,621,000 cells/l) of Oscillatoria sp. was observed in June 1974. In general, major blooms (greater than 20,000 cells/l) caused extremely low species diversities; high diversity values were usually found in the absence of blooming populations.

Mean standing crop values for Nueces and Corpus Christi Bays fluctuated widely throughout the study period (Figure 7-4). The mean values in Corpus



Base by US Geological Survey, 1956

Figure 7-2. Corpus Christi Bay, Hydrologic and Biologic Sample Sites (289)



Base by US Geological Survey, 1956

Figure 7-3. Copano-Aransas Bay, Hydrologic and Biologic Sample Sites (289)

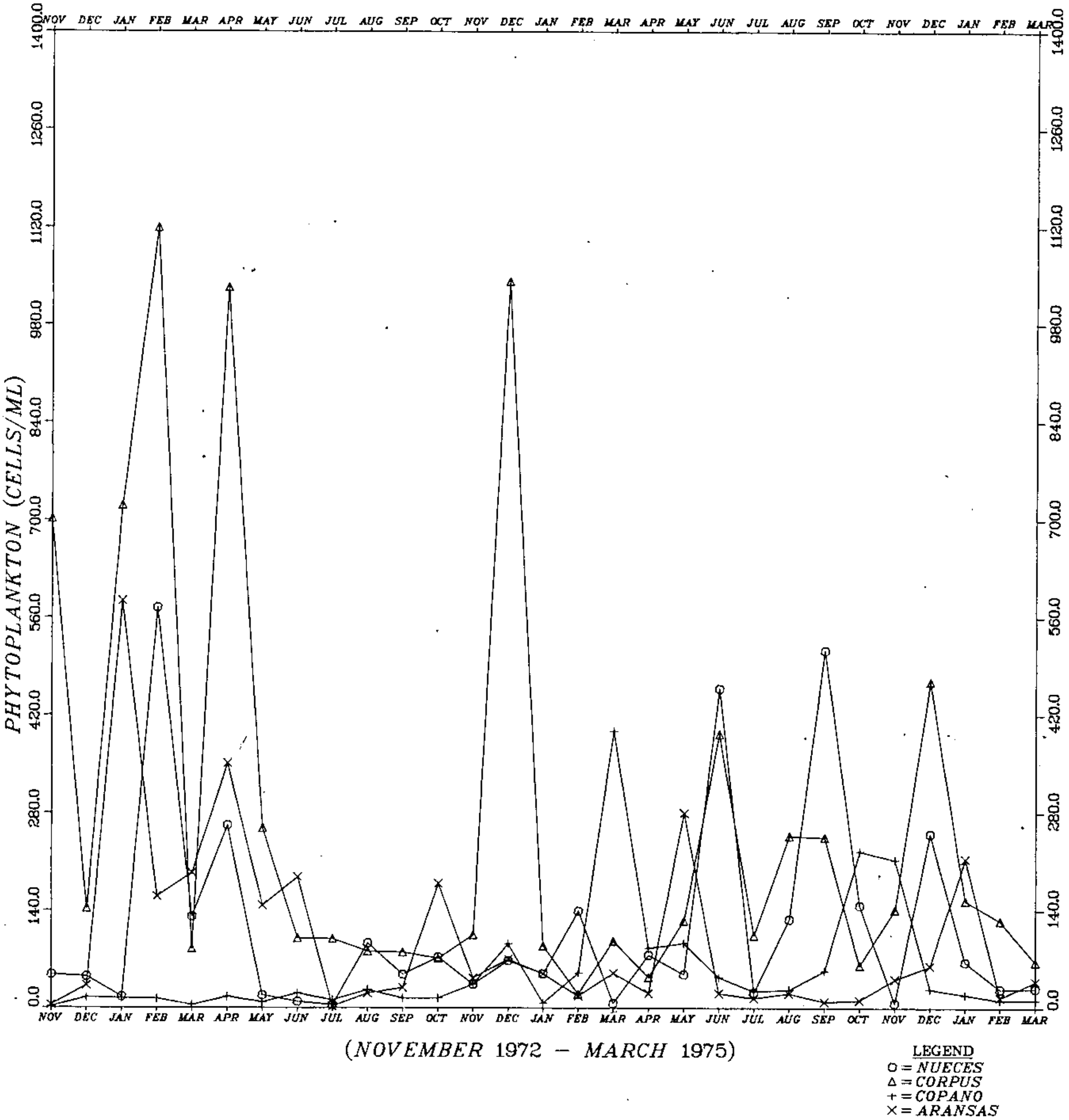


Figure 7-4. Mean Monthly Phytoplankton Densities in Nueces and Mission-Aransas Estuaries, November 1972-March 1975

Christi Bay, however, were generally higher than in Nueces Bay. The four sites in Copano Bay generally exhibited low standing crop values. Populations in Aransas Bay were generally greater than those in Copano Bay and similar to those of Nueces Bay. Blooms of freshwater forms, especially Anabaena sp., Nostoc sp., Chroococcus sp., Merismopedia sp. and others, were observed concommittant with lowering salinities. In general, patterns of extreme abundance were often followed within a month's time by extremely depauperate conditions.

Results of Analyses

Nueces and Mission-Aransas estuarine phytoplankton densities observed during the University of Texas Marine Science Institute study (289) were similar to values reported for other marine areas and estuaries of Texas. Average standing crops for the study period were 790,000 cells/l in Nueces Bay, 276,000 cells/l in Corpus Christi Bay, 55,000 cells/l in Copano Bay, and 100,000 cells/l in Aransas Bay. Moseley et al. (18) found phytoplankton densities of 730,000 cells/l in Cox Bay, while Espey, Huston and Associates (46) reported phytoplankton densities of 133,000 cells/l from Sabine Lake.

Salinity and zooplankton predation exerted the most obvious influence on phytoplankton populations during this study. Salinity regimes in each bay system resulted in distinctly different populations. Oscillatoria sp., Anabaena sp., Anabaenopsis sp., Merismopedia sp., coccoid and filamentous blue-green algae, Stichococcus sp., and others were most often collected in the lower salinity bays, Copano and portions of Aransas and Nueces. Certain species in this group, including Oscillatoria sp., coccoid blue-greens, and Anabaena sp., have been found in Corpus Christi Bay in "lower than normal" salinity regimes for that bay. Other species including Thalassionema nitzschoides, Thalassiosira sp., Chaetoceros affinis, C. curvisetus, C. compressus, and Nitzschia seriata were collected primarily in higher salinity waters. Several "opportunistic" species such as Asterionella japonica, Skeletonema costatum, and to a lesser extent Trichodesmium sp. and Thalassiothrix frauenfeldii, were observed in both high and low salinity waters.

The regular decrease in phytoplankton populations in Corpus Christi Bay (and to a limited extent in Nueces Bay) in February-March throughout the study usually coincided with the springtime warming of the bay water. (This phenomenon was not observed in Aransas or Copano Bays). According to Holland et al. (289), however, the tremendous depletion of phytoplankton populations was probably due to blooms of the zooplankton organism, Noctiluca scintillans, rather than water temperature, per se. Tremendous phytoplankton blooms in Nueces and Copano Bays in September-October 1974 occurred as a result of decreased salinity and lowered levels of zooplankton grazing.

Phytoplankton species vary markedly in ability to withstand changes in salinity. Accurate halobion classification of most species found in the Nueces and Mission-Aransas estuaries is impossible due to insufficient culture experimentation on salinity optima and tolerances. Chu (20) noted that although cell division can continue in freshwater for most estuarine species, most freshwater species cannot grow in salinities exceeding 2 ppt. Foerster (55) found, however, that many freshwater species can resume growth after exposure to seawater if placed in a freshwater medium.

Estuarine plankton were divided by Perkins (178) 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 limited survival potential." The Nueces and Mission-Aransas estuaries apparently support phytoplankton populations derived from the entire range described above.

Water temperature is a major factor in phytoplankton distribution in many areas. Temperature acts directly by controlling the rates of metabolism and growth (154, 56) and the rates of photosynthetic and respiratory processes. Indirectly, the effects of temperature on predatory zooplankton populations, water movement (spring and fall turn overs), and water viscosity are extremely important to the maintenance and distribution of phytoplankton populations. The lack of visible direct effects on phytoplankton populations in the study area was attributed to the relative constancy of water temperatures through time. Holland et al. (289) reported that water temperatures generally fall between 15° C and 30° C in the Corpus Christi Bay region, with extreme low temperatures occurring during December, January, and February. Mean temperatures dropped below 15° C only during the first winter of the study. Indirect effects, especially the regular zooplankton "blooms," had significant effects, as described above, on phytoplankton standing crops in Corpus Christi and Nueces Bays. Temperature effects on water viscosity and nutrient enriching turnovers in the study area were negligible due to the shallowness and the wind-driven hydrodynamic aspects of the bay waters.

Zooplankton

Data Collection

According to Holland et al. (289), a total of 319 zooplankton organisms representing 16 phyla were identified during the 30-month study. The most prominent phylum was the Arthropoda, which accounted for 73 percent of the organisms identified. The chordates accounted for eight percent, the annelids for five percent, and the rotifers for three percent. The remaining 12 phyla (including four miscellaneous organisms) accounted for 11 percent. The freshwater zooplankton assemblages included such organisms as the cyclopoid copepods of the genus _Cyclops_ and cladoceran water fleas of the genus _Daphnia_. The brackish or estuarine species were commonly represented by the calanoid copepods _Acartia tonsa_ and _Paracalanus crassirostris_, or the cyclopoid copepod _Oithona_ sp. Marine species from the neritic Gulf waters were represented by the calanoid copepods _Centropages hamatus_ and _Labidocera aestiva_, the bioluminescent dinoflagellate _Noctiluca scintillans_, and the chordate larvacean _Oikopleura_.

Mean monthly zooplankton standing crops in Nueces Bay ranged from 7,186 to 10,373 individuals/m^3 during 1972 (beginning in October), from 832 to 6,411,456 in 1973, from 1,509 to 8,027,855 in 1974, and from 12,375 to 44,546 in 1975 (through March). Ranges in Corpus Christi Bay were 1,722 to 81,195 individuals/m^3 in 1972, 4,467 to 53,657,037 in 1973, 4,694 to 10,190,122 in 1974, and 20,640 to 431,488 in 1975. Copano Bay mean standing crops ranged from 5,724 to 7,813 individuals/m^3 in 1972, 2,758 to 53,536 in 1973, 1,296 to 19,470 in 1974, and 6,383 to 12,938 in 1975. Values in Aransas Bay ranged from 2,497 to 14,473 individuals/m^3 in 1972, 2,531 to 36,156 in 1973, 6,282 to 3,008,679 in 1974, and 8,091 to 14,637 in 1975.

Zooplankton populations illustrated greater seasonal fluctuations than did phytoplankton. Peaks in standing crops were observed during the early spring each year of the study. Mean monthly densities showed tremendous variation — up to two orders of magnitude — over short periods of time. The mean monthly density for all stations ranged from 3,791 individuals/m^3 in January 1973 to 14,183,963 individuals/m^3 in March 1973.

Standing crops of brackish water-marine zooplankton and freshwater zooplankton at stations 38-2 (Nueces Bay), 200-2 (Corpus Christi Bay), and 44-2 and 54-3 (Copano Bay) were apparently directly affected by salinity changes. Other stations were affected by freshwater inflow, but these four stations were closest to sources of freshwater inflow. Table 7-1 illustrates the effects of salinity changes on brackish water-marine zooplankton and freshwater zooplankton at these selected stations from April 1974 through March 1975. Decreases in standing crops of brackish water-marine zooplankton and increases in freshwater zooplankton resulted from major influxes of freshwater in Nueces Bay at station 38-2 in August and September 1974 and in Copano Bay at stations 44-2 and 54-3 in September 1974. Conversely, salinity increases at stations 44-2 and 54-3 in November 1974 produced increased numbers of brackish water-marine zooplankton.

Although some species were found during certain seasons or only in a certain bay system, a number of organisms occurred throughout the study period in all areas. Some of the common species included Acartia tonsa, Paracalanus crassirostris, Oithona spp., Pseudodiaptomus coronatus, and barnacle nauplii.

Acartia tonsa was the dominant zooplankton in the system. This species was nearly ubiquitous throughout the salinity/temperature ranges. The lowest catches, however, occurred during periods of low salinity. Paracalanus crassirostris populations were apparently restricted from becoming established in large numbers in Nueces and Copano Bays because of the low salinities. Comparable numbers occurred in Corpus Christi and Aransas Bays with no seasonal preference indicated. Oithona spp. exhibited a preference for the warmer months of spring and summer in Copano and Aransas Bays. This seasonal pattern was not evident in Nueces and Corpus Christi Bays, indicating the probable presence of a mixture of species with different temperature preferences. The warmer months of spring, summer, and fall produced the highest catches of Pseudodiaptomus coronatus, indicating perhaps that reproduction is induced by warmer temperatures. Barnacle nauplii were abundant throughout the year with greatest catches occurring during the colder months.

Neritic species which appeared in the estuaries on a seasonal schedule included such species as Centropages velificatus, C. hamatus, and Noctiluca scintillans. Temperature and to a lesser degree, salinity, acted to separate the ecological niches of C. velificatus and C. hamatus. A warm water, stenohaline species, C. velificatus, was collected primarily in lower Corpus Christi and Aransas Bays in October 1972, May - November 1973, April-December 1974 and March 1975. The cooler water, euryhaline species, C. hamatus, was collected throughout the systems from November 1972-April 1973, December 1973-March 1974, and November 1974-March 1975. The seasonal occurrence of N. scintillans was apparently associated with cooler temperatures of winter and

Table 7-1. Effect of Salinity Changes, on Zooplankton Standing Crop a/ at Selected Stations (289).

		Nueces Bay Station 38-2			Corpus Christi Bay Station 200-2		
		Salinity (ppt)	Brackish-Marine Zooplankton	Freshwater Zooplankton	Salinity (ppt)	Brackish-Marine Zooplankton	Freshwater Zooplankton
Apr.	1974	17.40	36,093	0.0	25.30	12,541	0.0
May	1974	12.00	6,747	0.0	25.00	3,436	0.0
June	1974	13.40	17,551	0.0	26.00	15,083	0.0
July	1974	19.30	3,028	0.0	29.00	5,330	0.0
Aug.	1974	0.40	1,565	3,680.0	35.20	21,043	0.0
Sept.	1974	0.20	168	3,867.0	28.70	34,327	0.0
Oct.	1974	10.90	2,480	0.0	29.20	8,110	0.0
Nov.	1974	17.10	1,181	0.0	21.30	3,895	0.0
Dec.	1974	5.50	435	8.0	25.40	1,373	0.0
Jan.	1975	15.20	1,721	1.0	27.20	8,257	0.0
Feb.	1975	14.10	1,178	0.0	33.60	226,795	0.0
Mar.	1975	17.00	9,280	0.0	31.00	28,388	0.0

		Copano Bay					
		Station 44-2			Station 54-3		
		Salinity (ppt)-	Brackish-Marine Zooplankton	Freshwater Zooplankton	Salinity (ppt)	Brackish-Marine Zooplankton	Freshwater Zooplankton
Apr.	1974	9.40	10,890	0.0	9.00	7,100	0.0
May	1974	6.50	14,994	1.0	11.50	3,814	0.0
June	1974	5.90	4,177	21.0	8.60	10,427	0.0
July	1974	8.80	6,386	0.0	9.30	16,298	0.0
Aug	1974	11.50	1,802	0.0	11.50	5,338	0.0
Sept.	1974	0.20	104	1,708.0	0.40	176	1,319.0
Oct.	1974	4.20	388	0.0	6.20	9,923	0.0
Nov.	1974	6.40	10,565	0.0	6.5	35,055	0.0
Dec.	1974	5.10	17,973	20.0	5.00	7,488	0.0
Jan.	1975	7.60	5,078	2.0	8.0	10,209	0.0
Feb.	1975	9.70	4,191	1.0	11.20	20,904	0.0
Mar.	1975	10.60	8,390	0.0	10.20	11,702	0.0

a/ Counts are individuals/m^3

spring. Greatest concentrations were collected in Corpus Christi and lower Nueces and Aransas Bays. Populations in upper Nueces, Copano, and Aransas Bays were restricted due to low salinities.

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 consist of animal species whose earliest life stages are planktonic but are otherwise not considered to be plankton (e.g., larval stages of barnacles, oysters, shrimp, crabs, and fish).

Many zooplankton species found in the Nueces and Mission-Aransas estuaries are widely distributed along the coasts of the United States, while others may even have a world wide distribution. For example, Green (62) 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 Holland study. Holland et al. (289) reported that naupliar larvae and calanoid copepods were the dominant zooplankton forms in the Nueces and Mission-Aransas estuaries. This study is in agreement with zooplankton studies conducted by James (350) and Espey, Huston and Associates (46) in Sabine Lake, Gilmore et al. (257) in Lavaca Bay, and Matthews et al. (255) in San Antonio Bay. Maximum and minimum mean monthly densities in the Nueces and Mission-Aransas estuaries were also similar to results from the studies mentioned above (Table 7-2).

Holland et al. (289) found that temperature and salinity were the two most important factors regulating the species composition, seasonal occurrence, and distribution of zooplankton populations in the Nueces and Mission-Aransas estuaries. The ecological niches for zooplankton are such that optimal conditions for growth and survival occur at different times during the year for different species. Optimal conditions for a given species result in high numbers of individuals for that species as long as favorable conditions last. If conditions are favorable for more than one species at the same time, the dominant or more competitive species will be found in the highest numbers followed by smaller increases in populations of the other species involved.

Freshwater inflow can influence zooplankton in several ways. Estuarine zooplankton standing crop composition can be altered by importation of freshwater species. Inflow can also transport zooplankton food resources into the system in the form of phytoplankton and detritus; however, zooplankton communities may also be adversely affected by increased river inflows. Sudden shifts in salinity and flushing out of autochthonous populations can decrease zooplankton standing crops. Perkins (178) reports that the primary factor influencing the composition and abundance of estuarine zooplankton is development rate versus flushing time. In addition, Holland et al. (289) found that freshwater inflow/salinity changes had a direct effect on the standing crop of brackish water-marine zooplankton in adjacent estuarine systems of the Corpus

Table 7-2. *Range of Mean Monthly Zooplankton Densities* (individuals/m^3)

System	Minimum	Maximum
Nueces Bay (289)	832 (Oct. 1973)	8,027,855 (Feb. 1974)
Corpus Christi Bay (289)	1,722 (Dec. 1972)	53,657,037 (Mar. 1973)
Copano Bay (289)	1,296 (Sept. 1974)	53,536 (Feb. 1973)
Aransas Bay (289)	2,497 (Dec. 1972)	3,008,679 (Feb. 1974)
Sabine Lake (46)	381 (Apr. 1975)	20,042 (Oct. 1974)
Lavaca Bay (257)	1,980 (Oct. 1973)	27,846 (Feb. 1974)
San Antonio Bay (255)	820 (June 1973)	46,296 (Feb. 1973)

Christi Bay complex. In all cases the result was the same, a decrease in the standing crop of brackish water-marine zooplankton and an increase in freshwater zooplankton whenever inflows were great and salinities depressed. Saltwater intrusions, on the other hand, act to (1) transport marine zooplankton into the system; (2) transport marine phytoplankton as a food source; and (3) increase salinity.

Benthos

Data Collection

According to Holland et al. (289), 395 benthic species representing 14 phyla were collected from sediment samples during the 30-month study. Invertebrates accounted for 379 species. The remaining 16 taxa included one hemichordate, two urochordates, one cephalochordate, and 12 chordates. The most prominent phylum was the Annelida which accounted for 32 percent (126 taxa) of the species identified. The Mollusca and the Arthropoda each accounted for 29 percent, and the remaining 11 phyla accounted for 10 percent.

The most prominent group of organisms, numerically, spatially, and temporally, collected during the study were the polychaetes, phylum Annelida. One hundred twenty-six polychaete species were collected, 40 of which had not been previously reported from the study area. The most abundant polychaete, *Mediomastus californiensis*, was ubiquitous throughout the study area. Other polychaetes that were practically ubiquitous were *Streblospio benedicti*, *Prionospio pinnata*, *Cossura delta*, *Glycinde solitaria*, and *Gyptis vittata*.

The second most taxonomically diverse phylum was the Mollusca. Of the 114 taxa enumerated, 68 were pelecypods, 44 were gatropods, one was an amphinurian, and one was a scaphapod. In general, although the molluscs were taxonomically diverse, they were not numerically abundant. *Mulinia lateralis*, *Lyonsia hyalina floridana*, and *Macoma mitchelli* were the most abundant pelecypods. The gastropods were never numerically dominant.

The phylum Arthropoda was represented by 112 taxa, of which 108 were crustaceans. Three insect species were collected; however, these were thought to be "accidentals" brought in by freshwater inflow. The amphipods and decapods comprised the bulk of the arthropods, both taxonomically and numerically. Only limited numbers of copepods, mysids, barnacles, cumaceans, and isopods were collected.

The mean monthly number of benthic organisms collected per 0.5 ft^3 sample ranged from 67 (December 1973) to 3,081 (April 1973) in Nueces Bay, from 148 (October 1973) to 1,368 (December 1972) in Corpus Christi Bay, from 4 (November 1972) to 1,302 (December 1974) in Copano Bay, and from 22 (October 1972) to 364 (January 1975) in Aransas Bay. Copano Bay generally had the lowest mean monthly standing crops of the four bay systems studied. Aransas Bay sites were among the least variable in mean monthly standing crops through time. For the total project period, Corpus Christi Bay had the highest mean monthly standing crop values followed by Nueces, Aransas, and Copano Bays, in that order (Figure 7-5). According to Holland et al. (289), Corpus Christi and Nueces Bays also exhibited the highest species diversity while Copano Bay had the lowest.

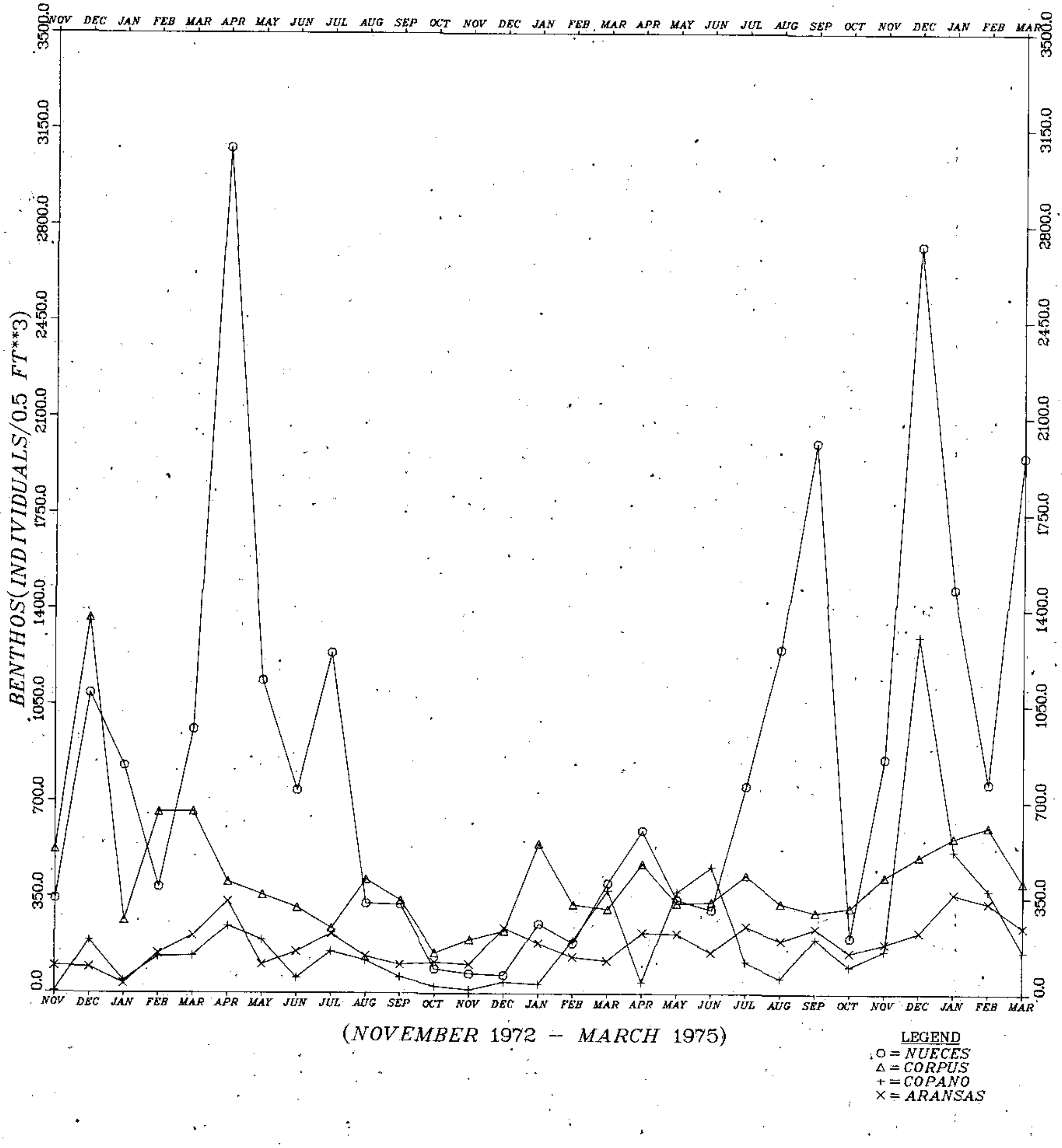


Figure 7-5. Mean Monthly Benthos Densities in Nueces and Mission-Aransas Estuaries, November 1972-March 1975

Holland et al. (289) performed cluster analysis of 104 selected benthos species in each of the two major bay areas (Copano-Aransas and Corpus Christi-Nueces) for the period October 1972 - December 1974. From the analysis it became readily apparent that the two bay regions were distinctly different in the clusters of organisms inhabiting them. Less well-defined clusters appeared in the Copano-Aransas Bay system, although each bay system exhibited a unique group of organisms that was more or less ubiquitous through space and time. In the Corpus Christi-Nueces Bay system, this group included the polychaetes Mediomastus californiensis, Streblospio benedicti, Prionospio pinnata, Glycinda solitaria, Gyptis vittata, and Cossura delta. The molluscs Mulinia lateralis, Lyonsia hyalina floridana and the rhynchocoel Cerebratulus lacteus were often clustered with this group. The Copano-Aransas Bay system exhibited a smaller, less consistent, and "less ubiquitous" group which most often contained the polychaetes Mediomastus californiensis and Streblospio benedicti. Several other polychaetes were sporadically grouped with this cluster to form a "nearly" ubiquitous group.

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 (62).

The benthic invertebrates of the South Texas estuaries comprise a rich and diverse fauna, incorporating Gulf, southern Atlantic and sub-tropical fauna. A large number of benthic species were recorded for the first time along the Texas coast; however, the composition of the benthic fauna from this study was similar to that of other studies along the Texas coast (289). Polychaetous annelids comprised 32 percent of the faunal list. Molluscs and arthropods each comprised approximately 30 percent of the benthic organisms found during the study.

Harper (216) studied the distribution of benthic organisms in undredged control areas of San Antonio Bay and found an almost logarithmic decrease in benthic populations with increased salinity. Holland et al. (289) also found this to be true in Nueces Bay where an inverse relation was found between salinity and standing crop. On the other hand, Harper (216) found that increases in benthic populations, associated with decreased salinity, were 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. Gilmore et al. (257) reported that benthic populations in Lavaca Bay were not significantly related to freshwater inflows; however, significant relationships were discovered between benthos and such hydrological parameters as bottom salinity, turbidity, total carbon, organic nitrogen, and nitrate.

Although monthly benthos standing crop values were generally influenced by salinities, sediment type was also found to be a major factor affecting benthic invertebrates. This was demonstrated most dramatically when site

122-12 in Corpus Christi Bay was moved off the shell pad at the marking oil well after 3 months of collecting. Numbers of species and standing crops both noticeably declined. Many species including *Pomatholeios kraussi*, *Petrolisthes armatus*, *Nereis succinea*, *Stauronereis rudolphi*, *Rhithropanopeus harrissi*, *Panopeus herbstii*, and *Eurypanopeus depressus* were not collected subsequently at that site.

Holland's cluster analysis revealed two "groups" of benthic organisms: those with little or no limitations on the distribution (the ubiquitous and sub-ubiquitous groups) and those with environmental limitations, primarily substrate and salinity. The latter group of organisms included those (1) consistently found in or on oyster clumps, (2) requiring a shelly substrate, and (3) able to survive without large amounts of shell. The sediment type partially masked the lesser effects of salinity. For example, most specimens collected in the high salinity areas of the bays were found on a shelly substrate. Since there was more than one type of substrate at the lower bay sites, it was not clear which factor, salinity or substrate, controlled the organisms' occurrence. In general, Holland found that standing crops were directly related to salinity. Larger populations and greater diversities were accompanied by higher salinities. Conversely, lowered salinity regimes following flood events yielded lower standing crops and diversities.

Summary

The community composition, distribution, density, and seasonality of the phytoplankton, zooplankton, and benthic invertebrates of the Nueces and Mission-Aransas estuaries were employed 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).

Five phytoplankton divisions represented by 248 taxa were collected from the Nueces and Mission-Aransas estuaries. The most taxonomically dominant class was the Chrysophyta, the diatoms, which accounted for 62 percent of the total number of phytoplankton species collected. Salinity and zooplankton predation exerted the most obvious influence on phytoplankton populations during this study. Salinity regimes in each bay system resulted in distinctly different populations.

A total of 319 zooplankton taxa representing 16 phyla were identified during the 30-month study. The Arthropoda accounted for 73 percent of the organisms identified. Holland et al. (289) found that temperature and salinity were the two most important factors regulating the species composition, seasonal occurrence, and distribution of zooplankton populations.

Fourteen phyla represented by 395 benthic species were collected from the Nueces and Mission-Aransas estuaries. The polychaetes, phylum Annelida, were the most prominent group of organisms collected. In general, Holland found that standing crops were directly related to salinity.

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

CHAPTER VIII

FISHERIES

Introduction

Virtually all (97.5 percent) of the coastal fisheries species are considered estuarine-dependent (76). During the five year period, 1972 through 1976, commercial landings of finfish and shellfish in Texas average 97.3 million pounds (44.2 million kg) annually (373-377). Approximately 75 percent of the harvest was taken offshore in the Gulf of Mexico and the remainder was taken inshore in the bays and estuaries. Computed on the basis of two general fisheries components, the finfish harvest distribution was approximately 28 percent offshore and 72 percent inshore, while the shellfish harvest was of an opposite distribution with about 21 percent inshore and 79 percent offshore. Specifically, the offshore harvests accounted for about six percent of the total Texas red drum (redfish) landings, 17 percent of spotted seatrout landings, 60 percent of white shrimp landings, and 95 percent of brown and pink shrimp landings.

With respect to the 1972 through 1976 commercial Texas bay landings, bays of the Mission-Aransas estuary contributed an average 14.6 percent of finfish landings and 12.9 percent of shellfish landings, while bays of the Nueces estuary contributed an average 10.7 percent of finfish landings and 4.7 percent of shellfish landings. Since the Gulf inlet, Aransas Pass, serves as the major migrational route for coastal fisheries species dependent upon these estuaries, they can be considered together in terms of their contribution to the fisheries harvest. Thus, the combined estuaries contributed 25.3 percent of finfish landings and 17.6 percent of shellfish landings in Texas bays. By comparison, the largest Texas estuary, the Trinity-San Jacinto estuary, contributed an average 11.0 percent of finfish landings 45.4 percent of shellfish landings from Texas bays during the same period (232).

Based on the five year inshore-offshore commercial landings distribution, the average contribution of the Mission-Aransas estuary to total Texas commercial landings is estimated at 1,101,500 pounds (499,600 kg) of fish and 11,584,000 pounds (5.3 million kg) of shellfish annually. In addition, the commercial fish harvest has been estimated to account for approximately 52.9 percent of the total fish harvest in the estuary, with the remainder (47.1 percent) going to the sport or recreational catch (259). Thus, an additional 980,800 pounds (444,900 kg) of sport catch can be computed which raises the estimated average annual fish harvest contribution from the estuary (both inshore and offshore) to 2,082,300 pounds (944,500 kg). The average harvest contribution of all fisheries species (fish and shellfish) dependent on the estuary is therefore estimated at 13.7 million pounds (6.2 million kg) annually.

Similarly, the average contribution of the Nueces estuary to total Texas commercial landings is estimated at 809,000 pounds (367,000 kg) of fish and 4,249,500 pounds (1.9 million kg) of shellfish annually. In addition, the commercial fish harvest has been estimated to account for 49.9 percent and the sport harvest 50.1 percent of the total fish harvest in the estuary (260). Thus, an additional 812,300 pounds (368,500 kg) of sport catch can be computed which raises the estimated average annual fish harvest contribution from the estuary to 1,621,300 pounds (735,400 kg). The average harvest contribution of all fisheries species (fish and shellfish) from the estuary is therefore estimated at 5.9 million pounds (2.7 million kg) annually. Taken together, the Nueces and Mission-Aransas estuaries are estimated to contribute to an annual harvest of about 19.6 million pounds (8.9 million kg) of fish and shellfish dependent upon these estuarine systems.

Previous research has described the general ecology, utilization and management of the coastal fisheries (321, 264, 158, 156, 71, 194, 190), and has provided information on Texas tidal waters (303, 308, 378, 180) and the relationship of freshwater inflow to estuarine productivity (395). Also, prior studies in the Nueces and Mission-Aransas estuaries have included the ecology of Corpus Christi bay (171), sampling of fish stocks and macroinvertebrates in Redfish and Corpus Christi bays (317, 302, 299), brine stressed areas in Mission River and Aransas Bay (247) and in Chiltipin Creek and upper Copano Bay (162), summer fish diversity in Aransas Bay (161), and freshwater needs of fish and wildlife resources in the Nueces-Corpus Christi bay area (95). The importance of the major Gulf inlet, Aransas Pass, has been investigated with respect to tidal exchanges (201) and the seasonal migrations of estuarine-dependent organisms (297, 27, 104, 28). In particular, Copeland (297) considered a very conservative estimate of the protein-rich biomass of organisms produced in the highly productive bays served by the inlet to approximate 256.8 million pounds (116.5 million kg) annually or 514 pounds (233 kg) per acre, computed on the basis of one-half million acres of bay habitat involved. Additionally, an experimental methodology for investigating freshwater inflow requirements has been developed and applied to the Corpus Christi bay system using the spotted seatrout (Cynoscion nebulosus) as the key management species (281, 124). However, multivariate equational models of fisheries production from several important species as a function of the effects of seasonal freshwater inflows have not been previously constructed.

Data and Statistical Methods

Direct analysis of absolute fisheries biomass fluctuations as a function of freshwater inflow is not possible. Accurate biomass estimation requires either considerable experimental calibration of current sampling methods (118) or the development and application of higher technologies such as the use of high resolution, computer interpreted, sonar soundings for estimation of absolute fish abundance (34). 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 (118).

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 (97, 79, 78, 352, 211, 210). 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 Texas Landings publications (380-

386, 370-377) which report inshore harvests from the various bays and offshore harvests from the Gulf of Mexico. Since the offshore harvests represent collective fisheries production from the region's estuaries, it is the inshore harvests reported by estuarine area that provide fisheries data related to a particular estuary.

Commercial inshore harvests from bays of the Mission-Aransas, Nueces, and combined estuaries are tabulated for several important fisheries components (Tables 8-1, 8-2, and 8-3). 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 more reliable records available from 1962 to 1976. This 15-year interval includes both wet and dry climatic cycles and is sufficient in length to identify positive and negative fisheries responses to seasonal inflow, as well as quantify the seasonal freshwater inflow needs of the fisheries components.

The finfish component of the fisheries harvest is specific for the combined harvests of croaker (mostly *Micropogon undulatus* Linnaeus), black drum (*Pogonias cromis* Linnaeus), red drum or redfish (*Sciaenops ocellata* Linnaeus), flounders (*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 estuaries is discussed in Chapter IV and is tabulated here on the basis of six analytical categories: (1) freshwater inflow from Mission and Aransas rivers (FINMA) contributed to the Mission-Aransas estuary (Table 8-4), (2) combined freshwater inflow to Mission-Aransas estuary (FINCma) from all contributing river and coastal drainage basins (Table 8-5), (3) freshwater inflow at Nueces delta (FINND) contributed to the Nueces estuary (Table 8-6), (4) combined freshwater inflow to Nueces estuary (FINCn) from all contributing river and coastal drainage basins (Table 8-7), (5) freshwater inflow from Mission, Aransas, and Nueces rivers (FINMAN) contributed to Mission-Aransas and Nueces estuaries when they are considered together as an interrelated estuarine area (Table 8-8), and (6) combined freshwater inflow to Mission-Aransas and Nueces estuaries (FINCman) from all contributing river and coastal drainage basins (Table 8-9). 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

Table 8-1. Commercial Fisheries Harvests in the Mission-Aransas Estuary a/, 1962-1976 (370-377, 380-386)

Year	Commercial Fisheries Harvests (thousands of pounds)								
	Shellfish b/	White Shrimp	Brown & Pink Shrimp	Blue Crab	Bay Oyster	Finfish c/	Spotted Seatrout	Red Drum	Black Drum
1962	2054.1	249.9	195.7	1605.4	3.1	716.0	335.8	112.3	173.1
1963	482.1	279.3	76.9	125.2	0.7	856.8	360.7	104.4	286.9
1964	886.8	592.3	182.2	112.3	0.3 d/	548.7	185.3	69.3	171.4
1965	985.3	723.1	222.6	39.6	0.3 d/	548.6	187.0	64.3	180.7
1966	823.9	320.8	482.9	19.3	0.9	465.3	134.4	88.7	65.7
1967	647.5	252.4	235.7	155.6	3.8	291.2	110.8	55.3	57.4
1968	1955.1	1736.6	12.7	197.5	8.3	448.9	199.0	105.6	59.7
1969	1503.1	572.5	162.5	724.2	43.9	395.9	148.7	151.4	50.7
1970	2325.3	1068.4	258.6	878.1	120.2	418.8	123.0	160.7	77.8
1971	1044.5	343.8	78.9	591.8	30.0	578.1	181.0	222.2	114.0
1972	2609.6	1072.6	137.5	1338.9	60.6	654.3	228.1	264.1	91.7
1973	3153.5	993.6	877.3	1272.7	9.9	672.0	225.5	229.2	129.0
1974	2006.4	706.3	210.9	1079.3	9.9	674.5	202.5	244.0	118.4
1975	2089.0	625.1	559.0	892.5	12.4	673.1	152.8	282.0	118.1
1976	2420.0	608.9	475.4	1318.8	16.9	1108.9	283.2	484.3	173.2
Mean	1665.7	676.4	277.9	690.1	21.4	603.4	203.9	175.9	124.5
±S.E. e/	±210.1	±105.1	±58.9	±142.9	±8.4	±52.3	±19.0	±29.7	±16.5

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a/ Estuary ranks fourth in shellfish and third 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/ No harvest data; minimum values estimated by curve fit

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

Table 8-2. Commercial Fisheries Harvests in the Nueces Estuary a/, 1962-1976 (370-377, 380-386)

	Commercial Fisheries Harvests (thousands of pounds)							
Year	Shellfish b/	White Shrimp	Brown & Pink Shrimp	Blue Crab	Finfish c/	Black Drum	Spotted Seatrout	Red Drum
1962	395.4	196.7	115.5	83.2	77.3	8.0	12.0	7.0
1963	236.5	95.8	95.4	45.3	78.0	13.7	12.1	6.4
1964	295.3	242.9	52.4	—	56.3	18.5	15.7	2.8
1965	567.2	226.7	226.8	113.7	59.1	19.8	18.3	2.6
1966	657.2	469.9	187.3	—	78.5	24.8	19.2	13.2
1967	514.7	343.2	171.5	—	247.4	112.7	79.1	25.4
1968	634.3	633.7	0.6	—	111.7	42.2	48.5	14.5
1969	479.8	238.5	88.8	152.5	91.7	38.2	28.5	16.7
1970	345.7	206.8	138.9	—	110.0	26.2	36.6	38.7
1971	203.9	84.1	19.3	100.5	193.8	63.1	42.4	72.6
1972	521.2	397.0	53.5	70.7	312.4	102.9	88.9	101.5
1973	1,263.3	849.9	372.1	41.1	611.0	220.2	156.7	153.3
1974	801.5	320.3	154.9	326.3	744.7	201.1	178.1	214.1
1975	1,057.8	531.4	399.7	125.7	661.6	205.7	129.9	167.6
1976	860.8	395.8	341.3	123.7	549.4	161.7	110.9	121.9
Mean	589.0	348.8	161.2	118.3 e/	265.5	83.9	65.1	63.9
±S.E. d/	±78.0	±53.5	±32.4	±25.7	±64.1	±20.1	±14.4	±18.2

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a/ Estuary ranks sixth in Shellfish and seventh in Finfish commercial harvests out of eight Texas estuarine areas

b/ Includes blue crab, 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 percent confidence limits about the mean

e/ N = 10 years; for all other means N = 15 years

Table 8-3. Commercial Fisheries Harvests in the Nueces and Mission-Aransas Estuaries, 1962-1976 (370-377, 380-386)

Year	Commercial Fisheries Harvests (thousands of pounds)							
	Shellfish a/	White Shrimp	Brown & Pink Shrimp	Blue Crab	Finfish b/	Spotted Seatrout	Red Drum	Black Drum
1962	2,449.5	446.6	311.2	1,688.6	793.3	347.8	119.3	181.1
1963	718.6	375.1	172.3	170.5	933.6	372.8	110.8	300.6
1964	1,182.1	835.2	234.6	112.3 c/	605.0	201.0	72.1	189.9
1965	1,552.5	949.8	449.4	153.3	607.7	205.3	66.9	200.5
1966	1,481.1	790.7	670.2	19.3 c/	543.8	153.6	101.9	90.5
1967	1,162.2	595.6	407.2	155.6 c/	538.6	189.9	80.7	170.1
1968	2,589.4	2,370.3	13.3	197.5 c/	560.6	247.5	120.1	101.9
1969	1,982.9	811.0	251.3	876.7	487.6	177.2	168.1	88.9
1970	2,671.0	1,275.2	397.5	878.1 c/	528.8	159.6	199.4	104.0
1971	1,248.4	427.9	98.2	692.3	771.9	223.4	294.8	177.1
1972	3,130.8	1,469.6	191.0	1,409.6	966.7	317.0	365.6	194.6
1973	4,416.6	1,843.5	1,249.4	1,313.8	1,283.0	382.2	382.5	349.2
1974	2,807.9	1,026.6	365.8	1,405.6	1,419.2	380.6	458.1	319.5
1975	3,146.8	1,156.5	958.7	1,018.2	1,334.7	282.7	449.6	323.8
1976	3,280.6	1,004.7	816.7	1,442.5	1,658.3	394.1	606.2	334.9
Mean	2,254.7	1,025.2	439.1	768.9	868.9	269.0	239.7	208.4
±S.E.d/	±265.5	±141.4	±88.8	±153.3	±98.9	±23.1	±44.7	±24.3

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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

c/ Harvest from Mission-Aransas estuary only

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

Table 8-4. Seasonal Freshwater Inflow Volumes from Mission and Aransas Rivers Contributed to Mission-Aransas 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	14.1	21.9	1.0	33.0	2.0
1960	12.0	48.0	7.0	177.0	90.0
1961	65.1	12.9	6.0	6.0 a/	1.0
1962	0.0	15.0	0.0	14.0	4.0
1963	0.0	0.9	0.0	1.0 b/	1.0
1964	0.9	2.1	29.0	0.0	0.0
1965	20.1	23.1	0.0	1.0	5.0
1966	3.9	170.1	14.0	2.0	0.0
1967	0.0	9.9	9.0	796.0 c/	6.0
1968	8.1	168.0	23.0	13.0	2.0
1969	68.1	24.9	3.0	0.0	7.0
1970	9.9	78.0	5.0 d/	3.0	0.0
1971	0.0	0.9	15.0	612.0 e/	6.0
1972	6.9	188.1	23.0	29.0	4.0
1973	5.1	243.9	12.0	279.0 f/	9.0
1974	8.1	23.1	3.0	182.0	10.0
1975	3.0	3.0	2.0	7.0	17.0
1976	3.9	50.1	101.0	55.0	98.0
Mean g/	12.7	60.2	14.1	122.8	14.6
± S.E.	±4.8	±18.1	±5.5	±53.8	±6.9

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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 mean; two standard errors provide approximately 95 percent confidence limits about the mean

Table 8-5. Seasonal Volumes of Combined Freshwater Inflow a/ Contributed to Mission-Aransas 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	44.1	78.0	18.0	141.0	5.0
1960	27.0	132.9	23.0	518.0	290.0
1961	203.1	36.0	24.0	54.0 b/	4.0
1962	0.0	21.0	2.0	19.0	15.0
1963	2.1	5.1	2.0	3.0 c/	4.0
1964	6.0	9.9	75.0	7.0	5.0
1965	30.0	51.9	2.0	8.0	20.0
1966	21.0	393.9	22.0	6.0	2.0
1967	3.9	39.9	25.0	1,463.0 d/	8.0
1968	20.1	579.9	73.0	37.0	4.0
1969	105.1	96.0	8.0	5.0	44.0
1970	33.9	195.0	21.0 e/	120.0	2.0
1971	3.0	9.0	33.0	1,070.0 f/	37.0
1972	26.1	402.0	59.0	55.0	6.0
1973	9.0	467.1	26.0	554.0 g/	12.0
1974	12.9	90.0	9.0	325.0	94.0
1975	5.1	6.9	8.0	32.0	25.0
1976	6.9	84.9	246.0	103.0	224.0
Mean h/	31.1	150.0	37.6	251.1	44.5
± S.E.	±11.7	±42.7	±13.3	±97.1	±19.2

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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 mean; two standard errors provide approximately 95 percent confidence limits about the mean

Table 8-6. Seasonal Freshwater Inflow Volumes at Nueces Delta Contributed to Nueces 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	29.1	6.9	49.0	265.0	18.0
1960	6.0	15.9	62.0	204.0	160.0
1961	123.9	89.1	63.0	9.0 a/	4.0
1962	3.9	2.1	2.0	2.0	0.0
1963	3.0	3.9	4.0	1.0 b/	0.0
1964	0.0	0.9	3.0	186.0	18.0
1965	93.0	203.1	4.0	2.0	1.0
1966	2.1	263.1	7.0	2.0	2.0
1967	2.1	3.9	7.0	1,815.0 c/	32.0
1968	272.1	303.9	29.0	15.0	0.0
1969	6.0	8.1	1.0	55.0	116.0
1970	32.1	242.1	15.0 d/	3.0	1.0
1971	0.0	0.0	838.0	1,681.0 e/	95.0
1972	27.9	156.9	5.0	29.0	3.0
1973	2.1	255.0	123.0	557.0 f/	72.0
1974	39.9	12.9	61.0	171.0	17.0
1975	20.1	201.0	65.0	10.0	0.0
1976	0.0	63.0	187.0	249.0	372.0
Mean g/	36.9	101.8	84.7	292.0	50.6
± S.E.	±16.0	±26.7	±45.8	±129.6	±22.0

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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 mean; two standard errors provide approximately 95 percent confidence limits about the mean

Table 8-7. Seasonal Volumes of Combined Freshwater Inflow a/ Contributed to Nueces 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	39.9	24.0	58.0	277.0	22.0
1960	11.1	26.1	69.0	244.0	205.0
1961	141.0	99.0	79.0	16.0 b/	8.0
1962	9.9	12.0	9.0	7.0	4.0
1963	9.9	12.9	11.0	7.0 c/	4.0
1964	6.0	9.9	11.0	192.0	22.0
1965	99.9	213.0	11.0	7.0	6.0
1966	12.0	303.0	16.0	10.0	9.0
1967	12.0	20.1	15.0	1,994.0 d/	38.0
1968	281.1	363.9	52.0	23.0	7.0
1969	17.1	24.9	13.0	63.0	124.0
1970	42.0	267.9	50.0 e/	23.0	9.0
1971	12.9	12.9	860.0	1,756.0 f/	102.0
1972	44.1	179.1	22.0	44.0	11.0
1973	12.9	290.1	133.0	649.0 g/	80.0
1974	50.1	26.1	67.0	177.0	22.0
1975	30.9	227.1	77.0	34.0	9.0
1976	12.9	84.9	234.0	267.0	389.0
Mean h/	47.0	122.1	91.4	321.7	59.5
± S.E.	±16.1	±29.2	±47.4	±138.9	±23.2

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

Table 8-8. Seasonal Freshwater Inflow Volumes from Nueces, Mission and Aransas Rivers Contributed to Nueces and Mission-Aransas Estuaries, 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	43.2	28.8	50.0	298.0	20.0
1960	18.0	63.9	69.0	381.0	250.0
1961	189.0	102.0	69.0	15.0 a/	5.0
1962	3.9	17.1	2.0	16.0	4.0
1963	3.0	4.8	4.0	2.0 b/	1.0
1964	0.9	3.0	32.0	186.0	18.0
1965	113.1	226.2	4.0	3.0	6.0
1966	6.0	433.2	21.0	4.0	2.0
1967	2.1	13.8	16.0	2,611.0 c/	38.0
1968	280.2	471.9	52.0	28.0	2.0
1969	74.1	33.0	4.0	55.0	123.0
1970	42.0	320.1	20.0 d/	6.0	1.0
1971	0.0	0.9	853.0	2,293.0 e/	101.0
1972	34.8	345.0	28.0	58.0	7.0
1973	7.2	498.9	135.0	836.0 f/	81.0
1974	48.0	36.0	64.0	353.0	27.0
1975	23.1	204.0	67.0	17.0	17.0
1976	3.9	113.1	288.0	304.0	470.0
Mean g/	49.6	162.0	98.8	414.8	65.2
± S.E.	±17.7	±41.7	±47.1	±182.3	±28.1

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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 mean; two standard errors provide approximately 95 percent confidence limits about the mean

Table 8-9. Seasonal Volumes of Combined Freshwater Inflow a/ Contributed to Nueces and Mission-Aransas Estuaries, 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	84.0	102.0	76.0	418.0	27.0
1960	38.1	159.0	92.0	762.0	495.0
1961	344.1	135.0	103.0	70.0 b/	12.0
1962	9.9	33.0	11.0	26.0	19.0
1963	12.0	18.0	13.0	10.0 c/	8.0
1964	12.0	19.8	86.0	199.0	27.0
1965	129.9	264.9	13.0	15.0	26.0
1966	33.0	696.9	38.0	16.0	11.0
1967	15.9	60.0	40.0	3,457.0 d/	46.0
1968	301.2	943.8	125.0	60.0	11.0
1969	122.1	120.9	21.0	68.0	161.0
1970	75.9	462.9	71.0 e/	143.0	11.0
1971	15.9	21.9	893.0	2,826.0 f/	139.0
1972	70.2	581.1	81.0	99.0	17.0
1973	21.9	757.2	159.0	1,203.0 g/	92.0
1974	63.0	116.1	76.0	502.0	116.0
1975	36.0	234.0	85.0	66.0	34.0
1976	19.8	169.8	480.0	370.0	613.0
Mean h/	77.7	272.0	136.8	572.8	104.0
± S.E.	±22.8	±67.9	±50.9	±233.7	±40.5

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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 mean; two standard errors provide approximately 95 percent confidence limits about the mean

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

A time series analysis of the fisheries components from the Nueces and Mission-Aransas estuaries was performed utilizing the University of California biomedical (BMD) computer program for the stepwise multiple regression procedure (15). 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:

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

$$a_6 Q_{6,t-b_6} + e$$

where a_0 is the intercept harvest value, $a_1 \ldots a_6$ 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 8-10),

$Q_{2,t-b_2}$ = 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 8-10),

$Q_{3,t-b_3}$ = 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 8-10),

$Q_{4,t-b_4}$ = 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 8-10),

$Q_{5,t-b_5}$ = 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 8-10),

$Q_{6,t-b_6}$ = annual (January-December) mean monthly freshwater inflow in thousands of acre-feet at year $t-b_6$, where b_6 is a positive integer (Table 8-10).

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

$$\ln H_t = a_0 + a_1 (\ln Q_{1,t-b_1}) + \ldots + a_6 (\ln Q_{6,t-b_6}) + e$$

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 ($Q_1 \ldots Q_6$) 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 probable lagged effect, in time, of freshwater inflow upon production and subsequent harvest of a particular fisheries component (Table 8-10). This is a standard procedure since it has been long recognized that environmental factors affecting growth and survival of the young in critical developmental periods can show their effect some time later when the affected age-class matures and enters the commercially exploited adult population (67, 152). Early articulation of this idea was put forth by the Norwegian fishery scientist Johan Hjort in 1914 (100) 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 (188). 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 (67, 187). 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.

Table 8-10. Time Series Alignments of Dependent/Independent Data Variates for Fisheries Regression Analysis

H_t Fisheries Component	$Q_{1,t-b_1}$ (Jan.-Mar.)	$Q_{2,t-b_2}$ (Apr.-Jun.)	$Q_{3,t-b_3}$ (Jul.-Aug.)	$Q_{4,t-b_4}$ (Sep.-Oct.)	$Q_{5,t-b_5}$ (Nov.-Dec.)	$Q_{6,t-b_6}$ (Jan.-Dec.)
Shellfish a/ All Penaeid Shrimp White Shrimp 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	inflow 1-year antecedent to harvest
(1962-1976)	(1962-1976)	(1962-1976)	(1962-1976)	(1962-1976)	(1961-1975)	(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	(not applicable)
(1962-1976)	(1961-1975)	(1961-1975)	(1961-1975)	(1961-1975)	(1961-1975)	
Finfish b/ Spotted Seatrout Red Drum Black 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	(not applicable)
(1962-1976)	(1959-1975)	(1959-1975)	(1959-1975)	(1959-1975)	(1959-1975)	

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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

Fisheries Analysis Results

Shellfish

Analysis of the multi-species shellfish fisheries component involves transformation of the regression variables to natural logarithms (ln) and results in a significant natural log equation for each of the six freshwater inflow categories (Table 8-11). 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 equation. The best significant equation (fifth equation of Table 8-11) explains 70 percent of the observed variation in shellfish harvest from both estuaries considered together and is highly significant ($\alpha = 0.5\%$) for correlation of natural log transformed harvests to natural log transformed spring (Q_2), autumn (Q_4), and late fall (Q_5) season freshwater inflows from Mission, Aransas, and Nueces rivers (FINMAN).

The estimated effect of a correlating seasonal inflow on harvest is computed by holding all other correlating seasonal inflows in the best significant equation constant at their respective mean values, while varying the seasonal inflow of interest from its lower to upper observed bounds. Repeating this process for each correlating seasonal inflow in the best significant equation and plotting the results in non-transformed units permits illustration of the curvilinear effects of individual seasonal inflows on the estimate of inshore commercial shellfish harvest from the estuaries (Figure 8-1). For example, Panel A of Figure 8-1 shows the estimate of annual harvest increasing from about 1.1 million pounds to 2.8 million pounds as the inflow during the April-June (Q_2) seasonal interval increases from its observed lower bounds of 300 acre-feet per month to its observed upper bounds of 166.3 thousand acre-feet per month. Thus, the positive (+) sign on the regression coefficient (a_2) for the correlating Q_2 inflow term in the best significant equation is illustrated as a curve of positive slope relating increasing spring season inflow to an increasing estimate of annual shellfish harvest. It is noted that this curve 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_4 and Q_5) in the best significant equation at specified levels of interest other than their mean observed values. For instance, if the positively correlating September-October (Q_4) inflow is specified at some level lower than its mean of 29.4 thousand acre-feet per month while the November-December (Q_5) inflow remains at its mean observed value, then the estimated harvest response to April-June (Q_2) inflow would be similar to that shown in Panel A (Figure 8-1) and would have the identical positive slope; however, the computed line would be shifted downward and parallel to that which is graphed. Analogous circumstances exist for each of the harvest responses illustrated, but to facilitate comparisons only the seasonal inflow of interest in each panel graph is varied, while all others in the best significant equations are held constant at their respective mean values.

Panel B (Figure 8-1) exhibits the positive response of inshore shellfish harvest to autumn season freshwater inflow from Mission, Aransas, and Nueces rivers. The estimate of harvest increases 2.1 times (from about 1.4 to 2.9

Table 8-11. Equations of Statistical Significance Relating the Shellfish Fisheries Component to Freshwater Inflow Categories a/

Mission-Aransas Estuary Shellfish Harvest = f (Seasonal FINMA b/)
Significant Natural Log Equation ($\alpha = 5.0\%$; $r^2 = 52\%$; S.E. Est. = ± 0.4442)

$$\ln H_{sf} = 6.9323 + \underset{(0.0693)}{0.1167} (\ln Q_2) + \underset{(0.0442)}{0.0547} (\ln Q_4) + \underset{(0.0886)}{0.1544} (\ln Q_5)$$

	$\ln H_{sf}$	$\ln Q_2$	$\ln Q_4$	$\ln Q_5$
upper bounds	8.0563	4.3981	5.9865	2.1401
lower bounds	6.1782	-1.2040	-2.3026	-2.3026
mean	7.2822	1.9274	1.7755	0.1808

Mission-Aransas Estuary Shellfish Harvest = f (Seasonal FINCm·a c/)
Significant Natural Log Equation ($\alpha = 5.0\%$; $r^2 = 29\%$, S.E. Est. = ± 0.4996)

$$\ln H_{sf} = 6.5331 + \underset{(0.1038)}{0.2388} (\ln Q_6)$$

	$\ln H_{sf}$	$\ln Q_6$
upper bounds	8.0563	4.8544
lower bounds	6.1782	0.2624
mean	7.2822	3.1368

Nueces Estuary Shellfish Harvest = f (Seasonal FINND d/)
Highly Significant Natural Log Equation ($\alpha = 0.5\%$; $r^2 = 64\%$; S.E.Est. = ± 0.3398)

$$\ln H_{sf} = 5.5915 + \underset{(0.0409)}{0.1892} (\ln Q_2) + \underset{(0.0381)}{0.0895} (\ln Q_4)$$

	$\ln H_{sf}$	$\ln Q_2$	$\ln Q_4$
upper bounds	7.1413	4.6181	6.8107
lower bounds	5.3176	-2.3026	-0.6931
mean	6.2534	2.1640	2.8203

Table 8-11. Equations of Statistical Significance Relating the Shellfish Fisheries Component to Freshwater Inflow Categories a/ (cont'd.)

Nueces Estuary Shellfish Harvest = f (Seasonal FINCn e/)
Significant Natural Log Equation (α = 5.0%; r^2 = 46%; S.E. Est. = ± 0.4201)

$$\ln H_{sf} = 5.1980 + 0.2601\ (\ln Q_2) + 0.0720\ (\ln Q_4)$$

(0.0822) (0.0601)

	$\ln H_{sf}$	$\ln Q_2$	$\ln Q_4$
upper bounds	7.1413	4.7983	6.9048
lower bounds	5.3176	1.1939	1.2528
mean	6.2534	3.0785	3.5355

Mission-Aransas and Nueces Estuaries Shellfish Harvest = f (Seasonal FINMAN f/)
Highly Significant Natural Log Equation (α = 0.5%; r^2 = 70%, S.E. Est. = ± 0.3105)

$$\ln H_{sf} = 6.6528 + 0.1461\ (\ln Q_2) + 0.1026\ (\ln Q_4) + 0.1124\ (\ln Q_5)$$

(0.0588) (0.0378) (0.0738)

	$\ln H_{sf}$	$\ln Q_2$	$\ln Q_4$	$\ln Q_5$
upper bounds	8.3931	5.1138	7.0445	4.1190
lower bounds	6.5773	-1.2040	0.0000	-0.6931
mean	7.6110	2.9431	3.3814	1.6134

Mission-Aransas and Nueces Estuaries Shellfish Harvest = f (Seasonal FINCm·a·n g/)
Significant Natural Log Equation (α = 2.5%; r^2 = 60%; S.E.Est. = ± 0.3604)

$$\ln H_{sf} = 6.3103 - 0.1918\ (\ln Q_1) + 0.2383\ (\ln Q_2) + 0.2119\ (\ln Q_6)$$

(0.1358) (0.0971) (0.1088)

	$\ln H_{sf}$	$\ln Q_1$	$\ln Q_2$	$\ln Q_6$
upper bounds	8.3931	4.6092	5.7513	5.7829
lower bounds	6.5773	1.1939	1.7918	1.6292
mean	7.6110	2.5048	3.8881	4.0326

Table 8-11. Equations of Statistical Significance Relating the Shellfish Fisheries Component to Freshwater Inflow Categories a/ (cont'd)

Where:

$\ln H_{sf}$ = natural log, inshore commerical shellfish harvest, in thousands of pounds;

$\ln Q$ = natural log, mean monthly freshwater inflow, in thousands of acre-feet:

Q_1 = Jan.-Mar.	Q_4 = Sept.-Oct.
Q_2 = Apr.-Jun.	Q_5 = Nov.-Dec.
Q_3 = Jul.-Aug.	Q_6 = Jan.-Dec.

a/ Standard error of each regression coefficient is shown in parentheses beneath the coefficients of the regression equations

b/ Freshwater inflow from Mission and Aransas River Basins

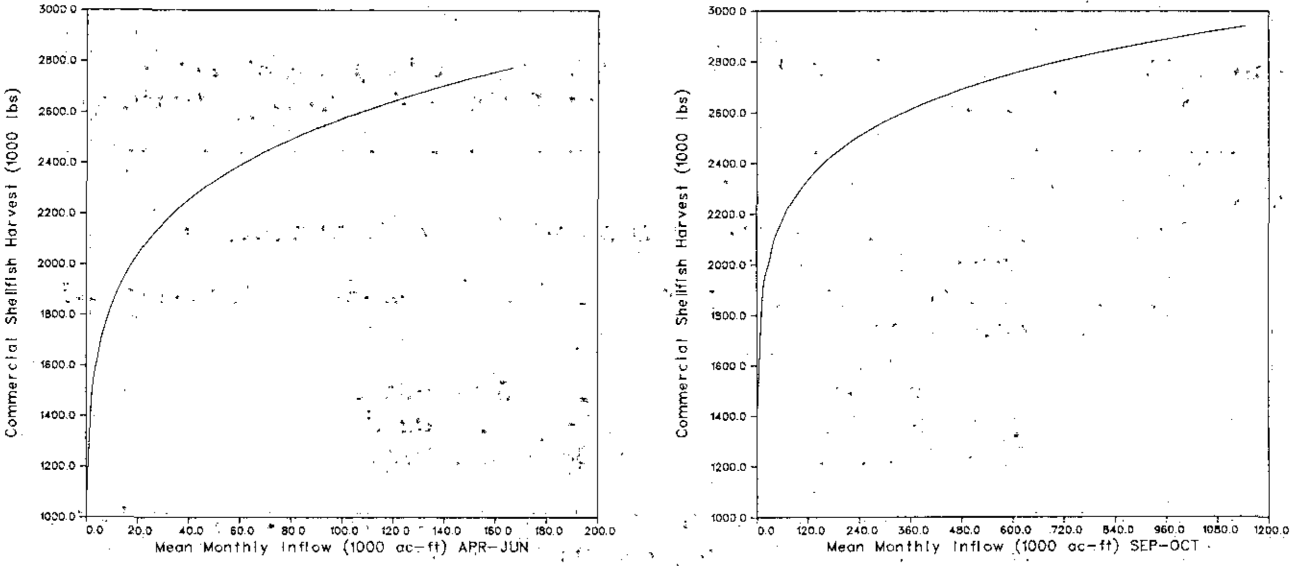
c/ Combined freshwater inflow to Mission-Aransas estuary from all contributing river and coastal drainage basins

d/ Freshwater inflow at Nueces delta

e/ Combined freshwater inflow to Nueces estuary from all contributing river and coastal drainage basins

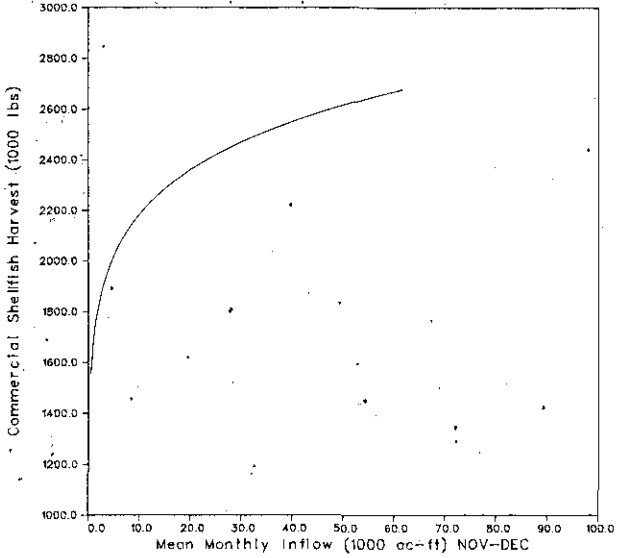
f/ Freshwater inflow from Mission, Aransas, and Nueces River Basins

g/ Combined freshwater inflow to Mission-Aransas and Nueces estuaries from all contributing river and coastal drainage basins



A. regression coefficient = +0.1461,
standard error = ±0.0588

B. regression coefficient = +0.1026,
standard error = ±0.0378



C. regression coefficient = +0.1124,
standard error = ±0.0738

Figure 8-1. Mission-Aransas and Nueces Estuaries Shellfish Harvest as a Function of Seasonal Inflow from Mission, Aransas, and Nueces Rivers, Where All Other Seasonal Inflows in the Multiple Regression Equation are Held Constant at Their Mean Values

million pounds annually) as the September-October (Q_4) inflow increases from its observed lower bounds of 1.0 thousand acre-feet per month to its observed upper bounds of 1,146.5 thousand acre-feet per month.

Panel C (Figure 8-1) shows another positive harvest response to late fall season freshwater inflow. In this case, the estimtae of shellfish harvest increases 1.7 times (from about 1.6 to 2.7 million pounds annually) as the November-December (Q_5) inflow increases from 500 acre-feet per month to 61.5 thousand acre-feet per month.

Considered together, Panels A, B and C in Figure 8-1 illustrate strong positive statistical responses of inshore commercial shellfish harvest from combined Nueces and Mission-Aransas estuaries landings to spring (Q_2) and autumn (Q_4) season inflow, and a slightly weaker positive harvest response to late fall (Q_5) season inflow over the observed ranges of these seasonal inflows from Nueces, Mission, and Aransas rivers. Based on the statistical regression model described by the best significant equation, maximization of shellfish harvest can be achieved by increasing spring, autumn, and late fall inflows from the contributing rivers.

All Penaeid Shrimp

Analysis of the fisheries component for all penaeid shrimp (i.e., white, brown, and pink shrimp) yields a significant equation for all freshwater inflow categories (Table 8-12). The best significant equation (fifth equation, Table 8-12) accounts for 88 percent of the observed variation in penaeid shrimp harvest from both estuaries considered together and is very highly significant (α = 0.1%) for correlation of natural log transformed harvests to natural log transformed spring (Q_2), summer (Q_3), and autumn (Q_4) season freshwater inflows from Mission, Aransas, and Nueces rivers (FINMAN).

The effect of each of the correlating inflow terms 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 inflow of interest over its observed range and computing the estimated harvest response (Figure 8-2). The estimate of inshore penaeid shrimp harvest increases 4.5 times (from about 0.5 to 2.2 million pounds annually) as April-June (Q_2) inflow increases from the observed lower bounds of 300 acre-feet per month to the observed upper bounds of 166.3 thousand acre-feet per month (Panel A, Figure 8-2). Thus, the penaeid shrimp fisheries component is shown to have a strong positive relationship with spring season inflow from the contributing rivers. A weaker, more variable positive response to summer inflow results in the estimate of harvest increasing from about 1.2 to 1.5 million pounds annually as the July-August (Q_3) inflow increases over the observed range of 1.0 to 426.5 thousand acre-feet per month (Panel B, Figure 8-2). The estimate of harvest increases 1.5 times (from about 1.1 to 1.6 million pounds annually) as the September-October (Q_4) inflow increases over the observed range of 1.0 to 1,146.5 thousand acre-feet per month (Panel C, Figure 8-2), indicating another weakly positive relationship of harvest to autumn season inflow. Maximization of penaeid shrimp harvest is therefore statistically related to increasing spring (Q_2), summer (Q_3), and autumn (Q_4) season inflows from the contributing rivers.

Table 8-12. Equations of Statistical Significance Relating the All Penaeid Shrimp Fisheries Component to Freshwater Inflow Categories a/

Mission-Aransas Estuary All Shrimp Harvest = f (Seasonal FINMA b/)
Highly Significant Natural Log Equation ($\alpha = 1.0\%$; $r^2 = 71\%$; S.E. Est. = ± 0.3243)

$$\ln H_{as} = \underset{(0.0663)}{6.5132 + 0.1140\,(\ln Q_1)} + \underset{(0.0625)}{0.0879\,(\ln Q_2)} + \underset{(0.0490)}{0.0581\,(\ln Q_3)}$$

$$+ \underset{(0.0657)}{0.0714\,(\ln Q_5)}$$

	$\ln H_{as}$	$\ln Q_1$	$\ln Q_2$	$\ln Q_3$	$\ln Q_5$
upper bounds	7.5342	3.1224	4.3981	3.9220	2.1401
lower bounds	5.8755	-2.3026	-1.2040	-2.3026	-2.3026
mean	6.7455	-0.0214	1.9274	0.9038	0.1808

Mission-Aransas Estuary All Shrimp Harvest = f (Seasonal FINCm·a c/)
Highly Significant Equation ($\alpha = 0.5\%$; $r^2 = 67\%$; S.E. Est. = ± 287.0)

$$H_{as} = 550.1 + \underset{(1.2)}{5.4\,(Q_2)} + \underset{(6.3)}{11.7\,(Q_5)}$$

	H_{as}	Q_2	Q_5
upper bounds	1870.9	193.3	47.0
lower bounds	356.2	1.7	1.0
mean	954.3	54.5	9.4

Nueces Estuary All Shrimp Harvest = f (Seasonal FINND d/)
Highly Significant Natural Log Equation ($\alpha = 0.5\%$; $r^2 = 72\%$; S.E.Est. = ± 0.3731)

$$\ln H_{as} = 5.3056 + \underset{(0.0519)}{0.2594\,(\ln Q_2)} + \underset{(0.0418)}{0.0838\,(\ln Q_4)} - \underset{(0.0498)}{0.0514\,(\ln Q_5)}$$

	$\ln H_{as}$	$\ln Q_2$	$\ln Q_4$	$\ln Q_5$
upper bounds	7.1082	4.6181	6.8107	4.0604
lower bounds	4.6386	-2.3026	-0.6931	-2.3026
mean	6.0722	2.1640	2.8203	0.6078

Table 8-12. Equations of Statistical Significance Relating the All Penaeid Shrimp Fisheries Component to Freshwater Inflow Categories a/ (cont'd)

Nueces Estuary All Shrimp Harvest = f (Seasonal FINCn e/)
Significant Natural Log Equation (α = 2.5%; r^2 = 53%; S.E. Est. = ± 0.4622)

$$\ln H_{as} = 5.2432 - 0.1551 (\ln Q_1) + 0.3717 (\ln Q_2)$$
$$(0.1495) \qquad (0.1089)$$

	$\ln H_{as}$	$\ln Q_1$	$\ln Q_2$
upper bounds	7.1082	4.5401	4.7983
lower bounds	4.6386	0.6931	1.1939
mean	6.0722	2.0327	3.0785

Mission-Aransas and Nueces Estuaries All Shrimp Harvest = f (Seasonal FINMAN f/)
Very Highly Significant Natural Log Equation (α = 0.1%; r^2 = 88%; S.E. Est. = ± 0.1986)

$$\ln H_{as} = 6.1778 + 0.2389 (\ln Q_2) + 0.0410 (\ln Q_3) + 0.0551 (\ln Q_4)$$
$$(0.0287) \qquad (0.0424) \qquad (0.0325)$$

	$\ln H_{as}$	$\ln Q_2$	$\ln Q_3$	$\ln Q_4$
upper bounds	8.0369	5.1138	6.0556	7.0445
lower bounds	6.2655	-1.2040	0.0000	0.0000
mean	7.1759	2.9431	2.6465	3.3814

Mission-Aransas and Nueces Estuaries All Shrimp Harvest = f (Seasonal FINCm·a·n g/)
Very Highly Significant Natural Log Equation (α = 0.1%; r^2 = 78%; S.E.Est. = ± 0.2577)

$$\ln H_{as} = 5.7307 + 0.3226 (\ln Q_2) + 0.0453 (\ln Q_4)$$
$$(0.0495) \qquad (0.0375)$$

	$\ln H_{as}$	$\ln Q_2$	$\ln Q_4$
upper bounds	8.0369	5.7513	7.4550
lower bounds	6.2655	1.7918	1.6094
mean	7.1759	3.8881	4.2212

Table 8-12. Equations of Statistical Significance Relating the All Penaeid Shrimp Fisheries Component to Freshwater Inflow Categories a/ (cont'd)

Where:

H_{as} = inshore commercial penaeid shrimp harvest, in thousands of pounds;
$\ln H_{as}$ = natural log of H_{as};
Q = mean monthly freshwater inflow, in thousands of acre-feet;
$\ln Q$ = natural log of Q:

Q_1 = Jan.-Mar.
Q_2 = Apr.-Jun.
Q_3 = Jul.-Aug.
Q_4 = Sept.-Oct.
Q_5 = Nov.-Dec.

a/ Standard error of each regression coefficient is shown in parentheses beneath the coefficients of the regression equations

b/ Freshwater inflow from Mission and Aransas River Basins

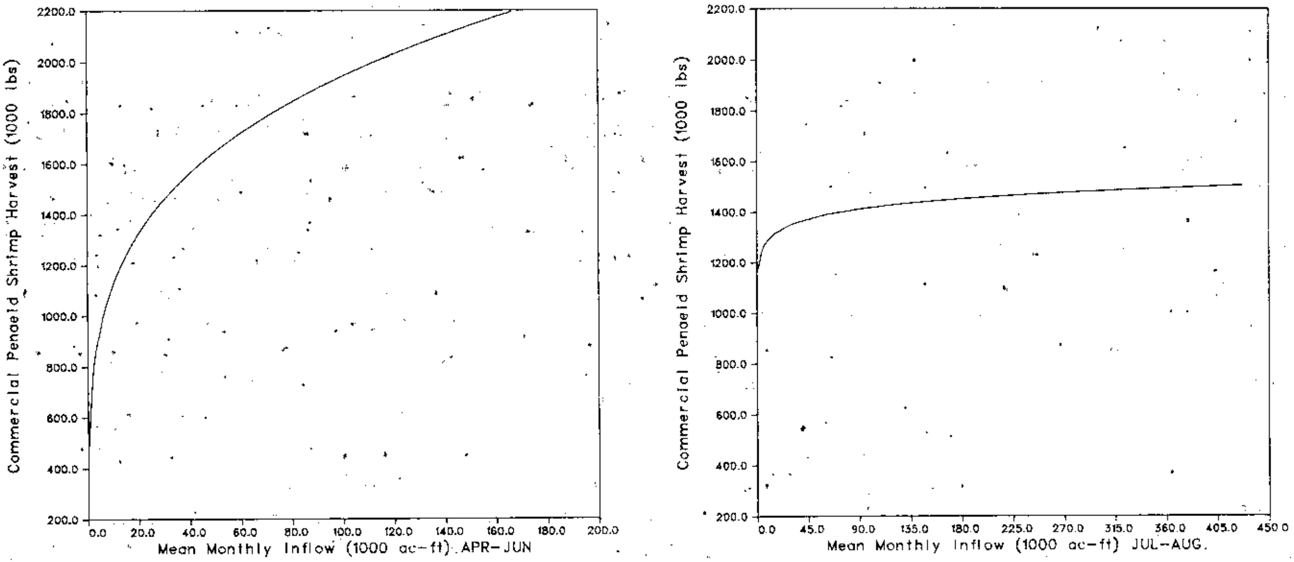
c/ Combined freshwater inflow to Mission-Aransas estuary from all contributing river and coastal drainage basins

d/ Freshwater inflow at Nueces delta

e/ Combined freshwater inflow to Nueces estuary from all contributing river and coastal drainage basins

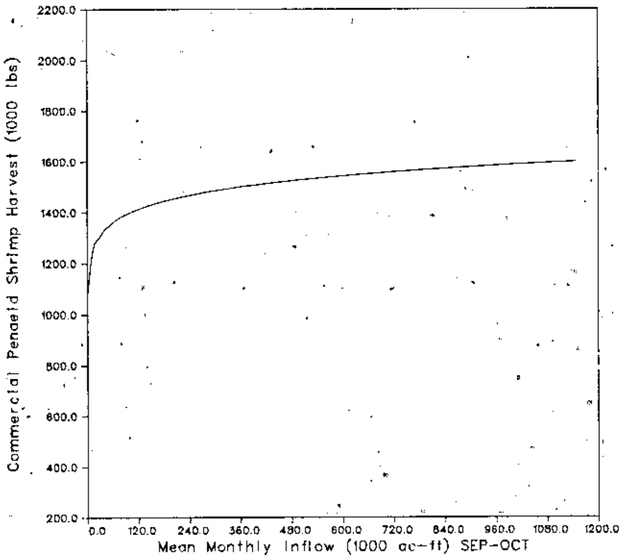
f/ Freshwater inflow from Mission, Aransas, and Nueces River Basins

g/ Combined freshwater inflow to Mission-Aransas and Nueces estuaries from all contributing river and coastal drainage basins



A. regression coefficient = +0.2389,
standard error = ±0.0287

B. regression coefficient = +0.0410,
standard error= ±0.0424



C. regression coefficient = +0.0551,
standard error = ±0.0325

Figure 8-2. Mission-Aransas and Nueces Estuaries Penaeid Shrimp Harvest as a Function of Seasonal Inflow from Mission, Aransas, and Nueces Rivers, Where All Other Seasonal Inflows in the Multiple Regression Equation are Held Constant at Their Mean Values.

White Shrimp

Analysis of the white shrimp fisheries component also results in a significant regression equation for each of the freshwater inflow categories (Table 8-13). The best significant equation (fifth equation, Table 8-13) explains 84 percent of the observed harvest variation and is very highly significant (α = 0.1%) for correlation of natural log transformed white shrimp harvests from both estuaries to natural log transformed winter (Q_1), spring (Q_2), summer (Q_3), and autumn (Q_4) season freshwater inflows from Mission, Aransas, and Nueces rivers (FINMAN). The estimate of harvest increases 2.4 times above its minimum values when both January-March (Q_1) and April-June (Q_2) inflows are varied over their observed ranges (Panels A and B, Figure 8-3), indicating strong positive relationships with increasing winter and spring inflows. Smaller, more variable positive responses to summer and autumn season inflows result in the estimated harvest increasing 1.8 and 1.4 times their minimum, respectively, as July-August (Q_3) and September-October (Q_4) inflows are varied from their lower to upper observed bounds (Panels C and D, Figure 8-3). Consequently, maximization of white shrimp harvest is statistically related to increasing winter, spring, summer, and autumn season inflows to the estuaries from the contributing rivers.

Brown and Pink Shrimp

Analysis of the brown and pink shrimp fisheries component yields only three significant regression equations (Table 8-14). The best significant equation (second equation, Table 8-14) accounts for 56 percent of the observed harvest variation and is significant (α = 2.5%) for correlation of inshore brown and pink shrimp harvests from both estuaries to winter (Q_1), spring (Q_2), and one-year antecedent annual (Q_6) freshwater inflows from Mission, Aransas, and Nueces rivers (FINMAN). A strong negative relationship to winter inflow results in the estimate of annual harvest declining 112 percent as January-March (Q_1)inflow is varied over its observed range (Panel A, Figure 8-4). The estimate of annual harvest increases 4.3 times its minimum value as April-June (Q_2) inflow increases over its observed range, indicating a strong positive response to spring season inflow (Panel B, Figure 8-4). An additional negative response to one-year antecedent annual (Q_6) inflow results in the estimate of annual harvest declining 79 percent (Panel C, Figure 8-4). Therefore, maximization of brown and pink shrimp harvest is statistically related to increasing spring season inflow and decreasing winter and annual inflows to the estuaries from the contributing rivers. It is noted that the negative harvest response to winter inflow is in apparent conflict with the positive relationship of white shrimp harvest to winter inflow.

Blue Crab

Analysis of the blue crab fisheries component results in five significant regression equations (Table 8-15). The best significant equation (third equation, Table 8-15) explains 91 percent of the observed harvest variation and is highly significant (α = 1.0%) for correlation of Nueces estuary blue crab harvests to one-year antecedent winter (Q_1), spring (Q_2), autumn (Q_4), and late fall (Q_5) season inflows to the estuary from all contributing river and coastal drainage basins ($FINC_n$). The effects of each of the correlating seasonal inflows are positive for increasing January-March (Q_1)

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

Mission-Aransas Estuary White Shrimp Harvest = f (Seasonal FINMA b/)
Highly Significant Equation ($\alpha = 0.5\%$; $r^2 = 68\%$; S.E. Est. = $\pm$ 259.6)

$$H_{ws} = 422.5 + 4.2\,(Q_2) - 0.8\,(Q_4) + 11.5\,(Q_6)$$
$$\qquad\qquad (2.9) \qquad\quad (0.6) \qquad\quad (3.8)$$

	H_{ws}	Q_2	Q_4	Q_6
upper bounds	1736.6	81.3	398.0	68.4
lower bounds	249.9	0.3	0.0	0.3
mean	676.4	22.2	66.5	18.5

Mission-Aransas Estuary White Shrimp Harvest = f (Seasonal FINCm·a c/)
Highly Significant Equation ($\alpha = 1.0\%$; $r^2 = 71\%$, S.E. Est. = $\pm$ 260.6)

$$H_{ws} = 339.2 + 2.6\,(Q_2) + 2.1\,(Q_3) - 0.4\,(Q_4) + 4.9\,(Q_6)$$
$$\qquad\qquad (1.3) \qquad\quad (2.3) \qquad\quad (0.3) \qquad\quad (2.3)$$

	H_{ws}	Q_2	Q_3	Q_4	Q_6
upper bounds	1736.6	193.3	123.0	731.5	128.3
lower bounds	249.9	1.7	1.0	1.5	1.3
mean	676.4	54.5	20.4	126.9	40.6

Nueces Estuary White Shrimp Harvest = f (Seasonal FINND d/)
Highly Significant Natural Log Equation ($\alpha = 0.5\%$; $r^2 = 74\%$; S.E.Est. = $\pm$ 0.3696)

$$\ln H_{ws} = 4.8557 + 0.2589\,(\ln Q_2) - 0.0876\,(\ln Q_3) + 0.1573\,(\ln Q_4)$$
$$\qquad\qquad (0.0471) \qquad\quad (0.0638) \qquad\quad (0.0512)$$

	$\ln H_{ws}$	$\ln Q_2$	$\ln Q_3$	$\ln Q_4$
upper bounds	6.7451	4.6181	6.0379	6.8107
lower bounds	4.4320	-2.3026	-0.6931	-0.6931
mean	5.6797	2.1640	2.0536	2.8203

Table 8-13. Equations of Statistical Significance Relating the White Shrimp Fisheries Component to Freshwater Inflow Categories a/ (cont'd.)

Nueces Estuary White Shrimp Harvest = f (Seasonal FINCn e/)
Highly Significant Natural Log Equation ($\alpha = 1.0\%$; $r^2 = 65\%$; S.E. Est. = ± 0.4251)

$$\ln H_{ws} = 4.3187 + \underset{(0.0913)}{0.4148\,(\ln Q_2)} - \underset{(0.1139)}{0.2077\,(\ln Q_3)} + \underset{(0.0811)}{0.1947\,(\ln Q_4)}$$

	$\ln H_{ws}$	$\ln Q_2$	$\ln Q_3$	$\ln Q_4$
upper bounds	6.7451	4.7983	6.0638	6.9048
lower bounds	4.4320	1.1939	1.5041	1.2528
mean	5.6797	3.0785	2.9096	3.5355

Mission-Aransas and Nueces Estuaries White Shrimp Harvest = f (Seasonal FINMAN f/)
Very Highly Significant Natural Log Equation ($\alpha = 0.1\%$; $r^2 = 84\%$, S.E. Est. = ± 0.2492)

$$\ln H_{ws} = 5.8000 + \underset{(0.0549)}{0.1288\,(\ln Q_1)} + \underset{(0.0510)}{0.1418\,(\ln Q_2)} + \underset{(0.0559)}{0.0941\,(\ln Q_3)} + \underset{(0.0408)}{0.0505\,(\ln Q_4)}$$

	$\ln H_{ws}$	$\ln Q_1$	$\ln Q_2$	$\ln Q_3$	$\ln Q_4$
upper bounds	7.7708	4.5369	5.1138	6.0556	7.0445
lower bounds	5.9272	-2.3026	-1.2040	0.0000	0.0000
mean	6.8044	1.3005	2.9431	2.6465	3.3814

Mission-Aransas and Nueces Estuaries White Shrimp Harvest = f (Seasonal FINCm·a·n g/)
Very Highly Significant Equation ($\alpha = 0.1\%$; $r^2 = 80\%$ S.E.Est. = ± 277.4)

$$H_{ws} = 477.4 + \underset{(3.5)}{6.5\,(Q_1)} + \underset{(0.9)}{3.4\,(Q_2)} + \underset{(2.9)}{3.1\,(Q_5)}$$

	H_{ws}	Q_1	Q_2	Q_5
upper bounds	2370.3	100.4	314.6	84.0
lower bounds	375.1	3.3	6.0	4.0
mean	1025.2	20.9	100.0	24.6

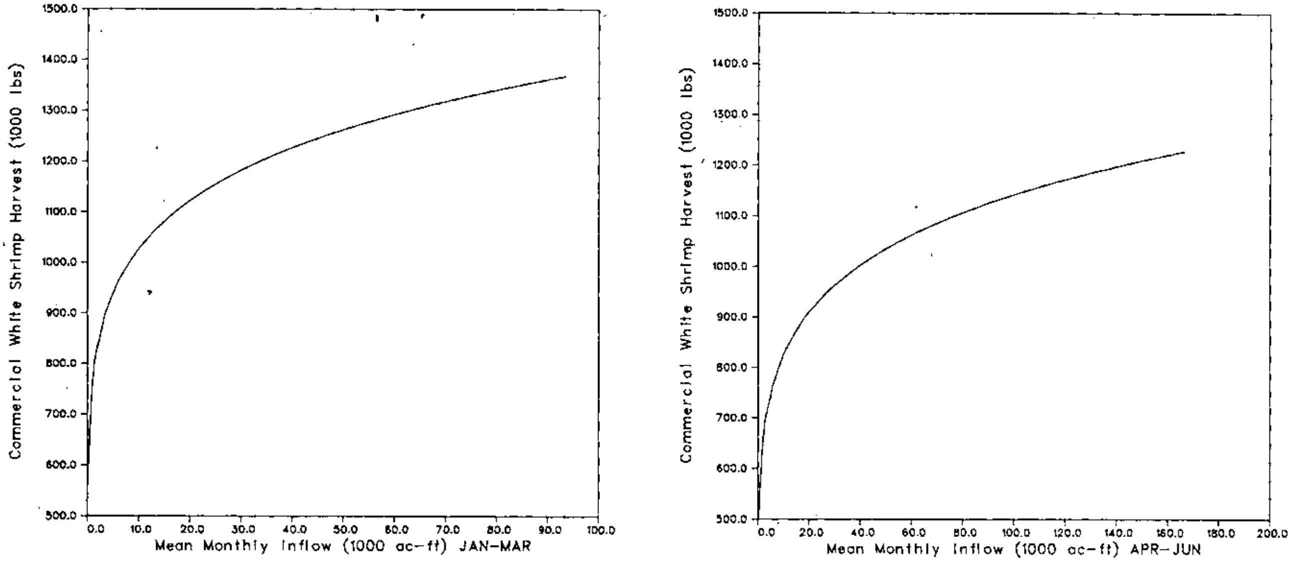
Table 8-13. Equations of Statistical Significance Relating the White Shrimp Fisheries Component to Freshwater Inflow Categories a/ (cont'd)

Where:

H_{ws} = inshore commercial white shrimp harvest, in thousands of pounds;
$\ln H_{ws}$ = natural log of H_{ws}
Q = mean monthly freshwater inflow, in thousands of acre-feet;
$\ln Q$ = natural log of Q:

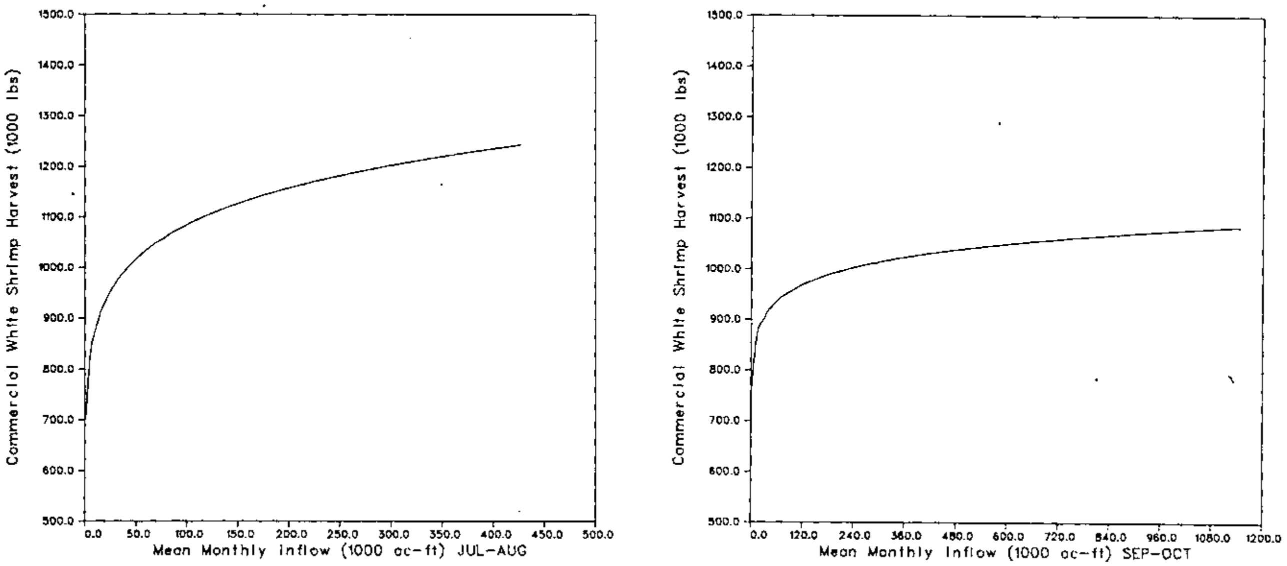
Q_1 = Jan.-Mar.
Q_2 = Apr.-Jun.
Q_3 = Jul.-Aug.
Q_4 = Sept.-Oct.
Q_5 = Nov.-Dec.
Q_6 = Jan.-Dec.

a/ Standard error of each regression coefficient is shown in parentheses beneath the coefficients of the regression equations
b/ Freshwater inflow from Mission and Aransas River Basins
c/ Combined freshwater inflow to Mission-Aransas estuary from all contributing river and coastal drainage basins
d/ Freshwater inflow at Nueces delta
e/ Combined freshwater inflow to Nueces estuary from all contributing river and coastal drainage basins
f/ Freshwater inflow from Mission, Aransas, and Nueces River Basins
g/ Combined freshwater inflow to Mission-Aransas and Nueces estuaries from all contributing river and coastal drainage basins



A. regression coefficient = +0.1288,
standard error = ±0.0549

B. regression coefficient = +0.1418,
standard error = ±0.0510



C. regression coefficient = +0.0941,
standard error = ±0.0559

D. regression coefficient = +0.0505,
standard error = ±0.0408

Figure 8-3. Mission-Aransas and Nueces Estuaries White Shrimp Harvest as a Function of Seasonal Inflow from Mission, Aransas, and Nueces Rivers, Where All Other Seasonal Inflows in the Multiple Regression Equation are Held Constant at Their Mean Values

Table 8-14. Equations of Statistical Significance Relating the Brown and Pink Shrimp Fisheries Component to Freshwater Inflow Categories a/

Mission-Aransas Estuary Brown and Pink Shrimp Harvest = f (Seasonal FINMA b/)
Significant Equation ($\alpha = 5.0\%$; $r^2 = 42\%$; S.E. Est. = ± 188.0)

$$H_{bps} = 264.5 + 5.7\,(Q_2) - 6.1\,(Q_6)$$
$$\qquad\qquad (2.1) \qquad\quad (2.8)$$

	H_{bps}	Q_2	Q_6
upper bounds	877.3	81.3	68.4
lower bounds	12.7	0.3	0.3
mean	277.9	22.2	18.5

Mission-Aransas Estuary Brown and Pink Shrimp Harvest = f (Seasonal FINCm·a c/)
(no significant equation)

Nueces Estuary Brown and Pink Shrimp Harvest = f (seasonal FINND d/)
(no significant equation)

Nueces Estuary Brown and Pink Shrimp Harvest = f (seasonal FINCn e/)
(no significant equation)

Mission-Aransas and Nueces Estuaries Brown and Pink Shrimp Harvest = f (seasonal FINMAN f/)
Significant Equation ($\alpha = 2.5\%$, $r^2 = 56\%$, S.E. Est. = ± 255.9)

$$H_{bps} = 396.8 - 6.4\,(Q_1) + 4.0\,(Q_2) - 1.6\,(Q_6)$$
$$\qquad\qquad (3.5) \qquad\quad (1.2) \qquad\quad (1.1)$$

	H_{bps}	Q_1	Q_2	Q_6
upper bounds	1249.4	93.4	166.3	270.6
lower bounds	13.3	0.0	0.3	1.3
mean	439.1	14.3	60.5	65.7

Table 8-14. Equations of Statistical Significance Relating the Brown and Pink Shrimp Fisheries Component to Freshwater Inflow Categories a/ (cont'd)

Mission-Aransas and Nueces Estuaries Brown and Pink Shrimp Harvest = f (seasonal FINCm·a·n g/)
Significant Equation ($\alpha = 5.0\%$, $r^2 = 50\%$, S.E. EST. = $\pm$ 274.2)

$$H_{bps} = 470.4 - \underset{(3.9)}{7.4\,(Q_1)} + \underset{(0.9)}{2.4\,(Q_2)} - \underset{(1.0)}{1.3\,(Q_6)}$$

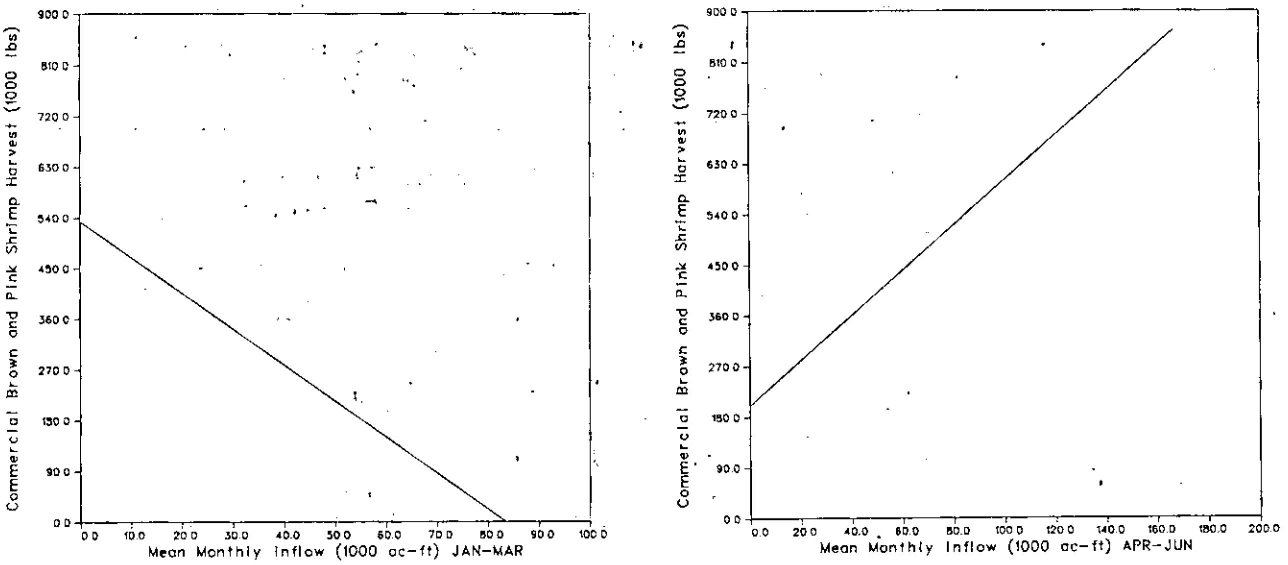
	H_{bps}	Q_1	Q_2	Q_6
upper bounds	1249.4	100.4	314.6	324.7
lower bounds	13.3	3.3	6.0	5.1
mean	439.1	20.9	100.0	94.7

Where:

H_{bps} = inshore commercial brown and pink shrimp harvest, in thousands of pounds
Q = mean monthly freshwater inflow, in thousands of acre-feet;

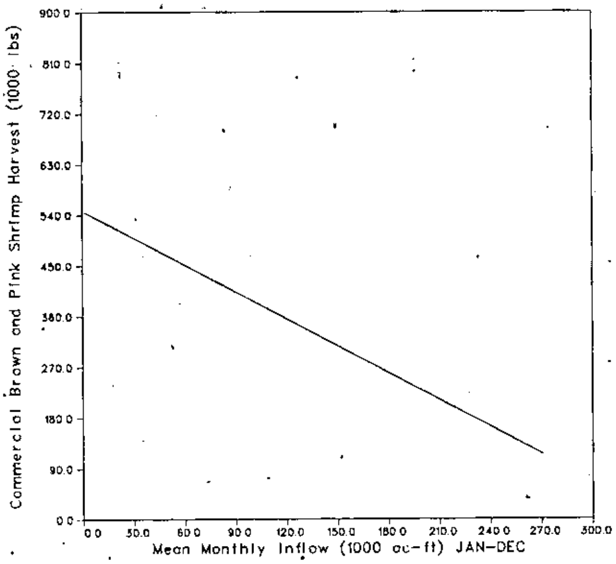
Q_1 = Jan.-Mar.
Q_2 = Apr.-Jun.
Q_3 = Jul.-Aug.
Q_4 = Sept.-Oct.
Q_5 = Nov.-Dec.
Q_6 = Jan.-Dec.

a/ Standard error of each regression coefficient is shown in parentheses beneath the coefficients of the regression equations
b/ Freshwater inflow from Mission and Aransas River Basins
c/ Combined freshwater inflow to Mission-Aransas estuary from all contributing river and coastal drainage basins
d/ Freshwater inflow at Nueces delta
e/ Combined freshwater inflow to Nueces estuary from all contributing river and coastal drainage basins
f/ Freshwater inflow from Mission, Aransas, and Nueces River Basins
g/ Combined freshwater inflow to Mission-Aransas and Nueces estuaries from all contributing river and coastal drainage basins



A. regression coefficient (slope) = -6.4,
standard error = ±3.5

B. regression coefficient (slope) = +4.0,
standard error = ±1.2



C. regression coefficient (slope) = -1.6,
standard error = ±1.1

Figure 8-4. Mission-Aransas and Nueces Estuaries Brown and Pink Shrimp Harvest as a Function of Seasonal Inflow from Mission, Aransas, and Nueces Rivers, Where All Other Seasonal Inflows in the Multiple Regression Equation are Held Constant at Their Mean Values

Table 8-15. Equations of Statistical Significance Relating the Blue Crab Fisheries Component to Freshwater Inflow Categories a/

Mission-Aransas Estuary Blue Crab Harvest = f (seasonal FINMA b/)
Significant Natural Log Equation (α = 5.0%, r^2 = 50%, S.E. Est. = ± 1.1197)

$$\ln H_{bc} = 5.2663 + 0.3548\,(\ln Q_1) + 0.1887\,(\ln Q_3) + 0.2891\,(\ln Q_4)$$

(0.1741) (0.1822) (0.1250)

	$\ln H_{bc}$	$\ln Q_1$	$\ln Q_3$	$\ln Q_4$
upper bounds	7.3811	3.1224	2.6741	5.9865
lower bounds	2.9601	-2.3026	-2.3026	-2.3026
mean	5.9308	0.1663	0.7156	1.6278

Mission-Aransas Estuary Blue Crab Harvest = f (seasonal FINCm·a c/)
(no significant equation)

Nueces Estuary Blue Crab Harvest = f (seasonal FINND d/)
Highly Significant Equation (α = 1.0%, r^2 = 91%, S.E. Est. = ± 32.8)

$$H_{bc} = 52.0 + 0.5\,(Q_1) + 0.5\,(Q_2) - 0.6\,(Q_4) + 11.2\,(Q_5)$$

(0.5) (0.4) (0.1) (2.0)

	H_{bc}	Q_1	Q_2	Q_4	Q_5
upper bounds	326.3	90.7	101.3	840.5	47.5
lower bounds	41.1	0.0	0.0	1.0	0.0
mean	118.3	17.4	42.1	133.2	10.5

Nueces Estuary Blue Crab Harvest = f (seasonal FINCn e/)
Highly Significant Equation (α = 1.0%, r^2 = 91%, S.E. Est. = ± 32.7)

$$H_{bc} = 20.7 + 0.6\,(Q_1) + 0.2\,(Q_2) - 0.7\,(Q_4) + 12.4\,(Q_5)$$

(0.5) (0.4) (0.1) (2.3)

	H_{bc}	Q_1	Q_2	Q_4	Q_5
upper bounds	326.3	93.7	121.3	878.0	51.0
lower bounds	41.1	2.0	3.3	3.5	2.0
mean	118.3	21.0	49.6	146.1	13.7

Table 8-15. Equations of Statistical Significance Relating the Blue Crab Fisheries Component to Freshwater Inflow Categories a/ (cont'd.)

Mission-Aransas and Nueces Estuaries Blue Crab Harvest = f (seasonal FINMAN f/)
Significant Natural Log Equation ($\alpha = 2.5\%$, $r^2 = 82\%$, S.E. Est. = $\pm$ 0.4589)

$$\ln H_{bc} = 4.5584 + \underset{(0.1159)}{0.1059} (\ln Q_1) + \underset{(0.1148)}{0.1516} (\ln Q_2) + \underset{(0.1027)}{0.4690} (\ln Q_3)$$

	$\ln H_{bc}$	$\ln Q_1$	$\ln Q_2$	$\ln Q_3$
upper bounds	7.4317	4.5369	5.1138	6.0556
lower bounds	5.0324	-2.3026	-1.2040	0.0000
mean	6.6799	1.6215	3.0354	3.1758

Mission-Aransas and Nueces Estuaries Blue Crab Harvest = f (seasonal FINCman g/)
Significant Natural Log Equation ($\alpha = 5.0\%$, $r^2 = 64\%$, S.E. Est. = $\pm$ 0.5968)

$$\ln H_{bc} = 3.4886 + \underset{(0.1353)}{0.3259} (\ln Q_2) + \underset{(0.1869)}{0.4908} (\ln Q_3)$$

	$\ln H_{bc}$	$\ln Q_2$	$\ln Q_3$
upper bounds	7.4317	5.7513	6.1014
lower bounds	5.0324	1.8871	1.7047
mean	6.6799	3.9680	3.8678

Where:
H_{bc} = inshore commercial blue crab harvest, in thousands of pounds;
$\ln H_{bc}$ = natural log of H_{bc}
Q = mean monthly freshwater inflow, in thousands of acre-feet;
$\ln Q$ = natural log of Q:

Q_1 = Jan.-Mar.
Q_2 = Apr.-Jun.
Q_3 = Jul. Aug.
Q_4 = Sept.-Oct.
Q_5 = Nov. -Dec.

a/ Standard error of each regression coefficient is shown in parentheses beneath the coefficients of the regression equations
b/ Freshwater inflow from Mission and Aransas River Basins
c/ Combined freshwater inflow to Mission-Aransas estuary from all contributing river and coastal drainage basins
d/ Freshwater inflow at Nueces delta
e/ Combined freshwater inflow to Nueces estuary from all contributing river and coastal drainage basins
f/ Freshwater inflow from Mission, Aransas, and Nueces River Basins
g/ Combined freshwater inflow to Mission-Aransas and Nueces estuaries from all contributing river and coastal drainage basins

inflow (Panel A, Figure 8-5), positive for increasing April-June (Q_2) inflow (Panel B, Figure 8-5), negative for increasing September-October (Q_4) inflow (Panel C, Figure 8-5), and positive for increasing November-December (Q_5) inflow (Panel D, Figure 8-5). In particular, the estimate of annual harvest declines 291 percent as autumn season inflow is increased to its upper observed bounds, while the estimate of annual harvest increases 16.7 times its minimum value in response to increased late fall season inflow. Maximization of blue crab harvest is thus statistically related to decreasing autumn season inflow and increasing winter, spring, and late fall season inflows to Nueces estuary.

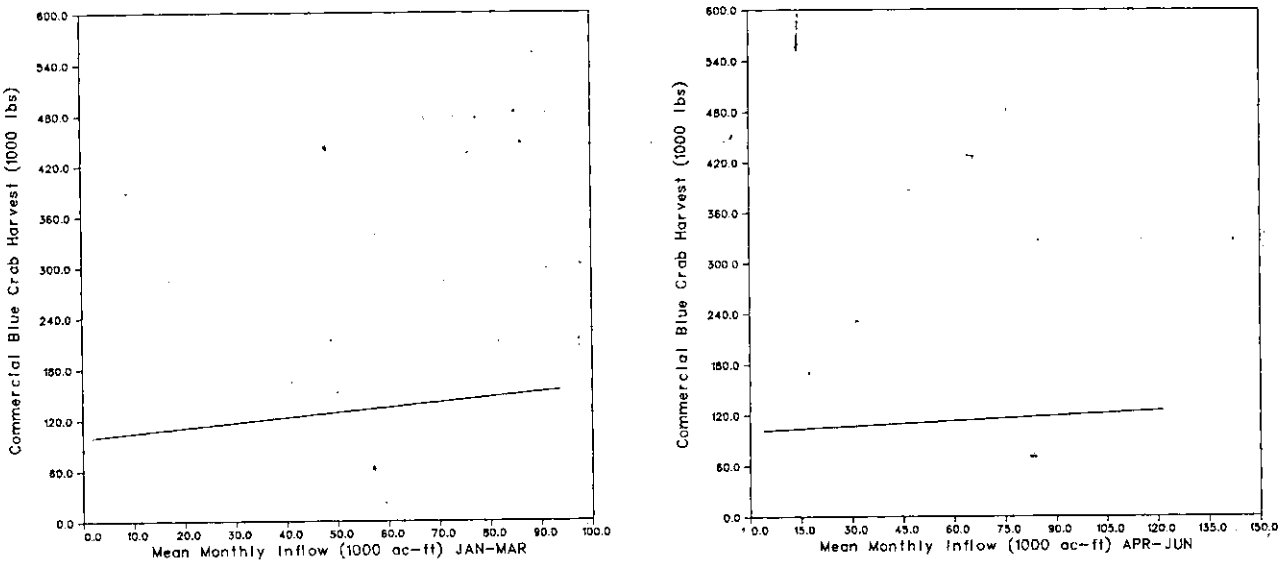
Bay Oyster

Analysis of the bay oyster fisheries component gives only two significant regression equations (Table 8-16). The best significant equation (first equation, Table 8-16) accounts for 53 percent of the observed harvest variation and is significant (α = 5.0%) for correlation of natural log transformed oyster harvests from the Mission-Aransas estuary to one-year antecedent, natural log transformed winter (Q_1), summer (Q_3), and late fall (Q_5) season freshwater inflows to the estuary from Mission and Aransas rivers (FINMA). Oyster harvest is positively correlated to all three of the seasonal inflows. The estimate of harvest increases 5.2 times its minimum value in response to increased January-March (Q_1) inflow (Panel A, Figure 8-6), 17.5 times its minimum in response to increased July-August (Q_3) inflow (Panel B, Figure 8-6), and 14.8 times its minimum in response to increased November-December (Q_5) inflow (Panel C, Figure 8-6). Therefore, maximization of oyster harvest is statistically related to increasing winter, summer, and late fall season inflows from the Mission and Aransas rivers.

Finfish

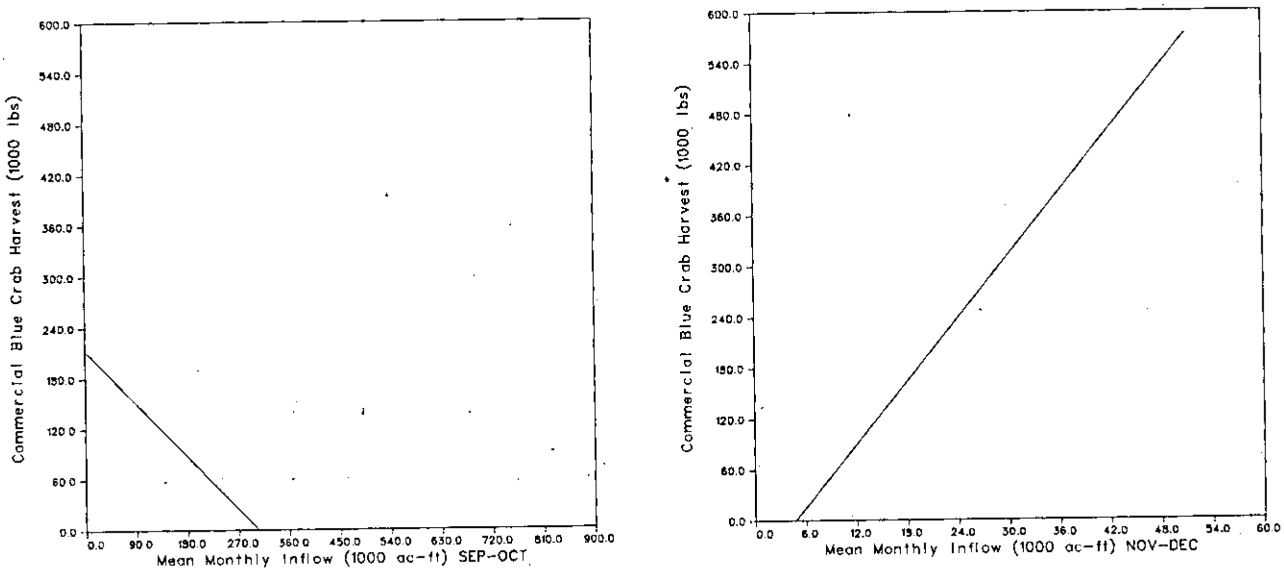
Analysis of the multi-species finfish component of commercial fisheries landing results in a significant regression equation for each of the six inflow categories (Table 8-17). The best significant equation (fourth equation, Table 8-17) involves logarithmic transformation of the regression variables, explains 92 percent of the observed harvest variation, and is very highly significant (α = 0.1%) for correlation of Nueces estuary finfish harvests to all seasonal inflows (Q_1 through Q_5) contributed to the estuary from its combined river and coastal drainage basins ($FINC_n$).

Curvilinear responses of the harvest estimate to each of the correlating seasonal inflows are strongly negative to increased January-March (Q_1) inflow (Panel A, Figure 8-7), strongly positive to increased April-June (Q_2) inflow (Panel B, Figure 8-7), positive to July-August (Q_3) inflow (Panel C, Figure 8-7), negative to September-October (Q_4) inflow (Panel D, Figure 8-7), and positive to November-December (Q_5) inflow (Panel E, Figure 8-7). In particular, the estimate of finfish harvest decreases 92 percent in response to increasing winter (January-March) inflow and increases 23.6 times its minimum value in response to increasing spring (April-June) inflow (Panels A and B, respectively). The regression model of finfish harvest described by the best significant equation indicates that harvest maximization is statistically related to increasing spring, summer, and late fall season inflows, while diminishing winter and autumn season inflows contributed to the Nueces estuary. Such an inflow regime would be generally beneficial to blue crab and



A. regression coefficient (slope) = +0.6, standard error = ±0.5

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



C. regression coefficient (slope) = -0.7, standard error = ±0.1

D. regression coefficient (slope) = +12.4, standard error = ±2.3

Figure 8-5. Nueces Estuary Blue Crab Harvest as a Function of Seasonal Inflow to the Estuary 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 8-16. Equations of Statistical Significance Relating the Bay Oyster Fisheries Component to Freshwater Inflow Categories a/

Mission-Aransas Estuary Bay Oyster Harvest = f (seasonal FINMA b/)
Significant Natural Log Equation ($\alpha = 5.0\%$, $r^2 = 53\%$, S.E. Est. = ± 1.4654)

$$\ln H_{bo} = 1.2820 + \underset{(0.2097)}{0.3019} (\ln Q_1) + \underset{(0.2307)}{0.5685} (\ln Q_3) + \underset{(0.2675)}{0.6028} (\ln Q_5)$$

	$\ln H_{bo}$	$\ln Q_1$	$\ln Q_3$	$\ln Q_5$
upper bounds	4.7892	3.1224	2.6741	2.1401
lower bounds	-1.2040	-2.3026	-2.3026	-2.3026
mean	1.8480	0.1663	0.7156	0.1808

Mission-Aransas Estuary Bay Oyster Harvest = f (seasonal FINCm·a c/)
Significant Natural Log Equation ($\alpha = 5.0\%$, $r^2 = 42\%$, S.E. Est. = ± 1.5580)

$$\ln H_{bo} = -0.3745 + \underset{(0.2582)}{0.5156} (\ln Q_1) + \underset{(0.2078)}{0.4880} (\ln Q_4)$$

	$\ln H_{bo}$	$\ln Q_1$	$\ln Q_4$
upper bounds	4.7892	4.2151	3.8501
lower bounds	-1.2040	-2.3026	0.0000
mean	1.8480	1.3262	3.1532

Where:

$\ln H_{bo}$ = natural log, commercial bay oyster harvest, in thousands of pounds;

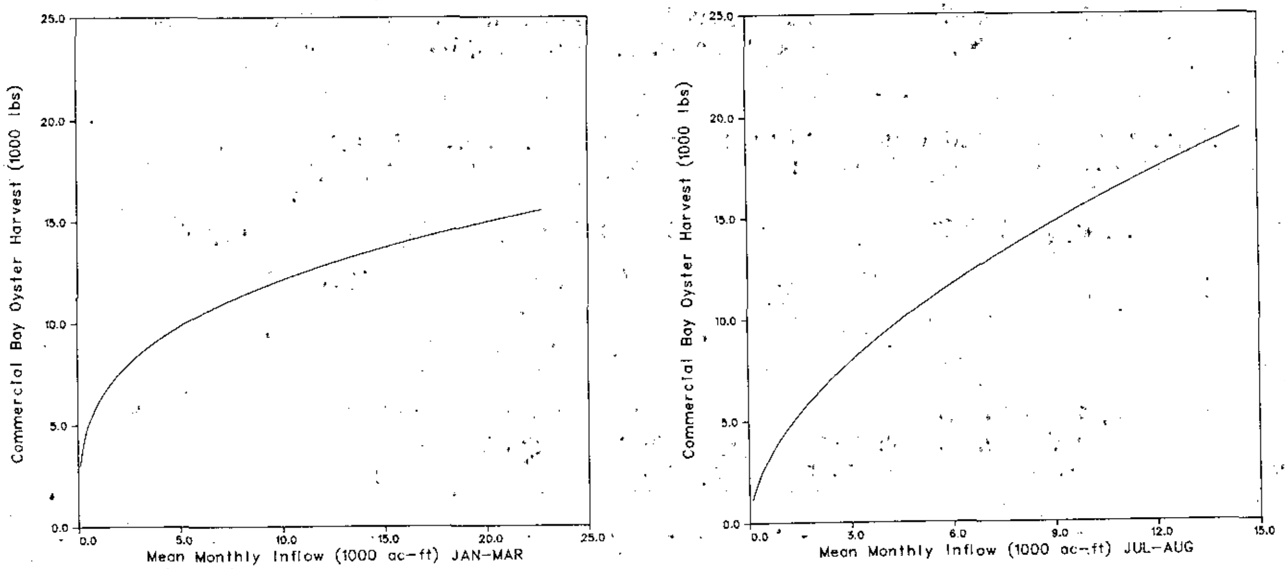
$\ln Q$ = natural log, mean monthly freshwater inflow, in thousands of acre-feet:

Q_1 = Jan.-Mar.
Q_2 = Apr.-Jun.
Q_3 = Jul.-Aug.
Q_4 = Sept.-Oct.
Q_5 = Nov.-Dec.

a/ Standard error of each regression coefficient is shown in parentheses beneath the coefficients of the regression equations

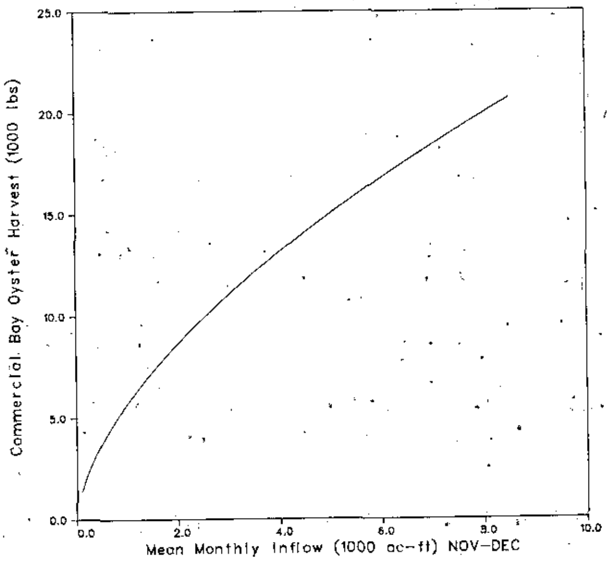
b/ Freshwater inflow from Mission and Aransas River Basins

c/ Combined freshwater inflow to Mission-Aransas estuary from all contributing river and coastal drainage basins



A. regression coefficient = +0.3019,
standard error = ±0.2097

B. regression coefficient = +0.5685,
standard error = ±0.2307



C. regression coefficient = +0.6028,
standard error = ±0.2675

Figure 8-6. Mission-Aransas Estuary Oyster Harvest as a Function of Seasonal Inflow from Mission and Aransas Rivers, Where All Other Seasonal Inflows in the Multiple Regression Equation are Held Constant at Their Mean Values

Table 8-17. Equations of Statistical Significance Relating the Finfish Fisheries Component to Freshwater Inflow Categories a/

Mission-Aransas Estuary Finfish Harvest = f (seasonal FINMA b/)
Significant Natural Log Equation ($\alpha = 2.5\%$, $r^2 = 59\%$, S.E. Est. = ± 0.2387)

$$\ln H_{ff} = 6.4586 - \underset{(0.0609)}{0.0911} (\ln Q_1) - \underset{(0.1214)}{0.1588} (\ln Q_3) + \underset{(0.0747)}{0.2580} (\ln Q_5)$$

	$\ln H_{ff}$	$\ln Q_1$	$\ln Q_3$	$\ln Q_5$
upper bounds	7.0111	2.3158	2.1203	2.7621
lower bounds	5.6740	-2.3026	0.0000	-0.1823
mean	6.3516	1.0754	1.4565	0.8617

Mission-Aransas Estuary Finfish Harvest = f (seasonal FINCm.a c/)
Highly Significant Natural Log Equation ($\alpha = 1.0\%$, $r^2 = 72\%$, S.E. Est. = ± 0.2067)

$$\ln H_{ff} = 6.5088 - \underset{(0.0671)}{0.1384} (\ln Q_1) - \underset{(0.1375)}{0.2626} (\ln Q_3) + \underset{(0.0364)}{0.0484} (\ln Q_4)$$

$$+ \underset{(0.0723)}{0.2646} (\ln Q_5)$$

	$\ln H_{ff}$	$\ln Q_1$	$\ln Q_3$	$\ln Q_4$	$\ln Q_5$
upper bounds	7.0111	3.4166	2.9957	5.6342	3.9416
lower bounds	5.6740	-0.1054	1.5404	1.0986	0.8473
mean	6.3516	2.0560	2.5169	4.1347	2.2226

Nueces Estuary Finfish Harvest = f (seasonal FINND d/)
Very Highly Significant Natural Log Equation ($\alpha = 0.1\%$, $r^2 = 87\%$, S.E. Est. = ± 0.3845)

$$\ln H_{ff} = 3.8284 - \underset{(0.1387)}{0.6591} (\ln Q_1) + \underset{(0.1240)}{0.7123} (\ln Q_2) + \underset{(0.0734)}{0.1947} (\ln Q_3)$$

	$\ln H_{ff}$	$\ln Q_1$	$\ln Q_2$	$\ln Q_3$
upper bounds	6.6130	3.5400	4.1500	5.0814
lower bounds	4.0307	-0.2657	-0.2657	0.4055
mean	5.1634	2.2676	3.2473	2.6534

Table 8-17. Equations of Statistical Significance Relating the Finfish Fisheries Component to Freshwater Inflow Categories a/ (cont'd)

Nueces Estuary Finfish Harvest = f (seasonal FINCn e/)
Very Highly Significant Natural Log Equation ($\alpha = 0.1\%$, $r^2 = 92\%$, S.E. Est. = ± 0.3274)

$$\ln H_{ff} = 3.4071 \underset{(0.1922)}{- 0.9818} (\ln Q_1) \underset{(0.1623)}{+ 1.0597} (\ln Q_2) \underset{(0.1143)}{+ 0.2675} (\ln Q_3) \underset{(0.0982)}{- 0.1964} (\ln Q_4) \underset{(0.1723)}{+ 0.2467} (\ln Q_5)$$

	$\ln H_{ff}$	$\ln Q_1$	$\ln Q_2$	$\ln Q_3$	$\ln Q_4$	$\ln Q_5$
upper bounds	6.6130	3.6323	4.3351	5.1309	6.0117	3.6678
lower bounds	4.0307	1.0531	1.3524	1.6422	1.6094	0.9808
mean	5.1634	2.6454	3.5277	3.1713	4.5536	2.6805

Mission-Aransas and Nueces Estuaries Finfish Harvest = f (seasonal FINMAN f/)
Highly Significant Natural Log Equation ($\alpha = 0.5\%$, $r^2 = 83\%$, S.E. Est. = ± 0.2105)

$$\ln H_{ff} = 6.1156 \underset{(0.0815)}{- 0.2266} (\ln Q_1) \underset{(0.0844)}{+ 0.1770} (\ln Q_2) \underset{(0.0734)}{+ 0.1943} (\ln Q_3) \underset{(0.0578)}{- 0.1317} (\ln Q_4) \underset{(0.0861)}{+ 0.1943} (\ln Q_5)$$

	$\ln H_{ff}$	$\ln Q_1$	$\ln Q_2$	$\ln Q_3$	$\ln Q_4$	$\ln Q_5$
upper bounds	7.4135	3.7849	4.6260	5.1319	6.2751	3.8250
lower bounds	6.1895	-0.1431	1.0176	1.8458	1.7047	0.5108
mean	6.6836	2.5873	3.7537	3.1540	4.7316	2.5754

Mission-Aransas and Nueces Estuaries Finfish Harvest = f (seasonal FINCm.a.n g/) Significant Equation ($\alpha = 2.5\%$, $r^2 = 74\%$, S.E. Est. = ± 244.3)

$$H_{ff} = 635.6 \underset{(5.1)}{- 13.6} (Q_1) \underset{(1.4)}{+ 3.4} (Q_2) \underset{(1.5)}{+ 2.4} (Q_3) \underset{(0.4)}{- 0.5} (Q_4) \underset{(3.1)}{+ 9.0} (Q_5)$$

	H_{ff}	Q_1	Q_2	Q_3	Q_4	Q_5
upper bounds	1658.3	55.5	189.0	188.8	688.0	89.0
lower bounds	487.6	3.8	7.9	15.2	17.7	6.5
mean	868.9	28.3	98.0	60.7	306.5	33.8

Table 8-17. Equations of Statistical Significance Relating the Finfish Fisheries Component to Freshwater Inflow Categories a/ (cont'd)

Where:

H_{ff} = inshore commercial finfish harvest, in thousands of pounds;
$\ln H_{ff}$ = natural log of H_{ff};
Q = mean monthly freshwater inflow, in thousands of acre-feet;
$\ln Q$ = natural log of Q:

Q_1 = Jan.-Mar.
Q_2 = Apr.-Jun.
Q_3 = Jul.-Aug.
Q_4 = Sept.-Oct.
Q_5 = Nov.-Dec.

a/ Standard error of each regression coefficient is shown in parentheses beneath the coefficients of the regression equations

b/ Freshwater inflow from Mission and Aransas River Basins

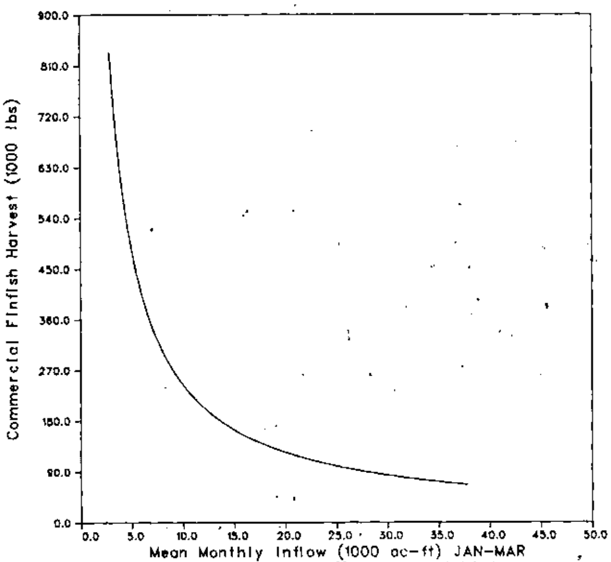
c/ Combined freshwater inflow to Mission-Aransas estuary from all contributing river and coastal drainage basins

d/ Freshwater inflow at Nueces delta

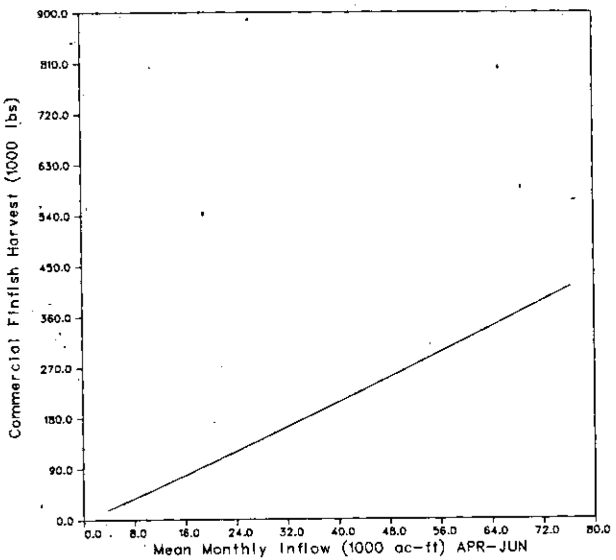
e/ Combined freshwater inflow to Nueces estuary from all contributing river and coastal drainage basins

f/ Freshwater inflow from Mission, Aransas, and Nueces River Basins

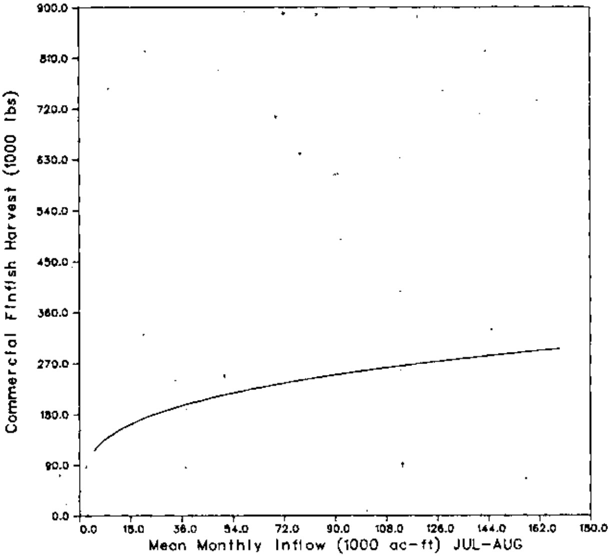
g/ Combined freshwater inflow to Mission-Aransas and Nueces estuaries from all contributing river and coastal drainage basins



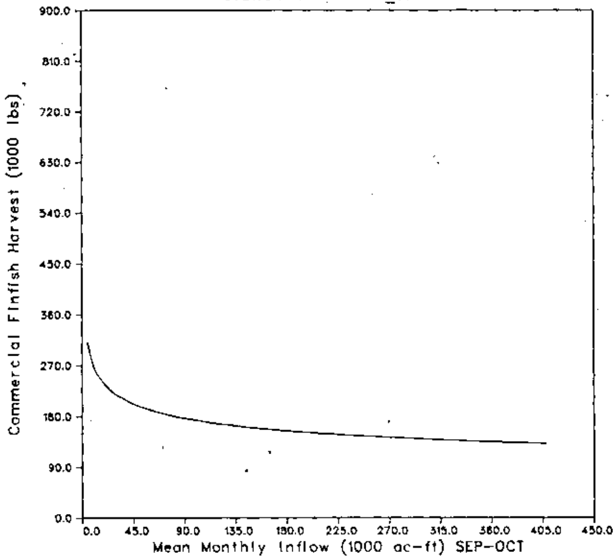
A. regression coefficient = —0.9818,
standard error = ±0.1922



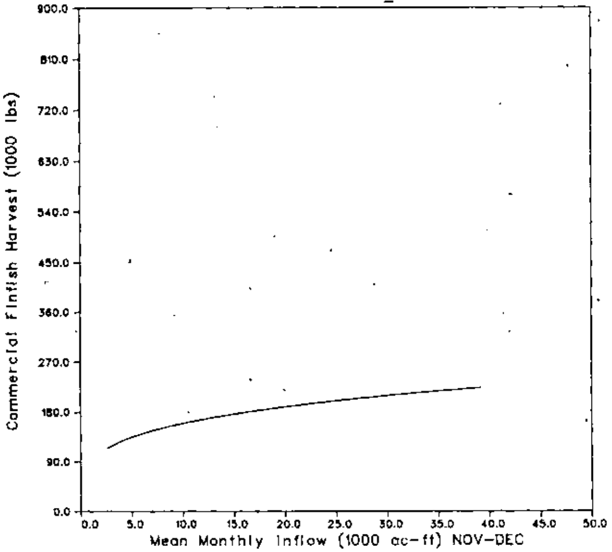
B. regression coefficient = +1.0597,
standard error = ±0.1623



C. regression coefficient = +0.2675,
standard error = ±0.1143



D. regression coefficient = —0.1964,
standard error = ±0.0982



E. regression coefficient = +0.2467,
standard error = ±0.1723

Figure 8-7. Nueces Estuary Finfish Harvest as a Function of Seasonal Inflow to the Estuary from Combined River and Coastal Drainage Basins, Where All Other Seasonal Inflows in the Multiple Regression Equation are Held Constant at Their Mean Values

penaeid shrimp harvests, although some conflict is noted for freshwater inflow needs during winter and autumn seasons.

Spotted Seatrout

Analysis of the spotted seatrout fisheries component also gives a significant regression equation for each of the six freshwater inflow categories (Table 8-18). The best significant equation (fourth equation, Table 8-18) accounts for 92 percent of the observed harvest variation and is very highly significant (α = 0.1%) for correlation of natural log transformed Nueces estuary spotted seatrout harvests to natural log transformed winter (Q_1), spring (Q_2), and summer (Q_3) season freshwater inflows contributed to the estuary from its combined river and coastal drainage basins ($FINC_n$).

The harvest response to January-March (Q_1) inflow is negative with an estimated 92 percent decrease in annual harvest as inflow increases to the observed upper bounds (Panel A, Figure 8-8). A strong positive response to April-June (Q_2) inflow results in the estimate of harvest increasing 22.9 times its minimum value (Panel B, Figure 8-8). Another positive response to July-August (Q_3) inflow increases the estimate of harvest 2.0 times its minimum value (Panel C, Figure 8-8). For the three correlating seasonal inflows, responses are similar to the general finfish component and indicate that maximization of harvest is related to increasing spring and summer (especially spring) season inflows and decreasing winter inflows to the Nueces estuary.

Red Drum

Significant regression equations result from analysis of the six freshwater inflow categories (Table 8-19). The best significant equation (fourth equation, Table 8-19) explains 91 percent of the observed harvest variation and is very highly significant (α = 0.1%) for correlation of Nueces estuary red drum harvests to seasonal inflows (Q_1 through Q_5) contributed to the estuary from its combined river and coastal drainage basins ($FINC_n$), when data variates are transformed to natural logarithms.

Curvilinear harvest responses are similar to those of the finfish and spotted seatrout fisheries components, exhibiting a strong negative response to January-March (Q_1) inflow (Panel A, Figure 8-9), a strong positive response to April-June (Q_2) inflow (Panel B, Figure 8-9), another positive response to July-August (Q_3) inflow (Panel C, Figure 8-9), a weak negative response to September-October (Q_4) inflow (Panel D, Figure 8-9), and a positive response to November-December (Q_5) inflow (Panel E, Figure 8-9). The greatest changes in harvest occurred as the estimate decreased 94 percent in response to increasing winter inflow (Panel A) and increased approximately 132 times its minimum value as spring inflow increased to its upper bounds (Panel B). Thus, maximization of red drum production is indicated by the regression model of harvest to be related to increased spring, summer, and late fall inflows, with diminished seasonal inflows to Nueces estuary during winter and autumn.

Table 8-18. Equations of Statistical Significance Relating the Spotted Seatrout Fisheries Component to Freshwater Inflow Categories a/

Mission-Aransas Estuary Spotted Seatrout Harvest = f (seasonal FINMA b/)
Highly Significant Equation ($\alpha = 0.5\%$, $r^2 = 81\%$, S.E. Est. = ± 37.6)

$$H_{ss} = 220.1 - \underset{(3.4)}{3.2\,(Q_1)} - \underset{(6.2)}{12.4\,(Q_3)} + \underset{(0.2)}{0.2\,(Q_4)} + \underset{(2.5)}{11.5\,(Q_5)}$$

	H_{ss}	Q_1	Q_3	Q_4	Q_5
upper bounds	360.7	10.1	8.3	153.3	15.8
lower bounds	110.8	0.1	1.0	0.3	0.8
mean	203.9	4.6	4.9	67.0	3.9

Mission-Aransas Estuary Spotted Seatrout Harvest = f (seasonal FINCm.a c/)
Very Highly Significant Equation ($\alpha = 0.1\%$, $r^2 = 80\%$, S.E. Est. = ± 37.2)

$$H_{ss} = 195.5 - \underset{(2.3)}{4.3\,(Q_3)} + \underset{(0.1)}{0.1\,(Q_4)} + \underset{(0.7)}{3.5\,(Q_5)}$$

	H_{ss}	Q_3	Q_4	Q_5
upper bounds	360.7	20.0	279.8	51.5
lower bounds	110.8	4.7	3.0	2.3
mean	203.9	13.4	134.0	14.3

Nueces Estuary Spotted Seatrout Harvest = f (seasonal FINND d/)
Very Highly Significant Natural Log Equation ($\alpha = 0.1\%$, $r^2 = 89\%$, S.E. Est. = ± 0.3477)

$$\ln H_{ss} = 2.6581 - \underset{(0.1255)}{0.8110\,(\ln Q_1)} + \underset{(0.1122)}{0.8542\,(\ln Q_2)} + \underset{(0.0664)}{0.0741\,(\ln Q_3)}$$

	H_{ss}	$\ln Q_1$	$\ln Q_3$	$\ln Q_3$
upper bounds	5.1823	3.5400	4.1500	5.0814
lower bounds	2.4849	-0.2657	-0.2657	0.4055
mean	3.7895	2.2676	3.2473	2.6534

Table 8-18. Equations of Statistical Significance Relating the Spotted Seatrout Fisheries Component to Freshwater Inflow Categories a/ (Cont'd)

Nueces Estuary Spotted Seatrout Harvest = f (seasonal FINCn e/)
Very Highly Significant Natural Log Equation ($\alpha = 0.1\%$, $r^2 = 92\%$, S.E. Est. = ± 0.3028)

$$\ln H_{ss} = 1.9996 - \underset{(0.1464)}{0.9582} (\ln Q_1) + \underset{(0.1214)}{1.0457} (\ln Q_2) + \underset{(0.0736)}{0.2005} (\ln Q_3)$$

	$\ln H_{ss}$	$\ln Q_1$	$\ln Q_2$	$\ln Q_3$
upper bounds	5.1823	3.6323	4.3351	5.1309
lower bounds	2.4849	1.0531	1.3524	1.6422
mean	3.7895	2.6454	3.5277	3.1713

Mission-Aransas and Nueces Estuaries Spotted Seatrout Harvest = f (seasonal FINMAN f/)
Highly Significant Equation ($\alpha = 0.5\%$, $r^2 = 76\%$, S.E. Est. = ± 49.5)

$$H_{ss} = 210.7 - \underset{(1.1)}{3.9} (Q_1) + \underset{(0.4)}{0.6} (Q_2) + \underset{(0.9)}{4.8} (Q_5)$$

	H_{ss}	Q_1	Q_2	Q_5
upper bounds	394.1	44.0	102.1	45.8
lower bounds	153.6	0.9	2.8	1.7
mean	269.0	18.3	58.1	19.5

Mission-Aransas and Nueces Estuaries Spotted Seatrout Harvest = f (seasonal FINCm.a.n g/)
Very Highly Significant Equation ($\alpha = 0.1\%$, $r^2 = 77\%$, S.E. Est. = ± 48.5)

$$H_{ss} = 208.9 - \underset{(1.0)}{1.9} (Q_1) + \underset{(0.2)}{0.5} (Q_3) + \underset{(0.6)}{2.5} (Q_5)$$

	H_{ss}	Q_1	Q_3	Q_5
upper bounds	394.1	55.5	188.8	89.0
lower bounds	153.6	3.8	15.2	6.5
mean	269.0	28.3	60.7	33.8

Table 8-18. Equations of Statistical Significance Relating the Spotted Seatrout Fisheries Component to Freshwater Inflow Categories a/ (Cont'd)

Where:

H_{ss} = inshore commercial spotted seatrout harvest, in thousands of pounds

ln H_{ss} = natural log of H_{ss};

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

ln Q = natural log of Q:

Q_1 = Jan.-Mar.

Q_2 = Apr.-Jun.

Q_3 = Jul.-Aug.

Q_4 = Sept.-Oct.

Q_5 = Nov.-Dec.

a/ Standard error of each regression coefficient is shown in parentheses beneath the coefficients of the regression equations

b/ Freshwater inflow from Mission and Aransas River Basins

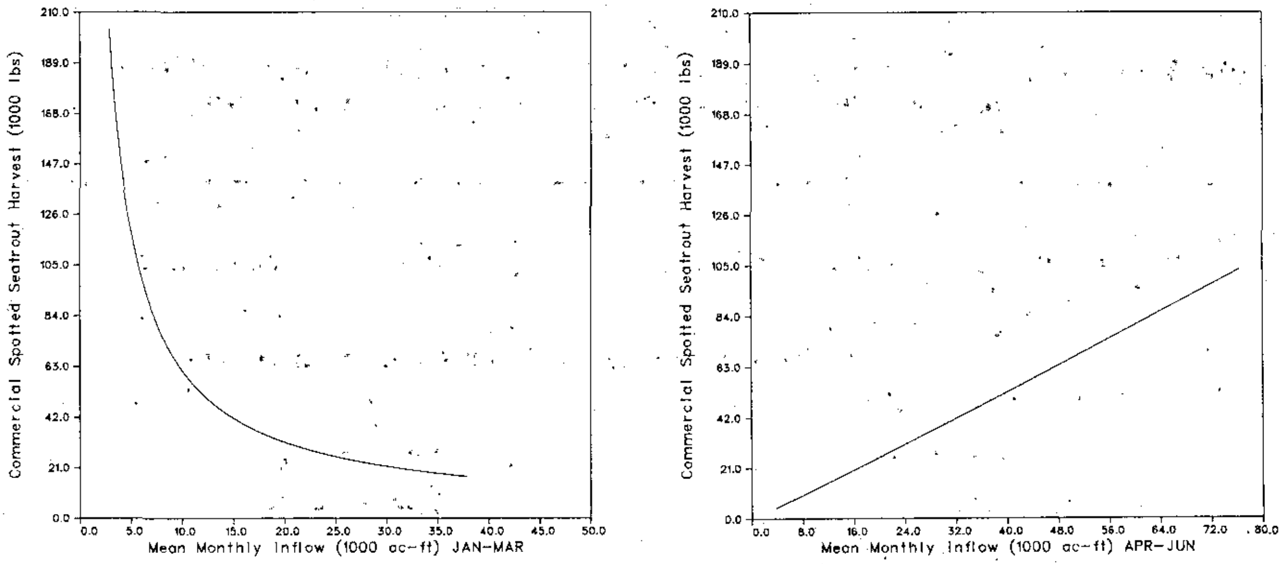
c/ Combined freshwater inflow to Mission-Aransas estuary from all contributing river and coastal drainage basins

d/ Freshwater inflow at Nueces delta

e/ Combined freshwater inflow to Nueces estuary from all contributing river and coastal drainage basins

f/ Freshwater inflow from Mission, Aransas, and Nueces River Basins

g/ Combined freshwater inflow to Mission-Aransas and Nueces estuaries from all contributing river and coastal drainage basins

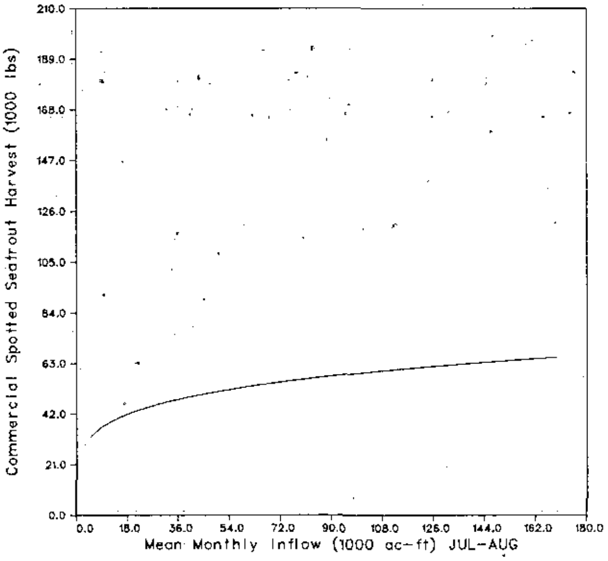


A. regression coefficient = —0.9582,

standard error = ±0.1464

B. regression coefficient = +1.0457,

standard error = ±0.1214



C. regression coefficient = +0.2005,

standard error = ±0.0736

Figure 8-8. Nueces Estuary Spotted Seatrout Harvest as a Function of Seasonal Inflow to the Estuary 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 8-19. Equations of Statistical Significance Relating the Red Drum Fisheries Component to Freshwater Inflow Categories a/

Mission-Aransas Estuary Red Drum Harvest = f (seasonal FINMA b/)
Highly Significant Natural Log Equation (α = 1.0%, r^2 = 54%, S.E. Est. = ± 0.4636)

$$\ln H_{rd} = 3.9294 + \underset{(0.1482)}{0.2644\,(\ln Q_2)} + \underset{(0.0713)}{0.1096\,(\ln Q_4)}$$

	$\ln H_{rd}$	$\ln Q_2$	$\ln Q_4$
upper bounds	6.1827	3.9233	5.0326
lower bounds	4.0128	0.6931	-1.0986
mean	4.9843	2.7116	3.0822

Mission-Aransas Estuary Red Drum Harvest = f (seasonal FINCm.a c/)
Highly Significant Natural Log Equation (α = 1.0%, r^2 = 54%, S.E. Est. = ± 0.4646)

$$\ln H_{rd} = 3.5636 + \underset{(0.1577)}{0.2000\,(\ln Q_2)} + \underset{(0.1007)}{0.1682\,(\ln Q_4)}$$

	$\ln H_{rd}$	$\ln Q_2$	$\ln Q_4$
upper bounds	6.1827	4.7241	5.6342
lower bounds	4.0128	1.3863	1.0986
mean	4.9843	3.6249	4.1347

Nueces Estuary Red Drum Harvest = f (seasonal FINND d/)
Very Highly Significant Natural Log Equation (α = 0.1%, r^2 = 89%, S.E. Est. = ± 0.5886)

$$\ln H_{rd} = 0.7689 - \underset{(0.2239)}{1.0121\,(\ln Q_1)} + \underset{(0.2058)}{1.3291\,(\ln Q_2)} - \underset{(0.1569)}{0.1893\,(\ln Q_4)}$$

$$+ \underset{(0.1779)}{0.5934\,(\ln Q_5)}$$

	$\ln H_{rd}$	$\ln Q_1$	$\ln Q_2$	$\ln Q_4$	$\ln Q_5$
upper bounds	5.3664	3.5400	4.1500	5.9345	3.5648
lower bounds	0.9555	-0.2657	-0.2657	0.6931	-0.4055
mean	3.3318	2.2676	3.2473	4.3732	2.3088

Table 8-19. Equations of Statistical Significance Relating the Red Drum Fisheries Component to Freshwater Inflow Categories a/ (cont'd)

Nueces Estuary Red Drum Harvest = f (seasonal FINCn e/)
Very Highly Significant Natural Log Equation ($\alpha = 0.1\%$, $r^2 = 91\%$, S.E. Est. = ± 0.5574)

$$\ln H_{rd} = -1.1544 - \underset{(0.3273)}{1.0758(\ln Q_1)} + \underset{(0.2764)}{1.6399\ (\ln Q_2)} + \underset{(0.1946)}{0.2928\ (\ln Q_3)}$$

$$-\underset{(0.1673)}{0.1845\ (\ln Q_4)} + \underset{(0.2934)}{0.5442\ (\ln Q_5)}$$

	$\ln H_{rd}$	$\ln Q_1$	$\ln Q_2$	$\ln Q_3$	$\ln Q_4$	$\ln Q_5$
upper bounds	5.3664	3.6323	4.3351	5.1309	6.0117	3.6678
lower bounds	0.9555	1.0531	1.3524	1.6422	1.6094	0.9808
mean	3.3318	2.6454	3.5277	3.1713	4.5536	2.6805

Mission-Aransas and Nueces Estuaries Red Drum Harvest = f (seasonal FINMAN f/)
Highly Significant Natural Log Equation ($\alpha = 0.5\%$, $r^2 = 81\%$, S.E. Est. = ± 0.3854)

$$\ln H_{rd} = 2.9314 - \underset{(0.1353)}{0.2071\ (\ln Q_1)} + \underset{(0.1309)}{0.4274\ (\ln Q_2)} + \underset{(0.1344)}{0.2291\ (\ln Q_3)}$$

$$+\underset{(0.1406)}{0.1950}\ (\ln Q_5)$$

	$\ln H_{rd}$	$\ln Q_1$	$\ln Q_2$	$\ln Q_3$	$\ln Q_5$
upper bounds	6.4072	3.7849	4.6260	5.1319	3.8250
lower bounds	4.2032	-0.1431	1.0176	1.8458	0.5108
mean	5.2247	2.5873	3.7537	3.1540	2.5754

Mission-Aransas and Nueces Estuaries Red Drum Harvest = f (seasonal FINCm.a.n g/)
Very Highly Significant Natural Log Equation ($\alpha = 0.1\%$, $r^2 = 82\%$, S.E. Est. = ± 0.3715)

$$\ln H_{rd} = 2.1482 - \underset{(0.1662)}{0.2812\ (\ln Q_1)} + \underset{(0.1280)}{0.4435\ (\ln Q_2)} + \underset{(0.1672)}{0.3647\ (\ln Q_3)}$$

$$+\underset{(0.1597)}{0.2144}\ (\ln Q_5)$$

	$\ln H_{rd}$	$\ln Q_1$	$\ln Q_2$	$\ln Q_3$	$\ln Q_5$
upper bounds	6.4072	4.0158	5.2416	5.2409	4.4886
lower bounds	4.2032	1.3262	2.0626	2.7191	1.8718
mean	5.2247	3.1401	4.3007	3.7378	3.2128

Table 8-19. Equations of Statistical Significance Relating the Red Drum Fisheries Component to Freshwater Inflow Categories a/ (cont'd)

Where:

$\ln H_{rd}$ = natural log, inshore commercial red drum harvest, in thousands of pounds;

$\ln Q$ = natural log, mean monthly freshwater inflow, in thousands of acre-feet:

Q_1 = Jan.-Mar.

Q_2 = Apr.-Jun.

Q_3 = Jul.-Aug.

Q_4 = Sept.-Oct.

Q_5 = Nov.-Dec.

a/ Standard error of each regression coefficient is shown in parentheses beneath the coefficients of the regression equations

b/ Freshwater inflow from Mission and Aransas River Basins

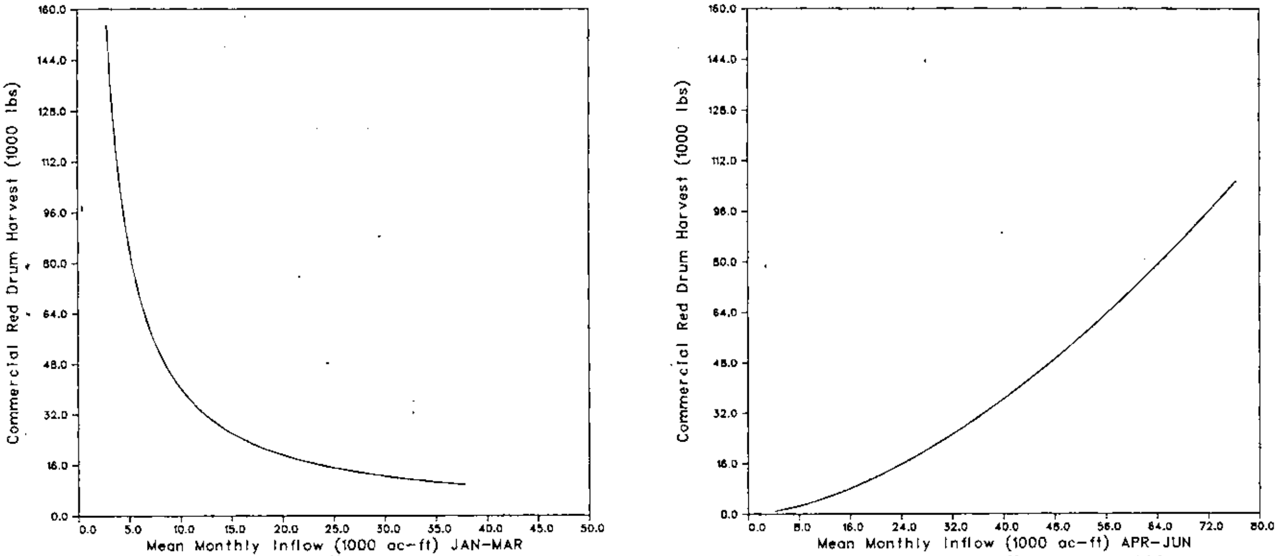
c/ Combined freshwater inflow to Mission-Aransas estuary from all contributing river and coastal drainage basins

d/ Freshwater inflow at Nueces delta

e/ Combined freshwater inflow to Nueces estuary from all contributing river and coastal drainage basins

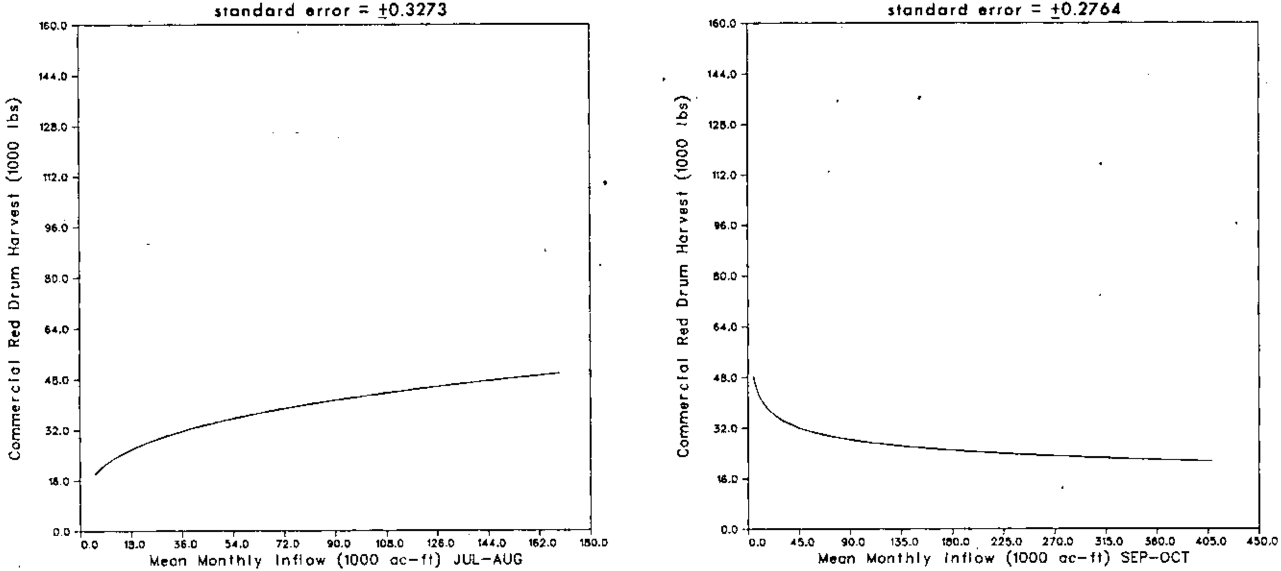
f/ Freshwater inflow from Mission, Aransas, and Nueces River Basins

g/ Combined freshwater inflow to Mission-Aransas and Nueces estuaries from all contributing river and coastal drainage basins



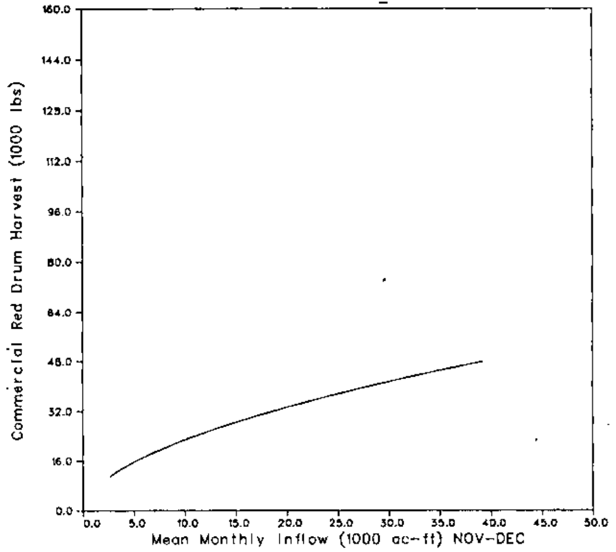
A. regression coefficient = —1.0758, standard error = ±0.3273

B. regression coefficient = +1.6399, standard error = ±0.2764



C. regression coefficient = +0.2928, standard error= ±0.1946

D. regression coefficient = —0.1845, standard error = ±0.1673



E. regression coefficient = +0.5442, standard error = ±0.2934

Figure 8-9. Nueces Estuary Red Drum Harvest as a Function of Seasonal Inflow to the Estuary from Combined River and Coastal Drainage Basins, Where All Other Seasonal Inflows in the Multiple Regression Equation are Held Constant at Their Mean Values

Black Drum

Analysis of the black drum fisheries component additionally results in natural log regression equations for each of the freshwater inflow categories (Table 8-20). The best significant equation (fourth equation, Table 8-20) accounts for 92 percent of the observed harvest variation and is highly significant (α = 0.1%) for correlation of Nueces estuary black drum harvests to winter, spring, summer, and autumn season inflows to the estuary from its contributing river and coastal drainage basins.

Seasonal freshwater inflow information is again similar to the previously discussed finfish, spotted seatrout, and red drum fisheries components, although the presence or absence of a statistically significant response to Nueces estuary autumn and late fall inflows is not uniform among the components. The curvilinear harvest responses are strongly negative to January-March (Q_1) inflow (Panel A, Figure 8-10), strongly positive to April-June (Q_2) inflow (Panel B, Figure 8-10), positive to July-August (Q_3) inflow (Panel C, Figure 8-10), and negative to September-October (Q_4) inflow (Panel D, Figure 8-10). It is noted that the estimate of annual harvest decreases 96 percent as winter inflow increases (Panel A), and increases about 67 times the minimum harvest estimate as spring inflow varies over its observed range (Panel B). Maximization of black drum harvest is therefore statistically related to increased spring and summer inflows, and decreased winter and autumn inflows to Nueces estuary.

Fisheries Component Summary

The fisheries analysis involves 10 fisheries components and six freshwater inflow source categories in the analytical design, allowing a maximum 60 potentially significant equations. The analysis results in 52 regression equations of statistical significance and is thus successful for 87 percent of correlations attempted. Although each of the inflow categories can potentially produce 10 significant equations, the analysis yields 10 equations with freshwater inflow from Mission and Aransas rivers (FINMA), eight equations with combined freshwater inflow to Mission-Aransas estuary from its contributing river and coastal drainage basins (FINCma), eight equations with freshwater inflow at Nueces delta (FINND), eight equations with combined inflow to Nueces estuary from its contributing river and coastal drainage basins (FINCn), nine equations with freshwater inflow from Mission, Aransas, and Nueces rivers (FINMAN), and nine equations with freshwater inflow to Mission-Aransas and Nueces estuaries from all contributing river and coastal drainage basins (FINCman).

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 8-21). Therefore, the seasonal inflow needs of the fisheries components can reinforce each other. However, where seasonal inflow needs are of opposite signs, the fisheries components become competitive in terms of inflow management. Altogether, these results support the hypothesis that seasonal freshwater inflow has a significant impact on the estuary's fisheries, and by ecological implication, on the "health" of the ecosystem.

Table 8-20. Equations of Statistical Significance Relating the Black Drum Fisheries Component to Freshwater Inflow Categories a/

Mission-Aransas Estuary Black Drum Harvest = f (seasonal FINMA b/)
Highly Significant Natural Log Equation ($\alpha = 1.0\%$, $r^2 = 64\%$, S.E. Est. = $\pm$ 0.3431)

$$\ln H_{bd} = 5.3600 - \underset{(0.0876)}{0.1820} (\ln Q_1) - \underset{(0.1745)}{0.4952} (\ln Q_3) + \underset{(0.1074)}{0.3039} (\ln Q_5)$$

	$\ln H_{bd}$	$\ln Q_1$	$\ln Q_3$	$\ln Q_5$
upper bounds	5.6591	2.3158	2.1203	2.7621
lower bounds	3.9259	-2.3026	0.0000	-0.1823
mean	4.7049	1.0754	1.4565	0.8617

Mission-Aransas Estuary Black Drum Harvest = f (seasonal FINCm.a c/)
Highly Significant Natural Log Equation ($\alpha = 0.5\%$, $r^2 = 60\%$, S.E. Est. = $\pm$ 0.3489)

$$\ln H_{bd} = 4.6116 - \underset{(0.0868)}{0.2088} (\ln Q_2) + \underset{(0.1019)}{0.3825} (\ln Q_5)$$

	$\ln H_{bd}$	$\ln Q_2$	$\ln Q_5$
upper bounds	5.6591	4.7241	3.9416
lower bounds	3.9259	1.3863	0.8473
mean	4.7049	3.6249	2.2226

Nueces Estuary Black Drum Harvest = f (seasonal FINND d/)
Very Highly Significant Natural Log Equation ($\alpha = 0.1\%$, $r^2 = 88\%$, S.E. Est. = $\pm$ 0.4342)

$$\ln H_{bd} = 3.1912 - \underset{(0.1622)}{1.0776} (\ln Q_1) + \underset{(0.1516)}{1.1504} (\ln Q_2) - \underset{(0.0945)}{0.1246} (\ln Q_4)$$

	$\ln H_{bd}$	$\ln Q_1$	$\ln Q_2$	$\ln Q_4$
upper bounds	5.3945	3.5400	4.1500	5.9345
lower bounds	2.0794	-0.2657	-0.2657	0.6931
mean	3.9384	2.2676	3.2473	4.3732

Table 8-20. Equations of Statistical Significance Relating the Black Drum Fisheries Component to Freshwater Inflow Categories [a] (cont'd)

Nueces Estuary Black Drum Harvest = f (seasonal FINCn [e])
Very Highly Significant Natural Log Equation ($\alpha = 0.1\%$, $r^2 = 92\%$, S.E. Est. = $\pm$ 0.3534)

$$\ln H_{bd} = 2.4260 - \underset{(0.1787)}{1.2457\ (\ln Q_1)} + \underset{(0.1642)}{1.4119\ (\ln Q_2)} + \underset{(0.0905)}{0.2493\ (\ln Q_3)}$$

$$- \underset{(0.0921)}{0.2116\ (\ln Q_4)}$$

	$\ln H_{bd}$	$\ln Q_1$	$\ln Q_2$	$\ln Q_3$	$\ln Q_4$
upper bounds	5.3945	3.6323	4.3351	5.1309	6.0117
lower bounds	2.0794	1.0531	1.3524	1.6422	1.6094
mean	3.9384	2.6454	3.5277	3.1713	4.5536

Mission-Aransas and Nueces Estuaries Black Drum Harvest = f (seasonal FINMAN [f])
Highly Significant Natural Log Equation ($\alpha = 1.0\%$, $r^2 = 78\%$, S.E. Est. = $\pm$ 0.2874)

$$\ln H_{bd} = 5.2142 - \underset{(0.1113)}{0.2872\ (\ln Q_1)} + \underset{(0.1152)}{0.1356\ (\ln Q_2)} + \underset{(0.1002)}{0.2525\ (\ln Q_3)}$$

$$- \underset{(0.0790)}{0.2332\ (\ln Q_4)} + \underset{(0.1176)}{0.2179\ (\ln Q_5)}$$

	$\ln H_{bd}$	$\ln Q_1$	$\ln Q_2$	$\ln Q_3$	$\ln Q_4$	$\ln Q_5$
upper bounds	5.8556	3.7849	4.6260	5.1319	6.2751	3.8250
lower bounds	4.4875	-0.1431	1.0176	1.8458	1.7047	0.5108
mean	5.2342	2.5873	3.7537	3.1540	4.7316	2.5754

Mission-Aransas and Nueces Estuaries Black Drum Harvest = f (seasonal FINCm.a.n [g])
Significant Natural Log Equation ($\alpha = 2.5\%$, $r^2 = 66\%$, S.E. Est. = $\pm$ 0.3356)

$$\ln H_{bd} = 4.8033 - \underset{(0.1384)}{0.2704\ (\ln Q_1)} + \underset{(0.1494)}{0.3307\ (\ln Q_3)} - \underset{(0.0888)}{0.1858\ (\ln Q_4)}$$

$$+ \underset{(0.1485)}{0.3122\ (\ln Q_5)}$$

	$\ln H_{bd}$	$\ln Q_1$	$\ln Q_3$	$\ln Q_4$	$\ln Q_5$
upper bounds	5.8556	4.0158	5.2409	6.5338	4.4886
lower bounds	4.4875	1.3262	2.7191	2.8717	1.8718
mean	5.2342	3.1401	3.7378	5.1630	3.2128

Table 8-20. Equations of Statistical Significance Relating the Black Drum Fisheries Component to Freshwater Inflow Categories a/ (cont'd)

Where:

$\ln H_{bd}$ = natural log, inshore commercial black drum harvest, in thousands of pounds

$\ln Q$ = natural log, mean monthly freshwater inflow, in thousands of acre-feet:

Q_1 = Jan.-Mar.

Q_2 = Apr.-Jun.

Q_3 = Jul.-Aug.

Q_4 = Sept.-Oct.

Q_5 = Nov.-Dec.

a/ Standard error of each regression coefficient is shown in parentheses beneath the coefficients of the regression equations

b/ Freshwater inflow from Mission and Aransas River Basins

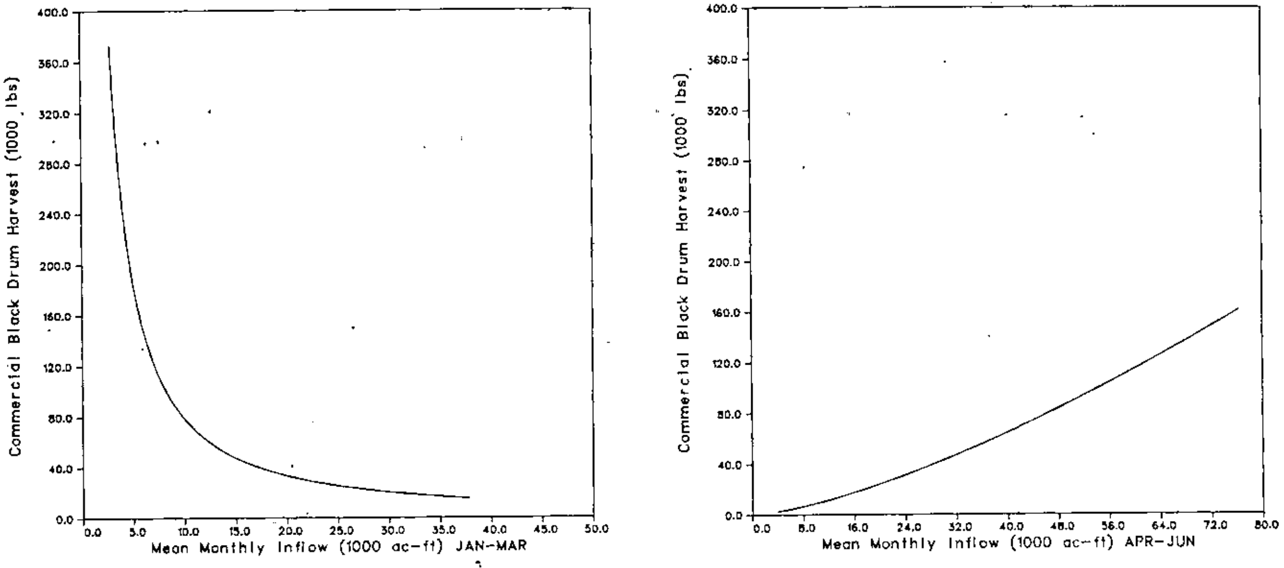
c/ Combined freshwater inflow to Mission-Aransas estuary from all contributing river and coastal drainage basins

d/ Freshwater inflow at Nueces delta

e/ Combined freshwater inflow to Nueces estuary from all contributing river and coastal drainage basins

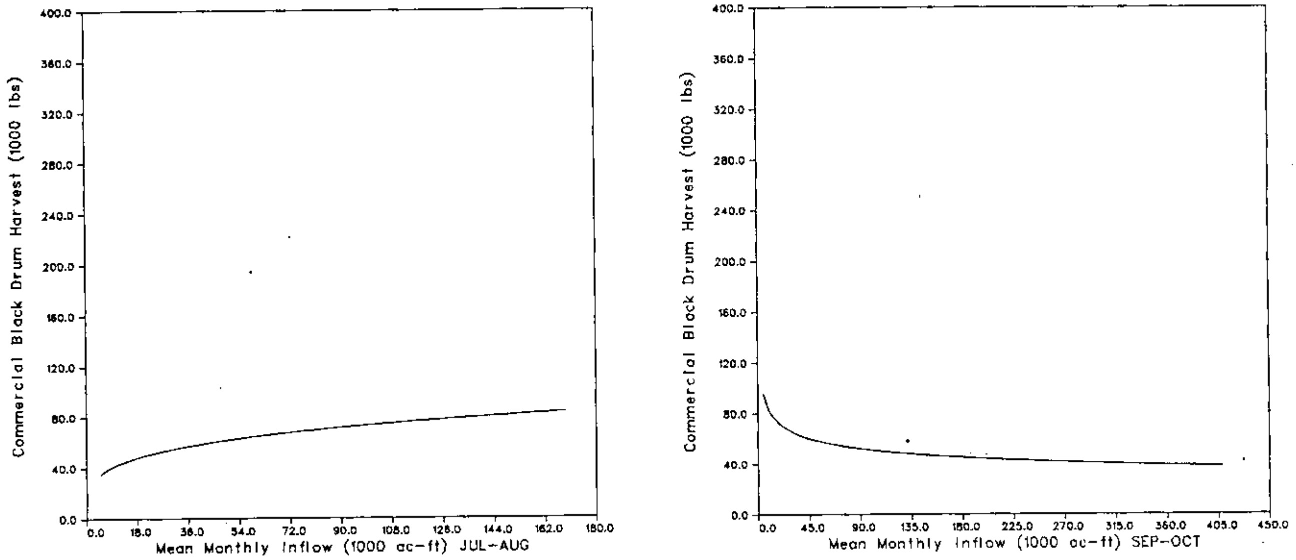
f/ Freshwater inflow from Mission, Aransas, and Nueces River Basins

g/ Combined freshwater inflow to Mission-Aransas and Nueces estuaries from all contributing river and coastal drainage basins



A. regression coefficient = —1.2457,
standard error = ±0.1787

B. regression coefficient = +1.4119,
standard error = ±0.1642



C. regression coefficient = +0.2493,
standard error= ±0.0905

D. regression coefficient = —0.2116,
standard error = ±0.0921

Figure 8-10. Nueces Estuary Black Drum Harvest as a Function of Seasonal Inflow to the Estuary 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 8-21. 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.)	Annual Inflow Q_6 (Jan.-Dec.)	Explained Variation r^2 (%)	Significance Level α (%)
Shellfish								
FINMA a/		+		+	+		52	5.0
FINCma b/						+	29	5.0
FINND c/		+		+			64	0.5
FINCn d/		+		+			46	5.0
FINMAN e/		+		+	+		70	0.5
FINCman f/	−	+				+	60	2.5
All Shrimp								
FINMA	+	+	+		+		71	1.0
FINCm		+			+		67	0.5
FINND		+		+	−		72	0.5
FINCn	−	+					53	2.5
FINMAN		+	+	+			88	0.1
FINCman		+		+			78	0.1
White Shrimp								
FINMA		+		−		+	68	0.5
FINCma		+	+	−		+	71	1.0
FINND		+	−	+			74	0.5
FINCn		+	−	+			65	1.0
FINMAN	+	+	+	+			84	0.1
FINCman	+	+			+		80	0.1
Brown and Pink Shrimp								
FINMA		+				−	42	5.0
FINCma								
FINND								
FINCn								
FINMAN	−	+				−	56	2.5
FINCman	−	+				−	50	5.0
Blue Crab								
FINMA	+		+	+			50	5.0
FINCma								
FINND	+	+		−	+		91	1.0
FINCn	+	+		−	+		91	1.0
FINMAN	+	+	+				82	2.5
FINCman		+	+				64	5.0
Bay Oyster								
FINMA	+		+		+		53	5.0
FINCma	+			+			42	5.0
FINND								
FINCn								
FINMAN								
FINCman								

(continued)

Table 8-21. Positive (+) and Negative (-) Correlation of Fisheries Components to Seasonal Freshwater Inflow Categories (cont'd.)

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.)	Annual Inflow Q_6 (Jan.-Dec.)	Explained Variation r^2 (%)	Significance Level α (%)
Finfish								
FINMA	-		-		+		59	2.5
FINCma	-		-	+	+		72	1.0
FINND	-	+	+				87	0.1
FINCn	-	+	+	-	+		92	0.1
FINMAN	-	+	+	-	+		83	0.5
FINCman	-	+	+	-	+		74	2.5
Spotted Seatrout								
FINMA	-		-	+	+		81	0.5
FINCma			-	+	+		80	0.1
FINND	-	+	+				89	0.1
FINCn	-	+	+				92	0.1
FINMAN	-	+			+		76	0.5
FINCman	-		+		+		77	0.1
Red Drum								
FINMA		+		+			54	1.0
FINCma		+		+			54	1.0
FINND	-	+		-	+		89	0.1
FINCn	-	+	+	-	+		91	0.1
FINMAN	-	+	+		+		81	0.5
FINCman	-	+	+		+		82	0.1
Black Drum								
FINMA	-		-		+		64	1.0
FINCma		-			+		60	0.5
FINND	-	+		-			88	0.1
FINCn	-	+	+	-			92	0.1
FINMAN	-	+	+	-	+		78	1.0
FINCman	-		+	-	+		66	2.5
Summary:								
FINMA	(+)=3 (-)=3	(+)=5 (-)=0	(+)=3 (-)=3	(+)=4 (-)=1	(+)=6 (-)=0	(+)=1 (-)=1		
FINCma	(+)=1 (-)=1	(+)=3 (-)=1	(+)=1 (-)=2	(+)=4 (-)=1	(+)=4 (-)=0	(+)=2 (-)=0		
FINND	(+)=1 (-)=4	(+)=8 (-)=0	(+)=2 (-)=1	(+)=3 (-)=3	(+)=2 (-)=1	(+)=0 (-)=0		

(continued)

Table 8-21. Positive (+) and Negative (-) Correlation of Fisheries Components to Seasonal Freshwater Inflow Categories (cont'd.)

	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.)	Annual Inflow Q_6 (Jan.-Dec.)
Summary (cont'd)						
FINCn	(+)=1 (-)=5	(+)=8 (-)=0	(+)=4 (-)=1	(+)=2 (-)=4	(+)=3 (-)=0	(+)=0 (-)=0
FINMAN	(+)=2 (-)=5	(+)=9 (-)=0	(+)=6 (-)=0	(+)=3 (-)=2	(+)=5 (-)=0	(+)=0 (-)=1
FINCman	(+)=1 (-)=6	(+)=7 (-)=0	(+)=5 (-)=0	(+)=1 (-)=2	(+)=5 (-)=0	(+)=1 (-)=1

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a/ Freshwater inflow from Mission and Aransas River Basins.
b/ Combined freshwater inflow to Mission-Aransas estuary from all contributing river and coastal drainage basins.
c/ Freshwater inflow to Nueces delta.
d/ Combined freshwater inflow to Nueces estuary from all contributing river and coastal drainage basins.
e/ Freshwater inflow from Mission, Aransas, and Nueces River Basins.
f/ Combined freshwater inflow to Mission-Aransas and Nueces estuaries from all contributing river and coastal drainage basins.

Freshwater Inflow Effects

Introduction

The hydrologic importance of both tidal inlets and freshwater inflow for ecological preservation of estuaries has been recognized (130, 282). 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, 170, 137, 134, 172). Consequently, the addition of supplemental freshwater inflow for purposes of ecological maintenance and maximization of seafood production has been recommended for the Gulf estuaries of Texas (130, 337), Mississippi and Louisiana (53).

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 (4) which may be reflected in physiological adaptation to the estuarine environment (115, 114, 405, 406), in species distribution patterns and community diversity (82, 72, 77, 58, 84, 22, 120), and ultimately in species evolution (111). Previous research emphasizing Texas estuarine-dependent species has dealt with several aspects of the inflow/salinity relationship including environmental limits (319), tolerance to hypersaline waters (76, 93, 7), and rapid recovery of typical estuarine community species at the end of a severe drought (103). In addition, salinity changes resulting from man's development of an estuary and its contributing river and coastal drainage basins have been reviewed relevant to many Texas estuarine-dependent species (80, 354), and their diseases and symbionts (174).

While plants provide an estuary's primary production, most secondary production comes from the invertebrate bay fauna. For the invertebrates, inflow/salinity effects have a demonstrated physiological basis (8, 349, 116, 125, 347) and are effective at modifying species distribution (290, 304, 176). The brackish water clam (Rangia cuneata) has been suggested as an indicator of ecological effects associated with salinity changes because of its sensitivity (215); 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 (138).

Shrimp

The Gulf of Mexico shrimp fishery is the most valuable fishery in the United States (64) and the Gulf estuaries play a crucial role in the production of this renewable resource (66, 121). 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 (129), brown shrimp (24), pink shrimp (29), and other species in the genus Penaeus (396). Other information especially important for management of this fishery resource comes from research on shrimp spawning and early larval stages (358, 309, 328, 394), seasonal migration behavior (351, 27, 258), utilization of estuarine nursery habitats (72), and major enivronmental factors influencing species population dynamics and production (217, 86, 144, 143, 31, 133). Species-specific responses to inflow/salinity conditions in the estuary are fundamentally physiological (5, 12, 224, 221, 123, 356), and therefore directly influence not only growth and survival of the postlarval shrimp (421, 422, 420, 404), but the distribution of the bay shrimp populations as well (316, 83, 293).

Results of the fisheries analysis (i.e., shellfish, all penaeid shrimp, white shrimp, and brown and pink shrimp fisheries components) support the importance of freshwater inflow to shrimp production and provide quantified data on the responses of commercial inshore harvests from the Mission-Aransas and Nueces estuaries to seasonal fluctuations of the six analyzed inflow categories (i.e., FINMA, FINCma, FINND, FINCn, FINMAN, and FINCman). The equational models indicate a particularly notable seasonal dichotomy in the harvest responses of shrimp species to winter (January-March) inflow. For this season, the white shrimp fisheries component exhibits positive responses to FINMAN and FINCman inflow categories, while the brown and pink shrimp fisheries component gives strong negative responses to the same inflow categories (Table 8-21). The difference may possibly be explained by negative effects of increased winter inflow on the late winter migrations of brown shrimp larvae and postlarvae into the estuaries. Unfavorable estuarine conditions during this critical period can reduce survival and growth, resulting in decline of the subsequent brown shrimp harvest. The uniformly positive response to spring (April-June) inflow supports the recognized importance of this season's freshwater inflow to shrimp populations. In general, seasonal shrimp responses to summer (July-August), autumn (September-October), and late fall (November-December) inflows are also positive, except for the negative responses of the white shrimp fisheries component to summer inflow (FINND and FINCn inflow categories) and autumn inflow (FINMA and FINCma).

Blue Crab

Another major crustacean fishery species is the estuarine-dependent blue crab (Callinectes sapidus Rathbun, 1896). Previous research has described blue crab taxomony (250, 291), life history (360, 249), migration behavior (297, 104, 258), and responses to environmental factors such as salinity (195, 30, 218, 122) and storm water runoff (127). Except for the strong negative responses to autumn inflow (FINND and FINCn inflow categories), other seasonal responses indicate positive relationships to freshwater inflow (Table 8-21).

Bay Oyster

The American oyster (Crassostrea virginica Gmelin) is a molluscan shellfish species that has been harvested from Texas bay waters virtually since the aboriginal Indians arrived many thousands of years ago and it continues today as the only estuarine bivalve (a type of mollusc) of current commercial interest in the State. Because of man's historical interest in greater development and utilization of this fishery resource (e.g., raft farming, artificial reef formation, etc.), scientific information is available on the oyster's general ecology and life history (389, 409), as well as geographic variation of its populations (197). The effects of inflow/salinity are particularly important and have stimulated considerable research covering a wide range of subjects including effects on oyster distribution (312, 142, 42), gametogenesis (development of viable eggs and sperm) and spawning (359, 13, 132, 189), eggs and larvae (6, 39, 390, 393, 96), respiration (320, 403), free amino acids which are protein building blocks (146), and the effects on oyster reef growth and mortality (74, 301), abundance of faunal associates (74, 413), and reef diseases (223, 174).

Previous studies have described the Texas oyster fishery (261) and the State's major oyster producing areas (397, 265). Numerous oyster reefs have been recently inventoried in the Nueces and Mission-Aransas estuaries with many located in Copano Bay and the northeastern area of Aransas Bay (378). Classified "polluted areas" are closed to harvest by the Texas Department of Health under authority of Section 76.202, Parks and Wildlife Code, until such time as sampling indicates a return of healthy estuarine conditions. Currently, the areas closed include virtually all of Redfish Bay, nearshore waters around Live Oak Peninsula, and the nearshore waters around Corpus Christi Bay.

Only oyster harvests from the Mission-Aransas estuary were continuous enough for analysis. The results indicate positive harvest responses to winter, summer, and late fall season inflows from Mission and Aransas rivers (FINMA inflow category), while combined inflow to the estuary (FINCma) in winter and autumn seasons also relates positively to oyster harvest (Table 8-21).

Finfish

Estuaries play a vital functional role in the life cycle and production of most coastal fish species (357, 108, 136, 254, 105). Environmental sensitivity of the estuarine-dependent fishes has allowed the use of species diversity indices as indicators of pollution (298). Although migration does occur across the boundary between riverine and estuarine habitats by both freshwater and estuarine-dependent marine fishes (169, 186), there is a predominance of young marine fishes found in this low salinity area (75).

In general, seasonal variations in estuarine fish abundance are related to life history and migrational behavior (81, 323, 322, 106, 297, 104, 258, 193, 264, 292, 418). The primary effects of inflow/salinity are physiological (102, 107, 126), and are particularly important for the survival of the early life stages (101), the metabolism (i.e., metabolic stresses) of adult bay populations (315, 318, 325, 286, 408), and juvenile rates of adaptability (287, 288). Low temperature extremes can also interact physiologically with salinity stress to produce dramatic fish mortality (69, 70, 73).

The multi-species finfish component of the fisheries analysis exhibits only negative relationships between harvest and winter inflow from all six of the freshwater inflow categories (Table 8-21). In opposite, harvest responses are uniformly positive to spring and late fall inflows. In addition, four of six computed responses to summer inflow are also positive. Negative responses are indicated for autumn inflow, except in the category for combined inflow to the Mission-Aransas estuary (FINCma).

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 (357, 222, 105). The sciaenid genus Cynoscion contains four species in the Western Atlantic and Gulf of Mexico (three in Texas waters) with the most valued fishery species, the spotted seatrout (Cynoscion nebulosus Cuvier), also recognized as the most divergent of the four seatrout species (392). The greater restriction and estuarine-dependence of this species are reflected in its nearly exclusive utilization of estuarine habitats (65, 212, 59) and the increased genetic differences among populations in separate bays (412). Previous research has described spotted seatrout life history and seasonal abundance in Texas waters (361, 323, 244, 245, 322, 106, 104, 258), 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 (285, 286, 313, 408, 287, 288).

Harvest responses to seasonal inflow are similar to those obtained in analysis of the general finfish component. Thus, responses of the spotted seatrout component are negative to winter inflow and positive to spring and late fall inflows (Table 8-21). In addition, only inflow to the Mission-Aransas estuary (FINMA and FINCma) results in negative harvest responses to summer inflow. Inflow to this estuary also gives the only significant spotted seatrout responses to autumn inflow and they are positive for this tropical storm dominated season.

Red Drum

Another important sciaenid species is the red drum or redfish (Sciaenops ocellata Linnaeus). Prior studies have reported on the general biology, food (prey) items, and seasonal distribution of the red drum (361, 323, 244, 245, 148, 324, 322, 106, 419, 104, 258, 105, 173). 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 (286, 408, 287, 288). Similar to results from the finfish and spotted seatrout fisheries components, analysis of the red drum component also shows the general negative harvest response to winter inflow and positive responses to spring, summer, and late fall inflows (Table 8-21). Autumn inflows again relate positively to the Mission-Aransas estuary harvest and negatively to the Nueces estuary harvest.

Black Drum

The black drum (Pogonias cromis Linnaeus) is also a sciaenid species of commercial and recreational interest. The general biology and life history aspects, including migrations and seasonal distributions, have been reported previously (323, 105, 258, 361, 324, 322, 357). In addition, the effects of inflow/salinity on the metabolism (i.e., metabolic stresses) of this broadly tolerant species have been investigated as salt concentration varies from an optimum of about 20-25 ppt salinity (286, 408). The seasonal importance of freshwater inflow to the species' production and harvest are demonstrated by the fisheries analysis. In general the harvest responses are negative to winter and autumn inflow, and positive to spring, summer, and late fall season inflows (Table 8-21). As with the previous finfish and spotted seatrout fisheries components, the computed black drum harvest response is only negative for summer inflow to the Mission-Aransas estuary.

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 can yield information about the exceedance frequencies of seasonal inflow to the estuary, including the frequency (percent) at which short-term average (arithmetic and geometric mean) inflow conditions were exceeded in the long-term record (Table 8-22). Exceedance frequencies of the short-term seasonal inflows for the six freshwater inflow categories vary both above and below the 50 percent frequency level, however, only 36 percent of the seasonal inflows are equal to or above this level. Since lower exceedance frequencies indicate higher inflow, the short-term data bases are indicated as generally "wetter" than the long-term temporal median inflows.

Although the central seasonal tendencies of the short-term record are given as average (arithmetic and geometric mean) inflow conditions, the long-term central tendencies are expressed by both average (arithmetic and geometric mean) inflow conditions and the 50 percent exceedance frequency inflows which reflect the temporal median inflows to the estuaries from the freshwater source categories (89). 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 8-23). It is noted that substitution of the long-term average inflows in the fisheries equations involves using arithmetic mean seasonal inflows as input to linear equations and geometric mean seasonal inflows as input to the natural log (ln) equations.

There are 31 positive and 21 negative shifts of the harvest estimates in response to the long-term average inflows, and 27 positive and 25 negative harvest shifts in response to the 50 percent exceedance frequency inflows, for a total of 104 computed harvest responses (58 positive and 46 negative). The harvest responses are variable among the fisheries components and range from an estimated +182.3 percent shift in black drum harvest (FINND inflow category) to an estimated -37.6 percent shift in white shrimp harvest (FINCma), when compared to the fisheries harvest levels resulting from the observed short-term interval. The results reflect not only differences in inflow quantity, but also differences in the seasonal distributions of inflow from the freshwater source categories. Shellfish equational models (i.e., shellfish, penaeid shrimp, blue crab, and bay oyster fisheries components) yield 32 positive and 24 negative harvest shifts in response to input of the long-term seasonal inflows. In addition, equational models for the fishes (i.e., finfish, spotted seatrout, and red and black drum components) respond to longterm inflows with 26 positive and 22 negative harvest shifts. Therefore, the results suggest that overall there are only slight net benefits associated with fisheries harvests based on the long-term inflows, since responses are near evenly split between positive and negative shifts in harvest from the mean levels observed during the short-term interval. However, it is noted

Table 8-22. Comparison of Short-Term and Long-Term Seasonal Inflow, Including Inflow Exceedance Frequencies

Freshwater Inflow Category and Season	Geometric 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
FINMA d/								
Q_1 (Jan. – March)	2.9 (83)	3.5 (75)	8.8 (42)	14	5	30	6	1
Q_2 (April – June)	20.6 (53)	18.8 (54)	45.2 (35)	46	14	132	18	1
Q_3 (July – Aug.)	4.9 (60)	4.1 (64)	8.6 (48)	20	5	44	4	1
Q_4 (Sept. – Oct.)	11.8 (55)	10.2 (57)	43.6 (32)	72	10	164	12	1
Q_5 (Nov. – Dec.)	2.4 (67)	2.4 (67)	4.7 (39)	7	3	14	2	1
Total	42.6	39.0	110.9	159	37	384	42	5
FINCma e/								
Q_1 (Jan. – March)	19.0 (40)	11.3 (53)	23.4 (34)	33	10	69	12	1
Q_2 (April – June)	163.5 (20)	58.9 (43)	112.6 (29)	115	38	330	39	3
Q_3 (July – Aug.)	40.8 (29)	14.8 (50)	24.8 (40)	54	12	132	12	1
Q_4 (Sept. – Oct.)	253.8 (18)	46.8 (52)	124.9 (32)	156	35	412	40	1
Q_5 (Nov. – Dec.)	18.8 (27)	9.9 (42)	18.5 (27)	23	6	46	6	1
Total	495.9 j/	141.7	304.2	381	101	989	109	7
FINND f/								
Q_1 (Jan. – March)	5.8 (66)	52.2 (23)	29.0 (36)	51	8	108	9	1
Q_2 (April – June)	26.1 (63)	126.4 (43)	77.2 (52)	173	43	606	57	1
Q_3 (July – Aug.)	15.6 (54)	120.4 (16)	28.4 (43)	80	19	192	20	2
Q_4 (Sept. – Oct.)	33.6 (56)	266.3 (24)	158.6 (33)	325	57	808	58	4
Q_5 (Nov. – Dec.)	3.7 (67)	21.0 (35)	20.1 (36)	35	8	84	8	1
Total	84.8	586.3 j/	313.3	664	135	1,798	152	9
FINCn g/								
Q_1 (Jan. – March)	22.9 (44)	63.1 (19)	42.3 (28)	63	22	117	21	3
Q_2 (April – June)	65.2 (55)	148.8 (37)	102.1 (47)	198	89	522	90	15
Q_3 (July – Aug.)	36.7 (49)	136.0 (17)	47.7 (42)	96	41	204	40	8
Q_4 (Sept. – Oct.)	68.6 (55)	292.1 (26)	189.9 (35)	276	98	750	96	12
Q_5 (Nov. – Dec.)	15.6 (49)	27.4 (34)	29.2 (33)	43	18	88	18	4
Total	209.0	667.4 j/	411.2	676	268	1,681	265	42
FINMAN h/								
Q_1 (Jan. – March)	11.0 (57)	15.2 (52)	39.9 (32)	65	13	138	15	1
Q_2 (April – June)	56.9 (57)	62.4 (56)	128.0 (46)	219	72	717	84	6
Q_3 (July – Aug.)	28.2 (50)	47.9 (39)	46.9 (40)	100	26	246	28	2
Q_4 (Sept. – Oct.)	58.8 (54)	74.1 (52)	226.9 (32)	397	84	968	84	6
Q_5 (Nov. – Dec.)	10.0 (50)	10.7 (48)	26.3 (30)	42	11	92	12	2
Total	164.9	210.3	468.0	823	206	2,161	233	17
FINCman i/								
Q_1 (Jan. – March)	36.7 (45)	46.9 (39)	69.3 (29)	96	34	195	33	6
Q_2 (April – June)	146.5 (51)	158.6 (50)	221.3 (41)	313	154	813	153	30
Q_3 (July – Aug.)	65.1 (48)	95.7 (38)	84.0 (41)	150	66	330	64	12
Q_4 (Sept. – Oct.)	136.2 (53)	179.5 (48)	349.4 (32)	432	172	1,044	172	28
Q_5 (Nov. – Dec.)	29.5 (42)	30.2 (41)	49.7 (28)	66	27	130	26	6
Total	414.0	510.9	773.7	1,057	453	2,512	448	82

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a/ Short-term inflow data bases, with seasonal volumes in thousands of acre-feet:
D_s = inflow (Nov. 1961 – Oct. 1976) natural log transformed, except for FINCma category, and used in analysis of Shellfish, All Shrimp, White Shrimp, and Brown and Pink Shrimp fisheries component
D_{s-1} = 1-year antecedent inflow (Jan. 1961 – Dec. 1975) natural log transformed, except for FINND and FINCn categories, and 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, Red Drum, and Black 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

d/ Freshwater inflow from Mission and Aransas River Basins

e/ Freshwater inflow to Mission-Aransas estuary from combined river and coastal drainage basins

f/ Freshwater inflow at Nueces delta

g/ Freshwater inflow to Nueces estuary from combined river and coastal drainage basins

h/ Freshwater inflow from Mission, Aransas, and Nueces River Basins

i/ Freshwater inflow to Mission-Aransas and Nueces estuaries from combined river and coastal drainage basins

j/ Arithmetic mean value

Table 8-23. 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.

	Mission and Aransas Rivers Inflow FINMA a/			Combined Estuary Inflow FINCma b/			Nueces Delta Inflow FINND c/		
Fisheries Component	Short-Term: Mean Inflow: Harvest e/	Long-Term Mean-Inflow Harvest (Shift) f/	Long-Term 50%EF d/ Inflow Harvest (Shift)	Short-Term Mean Inflow: Harvest	Long-Term Mean Inflow Harvest (Shift)	Long-Term 50% EF Inflow Harvest (Shift)	Short-Term: Mean Inflow: Harvest	Long-Term Mean-Inflow Harvest (Shift)	Long-Term 50%EF Inflow Harvest (Shift)
Shellfish	1,454.2	1,426.1 (- 1.9)	1,393.3 (- 4.2)	1,454.2	1,143.4 (-21.4)	1,164.4 (-19.9)	519.8	598.9 (+ 15.2)	632.7 (+21.7)
All Shrimp	850.2	888.0 (+ 4.4)	888.9 (+ 4.6)	954.3	891.5 (- 6.6)	655.4 (-31.3)	433.6	495.6 (+ 14.3)	533.9 (+23.1)
White Shrimp	676.4	610.9 (- 9.7)	483.2 (-28.6)	676.4	620.1 (- 8.3)	422.2 (-37.6)	292.9	355.9 (+ 21.5)	382.2 (+30.5)
Brown & Pink Shrimp	277.9	270.6 (- 2.6)	277.4 (- 0.2)	(no equation)			(no equation)		
Blue Crab	376.5	439.5 (+ 16.8)	473.9 (+25.9)	(no equation)			118.3	187.9 (+ 58.8)	90.4 (-23.6)
Bay Oyster	6.3	9.0 (+ 42.4)	6.6 (+ 4.8)	6.3	5.2(- 18.5)	6.1 (- 3.2)	(no equation)		
Finfish	573.4	584.7 (+ 2.0)	536.7 (- 6.4)	573.4	545.0 (- 4.9)	534.9 (- 6.7)	174.8	248.4 (+ 42.1)	284.3 (+62.6)
Spotted Seatrout	203.9	128.8 (- 36.8)	201.6 (- 1.1)	203.9	127.5 (-37.5)	182.2 (-10.6)	44.2	74.0 (+ 67.3)	85.9 (+94.3)
Red Drum	146.1	91.2 (- 37.6)	99.4 (-32.0)	146.1	94.9 (-35.0)	97.6 (-33.2)	28.0	33.2 (+ 18.7)	42.8 (+52.9)
Black Drum	110.5	139.3 (+ 26.1)	133.0 (+20.4)	110.5	90.2 (-18.4)	89.7 (-18.8)	51.3	119.1 (+132.0)	144.8(+182.3)

(continued)

Table 8-23. 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. (cont'd)

	Combined Nueces Inflow FINCn g/					Mission, Aransas, and Nueces Rivers Inflow: FINMAN h/					Combined Estuaries Inflow FINCman i/				
Fisheries Component	Short-Term: Mean Inflow: Harvest e/	Long-Term Mean-Inflow Harvest	(Shift) f/	Long-Term 50%EF d/ Inflow Harvest	(Shift)	Short-Term: Mean Inflow: Harvest	Long-Term Mean Inflow Harvest	(Shift)	Long-Term 50% EF Inflow Harvest	(Shift)	Short-Term: Mean Inflow: Harvest	Long-Term Mean-Inflow Harvest	(shift)	Long-Term 50%EF Inflow Harvest	(Shift)
Shellfish	519.8	578.2	(+ 11.2)	579.0	(+ 11.4)	2,020.3	2,191.2	(+ 8.5)	2,263.2	(+12.0)	2,020.3	1,905.6	(- 5.7)	1,909.1	(- 5.5)
All Shrimp	433.6	489.9	(+ 13.0)	495.5	(+14.3)	1,307.5	1,405.5	(+ 7.5)	1,462.7	(+11.9)	1,307.5	1,343.4	(+ 2.7)	1,340.6	(+ 2.5)
White Shrimp	292.9	349.1	(+ 19.2)	351.1	(+19.9)	901.8	962.6	(+ 6.7)	1,009.2	(+11.9)	1,025.2	1,142.3	(+11.4)	762.6	(-25.6)
Brown & Pink Shrimp		(no equation)				439.1	440.2	(+ 0.3)	445.8	(+ 1.5)	439.1	369.4	(-15.9)	462.9	(+ 5.4)
Blue Crab	118.3	216.5	(+ 83.0)	108.9	(- 7.9)	796.2	600.9	(-24.5)	646.6	(-18.8)	796.2	657.3	(-17.4)	646.1	(-18.9)
Finfish	174.8	278.4	(+ 59.3)	294.1	(+68.2)	799.2	798.9	(- 0.0)	820.1	(+ 2.6)	868.9	924.0	(+ 6.3)	810.2	(- 6.8)
Spotted Seatrout	44.2	69.5	(+ 57.1)	73.1	(+65.4)	269.0	270.7	(+ 0.6)	236.8	(-12.0)	269.0	268.1	(- 0.3)	236.5	(-12.1)
Red Drum	28.0	37.5	(+ 33.9)	40.0	(+42.9)	185.8	135.1	(-27.3)	144.9	(-22.0)	185.8	155.3	(-16.4)	153.2	(-17.5)
Black Drum	51.3	105.6	(+105.7)	113.5	(+121.2)	187.8	215.2	(+14.7)	219.0	(+16.6)	187.8	198.0	(+ 5.5)	195.2	(+ 3.9)

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a/ Freshwater inflow from Mission and Aransas River Basins
b/ Combined freshwater inflow to Mission-Aransas estuary from all contributing river and coastal drainage basins
c/ Freshwater inflow at Nueces Delta
d/ EF = exceedance frequency
e/ Mean inshore harvest, in thousands of pounds
f/ Shift in percent increase (+) or decrease (-) of harvest estimate
g/ Combined freshwater inflow to Nueces Estuary from all contributing river and coastal drainage basins
h/ Freshwater inflow from Mission, Aransas, and Nueces River Basins
i/ Combined freshwater inflow to Mission-Aransas and Nueces estuaries from all contributing river and coastal drainage basins

that of 32 harvest shifts associated with long-term inflows to the Nueces estuary (FINND and FINCn inflow categories), all are positive except for two negative blue crab harvest shifts.

While management policies could favor the specific seasonal inflow needs of preferred fisheries components, it is in reality difficult and in many cases impossible to maximize the harvests from more than one fisheries component at the same time because of competitive seasonal inflow needs among the species. Nevertheless, management scenarios for inflow can be developed that predict good harvest levels from several of the fisheries components simultaneously (see Chapter IX).

Summary

Virtually all of the Gulf fisheries species are estuarine-dependent. Commercial inshore harvests (1962-1976) from bays of the Mission-Aransas estuary rank fourth in shellfish and third in finfish, while bays of the Nueces estuary rank sixth in shellfish and seventh in finfish of eight major Texas estuarine areas. In addition, the sport or recreational finfish harvest is approximately equal to the commercial finfish harvest in the estuaries. For the 1972 through 1976 interval, the average annual sport and commercial harvest (inshore and offshore) of fish and shellfish dependent upon the Nueces and Mission-Aransas estuaries is estimated at 19.6 million pounds (8.9 million kg; 81 percent shellfish).

Although a large portion of each Texas estuary's fisheries production is harvested offshore in collective association with fisheries production from other regional estuaries, inshore bay harvests are useful as relative indicators of the year-to-year variations in an estuary's surplus production (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 87 percent of the correlations attempted between the harvests and the seasonal freshwater inflows to the Nueces and Mission-Aransas estuaries. The analysis of harvest as a function of the seasonal inflows results in 52 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 commercial harvests of seafood organisms from the estuaries. The analysis also supports existing scientific information on the seasonal importance of freshwater inflow to the estuaries. Virtually all harvest responses to spring (April-June) and late fall (November-December) inflows are estimated to be positive for increased inflow in these seasons. In addition, most estimated harvest responses to increased summer (July-August) inflow are also positive. Although several shellfish organisms (i.e., white shrimp, blue crab, and oyster) are estimated to relate positively to winter (January-March) inflow, all fisheries components containing fish species (e.g., spotted seatrout, redfish, and black drum) are estimated to relate negatively to this season's inflow. Harvest responses to autumn (September-October) inflow are more variable than responses to other seasons, possibly because the season is tropical storm dominated. In general, most shellfish organisms relate positively to autumn season inflow while fish species relate negatively. Exceptions occur with the positive relationships of spotted sea trout and red drum harvests to Mission-Aransas estuary inflow during the autumn season.

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

CHAPTER IX

ESTIMATED FRESHWATER INFLOW NEEDS

Introduction

In previous chapters, the various physical, chemical and biological factors affecting the Nueces and Mission-Aransas estuaries 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 establishing estimates of the freshwater inflow needs for these estuaries, based upon historical data.

Methodology for Estimating Selected Impacts of Freshwater Inflow Upon Estuarine Productivity

The response of an estuary to freshwater inflow is due to a number of factors and a variety of interactions. These include changes in salinity due to mixing of fresh and saline water, fluctuations in biological productivity arising from variations in nutrient inflows, and many other phenomena.

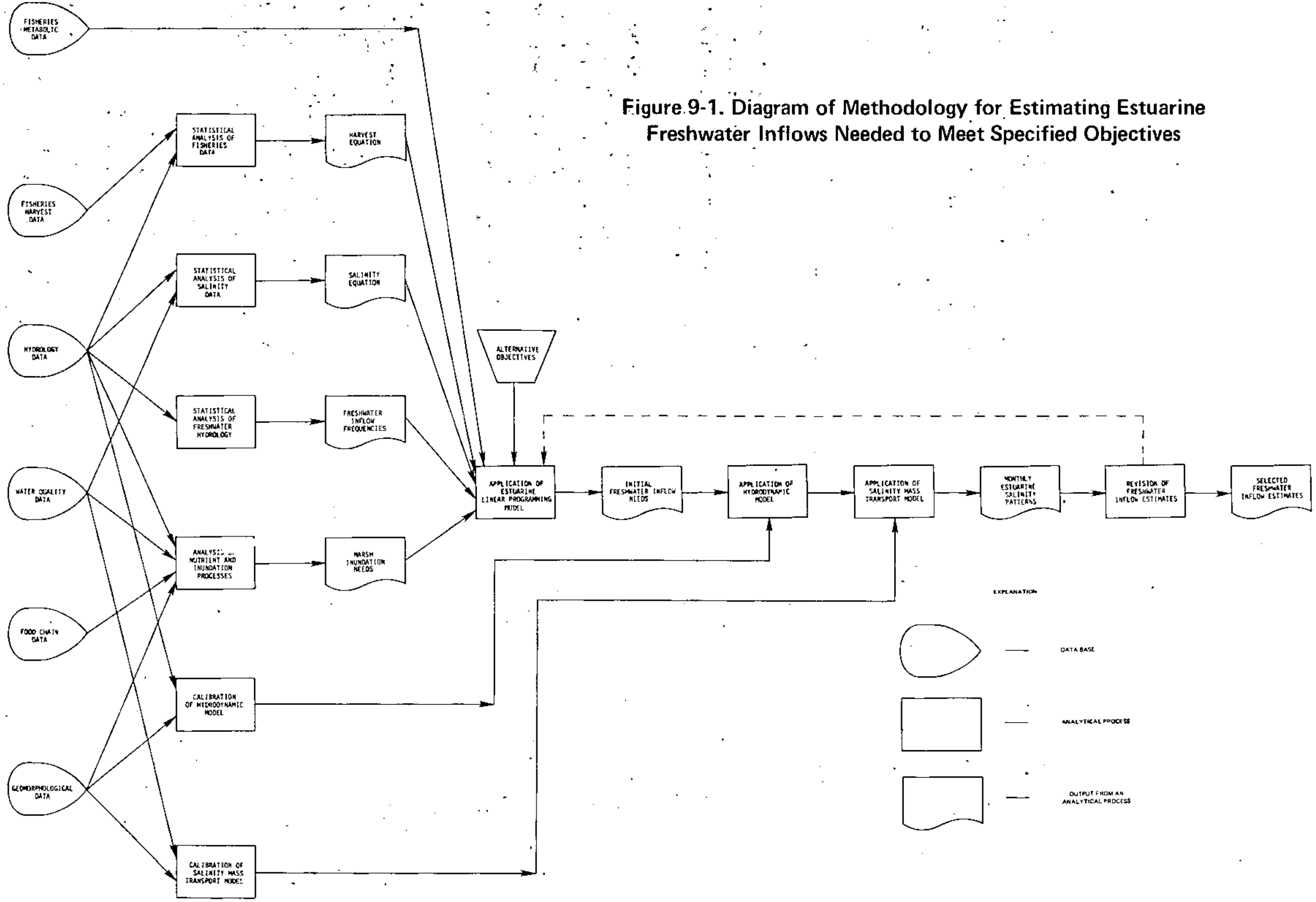
The methodology presented here incorporates major interacting elements described in previous chapters (Figure 9-1). The methodology includes the use of data bases and certain analytical processes described herein. Data for these analyses include six groups: (1) salinity data for finfish and shellfish, (2) commercial fisheries harvest data, (3) hydrologic data of fresh and saline water, (4) water quality data, (5) aquatic food chain data, and (6) terrestrial and aquatic, 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 fisheries 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 inflow needs.

Application of the Methodology to Compute Estimates of Freshwater Inflow Levels Needed to Meet Selected Objectives

The schematic indicated in Figure 9-1 shows the sequence of steps utilized in computing the freshwater inflow needs to achieve specified objectives as expressed in terms of salinity, marsh inundation, and productivity. The six data bases developed for the Nueces and Mission-Aransas estuaries provide the fundamental information of the system. These data were

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



used in previous sections of these analyses. The relationships and results are incorporated into the Estuarine Linear Programming Model to compute estimates of effects of various levels of monthly freshwater inflows upon nearshore salinities, marsh inundation and fisheries harvests in these estuaries. 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 each entire estuary. Should the computed salinity conditions in certain critical areas of these estuaries 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 constraints.

The data bases and analytical processes utilized in this chapter have been described in detail in previous chapters. Only the procedures necessary to establish salinity bounds, estimate marsh inundation needs, and apply the Estuarine Linear Programming Model are presented in this chapter.

Salinity Bounds for Fish and Shellfish Species

The effects of salinity on estuarine-dependent fisheries organisms are fundamentally physiological, and influence growth, survival, distribution, and ecological relationships (see Chapter VIII).

Specific information on salinity limits, preferences and/or optima for selected fisheries species has been tabulated from the scientific literature and TDWR 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.

Data on salinity effects, combined with life cycle information, were utilized to provide seasonal bounds on estuarine salinity within which fish and shellfish can survive, grow, and maintain viable populations (Table 9-2). Since universal consensus is not evident for precise viability salinity limits, the 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 these estuaries below the "Null Zone" [1]: (1) in upper Copano Bay near

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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 (379, 90).

Table 9-1. Salinity Limits, Preferences, and Optima for Selected Texas Estuarine-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	421
			5-15	increased growth at this range (and >25°C) more than two times tissue production of postlarvae at 25-35 ppt	420
			28.0	median salinity average of postlarval distribution (May-July) in laboratory gradient tanks	221
			21.0	median salinity average of postlarval distribution (Aug.-Nov.) in laboratory gradient tanks	221
		47.96		field collection of small white shrimp (23-76 mm) in Laguna Madre de Tamaulipas (Mexico)	98
	0.42			lower distribution limit in Grand and White Lakes (La.); young shrimp 140 more abundant at 0.7-0.8 ppt	84
			27.6-28.3	isosmotic salinity conditions for shrimp ≥ 100 mm length; osmoregulation below 27.6 ppt better than brown shrimp	155
	1	34	1-20	field distribution in Caminada Bay (La.) and range for 91.1% of juveniles collected	31
	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	316
	2.9	45.3		field distribution in Mesquite Bay (Tex.)	103
	2	45		field distribution in bays and lagoons of northwestern Gulf of Mexico (Tex.)	93
			< 10	preference based on population distributions	83
	0	38		optimum catch over entire salinity range with 20-38°C temperatures	319
Penaeus aztecus (brown shrimp)					
	2	40		range of equal postlarval growth over 23-25°C temperature; survival 90-100% in laboratory	421
	< 10			marked reduction in postlarval tolerance at low (7-15°C) temperatures to low (5 ppt) salinity	422
			15-35	range of increased postlarval growth at temperatures >25°C; decreased growth below 15 ppt	420
	< 5	> 40		range at which 80% of 10-15 mm postlarvae survive; 12 hr. acclimation	420
			> 15	appeared to enhance survival and growth of postlarvae in Barataria Bay (La.)	205
			> 15	commercial catches poor in years when postlarvae were present in Louisiana bays with < 15 ppt	145
			29.9	median salinity average of postlarval distribution (March-April) in laboratory gradient tank	221
			20.6	median salinity average of postlarval distribution (May-July) in laboratory gradient tank	221
			10.0-19.9	range at which juveniles were more abundant based on population distributions	83
	0.2	30	10-30	field distribution in Caminada Bay (La.) and range for 91.8% of juveniles collected	31
			< 17	preference of juvenile (70 mm) shrimp in laboratory at >26°C temperature	356
			15-25	optimal range for subadult (95 mm) shrimp in laboratory at <25°C temperature	356
			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	404
			27.6-28.3	isosmotic salinity conditions for shrimp > 100 mm length; osmoregulation above 28.3 ppt better than white shrimp	155
	2.1	36.6	15.0-19.9	field distribution in Copano and Aransas Bays (Tex.) and range of greater abundance	316
		69.0		field collection in Laguna Madre (Tex.)	295
	0.8			lower distribution limit in Grand and White Lakes (La.)	84
	0.22			field collection in St. Lucie Estuary (Fla.)	68
	5	70		field distribution in bays and lagoons of northwestern Gulf of Mexico (Tex.)	93
	0.1			field collection (North Carolina)	416
			5	acclimation at low (5 ppt) salinity provides near-optimum resistance to high temperatures and 5-25 ppt salinities in laboratory tests	414
	9	40		no optimum salinity established with 20-35°C temperatures	319
Callinectes sapidus (blue crab)					
	22.9	32.4	≥ 30.0	range for capture of egg-bearing females near Aransas Pass (Tex.)	316
			23-28	optimum range for hatching of eggs (Virginia)	195
			> 20	occurrence of spawning and early development	249
			< 1.9	peak abundance of juvenile blue crabs in Texas bays (1965)	249
	< 1.0		2-21	lethal limit at optimum (29°C) temperature and range of little effect on juvenile growth and survival	216
	0			observed freshwater populations in Louisiana	81
	2.0	37.2	10.0-20.0	field distribution in Copano and Aransas Bays (Tex.) and range of greater abundance	316
		117		field collection in Laguna Madre de Tamaulipas (Mexico); high salinity briefly tolerated	84
		45		blue crabs observed leaving upper Laguna Madre (Tex.) area as salinity increased	256
	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	60
	0	40	0-27	optimum range with 10-35°C temperatures	319
			10-30	range of no effect on metabolic consumption of oxygen (respiration)	122
Crassostrea virginica (American bay oyster)					
	< 6			gametogenesis inhibited by prolonged low salinity exposure; up to 3-4 months required to regain normal gonadal activity after salinity increases towards the optimum	13
	5-7.5			normal gonadal development near 7.5 ppt; however, oysters with previously ripe gonads spawn when subjected to low (5 ppt) salinities	131
			20-21	larval spat setting requirement in Galveston Bay (Tex.)	359
	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	116

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

Species	Limits Min. (ppt)	Limits Max. (ppt)	Preference or Optimum (ppt)	Remarks	Reference
			19-30	maximum survival (80% contour plot) in lab of 2-day larvae at 19-30.5°C temperatures	393
			8-30.5	maximum survival (60% contour plot) in lab of 8-day larvae at temperatures > 21°C	393
			>33	maximum growth (100% contour plot) in lab of 8-day larvae at temperatures > 19°C	393
			18-35	optimum (80% contour plot) for both larval survival and growth at temperatures > 30°C	393
			15-22.5	optimum for juvenile growth and development	19
	1.5	39.0		early experimentally derived salinity limits	6
	0-2			oysters can survive freshwater (0ppt) for several days; increasing to about a month at 2 ppt salinity	316
			15-30	optimum range of salt content	261
	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)	389
		43.5-45		distribution limit in Redfish and Corpus Christi Bays (Tex.)	301
			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.)	265
			15-30	best growth in reasonably stable salinity	174
	3			lower tolerance limit about 3 ppt	80
	8-10			lower limit of predator Thais haemastoma, a gastropod oyster drill or conch	80 316
	< 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	310
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	212
			> 30	spawning occurs in estuarine areas of higher salinity (La.)	193
		≤ 60	< 45	"young" collected up to about 60 ppt in Laguna Madre (Tex.); no spawning if salinity > 45 ppt	295
		< 55	15-35	absent above 55 ppt in Baffin and Alazan Bays (Tex.); most abundant range 15-35 ppt	294
	2.3	34.9	5-20	field distribution in Copano and Aransas Bays (Tex.); over 80% collected in 5-20 ppt	320
	< 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	313
Sciaenops ocellata (red drum)	2.1	32.4	< 15	field distribution in Copano and Aransas Bays (Tex.); greater abundance below 15 ppt	320
	0	> 50	20-40	field distribution (Tex.); range of preference (most abundant in 30-35 ppt); young mature in 3-5 years	321
			< 50	populations in Laguna Madre (Tex.) severely limited by >50 ppt	295
	5-10	40-45	20-25	operational limits; range of optimum metabolic condition at 20-28°C temperatures	286
Pogonias cromis (black drum)	2.6	34.9	<15	field distribution in Copano and Aransas Bays (Tex.); most abundant range 10.0-15.0 ppt	320
	<5	77		field distribution in bays and lagoons of northwestern Gulf of Mexico (Tex.)	93
	0	80		field distribution (Tex.); usual range in Laguna Madre 25-50 ppt	321
	5	40-45	20-30	operational limits; range of optimum metabolic condition at 20-28 °C temperatures; maximum swimming performance at 28 °C and 20 ppt	286

Table 9-2. Salinity Characteristics of Upper Nueces Bay and Upper Copano Bay

Month	Salinity in Upper Nueces Bay a/ (ppt)			Salinity in Upper Copano Bay b/ (ppt)		
	Upper c/ Viability Limit	Lower c/ Viability Limit	Historic Median	Upper c/ Viability Limit	Lower c/ Viability Limit	Historic Median
January	30	10	27	30	10	16
February	30	10	26	30	10	15
March	25	10	26	25	10	15
April	20	5	25	20	5	15
May	20	5	19	20	5	12
June	20	5	14	20	5	11
July	25	10	16	25	10	15
August	25	10	20	25	10	18
September	20	5	18	20	5	14
October	20	5	15	20	5	13
November	30	10	18	30	10	14
December	30	10	25	30	10	15

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a/ Represented by sampling site 2 on linesite 53 (Figure 3-11)

b/ Represented by the average of sampling sites 44-1, 44-2, 54-2 and 54-3 (Figure 3-12)

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

Mission Bay and (2) in upper Nueces Bay near the Nueces River delta. The limits are expressed as mean (average) monthly salinities for general limits of viability. From both locations, salinities generally increase towards the Gulf inlet (Aransas Pass) and eventually attain seawater concentration (35 ppt). The salinity gradient in the estuary is thus steeper during seasons of higher inflow (e.g., the spring) and less distinct during seasonal low inflow (e.g., the summer). Moreover, the estuarine-dependent species have adapted their life cycle to the natural freshwater inflow regime and are today productively associated with local and State economies.

Although the fisheries species can generally tolerate salinities greater or less than the monthly specified viability range, foraging for food and production of body tissue (growth) becomes increasingly more difficult under extreme salinities, and may eventually cease altogether because body maintenance requirements consume an increasing amount of an organism's available energy under unfavorable conditions. High mortality and low production are expected during prolonged extremes of primary environmental factors such as salinity and temperature.

Monthly Salinity Conditions

The salinities within an estuarine system fluctuate with variations in freshwater inflow. During periods of flood or drought, salinity regimes may be so altered from normal conditions that motile species commonly residing in an estuary may migrate to other areas where the environmental conditions are more suitable. Generally, however, the estuarine-dependent species in an estuary will 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 restricted.

The median monthly salinity is a measure of the normal monthly salinity condition at a point in an estuary. The median monthly salinity is that value for which one-half of the observed average monthly salinities exceed the value and one-half are less. The median monthly salinity thus reflects an "expected" salinity in the estuary and represents a numerical value exceeded 50 percent of the time. Median historic salinities have been computed for the two locations in upper Nueces and Copano Bay (Table 9-2) for which the salinity regression equations were developed in Chapter V.

Marsh Inundation Needs

The periodic inundation of deltaic marshes serves to maintain shallow protected habitats for postlarval and juvenile stages of several important estuarine species, provides a suitable fluid medium for nutrient exchange processes, and acts as a transport mechanism to move detrital food materials from the deltaic marsh into the open estuary. The areal extent of deltaic marsh inundation is a function of the channel capacity, discharge rate and volume, wind direction, and tidal stage.

Historically, the discharge rates of Texas rivers have fluctuated on a seasonal basis. Monthly freshwater inflows usually peak in the spring and early fall, reflecting the increased rainfall and surface runoff that normally 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 biological productivity.

The three river deltas of the Nueces and Mission-Aransas estuaries (the Nueces, Aransas, and Mission River deltas) are periodically inundated by both fresh and saline waters.[1] 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.

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 each delta associated with an estuary. 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. The areal extent of the deltas associated with the Mission and Aransas Rivers is quite small compared to other major river deltas on the Texas Gulf Coast. Therefore, the Nueces River delta is regarded as the only major deltaic system in the Nueces and Mission-Aransas estuaries, and hence freshwater inundation needs are assessed only for that delta.

Daily gaged discharge data for the Nueces River near Mathis for the period of record (1939-1976) were examined to arrive at monthly and seasonal distributions of discharge events with peak flows of 5,000 ft^3/sec or greater (142 m^3/sec) (Table 9-3). The 5,000 ft^3/sec peak discharge was determined from field observations to be the flow necessary to achieve appreciable inundation of the Nueces delta. It was apparent that more inundation events have occurred in the late spring and summer months of May, June, and July than during any other seasonal period. The data also suggest that additional inundation events in the Nueces delta have occurred most often in the early fall (September and October). Floods in these months are usually due to tropical storms. According to the biological evidence, spring inundation events are necessary for (1) adequate physical wetting of the marsh plant communities, (2) nutrient exchange and biogeochemical cycling of carbon, nitrogen and phosphorus, (3) transport of detrital food materials, and (4) reduction of salinity to suit the needs of juvenile, estuarine-dependent organisms utilizing the "nursery" habitats of the marsh and adjacent shallow water areas. In the tropical storm-dominated fall season, less frequent inundation events occur; however, maintenance benefits are still provided to the estuary by these inflows.

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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 (277, 278). 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.

Table 9-3. Peak Gaged Daily Discharges for Discrete Flood Events Greater Than 5000 ft^3/sec in the Nueces River Delta, 1939-1976. a/

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
					ft^3/sec						
29,500	31,000	9,330	22,700	27,400	18,300	49,000	27,100	125,000	46,600	13,700	5,610
10,800	12,400		15,600	18,900	13,000	19,500		56,800	33,000	6,960	
7,280				15,100	12,900	18,400		27,400	21,000	5,990	
				12,800	12,200	10,800		22,500	11,600		
				10,500	11,200	8,420		20,200	11,000		
				10,300	9,810	8,390		19,500	9,810		
				10,000	7,260	7,210		18,700	9,700		
				8,500	6,370	5,000		16,900	8,800		
				8,100	6,080			15,100	8,160		
				6,680	5,840			10,600	7,520		
				5,800	5,480			7,500	6,520		
				5,520	5,320			6,650	6,030		
				5,500	5,170			5,250	5,780		
				5,240				5,240			

Median peak flood discharge
May-July = 8,500 ft^3/sec
September-October = 11,000 ft^3/sec

a/ Flow rates recorded at the Mathis streamgage.

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 May, June, and July; those that occur in September and October; and the total that occurs during the year, it is evident that a median of two inundation events have occurred per year in the Nueces delta over the period of record (Table 9-4). In order to maintain the historical inundation frequency, the Nueces River delta would need to receive two flood events per year with peak 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 May would be expected to extend favorable habitat conditions for larval and juvenile stages of many estuarine dependent species. The May through July median daily peak discharge over the period of record has been 8,500 ft^3/sec (241 m^3/sec), while that of the period September and October has been 11,000 ft^3/sec (312 m^3/sec).

The daily gaged flow hydrograph of several past spring and fall floods with daily flow peaks near the median were plotted to establish the total volume of water associated with flood events. The total flood volumes for the spring and fall flood were estimated to be 79.0 and 139.0 thousand acre-feet (98 and 172 million m^3), respectively.

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 Nueces and Mission-Aransas River Basins[1/]. A Linear Programming optimization procedure is used to compute the monthly freshwater inflows from the Nueces and Mission-Aransas River Basins needed to meet specified salinity, marsh inundation and commercial bay fisheries levels. The quantifications of salinity and commercial fisheries harvest as functions of seasonal freshwater inflow are represented by the statistical regression equations given in Chapters V and VIII, respectively. The harvest equation utilized for a given species or group 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 error for the harvest estimate) for the combined freshwater inflow to both estuaries.

Specification of Objectives. The criteria or objectives in this optimization formulation can be any desired estuarine condition. One objective of interest

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[1/] Additional freshwater inflows are contributed to the estuary from the Nueces-Rio Grande and San Antonio-Nueces 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 (see Table 9-6).

Table 9-4. Frequency of Annual and Seasonal Flood Events with Peak Daily Gaged Flows Greater than 5,000 ft^3/sec in the Nueces River Delta, 1939-1976

Number of Occurrences over Period of Record

Number of Events per Period	May-July		September-October		Total Annual	
(x)	Freq.(f)a/	f*xb/	Freq.(f)	f*x	Freq.(f)	f*x
0	15	0	18	0	10	0
1	15	15	15	15	7	7
2	3	6	4	8	5	10
3	4	12	1	3	9	27
4	1	4			5	20
5					1	5
6					1	6
Σf*x		37		26		75
Number of Years = 38						
Mean Number Inundation events per year		.97		.70		2.0
Median Number Inundation events per year		1		1		2

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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.

is to compute the minimum annual inflow to the estuary that meets the constraints on the salinity regime and marsh inundation. Another alternative could be to compute the estimated quantity of freshwater inflow to maximize the estimated commercial harvests in the estuary. This harvest could be either for an individual fisheries species, a weighted sum of the harvests of a group of the commercially important species (e.g., shellfish) or other combinations.

Computation Constraints for the Model. A set of constraints in the model relate freshwater inflow to various environmental and statistical limits. These constraints include:

(1) upper and lower limits for the seasonal inflows used in the regression equations which estimate annual commercial bay 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 viability 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 to both estuaries while meeting salinity viability limits and marsh inundation needs;

Alternative II, Maintenance of Fisheries Harvests
Objective: minimize annual combined inflow to both estuaries while providing freshwater inflows sufficient to provide predicted combined annual commercial bay harvests from both estuaries for red drum, spotted seatrout, white shrimp, and blue crabs at levels no less than their mean 1962 through 1976 historical values, satisfying marsh inundation needs, and meeting viability limits for salinity;

Alternative III, Finfish Harvest Enhancement
Objective: maximize the total annual commercial bay harvest of all finfish in the estuary while observing salinity viability limits and marsh inundation needs, and utilizing annual combined inflows to each estuary no greater than their average historical inflows over the 1941 through 1976 period.

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 Nueces and Mission-Aransas estuaries; however, they provide a range of alternatives: survival or subsistence (Alternative I), maintenance of bay harvest levels (Alternative II), and finfish bay harvest enhancement

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

	Alternatives		
	I	II	III
Criteria:			
• Maximize Annual Harvest of All Finfish			x
• Least Possible Annual Combined Inflow	x	x	
Constraints:			
• Annual Inflow from the Nueces and Mission-Aransas River Basins are each no greater than their Average Annual Historical Values (1941-1976)			x
• Predicted Annual Combined Spotted Seatrout and Red Drum Commercial Harvests for both estuaries are no less than their Average Annual Values (1962-1976)		x	
• Predicted Annual Combined White Shrimp and Blue Crab Commercial Harvests for both estuaries 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 Nueces River Basin Inflows for Marsh Inundation of the Nueces Delta	x	x	x

(Alternative III). An additional enhancement alternative which could be evaluated is the maximization of the shrimp (or shellfish) commercial harvests in the estuary.

Alternative I: Subsistence. The objective of Alternative I (Subsistence) is to minimize total annual freshwater inflows from the Nueces and Mission-Aransas River Basins while meeting specified bounds on salinity in Nueces and Copano Bays (Table 9-2) and satisfying marsh inundation needs for the Nueces delta.[1/] The upper salinity bound for each month at each of the two key locations is taken as the minimum of the upper 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 689.6 thousand acre-feet (850 million m^3) with 397.0 thousand acre-feet (489 million m^3) from the Nueces River Basin, 46.2 thousand acre-feet (57 million m^3) from the Mission-Aransas River Basin and 246.4 thousand acre-feet (304 million m^3) from the San Antonio-Nueces (excluding the Mission and Aransas River Basins) and Nueces-Rio Grande Coastal Basins (Table 9-6).

Monthly freshwater inflow needs generated by the Estuarine Linear Programming Model for Alternative I provide salinities which closely approximate those for the required upper bounds during most months of the year (Figures 9-2 and 9-3). Nueces River Basin inflows during the months of May and September provide salinities lower than the maximum required as a consequence of meeting marsh inundation requirements in the Nueces River delta.

Comparisons between the mean historical combined inflows and the estimated freshwater inflow needs are made for each month (Figures 9-4 and 9-5), for the Nueces and Mission-Aransas River Basins. The estimated monthly freshwater inflow needs are less than the mean historical inflows except for the month of April from the Nueces River Basin.[2/] The distribution of the freshwater inflow needs between basins is illustrated in Figure 9-6. The ungaged inflow from the coastal basins is of major significance, since it is more than 35 percent of total inflow on the average.

Implementation of Alternative I for the Nueces and Mission-Aransas estuaries under the inflow regime indicated in Table 9-6 is projected to result in increases in the majority of commercial bay fisheries harvest categories over the average historical levels in the 1962 through 1976 period (Figure 9-7). The all-finfish category is predicted to have an annual harvest of 858.2 thousand pounds (389 thousand kg), or a one percent decrease from the average; all-shellfish harvest, a 30 percent increase above mean 1962 through

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[1/] Nueces delta inundation needs include inundation volumes of 79,000 ac-ft (98 million m^3) for the period May through July, peak daily discharge of 8,500 ft^3/sec (241 m^3/sec) at Mathis, and 139,000 ac-ft (172 million m^3) for September-October (11,000 ft^3/sec or 312 m^3/sec at Mathis).

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

Table 9-6. Freshwater Inflow Needs of the Nueces and Mission-Aransas Estuaries under Alternative I a/

Month	Aransas and Mission River Basin		Nueces River Basin		Coastal Basins Total Inflow		Combined Inflow d/	
	Total Inflow Needs	Gaged Inflow Need From Mission River Basin b/	Total Inflow Needs	Inflow Need from Gaged Portion of the Basin c/	San Antonio-Nueces	Nueces-Rio Grande	Mission-Aransas Estuary	Nueces Estuary
	Thousands of Acre-Feet							
January	1.9	.7	8.4	6.5	4.0	1.0	5.9	9.4
February	3.4	1.2	9.2	7.2	11.0	1.9	14.4	11.1
March	2.4	.9	9.9	7.9	2.0	.2	4.4	10.1
April	4.5	1.5	24.4	21.5	12.0	2.2	16.5	26.6
May	9.9	2.9	79.0 e/	72.8	30.0	5.0	39.9	84.0
June	5.4	1.8	34.0	30.5	23.0	4.0	28.4	38.0
July	2.0	.8	22.6	19.8	16.0	3.7	18.0	26.3
August	2.3	.8	14.6	12.2	14.0	2.7	16.3	17.3
September	5.9	1.9	139.0 e/	129.2	50.0	9.1	55.9	148.1
October	3.6	1.2	34.3	30.8	32.0	5.5	35.6	39.8
November	2.4	.9	13.4	11.2	5.0	.6	7.4	14.0
December	2.5	.9	8.2	6.2	10.0	1.5	12.5	9.7
Annual	46.2	15.5	397.0	355.8	209.0	37.4	255.2	434.4

a/ All inflows are mean monthly values

b/ These values computed using regression equations relating monthly river basin inflow to the estuary with monthly gaged inflows at USGS Station on the Mission River near Refugio (#08189500)

c/ These values computed using regression equations relating monthly river basin inflow to the estuary with monthly gaged inflows at USGS Station on the Nueces River near Mathis (#08211000)

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

e/ Volume of median seasonal flood flow events

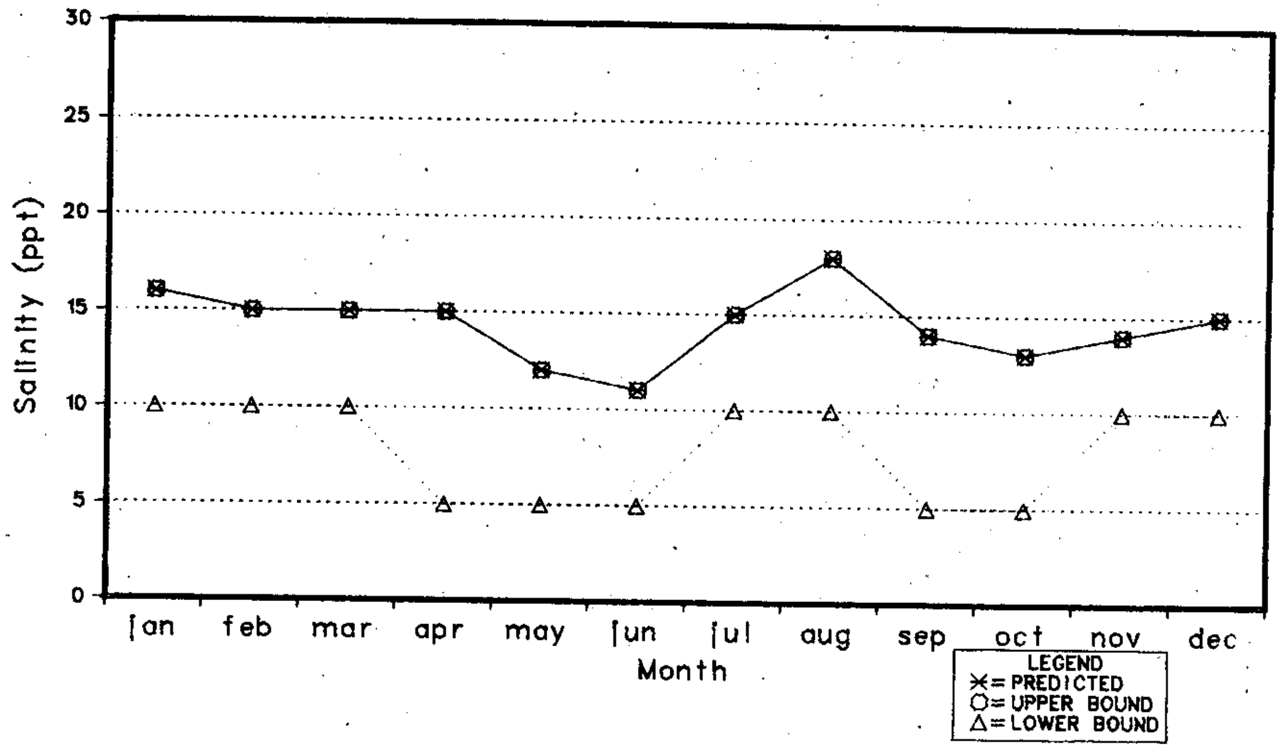

Figure 9-2. Average Monthly Salinities in Upper Copano Bay Under Alternative I

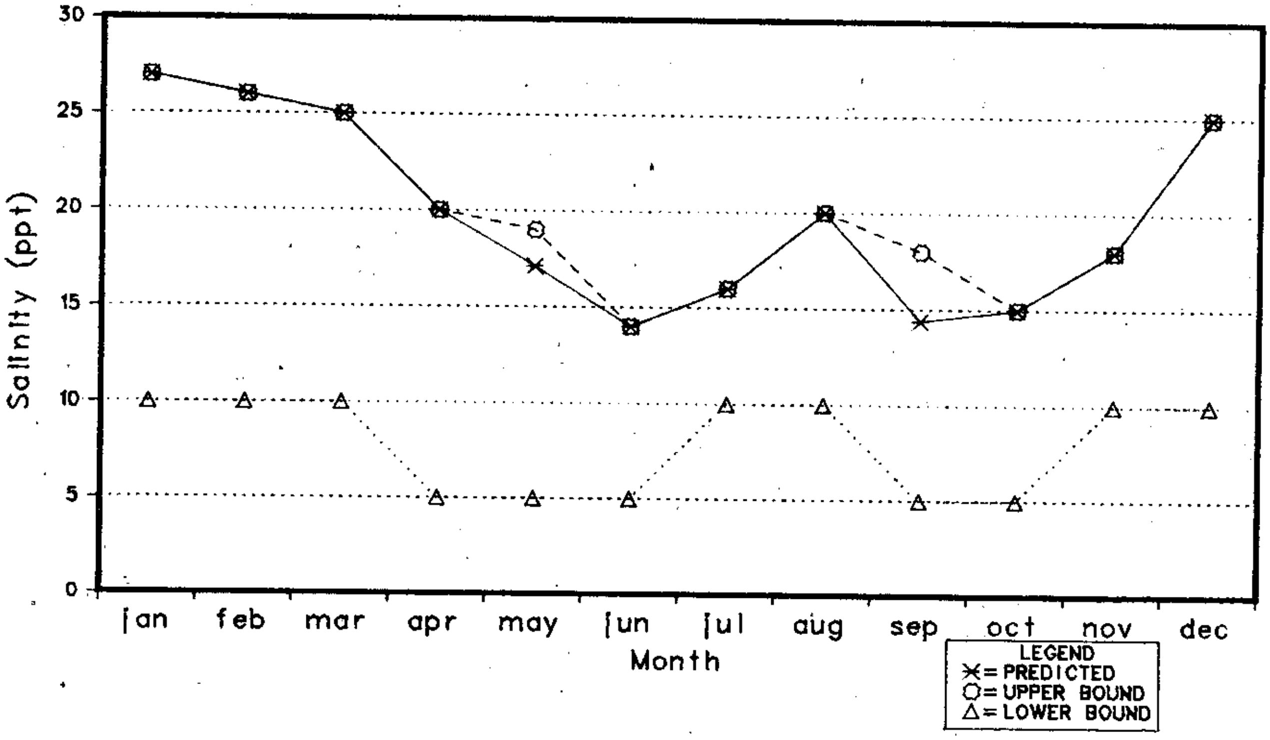

Figure 9-3. Average Monthly Salinities in Upper Nueces Bay Under Alternative I

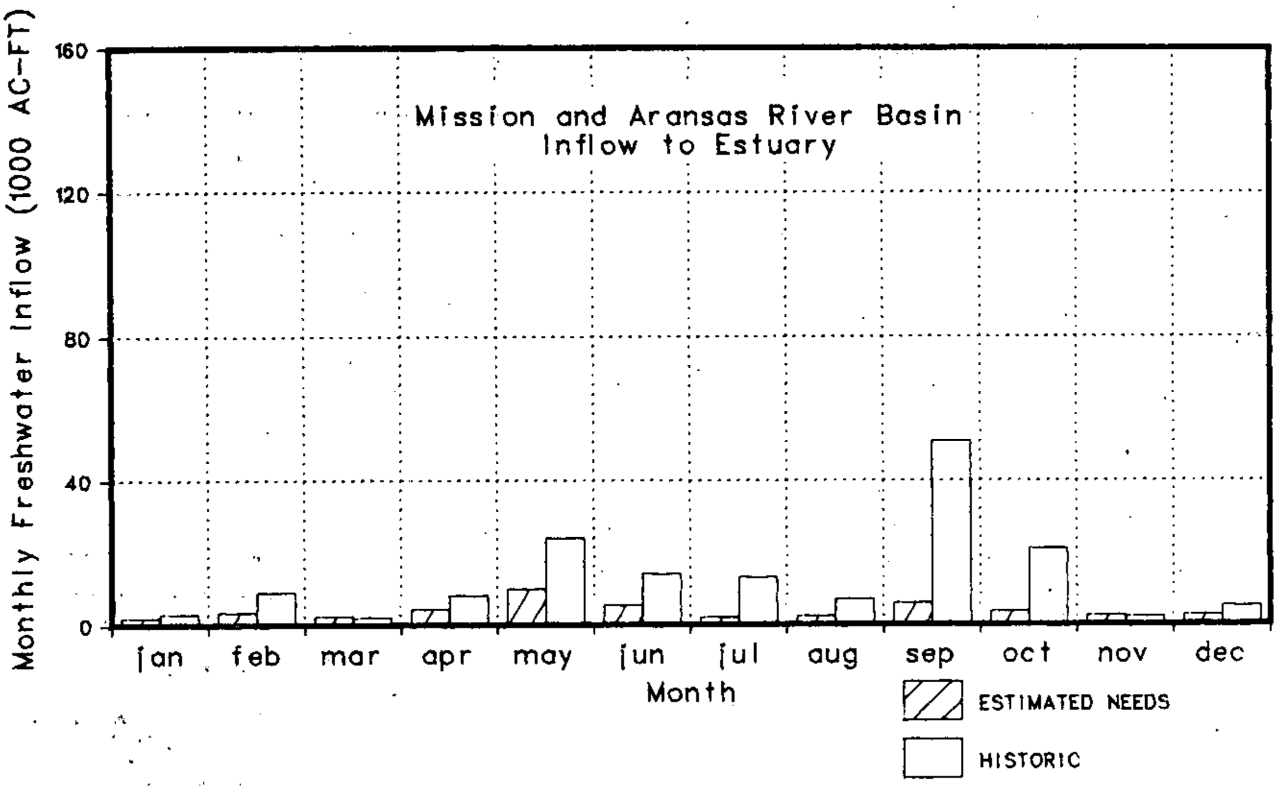

Figure 9-4. Comparison Between Mean Historical Freshwater Inflow and Inflow Needs for the Mission-Aransas Estuary from the Mission and Aransas Basins Under Alternative I

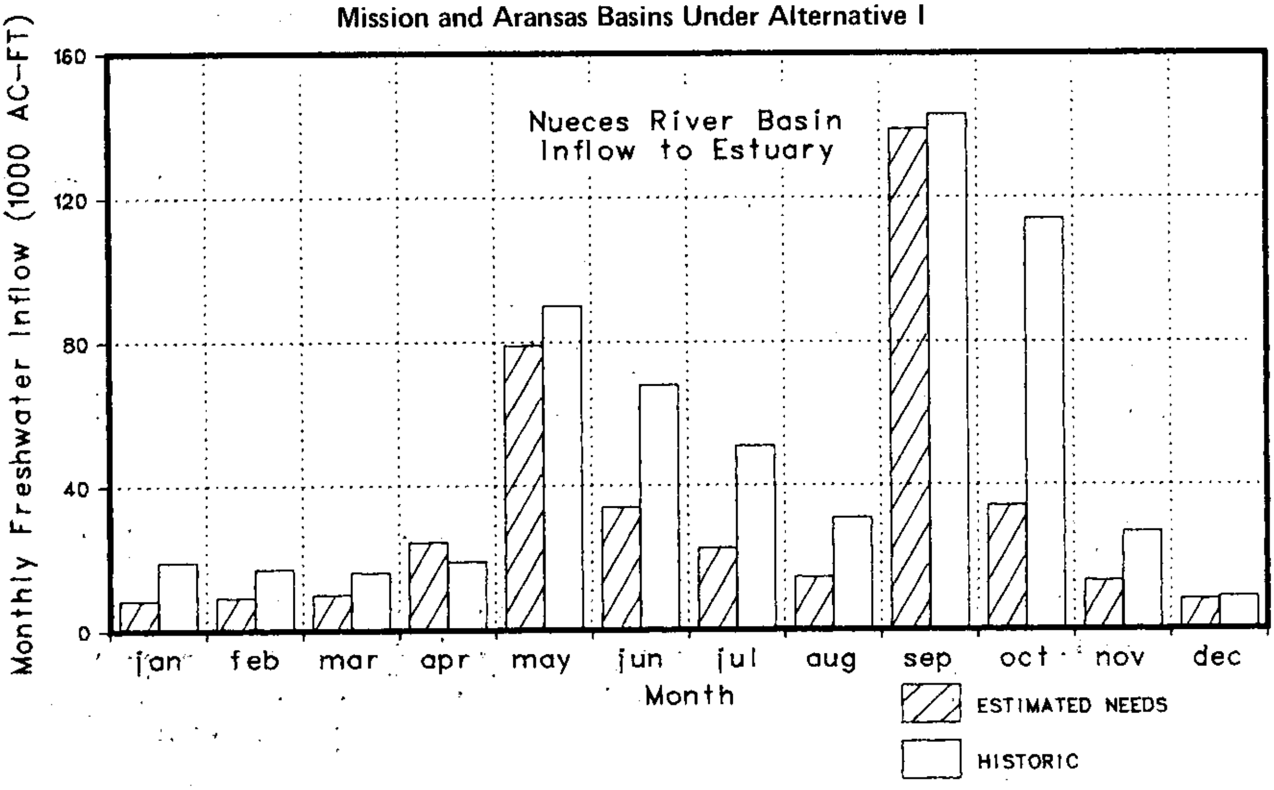

Figure 9-5. Comparison Between Mean Historical Freshwater Inflow and Inflow Needs for the Nueces Estuary from the Nueces River Basin Under Alternative I

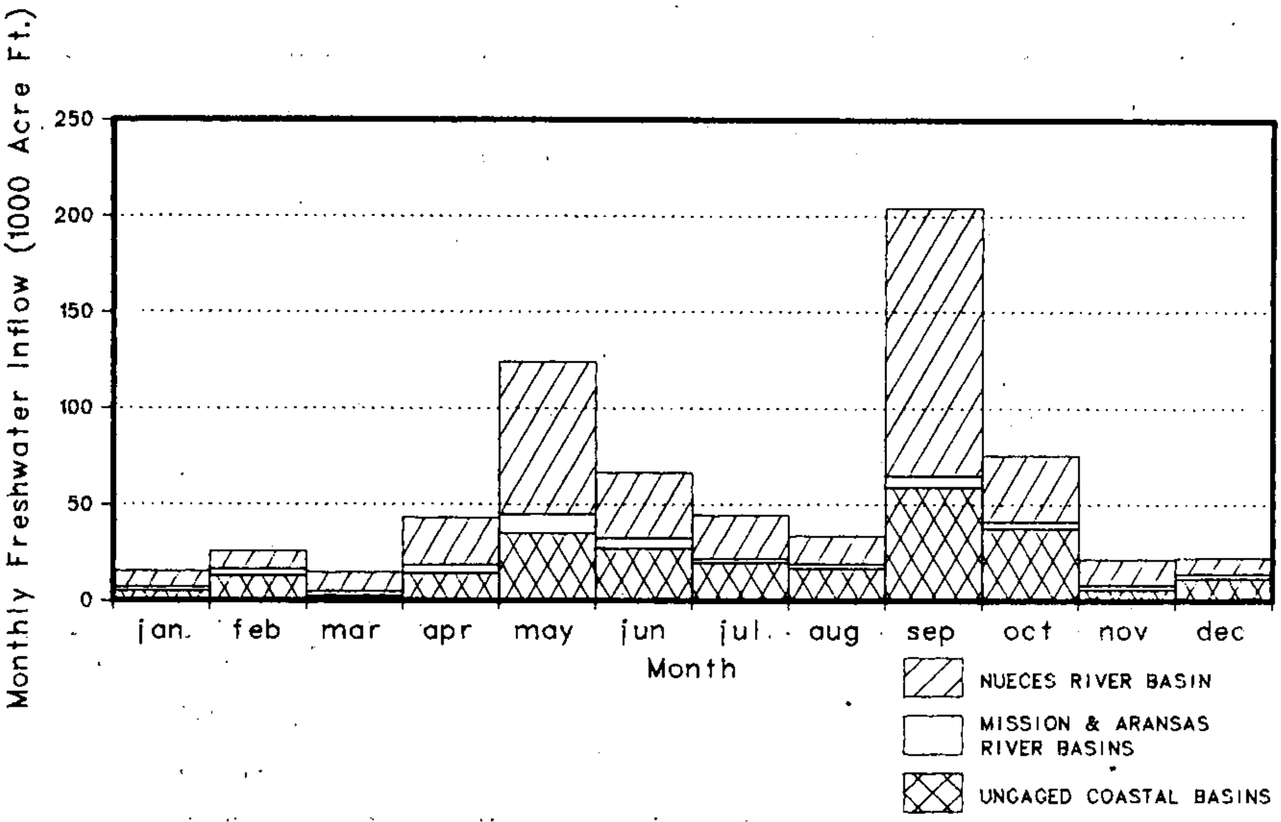

Figure 9-6. Estimated Freshwater Inflow Needs for the Nueces and Mission-Aransas Estuaries Under Alternative I

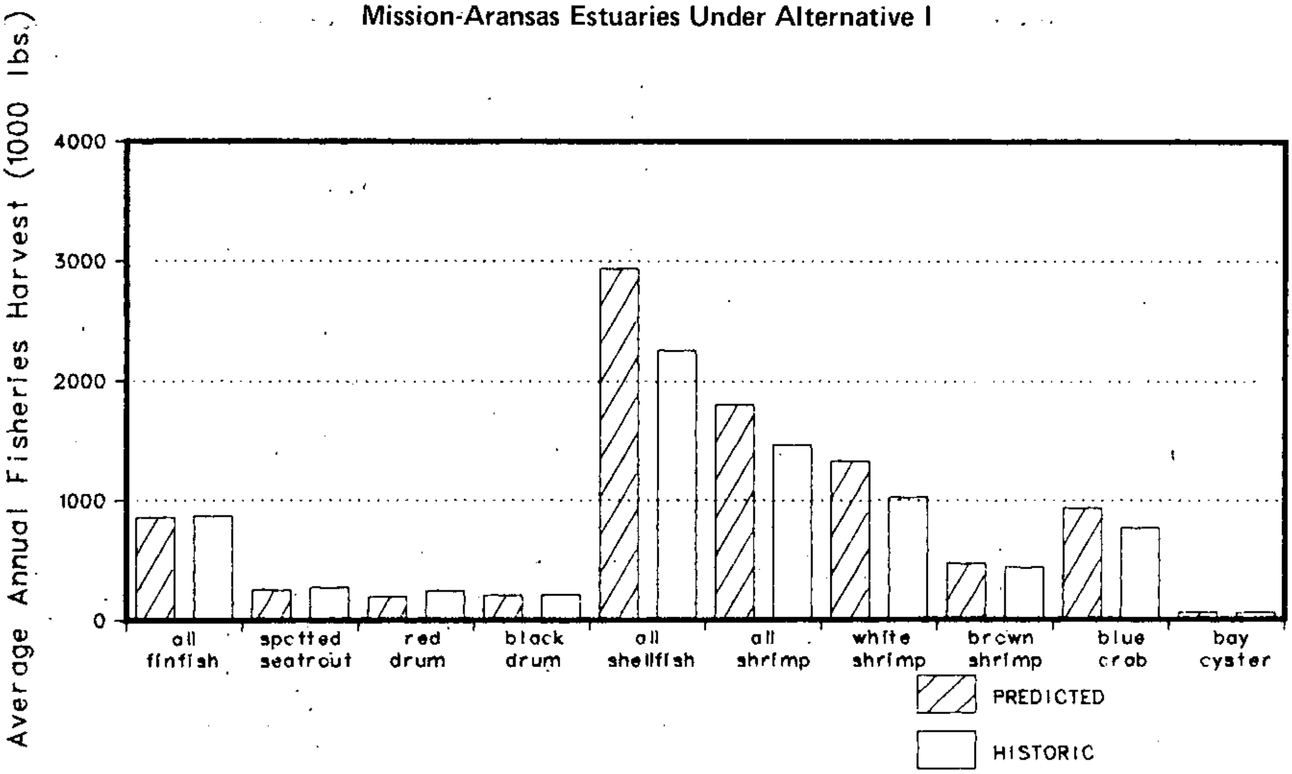

Figure 9-7. Comparison Between Mission-Aransas and Nueces Estuaries Historical Fisheries Harvests and Predicted Harvests Under Alternative I

1976 historical levels; and blue crab, a predicted 21 percent increase in harves above historical levels. The harvest of red drum had the greatest projected decrease from historical values with a projected decline of 20 percent.

Under the inflow regime given in Table 9-6, the total commercial fishery harvest is estimated to be greater than the mean historical value, even though the annual inflow is significantly less than the historical average. Upon examination of the predictive harvest equations (see Chapter VIII), it was determined the seasonal inflow regime for this alternative provided a greater portion of the annual inflow in the April-June season, which is generally the season most influencial to the harvest. In addition, monthly freshwater inflows needed are significantly greater than the historic median (50 percent frequency) inflow level and thus would tend to give higher than average harvests since the average historical harvests are most influenced by the median inflows than the average freshwater inflows.

Alternative II: Maintenance of Fisheries Harvest. The objective of Alternative II (Maintenance of Fisheries Harvests) is to minimize combined freshwater inflow to the estuaries while providing inflows sufficient to generate predicted annual commercial bay harvests of red drum, seatrout, white shrimp, and blue crab at levels no less than their mean 1962 through 1976 historical values, satisfying marsh inundation needs, and meeting viability 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 746.5 thousand acre-feet (920 million m^3) annually, of which 246.4 thousand acre-feet (304 million m^3) are contributed from the coastal basins. The computed annual contributions of the Nueces and Mission-Aransas River Basins were 440.3 thousand (542 million m^3) and 59.8 thousand acre-feet (74 million m^3), respectively. This combined yearly volume of 500.1 thousand acre-feet represents 66 percent of the combined average 1941 through 1976 historical inflows from the Nueces and Mission-Aransas River Basins.

The Estuarine LP Model does not specify unique monthly inflows from the Nueces River Basin or Mission-Aransas River Basin in the summer (July and August) and late fall (November and December) seasons. The inflows in these seasons that are greater than the inflows 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 seasonal inflows. It was decided to distribute the inflows from the above seasons to individual months based upon the historical (1941-1976) inflow distribution within each monthly grouping (see Chapter III), while observing monthly salinity and inundation needs.

Monthly freshwater inflow needs generated for Alternative II provide salinities in upper Copano Bay (Figure 9-8) and upper Nueces Bay (Figure 9-9) which are lower during the months of July, August, November and December than those under Alternative I, but which continue to closely approximate the upper salinity bound in the majority of the remaining months. Predicted salinities are lower for this alternative than those for Alternative I during critical months of fisheries productivity since additional inflow is supplied in those months to increase fisheries harvests under Alternative II.

Table 9-7. Freshwater Inflow Needs of the Nueces and Mission-Aransas Estuaries under Alternative II a/

Month	Aransas and Mission River Basin: Total Inflow Needs	Aransas and Mission River Basin: Gaged Inflow Need From Mission River Basin b/	Nueces River Basin: Total Inflow Needs	Nueces River Basin: Inflow Need from Gaged Portion of the Basin c/	Coastal Basins Total Inflow: San Antonio-Nueces	Coastal Basins Total Inflow: Nueces-Rio Grande	Combined Inflow d/: Mission-Aransas Estuary	Combined Inflow d/: Nueces Estuary
	Thousands of Acre-Feet							
January	1.9	.7	8.4	6.5	4.0	1.0	5.9	9.4
February	3.4	1.2	9.2	7.2	11.0	1.9	14.4	11.1
March	2.4	.9	9.9	7.9	2.0	.2	4.4	10.1
April	4.4	1.5	24.4	21.5	12.0	2.2	16.5	26.6
May	9.9	2.9	79.0 g/	72.8	30.0	5.0	39.9	84.0
June	5.4	1.8	34.0	30.5	23.0	4.0	28.4	38.0
July	9.5 e/	2.8	38.2 e/	34.5	16.0	3.7	25.5	41.9
August	5.5 e/	1.8	23.2 e/	20.4	14.0	2.7	19.5	25.9
September	5.9	1.9	139.0 g/	129.2	50.0	9.1	55.9	148.1
October	3.6	1.2	34.3	30.8	32.0	5.5	35.6	39.8
November	2.4 f/	.9	30.5 f/	27.2	5.0	.6	7.4	31.1
December	5.5 f/	1.8	10.2 f/	8.1	10.0	1.5	15.5	11.7
Annual	59.8	19.4	440.3	396.6	209.0	37.4	268.8	477.7

a/ All inflows are mean monthly values

b/ These values computed using regression equations relating monthly river basin inflow to the estuary with monthly gaged inflows at USGS Station on the Mission River near Refugio (#08189500)

c/ These values computed using regression equations relating monthly river basin inflow to the estuary with monthly gaged inflows at USGS Station on the Nueces River near Mathis (#08211000)

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

e/ Total seasonal freshwater inflow need distributed to each estuary according to the Nueces and Mission-Aransas River Basins historical (1941-1976) monthly freshwater inflow in the season (July and August)

f/ Total seasonal freshwater inflow need distributed to each estuary according to the Nueces and Mission-Aransas River Basins historical (1941-1976) monthly freshwater inflow in the season (November and December)

g/ Volume of median seasonal flood flow events

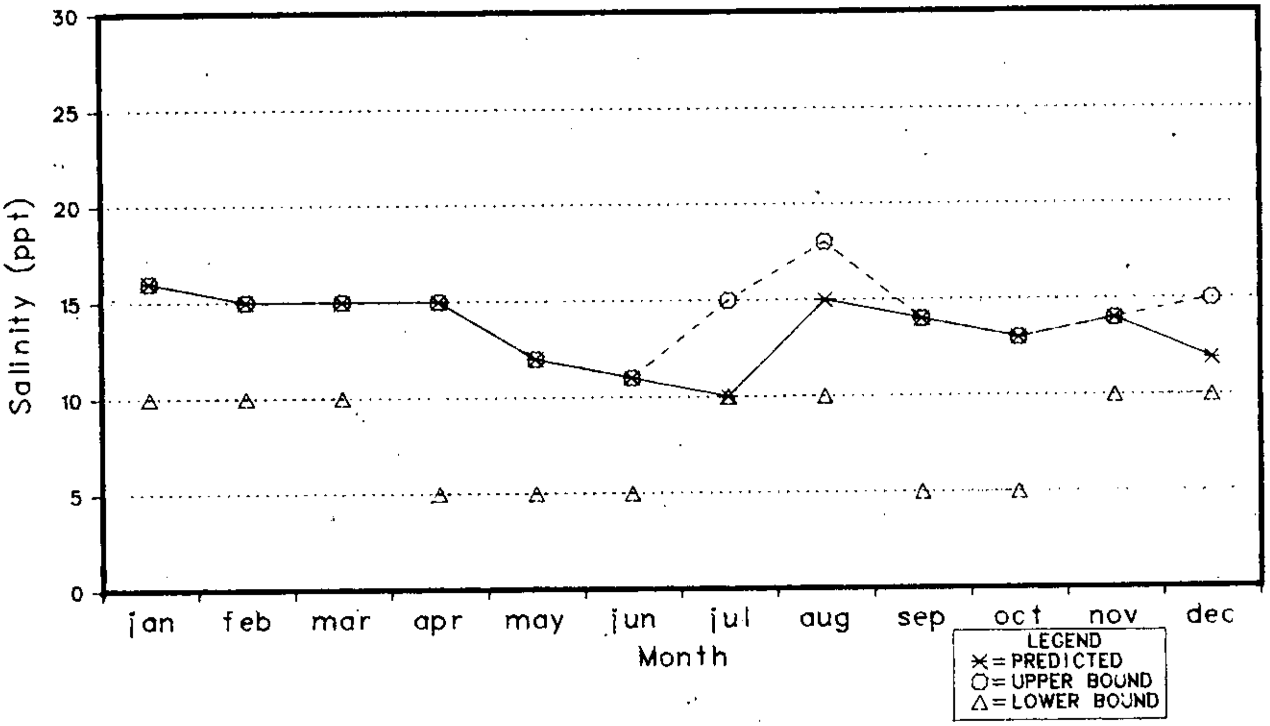

Figure 9-8. Average Monthly Salinity in Upper
Copano Bay Under Alternative II

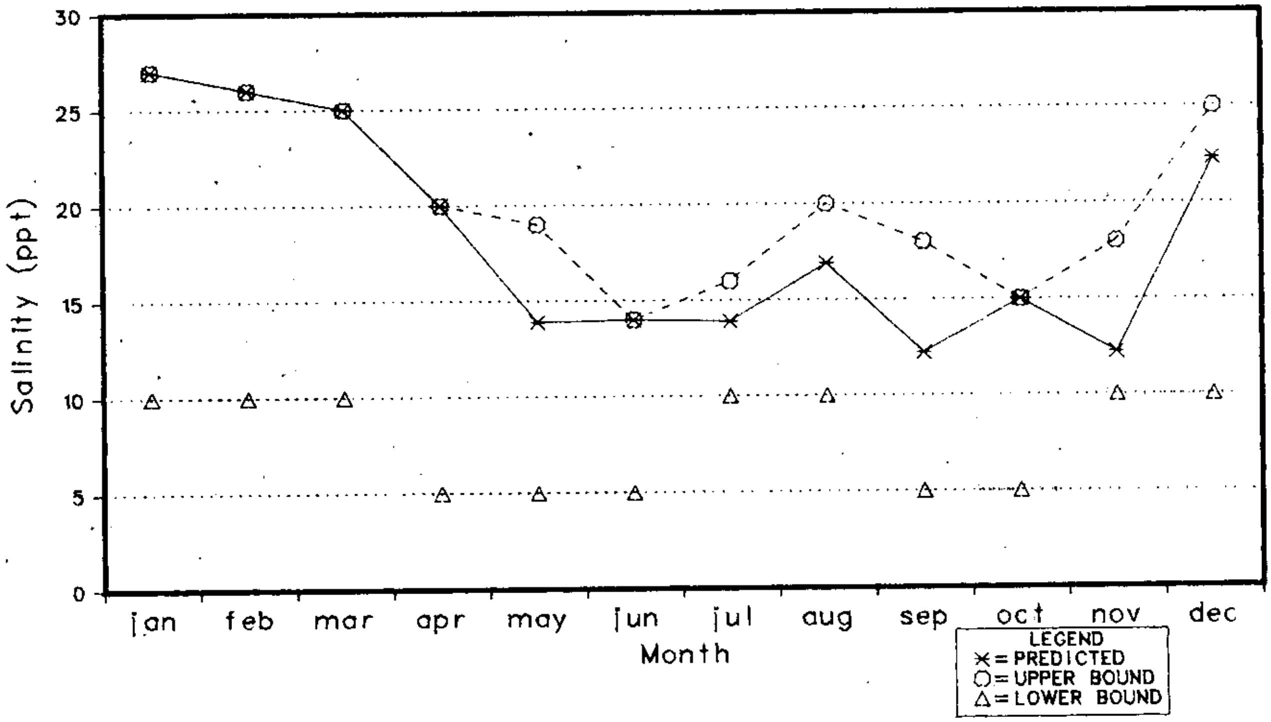

Figure 9-9. Average Monthly Salintiy in Upper
Nueces Bay Under Alternative II

Comparisons between the mean historical 1941 through 1976 combined inflows and estimated freshwater inflow needs for Alternative II were made for the Nueces and Mission-Aransas River Basins (Figures 9-10 and 9-11). The average historical inflows from the Nueces Basin are generally greater for each month than the freshwater inflow needs under this alternative. Notable exceptions are the months of April, November, and December. From the Mission-Aransas Basin, larger inflows than under Alternative I are needed in July, August, November and December to increase the finfish harvest. The Estuarine Linear Programming Model distributed the combined monthly inflows to achieve Alternative II (Maintenance of Fisheries Harvests) as indicated in Figure 9-12.

Implementation of Alternative II for the Nueces and Mission-Aransas estuaries under the inflow regime indicated in Table 9-7 is projected to increase commercial fisheries harvests above average historical levels over the 1962 through 1976 period for all harvest groups (Figure 9-13). The all-shellfish harvest is projected to be 39 percent greater than the historical annual average, while the all-finfish harvest is estimated to be 25 percent greater than the mean historical 1962 through 1976 harvest.

Alternative III: Finfish Harvest Enhancement. The objective of Alternative III (Finfish Harvest Enhancement) is to maximize the annual estuarine commercial finfish bay harvest for both estuaries combined while observing salinity viability limits and marsh inundation needs, and utilizing annual Nueces and Mission-Aransas River Basins inflows at levels no greater than their respective average historical 1941 through 1976 annual inflows.

The Estuarine Linear Programming Model was utilized to determine an optimal set of monthly river basin inflows to meet the stated objective (Table 9-8). The annual combined inflow[1/] from freshwater sources needed to maximize the finfish harvest was estimated 1.009 million acre-feet (1,243 million m^3). The total annual contribution from the Nueces River Basin was estimated at 604 thousand acre-feet (744 million m^3), while the corresponding Mission-Aransas River Basin contribution was 159 thousand acre-feet (196 million m^3). The remaining annual freshwater contribution of 246.4 thousand acre-feet (304 million m^3) was the historical average annual inflow from the San Antonio-Nueces (excluding the Mission-Aransas River Basin) and the Nueces-Rio Grande Coastal Basins. As with Alternative II, seasonal inflows were distributed monthly, where necessary, on the basis of historical inflows as indicated in Table 9-8, consistent with the minimum monthly needs.

Monthly freshwater inflow needs generated for Alternative III provide salinities (Figures 9-14 and 9-15) which are lower in the majority of months for both Copano and Nueces Bays than those under Alternative II (Figures 9-8 and 9-9). The summer and late fall months, in particular, for Nueces Bay (Figure 9-15) have salinities considerably lower than those under Alternatives I or II. Salinity in Copano Bay is also markedly lower under Alternative III in the spring, summer, and late fall months, where inflows are required to maximize the finfish harvest (Figure 9-14).

Comparisons between mean historical 1941 through 1976 combined inflows and estimated freshwater inflow needs under Alternative III have been made for

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

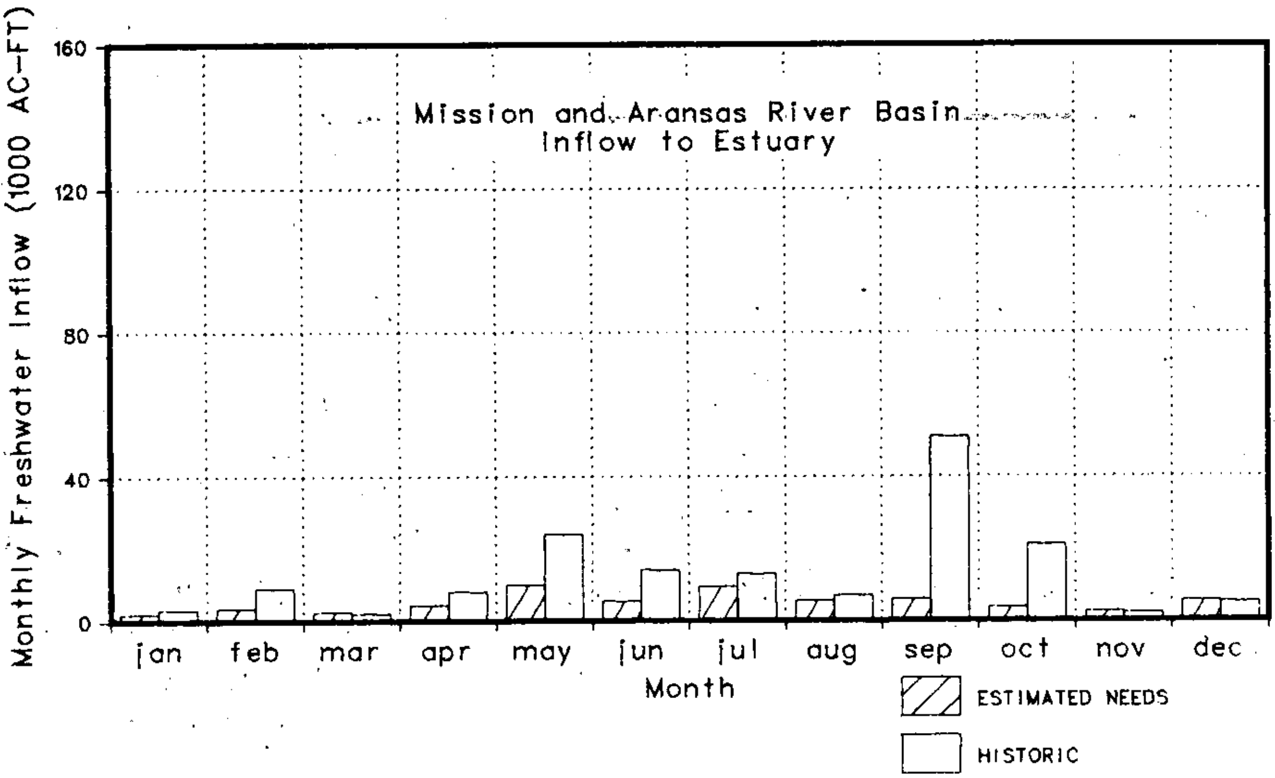

Figure 9-10. Comparison Between Mean Historical Freshwater Inflow and Inflow Needs for the Mission-Aransas Estuary from the Mission and Aransas Basins Under Alternative II

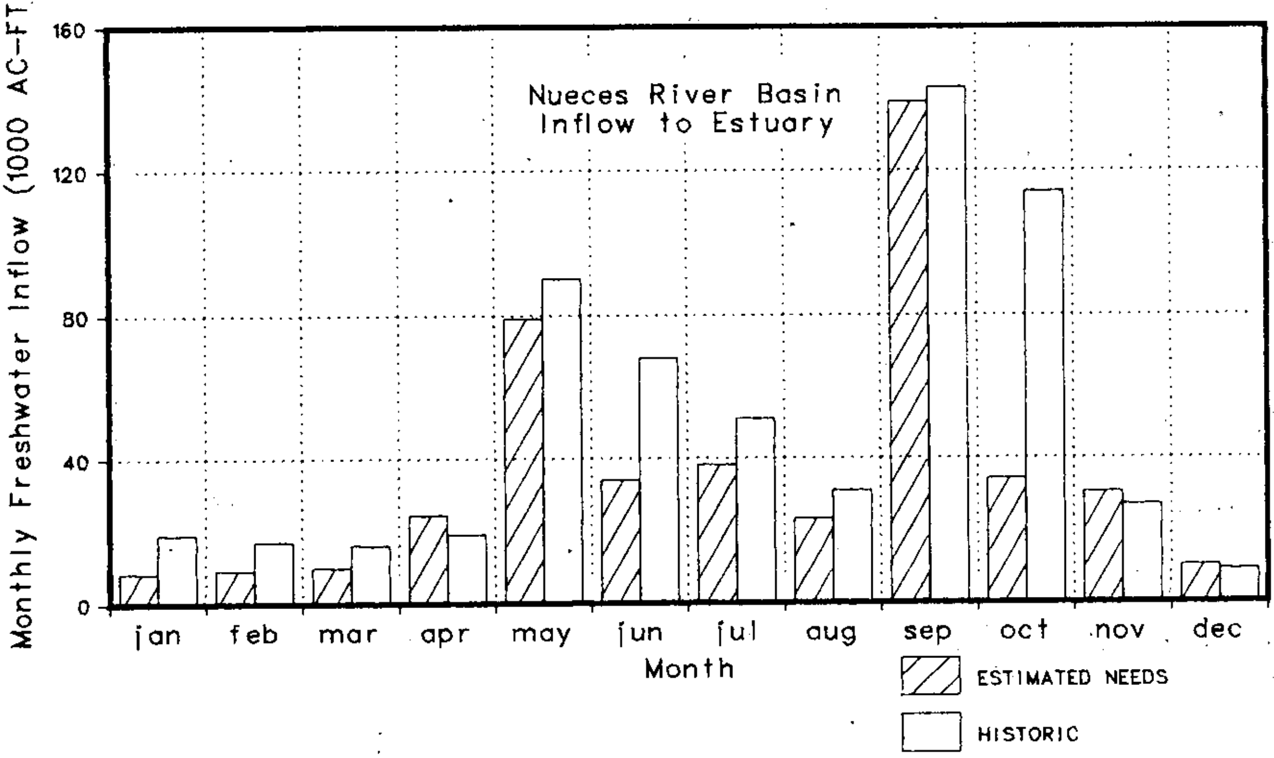

Figure 9-11. Comparison Between Mean Historical Freshwater Inflow and Inflow Needs for the Nueces Estuary from the Nueces River Basin Under Alternative II

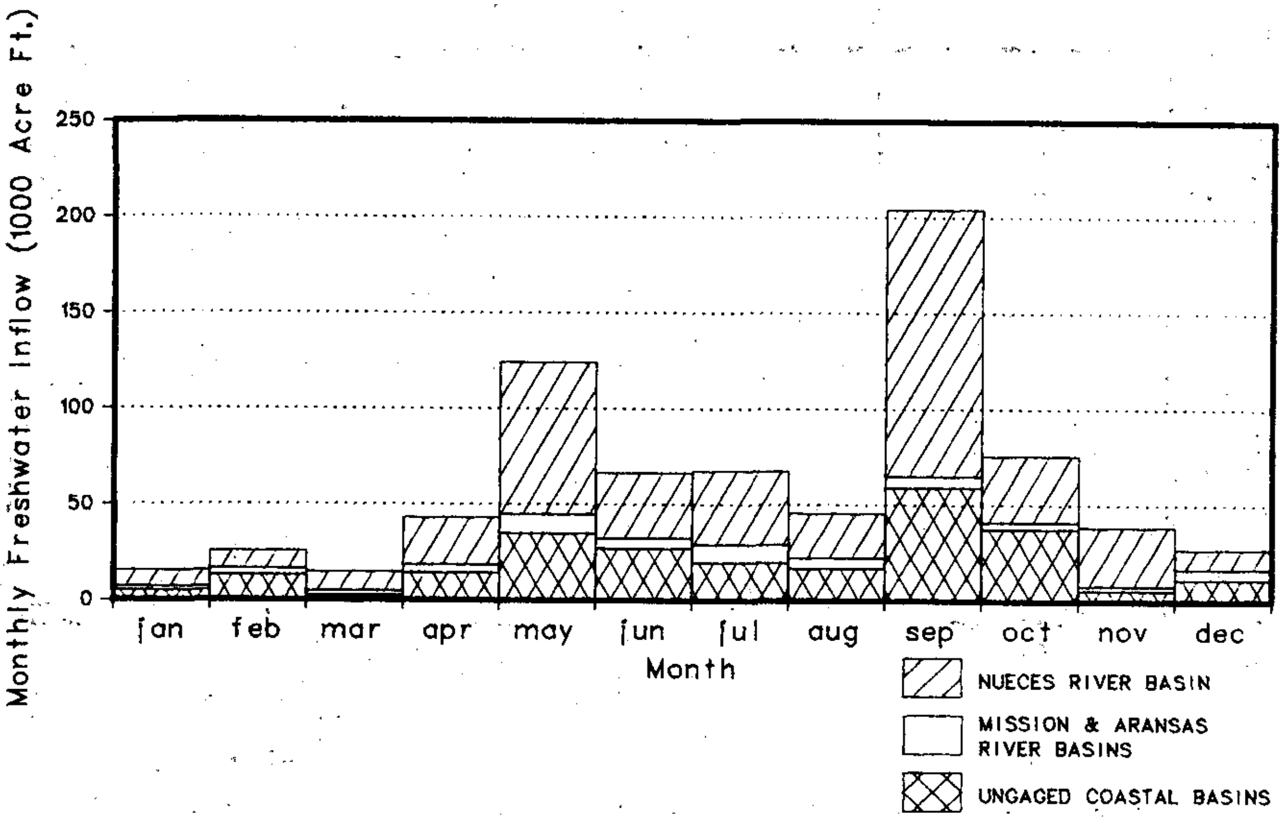

Figure 9-12. Estimated Freshwater Inflow Needs for the Nueces and Mission-Aransas Estuaries Under Alternative II

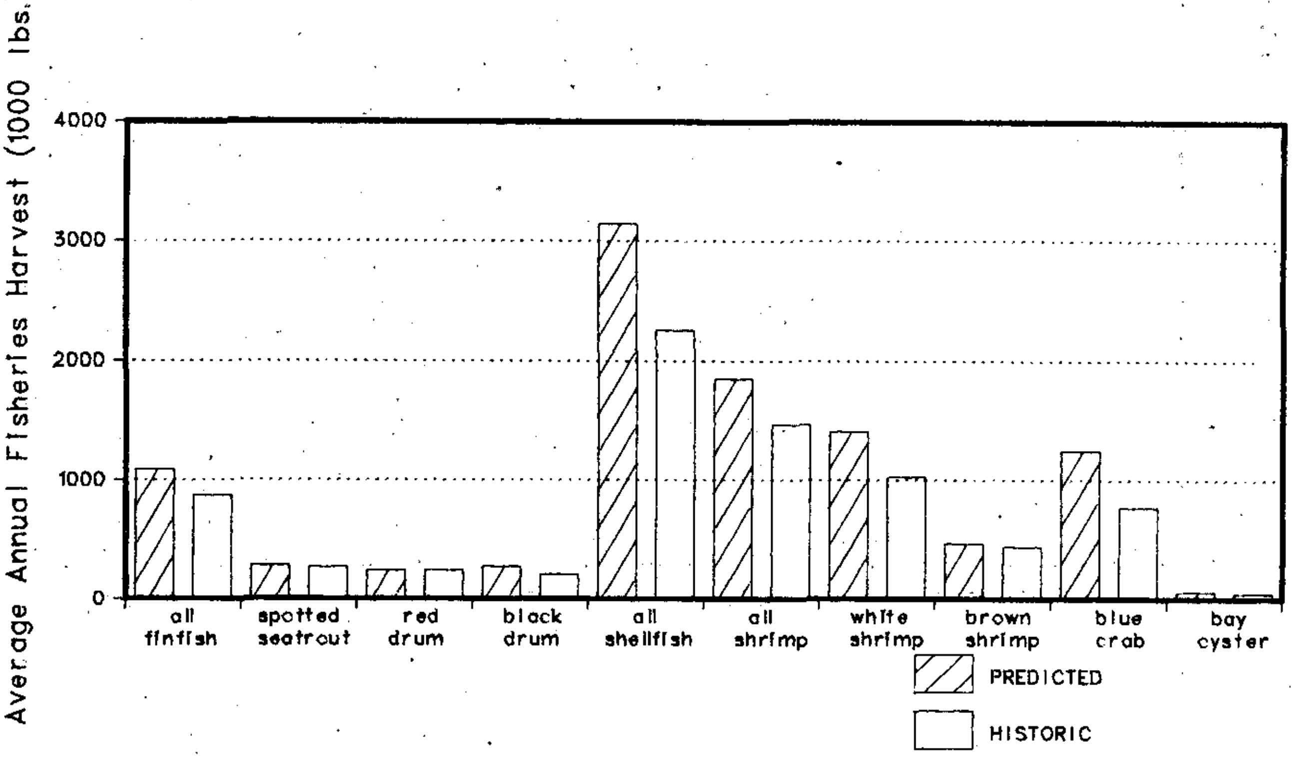

Figure 9-13. Comparison Between Mission-Aransas and Nueces Estuaries Historical Fisheries Harvests and Predicted Harvests Under Alternative II

Table 9-8. Freshwater Inflow Needs of the Nueces and Mission-Aransas Estuaries under Alternative III a/

Month	Aransas and Mission River Basin		Nueces River Basin		Coastal Basins Total Inflow		Combined Inflow d/	
	Total Inflow Needs	Gaged Inflow Need From Mission River Basin b/	Total Inflow Needs	Inflow Need from Gaged Portion of the Basin c/	San Antonio-Nueces	Nueces-Rio Grande	Mission-Aransas Estuary	Nueces Estuary
	Thousands of Acre-Feet							
January	1.9	.7	8.4	6.5	4.0	1.0	5.9	9.4
February	3.4	1.2	9.2	7.2	11.0	1.9	14.4	11.1
March	2.4	.9	9.9	7.9	2.0	.2	4.4	10.1
April	13.8 e/	3.9	24.4	21.5	12.0	2.2	25.8	26.6
May	41.3 e/	9.9	79.0 g/	66.7	30.0	5.0	71.3	84.0
June	24.1 e/	6.3	48.6	50.1	23.0	4.0	47.1	52.6
July	9.5	2.8	91.2 f/	84.2	16.0	3.7	25.5	94.9
August	37.3	9.1	55.4 f/	50.6	14.0	2.7	51.3	58.1
September	5.9	1.9	139.0 g/	129.2	50.0	9.1	55.9	148.1
October	3.6	1.2	34.3	30.8	32.0	5.5	35.6	39.8
November	5.9	1.9	47.2	42.9	5.0	.6	10.9	47.8
December	9.9	2.9	57.4	52.5	10.0	1.5	19.9	58.9
Annual	159.0	42.7	604.0	550.1	209.0	37.4	368.0	641.4

a/ All inflows are mean monthly values

b/ These values computed using regression equations relating monthly river basin inflow to the estuary with monthly gaged inflows at USGS Station on the Mission River near Refugio (#08189500)

c/ These values computed using regression equations relating monthly river basin inflow to the estuary with monthly gaged inflows at USGS Station on the Nueces River near Mathis (#08211000)

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

e/ Total seasonal freshwater inflow need distributed according to the Mission-Aransas River Basin historical (1941-1976) monthly freshwater inflow in the season (April, May and June)

f/ Total seasonal freshwater inflow need distributed according to the Nueces River Basin historical (1941-1976) monthly freshwater inflow in the season (July and August)

g/ Volume of median seasonal flood flow events

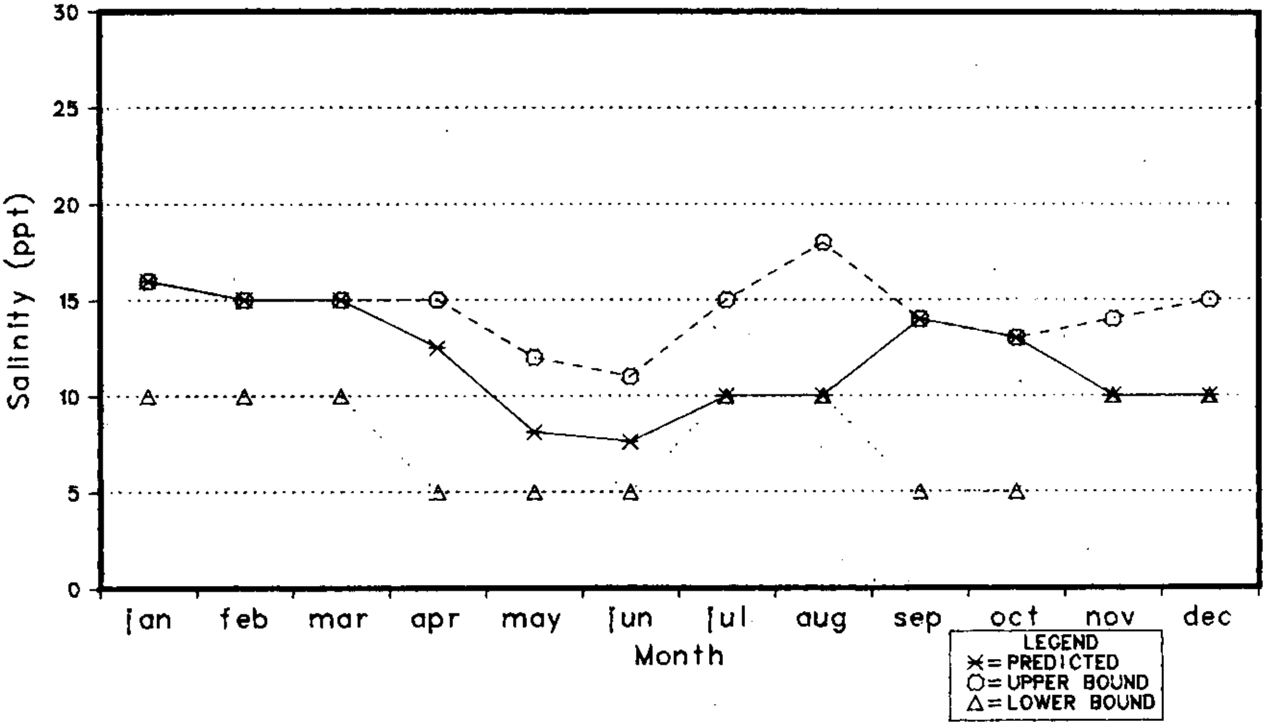

Figure 9-14. Average Monthly Salinity in Upper Copano Bay Under Alternative III

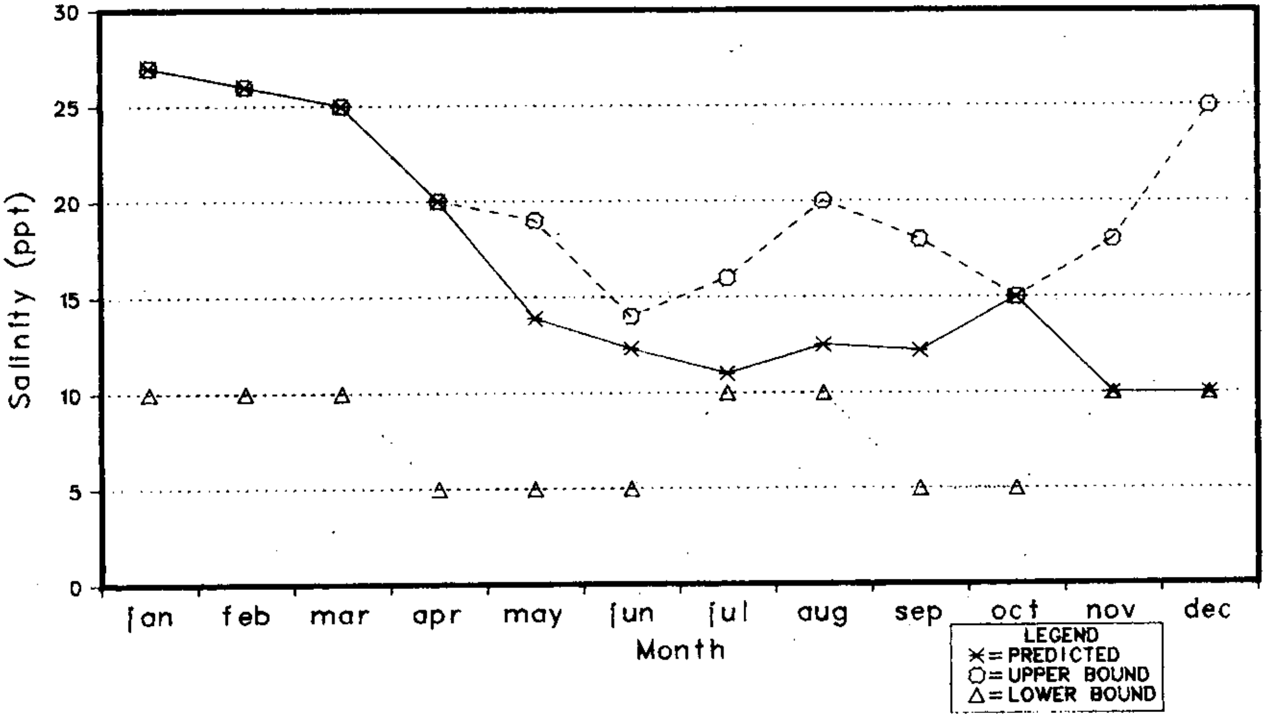

Figure 9-15. Average Monthly Salinity in Upper Nueces Bay Under Alternative III

the Nueces and Mission-Aransas Basins (Figures 9-16 and 9-17). The average historical inflows for the Mission-Aransas Basin are higher than freshwater inflow needs under Alternative III for the winter and early fall months, somewhat lower than the estimated needs in the spring and late fall season, and much lower than the needs for shellfish enhancement in August. Historical inflows from the Nueces Basin are higher than the estimated needs under Alternative III for all freshwater needs except in the summer and late fall seasons, when freshwater needs for finfish harvest enhancement are most substantial. The Estuarine Linear Programming Model distributes the monthly inflows to achieve Alternative III (Finfish Harvest Enhancement) as indicated in Figure 9-18.

According to this analysis, implementation of Alternative III for the Nueces and Mission-Aransas estuaries under the inflow regime indicated in Table 9-8 would result in an estimated 91 percent increase in the annual commercial all-finfish harvest above the mean 1962 through 1976 historical level (Figure 9-19). Projected increases above mean harvests for the 1962 though 1976 period in individual fishery harvest categories under Alternative III include 50 percent in spotted seatrout, 43 percent in the all-shrimp harvest, 65 percent in blue crab, and 58 percent increase in white shrimp 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 estuaries is satisfactory (Figure 9-1). The Estuarine Linear Programming Model considers salinities only at two points in the Nueces and Mission-Aransas estuaries near the major sources of freshwater inflow. To determine circulation and salinity patterns throughout these estuaries it is necessary to apply the tidal hydrodynamic and salinity mass transport models (described in Chapter V) using the estimates of monthly freshwater inflow needs obtained from the Estuarine Linear Programming Model. If the circulation patterns and salinity gradients predicted by the hydrodynamic and transport models are acceptable, then the tentative monthly freshwater inflow needs may be accepted. Should the estimated estuarine conditions not be satisfactory, then the constraints upon the Estuarine Linear Programming Model must be modified, and the model again used to compute new estimates.

Salinity patterns of an 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 Corpus Christi 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 Corpus Christi Bay is not evaluated since it was not anticipated that the monthly inflows under the three alternatives would give salinities lower than 10 ppt.

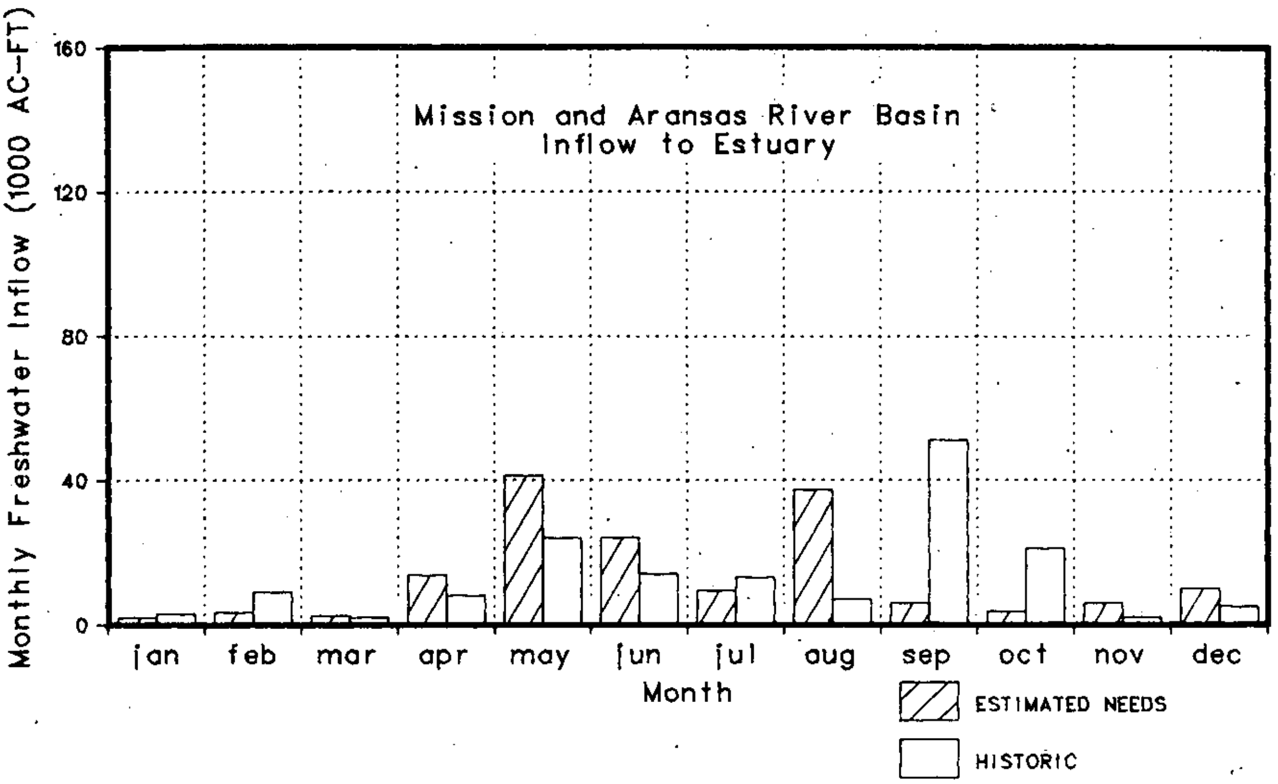

Figure 9-16. Comparison Between Mean Historical Freshwater Inflow and Inflow Needs for the Mission-Aransas Estuary from the Mission and Aransas Basins Under Alternative III

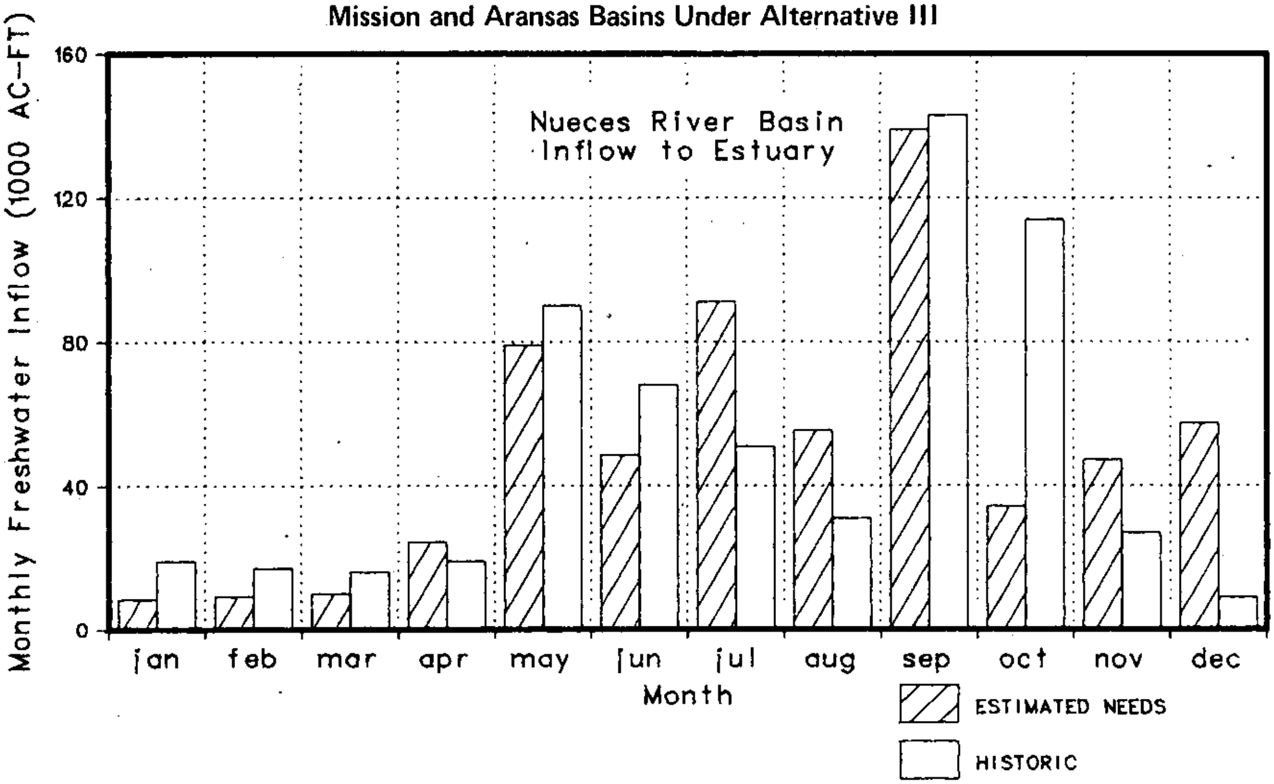

Figure 9-17. Comparison Between Mean Historical Freshwater Inflow and Inflow Needs for the Nueces Estuary from the Nueces River Basin Under Alternative III

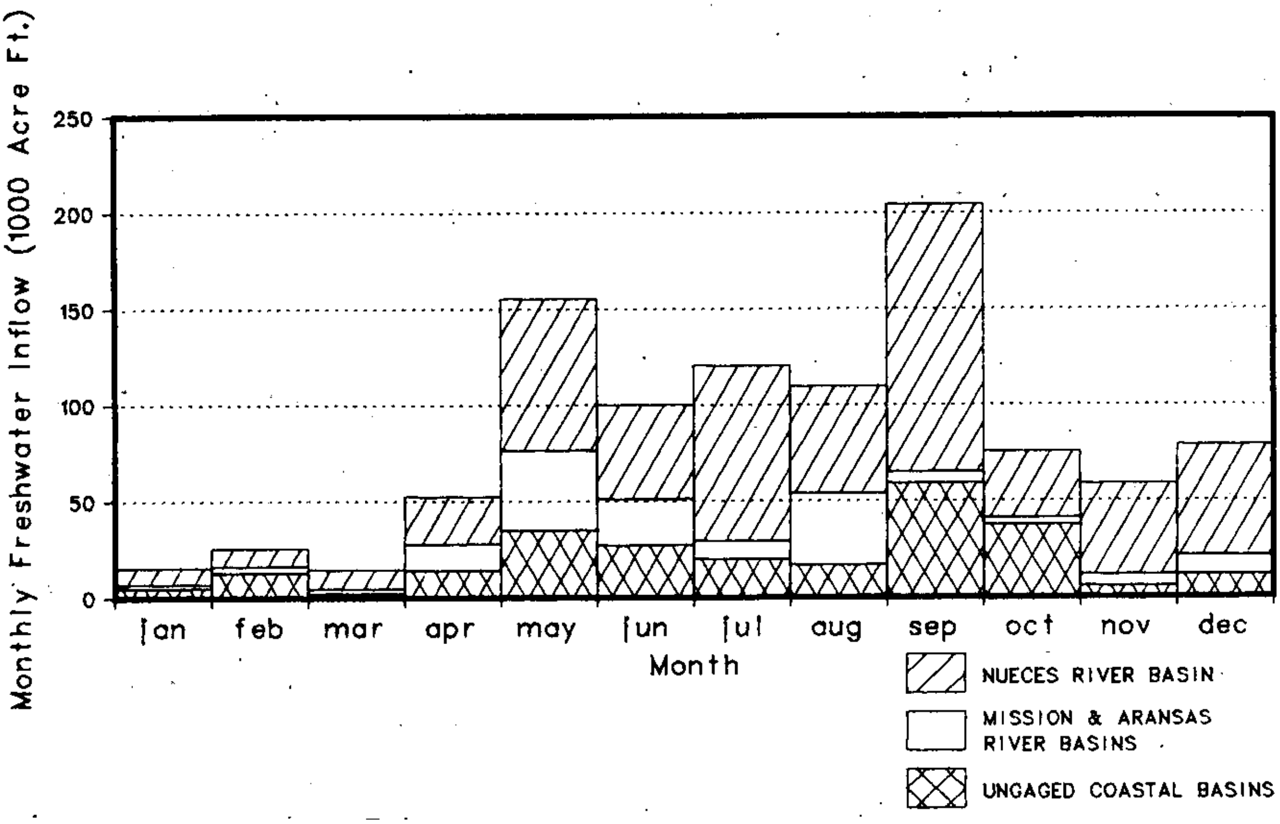

Figure 9-18. Estimated Freshwater Inflow Needs for the Nueces and Mission-Aransas Estuaries Under Alternative III

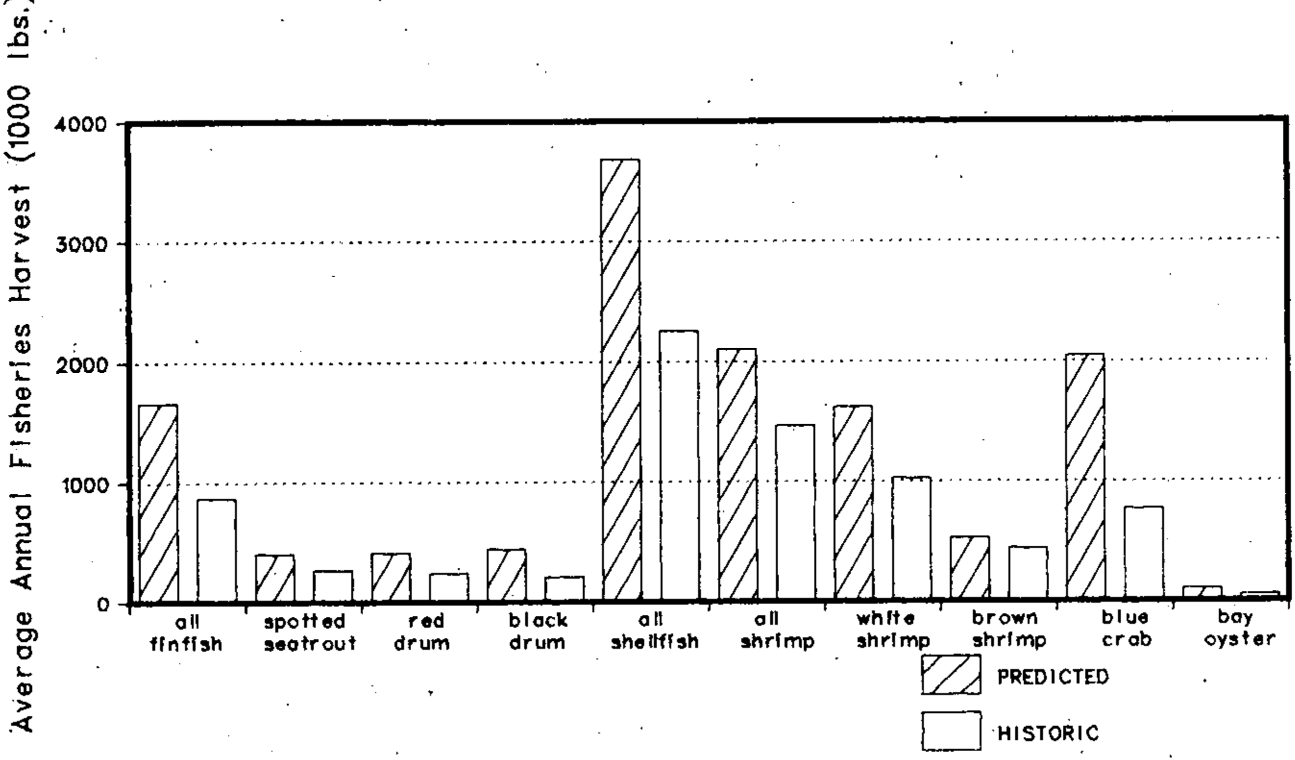

Figure 9-19. Comparison Between Mission-Aransas and Nueces Estuaries Historical Fisheries Harvests and Predicted Harvests Under Alternative III

Simulation of Mean Monthly Circulation Patterns. The estimated monthly freshwater inflow needs to the Nueces and Mission-Aransas estuaries under Alternative I were 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 Nueces and Mission-Aransas estuaries 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 41 x 28 computational matrix representing the Nueces and Mission-Aransas estuaries. The computed net flows are the average of the instantaneous flows calculated by the model over the tidal cycle. Thus, the circulation pattern represented by these net flows should not be interpreted as a set of currents that can be observed at any time during the tidal cycle, but rather as a representation of the net movement of water created by the combined action of the Gulf tides, freshwater inflow, and meteorological conditions during the tidal cycle.

The resultant circulation patterns can best be illustrated in the form of vector plots, wherein each vector (or arrow) represents the net flow through a computational cell. The orientation of the vector represents the direction of flow, and the length of the vector represents the magnitude of flow, with one inch corresponding to a flow rate of approximately 22,000 ft^3/sec (623 m^3/sec).

The flow circulations in the Nueces and Mission-Aransas estuaries were simulated for historical average meteorological conditions and estimated freshwater inflow needs under Alternative I for each monthly period. Examination of the circulation plots for each of the numerical simulations (using the monthly inflow needs) reveals that the simulated general circulation patterns in the Nueces and Mission-Aransas estuaries are similar for all months (Figures 9-20 through 9-31). The simulated circulation patterns in these estuaries appeared to be wind-dominated. The prevailing southeasterly wind generates the predominant current which moves water from the eastern portion of Corpus Christi Bay, through Redfish, Aransas and Carlos Bays into Mesquite Bay of the Guadalupe estuary.

The circulation pattern in upper Corpus Christi Bay generally consists of two closed circulation eddies: a clockwise circulation vortex in the southern portion of the bay and a counter-clockwise vortex in the northern portion of the bay. The simulated net flow circulation in Nueces Bay are not significantly influenced by the currents in Corpus Christi Bay since the net flow contribution between the two bays is from Nueces Bay to Corpus Christi Bay.

The simulated Copano Bay circulation patterns are relatively unaffected by the currents in Aransas Bay, nearby. The net flow exchange between Copano and Aransas Bays is relatively small compared to the exchange between the other bays of the Nueces and Mission-Aransas estuaries.

Simulated net flow between the Nueces estuary and Laguna Madre is predominantly in a northeasterly direction into Corpus Christi Bay through the dredged channels, including the Intracoastal Waterway. Only during the month of September is the flow direction reversed, with Corpus Christi Bay contributing water into Laguna Madre. The simulated net flow through Aransas Pass is predominantly directed out of the Nueces estuary and into the Gulf of Mexico. Only during the months of September and October are the simulated net

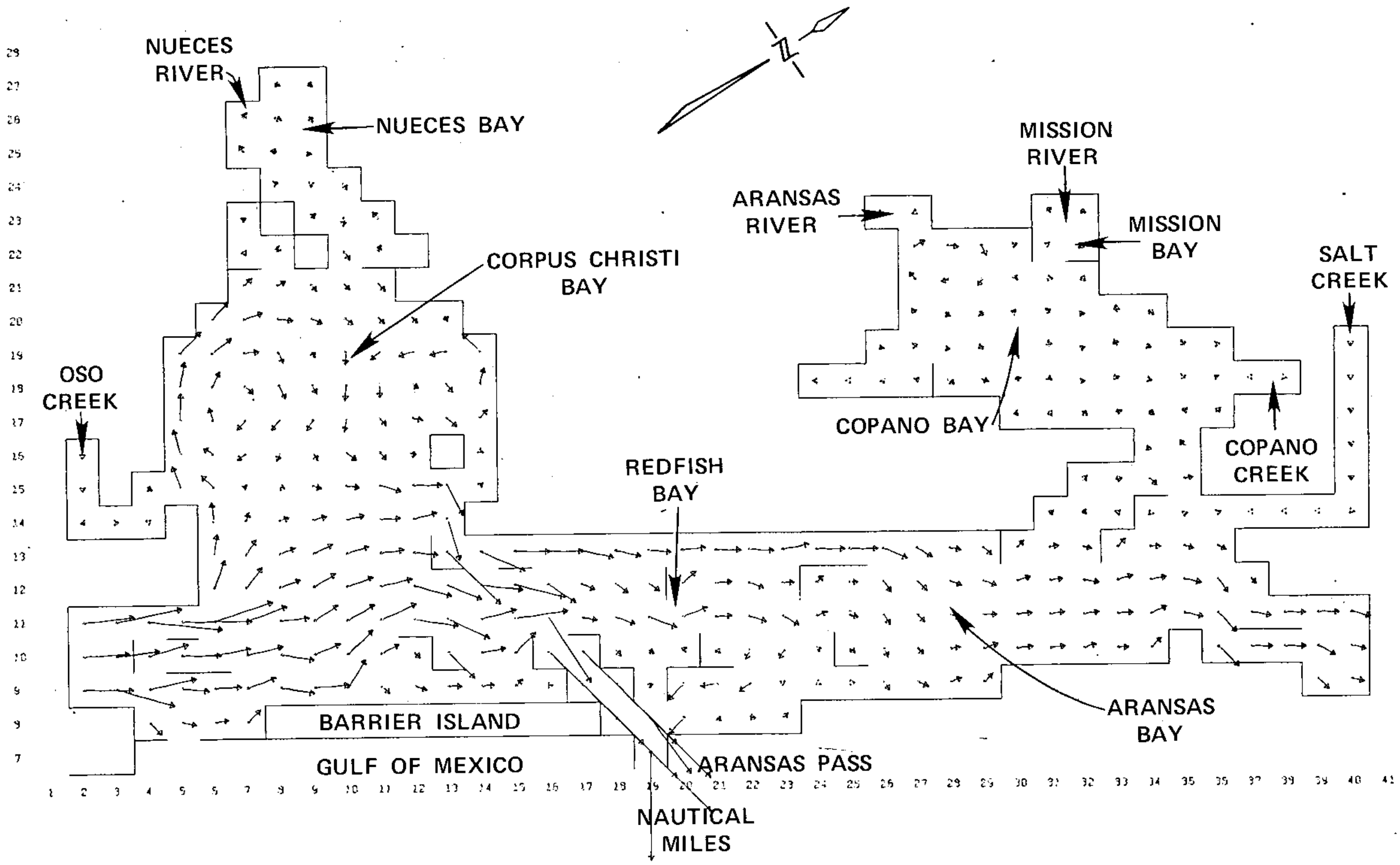

Figure 9-20. Simulated Net Steady-State Flows in the Nueces and Mission-Aransas Estuaries Under January Freshwater Inflow Needs, Alternative I

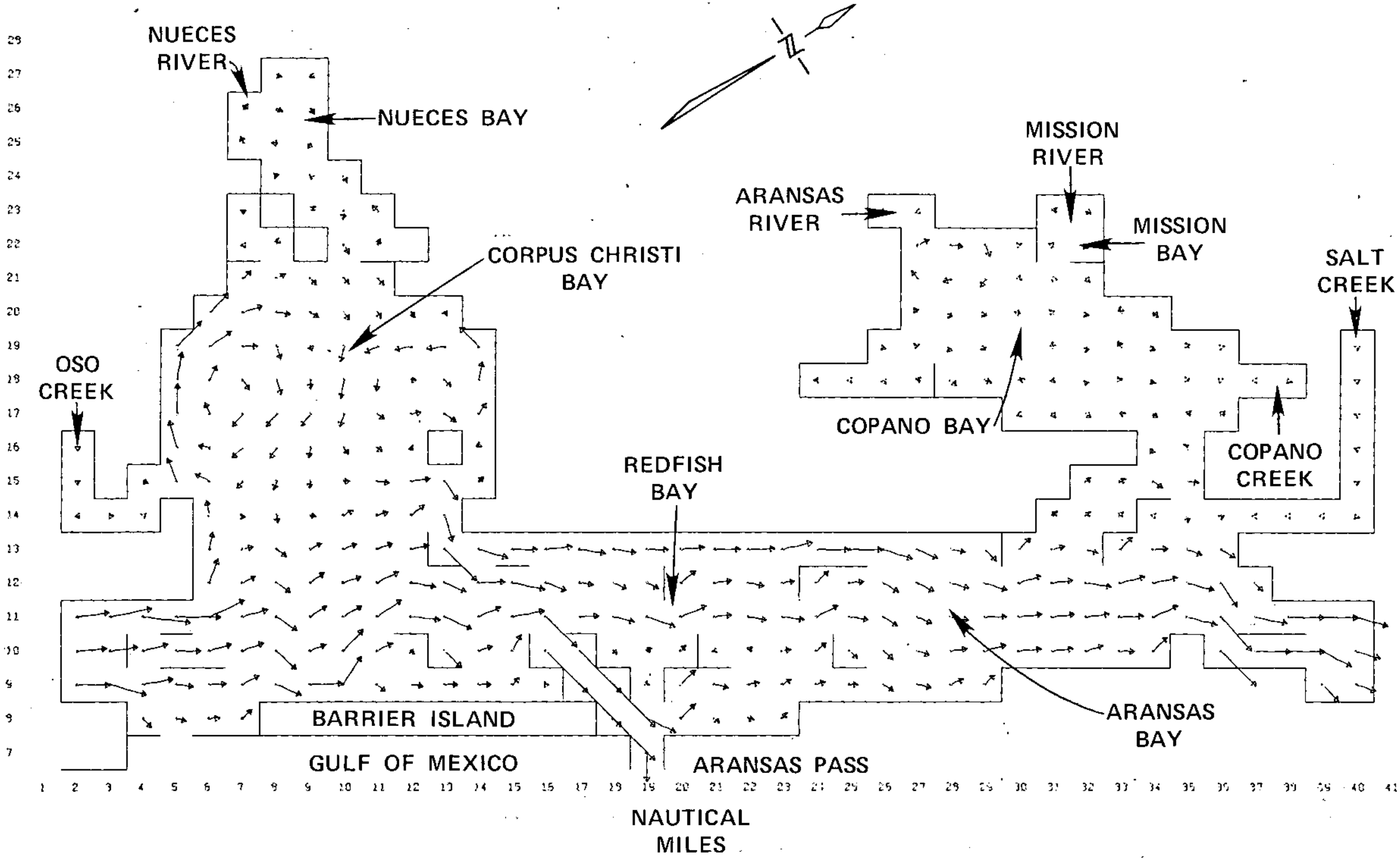

Figure 9-21. Simulated Net Steady-State Flows in the Nueces and Mission-Aransas Estuaries Under February Freshwater Inflow Needs, Alternative I

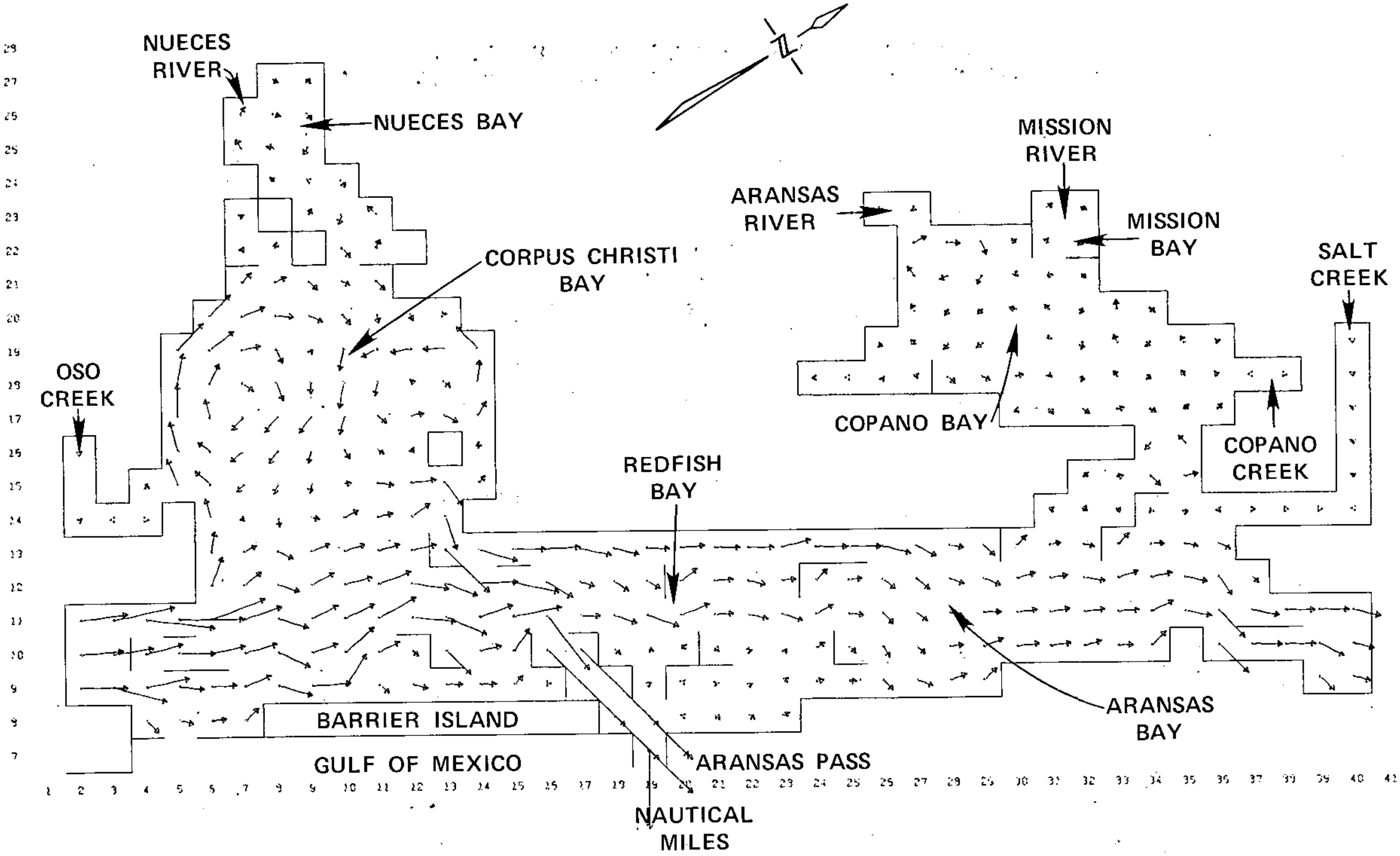

Figure 9-22. Simulated Net Steady-State Flows in the Nueces and Mission-Aransas Estuaries Under March Freshwater Inflow Needs, Alternative I

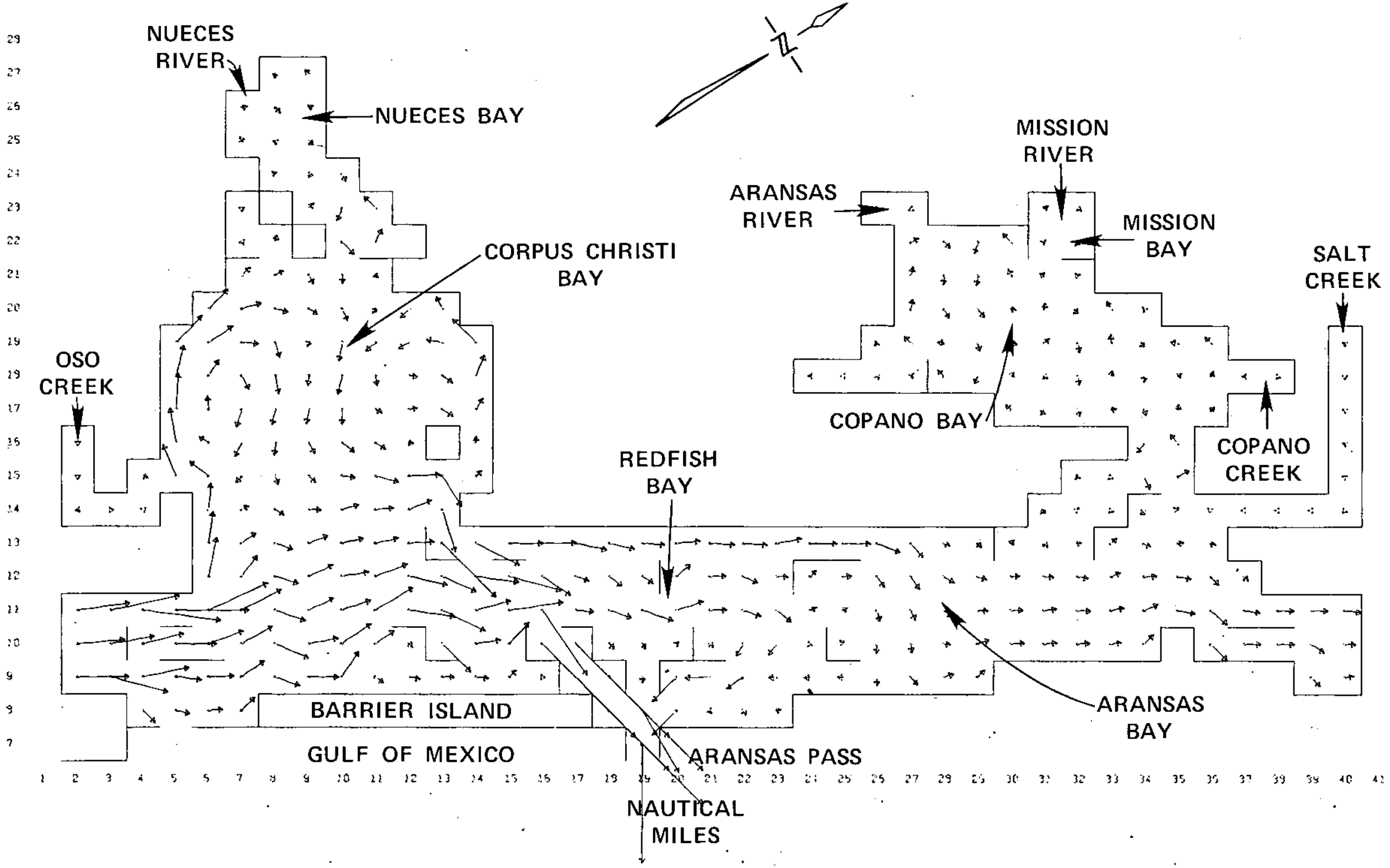

Figure 9-23. Simulated Net Steady-State Flows in the Nueces and Mission-Aransas Estuaries Under April Freshwater Inflow Needs, Alternative I

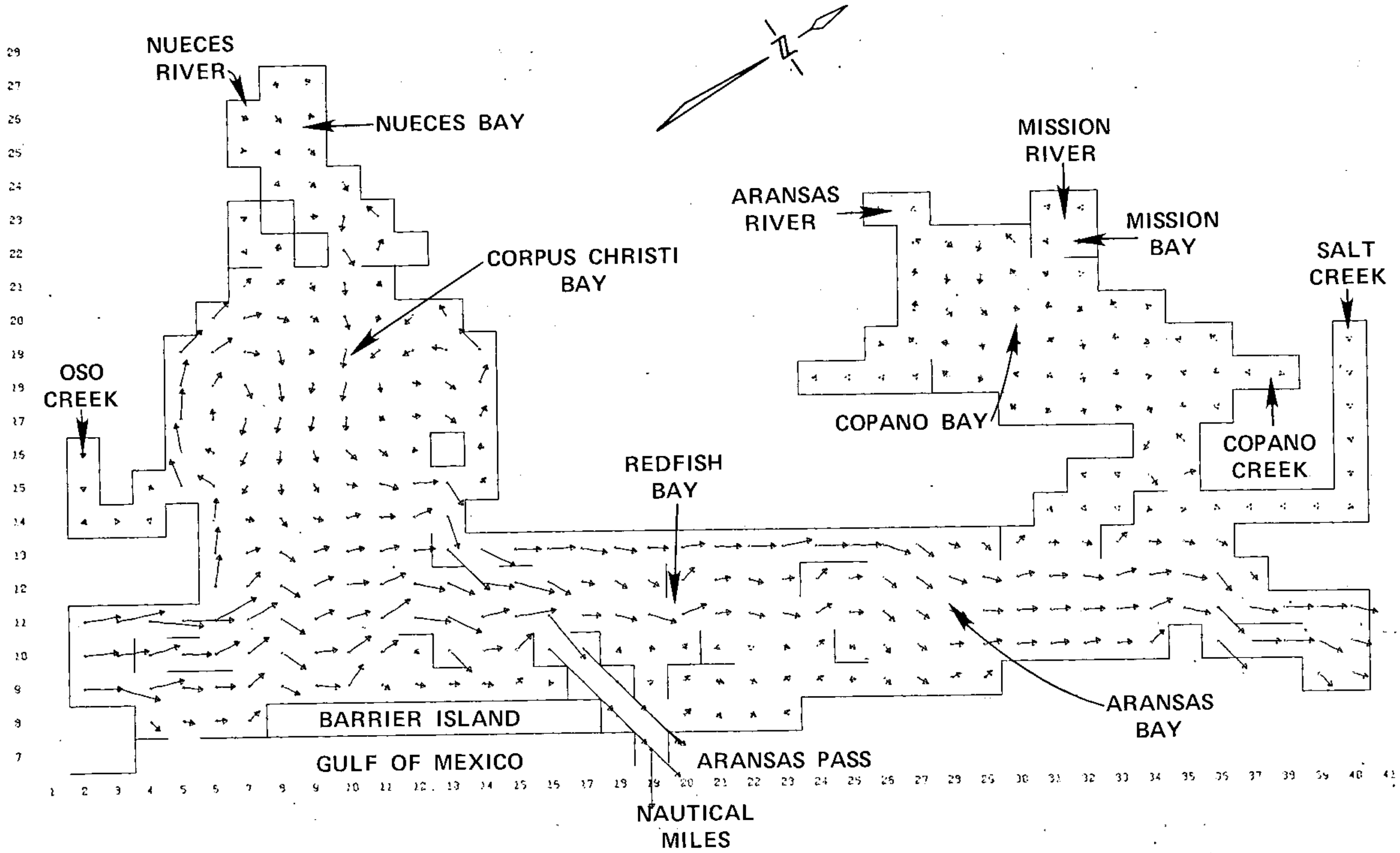

Figure 9-24. Simulated Net Steady-State Flows in the Nueces and Mission-Aransas Estuaries Under May Freshwater Inflow Needs, Alternative I

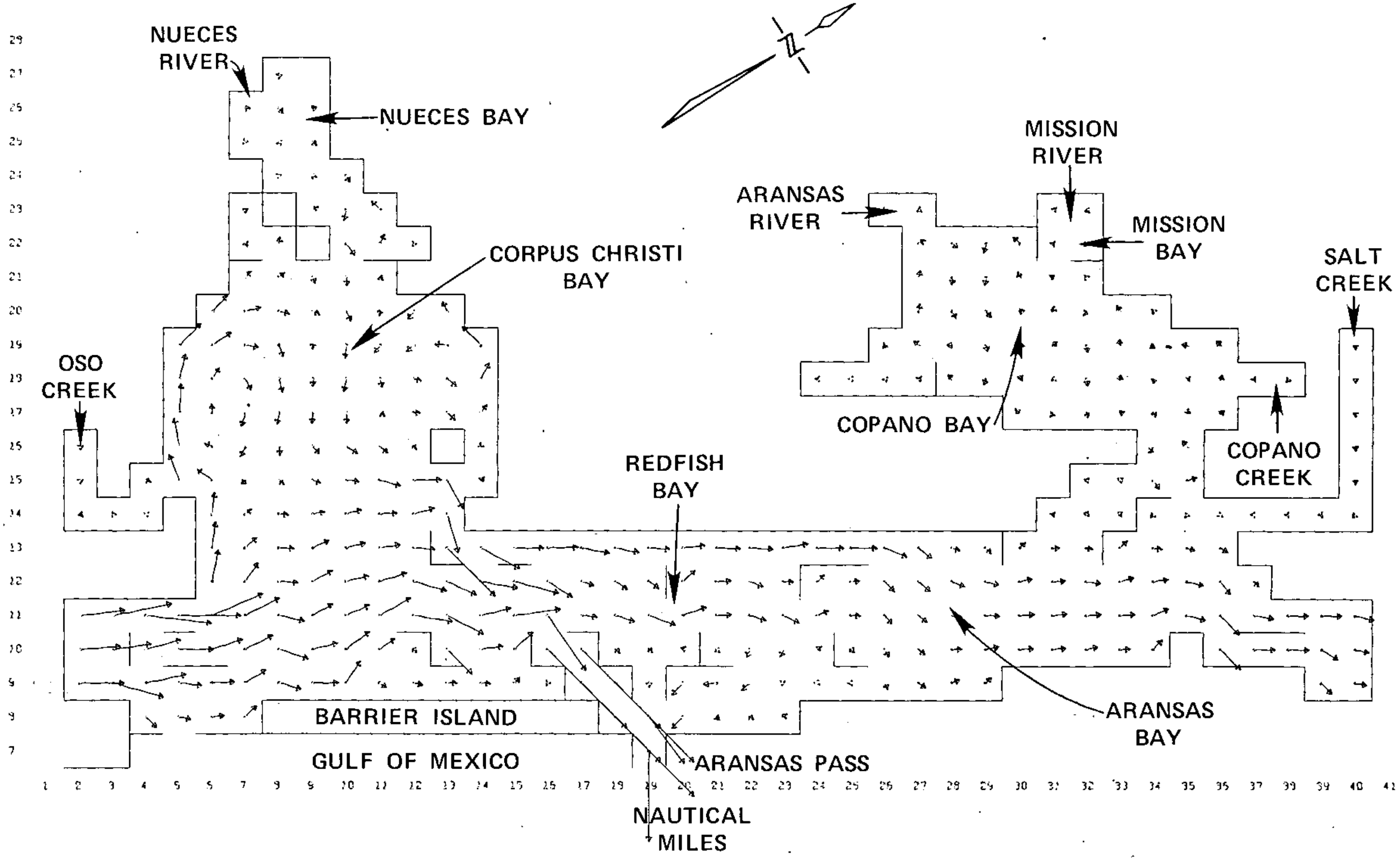

Figure 9-25. Simulated Net Steady-State Flows in the Nueces and Mission-Aransas Estuaries Under June Freshwater Inflow Needs, Alternative I

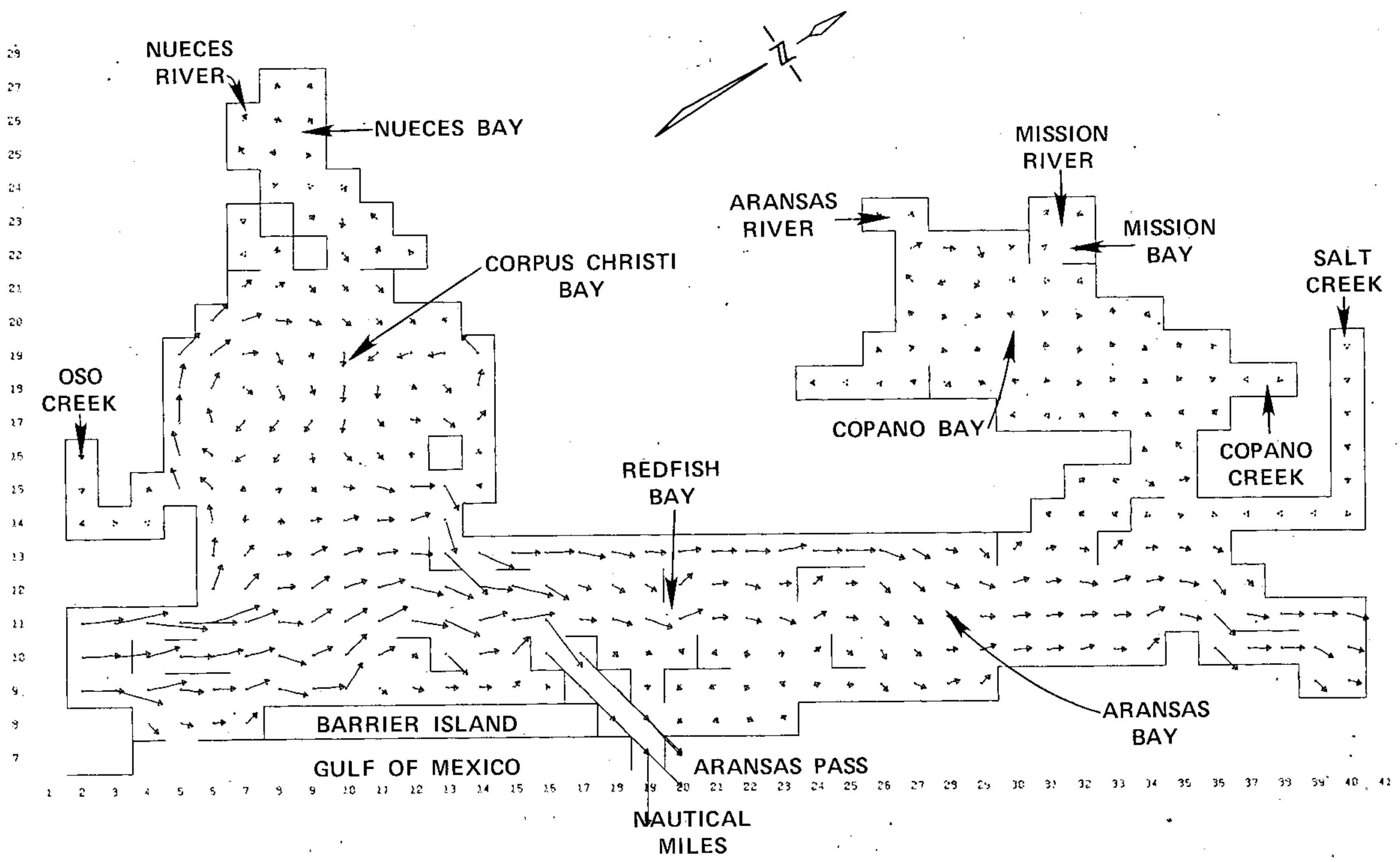

Figure 9-26. Simulated Net Steady-State Flows in the Nueces and Mission-Aransas Estuaries Under July Freshwater Inflow Needs, Alternative I

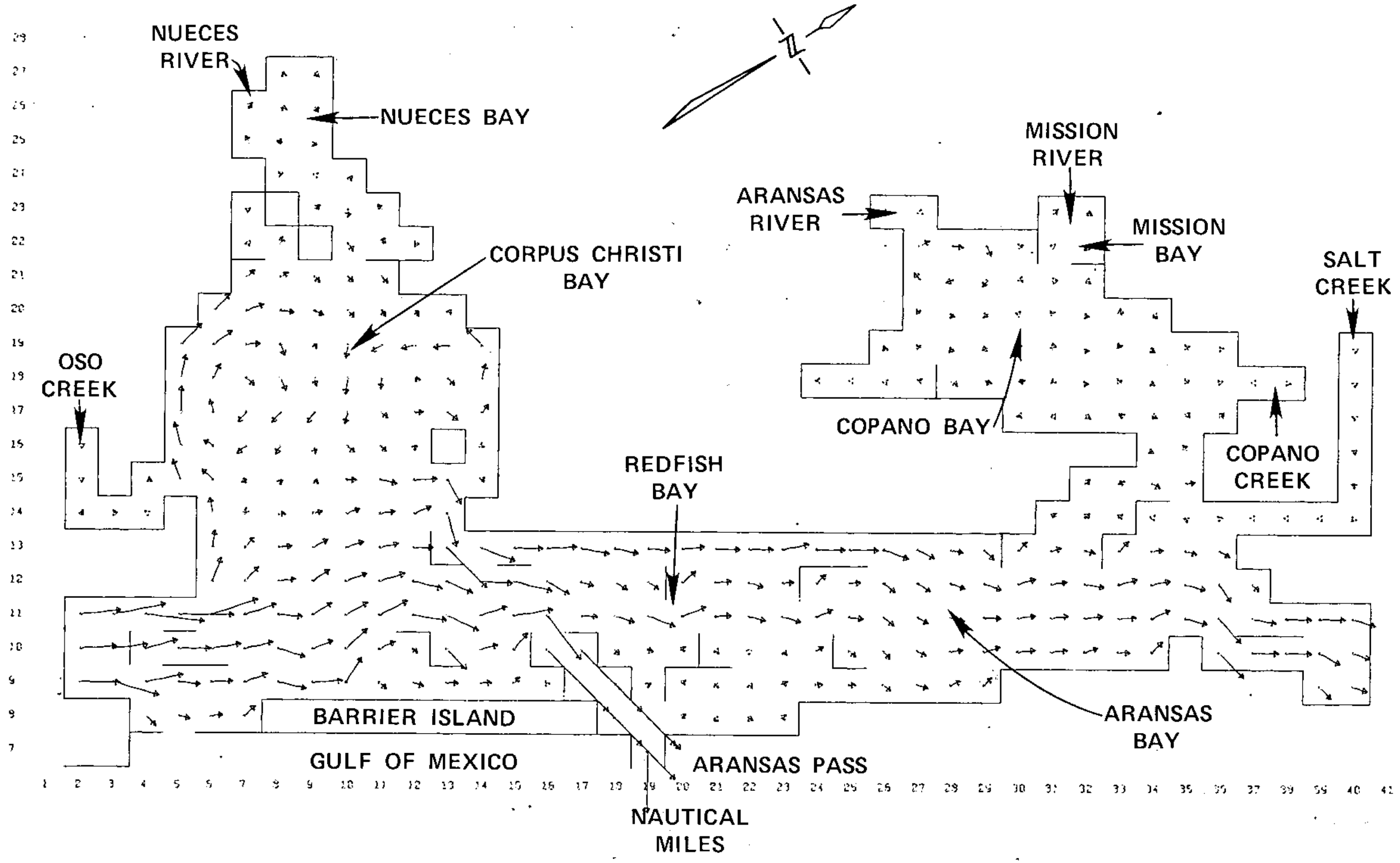

Figure 9-27. Simulated Net Steady-State Flows in the Nueces and Mission-Aransas Estuaries Under August Freshwater Inflow Needs, Alternative I

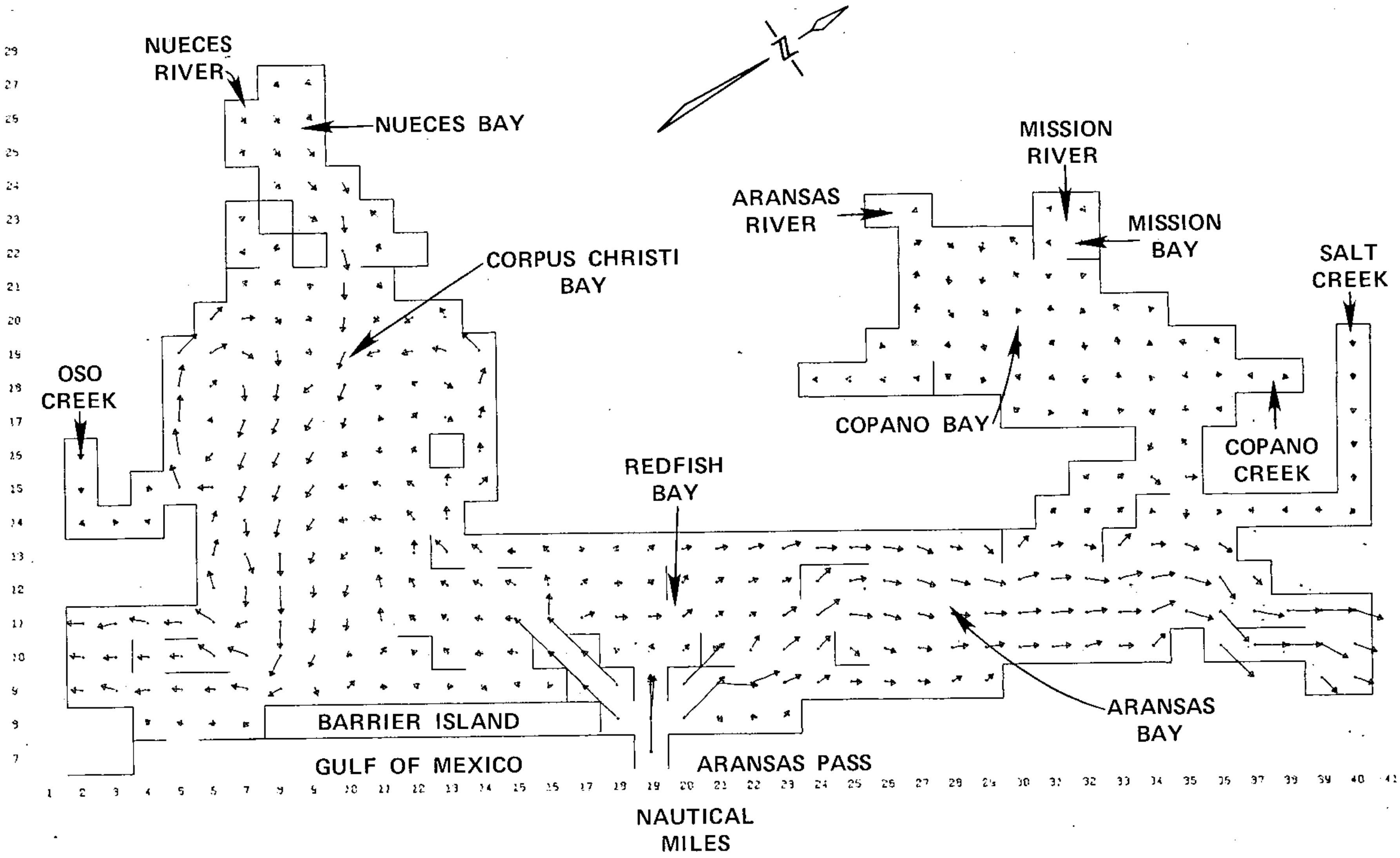

Figure 9-28. Simulated Net Steady-State Flows in the Nueces and Mission-Aransas Estuaries Under September Freshwater Inflow Needs, Alternative I

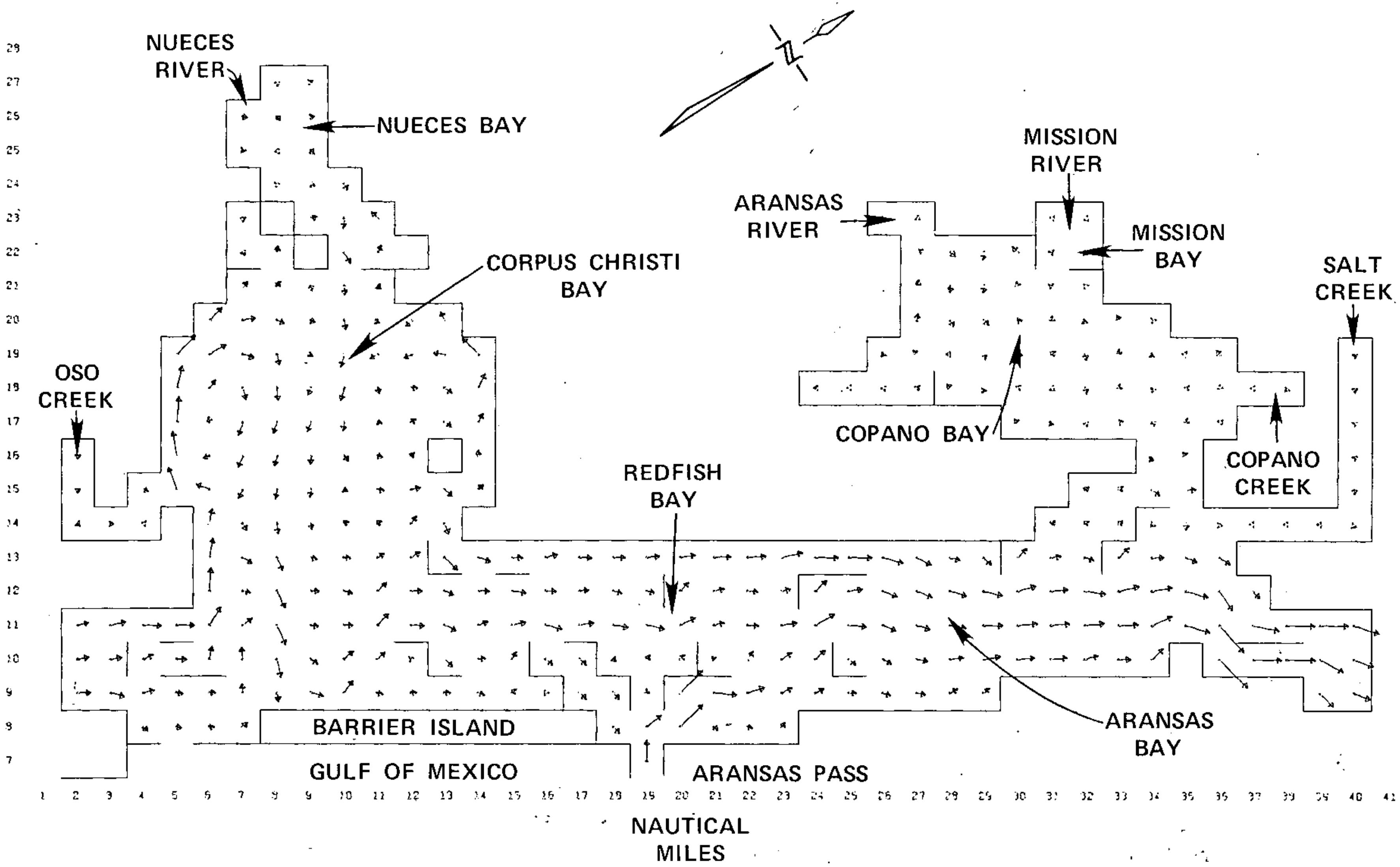

Figure 9-29. Simulated Net Steady-State Flows in the Nueces and Mission-Aransas Estuaries Under October Freshwater Inflow Needs, Alternative I

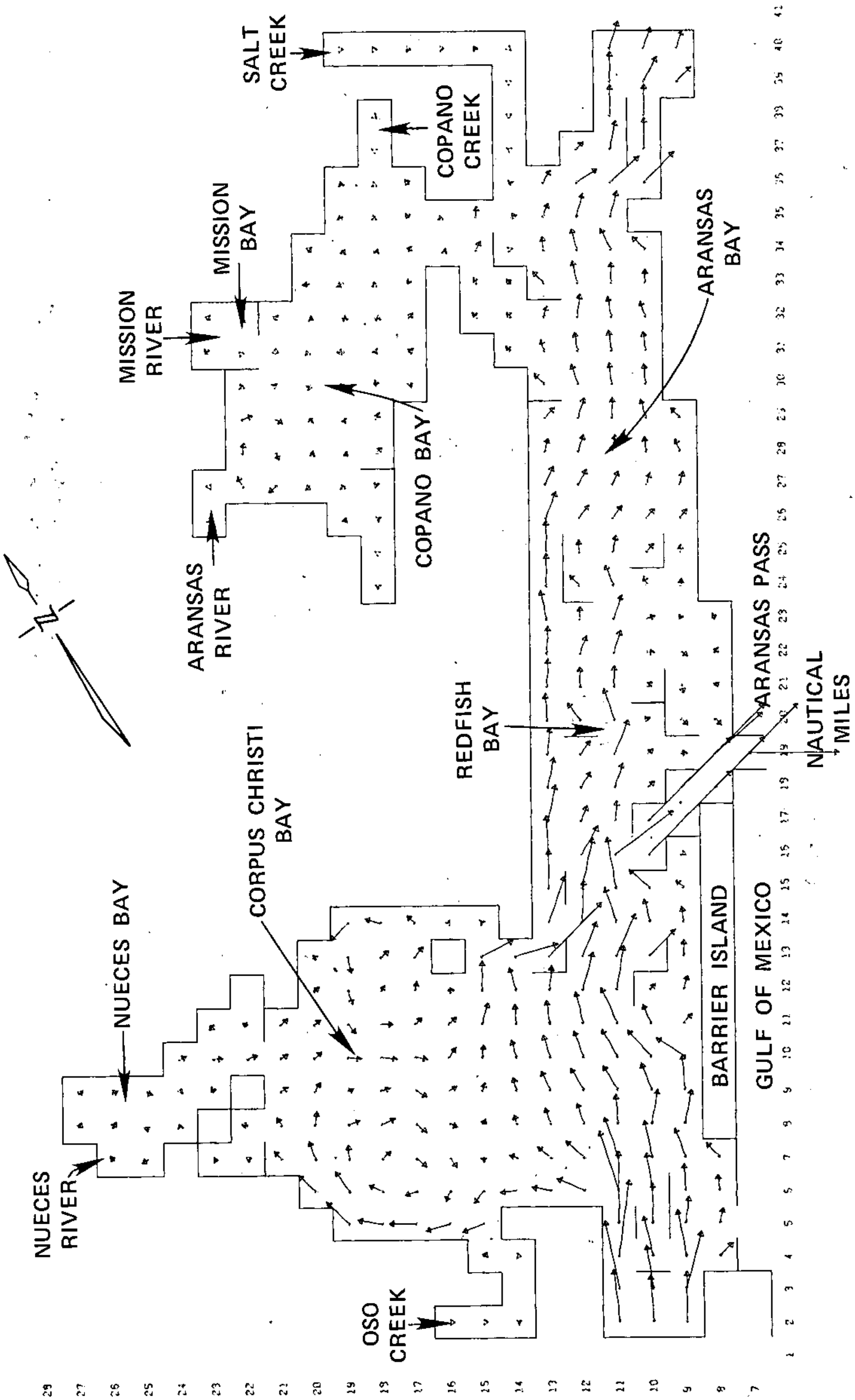

Figure 9-30. Simulated Net Steady-State Flows in the Nueces and Mission-Aransas Estuaries Under November Freshwater Inflow Needs, Alternative I

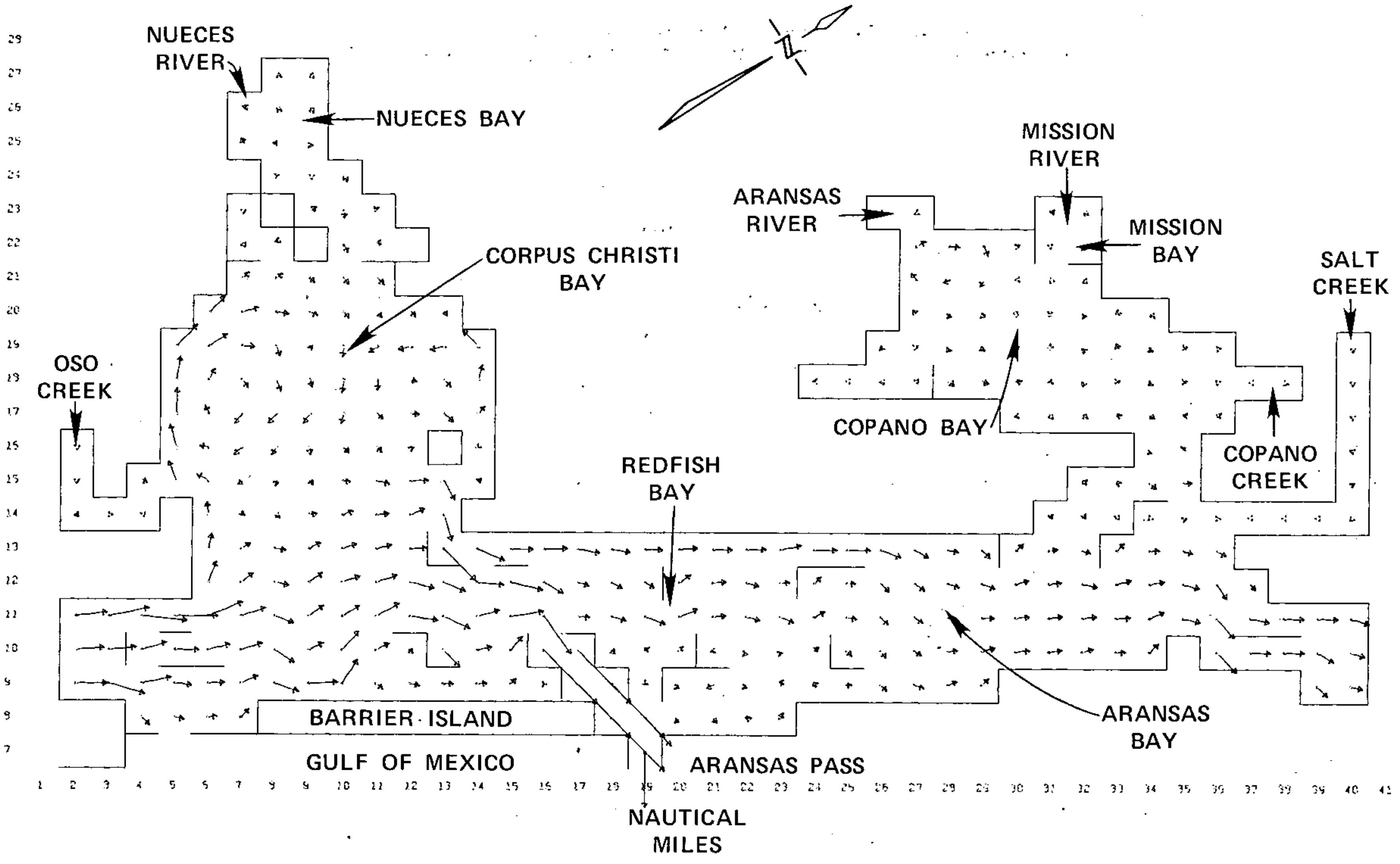

Figure 9-31. Simulated Net Steady-State Flows in the Nueces and Mission-Aransas Estuaries Under December Freshwater Inflow Needs, Alternative I

flows directed into the estuary through Aransas Pass. The simulated monthly flows at the exchange points between the Mission-Aransas and Guadalupe estuaries (Cedar Dugout and the Intracoastal Waterway) are always directed from the Mission-Aransas estuary into Mesquite Bay (the most westerly portion of the Guadalupe estuarine system).

Simulated Salinity Patterns. The hydrodynamic simulations resulting from the monthly inflows of Alternative I were used to provide the basic flow circulation information to execute the salinity transport model. The application of the salinity model was undertaken for each of the Alternative I monthly inflow needs. An evaluation of the simulated monthly salinities in the Nueces and Mission-Aransas estuaries resulting from these model operations reveals a relatively consistent salinity distribution pattern for all of the months (Figures 9-32 through 9-43).

The simulated salinities in the lower portion of Nueces Bay range from 10 ppt to slightly less than 20 ppt. The simulated salinities throughout most of Corpus Christi Bay ranged from a low of 20 to near 25 ppt, increasing to a high of 30 ppt in the area adjacent to Laguna Madre.

Redfish Bay has simulated salinities ranging from near 20 ppt to over 25 ppt in the Aransas Pass area. The simulated salinities in Aransas Bay decreased from approximately 25 ppt in the vicinity of Aransas Bay to near 10 ppt in the extreme northern portion adjacent to Lamar Peninsula. Copano, Mission and Saint Charles Bays have simulated salinities of less than 10 ppt.

In all of the months, the salinities in the middle portion of Corpus Christi Bay are simulated at under 25 ppt; thus, meeting the criterion given previously. Further refinement of the estimated monthly freshwater inflow needs for the three Alternatives is therefore not considered necessary at this time.

Interpretation of the Physical Significance of the Estimated Freshwater Inflow

The monthly freshwater inflow estimated in this report for the Nueces and Mission-Aransas estuaries from the Nueces and Mission 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.

A wide variability of freshwater inflow occurs in Texas estuaries from year to year, through drought and flood cycles. The monthly freshwater inflow levels received by the estuary fluctuate about the average inflow due to natural hydrologic variability. Such fluctuations are expected to continue to exist for practically any average level of inflow that might occur or that might be specified. It is not likely that sufficient control can be exerted to completely regulate the inflow extremes. In fact, to do so may be detrimental to the process of natural selection and other aspects of these vast living systems. However, some provision may be needed to prevent an increase in the frequency of periods of low flows. Such a provision could specify minimum monthly inflows required to keep salinities below the upper viability limits given for key estuarine-dependent species (Tables 9-1 and 9-2).

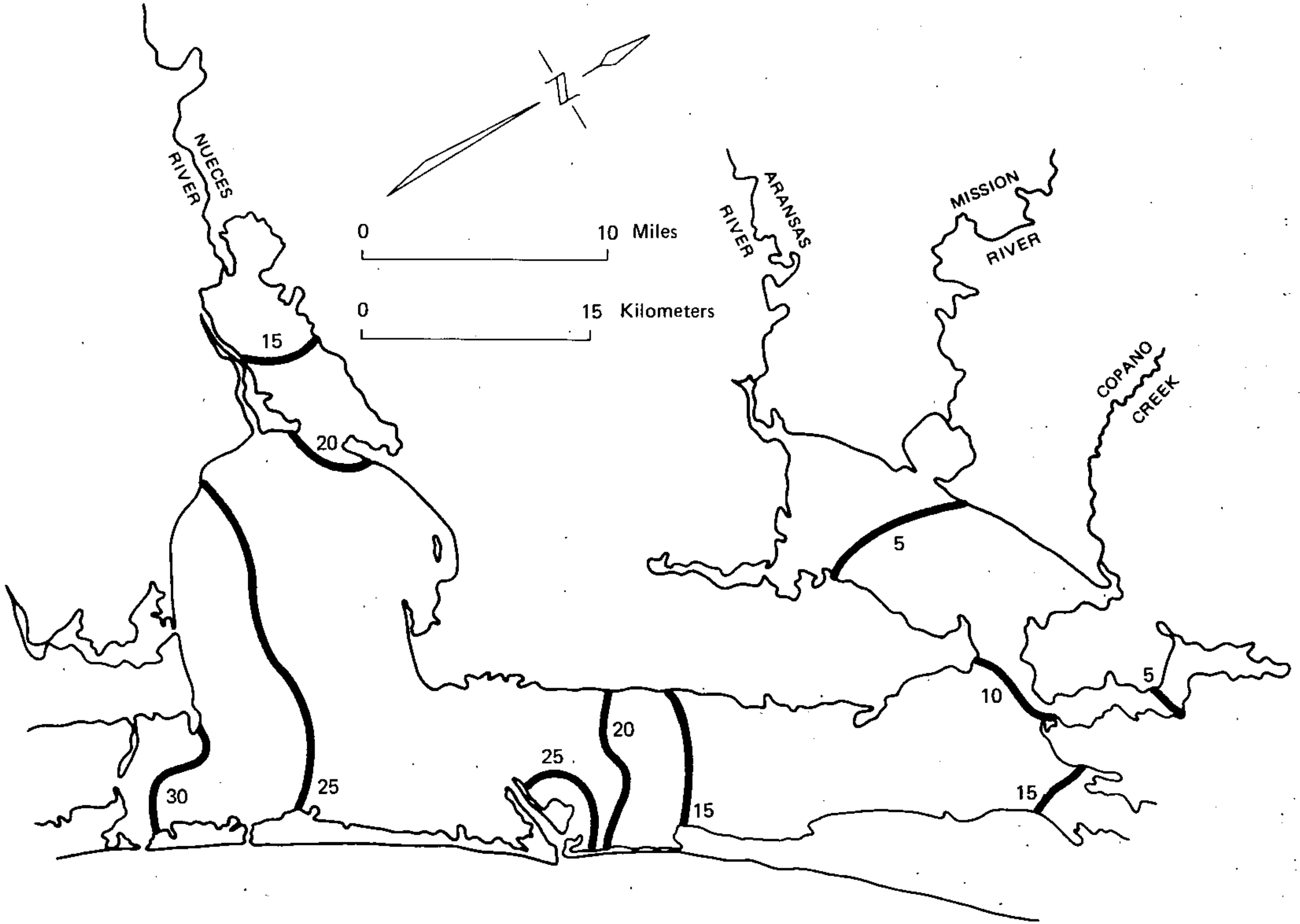

Figure 9-32. Simulated Salinities in Nueces and Mission-Aransas Estuaries Under January Freshwater Inflow Needs, Alternative I (ppt)

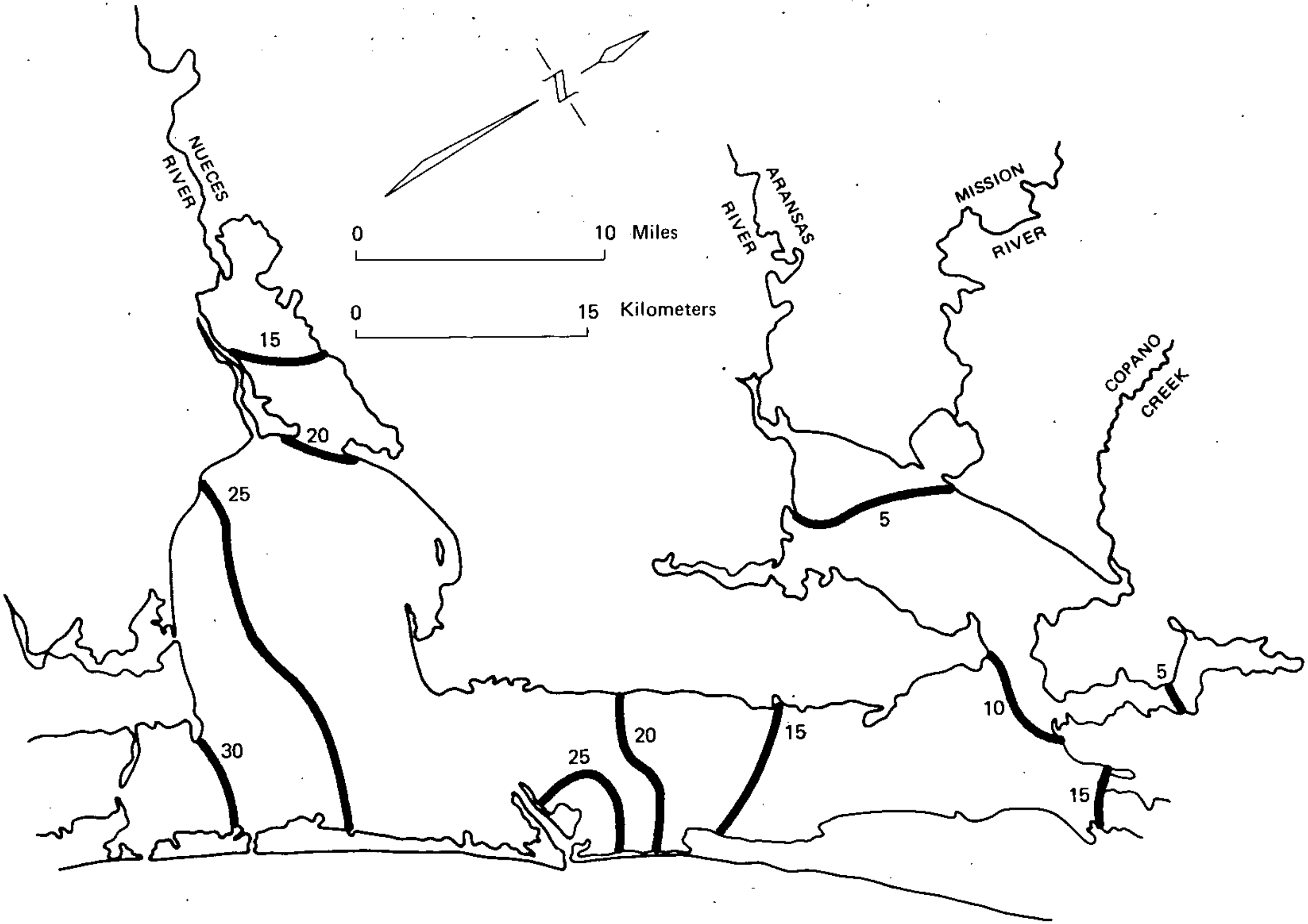

Figure 9-33. Simulated Salinities in the Nueces and Mission-Aransas Estuaries Under February Freshwater Inflow Needs, Alternative I (ppt)

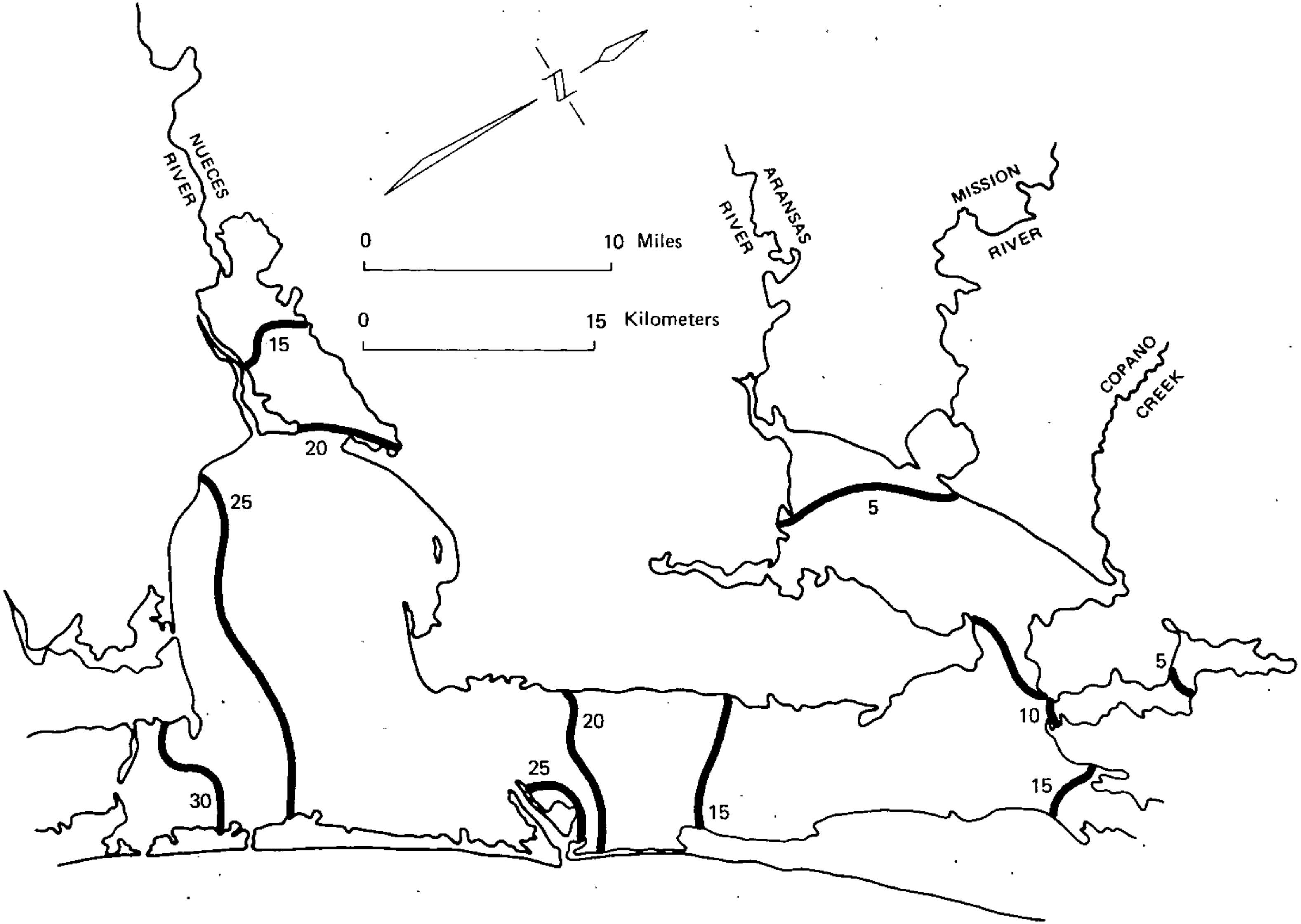

Figure 9-34. Simulated Salinities in the Nueces and Mission-Aransas Estuaries Under March Freshwater Inflow Needs, Alternative I (ppt)

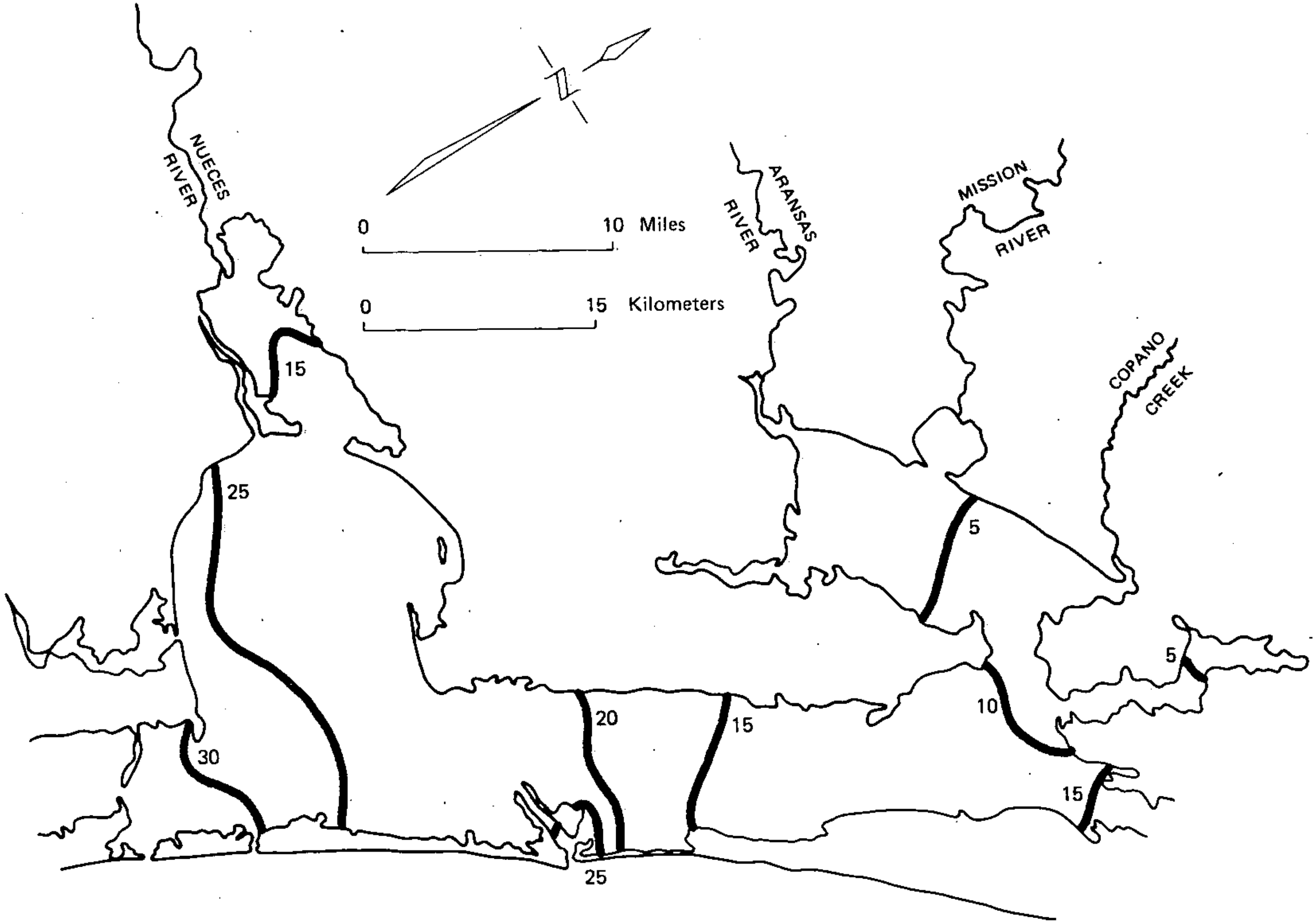

Figure 9-35. Simulated Salinities in the Nueces and Mission-Aransas Estuaries Under April Freshwater Inflow Needs, Alternative I (ppt)

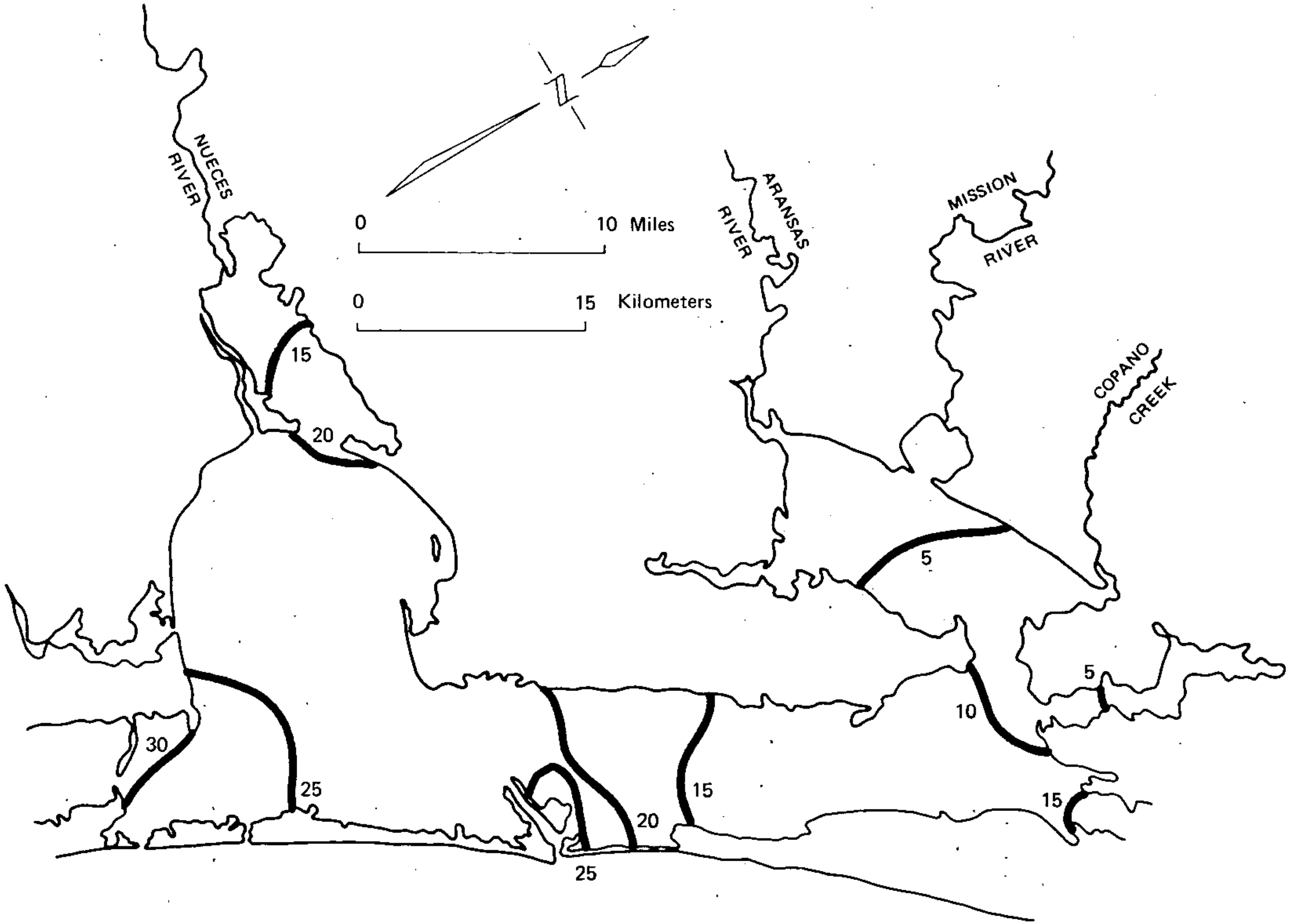

Figure 9-36. Simulated Salinities in the Nueces and Mission-Aransas Estuaries Under May Freshwater Inflow Needs, Alternative I (ppt)

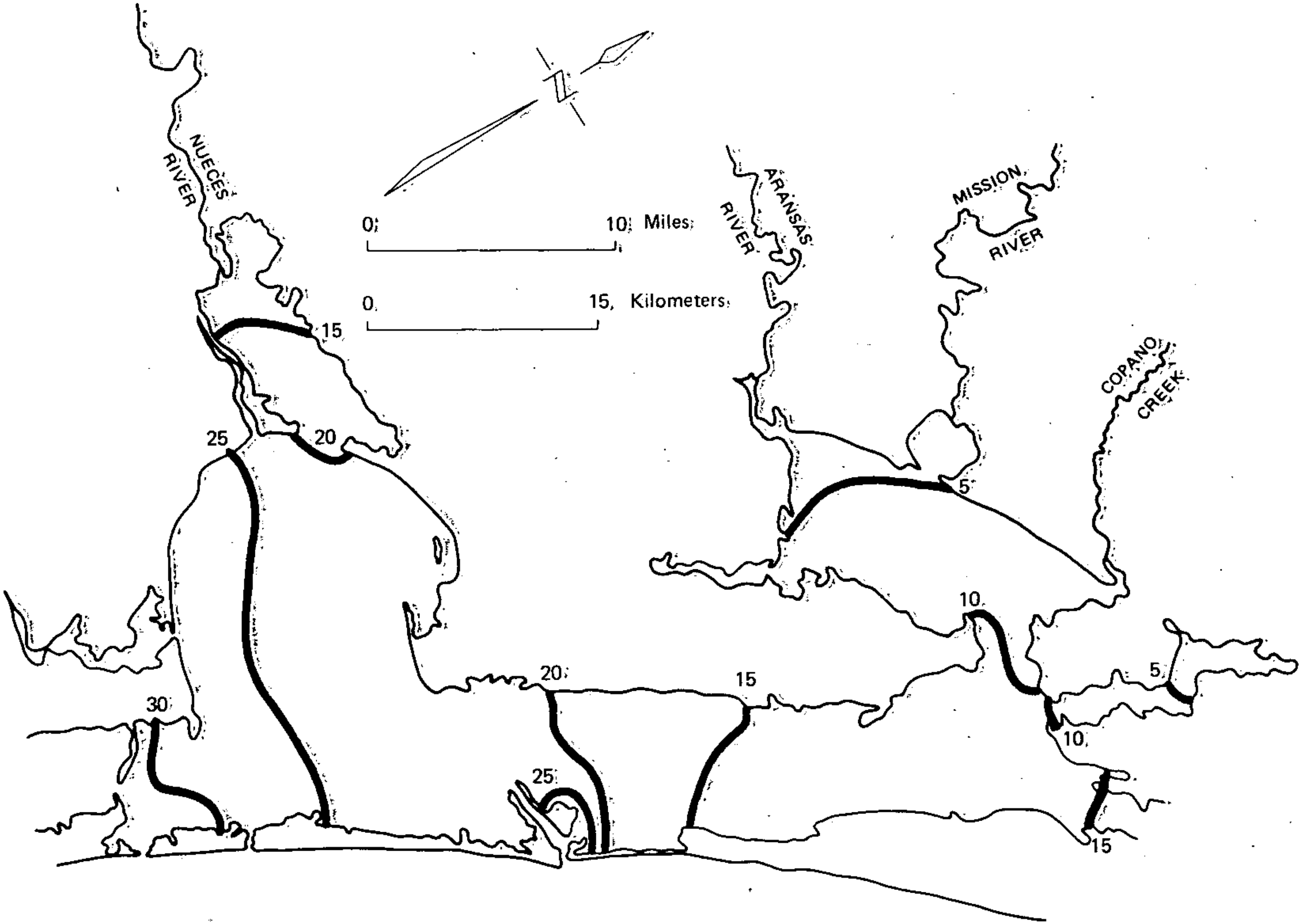

Figure 9-37. Simulated Salinities in the Nueces and Mission-Aransas Estuaries Under June Freshwater Inflow Needs, Alternative I (ppt)

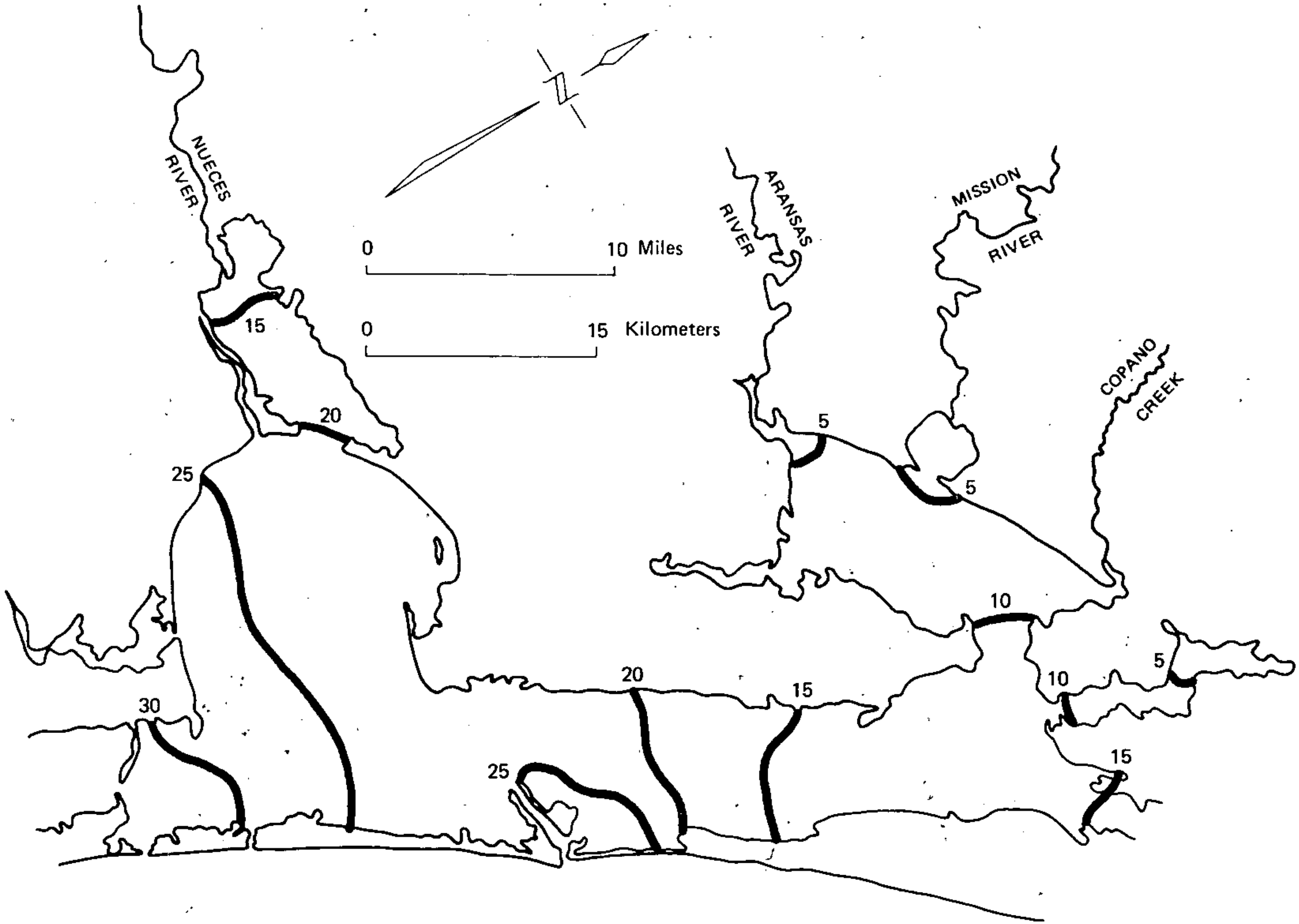

Figure 9-38. Simulated Salinities in the Nueces and Mission-Aransas Estuaries Under July Freshwater Inflow Needs, Alternative I (ppt)

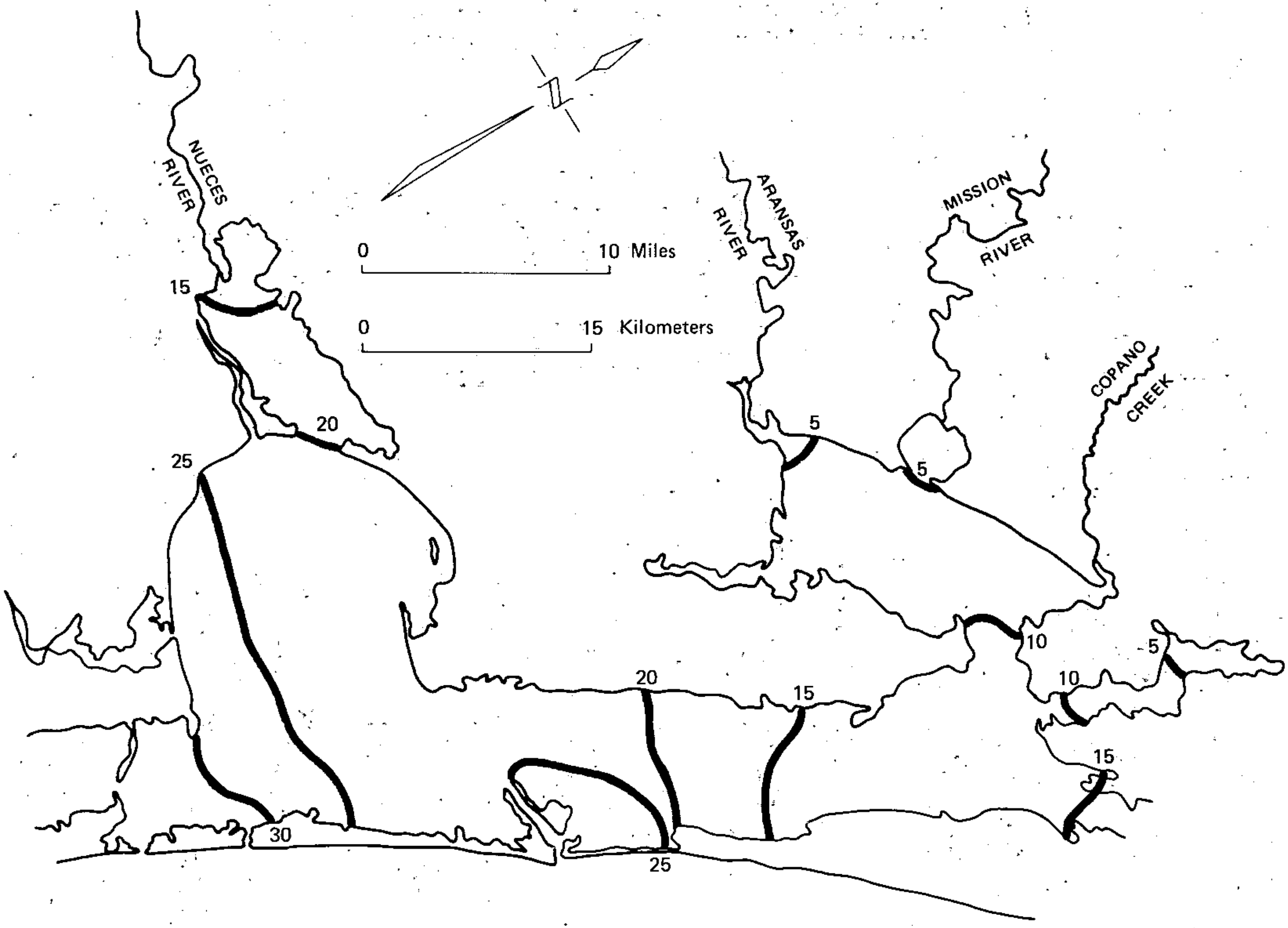

Figure 9-39. Simulated Salinities in the Nueces and Mission-Aransas Estuaries Under August Freshwater Inflow Needs, Alternative I (ppt)

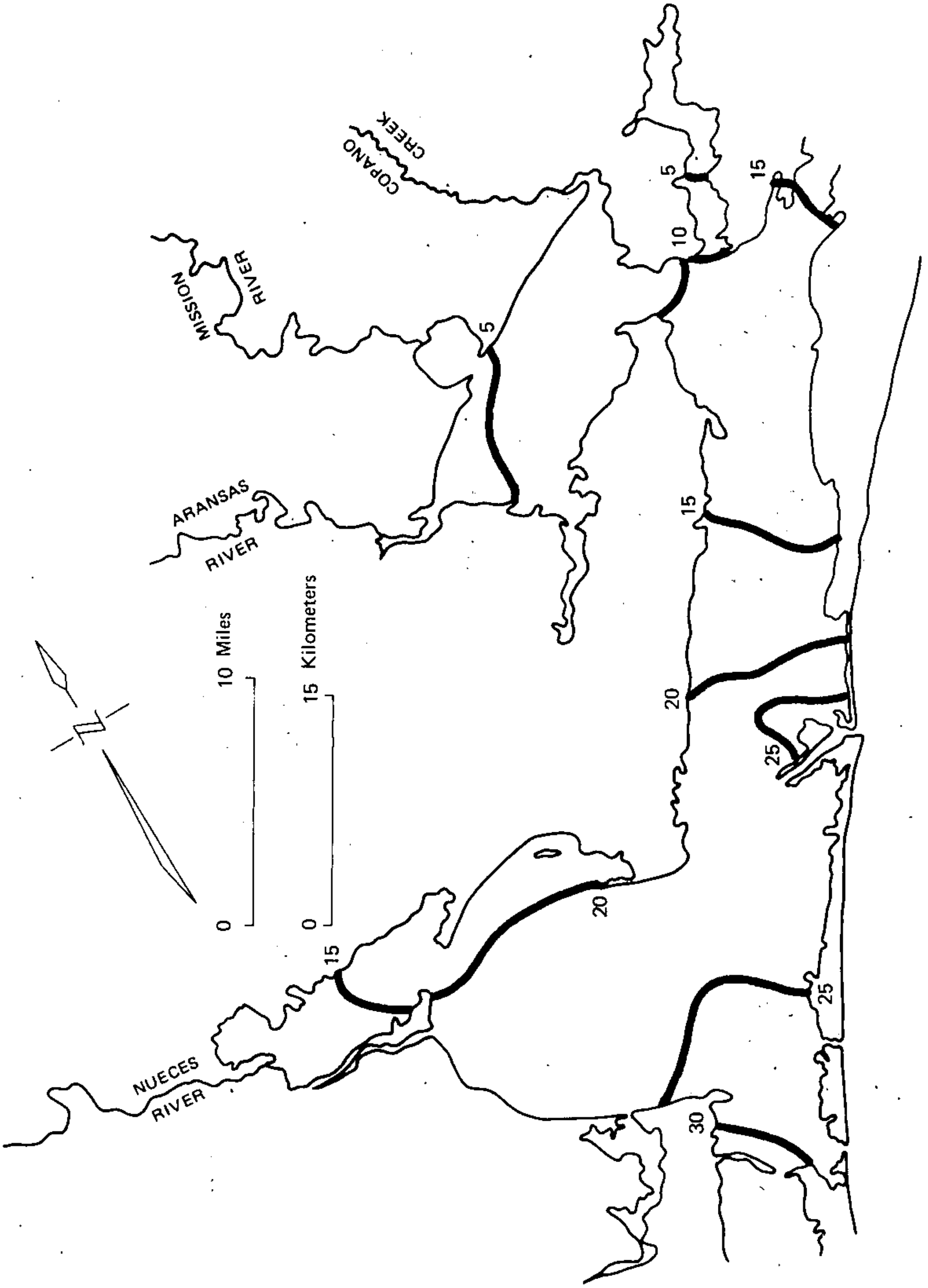

Figure 9-40. Simulated Salinities in the Nueces and Mission-Aransas Estuaries Under September Freshwater Inflow Needs, Alternative I (ppt)

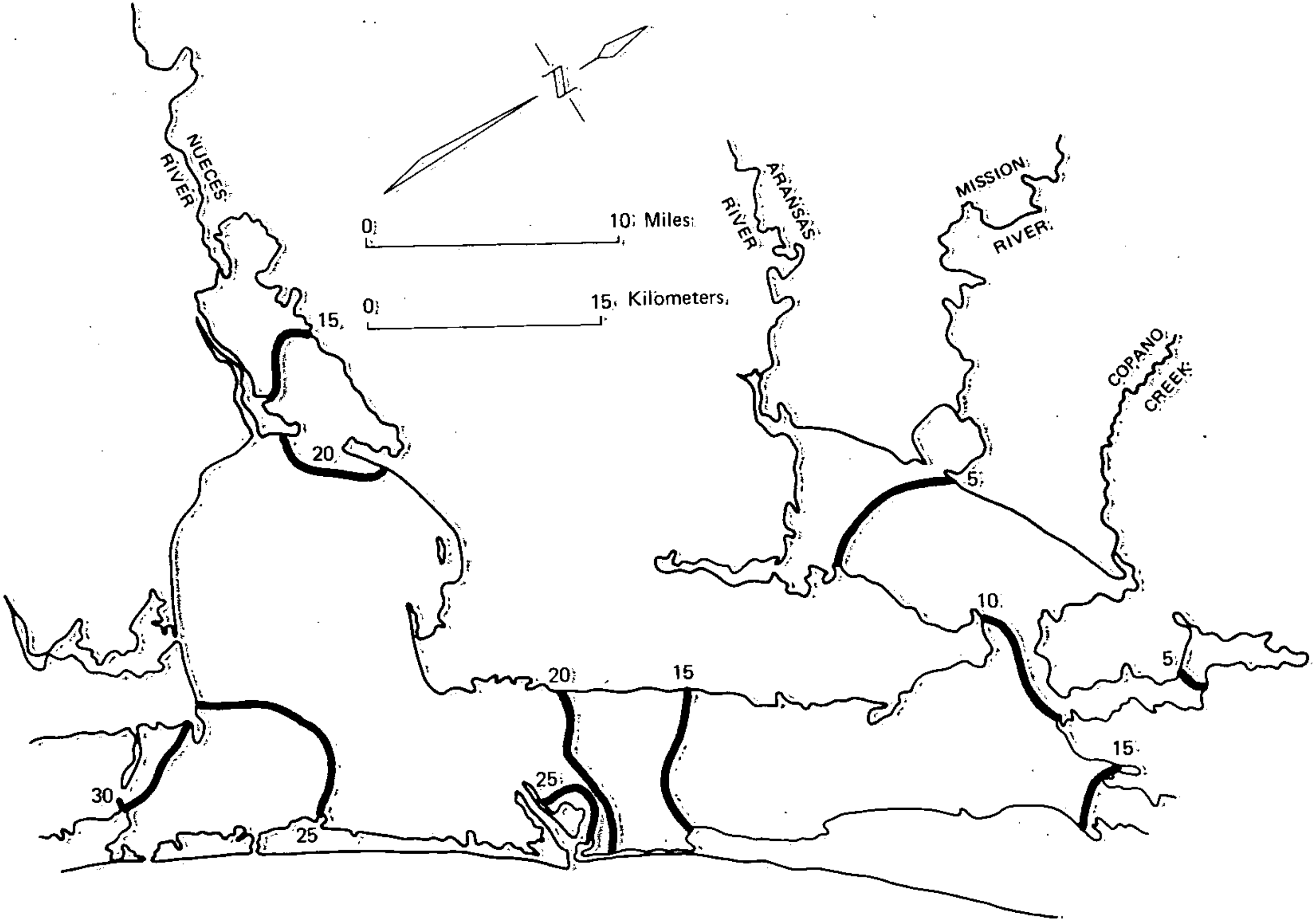

Figure 9-41. Simulated Salinities in the Nueces and Mission-Aransas Estuaries Under October Freshwater Inflow Needs, Alternative I (ppt)

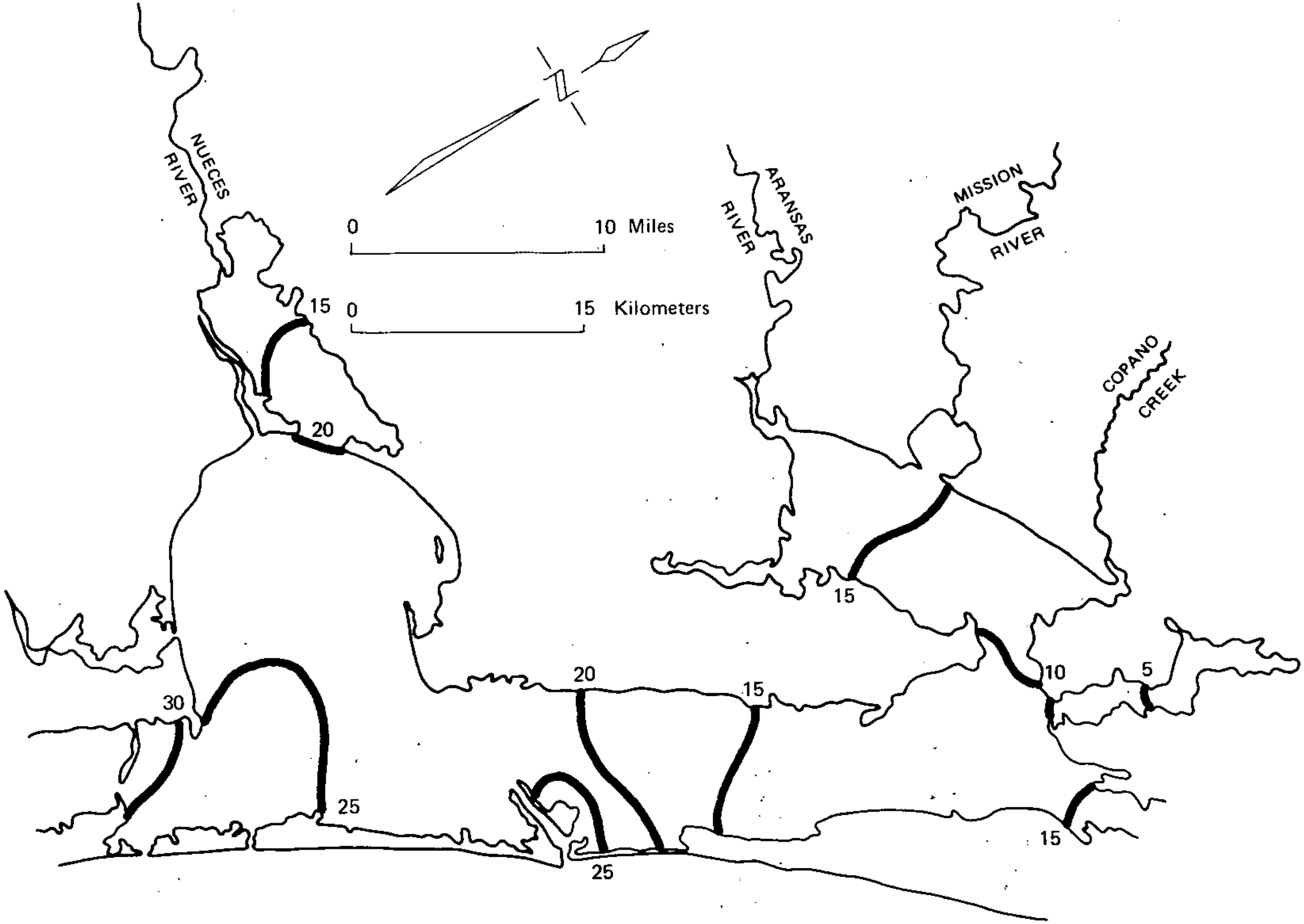

Figure 9-42. Simulated Salinities in the Nueces and Mission-Aransas Estuaries Under November Freshwater Inflow Needs, Alternative I (ppt)

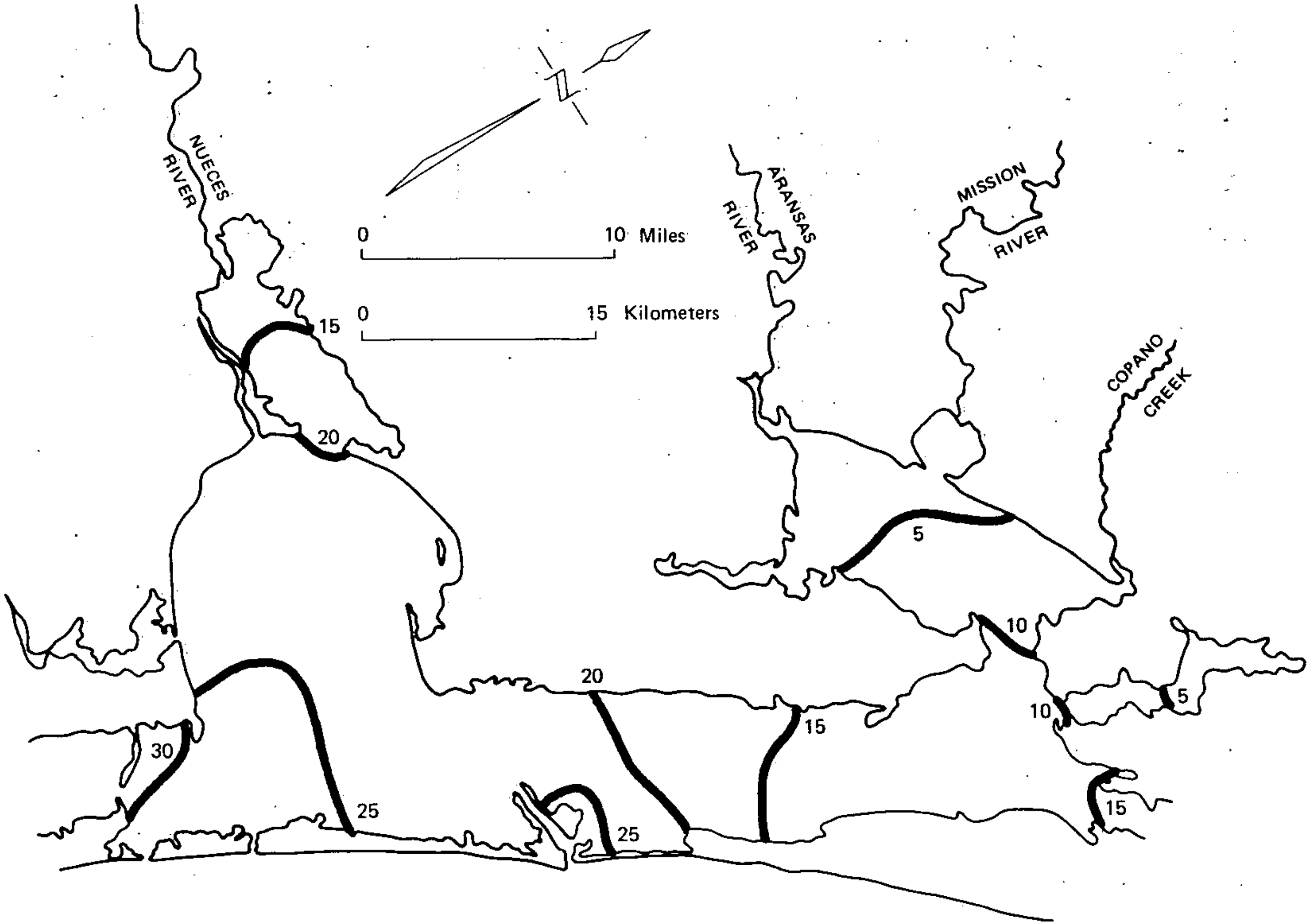

Figure 9-43. Simulated Salinities in the Nueces and Mission-Aransas Estuaries Under December Freshwater Inflow Needs, Alternative I (ppt)

Summary

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

Monthly salinity limits are established at locations in these estuaries below the "Null Zone" near the inflow points of the Nueces and Mission River Basins. These upper and lower limits on monthly salinity provide a range within which viable metabolic activity can be maintained and normal historical salinity conditions are observed.

Marsh inundation needs, for the flushing of nutrients from riverine marshes into the open bays, are computed and specified for the Nueces River delta. The Mission-Aransas River delta is limited in areal extent and far smaller than the Nueces delta. As a result, no inflow requirements for inundation of the Mission-Aransas River delta are specified from the Mission-Aransas River Basin. The Nueces River delta is frequently submerged by floods from the Nueces River. Based upon historical conditions and gaged streamflow records, freshwater inflow needs for marsh inundation are estimated at 79.0 thousand acre-feet (98 million m^3) and 139.0 thousand acre-feet (172 million m^3) in the months of May and September, respectively. These volumes correspond to flood events with peak daily flow rates of 8,500 ft^3/sec (241 m^3/sec) and 11,000 ft^3/sec (312 m^3/sec), respectively.

Estimates of the freshwater inflow needs for the Nueces and Mission-Aransas estuaries 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 Nueces and Mission-Aransas River basins which best achieve a specified objective.

The monthly freshwater inflow needs for the Nueces and Mission-Aransas estuaries were estimated for each of three alternatives.

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

Alternative II (Maintenance of Fisheries Harvests): minimization of annual combined inflow to both estuaries while providing freshwater inflow sufficient to give predicted annual commercial bay harvests of red drum, seatrout, white shrimp, and blue crab at levels no less than their mean historical 1962 through 1976 values, satisfying marsh inundation needs, and meeting viability limits for salinity; and

Alternative III (Finfish Harvest Enhancement): maximization of the total annual bay commercial harvest of all finfish while meeting salinity limits, satisfying marsh inundation needs, and utilizing annual combined inflows to each estuary at levels no greater than their individual average annual historical inflows over the 1941 through 1976 period.

Under Alternative I (Subsistence), the Nueces and Mission-Aransas system, which has functioned as both a commercial shellfish and finfish producing system in the past, can continue to be important fisheries producing estuaries with substantially less freshwater inflow. Freshwater inflows totaling 0.69 million acre-feet (850 million m^3) annually are predicted to satisfy the basic salinity gradient and marsh inundation needs, with a resulting predicted increase in commercial shellfish bay harvests of 30 percent and a one percent decrease in finfish bay harvests from average annual harvests for the period 1962 through 1976.

Under Alternative II (Maintenance of Fisheries Harvests), the predicted annual commercial bay harvests of red drum, spotted seatrout, white shrimp, and blue crab are required to be at least as great as their historical 1962 through 1976 average levels. The marsh inundation needs and salinity limits must also be satisfied. To satisfy these criteria, a total annual freshwater inflow of 0.75 million acre-feet (920 million m^3) is needed.

Under Alternative III (Finfish Harvest Enhancement), the Nueces and Mission-Aransas estuaries combined annual freshwater inflow needs were limited to the average annual inflow of 1.009 million acre-feet (1,243 million m^3), distributed in a seasonally unique manner, to achieve the objective of maximizing the total annual predicted commercial bay harvest of finfish. This objective is achieved, using all of the allowed 1941 through 1962 average freshwater inflow, with a predicted 91 percent increase in the annual finfish bay harvest, above average historic 1962 through 1976 levels, and an estimated gain of 64 percent in total commercial shellfish harvest (including a predicted 65 percent increase in the commercial harvest of blue crab).

The numerical tidal hydrodynamic and salinity mass transport models were applied to the Nueces and Mission-Aransas estuaries 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.

The net circulation patterns simulated by the tidal hydrodynamic model indicate that the dominant net circulation pattern in the Nueces and Mission-Aransas estuaries is a net movement of water from Laguna Madre through Corpus Christi, Redfish, Aransas and Carlos Bays and into the Guadalupe estuary. Simulated net flows in Copano and Nueces Bays are governed by internal circulation currents rather than by circulation patterns in adjacent bay systems.

Simulated steady-state, monthly salinities for the set of monthly inflows specified under Alternative I indicate similar patterns in these estuaries over all months. Average simulated salinities in Corpus Christi Bay are less than 25 parts per thousand (ppt) except near the entrance to Laguna Madre and Aransas Pass. The simulated mean salinities for Saint Charles and Copano Bays are less than 10 ppt. Salinities simulated for Nueces Bay are under 20 ppt, with salinities near 15 ppt in the middle portion of the bay. In Redfish and Aransas Bays, simulated salinities average over 20 ppt in the former and between 10 and 15 ppt in the latter bay.

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

Since the middle portion of Corpus Christi 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 that objective, throughout the estuary.

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

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

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APPENDIX

List of Persons Receiving the Draft Report

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Executive Director	Texas Coastal and Marine Council, Austin
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John Poerner	Railroad Commission of Texas, Austin
Edward Vetter	Texas Energy and Natural Resources Council, Austin
Mark White	Attorney General of Texas, Austin
Mit Spears	Governor's Budget and Planning Office, Austin
A. R. Schwartz	Texas Senate, Galveston
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
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Murray Walton	Wildlife Management Institute, Dripping Springs
Donald Moore	National Marine Fisheries Service, Galveston
Stuart Henry	Sierra Club, Austin
Robert E. Smith	U. S. Geological Survey, Houston
Ralph Rayburn	Texas Shrimp Association, Austin

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Adlene Harrison	Environmental Protection Agency, Dallas
Glade Woods*	National Oceanigraphic and Atmospheric Administration, Bay St. Louis, Mississippi
Carl Oppenheimer*	University of Texas Marine Science Institute, Port Aransas
Carlos Truan	Texas Senate, Corpus Christi
Vito Blomo*	Gulf of Mexico Fishery Management Council, Tampa, Florida

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* Indicates a letter was received from the named individual--or his (her) respective agency--in reply to the Texas Department of Water Resources' request for comments on the draft report.