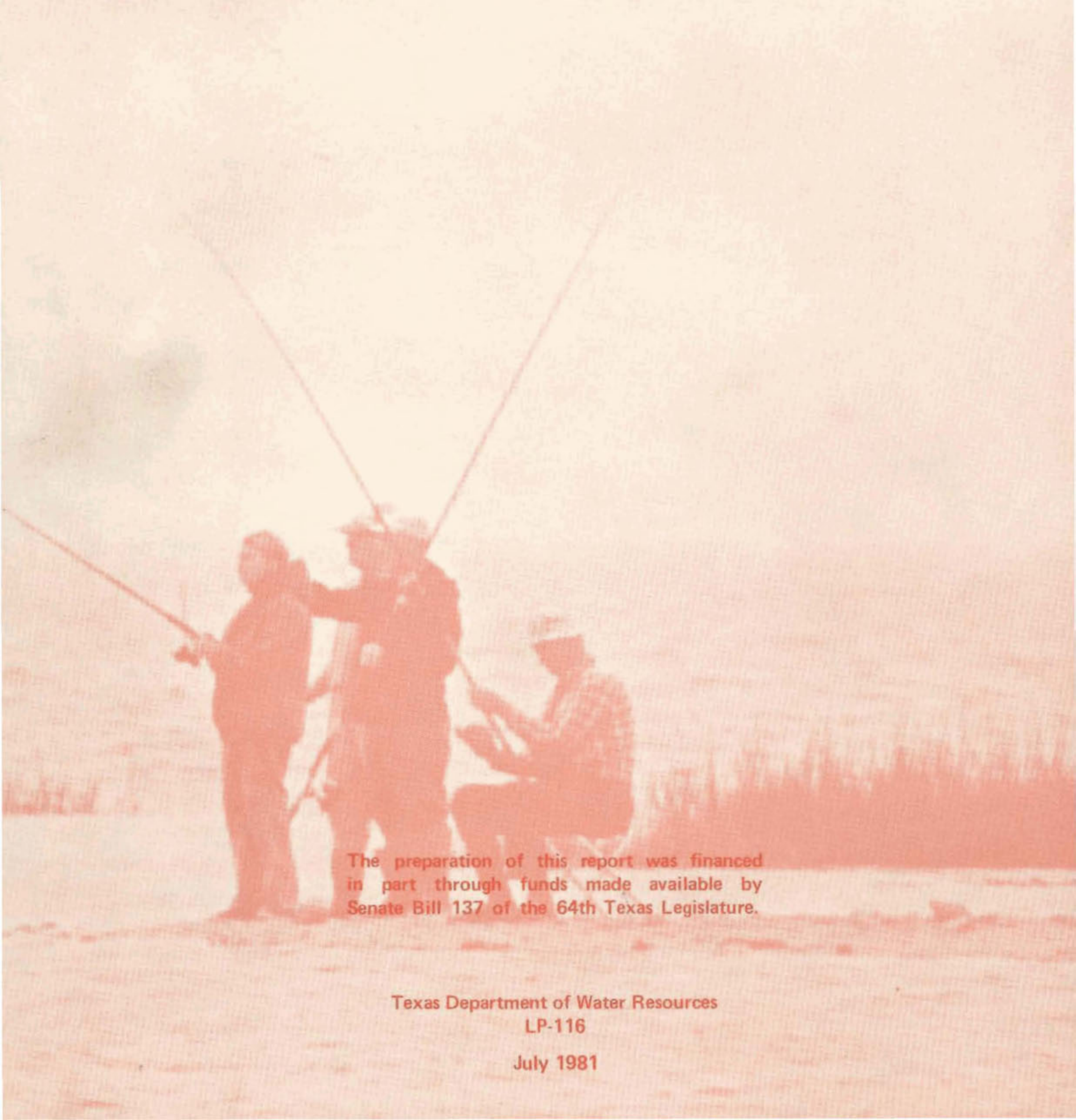
SABINE-NECHES ESTUARY:
A Study of the Influence of Freshwater Inflows



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Texas Department of Water Resources

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July 1981

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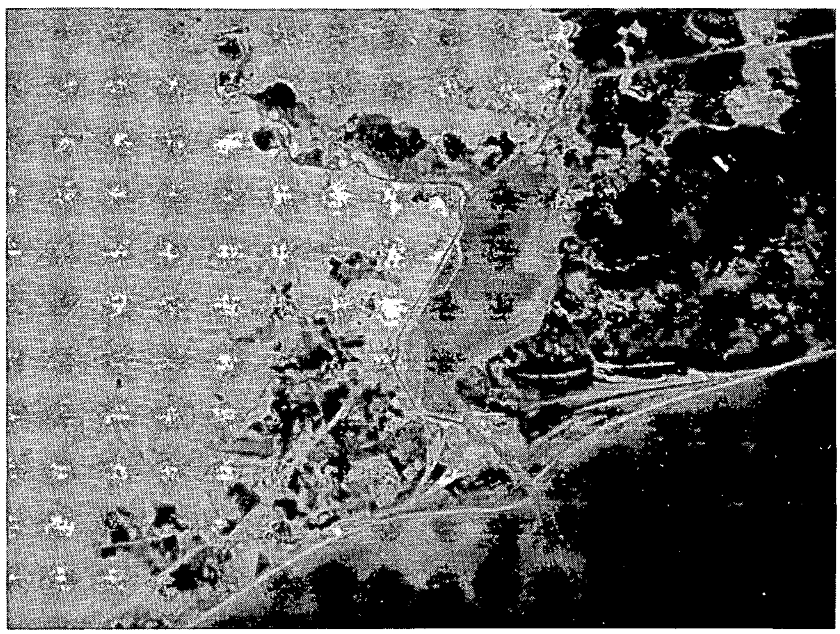

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TEXAS DEPARTMENT OF WATER RESOURCES

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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 inflows 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, as well as a contributor to the near-shore fisheries productivity of the Gulf of Mexico. This report analyzes the interrelationships between freshwater inflows and estuarine productivity, and establishes the seasonal and monthly freshwater inflow needs, for a range of alternative management policies, for the Sabine-Neches estuary of Texas.

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

Description of the Estuary and the Surrounding Area

The Sabine-Neches estuary covers about 100 square miles (259 km^2) and includes Sabine Lake, the Sabine-Neches and Port Arthur Canals, and Sabine Pass. Basins contributing inflow to the estuary include the entire Sabine and Neches Basins and part of the Neches-Trinity Coastal Basin.

Neither the Sabine nor the Neches River forms a characteristic deltaic alluvial fan at its mouth. However, marsh areas normally associated with delta plains are found in the lower parts of the coastal areas and river valleys near the estuary. Most of the shoreline areas associated with the Sabine-Neches estuary are either balanced between erosion and deposition or have been stabilized by man.

Land use in the Golden Triangle (Beaumont, Orange, and Port Arthur) is mostly urban and industrial. Agricultural use includes irrigated and dryland crops, primarily soybeans, and ranching activities.

The Sabine-Neches estuary contributes a relatively small harvest to the Texas commercial fishing industry and ranks last overall of eight Texas estuarine systems in the production of estuarine-dependent fisheries species. The annual commercial bay harvest of finfish and shellfish in this estuary has averaged 947,100 pounds (429,600 kg; 97.9 percent shellfish) during the 1962 through 1976 interval. However, a large portion of each estuary's production of fish and shellfish is caught in the Gulf by commercial and sport fishermen. When these harvests are considered, the total contribution of the estuary to the Texas coastal fisheries (all species) is estimated at 4.8 million pounds (2.2 million kg; 85.2 percent shellfish) annually for a recent five year period (1972-1976). Penaeid shrimp and blue crab catches dominate the shellfish harvests.

Total economic impact of the estuary's commercial fish and shellfish harvests on the State is estimated at $18.7 million per year, using an input-output analysis and 1976 dollar values. Similarly, the estuary's total sport and recreational fishing impact on Texas is estimated at $2.0 million annually.

Hydrology

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

Freshwater inflows in terms of annual and monthly average values over the 1941 to 1976 period varied widely from the mean as a result of recurrent drought and flood conditions. On the average, total freshwater inflow (excluding direct precipitation) to the estuary from 1941 through 1976 is computed at approximately 13.0 million acre-feet (16.03 billion m^3) per year, of which an estimated 11.18 million acre-feet (13.78 billion m^3) were contributed from gaged drainage areas of the Sabine and Neches River Basins.

In general, the water quality of gaged inflows to the estuary from the Sabine-Neches estuary has been very good. No parameters were found in violation of Texas stream standards. Studies of past water quality in and around the estuary have noted the occurrence of heavy metals in sediment samples. Locally, bottom sediment samples from the Sabine-Neches estuary have exceeded the U. S. Environmental Protection Agency criteria for metals in sediment (prior to dredging) for arsenic, cadmium, copper, lead and zinc. Bottom sediments collected and analyzed for herbicides and pesticides showed only heptaclor and heptaclor expoxide occurring in local areas in concentrations equal to or greater than the analytical detection limit during the period 1969, and 1974 through 1978.

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, biological, and chemical 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 Sabine-Neches estuary.

Statistical analyses were undertaken to quantify the relationship between the combined freshwater inflows from the Sabine and Neches Rivers and salinities in upper Sabine Lake. Utilizing gaged daily river flows in the Sabine and Neches Rivers and observed salinities, a set of monthly predictive salinity equations were derived by regression analyses for a point in the upper estuary two miles south of the Sabine-Neches Canal. These equations predict the mean monthly salinity as a function of the mean monthly gaged freshwater inflow rate.

Nutrient Processes

The interdelta wetlands are important sources of nutrients for the estuarine system. Periodic inundation events are natural and necessary in order for the marshes of the Sabine Lake system to deliver their potential nutritive materials (e.g., plant detritus) to the open waters of the estuary. This will occur as freshwater moving across the wetlands sweeps decayed organic material out into the estuary. After the initial pulse of material is flushed out, nutrient release rates decrease rapidly until they reach seasonal equilibrium. Pulses of increased freshwater discharge and the resulting marsh inundation appear to be important mechanisms contributing to increased marsh production and nutrient transport from those marshes to the estuary.

Aerial photographic studies of key coastal wetlands in the Sabine-Neches estuary provided baseline characterization of the marsh vegetative communities and insight into on-going wetland processes. Overall, except for the Sea Rim State Park area, the coastal marshes in the Sabine Pass area are being rapidly diminished due to increased urbanization and industrialization. This area is dominated by such man-made features as the Gulf Intracoastal Waterway, Port Arthur Canal, the Sabine Pass jetties, roads, drainage canals, drilling rigs and pipelines. Besides the industrial scars, this area is also marked by the patchwork appearance of pastures periodically burned off in the expectation of encouraging short-term growth of pasturage. The Keith Lake Water Exchange Pass was reestablished in 1977 to restore connection with the estuary and allow migration of juvenile fish and shellfish to and from the associated marsh "nursery" areas. 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 in regard to water development, power development, navigational facilities, oil and gas production, and expansion of agricultural and cattle-raising activities in the coastal zone.

Primary and Secondary Production

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

Sabine Lake phytoplankton populations observed during recent studies were low in comparison to values reported for other estuarine areas of Texas. No significant relationships between flow rate and phytoplankton density were demonstrated from the available data. An unusually low nitrogen to phosphorus ratio of only 4:1 strongly suggests that nitrogen is more likely to limit phytoplankton growth in the Sabine-Neches estuary than phosphorus.

Zooplankton populations in Sabine Lake experienced greater seasonal fluctuations than did phytoplankton. Mean monthly densities showed tremendous variation—up to two orders of magnitude—over short periods of time. Results of analyses indicate that zooplankton populations in Sabine Lake are probably reduced at high flow rates due to the joint effects of flushing losses and decreases in salinity.

A total of 50 benthic species representing six phyla were collected from Sabine Lake. The lowest average standing crops were recorded at the stations farthest removed from either the mouth of the Sabine River or from Sabine Pass. Although this perhaps is indicative of some dependence of benthic populations on river and/or Gulf exchange, no statistical relationships were found between total standing crop (or species numbers) and either salinity or river flow.

In Texas estuaries, 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-chemical requirements for that particular assemblage are met. If freshwater inflow is decreased, either partially or totally, the community composition will generally shift toward the marine forms.

Fisheries

Virtually all of the Gulf fisheries species are estuarine-dependent. Commercial inshore harvests (1962-1976) from bays of the Sabine-Neches estuary rank fifth in shellfish and eighth in finfish of eight major Texas estuarine areas. In addition, the sport or recreational finfish harvest far exceeds the commercial finfish harvest in the estuary. For the 1972 through 1976 interval, the average annual sport and commercial harvest of fish and shellfish dependent upon the Sabine-Neches estuary is estimated at 4.8 million pounds (2.2 million kg; 85.2 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 can be useful 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 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 multiple regression analysis was undertaken for the 1962 through 1976 time series of annual commercial harvests and their associated seasonal freshwater inflows to the Sabine-Neches estuary. However, the analysis is not considered entirely successful because the data and analysis suffer from several problems: (1) the time-series data bases of most fisheries species in the Sabine-Neches estuary are discontinuous and contain few observations, (2) fisheries harvest levels are relatively low in the estuary, and (3) the harvest data may not be an adequate relative measure of the absolute shifts in fisheries abundance from year to year since the ecosystem appears ecologically stressed, exhibits low biomass production in most trophic (nutritional) compartments of the foodweb, and its fisheries resources are shared with Louisiana. As a result of these difficulties, probable spurious relationships appear in the analysis (e.g., the positive response of fisheries harvests to increasing summer inflow). Sabine Lake fisheries harvest responses computed in the analysis are predominantly negative to spring (April-June) and autumn (September-October) inflows, and positive to winter (January-March), summer (July-August), and late fall (November-December) inflows. However, as mentioned before, these results are of questionable predictive value.

On the other hand, successful application of the analytical techniques to the 1959 through 1976 time-series of harvests from the Texas offshore shrimp fishery produced three statistically significant multiple regression equations. The best significant equation is highly significant and explains 70 percent of annual variance in combined shrimp harvests as a function of fishing effort and seasonal freshwater inflows to five major Texas estuaries (i.e., Trinity-San Jacinto, Lavaca-Tres Palacios, Guadalupe, Mission-Aransas, and Nueces estuaries) from their contributing river and coastal drainage basins. The equational harvest models for white, brown, and pink shrimp provide numerical estimates of the effects of fishing effort and variable seasonal inflows on commercial offshore harvests of these estuarine-dependent penaeid shrimp species. They also support existing scientific information on the seasonal importance of freshwater inflow to the estuaries. In this case, offshore shrimp harvests are computed to relate positively to fishing effort (trips per year) and spring (April-June) inflow, and negatively to winter (January-March), summer (July-August), and autumn (September-October) inflows.

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 estuaries to be viable and productive because there are no guarantees for estuarine productivity based on inflow alone, since many other biotic and abiotic factors are capable of influencing this production. However, most of these other factors are largely beyond human control, whereas man's activities can restrict freshwater inflows or alter its seasonal regime to the detriment of fish and wildlife resources.

Estimated Freshwater Inflow Needs

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

Monthly mean salinity bounds were established at a location in the estuary near the inflow points of the Sabine and Neches 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 historical salinity conditions.

Marsh inundation needs, for the flushing of nutrients from riverine marshes into the open bays were computed and specified for the Sabine-Neches interdelta. The interdelta areas are frequently submerged by floods from the Sabine and Neches Rivers. Based upon historical conditions and gaged streamflow records, freshwater inflow for marsh inundation needed to sustain historical inundation magnitude and annual frequency were estimated and specified for the Sabine River near Ruliff at 802.0 thousand acre-feet (989 million m^3) in May and October and 480.3 thousand acre-feet (592 million m^3) in April, May and October for the Neches River at Evadale. These volumes correspond to flood events with peak flow rates of 28,000 ft^3/sec (792 m^3/sec) and 18,000 ft^3/sec (510 m^3/sec), respectively.

Evaluation of Estuarine Alternatives

Estimates of the freshwater inflow needs for the Sabine-Neches estuary were to be computed by representing the interactions among freshwater inflows, estuarine salinity and fisheries harvests within an Estuarine Linear Programming Model. The model computes the combined monthly freshwater inflows from the Sabine and Neches River basins which best achieve a specified objective.

The monthly freshwater inflow needs for the Sabine-Neches estuary were to be estimated for each of three selected alternatives:

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

Alternative II (Maintenance of Fisheries Harvests): minimization of annual combined inflow while providing annual commercial harvests of red drum, seatrout, and shrimp, at levels no less than their mean historical (1962-1976) values, satisfying marsh inundation needs, and meeting viability limits for salinity; and

Alternative III (Shrimp Harvest Enhancement): maximization of the total annual commercial harvest of shrimp while meeting viability limits for salinity, satisfying marsh inundation needs, and utilizing an annual combined inflow no greater than the average historical (1941-1976) combined inflow.

Other alternatives, such as those considering freshwater species or habits, could be evaluated if suitable salinity limits for maintaining a viable population were developed.

Under Alternative I (Subsistence), the Sabine-Neches estuarine system is estimated to need freshwater inflows totaling 8.78 million acre-feet (10.8 billion m^3) annually to satisfy the basic salinity gradient and marsh inundation needs. The portion of the annual inflow need that is estimated to come from gaged areas of the Sabine and Neches River Basins is 5.69 million acre-feet (7.02 billion m^3). The monthly distribution of these inflows and the average historical (1941-1976) inflows are given in Figure 1-1. It was not possible to derive estimates of commercial fisheries harvests since the monthly inflows for this Alternative were not within the range of observed inflows utilized to develop the harvest equations.

Alternatives II (Maintenance of Fisheries Harvests) and III (Shrimp Harvest Enhancement) were found to be infeasible; that is, no set of monthly inflows could simultaneously satisfy the upper and lower limits on salinity, inundation flows, and bounds on the seasonal inflows for which the fisheries harvest equations were valid.

Estuarine Circulation and Salinity Patterns

The numerical tidal hydrodynamic and salinity mass transport models were applied to the Sabine-Neches estuary to determine the effects of the estimated freshwater inflow needs for Alternative I 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 for the Alternative I monthly inflows indicate that freshwater inflows would dominate the net water movements within the Sabine-Neches estuary. For all twelve months simulated, the simulated net flow circulation in Sabine Lake is from north to south.

Simulated salinities in Sabine Lake under the Alternative I monthly inflows are 5-15 ppt, except for the highest inflow months of May and October when the simulated salinity range is from 1-10 ppt. Since the middle portion of Sabine Lake has simulated salinities in all months below a target maximum allowable concentration of 25 ppt, the freshwater inflow needs established by the Estuarine Linear Programming Model would be adequate to sustain the salinity gradients specified, within the objectives, throughout the estuary.

Significance of Freshwater Inflow Need Estimates

The estimated monthly freshwater inflow needs derived in this report are the best statistical estimates of the monthly inflows satisfying a specified objective for marsh inundation and salinity gradient regimes. 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 an 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.

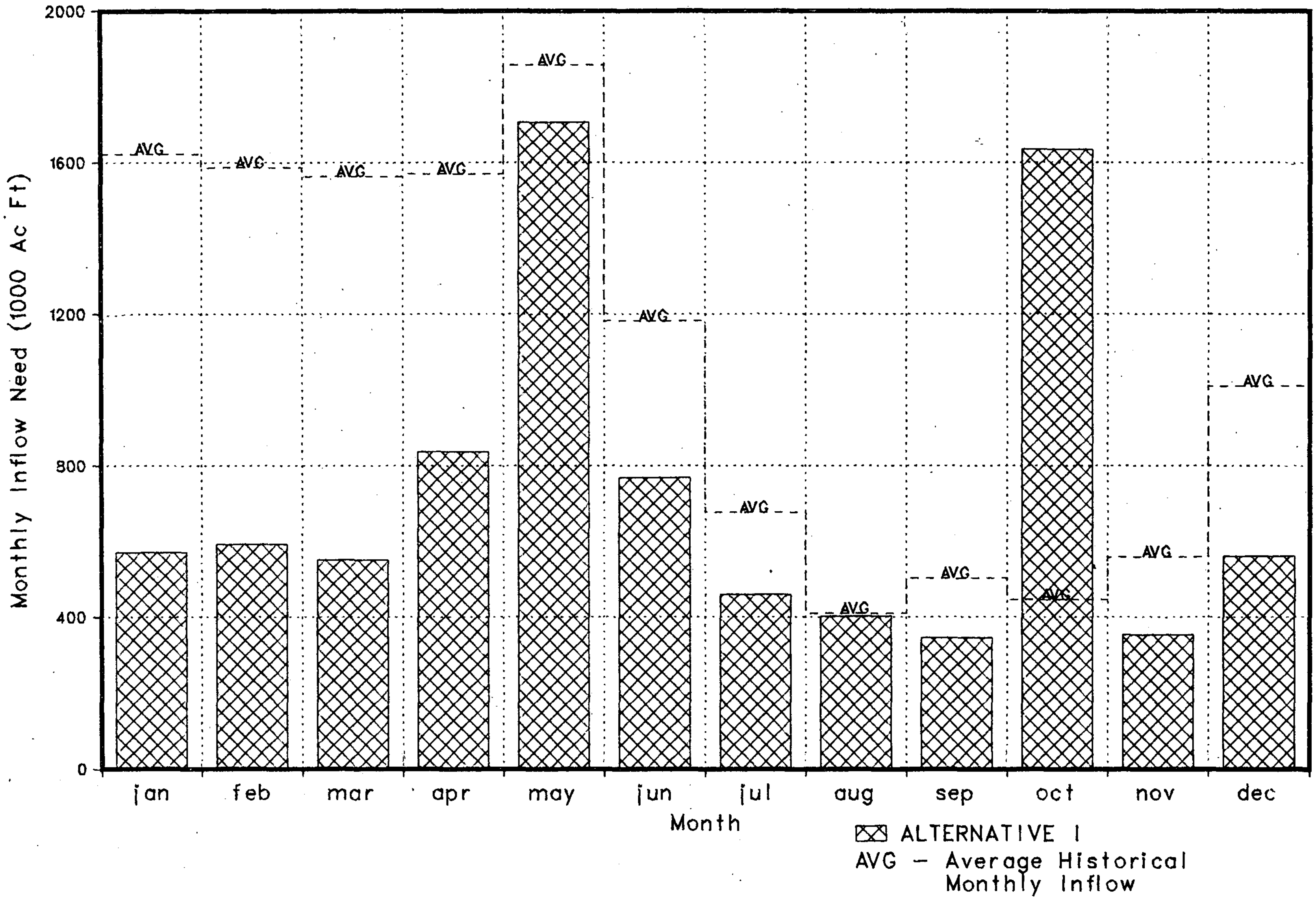


Figure 1-1. Estimated Monthly Freshwater Inflow Needs for the Sabine-Neches Estuary Under Alternative I

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 Sabine-Neches estuary. In succeeding chapters, biotic and abiotic factors are conceptually related, enabling the use of numerical analysis for the identification of maintenance needs. Many estuarine maintenance needs are directly related to freshwater inflow and associated quality constituents. In some cases, these needs may be exceeded in importance by the basic availability of substrate and/or habitat in the ecosystem.

Fundamental to these discussions is the concept of seasonal dynamics; that is, the environmental needs of an estuarine ecosystem are not static annual needs. In fact, dynamic equilibrium about the productive range is both realistic and desirable for an estuarine environment. Extended periods of inflow conditions which consistently fall below maintenance levels can, however, lead to a degraded estuarine environment, loss of important "nursery" functions for estuarine-dependent fish and shellfish resources, and a reduction in the potential for assimilation of organic and nutritive wastes. During past droughts, Texas estuaries severely declined in their production of economically important fishery resources and began to take on characteristics of marine lagoons, including the presence of starfish and sea urchin populations (194). 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 Sabine-Neches estuary.

Estuarine Environment

Introduction

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

Physical and Chemical Characteristics

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

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

Texas has about 373 miles (600 kilometers) of open-ocean or Gulf shoreline and 1,419 miles (2,290 kilometers) of bay shoreline, along which are located seven major estuarine systems and three smaller estuaries (Figure 2-1). Eleven major river basins, ten with headwaters originating within the boundaries of the state, have estuaries of major or secondary importance. These estuarine systems have a total open-water surface area of more than 1.5 million acres (607,000 hectares) with more than 1.1 million acres (445,000 hectares) of adjacent marshlands and tidal flats (385). Physical characteristics of the Sabine-Neches estuary are described in Chapter III.

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

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

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

The hydrology of the Sabine-Neches estuary is described in Chapter IV.

Water Quality. The factors which affect the water quality of aquatic ecosystems and their importance to the various biological components include

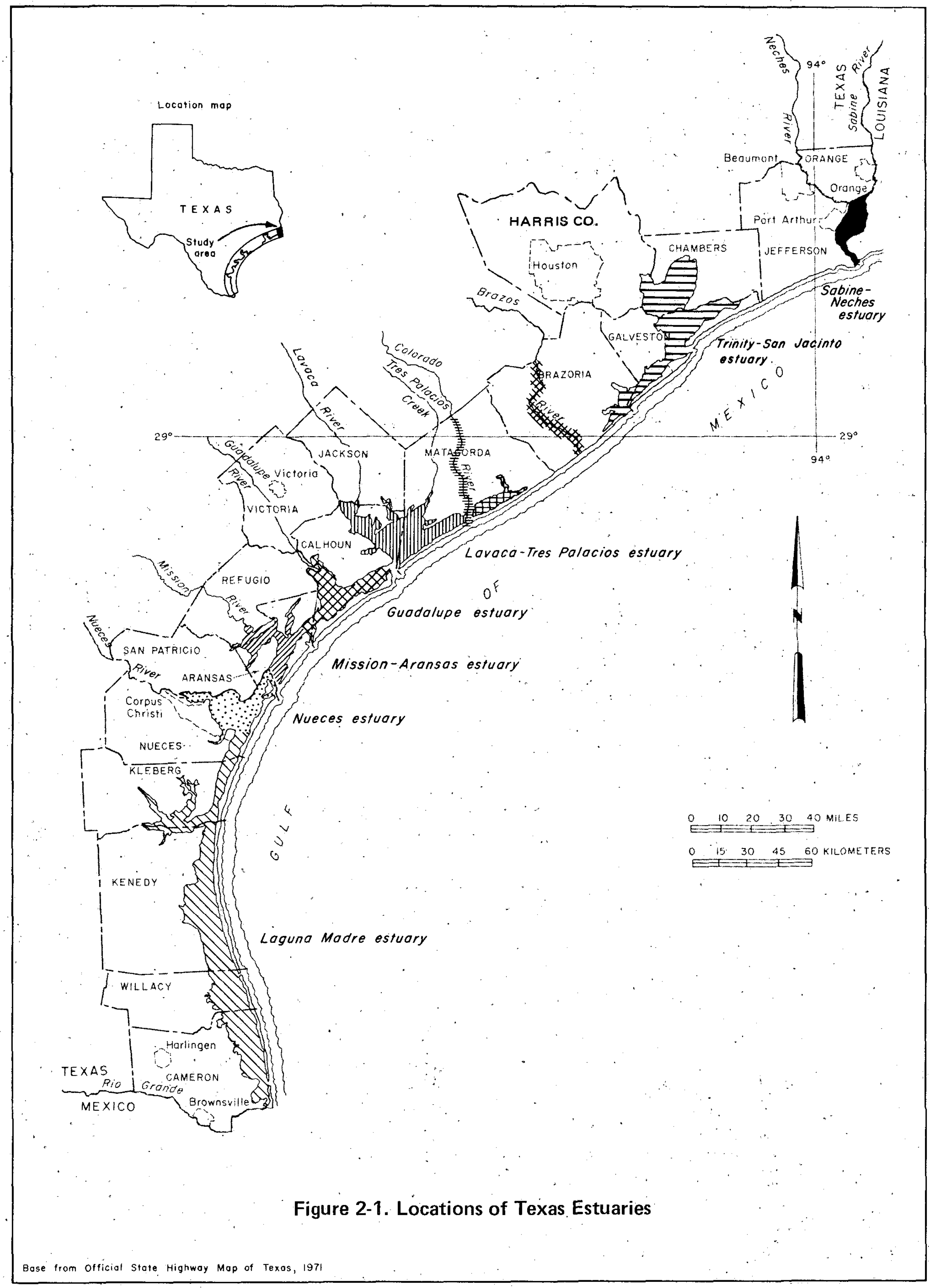


Figure 2-1. Locations of Texas Estuaries

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, benthic infauna, shellfish, and finfish.

Salinity, temperature, and potentially catastrophic events (e.g., hurricanes) are factors that largely control and influence species composition in these ecosystems. While the number of species generally remains low, numbers of organisms within a single species may be high, fluctuating with the seasons and with hydrologic cycles (208, 78, 203). 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 Sabine-Neches estuary are described in detail in Chapters VII and VIII.

Food Chain. To evaluate the effects of freshwater inflow on an estuary, it is necessary to consider the significant interactions among dominant organisms for each of the estuary's trophic (production) levels. A complicated food web consisting of several food chains exists among the trophic levels of an estuarine ecosystem, with water the primary medium of life support (49, 158, 51, 110, 182, 236). The aquatic ecosystem can be conceptualized as comprising of four major components, all interrelated through various life processes (Figure 2-2):

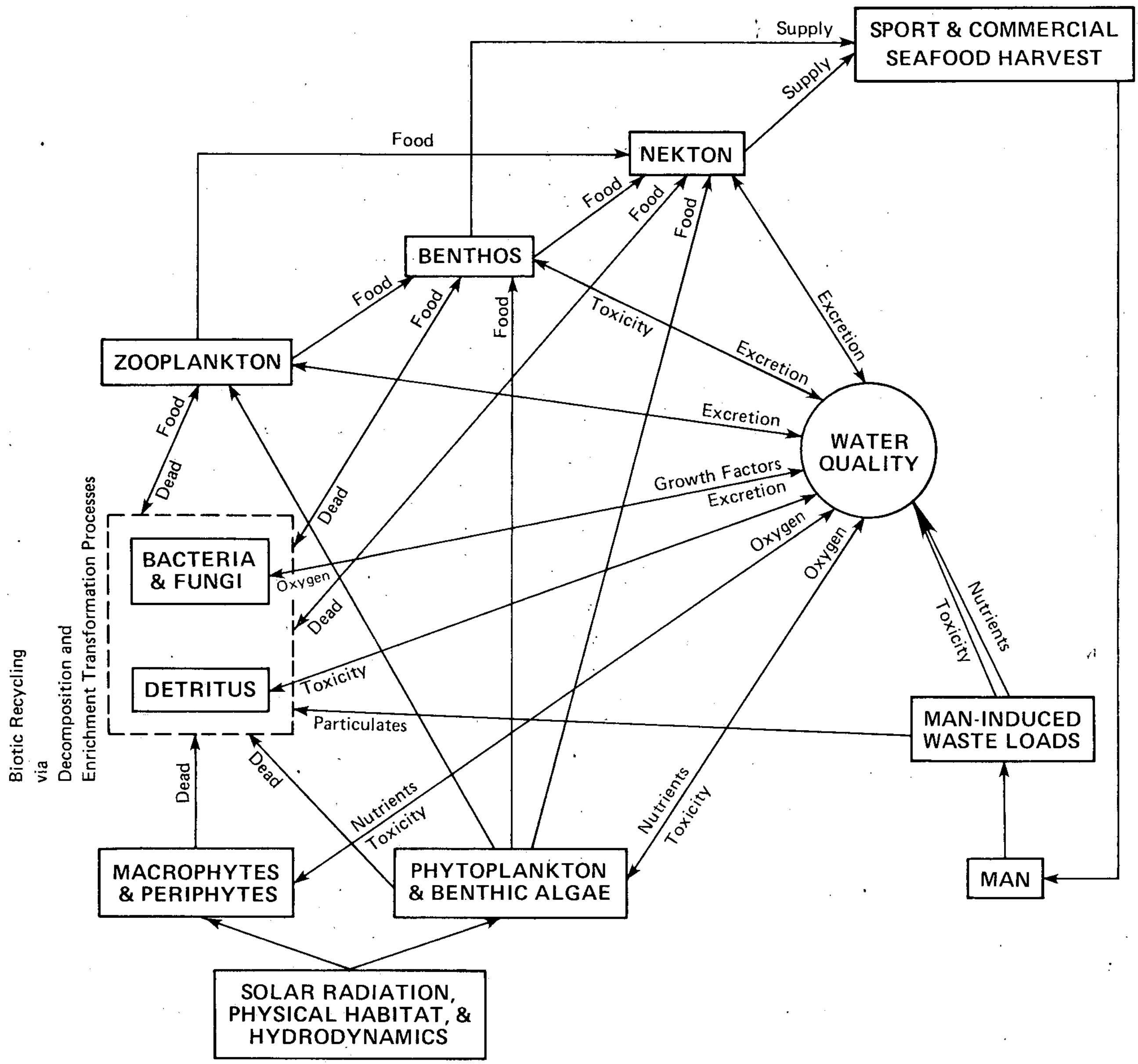


Figure 2-2. Component Schematic Diagram of a Generalized Texas Estuarine Ecosystem

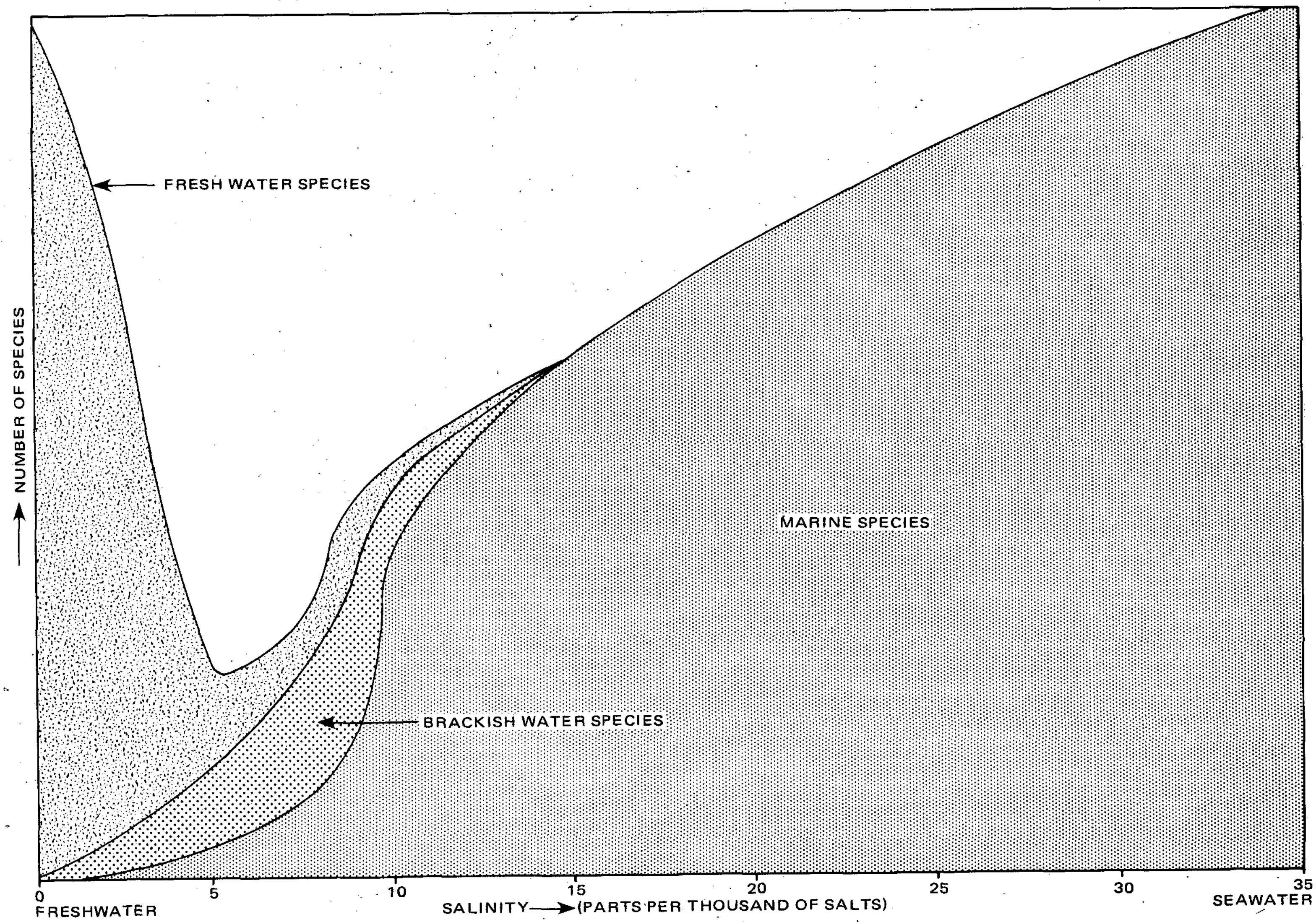


Figure 2-3. Species Composition of Estuarine Environments (208)

1. Chemical parameters including basic substances essential to life such as carbon dioxide (CO_2), nitrate (NO_3), ammonia (NH_3), phosphate (PO_4), and dissolved oxygen (DO),

2. Producers including autotrophic organisms such as vascular plants and algae that can transform basic substances into living cellular material through utilization of sunlight by photosynthesis,

3. Consumers (herbivores, omnivores, and predators) including heterotrophic organisms such as zooplankton, shellfish, and fish species that utilize other biota as basic food material, and

4. Decomposers including bacteria in both liquid and solid (sediment) phases and fungi.

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

Life Cycles. Many organisms of estuarine systems are not permanent residents, in that they spend only part of their life cycle in the estuary. Migration patterns constitute an integral part of the life history of many estuarine-dependent species (213). 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 (134, 430), and/or for protection against predators and parasites (139, 192). Juvenile forms use the shallow "nursery" areas during early growth (91), migrating back to the Gulf of Mexico in their adult or sub-adult life stage.

For high marsh productivity to occur, the timing of freshwater inflow, inundation (irrigation) of marshes, and nutrient stimulation (fertilization) of estuarine plants must coincide with the subtropical climatic regime of the Gulf region. Nature's seasons provide environmental cues, such as increases or decreases in salinity and temperature, that enable estuarine-dependent species to reproduce and grow successfully in the coastal environments; that is, 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 distant from the seasonal optimum. Further, the entire ecosystem can lose productivity through disruption of energy flow and become altered by slight, but chronic stresses (450).

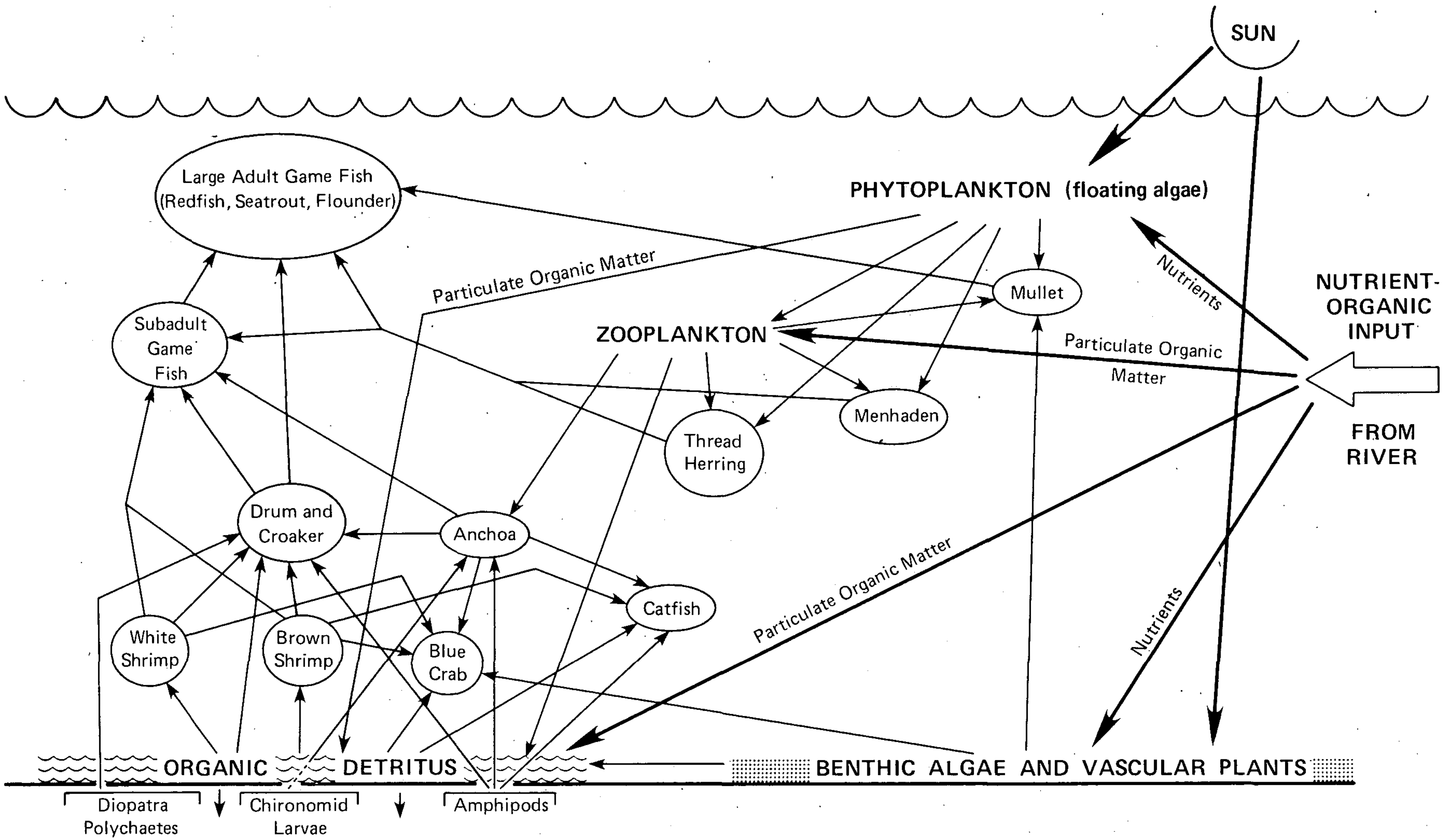


Figure 2-4. Simplified Trophic Relationships in a Texas Estuary [after WRE(437)]

Virtually all (97.5%) of the Gulf fisheries species are considered estuarine-dependent (92); however, the seasonal aspects of their life cycles are quite different. Some species, such as the redfish (red drum), spawn in the fall and the young are particularly dependent on migration to and utilization of the "nursery" habitats during this season. Others, such as the penaeid shrimp, spawn primarily in the spring and early summer, and their young move inshore to shallow, low salinity estuarine areas for growth and development at this time. Not all estuarine-dependent species are migratory between the marine and estuarine environments; however, there are few true year-round residents (e.g., bay oysters) capable of completing their life cycle totally within the estuary (175).

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 (58). Throughout the world, only tropical rain forests, coral reefs, and some algal beds produce more abundantly per unit of area (182, 324).

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 (44, 110, 157). Because of high plant productivities an estuarine marsh can assimilate, if necessary, substantial volumes of nutrient-rich municipal and industrial wastes (426, 427) and incorporate them into the yield of organic material which supports higher trophic level production, such as fishery species. Such high food density areas serve as "nursery" habitats for many economically important estuarine-dependent species, as well as providing food and cover for a variety of water fowl and mammals. Delta marshes may serve other beneficial functions acting as a temporary floodwater storage area and/or aiding in erosion control by absorbing potentially destructive wave energy.

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

Summary

Texas has seven major estuarine systems and several smaller estuaries that are located along approximately 373 miles (600 km) of coastline. These estuarine systems have a total open-water surface area of more than 1.5 million acres (607,000 ha) with more than 1.1 million (445,000 ha) 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 create physiological (metabolic) stresses that can inhibit reproduction and growth, and may have long-lasting effects on the estuary.

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

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

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

Evaluation of Individual Estuarine Systems

Introduction

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

Mathematical Modeling

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

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

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

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

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

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

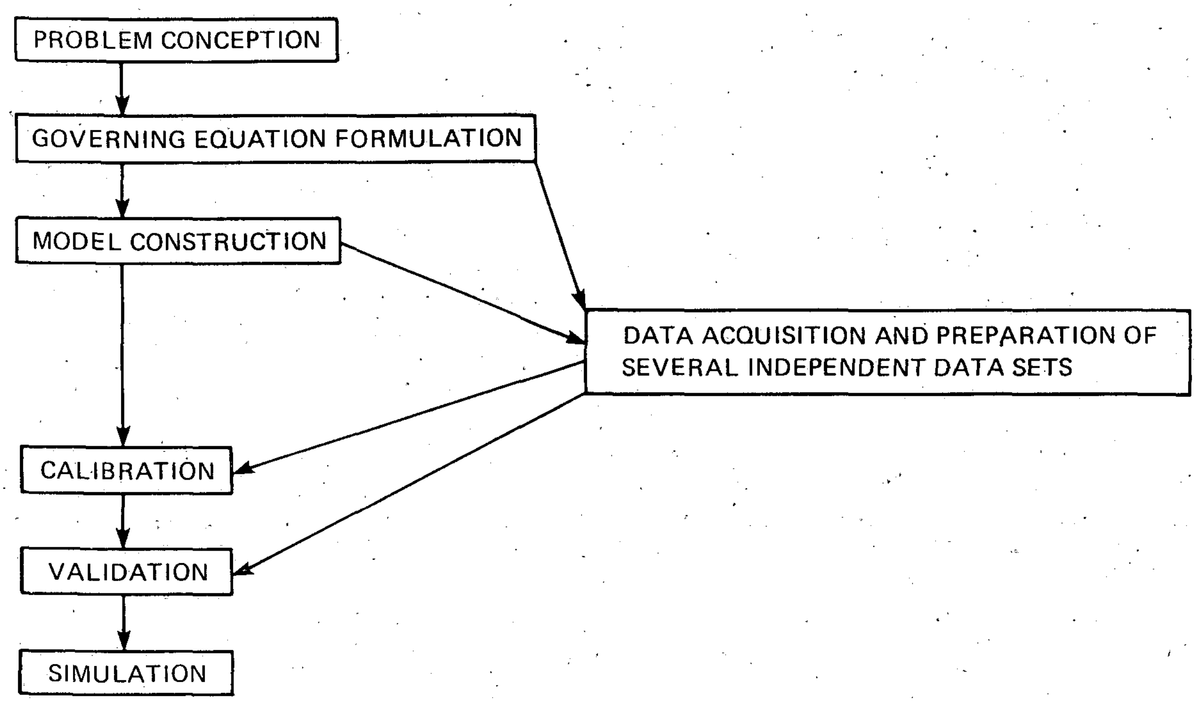


Figure 2-5. Flow Diagram of Model Development

Key Indicators of Estuarine Conditions

The large number of complex interactions of physical, chemical, and biological parameters make it difficult to completely define the interrelationships of an estuarine ecosystem. Major environmental factors and identifiable biological populations can be used, however, as "key indicators" to understand and demonstrate the response of higher food chain organisms, such as shellfish and finfish, to major changes in the ecosystem (229, 182). Physical and chemical constituents of prime importance to the estuarine ecosystem include freshwater inflow, circulation and salinity patterns, and nutrients. Chapters IV, V and VI quantify each of these factors to assess their relationship in estuarine productivity.

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

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

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

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

(2) Critical Period. An understanding of the concept of "critical period" is necessary in order to understand the importance of freshwater inflow to Texas estuarine systems (116, 171). There are basically two types of critical periods that must be considered--long term and seasonal. The first, or more general type, is that resulting from extended years of drought with extreme low freshwater inflow, creating stressful or lethal conditions in the estuary. A second type of critical period occurs on a seasonal basis, whereby lowered freshwater inflow affects the growth and maturation of delta marsh habitats, the utilization of "nursery" areas by juvenile fish and shellfish,

and the transport of sediment and nutritive substrate materials (especially detritus) to the estuary.

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

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

(3) Circulation. The movement of waters within an estuary largely determines the distribution of biotic and abiotic constituents in the system. To study the movement of estuarine waters under varying conditions, tidal hydrodynamic mathematical models have been developed and applied to individual Texas estuaries (169, 438). Each model computes velocities and water surface elevations at node points of a computational grid superimposed on an estuary. Estuarine characteristics along any given vertical line (the water column) are assumed to be homogeneous.

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

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

(4) Salinity. A knowledge of the distribution of salinities over time at points throughout an estuary is vital to the understanding of environmental conditions within the system. To better assess the variations in salinity, salinity transport mathematical models have been developed (169, 170, 439) to simulate the salinity changes in response to dispersion, molecular diffusion and tidal hydrodynamics. These are companion models to the hydrodynamic models 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 plots as 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 (44, 157). A hypothetical cross section of a typical salt water marsh is illustrated in Figure 2-7. Note the typical low channel banks which may be inundated by high tides and high river flows. Inorganic materials and organic detritus transported and deposited in salt marshes by river floods are assimilated in the marshes through biological action and converted to organic tissue. This conversion is accomplished by the primary producers (phytoplankton and macrophytes) of the marsh ecosystem. The primary producers and organic materials produced in the marsh are then transported to the bay system by the inundation and subsequent dewatering process. This process is controlled by the tidal and river flood stages.

To properly evaluate the transport processes through a deltaic river marsh it is necessary to estimate the complex tidal and freshwater inflow interactions. A mathematical model (set of equations) based upon the appropriate physical laws was developed for determining flows, water depths, and nutrient transport in a river delta (54). This model applies in cases of both low-flow and flood conditions. The results of freshwater inflows upon the marsh inundation and dewatering processes are estimated through the application of this marsh inundation model (see Chapter V).

Biological Indicators. Terms like "biological indicators", "ecological indicators", "environmental indicators", and others found in the scientific

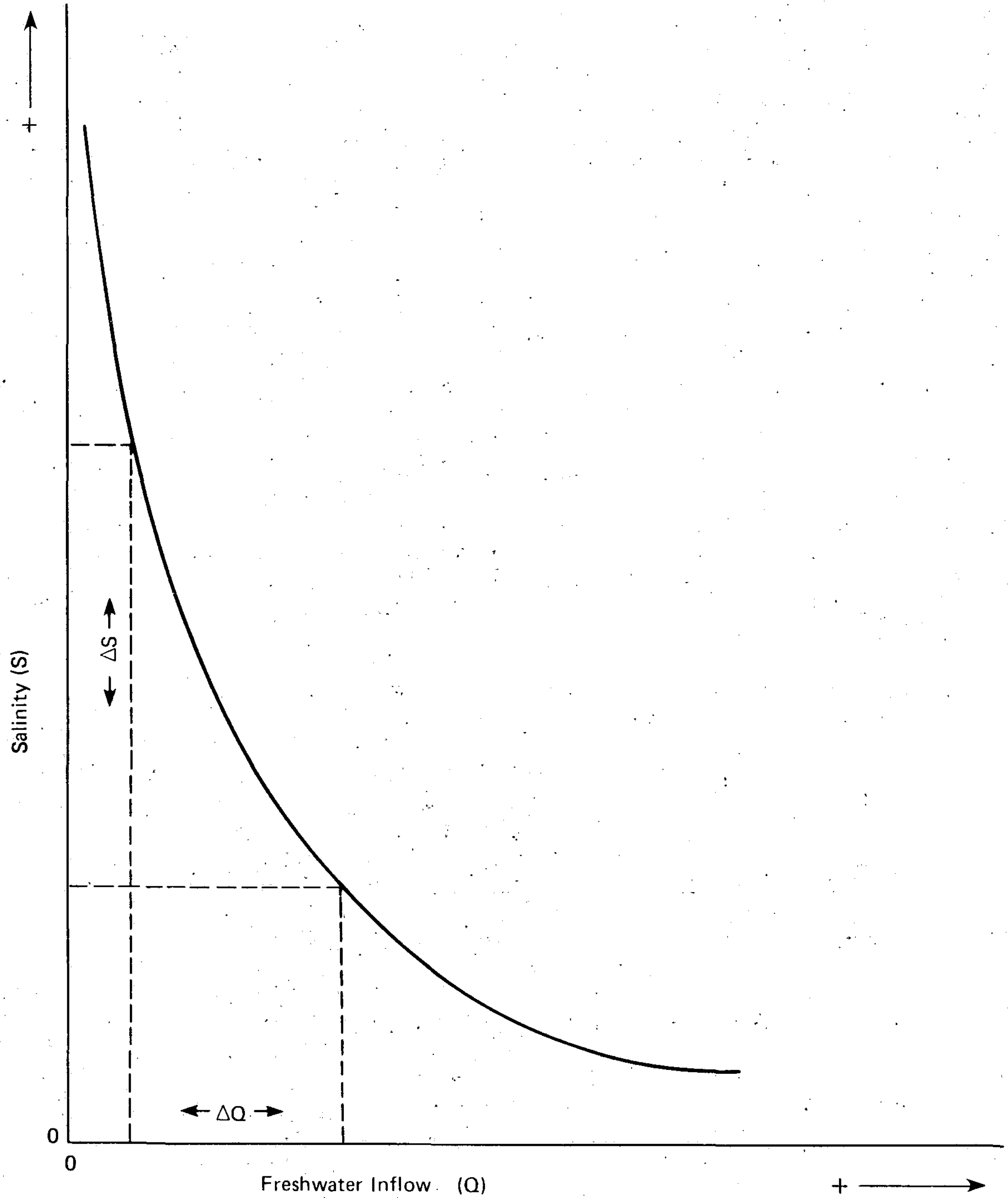


Figure 2-6. Typical Variation of Freshwater Inflow
Versus Salinity in a Texas Estuary

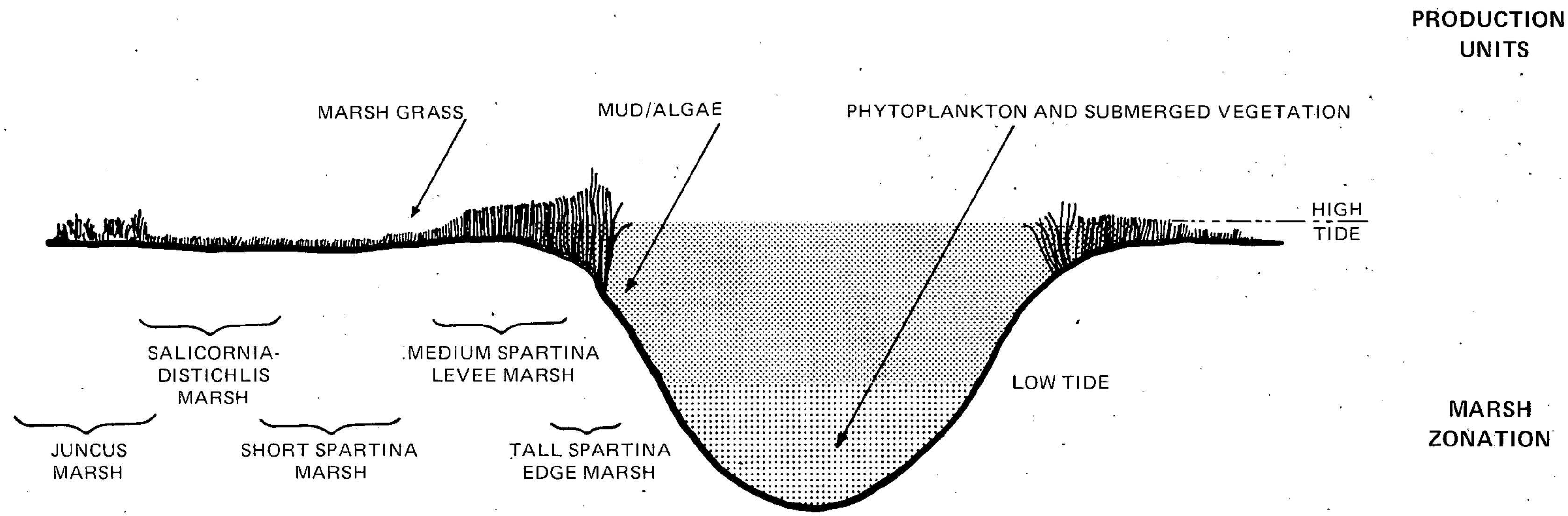


Figure 2-7. Zonation of a Salt Marsh in a Texas Estuary (264)

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 lifecycle to permit observation of changes in organism densities and productivity in association with observations of environmental change.

Dr. Eugene Odum has remarked that "ecologists constantly employ such organisms as indicators in exploring new situations or evaluating large areas" (182). Odum also notes that large species often serve as better indicators than small species because a larger and more stable biomass or standing crop can be supported with a given energy flow. The turnover of small organisms may be so great that the particular species present at any one moment may not be very useful as a biological indicator.

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

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

(1) Aquatic Ecosystem Model. Attempts to understand the complex interactions within Texas estuarine ecosystems have lead to the development of a sophisticated estuarine ecologic model (ESTECO; 264, 437). The model was formulated to provide a systematic means of predicting the response of estuarine biotic and abiotic constituents to environmental changes. Ecological modeling techniques involve the use of mathematical relationships, based on scientific evidence, to predict changes in estuarine constituents.

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

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

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

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

The described relationships are useful in defining the possible impacts and interactions between freshwater inflows and the biomass production in various trophic levels. Many of the complicated relationships among trophic levels within an aquatic ecosystem are not yet completely understood and data about them are not available, so the mathematical representations required to describe such phenomena have not been adequately defined. Therefore, regression techniques are being used in these studies as a 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 (304, 305) and Wakeman (435) have reported on the stress of salinity changes upon the metabolic activities of several Texas estuarine fish species. For example, Wakeman measured the maximum sustained swimming speeds of four estuarine fish species (i.e., spotted seatrout, sheepshead, and black and red

drum) at 28 degrees Celsius over a range of salinities (10-40 parts per thousand, ppt) normally encountered in the estuary to determine their optima. All of these species are of commercial and recreational importance; therefore, results of these metabolic research studies are valuable in the planning and management of the Texas estuarine systems and their production of renewable fish resources. Salinity ranges and salinity optima have also been determined for several other estuarine-dependent fish and shellfish species (including shrimp, crabs, and oysters), and are presented in Chapter IX.

Analyzing the Estuarine Complex

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

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

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

Determination of Freshwater Inflow Needs. (1) Estuarine Inflow Model. In order to establish an estimate of the freshwater inflow needs for an estuary, mathematical techniques are applied to integrate the large number of relationships and 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 (47) 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.

<u>(2). Model Interactions</u>. The estuarine linear programming model incorporates the 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 Sabine-Neches estuary is discussed in Chapter IX.

<u>Techniques for Meeting Freshwater Inflow Needs</u>. 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) <u>Freshwater Inflow Management</u>. 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.

<u>Water Rights Allocation</u>. 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 72 percent complete. Although the adjudication program is being accelerated, several years will be required to complete ajudication for the remaining basins. Final judgements have been rendered by the appropriate District Courts and certificates of adjudication have been issued in portions of the Rio Grande, Colorado, San Antonio, and Guadalupe Basins.

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

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

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

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

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

Sabine-Neches estuary, but other ongoing studies by the Department of Water Resources do address such problems.

(3) Land Management. The uses of watershed areas are of particular importance to the contribution of nutrient materials from the land areas surrounding Texas estuaries. In coastal areas, significant contributions of nutrients are provided to the estuary by direct runoff. Removal of marsh grasses in coastal areas through overgrazing by livestock and through drainage improvement practices can result in substantial reductions in the volume of nutrients contributed to an estuary. This report does not consider land management techniques in detail, although land management is an alternative technique in any coastal zone management plan.

Summary

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

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

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

CHAPTER III

DESCRIPTION OF THE ESTUARY AND THE SURROUNDING AREA

Physical Characteristics

Introduction

The Sabine-Neches estuary covers about 100 square miles (259 km^2) and includes Sabine Lake, the Sabine-Neches Canal, the Port Arthur Canal and Sabine Pass (Figure 3-1). Water depths at mean low water vary from generally 10 feet (3 m) or less in Sabine Lake to greater than 40 feet (12 m) in dredged areas of the rivers, canals and pass.

This study area lies in the Upper Coast climatological division of Texas. Its climatic type is classified as subtropical (humid with warm summers). The proximity of the Gulf of Mexico provides an abundant moisture source, high relative humidities and the sea breeze, which prevents extremely high temperatures in summer and moderates the cool of winter. Polar Canadian air masses frequent the area in winter, causing brief periods of cool, foggy and rainy weather. Rainfall is fairly evenly distributed throughout the year. Some heavier rainfall occurrences during late summer (August) and early fall (September and October) are associated with tropical disturbances (e.g., hurricanes).

The annual surface evaporation rate computed from air temperature, dew point temperature, wind movement and solar radiation in the area is about 50 inches (127 cm). The average annual relative humidity ranges daily from 91 to 62 percent.

Influence of Contributory Basins

The Sabine-Neches estuary contributing inflow basins include the Sabine and Neches River Basins and part of the Neches-Trinity Coastal Basin (Figure 3-2). Total contributing area to the estuary is 20,180 square miles (52,266 km^2).

Total drainage area of the Sabine River Basin is 9,756 square miles (25,200 km^2). The headwaters of the Sabine are in northwestern Hunt County, at an elevation of about 650 feet (198.1 m) mean sea level. The river flows in a generally southeasterly direction to Logansport, Louisiana, where it becomes the Texas-Louisiana boundary. From this point, the river flows in a southerly direction to Sabine Lake. The major tributaries from Texas are Lake Fork and Big Sandy Creeks, Cherokee Bayou, Martin Creek, Murvaul Bayou, Socagee and Tenaha Creeks, Palo Gaucho Bayou, Little Cow, Big Cow, and Cypress Creeks, and Cow Bayou. Those tributaries entering from Louisiana are Caster, San Patricio, San Miguel, Toro, and Anacoco Bayous.

Average annual runoff for the Sabine River and tributaries ranges from about 500 acre-feet per square mile (2,382 m^3/ha) near the headwaters to

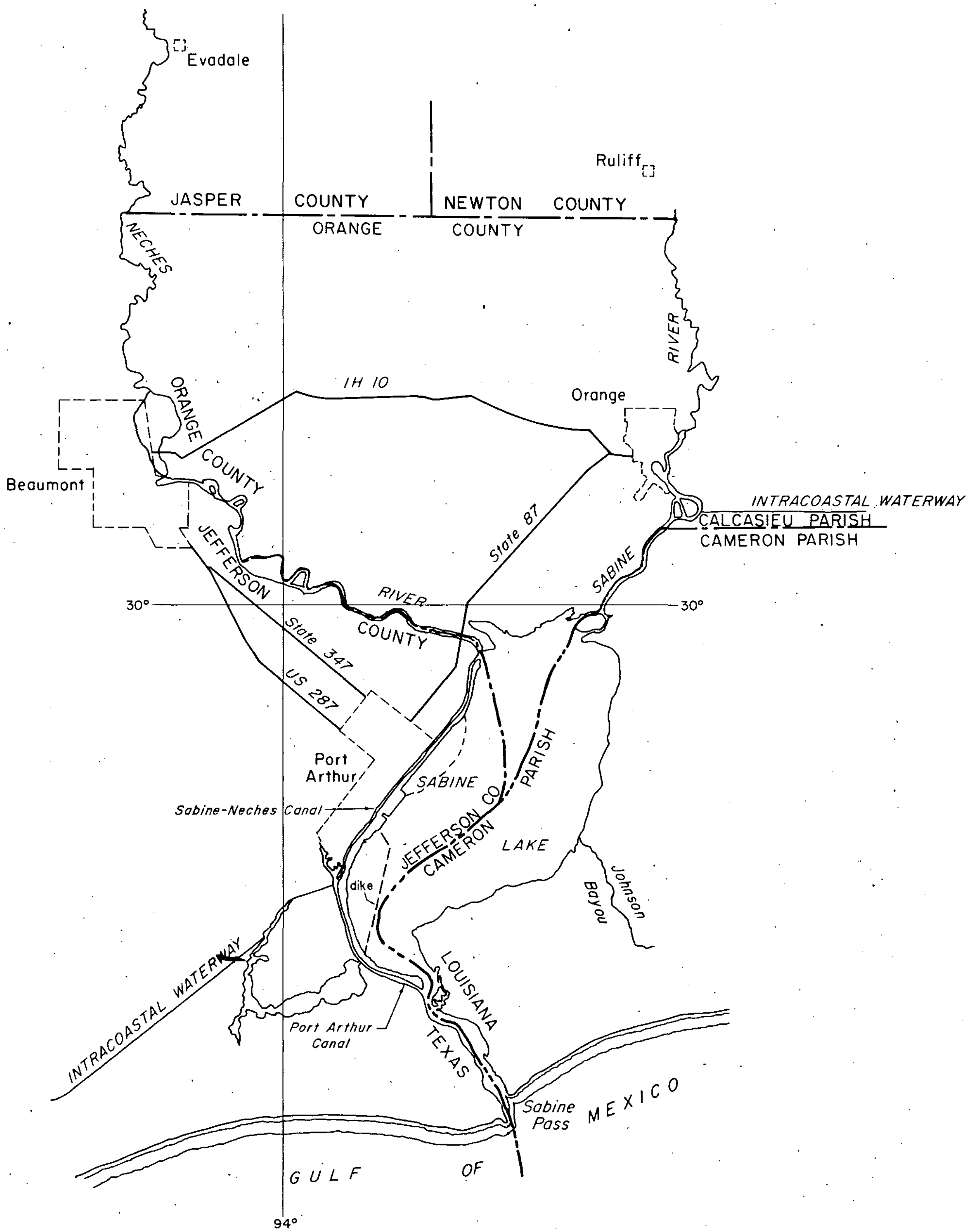


Figure 3-1. Sabine-Neches Estuary

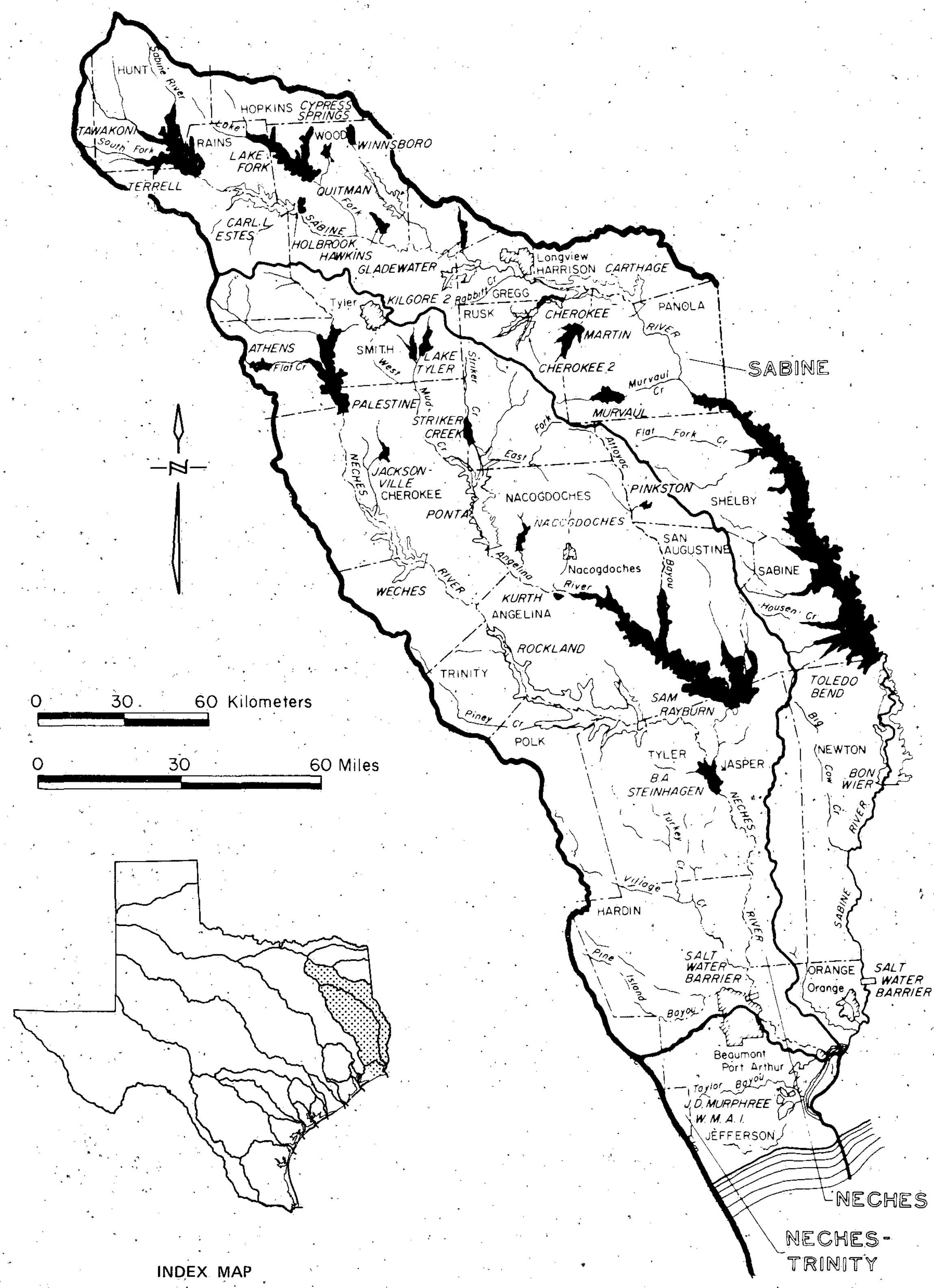


Figure 3-2. Basins Contributing to the Sabine-Neches Estuary

about 900 acre-feet per square mile (4,287 m^3/ha) near Sabine Lake. During periods of drought, average runoff in the Basin has been reduced to about 200 acre-feet per square mile (953 m^3/ha).

The total drainage area of the Neches River Basin is 10,010 square miles (25,926 km^2). Headwaters of the basin occur in southeastern Van Zandt County at an elevation of about 600 feet (182.9 m) above mean sea level and runoff flows in a southeasterly direction to Sabine Lake. The largest tributary to the Neches River is the Angelina River. The total drainage area of the Angelina River is slightly over 2,800 square miles (9,842 km^2). Two other major tributaries downstream from the Angelina River are Village Creek and Pine Island Bayou with drainage areas of 1,110 and 660 square miles (2,875 and 1,709 km^2) respectively.

Average annual runoff ranges from about 400 acre-feet per square mile (1,905 m^3/ha) at the headwaters to about 800 acre-feet per square mile (3,810 m^3/ha) near Sabine Lake. During drought conditions, annual flow has been reduced to about 200 acre-feet per square mile (953 m^3/ha).

About 340 square miles (881 km^2) of the Neches-Trinity Basin contributes runoff to the estuary. The major tributary of this coastal area is Taylor Bayou. A small coastal area in Louisiana adjacent to Sabine Lake also contributes flow to the estuary.

The first major reservoir completed in the contributory basins was Lake Cherokee by the Cherokee Water Company. This project was completed in 1948. Since that time 20 additional reservoirs have been completed (Table 3-1).

Geological Resources

Sedimentation and Erosion. The Sabine-Neches estuary's main sources of sediment are the Sabine and Neches Rivers. Sediment production rates range from 0.82 acre-feet/square mile (3.9 m^3/ha) in the upper Sabine Basin to 0.23 acre-feet/square mile (1.09 m^3/ha) over most of the rest of the basin annually. Sediment production rates in the Neches Basin are fairly uniform with a range of 0.23 to 0.27 acre-feet/square mile (1.09 m^3/ha to 1.3 m^3/ha) annually. Suspended sediment from the headwaters of the Sabine and Angelina Rivers is trapped in Toledo Bend and Sam Rayburn Reservoirs. Sediment from below these reservoirs and from the Neches River is carried downstream, ultimately to be deposited in the Sabine-Neches estuary.

Neither the Sabine nor the Neches River forms a delta at its mouth (291). Marsh areas normally associated with delta plains are found in the lower parts of the coastal areas and river valleys, generally at elevations less than five feet (1.5 m) above sea level. 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 enlarged secondary bay areas. At present, marsh surface-water level relationships are stable. Sedimentation rates and subsidence apparently are in equilibrium. Other important sources of estuarine sediments include:

Table 3-1. Reservoirs of Contributing Basins, Sabine-Neches Estuary

Reservoir Name	Type of Use(s) a/	Year Dam Completed	Surface Area b/ Acres	Conservation Pool Elevation ft (msl)	Conservation Pool Storage c/: thousand ac-ft	Flood Control Storage thousand ac-ft	Total Storage thousand ac-ft
Sabine River Basin							
Lake Tawakoni	W.S.	1960	36,700	437.5	936.2		936.2
Lake Holbrook	W.S.,R.	1962	653	372.0	7.9		7.9
Lake Fork	W.S.	1978	27,690	403.0	675.8		675.8
Lake Quitman	W.S.,R.	1962	814	395.0	7.4		7.4
Lake Hawkins	W.S.,R.	1962	776	343.75	11.8		11.8
Lake Winnsboro	W.S.,R.	1966	806	419.0	8.1		8.1
Lake Gladewater	W.S.	1952	800	300.0	6.9		6.9
Lake Cherokee	W.S.	1948	3,987	280.0	46.7		46.7
Martin Lake	W.S.	1974	5,020	306.0	77.6		77.6
Murvaul Lake	W.S.	1958	3,820	265.3	45.8		45.8
Toledo Bend Res.	W.S,H.E.	1969	181,600	172.0	4,477.0		4,477.0
Neches River Basin							
Lake Athens	W.S.	1963	1,520	440.0	32.7		32.7
Lake Palestine	W.S.	1971	25,560	345.0	411.8		411.8
Lake Jacksonville	W.S.,R.	1957	1,320	422.0	30.5		30.5
Lake Tyler	W.S.	1949	4,800	375.38	80.9		80.9
Striker Creek Res.	W.S.	1957	2,400	282.0	26.9		26.9
Lake Nacogdoches	W.S.	1977	2,210	279.0	40.1		40.1
Pinkston Res.	W.S.	1978	523	298.0	7.3		7.3
Lake Kurth e/	W.S.	1961	700	197.5	16.2		16.2
Sam Rayburn Res.	W.S.H.E..F.C	1965	114,500	164.0	2,898.2	1,544.2	4,442.4
B.A. Steinhagen	W.S.	1951	16,830	83.0	124.7		124.7

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

(1) Direct runoff or drainage from contiguous land and marsh areas to the estuary.

(2) Wind blown sediment, important in areas near sand dunes and non-urbanized areas; and

(3) Normal ecological and biological processes producing organic sediment from the marine life and aquatic vegetation, often making up a large percentage of total estuarine sediments.

The mainland shore is characterized by near vertical bluffs cut into Pleistocene sand, silt, and mud (Figure 3-3). These bluffs extend a few feet above the river valleys. Erosion of these bluffs furnishes sediment to the adjacent lakes, marshes, and bays. The type of sediment deposited depends on whether the adjacent bluff is composed of predominantly sand or mud. Energy levels (erosional capacity) in the Sabine-Neches estuary are dominated by wind action since the range of astronomical tides is only about 0.5 foot (0.15 m). Winds blowing across the bay generate tides of two or three feet (0.6 or 1 m) and cause a change in water level at the shoreline (291). The changes in water levels produced by the wind are called wind tides.

Shoreline and vegetation changes within the Sabine-Neches estuarine system and in other areas of the Texas Gulf Coast are the result of natural processes (325, 291, 249). Shorelines are in a state of erosion, accretion, or are stabilized either naturally or artificially. Erosion produces a net loss in land; accretion produces a net gain in land; and equilibrium conditions produce no net change in land area.

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

Processes that are responsible for the present shoreline configuration and that are continually modifying shorelines in the Sabine-Neches estuary include astronomical and wind tides, longshore currents, normal wind and waves, hurricanes, river flooding, and slumping along cliffed shorelines. Astronomical tides are low, ranging from about 0.5 foot (0.15 m) in the bays to a maximum of about two feet (0.6 m) along the Gulf shoreline. Wind is a major factor influencing coastal processes. It can raise or lower water level along the Gulf and/or mainland shore according to the direction it is blowing. Wind also generates waves and longshore currents (201, 108, 325).

The seasonal threat of wind and water damage associated with tropical cyclones occurring in the Gulf of Mexico exists each year from June through October. Wind damage from hurricanes and associated tornadoes can be costly, but the most severe losses occur from the flooding brought by heavy rains and high storm surges along the Coast. Gulf and mainland shorelines may be drastically altered during the approach, landfall, and inland passage of hurricanes (221). Storm surge flooding and attendant breaking waves may erode Gulf shorelines tens to hundreds of feet. Washovers along the barrier islands and peninsulas are common, and salt-water flooding may be extensive along the mainland shorelines.

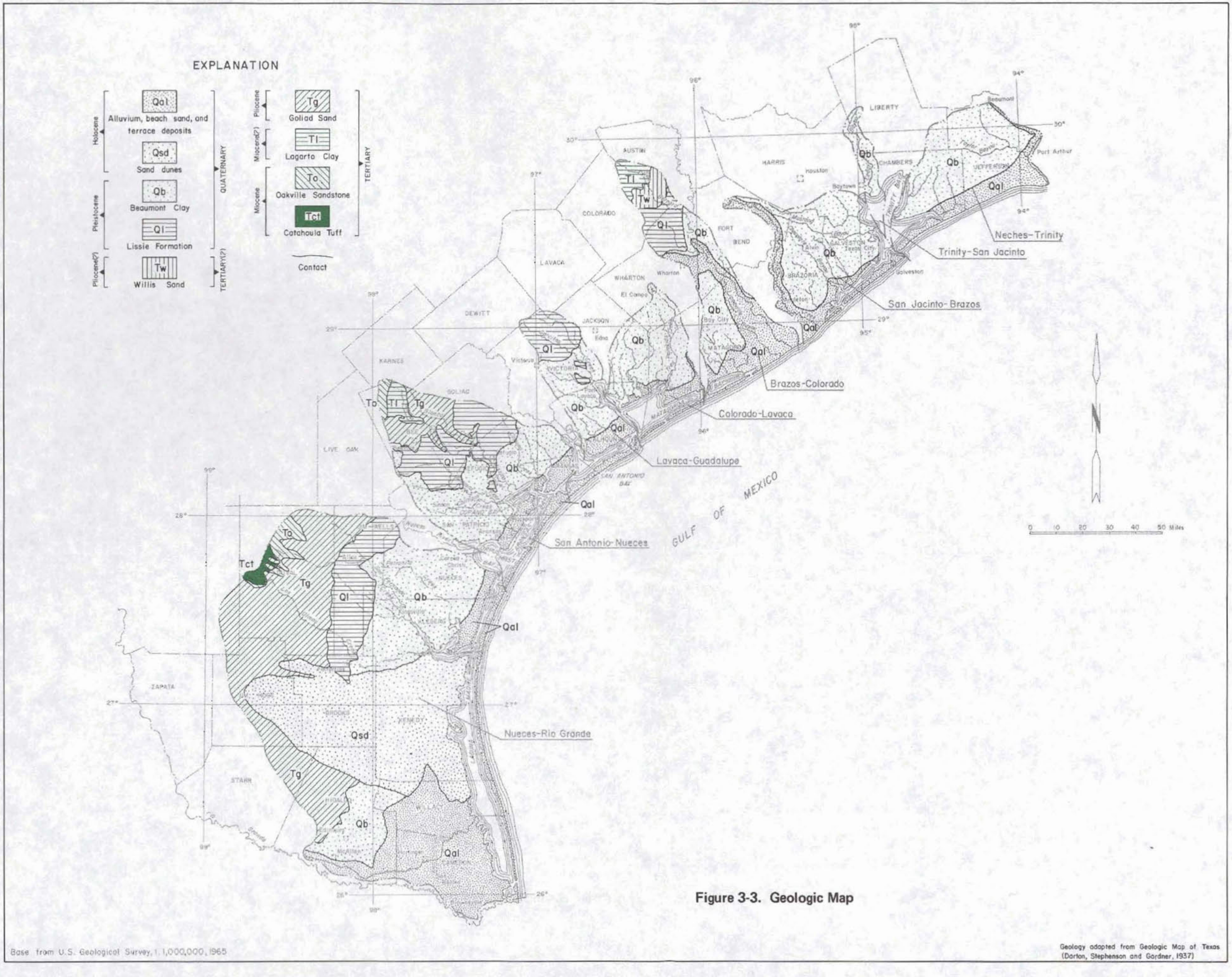


Figure 3-3. Geologic Map

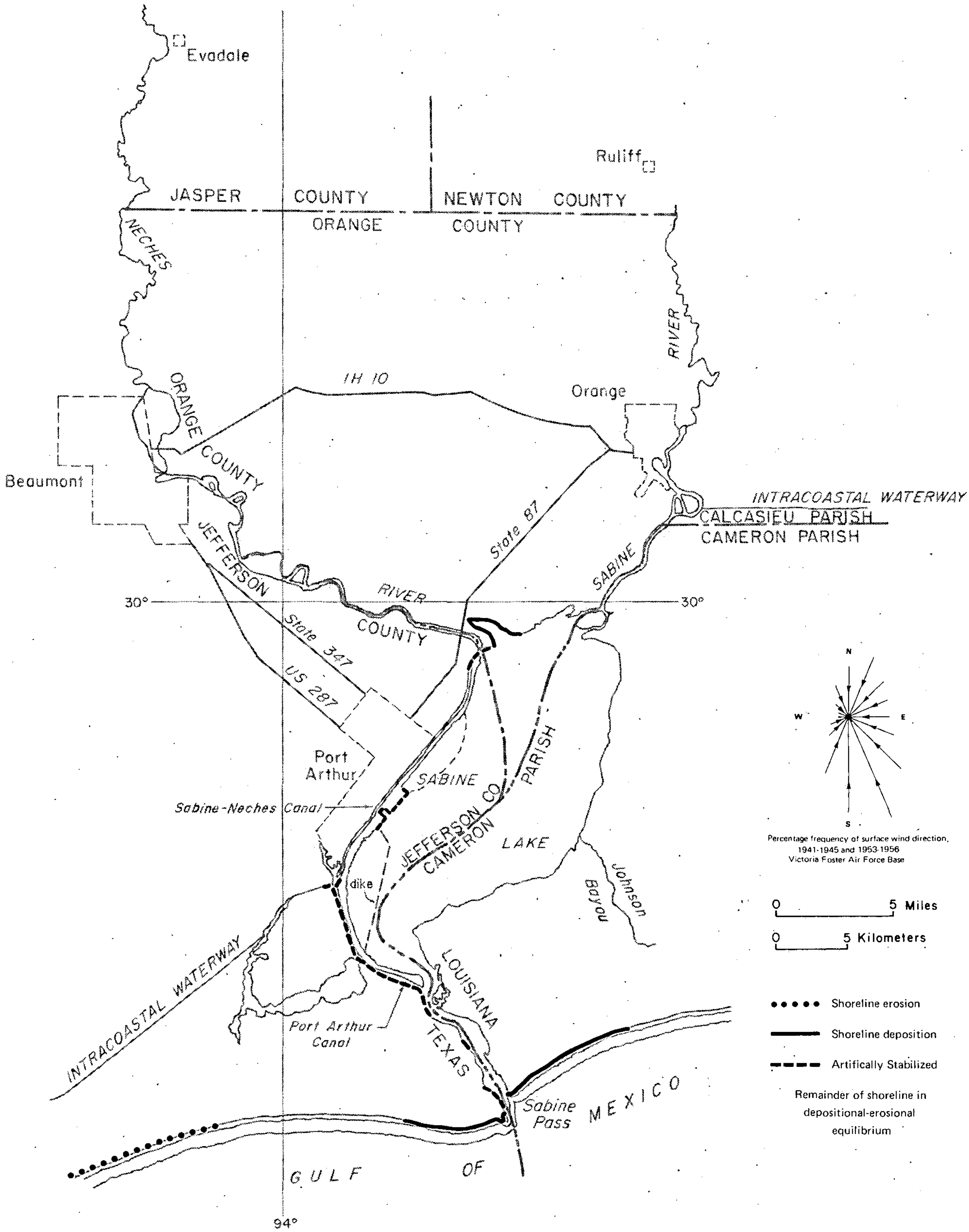


Figure 3-4. Shoreline Physical Processes, Sabine-Neches Estuary (291)

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

Mineral and Energy Resources. Resources of the Texas coastal zone include oil and natural gas (Figure 3-5), which serve not only for fuel but also provide raw material for many petrochemical processes. In addition, the area contains important resources of chemical raw materials--sulphur and salt.

The production of oil, natural gas, and natural gas liquids plays a prominent role in the total economy of the area surrounding the Sabine-Neches estuary (290). 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.

Sulphur occurs within the Texas coastal zone primarily as a native deposit in the caprock of some salt domes, but it is also recovered from sour gas. Individual consumers rarely use sulphur directly, but it is indirectly used in the manufacture of more than 70 different products.

The numerous salt domes of the coastal zone provide an almost limitless supply of high-grade sodium chloride. Most of the salt mined is used as salt brine, primarily as a chemical feedstock in the manufacture of chlorine, soda ash, other chemicals, and soap. A relatively small percentage is used in water-softening products, food processing, and agriculture.

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

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

Oyster reefs are not as well developed in the Sabine-Neches estuary as in the other estuaries from Galveston south to Corpus Christi Bay. Although oysters are present in a few areas, principle shell production is from the claim *Rangia* (291).

Groundwater Resources. Groundwater resources in the area of the Sabine-Neches estuary occur in a thick sedimentary sequence of interbedded gravel, sand,

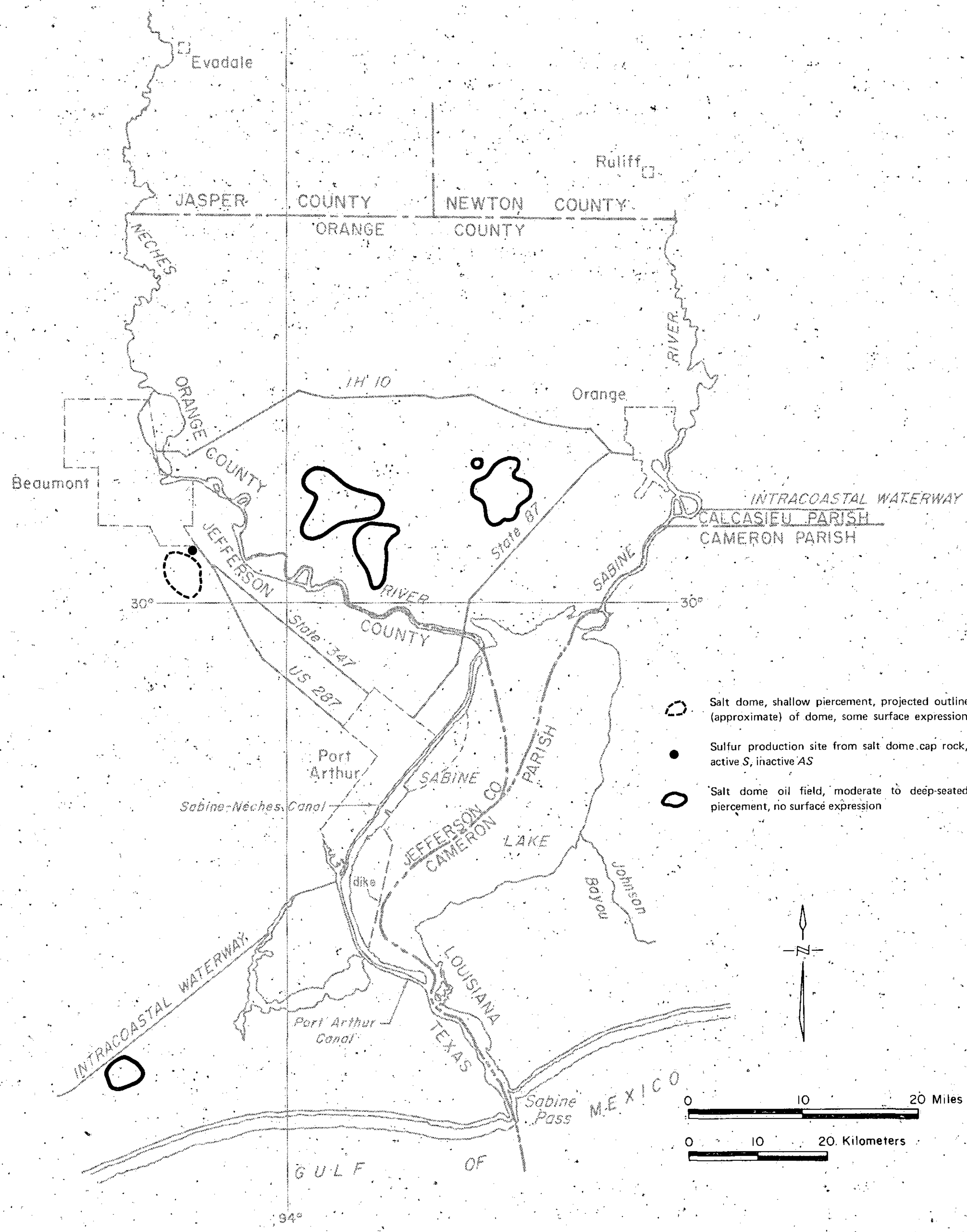


Figure 3-5. Oil and Gas Fields, Sabine-Neches Estuary (291)

silt, and clay. The stratigraphic units included in this sequence are the Catahoula, Oakville and Goliad Formations of Tertiary Age, and the Lissie and Beaumont Formations of Quaternary Age. These ancient sedimentary units are not uniform in composition and thickness, but were deposited by the same natural processes that are now active in shaping the coastline. Thick layers of sand and gravel representing ancient river channel deposits grade laterally into silt and clay beds which were deposited by the overbank flooding of ancient rivers. Individual beds of predominantly sand and clay interfinger with each other and generallly 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 Sabine-Neches estuary this fresh (up to 1,000 mg/l total dissolved solids) to slightly saline (1,000 to 3,000 mg/l total dissolved solids) portion of the aquifer extends to a maximum depth of about 3,000 feet (914 m). Approximately 50 percent of the thickness is made up of water-bearing sand (267). Well yields for large-capacity wells average about 1,800 gallons per minute, but some reach 3,500 gallons per minute. Water from the Gulf Coast Aquifer is suitable for most purposes, generally having less than 500 parts per million dissolved solids. The water is generally soft, but the iron content in some places exceeds 0.3 parts per million and may require treatment for somes uses. In local areas the pH may be less than 7; and the water, corrosive.

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

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 (291).

The Sabine estuary includes areas of both the Coastal Prairie land resource area and the Coastal Marsh land resource area (251). Native vegetation consists of coarse grasses with a narrow fringe of trees along the streams. Much of the area is in urban and industrial land use in the Golden Triangle area of Beaumont, Orange and Port Arthur (Figure 3-6). Marsh land constitutes a sizeable percentage of land near the estuary with vegetation of saltgrass, cordgrass and weeds. Soils are mainly clays, often saline, or man-made saline clays placed during excavation or construction.

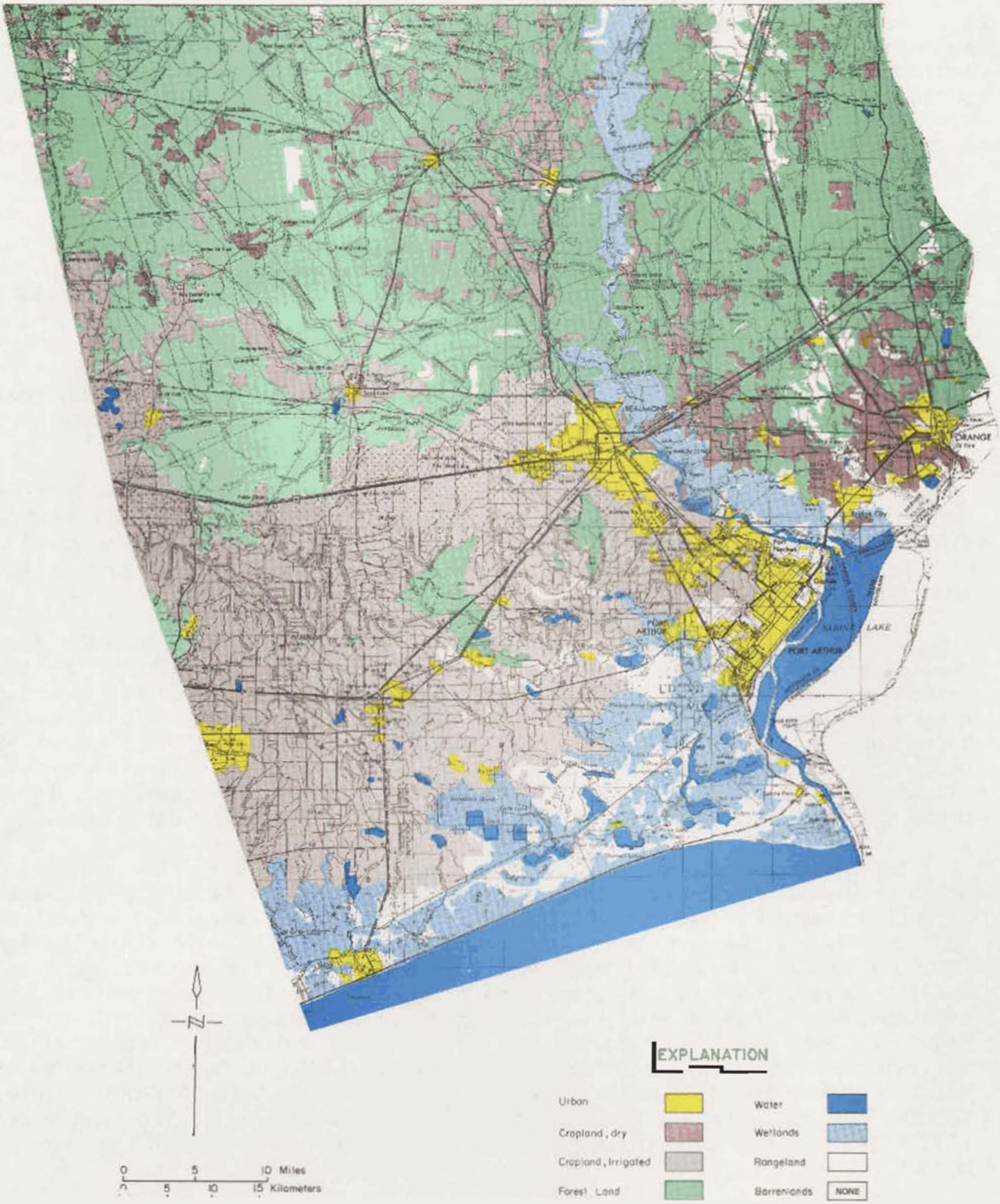


Figure 3-6. Land Use/Land Cover, Sabine-Neches Estuary (258)

Agricultural land use is comprised of irigated rice, dryland crops and ranching activities (258). Results of studies on rice irrigation return flow indicate that about 30 percent of the water applied for irrigation returns as surface flow to the drainage system (253). Soybeans are the only significant dryland crop produced in the area. Cypress and water tolerant hardwoods in swamps areas and pines on the upland soils are the main vegetation in forested areas.

State-owned recreational facilities in the immediate vicinity of the Sabine-Neches estuary include Sabine Pass Battleground State Park, Sea Rim State Scenic Park and J.D. Murphree Wildlife Management Area. Archeological sites indicate extensive utilization of the region (350). An important historic site is the Sabine Pass Battleground (Figure 3-7). In 1863, Sabine Pass was the site of a Civil War battle in which Richard W. Dowling and a small Conferate force repelled an attempted naval invasion of Texas by Union gunboats. In addition, there are two national register sites, one national landmark and approximately 230 miles (370 km) of proposed scenic waterways (286, 287).

Since 1962, fisheries resources commercially caught within the Sabine-Neches estuary have averaged 947.1 thousand pounds (429.6 thousand kg) of finfish and shellfish landings annually. Shellfish constitute a major portion of the commercial landings with the blue crab harvest alone accounting for about 78 percent of the total Sabine Lake fisheries landings.

The fishing resources of this estuary system also include many fish species preferred by sport fishermen. Sport creel studies conducted by the Texas Parks and Wildlife Department (282) show that an estimated 485 thousand fish (all species) totaling more than 487 thousand pounds (221 kg) were harvested during the year September, 1975 through August, 1976. Over 65 percent of the sport harvest (number of fish) was attributed to three species: (1) Atlanta croaker, (2) spotted seatrout; and (3) southern flounder. Other preferred species included red and black drum, sheepshead, and gafftopsail.

In addition to sport fishing, the natural resources of the bay and inland areas provide a variety of recreational opportunities for the people of Texas, as well as visitors from other states. Water-oriented recreational activities such as boating, skiing, and swimming are available with approximately 44.8 thousand surface acres (181 million m^2) of bay waters for recreational use. Wildlife resources of the area enhance the recreation opportunities for sightseeing and nature studies, with esthetic benefits accruing both to the naturalist and environmentalist. The inland areas and marshes contiguous to the estuary system provide terrestrial and aquatic habitat for many species of wildlife including the endangered American alligator, the Atlantic Ridley turtle, the red wolf and brown pelican. Approximately 141.3 thousand acres (572 million m^2) of marshland are available to outdoor sportsmen for hunting opportunities.

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,

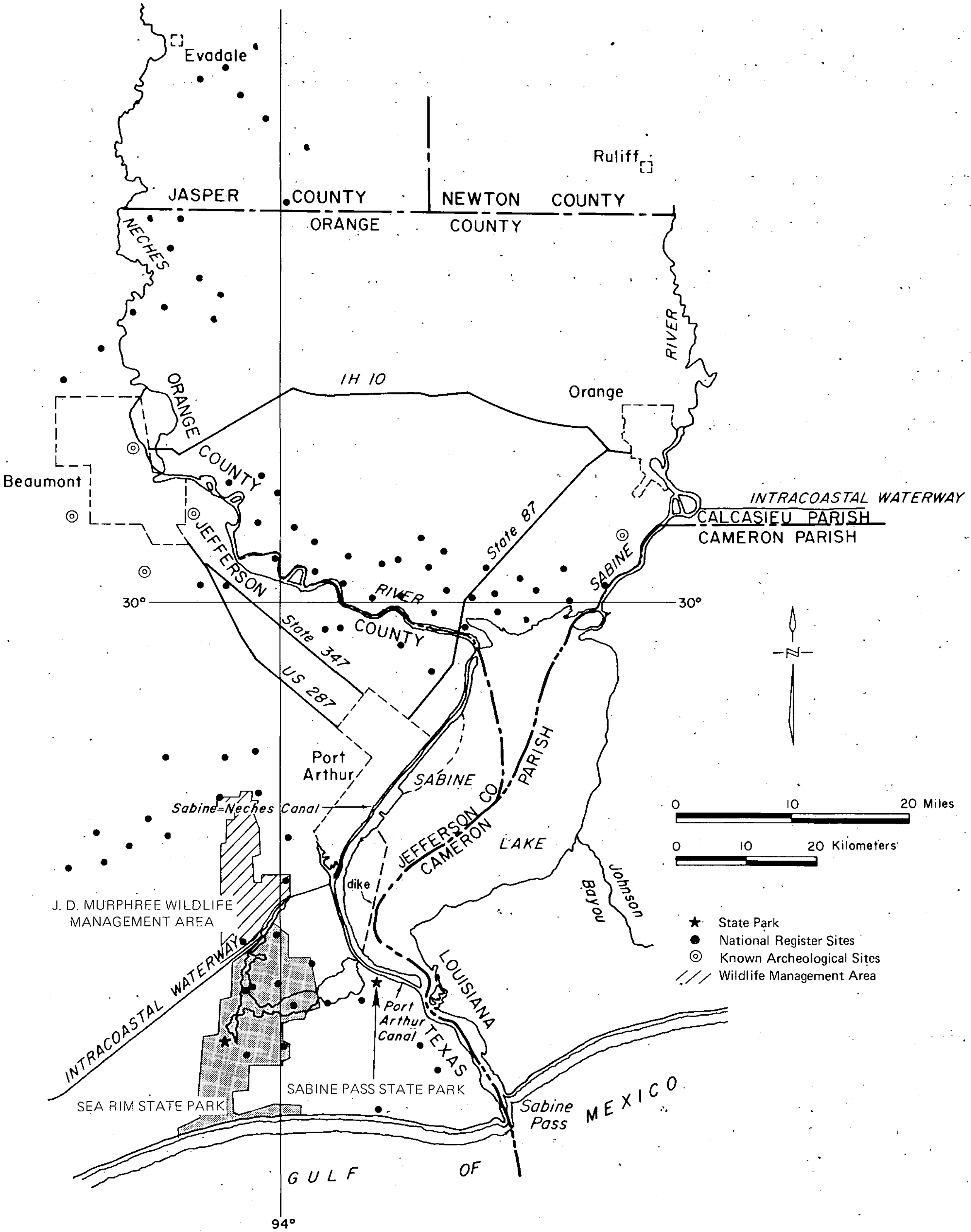


Figure 3-7. Natural Resources, Sabine-Neches Estuary (357)

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 is now collecting extensive data in all estuarine systems of the Texas Coast (Figures 3-8 and 3-9, 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 Sabine-Neches estuary, September 9-12 and July 21-24, 1975. Tidal amplitudes were measured simulataneously at numerous locations throughout the estuary (Figure 3-9). Tidal flow measurements were made at several different bay cross-sections. In addition, conductivity data were collected at many of the sampling stations shown in Figures 3-8 and 3-9. 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 Sabine-Neches estuary is reflected in the direct and indirect linkages of bay-supported resources to the economies of Jefferson and Orange Counties. Trends in population, employment, earnings by industry sector, and personal income levels are presented here for the two counties.

Population. The population of the two county study area experienced an annual growth of 0.18 percent between 1970 and 1975, lower than the statewide figure of 1.7 percent for the same period. Orange County had annual growth (1.4 percent) slightly lower than the statewide average, while Jefferson County had a slight annual growth in population (0.17 percent). In 1975, the population

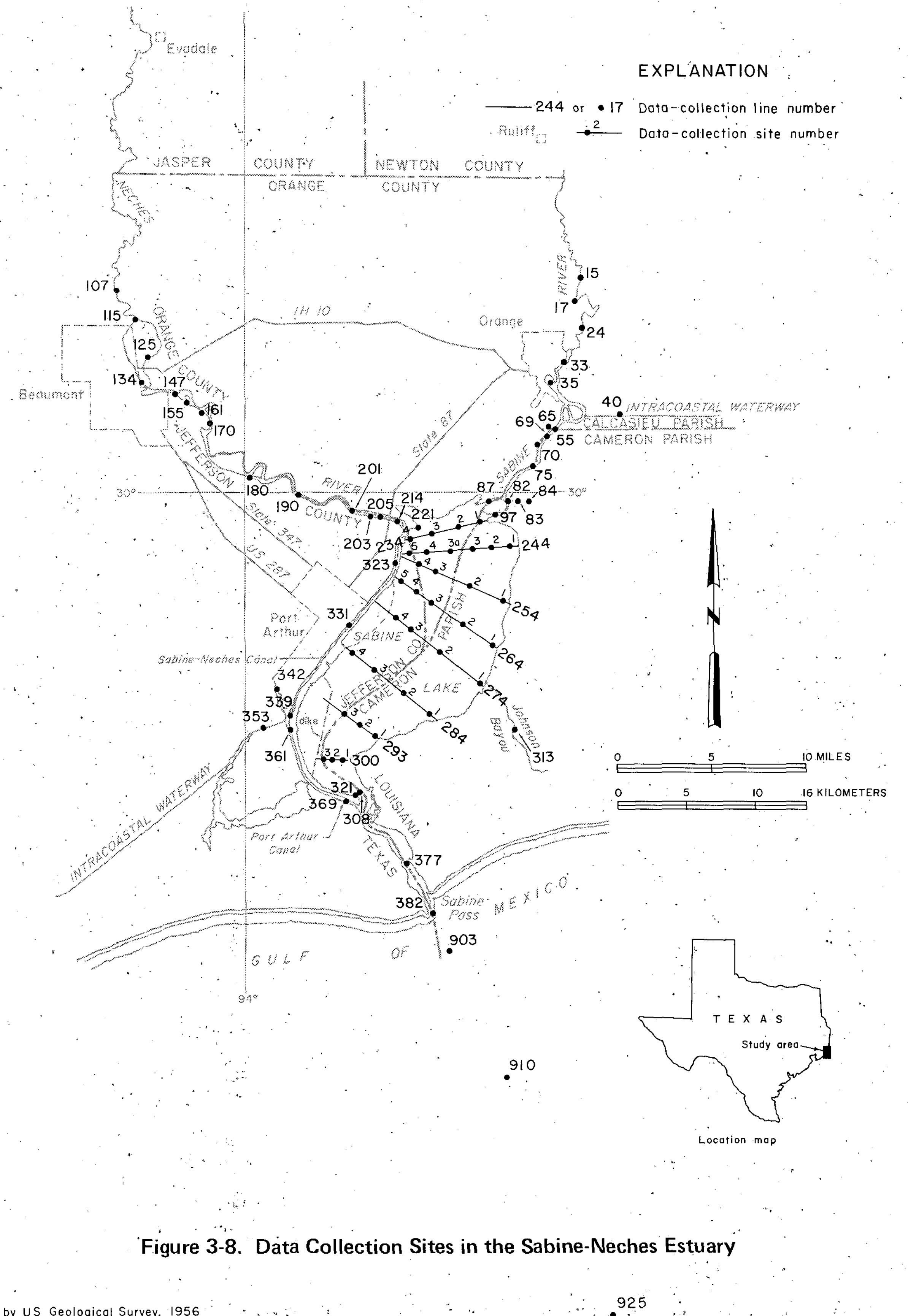


Figure 3-8. Data Collection Sites in the Sabine-Neches Estuary

Base by US Geological Survey, 1956

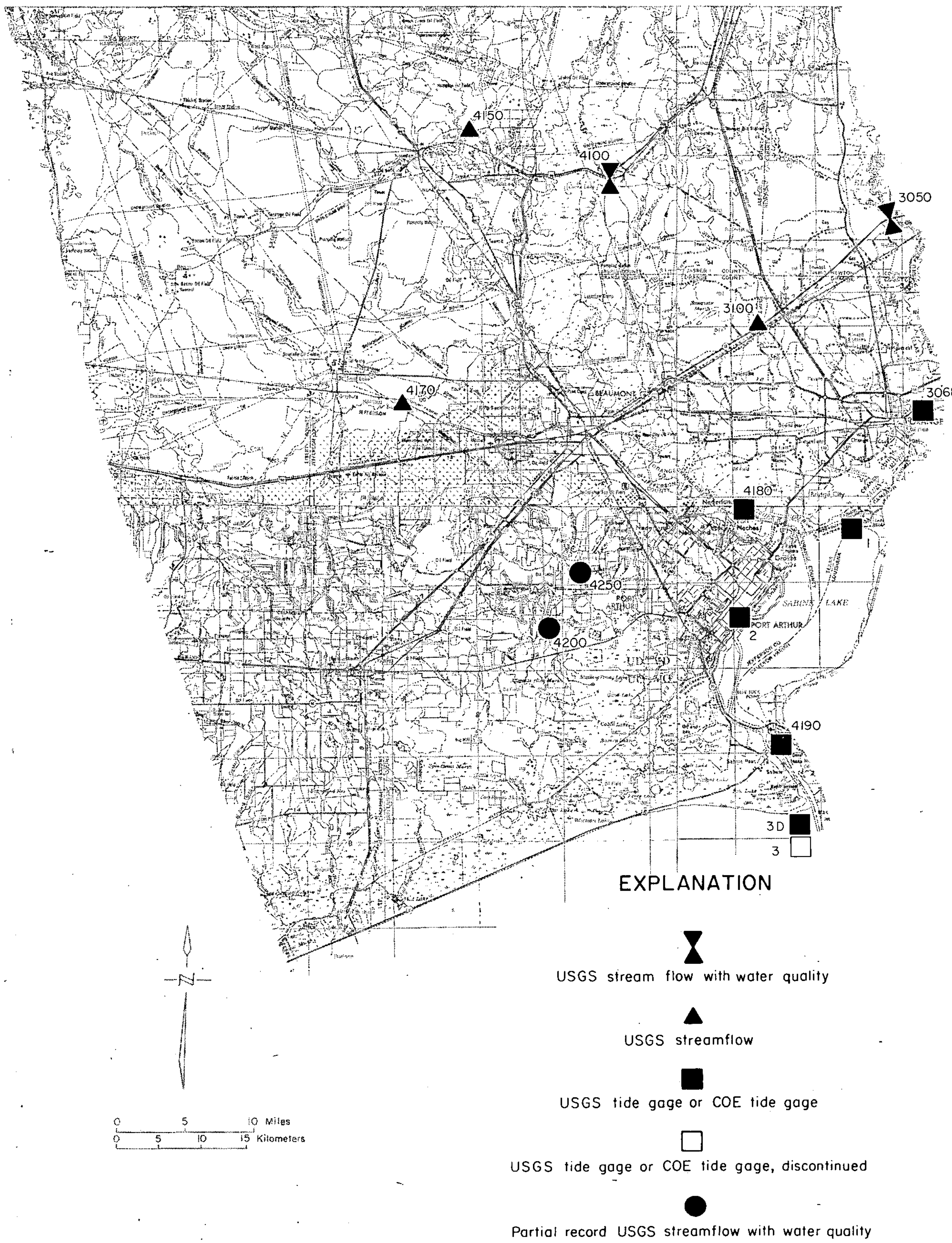


Figure 3-9. Locations of Gaging Stations, Sabine-Neches Estuary

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

Station Number	Station Description	Period of Record	Operating Entity	Type of Record
	<u>Tide Gages</u>			
1	North Sabine Lake	1966-	COE	Continuous Recording
2	Corps of Engineer Area Office, Port Arthur	1934-	COE	Continuous Recording
3	Southwest Jetty, Sabine Pass	1965-77	COE	Continuous Recording
3D	Southwest Jetty S.P. Pilot Sta.	1977-	COE	Continuous Recording
3068	Sabine River at Orange	1974-	USGS	Continuous Recording
4180	Neches River nr. Port Neches	1974-	USGS	Continuous Recording
4190	Sabine Lake nr. Sabine Pass	1974-	USGS	Continuous Recording
	<u>Streamflow Gages</u>			
3050	Sabine River nr. Ruliff	1948-	USGS	Continuous Recording
3100	Cow Bayou nr. Mauriceville	1952-	USGS	Continuous Recording
4100	Neches River at Evadale	1921-	USGS	Continuous Recording
4150	Village Creek nr. Kountz	1939-	USGS	Continuous Recording
4170	Pine Island Bayou nr. Sour Lake	1967-	USGS	Continuous Recording
	<u>Partial Record Streamflow Sta.</u>			
4200	Taylor Bayou nr. La Belle	1954-	USGS	Intermittent Recording
4250	Hillebrandt Bayou nr. Lovelle Lake	1954-	USGS	Intermittent Recording

of the two county area was 320,400 with Jefferson County accounting for 72.2 percent of the projected total.

Population forecasts for the period 1975 to 2030 project an increase in the population of the study area of 0.71 percent per annum up to the year 2030. Jefferson County is projected to remain the most populated, accounting for 66.2 percent of the study area population in the year 2030. Orange County, however, has the highest projected growth rate, growing by 1.4 percent per annum from 1970 (22.4 percent of the study area population) to 2030 (33.8 percent of the study area population). Details of population estimates for the two county area are presented in Table 3-3.

Income. Real personal income for the two county study area accounted for less than three percent of the statewide estimate in 1970. Jefferson County with an estimated $851 million accounted for more than 80 percent of the region's share of total personal income.

Employment. In 1970, an estimated 114,276 persons were employed in the study area, with 89,848 of these (79 percent) working in Jefferson County (Table 3-4). Orange County, with 24,428 employed persons, comprised the remaining portion of the regions total employment in 1970.

Over eighty percent of the region's employed labor force is distributed among eight major industrial sectors (Table 3-4). More workers are involved in manufacturing than any other sector.

Industry. The basic industries in the area are manufacturing, agriculture-forestry-fisheries, and mining. These sectors account for 33 percent of all employment in the study area. In addition to the basic sectors are the service sectors: wholesale and retail trade, professional services, civilian government, and amusement and recreation. These employ 39.8 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 construction sector accounts for about eight percent of regional employment.

By far the most important basic sector, in terms of total earnings (42.9 percent), is manufacturing (Table 3-5). Most of the manufacturing activities are concentrated in petrochemical production, shipbuilding, oil field supplies, and steel mills.

The mineral wealth of the area is also an important factor in its economy. Crude oil production in 1977 exceeded 4 million barrels. Eighty percent of regional crude oil production is from Jefferson County. Natural gas production (gas well and casinghead gas) in 1977 was over 81 billion cubic feet (290). Other minerals produced include sulphur, salt, clays, and sand, and gravel. The annual average value of mineral production in the study area is estimated at over $115 million annually (12).

The two county area had over $27 million in crop production in 1977, chiefly from rice and soybeans. Livestock receipts (primarily for beef cattle) in 1977 were over $5 million, for a regional agricultural output of over $33 million in that year (253). Forestry is also a significant industry

Table 3-3. Population Estimates and Projections, Area Surrounding Sabine-Neches Estuary, 1970-2030 (261)

County	1970	1975	1980	1990	2000	2010	2020	2030	1970-2000 Annual % Change	1970-2030 Annual % Change
Jefferson	246,402	244,300	247,400	249,300	254,100	265,500	287,400	321,700	0.10	0.45
Annual % Change		0.17	0.25	0.08	0.19	0.44	0.80	1.1		
Orange	71,170	76,100	81,900	93,000	105,500	119,700	138,800	164,200	1.3	1.4
Annual % Change		1.4	1.5	1.3	1.3	1.3	1.5	1.7		
Area Total	317,572	320,400	329,300	342,300	359,600	385,200	426,200	485,900	0.42	0.71
Annual % Change		1.8	0.55	0.39	0.49	0.69	1.0	1.3		
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 Sabine-Neches Estuary, 1970 (256)

Sector	1970 Jefferson	1970 Orange	1970 Total	Percent of Total Employment of Study Area
Wholesale and Retail Trade	18,466	4,761	23,227	20.3
Manufacturing	25,325	8,827	34,152	29.9
Professional Services	14,912	3,185	18,097	15.8
Construction	6,416	2,491	8,907	7.8
Agriculture, Forestry, and Fisheries	1,030	200	1,230	1.1
Mining	1,888	356	2,244	2.0
Civilian Government	2,950	691	3,641	3.2
Amusement and Recreation	506	102	608	0.53
All Other	18,355	3,815	22,170	19.4
Total	89,848	24,428	114,276	100.0

Table 3-5. Earnings by Industrial Sector, Area Surrounding Sabine-Neches Estuary, 1970 (255)

Sector	1970			
	Jefferson	Orange	Area Total	Percent of Total Earnings in Study Area
	(Thousands of 1967 Dollars)			
Wholesale and Retail Trade	105,052	17,989	123,041	13.3
Manufacturing	324,357	72,359	396,716	42.9
Professional Services	61,546	8,730	70,276	7.6
Construction	57,702	14,879	72,581	7.8
Agriculture, Forestry, and Fisheries	9,251	1,193	10,444	1.1
Mining	3,807	477	4,284	0.46
Civilian Government	78,686	12,241	90,927	9.8
Amusement and Recreation	1,739	233	1,972	0.21
All Other	136,053	18,615	154,668	16.7
County Total	778,193	146,716	924,909	100.0

in the area, with an annual average production of over $2.5 million in forestry products (12). The bay-supported commercial fishing industry is discussed in detail in the following section.

Summary. The two county area possesses abundant natural and man-made resources. Examination of projected trends in population, employment, 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 health 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. In view of this situation, water-oriented outdoor recreational potential may hold the key to economic progress for the area and may provide the vehicle for boosting income levels and job opportunities.

Economic Importance of Sport and Commercial Fishing

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

Sport Fishing Data Base. In cooperation with the Texas Parks and Wildlife Department, three types of sample surveys were conducted for the purpose of obtaining the data necessary for these studies of sport fishing in the Sabine-Neches estuary (282). The survey included: (1) personal interviews; (2) roving counts; and (3) motor vehicle license plates counts. Personal interviews of a sample of sport fishing parties on a randomly selected sample of weekend days and weekdays were conducted at major access points to the Sabine-Neches estuary for the purpose of obtaining sample data pertaining to fish catch, cost of fishing trip, and personal opinion information. Concurrent with the personal interview sample survey, counts of sport fishermen and boat trailers were made at a statistically randomized sample of boat ramps and wade-bank areas to estimate the number of sport fishing parties in the bay area. Data from the personal interview sample and fishermen counts conducted during the period September 1, 1975 through August 31, 1976 were used in this analysis. A motor vehicle license plate sample survey was conducted during the summer of 1977 to obtain additional information on sport fishing visitation patterns by county of origin.

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

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

The estimated number of fishing parties at the Sabine-Neches estuary for the study period is stated as follows:

$$T = Z + W$$

where:

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

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

$$Z = \sum_{k=1}^{4} z_k;$$ (k = 1, 2, 3, and 4) and pertains to the calendar quarters of the year beginning with September 1, 1975.

where:

Z = Estimated number of boat parties fishing in the Sabine-Neches estuary for the period September 1, 1976 through August 31, 1976.

z_k = Estimated number of boat parties fishing in the Sabine-Neches estuary during the kth calendar quarter of the study period.

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

where:

W = Estimated number of wade-bank parties fishing in the Sabine-Neches estuary for the period September 1, 1976 through August 31, 1977.
W_k = Estimated number of wade-bank parties fishing in the Sabine-Neches estuary during the kth calendar quarter of the study period.

The equation and definitions presented above give the results of the sample estimates of the types of fishing in the estuary. The typical quarterly sample analysis and individual computing methods are stated and defined below for the general case, for weekends. An identical definition pertains to weekend day and is not repeated here. The results for weekdays and weekend days were summed to obtain estimates for the entire quarter.

For boat fishing:

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

where:

z_k = Estimated number of boat fishing parties on 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 weekdays.

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

r = Number of sample boat sites within the study area (11 boat sites for the Sabine-Neches estuary),

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.

For Wade-bank fishing:

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

where:

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

r = Sample wade-bank sites within the study area (14 wade-bank sites for the Sabine-Neches estuary),

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

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

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

These typical terms of 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 106 thousand fishing parties visited the estuary during the period September 1, 1975 through August 31, 1976 (Table 3-6). Seasonal visitation as a percentage of annual visitation ranged from a high of almost 38 percent for the summer quarter to a low of approximately 13 percent during the winter quarter. The distribution of fishing parties by strata indicates that wade-bank fishing accounted for 64.6 percent of annual visitation followed by boat fishing with 35.4 percent (Table 3-6).

Sport Fishing Visitation Patterns. Although the personal interview information included the county of residence of the interviewee, the number of interviews (981 in all) was too small to estimate a general visitation pattern to the estuary system. Thus, an intensive survey was undertaken in the summer of 1977 to observe, in conjunction with the roving count, the motor vehicle license plate numbers of fishing parties. From the license plate numbers, the vehicle's registration county, presumably the fishing party's county of residence, could be determined. In this way, the effective sample size was increased.

The results of the survey show that over 89 percent of fishermen at the Sabine-Neches estuary came from the following four counties: Jefferson (61.8 percent of the summer 1977 visitation), Orange (16.0 percent), Harris (9.3 percent), and Hardin (2.2 percent). A more general visitation pattern distinction of "local," "nonlocal" and "out-of-state" was also made. "Local", for the purposes of this study, includes counties within approximately 60 miles of the estuary area. For the Sabine-Neches estuary, these counties are Hardin, Jefferson and Orange. "Nonlocal" includes all other Texas counties.

Since it is expected that the proportions of local and nonlocal bay sportfishermen 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

Table 3-6. Estimated Seasonal Sport Fishing Visitation to the Sabine-Neches Estuary, 1975-1976 a/

Season b/	Boat	Wade-Bank	Total - All Strata
	thousands of parties		
Fall	8.3 (2.40)	18.3 (2.09)	26.6 (2.30)
Winter	3.0 (2.40)	8.9 (1.95)	11.9 (2.23)
Spring	9.8 (2.34)	17.6 (2.36)	27.4 (2.35)
Summer	16.5 (2.45)	23.4 (2.26)	40.0 (2.42)
Total All Seasons	37.6 (2.40)	68.3 (2.17)	105.8 (2.32)

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

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

Table 3-7. Estimated Seasonal Sport Fishing Visitation Patterns at the Sabine-Neches Estuary, 1975-1976

Visitation	Fall	Winter	Spring	Summer	Total-Annual
			thousands of parties		
Local	24.9	10.7	16.9	32.0	84.6
Nonlocal	1.6	1.2	10.4	7.8	21.0
Out-of-State	0.1	0.0	0.1	0.1	0.3
Total Visitation	26.6	11.9	27.4	40.0	105.8

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

Average Cost per Party	Boat	Wade-Bank	Weighted Average
		1976 dollars	
Local	8.75	4.52	7.72
Nonlocal	8.20	4.23	6.49

of fishing party expenditure data was grouped by origin (local or nonlocal) and strata (boat or wade-bank). 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). Over 39 percent of the estimated $628.9 thousand in expenditures were made during the summer and less than 11 percent were made during the winter quarter (Table 3-9).

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

Indirect impacts are the dollar values of goods and services that are used to supply the sectors which have made direct sales to fishing parties. Each directly affected sector has supplying sectors from which it purchases materials and services. The total amount of these successive rounds of purchases is known as the indirect effect. The total business effects of purchases of supplies and services by fishing parties upon the regional and state economies include the direct and indirect incomes resulting from the direct fishing business. Each economic sector pays wages, salaries and other forms of income to employees, owners and stockholders who in turn spend a portion of these incomes on goods and services. In this study, the method used to calculate this total impact is input-output analysis, using the Texas Input-Output Model (265) and regional input-output tables derived from the State model (270).1/

The expenditure data collected by personal interviews of a sample of fishing parties at the Sabine-Neches estuary (Table 3-9) indicated only the magnitude of variable expenditures by sport fishermen. To estimate the sectoral distribution of all expenditures, the interview data were supplemented with data from estimated retail sales in 1975 by marine sport fishing related industries in the West Gulf of Mexico region (Mississippi delta to Mexican border) (416). 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

1/ Input-Output relationships were estimated for Hardin, Jefferson and Orange Counties.

Table 3-9. Estimated Sport Fishing Expenditures by Season and Fishing Party Type, Sabine-Neches Estuary, 1975-1976

Season a/	Boat	Wade-Bank	Total	Percent
		thousands of 1976 dollars		
Fall	72.0	82.3	154.3	24.53
Winter	26.0	40.0	66.0	10.50
Spring	83.3	77.6	160.9	25.58
Summer	143.2	104.5	247.7	39.39
Total	324.5	304.4	628.9	100.0

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

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 Sabine-Neches estuary were over $615.2 thousand. In addition, there were an estimated $13.7 thousand spent outside the region, within Texas (Table 3-10). Most of the expenditure impact, over 97 percent, accrues to the region. However, when the total impacts are calculated, the regional gross impact of over $998.3 million accounts for less than half (49 percent) of the gross dollar value statewide (Table 3-11). This spreading of impact results from business and industry market linkages among regional establishments and suppliers throughout the State.

A significant portion (over 36 percent) of the direct expenditures by sport fishermen in the region results in increased personal incomes for regional households directly affected by the sport fishing industry. From these data it is estimated that regional households received an increased annual income of over $311.9 thousand from the sport fishing business in the area (Table 3-11). Statewide, the income impact amounted to over $580.9 thousand, annually.

The input-output analysis estimated a total of 38 full time job equivalents directly related to sport fishing in the Sabine-Neches estuary region in 1975 through 1976. The total employment impact to the state economy was 68 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 state tax revenues amounted to $21 thousand, with $7.9 thousand collected in the local region. Over $13 thousand in state revenues were received from the rest of the State and not from the surrounding estuarine region. Total tax revenue impacts for local jurisdictions within the region were an estimated $14.1 thousand resulting from direct, indirect and induced sport fishing expenditures, compared with almost $33 thousand statewide (Table 3-11).

The data show that sport fishing in the Sabine-Neches 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 $2.0 million represents a contribution to the State's economy from only the variable expenditures by sport fishermen in the estuary region and does not include the effects of purchases of sport fishing equipment.

Economic Impact of Commercial Fishing. The analysis of the commercial fishing industry in the Sabine-Neches estuary was somewhat limited by the availability of estuary-specific data. Estimates were made of the inshore-offshore catch associated with the estuary. However, the specific markets into which the fisheries catches were marketed are not known. Thus, for this portion of the analysis it was assumed that the markets were in Texas and that the statewide average prices were appropriate and applicable.

The average annual commercial fishing contribution of the estuary was estimated at 6,800 pounds (3,084 kg) of finfish and 4,113,700 pounds (1.9 million kg) of shellfish for the period 1972 through 1976. Using average 1976 dockside finfish and shellfish prices ($.357 per lb. and $1.456 per lb.,

Table 3-10. Estimated Sport Fishing Variable Expenditures by Sector, Sabine-Neches Estuary, 1975-1976

	Bait	Travel	Food	Lodging	Recreation a/	Total
	thousands of 1976 dollars					
Total	150.1	144.2	160.8	48.9	124.9	628.9 b/

a/ Marinas, boat fuel, and boat rental
b/ Adjusted for travel expenditures outside the study area of $13.7 thousand Expenditures in the region = $615.2 thousand

Table 3-11. Direct and Total a/ Economic Impact from Sport Fishing Expenditures, Sabine-Neches Estuary, 1975-1976 b/

	Direct c/		Total	
	Regional	State	Regional	State d/
Output (thousands)	$615.2	$628.9	$998.3	$2,035.3
Employment (Man-Years)	38	40	46	68
Income (thousands)	$226.8	$233.6	$311.9	$ 580.9
State Tax Revenues (thousands)	e/	$ 5.2	$ 7.9	$ 21.1
Local Tax Revenues (thousands)	e/	$ 7.8	$ 14.1	$ 32.7

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

respectively), the direct commercial value of fish attributed to the estuary was estimated at $5.99 million (1976 dollars) (384). Shellfish constituted approximately 99 percent of this value.

The Texas economy-wide total business resulting from commercial fish catch attributed to the Sabine-Neches estuary was estimated using the 1972 Texas Input-Output Model fisheries sector multipliers. Total value of the catch was $5.99 million in 1976, direct employment in the fisheries sector was 218, and direct salaries to fisheries employees was $2.0 million (Table 3-12).

Gross Texas business resulting from fishing, processing, and marketing the catch attributed to the estuary in 1976 was estimated at $18.66 million. Indirect supporting and marketing activities provided an additional 218 full time equivalent jobs regionally and an additional 245 full time equivalent jobs Statewide. Gross personal income in Texas attributed to the estuarine fishing and supporting sectors was estimated at $5.13 million, state taxes at $169.6 thousand, and taxes paid to local units of governments throughout Texas, as a results of this fishery business, at $235.5 thousand in 1976 (Table 3-12).

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

Sport fishing expenditures exert an effect upon the economies of the local regions where fishing occurs and upon the entire State because of transportation expenses, sport fishing equipment sales, and service sector supply and demand linkages directly and indirectly associated with fishing expenses. Direct business effects include expenditures for goods and services purchased by sport fishermen (transportation, food, lodging, equipment). Indirect impacts are the dollar value of goods and services that are used to 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 $615 thousand. In addition, there was an estimated $13.7 thousand spent outside the region, within Texas.

Over 36 percent of the direct expenditures by sport fishermen in the region resulted in increased personal incomes for regional households directly affected by the sport fishing industry. Statewide, the income impact amounted to over $580 thousand, annually. In addition, the total employment impact to the State economy was 68 full-time job equivalents.

Revenues to State and local government (including schools) were positively impacted by the increased business activity and gross dollar flows from the sport fishing industry. The total statewide State tax revenues amounted to almost $21 thousand. Overall, sport fishing resulted in a larger economic impact in areas outside the region than locally.

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

	Fishing Sector	Total	
		Regional	State
Output (1000's 1976 $)	5,992.0	9,701.0	18,665.0
Employment (Man-Years)	218	290	464
Income (thousands 1976 $)	2,001.9	3,191.1	5,131.9
State Tax Revenues (thousands 1976 $)	22.8	73.1	169.6
Local Tax Revenues (thousands 1976 $)	26.9	157.0	235.5

a/ Total = direct, indirect and induced

Estimates were made of the total (inshore+offshore) commercial fisheries harvest dependent upon the Sabine-Neches estuary. The average annual commercial fisheries contribution was estimated at 4,120,500 pounds (1.9 million kg) of finfish and shellfish for the period 1972 through 1976. The total value of the catch was $5.99 million in 1976, direct employment in the commercial fisheries sector was 218, and direct salaries to employees were $2.0 million.

CHAPTER IV

HYDROLOGY

Introduction

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

Freshwater Inflows

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

Gaged Inflows from the Sabine and Neches Basins

The Sabine and Neches Basins have a total gaged drainage area of 18,569 square miles (48,314 km^2). This inflow enters the estuary at the northern and western edge of Sabine Lake. Gaged contributions of the Sabine and Neches River Basins to the estuary have averaged 11,184,000 acre-feet/year (13,739 million m^3/yr) over the period 1941 through 1976 (Table 4-1). Gaged yields from the Sabine Basin and Neches Basin (1941 through 1976) have averaged 545 acre-feet per square mile (2,595 m^3/ha) and 653 acre-feet per square mile (3,109 m^3/ha), respectively. Gaged Sabine and Neches Basin inflows have accounted for 86 percent of the combined inflow[1/] and 85 percent of the total freshwater inflow[2/] to the Sabine-Neches estuary over the 1941 through 1976 period (Table 4-2).

Ungaged Runoff Contributions

Ungaged drainage areas contributory to the Sabine-Neches estuary include some 1,962 square miles (5,107 km^2) in the Trinity-Neches Coastal Basin, the

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

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

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

MONTH	GAGED SABINE FLOW	GAGED NECHES FLOW	TOTAL GAGED FLOW	UNGAGED INFLOW	RETURN FLOWS	NEC-SABINE RIVER DIVERSIONS	COMBINED INFLOW	PRECIPITATION ON BAY	TOTAL FRESHWATER INFLOW	BAY EVAPORATION LOSSES	FRESHWATER INFLOW BALANCE
AVERAGE OVER ALL YEARS											
JANUARY	802	639	1441	177	24	19	1623	16	1639	7	1632
FEBRUARY	763	617	1380	205	21	19	1587	16	1603	7	1596
MARCH	805	634	1439	125	27	28	1563	12	1575	9	1566
APRIL	761	613	1374	218	32	54	1570	17	1587	10	1577
MAY	871	797	1668	218	41	70	1857	18	1875	14	1861
JUNE	600	452	1052	161	44	75	1182	18	1200	17	1183
JULY	309	230	539	171	43	77	676	24	700	19	681
AUGUST	180	135	315	117	35	57	410	20	430	20	410
SEPTEMBER	189	134	323	191	27	38	503	23	526	18	508
OCTOBER	150	155	305	139	28	26	446	14	460	17	443
NOVEMBER	231	244	475	78	25	19	559	15	574	12	562
DECEMBER	477	385	862	143	24	19	1010	20	1030	9	1021
TOTALS	6136	5035	11173	1943	371	501	12986	213	13199	159	13040
AVERAGE	511	420	931	162	31	42	1082	18	1100	13	1087

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

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

MONTH	GAGED SABINE FLOW	GAGED NECHES FLOW	TOTAL GAGED FLOW	UNGAGED INFLOW	RETURN FLOWS	NEC-SABINE RIVER DIVERSIONS	COMBINED INFLOW	PRECIPITATION ON BAY	TOTAL FRESHWATER INFLOW	BAY EVAPORATION LOSSES	FRESHWATER INFLOW BALANCE
1941	10885	9663	20548	3130	189	136	23731	278	24009	137	23872
1942	6650	5455	12105	2682	196	274	14709	250	14959	147	14812
1943	3005	2297	5302	2403	241	338	7606	270	7878	156	7722
1944	9732	9218	18950	3320	291	408	22153	260	22413	152	22261
1945	12132	9284	21416	3074	287	404	24373	283	24656	154	24502
1946	13081	11121	24202	4145	626	236	28737	268	29005	149	28856
1947	7290	6576	13866	983	356	465	14740	183	14923	148	14775
1948	5429	3546	8975	598	723	877	9419	134	9553	148	9405
1949	7460	6139	13599	3640	702	826	17115	251	17366	160	17206
1950	10241	8486	18727	2312	732	878	20893	191	21084	170	20914
1951	3155	1634	4789	904	829	1009	5513	168	5681	157	5524
1952	4672	3245	7917	2010	746	896	9775	260	10035	172	9863
1953	9121	6907	16028	1738	850	1009	17607	203	17810	180	17630
1954	2848	1697	4545	323	849	1014	4703	131	4834	199	4635
1955	4045	2669	6714	1138	193	324	7721	226	7947	176	7771
1956	2553	1294	3847	1264	289	418	4982	195	5177	187	4990
1957	9623	6530	16153	2340	191	300	18384	251	18635	161	18474
1958	7230	5310	12540	1634	209	345	14038	237	14275	162	14113
1959	4732	4267	8999	2871	207	339	11738	290	12028	170	11858
1960	5481	5237	10718	1281	228	388	11839	233	12072	182	11890
1961	9399	8302	17701	2953	214	366	20502	237	20739	172	20567
1962	4094	3451	7545	432	257	445	7789	132	7921	173	7748
1963	2038	1738	3776	1994	261	421	5610	245	5855	149	5706
1964	2361	2196	4557	953	249	359	5400	180	5580	149	5431
1965	3080	1591	4671	506	266	420	5023	133	5156	174	4982
1966	3603	3266	6869	2880	259	372	9636	276	9912	134	9778
1967	1343	1140	2483	858	290	457	3174	182	3356	162	3194
1968	4645	5199	9844	2346	299	490	11999	246	12245	151	12094
1969	7866	6804	14670	1690	306	515	16151	181	16332	162	16170
1970	3432	2104	5536	2586	292	461	7953	212	8165	156	8009
1971	2303	1235	3538	799	308	501	4144	174	4318	191	4127
1972	4498	2751	7249	1487	302	474	8564	217	8781	181	8600
1973	11112	10964	22076	3738	308	483	25639	278	25917	175	25742
1974	8528	8017	16545	1541	330	534	17882	211	18093	187	17906
1975	9068	7997	17065	2129	315	532	18977	259	19236	175	19061
1976	4460	4098	8558	1507	311	524	9852	230	10082	183	9899
TOTAL	221195	181428	402623	70189	13501	18240	468073	7955	476028	5941	470087
AVERAGE	6144	5040	11184	1950	375	507	13002	221	13223	165	13058
MEDIAN	5080	4733	9421	1866	291	451	11788	231	12050	166	11874
PERCENT	46.5+	38.2=	84.6	+ 14.8	+ 2.9	- 3.9	= 98.4	+ 1.7	= 100.0	1.3	
PERCENT	47.3+	38.8=	86.1	+ 15.0	+ 2.9	- 3.9	= 100.0	1.7			

a/ Units are thousands of acre-feet.

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

Black Bayou Watershed, Louisiana, the Sabine River Basin, and the Neches River Basin. To facilitate the study of inflow contributions, the ungaged drainage contributing to the Sabine-Neches estuary was divided into six subbasins (Figure 4-1). Using a Thiessen network (361), the weighted daily precipitation was determined for each subbasin (Table 4-2). 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 gaged subbasins located within the contributing drainage area (354). Statistical correlations between monthly total inflow and simulated runoff were used to determine the "goodness of fit" of the calibration procedure. The calibrated model was then applied to the ungaged subbasin to calculate the ungaged runoff (Table 4-3).

During the period 1941 through 1976, ungaged runoff averaged 1,950,000 acre-feet/year (6.95 billion m^3/yr) and runoff yield averaged 994 acre-feet/mi^2 (4,736 m^3/ha). Ungaged inflow accounted for 15 percent of the combined inflow and 14.8 percent of the total freshwater inflow to the Sabine-Neches estuary over the 1941 through 1976 period (Table 4-2).

Ungaged Return Flows

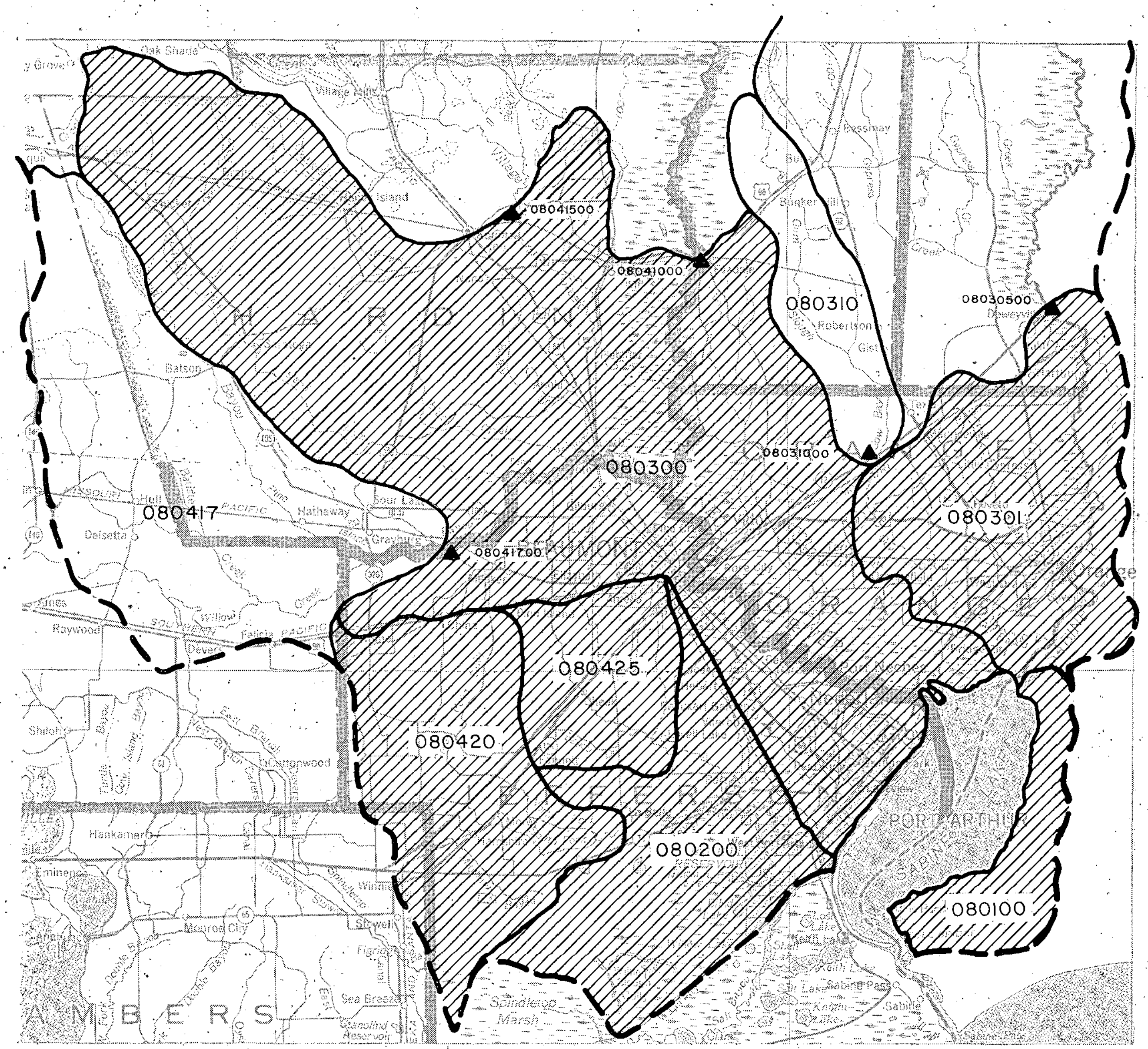
Return flows from municipalities and industries within the ungaged subbasins were estimated from data provided by the Texas Department of Water Resources (TDWR) self-reporting system. Irrigation return flows in ungaged areas were calculated using agency data collected in rice irrigation return flow studies (355, 358). Average return flows over the 1941 through 1976 period were approximately 375,000 acre-feet per year (462.9 million m^3/yr). Estimated ungaged return flow accounted for 2.9 percent of the combined inflow and 2.9 percent of the total freshwater inflow to the Sabine-Neches estuary (Table 4-2) over the 1941 through 1976 period.

Diversions

Reported diversion records for municipal, industrial and irrigation use within the ungaged subbasins were provided by the Texas Department of Water Resources (TDWR) reported water usage system. Average diversions over the 1941 through 1976 period were approximately 507,000 acre-feet per year (625.9 million m^3/yr). Estimated diversions accounted for 3.9 percent of the combined inflow and 3.9 percent of the total freshwater inflow to the Sabine-Neches estuary (Table 4-2) over the 1941 through 1976 period.

Combined Inflow

A category of "combined inflow" was obtained by aggregating gaged Sabine and Neches River contributions, and ungaged runoff. Over the period 1941 through 1976, combined inflow averaged 13,002,000 acre-feet/year (16.05 billion m^3/yr) (Table 4-2). Combined inflow accounted for 98 percent of the total freshwater inflow to the Sabine-Neches estuary over the 1941 through 1976 period. Average monthly distributions of combined inflow are shown in Figure 4-2. Wide variations in monthly combined inflow have occurred throughout the period of record (Figure 4-3).



EXPLANATION

Ungaged Drainage Areas

080420 Subbasin Number (See Table 4-3)

▲ 080451500 U.S.G.S. Gaging Station

0 30 60 Kilometers

0 30 60 Miles

Figure 4-1. Ungaged Areas Contributing to Sabine-Neches Estuary

Table 4-3. Runoff from Ungaged Areas, Sabine-Neches Estuary

Subbasin Description	Drainage Area (mi^2)	Weighted Precipitation: NWS a/ Station No.	Weighted Precipitation: Weight b/ Factor	Average Runoff ac-ft/mi^2 (1941-1976)	Average Curve Number c/ / Beta $x10^{-6}$ d/	Explained Variation: Annual r^2	Explained Variation: Monthly r^2	Gaged: USGS Station No.	Gaged: Period of Record
80100 Black and Johnsons Bayou (Louisiana)	100.0	7174 6664 2436	.08 .63	873	80/104.4				
80200 Neches-Trinity Ungaged	287.0	7174 6664	.87 .18	810	80/96.2				
80300 Neches ungaged	864.0	7174 2436 4878 9480	.33 .20 .39 .08	1030	85/80.5				
80301 Sabine ungaged	321.0	7174 6664 2436	.08 .63 .29	873	80/104.4				
80310 Cow Bayou near Mauriceville	93.3	6664 0611 2436 4819 4878	.02 .07 .47 .24 .20	852	83.8/91.4	.60	.61	08031000	1953-1976
80417 Pine Island Bayou near Sour Lake	336.0	0611 4878 5196 9480	.05 .19 .65 .11	897	86.1/81.7	.85	.60	08041700	1968-1976
80420 Taylor Bayou near near La Belle	262.0	7174 0235 0611	.33 .33 .34	1247	89/59.2				
80425 Hillebrandt Bayou near Lovelle Lake	128.0	0611 7174	.72 .28	1036	85/80.3				
Sabine River near Ruliff	9,329.0			653				08030500	1941-1976
Neches River at Evadale	7,951.0			532				08041000	1941-1976
Village Creek near Kountze	860.0			674				08041500	1941-1976

a/ National Weather Service
b/ Percentage of area of influence expressed as a factor (313)
c/ An assigned parameter for a particular hydrologic soil-cover complex (303)
d/ Soil moisture depletion coefficient (303)

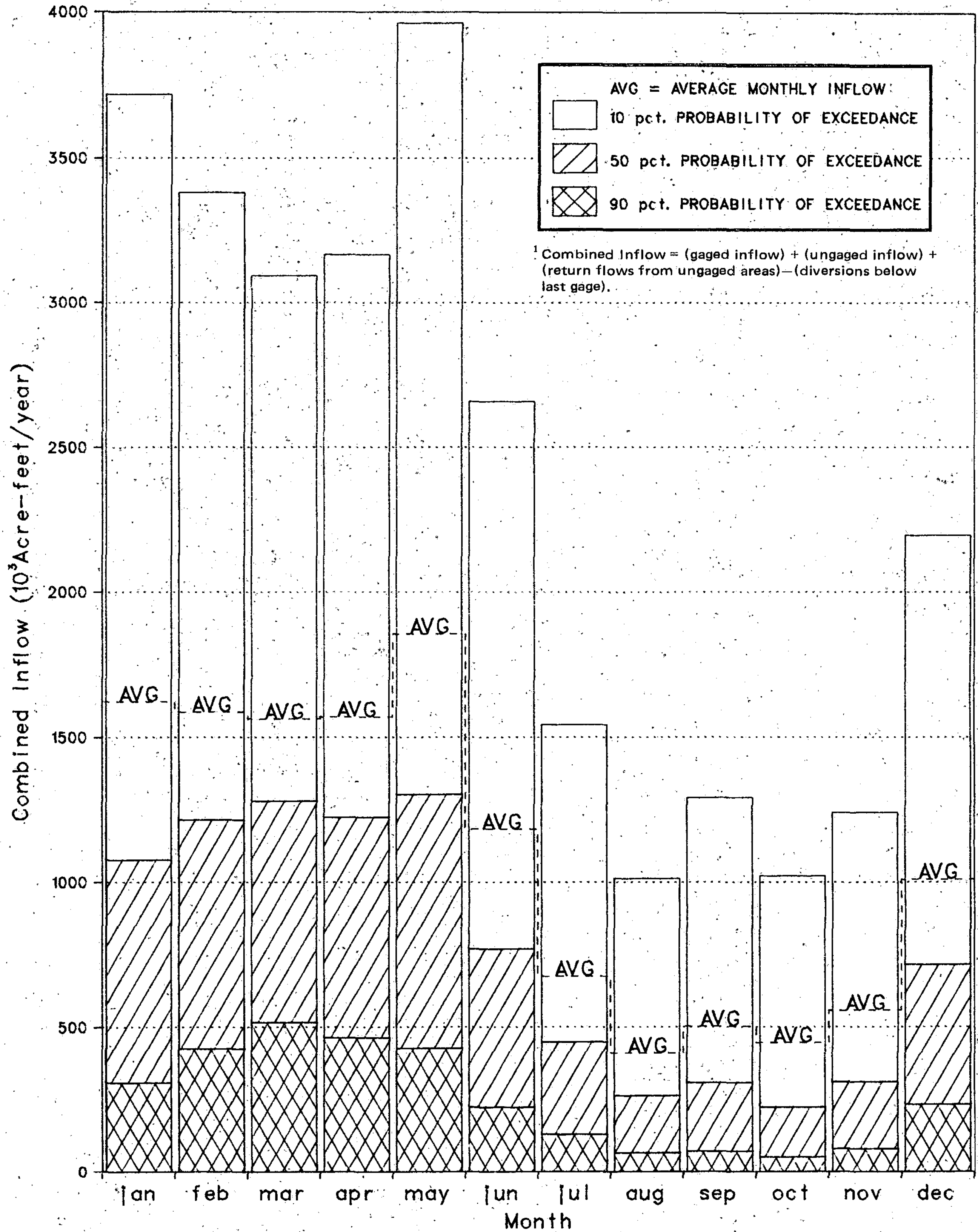


Figure 4-2. Monthly Distribution of Combined Inflow,[1] Sabine-Neches Estuary, 1941-1976

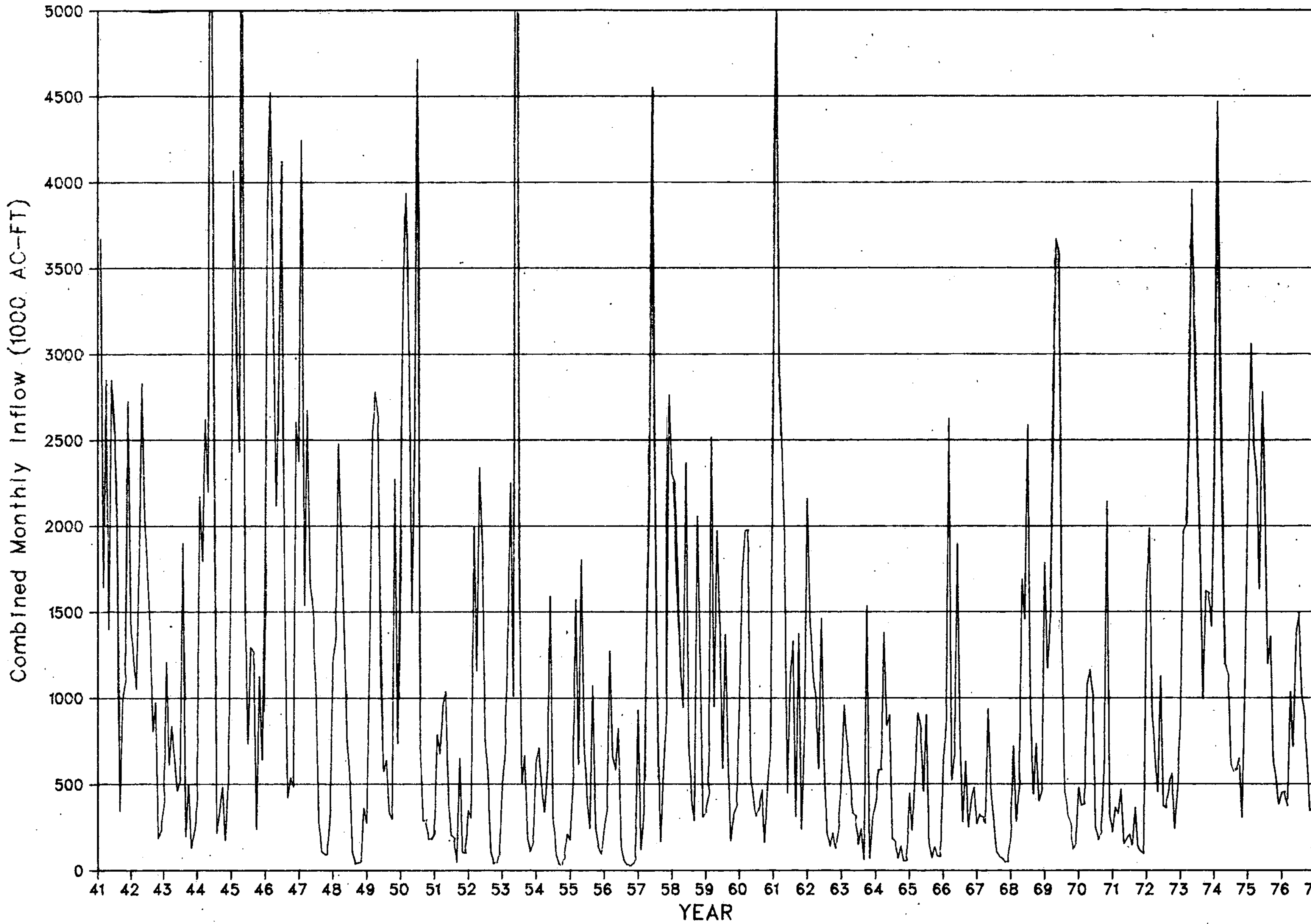


Figure 4-3. Combined Monthly Inflow to the Sabine-Neches Estuary, 1941-1976

Precipitation on the Estuary

Direct precipitation on the 43,960 acre (17,798 ha) surface area of the Sabine-Neches estuary was calculated using Thiessen-weighted precipitation techniques (385, 361). Over the 1941 through 1976 period, annual mean precipitation amounted to 221,000 acre-feet/year (270 million m^3/year). Direct precipitation accounted for 1.7 percent of the total freshwater inflow to the Sabine-Neches estuary over the period 1941 through 1976 (Table 4-2).

Total Freshwater Inflow

Total freshwater inflow includes gaged Sabine and Neches River contributions, ungaged runoff, and direct precipitation on the estuary. For the 1941 through 1976 period, average annual freshwater inflow amounted to 13,223,000 acre-feet (16.34 billion m^3). Average monthly distributions of total freshwater inflow are shown in Figure 4-4.

Bay Evaporation Losses

Gross surface evaporation rates for the estuary were calculated from Texas Department of Water Resources pan evaporation data (356). Since the reduction in evaporation due to estuarine salinity is never in excess of a few percent (over an extended period of time), salinity effects were omitted in the estimation of evaporation rates. Over the period 1941 through 1976, mean evaporation over the 43,960 acre (17,798 ha) estuary surface averaged 165,000 acre-feet/year (200 million m^3/yr). When compared to total freshwater inflow, evaporation on the estuary's surface was about 1.3 percent of total inflow over the 1941 through 1976 period.

Freshwater Inflow Balance

A freshwater inflow balance for the period of 1941 through 1976 is shown in Table 4-2. For the 1941 through 1976 period, the mean freshwater inflow balance amounted to 13,058,000 acre-feet/year (16.14 billion m^3/yr).

Variations in Inflow Components through Drought and Flood Cycles

Although previous paragraphs have described the components of freshwater inflow in terms of annual and monthly average values over the 1941 through 1976 period, there have been wide variations from the mean as a result of recurrent drought and flood conditions. Monthly inflows and their corresponding exceedance frequencies are shown in Table 4-4. The "50%" column for each component inflow represents a 50 percent probability that the corresponding inflow will be exceeded in the given month. These values can be compared to average values given in Table 4-1. Columns marked "10%" (probability of exceedance) indicate component values for wet year conditions, one year in ten. Columns marked "90%" (probability of exceedance) indicate component values for drought conditions, one year in ten. Further illustration of near limit probabilities are provided by Figures 4-2 and 4-4 for combined inflow and total freshwater inflow, respectively.

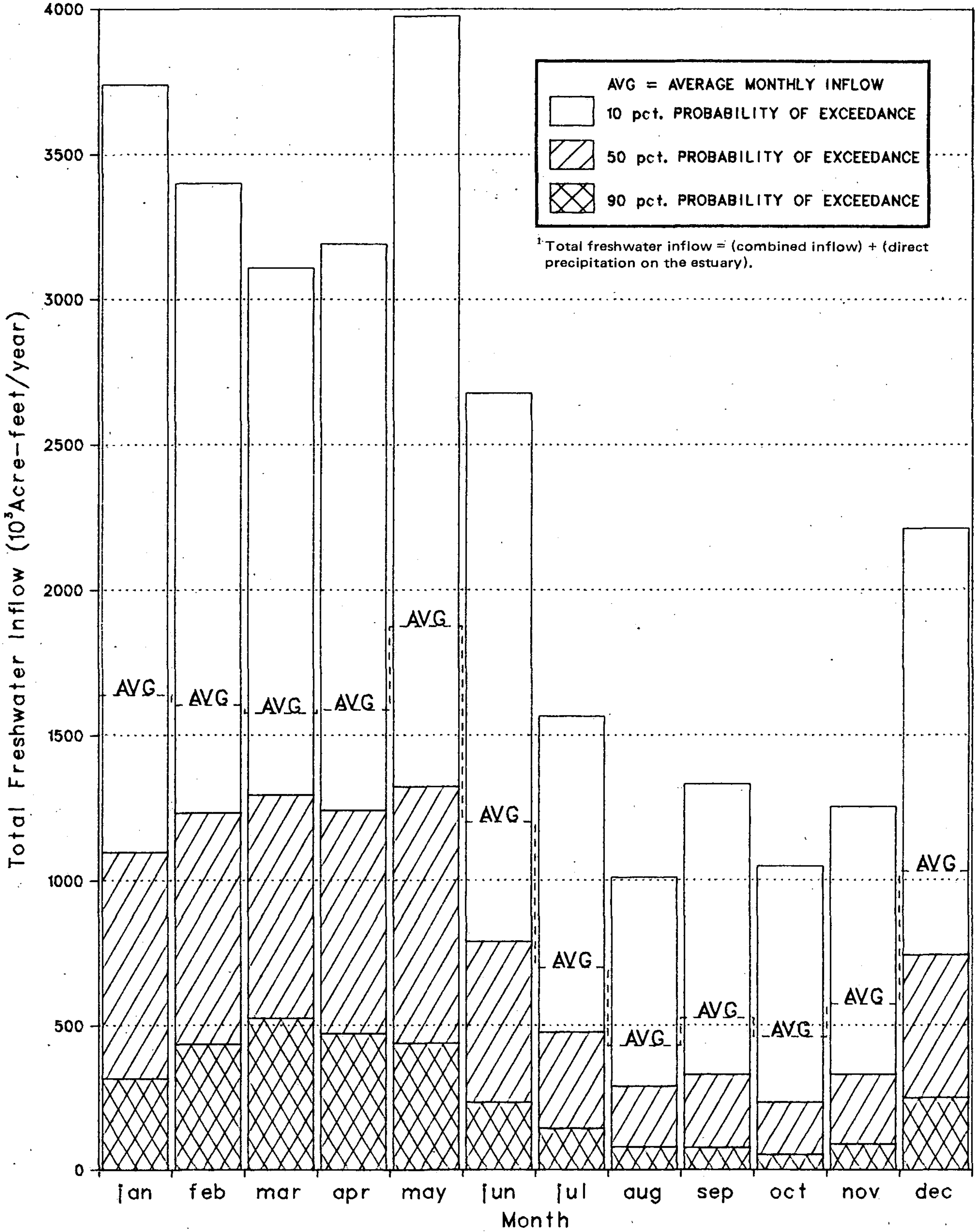


Figure 4-4. Monthly Distribution of Total Freshwater Inflow,[1] Sabine-Neches Estuary, 1941-1976

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

Month	Gaged Sabine Basin Inflow			Gaged Neches Basin Inflow			Total Ungaged Inflow			Ungaged Inflow			Combined Inflow			Precipitation on Bay			Total Freshwater Inflow			Bay Evaporation Losses		
	10%	50%	90%	10%	50%	90%	10%	50%	90%	10%	50%	90%	10%	50%	90%	10%	50%	90%	10%	50%	90%	10%	50%	90%
January	1,805	538	160	1,625	377	84	3,324	934	261	557	81	11	3,720	1,077	309	34	14	5	3,741	1,097	318	10	8	6
February	1,601	595	214	1,451	436	125	2,928	1,049	368	607	108	15	3,381	1,215	426	33	13	5	3,400	1,232	436	10	7	5
March	1,586	661	269	1,326	490	178	2,861	1,164	465	447	57	4	3,093	1,280	517	25	11	4	3,108	1,294	526	11	9	8
April	1,563	588	215	1,188	484	198	2,702	1,084	430	692	91	11	3,166	1,224	464	36	14	5	3,191	1,241	473	14	11	8
May	1,853	604	197	1,751	542	166	3,495	1,175	397	698	90	7	3,963	1,303	427	41	14	5	3,976	1,323	439	17	14	12
June	1,341	395	117	966	306	99	2,276	717	228	471	58	6	2,658	771	224	43	14	5	2,678	790	235	21	17	14
July	673	214	68	459	168	63	1,118	391	139	488	65	6	1,544	449	130	44	21	10	1,566	477	145	23	19	15
August	403	126	39	275	95	34	666	228	78	336	38	3	1,013	264	66	39	17	8	1,010	290	81	24	21	18
September	441	122	33	296	85	25	727	211	62	575	79	0	1,292	309	71	56	16	5	1,332	330	78	22	18	15
October	330	94	27	359	83	20	685	182	49	381	18	0	1,022	224	51	37	8	1	1,048	234	54	21	17	14
November	488	136	39	555	111	23	1,022	256	67	246	24	0	1,240	312	80	30	13	5	1,254	331	90	15	12	10
December	1,026	327	106	950	229	54	1,905	571	174	335	94	14	2,197	717	234	35	19	10	2,212	743	250	12	9	7

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

Quality of Gaged Inflows

Three USGS gaging stations monitor the quality of inflows to the Sabine-Neches estuary: Station No. 08030500 (Sabine River near Ruliff), Station No. 08041000 (Neches River at Evadale), and Station No. 08041700 (Pine Island Bayou near Sour Lake). The range of water quality parameters that were experienced in the 1977 water year are tabulated in Figure 4-5. During the period, 10-12 samples were available for most parameters, although nutrient data were lacking at the Pine Island Bayou station near Sour Lake.

Student's t-test were performed on the data to determine if any statistical differences (two-tailed test) were evident among the sample means for the three gaging stations. It was found that for many parameters the difference between the mean values was not statistically significant. However, sample means from the Neches River at Evadale were significantly higher (statistically) than the other two stations for silica, magnesium and sulfate. The Pine Island Bayou station near Sour Lake had mean values for calcium and chloride that were significantly higher (statistically) than the other two stations.

In general, the water quality of flows draining to the Sabine-Neches estuary has been very good. No parameters were found in violation of Texas stream standards.

Quality of Estuarine Waters

Nutrient Concentrations in the Sabine-Neches Estuary

Historical concentrations of carbon, nitrogen, and phosphorus in Texas estuarine systems are largely unknown. Until 1968, water quality parameters in the open bays had not been monitored on a regular long-term basis. A regular program of water quality data collection in Texas estuaries was initiated by the cooperative efforts of the U.S. Geological Survey and the Texas Department of Water Resources. Concurrent with the cooperative efforts of these two agencies, additional nutrient data were also made available through contract work performed by Espey, Huston, and Associates, Inc. from 1974 to 1975 (55). Manpower and monetary constraints now limit the number of sites and frequency of sampling.

Available data can be used to determine general 1969 through 1977 concentrations of carbon, nitrogen, and phosphorus (CNP) in the Sabine-Neches estuary. For the study, the estuary was considered as one entire segment. 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 in open waters.

The Sabine and Neches Rivers, are the major sources of freshwater inflow into the estuary with the Sabine River accounting for 46.5 percent and the Neches River accounting for 38.2 percent of the mean annual total freshwater inflows into the estuary. The CNP concentrations in Sabine-Neches estuary would, therefore, be expected to exhibit a decreasing gradient from Upper Sabine Lake outward into the Gulf of Mexico.

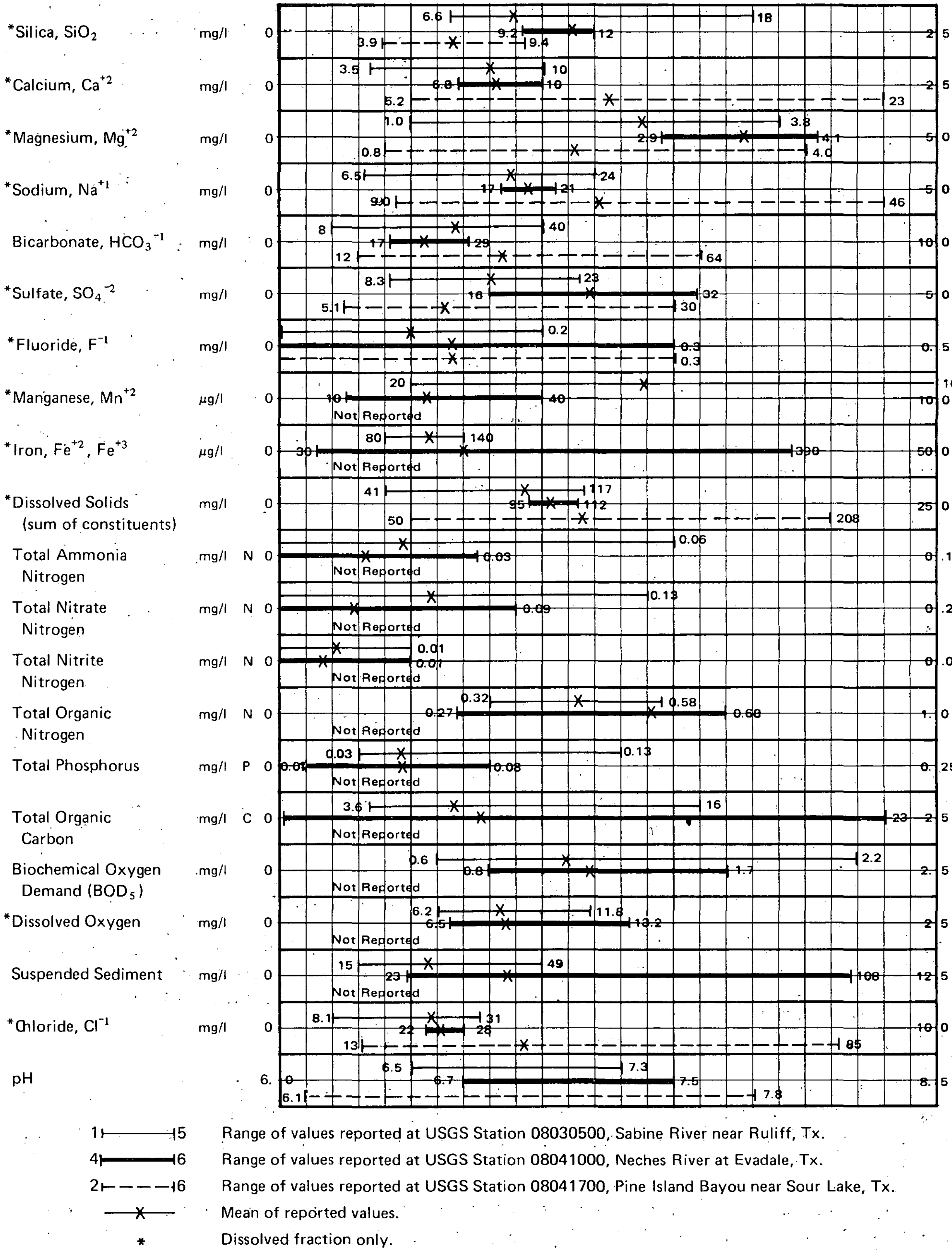


Figure 4-5. Range of Values for Water Quality Parameters, Gaged Inflow to Sabine-Neches Estuary, October 1976-September 1977

Ammonia nitrogen, nitrate nitrogen, and nitrite 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 nitrogen, total phosphorus, total Kjeldahl nitrogen, and total organic carbon data were summed and averaged, respectively, for each of the following seasons: 1) winter (January, February, and March); 2) spring (April, May, and June); 3) summer (July and August); 4) autumn (September and October); and 5) late fall (November and December) to arrive at seasonal averages for the year, for the period 1969 through 1977. Average seasonal nutrient isolines and spatial representations were then determined for total nitrogen, total phosphorus, total organic carbon, and total Kjeldahl nitrogen for each of the seasons of the year, for the period 1969 through 1977 (Figures 4-6 through 4-25). The total nitrogen concentrations ranged from near zero to 1.11 mg/l. The average seasonal total nitrogen concentrations showed a decreasing gradient from Upper Sabine Lake to Sabine Pass in all seasons except late fall. The total phosphorus concentrations, however, ranged from near zero to 0.43 mg/l. The average seasonal concentrations were relatively uniform throughout the year and were less than 0.10 mg/l in all seasons except winter. The total organic carbon ranged from 3.0 mg/l to 31.0 mg/l. The available data showed that the lowest average seasonal total organic carbon concentrations (of less than 7-9 mg/l) occurred in both summer, and autumn during which times the freshwater inflows into the Sabine-Neches estuary were lower than any other seasons of the year. Total Kjeldahl nitrogen ranged from 0.11 mg/l to 1.44 mg/l. Only in spring (a high inflow season) did the total Kjeldahl nitrogen concentrations show a definite decreasing concentration gradient from Upper Sabine Lake to Sabine Pass.

Heavy Metals

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

Samples of the bottom sediments in the Sabine-Neches estuary are available for the period of record (1968, and 1973 to 1978) at only six data collection sites shown in Figure 4-26. Sampling efforts have been 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), copper (Cu), iron (Fe), lead (Pb), managanese (Mn), mercury (Hg), nickel (Ni), strontium (Sr), and zinc (Zn).

Statistical analyses were not possible due to the limited number of samples for the period of record (1968, and 1973 to 1978). The range of values for heavy metals detected in the Sabine-Neches estuary are listed in Table 4-5.

Accumulation of metals in bottom deposits may not be detectable in overlying water samples, yet still exert an influence from time to time. Wind and tide induced water movements, ship traffic and dredging activities are some physical processes that can cause mixing of materials from the sediment into the water; chemical changes resulting from seasonal temperature fluctuation, oxygenation, and respiration can influence the rate of movement and distribution of dissolved substances between water and sediment.

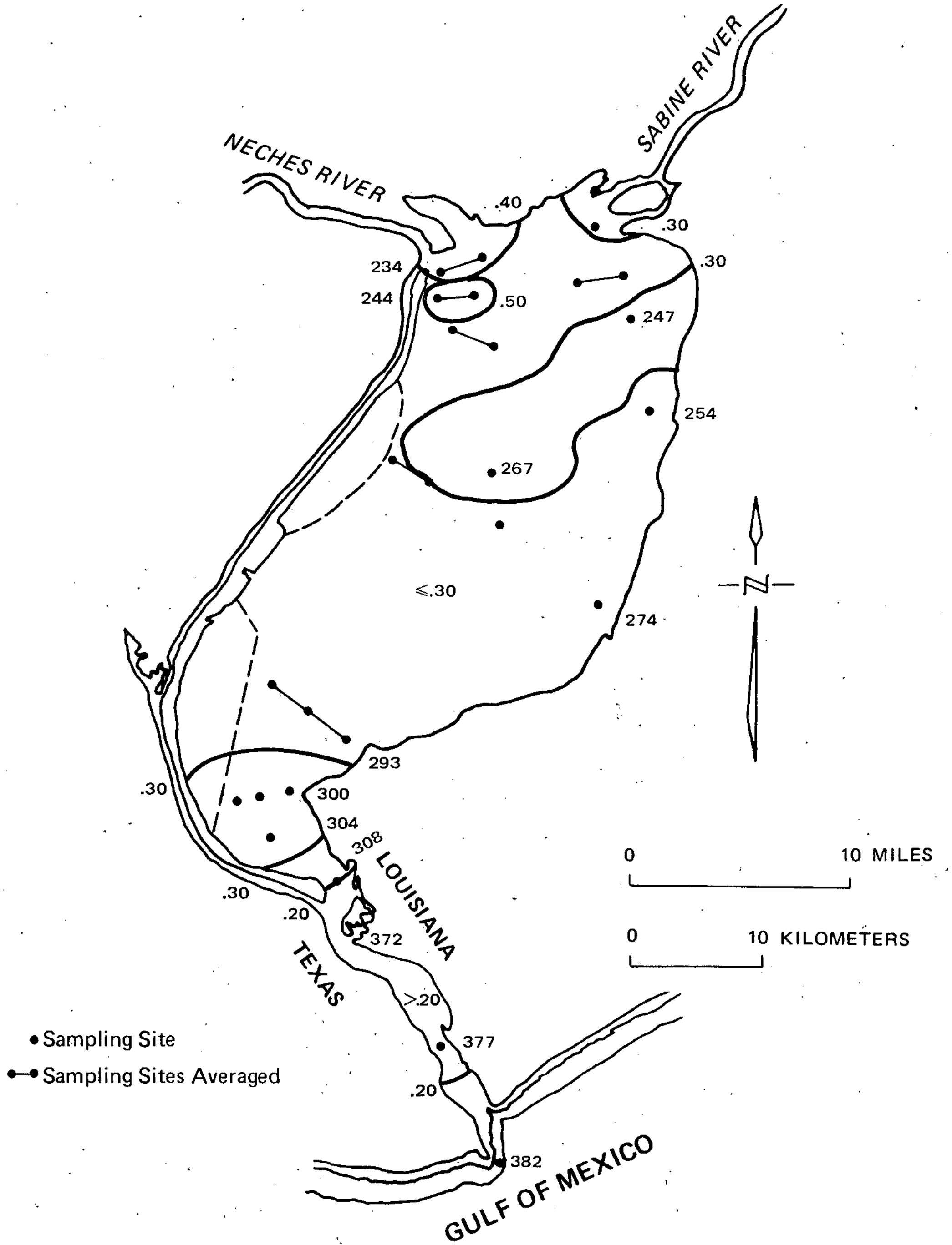


Figure 4-6. Average Seasonal Concentrations of Total Nitrogen, Winter (January, February, and March) 1969-1977

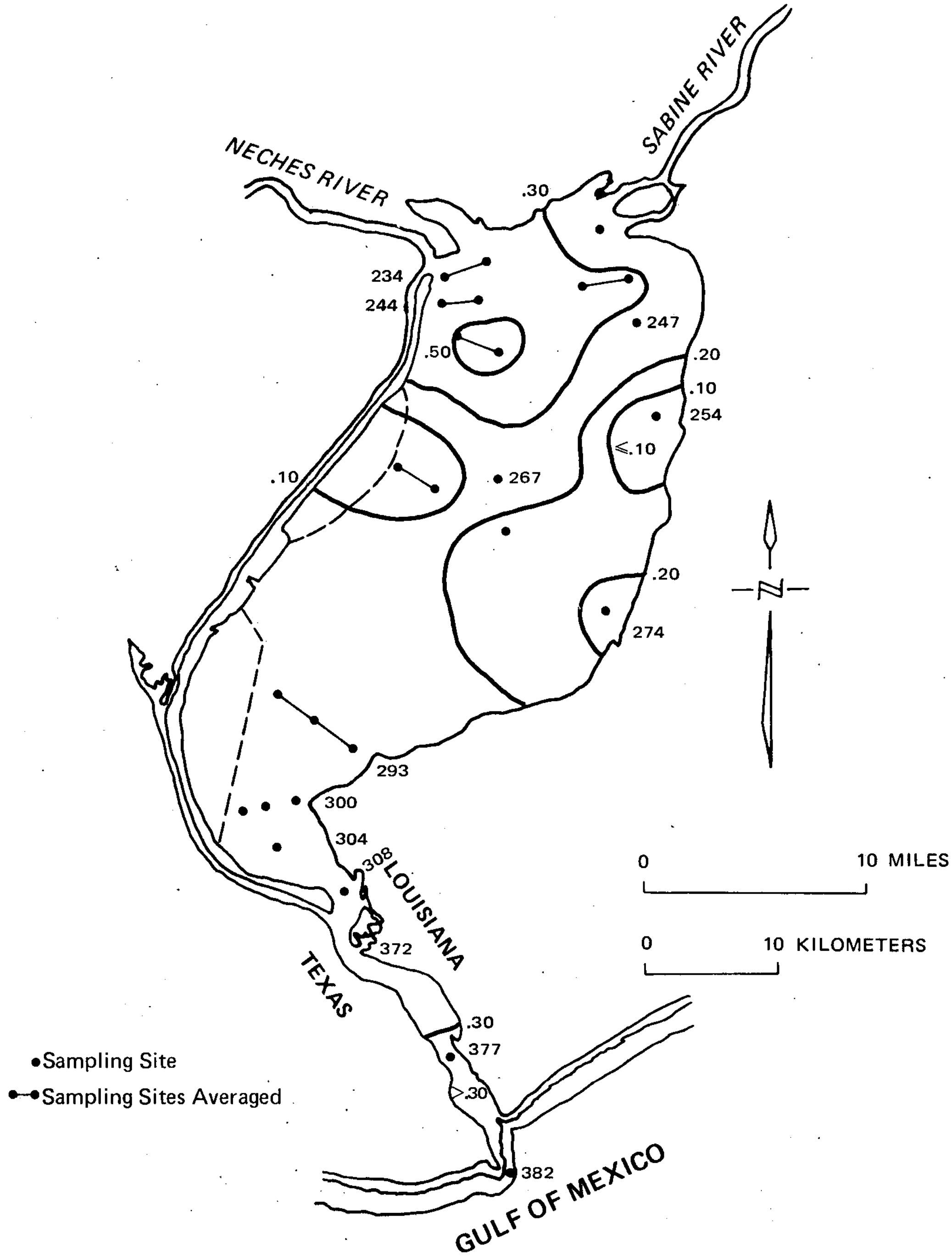


Figure 4-7. Average Seasonal Concentrations of Total Nitrogen, Spring (April, May, and June) 1969-1977

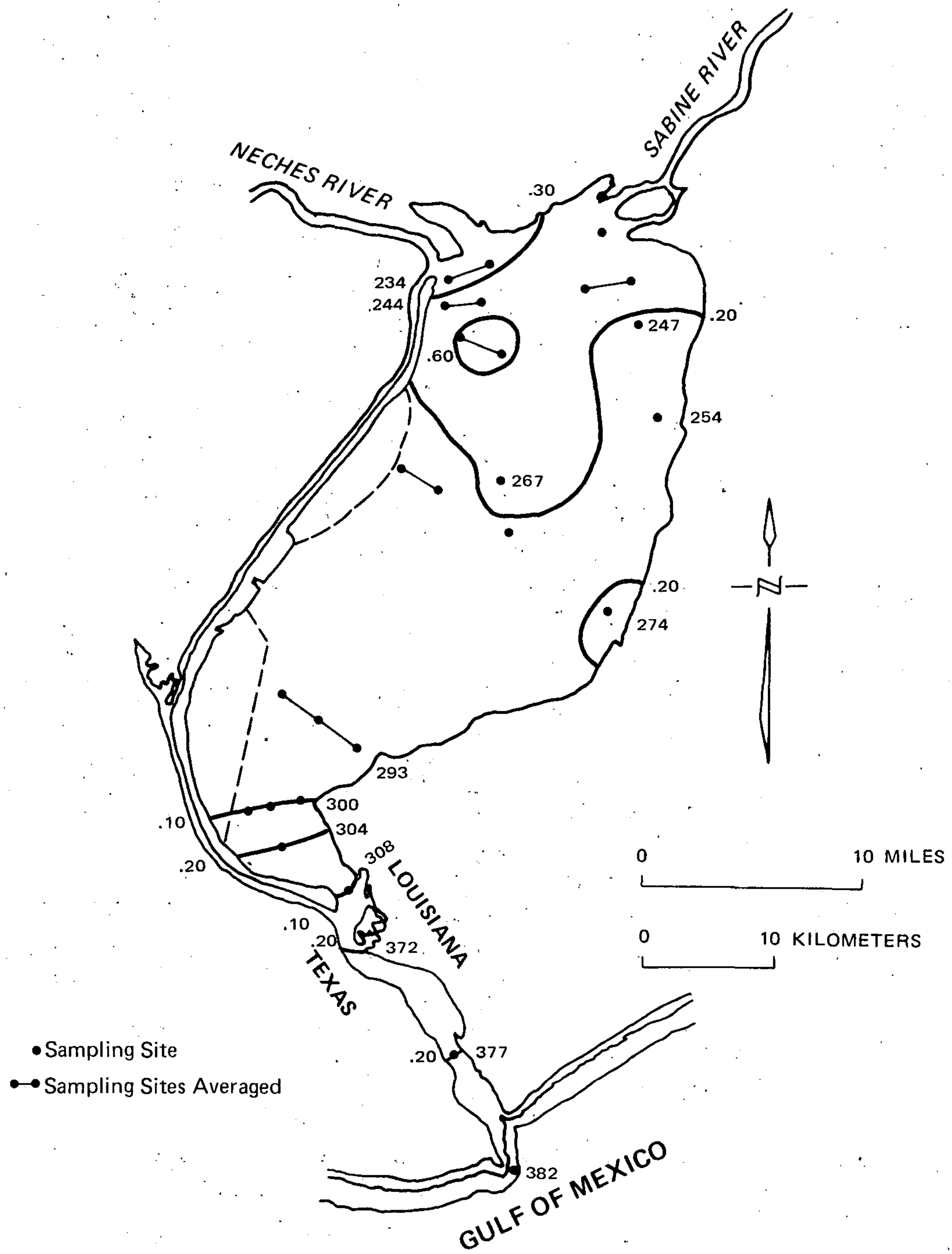


Figure 4-8. Average Seasonal Concentrations of Total Nitrogen, Summer (July and August) 1969-1977

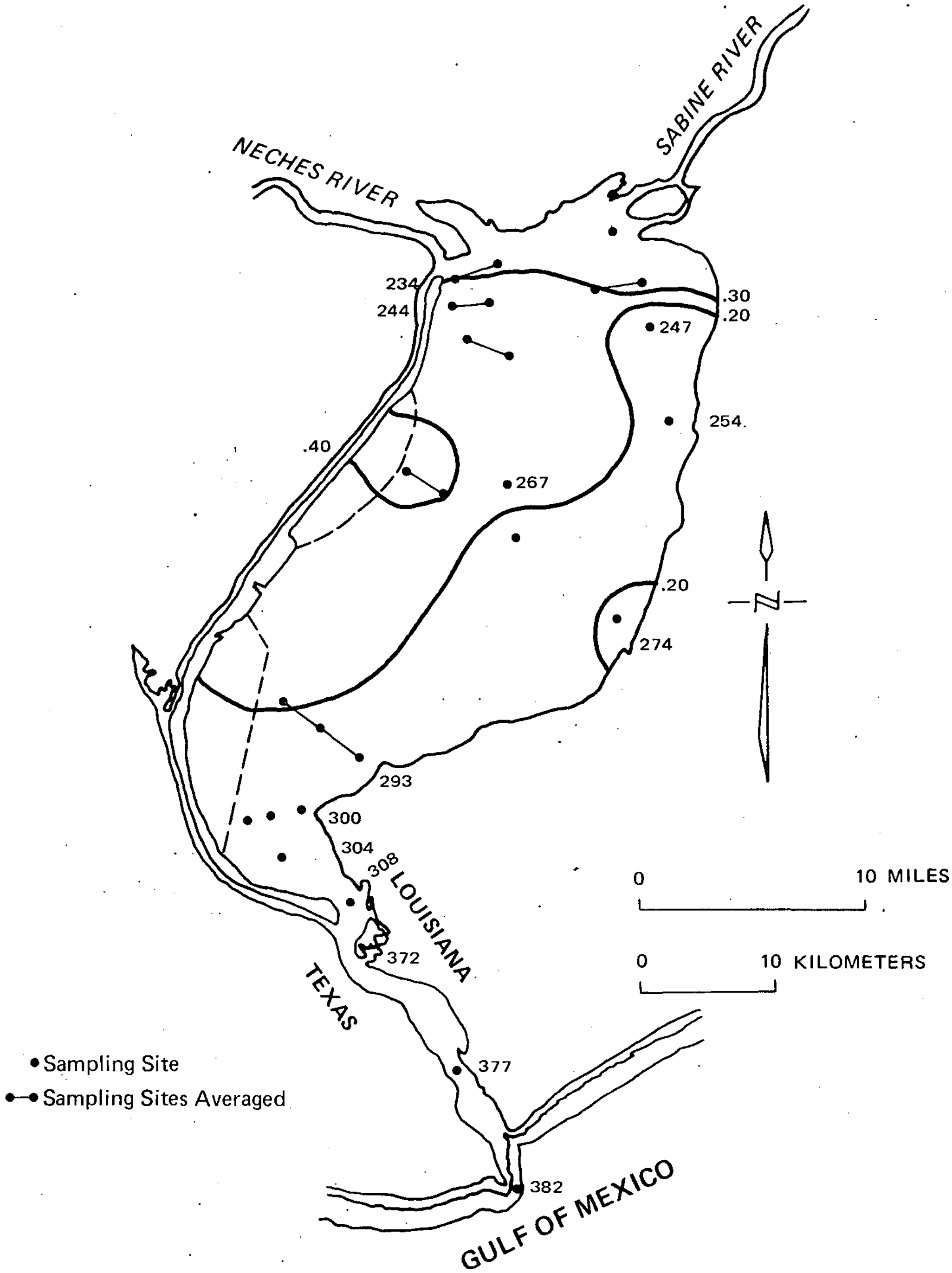


Figure 4-9. Average Seasonal Concentrations of Total Nitrogen, Autumn (September and October) 1969-1977

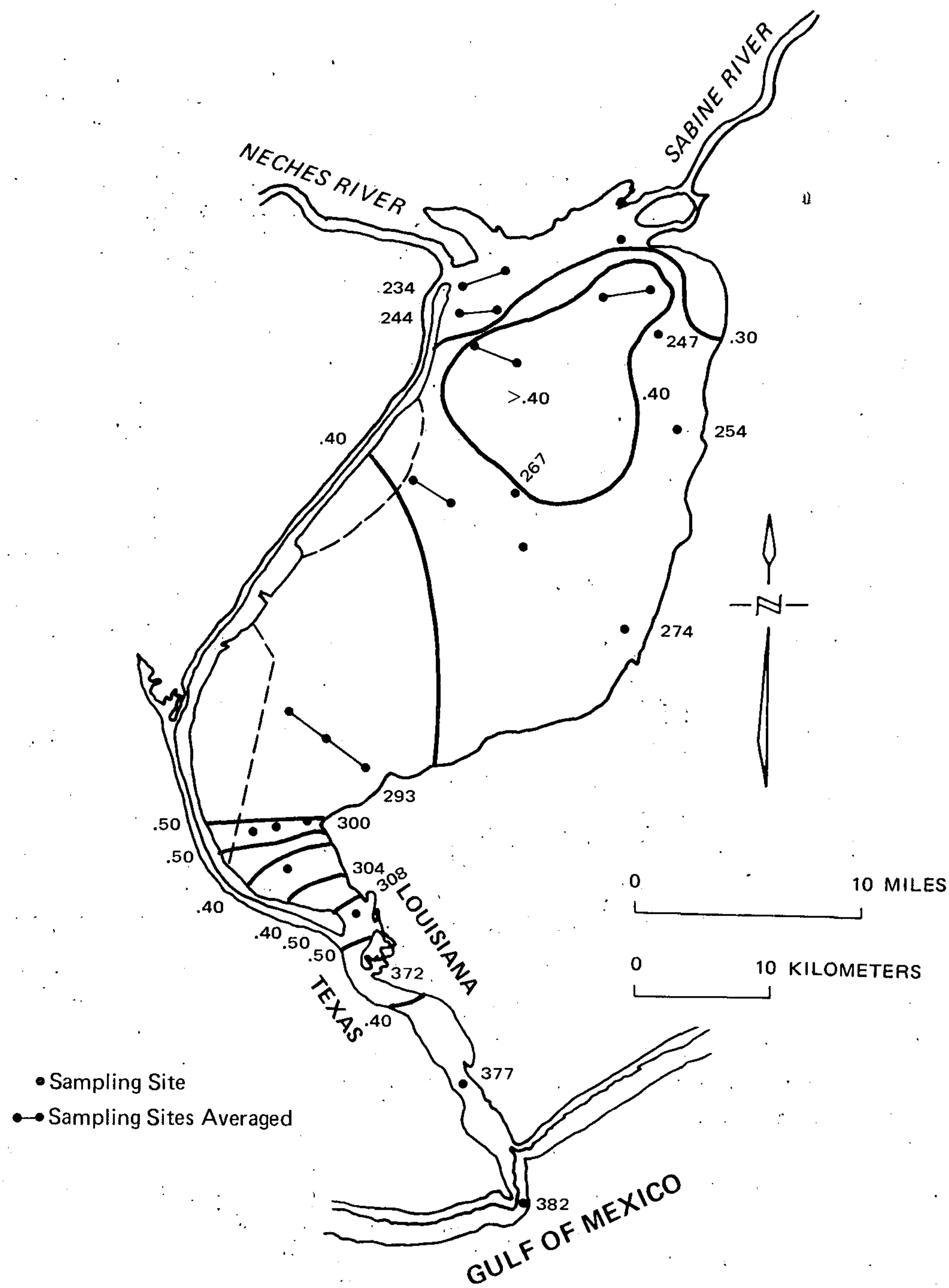


Figure 4-10. Average Seasonal Concentrations of Total Nitrogen, Late Fall (November and December) 1969-1977

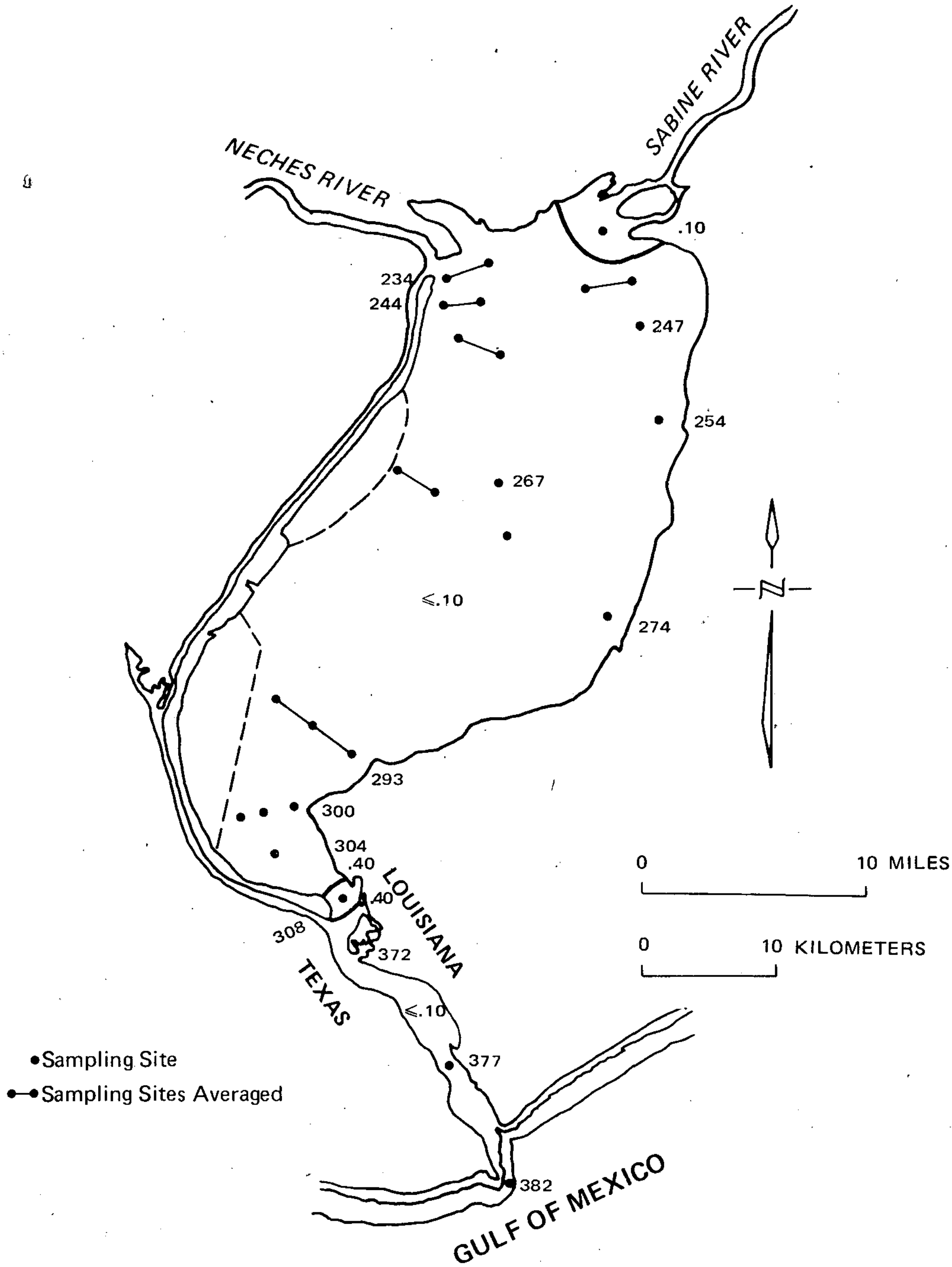


Figure 4-11. Average Seasonal Concentrations of Total Phosphorus, Winter (January, February, and March) 1969-1977

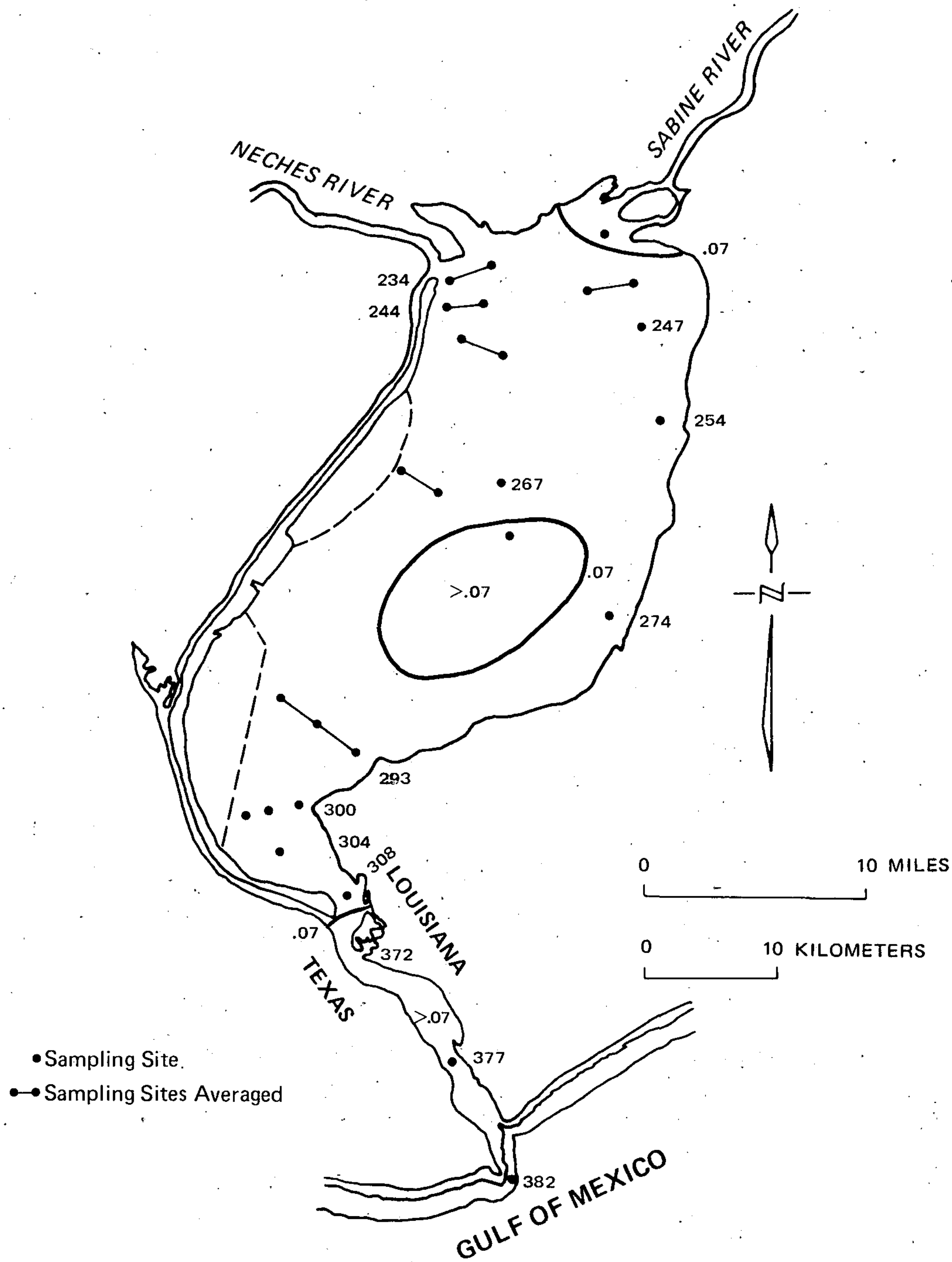


Figure 4-12: Average Seasonal Concentrations of Total Phosphorus, Spring (April, May, and June) 1969-1977

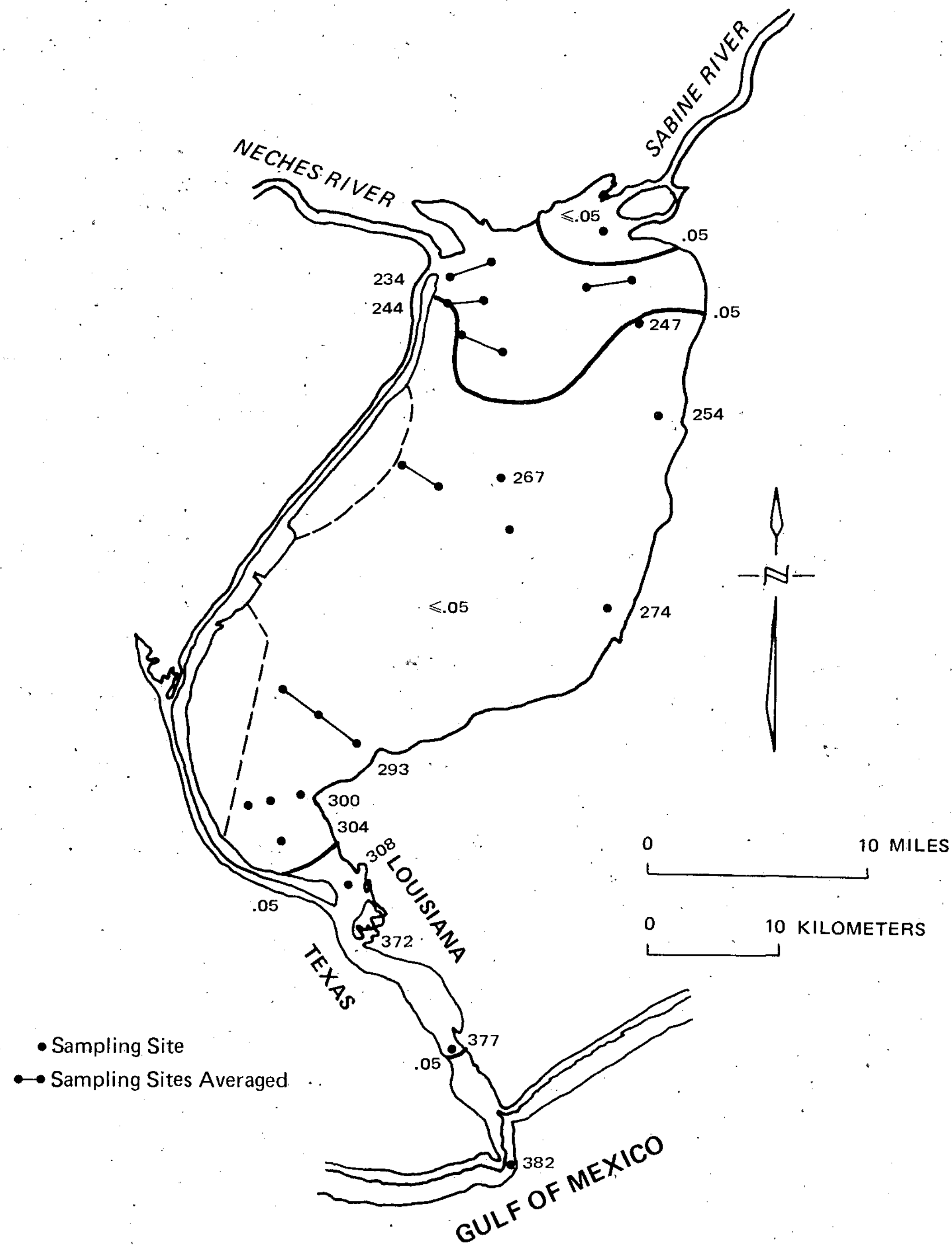


Figure 4-13. Average Seasonal Concentrations of Total Phosphorus, Summer (July and August) 1969-1977

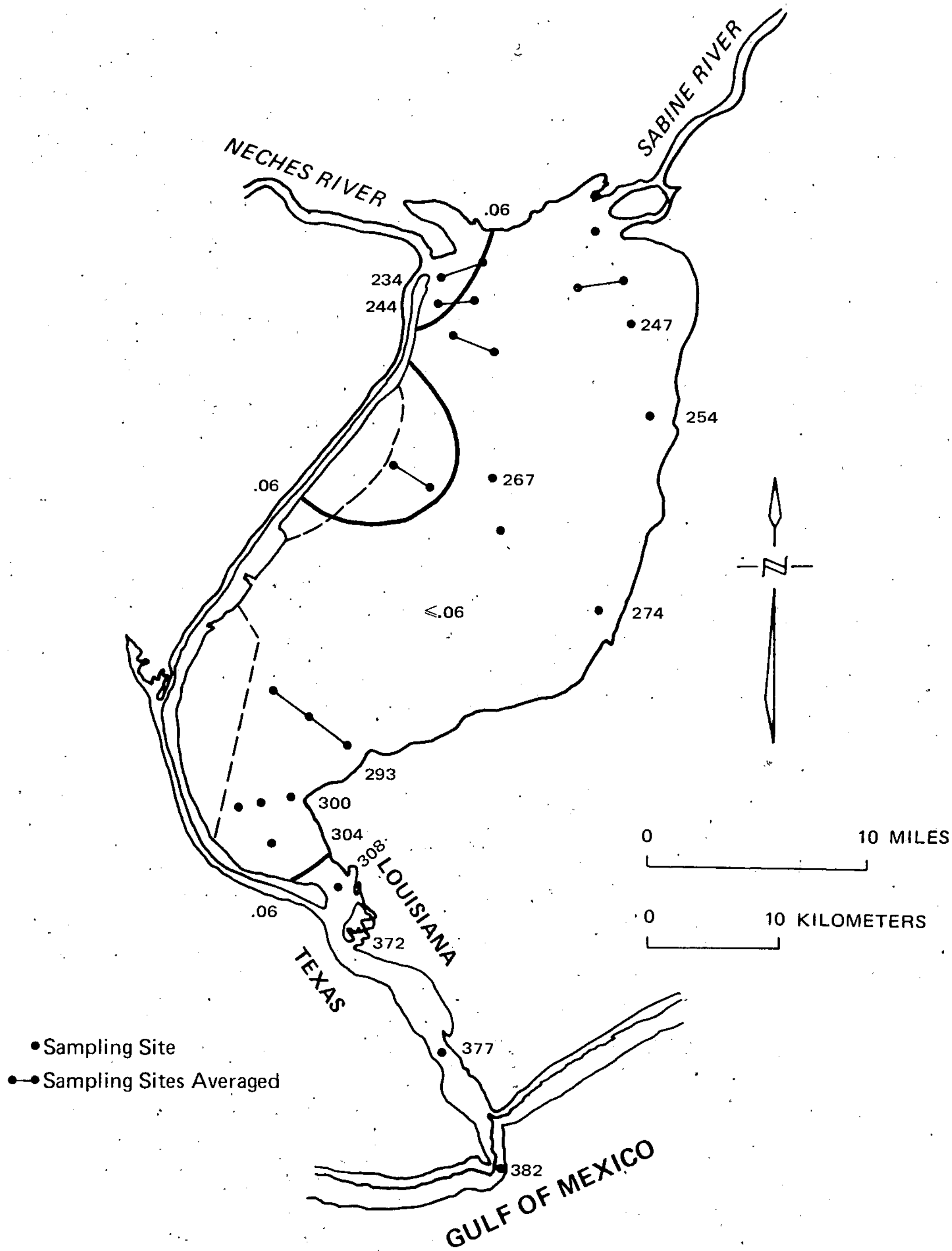


Figure 4-14. Average Seasonal Concentrations of Total Phosphorus, Autumn (September and October) 1969-1977

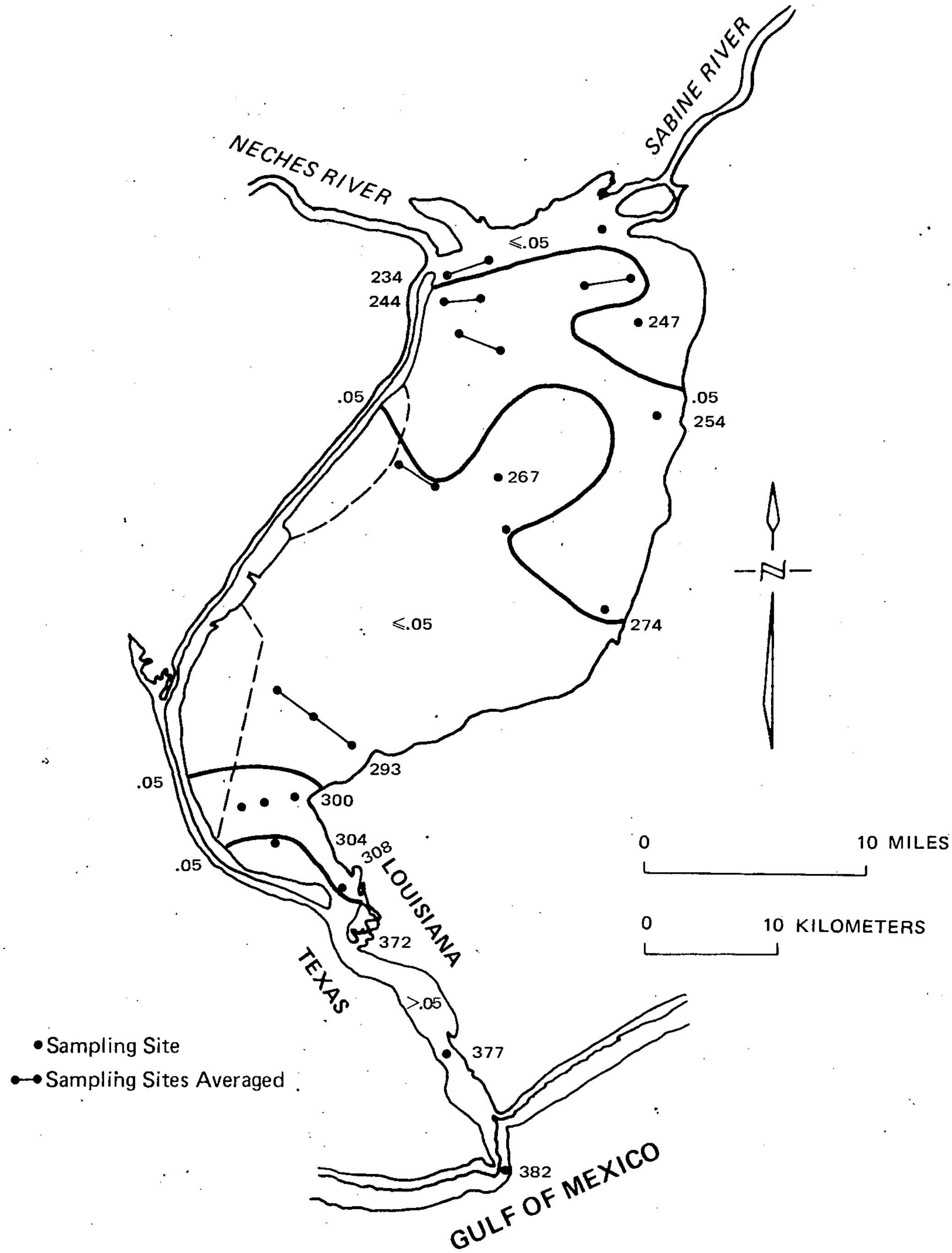


Figure 4-15. Average Seasonal Concentrations of Total Phosphorus, Late Fall (November and December) 1969-1977

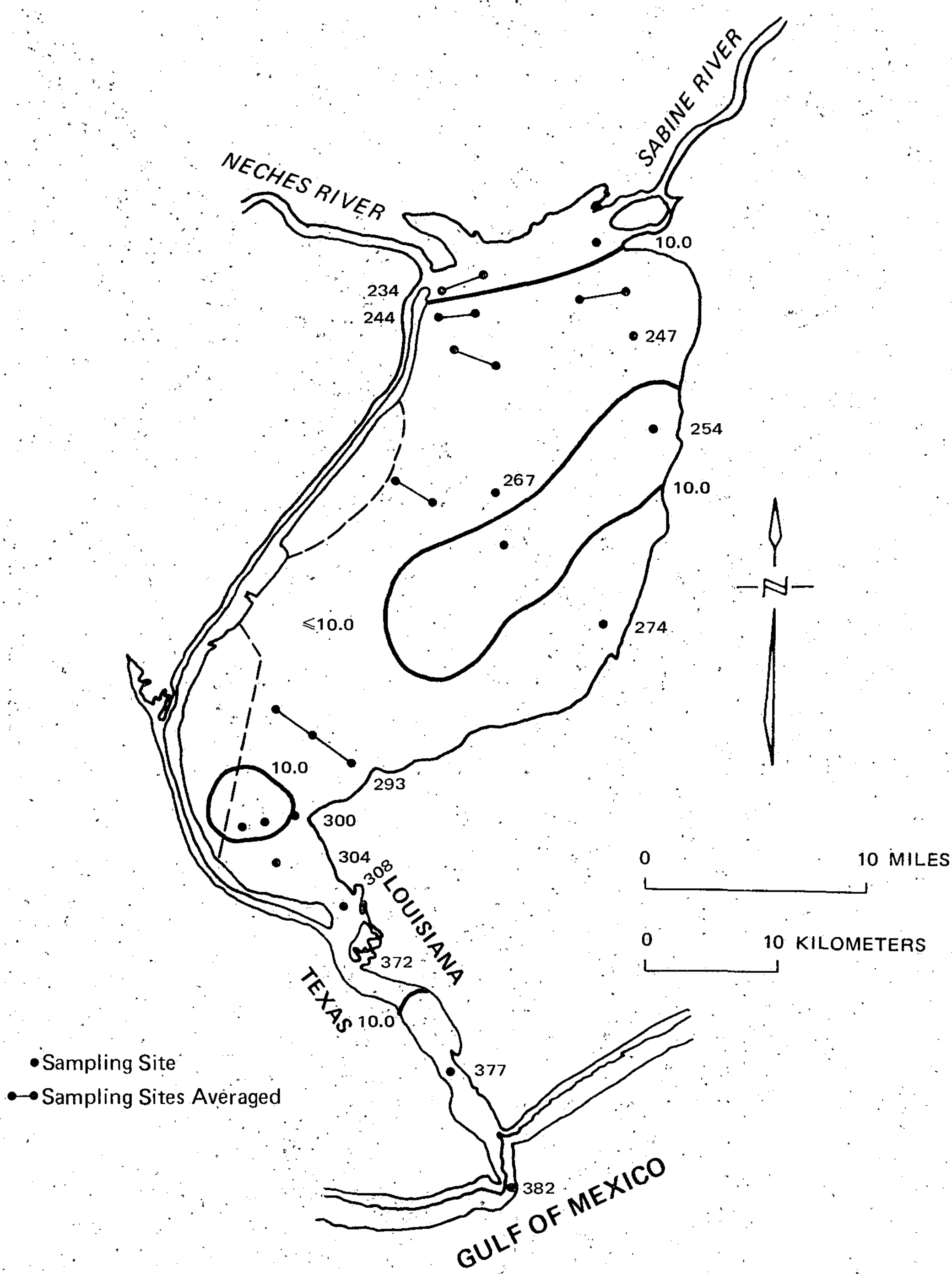


Figure 4-16. Average Seasonal Concentrations of Total Organic Carbon, Winter (January, February, and March) 1969-1977

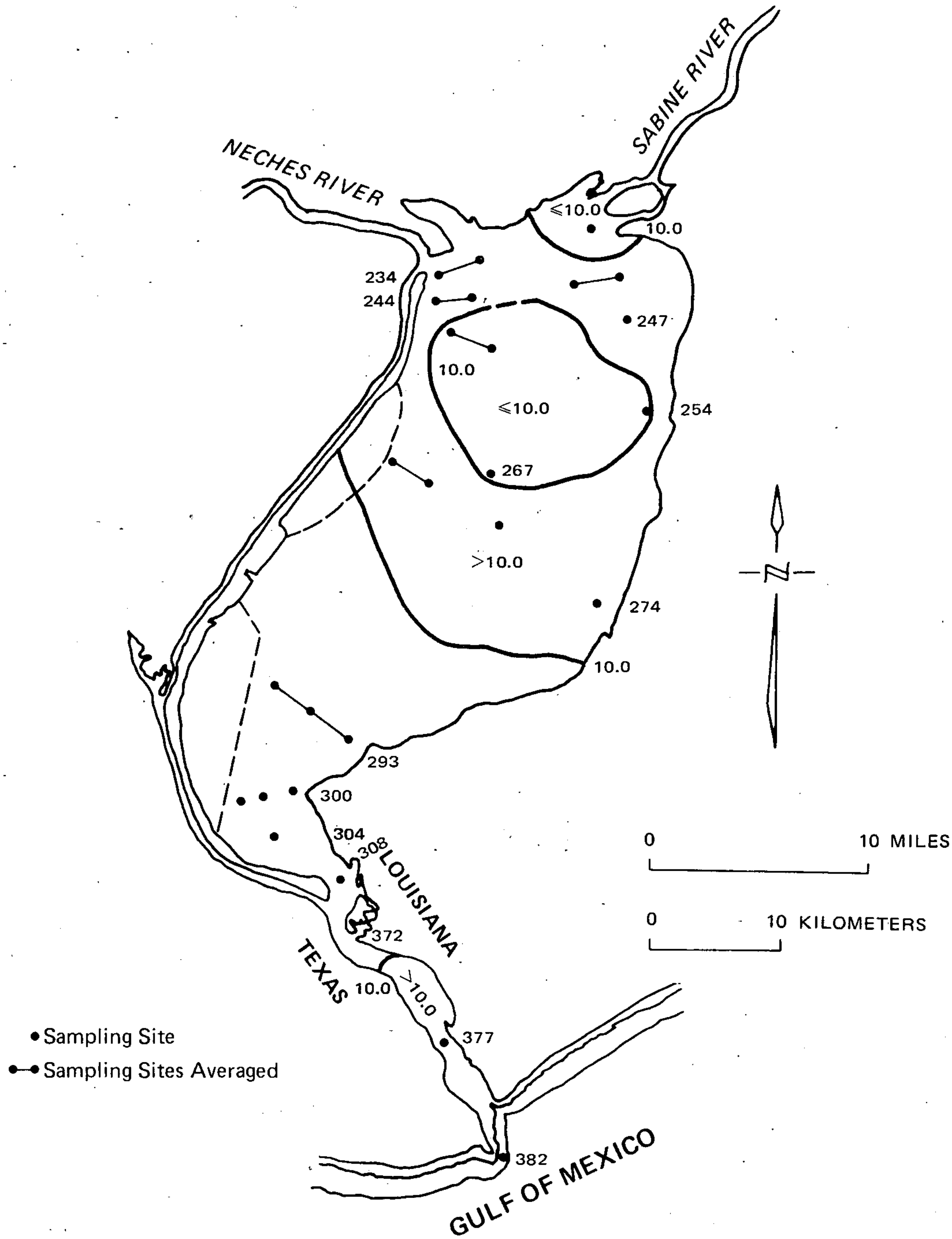


Figure 4-17. Average Seasonal Concentrations of Total Organic Carbon, Spring (April, May, and June) 1969-1977

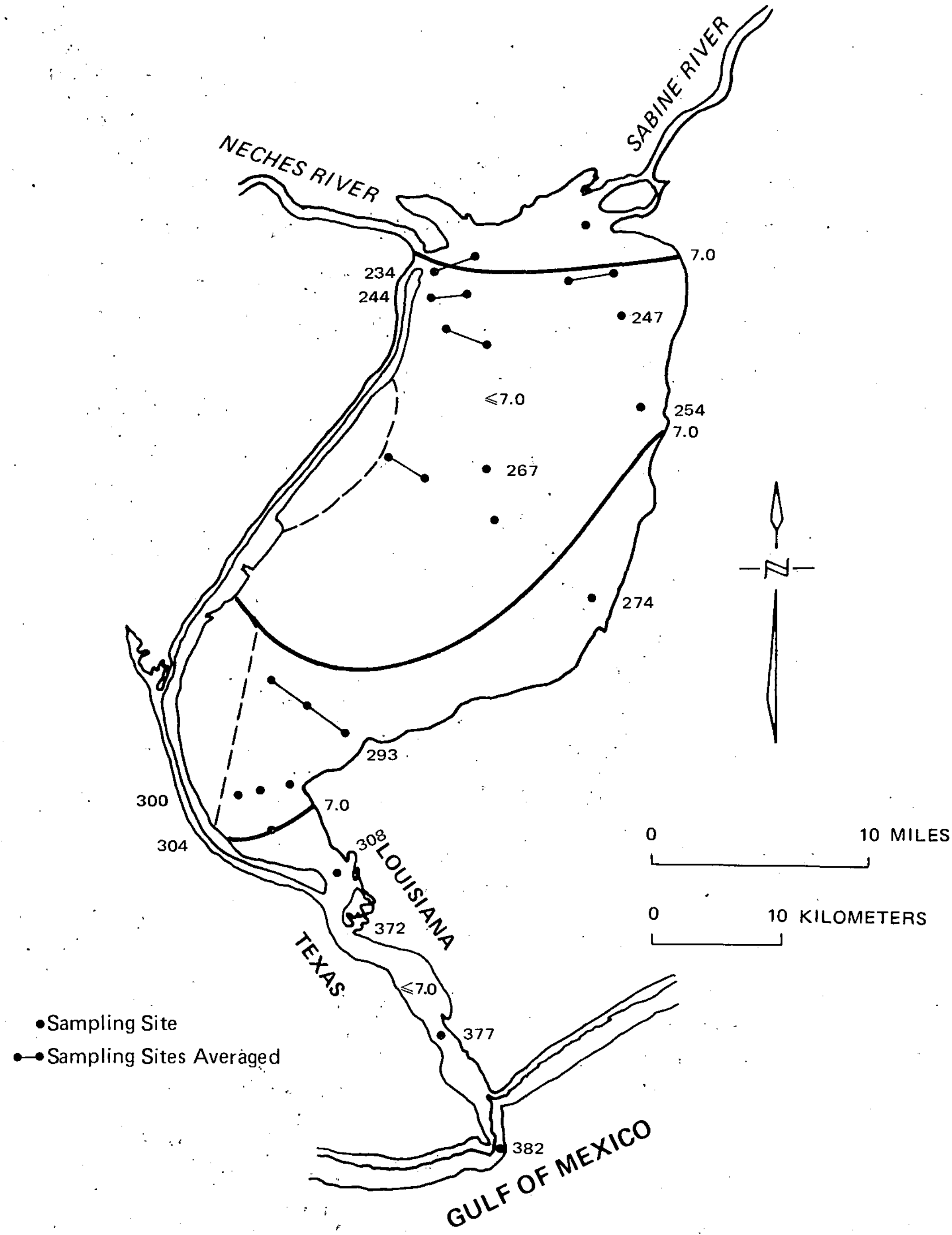


Figure 4-18. Average Seasonal Concentrations of Total Organic Carbon, Summer (July and August) 1969-1977

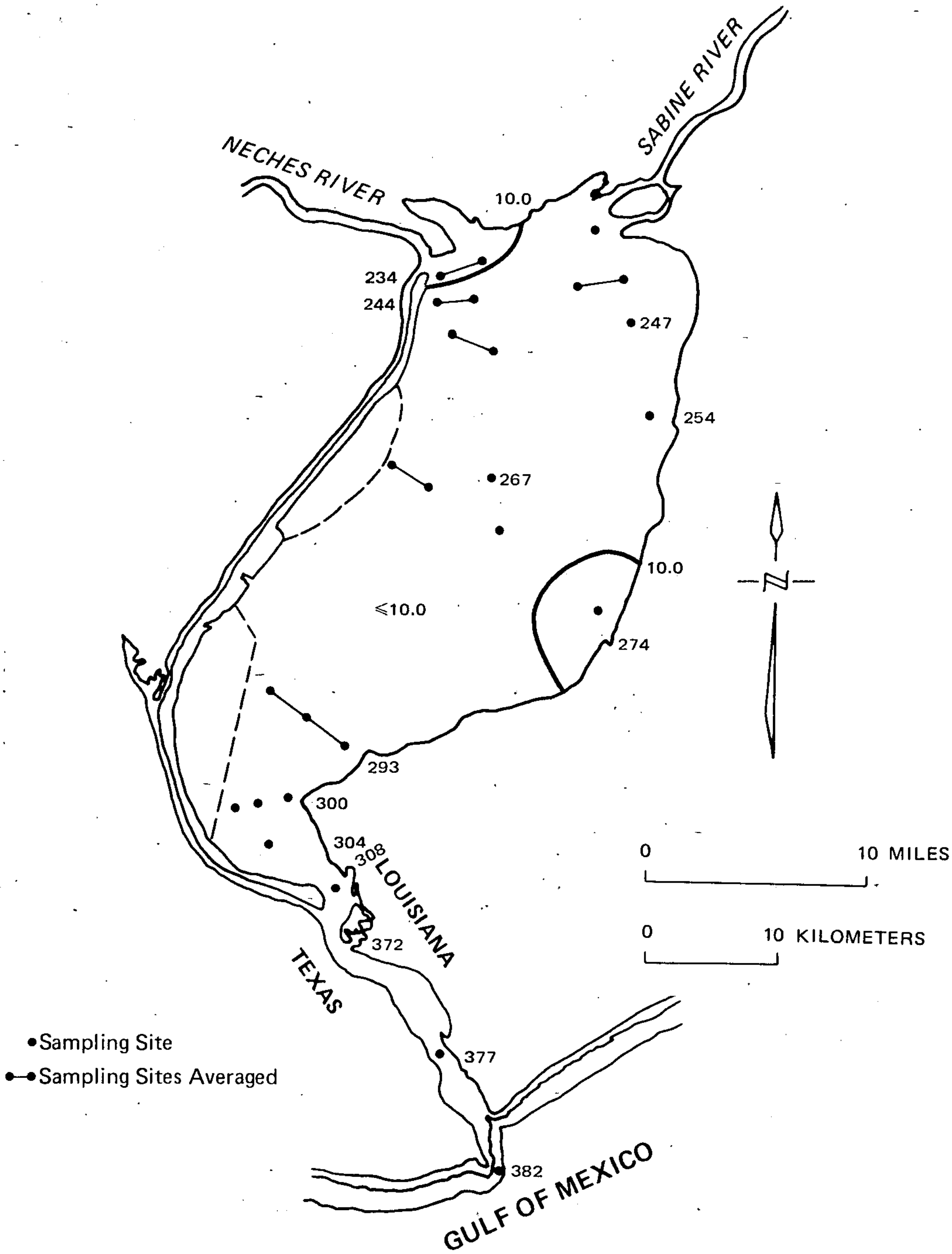


Figure 4-19. Average Seasonal Concentrations of Total Organic Carbon, Autumn (September and October) 1969-1977

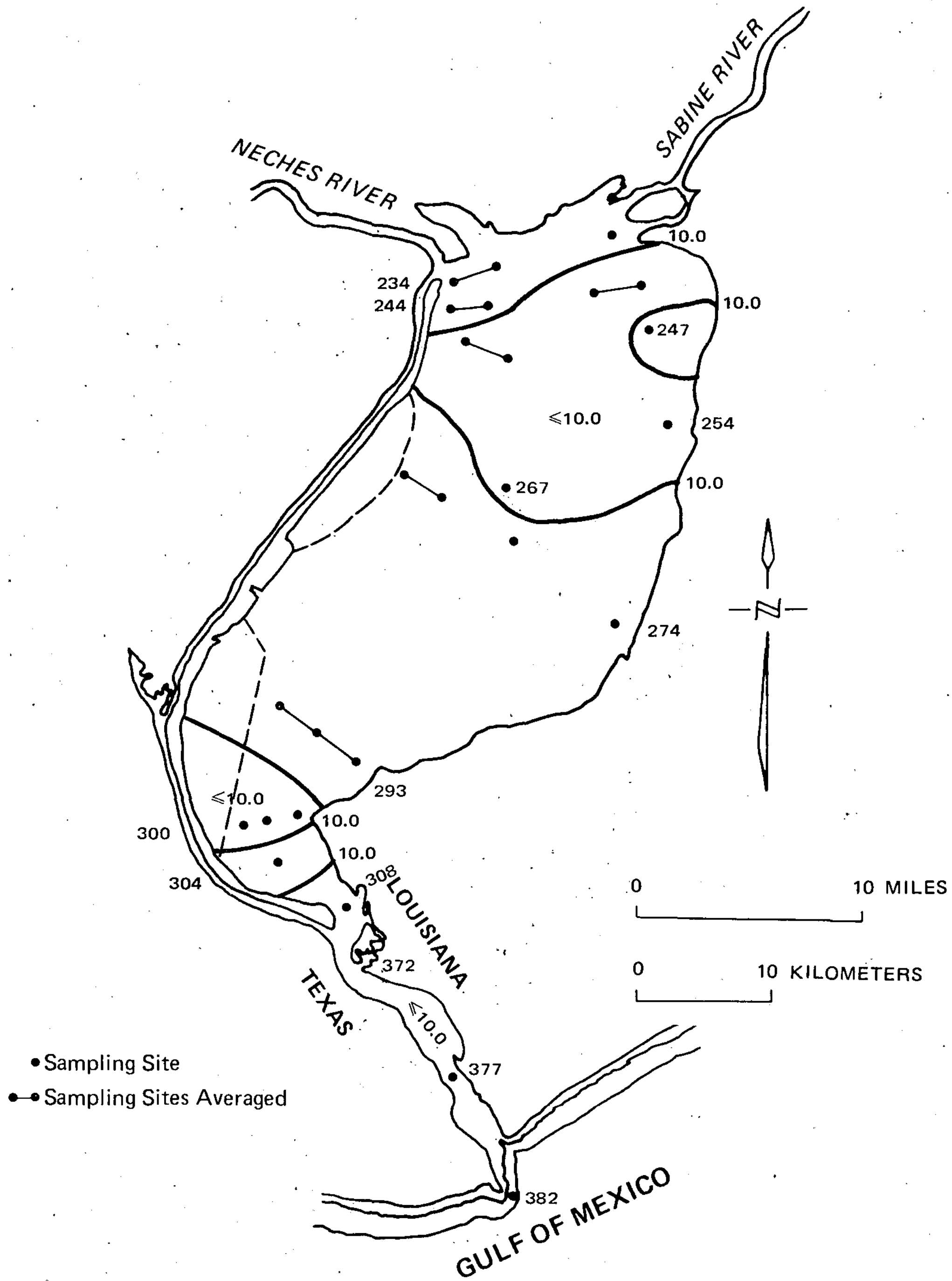


Figure 4-20. Average Seasonal Concentrations of Total Organic Carbon, Late Fall (November and December) 1969-1977

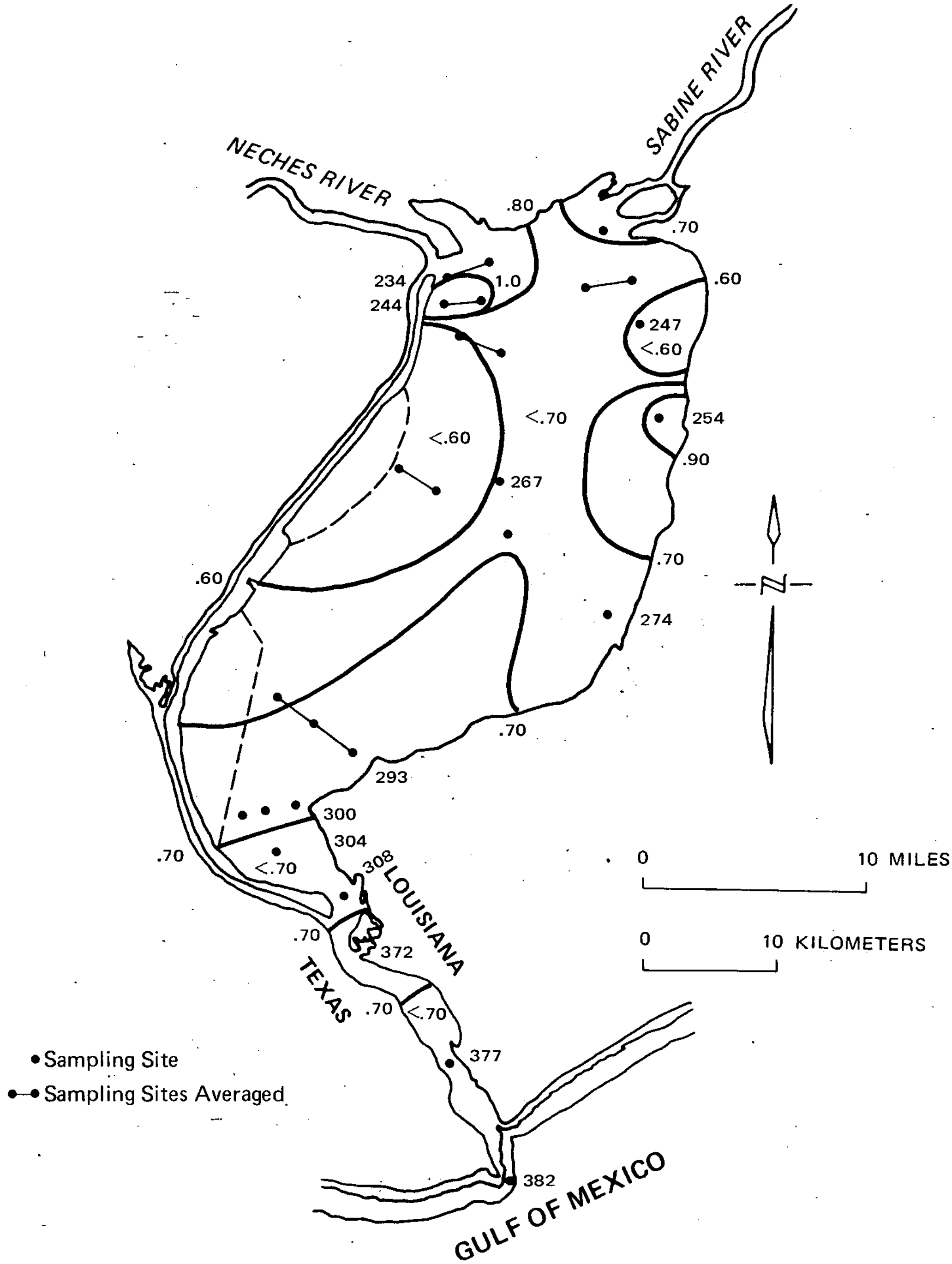


Figure 4-21. Average Seasonal Concentrations of Total Kjeldahl Nitrogen, Winter (January, February, and March) 1969-1977

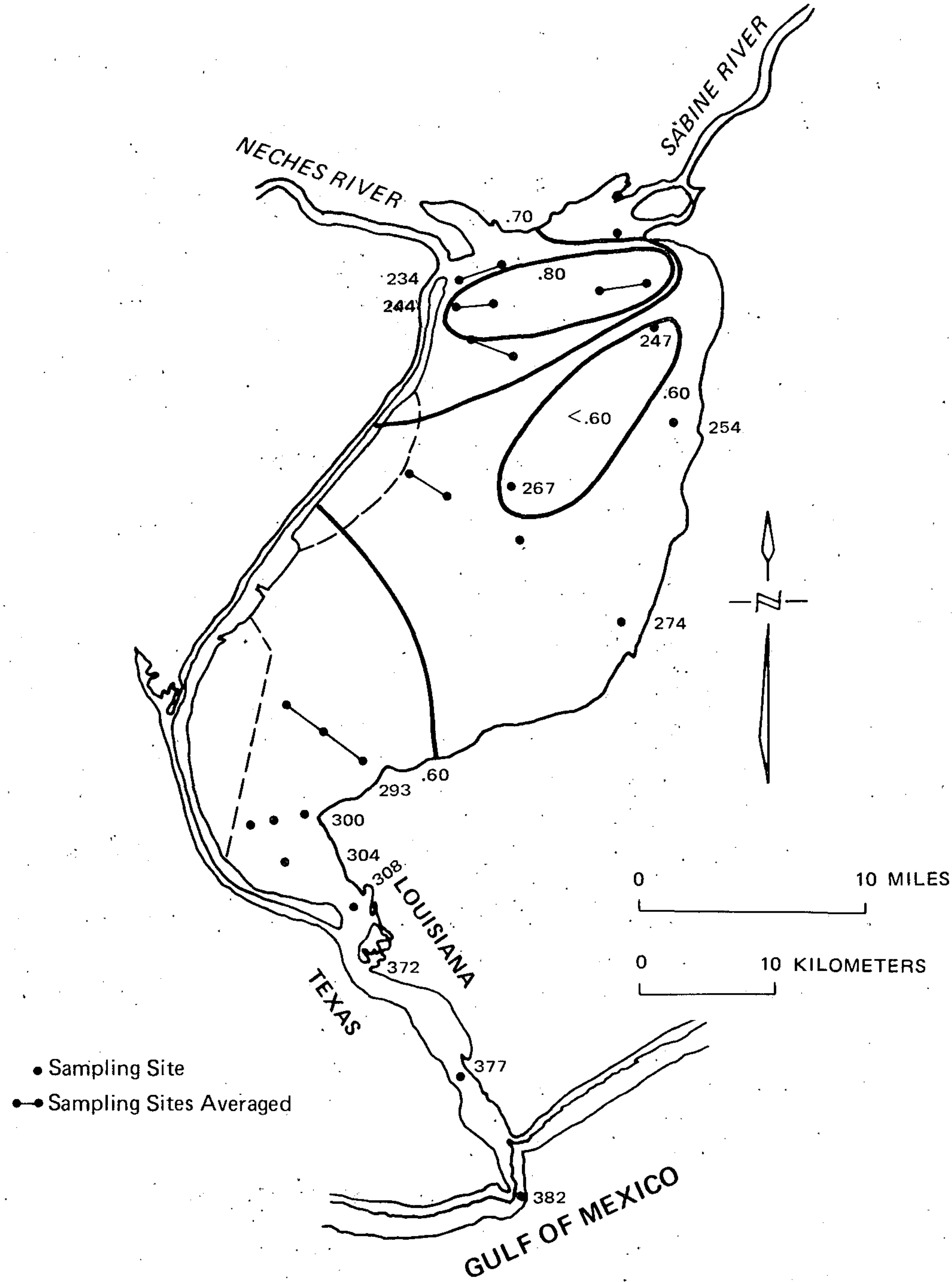


Figure 4-22. Average Seasonal Concentrations of Total Kjeldahl Nitrogen, Spring (April, May, and June) 1969-1977

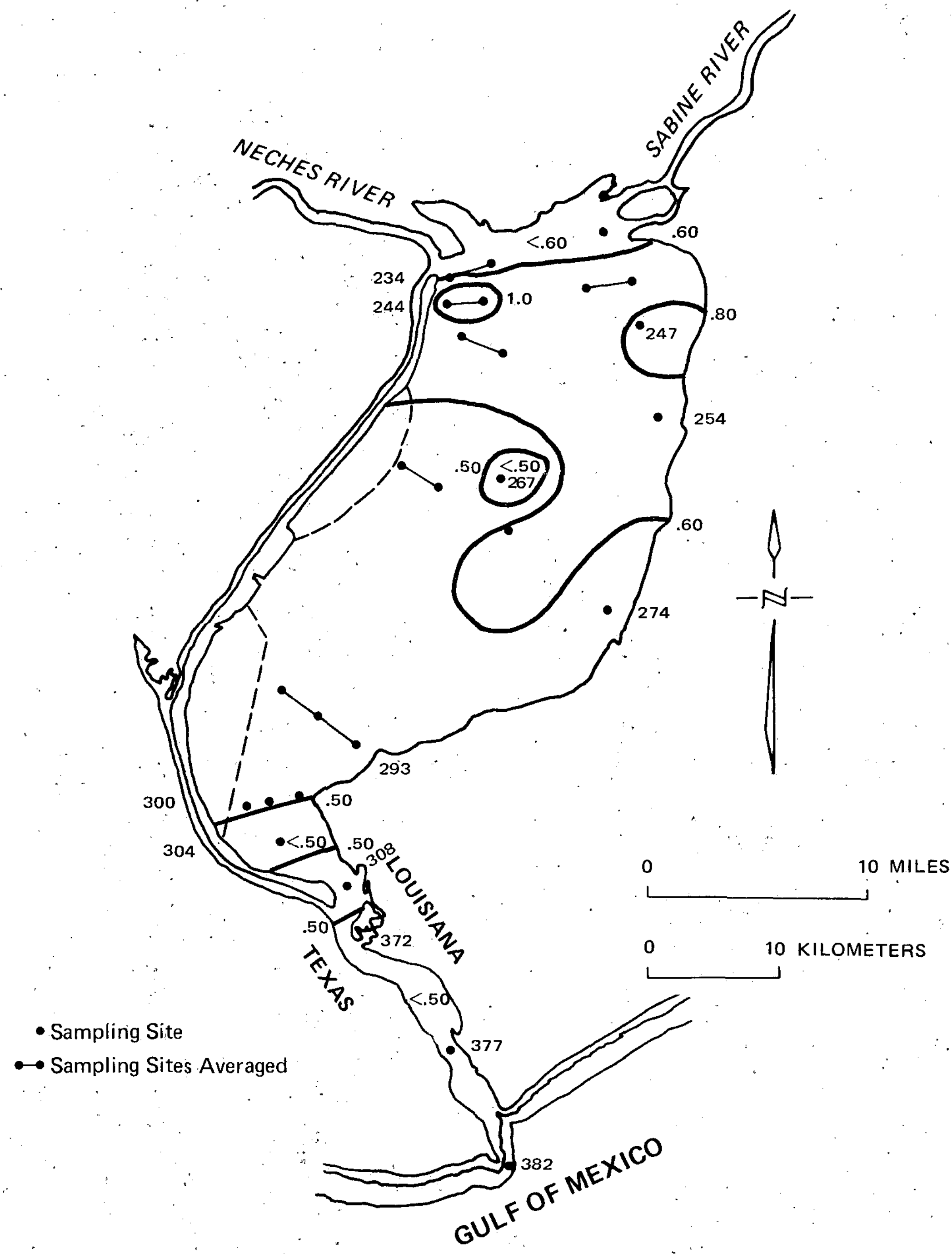


Figure 4-23. Average Seasonal Concentrations of Total Kjeldahl Nitrogen, Summer (July and August) 1969-1977

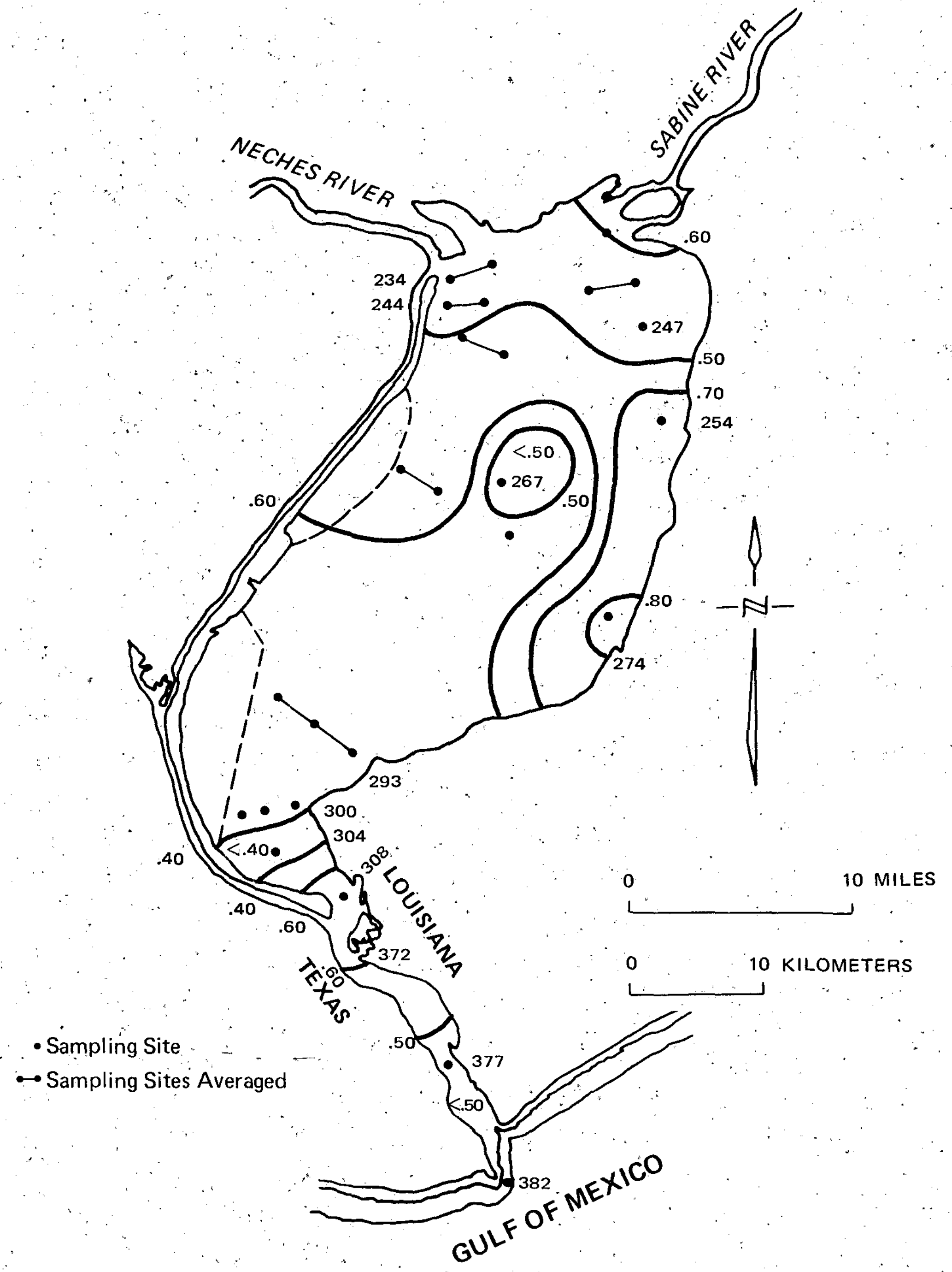


Figure 4-24. Average Seasonal Concentrations of Total Kjeldahl Nitrogen, Autumn (September and October) 1969-1977

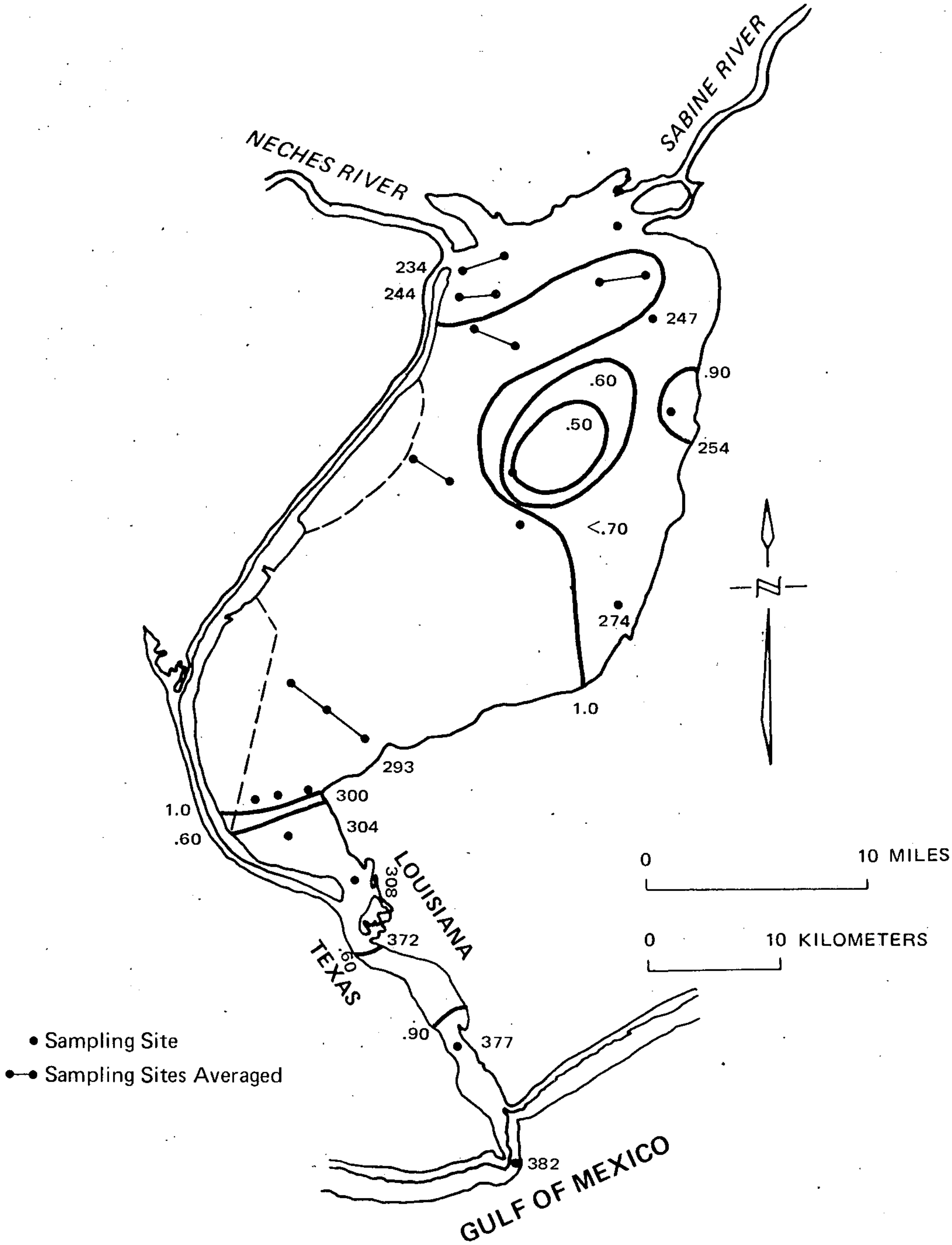


Figure 4-25. Average Seasonal Concentrations of Total Kjeldahl Nitrogen, Late Fall (November and December) 1969-1977

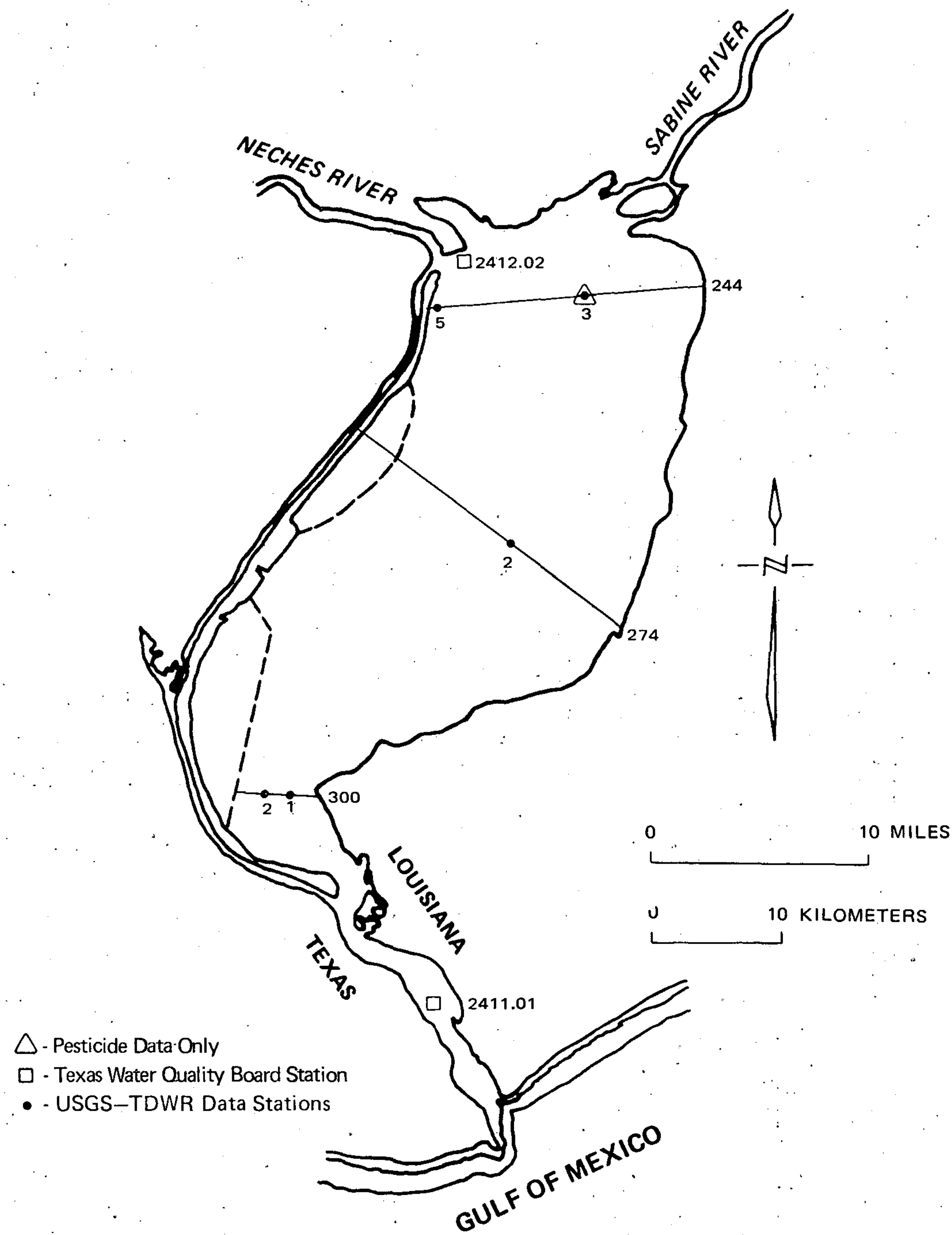


Figure 4-26. Heavy Metals and Herbicides and Pesticides Data-Collection Sites in the Sabine-Neches Estuary

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

Parameter \ Station Location & USGS Station Number	Sabine-Neches Estuary					
	2412.02 b/	244.5 c/	274.2 c/	300.1 & 300.2 c/	2411.01 b/	Dredge Criteria
	Units mg/kg					
Arsenic	2.2-3.2	3.3	5.0*	1.0-5.0*	<0.94-4.6	5
Cadmium	.50-1.5	0.0	<10.0*	0.0-<10.0*	0.28-1.0	2
Cobalt	-	6.2	<10.0	7.7-<10.0	-	-
Copper	1.5-11.0	7.0	<10.0	4.7-<10.0	0.84-13.0	50
Iron	-	13,000	—	10,000	—	—
Lead	8.1-25.0	10.0	<10.0	10.0	5.4-19.0	50
Manganese	180-520	420	170	210-340	450-1400	—
Mercury	0.29 d/	—	0.10	0.0-.10	0.54-1.09*	1
Nickel	5.2-17.0	14.0	—	12.0	18.0-21.0	50
Strontium	—	—	—	28.0	—	—
Zinc	26-72	42.0	40.0	20-40.0	57-79*	75

a/ Includes data from ref. (267 and 415)
b/ Data collected at station from 1974-1978 (at most 4 samples for each parameter)
c/ Data collected at station from 1973-1974
d/ Data collected in 1968
* Denotes at least one sample in violation of EPA's dredge spoil criteria

Microorganisms living on the bottom (benthos) also play an important role in the circulation of metals by taking them up from the sediment, sometimes converting them to more toxic forms. Heavy metals in sediment and water may pose a threat to edible shellfish such as oysters and crabs as these organisms generally concentrate certain metals in their bodies when feeding in polluted areas. Reduction 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 Sabine-Neches estuary may exceed the U.S. EPA criteria for metals in the sediments (prior to dredging) for the following constituents arsenic, cadmium, mercury and zinc (Table 4-5).

Herbicides and Pesticides

Samples of the bottom sediments in the Sabine-Neches estuary were collected at three data collection sites for the period 1969, and 1974 to 1978, by the USGS and the Texas Department of Water Resources in cooperation with other interested agencies (Figure 4-26). The data were analyzed for pesticides and herbicides (Table 4-6). The parameters detected were aldrin, DDD, DDE, DDT, dieldrin, endrin, heptachlor, heptachlor expoxide, and silvex. Statistical analyses were not possible due to the very limited data base.

Summary

Sources of freshwater inflow to the Sabine-Neches estuary include gaged inflow from the contributing rivers and streams; gaged runoff; return flows from municipal, industrial and agricultural sources; and, precipitation on the estuary. Measurement of freshwater inflow adds to the understanding of inflow timing and volumes and their influence on bay productivity. To acquire accurate inflow measurements, gaged stream flows require adjustment to reflect any withdrawals or return flow 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. Average annual freshwater inflow to the estuary (1941-1976) is estimated at 13,223,000 acre-feet (16.34 billion m^3).

In general, the water quality of gaged inflows to the Sabine-Neches estuary has been very good. No parameters were found in violation of Texas stream standards. Studies of past water quality in and around the estuary have pinpointed the occurrence of heavy metals in sediment samples. Locally, bottom sediment samples from the Sabine-Neches estuary have exceeded the U.S. Environmental Protection Agency criteria for metals in sediments (prior to dredging) for arsenic, cadmium, mercury and zinc. Bottom sediments collected and analyzed for herbicides and pesticides showed aldrin, DDD, DDE, DDT, dieldrin, endrin, heptachlor, heptachlor expoxide and silvex occurring in local areas in concentrations equal to or greater than the analytical detection limit for the period 1969, and 1974 through 1978.

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

Table 4-6. Range of Pesticide/Herbicide Concentrations in Sediment, Sabine-Neches Estuary, (1974-1978) a/ b/

USGS Sampling Station / Parameter	2412.02 c/	244.3 d/	2411.01 c/
	Units µg/kg		
Aldrin	0.1-<1.0	—	0.1-<5.0
DDD	0.1-<3.0	1.1	0.1-<5.0
DDE	0.1-<2.0	1.6	0.1-<5.0
DDT	0.1-<5.0	—	0.1-<5.0
Dieldrin	0.1-<3.0	—	0.1-<5.0
Endrin	0.1-<3.0	—	0.1-<5.0
Heptachlor	0.1-<1.0	—	0.1-<5.0
Heptachlor Expoxide	0.1-<1.0	—	0.1-<5.0
Silvex	0.1-<20.0	—	0.1-<10.0

a/ Includes data from references (267 and 415)
b/ Lowest limit of detection is 0.1 µg/kg.
c/ Data collected at station from 1974 to 1978 (at most three samples for each parameters)
d/ Data collected at station in 1969

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 Sabine-Neches estuary.

Description of the Estuarine Mathematical Models

Description of Modeling Process

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

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

Because of the nonlinearities of tidal equations, direct solutions in closed form can seldom 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.

Numerical methods are well adapted to discretized systems where the transfer functions may be taken to be time independent over short time intervals. The development of high-speed digital computers with large memory 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 Dynamic Estuary Model (DEM) was applied to the Sabine-Neches estuary by Water Resources Engineers, Inc. (WRE) under contract to the Texas Water Development Board. The DEM is designed to simulate the hydrodynamic and salinity transport characteristics in an estuarine system (438), and is particularly well suited to the Sabine-Neches estuary because of the model's ability to accurately describe tidal flows and velocities in narrow channels and canals such as Sabine Pass, Port Arthur and Sabine-Neches Canals, and Sabine and Neches Rivers. The model was originally developed by WRE under contract to the Division of Water Supply and Pollution Control of the U.S. Public Health Service (441). Additional developments and refinements were made by the Federal Water Quality Administration for use in studies of the San Francisco and San Diego Bay estuaries (68).

The model simulates the unsteady flow and dispersional characteristics of an estuary wherein vertical stratification is either absent or is limited to relatively small areas within the estuary. The model consists of two separate but compatable components: the hydraulics program and the conservative transport program (Figure 5-1). The hydraulics program computes temporal histories of tidal amplitudes, flows, and velocities throughout the estuary. These are then used as input to the conservative transport program to compute the tidally varying concentrations of two conservative constituents. These concentra-

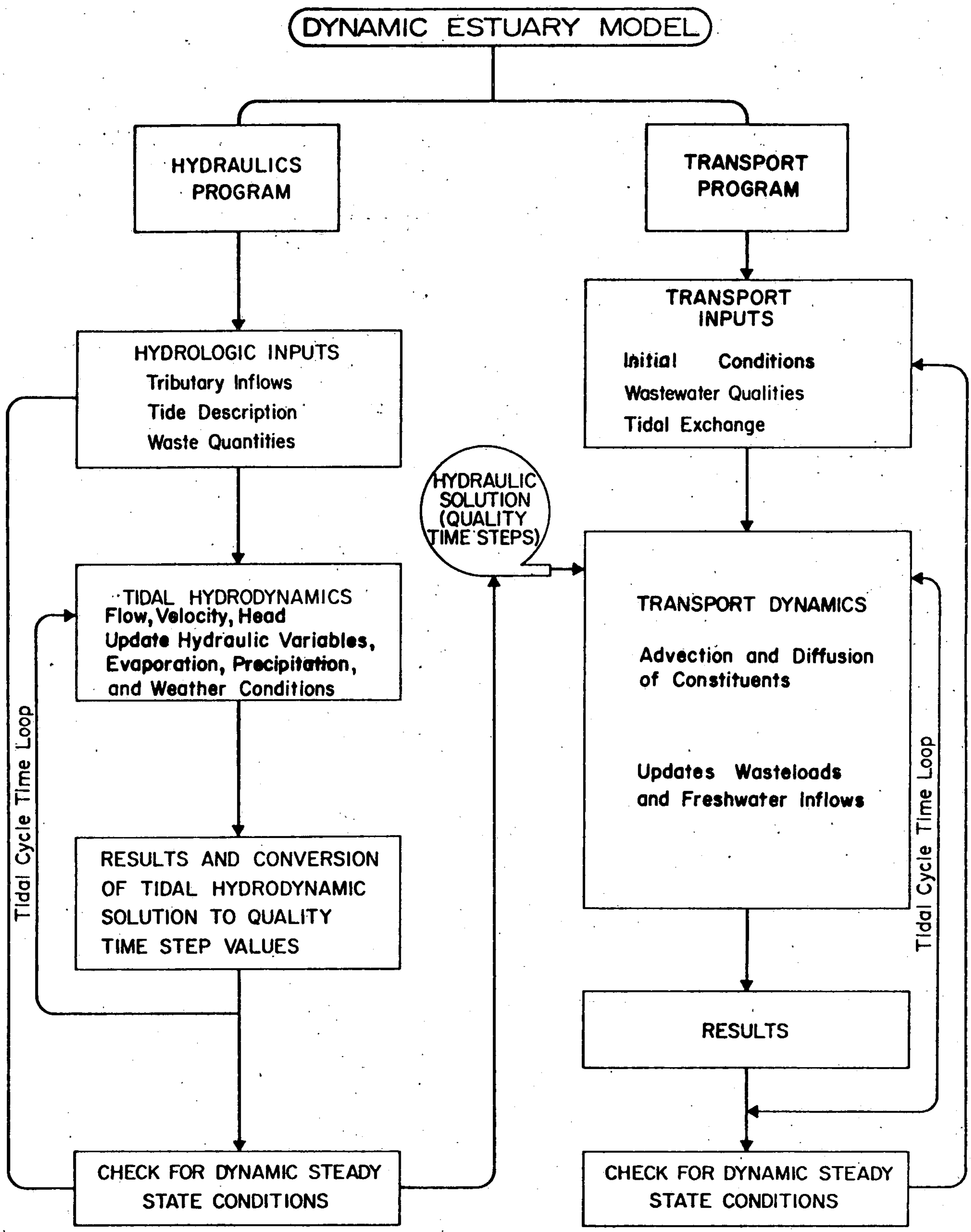


Figure 5-1. Dynamic Estuary Model Logic Diagram (438)

tions represent vertically averaged values that vary over the tidal cycle under the influence of the Gulf tidal exchange, other input source concentrations, evaporation, and rainfall.

Hydraulics Program. To simulate the movement of water in an estuary that is under tidal influence, the problem is essentially one of solving the equations of long wave propagation in a shallow water system. This is done by representing the estuary with a network of interconnected channels (links) and junctions (nodes). The junctions are located at points in the system where any of the following events occur:

1) a major tributary or waste discharge enters the system;

2) an existing water quality monitoring station occurs;

3) a significant change in estuary geometry occurs; or

4) a break in the network is necessary merely to allow the chosen time step to be consistent with the lengths of channels and their velocities.

One junction is also set at the boundary between the estuary and the Gulf. Channels are described by a length, a width, a cross-sectional area, a frictional resistance coefficient (Mannings "n"), and a mid-point depth. Junctions are described by a surface area, a volume, a depth at mean tide, and any accretion to or depletion from the system at that point, i.e., freshwater inflow, waste discharge, or diversion. A set of one-dimensional equations of motion for the channels and a set of equations of continuity for the junctions are solved simultaneously to yield the time variation of flow and velocity in the channels and the water surface elevation at the junctions over the tidal cycle.

Neglecting the Bernoulli terms and the Coriolis acceleration and assuming a straight channel of uniform cross-section, the one-dimensional equation of motion for a open channel can be written as:

$$\frac{\partial U}{\partial t} = -U \frac{\partial U}{\partial x} - g\frac{\partial H}{\partial x} - K|U|U + C_D \frac{\rho a}{\rho w} W \cos\Psi$$

The one dimensional equation of continuity for unsteady flow can be expressed as:

$$\frac{\partial H}{\partial t} = -\frac{1}{b} \frac{\partial (UA)}{\partial x} + r - e$$

where

x = distance along the channel axis
U = velocity along x-axis
t = time
H = water surface elevation
g = acceleration of gravity
K = frictional resistance coefficient
b = mean channel width

A = cross-sectional area of the channel
r = rainfall rate
e = evaporation rate
C_D = dimensionless wind stress coefficient
ρa = density of air
ρw = density of water
ψ = angle between wind velocity vector and x-axis.

The hydraulics program solves the equation of motion for each channel and the equation of continuity at each junction using a modified two-step Runge-Kutta procedure (68). The time step chosen should correspond roughly to the average travel time in the channels, and should be an integer part of the time step used in the conservative transport program. In addition, the explicit formulation used in the hydraulics program requires for a numerically stable solution that $\Delta t \leq l_i/c$, where t is the computational time step, l_i is the length of channel i, and c is the celerity of a shallow water wave. The celerity of shallow water wave for a given channel can be roughly determined from the relationship, $c = \sqrt{gy}$, where g is the acceleration of gravity and y is the maximum channel depth.

This solution results in spatial and temporal descriptions of velocities and flows in channels and water surface elevations at junctions, until dynamic equilibrium is reached, wherein the velocities and flows in each channel and the heads at each junction repeat themselves at intervals equal to the period of the tide imposed at the Gulf boundary of the system. These results, based on a specified hydraulic time step, are then converted to average values for each transport time step, which is an integer multiple of the hydraulic time step.

The following data comprise the basic set for applying the hydraulic program. Time varying data should be supplied at hourly intervals.

Physical Data

- topographic description of 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
- rainfall history
- site evaporation

Conservative Transport Program. The transport process as applied to salinity or any other conservative constituent can be described through the convective-dispersion equation which is derivable from the prinicple of mass conservation (68). For the case of vertically-mixed, one-dimensional channel flow, this equation can be written as:

$$\frac{\partial c}{\partial t} = U_i \frac{\partial c}{\partial x} + K_d \frac{\partial^2 c}{\partial x^2} \pm Q_j C_j$$

where

- c = salinity or concentration of any conservative constituent
- t = time
- U_i = velocity in channel i
- x = distance along channel axis
- K_d = diffusion coefficient
- Q_j = diversion or discharge at junction j
- C_j = concentration at junction j if Q_j is a diversion or the concentration specified if Q_j is a discharge.

The conservative transport program solves the above equation by performing a routing procedure based on the conservation of mass. When the mass inflow to a junction is larger than the outflow, the concentration of the mass in the junction increases, and vice versa. A stepwise procedure is used to compute the mass at a junction at each time step. Mass transfers are made between junctions through advection and diffusion along with external withdrawals and additions. The adjusted constituent mass at each junction is divided by the new junction volume to determine the new concentration and the cycle is repeated with a new set of velocities for the next time step. This explicit step-forward technique yields a temporal and spatial description of constituent concentrations for the estuary. The computational time step for the transport program can be varied from run-to-run with the only restrictions being: (1) the transport time step must be an integer multiple of the hydraulic time step since the transport program is provided with new velocities at each time step by the hydraulic program, (2) the transport time step must be such that the period of the tide used in the hydraulic program is an integer multiple of it, and (3) the transport time step must be such that the transport solution remains stable.

The basic data set required to operate the conservative transport program consists of a time history of channel velocities and junction water surface elevations, i.e., the output from the hydraulics program, the location and source concentration of all freshwater inflows, waste discharges, and diversions, the concentration at the Gulf boundary, and an initial concentration distribution within the estuary.

Application of the Dynamic Estuary Model Sabine-Neches Estuary

Network Configuration

The major portion of the link-node network used to describe the Sabine-Neches estuary is shown in Figure 5-2. Major features of this configuration include the channel element orientation used to describe the main tidal flow in Sabine Lake proper, and the well defined channels of the Neches and Sabine Rivers. To minimize difficulties with boundary conditions, the network extends from the Gulf at the downstream boundary to or beyond the limits of tidal effects on inflowing streams, so that freshwater inflows can be con-

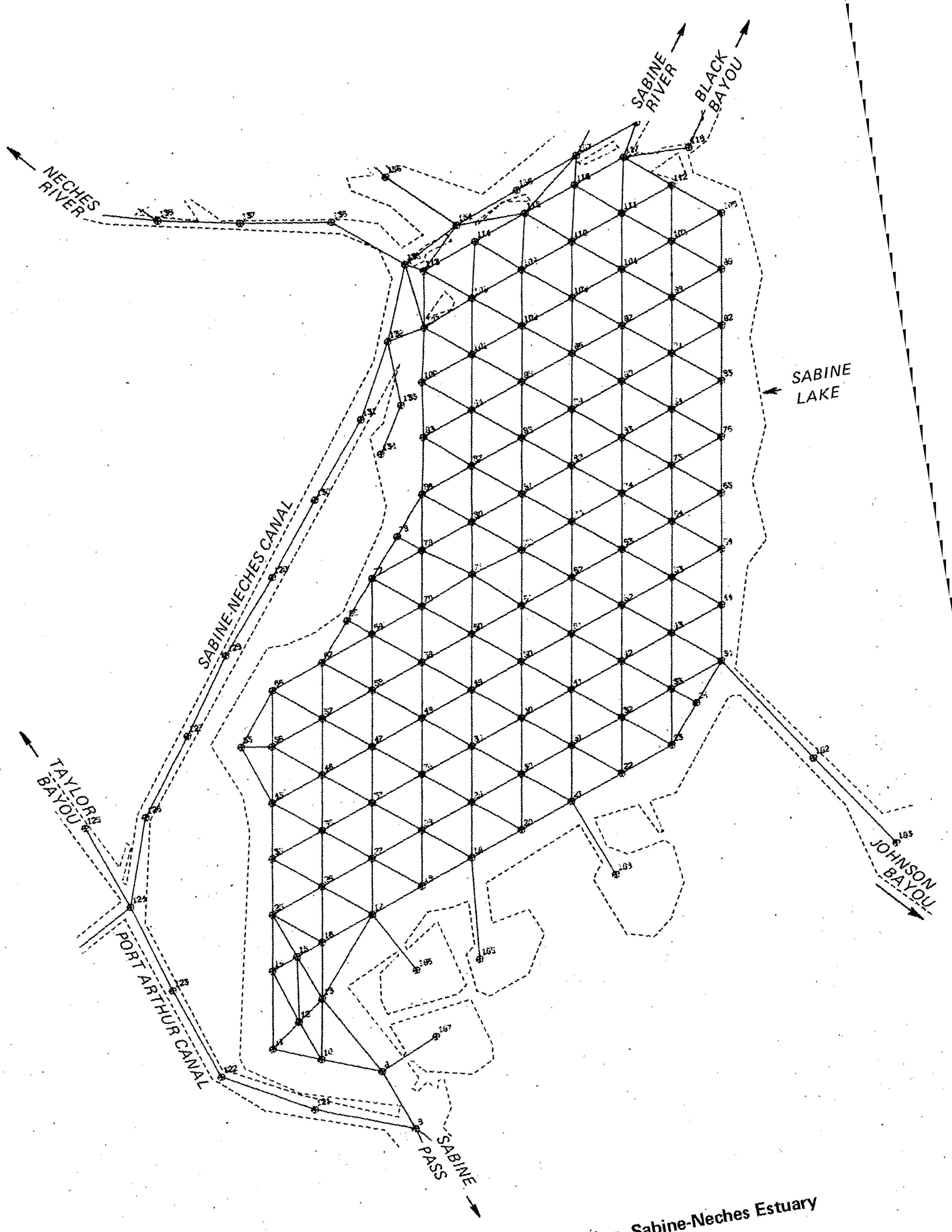


Figure 5-2. Link-Node Configuration, Sabine-Neches Estuary

sidered steady. This network reduces problems associated with dynamic boundary conditions, such as varying salinity concentrations at the seaward boundary. Other considerations which influenced the location of the network boundaries are: (1) overall model size, (2) scale of network elements included in location of specific points where quality predictions were required, (3) location of existing or planned sampling stations, (4) availability of data for verification, (5) degree of network detail desired, and (6) computer time required for solution.

Channel elements are oriented in directions which minimize the variation in depth between junctions. Network elements which represent the dredged or naturally scoured deepwater channels of the system are oriented parallel to these main channels of flow. For the wide shallow portions of Sabine Lake where the principle direction of the flow is not well defined by channelization, the network is laid out in a grid pattern with the orientation of any particular channel element being relatively unimportant.

In areas with well defined channels, the model network essentially follows the prototype configuration, i.e., if a significant channel exists in the prototype, it is represented by a channel element of series of elements in the model network. Since in some cases the desired network scale dictates channel element lengths, some prototype channels have been divided into a series of channel elements in the model network. The channels of the network are connected by nodes or "junctions". These network junctions not only exist for all real junctions in the prototype, but also must connect all channel elements in the network.

Channel Parameters

The parameters associated with the channels of the network are length, width, cross-sectional area, bottom friction (Manning's "n"), velocity (or flow rate) and hydraulic radius. The network channel lengths (distance between junctions) are governed by the computational stability criteria discussed previously and by the actual length between real junctions in the prototype. Typical channel lengths in Sabine Lake vary between 3,000 feet and 5,000 feet, while in the river they extend from 3,000 feet to 7,000 feet.

There is no apparent restriction on the width of network channels although common sense would dictate that the width of a channel not be so wide that the mean velocity prediction for the channel would mask important velocity patterns. For representing well defined channels such as the rivers, the network channel widths are merely the mean bank-to-bank widths. For the embayment portions of Sabine Lake, the grid network channels typically have widths of 2,000 to 4,000 feet.

The cross-sectional area of a channel is dependent on the width of the channel and on the head or water surface elevations at the ends (junctions). Since the head fluctuates with time, the cross-sectional area is continually changing within the model. For computational purposes an initial cross-sectional area is assigned to a channel which is determined from the heads initially assigned to the junctions at both ends of the channel. As the heads fluctuate, a corresponding adjustment is made for the channel cross-sectional area.

The network channels have been assigned "typical" Manning's roughness coefficients normally associated with natural channels. These coefficients vary between 0.035 and 0.12, with the smaller coefficients assigned to the Sabine Lake area and the larger coefficients used for the channels of rivers and canals.

Channel widths and lengths for the Sabine Lake model were scaled from navigation charts published by the U. S. Coast and Geodetic Survey. Depths at mean low water (MLW) were read directly from these charts and cross-sectional areas were determined from these soundings. These depths were adjusted to the mean sea level (MSL) datum selected for the model, and for certain channels near the periphery of the network. These depths were increased somewhat above those indicated on the charts in order to adequately represent the volume of the system. Since there is no provision for allowing a junction to "run dry" in the model, the network has been extended in most cases only to the MSL line. There is also no provision for increasing or decreasing the surface area of the system as the tide rises and falls; therefore, in areas of tidal flats, depths of peripheral channels have been increased slightly to adequately represent the volume of the system at higher tidal stages.

Junction Parameters

The parameters associated with the junctions of the network are surface area, volume, head, and any external inflow or outflow to or from the system. For junctions in those portions of the network with well defined channels, individual surface areas generally have been taken as the sum of the surface areas of each half-channel entering the junction. For junctions in the open water areas of Sabine Lake where the network is comprised of uniform triangular elements, surface areas were computed using the geometric properties of the elements and assigned to junctions accordingly. In some cases, junction surface areas were determined by laying out a polygon network similar to the Thiessen polygon method frequently used for estimating the area of influence of a rain gage on a watershed. The area for each junction was then computed based on the dimensions of the polygon surrounding it or, for complex polygons, by planimetering.

Junction volumes are computed by multiplying the surface area of the junction by a depth which represents the mean depth of the half-channels (weighted according to surface area) entering the junction. The junction volume varies with time as the head at the junction varies.

The head at each junction represents the elevation of the water surface above a horizontal datum. The selection of the datum is arbitrary, and in fact can be changed from one solution to another. Normally, however, the same datum is used for all solutions since it is usually advantageous to utilize the solution from one run as the starting condition for subsequent runs. This procedure minimizes the number of interactions required to converge to a steady state solution, particuarly when there is a great deal of hydraulic similarity between the runs.

Any external inflow or outflow to or from the system is handled through the addition to, or removal from, the junction volumes. At every junction in the network, the net inflow or outflow is specified. River flows, wastewater discharges and precipitation are treated identically as external inflows, and diversions, exportations, consumptive use, and evaporation are treated as outflows from the system.

Network Numbering System

To facilitate the computational procedures, all junctions of the network have been numbered consecutively beginning with one. A separate but similar numbering system for the channels also has been established. Each junction has from one to eight channels entering it. A channel must have a junction at each end; thus dead-end bayous such as occur in the Sabine Lake estuarine system must end with a junction. Associated with each junction number are from one to eight channel numbers; and associated with each channel number are two junction numbers. For the Sabine-Neches estuary the junctions are numbered from one through 198 and the channels from one through 384, with junction one being the node representing the Gulf boundary and channel one being the initial link leading from the Gulf through Sabine Pass.

Model Calibration Procedure

Application of the DEM to the Sabine-Neches estuary, and the model's subsequent calibration, involved simulating both the hydrodynamic and salinity behavior of the system under a variety of historic hydrologic, meteorologic, and tidal conditions. Based on comparisons of model results with corresponding prototype measurements, appropriate adjustments were made to the model to improve its simulation accuracy. In this process, changes in Manning's "n" values, channel geometric properties, and numerical formulations were incorporated into the models. Additional simulations were then performed and the entire procedure was repeated until satisfactory reproductions of real conditions were achieved using similar model parameters and coefficients for different intput or "existing" conditions.

In order to operate the model during the calibration process to simulate prototype conditions, several different types of data are required. These include:

1. gulf tidal conditions,
2. freshwater inflows from rivers and streams,
3. local runoff,
4. municipal and industrial return flows,
5. diversions,
6. withdrawals,
7. wind conditions,
8. rainfall and evaporation,
9. salinity concentrations for system inflows in items 2, 3, 4 and 5,
10. gulf salinity concentrations,
11. tidal elevations throughout the system,
12. tidal flows in interior channels,
13. tidal velocities throughout the system, and
14. salinity concentrations throughout the system.

The first ten types of data are system "driving variables", and they are specified in the models to "excite" the system. The last four are used for comparison with simulated results to evaluate the accuracy of the model simulations.

A compilation of the above data for a specified historical period of time is referred to in this study as a "data package", and it is through the successive application of the models to several different data packages that the models ultimately become calibrated and verified. The continued operaton of the models using new data packages is also necessary to establish reliability, to obtain confidence in the models' usage, and to make the finer adjustments and modifications required to achieve good simulations for a broad range of conditions. Data packages necessary for the calibration and verification of the estuary models were obtained through a cooperative program with the U. S. Geological Survey. Especially important were two comprehensive data collection efforts conducted in the estuary during September 1974 and July 1975.

The initial calibration and verification of the Sabine-Neches estuary model has been reported by WRE (438, 439). A representative sample of the results of the final calibration of the model using data obtained during the July 1975 field study are presented in Figures 5-3 to 5-5 to demonstrate the ability of the model to simulate observed values of tidal amplitude, flow, and salinity throughout several tidal cycles at several locations in the estuary.

Freshwater Inflow/Salinity Regression Analysis

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

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

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

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

or

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

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

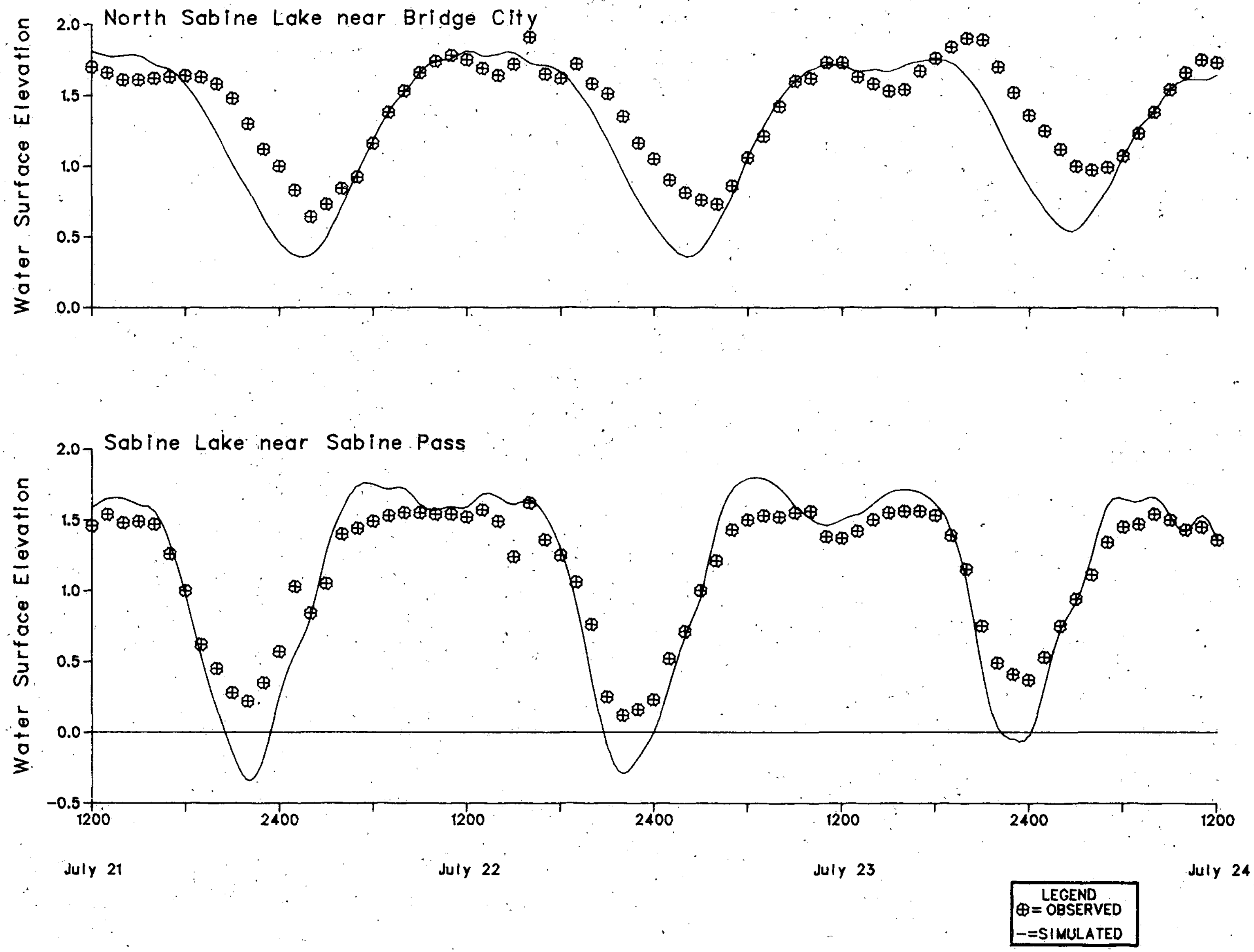


Figure 5-3. Comparison of Observed and Simulated Tidal Elevations
Sabine-Neches Estuary, July 21-24, 1975

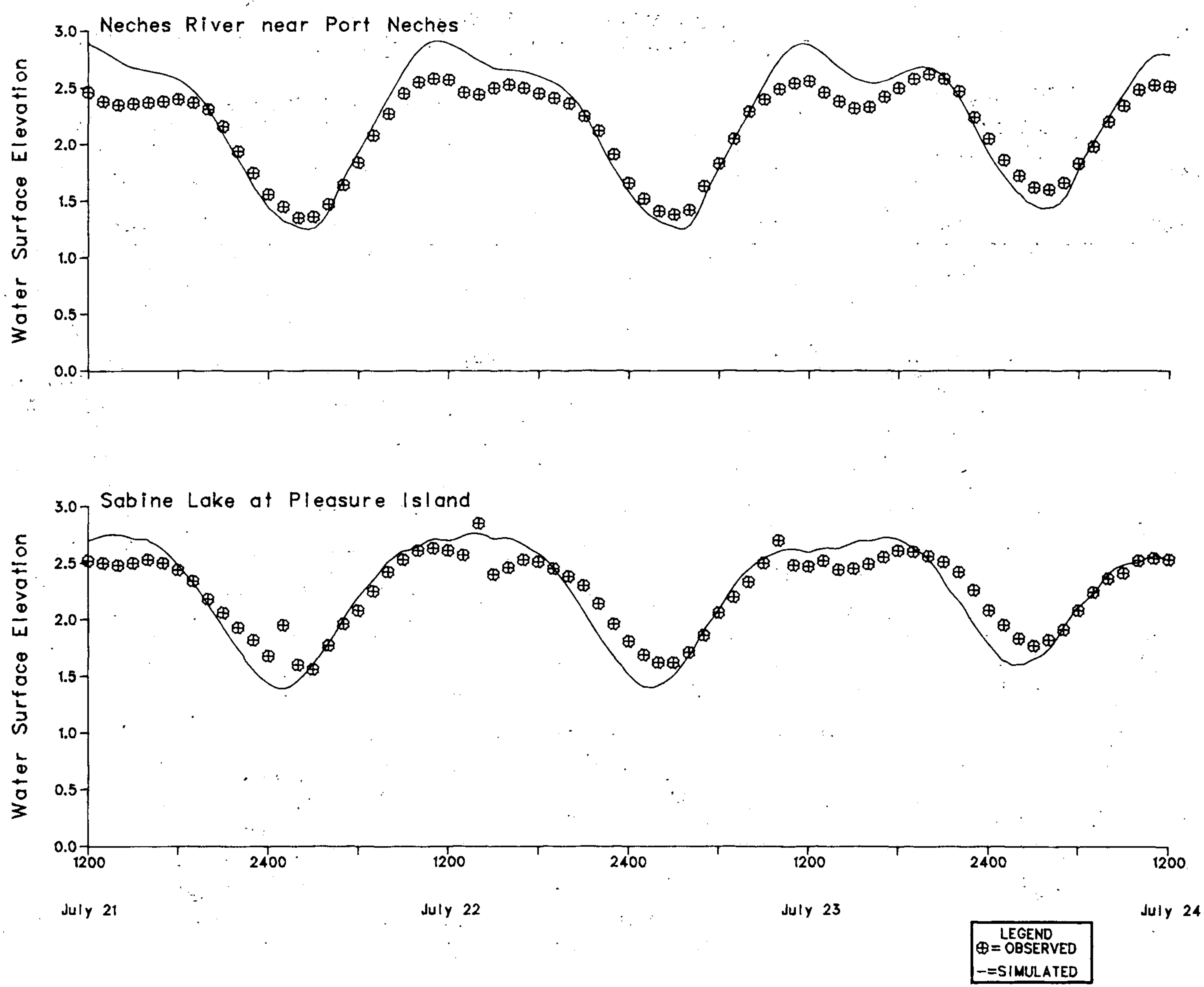


Figure 5-3. Comparison of Observed and Simulated Tidal Elevations
Sabine-Neches Estuary, July 21-24, 1975—Continued

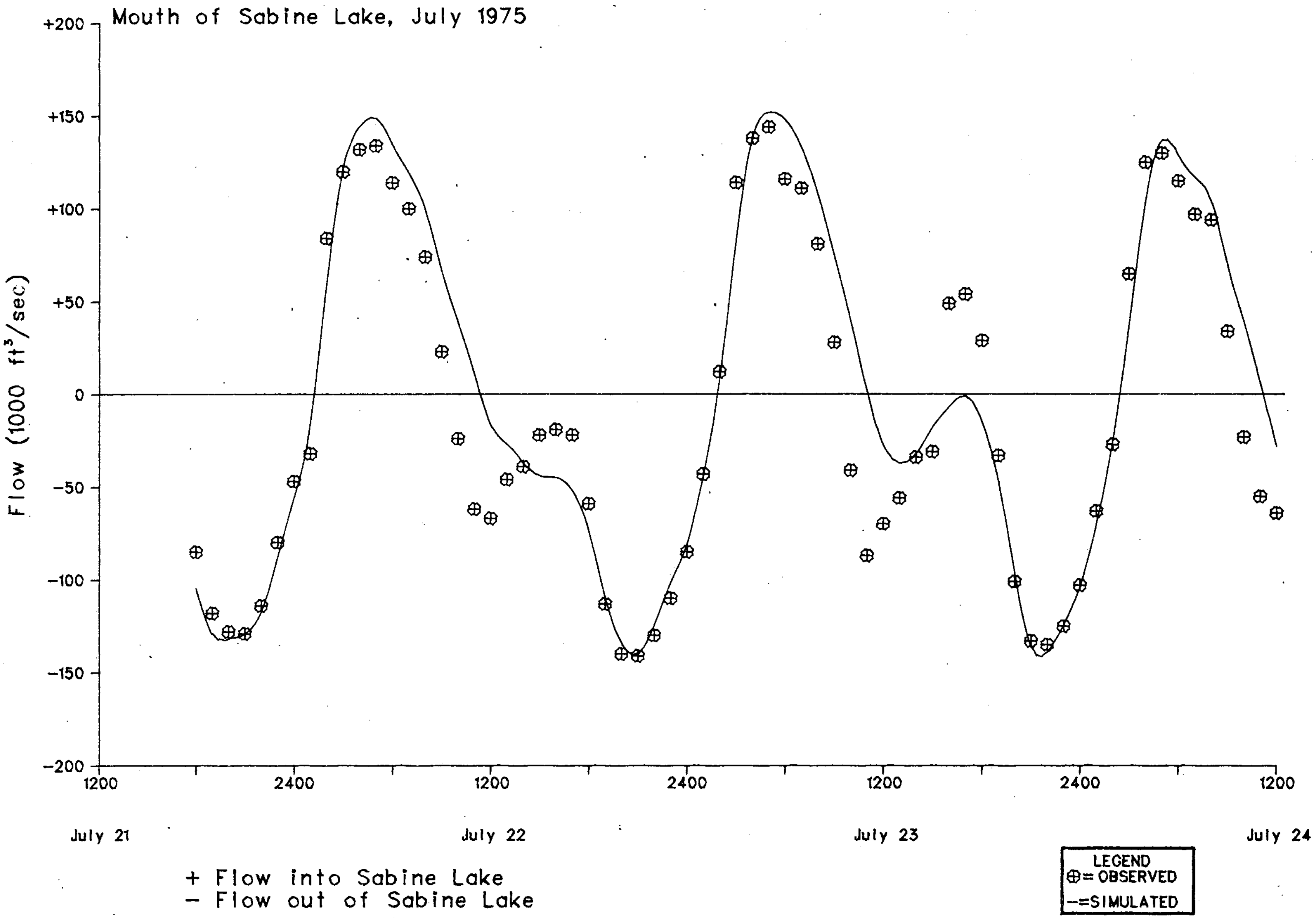


Figure 5-4. Comparison of Observed and Simulated Flows, Sabine-Neches Estuary, July 21-24, 1975

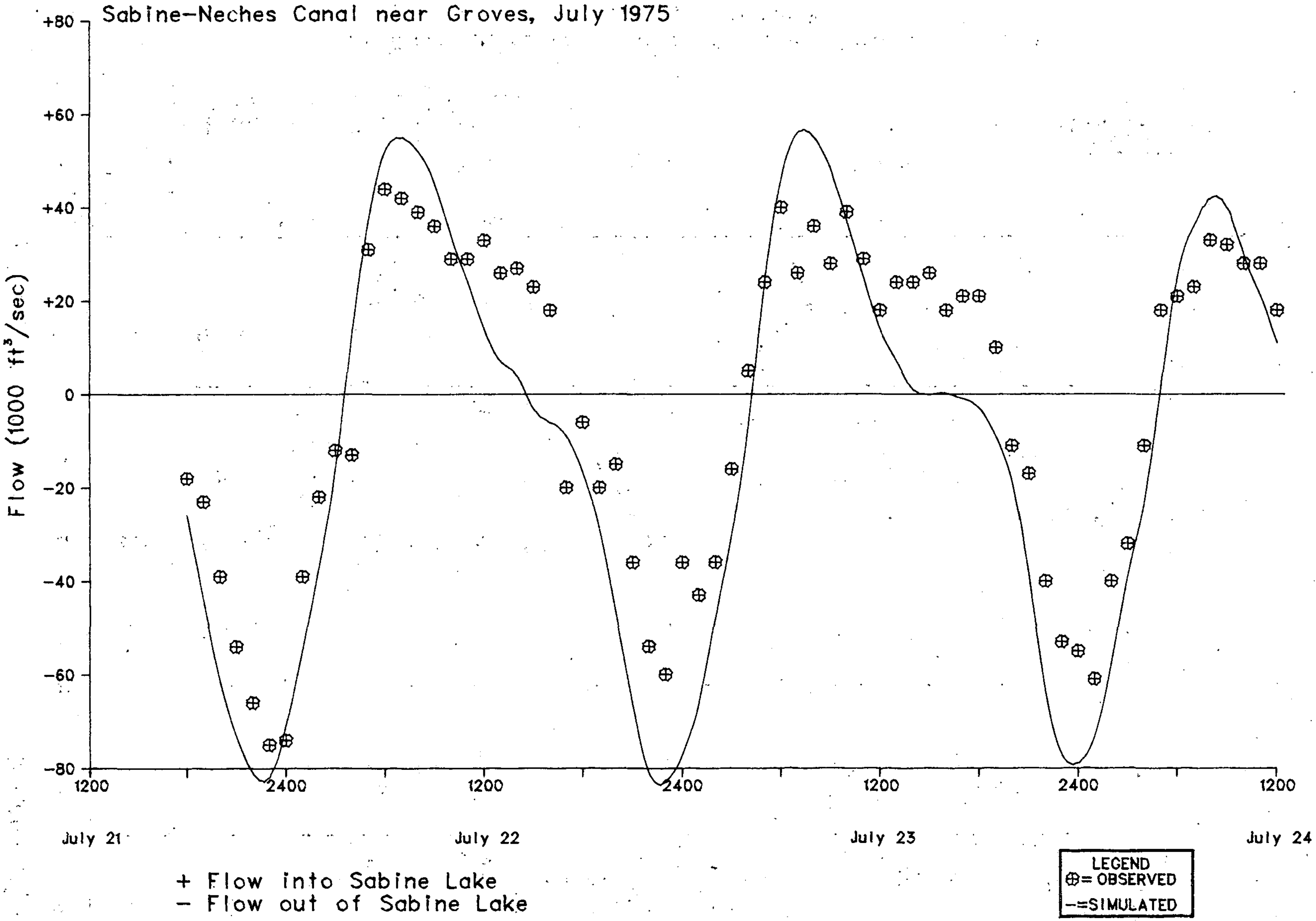


Figure 5-4. Comparison of Observed and Simulated Flows, Sabine-Neches Estuary, July 21-24, 1975—Continued

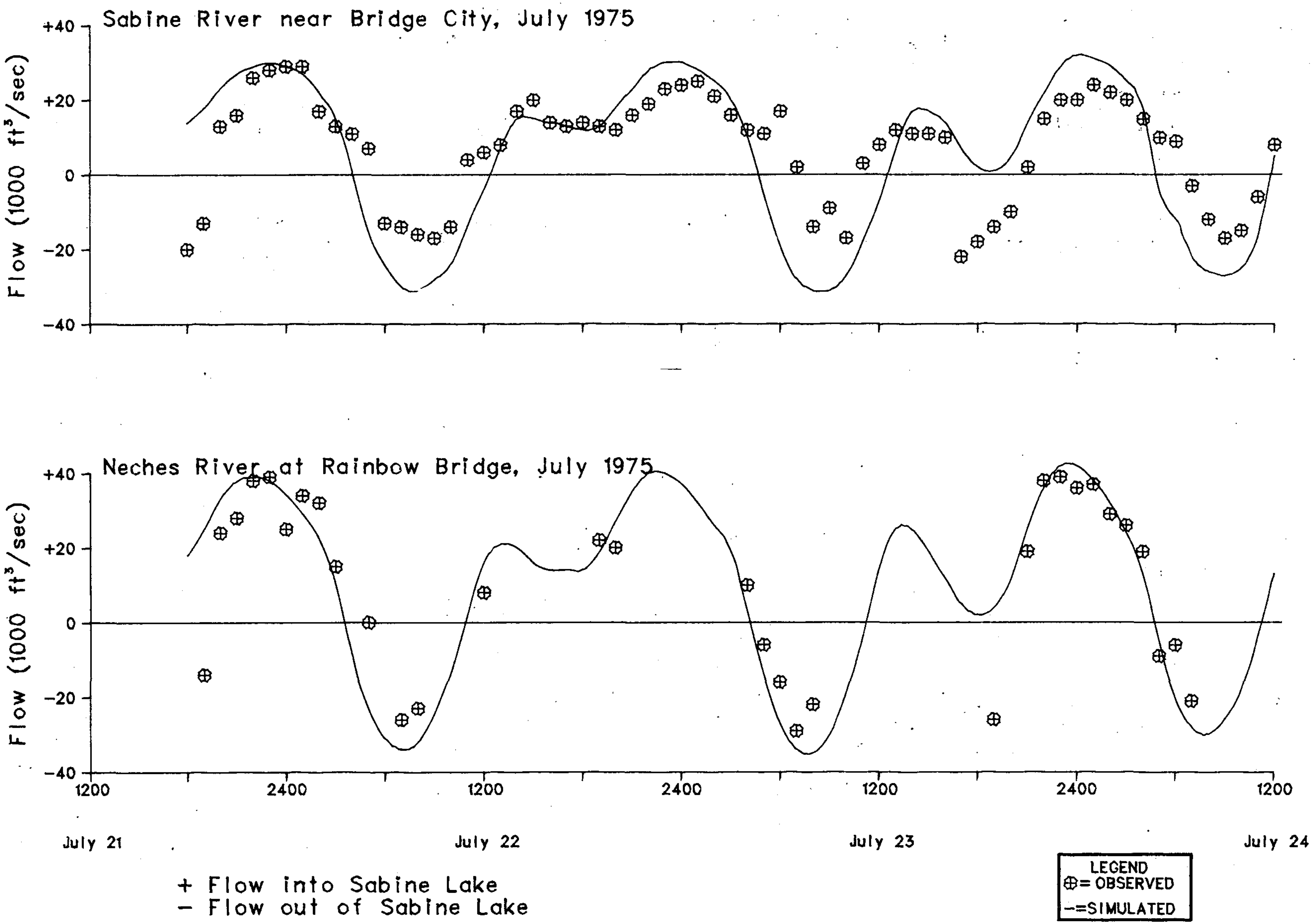


Figure 5-4. Comparison of Observed and Simulated Flows, Sabine-Neches Estuary, July 21-24, 1975—Continued

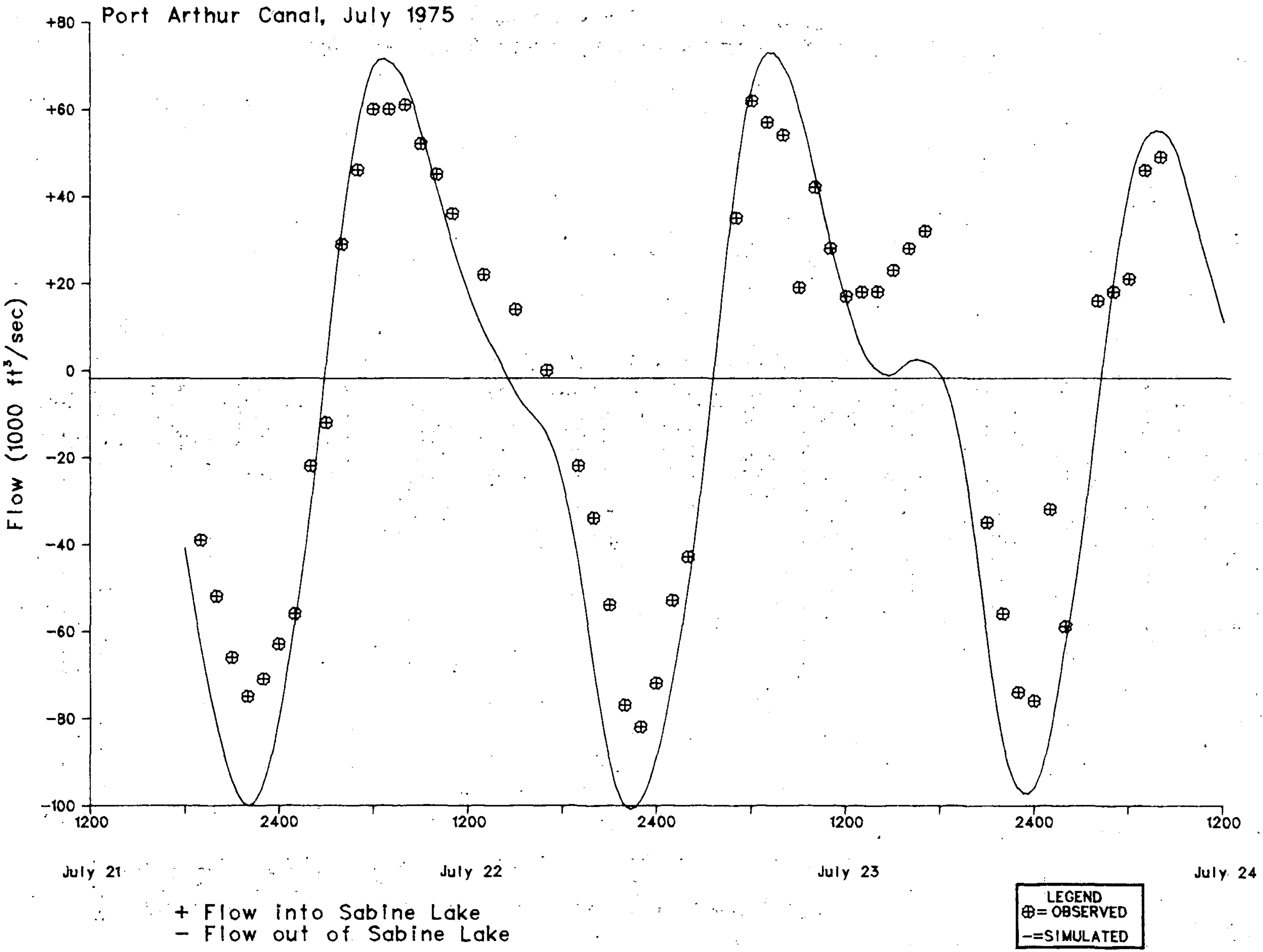


Figure 5-4. Comparison of Observed and Simulated Flows, Sabine-Neches Estuary, July 21-24, 1975—Continued

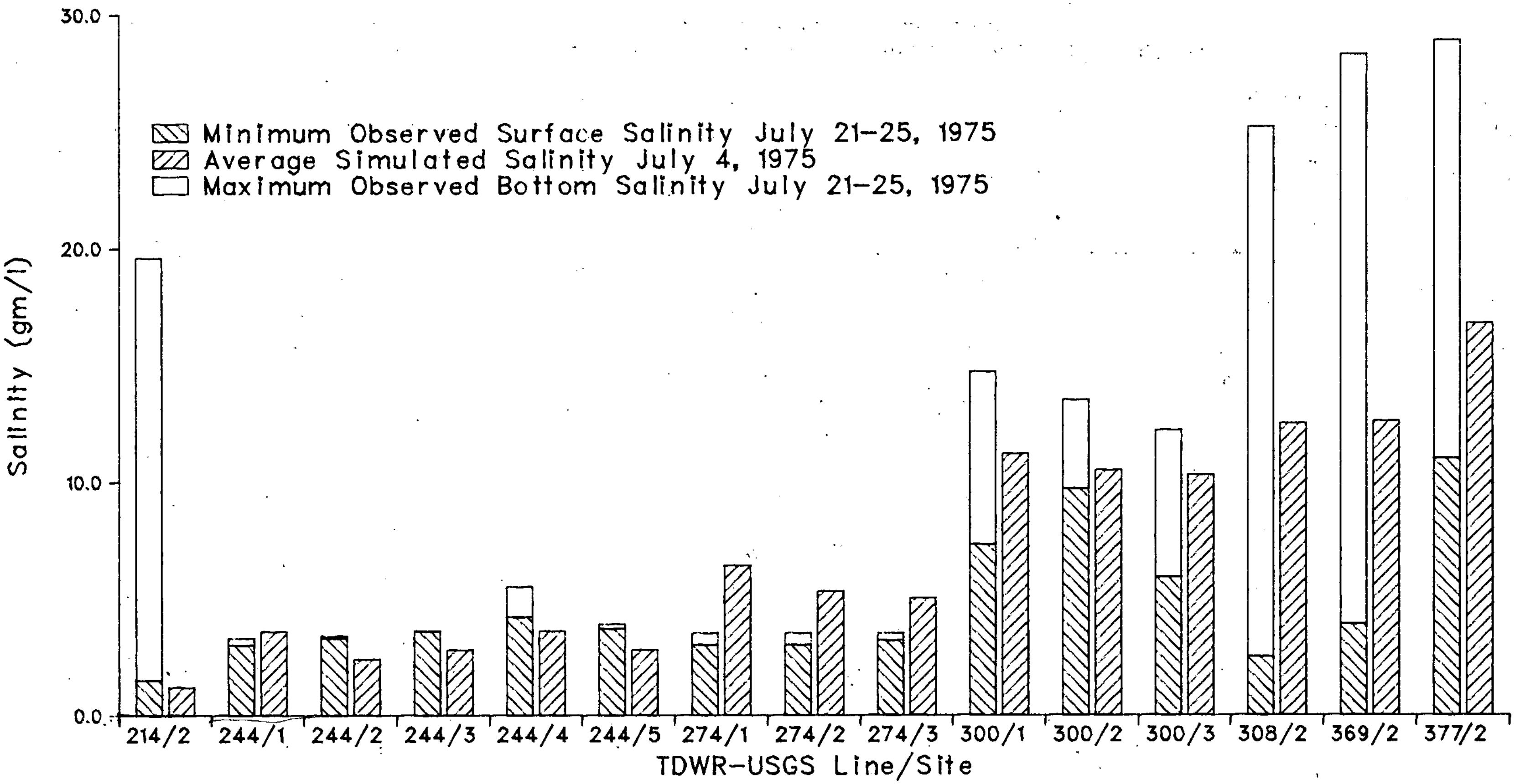


Figure 5-5. Comparison of Observed and Simulated Salinitites, Sabine-Neches Estuary, July 21-24, 1975

regression coefficients. The term $\sum_{i=1}^{n} Q_{t-i}$ in Equations [1] and [2] represents the antecedent inflow conditions, while Q_{t-k} represents the present inflow condition taking into consideration streamflow time lag between the gage and the estuary. The regression coefficients were determined using a step-wise multiple regression procedure (20).

The regression equations developed for Sabine Lake used the salinities obtained by the Texas Department of Water Resources and the U. S. Geological Survey cooperative data collection program and the sum of the gaged streamflows recorded for the Neches River at Evadale and the Sabine River near Ruliff (Table 5-1). There are no significant differences among salinities measured at line-sites 244-2, 244-3, 244-4, 254-2, 254-3, and 254-4 (Figure 3-8). The daily average salinity of line-site 244-4 is related to the daily gaged streamflow by

$$S_t = -4.3 + 646.3 \ Q_{t-9}^{-0.5} + 1743.7 \ (\sum_{i=1}^{29} Q_{t-i})^{-0.5} \qquad [3]$$

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

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

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

where S_m and Q_m are monthly average salinity and gaged flow in ppt and ft^3/sec, respectively, C_0 and C_1 are regression coefficients, and (ts_e) is a random component. The frequency analyses for Sabine Lake indicates that both monthly salinity data and monthly gaged streamflows are approximately log-normal distributed. Therefore, the random component has a normal distribution and can be expressed by ts_e (69), 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 Sabine Lake (Table 5-2) for the twelve months (r) ranged from 0.83 to 0.97, which are highly significant (α = .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

$$S_y = 44102.1 \ Q_y^{-1.021} \qquad [5]$$

Table 5-1. Description of Data for Regression Analysis, Sabine Lake

Bay	Salinity		Inflow		Number of Observations for Regression
	Station Line-Site	Period	USGS Station	Period	
Sabine Lake	244-4	Jul. 1968 to Jun. 1977	Neches River at Evadale and Sabine River near Ruliff	Jan. 1925 to Jun. 1977	30
Sabine Lake	244-2 & 3 254-2,3 & 4	Jul. 1968 to Jun. 1977			

Table 5-2. Results of Salinity Regression Analysis, Sabine Lake

Station a/	Class	Regression Equation (S in ppt and Q in ft³/sec)		Correlation Coefficient r	Explained Variation r^2	Standard Error of Estimate s_e	F-test
TDWR-USGS line-site 244-4	Daily	$S_t = -4.3 + 646.3\ Q_{t-9}^{-0.5} + 1743.9\ \left(\sum_{i=1}^{29} Q_{t-i}\right)^{-0.5}$		0.88	0.77	2.51	**
	Jan.	$S = 920{,}436.3\ Q^{-1.3186}$,	$2{,}600 \le Q \le 65{,}600$	0.87	0.75	0.671	**
	Feb.	$S = 6{,}695{,}345.3\ Q^{-1.542}$,	$4{,}000 \le Q \le 72{,}750$	0.86	0.73	0.728	**
	Mar.	$S = 2{,}874{,}918.7\ Q^{-1.455}$,	$3{,}500 \le Q \le 66{,}560$	0.88	0.77	0.580	**
	Apr.	$S = 4{,}033{,}794.1\ Q^{-1.496}$,	$3{,}000 \le Q \le 90{,}100$	0.86	0.73	0.675	**
	May	$S = 563{,}062.0\ Q^{-1.281}$,	$3{,}000 \le Q \le 112{,}800$	0.86	0.73	0.658	**
	Jun.	$S = 1{,}437{,}811.7\ Q^{-1.425}$,	$2{,}000 \le Q \le 64{,}700$	0.91	0.82	0.624	**
	Jul.	$S = 8{,}104.9\ Q^{-0.824}$,	$1{,}000 \le Q \le 26{,}300$	0.91	0.82	0.323	**
	Aug.	$S = 2{,}755.1\ Q^{-0.691}$,	$750 \le Q \le 32{,}500$	0.97	0.94	0.157	**
	Sep.	$S = 1{,}319.6\ Q^{-0.582}$,	$730 \le Q \le 17{,}300$	0.92	0.84	0.238	**
	Oct.	$S = 1{,}291.4\ Q^{-0.579}$,	$650 \le Q \le 19{,}700$	0.89	0.80	0.273	**
	Nov.	$S = 2{,}499.3\ Q^{-0.644}$,	$1{,}000 \le Q \le 44{,}050$	0.90	0.81	0.329	**
	Dec.	$S = 93{,}079.2\ Q^{-1.061}$,	$2{,}500 \le Q \le 91{,}900$	0.83	0.69	0.653	**
	All Months	$S = 44{,}102.1\ Q^{-1.021}$,	$1{,}400 \le Q \le 112{,}800$	0.88	0.78	0.648	**

** Indicates highly significant ($\alpha = 0.01$).

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 5-6. The other statistics of equation [5] are listed in Table 5-2.

The above freshwater inflow-salinity relationships can be used to provide preliminary estimates of the response of the estuary to proposed freshwater inflow regimes. Such a technique allows a quick screening of the inflow regimes that have the least desirable impact on salinity 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.

The Dynamic Estuary Model was applied to the Sabine-Neches estuary, with the model representation of the system including Sabine Pass, Sabine Lake, the Port Arthur and Sabine-Neches Canals, and a portion of the Sabine and Neches Rivers. The Dynamic Estuary Model was calibrated and verified for the estuary.

Statistical analyses were undertaken to quantify the relationship between freshwater inflows from the Sabine and Neches Rivers and salinities in upper Sabine Lake. Utilizing gaged daily river flows in the Sabine and Neches Rivers and observed salinities, a set of monthly predictive salinity equations was derived utilizing regression analyses for the above indicated area of the estuary. These equations predicted the mean monthly salinity as a function of the mean monthly freshwater inflow rate.

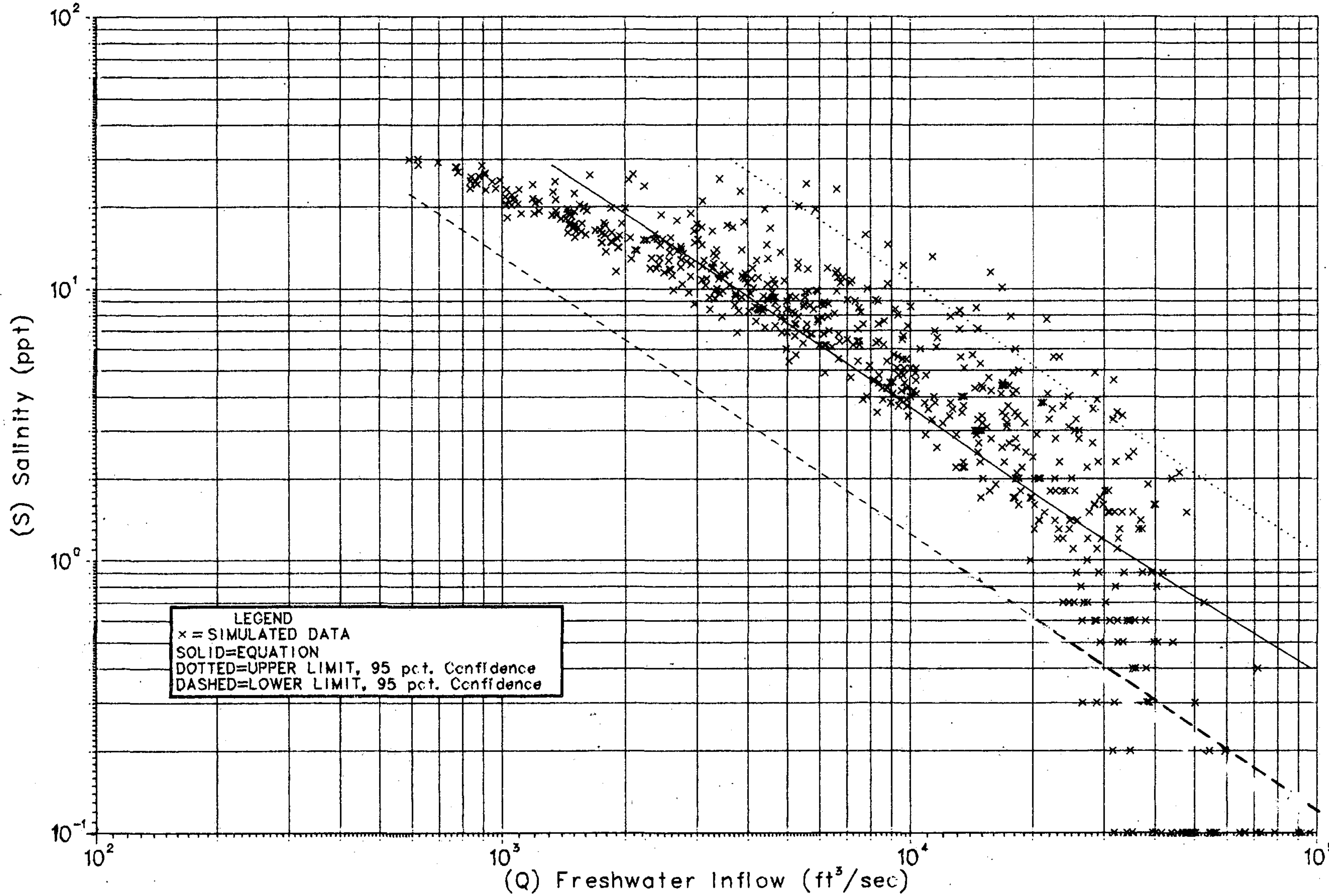


Figure 5-6. Average Monthly Salinity versus Average Monthly Gaged Inflow, Sabine Lake, 1925-1976

CHAPTER VI

NUTRIENT PROCESSES

Introduction

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

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

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; nitrogen to phosphorus ratios for a variety of phytoplankton species are usually in the range of 10-12:1 (137). Nitrogen and phosphorus are considered to be the "critical" nutrients in aquatic ecosystems since carbon is rarely, if ever, limiting due to the readily available supply of atmospheric CO_2 and the ability of autotrophic organisms to use this form.

The amount of nitrogen required in an aquatic ecosystem is generally greater than phosphorus; biological productivity is therefore most likely to be nitrogen-limited. This has been reported to be the case in a number of estuaries (128, 153, 215, 426, 428) including those in Texas (348, 349).

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 or industrial waste effluents, or species 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 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 (224). The basic methodology includes a determination of mean annual flow magnitudes and mean annual concentrations of nutrient species; simple multiplication is used to arrive at a loading in pounds (or kilograms) per day. Daily discharge records of the major rivers and tributaries that empty into Texas bays and estuaries have been maintained historically by the U. S. Geological Survey, in cooperation with the Texas Department of Water Resources. Prior to the late 1960's, however, nutrient concentration and water quality data were not systematically collected for these rivers.

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

Gaged freshwater discharges enter the Sabine-Neches estuary from two major sources: the Sabine River and the Neches River and their tributaries. The mean annual total discharge measured at the closest non-tidally influenced gage for these inflow sources is about 11.28 million acre-feet (13.92 billion m^3). The Sabine River and Cow Bayou contribute an average annual inflow of 6.16 million acre-feet (54.6 percent of the total) to Sabine Lake. Contributions from the mainstem Neches River, Village Creek, and Pine Island Bayou are about 5.12 million acre-feet (45.4 percent of the total).

U. S. Geological Survey discharge and water quality data (over the period of record 1970 through 1977) were used to calculate the potential loading contributions from the Sabine River near Ruliff and Cow Bayou near Mauriceville and from the Neches River at Evadale, Village Creek near Kountze, and Pine Island Bayou near Sour Lake. (The only nutrient concentration data available for Cow Bayou, Village Creek, and Pine Island Bayou were from the Texas Department of Water Resources statewide water quality monitoring network and included only nitrates, ammonia, total phosphorus, and total organic carbon.) The results of analysis of nutrient loadings from each freshwater source should be interpreted as estimates based on limited data. The estimated loadings reflect the order of magnitude and range that might be expected during periods of similar climatic and streamflow conditions.

Studies were conducted in Sabine Lake in September 1974 and July 1975 to gain insight into nutrient contributions from the brackish intertidal marshes to the estuary. These studies involved intensive diurnal hydrodynamic and biogeochemical field sampling over a one or two day period. As is the case with riverine water quality, an analysis of the interdeltaic 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 mean monthly organic nitrogen concentrations in the Sabine River near Ruliff ranged from 0.33 mg/l to 0.64 mg/l. Mean monthly organic nitrogen concentrations in the Neches River at Evadale were consistently within a similar range (Figure 6-1). No obvious seasonal patterns of organic nitrogen concentration were apparent from the available data.

Mean monthly inorganic nitrogen concentrations in the Sabine River ranged from 0.038 mg/l to 0.214 mg/l, with ten values exceeding 0.1 mg/l. Values in the Neches River were generally lower, ranging from 0.053 mg/l to 0.217 mg/l, with only five mean monthly concentrations exceeding 0.1 mg/l. Inorganic nitrogen concentrations appear to decline from an early springtime high to a low in the summer and then rise again to a fall peak (Figure 6-2). Inorganic nitrogen concentrations in Cow Bayou, Village Creek, and Pine Island Bayou would most likely exceed those values illustrated in Figure 6-2 based on limited data available from the statewide monitoring network.

Mean monthly total phosphorus concentrations in the Sabine and Neches Rivers were generally less than 0.1 mg/l with little seasonal variation in either river (Figure 6-3). Limited data indicated that total phosphorus concentrations in Cow Bayou were historically greater than those in the Sabine River near Ruliff while values in Village Creek and Pine Island Bayou generally compared favorably with those found in the Neches River at Evadale.

Mean monthly total organic carbon values ranged from 7.0 mg/l to 11.8 mg/l in the Sabine River and from 3.7 mg/l to 17.0 mg/l in the Neches River. Variations were greater in the Neches River although no seasonal trends were apparent in either river (Figure 6-4). Again, limited statewide monitoring network data indicated greater total organic carbon (TOC) concentrations in Cow Bayou, Village Creek, and Pine Island Bayou.

The potential ranges for nutrient contributions from each stream influent to the Sabine-Neches estuary are presented in Table 6-1 through Table 6-4. Nutrient contributions (in kilograms/day) were calculated using maximum and minimum concentrations observed for each of the twelve months over the period of record (1970 through 1977) and the mean monthly gaged discharge for each stream. Since data for Cow Bayou, Village Creek and Pine Island Bayou were limited or non-existent in some cases, nutrient loadings from these sources were calculated using the same maximum and minimum concentrations observed in the respective Sabine and Neches Rivers. As previously mentioned, however, nutrient concentrations in these tributary streams were undoubtedly greater than values in the mainstem rivers near Ruliff and at Evadale; therefore, potential loadings from these sources as presented in Tables 6-1 through 6-4 should be considered somewhat lower than expected values. The total nutrient contribution and discharge to Sabine Lake is the summation of the respective parameters in these tables.

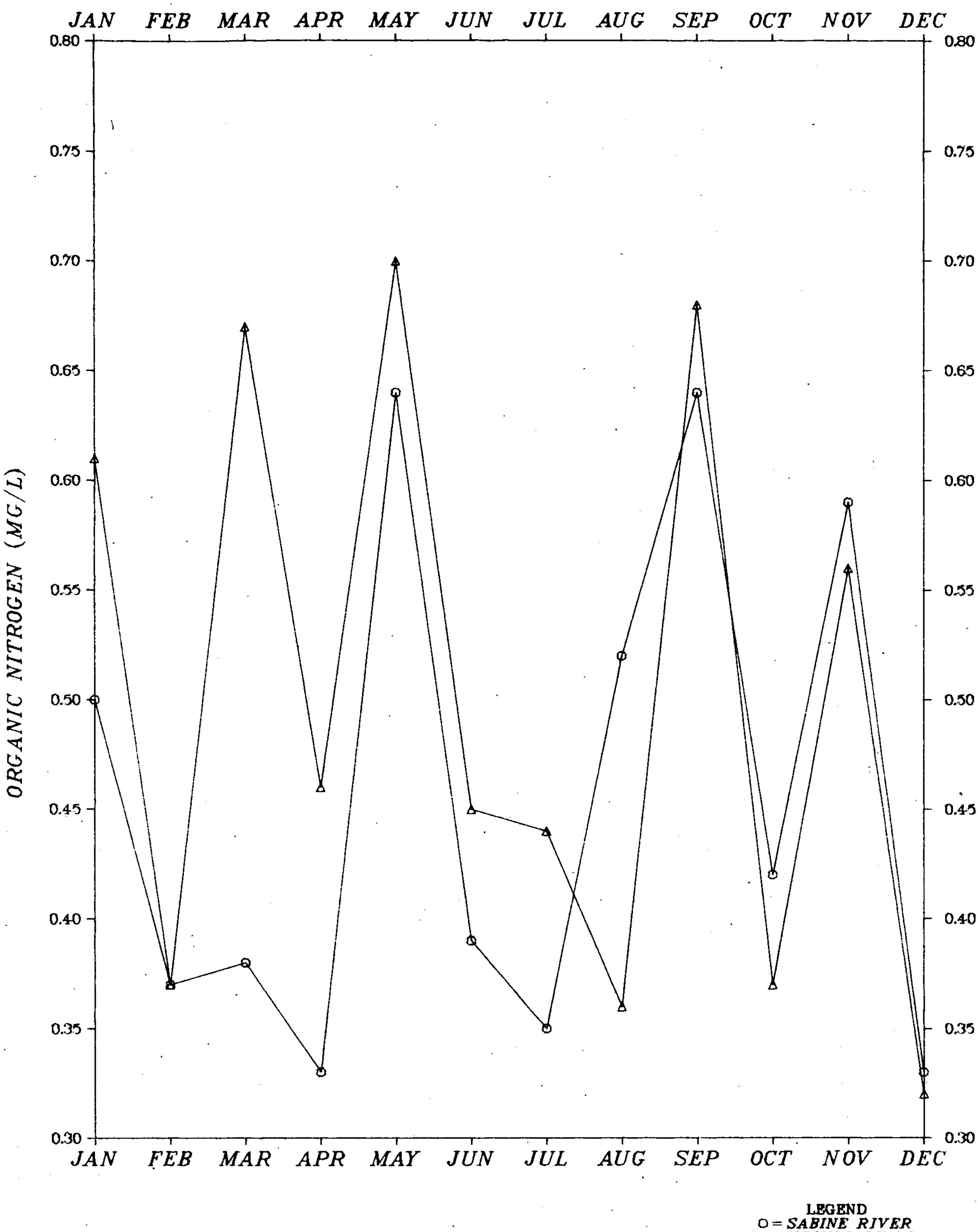


Figure 6-1. Mean Monthly Organic Nitrogen Concentrations in Rivers Contributing to the Sabine-Neches Estuary, 1970-1977

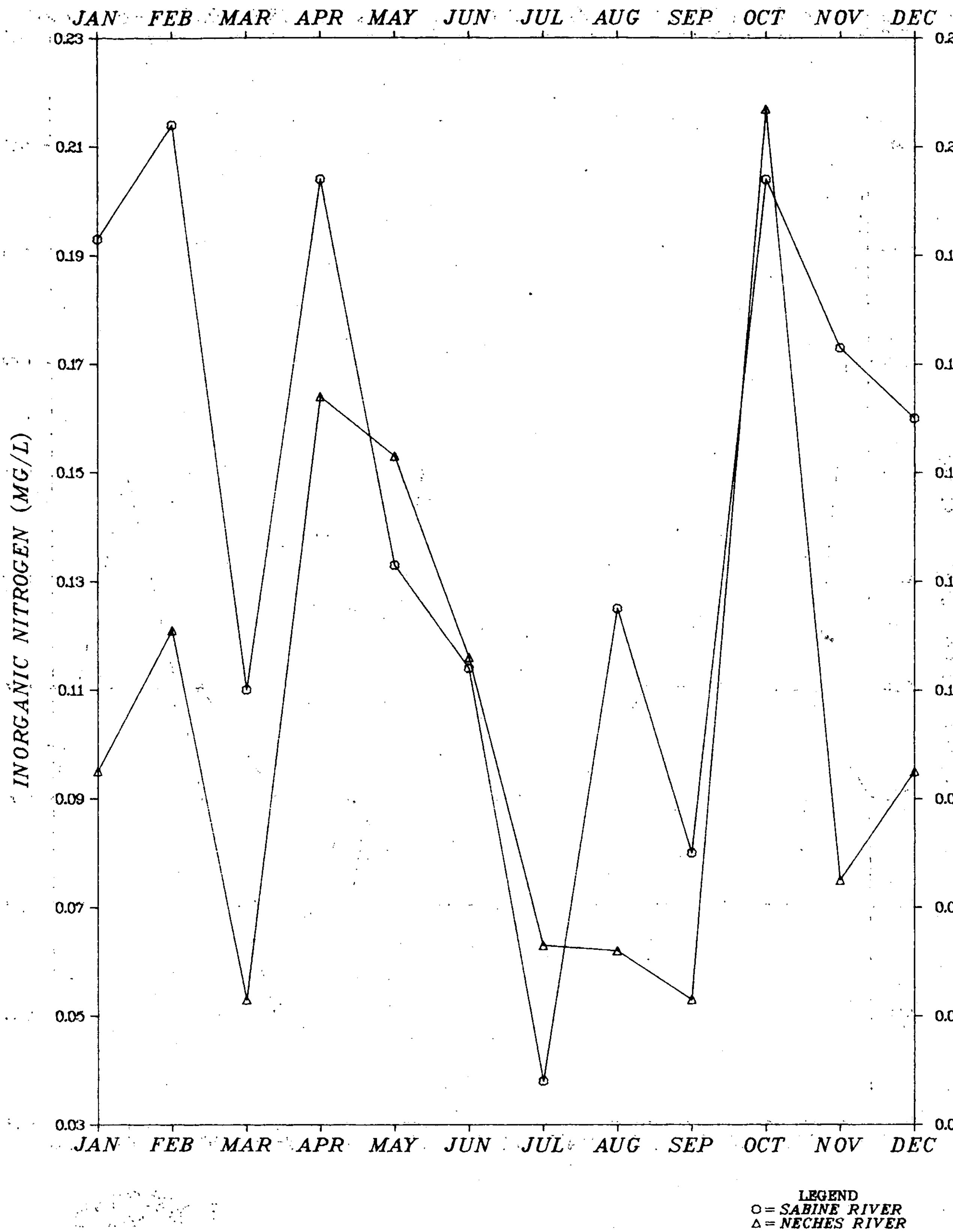


Figure 6-2. Mean Monthly Inorganic Nitrogen Concentrations in Rivers Contributing to the Sabine-Neches Estuary, 1970-1977

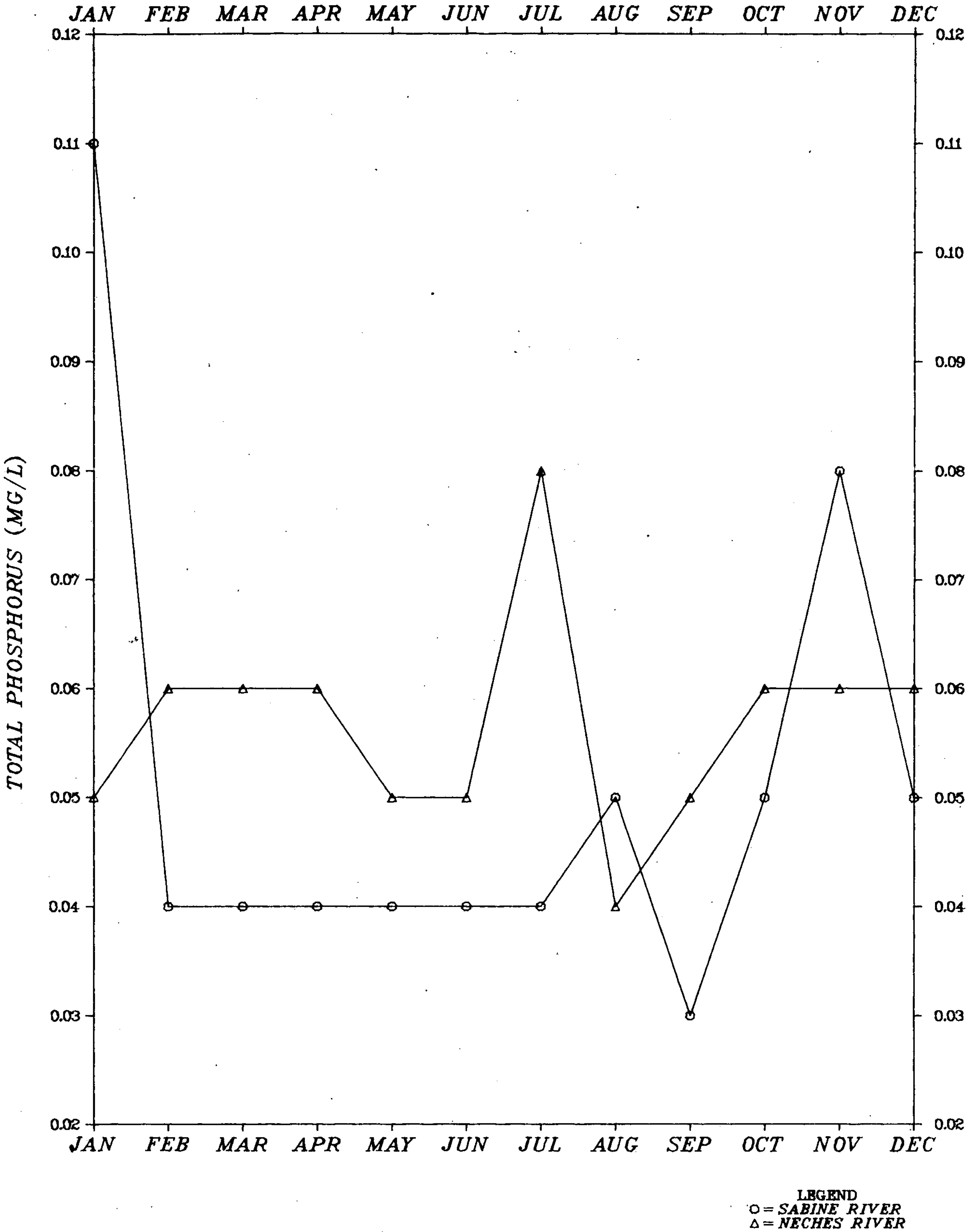


Figure 6-3. Mean Monthly Total Phosphorus Concentrations in Rivers Contributing to the Sabine-Neches Estuary, 1970-1977

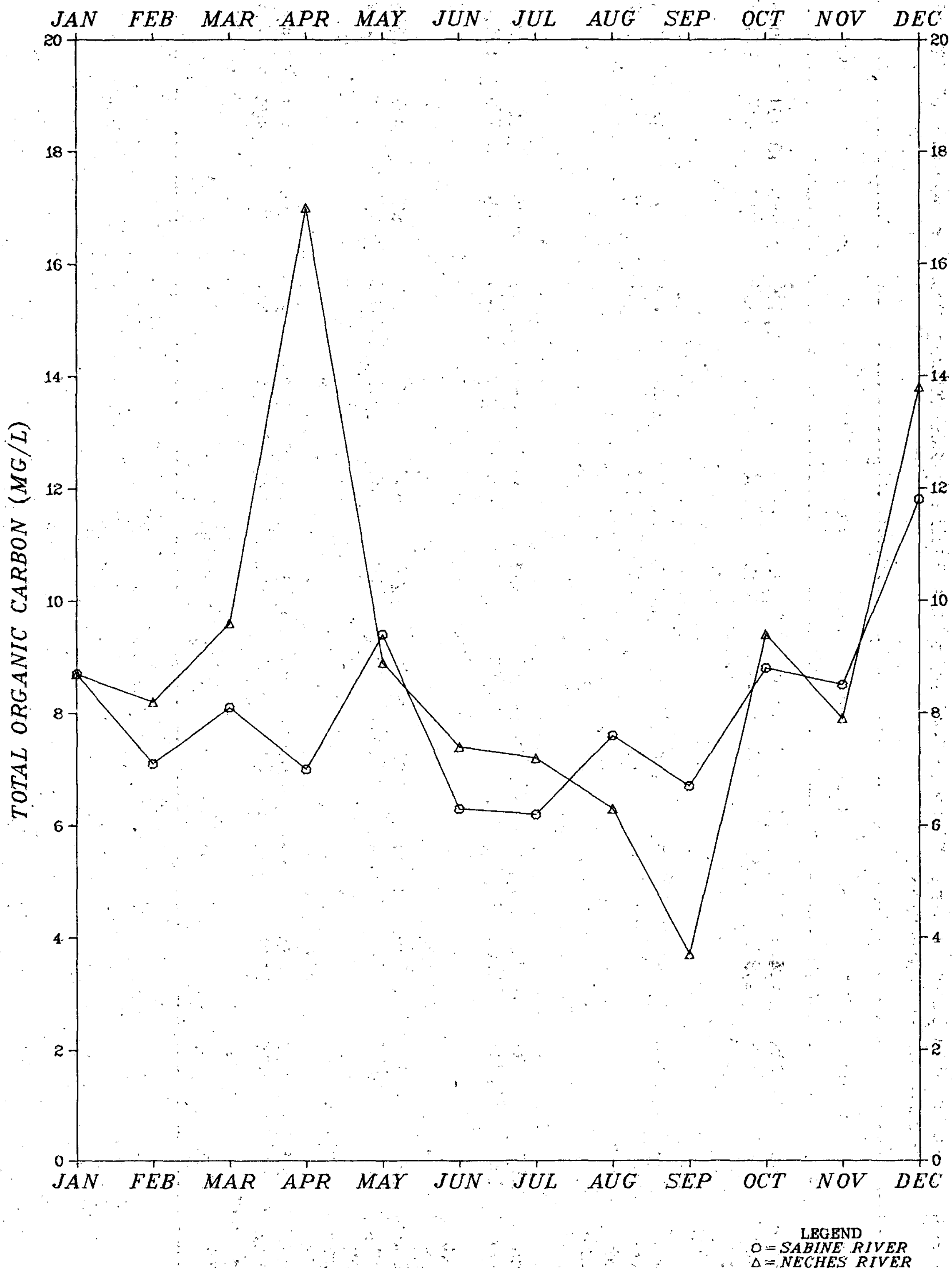


Figure 6-4. Mean Monthly Total Organic Carbon Concentrations in Rivers Contributing to the Sabine-Neches Estuary, 1970-1977

Table 6-1. Range of Expected Organic Nitrogen Loading to the Sabine-Neches Estuary Based on Mean Monthly Gaged Discharges (kilograms/day)

		Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec
Sabine River near Ruliff	High	22,218	21,441	13,832	16,467	32,397	17,186	5,947	8,111	5,349	5,965	10,351	11,076
	Low	7,842	4,972	9,880	5,903	17,445	2,210	506	885	4,356	913	2,917	3,303
Cow Bayou near Mauriceville	High	296	313	117	190	249	125	50	48	161	118	147	174
	Low	104	73	83	68	134	16	4	5	131	18	41	52
Neches River at Evadale	High	14,836	16,110	20,036	13,538	28,553	12,339	4,934	3,061	2,999	3,309	5,267	7,294
	Low	11,781	3,604	11,157	5,587	7,709	3,006	626	822	2,745	146	3,728	1,408
Village Creek near Kountze	High	2,436	2,329	2,319	1,602	3,088	1,516	655	427	530	627	937	1,255
	Low	1,935	521	1,291	661	834	369	83	115	485	28	663	242
Pine Island near Sour Lake	High	1,037	645	889	894	1,341	1,370	281	343	330	412	685	807
	Low	824	144	495	369	362	334	36	92	302	18	485	156

Table 6-2. Range of Expected Inorganic Nitrogen Loading to the Sabine-Neches Estuary Based on Mean Monthly Gaged Discharges (kilograms/day)

		Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec
Sabine River near Ruliff	High	16,010	13,983	6,257	15,535	8,900	8,347	759	2,876	841	2,739	2,823	7,423
	Low	1,634	2,797	988	1,553	2,848	1,031	308	391	382	432	1,035	1,749
Cow Bayou near Mauriceville	High	213	204	53	179	69	61	6	17	25	54	40	117
	Low	22	41	8	18	22	8	3	2	12	9	15	27
Neches River at Evadale	High	3,273	5,087	3,188	7,306	7,709	3,322	1,096	1,005	296	1,363	729	3,545
	Low	873	1,484	2,732	645	1,999	870	235	132	211	243	567	384
Village Creek near Kountze	High	537	735	369	865	834	408	145	140	52	258	130	610
	Low	143	215	316	76	216	107	31	18	37	46	101	66
Pine Island near Sour Lake	High	229	204	142	482	362	369	62	113	33	169	95	392
	Low	61	59	121	43	94	97	13	15	23	30	74	42

Table 6-3. Range of Expected Phosphorus Loading to the Sabine-Neches Estuary Based on Mean Monthly Gaged Discharges (kilograms/day)

		Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec
Sabine River near Ruliff	High	7,188	1,554	1,976	2,486	2,492	1,596	759	811	306	487	1,223	1,360
	Low	980	311	659	311	712	246	380	147	153	243	470	389
Cow Bayou near Mauriceville	High	96	23	17	29	19	12	6	5	9	10	17	21
	Low	13	5	6	4	5	2	3	1	5	5	7	6
Neches River at Evadale	High	1,527	3,604	1,594	1,934	1,713	1,107	861	274	296	389	486	1,024
	Low	655	212	911	215	1,142	316	392	91	127	195	405	384
Village Creek near Kountze	High	251	521	184	229	185	136	114	38	52	74	86	176
	Low	107	31	105	25	124	39	52	13	22	37	72	66
Pine Island near Sour Lake	High	107	144	71	128	80	123	49	31	33	48	63	113
	Low	46	8	40	14	54	35	22	10	14	24	53	42

Table 6-4. Range of Expected Total Organic Carbon Loading to the Sabine-Neches Estuary Based on Mean Monthly Gaged Discharges (kilograms/day)

		Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec
Sabine River near Ruliff	High	313,660	279,664	329,339	254,767	498,417	243,056	92,370	81,109	99,336	109,560	94,096	310,988
	Low	248,314	111,866	214,070	180,201	217,167	98,204	63,267	36,130	25,980	18,260	60,222	155,449
Cow Bayou near Mauriceville	High	4,178	4,085	2,780	2,933	3,836	1,774	770	484	2,995	2,169	1,333	4,888
	Low	3,308	1,634	1,807	2,075	1,672	717	528	216	783	361	853	2,444
Neches River at Evadale	High	191,992	178,056	250,452	687,626	342,632	129,715	68,131	33,807	17,316	97,324	79,416	294,338
	Low	187,629	169,577	177,593	150,418	202,724	105,987	50,119	22,386	13,515	17,518	48,622	81,903
Village Creek near Kountze	High	31,528	25,741	28,984	81,377	37,055	15,936	9,041	4,720	3,059	18,447	14,124	50,658
	Low	30,812	24,515	20,552	17,801	21,924	13,021	6,651	3,125	2,388	3,321	8,647	14,096
Pine Island near Sour Lake	High	13,424	7,133	11,118	45,389	16,096	14,407	3,876	3,785	1,907	12,106	10,324	32,567
	Low	13,119	6,794	7,884	9,929	9,523	11,772	2,851	2,506	1,489	2,179	6,231	9,062

Marsh Vegetative Production

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

Perhaps the most striking 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 (182, 183). Marshes of the Atlantic and Gulf coasts are no exception since the inhabiting rooted vascular plants have adapted advantageously to the estuarine environment and are known to exhibit high biomass production (324, 434, 43, 206, 326, 319, 370, 13). As a result, the marshes are large-scale contributors to estuarine productivity, providing a major source of particulate (i.e., detrital) substrate and nutrients to the microbial transformation processes at the base of the food-web which enrich the protein levels and food value for consuming organisms (48, 49, 236, 185, 449, 158, 157, 44, 197, 51, 135, 230, 105, 104, 110). Recent research has demonstrated a correlation between the area of intertidal salt marsh vegetation and the commercial harvests of penaeid shrimp (368). For Texas estuaries, the statistical relationship indicates at least 30 pounds of shrimp harvested (heads-off weight) per acre of intertidal marsh (33.6 kg/ha).

Marsh areas may be of greater ecological value if sectioned into small tracts by the drainage channels of transecting bayous and creeks (79). The rationale for this suggestion is found in "edge-effect" benefits; that is, a higher edge length to marsh area ratio provides more interface and a greater opportunity for exchange of nutrients and organisms across the boundary between open aquatic and marsh habitats. Deltaic marshes at the headwaters of an estuary generally exhibit a dendritic pattern of drainage channels and are especially important because they form a vital link between an inflowing river and its resulting estuary. Here, the direct effects of freshwater inflow/salinity fluctuations are primarily physiological, affecting both seed germination and plant growth, and are ultimately reflected in the competitive balance among plant species and the presence of vegetative "zones" in the marsh (315, 199, 193, 181, 102, 222).

The Sabine-Neches estuary receives its major input from the Sabine and Neches Rivers and the interdelta marshes. These wetland associations, which span the distance between the intertidal and upland floodplain areas, consist of tidal flats, transition zones, and wetland meadows. The marshes west of Sabine Pass are dominated by a mixture of *Spartina patens* and *S. spartinae*. The small, isolated marsh lying between the outlets of the Sabine and Neches Rivers is also dominated by this *Spartina* mixture in varying ratios. The lower wetlands contain mixtures of *Phragmites australis* and, in other areas, *S. alterniflora*. This "non-forested wetland" category comprises approximately 41,000 acres (16,600 hectares) in the Neches-Sabine area (249), and the dominant vegetation can be described as halophytic (52).

Specific estimates of above-ground net primary production of rooted vascular plants (macrophytes) are not available for the wetlands of the

Sabine-Neches estuary; however, such values are expected to be similar to those reported from other Texas deltaic marshes where macrophyte production has been measured. Average annual net production varies from 7,000 dry weight pounds per acre (785 g/m^2) in the Nueces River delta to 11,700 pounds per acre (1,319 g/m^2) and 10,800 pounds per acre (1,211 g/m^2) in the Lavaca and Guadalupe deltaic marshes, respectively (58). Adams and Tingley (59) estimated an annual net production of 7,220 dry weight pounds per acre (820 g/m^2) in the nearby wetlands of the Trinity River delta.

Although the high productivity of these deltaic marsh habitats makes available large amounts of detritus for potential export to the estuary, 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 vegetation zones may go into peat production and is not exported (33). Teal (236) estimated 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. It should be noted, however, that in the Sabine-Neches estuary, as in many other parts of east Texas and Louisiana, the higher S. patens and S. spartinae dominant marshes are also regularly flooded by the prevailing freshwater inflows and probably contribute significantly to the nutrient/detrital export.

In many coastal areas the production and nutritive contribution of emergent vascular plants 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 bed is highly productive, provides valuable habitat (food and cover) to economically important estuarine-dependent fish and shellfish, and stabilizes the bottom of the estuary (177, 131, 18). However, low salinity and inorganic nitrogen concentrations, as well as light limitations, may be inhibiting primary production in Sabine Lake (55). Potentially this relates to Diener's report (385) of only unmeasured amounts of Ruppia martima as the estuary's submerged vegetation.

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 sediments as flow velocities decrease. These nutrients are incorporated into plant biomass during growth periods and are sloughed off and exported to the bay as detrital material during periods of plant senescence and/or periods of inundation and increased flows into the open bay. The Sabine Lake estuarine habitat includes not only the lake proper but thousands of acres of brackish water marshes which extend clockwise around the periphery of the lake from the Old River Cove area to the Intracoastal Waterway. The numerous bayous and channels provide important passageways for the movement of estuarine-dependent organisms and transport of nutrients into the lake system. The salinity of Sabine Lake and its contiguous marshes and the stability of the salinity regime itself have been changing rapidly due to channelization and levee construction which began prior to 1900, and to altered river inflows as related to upstream reservoir development and diversion of water for municipal, industrial, and agricultural purposes. These physical modifications, combined with the relative paucity of data in this system compared to other Texas estuaries, makes the problem of establishing baseline data quite difficult.

Studies by Armstrong et al. (293), Dawson and Armstrong (298) and Armstrong and Brown (297) were conducted to determine the rates at which nutrients exchange with the marshes in Texas bays, particularly upper Lavaca Bay, and the effects of freshwater flows on these exchange rates. More recently, nutrient exchange rates have been determined for marsh systems in Nueces and San Antonio Bay (296), the Colorado River delta (295), and the Trinity River delta (299). As yet, however, similar studies are lacking for the Sabine-Neches estuary. Exchange rates from other Texas coastal marsh systems are shown in Table 6-5.

Carbon, nitrogen, and phosphorus exchange rates in other Texas marsh systems tended to follow seasonal patterns, with similar patterns from species to species. The order of magnitude of exchange rates was also similar in the marshes of the Nueces, San Antonio, Lavaca, and Colorado River deltas. 1/ Generally, the studies revealed that, almost without exception, the organic forms (volatile suspended solids, VSS; biochemical oxygen demand, BOD_5; total organic carbon, TOC; and unfiltered total phosphorus, TP) were exported; of the inorganic forms, only nitrogen was imported while phosphorus was exported. The deltaic marshes generally released TOC year-round with greatest rates occurring in winter and summer; TP was also generally exported in greatest quantities in late winter and summer. Nitrate nitrogen and ammonia nitrogen were continually absorbed while nitrate nitrogen and total Kjeldahl nitrogen were neither absorbed nor released in sizeable amounts.

The interdelta wetlands are important sources of nutrients for the estuary. Periodic inundation events are necessary in order for these marshes to deliver their potential nutrient stores to the open waters of Sabine Lake. This occurs as flood waters from the Neches and Sabine Rivers moving across the area sweep decayed macrophytic and dried algal mat material out of the system. Following a period of emersion, a sudden inundation event over the interdelta region will result in a short period of high nutrient release from the established vegetation and sediments (298). This period may last for one or two days and is followed by a rapid decrease in release rates toward the seasonal equilibrium. During periods of high river discharge and/or extremely high tides that immediately follow prolonged dry periods, the contribution of carbon, phosphorus, and nitrogen from the interdelta wetlands to the estuarine system can be expected to increase dramatically. It is very likely that the mode of export in the Sabine-Neches estuarine system is similar to that of the other Texas marshes; that is, the export is driven by normal tidal action, wind tides, and flood flows flushing the nutrients out of the marshes into the adjacent waters.

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

1/ The exchange rates in the Trinity River delta were similar to, but somewhat lower than, those measured for the other systems.

Table 6-5. Summary of Nutrient Exchange Rates (299)

	DOC a/	POC b/	VSS c/	Nitrogen Total	Nitrogen Organic	P d/	Tide Range	Inundation Regularity
			(kg/ha/d)					
Saltwater Marsh								
Pomeroy et al. (301)						-0.1	large	high
Reimold (207)						-6.3	large	high
Settlemyer et al. (219)			-18.4			-0.18	medium	high
Woodwell et al. (451)	0.23	+1.6					medium	high
Odum and de la Cruz (184)			-2 to 28				large	high
Brackish Marsh								
Stevenson et al. (231)				-0.029		-0.025	medium	medium
Armstrong et al. (8)								
Lavaca Bay								
Flood Drainage	-12.6			-1.3	-1.2	-0.1	small	low
Small Net Exchange	-0.94		-1.5	-0.21	-0.21	<-0.01	small	low
Normal w/Drying	-27.3		-83.6	-1.2	-1.1	-0.16	small	low
Dawson and Armstrong (298)								
Normal Tidal Exchange	-2.3			-0.39		-0.08	small	low
Following Drying	-5.9			-2.1		-0.19	small	low
Armstrong and Brown (297)								
Sediment Only				-0.74		-0.1	none	none
Armstrong and Gordon (296)								
Nueces Bay (Reactors)	-1.62		-3.08	-0.08		-0.03	small	high
San Antonio Bay (Reactors)	-2.42		-3.54	-0.02		-0.08	small	high
Copano Bay (Linear Marsh)	-3.75		-0.86	-0.06		0.00		
Armstrong and Gordon (295)								
Colorado River Delta (Reactors)	-0.46		-0.18	0.0	0.0	0.00	none	none
Armstrong et al. (299)								
Trinity River Delta (Reactors)	0.0		-0.86	0.01	0.0	0.02	none	none
Trinity River Delta (Linear Marsh)	-1.36		0.40	-0.05		-0.02		

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

destruction, loss or degradation of wetlands, and to preserve and enhance the natural and beneficial values of wetlands..."

In pursuit of this goal, the Texas Department of Water Resources has funded aerial photographic studies with the Texas A & M Remote Sensing Center to provide baseline characterization of key coastal wetlands in Texas in order to comparatively evaluate the various components of the marsh systems. The following description of the Sabine Lake marshes is a by-product of seasonal aerial photographic studies conducted during the 1978 through 1979 growing season (159).

An extensive, low-lying marsh traversed by Old River Bayou as well as by roads, dikes, and canals, lies northeast of the Neches River outlet. These marshes are interrupted along the eastern end by a ridge of higher, cultivated ground which extends nearly to the Sabine River. Beyond the ridges lie the marshes of Cow Bayou. The bayou has been straightened significantly by channelization, the dredge spoil forming banks sustain small forested wetlands.

A relict dune ridge, along which the coastal portion of State Highway 87 is situated, separates the flat, low-lying inland marshes west of Sabine Pass form slightly undulating wetlands fronting on the Gulf. This area is dominated by such man-made features as the Gulf Intracoastal Waterway, Port Arthur Canal, the Sabine Pass jetties, roads, drainage canals, drilling rigs and pipelines. Besides the industrial scars, this area is also marked by the patchwork appearance of pastures periodically burned off in the expectation of encouraging short-term growth of pasturage. South of Keith Lake, including Salt Bayou, Shell Lake, Mud Lake, Salt Lake, and Fence Lake, are extensive, low-lying pond-filled marshes, many of which have been drained to allow increased grazing activities.

The least modified coastal marshes appear to be those within the confines of Sea Rim State Park. Even so, the practice of periodic burnoff, undertaken to maintain the bird habitat within the park, also occurs here.

The construction of spoil levees by the Corps of Engineers in 1966 closed the Keith Lake Channel eliminating the connection with the Gulf of Mexico and its tidal influences. The two points of access still available to estuarine organisms were so circuitous that the Keith Lake complex, including over 84.9 square miles (54,340 acres), was effectively sealed as a prime nursery habitat. The impact of this activity plus the disruption of freshwater drainage patterns due to the construction of the Gulf Intracoastal Waterway across the southern portion of Jefferson County resulted in reduced productivity in the Keith Lake complex. 1/ The Keith Lake Water Exchange Pass was re-established in mid-September 1977 to retard and/or reverse this decline in biological productivity by providing a more direct access for larval and juvenile fish and crustaceans into the marsh nursery grounds.

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

1/ As late as 1964, Keith Lake was reported as one of the three best zones in Texas for shrimp production (276).

which there is a healthy seasonal cycle of emergence-to-maturation-to-senescence-to-detrial utilization. Acre for acre, the wetlands are among the most productive areas on earth. Therefore, the direct and indirect impacts of water development, power development, navigational development, oil and gas production, and expansion of agricultural and cattle-raising activities in the coastal zone should be of considerable interest.

Summary

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

Aerial photographic studies of the Sabine Lake marshes have provided an insight into on-going wetland processes. Overall, except for the Sea Rim State Park area, the coastal marshes in the Sabine Pass area are being rapidly diminished due to increased urbanization and industrialization. This area is dominated by such man-made features as the Gulf Intracoastal Waterway, Port Arthur Canal, the Sabine Pass jetties, roads, drainage canals, drilling rigs and pipelines. Besides the industrial scars, this area is also marked by the patchwork appearance of pastures periodically burned off in the expectation of encouraging short-term growth of pasturage. The Keith Lake Water Exchange Pass was re-established in 1977 to retard and/or reverse the decline in biological productivity experienced by the marsh ecosystem. The long-range condition of the wetlands environment will be considerably affected by the kinds of decisions which are made over the next few years with regard to water development, power development, navigational developmet, oil and gas production, and expansion of agricultural and cattle-raising activities in the coastal zone.

CHAPTER VII

PRIMARY AND SECONDARY BAY PRODUCTION

Introduction

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

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

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

Data presented in this report for each of the lower food chain categories (i.e., phytoplankton, zooplankton, and benthos) were obtained from a study performed by Espey, Huston and Associates, Inc. (Austin, Tex.) (55) under

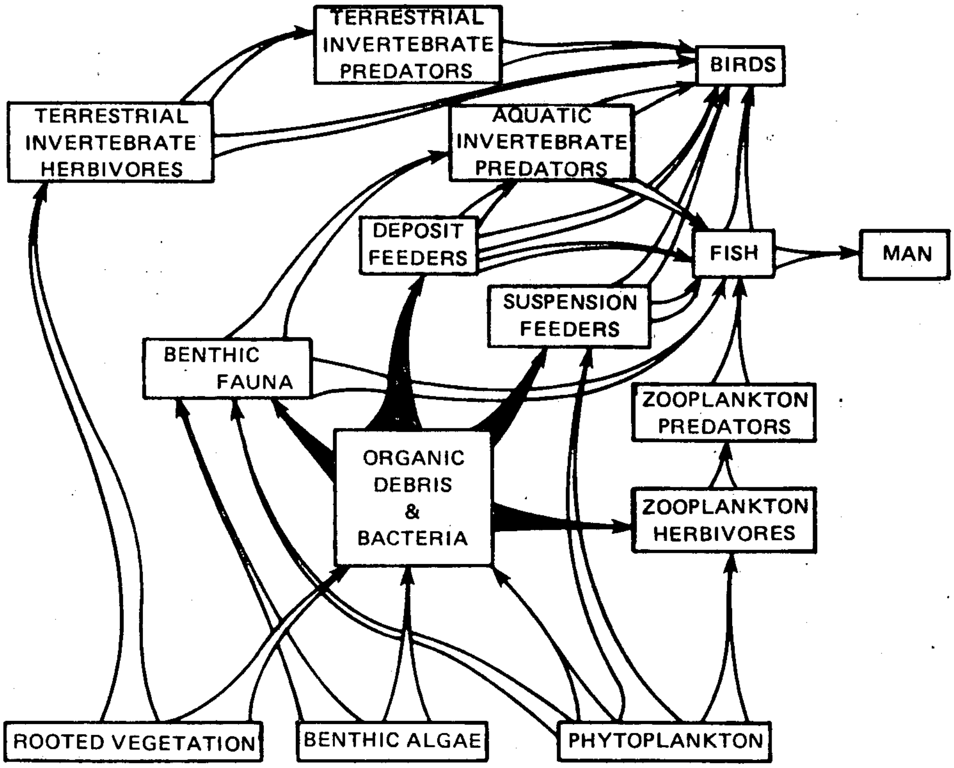


Figure 7-1. Estuarine Food-Web Relationships Between Important Ecological Groups (78)

contract with the Texas Department of Water Resources. The specific objectives of the study were:

(1) to survey the benthic, planktonic, and nektonic communities and their seasonal fluctuations in Sabine Lake;

(2) to determine the primary productivity of the Sabine Lake estuary over a one-year sampling period; and

(3) to compare the system's nutrient supply and primary productivity with freshwater inflows.

Hydrographic, chemical, and biological samples were collected monthly from Sabine Lake from September 1974 through August 1975, excluding January. Plankton and benthos samples were collected at stations 17 through 24 while nekton was collected at stations 17 through 25 (Figure 7-2). Nutrient chemistry and primary production samples were collected at stations shown in Figure 7-3.

Phytoplankton

Data Collection

Phytoplankton concentrations in a single sample ranged from 12,411 cells/l at stations 18 and 23 in November 1974 to 508,870 cells/l at station 24 in August 1975. Mean monthly densities ranged from 70,800 cells/l in November 1974 to 196,800 cells/l in June 1975 with the highest concentrations occurring in spring and summer. The overall mean density for all stations (excluding station 18 in the Sabine River) was 113,118 cells/l. Mean annual standing crops ranged from 48,516 cells/l at site 22 in the southwestern portion of the lake to 244,843 cells/l at riverine site 18. The lowest average densities occurred at stations 20 and 22, near the center of the lake.

Sabine Lake phytoplankton communities were composed of a mixture of freshwater and marine forms, with green algae and diatoms generally being the dominant groups. The mean percentage representation of each group averaged over all stations for the entire study period was:

Diatoms	45.0%
Green algae	36.4%
Blue-green algae	4.6%
Euglenoids	7.1%
Dinoflagellates	5.5%
Others	1.4%

The diatoms were most prominent in September 1974 (Figure 7-4) when an unusually high density of marine forms occurred. The increase in dinoflagellates in October 1974 was due primarily to populations of *Prorocentrum aporum*. The small blue-green component (*Merismopedia glauca*, *Microcystis* sp., *Oscillatoria* sp., and *Coelosphaerium* sp.) reached maximum densities in September 1974 and July and August 1975, but never constituted more than 14.1 percent of the total phytoplankton community. Thirty-two percent of the total standing crop in July 1975 was composed of the euglenoid *Trachelomonas* sp.

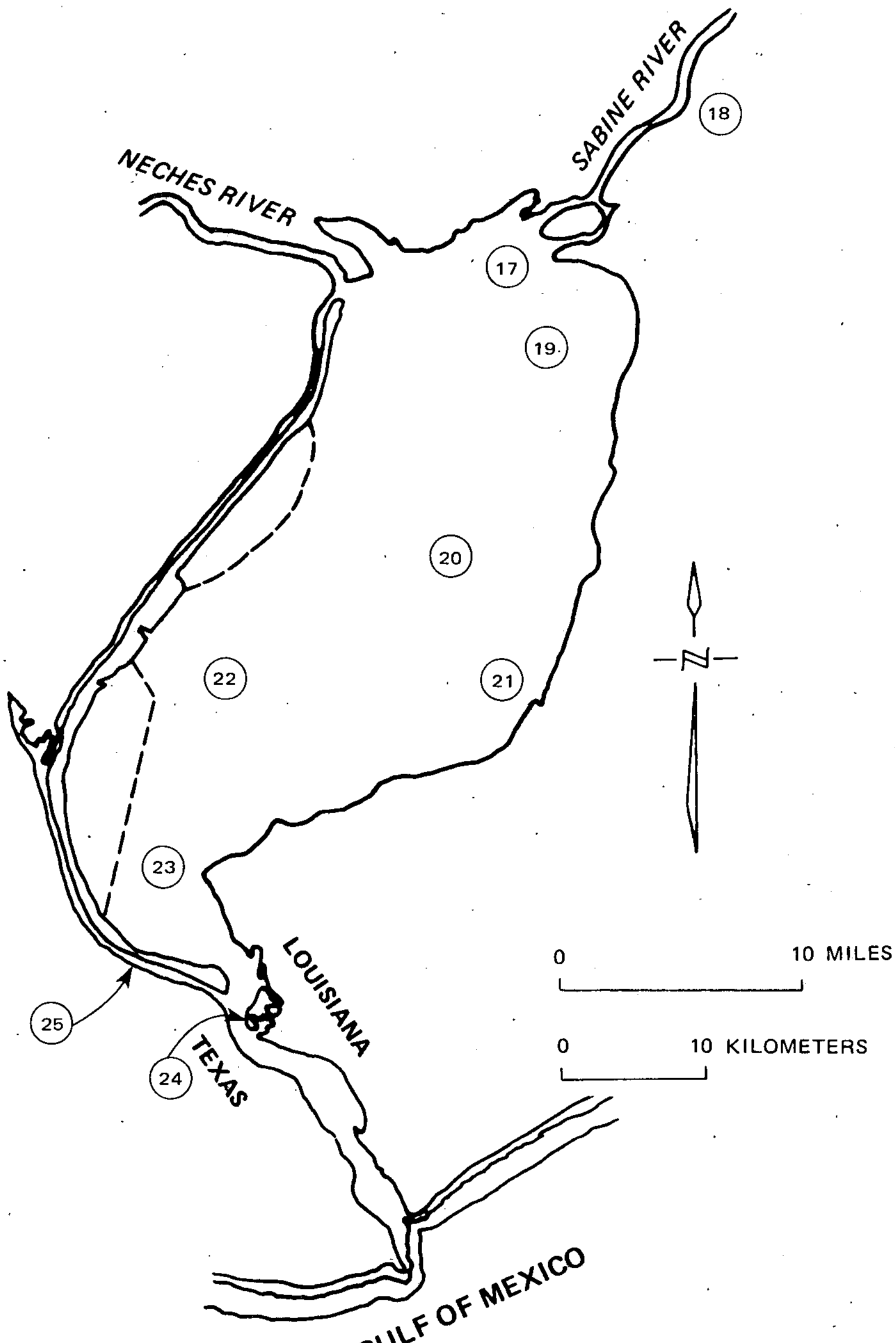


Figure 7-2. Sabine Lake Hydrographic and Biologic Sampling Stations (55)

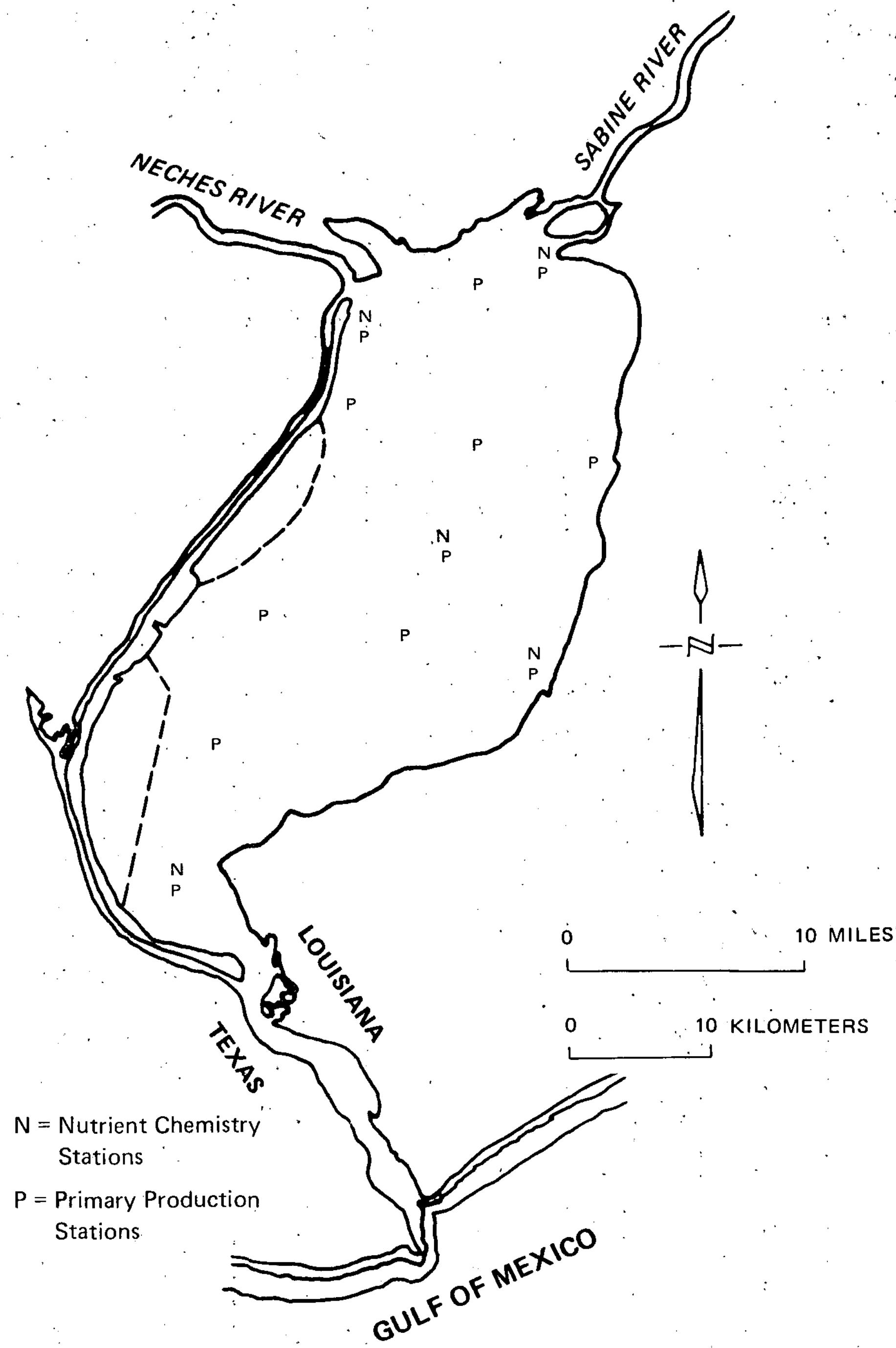


Figure 7-3. Sabine Lake Primary Production and Nutrient Chemistry Stations (55)

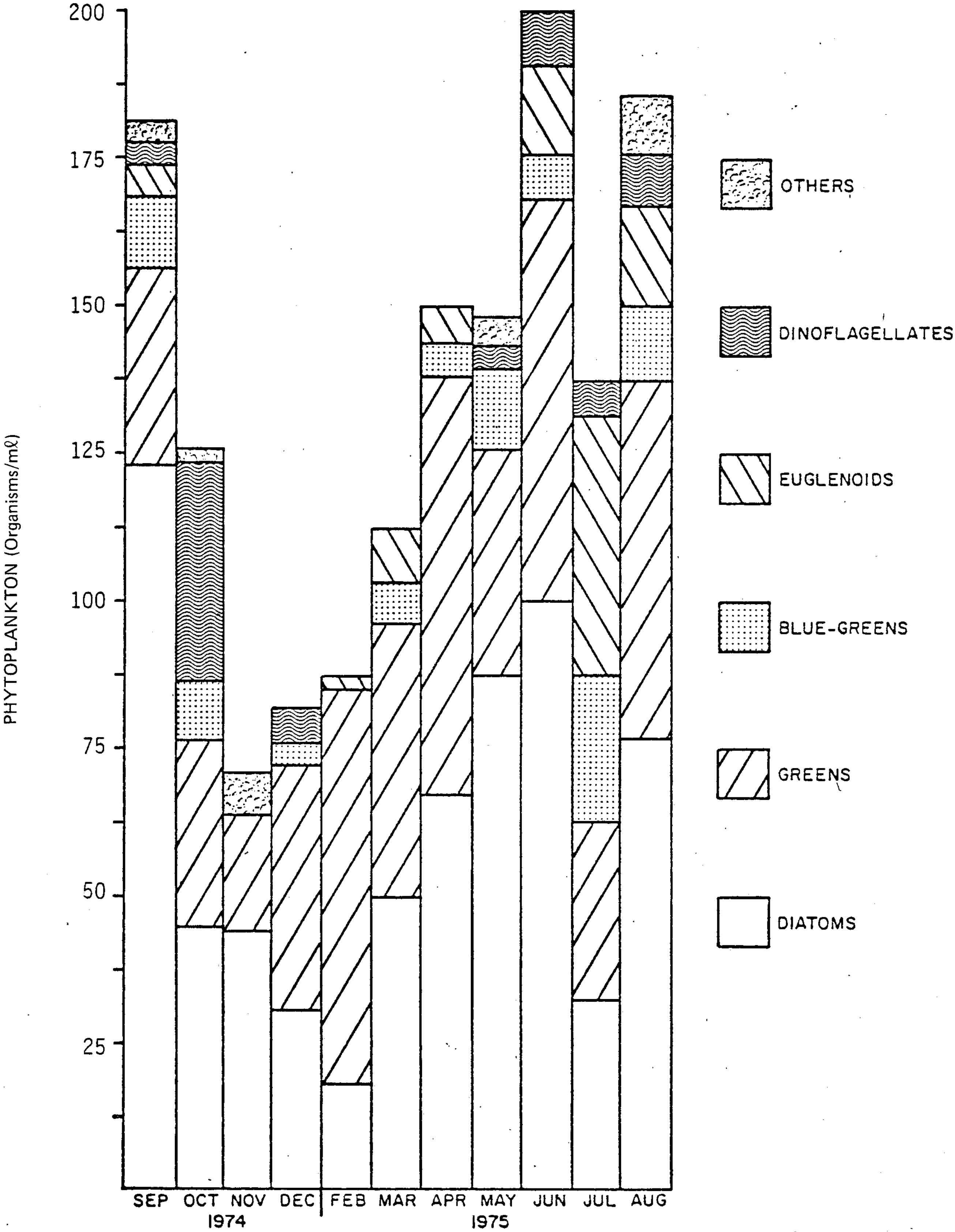


Figure 7-4. Seasonal Succession of Sabine Lake Phytoplankton Groups (55)

The percent composition for each station, averaged over all sampling dates, is shown in Table 7-1. Green algae and diatoms constituted over 70 percent of the total standing crop at all stations. Station 24, at the northern end of Sabine Pass, and station 21, on the southeast lake margin near Johnson Bayou, had the lowest representation of green algae, 26.8 percent and 17.9 percent, respectively. As expected, the bluegreen algae were most abundant at riverine station 18.

The average monthly densities of the nine most prominent phytoplankton taxa are listed in Table 7-2. The diatom Cyclotella meneghiniana, reported to be a halophilous freshwater species (165), was ubiquitous throughout the year. The common marine diatom Skeletonema costatum maintained relatively high populations in the spring and summer months, except for a conspicuous absence in July 1975. Melosira crenulata, a freshwater diatom, was prevalent from March through June 1975. The green algae Chlamydomonas sp. and Chlorococcum sp. maintained high winter populations while Kirchneriella sp. and Ankistrodesmus sp. were prevalent in later winter and early spring.

Results of Analyses

Sabine Lake phytoplankton populations observed during the EH&A study were low in comparison to values reported for other estuarine areas of Texas. Average standing crop for the entire study period was 133,000 cells/l. Moseley et al. (23) found average phytoplankton densities of 730,000 cells/l in Cox Bay, while Holland et al. (308) observed average standing crops of 790,000 cells/l in Nueces Bay.

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

Estuarine plankton were divided by Perkins (196) into three components: "(1) autochthonous populations, the permanent residents; (2) temporary authochthonous populations, introduced from an outside area by water movements, are capable of limited proliferation only and are dependent upon reinforcement from the parent populations; and (3) allochthonous populations, recently introduced from freshwater or the open sea, are unable to propagate and have a limited survival potential." Results indicate that the Sabine Lake system supports a phytoplankton population based on allochthonous or temporary authochthonous components due to the high inflow rates from freshwater sources and the relatively low productivity of Sabine Lake (55).

Freshwater inflows from river sources may act to import freshwater phytoplankton species into the system. This input may be substantial as evidenced by the high phytoplankton densities at station 18 in the Sabine River compared to the main lake stations. Although river flows function to lower salinities and to transport nutrients, detritus, and dissolved organic materials into the system, the rate of river flow can also have contrasting effects. More nutrients and freshwater plankton may be imported to the system with increased flow rates, thereby increasing standing crops and primary production. At very

Table 7-1. Percent Abundance of Sabine Lake Phytoplankton Groups by Station, September 1974 through August 1975 (55)

Station a/	Green Algae	Diatoms	Blue-green Algae	Euglenoids	Dinoflagellates	Others	Estimated Mean Annual Total (No./l)
17	54.0	35.6	6.7	3.0	0.6	0	183,858
18	40.2	46.2	10.3	1.9	0	1.4	244,843
19	42.1	44.2	4.6	5.4	3.0	0.8	151,102
20	37.4	46.6	1.3	8.1	6.6	0	84,622
21	17.9	53.0	7.5	5.3	16.3	0	151,193
22	41.0	38.1	7.1	9.4	2.2	2.2	48,516
23	35.9	48.6	1.0	6.8	3.9	3.9	115,086
24	26.8	49.2	4.0	12.0	5.2	2.8	197,452
Mean (excludes station 18)	36.4	45.0	4.6	7.1	5.5	1.4	133,118

a/ Refer to Figure 7-2 for locations of stations 17 through 24

Table 7-2. Average Monthly Densities (organisms/ml) of Major Phytoplankton Species in Sabine Lake, September 1974 through August 1975 (55)

	1974				1975						
	Sep.	Oct.	Nov.	Dec.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.
Diatoms											
Cyclotella meneghiniana	35.5	17.7	1.7	12.4	7.1	24.8	19.5	17.7	12.4	15.9	14.1
Skeletonema costatum	5.3	0	1.7	0	0	7.1	16.0	24.8	56.7	0	53.2
Melosira crenulata	0	0	0	0	7.1	14.2	14.2	21.3	21.3	0	0
Green Algae											
Chlorococcum sp.	3.6	12.4	1.8	21.3	10.6	8.9	0	0	10.6	1.8	3.6
Chlorella sp.	5.3	1.8	0	7.1	0	0	15.9	10.6	3.6	5.3	3.6
Chlamydomonas sp.	12.4	7.1	5.3	8.9	10.6	1.8	8.9	12.4	26.6	7.1	21.3
Ankistrodesmus sp.	5.3	0	0	0	7.1	10.6	8.9	1.8	1.8	1.8	1.8
Kirchneriella obesa	1.8	3.5	3.5	0	19.5	8.9	12.4	1.8	1.8	1.8	0
Euglenoids											
Euglena sp.	3.5	0	7.1	0	1.8	10.6	3.6	1.8	10.6	3.6	3.6

high flow rates (flood conditions) the high turbidities, salinity changes, and flushing of indigenous populations may actually depress phytoplankton abundance and productivity.

Correlation analysis of average monthly combined flows of the Sabine and Neches Rivers versus mean monthly phytoplankton densities (averaged over all main lake stations) revealed a lack of statistical correlation (Figure 7-5). A more detailed analysis in which the monthly combined river inflows were separately correlated against average standing crops in (1) the upper lake (stations 17 and 19); (2) margin areas (stations 21 and 23); (3) the middle lake (stations 20 and 22); and (4) Sabine Pass (station 24) also yielded non-significant correlations ($\alpha > 0.05$). These results imply that no relationship between flow rate and phytoplankton density can be demonstrated from the available data.

Phytoplankton species vary markedly in their ability to withstand changes in salinity. Accurate halobion classification of most species found in Sabine Lake is impossible due to insufficient culture experimentation on salinity optima and tolerances. Chu (26) noted that although cell division can continue in freshwater for most estuarine species, most freshwater species cannot grow in salinities exceeding 2 ppt. Foerster (70) found, however, that many freshwater species can resume growth after exposure to seawater if placed in a freshwater medium.

Sabine Lake phytoplankton were designated as marine, brackish water, or freshwater species based on descriptions in Lowe (165), Smith (223), Patrick and Reimer (195), Curl (330), and Cupp (45). A significant correlation ($r = 0.83$, $\alpha < 0.01$) was discovered between seasonal percentage of saltwater forms and average salinity, implying that the phytoplankton community structure was greatly influenced by influxes of autochthonous marine forms during periods of massive saltwater intrusions (Figure 7-6). The grouping of stations based on representation of marine phytoplankton is shown in Table 7-3. Those stations in the northern half of the lake closest to freshwater inflow sources had from nine percent to 12 percent saltwater species while stations in the southern half ranged from 22 percent to 29 percent.

Nutrient data collected at stations 17, 20, 21, 23, and 24 included ammonia, organic nitrogen, nitrite and nitrate nitrogen, total nitrogen, ortho- and total phosphorus, and total organic carbon. Temperature, dissolved oxygen, salinity and/or conductivity, and water depth were recorded at the eight stations in Sabine Lake, concurrent with plankton sampling. Inorganic nitrogen concentrations exhibited small seasonal variation and showed little relation to phytoplankton standing crops (55). An unusually low nitrogen/phosphorus (N/P) ratio of only 4:1 was discovered, strongly suggesting that nitrogen is more likely to limit phytoplankton growth in Sabine Lake than phosphorus. Wetzel (445) reported that most aquatic systems generally have an N/P ratio closer to ten. Using Vollenweider's rough index of lake trophic status (433) based on nutrient abundance, Sabine Lake would be designated as oligo-mesotrophic with respect to nitrogen levels; total phosphate concentrations would lead to an eutrophic classification. These observations are in concurrence with Williams (153) who reported that nitrogen is the most frequent limiting nutrient in estuaries.

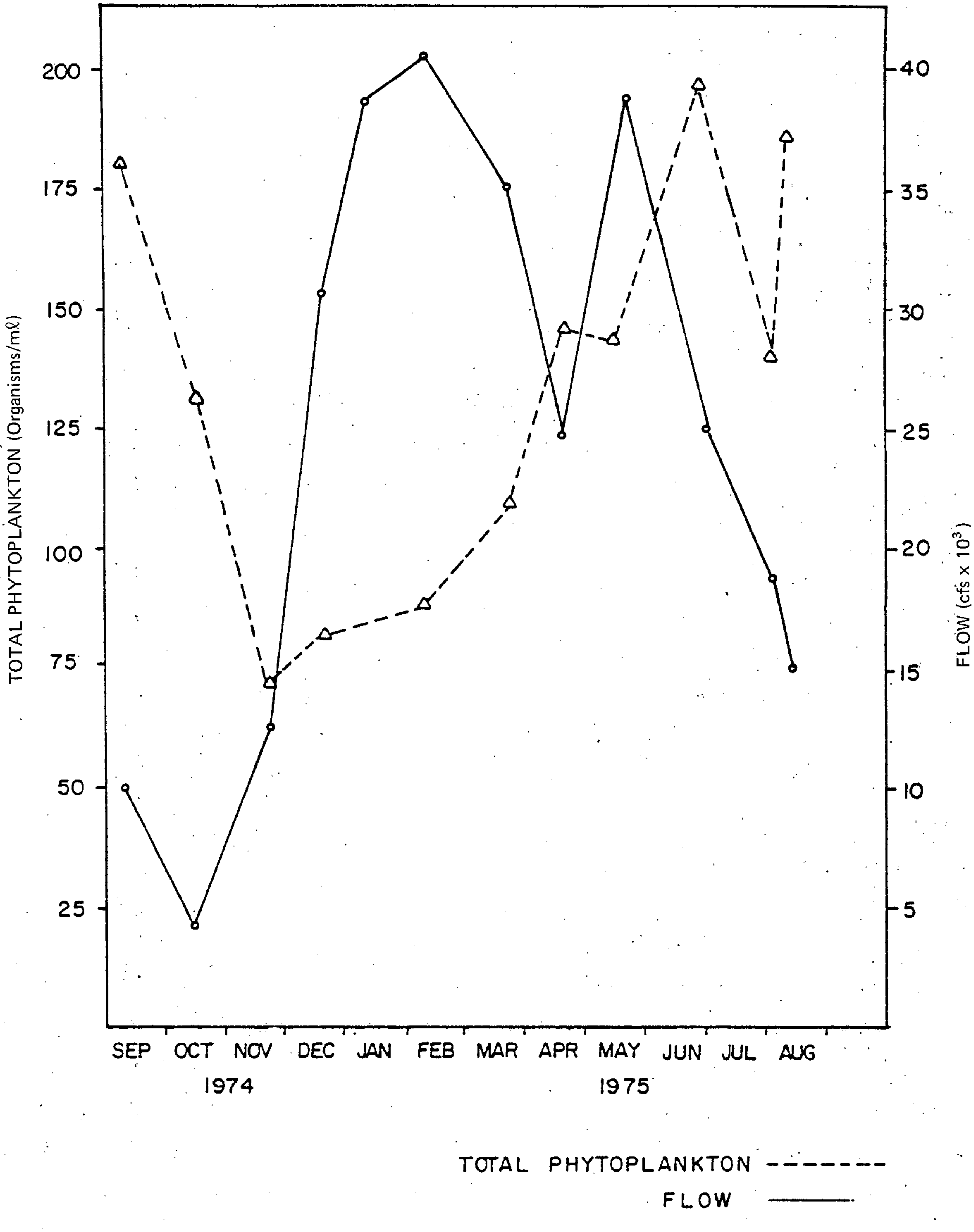


Figure 7-5. Sabine Lake Total Phytoplankton and Combined River Flow (55)

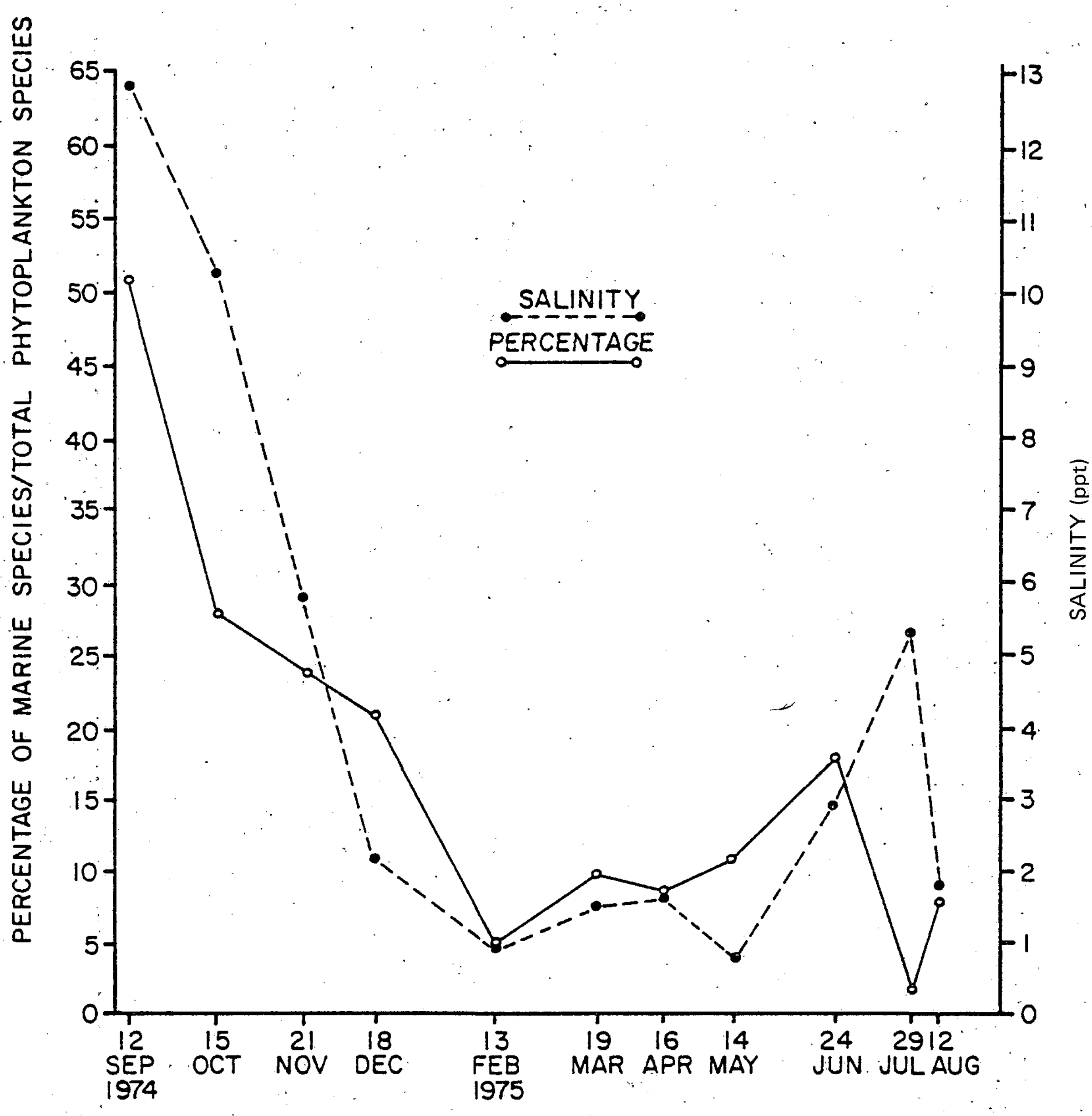


Figure 7-6. Salinity and the Occurrence of Marine Phytoplankton in Sabine Lake (55)

Table 7-3. Mean Annual Percentage of Marine Phytoplankton in Sabine Lake, September 1974 through August 1975 (55)

Station	Location	Percent of Brackish and Marine Species Compared to Total Species Number	Average Salinity (ppt)
17	Northeast corner	12	2.12
19	Northeast margin	10	---
20	Mid-lake	9	2.85
21	Southeast margin	27	3.03
22	Southwest of center	22	---
23	Southern end	25	4.68
24	Sabine Pass	29	6.84

Surface temperatures ranged from 11.0°C in January 1975 to 29.8°C in July 1975. A significant correlation ($r = -0.82$, $\alpha < 0.01$) was discovered between average temperatures and average phytoplankton densities (Figure 7-7). However, since increased intensity and duration of light and low river flows are also associated with warmer temperatures, there are most likely a combination of primary seasonal controlling factors of Sabine Lake phytoplankton.

Zooplankton

Data Collection

Zooplankton populations in Sabine Lake illustrated greater seasonal fluctuations than did phytoplankton. Mean monthly densities showed tremendous variation--up to two orders of magnitude--over short periods of time. Mean monthly standing crops ranged from 20,042 organisms/m^3 in October 1974 to 381 organisms/m^3 in April 1975. The overall mean density for all stations was 7,100 organisms/m^3. Mean annual densities were similar for all lake stations (excluding station 18 in the Sabine River), ranging from 4,672 organisms/m^3 at station 21 to 8,268 organisms/m^3 at station 24.

The zooplankton community of Sabine Lake can be summarized as follows:

1. Calanoid copepods of the genus *Acartia* (mostly *A. tonsa*, the dominant zooplankton of most Texas estuaries).

2. Other adult copepods (e.g., *Oithona*, *Cyclops*, *Macrocyclops*, and *Macrosetella*).

3. Immature copepods (i.e., naupliar larvae and copepodites).

4. Cladocerans, almost entirely freshwater forms such as *Bosmina longirostris* and *Pseudosida bidentata.*

5. Rotifers, also primarily freshwater forms, including *Asplancha priodonta*, *Brachionus*, and *Keratella*.

6. Miscellaneous crustaceans not included above such as ostracods, barnacle nauplii, shrimp larvae, and crab zoea.

7. Others, such as immature gastropods, annelid larvae, fish larvae, nematodes, dipteran larvae, etc.

Over the entire study period the mean percentage representation of these groups in Sabine Lake was:

Acartia	84.6%
Other copepods	4.1%
Immature copepods	1.9%
Cladocera	1.3%
Rotifera	0.3%
Misc. crustaceans	5.8%
Others	2.0%

The Acartia were particularly prevalent in September and October 1974 and July and August 1975, with densities exceeding 10,000 organisms/m^3 in all

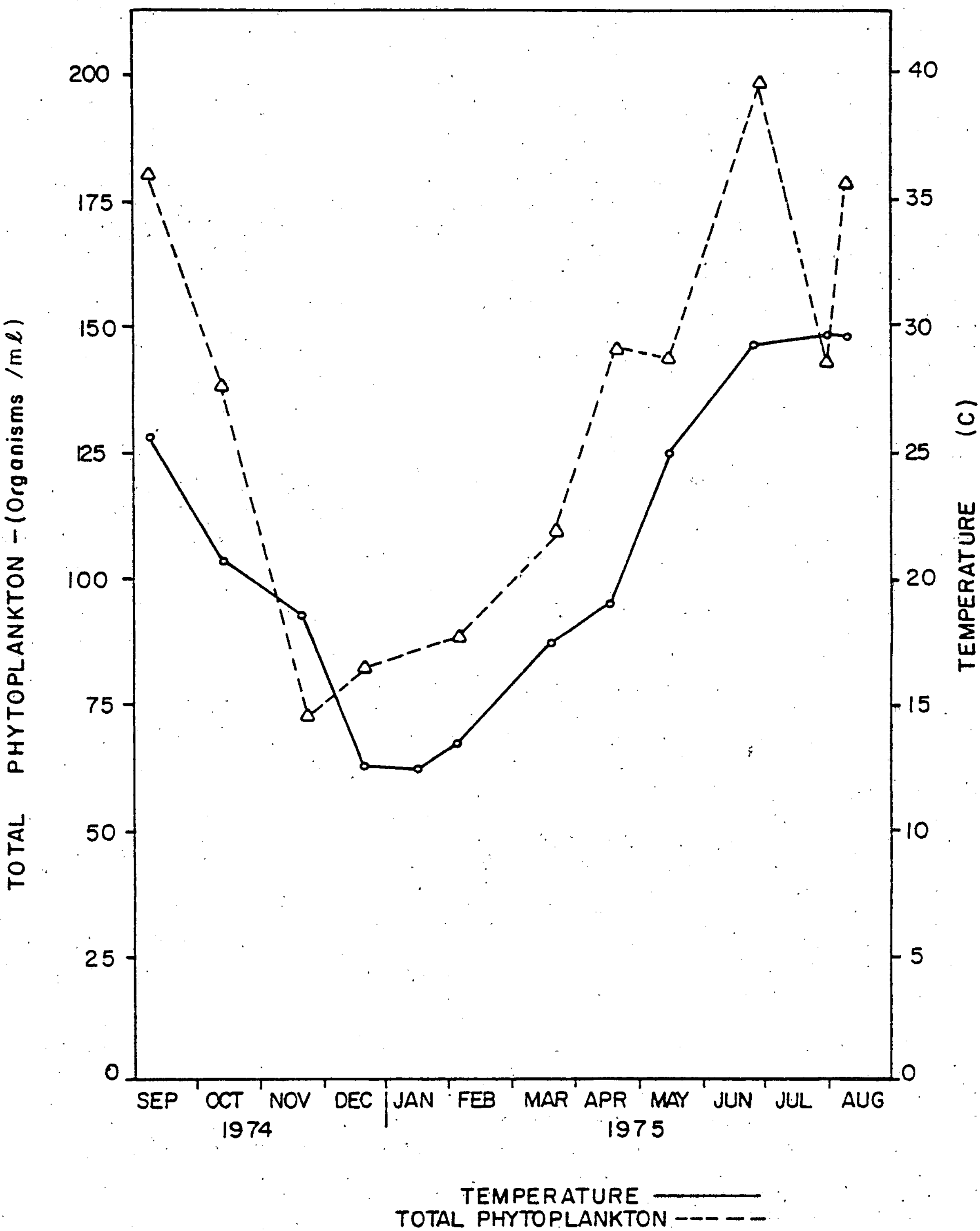


Figure 7-7. Sabine Lake Total Phytoplankton and Temperature (55)

four months. Other copepods, including adults and immature forms, reached maximum densities in September 1974 (2,000 and 820 organisms/m^3, respectively). Peak cladoceran populations occurred in June 1975 (440 organisms/m^3), while the rotifers reached maximum densities in June and July 1975. Little variation between months was evident when standing crops were averaged over all eight stations. Isolated high values for one or two stations accounted for the apparent differences (e.g., the peak population months of September 1974 and August 1975).

Although Acartia was ubiquitous throughout the system, peak populations were recorded at the more marine southern stations (22, 23 and 24); riverine collections from station 18 contained relatively low numbers of Acartia. The "miscellaneous" crustaceans followed the same general trend but had their third highest density at station 17 near the mouth of the Sabine River. Conversely, the rotifers and cladocerans, predominantly freshwater organisms, were most numerous at the upper stations (17 and 20). Rotifers, in particular, were virtually absent from the lower stations.

Results of Analyses

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

Many zooplankton species found in Sabine Lake are widely distributed along the coasts of the United States, while others may even have a worldwide distribution. For example, Green (78) reports that Acartia tonsa may be found in the Central Baltic Sea area; Brachionus quadridentata is also known from parts as distant as the Aral Sea of Russia.

Other zooplankton studies conducted in estuaries and bays along the Texas coast have produced similar results to the EH&A study. As previously mentioned, the calanoid copepod Acartia tonsa was the dominant zooplankton in Sabine Lake. This agrees with other studies of Sabine Lake (365), Lavaca Bay (280), San Antonio Bay (278), and the Nueces and Mission-Aransas estuaries (308). Maximum and minimum monthly densities in Sabine Lake are comparable to results from the above studies (Table 7-4).

Freshwater inflows can influence zooplankton in several ways. Estuarine zooplankton community composition can be altered by importation of freshwater species. Inflows can also transport zooplankton food resources into the system in the form of phytoplankton and detritus. However, zooplankton communities may also be adversely affected by increased river inflows. Sudden shifts in salinity and flushing out of autochthonous populations can decrease zooplankton standing crops. Indeed, Perkins (196) reported that the primary factor influencing the composition and abundance of estuarine zooplankton is development rate versus flushing time. Saltwater intrusions, on the other hand, act to (1) transport marine zooplankton into the system, (2) transport marine phytoplankton as a food source, and (3) increase salinity.

Mean monthly zooplankton standing crops from the Sabine Lake study are compared with monthly river flows in Figure 7-8. High inflows from December

Table 7-4. Range of Mean Monthly Zooplankton Densities in Texas Estuaries (individuals/m^3)

System	Minimum	Maximum
Sabine Lake (55)	381 (Apr. 1975)	29,042 (Oct. 1974)
Trinity Bay (66)	1,235 (Dec. 1975)	190,560 (Apr. 1976)
Lavaca Bay (280)	1,980 (Oct. 1973)	27,846 (Feb. 1974)
San Antonio Bay (278)	820 (Jun. 1973)	46,296 (Feb. 1973)
Nueces Bay (308)	832 (Oct. 1973)	8,027,855 (Feb. 1974)
Corpus Christi Bay (308)	1,722 (Dec. 1972)	53,657,037 (Mar. 1973)
Copano Bay (308)	1,296 (Sep. 1974)	53,536 (Feb. 1973)
Aransas Bay (308)	2,497 (Dec. 1972)	3,008,679 (Feb. 1974)

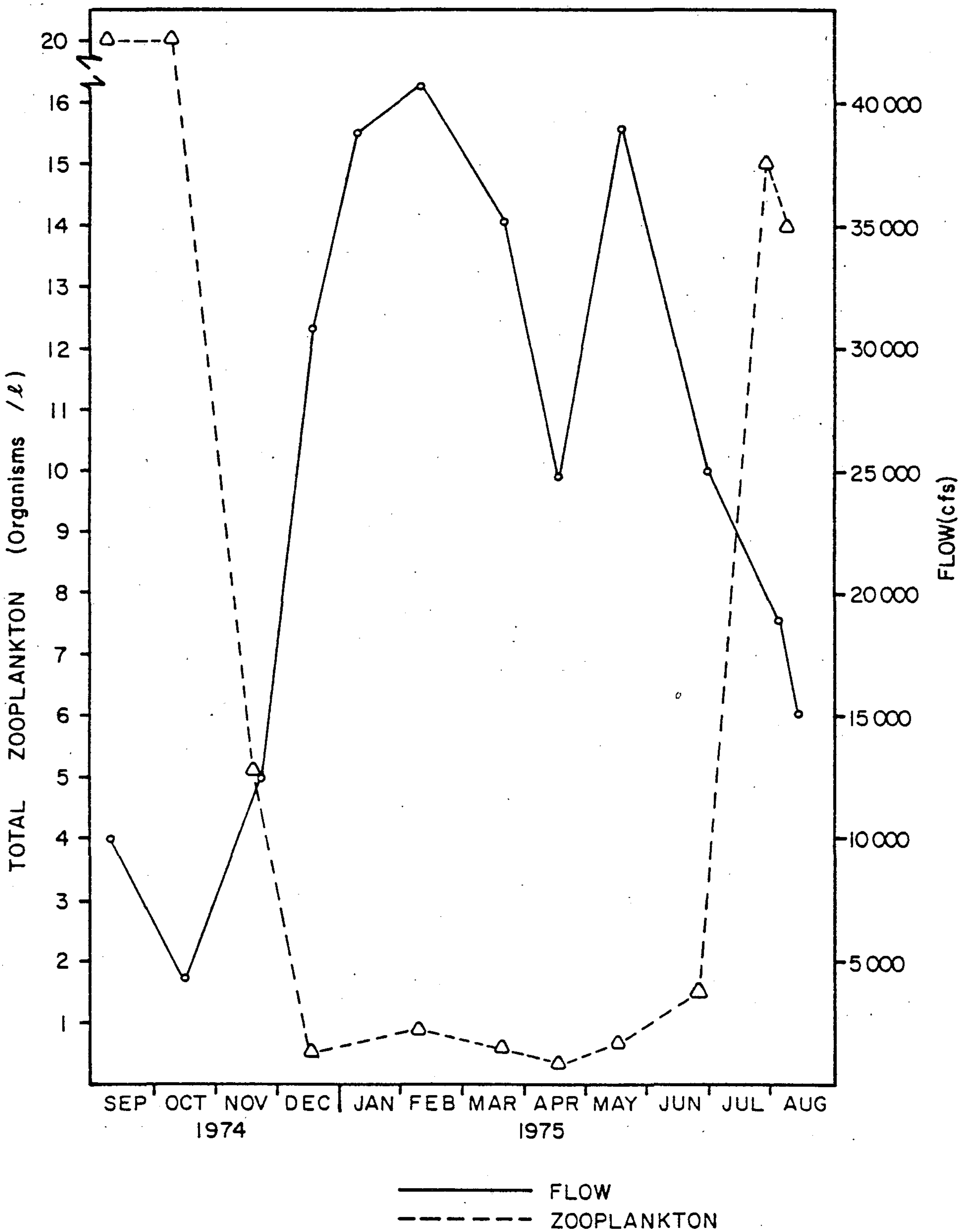


Figure 7-8. Sabine Lake Total Zooplankton and Average Daily Combined River Flow (55)

1974 through June 1975 were accompanied by low zooplankton populations; conversely the zooplankton blooms in September 1974 and July–August 1975 occurred during periods of low flows. Espey, Huston and Associates, Inc. (55) discovered negative correlations between river flows and zooplankton densities at the upper lake stations (17 and 19) ($r = -0.604, \alpha < 0.05$) and the mean densities for all stations (17, 19, 20, 21, 22, 23 and 24) ($r = -0.846, \alpha < 0.01$). These results imply that zooplankton standing crops in Sabine Lake are probably reduced at high flow rates due to the joint effects of flushing losses and decreases in salinity. Mean monthly salinities (average of stations 17, 20, 21, 23 and 24) were positively correlated with total zooplankton densities (average of all stations excluding 18) ($r = 0.82$, $\alpha < 0.01$), as illustrated in Figure 7-9. However, strong cross-correlations between salinity, temperature, and flow rate hinder the separation of individual effects of these variables.

A positive correlation ($\alpha < 0.05$) was discovered between the percent Acartia abundance, with respect to the total zooplankton abundance in each sample, and salinity. The Acartia populations reached maximum densities during periods of relatively low flows, high salinities, and warm temperatures (i.e., September through October 1974 and July through August 1975). The percent abundance of rotifers and cladocerans was negatively correlated ($\alpha < 0.01$) with salinity, implying that these organisms were only successful in less saline areas.

Unlike the phytoplankton, substantial autochthonous populations of zooplankton appeared to successfully grow and reproduce in Sabine Lake. This conclusion is based on the presence of Acartia blooms at stations removed from the source of marine input (i.e., Sabine Pass). Acartia is capable of sustained periods of growth and reproduction throughout the estuary (Table 7-5).

Acartia, the dominant zooplankter of the system, is probably an important food source to some species of larval and juvenile fishes in Sabine Lake. Therefore, any environmental perturbations, such as change in flow rate, may indirectly affect zooplanktivorous fish populations by altering their food supply.

Benthos

Data Collection

A total of 50 benthic species representing six phyla were collected during the Sabine Lake study. The most prominent phyla were the Crustacea which accounted for 40 percent of the species identified, followed by the Mollusca with 28 percent, and the Annelida with 22 percent.

Mean monthly densities ranged from a high of 642 individuals/m^2 in September 1974 to a low of 118 individuals/m^2 in December 1974. The overall mean density for the entire study was 308 organisms/m^2. Occasional peak populations in individual samples precluded any correlation between samples. For example, standing crops in May ranged from zero at station 19 to 1,952 organisms/m^2 at nearby station 17. Little variation between months was evident when standing crops were averaged over all eight stations. Isolated high values for one or two stations accounted for the apparent differences (e.g., the peak population months of September 1974 and August 1975).

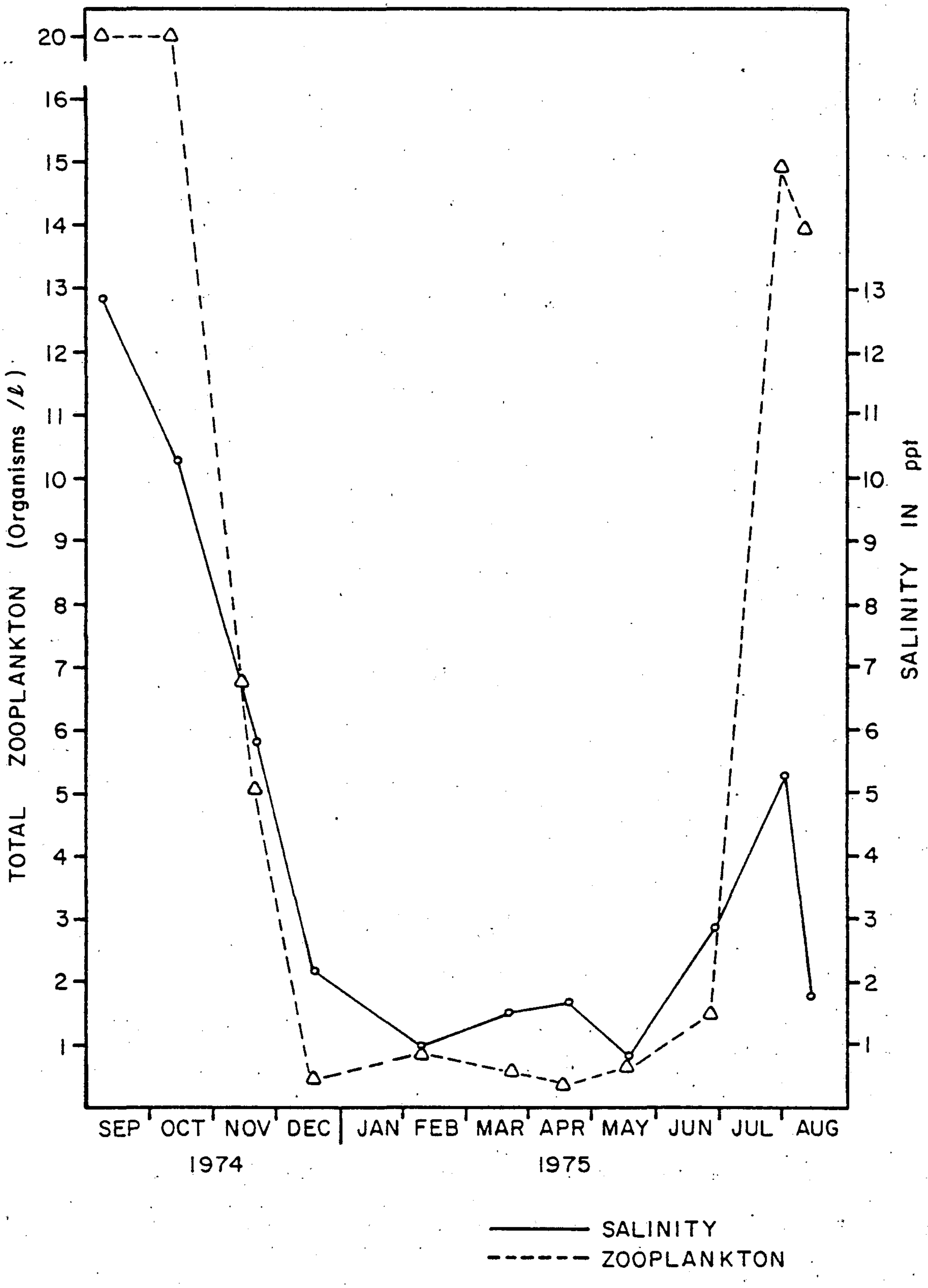


Figure 7-9. Sabine Lake Total Zooplankton and Salinity (55)

Table 7-5. Estimated Abundance (no/m^3) and Percentage of Major Zooplankton Groups by Station in Sabine Lake, September 1974 through August 1975 (55)

Station	Acartice	Other Adult Copepoda	Immature Copepoda	Cladocera	Rotifera	Macro-crustacea	Other	Total
17	4,678 77.3%	294 5.1%	112 1.9%	210 3.6%	37 0.6%	354 6.1%	310 5.3%	5,995
18	762 50.8%	144 9.5%	84 5.5%	191 12.5%	18 1.2%	92 6.1%	218 14.4%	1,509
19	5,414 92.0%	86 1.5%	36 0.6%	71 1.2%	83 1.4%	147 2.5%	45 0.8%	5,882
20	5,705 89.0%	222 3.5%	22 0.3%	162 2.5%	72 1.1%	149 2.3%	72 1.1%	6,384
21	4,672 87.9%	159 3.0%	76 1.4%	69 1.3%	3 0.1%	243 4.6%	94 1.8%	5,316
22	7,162 94.3%	89 1.2%	77 1.0%	74 1.0%	1 0.0%	88 1.2%	103 1.4%	7,594
23	6,520 76.2%	705 1.5%	130 1.5%	32 0.0%	4 0.0%	958 11.2%	208 2.4%	8,557
24	8,268 81.3%	481 4.8%	496 4.9%	4 0.0%	8 0.1%	685 6.8%	208 2.1%	10,150
Mean (excluding Station 18)	6,058 85.0%	291 4.1%	136 1.9%	89 1.3%	30 0.4%	375 5.3%	!49 2.1%	7,!20

Bottom salinities followed the general pattern of river discharges with highest values recorded in the fall and following summer. The highest salinities during almost all months were recorded at stations 23 and 24, and in only one sample (station 23, May) did the salinity at either station fall below 1.0 ppt. All other stations exhibited winter and spring salinity values below 1.0 ppt with much lower peak values than stations 23 and 24. Stations 17, 18, and 19 exhibited slightly different salinity patterns than stations 20, 21, and 22, presumably due to the more direct river influence.

The relative abundance of the polychaetes, molluscs, crustaceans, and others at each station by month is illustrated in Figure 7-10. The polychaetes dominated stations 23 and 24, those stations most influenced by Gulf waters. Five of the six upper and mid-lake stations (17, 18, 19, 20, and 22) were dominated by polychaetes during the fall and by pelecypods (Mollusca) during the remainder of the year.

An unidentified capitellid polychaete and the clam Rangia cuneata were the dominant[1/] benthic species during the study. These two organisms were ubiquitous throughout the lake and often comprised a large percentage of the total numbers collected. Juvenile pelecypods were present at all stations except 24, but reached maximum densities toward the Sabine River. Polychaete #3, on the other hand, was present at all stations, but tended to increase in relative abundance toward the higher salinity waters of Sabine Pass (Table 7-6).

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 (78).

Benthic diversity generally decreases with distance moved upstream in an estuary. From a minimum, at a salinity of 5.0 ppt, species numbers gradually increase seaward to a maximum of about 35 ppt, the normal salinity of seawater, and decline once more with increasing salinity (109). This was found to be true in Lavaca and San Antonio Bays where benthic diversities declined from the high salinity lower bays to the low salinity upper bays and riverine areas. Diversities were highest during late winter and early spring when freshwater inflows were low (278, 280). No such pattern was evident, however, in the benthic populations from the Sabine Lake study. Diversities were generally variable from month to month with no apparent seasonal trends.

Harper (241) studied the distribution of benthic organisms in undredged control areas of San Antonio Bay and found an almost logarithmic decrease in

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1/ An organism was considered dominant if it constituted 30 percent or more of the standing crop of a particular collection.

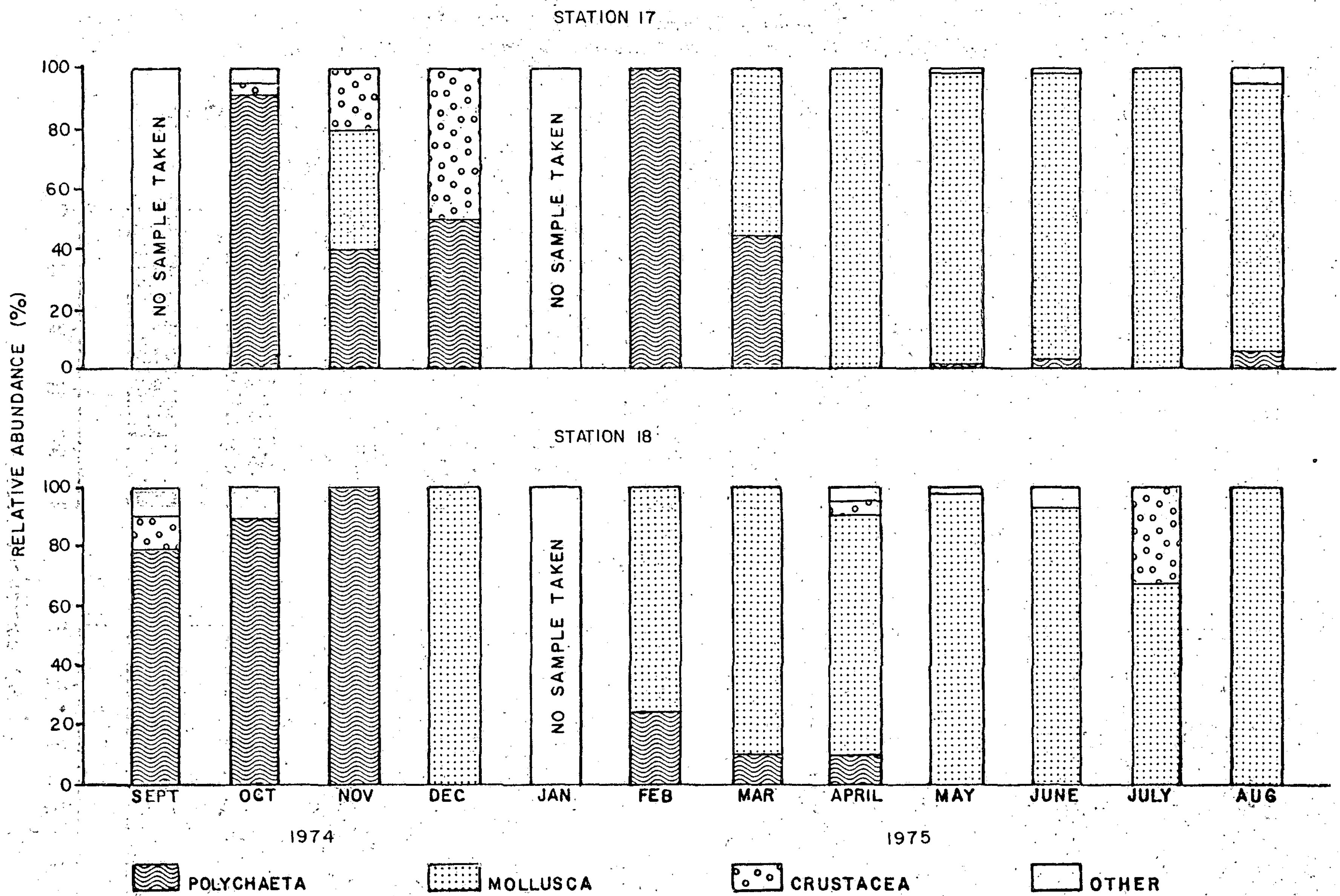

Figure 7-10. Relative Abundance of Major Benthic Groups in Sabine Lake, September 1974-August 1975 (55)

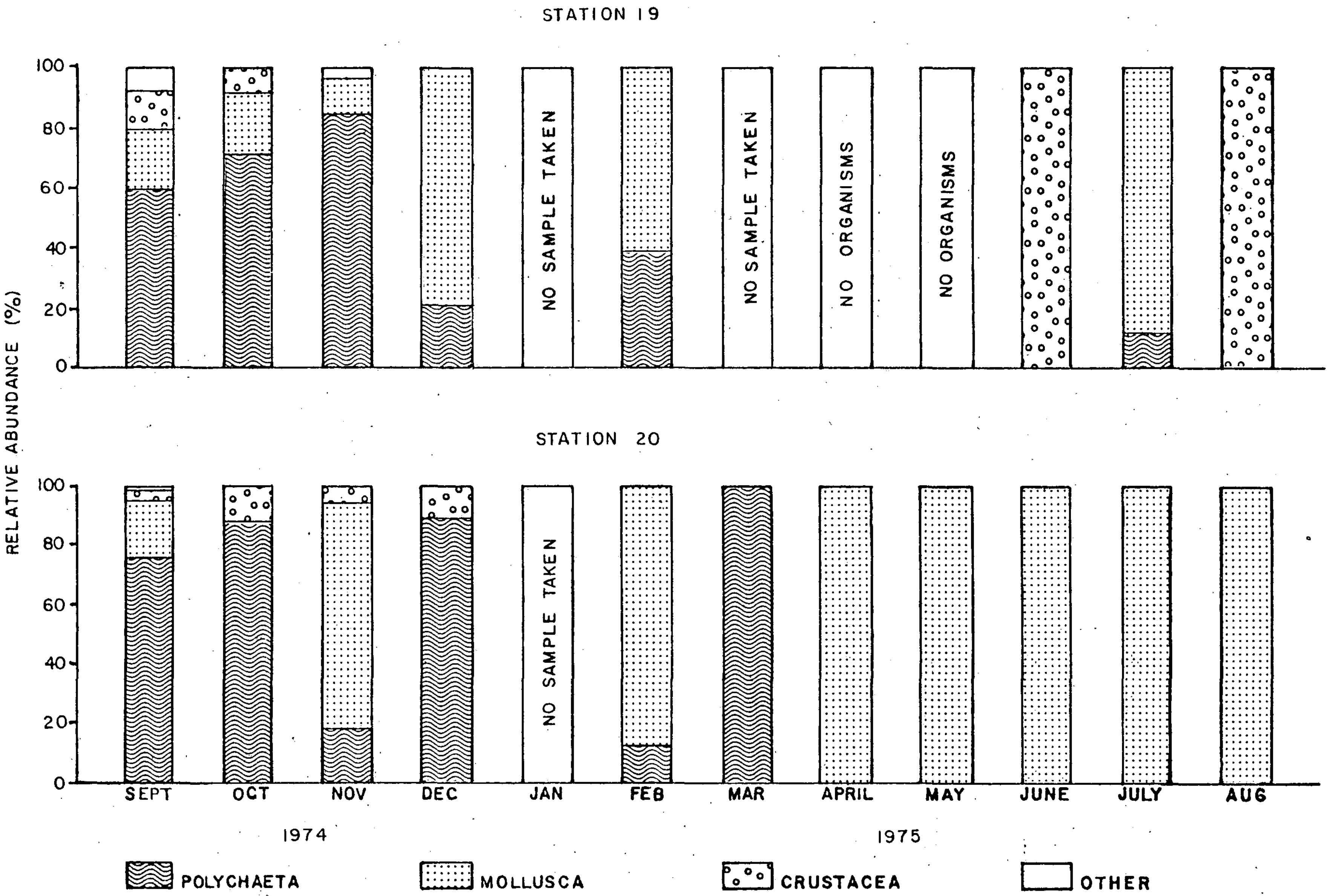

Figure 7-10. Relative Abundance of Major Benthic Groups in Sabine Lake, September 1974-August 1975 (55)—Continued

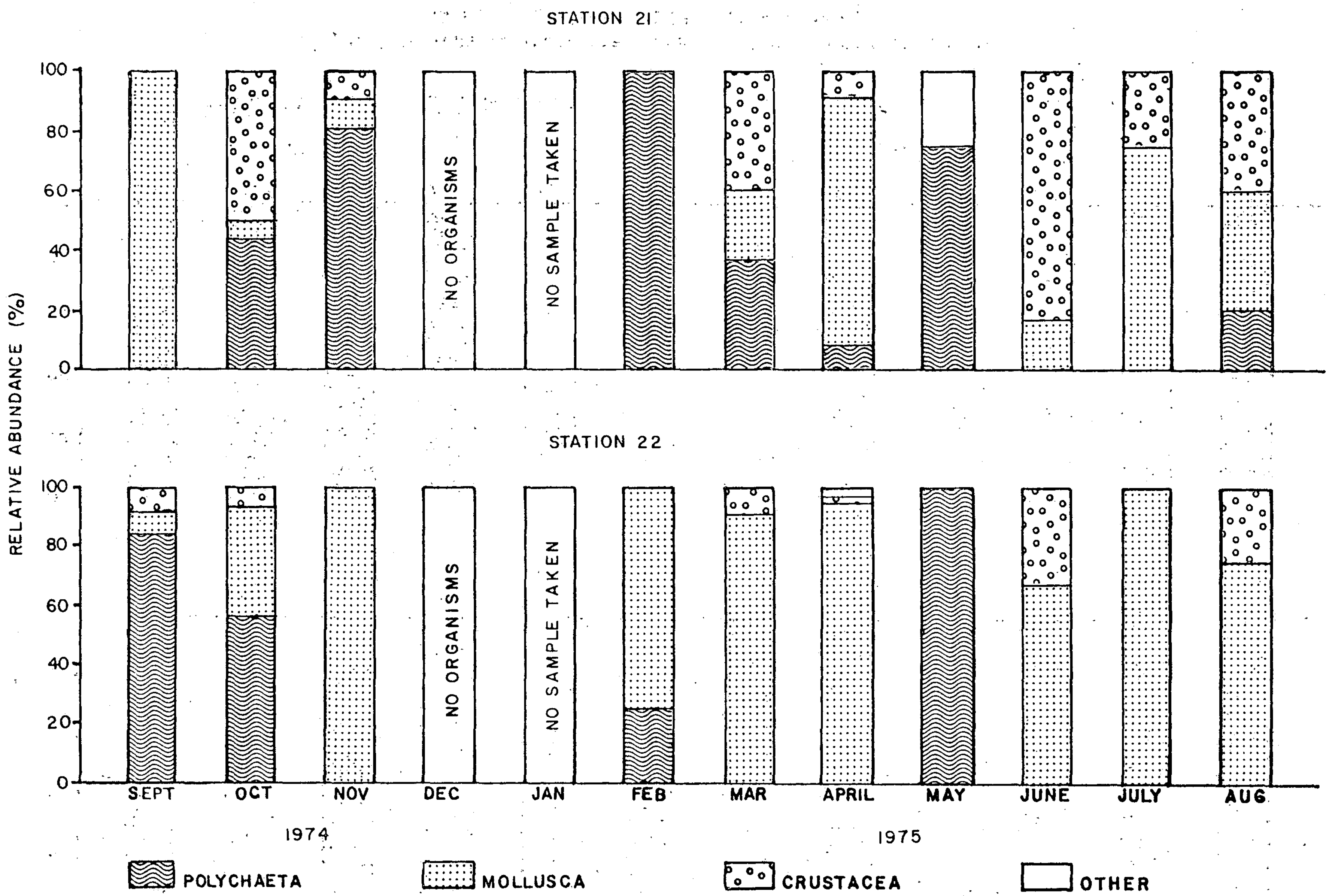

Figure 7-10. Relative Abundance of Major Benthic Groups in Sabine Lake, September 1974-August 1975 (55)—Continued

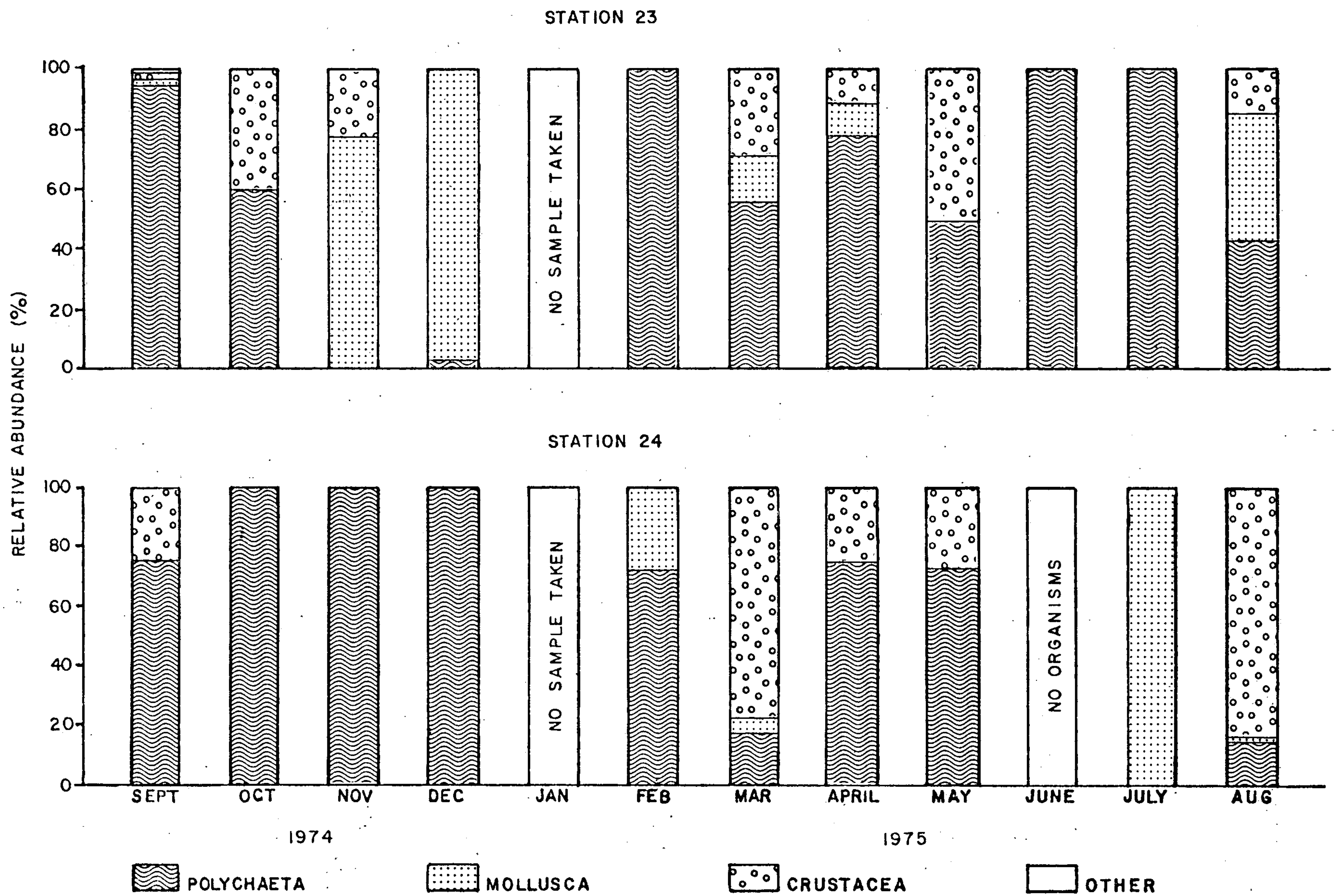

Figure 7-10. Relative Abundance of Major Benthic Groups in Sabine Lake, September 1974-August 1975 (55)—Continued

Table 7-6. Number of Months in Which Each Organisms Constituted 30 Percent or more of the Total Standing Crop (55)

Organism \ Station	17	18	19	20	21	22	23	24
Capitellidae	2	2	3	3	1	2	3	1
Rangia cuneata	2	3		4	2	7	1	
Pelecypod juvenile	3	4	2	2	1			
Polychaete #3				1	1		5	3
Littoridina sphinctostoma		1	1				1	
Isopoda					1			
Nereis succinea								2
Rangia juvenile	1							
Mytilus edulis				1				
Penaeid juvenile					1			
Balanus balanus								1

benthic populations with increased salinity. Holland et al. (308) also found this to be true in Nueces Bay, where an inverse relationship was discovered between salinity and standing crop. Gilmore et al. (280) reported that benthic populations in Lavaca Bay were not statistically related to freshwater inflows; significant relationships were discovered, however, with such hydrological parameters as bottom salinity, turbidity, total carbon, organic nitrogen and nitrate.

The lowest average standing crops in Sabine Lake were recorded at the stations farthest removed from either the mouth of the Sabine River or from Sabine Pass (stations 19, 20, 21, and 22). Although this perhaps is indicative of some dependence of benthic populations on river and/or gulf exchange, no relationships were discovered between total standing crop (or species numbers) and either salinity or river flow (averaged over the month preceding the sample) (55).

Although not statistically correlated with inflows or salinity, it appears likely that the benthic community structure was influenced by these factors nevertheless. For example, the low standing crops encountered during most of the study appeared to be related to the flow regime. The low benthic populations found at most stations, beginning in December 1974, were most likely in response to high river discharges and subsequent low salinities which persisted throughout the winter and spring. This conclusion is supported by species distribution data. For example, Rangia cuneata, which is generally encountered in lower salinity regimes than polychaetes (159, 7), and juvenile pelecypods (here mostly juvenile Rangia cuneata) were most abundant during spring months when salinities were low. The Crustacea and polychaetes, on the other hand, were characteristically found coincident with higher salinities. The presence of crustacean dominants was restricted to Johnson's Bayou (station 21) and Sabine Pass (station 24); the number of crustacean taxa collected at the upper lake stations 17, 18, and 19 was roughly half that from the other stations. The polychaetes were most prevalent in the highest salinity waters of stations 23 and 24; their disappearance coincident with the November through December salinity drop was probably an indirect result of the increased flow regime.

Summary

The community composition, distribution, abundance, and seasonality of the phytoplankton, zooplankton, and benthic invertebrates of the Sabine-Neches estuary can be 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).

Sabine Lake phytoplankton populations observed during the EH&A study were low in comparison to values reported for other estuarine area of Texas. Average standing crop for the entire study period was 133,000 cells/l. No significant relationships between flow rate and phytoplankton density were demonstrated from the available data. An unusually low N/P ratio of only 4:1 strongly suggests that nitrogen is more likely to limit phytoplankton growth in Sabine Lake than phosphorus.

Zooplankton populations in Sabine Lake illustrated greater seasonal fluctuations than did phytoplankton. Mean monthly densities showed tremendous variation--up to two orders of magnitude--over short periods of time. The calanoid copepods of Acartia, primarily Acartia tonsa, composed about 85 percent of the total standing crop during the study. Results of analyses indicate that zooplankton populations in Sabine Lake are probably reduced at high flow rates due to the joint effects of flushing losses and extreme decreases in salinity.

A total of 50 benthic species representing six phyla were collected from Sabine Lake. The lowest average standing crops were recorded at the stations farthest removed from either the mouth of the Sabine River or from Sabine Pass. Although this perhaps is indicative of some dependence of benthic populations on river and/or Gulf exchange, no statistical relationships were developed between total standing crop (or species numbers) and either salinity or river flow.

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

CHAPTER VIII

FISHERIES

Introduction

Virtually all (97.5 percent) of the coastal fisheries species are considered estuarine-dependent (92). 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 (380-384). 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.

The Sabine-Neches estuary is the smallest of eight major Texas estuarine systems and ranks fifth in shellfish and eighth in finfish harvests. With respect to commercial Texas bay landings from 1972 through 1976, the Sabine-Neches estuary (Sabine Lake) contributed an average 0.1 percent of finfish landings and 4.6 percent of shellfish landings made from Texas bays. Based on the five year inshore-offshore commercial landings distribution, the average contribution of the estuary to total Texas commercial landings (bays and Gulf) is estimated at 6,800 pounds (3,084 kg) of fish and 4,113,700 pounds (1.9 million kg) of shellfish annually. In addition, the commercial fish harvest has been estimated to account for only about one percent (0.95 percent) of the total fish harvest in the estuary, with the remainder going to the sport or recreational catch (282). Thus, an additional 707,800 pounds (321,050 kg) of sport catch can be computed which raises the estimated average annual fish harvest contribution from the estuary (both inshore and offshore) to 714,600 pounds (324,140 kg). The average harvest contribution of all fisheries species (fish and shellfish) from the estuary is therefore estimated at 4.8 million pounds (2.2 million kg) annually.

Previous research has described the general ecology, utilization and management of the coastal fisheries (341, 123, 176, 174, 87, 217, 213, 386), and has provided information on Texas tidal waters (322, 327, 385, 198) and the relationship of freshwater inflow to estuarine productivity (402). Also, prior studies of the Sabine-Neches estuary have reported on the estuary's general ecology (386, 55), fisheries (397, 15, 288, 446, 363, 55), and restoration of the associated Keith Lake complex (276, 228, 444). In particular, the U. S. Bureau of Sport Fisheries and Wildlife (397) estimated the 1962 commercial fish and shellfish harvest from Sabine Lake and adjacent offshore Gulf waters at about 19.3 million pounds (8.7 million kg). This harvest estimate included approximately 14.8 million pounds (6.7 million kg) of menhaden and 4.3 million pounds (2.0 million kg) of penaeid shrimp. It is of interest to note that the Texas fishery for menhaden (schooling, shad-like marine fishes of the genus Brevoortia) began in 1950 (284), but essentially ended with the closure of the menhaden fish plant at Sabine Pass, Texas in 1972 (380). The Bureau also concluded that a moderate reduction in freshness of the estuay would provide sport and commercial fisheries benefits to the estuary and associated Gulf waters; however, they cautioned that total freshwater inflow from Sabine and Neches Rivers should never be less than 1.1 million acre-feet per year, of which the Sabine River should contribute at least 600,000 acre-feet per year.

Other ecological investigations (15, 446, 363) have reported on the effects of major reservoir construction (i.e., Sam Rayburn Reservoir, Neches River, 1965; Toledo Bend Reservoir, Sabine River, 1966) in the contributing river basins and channelization of Sabine Lake that was initiated late in the nineteenth century (i.e., 12 foot channel, 1878; 15 foot channel, 1880) with the dredging of the outer bar to the estuary. Subsequent deepening of the channels in the twentieth century (e.g., 40 foot channel to Beaumont, 1967) increased the intrusion of saline Gulf waters and apparently contributed to the development of commercial fisheries production for estuarine-dependent species (e.g., menhaden, shrimp, and crabs). Previously, Sabine Lake exhibited characteristics of a freshwater body, including very low salinities and populations of freshwater fish species (363, 364). However, accumulating detrimental alterations of the ecosystem and unfavorable estuarine conditions have also contributed to the severe decline of commercial fisheries production. Consequently, the fisheries harvest record varies widely and produces a discontinuous time series data base which creates problems for statistical analysis of the effects of freshwater inflow.

Data and Statistical Methods

Direct analysis of absolute fisheries biomass fluctuations as a function of freshwater inflow is not possible because accurate biomass estimation requires either considerable experimental calibration of current sampling methods (136) 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 (46). 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 (136).

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 (114, 95, 94, 367, 234, 233). Therefore, commercial harvest can be useful as a relative indicator of fisheries abundance, especially if the harvest is not critically limited below the production available for harvest on a long-term basis (i.e., the surplus production) by market conditions. Similarly, annual harvest variations can provide relative estimates of the fisheries biomass fluctuations occurring from year to year.

In Texas, commercial harvest data are available from the Texas Landings publications (387-393, 377-384) which report inshore harvests from the bays and offshore harvests from the Gulf of Mexico. Since the offshore harvests reported in Texas Landings represent collective fisheries production from the western Gulf region's estuaries, it is the inshore harvests reported by estuarine area that provide fisheries data related to a particular estuary. In addition, the shrimp fishery is partitioned into shrimp fishing grid zones in the Gulf Coast Shrimp Data publications (404-413, 418-425), which report the quantity and value of the commercial catch by species and the effort (number of fishing trips) in each area of capture at each trawling depth. Data from this record may also be useful in assessing the effects of seasonal freshwater inflows on estuarine "nursery" habitats.

Commercial harvests from the Sabine-Neches estuary are tabulated for several important fisheries components (Table 8-1). By using inshore harvest data since 1962, data inconsistencies with earlier years and problems of rapidly increasing harvest effort as the commercial fisheries developed in Texas are avoided. For example, landings data for the penaeid shrimp fishery are better than for most of the fisheries components because of the high demand for this seafood. Nevertheless, landings data from the turn of the century to the late 1940's are incomplete and report only the white shrimp harvest. Exploitation of the brown shrimp began in 1947 with night trawling in 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 inshore (bay) fisheries analysis utilizes the more reliable records available from 1962 to 1976. This 15-year interval includes both wet and dry climatic cycles and may be 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 (Pogonis 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), brown and pink shrimp (Penaeus aztecus Ives and P. duorarum Burkenroad; mostly P. aztecus). Other fisheries components are generally given as a single species or species group of interest.

Freshwater inflow to the estuary is discussed in Chapter IV and is tabulated here on the basis of two analytical categories: (1) freshwater inflow from Sabine and Neches Rivers (Table 8-2) and (2) combined freshwater inflow to the estuary from all contributing river and coastal drainage basins (Table 8-3). Each inflow category is thus specified by its historical record of seasonal inflow volumes.

The effects of freshwater inflow on an estuary and its fisheries production involve intricate and imperfectly understood physical, chemical, and biological pathways. Moreover, a complete hypothesis does not yet exist from which an accurate structural model can be constructed that represents the full spectrum of natural relationships. As a result, an alternative analytical procedure must be used which provides a functional model; that is, a procedure which permits estimation of harvest as a unique function of inflow. In this case, the aim is a mathematical description of relations among the variables

Table 8-1. Commercial Fisheries Harvests in the Sabine-Neches Estuary a/, 1962-1976 (387-393, 377-384)

Year	Commercial Fisheries Harvests (thousands of pounds)							
	Shellfish b/	White Shrimp	Brown & Pink Shrimp	Blue Crab	Finfish c/	Spotted Seatrout	Red Drum	Black Drum
1962	639.5	398.3	3.9	237.3	12.5	10.0	2.5	—
1963	1,426.1	1,151.6	170.0	104.5	25.8	13.5	8.8	3.5
1964	519.3	247.2	—	272.1	7.8	5.2	2.6	—
1965	1,053.3	529.0	15.1	509.2	51.5	16.6	13.4	0.6
1966	640.6	82.1	2.7	555.8	22.8	4.3	6.3	0.6
1967	799.2	18.4	5.1	775.7	37.3	15.6	15.9	1.6
1968	867.8	75.7	3.3	788.8	57.2	46.2	9.1	1.2
1969	929.8	104.2	—	825.6	11.6	—	4.0	0.8
1970	709.8	21.9	2.9	685.0	0.5	—	—	—
1971	1,960.5	37.4	5.1	1,918.0	—	—	—	—
1972	1,298.0	9.3	—	1,288.7	—	—	—	—
1973	1,358.2	—	—	1,358.2	6.1	4.0	0.7	1.4
1974	560.8	—	—	560.8	—	—	—	—
1975	621.3	0.4	—	620.9	3.8	0.7	0.5	0.6
1976	522.4	8.2	—	514.2	3.5	0.4	2.8	—
Mean	927.1	206.4	26.0	734.3	20.0	11.7	6.1	1.3
±S.E. d/	±107.9	±91.2	±90.2	±122.4	±5.6	±4.3	±1.6	±0.3
(N) e/	(15)	(13)	(8)	(15)	(12)	(10)	(11)	(8)

a/ Estuary ranks fifth in shellfish and eighth in finfish commercial harvests of eight major Texas estuarine systems

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

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

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

e/ N = number of observations (years)

Table 8-2. Seasonal Freshwater Inflow Volumes from Sabine and Neches Rivers Contributed to Sabine-Neches 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	3,450.9	3,744.9	1,517.0	417.0	1,279.0
1960	5,511.0	1,191.9	512.0	554.0	3,239.0
1961	10,389.9	3,126.9	1,478.0	1,396.0 a/	2,710.0
1962	3,618.0	2,493.0	288.0	285.0	628.0
1963	1,991.1	699.9	223.0	1,231.0 b/	577.0
1964	2,301.9	1,809.0	127.0	120.0	384.0
1965	1,547.1	2,079.9	182.0	151.0	583.0
1966	3,693.0	2,829.9	544.0	515.0	605.0
1967	824.1	1,386.0	95.0	64.0 c/	200.0
1968	1,299.0	5,103.0	1,308.0	1,025.0	2,144.0
1969	5,298.0	8,303.1	709.0	355.0	515.0
1970	1,668.9	2,166.0	302.0 d/	2,161.0	504.0
1971	1,071.0	387.0	309.0	143.0 e/	1,558.0
1972	3,327.9	1,590.9	755.0	687.0	1,261.0
1973	6,111.0	8,633.1	2,596.0	2,861.0 f/	3,629.0
1974	9,045.9	2,648.1	1,067.0	884.0	3,222.0
1975	7,599.0	6,144.0	2,247.0	1,080.0	712.0
1976	1,752.0	3,243.0	1,836.0	892.0	1,248.0
Mean	3,916.7	3,198.9	894.2	823.4	1,388.8
± S.E. g/	±671.4	±564.3	±181.8	±175.2	±262.7

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% confidence limits about the mean

Table 8-3. Seasonal Volumes of Combined Freshwater Inflow a/ Contributed to Sabine-Neches 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	3,891.9	4,025.1	1,993.0	486.0	1,342.0
1960	5,655.0	1,301.1	821.0	650.0	3,412.0
1961	10,827.0	3,486.9	1,641.0	1,612.0 b/	2,935.0
1962	3,669.0	2,642.1	372.0	341.0	765.0
1963	2,237.1	801.0	302.0	1,602.0 c/	668.0
1964	2,544.0	1,923.0	238.0	191.0	504.0
1965	1,680.9	2,196.0	251.0	219.0	676.0
1966	3,995.1	3,324.9	912.0	653.0	751.0
1967	903.0	1,718.1	191.0	116.0 d/	246.0
1968	1,469.1	5,736.0	1,410.0	1,138.0	2,246.0
1969	5,508.0	8,729.1	867.0	416.0	631.0
1970	1,821.0	2,447.1	389.0 e/	2,734.0	562.0
1971	1,161.9	540.0	503.0	249.0 f/	1,690.0
1972	3,593.1	1,952.1	854.0	801.0	1,364.0
1973	6,503.1	9,345.9	2,861.0	3,230.0 g/	3,699.0
1974	9,405.0	2,967.9	1,160.0	955.0	3,394.0
1975	7,851.9	6,549.9	2,555.0	1,187.0	833.0
1976	1,863.0	3,558.0	1,948.0	974.0	1,509.0
Mean	4,143.3	3,513.6	1,070.4	975.2	1,512.6
± S.E. h/	±690.3	±596.5	±195.2	±203.7	±267.4

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% confidence limits about the mean

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 Sabine-Neches estuary was performed utilizing the University of California biomedical (BMD) computer program for the stepwise multiple regression procedure (20). This statistical procedure computes a sequence of multiple linear regression eqautions 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:

$$H_t = a_0 + a_1 Q_{1,t-b_1} + \cdots + a_{n,t-b_n} + e$$

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

H_t = annual 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 8-4);

$Q_{2,t-b_2}$ = 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 8-4);

$Q_{3,t-b_3}$ = 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 8-4);

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

Table 8-4. Time Series Alignments of Dependent/Independent Data Variates for Fisheries Regression Analysis

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

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

$Q_{5,t-b_5}$ = 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 8-4);

MAX $Q_{n,t-b_n}$ = maximum monthly (January-December) mean monthly freshwater inflow in thousands of acre-feet at year $t-b_6$, where b_6 is a positive integer (Table 8-4).

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

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

where the variables are the same as defined above.

In practice, the time series for the dependent variable (H) is the aforementioned inclusive period 1962 through 1976, giving 15 annual harvest observations for the regression analysis. The independent variables ($Q_1 \ldots Q_n$) 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 different fisheries components. Depending upon the specific fisheries component being analyzed, the time factor (t-b) of the independent variables can be the same year as harvest (t-0), one-year antecedent to harvest (t-1), or a running average from three antecedent years before harvest

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

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 8-4). 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 (83, 171). Early articulation of this idea was put forth by the Norwegian fishery scientist Johan Hjort in 1914 (116) 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 (211). 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 (83, 210). However, the hypothesis that freshwater inflow is a primary factor influencing the estuary and its production of estuarine-dependent fisheries is well-founded and reasonable considering the substantial volume of previous scientific research demonstrating inflow effects on nutrient cycling, salinity gradients, and the metabolic stresses and areal distributions of estuarine organisms.

Fisheries Analysis Results

The analysis produces two statistically significant harvest equations each for all shrimp (Table 8-5), white shrimp (Table 8-6), brown and pink shrimp (Table 8-7), finfish (Table 8-8), spotted seatrout (Table 8-9), red drum (Table 8-10), and black drum (Table 8-11) fisheries components. Statistical information given for all reported regression equations includes: (1) level of statistical significance (α value); (2) multiple coefficient of determination (r^2 value); (3) standard error of the estimate for the dependent variable, fisheries harvest; (4) standard error of the regression coefficient associated with each independent variable, seasonal freshwater inflow; and (5) upper bounds, lower bounds, mean, and number of years the variables entering the equation were observed.

Qualitative harvest responses of the fisheries components to seasonal freshwater inflows are summarized in Table 8-12. Fisheries harvest responses are computed to be predominantly positive to winter (January-March) inflow, negative to spring (April-June) inflow, positive to summer (July-August) inflow, negative to autumn (September-October) inflow, and positive to late fall (November-December) inflow. However, the results are of questionable value because the data and analysis of this estuary's fisheries suffers from several analytical problems: (1) species harvest records are spotty and produce a discontinuous time series data base of few observations (i.e., minimum n = 8 years), (2) species harvest levels are relatively low, except for the blue crab fishery (1962 through 1976 average = 734.3 thousand pounds or 333.1 thousand kilograms per year), and (3) the harvest data may not be an adequate relative measure of the absolute shifts in fisheries abundance from year-to-year because the ecosystem appears ecologically stressed, exhibits low biomass production in many trophic (nutritional) compartments of the foodweb, and its fisheries resources are shared with Louisiana. In particular, chronic ecosystem stresses and the inconsistencies of the commercial fisheries affects the distribution of the harvest data (e.g., non-normal distribution) and its statistical application to the multiple regression analysis with seasonal freshwater inflow. As a result of these problems, probable spurious relationships between harvest and seasonal inflow are suggested by the analysis (e.g., the highly unlikely positive response of several fisheries harvests to increasing summer inflow). Consequently, results of this fisheries analysis are not useful for estimating the freshwater inflow needs of the Sabine-Neches estuary (see Chapter IX).

Table 8-5. Equations of Statistical Significance Relating the All Penaeid Shrimp Fisheries Component to Freshwater Inflow Categories a/

Sabine-Neches Estuary All Shrimp Harvest = f (seasonal FINSN b/)
Significant Equation (α = 2.5%, r^2 = 97%, S.E. Est. = ± 115.2)

$$H_{as} = 1,585.6 + \underset{(0.51)}{3.36}\,(Q_3) - \underset{(0.19)}{1.74}\,(Q_{-4}) + \underset{(0.00005)}{0.00041}\,(\text{Max } Q_{-5})^2$$

$$-\underset{(0.17)}{1.57}\,(\text{Max } Q_2)$$

	H_{as}	Q_3	Q_{-4}	$(\text{Max } Q_{-5})^2$	Max Q_2
upper bounds	1,321.6	654.0	1,080.5	4,431,025.0	2,299.0
lower bounds	23.5	47.5	32.0	28,224.0	155.0
mean (n=8)	315.3	203.2	315.4	678,244.4	1,068.4

Sabine-Neches Estuary All Shrimp Harvest = f (seasonal FINC c/)
Significant Equation (α = 2.5%, r^2 = 97%, S.E. Est. = ± 125.1)

$$H_{as} = 1,427.8 + \underset{(0.59)}{3.61}\,(Q_3) - \underset{(0.18)}{1.48}\,(Q_4) + \underset{(0.00005)}{0.00036}\,(\text{Max } Q_{-5})^2$$

$$-\underset{(0.18)}{1.51}\,(\text{Max}Q_2)$$

	H_{as}	Q_3	Q_{-4}	$(\text{Max } Q_{-5})^2$	Max Q_2
upper bounds	1,321.6	705.0	1,367.0	4,661,281.0	2,587.0
lower bounds	23.5	95.5	58.0	38,809.0	207.0
mean (n=8)	315.3	270.6	392.6	765,290.3	1,184.8

---

where,

H_{as} = inshore commercial penaeid shrimp harvest, in thousands of pounds;

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

Q_1 =	January-March	Q_4 =	September-October
Q_2 =	April-June	Q_5 =	November-December
Q_3 =	July-August	Q_{-n} =	One-year antecedent seasonal inflow

Table 8-5. Equations of Statistical Significance Relating the All Penaeid Shrimp Fisheries Component to Freshwater Inflow Categories a/ (cont'd.)

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

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

b/ FINSN = freshwater inflow from Sabine and Neches Rivers

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

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

Sabine-Neches Estuary White Shrimp Harvest = f (seasonal FINSN b/)
Significant Natural Log Equation (α = 5.0%, r^2 = 37%, S.E. Est. = $\pm$ 1.7631)

$$\ln H_{ws} = 10.9179 - \underset{(0.5083)}{1.2956} (\ln Q_3)$$

	$\ln H_{ws}$	$\ln Q_3$
upper bounds	7.0489	7.0242
lower bounds	-0.9163	3.8607
mean (n=13)	3.9413	5.3849

Sabine-Neches Estuary White Shrimp Harvest = f (seasonal FINC c/)
Significant Natural Log Equation (α = 2.5%, r^2 = 42%, S.E. Est. = $\pm$ 1.6864)

$$\ln H_{ws} = 13.3362 - \underset{(0.5786)}{1.6492} (\ln Q_3)$$

	$\ln H_{ws}$	$\ln Q_3$
upper bounds	7.0489	7.1527
lower bounds	-0.9163	4.5591
mean (n=13)	3.9413	5.6965

---

where,

$\ln H_{WS}$ = natural log, inshore commercial white shrimp harvest, in thousands of pounds;

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

Q_1 = January-March Q_4 = September-October
Q_2 = April-June Q_5 = November-December
Q_3 = July-August

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

b/ FINSN = freshwater inflow from Sabine and Neches Rivers

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

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

Sabine-Neches Estuary Brown and Pink Shrimp Harvest = f (seasonal FINSN b/)
Significant Equation (α = 5.0%, r^2 = 93%, S.E. Est. = $\pm$ 22.7)

$$H_{bps} = \underset{}{245.2} - \underset{(0.04)}{0.20\,(Q_{-4})} + \underset{(0.021)}{0.088\,(\text{Max } Q_{-5})} - \underset{(0.06)}{0.35\,(\text{Max } Q_2)}$$

$$+ \underset{(0.00002)}{0.00011\,(\text{Max } Q_2)^2}$$

	H_{bps}	Q_{-4}	Max Q_{-5}	Max Q_2	(Max Q_2)^2
upper bounds	170.0	1,080.5	2,105.0	2,299.0	5,285,401.0
lower bounds	2.7	32.0	168.0	155.0	24,025.0
mean (n=8)	26.0	315.4	580.1	1,068.4	1,576,808.6

Sabine-Neches Estuary Brown and Pink Shrimp Harvest = f (seasonal FINC c/)
Significant Equation (α = 5.0%, r^2 = 93%, S.E. Est. = $\pm$ 22.8)

$$H_{bps} = 239.4 - \underset{(0.03)}{0.14\,(Q_{-4})} + \underset{(0.020)}{0.076\,(\text{Max } Q_{-5})} - \underset{(0.06)}{0.32\,(\text{Max } Q_2)}$$

$$+ \underset{(0.00002)}{0.00009\,(\text{Max}Q_2)^2}$$

	H_{bps}	Q_{-4}	Max Q_{-5}	Max Q_2	(Max Q_2)^2
upper bounds	170.0	1,367.0	2,159.0	2,587.0	6,692,569.0
lower bounds	2.7	58.0	197.0	207.0	42,849.0
mean (n=8)	26.0	392.6	654.8	1,184.8	1,949,216.0

---

where,

- H_{bps} = inshore commercial brown and pink shrimp harvest, in thousands of pounds;
- Q = mean montly freshwater inflow, in thousands of acre-feet:
  - Q_1 = January-March
  - Q_2 = April-June
  - Q_3 = July-August
  - Q_4 = September-October
  - Q_5 = November-December
  - Q_{-n} = one-year antecedent seasonal inflow
- Max Q_n = maximum monthly freshwater inflow during seasonal interval (Q_n) in thousands of acre-feet

Table 8-7. Equations of Statistical Significance Relating the Brown and Pink Shrimp Fisheries Component to Freshwater Inflow Categories a/ (cont'd.)

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

b/ FINSN = freshwater inflow from Sabine and Neches Rivers

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

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

Sabine-Neches Estuary Finfish Harvest = f (seasonal FINSN b/)
Significant Natural Log Equation (α = 2.5%, r^2 = 68%, S.E. Est. = ± 0.9012)

$$\ln H_{ff} = 15.3597 + \underset{(0.7202)}{1.3821} (\ln Q_1) - \underset{(0.6723)}{2.1319} (\ln Q_2) - \underset{(0.6370)}{1.4348} (\ln Q_4)$$

	$\ln H_{ff}$	$\ln Q_1$	$\ln Q_2$	$\ln Q_4$
upper bounds	4.0466	7.8354	7.5684	6.6898
lower bounds	-0.6931	6.4712	6.1322	4.8013
mean (n=12)	2.3932	7.0416	6.7512	5.7870

Sabine-Neches Estuary Finfish Harvest = f (seasonal FINC c/)
Significant Natural Log Equation (α = 5.0%, r^2 = 67%, S.E. Est. = ± 0.9164)

$$\ln H_{ff} = 17.2499 + \underset{(0.7385)}{1.2921} (\ln Q_1) - \underset{(0.6810)}{2.2497} (\ln Q_2) - \underset{(0.6847)}{1.4383} (\ln Q_4)$$

	$\ln H_{ff}$	$\ln Q_1$	$\ln Q_2$	$\ln Q_4$
upper bounds	4.0466	7.8785	7.6478	6.7972
lower bounds	-0.6931	6.5617	6.3038	5.1039
mean (n=12)	2.3932	7.1074	6.8548	5.9926

---

where,

$\ln H_{ff}$ = natural log, inshore commercial finfish harvest, in thousands of pounds;

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

Q_1 = January-March; Q_2 = April-June; Q_3 = July-August; Q_4 = September-October; Q_5 = November-December

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

b/ FINSN = freshwater inflow from Sabine and Neches Rivers

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

Table 8-9. Equations of Statistical Significance Relating the Spotted Seatrout Fisheries Component to Freshwater Inflow Categories a/

Sabine-Neches Estuary Spotted Seatrout Harvest = f (seasonal FINSN b/)
Highly Significant Natural Log Equation (α = 0.5%, r^2 = 93%, S.E. Est. = ± 0.5247)

$$\ln H_{ss} = 20.9074 + \underset{(0.7125)}{1.2477} (\ln Q_1) - \underset{(0.7566)}{2.6771} (\ln Q_2) + \underset{(0.7076)}{0.7403} (\ln Q_3) - \underset{(0.4804)}{2.4585} (\ln Q_4)$$

	$\ln H_{ss}$	$\ln Q_1$	$\ln Q_2$	$\ln Q_3$	$\ln Q_4$
upper bounds	3.8330	7.8354	7.5684	6.8926	6.6898
lower bounds	-0.3567	6.4753	6.1322	4.4849	4.8013
mean (n=10)	1.7516	7.1313	6.6668	5.8396	6.3382

Sabine-Neches Estuary Spotted Seatrout Harvest = f (seasonal FINC c/)
Highly Significant Natural Log Equation (α = 1.0%, r^2 = 92%, S.E. Est. = ± 0.5486)

$$\ln H_{ss} = 23.5686 + \underset{(0.7388)}{0.9046} (\ln Q_1) - \underset{(0.8601)}{2.8193} (\ln Q_2) + \underset{(0.7966)}{0.9323} (\ln Q_3) - \underset{(0.4512)}{2.4346} (\ln Q_4)$$

	$\ln H_{ss}$	$\ln Q_1$	$\ln Q_2$	$\ln Q_3$	$\ln Q_4$
upper bounds	3.8330	7.8785	7.6478	6.9994	6.7972
lower bounds	-0.3567	6.5765	6.3038	4.8815	5.1039
mean (n=10)	1.7516	7.1953	6.7676	5.8874	6.0521

---

where,

$\ln H_{ss}$ = natural log, inshore commercial spotted seatrout harvest, in thousands of pounds;

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

Q_1 = January-March
Q_2 = April-June
Q_3 = July-August
Q_4 = September-October
Q_5 = November-December

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

b/ FINSN = freshwater inflow from Sabine and Neches Rivers

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

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

Sabine-Neches Estuary Red Drum Harvest = f (seasonal FINSN b/)
Significant Natural Log Equation (α = 2.5%, r^2 = 76%, S.E. Est. = $\pm$ 0.6556)

$$\ln H_{rd} = 4.7139 + \underset{(0.7335)}{1.7094} (\ln Q_1) - \underset{(0.6237)}{1,2346} (\ln Q_4) - \underset{(0.7947)}{1.3078} (\ln Q_5)$$

	$\ln H_{rd}$	$\ln Q_1$	$\ln Q_4$	$\ln Q_5$
upper bounds	2.7663	7.8354	6.6898	7.2093
lower bounds	-0.3567	6.4712	4.8013	5.4439
mean (n=11)	1.3476	7.0713	5.8168	6.3254

Sabine-Neches Estuary Red Drum Harvest = f (seasonal FINC c/)
Significant Natural Log Equation (α = 2.5%, r^2 = 77%, S.E. Est. = $\pm$ 0.6476)

$$\ln H_{rd} = 6.1403 + \underset{(0.7923)}{1.8551} (\ln Q_1) - \underset{(0.6147)}{1.3169} (\ln Q_4) - \underset{(0.8458)}{1.5675} (\ln Q_5)$$

	$\ln H_{rd}$	$\ln Q_1$	$\ln Q_4$	$\ln Q_5$
upper bounds	2.7663	7.8785	6.7972	7.2510
lower bounds	-0.3567	6.5617	5.1039	5.6306
mean (n=11)	1.3476	7.1377	6.0257	6.4424

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 = January-March; Q_4 = September-October
Q_2 = April-June; Q_5 = November-December
Q_3 = July-August

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

b/ FINSN = freshwater inflow from Sabine and Neches Rivers

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

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

Sabine-Neches Estuary Black Drum Harvest = f (seasonal FINSN b/)
Significant Equation (α = 5.0%, r^2 = 95%, S.E. Est. = ± 0.3472)

$$H_{bd} = 6.0 + \underset{(0.00046)}{0.00028\,(Q_1)} - \underset{(0.0019)}{0.0086\,(Q_2)} + \underset{(0.005)}{0.020\,(Q_3)} - \underset{(0.002)}{0.011\,(Q_4)}$$

	$\ln H_{bd}$	$\ln Q_1$	$\ln Q_2$	$\ln Q_3$	$\ln Q_4$
upper bounds	3.5	2168.8	1430.2	736.3	738.7
lower bounds	0.6	648.9	460.4	88.7	121.7
mean (n=8)	1.3	1072.8	774.3	267.8	331.6

Sabine-Neches Estuary Black Drum Harvest = f (seasonal FINC c/)
Highly Significant Equation (α = 0.5%, r^2 = 97%, S.E. Est. = ± 0.2219)

$$H_{bd} = 4.9 - \underset{(0.0007)}{0.0074\,(Q_2)} + \underset{(0.001)}{0.016\,(Q_3)} - \underset{(0.0007)}{0.0067\,(Q_4)}$$

	H_{bd}	Q_2	Q_3	Q_4
upper bounds	3.5	1585.1	812.5	831.0
lower bounds	0.6	546.7	131.8	164.7
mean (n=8)	1.3	866.4	342.2	405.8

---

where,

H_{bd} = inshore commercial black drum harvest, in thousands of pounds;

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

Q_1 = January-March; Q_2 = April-June; Q_3 = July-August; Q_4 = September-October; Q_5 = November-December

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

b/ FINSN = freshwater inflow from Sabine and Neches Rivers

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

Table 8-12. Positive (+) and Negative (-) Correlation of Fisheries Components to Seasonal Freshwater Inflow Categories

Fisheries Component	Winter Inflow Q_1 (Jan.-Mar.)	Spring Inflow (Apr.-Jun.) Q_2	Spring Inflow (Apr.-Jun.) Max Q_2	Spring Inflow (Apr.-Jun.) $(\text{Max } Q_2)^2$	Summer Inflow Q_3 (Jul.-Aug.)	Autumn Inflow Q_4 (Sept.-Oct.)	Late Fall Inflow (Nov.-Dec.) Q_5	Late Fall Inflow (Nov.-Dec.) Max Q_5	Late Fall Inflow (Nov.-Dec.) $(\text{Max } Q_5)^2$	Explained Variation r^2 (%)	Significance Level α (%)
All Shrimp											
FINSN a/				-	+	-			+	97	2.5
FINC b/				-	+	-			+	97	2.5
White Shrimp											
FINSN					-					37	5.0
FINC					-					42	2.5
Brown and Pink Shrimp											
FINSN			-	+		-		+		93	5.0
FINC			-	+		-		+		93	5.0
Finfish											
FINSN	+	-				-				68	2.5
FINC	+	-				-				67	5.0
Spotted Seatrout											
FINSN	+	-			+	-				93	0.5
FINC	+	-			+	-				92	1.0
Red Drum											
FINSN	+					-	-			76	2.5
FINC	+					-	-			77	2.5
Black Drum											
FINSN	+	-			+	-				95	5.0
FINC		-			+	-				97	0.5
Summary:											
FINSN	(+)=4 (-)=0	(+)=0 (-)=3	(+)=0 (-)=1	(+)=1 (-)=1	(+)=3 (-)=1	(+)=0 (-)=6	(+)=0 (-)=1	(+)=1 (-)=0	(+)=1 (-)=0		
FINC	(+)=3 (-)=0	(+)=0 (-)=3	(+)=0 (-)=1	(+)=1 (-)=1	(+)=3 (-)=1	(+)=0 (-)=6	(+)=0 (-)=1	(+)=1 (-)=0	(+)=1 (-)=0		

a/ Freshwater inflow from Sabine and Neches Rivers
b/ Combined freshwater inflow 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 (148, 301). 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 (37, 188, 155, 152, 190). Consequently, the addition of supplemental freshwater inflow for purposes of ecological maintenance and enhancing seafood production has been recommended for the Gulf estuaries of Texas (148, 353), Mississippi and Louisiana (67).

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 (133, 132, 431, 432), in species distribution patterns and community diversity (98, 93, 73, 100, 28, 138), and utlimately in species evolution (129). Previous research emphasizing Texas estuarine-dependent species has dealt with several aspects of the inflow/salinity relationship including environmental limits (339), tolerance to hypersaline waters (92, 109, 10), and rapid recovery of typical estuarine community species at the end of a severe drought (117). 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 (96, 369), and their diseases and symbionts (192).

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 (11, 362, 134, 143, 360) and are effective at modifying species distribution (309, 323, 194). The brackish water clam (Rangia cuneata) has been suggested as an indicator of ecological effects associated with salinity changes because of its sensitivity (239); 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 (156).

Shrimp

The Gulf of Mexico shrimp fishery is the most valuable fishery in the United States (80) and the Gulf estuaries play a crucial role in the production of this renewable resource (82, 139). 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 shrimmp (P. duorarum Burkenroad, 1939) also occurs in small numbers. Synopses of species life history and biological information are available for the white shrimp (146), brown shrimp (32), pink shrimp (40), and species in the genus Penaeus (403). Other information especially important for management of this fishery resource comes from research on shrimp spawning and early larval stages (373, 328, 347, 401), seasonal migration behavior (366, 38, 281), utilization of estuarine nursery habitats (88), and major environmental factors influencing species population dynamics and production (242, 103, 163, 162, 42, 151). Species-specific responses to inflow/salinity conditions in the estuary are fundamentally physiological (5, 19, 248, 244, 141, 371), and therefore directly influence not only growth and survival of the postlarval shrimp (455, 456, 454, 430), but the distribution of the bay shrimp populations as well (335, 99, 312).

Commercial penaeid shrimp fisheries production was established in Sabine Lake (Texas) and adjacent Calcasieu Lake (Louisiana) by 1960. Shrimp landings are of similar annual trends in both estuarine systems until 1966, when annual harvest and effort in each estuary began to exhibit diverging trends (Table 8-13). While the Calcasieu Lake shrimp fisheries developed to an annual harvest level of over two million pounds (907,200 kilograms; 1972-1976), the Sabine Lake shrimp fisheries began nearly a decade of decline that resulted in essentially no harvest from 1973 through 1975.

Although a reduction in the gross quantity of inflow to the Sabine-Neches estuary may be beneficial to estuarine-dependent fisheries (397, 55), such as the penaeid shrimp fishery, major reservoir development in the contributing river basins (e.g., Sam Rayburn Reservoir, Neches River Basin and Toledo Bend Reservoir, Sabine River Basin) appears not to have produced the beneficial effect. Indeed, it has been reported that the effect of Toledo Bend Reservoir on the seasonal hydrography of Sabine Lake was a decrease in winter and early spring inflows, and an increase in late spring and summer inflows that resulted in unfavorable summer salinity conditions for shrimp production (15, 446, 363). However, several other factors affecting the estuarine ecosystem also occurred at about this time. A chronological history of major events and shrimp harvest trends since 1958 is given as follows:

1958-1962: Commercial fisheries develop for estuarine-dependent species in Sabine and Calcasieu Lakes.

1961: No penaeid shrimp harvests reported in either Sabine or Calcasieu Lakes. Maximum winter (Jan.-Mar.) freshwater inflow to Sabine Lake during the 18-year (1959-1976) interval occurs. Inflow greater than average in all seasons except spring (Apr.-Jun.). Hurricane Carla strikes near Port Lavaca (Sep. 8-14).

1963: Maximum shrimp harvest and effort in Sabine Lake. First peak of shrimp fishery in Calcasieu Lake. Freshwater inflow lower than average in all seasons except autumn (Sep.-Oct.). Hurricane Cindy strikes near Port Arthur (Sep. 16-20).

1965: Impoundment of Neches River creates Sam Rayburn Reservoir with about 2.9 million acre-feet of conservation storage capacity and a firm yield of 820,000 acre-feet per year.

1966: Impoundment of Sabine River creates Toledo Bend Reservoir with about 4.5 million acre-feet of conservation storage capacity and a firm yield of about 1.8 million acre-feet per year (Texas' share is 904,500 acre-feet per year). Construction of spoil levees across Little Keith Lake disposal site eliminates natural channel to Keith Lake system

Table 8-13. Comparison of Sabine Lake and Calcasieu Lake Penaeid Shrimp Fisheries, 1958-1976 (404-413, 418-425)

Year	Sabine Lake			Calcasieu Lake		
	White Shrimp a/	Brown Shrimp b/	Harvest Effort c/	White Shrimp	Brown Shrimp	Harvest Effort
1958	--	--	--	96.2	--	412.0
1959	--	--	--	126.7	--	485.0
1960	1.6	2.9	12.0	10.2	345.0	944.0
1961	--	--	--	--	--	--
1962	398.3	3.9	2,922.0	891.1	393.3	6,207.0
1963	1,151.6	170.0	9,326.0	1,252.8	397.7	8,258.0
1964	247.2	--	1,822.0	682.5	77.7	4,351.0
1965	529.0	15.1	3,014.0	265.0	181.5	2,008.0
1966	82.1	2.7	1,276.0	321.7	210.6	2,562.0
1967	18.4	5.1	325.0	222.9	710.3	2,670.0
1968	75.7	3.3	599.0	306.2	360.4	2,065.0
1969	104.2	1.7	199.0	1,227.1	458.7	2,749.0
1970	24.6	7.6	232.0	790.2	937.7	2,305.0
1971	37.4	5.1	189.0	569.3	838.6	2,359.0
1972	9.3	--	23.0	1,049.2	1,248.7	2,774.0
1973	--	--	--	1,285.4	381.9	3,187.3
1974	--	--	--	1,392.4	996.8	3,040.7
1975	0.4	--	0.0 d/	1,276.4	378.3	2,904.6
1976	10.7	--	20.8	904.9	1,500.2	2,183.4
Mean	192.2	21.7	1,425.7	703.9	588.6	2,859.2
±S.E. e/	±85.6	±16.5	±669.9	±112.1	±101.9	±444.8
(N) f/	(14)	(10)	(14)	(18)	(16)	(18)

a/ White shrimp harvest weight, in thousands of pounds of whole shrimp, estimated by tail weight x 1.54
b/ Brown shrimp harvest weight, in thousands of pounds of whole shrimp, estimated by tail weight x 1.61
c/ Harvest effort, in number of fishing trips by shrimp vessels
d/ Trips reported as (.0) in 1975 Gulf Coast Shrimp Data
e/ Standard error of mean; two standard errors provide approximately 95 percent confidence limits about the mean
f/ N = number of observations (years)

and its shrimp "nursery" areas. Shrimp harvest drops an order of magnitude and effort declines 58 percent from previous year in Sabine Lake. Calcasieu Lake shrimp harvest and effort increase over previous year.

1967: Shrimp harvest and effort in Sabine Lake area at lowest level since 1961. Calcasieu Lake shrimp harvest and effort increase over previous year. Texas Shrimp Conservation Act passage associated with 91 percent reduction of licensed boats for bait shrimping and 30 percent increase of licensed commercial bay shrimp boats in Jefferson County (1966-1967 to 1967-1968 license year). Ship Channel increased from 36 to 40 feet depth. Leveeing of South Disposal Area (5.6 linear miles and 3,082 acres) in Sabine Lake.

1968: Leveeing of North Disposal Area (4.9 linear miles and 1,975 acres) in Sabine Lake.

1973: Shrimp harvest and effort drop to zero in Sabine Lake, while Calcasieu Lake exhibits largest peak harvests (1972-1975) in its shrimp harvest record (1958-1976). Sabine Lake experiences the highest seasonal inflows occurring in the 18-year (1959-1976) interval, except for winter inflow which is nevertheless about 56 percent larger than average. Hurricane Delia strikes near Galveston (Sep. 4-7).

1977: Keith Lake Water Exchange Pass re-established in September about six miles northwest of Sabine Pass and the Gulf of Mexico. Very low level of commercial shrimp harvest still exists in Sabine Lake.

In the end, the effects of estuary modifications and seasonal freshwater inflow levels, acting together, appear to have resulted in the decline of the Sabine-Neches shrimp fishery primarily through reduced habitat availability and unfavorable conditions for growth and survival of juvenile penaeid shrimp.

Blue Crab

Another major crustacean fishery species is the estuarine-dependent blue crab (Callinectes sapidus Rathbun, 1896). Previous research has described blue crab taxomony (274, 310), life history (375, 273), migration behavior (316, 118, 281), and responses to environmental factors such as salinity (218, 41, 243, 140) and storm water runoff (145).

In particular, More (273) suggests that the large inflow of freshwater into Sabine Lake, Galveston Bay, and San Antonio Bay has contributed to their blue crab productivity. Landings from the respective bays generally support this observation, since during the 1962 to 1976 interval annual commercial harvest of blue crabs averaged 734,300 pounds (333,078 kg) in Sabine Lake, 1.6 million pounds (725,760 kg) in the Trinity-San Jacinto estuary, 781,400 pounds (354,443 kg) in the Lavaca-Tres Palacios estuary, and 857,100 pounds (388,781 kg) in the Guadalupe estuary. In the more saline estuaries of the coastal bend and South Texas coast, the annual blue crab harvest has averaged 690,100 pounds (313,029 kg; Mission-Aransas estuary), 118,300 pounds (53,661 kg; Nueces estuary) and 111,200 pounds (50,440 kg; Laguna Madre). However, statistical correlation of Sabine Lake blue crab harvests to seasonally fluctuating freshwater inflows to the estuary was not successful, possibly because of the inconsistent fishing pressure exerted by part-time and full-time crab fishermen, the sharing of the fishery with Louisiana, and the effects of other environmental factors besides inflow. Nevertheless, the highest blue crab harvest years in Sabine Lake (i.e., over 1.2 million pounds or 544,320 kg per year from 1971 through 1973) are associated with freshwater inflows (i.e., 1970 through 1972 inflows one year antecedent to harvest) which are overall moderately below their seasonal averages. An exception occurs with the 1970 autumn (September-October) inflow which exceeds 2.5 times the season's 1959 through 1976 average; however, autumn inflow was also below average in 1971 and 1972.

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 (396, 436), as well as geographic variation of its populations (17, 220). The effects of inflow/ salinity are particularly important and have stimulated considerable research covering a wide range of subjects including effects on oyster distribution (331, 161, 53), gametogenesis (development of viable eggs and sperm) and spawning (374, 16, 150, 212), eggs and larvae (6, 50, 398, 400, 112, 111), respiration (340, 429), free amino acids which are protein building blocks (166), and the effects on oyster reef growth and mortality (90, 320), abundance of faunal associates (90, 77, 443), and reef diseases (247, 192). Texas studies have also described the oyster fishery (285) and the State's major oyster producing areas (414, 289).

Although the American oyster is occassionally collected in small numbers near Sabine Pass in the southern portion of Sabine Lake and in the Old River Cove area of northern Sabine Lake (363, 55), there are no viable reef communities to support a commercial oyster fishery. In addition, Sabine Lake is classified as a "polluted area" and is closed to oyster 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. Thus, the Sabine-Neches estuary becomes the only major Texas estuarine system not contributing to the oyster fishery during the 1962 through 1976 historical interval.

Finfish

Estuaries play a vital functional role in the life cycle and production of most coastal fish species (372, 126, 154, 277, 119). Environmental sensitivity of the estuarine-dependent fishes has allowed the use of species diversity indices as indicators of pollution (317). Although migration does occur across the boundary between riverine and estuarine habitats by both freshwater and estuarine-dependent marine fishes (187, 209), there is a predominance of young marine fishes found in this low salinity area (91).

In general, seasonal variations in estuarine fish abundance are related to life history and migrational behavior (97, 344, 343, 120, 316, 118, 288, 281, 216, 311, 452). The primary effects of inflow/salinity are physiological (122, 124, 144), and are particularly important for the survival of the early life stages (121) and the metabolism (i.e., metabolic stresses) of adult bay populations (334, 338, 346, 305, 435) and juvenile rates of adaptability (307, 306). Low temperature extremes can also interact physiologically with salinity stress to produce dramatic fish mortality (85, 86, 89).

Trawl sampling of Sabine Lake fish populations from September 1974 to August 1975 revealed that taxa such as the engraulid Anchoa mitchilli (bay anchovy), the sciaenid Micropogon undulatus (Atlantic croaker), and the other Sciaenidae (drums and seatrouts) exhibit nearly cosmopolitan distribution and importance among nine sampling stations spread throughout the estuary (55). In this study, Anchoa mitchilli accounted for 62.3 percent of all organisms collected, occurred in 75 percent of all samples made, and ranked first in abundance. Micropogon undulatus ranked second, the other Sciaenidae ranked third, and menhaden (Brevoortia spp.) ranked fourth in abundance. Another recent study of Sabine Lake fishes involved gill-net sampling of pass, shoreline, and open water stations in the estuary from November 1975 to March 1976 (288). Results indicate that 22.6 percent of the total fishes caught were black drum, 14.7 percent were red drum, 8.7 percent were spotted seatrout, less than one percent were southern flounder and sheepshead, and 54.1 percent were "others" (e.g., Gulf menhaden, Brevoortia patronus; gizzard shad, Dorosoma cepedianum; and alligator gar, Lepisosteus spatula). Here, the open water stations generally produced greater numbers of forage species (e.g., menhaden and shad), while pass and shoreline stations sampled more predators (e.g., drums and seatrouts). It is important to note that commercial finfish harvest in Sabine Lake has averaged only 20.0 thousand pounds (9.1 thousand kg) per year during 9.1 thousand the 1962 to 1976 interval and has been poor to nonexistent since 1970 (see Table 8-1). However, Breuer et al. (282) report that sport fish harvest accounted for about 99 percent (487,100 pounds or 220,900 kg) of the total fish harvest in Sabine Lake during a 12-month interval from September 1975 to August 1976.

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 (372, 245, 119). 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 (399). The greater restriction and estuarine-dependence of this species are reflected in its nearly exclusive utilization of estuarine habitats (81, 235, 74) and the increased genetic differences among populations in separate bays (442). Previous research has described spotted seatrout life history and seasonal abundance in Texas waters (376, 344, 268, 269, 343, 120, 118, 281), 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 (304, 305, 333, 435, 307, 306).

Sciaenid species occurred in 38 percent of trawl samples in Sabine Lake (Sept. 1974 through Aug. 1975) and ranked third in abundance; however, specimens identified as spotted seatrout occurred in only 2.1 percent of the samples (55). Spotted seatrout also accounted for 8.7 percent of the total fishes caught (Nov. 1975 through Mar. 1976) by gill-net sampling of Sabine Lake (288). Although commercial harvest has averaged only 11,700 pounds (5,300 kg) per year (1962-1976) and has been very low to non-existent since 1969 (see Table 8-1), a 12-month sport harvest (Sep. 1975 through Aug. 1976) of spotted seatrout has been recently estimated at 90,000 pounds (40,800 kg) or 18.5 percent by weight of the sport fish caught in Sabine Lake (282).

Red Drum

Another important sciaenid species is the red drum or redfish (Sciaenops ocellata Linnaeus). Prior studies have reported on the general biology, food items, and seasonal distribution of the red drum (376, 344, 268, 269, 168, 345, 343, 120, 453, 118, 281, 119, 191). 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 (305, 435, 307, 306).

Although red drum occurred in less than one percent of recent Sabine Lake trawl samples (55), they represented 14.7 percent of fishes caught by gill netting (288). Commercial red drum harvests have been very low to non-existent since 1970 and have averaged only 6,100 pounds (2,800 kg) per year in Sabine Lake during the 1962 to 1976 interval (see Table 8-1). However, sport harvest of red drum has been recently estimated at 94,300 pounds (42,800 kg) per year or 19.4 percent by weight of the sport fish caught in Sabine Lake (282).

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 (344, 119, 281, 376, 345, 343, 372). 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 (305, 435).

In Sabine Lake, black drum have been reported to occur in 2.9 percent of trawl samples (55) and to account for 22.6 percent of fish caught by gill netting (288). However, commercial black drum harvest has been low to non-existent throughout the 1962 to 1976 interval and has averaged only 1,300 pounds (590 kg) per year in Sabine Lake (see Table 8-1). Sport harvest is much greater, recently estimated at 61,800 pounds (28,000 kg) per year or 12.7 percent by weight of the sport fish caught in Sabine Lake (282).

Texas Offshore Shrimp Fishery

It is also important to analyze the effects of seasonal Texas freshwater inflow on offshore penaeid shrimp production and harvest because about 60 percent of white shrimp landings and 95 percent of brown and pink shrimp landings made in Texas are contributed from areas in the adjacent Gulf of Mexico. Significant analytical results thus become a useful supplement to equational harvest models developed for each of the major Texas estuaries and their unique seasonal inflow regimes.

The previously discussed stepwise multiple regression technique allows analysis of an 18-year (1959-1976) time series of offshore shrimp harvests as a function of fishing effort and associated seasonal freshwater inflows to major contributing Texas estuaries. Shrimp harvest and effort data are available for the Texas coast (Figure 8-1; Gulf Areas No. 18-21) in the Gulf Coast Shrimp Data publications (404-413, 418-425) and are tabulated here for white shrimp, brown and pink shrimp, and all penaeid shrimp harvest components (Table 8-14). Seasonal inflows to each major Texas estuary are computed to include inflow from all contributing river and coastal drainage basins (FINC inflow category). Summing across the Trinity-San Jacinto, Lavaca-Tres Palacios, Guadalupe, Mission-Aransas, and Nueces estuaries produces a seasonal inflow data base (i.e., $FINC_t$) that reflects both wet and dry climatic cycles experienced by these major Texas estuaries (Table 8-15). Laguna Madre freshwater inflow is omitted because it is relatively low and has not yet been reliably estimated for the historical period. In addition, the Sabine-Neches estuary is omitted because it is shared with Louisiana, presently exhibits a low level of shrimp production, and the offshore shrimp fishing zone (i.e., Gulf Area No. 17) is more closely associated with Louisiana (see Figure 8-1).

The analysis results in a statistically significant equational harvest model for each of the three shrimp fishery components (Table 8-16). The best significant equation (third equation, Table 8-16) involves natural log (ln) transformation of the data variates, explains 70 percent of the observed harvest variance, and is highly significant ($\alpha = 0.5\%$) for correlation of the multi-species, penaeid shrimp harvests to fishing effort and winter, spring, and summer season inflows.

The estimated effect of a correlating variable (e.g., seasonal inflow or fishing effort) on harvest is computed by holding all other correlating terms in the best significant equation constant at their respective mean values, while varying the term of interest from its lower to upper observed bounds. Repeating this process for each correlating variable in the best significant equation and plotting the results in non-transformed units permits illustration of the curvilinear effects of individual variables on the estimate of harvest. For example, Panel A of Figure 8-2 shows the estimate of annual offshore shrimp harvest decreasing 44.8 percent (from about 71.2 to 39.4 million pounds) as winter (January-March) inflow increases from its lower observed bounds of 163.2 thousand acre-feet per month to its upper observed bounds of 2.95 million acre-feet per month. Thus, the negative (-) sign on the regression coefficient for the Q_1 (winter) inflow term in the equation is illustrated as a curve with negative slope, relating increasing winter inflow to a decreasing estimate of harvest. It is noted that this curve can be shifted upward or downward in a parallel manner from that which is graphed by holding any of the other correlating terms in the equation at specified levels of

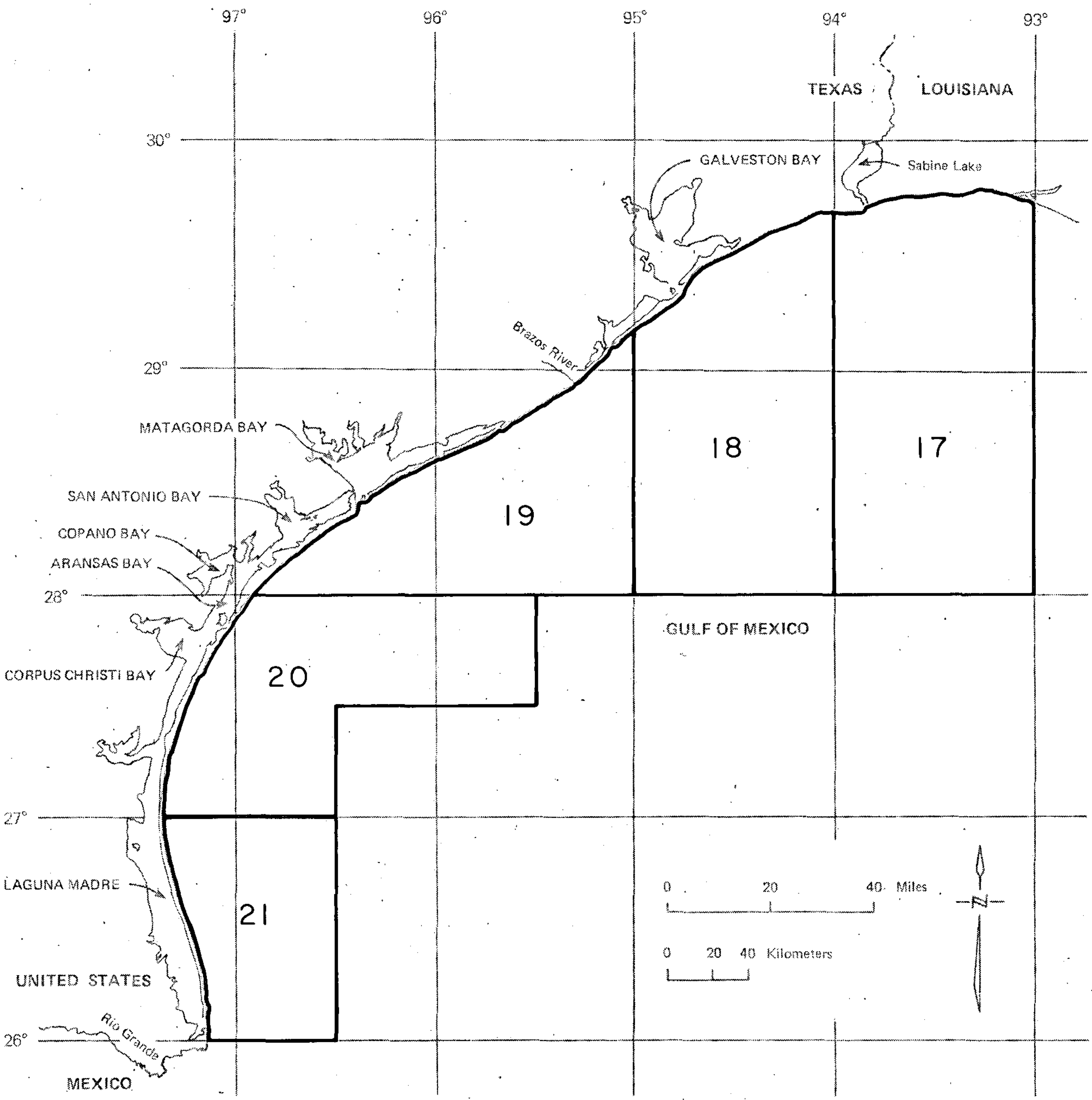

Figure 8-1. Map of National Marine Fisheries Service Shrimp Fishing Grid Zones Showing Gulf Areas No. 17-21

Table 8-14. Texas Commercial Shrimp Harvest and Effort in the Offshore Gulf (Areas No. 18-21), 1959 to 1976 (404-413, 418-425)

Year	White Shrimp a/		Brown and Pink Shrimp d/		All Penaeid Shrimp f/	
	lbs b/	effort c/	lbs e/	effort	lbs	effort
1959	4,277,743	18,652.9	47,311,623	21,686.1	51,592,152	21,686.1
1960	6,336,462	21,554.7	53,101,870	24,188.0	59,465,867	24,188.0
1961	6,240,155	16,211.4	24,773,362	19,454.6	31,050,650	19,454.6
1962	3,162,513	13,459.8	27,104,092	17,916.1	30,269,506	17,916.1
1963	4,573,640	12,668.0	40,592,144	17,754.8	45,244,076	17,754.8
1964	5,635,997	14,579.2	30,801,366	18,165.3	36,458,260	18,165.3
1965	4,531,994	12,188.4	41,855,585	17,336.3	46,406,506	17,336.3
1966	5,834,843	15,254.4	41,157,796	19,905.4	47,029,070	19,905.4
1967	5,014,429	17,893.5	78,147,849	24,612.4	83,189,953	24,612.4
1968	8,928,087	18,357.1	43,519,093	22,708.4	52,484,244	22,708.4
1969	9,911,925	18,620.3	38,104,981	23,754.6	48,031,282	23,754.6
1970	9,951,626	17,910.3	50,521,635	22,101.8	60,500,483	22,101.8
1971	7,949,383	19,050.6	52,083,596	23,051.4	60,068,753	23,051.4
1972	8,721,892	19,602.9	58,844,263	24,525.9	67,647,107	24,525.9
1973	11,057,976	19,831.2	37,406,803	24,245.3	48,494,746	24,245.3
1974	9,908,269	19,803.1	42,360,328	25,702.4	52,429,207	25,702.4
1975	6,379,017	16,523.6	39,807,954	19,749.1	46,203,131	19,749.1
1976	6,556,216	14,372.1	42,175,143	18,242.3	48,775,215	18,242.3
Mean	6,942,860	17,029.6	43,870,530	21,394.5	50,852,240	21,394.5
±S.E.g/	±549,870	±645.6	±2,883,060	±667.0	±2,978,100	±667.0

a/ Offshore harvest of white shrimp at ≤ 20 fathoms depth
b/ Whole shrimp weight estimated by white shrimp tail weight x 1.54
c/ Harvest effort in number of fishing trips by shrimp vessels
d/ Offshore harvest of brown and pink shrimp at all depths recorded
e/ Whole shrimp weight estimated by brown shrimp tail weight x 1.61 and pink shrimp tail weight x 1.60
f/ Offshore harvest of white, brown and pink penaeid shrimp at all depths recorded
g/ Standard error of mean; two standard errors provide approximately 95 percent confidence limits about the mean

Table 8-15. Seasonal Volumes of Combined Freshwater Inflow to Major Texas Estuaries, 1959-1976 a/

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	3,831.9	5,557.8	3,056.0	3,134.0	2,230.0
1960	4,554.9	4,912.2	2,422.0	4,414.0	6,507.0
1961	8,850.0	4,638.9	2,867.0	4,230.0 b/	2,516.0
1962	1,501.8	2,014.8	752.0	1,356.0	1,740.0
1963	1,685.1	1,197.0	414.0	316.0 c/	486.0
1964	2,064.9	1,154.7	561.0	1,406.0	1,697.0
1965	3,486.9	4,824.9	563.0	706.0	2,418.0
1966	3,843.9	9,804.6	1,739.0	921.0	542.0
1967	648.0	1,530.9	703.0	8,445.0 d/	1,537.0
1968	6,010.2	13,869.0	1,822.0	1,192.0	1,371.0
1969	5,259.9	8,723.1	741.0	903.0	1,589.0
1970	4,371.9	5,401.2	894.0 e/	2,972.0	481.0
1971	489.6	750.9	1,785.0	5,773.0 f/	3,554.0
1972	3,324.0	5,826.0	1,031.0	1,325.0	1,637.0
1973	5,555.7	13,936.2	2,935.0	8,988.0 g/	3,334.0
1974	5,280.0	3,771.9	1,042.0	4,041.0	7,250.0
1975	5,463.0	8,883.0	2,246.0	1,128.0	989.0
1976	916.8	4,797.0	2,499.0	2,015.0	5,195.0
Mean	3,729.9	5,644.1	1,559.6	2,959.2	2,504.1
± S.E. h/	± 522.9	±946.6	±217.2	±612.4	±468.0

a/ Includes combined inflow from all contributing river and coastal basins to the Trinity-San Jacinto, Lavaca-Tres Palacios, Guadalupe, Mission-Aransas, and Nueces estuaries

b/ Hurricane Carla, Sept. 8-14; near Port Lavaca

c/ Hurricane Cindy, Sept. 16-20; near Port Arthur

d/ Hurricane Beulah, Sept. 18-23; near Brownsville

e/ Hurricane Celia, Aug. 3-5; near Port Aransas

f/ Hurricane Fern, Sept. 9-13; near Port Aransas

g/ Hurricane Delia, Sept. 4-7; near Galveston

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

Table 8-16. Equations of Statistical Significance Relating Texas Offshore Penaeid Shrimp Harvest to Seasonal Freshwater Inflow and Texas Offshore Fishing Effort a/

Texas Offshore White Shrimp Harvest = f (seasonal $FINC_t$ b/ + E_0)
Highly Significant Equation (α = 0.5%, r^2 = 62%, S.E. Est. = ± 1587.5)

$$OH_{ws} = -2370.10 + 0.84\ (Q_2) - 1.71\ (Q_3) + 0.53\ (E_0)$$
$$\qquad\qquad (0.33) \qquad (0.97) \qquad (0.15)$$

	OH_{ws}	Q_2	Q_3	E_0
upper bounds	11,058.0	4,645.4	1,528.0	21,554.7
lower bounds	3,162.5	250.3	207.0	12,188.4
mean	6,942.9	1,881.4	779.8	17,029.6

Texas Offshore Brown and Pink Shrimp Harvest = f (seasonal $FINC_t$ + E_0)
Highly Significant Natural Log Equation (α = 1.0%, r^2 = 62%, S.E. Est. = ± 0.1896)

$$\ln OH_{bps} = -3.5182 - 0.2395\ (\ln Q_1) + 0.0871\ (\ln Q_2) - 0.0784\ (\ln Q_4)$$
$$\qquad\qquad (0.0867) \qquad (0.0834) \qquad (0.0657)$$
$$+ 1.5792\ (\ln E_0)$$
$$(0.4587)$$

	$\ln OH_{bps}$	$\ln Q_1$	$\ln Q_2$	$\ln Q_4$	$\ln E_0$
upper bounds	10.9827	7.9896	8.4436	8.4105	10.1543
lower bounds	10.1175	5.0950	5.5227	5.0626	9.7606
mean	10.6543	6.8792	7.2436	6.9300	9.9625

Texas Offshore All Shrimp Harvest = f (seasonal $FINC_t$ + E_0)
Highly Significant Natural Log Equation (α = 0.5%, r^2 = 70%, S.E. Est. = ± 0.1574)

$$\ln OH_{as} = -1.8209 - 0.2050\ (\ln Q_1) + 0.1339\ (\ln Q_2) - 0.0845\ (\ln Q_3)$$
$$\qquad\qquad (0.0723) \qquad (0.0762) \qquad (0.0686)$$
$$+ 1.3667\ (\ln E_0)$$
$$(0.2971)$$

	$\ln OH_{as}$	$\ln Q_1$	$\ln Q_2$	$\ln Q_3$	$\ln E_0$
upper bounds	11.3289	7.9896	8.4436	7.3317	10.1543
lower bounds	10.3179	5.0950	5.5227	5.3327	9.7606
mean	10.8077	6.8792	7.2436	6.4689	9.9625

Table 8-16. Equations of Statistical Significance Relating Texas Offshore Penaeid Shrimp Harvest to Seasonal Freshwater Inflow and Texas Offshore Fishing Effort a/ (cont'd.)

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where,

OH_{ws}	=	offshore Texas white shrimp harvest (Gulf Area No. 18-21, $\leq$ 20 fathoms), in thousands of pounds
$\ln OH_{bps}$	=	natural log, offshore Texas brown and pink shrimp harvest (Gulf Area No. 18-21, all depths), in thousands of pounds
$\ln OH_{as}$	=	natural log, offshore Texas all shrimp harvest (Gulf Area No. 18-21, all depths), in thousands of pounds
E_0	=	offshore harvest effort (Gulf Area No. 18-21, $\leq$ 20 fathoms for white shrimmp), in number of fishing trips
$\ln E_0$	=	natural log, offshore harvest effort (Gulf Area No. 18-21, all depths), in number of fishing trips
Q	=	mean monthly freshwater inflow, in thousands of acre-feet
ln Q	=	natural log of Q:

Q_1 = January-March
Q_2 = April-June
Q_3 = July-August
Q_4 = September-October
Q_5 = November-December

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

b/ Combined freshwater inflow to Trinity-San Jacinto, Lavaca-Tres Palacios, Guadalupe, Mission-Aransas, and Nueces estuaries from all contributing river and coastal drainage basins

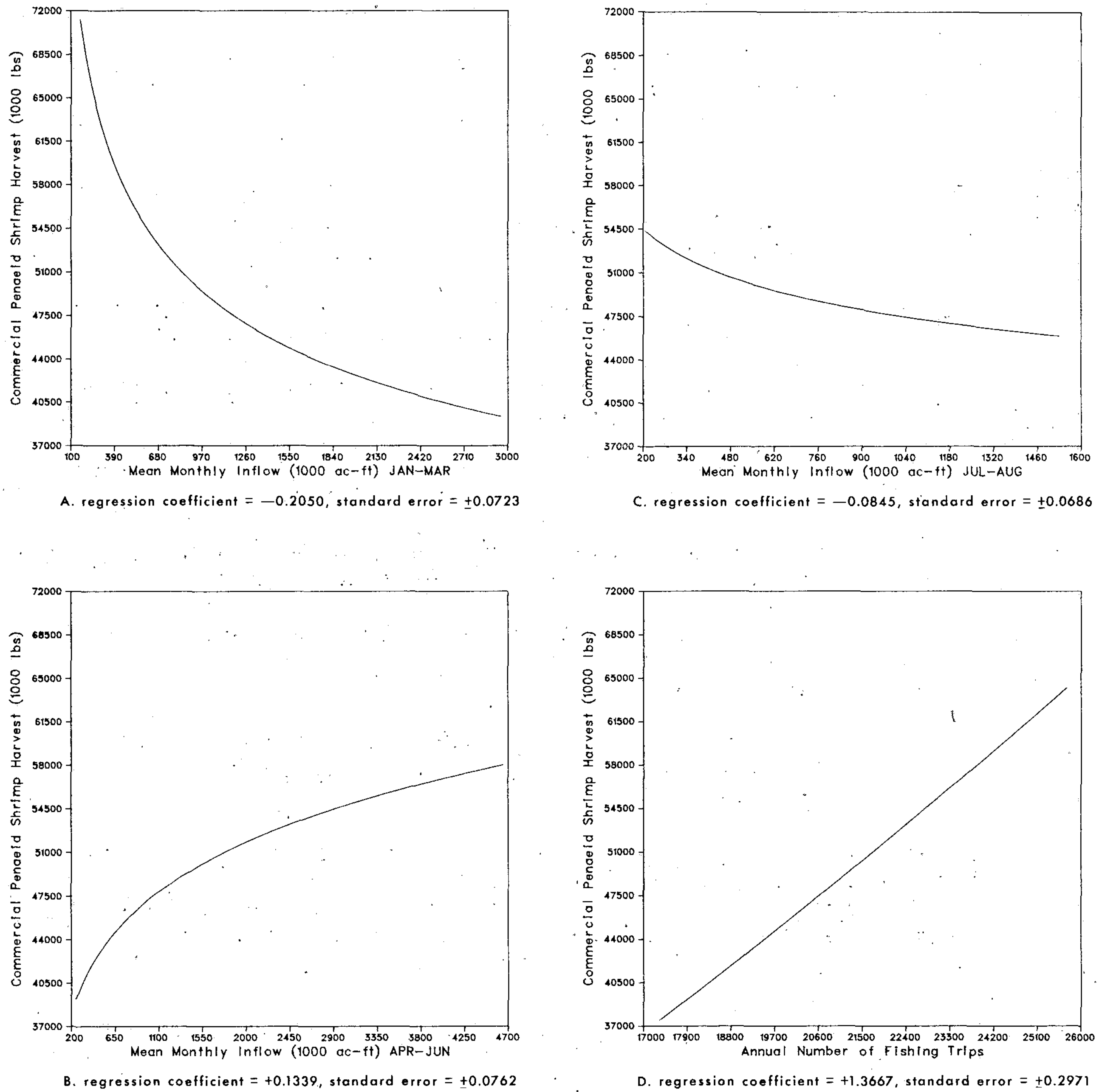

Figure 8-2. Texas Offshore Penaeid Shrimp Harvest as a Function of Fishing Effort and each Seasonal Inflow to Major Texas Estuaries from their Combined River and Coastal Drainage Basins, Where all Other Variables in the Natural Log Multiple Regression Equation are Held Constant at their Mean Values

interest other than their observed mean values. For instance, if the positively correlating spring (Q_2) inflow term is specified at some level higher than its mean of 1.4 million acre-feet per month while the other terms in the equation remain at their observed mean values, then the estimated harvest response to January through March (Q_1) inflow would be similar to that shown in Panel A and would have the identical negative slope; however, the computed curve would be shifted upward and parallel to that which is graphed. Analogous circumstances exist for each of the harvest responses illustrated, but to facilitate comparisons only the variable of interest in each panel is varied, while all others in the best significant equation are held constant at their respective mean values.

Panel B (Figure 8-2) exhibits the positive response of offshore shrimp harvest to spring season inflow. In this case, the estimate of annual harvest increases 1.5 times (from 39.2 to 58.0 million pounds) as April through June (Q_2) inflow increases over its observed range (from 250.3 thousand to 4.65 million acre-feet per month). The negative harvest response to summer inflow results in the annual harvest estimate declining 15.5 percent (from 54.4 to 45.9 million pounds) as July through August (Q_3) inflow increases from 207.0 thousand to 1.53 million acre-feet per month (Panel C, Figure 8-2).

As might be anticipated, fishing effort is positively related to the offshore shrimp harvest (Panel D, Figure 8-2). Specifically, the annual harvest estimate increases 1.7 times (from about 37.5 to 64.2 million pounds) as fishing effort increases from about 17.3 to 25.7 thousand fishing trips per year by shrimp vessels.

Harvest Response to Long- and Short-Term Inflow

The analysis of the Texas offshore shrimp fishery spans a short-term interval of 18 years (i.e., 1959-1976) where more compatible and complete fishery data exist; however, long-term inflow data are available for major Texas estuaries from 1941 to 1976 (i.e., 36 year interval). Average (arithmetic and geometric mean) seasonal inflows from both short-term and long-term intervals are tabulated for comparison (Table 8-17). In addition, a frequency analysis (i.e., Log-Pearson Type III) of the long-term interval produces information about levels of seasonal inflow to the estuaries at selected exceedance frequencies (i.e., 10 percent EF, 50 percent EF and 90 percent EF inflow; also Table 8-17). Although the central seasonal tendencies of the short-term interval are given as average inflow conditions, the long-term central tendencies are expressed both by average inflow conditions and by the 50 percent exceedance frequency inflows which reflect the temporal median inflows from the freshwater source categories (106). Both short-term average total inflows per year are slightly (< 3.0 percent) larger than their respective long-term inflows; however, the seasonal comparisons indicate that five short-term inflows (three arithmetic and two geometric mean seasonal inflows) are less than their respective long-term inflows and five are greater (two arithmetic and three geometric). Average inflows (short-term and long-term means) are greater than the long-term temporal median (i.e., 50% EF) inflow in all seasons except for the short-term D_{ln} (geometric mean) inflow of the winter (January-March) season.

When short-term and long-term average inflow conditions, as well as the long-term 50 percent exceedance frequency inflow conditions, are used

Table 8-17. Comparison of Short-Term and Long-Term Seasonal Freshwater Inflow Volumes to Major Texas Estuaries

Freshwater Inflow Category and Season	Short-Term Mean Seasonal Inflow a/		Long-Term Seasonal Inflow b/				
	D Mean Inflow	D_{ln} Mean Inflow	Arithmetic Mean Inflow	Geometric Mean Inflow	10% EF Inflow	50% EF Inflow	90% EF Inflow
$FINC_t$ c/							
Q_1 (Jan. - Mar.)	3,729.9	2,915.5	3,940	3,023	8,703	2,949	903
Q_2 (Apr. - Jun.)	5,644.1	4,197.4	5,747	4,284	12,795	4,134	1,215
Q_3 (Jul. - Aug.)	1,559.6	1,289.6	1,627	1,243	3,404	1,146	356
Q_4 (Sep. - Oct.)	2,959.2	2,044.9	2,580	1,784	5,920	1,546	382
Q_5 (Nov. - Dec.)	2,283.9	1,728.5	2,126	1,480	4,896	1,392	358
Total	16,176.7	12,175.9	16,020	11,814	35,718	11,167	3,214

a/ Short-term inflow data base, with seasonal volumes in thousands of acre-feet
D = inflow from November 1958 to October 1976 used in analysis of Texas offshore shrimp fishery
D_{ln} = natural log (ln) transformed inflow (Nov. 1958 to Oct. 1976)

b/ Selected exceedance frequencies (Log-Pearson Type III) and their respective seasonal inflow volumes, in thousand of acre-feet, from the long-term historical record (1941-1976)

c/ Combined freshwater inflow to the Trinity-San Jacinto, Lavaca-Tres Palacios, Guadalupe, Mission-Aransas, and Nueces estuaries from all contributing river and coastal drainage basins separately as input to the previously developed statistical harvest equations for the Texas offshore shrimp fishery, predicted harvest responses can be computed for comparison (Table 8-18). It is noted that substitution of the long-term average inflows in the shrimp equations involves using arithmetic mean seasonal inflows as input to the linear equations and geometric mean seasonal inflow as input to the natural log (ln) equations. There are three shifts (two negative, one positive) of the shrimp harvest estimates in response to long-term average inflows, and three harvest shifts (two positive, one negative) in response to the 50 percent exceedance frequency inflows. The harvest responses are variable among the shrimp fishery components and range from an estimated -1.6 percent shift in white shrimp harvest to an estimated +1.8 percent shift in brown and pink shrimp harvest, when compared to shrimp fishery component harvest levels resulting from the short-term interval. The results reflect not only small differences in inflow quantity, but also differences in the seasonal distributions of inflow from the freshwater source categories. In addition, they suggest that Texas offshore shrimp fishery harvests based on long-term seasonal inflows, particularly the long-term temporal median inflows, would be near or exceed the harvest levels observed to result from the short-term interval. Altogether, these results support the hypothesis that seasonal freshwater inflow to major Texas estuaries has a significant impact on the estuarine-dependent shrimp fishery, and by ecological implication, on the "health" of the estuarine ecosystems.

Although management policies could favor the specific seasonal inflow needs of preferred fisheries components (e.g., penaeid shrimp), it is in reality difficult and in many cases impossible to maximize harvests from more than one species at a time because of competitive seasonal inflow needs among the estuarine-dependent fisheries species. Nevertheless, management scenarios for inflow can be developed that predict good harvest levels from several fisheries species simultaneously. In general, the most prominent dichotomy that exists is between the responses of fish and shellfish species to freshwater inflow, with estuarine-dependent fish species commonly more tolerant to "drier" inflow conditions.

Summary

Virtually all of the Gulf fisheries species are estuarine-dependent. Commercial inshore harvests (1962-1976) from the Sabine-Neches estuary (i.e., Sabine Lake) rank fifth in shellfish and eighth in finfish of eight major Texas estuarine areas. In addition, the sport or recreational finfish harvest far exceeds the commercial finfish harvest in the estuary. For the 1972 through 1976 interval, the average annual sport and commercial harvest of fish and shellfish dependent upon the Sabine-Neches estuary is estimated at 4.8 million pounds (2.2 million kg; 85.2 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 often 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

Table 8-18. Estimated Average Harvest Responses from Texas Offshore Shrimp Component Equations Using Short-Term Mean Inflow, Long-Term Mean Inflow, and 50 Percent Exceedance Frequency Inflow

Shrimp Fishery Component (offshore)	Combined Freshwater Inflow $FINC_t$ a/		
	Short-Term Mean Inflow	Long-Term Mean-Inflow	Long-Term 50%EF b/ Inflow
	Harvest c/	Harvest (Shift) d/	Harvest (Shift)
White Shrimp	6,942.9	6,873.7 (-1.0)	6,833.3 (-1.6)
Brown and Pink Shrimp	42,374.4	42,553.0 (+0.4)	43,152.3 (+1.8)
All Penaeid Shrimp	49,399.7	49,333.0 (-0.1)	49,687.4 (+0.6)

a/ Combined freshwater inflow to Trinity-San Jacinto, Lavaca-Tres Palacios, Guadalupe, Mission-Aransas, and Nueces estuaries from all contributing river and coastal drainage basins

b/ EF = exceedance frequency; 50% EF inflow reflects the temporal median inflow to the estuaries

c/ Mean harvest of whole shrimp, in thousands of pounds

d/ Shift in percent increase (+) or decrease (-) of harvest 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 Sabine Lake fisheries landings was performed, but can not be considered entirely successful because the data and analysis suffer from several problems: (1) the time-series data bases of most fisheries species in Sabine Lake are discontinuous and contain few observations, (2) fisheries harvest levels are relatively low in the estuary, and (3) the harvest data may not be an adequate relative measure of the absolute shifts in fisheries abundance from year-to-year because the ecosystem appears ecologically stressed, exhibits low biomass production in most trophic (nutritional) compartments of the foodweb, and its fisheries resources are shared with Louisiana. As a result of these difficulties, probable spurious relationships appear in the analysis (e.g., the positive response of fisheries harvests to increasing summer inflow). Sabine Lake fisheries harvest responses computed from the analysis are predominantly negative to spring (April-June) and autumn (September-October) inflows, and positive to winter (January-March), summer (July-August), and late fall (November-December) inflows. However, as mentioned before, these results are of questionable predictive value.

On the other hand, successful application of the analytical techniques to the 1959 through 1976 time-series of harvests from the Texas offshore shrimp fishery produces three statistically significant multiple regression equations. The best significant equation is highly significant and explains 70 percent of the annual variance in combined penaeid shrimp harvests as a function of fishing effort and seasonal freshwater inflows to major Texas estuaries (i.e., Trinity-San Jacinto, Lavaca-Tres Palacios, Guadalupe, Mission-Aransas, and Nueces estuaries) from their contributing river and coastal drainage basins. The equational harvest models for white, brown, and pink shrimp provide numerical estimates of the effects of fishing effort and variable seasonal inflows on commercial offshore harvests of these estuarine-dependent penaeid shrimp species. They also support existing scientific information on the seasonal importance of freshwater inflow to the estuaries. In this case, offshore shrimp harvests are computed to relate positively to spring (April-June) inflow and fishing effort, and negatively to winter (January-March), summer (July-August), and autumn (September-October) inflows.

Where the estimated seasonal inflow needs of 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 each estuary. Whatever the decision, a freshwater inflow management regime can only provide an opportunity for the estuaries to be viable and productive because there are no guarantees for estuarine productivity based on inflow alone, since many other biotic and abiotic factors are capable of influencing this production. However, most of these other factors are largely beyond human control, whereas freshwater inflows can be restricted by man's activities so that fish and wildlife resources are adversely affected.

CHAPTER IX

ESTIMATED FRESHWATER INFLOW NEEDS

Introduction

In previous chapters, the various physical, chemical and biological factors affecting the Sabine-Neches estuary have been discussed. There has been a clear indication of the importance of the quality and quantity of freshwater inflows to the maintenance of a viable estuarine ecology. The purpose in Chapter IX is to integrate the elements previously described into a methodology for establishing estimates of the estuary's freshwater inflow needs, based upon historical data.

Methodology for Estimating Selected Impacts of Freshwater Inflow Upon Estuarine Productivity

The response of an estuary to freshwater inflow is subject to a number of factors and a variety of interactions. These include changes in salinity due to mixing of fresh and saline water, fluctuations in biological productivity arising from variations in nutrient inflows, and many other phenomena.

The methodology presented here incorporates major interacting elements described in previous chapters (Figure 9-1). The methodology includes the use of data bases and certain analytical processes described herein. Data for these analyses include six groups: (1) salinity data for finfish and shellfish, (2) commercial fisheries harvest data, (3) hydrologic data of freshwater and saline water, (4) water quality data, (5) aquatic food chain data, and (6) terrestial and aquatic geomorphic data of the estuary and the surrounding coastal area.

In this section data and results of previous sections, including (1) statistical analysis of relationships among freshwater inflow, commercial fishery harvest, and estuarine salinity; (2) estimates of marsh freshwater inundation needs; (3) estimates of nutrient exchange; and (4) records of historical freshwater inflow, are used in an Estuarine Linear Programming (LP) Model to compute estimates of the monthly freshwater inflows needed to achieve specified objectives. The tidal hydrodynamic and salinity transport models are then applied to compute salinity levels and circulation patterns throughout the estuary for a set of 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 utilizing 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 Sabine-Neches estuary provide the fundamental

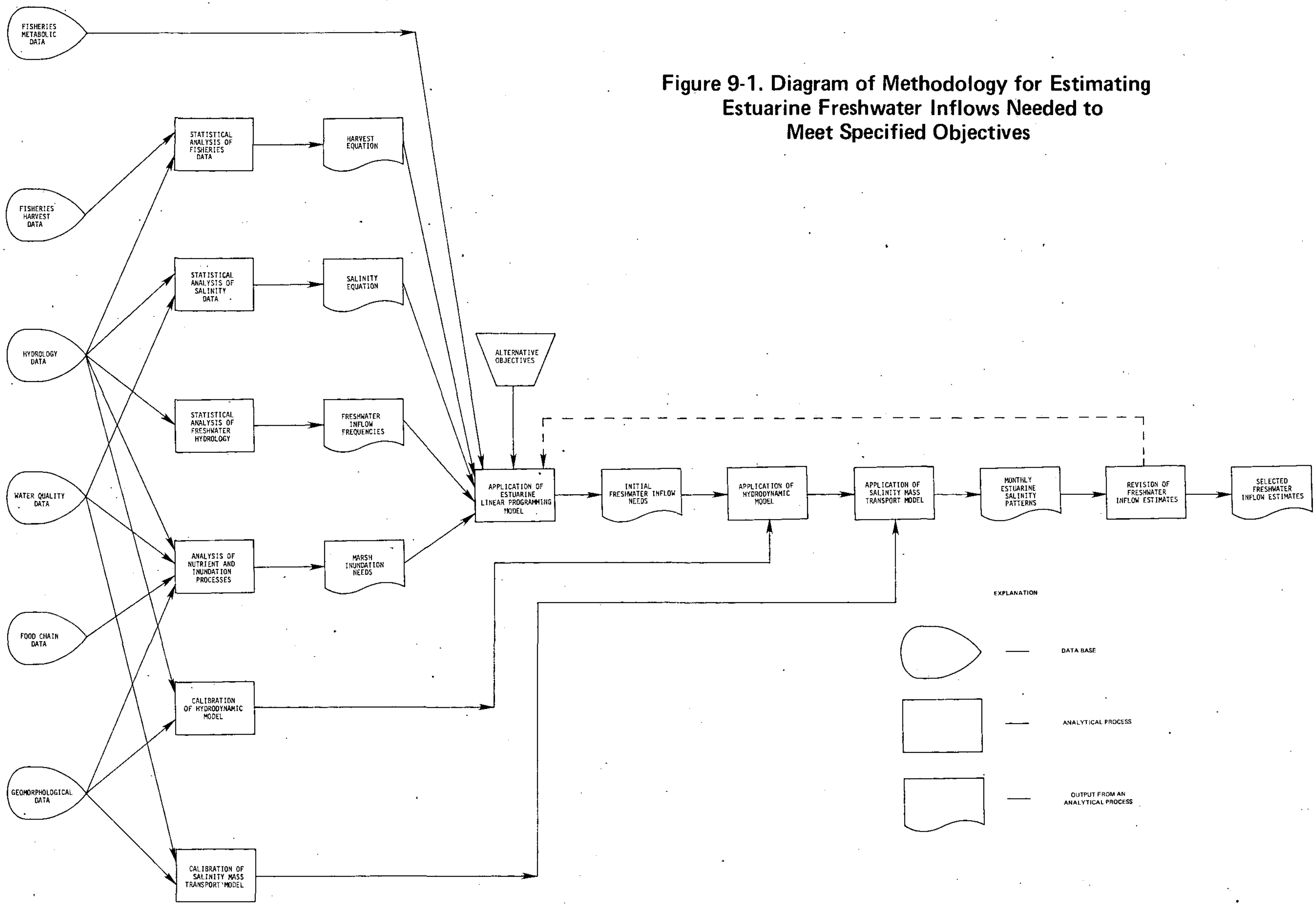

Figure 9-1. Diagram of Methodology for Estimating Estuarine Freshwater Inflows Needed to Meet Specified Objectives

information of the system. These data were used in previous sections of these analyses. The relationships and results are incorporated into the Estuarine Linear Programming Model to compute estimates of effects of various levels of monthly freshwater inflows upon near-shore salinities, marsh inundation and fisheries harvests in the estuary. This model uses an optimization technique to select the optimal or "best" monthly inflows for the objective specified. The estimated monthly inflows are then used as data inputs in the tidal hydrodynamic and salinity transport models to simulate the effects of the inflows upon circulation and salinity patterns in the entire estuary. Should the computed salinity conditions in certain critical areas of the estuary be unsatisfactorily high or low, then the freshwater inflow estimates would require appropriate modification. This revision of the estimates (indicated by the dashed line in Figure 9-1) would necessitate a revision of the constraints in the Estuarine Linear Programming Model.

The data bases and analytical processes utilized in this chapter have been described in detail in previous chapters. Only the procedures necessary to establish salinity bounds, estimate marsh inundation needs, and apply the Estuarine Linear Programming Model are presented in this chapter.

Salinity Bounds for Fish and Shellfish Species

The effects of salinity on estuarine-dependent fisheries organisms are fundamentally physiological, and influence growth, survival, distribution, and ecological relationships (see Chapter VIII).

Specific information on salinity limits, preferences and/or optima for selected fisheries species has been tabulated from the scientific literature and Texas Department of Water Resources research data (Table 9-1). The optimum condition for most of these species lies between 25 percent and 75 percent seawater (8.8-26.3 ppt). Young fish and shellfish commonly utilize estuarine "nursery" habitats that are below 50 percent seawater (less than 17.5 ppt), while adults seem to prefer salinities slightly higher than 50 percent seawater. In general, and within the tolerance limits, it is the season, not salinity per se, that is more important because of life cycle events such as spawning and migration. While the salinity limits for distribution of the species are ecologically informative, they are often physiologically too broad. Conditions encouraging good growth and 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 salinity viability limits, the seasonal bounds were established subjectively based upon the results available from scientific literature (Table 9-1). It is important to note that these limits are site specific and adjusted to a single control point normally below the "null zone"1/ in upper Sabine Lake near the Neches

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 (364, 93).

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

Species	Limits Min. (ppt)	Limits Max. (ppt)	Preference or Optimum (ppt)	Remarks	Reference
Penaeus setiferus (white shrimp)					
	< 2	> 40		range at which 80% of 8-50 mm (postlarvae to juvenile) shrimp survive; 48 hr. acclimation	454
			5-15	increased growth at this range (and >25°C) more than two times tissue production of postlarvae at 25-35 ppt	454
			28.0	median salinity average of postlarval distribution (May-July) in laboratory gradient tanks	244
			21.0	median salinity average of postlarval distribution (Aug.-Nov.) in laboratory gradient tanks	244
		47.96		field collection of small white shrimp (23-76 mm) in Laguna Madre de Tamaulipas (Mexico)	113
	0.42			lower distribution limit in Grand and White Lakes (La.); young shrimp 140 times more abundant at 0.7-0.8ppt	100
			27.6-28.3	isosmotic salinity conditions for shrimp ≥ 100 mm length; osmoregulation below 27.6 ppt better than brown shrimp	173
	1	34	1-20	field distribution in Caminada Bay (La.) and range for 91.1% of juveniles collected	42
	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	335
	2.9	45.3		field distribution in Mesquite Bay (Tex.)	117
	2	45		field distribution in bays and lagoons of northwestern Gulf of Mexico (Tex.)	109
			< 10	preference based on population distributions	99
	0	38		optimum catch over entire salinity range with 20-38°C temperatures	339
Penaeus aztecus (brown shrimp)					
	2	40		range of equal postlarval growth over 23-25°C temperature; survival 90-100% in laboratory	455
	< 10			marked reduction in postlarval tolerance at low (7-15°C) temperatures to low (5 ppt) salinity	456
			15-35	range of increased postlarval growth at temperatures >25°C; decreased growth below 15 ppt	454
	< 5	> 40		range at which 80% of 10-15 mm postlarvae survive; 12 hr. acclimation	454
			> 15	appeared to enhance survival and growth of postlarvae in Barataria Bay (La.)	226
			> 15	commercial catches poor in years when postlarvae were present in Louisiana bays with < 15 ppt	164
			29.9	median salinity average of postlarval distribution (March-April) in laboratory gradient tank	244
			20.6.	median salinity average of postlarval distribution (May-July) in laboratory gradient tank	244
			10.0-19.9	range at which juveniles were more abundant based on population distributions	99
	0.2	30	10-30	field distribution in Caminada Bay (La.) and range for 91.8% of juveniles collected	42
			< 17	preference of juvenile (70 mm) shrimp in laboratory at >26°C temperature	371
			15-25	optimal range for subadult (95 mm) shrimp in laboratory at <25°C temperature	371
			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	430
			27.6-28.3	isosmotic salinity conditions for shrimp ≥ 100 mm length; osmoregulation above 28.3 ppt better than white shrimp	173
	2.1	36.6	15.0-19.9	field distribution in Copano and Aransas Bays (Tex.) and range of greater abundance	335
		69.0		field collection in Laguna Madre (Tex.)	314
	0.8			lower distribution limit in Grand and White Lakes (La.)	100
	0.22			field collection in St. Lucie Estuary (Fla.)	84
	5	70		field distribution in bays and lagoons of northwestern Gulf of Mexico (Tex.)	109
	0.1			field collection (North Carolina)	448
			5	acclimation at low (5 ppt) salinity provides near-optimum resistance to high temperatures and 5-25 ppt salinities in laboratory tests	447
	9	40		no optimum salinity established with 20-35°C temperatures	339
Callinectes sapidus (blue crab)					
	22.9	32.4	≥ 30.0	range for capture of egg-bearing females near Aransas Pass (Tex.)	335
			23-28	optimum range for hatching of eggs (Virginia)	218
			> 20	occurrence of spawning and early development	273
			< 1.9	peak abundance of juvenile blue crabs in Texas bays (1965)	273
	< 1.0		2-21	lethal limit at optimum (29°C) temperature and range of little effect on juvenile growth and survival	243
	0			observed freshwater populations in Louisiana	97
	2.0	37.2	10.0-20.0	field distribution in Copano and Aransas Bays (Tex.) and range of greater abundance	335
		117		field collection in Laguna Madre de Tamaulipas (Mexico); high salinity briefly tolerated	113
		45		blue crabs observed leaving upper Laguna Madre (Tex.) area as salinity increased	279
	2	60		field distribution in bays and lagoons of northwestern Gulf of Mexico (Tex.)	109
			24.2	salinity for widest thermal tolerance zone in adult blue crab	75
	0	40	0-27	optimum range with 10-35°C temperatures	339
			10-30	range of no effect on metabolic consumption of oxygen (respiration)	140
Crasostrea virginica (American bay oyster)					
	< 6			gametogenesis inhibited by prolonged low salinity exposure; up to 3-4 months required to regain normal gonadal activity after salinity increases towards the optimum	16
	5-7.5			normal gonadal development near 7.5 ppt; however, oysters with previously ripe gonads spawn when subjected to low (5 ppt) salinities	149
			20-21	larval spat setting requirement in Galveston Bay (Tex.)	374
	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	134

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	400
			8-30.5	maximum survival (60% contour plot) in lab of 8-day larvae at temperatures > 21°C	400
			>33	maximum growth (100% contour plot) in lab of 8-day larvae at temperatures > 19°C	400
			18-35	optimum (80% contour plot) for both larval survival and growth at temperatures > 30°C	400
			15-22.5	optimum for juvenile growth and development	24
	1.5	39.0		early experimentally derived salinity limits	6
	0-2			oysters can survive freshwater (oppt) for several days; increasing to about a month at 2 ppt salinity	335
			15-30	optimum range of salt content	285
	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)	396
		43.5-45		distribution limit in Redfish and Corpus Christi Bays (Tex.)	320
			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	53
	≤ 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.)	289
			15-30	best growth in reasonably stable salinity	192
	3			lower tolerance limit about 3 ppt	96
	8-10			lower limit of predator Thais haemastoma, a gastropod oyster drill or conch	96 335
	< 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	329
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	235
			> 30	spawning occurs in estuarine areas of higher salinity (La.)	216
		≤ 60	< 45	"young" collected up to about 60 ppt in Laguna Madre (Tex.); no spawning if salinity > 45 ppt	314
		< 55	15-35	absent above 55 ppt in Baffin and Alazan Bays (Tex.); most abundant range 15-35 ppt	313
	2.3	34.9	5-20	field distribution in Copano and Aransas Bays (Tex.); over 80% collected in 5-20 ppt	344
	< 5	77		field distribution in bays and lagoons at northwestern Gulf of Mexico (Tex.)	109
	10	45	20	operational limits; optimum metabolic condition at 20-28°C temperatures	333

Species	Limits Min. (ppt)	Limits Max. (ppt)	Preference or Optimum (ppt)	Remarks	Reference
Sciaenops ocellata (red drum)					
	2.1	32.4	< 15	field distribution in Copano and Aransas Bays (Tex.); greater abundance below 15 ppt	344
	0	> 50	20-40	field distribution (Tex.); range of preference (most abundant in 30-35 ppt); young mature in 3-5 years	345
			< 50	populations in Laguna Madre (Tex.) severely limited by >50 ppt	313
	5-10	40-45	20-25	operational limits; range of optimum metabolic condition at 20-28°C temperatures	305
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	344
	<5	77		field distribution in bays and lagoons of northwestern Gulf of Mexico (Tex.)	109
	0	80		field distribution (Tex.); usual range in Laguna Madre 25-50 ppt	345
	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	305

Table 9-2. Salinity Characteristics of Upper Sabine Lake

Month	Salinity in Upper Sabine Lake a/ (ppt)		
	Upper b/ Viability Limit	Lower b/ Viability Limit	Median of Historic Salinity
January	20	10	3
February	20	10	2
March	20	10	2
April	15	5	3
May	15	1	3
June	15	1	4
July	20	10	8
August	20	10	11
September	15	5	15
October	15	5	16
November	20	10	14
December	20	10	10

a/ Represented by sampling site 4, linesite 244 (Figure 3-8).
b/ These values estimate the limits of long-term viable species activity at a control point in the estuary, and not individual organism survival limits.

and Sabine River deltas. The limits are expressed as mean (average) monthly salinities for general limits of viability. From this location, salinities generally increase towards the Gulf inlet (Sabine 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, estuarine-dependent species have adapted their life cycles to the natural freshwater inflow regime of most Texas estuaries, except failures such as the oyster in Sabine Lake.

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 will remain in the system during normal periodic salinity fluctuations. Should the normal salinity conditions be altered for prolonged periods due to natural or manmade causes, the diversity, distribution and productivity of species within an estuary will be depressed.

The median monthly salinity is a central tendency measure of the salinity range about which the monthly salinity fluctuates. The median monthly salinity is that value for which one-half of the observed average monthly salinities exceed the value and one-half are less. The median monthly salinity thus reflects the "expected" salinity in the estuary and represents a value exceeded one-half of the time. Median monthly salinities (Table 9-2) have been computed for the location in upper Sabine Lake for which the monthly salinity regression equations were developed (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.

Two major river deltas of the Sabine-Neches estuary (the Neches and Sabine River deltas) are periodically inundated.[1/] These deltas are subject to periodic inundation by freshwater due to discharge from the Sabine and Neches Rivers. 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 these deltas. 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 marsh area above Sabine Lake is subject to periodic flooding due to discharges from the Sabine River and the Neches River. The Sabine River at Ruliff and the Neches River at Evadale are the two most downstream stream-gage locations selected as indicators of flood stages for their respective rivers. Flood stage, according to the National Weather Service data files, occurs at discharge rates of 17,000 ft^3/sec (481 m^3/sec) at the Ruliff gage and 7,600 ft^3/sec (215 m^3/sec) at Evadale.

Daily gaged discharge data for the Sabine River near Ruliff and the Neches River at Evadale, for the period of record (1925-1976), were examined to arrive at monthly and seasonal distributions of discharge events with peak flows in excess of the flood stages noted above (Tables 9-3 and 9-4). It is apparent that more inundation events have occurred in the spring months of March through June than during any other seasonal period. Also, the data suggest that inundation events in the Sabine and Neches deltas have occurred more often in the winter and spring than in summer and fall. According to the biological evidence, spring inundation events are necessary for (1) adequate physical wetting of the marsh plant communities, (2) nutrient exchange and biogeochemical cycling of carbon, nitrogen and phosphorus, (3) transport of detrital materials, and (4) reduction of salinity to suit the needs of juvenile, estuarine-dependent organisms utilizing the "nursery" habitats of the marsh and adjacent shallow water areas. In the tropical-storm dominated fall season, less frequent inundation events occur; however, maintenance benefits are still provided to the estuary and dependent fall spawners such as the redfish.

If historical inundation events (peak daily flows greater than 17,000 ft^3/sec in the Sabine and 7,600 ft^3/sec in the Neches) are grouped by basin into those that occur in spring (March through June), those that occur in the winter (December through January), and the total that occurs during the

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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 (297, 298). 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 Discharges for Discrete Flood Events Greater Than 17,000 ft^3/sec on the Sabine River near Ruliff, 1925-1976 (Units in ft^3/sec)

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
52,900	84,000	62,800	83,500	120,000	78,100	41,300	67,000	41,300	0	50,000	38,000
52,200	63,700	45,600	51,600	75,000	61,200		52,000	36,500		39,600	33,400
52,200	62,000	40,100	47,500	61,900	47,500		29,800			28,200	31,600
41,200	54,700	38,700	47,300	53,700	45,700						31,300
34,900	38,400	37,600	38,700	46,000	25,700						29,800
31,200	33,500	33,900	33,900	40,900	25,500						29,500
30,400	32,800	32,000	32,700	40,600	23,700						23,400
29,000	30,600	31,200	32,200	40,500	22,200						22,600
28,600	30,400	31,200	29,700	28,600	20,700						21,100
27,300	29,900	30,100	26,800	28,100	18,800						20,100
27,100	28,600	24,900	26,800	25,200							
23,800	28,200	24,200	24,200	23,600							
22,800	25,000	23,800	23,800	23,400							
19,200	24,100	23,400	22,800	21,800							
19,200	24,100	22,800	22,700	20,100							
19,100	24,000	21,800	21,400								
18,500	23,700	20,700	21,000								
18,200	22,700	19,000	20,900								
	21,800	18,000	19,200								
	21,800		18,000								
	21,800										
	21,400										
	19,100										
	18,200										

Median peak flood discharge = 28,000 ft^3/sec

Table 9-4. Peak Discharges for Discrete Flood Events Greater Than 7,600 ft^3/sec on the Neches River at Evadale, 1925-1976 (Units in ft^3/sec)

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
40,400	56,000	73,400	53,000	92,100	67,500	19,800	16,000	14,900	21,000	47,100	59,600
34,600	32,600	28,400	39,200	80,000	46,000	13,400	13,700	9,110	13,000	30,000	35,600
26,900	24,900	27,800	30,100	64,100	30,600	11,400	10,400	8,900	10,200	16,000	21,200
26,800	24,800	24,000	30,000	55,000	20,800	9,100	9,960		10,100	8,600	21,200
21,000	22,800	23,800	28,600	30,500	19,700		9,050			8,400	16,800
20,800	22,600	21,400	27,000	27,800	18,000						14,500
19,800	20,600	21,400	24,400	25,000	16,300						14,200
19,300	19,000	20,000	23,200	24,600	15,400						13,600
18,000	18,800	17,900	20,600	23,200	11,900						13,400
17,900	18,000	17,200	20,000	22,200	10,300						12,100
17,200	17,300	16,800	19,000	21,300	9,750						10,400
16,200	15,700	15,400	18,800	21,100	9,500						9,060
15,500	13,400	15,200	16,500	20,800	9,320						8,860
14,100	11,800	14,900	16,500	19,200	8,940						
13,000	11,400	14,200	16,000	16,200	8,870						
11,800	11,400	12,400	15,300	14,100							
11,400	10,800	10,900	12,800	13,500							
11,200	9,810	9,390	12,200	13,200							
9,180	9,040	9,140	11,800	11,900							
8,770		8,660	10,500	11,700							
		8,640	10,300	10,600							
		8,400	8,480	10,600							
		8,380	8,420	9,630							
			7,600	8,770							

Median peak flood discharge = 18,000 ft^3/sec year, it is evident that a median of two inundation events have occurred per year in the lower Sabine River and three events per year in the lower Neches River over the period of record (Table 9-5 and 9-6). In order to maintain the historical inundation frequency, the Sabine and Neches River deltas would need to receive at least two and three flood events per year, respectively, in at least 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. Inundation events in April and May would be expected to extend favorable habitat conditions for larvae and juvenile stages of many estuarine-dependent organisms. Thus, it is recommended that one flood event from the Neches River Basin occur in April and one combined event from both river basins take place in May. Since each basin averages one additional inundation event, an additional combined flood from both basins is scheduled in the fall, specifically in the month of October. The median peak flood discharge over the period of record for the Sabine River near Ruliff has been 28,000 ft^3/sec (794 m^3/sec), while that for the Neches River at Evadale has been 18,000 ft^3/sec (510 m^3/sec).

It is recognized that the historical frequency of flood events in October is very low (Tables 9-3 and 9-4). However, scheduling additional flood events in October would probably be more beneficial to estuarine productivity than having floods in the January through March period, when they have historically occurred, since biological activity would be greater in the warmer October water temperatures.

The daily hydrographs of several past floods with peak daily flows near the median were plotted to established the total volume of water associated with flood events in each river basin. The total flood volumes for the median peak floods for the Sabine River near Ruliff and the Neches River at Evadale were estimated to be 802.0 and 480.3 thousand acre-feet (992 and 594 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 Sabine and Neches River Basins.1/ A Linear Programming (47) optimization procedure is used to compute the combined monthly freshwater inflows from the Sabine and Neches River Basins needed to meet specified salinity, marsh inundation and fisheries productivity levels. The quantifications of salinity and commercial fisheries harvest as functions of the freshwater inflows are the statistical regression equations given in Chapters V and VIII, respectively.

1/ Additional freshwater inflows are contributed to the estuary from the Black Bayou and Neches-Trinity 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.

Table 9-5. Frequency of Annual and Seasonal Flood Events Greater than 17,000 ft^3/sec for the Sabine River near Ruliff, 1925-1976

Number of Events per Period	Winter (December-February)		Spring (March-June)		Total Annual	
	Number of Occurrences over Period of Record					
(x)	Freq.(f) a/	f*x b/	Freq.(f)	f*x	Freq.(f)	f*x
0	15	0	9	0	4	0
1	23	23	26	26	11	11
2	10	20	15	30	13	26
3	4	12	2	6	11	33
4					9	36
5					4	20
Σf*x		55		62		126
Number of Years = 52						
Mean Number Inundation events per year		1.1		1.2		2.4
Median Number Inundation events per year		1		1		2

a/ Freq. (f) is the number of seasons or years in which the number of flood events greater than 17,000 ft^3/sec equaled x.

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

Table 9-6. Frequency of Annual and Seasonal Flood Events Greater than 7,600 ft^3/sec for the Neches River at Evadale, 1925-1976

Number of Events per Period	Number of Occurrences over Period of Record					
	Winter (December-February)		Spring (March-June)		Total Annual	
(x)	Freq.(f)a/	f*xb/	Freq.(f)	f*x	Freq.(f)	f*x
0	17	0	5	0	2	0
1	20	20	18	18	7	7
2	12	24	21	42	10	20
3	3	9	6	18	11	33
4			2	8	15	60
5					5	25
6					0	0
7					2	14
Σf*x		53		86		159
Number of Years = 52						
Mean Number Inundation events per year		1.0		1.7		3.1
Median Number Inundation events per year		1		2		3

a/ Freq. (f) is the number of seasons or years in which the number of flood events greater than 7,600 ft^3/sec equaled x.
b/ f*x stands for f multiplied by x.

The harvest equation utilized for a given species or group is the equation accounting for the most variance in the data (i.e., having the largest r^2 value).

Specification of Objectives. The criteria or objective in this optimization formulation can be any desired estuarine condition. One objective of interest is to compute the minimum annual inflow to the estuary needed to meet 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 harvest 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).

Computation Constraints for the Model. A set of constraints in the model relate freshwater inflow to various environmental and statistical limits specified as objectives. These constraints include:

(1) upper and lower limits for the seasonal inflows used in the regression equations which estimate annual commercial fisheries harvests,
(2) statistical regression equations relating mean monthly salinities to mean monthly freshwater inflows,
(3) upper and lower limits on the monthly flows used in computing the salinity regression relationships, and
(4) upper and lower limits on allowable monthly salinities (Table 9-2).

Alternative Estuarine Objectives

Three alternative objectives are considered as follows:

Alternative I, Subsistence
Objective: minimize annual combined inflow while meeting salinity viability limits and marsh inundation needs;

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

Alternative III, Shrimp Harvest Enhancement
Objective: maximize the total annual commercial harvest of shrimp while meeting viability limits for salinity, satisfying marsh inundation needs, and utilizing an annual combined inflow no greater than the average historical 1941-1976 combined inflow.

The objectives and constraints for the listed alternatives are indicated in Table 9-7. The three specified objectives are not the only possible options for the Sabine-Neches estuary; however, they provide a range of alternatives: survival or subsistence (Alternative I), maintenance of harvest levels

Table 9-7. Criteria and System Performance Restrictions for the Selected Estuarine Alternatives

	Alternative		
	I	II	III
Criteria:			
• Maximize Annual Harvest of Shrimp			x
• Least Possible Annual Combined Inflow	x	x	
Constraints:			
• Annual Inflow from the Sabine and Neches River Basin are each no greater than their Average Annual Historical Values (1941-1976)			x
• Predicted Annual Spotted Seatrout and Red Drum Commercial Harvests no less than their Average Annual Values (1962-1976)		x	
• Predicted Annual Shrimp Commercial Harvest no less than Average Harvest (1962-1976)		x	
• Upper and Lower Limits on Seasonal Inflows to Insure Validity of Predictive Harvest Equations		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 Sabine and Neches Basins Inflow for Marsh Inundation of the Sabine and Neches River deltas	x	x	x

Alternative II), and shrimp harvest enhancement (Alternative III). Additional alternatives could be considered based upon maintaining or enhancing fresh-water species or habitats, as well as estuarine species, if suitable salinity limits were available.

Alternative I: Subsistence. The objective of Alternative I (Subsistence) is to minimize total annual combined inflow while meeting specified bounds on salinity in upper Sabine Lake and satisfying marsh inundation needs for the Sabine and Neches River deltas.1/ The upper salinity bound for each month is the minimum of the upper salinity viability limit and the historic median salinity (Table 9-2), but no lower than the lower viability limit. This has the effect of restricting the range of salinity at a point for a number of months to a single salinity level, namely the minimum viability limit.

The marsh inundation needs specified earlier in this chapter for the Sabine-Neches delta were found to be in conflict with the lower limits established above during the month of October. From Table 9-2, the lower salinity limit in upper Sabine Lake for October is five parts per thousand (ppt); however, the inundation volume for the month gives a salinity level of four ppt. The lower limit on salinity during October in Sabine Lake was reduced to four ppt to accommodate the inundation event since it was judged that relatively little adverse impact would arise from the reduced salinity during that month.

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 8.78 million acre-feet (10.8 billion m^3), with about 7.5 million acre-feet (9.3 billion m^3) from the Sabine and Neches Basins, and 1.27 million acre-feet (1.57 billion m^3) from the Black Bayou and Neches-Trinity Coastal Basins (Table 9-8).

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 (Figure 9-2). Freshwater inflows during the months of May and October provide lower salinities as a consequence of meeting marsh inundation requirements.

Comparisons between the mean 1941-1976 historical combined inflows and the estimated freshwater inflow needs are made for each month (Figure 9-3), for the combined inflow from the Sabine and Neches River Basins. The estimated monthly freshwater inflow needs are less than the mean historical inflows except for the month of October.2/ The distribution of the

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1/ The Sabine and Neches River deltas inundation needs include inundation volumes of 802.0 thousand acre-feet from the Sabine Basin at the streamgage near Ruliff and 480.3 thousand acre-feet from the Neches Basin at the streamgage at Evadale. Inundation events of the above magnitudes are specified to occur in the months of April, May and October from the Neches Basin and in May and October from the Sabine Basin.

2/ This greater inflow need arises since the second marsh inundation event for the year is specified to occur in October, and that month is not a normal month for high inflows to the estuary (over the 1925 through 1976 period).

Table 9-8. Freshwater Inflow Needs of the Sabine-Neches Estuary under Alternative I a/

Period	Sabine and Neches River Basins		Total Inflow From Coastal Basins c/	Combined Inflow d/
	Estuary Inflow Need from the Basins	Estuary Inflow Need from Gaged Portion of the Basins b/		
	Thousands of Acre-Feet			
January	484.9	350.7	86.0	570.9
February	497.6	361.7	95.0	592.6
March	473.0	340.4	78.0	551.0
April	697.2	535.4 e/	140.0	837.2
May	1,555.7	1,282.3	151.0	1,706.7
June	630.7	477.5	138.0	768.7
July	316.7	204.3	143.0	459.7
August	287.0	178.5	116.0	403.0
September	233.7	132.2	112.0	345.7
October	1,555.7	1,282.3 f/	79.0	1,634.7
November	299.2	189.1	54.0	353.2
December	486.4	352.0	74.0	560.4
Annual	7,517.8	5,686.4	1,266.0	8,783.8

a/ All inflows are mean monthly values.

b/ These values computed using regression equations relating monthly inflows from Neches and Sabine River Basin to the estuary with monthly gaged flows at USGS Stations on the Sabine River near Ruliff and the Neches River near Evadale.

c/ The contributing coastal basins are the Black Bayou and the Neches-Trinity.

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

e/ Inundation needs specify that at least 480.3 thousand acre-feet of this total flow passes the stream-gage at Evadale on the Neches River.

f/ Inundation needs specify that 480.3 thousand acre-feet of this total flow passes the stream-gage at Evadale and 802 thousand acre-feet passes the stream-gage at Ruliff on the Sabine River.

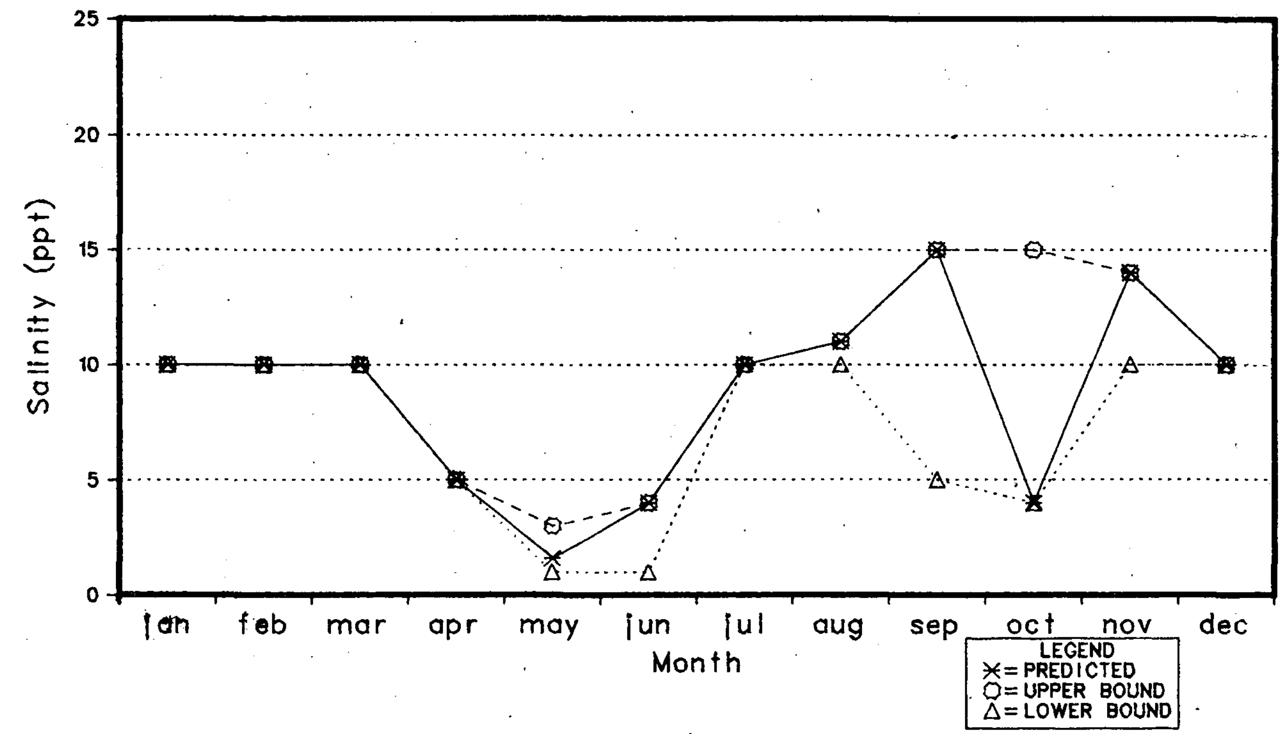

Figure 9-2. Average Monthly Salinities in Upper Sabine Lake Under Alternative I

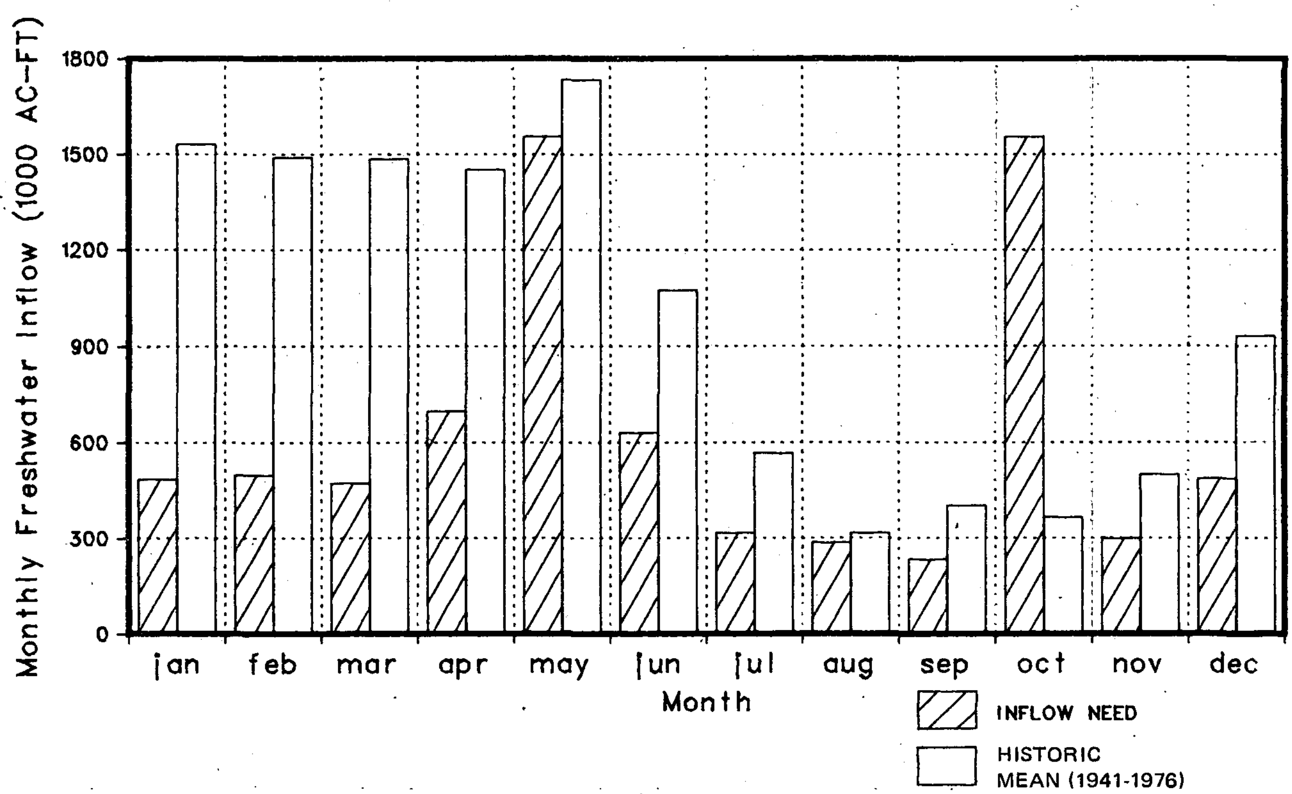

Figure 9-3. Comparison Between Mean Historical Freshwater Inflow and Inflow Needs Under Alternative I for the Sabine-Neches Estuary

freshwater inflow needs between the coastal basins and the Sabine and Neches River Basins is illustrated in Figure 9-4. The inflow from the Black Bayou and Neches-Trinity coastal basins is of major significance in some months, although it amounts to only about 17 percent of the total inflow need from the two major contributing river basins.

The monthly inflows for Alternative I give mean seasonal inflows which are not within the ranged of observed conditions for which the regression equations for commercial harvests (Chapter VIII) were derived. Thus, it is not valid to use the harvest equations as accurate predictors of harvest variations under this alternative. The underlying cause of this condition is the set of salinity bounds imposed on upper Sabine Lake (Table 9-2). Meeting these bounds has the impact of changing Sabine Lake from a fresh-brackish (oligohaline) transition condition to a definitely more estuarine (brackish-marine) salinity regime. This shift is believed to be beneficial to estuarine organism productivity in the estuary as indicated in Figure 2-3.

Alternative II: Maintenance of Fisheries Harvests. The objective of Alternative II (Maintenance of Fisheries Harvests) is to minimize combined inflow to the estuary while providing freshwater inflows sufficient to generate predicted annual commercial harvests of red drum, spotted seatrout, and shrimp at levels no less than their mean 1962-1976 historical values, satisfying marsh inundation needs, and meeting bounds for salinity.

It was determined that the conditions imposed on the inflows for this alternative were too restrictive to allow a solution. This reflects the circumstances noted in the discussion of Alternative I inflows where the harvest equations could not be used as valid predictors of commercial catch.

Alternative III: Shrimp Harvest Enhancement. The objective of Alternative III (Shrimp Harvest Enhancement) is to maximize the annual commercial harvest of shrimp while observing salinity limits and marsh inundation needs, and utilizing annual Sabine and Neches River Basin inflows no greater than their respective average 1941-1976 historical annual inflows.

As with Alternative II, no set of monthly inflows could satisfy the set of constraints indicated in Table 9-7. The salinity bounds for some months conflicted with the bounds on the seasonal inflows used in deriving the harvest equations, hence the harvest equations could not be used with validity.

Application of Tidal Hydrodynamic and Salinity Transport Models

The determination of preliminary estimates of freshwater inflow needs, described above, must be followed by additional steps in the methodology in order to insure that the resulting salinity distribution throughout the estuary is satisfactory (Figure 9-1). The Estuarine Linear Programming Model considers salinities only at a single point in the Sabine-Neches estuary near the major sources of freshwater inflow. To determine circulation and salinity patterns throughout the estuary it is necessary to apply the tidal hydrodynamic and salinity mass transport models (described in Chapter V) using the estimates of monthly freshwater inflow needs obtained from the Estuarine

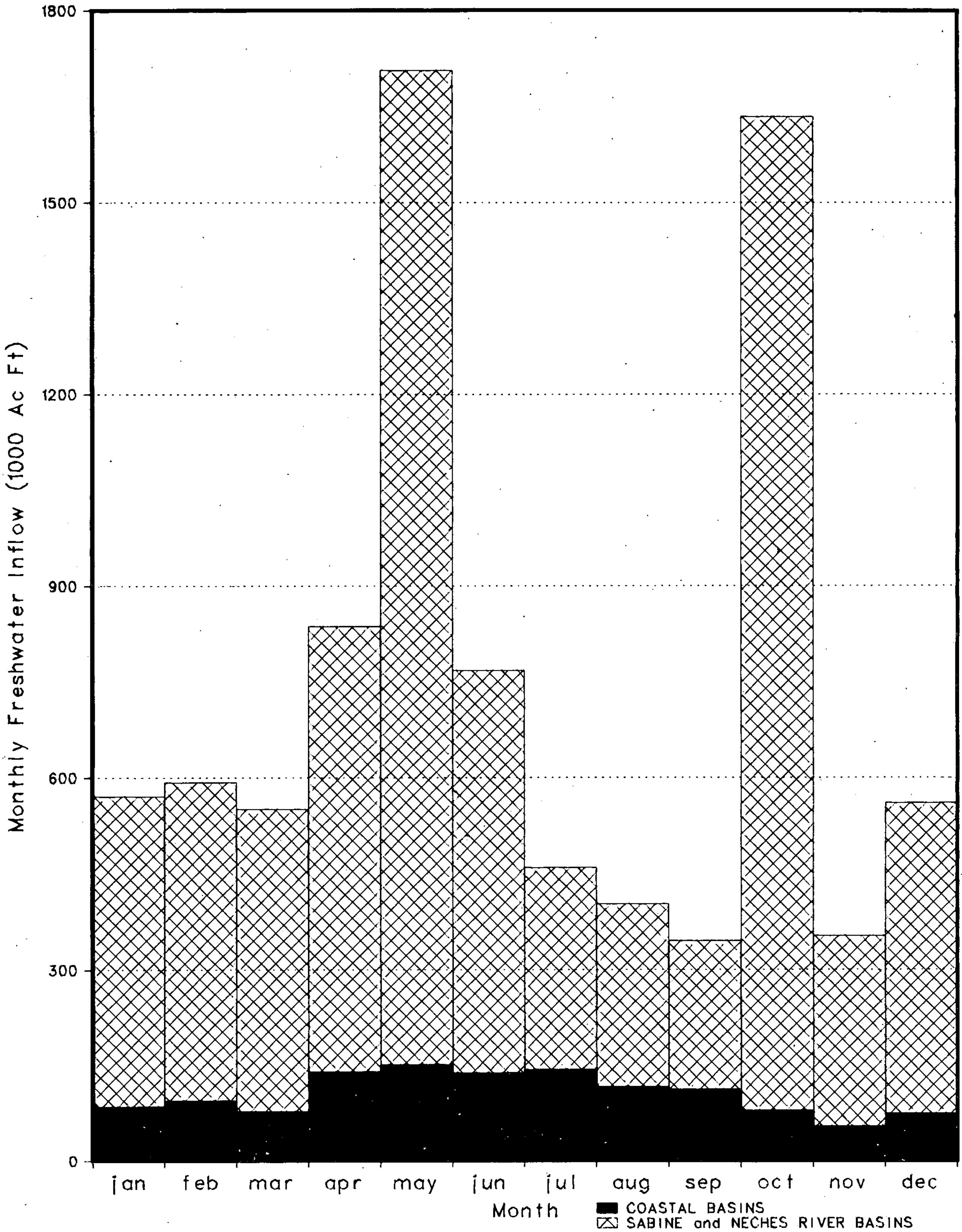

Figure 9-4. Estimated Freshwater Inflow Needs Under Alternative I for the Sabine-Neches Estuary

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 the estuary are of primary importance for insuring that predicted salinity gradients provide a suitable environment for the estuarine organisms. For high productivity, it is estimated that mean monthly mid-bay salinities in Sabine Lake should not exceed 20 parts per thousand (ppt) in any month under the projected monthly freshwater inflow needs.

Simulation of Mean Monthly Circulation Patterns. The estimated monthly freshwater inflow needs to the Sabine-Neches estuary 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 Sabine-Neches estuary for each month of the year.

The output of the tidal hydrodynamics model consists of a set of tidal amplitudes and net flows computed for each cell in the computational link-node system representing the Sabine-Neches estuary. The computed net flows are the average of the instantaneous flows calculated by the model over the tidal cycle. Thus, the circulation pattern represented by these net flows should not be interpreted as a set of currents that can be observed at any time during the tidal cycle, but rather as a representation of the net movement of water created by the combined action of the Gulf tides, freshwater inflow, and meteorological conditions during the tidal cycle.

The resultant circulation patterns can best be illustrated in the form of vector plots, wherein each vector (or arrow) represents the net flow through a computational cell. The orientation of the vector represents the direction of flow, and the length of the vector represents the magnitude of flow.

The flow circulation in the Sabine-Neches estuary was simulated for each monthly period under monthly historical average meteorological and tidal conditions and the estimated freshwater inflow needs for Alternative I. Examination of the vector plots for each of the numerical simulations revealed that the general net flow circulation patterns in the Sabine-Neches estuary are similar for all months (Figures 9-5 through 9-16). The simulated circulation patterns in the estuary appear to be dominated by the freshwater inflows from the Sabine and Neches Rivers. The largest simulated net flow in the estuary in each of the months occur in the Sabine-Neches and Port Arthur Canals. In all of the monthly simulations the magnitudes of the flows in Sabine Lake proper are significantly less than the flow rates in the Sabine-Neches and Port Arthur navigation channels. It is evident that these channels, being deeper than the remainder of the estuary, allow the freshwater inflows to substantially bypass the estuary's main habitat area (Sabine Lake).

The predominant simulated net current in Sabine Lake is from the mouths of the Neches and Sabine Rivers in the north to Sabine Pass in the south. The

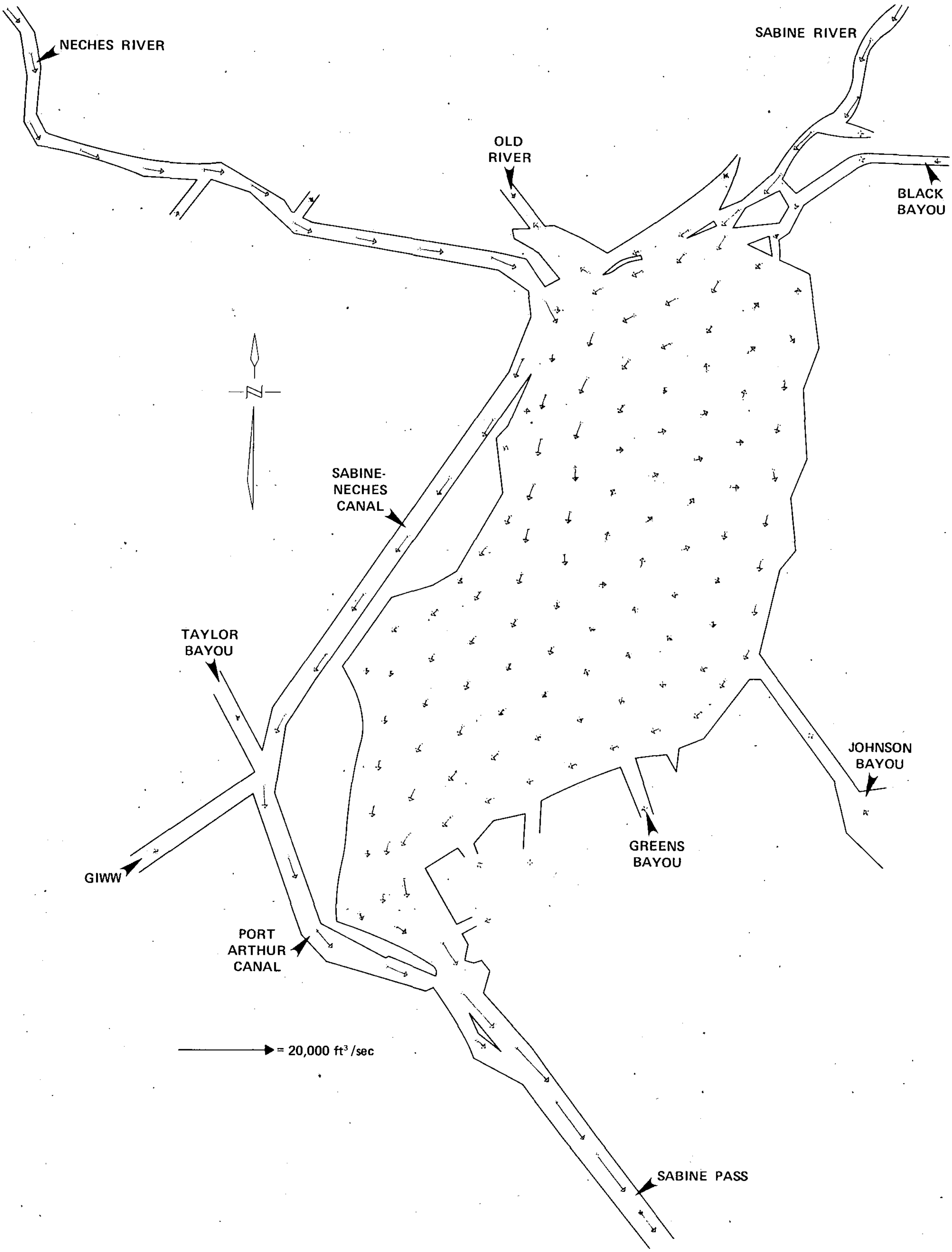

Figure 9-5. Simulated Net Steady-State Flows in the Sabine-Neches Estuary Under January Freshwater Inflow Needs, Alternative I

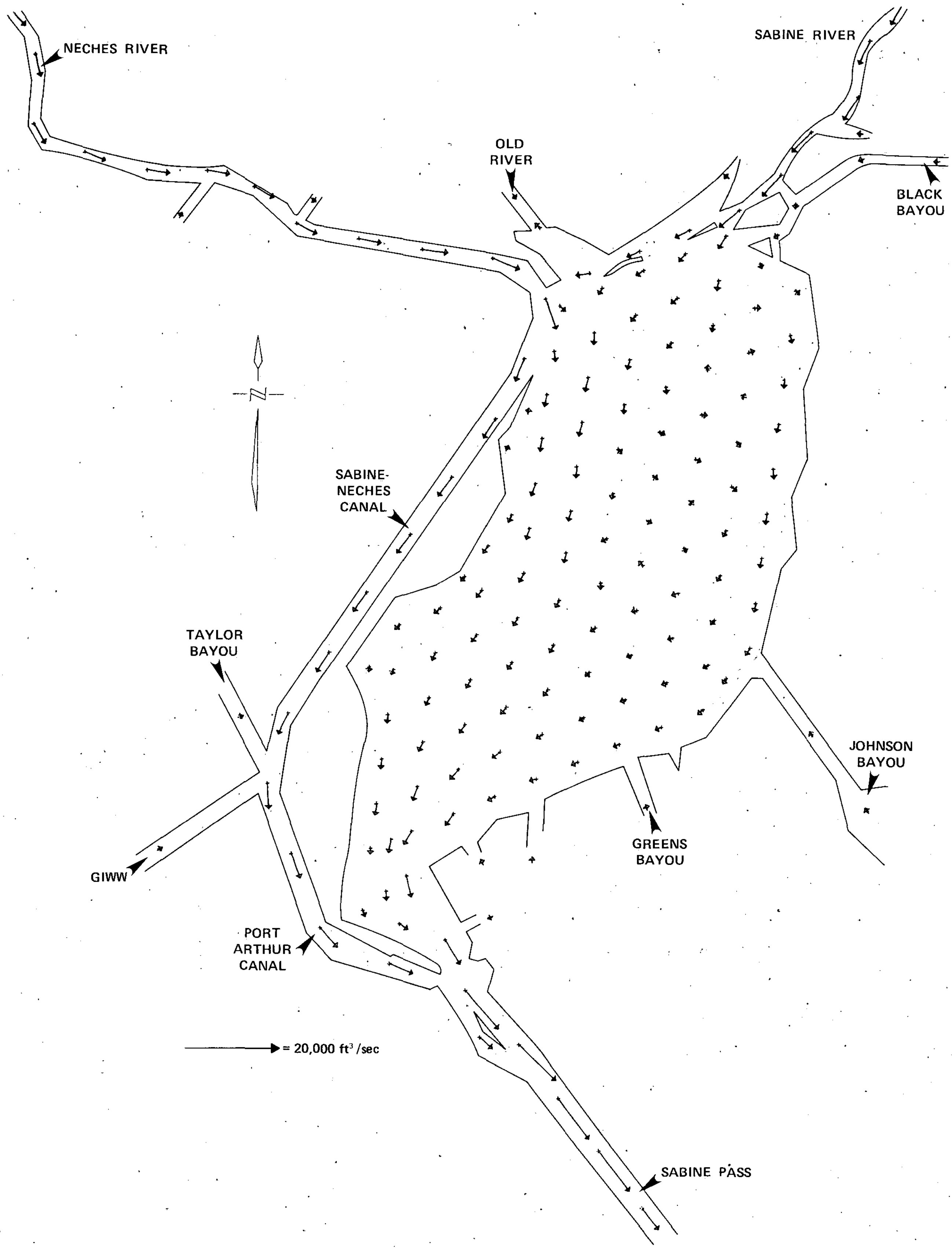

Figure 9-6. Simulated Net Steady-State Flows in the Sabine-Neches Estuary Under February Freshwater Inflow Needs, Alternative I

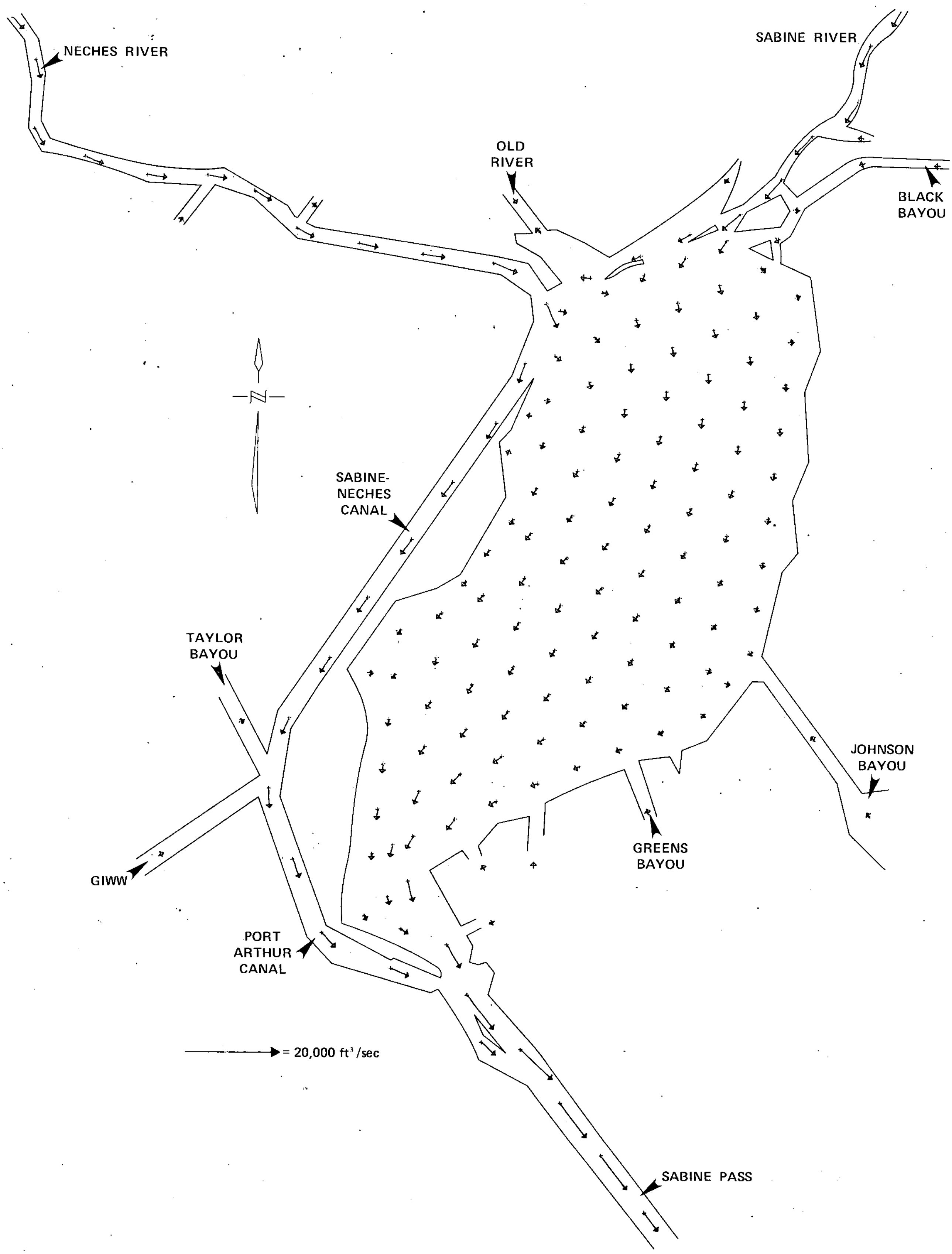

Figure 9-7. Simulated Net Steady-State Flows in the Sabine-Neches Estuary Under March Freshwater Inflow Needs, Alternative I

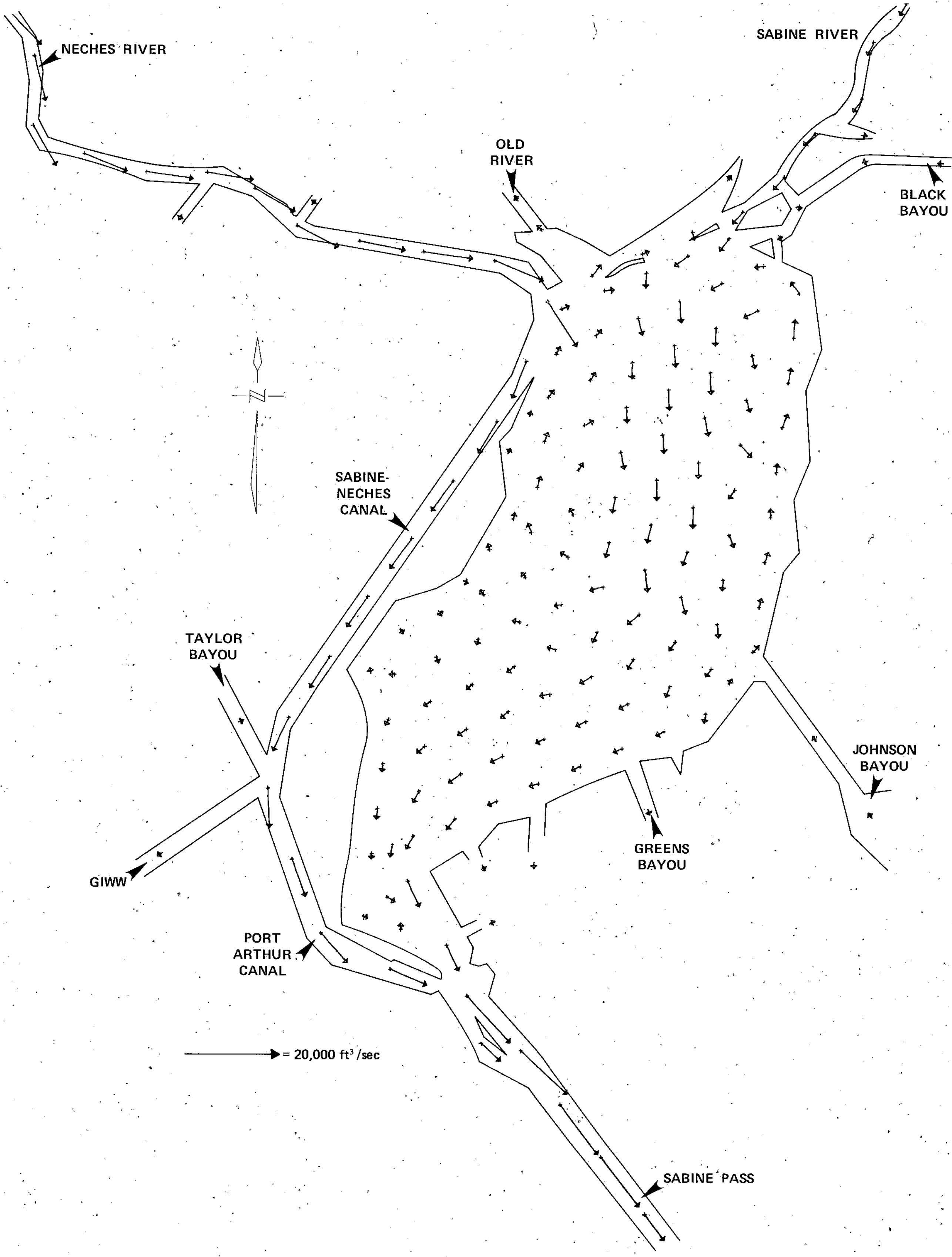

Figure 9-8. Simulated Net Steady-State Flows in the Sabine-Neches Estuary Under April Freshwater Inflow Needs, Alternative I

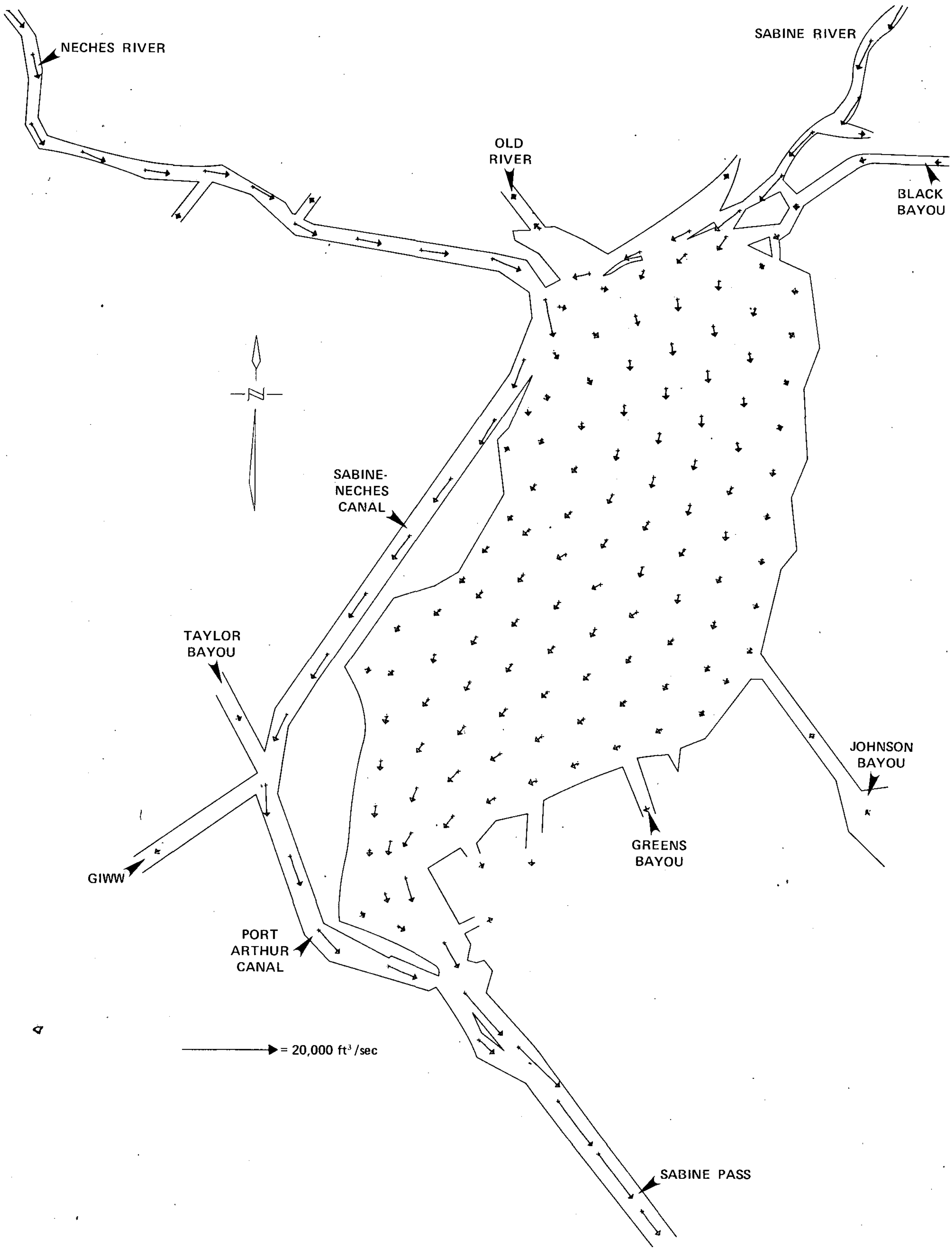

Figure 9-9. Simulated Net Steady-State Flows in the Sabine-Neches Estuary Under May Freshwater Inflow Needs, Alternative I

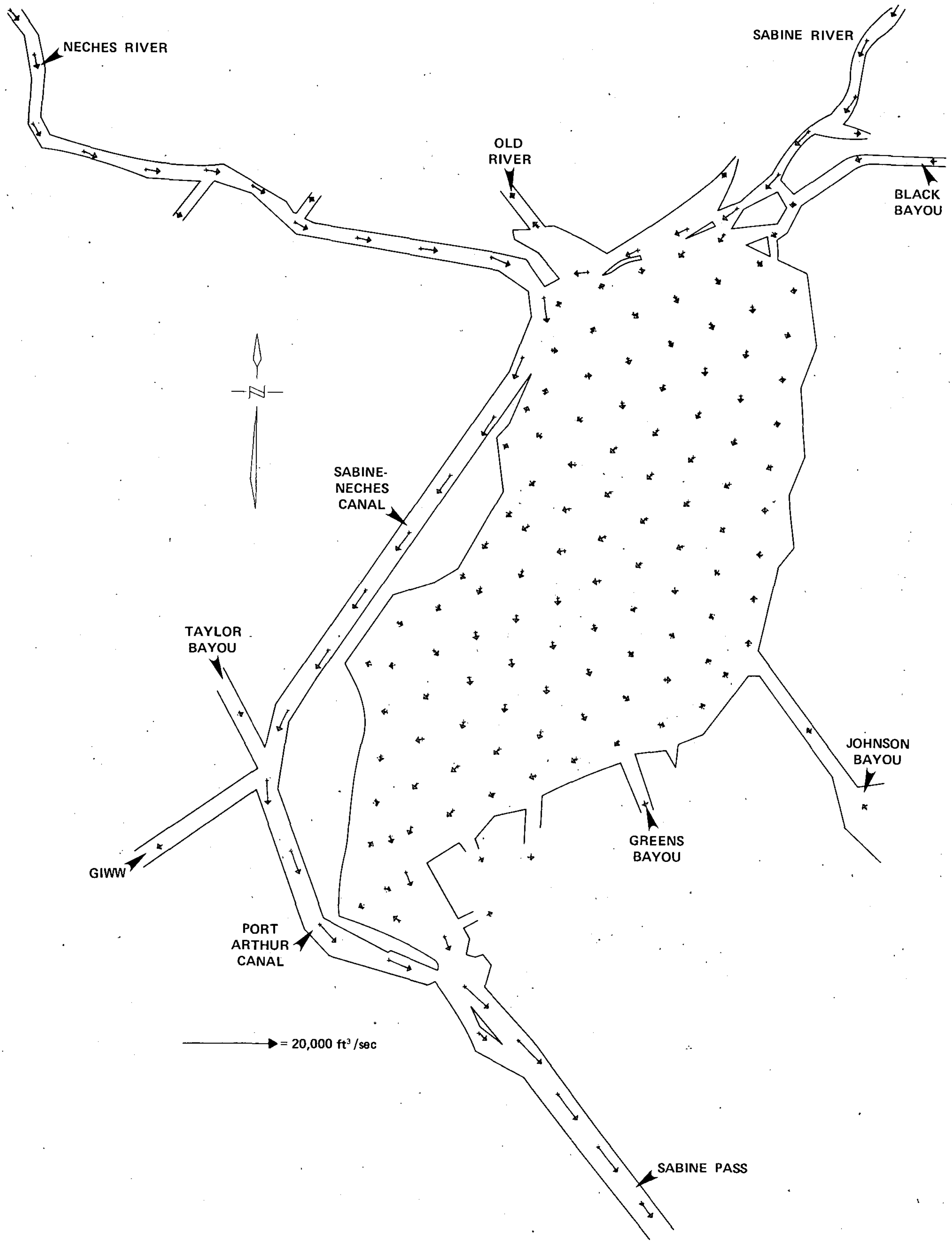

Figure 9-10. Simulated Net Steady-State Flows in the Sabine-Neches Estuary Under June Freshwater Inflow Needs, Alternative I

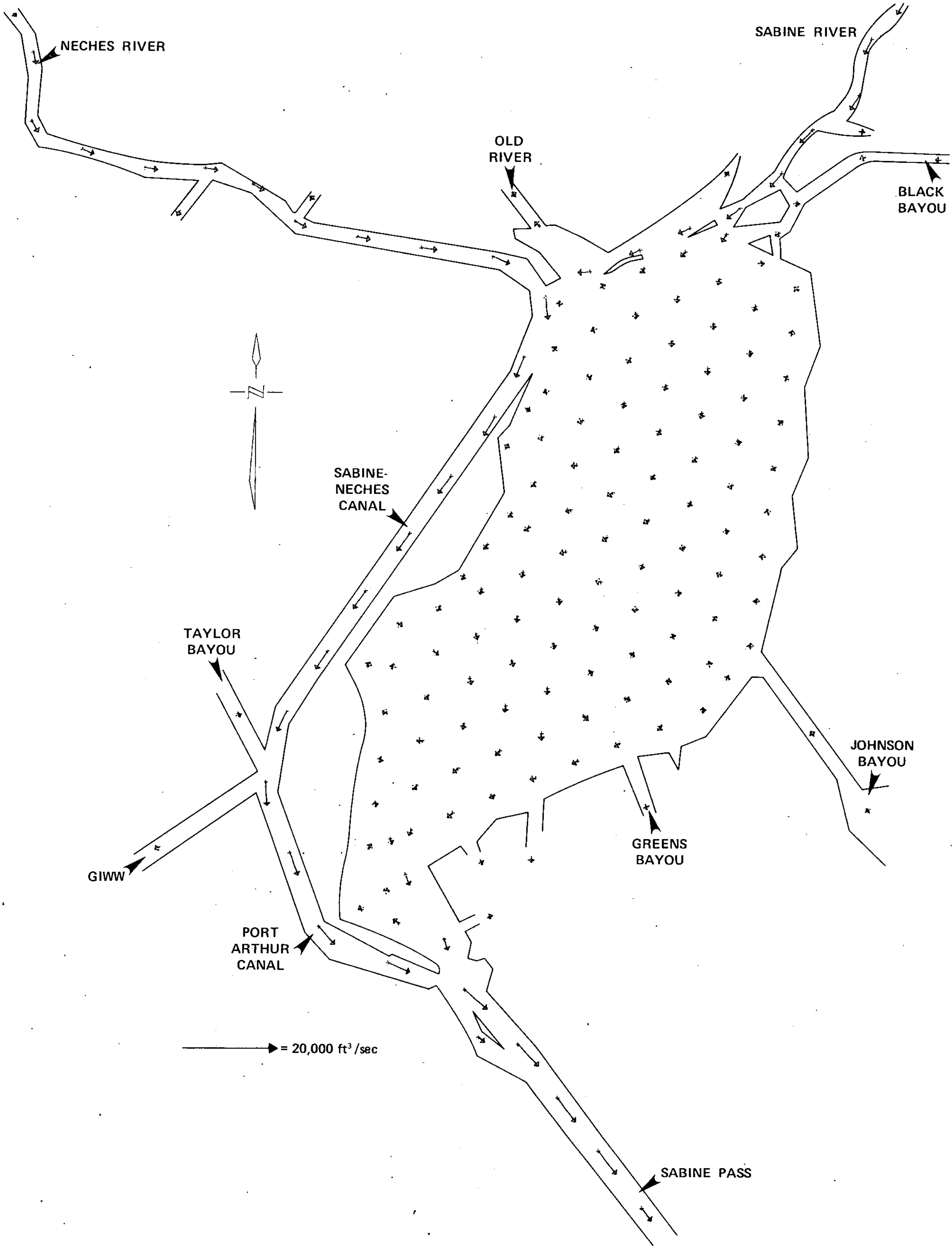

Figure 9-11. Simulated Net Steady-State Flows in the Sabine-Neches Estuary Under July Freshwater Inflow Needs, Alternative I

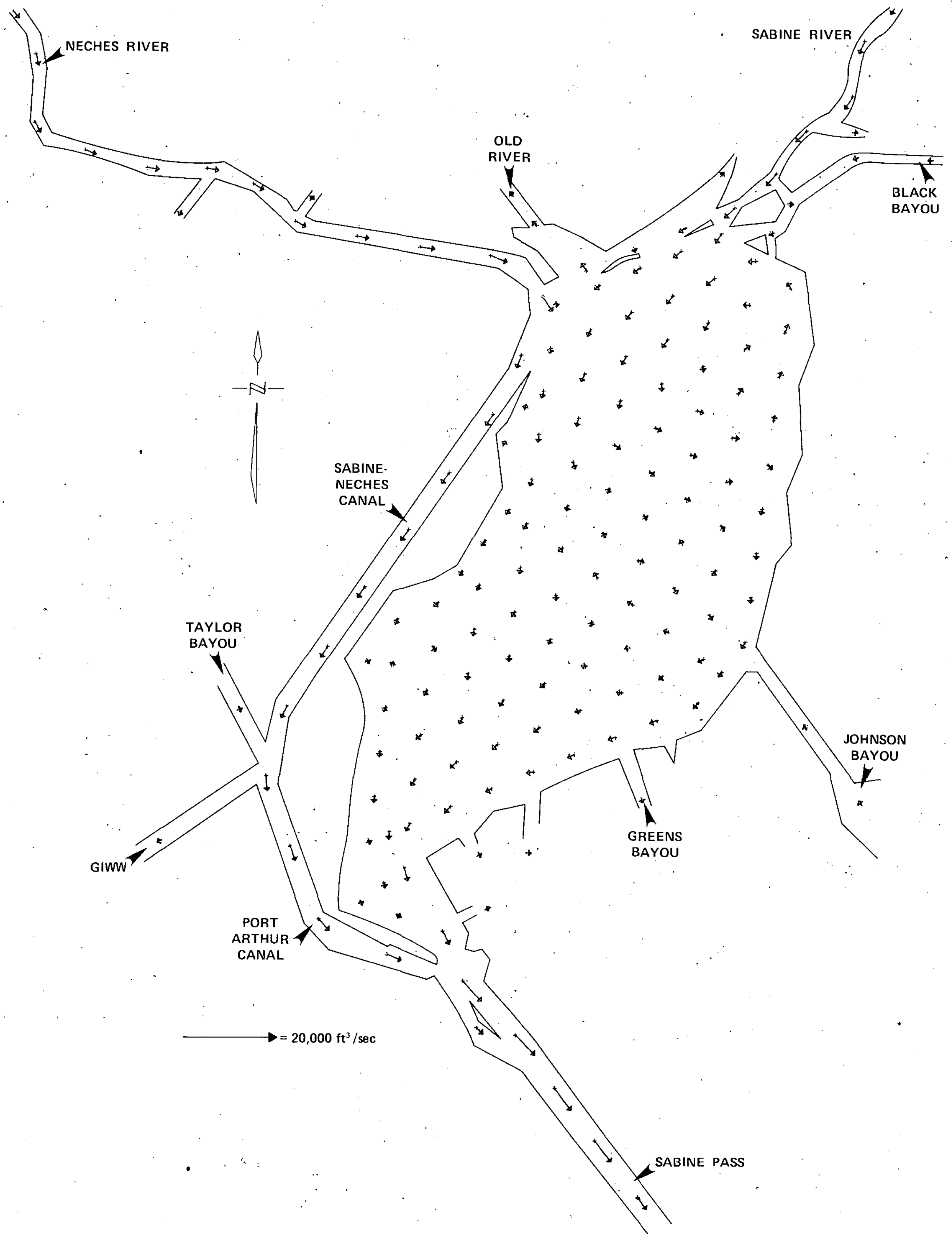

Figure 9-12. Simulated Net Steady-State Flows in the Sabine-Neches Estuary Under August Freshwater Inflow Needs, Alternative I

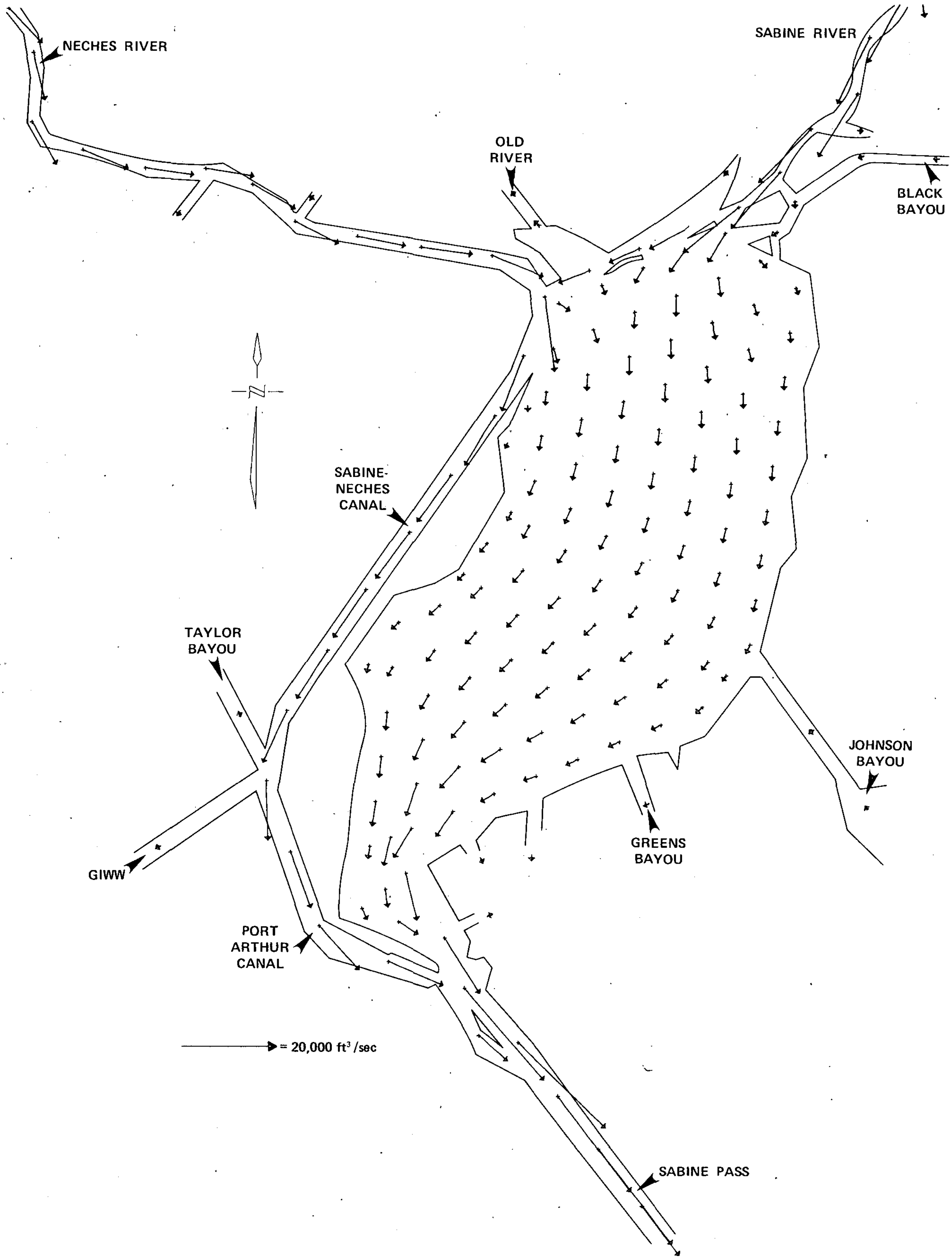

Figure 9-13. Simulated Net Steady-State Flows in the Sabine-Neches Estuary Under September Freshwater Inflow Needs, Alternative I

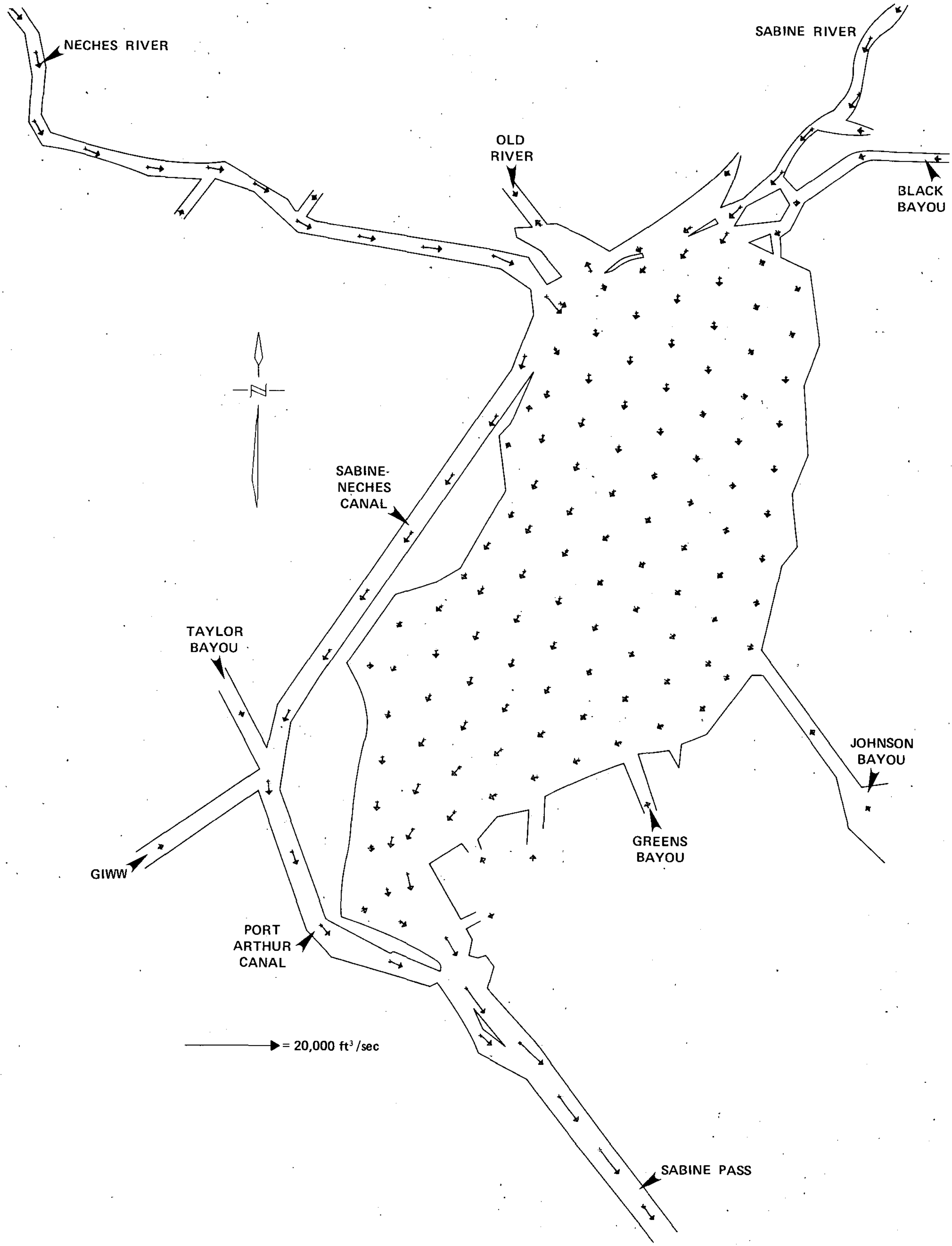

Figure 9-14. Simulated Net Steady-State Flows in the Sabine-Neches Estuary Under October Freshwater Inflow Needs, Alternative I

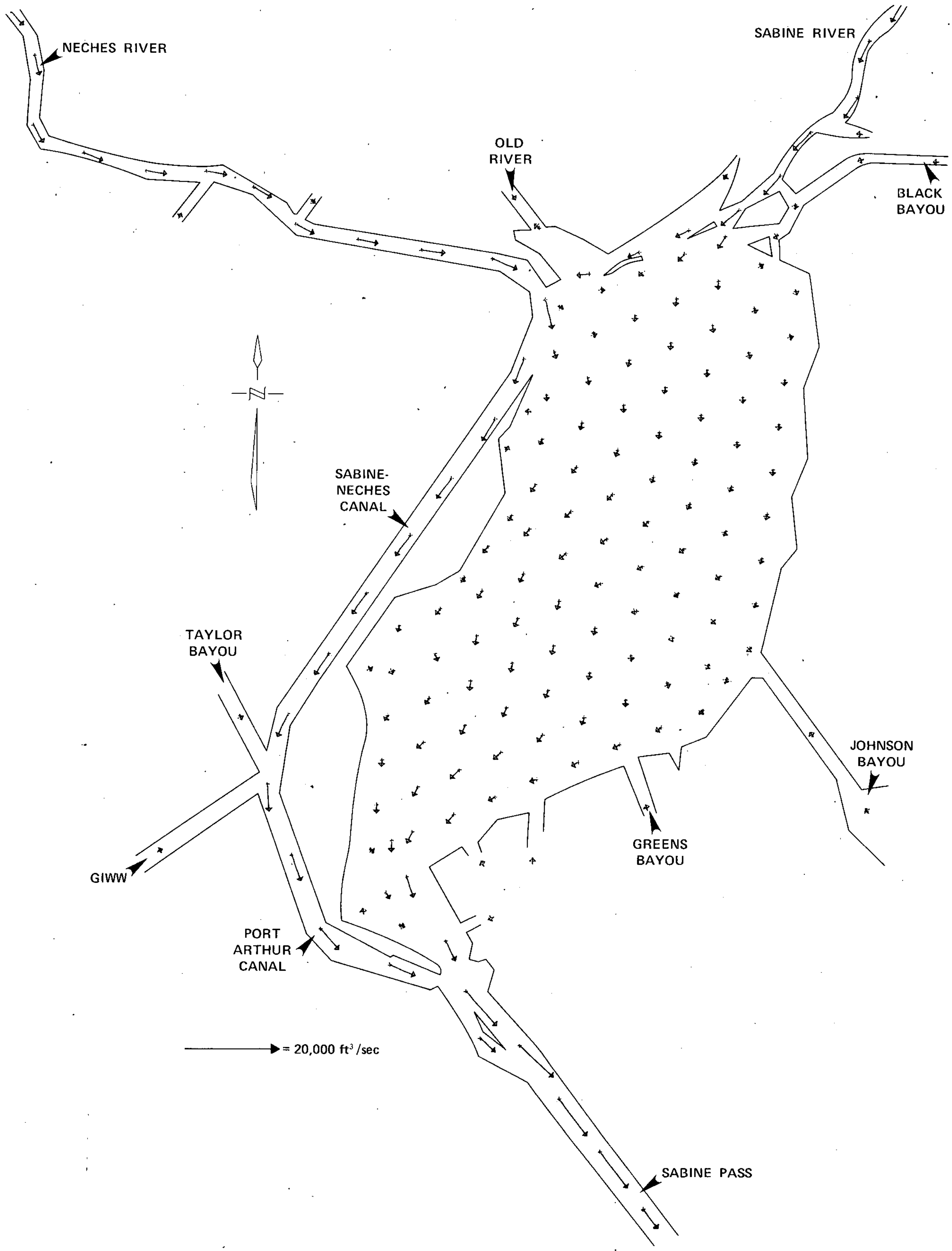

Figure 9-15. Simulated Net Steady-State Flow in the Sabine-Neches Estuary Under November Freshwater Inflow Needs, Alternative I

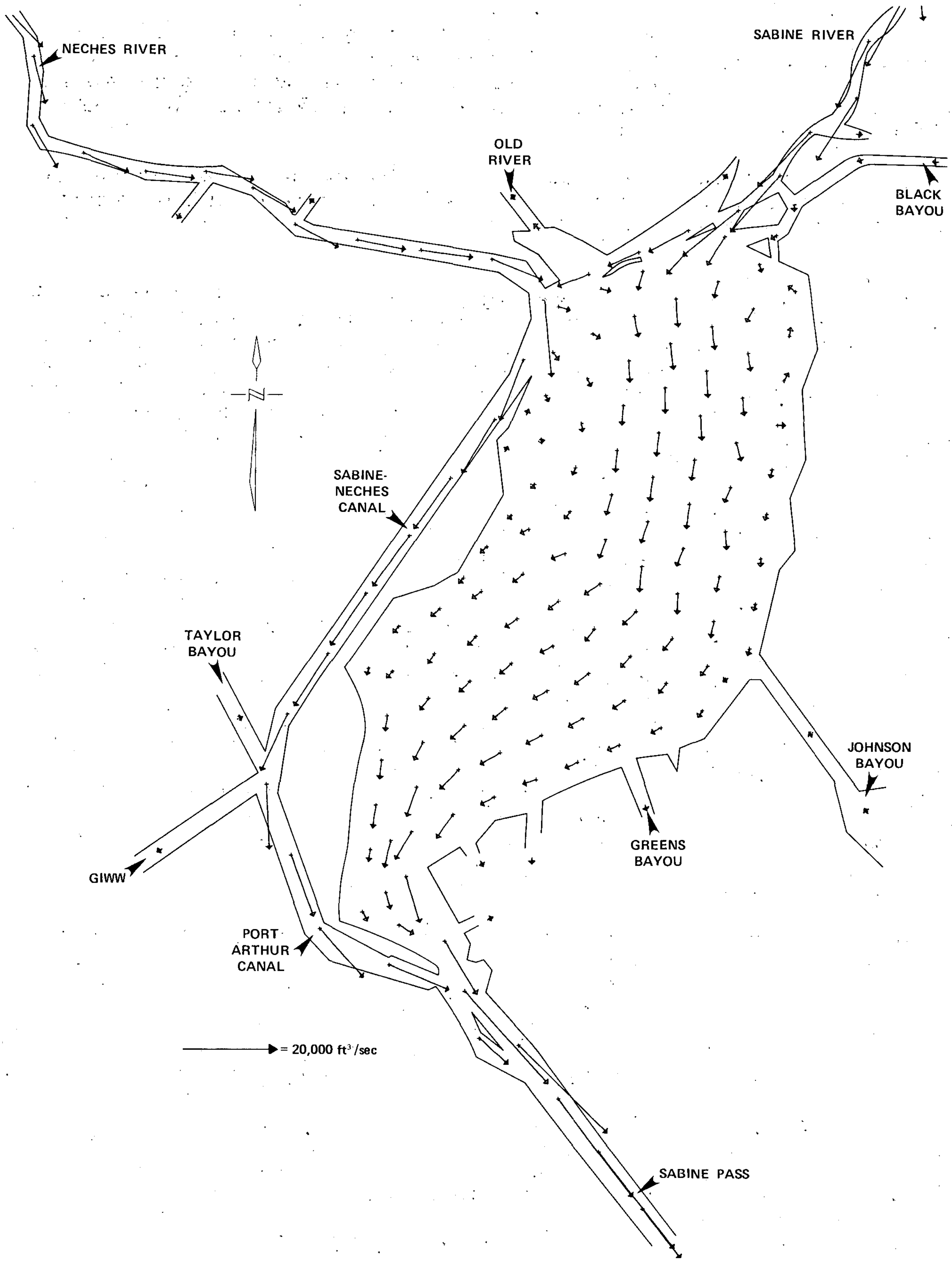

Figure 9-16. Simulated Net Steady-State Flows in the Sabine-Neches Estuary Under December Freshwater Inflow Needs, Alternative I

main body of Sabine Lake revealed little in the way of clockwise or counter-clockwise circulation patterns. Only during the month of April did the simulated net flows have appreciable currents flowing north along the eastern and western shores of Sabine Lake--counter to the predominant flow direction of north to south.

The simulated circulation patterns in the Sabine-Neches estuary did not seem to be affected by changes in the relative magnitude of inflow contributions from the two major river basins.

Simulation of Mean Monthly Salinity Patterns The monthly tidal amplitudes and flows calculated by the tidal hydrodynamic model were used as input to operate the salinity transport model to simulate the steady-state salinity distributions in the Sabine-Neches estuary under freshwater inflows equal to the Alternative I monthly freshwater inflow needs. The resulting steady-state salinity distributions are illustrated in the form of salinity contour plots (Figures 9-17 through 9-28) where lines of uniform salinity are shown in parts per thousand (ppt). An evaluation of the simulated monthly salinity levels in the Sabine-Neches estuary resulting from these model operations reveal two distinct monthly patterns of salinity in the estuary: the high inflow months (May and October) and the remaining months of the year.

The freshwater inflow needs for the months of May and October (Figures 9-21 and 9-26) specify inflows for marsh inundation through river flooding. The simulated salinities in Sabine Lake in these two months range from less than one part per thousand in the upper end to near 10 ppt in the southern end, with the large majority of the lake having salinities of less than three ppt.

The remainder of the months have simulated salinities in Sabine Lake appreciably greater than those simulated for May and October. The range of simulated salinities in Sabine Lake for these months is from five to eight ppt in the upper end to from 14 to 15 ppt near Sabine Pass. Simulated salinities in Sabine Lake near Sabine Pass are higher in April, September, and November than in the other months due to the relatively low inflow needs from the Sabine and Neches River Basins.

In all of the months, the salinities in the middle portion of Sabine Lake were simulated at under 20 ppt; thus, further refinement of the estimated monthly freshwater inflow needs for Alternative I is not considered necessary.

Interpretation of the Physical Significance of the Estimated Freshwater Inflow

The monthly freshwater inflows estimated in this report for the Sabine-Neches estuary from the Sabine and Neches River Basins represent the best statistical estimates of monthly inflows needed to satisfy a selected objective for the major estuarine factors of marsh inundation and salinity distribution. These estimates illustrate the complexity of the relationships between an estuarine ecosystem and freshwater inflows.

Freshwater inflows approximately equal to the estimated needs may give estuarine responses which are indistinguishable, on a statistical basis, from the desired conditions. Confidence limits can be obtained for changes in

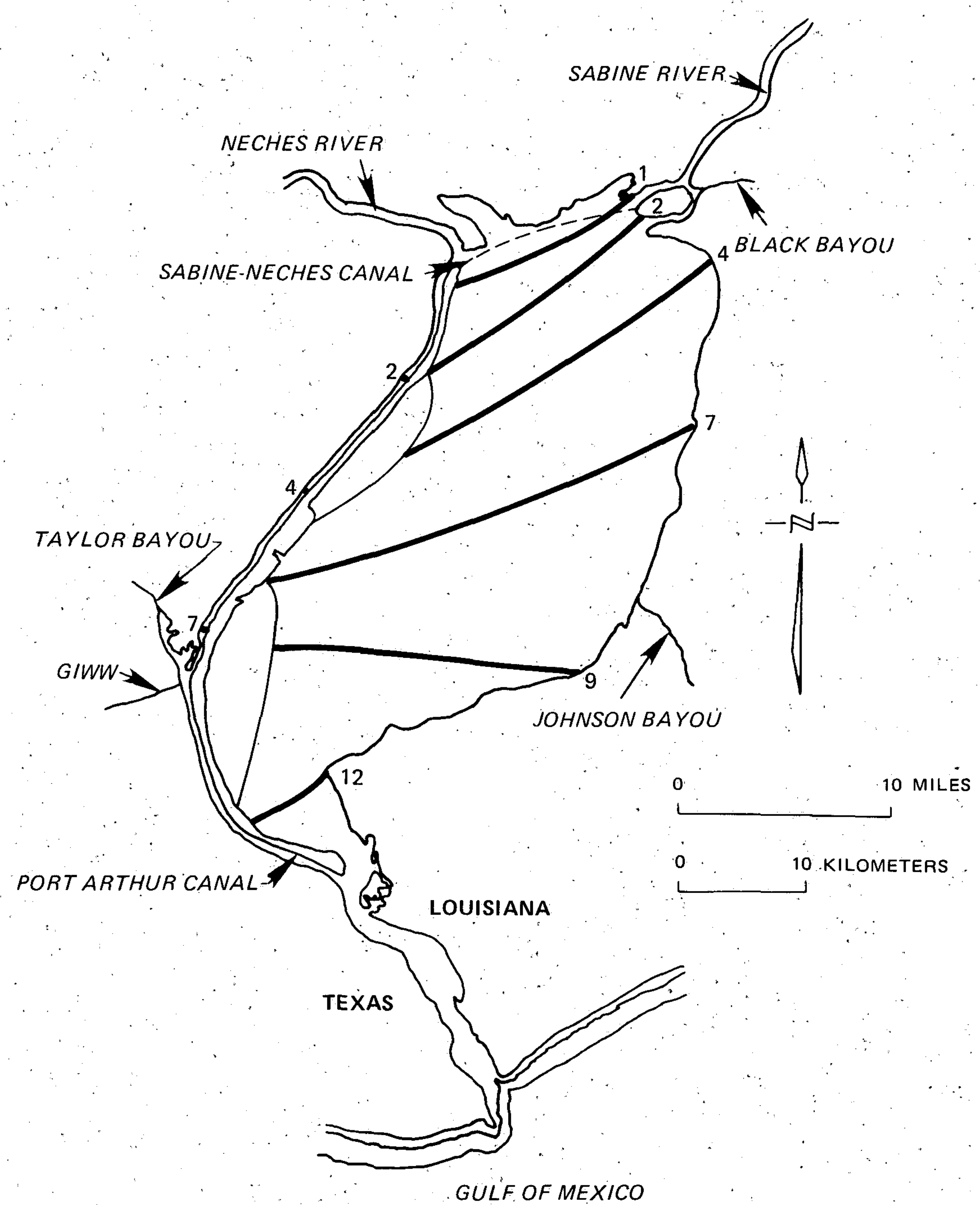

Figure 9-17. Simulated Salinities in the Sabine-Neches Estuary Under January Freshwater Inflow Needs, Alternative I (ppt)

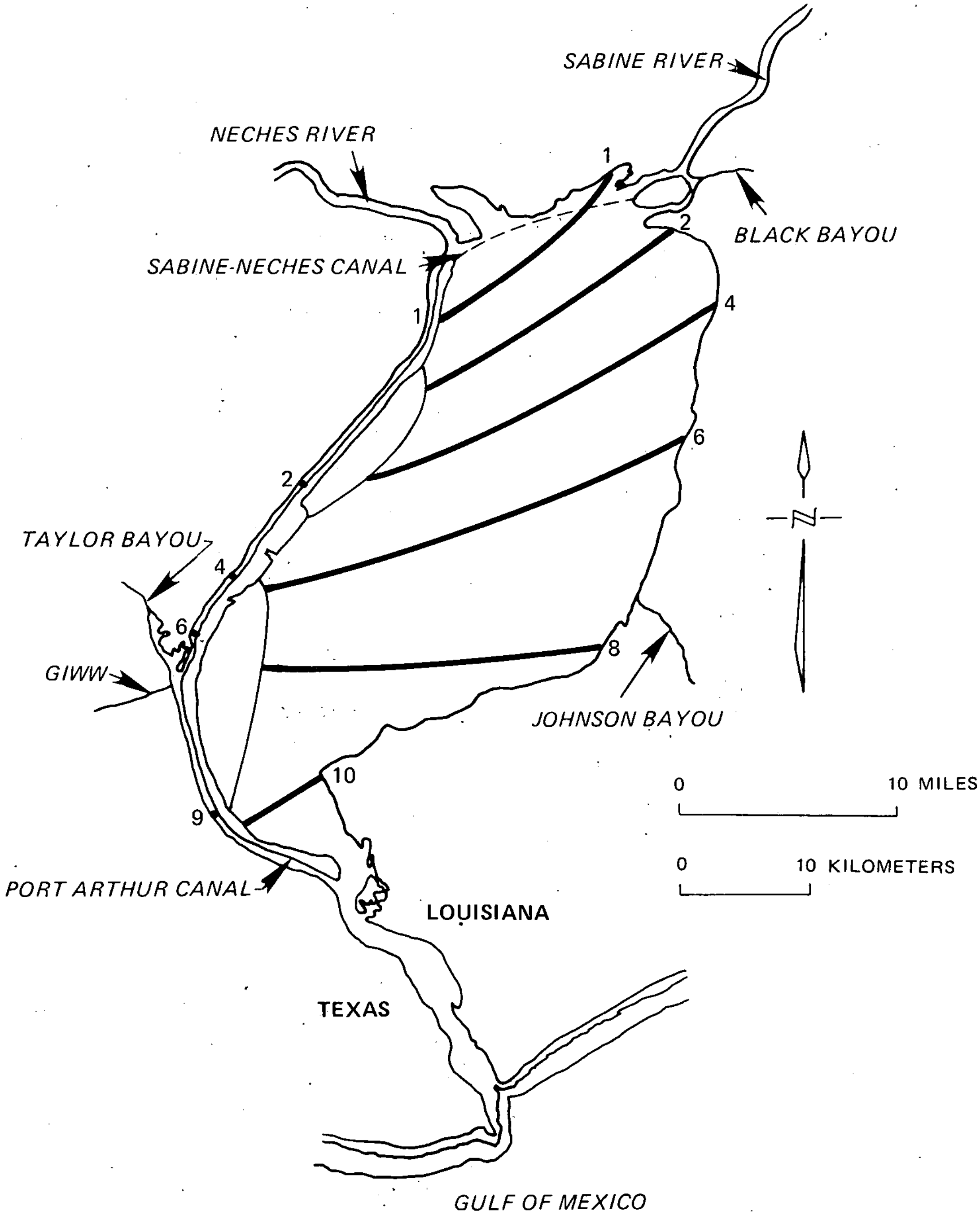

Figure 9-18. Simulated Salinities in the Sabine-Neches Estuary Under February Freshwater Inflow Needs, Alternative I (ppt)

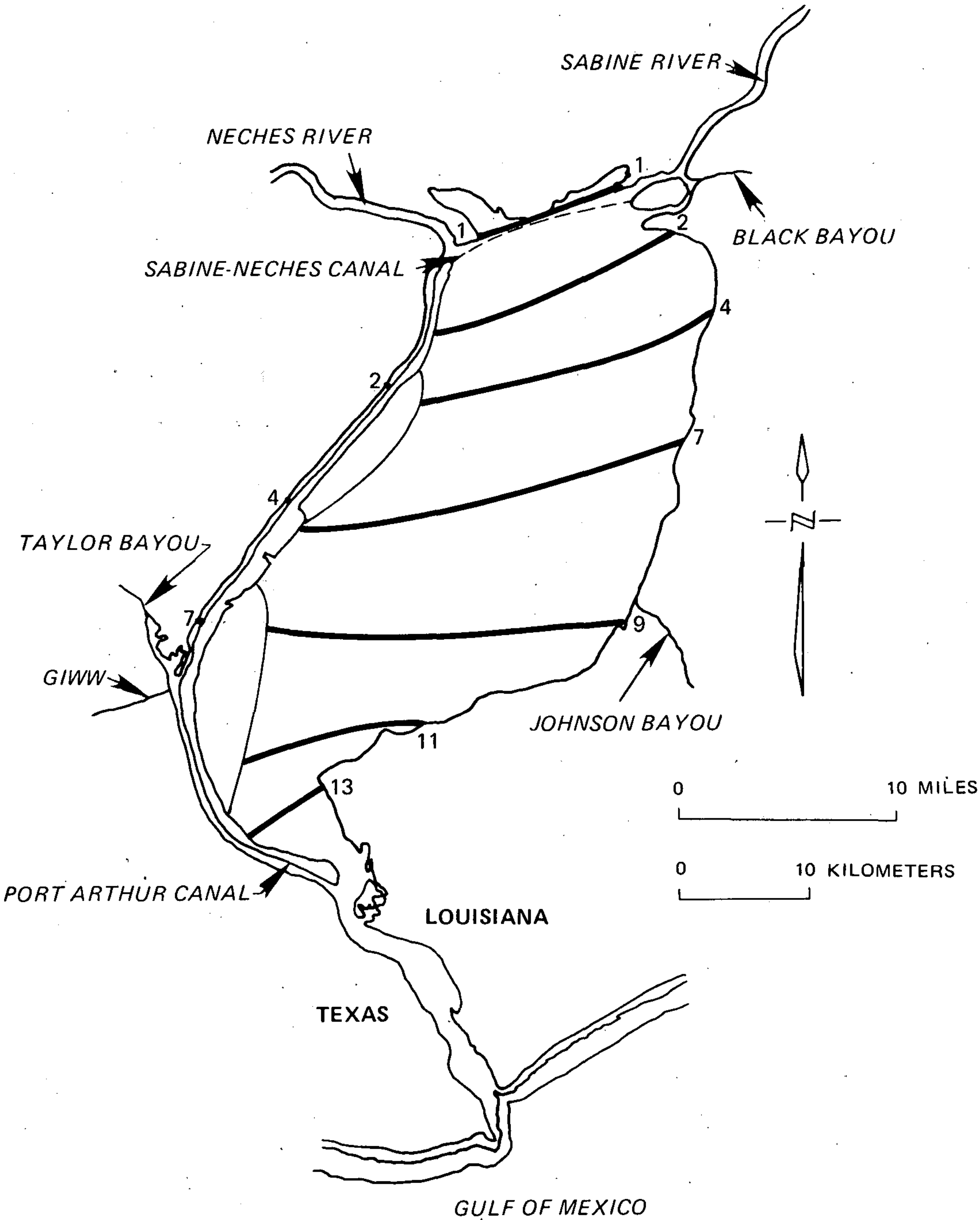

Figure 9-19. Simulated Salinities in the Sabine-Neches Estuary Under March Freshwater Inflow Needs, Alternative I (ppt)

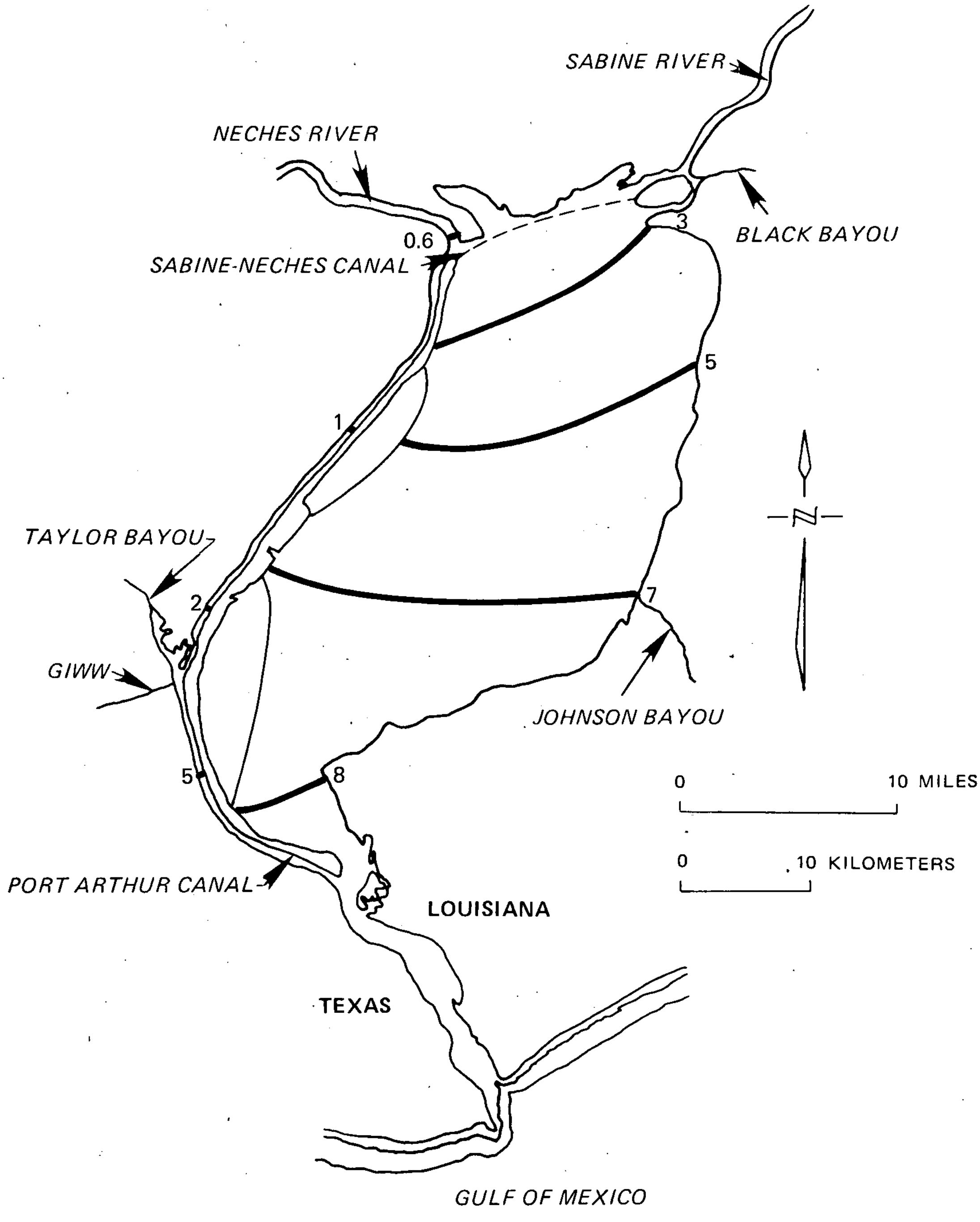

Figure 9-20. Simulated Salinities in the Sabine-Neches Estuary Under April Freshwater Inflow Needs, Alternative I (ppt)

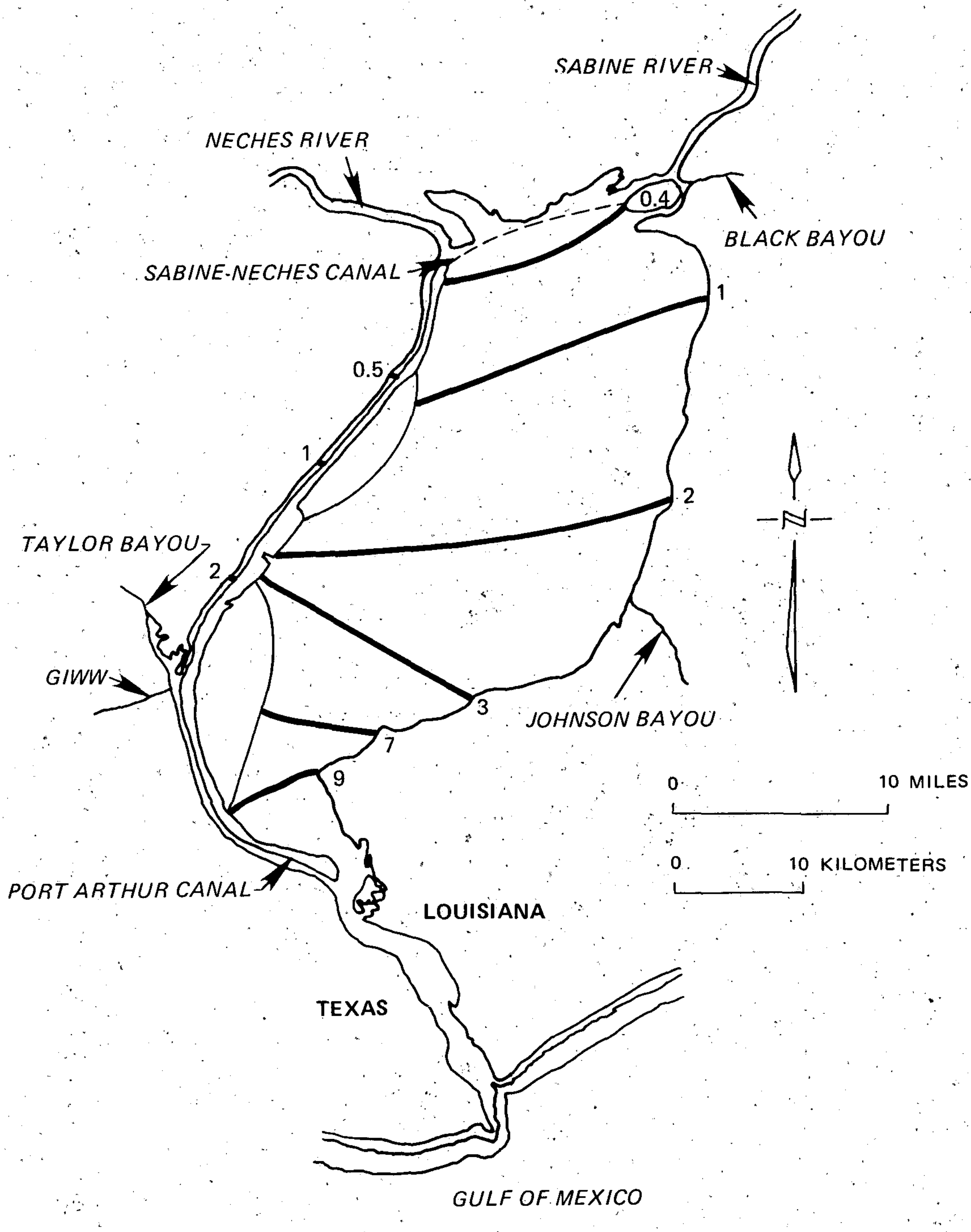

Figure 9-21. Simulated Salinities in the Sabine-Neches Estuary Under May Freshwater Inflow Needs, Alternative I (ppt)

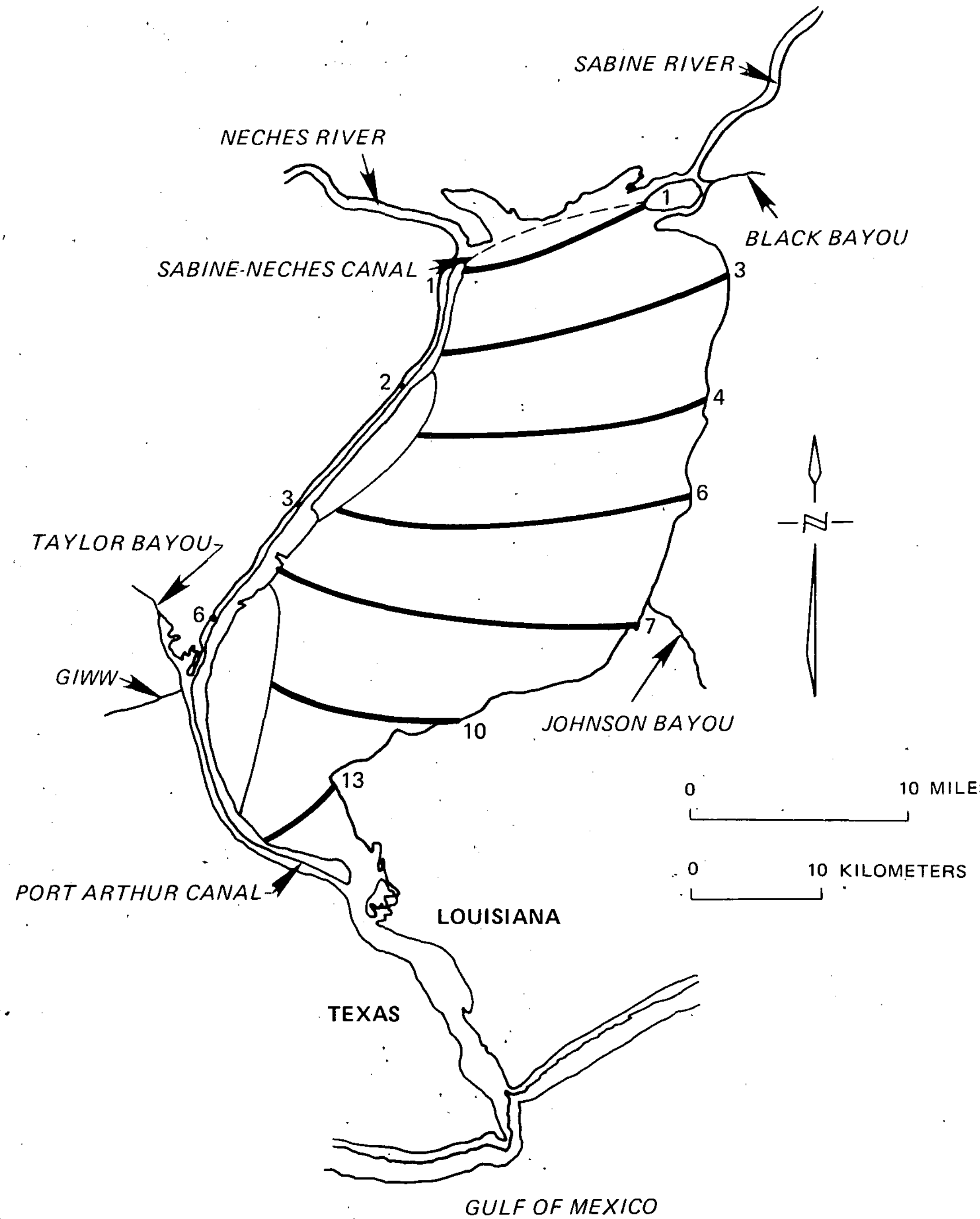

Figure 9-22. Simulated Salinities in the Sabine-Neches Estuary Under June Freshwater Inflow Needs, Alternative I (ppt)

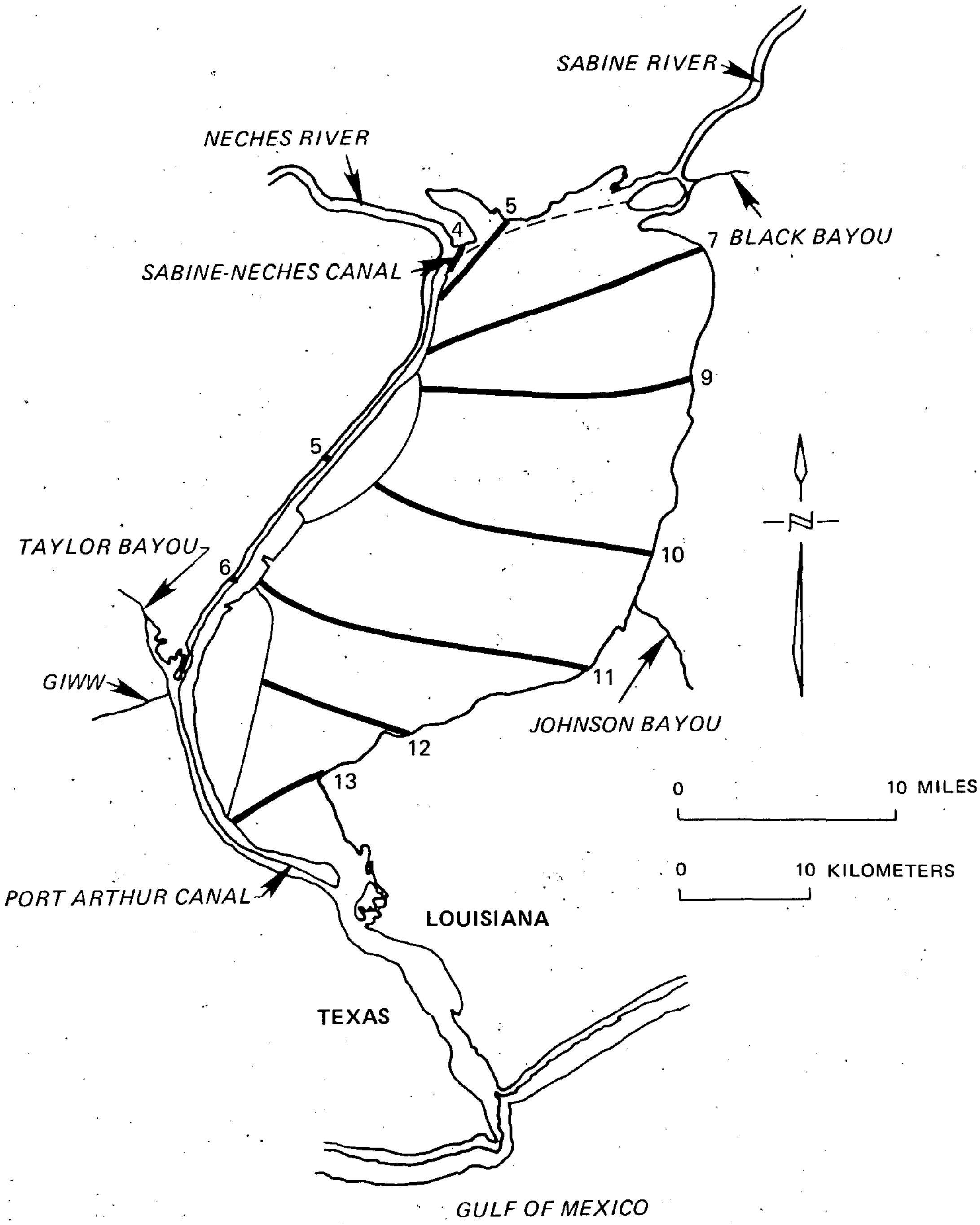

Figure 9-23. Simulated Salinities in the Sabine-Neches Estuary Under July Freshwater Inflow Needs, Alternative I (ppt)

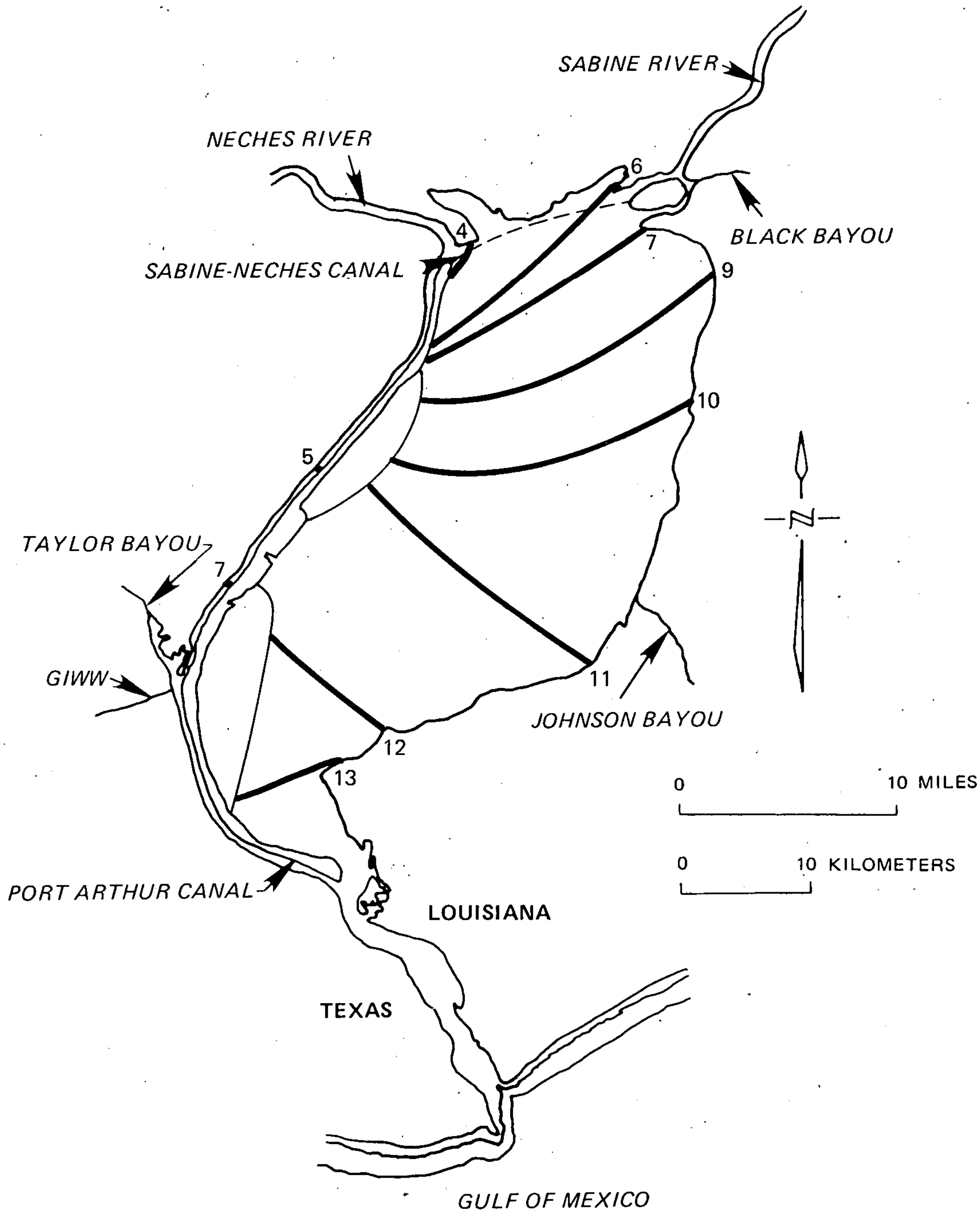

Figure 9-24. Simulated Salinities in the Sabine-Neches Estuary Under August Freshwater Inflow Needs, Alternative I (ppt)

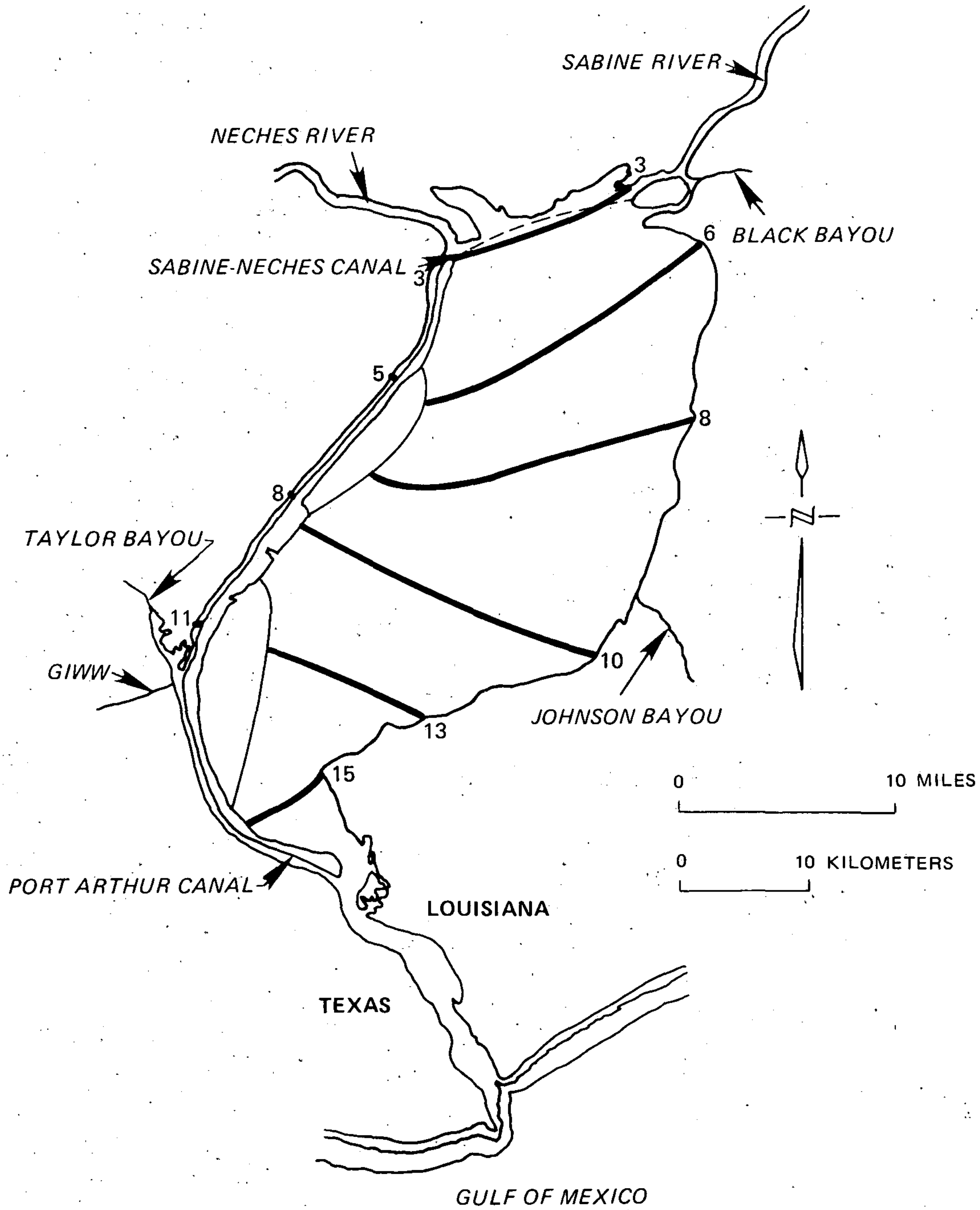

Figure 9-25. Simulated Salinities in the Sabine-Neches Estuary Under September Freshwater Inflow Needs, Alternative I (ppt)

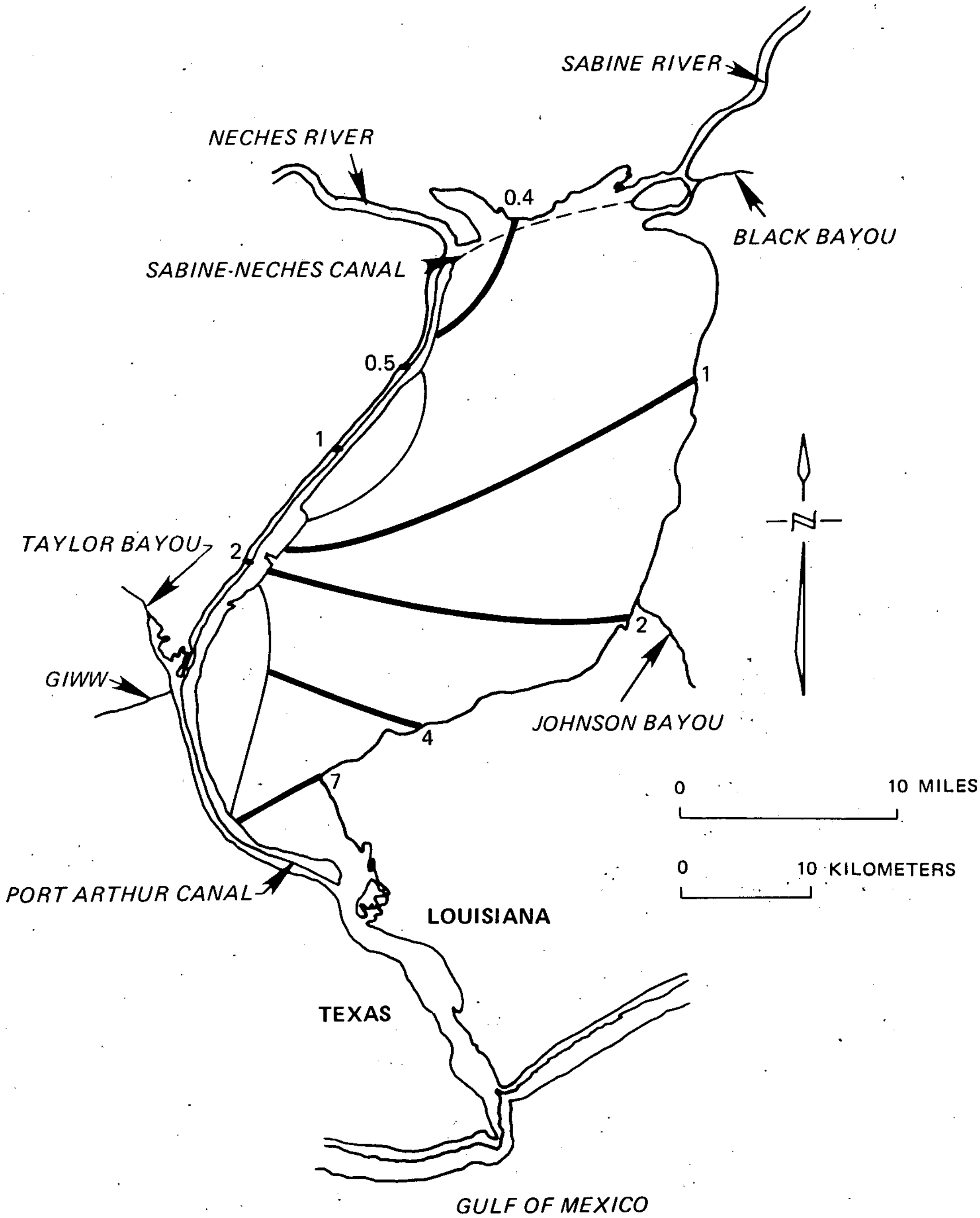

Figure 9-26. Simulated Salinities in the Sabine-Neches Estuary Under October Freshwater Inflow Needs, Alternative I (ppt)

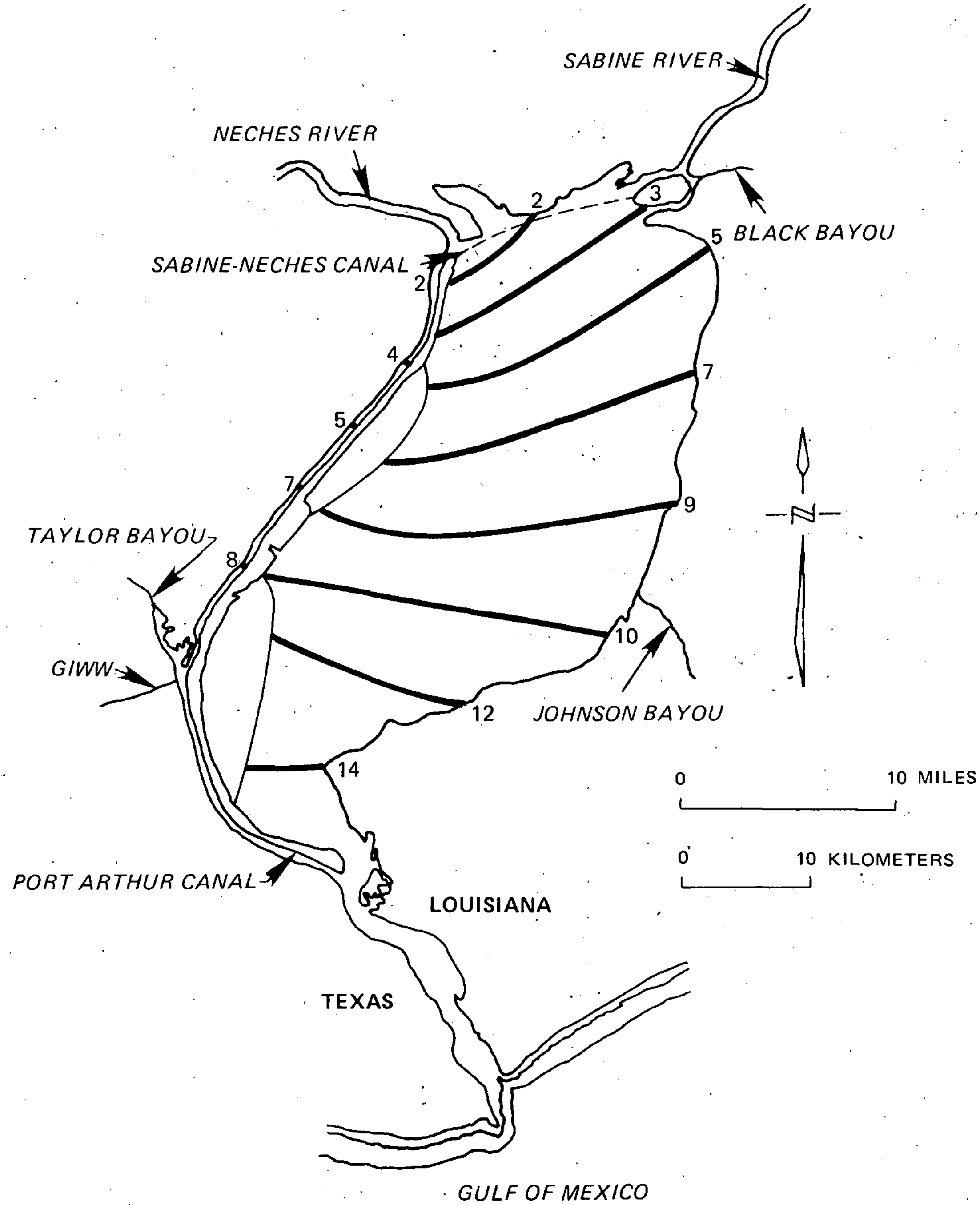

Figure 9-27. Simulated Salinities in the Sabine-Neches Estuary Under November Freshwater Inflow Needs, Alternative I (ppt)

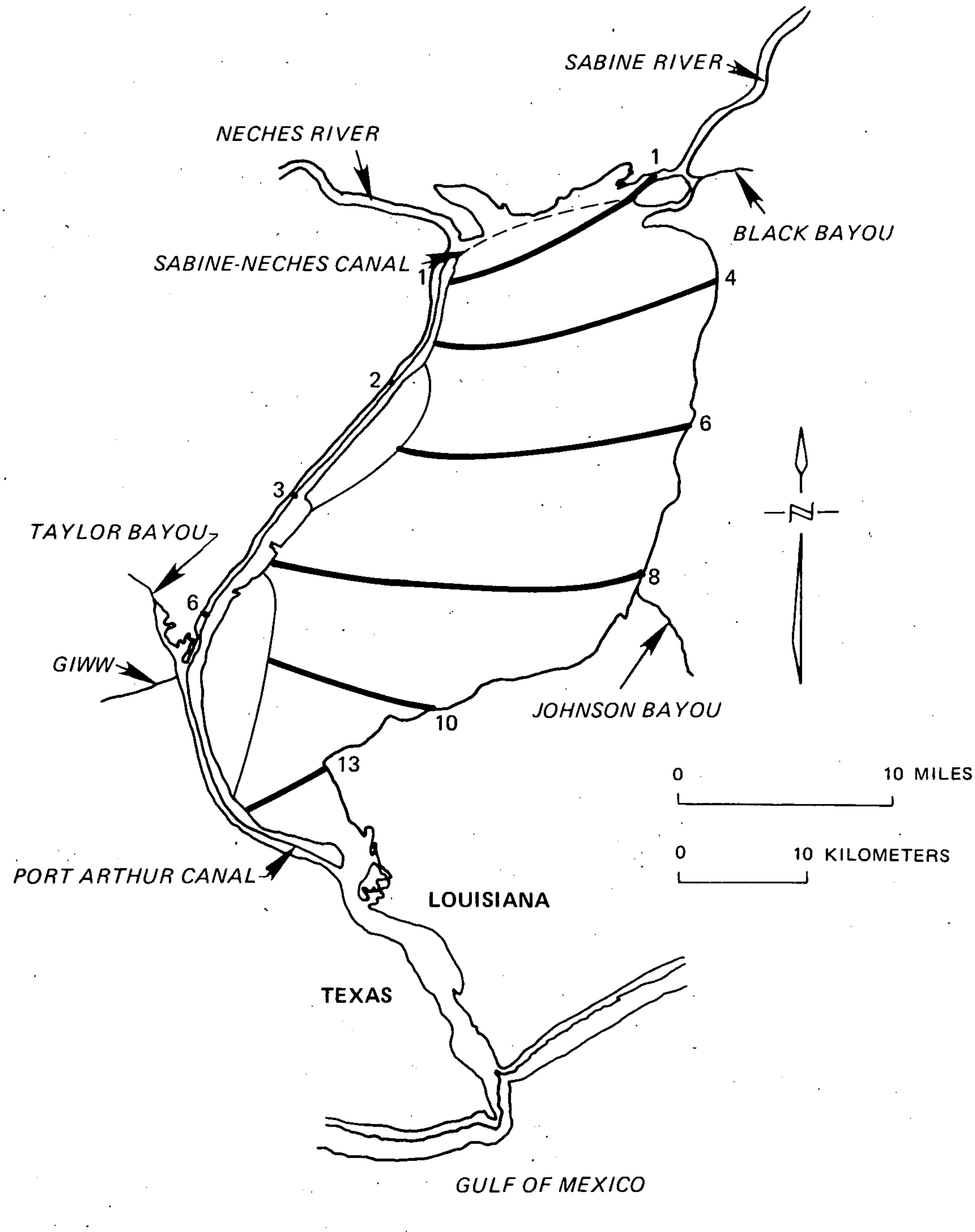

Figure 9-28. Simulated Salinities in the Sabine-Neches Estuary Under December Freshwater Inflow Needs, Alternative I (ppt)

estuarine conditions, such as salinity, using statistical techniques. It is not clear, however, as to the proper technique for determining confidence bounds on the actual monthly inflow estimates for those months where the individual confidence limits on the inflow needs for salinity and inundation must be combined into a single confidence interval.

A wide variability of freshwater inflow occurs in Texas estuaries from year to year, through drought and flood cycles. The monthly freshwater inflow levels received by the estuary fluctuate about the average inflow due to natural hydrologic variability. Such fluctuations are expected to continue to exist for practically any average level of inflow that might occur or that might be specified. It is not likely that sufficient control can be exerted to completely regulate the inflow extremes. In fact, to do so may be detrimental to the process of natural selection. However, some provision may be needed to prevent an increase in the frequency of periods of low flows. Such a provision could specify minimum monthly inflows required to keep salinities below the upper viability limits given for key estuarine-dependent species (Tables 9-1 and 9-2).

Summary

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

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

Marsh inundation needs for the flushing of nutrients from riverine marshes into the open bays are computed and specified for the Sabine and Neches deltas. The Sabine and Neches River deltas are frequently submerged by floods from the Sabine and Neches Rivers. Based upon historical conditions and gaged streamflow records, freshwater inflow needs for marsh inundation are estimated and specified for the Sabine River near Ruliff at 802.0 thousand acre-feet (989 million m^3) in May and October and 480.3 thousand acre-feet (592 million m^3) in April, May and October for the Neches River at Evadale. These volumes correspond to flood events with peak daily flow rates of 28,000 ft^3/sec (792 m^3/sec) and 18,000 ft^3/sec (510 m^3/sec), respectively.

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

Estimates of the monthly freshwater inflow needs for the Sabine-Neches estuary were evaluated for each of the three alternatives:

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

Alternative II (Maintenance of Fisheries Harvests): minimization of annual combined inflow while providing annual commercial harvests of red drum, seatrout, and shrimp, at levels no less than their mean historical (1962-1976) values, satisfying marsh inundation needs, and meeting viability limits for salinity; and

Alternative III (Shrimp Harvest Enhancement): maximization of the total annual commercial harvest of shrimp while meeting bounds for salinity, satisfying marsh inundation needs, and utilizing an annual combined inflow no greater than the average historical combined inflow for the period 1941-1976.

Under Alternative I (Subsistence), the Sabine-Neches system is estimated to need freshwater inflows totaling 8.78 million acre-feet (10.8 billion m^3) annually to satisfy the basic salinity gradient and marsh inundation needs. The portion of the annual inflow need that is estimated to come from gaged areas of the Sabine and Neches River Basins is 5.69 million acre-feet (7.02 billion m^3). Estimates of commercial fisheries harvests were not possible since the monthly inflows for this Alternative were not within the range of observed inflows utilized to derive the harvest equations.

Alternatives II (Maintenance of Fisheries Harvests) and III (Shrimp Harvest Enhancement) were found to be infeasible; that is, no set of monthly inflows could simultaneously satisfy the upper and lower limits on salinity, inundation flows, and bounds on the seasonal inflows for which the fisheries harvest equations are valid.

The numerical tidal hydrodynamic and salinity mass transport models were applied to the Sabine-Neches estuary to determine the effects of the estimated freshwater inflow needs for Alternative I 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 for the Alternative I inflow needs indicate that freshwater inflows dominate the net water movements of the Sabine-Neches estuary. For all twelve months simulated, the simulated net flow circulation in Sabine Lake is from north to south. Simulated salinities in Sabine Lake under the Alternative I monthly inflows are between five and 15 ppt, except for the highest inflow months of May and October when the simulated salinity range is from one to ten ppt. Since the middle portion of Sabine Lake has simulated salinities in all months below a target maximum allowable concentration of 20 ppt, the freshwater inflow needs established by the Estuarine Linear Programming Model would be adequate to sustain the salinity gradients specified, within the objectives, throughout the estuary.

The estimated monthly freshwater inflow needs derived in this report are the best statistical estimates of the monthly inflows satisfying a specified objective for marsh inundation and salinity regimes.

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

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APPENDIX

List of Persons Receiving the Draft Report

Name	Agency
Bob Armstrong	General Land Office Texas, Austin
Charles D. Travis*	Texas Parks & Wildlife Department, Austin
Executive Director	Texas Coastal & Marine Council, Austin
Robert Bernstein	Texas Department of Health, Austin
John Poerner	Railroad Commission of Texas, Austin
Edward Vetter	Texas Energy & Natural Resources Council, Austin
Mark White	Attorney General of Texas, Austin
Mit Spears	Governor's Budget & Planning Office, Austin
A.R. Schwartz	Texas Senate, Galveston
Jimmie Schindewolf	Houston Department of Public Works, Houston
Bill Clayton	Speaker, Texas House of Representatives, Austin
William P. Hobby	Lt. Governor of Texas, Austin
Emmett Gloyna	U.S. Water and Power Resources Service, Austin
James C. Donovan	U.S. Army Corps of Engineers, Dallas
Donald J. Palladino	U.S. Army Corps of Engineers, Fort Worth
James M. Sigler	U.S. Army Corps of Engineers, Galveston
Bill Waddle	Texas Water Conservation Association, Austin
Robert A. Thomas	Louisiana Nature Service Center, New Orleans, La.

List of Persons Receiving the Draft Report (cont'd.)

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William G. Wooley	U.S. Army Corps of Engineers, Galveston
J.B. Nixon	Lower Neches River Authority, Beaumont
Dale Yost	U.S. Geological Survey, Austin
Clark Hubbs	University of Texas at Austin
N.E. Armstrong	University of Texas at Austin
Pat Parker	University of Texas Marine Science Institute, Port Aransas
D.E. Wohlschlag	University of Texas Marine Science Institute, Port Aransas
Sergio G. Sandoval*	Instituto Nacional de Pesca, Tampico, MEX
R.J. Reimold	Georgia Department of Natural Resources, Brunswick, GA
M.A. Kjelson	U.S. Fish & Wildlife Service, Stockton, CA
Roy W. Hann, Jr.	Texas A&M University, College Station
Robert Schoen	U.S. Geological Survey, Reston, VA
Alejandro Yanez Arancibia*	Centro de Ciencias Del Mar, MEX
T.J. Conomos	U.S. Geological Survey, Menlo Park, CA
Charles Lyles	Gulf States Fisheries Commission, Ocean Springs, MISS
Joseph R. Higham	U.S. Fish & Wildlife Service, Austin
Sam Collins	Sabine River Authority, Orange
George F. Dibrell	Port Arthur City Manager, Port Arthur

List of Persons Receiving the Draft Report (cont'd.)

Name	Agency
Donald Moore	National Marine Fisheries Service, Galveston
Stuart Henry	Sierra Club
Robert E. Smith	U.S. Geological Survey, Houston
Ralph Rayburn	Texas Shrimp Commission, Austin
Catherine Perrine	League of Women Voters, Dallas
Paul Fore	U.S. Fish & Wildlife Service, Albuquerque
Sharron Stewart	Texas Environmental Coalition, Lake Jackson
Adlene Harrison	U.S. Environmental Protection Agency, Dallas
Feenan D. Jennings	Texas A&M University, College Station
Jack Runkles	Texas A&M University, College Station
Carl Oppenheimer*	University of Texas Marine Science Institute, Port Aransas
Vito Blomo	Gulf of Mexico Fishery Management Council, Tampa, FLA
William H. Stevenson*	National Marine Fisheries Service, St. Petersburg, Florida
Charles Curry	Orange City Manager, Orange
Ray Riley	Beaumont City Manager, Beaumont
Murray Walton	Wildlife Management Service, Dripping Springs

* Indicates a letter was received from the named individual--or his (her) respective agency--in reply to the TDWR's request for comments on the draft report.