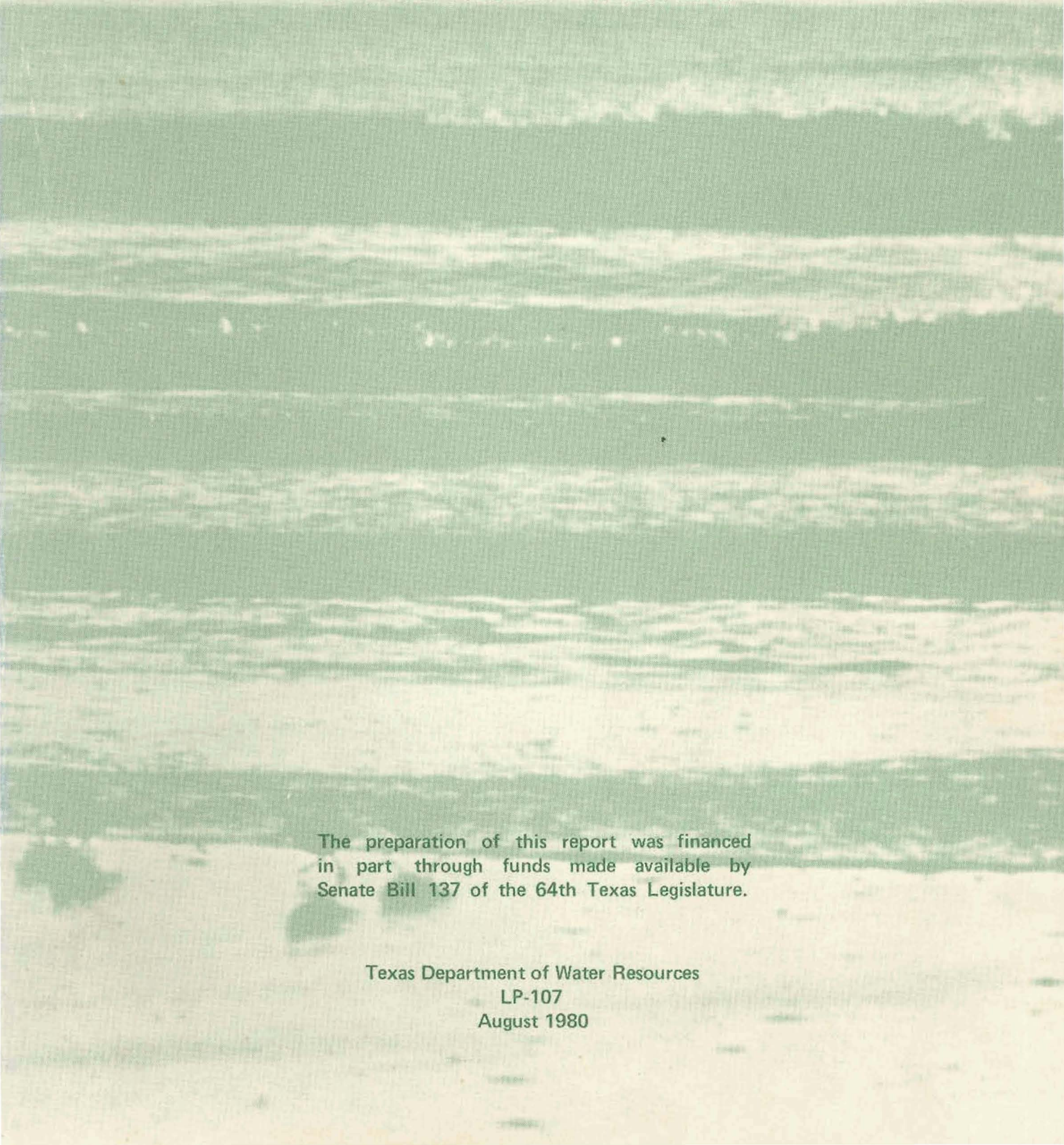
GUADALUPE ESTUARY:
A Study of the Influence of Freshwater Inflows



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Texas Department of Water Resources
LP-107
August 1980

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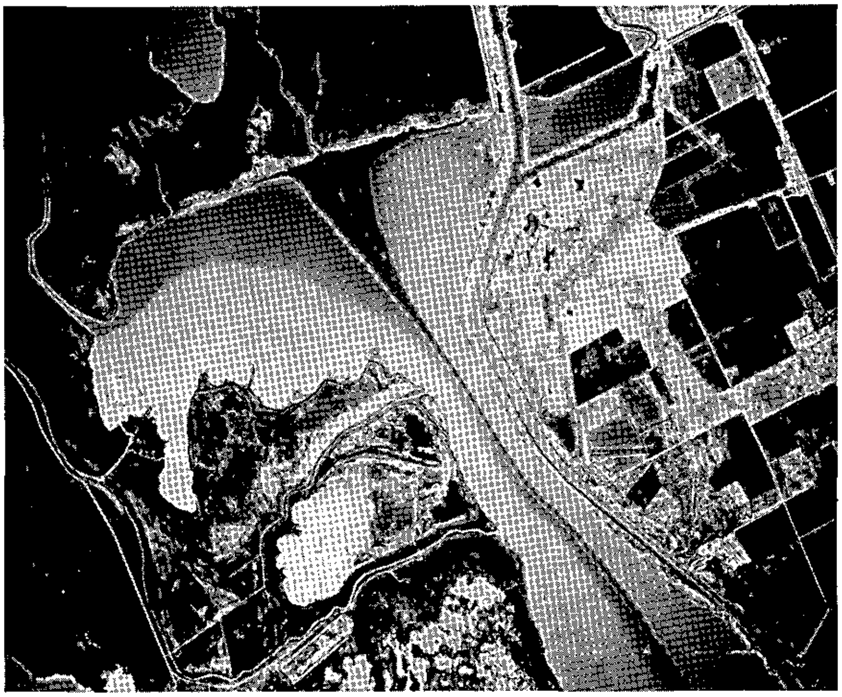

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PREFACE

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

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

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

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

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CHAPTER I

SUMMARY

Concepts and Methods

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

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

Description of the Estuary and the Surrounding Area

The Guadalupe estuary consists of San Antonio Bay, Espiritu Santo Bay, Mesquite Bay, and several smaller bays. Areas contributing inflow to the estuary include the entire Guadalupe and San Antonio River Basins plus parts of the Lavaca-Guadalupe and San Antonio-Nueces Coastal Basins.

The major marsh areas of the Guadalupe estuary are associated with the Guadalupe River delta. Active delta plains are covered with salt, brackish, and freshwater marshes. The Traylor sub-delta is actively expanding into Mission Lake. Most of the shorelines associated with the Guadalupe estuary are either in a state of equilibrium or accretion indicating that the sediment volume supplied to the Gulf and bay shorelines is sufficient to balance or exceed the amount of sediment removed by waves and longshore drift.

Land use in the area is dominated by agricultural and ranching activities. Rice is the principal irrigated crop even though other crops may receive supplemental irrigation water in dry years. Crops such as grain sorghum, corn and cotton are dryland crops produced in the area.

The Guadalupe estuary system is a significant part of the commercial fishing industry in Texas. Since 1962, the average annual commercial inshore catch (all species) in this estuarine system has exceeded 2.3 million pounds (1 million kg), ranking as the third most productive resource base for the Texas commercial bay fisheries. Shellfish, particularly shrimp, constitute the major portion of the commercial landings, accounting for 90 percent of the bay harvest weight.

The fishing resources of the estuary include many fish species preferred by sport fishermen. Studies by the Texas Parks and Wildlife Department indicate that an estimated 380 thousand fish (all species) totaling approximately 420 thousand pounds (200 thousand kg) were harvested in the bays of this estuary during the year 1975 through 1976. Species composition of the sport harvest is dominated by seatrout (73 percent) and red drum (10 percent of the total number of fish harvested).

A large portion of the estuary's production of fish and shellfish are caught offshore by sport and commercial fishermen. When these harvests are considered, the estuary's contribution to the Texas coastal fisheries is estimated at 13.4 million pounds (6.1 million kg; 93 percent shellfish) annually for a recent five-year period (1972-1976).

Hydrology

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

Freshwater inflows in terms of annual and monthly average values over the 1941 through 1976 period varied widely from the mean as a result of recurrent drought and flood conditions. On the average, the total freshwater inflow (excluding direct precipitation) to the estuary (1941-1976) consisted of 2.27 million acre-feet (2.8 billion m^3) annually, of which an estimated 1.8 million acre-feet (2.22 billion m^3) was contributed from gaged drainage areas.

In general, the water quality of gaged inflows to the Guadalupe estuary has been good. No parameters were found in violation of existing Texas stream standards, although one "total lead" sample from the San Antonio River was in violation of federal drinking water 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 Guadalupe estuary have exceeded the U.S. Environmental Protection Agency criteria for metals in sediments (prior to dredging) for arsenic, cadmium, chromium, mercury and zinc. Bottom sediments collected and analyzed during the period 1969 through 1975 for herbicides and pesticides showed DDD, DDE, DDT, dieldrin and silvex occurring in some local areas in concentrations equal to or greater than the analytical detection limit.

Circulation and Salinity

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

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

To properly evaluate the transport of water and nutrients through a deltaic marsh, it is necessary to describe and compute estimates of the complex tidal and freshwater inflow interactions. Therefore, a mathematical model was developed and applied to the Guadalupe delta to accurately simulate the passage of water and nutrients.

The extent of marsh inundation in the Guadalupe River delta was investigated utilizing the verified inundation model for this system. The flooded surface area of the Guadalupe delta was determined for six typical flood hydrographs under low, high and average tidal amplitudes.

Statistical analyses were also undertaken to quantify the relationship between freshwater inflows from the Guadalupe and San Antonio Rivers and salinities at selected points in San Antonio Bay. Utilizing gaged daily river flows and observed salinities, a set of monthly predictive salinity equations were derived utilizing regression analyses for an area of the estuary near the Guadalupe delta. These equations enable the prediction of the mean monthly salinity as a function of the mean monthly freshwater inflow rate.

Nutrient Processes

The marshes of the Guadalupe River delta are subject to periodic inundation during periods of increased river flows. High rates of organic carbon and organic nitrogen export (both particulate and dissolved) occur during the initial stages of these flood periods. After this initial pulse of material is flushed out, the steady state exchange rates appear to be slightly greater than those observed in the Lavaca River delta marshes. Pulses of increased freshwater discharge (i.e., flooding) and the resulting deltaic inundation appear to be important mechanisms contributing to increased nutrient transport from those marshes to the estuary.

Primary and Secondary Bay Production

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

Six phytoplankton divisions represented by a minimum of 60 taxa were collected from the Guadalupe estuary. Statistical tests indicated that the standing crops were not significantly related to either salinity or river inflow.

A total of 162 zooplankton taxa representing 12 phyla were identified. Species diversity and standing crops were reduced by heavy flooding. The recuperation period was short, however, and these parameters increased rapidly when salinities returned to their seasonal norms.

Fisheries

Virtually all of the Gulf fisheries species are estuarine-dependent. Commercial inshore harvests from bays of the Guadalupe estuary rank third in shellfish and sixth in finfish of eight major Texas estuarine areas. In addition, the sport or recreational finfish harvest is approximately equal to the commercial finfish harvest in the estuary. For the 1972 through 1976 interval, the average annual sport and commercial harvest of fish and shellfish dependent upon the estuary is estimated at 13.4 million pounds (6.1 million kg).

Although a large portion of each Texas estuary's fisheries production is harvested offshore in collective association with fisheries production from other regional estuaries, inshore bay harvests are useful as relative indicators of the year-to-year variations in an estuary's fisheries production. These variations are affected by the seasonal quantities and sources of 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 statistical analysis of the 1962 through 1976 commercial bay fisheries landings was successful for 80 percent of the correlations attempted between the annual commercial harvests and the seasonal freshwater inflows to the Guadalupe estuary. The analysis of harvest as a function of the seasonal inflows resulted in 16 statistically significant regression equations. These equational models provide numerical estimates of the effects of variable seasonal inflows contributed from the major freshwater sources on the commercial harvests of seafood organisms from the estuary. The analysis also supports existing scientific information on the seasonal importance of freshwater inflow to the estuary. All harvest responses to spring (April-June) inflow are estimated to be positive for increased inflow in this season. In addition, harvest responses to late fall (November-December) inflow are all positive, except for the weakly negative response of the shellfish component. The harvest responses to winter (January-March) and autumn (September-October) inflows are split between shrimp and fish components, with shrimp relating positively and fish relating negatively to inflow in these seasons. Increased summer (July-August) inflow relates negatively to all fisheries components, except for black drum and brown and pink shrimp which exhibit positive correlations to summer inflow.

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

Estimated Freshwater Inflow Needs

A methodology is presented which combines the analyses of the component physical, chemical and biological elements of the Guadalupe estuary into a sequence of steps which result in estimates of the freshwater inflow needed to achieve selected salinity, marsh inundation and fishery harvest objectives..

Monthly mean salinity bounds were specified for selected locations in the estuary near the inflow point of the Guadalupe River Basin. These upper and lower limits on monthly salinity were selected to provide a salinity range which will not exceed bounds for viable metabolic 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 Guadalupe River delta. Based upon historical gaged streamflow records and mathematical analyses using the Guadalupe delta inundation model, freshwater inflows for marsh inundation needed to maintain historical inundation magnitude and frequency were estimated at 125.0 thousand acre-feet (154 million m^3) in each of the months April, May, June, September, and October. This volume corresponds to a flood event with a peak flow rate of 12,500 ft^3/sec (354 m^3/sec).

Evaluation of Estuarine Alternatives

Estimates of the freshwater inflow needs for the Guadalupe estuary were computed by representing the interactions among freshwater inflows, estuarine salinity and fisheries harvests within an Estuarine Linear Programming Model. The model computes the monthly freshwater inflows from the Guadalupe River Basin which best achieves a specified objective.

The monthly freshwater inflow needs for the Guadalupe estuary were estimated for each of three selected alternatives.

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

Alternative II (Maintenance of Fisheries Harvests): minimization of annual combined inflow while providing freshwater inflows sufficient to supply predicted annual estuarine commercial bay harvests of red drum, seatrout, shrimp, and all shellfish 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 estuarine commercial harvest of shrimp while observing salinity limits, satisfying marsh inundation needs, and utilizing an annual combined inflow no greater than the average historical (1941-1976) combined inflow. In addition, it is required that the combined commercial bay harvests of all shellfish be no less than the average historical (1962-1976) harvest.

Under Alternative I (Subsistence), the Guadalupe system—which has functioned as both a commercial shellfish and finfish producing system in the past--can continue to be an important fisheries producing estuary with substantially less freshwater inflow, but with slightly reduced estimated harvests. Freshwater inflows totalling 1.6 million acre-feet (1.97 billion m^3) annually (of which 21 percent is estimated from ungaged areas) are predicted to satisfy the basic salinity gradient and marsh inundation needs, but with a resulting decrease of 13 percent in combined commercial finfish and shellfish bay harvests, from average values for the period 1962 through 1976 (Figure 1-1).

Under Alternative II (Maintenance of Fisheries Harvests), the predicted annual commercial bay harvests of red drum, spotted seatrout, shrimp, and all shellfish are each required to be at least as great as historical (1962-1976) average levels. Salinity limits and marsh inundation needs are also to be observed. To satisfy these criteria, it is estimated that an annual freshwater inflow of 2.02 million acre-feet (2.49 billion m^3) (20 percent from ungaged areas) is needed (Figure 1-1). The predicted annual total finfish and shellfish commercial harvest in the estuary is 2.37 million pounds (1.08 million kg), or approximately 99 percent of the 1962 through 1976 average.

Under Alternative III (Shrimp Harvest Enhancement), the Guadalupe estuary has an annual estimated freshwater need of 2.26 million acre-feet (2.8 billion m^3) (19 percent from ungaged areas)—distributed in a seasonally unique manner--to achieve the objective of maximizing the total annual predicted commercial harvest of shrimp, under the condition that the predicted combined shellfish harvest is at least as great as the 1962 through 1976 average (Figure 1-1). The water supplied to the estuary equals the historical average combined inflow (1941-1976). This inflow regime is predicted to give a 34 percent increase in shrimp estuarine harvest, at an estimated loss of 54 percent in total commercial finfish harvest. The total predicted commercial bay fisheries harvest is five percent less than the historical 1962 through 1976 average.

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

Estuarine Circulation and Salinity Patterns

To establish that the freshwater inflow needs specified above provide desired salinity gradients throughout the estuary, the numerical tidal hydrodynamic and salinity mass transport models were applied to the Guadalupe estuary. Their application determines the effects of the estimated freshwater inflow needs for Alternative I 1/ upon the average monthly net flow

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

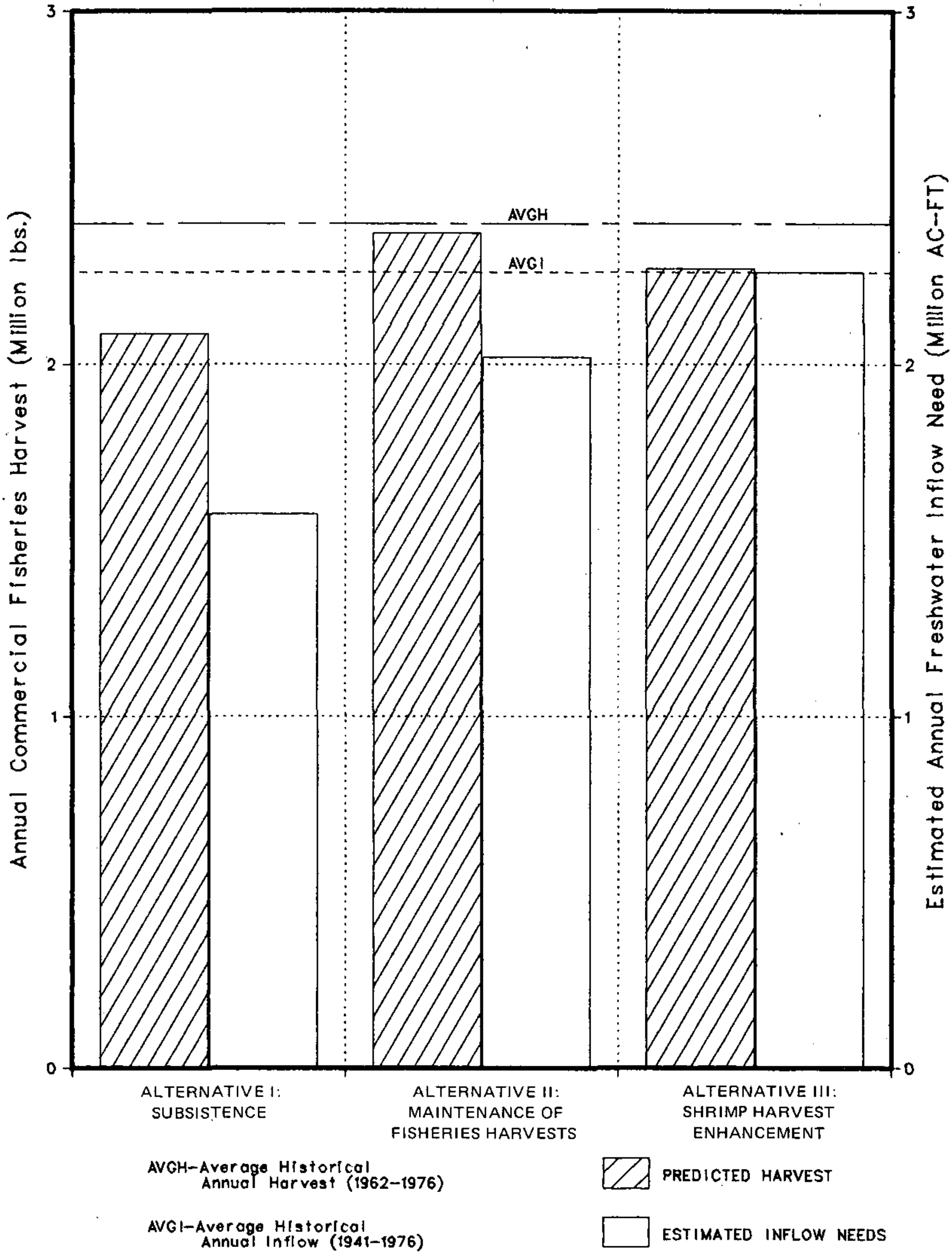

Figure 1-1. Predicted Annual Commercial Fisheries Harvest and Estimated Inflow Needs Under Three Alternatives for the Guadalupe Estuary

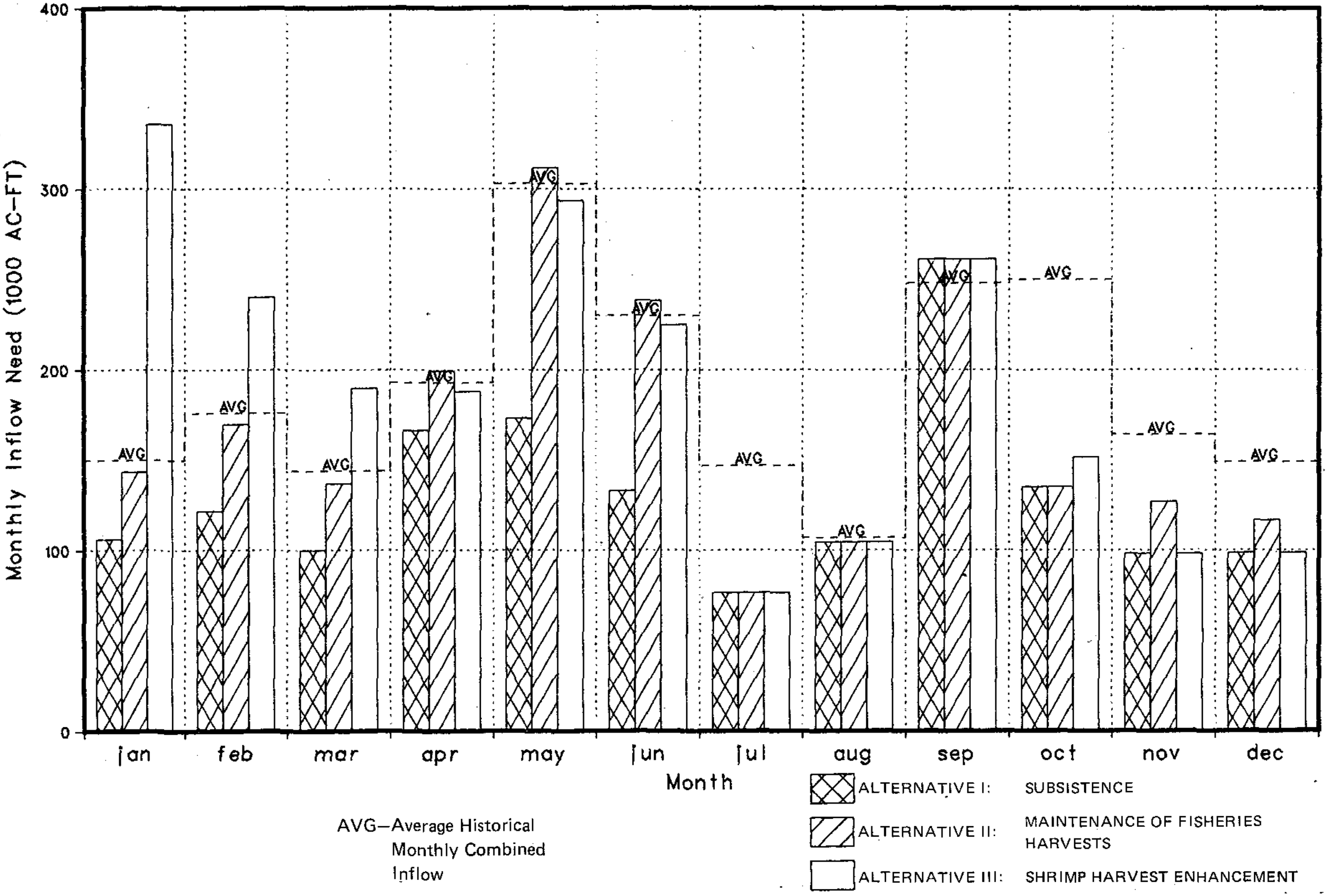

Figure 1-2. Estimated Monthly Freshwater Inflow Needs for the Guadalupe Estuary Under Alternatives I, II, III

circulation and salinity characteristics of the estuarine system. The monthly simulations utilized typical tidal and meteorological conditions observed historically for each month simulated.

The simulated salinities in the Guadalupe estuary for the estimated monthly freshwater inflow needs vary over a wide range. Salinities throughout the estuary are lowest in the month of June, with average simulated salinities of less than 25 parts per thousand (ppt) over the entire estuary. The highest levels of simulated salinities occur during the month of August, when salinities in Mesquite Bay near Cedar Bayou exceed 30 ppt. The simulated salinities for upper San Antonio Bay are generally less than 15 ppt throughout the year. The major portion of San Antonio Bay has simulated salinities of between 20 and 25 ppt; however, during the high freshwater inflow months of May and June, the salinities in the bay are between 10 and 20 ppt. Since the middle portion of San Antonio Bay has simulated salinities in all months below a target maximum allowable concentration of 25 ppt, the freshwater inflow needs established for Alternative I are adequate to sustain the desired salinity gradients specified throughout the estuary.

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

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

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 Guadalupe 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 (172). 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 Guadalupe 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., individual bays), lesser but recognizable units with characteristic chemical, physical and biological regimes. Primary, secondary, and tertiary bays, although interrelated, all require study for proper understanding and management of the complete system.

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

Texas has about 373 miles (600 kilometers) of open-ocean or Gulf shoreline and 1,419 miles (2,290 kilometers) of bay shoreline, along which are located seven major estuarine systems and three smaller estuaries (Figure 2-1). Eleven major river basins, ten with headwaters originating within the boundaries of the state, have estuaries of major or secondary importance. These estuarine systems have a total open-water surface area of more than 1.5 million acres (607,000 hectares) with more than 1.1 million acres (445,000 hectares) of adjacent marshlands and tidal flats (363). Physical characteristics of the Guadalupe 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 Guadalupe estuary is described in Chapter IV.

Water Quality. The factors which affect the water quality of aquatic ecosystems and their importance to the various biological components include nutrients, such as nitrogen and phosphorus; the basic cellular building block, carbon; trace elements necessary for biological growth; the presence of sufficient concentrations of dissolved oxygen for respiration of aerobic

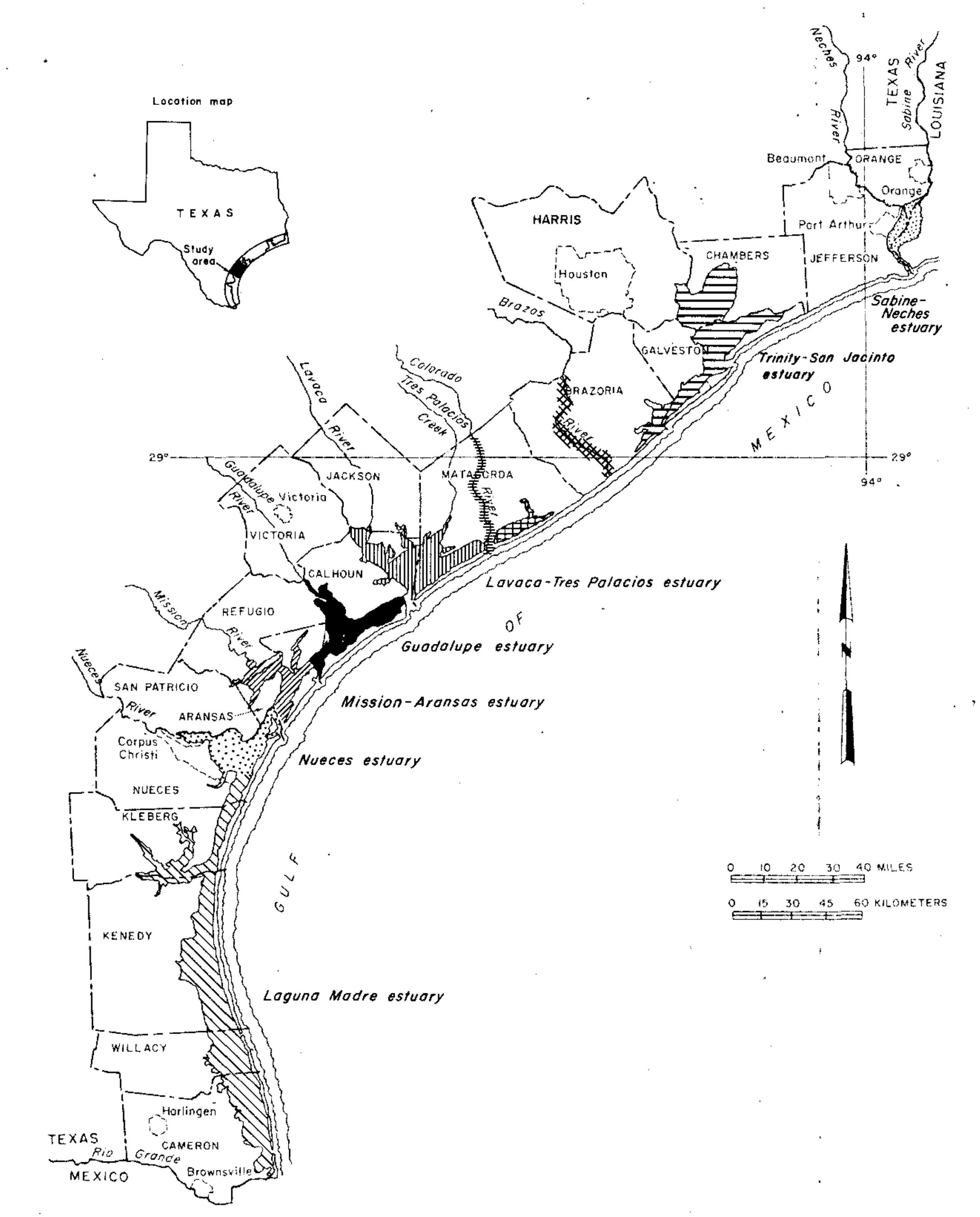

Figure 2-1. Locations of Texas Estuaries

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

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

Biological Characteristics

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

Salinity, temperature, and catastrophic events (e.g., hurricanes) are factors that largely control and influence species composition in these ecosystems. While the number of species generally remains low, numbers of organisms within a species fluctuate with the seasons and with hydrologic cycles (181, 65, 179). 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 Guadalupe 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 (38, 140, 41, 96, 162, 208). The aquatic ecosystem can be conceptualized as comprising four major components, all interrelated through various life processes (Figure 2-2):

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);

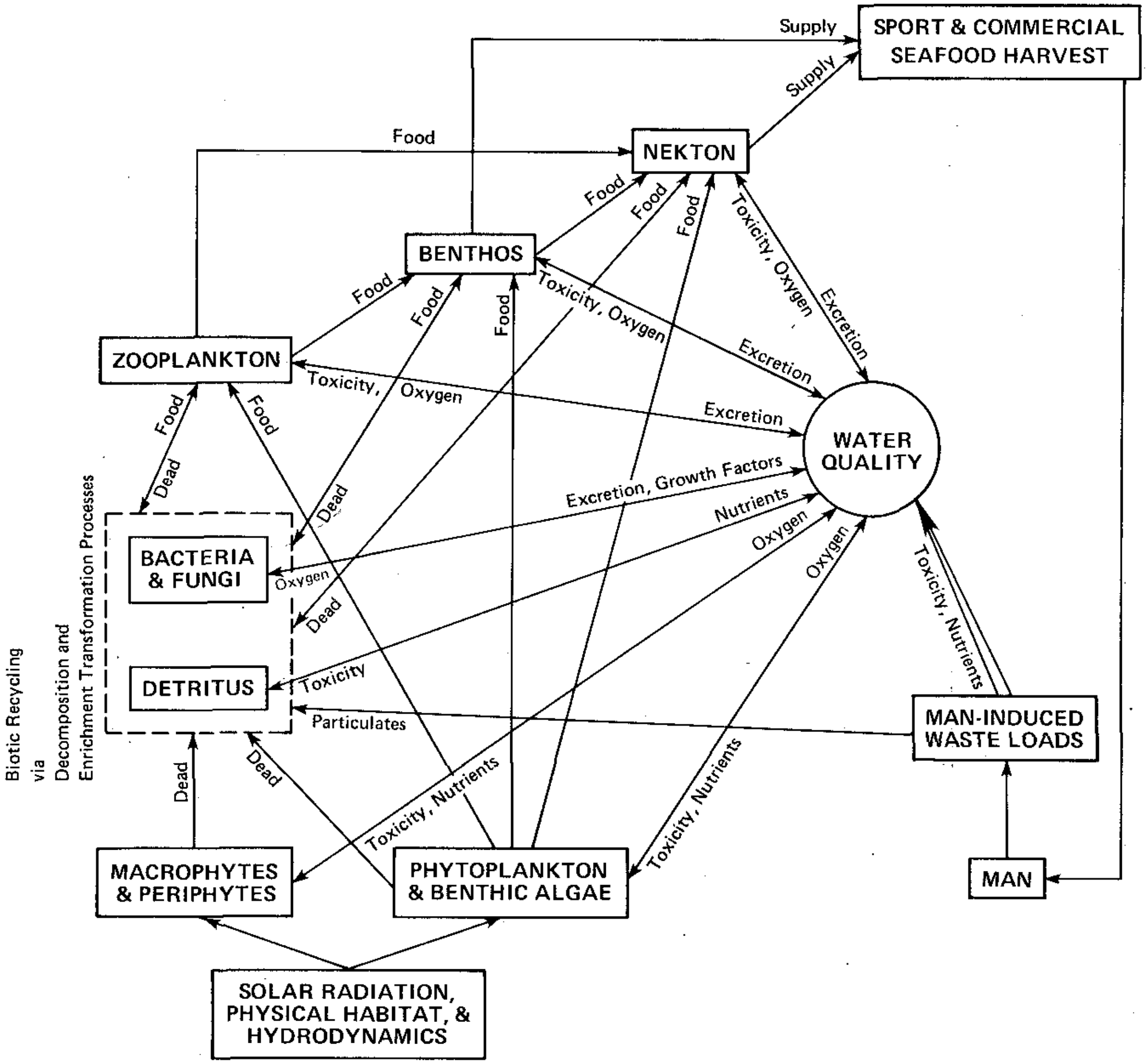

Figure 2-2. Component Schematic Diagram of a Generalized Texas Estuarine Ecosystem.

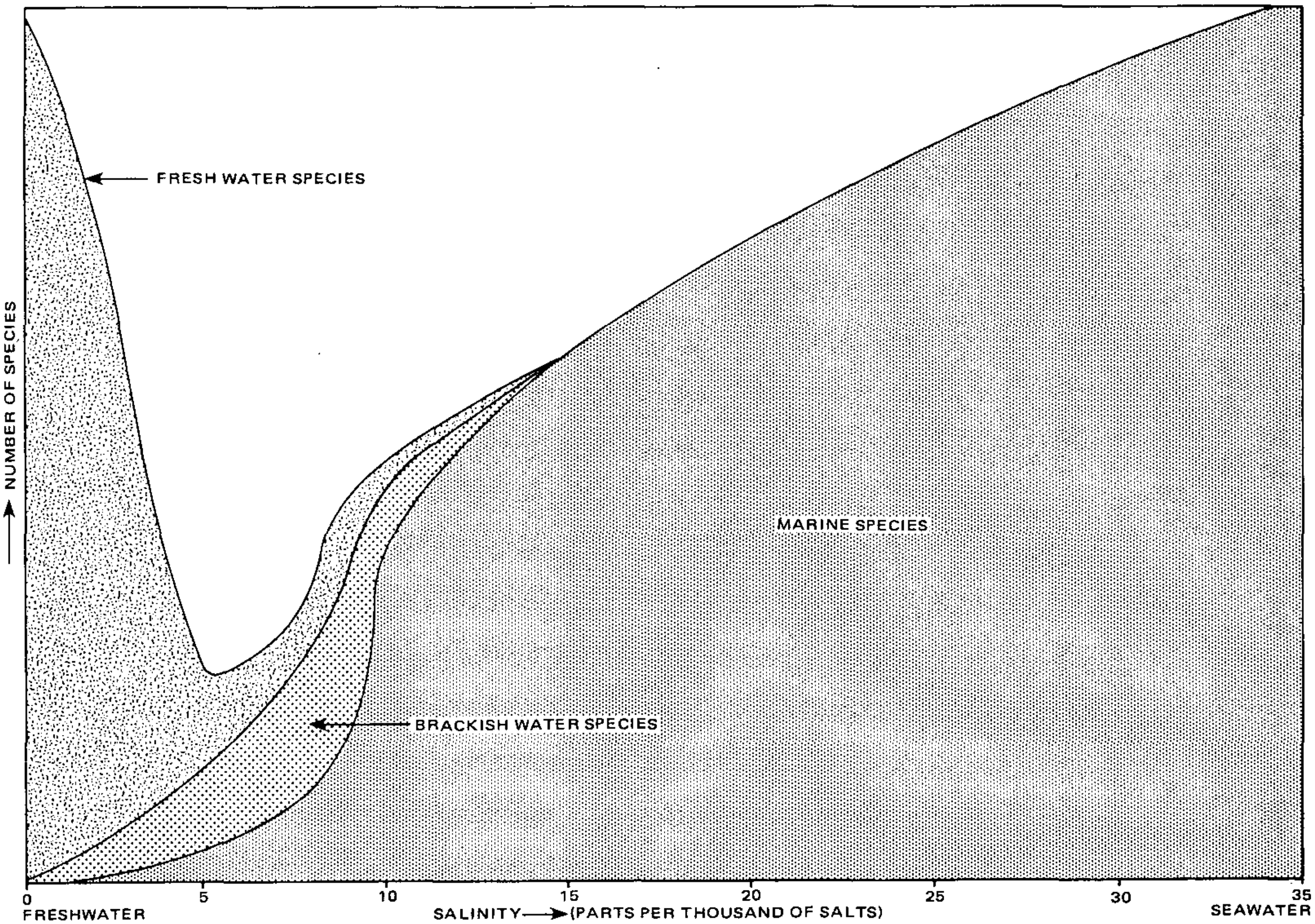

Figure 2-3. Species Composition of Estuarine Environments (181)

2. Producers including autotrophic organisms such as vascular plants and algae that can transform basic substances into living cellular material through utilization of sunlight by photosynthesis;
3. Consumers (herbivores, omnivores, and predators) including heterotrophic organisms such as zooplankton, shellfish, and fish species that utilize other biota as basic food material; and
4. Decomposers including bacteria in both liquid and solid (sediment) phases and fungi.

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

Life Cycles. Many organisms of estuarine systems are not permanent residents, in that they spend only part of their life cycle in the estuary. Migration patterns constitute an integral part of the life history of many estuarine-dependent species (186). 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 (117, 390), and/or for protection against predators and parasites (122, 170). Juvenile forms use the shallow "nursery" areas during early growth (78), migrating back to the Gulf of Mexico in their adult or sub-adult life stage.

For high ecosystem productivity to occur, the timing of freshwater inflow, inundation (irrigation) of marshes, and nutrient stimulation (fertilization) of estuarine plants must coincide with the subtropical climatic regime of the Gulf region. Nature's seasons provide environmental cues, such as increases or decreases in salinity and temperature, that enable estuarine-dependent species to reproduce and grow successfully in the coastal environments. These species have adapted their life cycles to the natural schedule of seasonal events in the ecosystem and also to reduce competition and predation. Coincidence of seasonal events, such as spring rains, inundation of marshes and increased nutrient cycling is made more complex by both antecedent events and ambient conditions. For example, winter inundation and nutrient stimulation of marshes may not be as beneficial to the estuarine system as similar events in the spring because low winter temperatures do not support high biological activity. Consequently, the growth and survival of many economically important seafood species will be limited if antecedent events and ambient conditions are unfavorable and far from the seasonal optimum. Further, the entire ecosystem can lose productivity through disruption of energy flow and become altered by slight, but chronic stresses (403).

Virtually all (97.5%) of the Gulf fisheries species are considered estuarine-dependent (79); however, the seasonal aspects of their life cycles are quite different. Some species, such as the redfish, spawn in the fall and the young are particularly dependent on migration to and utilization of the "nursery" habitats during this season. Others, such as the penaeid shrimp, spawn primarily in the spring and early summer, and their young move inshore

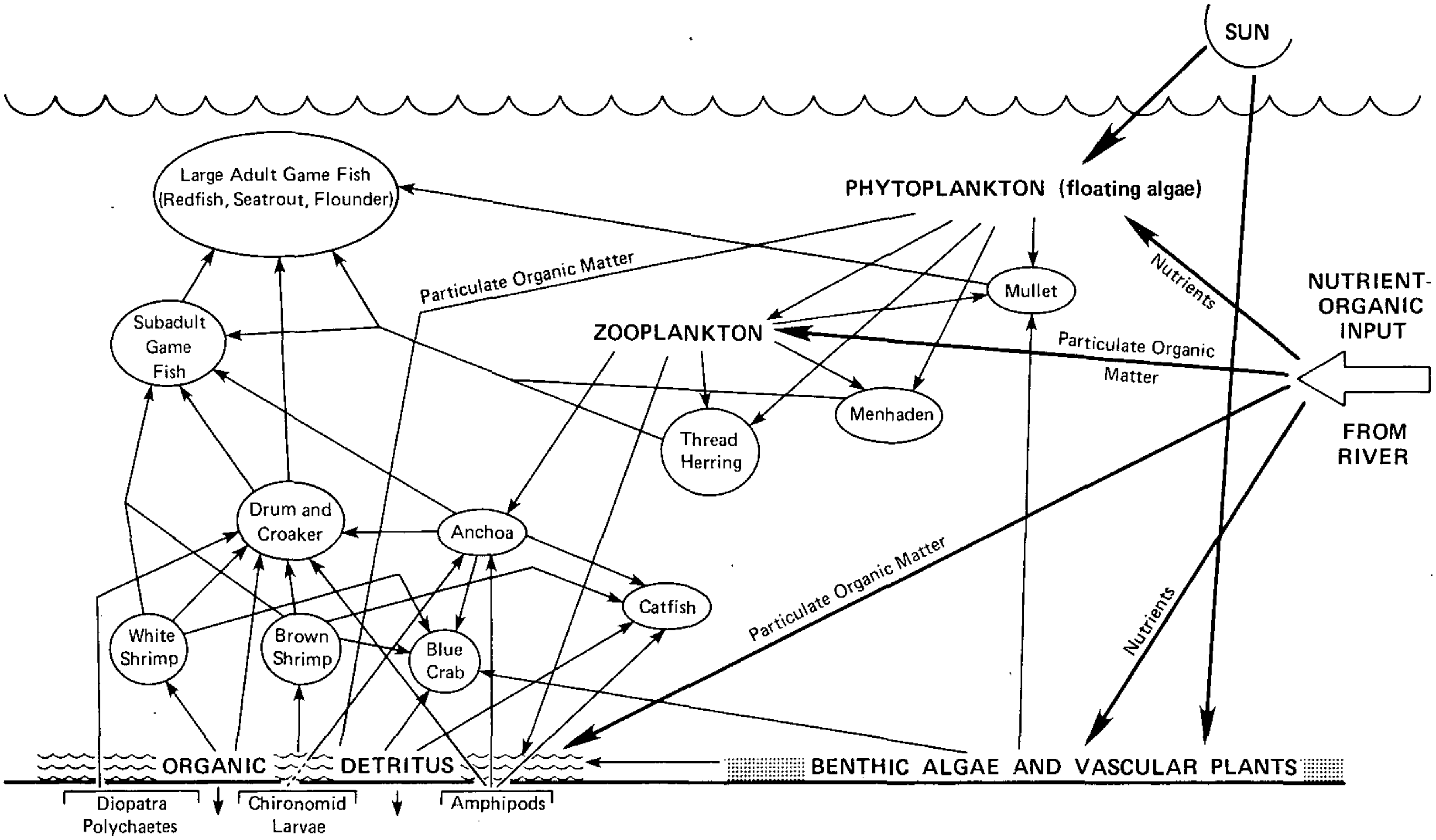

Figure 2-4. Simplified Trophic Relationships in a Texas Estuary [After WRE (396)]

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 (156).

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 (50). Throughout the world, only tropical rain forests, coral reefs, and some algal beds produce more abundantly per unit of area (162, 295).

Marsh production has been shown to be a major source of organic material supporting the estuarine food web in coastal areas from New England and the South Atlantic, to the Gulf of Mexico (34, 96, 139). Because of high plant productivities an estuarine marsh can assimilate, if necessary, substantial volumes of nutrient-rich municipal and industrial wastes (386, 387) and incorporate them into the yield of organic material which supports higher trophic level production, such as fisheries species. Such high food density areas serve as "nursery" habitats for many economically important estuarine-dependent species, and provide food and cover for a variety of water fowl and mammals. Delta marshes may serve other beneficial functions acting as a temporary floodwater storage area and/or aiding in erosion control by absorbing potentially destructive wave energy.

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

Summary

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

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

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

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

Evaluation of Individual Estuarine Systems

Introduction

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

Mathematical Modeling

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

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

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

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

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

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

Key Indicators of Estuarine Conditions

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

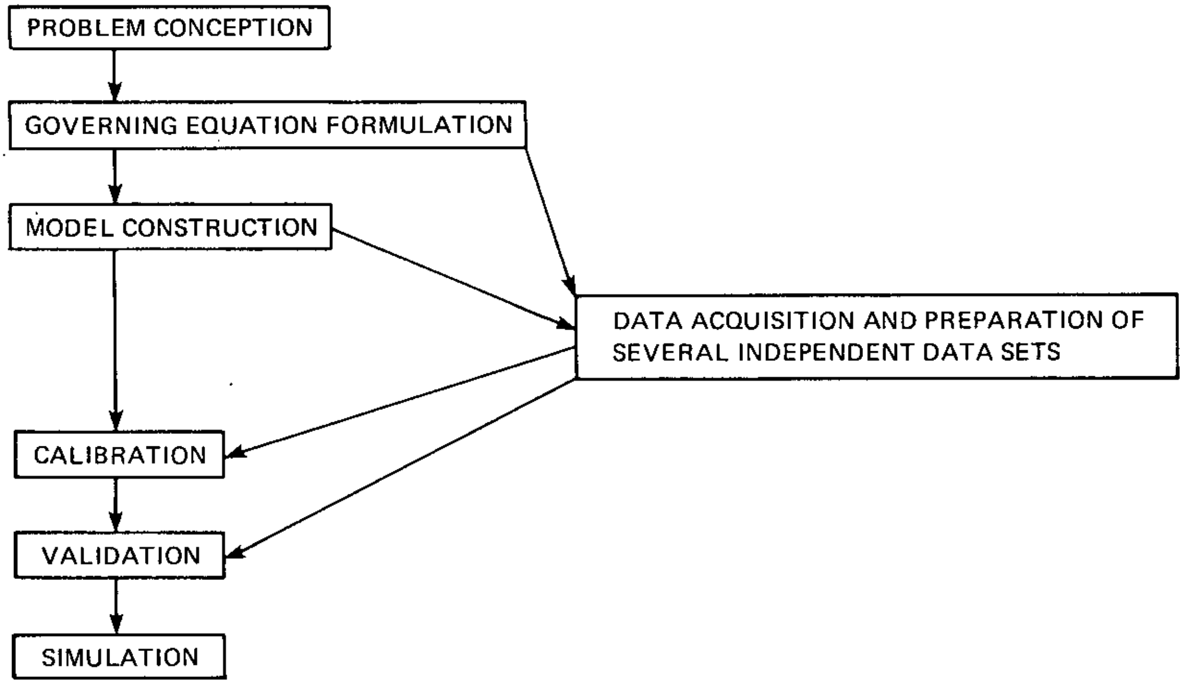

Figure 2-5. Flow Diagram of Model Development

to understand and demonstrate the response of higher food chain organisms, such as shellfish and finfish, to major changes in the ecosystem (202, 162). Physical and chemical constituents of prime importance to the estuarine ecosystem include freshwater inflows, circulation and salinity patterns, and nutrients. Chapters IV, V and VI quantify each of these factors to assess their relationship in estuarine productivity.

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

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

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

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

(2) Critical Period. An understanding of the concept of "critical period" is necessary in order to understand the importance of freshwater inflow to Texas estuarine systems. 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 (101, 151), 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 determine 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 (150). Each model computes velocities and water surface elevations at node points of a computational grid superimposed on an estuary. Estuarine characteristics along any given vertical line (the water column) are assumed to be homogeneous.

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

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

(4) Salinity. A knowledge of the distribution of salinities over time at points throughout the estuary is vital to the understanding of environmental conditions within the system. To better assess the variations in salinity, a salinity transport mathematical model has been developed (150) to simulate the salinity changes in response to dispersion, molecular diffusion and tidal hydrodynamics. This model is a companion model to the hydrodynamic model described previously.

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

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

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

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

(5) Nutrients. The productivity of an estuarine system depends upon the quantity of necessary nutrients such as carbon, nitrogen and phosphorus. Thus, the transportation and utilization of these nutrients in the system is of major importance. The most significant sources of nutrients for Gulf estuaries are the tidal marshes and river deltas (34, 139). A hypothetical cross-section of a typical salt water marsh is illustrated in Figure 2-7. Note the typical low channel banks which may be inundated by high tides and high river flows. Inorganic materials and organic detritus transported and deposited in salt marshes by river floods are assimilated in the marshes through biological action and converted to organic tissue. This conversion is accomplished by the primary producers (phytoplankton and macrophytes) of the marsh ecosystem. The primary producers and organic materials produced in the marsh are then transported to the bay system by the inundation and subsequent dewatering process. This process is controlled by the tidal and river flood stages.

To properly evaluate the transport processes through a deltaic river marsh it is necessary to estimate the complex tidal and freshwater inflow interactions. A mathematical model (set of equations) based upon the appropriate physical laws was developed for determining flows and water depths in a river delta (45). This model applies in cases of both low-flow and flood conditions. The effects of freshwater inflow upon the marsh inundation and dewatering processes are estimated through the application of this marsh inundation model (see Chapter V).

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

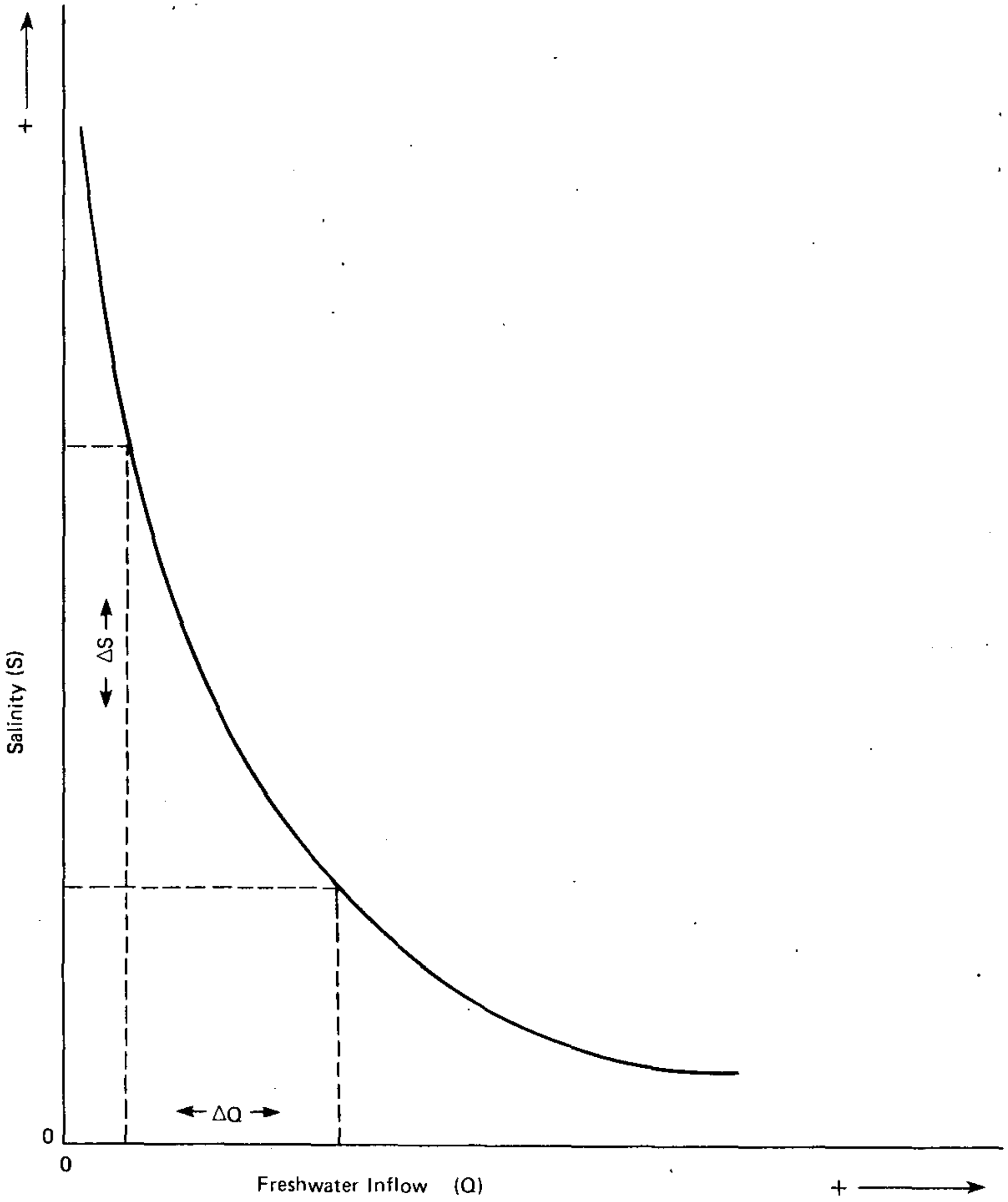

Figure 2-6. Typical Variation of Freshwater Inflow
Versus Salinity in a Texas Estuary

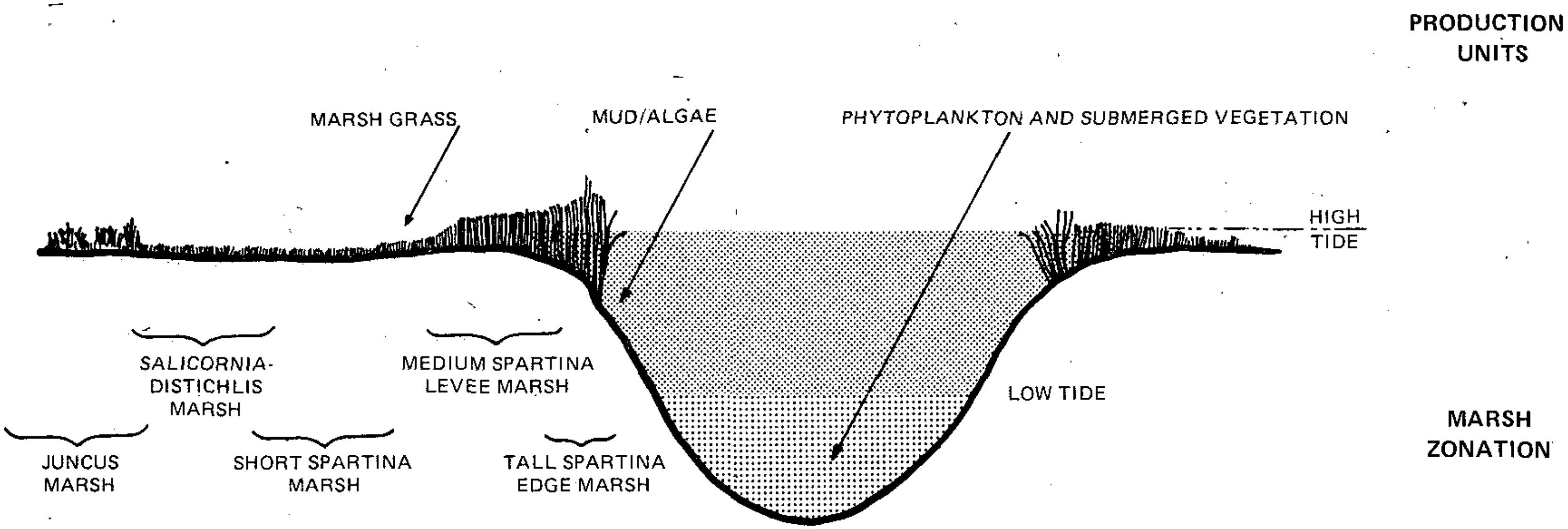

Figure 2-7. Zonation of a Salt Marsh in a Texas Estuary (235)

Dr. Eugene Odum has remarked that "ecologists constantly employ such organisms as indicators in exploring new situations or evaluating large areas" (162). Odum also notes that large species often serve as better indicators than small species because a larger and more stable biomass or standing crop can be supported with a given energy flow. The turnover of small organisms may be so great that the particular species present at any one moment may not be very useful as a biological indicator.

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

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

(1) Aquatic Ecosystem Model. Attempts to understand the complex interactions within Texas estuarine ecosystems have lead to the development of a sophisticated estuarine ecologic model, ESTECO (235). The model was formulated to provide a systematic means of predicting the response of estuarine biotic and abiotic constituents to environmental changes. Ecological modeling techniques involve the use of mathematical relationships, based on scientific evidence, to predict changes in estuarine constituents.

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

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

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

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

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

(3) Finfish Metabolic Stress Analysis. The health of organisms in an estuarine ecosystem is dependent upon a number of factors. Wohlschlag (277, 278, 279, 280) and Wakeman (394) have reported on the stress of salinity changes upon the metabolic activities of several Texas estuarine fish species. Wakeman (394) measured the maximum sustained swimming speeds of four estuarine fish species (i.e., spotted seatrout, sheepshead, and black and red drum) at 28 degrees Celsius over a range of salinities (10-40 parts per thousand, ppt) normally encountered in the estuary. All of these species are of commercial and recreational importance; therefore, results of these metabolic research studies are valuable in the planning and management of the Texas estuarine systems and their production of renewable fish resources. Salinity ranges and 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.

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

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

Determination of Freshwater Inflow Needs. (1) Estuarine Inflow Model. In order to establish an estimate of the freshwater inflow needs for an estuary, mathematical techniques are applied to integrate the large number of relationships and 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 (36) for the solution of linear programs. A linear program may be used to reach an optimum solution to a problem where a desired linear objective is maximized (or minimized) subject to satisfying a set of linear constraints.

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

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

(2) Model Interactions. The estuarine linear programming model incorporates 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 Guadalupe estuary is discussed in Chapter IX.

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

(1) Freshwater Inflow Management. The freshwater runoff from the regulated watersheds of the upstream river basins may be managed in several ways

to insure the passage of necessary flows to the estuaries. These include the granting of water rights for surface-water diversion and storage consistent with the freshwater inflow needs of the estuary.

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

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

The adjudication process is highly complex and, in many river basins, extremely lengthy. The procedures were designed to assure each claimant, as well as each person affected by a final determination of adjudication, all of the due process and constitutional protection to which each is entitled. Statewide adjudication is currently approximately 69 percent complete. Although the adjudication program is being accelerated, several years will be required to complete adjudication for the remaining basins. Final judgments have been rendered by the appropriate District Courts and certificates of adjudication have been issued in portions of the Rio Grande, Colorado, San Antonio and Guadalupe Basins.

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

Operations of Upstream Reservoirs in Contributing Basins. The control of surface-waters through impoundment and release from large storage reservoirs is a potential source of supplementary waters for the Texas estuaries. The Texas Water Plan specified the delivery of up to a total of 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. 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) <u>Elimination of Water Pollutants</u>. The presence of toxic pollutants in freshwater inflows can have a detrimental effect upon productivity of an estuarine ecosystem by suppressing biological activity. Historically, pollutants have been discharged into rivers and streams and have contaminated the coastal estuaries. Imposition of wastewater discharge and streamflow water quality standards by State and Federal governmental agencies has had and will continue to have a significant impact upon pollutants entering estuarine waters. Presence of toxic pollutants in the Texas estuaries will continue for the foreseeable future in some areas as compounds deposited in sediments become resuspended in the water column by dredging activities and when severe storms cause abnormally strong currents. This report does not include a comprehensive assessment of water pollution problems in the Guadalupe estuary, but other ongoing studies by the Department of Water Resources do address such problems.

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

Summary

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

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

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

Table 3-1. Reservoirs of Contributing Basins, Guadalupe Estuary

Reservoir Name	Type of Use(s) a/	Year Dam Completed	Surface Area b/ Acres	Pool Elevation ft (msl)	Pool Storage c/ thousand ac-ft	Flood Control Storage thousand ac-ft	Total Storage thousand ac-ft
Guadalupe River Basin							
Canyon Reservoir	F.C.,H.E.	1964	8,240	909.0	386.2	740.9	1,129.3
Lake Dunlap	H.E.	1928	410	575.0	3.5		3.5
Lake McQueeney	H.E.,R.	1928	396	528.7	5.0		5.0
H-4 Reservoir	H.E.	1931	696	332.0	6.5		6.5
Coleto Creek d/,e/	W.S., R.	—	3,100	98.0	35.0		35.0
San Antonio River Basin							
Olmos Reservoir	F.C.	1926	889	725.0	12.6	15.5	15.5
Medina Lake	Ir.	1913	5,575	1,064.2	254.0		254.0
Victor Braunig Lake	H.E.	1962	1,350	507.0	26.5		26.5
Calaveras Lake	H.E.	1969	3,450	385.0	62.8		62.8
Lavaca - Guadalupe Coastal Basin							
None							
San Antonio - Nueces Coastal Basin							
None							

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

b/ At conservation pool elevation

c/ Includes sediment storage

d/ Under construction

e/ Off channel reservoirs depending upon diversions from adjacent streams and/or reservoir releases for firm supply

River is of a type which develops under conditions of high sediment inflow into a relatively quiescent body of water.

Approximately ten miles (16 km) downstream from the confluence of the San Antonio River and the Guadalupe River, a significant bay-head delta is forming. "The Traylor sub-delta began actively prograding into Mission Lake following the artificial trenching between Guadalupe River and Mission Lake in 1935" (42, p. 130). This fan delta has advanced into Mission Lake about 1,800 feet (550 m) since it began forming. A significant portion of the Guadalupe River is diverted through this cut, thus furnishing abundant sediment for the formation of this relatively recent fan delta.

Substantial marsh areas in the Guadalupe estuary are associated with these deltas. Delta plains are covered with saline, brackish, and freshwater marshes. In order for marshes to propagate there must be a balance between sediment deposition and compactional subsidence. If there is excessive vertical accretion, marsh vegetation is replaced by mainland grasses, shrubs, and trees. Where subsidence is more rapid than deposition, the plants drown and erosion by waves and currents deepen the marshes to form lakes or enlarge the bay area. Deposition has almost ceased on the lower two-thirds of the Guadalupe delta as evidenced by the numerous lakes and extensive erosion. Lakes and ponds are an integral part to the coastal marsh-swamp complex. Water in these lakes and ponds varies from fresh to saline depending on climatological conditions and geographic location. Inland lakes such as Green Lake are fresh, while lakes and ponds associated with the Guadalupe delta (Long Lake) are temporarily brackish to saline.

The mainland shore is characterized by near vertical bluffs cut into Pleistocene fluvial and deltaic sand, silt, and mud (Figure 3-3). Erosion of these bluffs furnishes sediment to the adjacent lakes, marshes, and bays. The type of sediment deposited on the delta plain depends on whether the adjacent bluff is composed of predominantly sand or mud. Pleistocene overbank and bay muds have a high shrink-swell ratio causing desiccation cracks to form. Aided by the desiccation cracks, breaking waves cut into the base of these slopes. The process effectively removes slope support and the cliff fails by slumping. Energy levels (erosional capacity) in the Guadalupe estuary are dominated by wind action since the range of astronomical tides is only about 0.5 foot (0.15m). Winds blowing across the bay generate waves (or wind tides) and cause a change in water level at the shoreline.

Shoreline and vegetation changes within the Guadalupe estuary and in other areas of the Texas Gulf Coast are the result of natural processes (266). Shorelines are either in a state of erosion, accretion, or have been stablized either naturally or artificially. Erosion produces a net loss in land; accretion, a net gain in land; and equilibrium conditions, no net change in land area.

Most of the shorelines associated with the Guadalupe estuary are either in a state of equilibrium or accretion (Figure 3-4). This is an indication that the sediment volume being supplied to the Gulf shoreline and portions of the bay system shorelines is sufficient to balance the amount of sediment removed by wave action and longshore drift (262).

Processes that are responsible for the construction of shorelines and that are presently modifying shorelines in the Guadalupe estuary include

Figure 3-3. Geologic Map

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

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

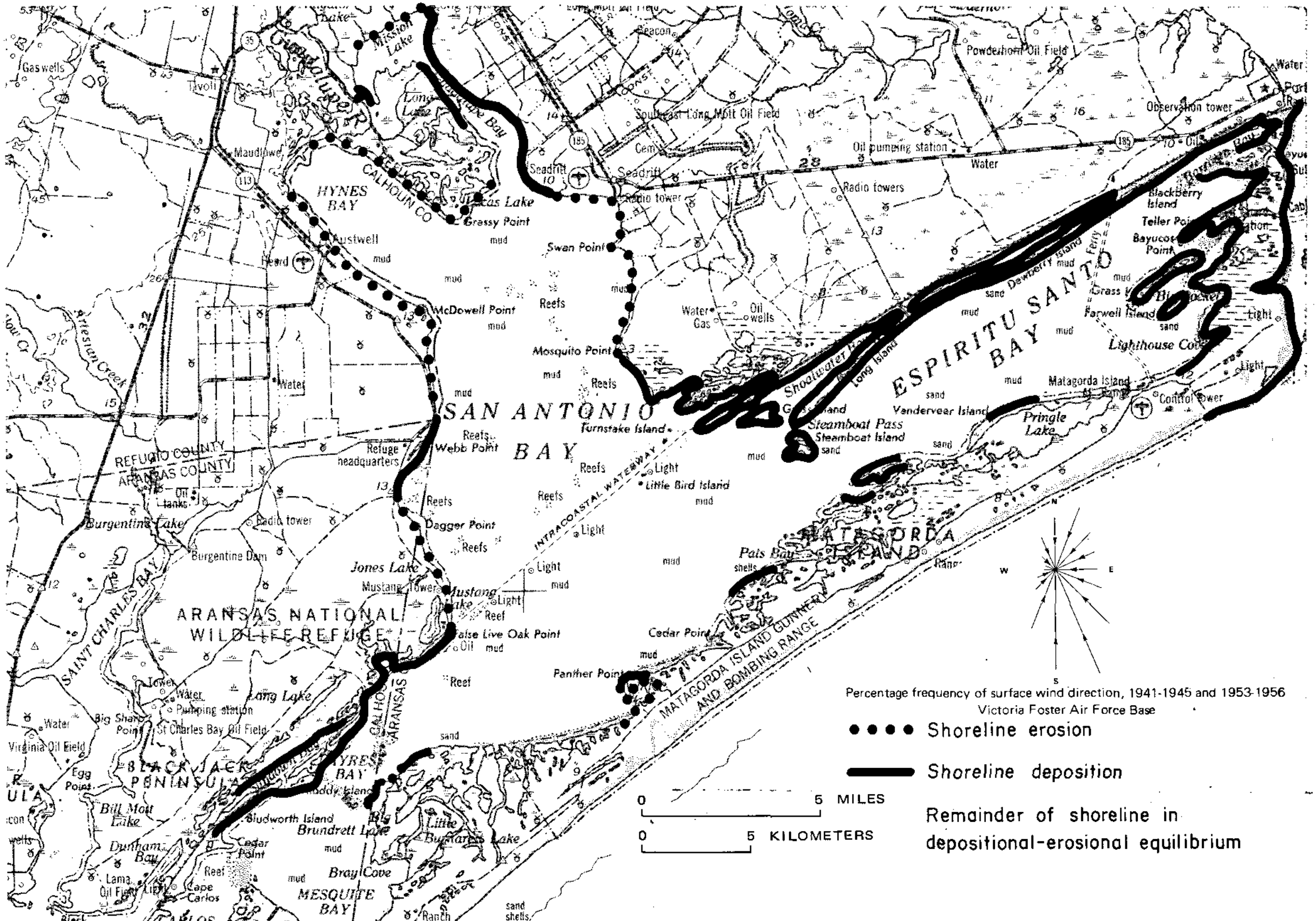

Figure 3-4. Shoreline Physical Processes, Guadalupe Estuary (262)

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 2 feet (0.6 m) along the Gulf shorelines. Wind is a major factor in influencing coastal processes; it can either raise or lower water levels along the Gulf and/or mainland shore according to the direction it is blowing. Wind can also generate waves and longshore currents (178, 94, 298).

The seasonal threat of wind and water damage associated with tropical cyclones entering the Gulf of Mexico exists each year from June through October. Wind damage from hurricanes and associated tornadoes can be costly, but the most severe losses occur from the flooding brought by heavy rains and high storm tides along the coast. Gulf and mainland shorelines may be drastically altered during the approach, landfall, and inland passage of hurricanes (94, 194). Storm surge flooding and attendant breaking waves erode Gulf shorelines from a few tens to hundreds of feet. Surge heights may range up to 15 feet (4.5 m) in some areas (261). Washovers along the barrier islands and peninsulas are common, and saltwater flooding may be extensive along the mainland shorelines.

Flooding of rivers and small streams normally corresponds either with spring thunderstorms or with the summer hurricane season. Rivers generally flood as a result of regional rainfall, but flooding along smaller streams may be activated by local thunderstorms (262). Some effects of flooding include: (1) overbank flooding into marsh areas of the floodplain and onto delta plains; (2) building of bay-head and oceanic deltas; (3) flushing of bays and estuaries; and (4) reduction of salinities.

Mineral and Energy Resources. Resources of the Texas coastal zone include oil and natural gas (Figure 3-5), which serve not only for fuel but also provide raw material for many petrochemical processes. In addition, the coastal zone contains important sources of chemical raw materials such as sulfur, salt, and shell for lime. The great abundance of these chemical and petroleum raw materials and their occurrence in a zone with ocean access helps to make this area one of the major petrochemical and petroleum-refining centers of the world.

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

Notably absent in the Texas coastal zone are 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.

Dredged shell with physical properties suitable for use as aggregate and road base has chemical properties suitable for lime, cement, and other chemical uses. If shell were not used, these resources would have to be transported approximately 150 miles (240 km) from the nearest Central Texas source.

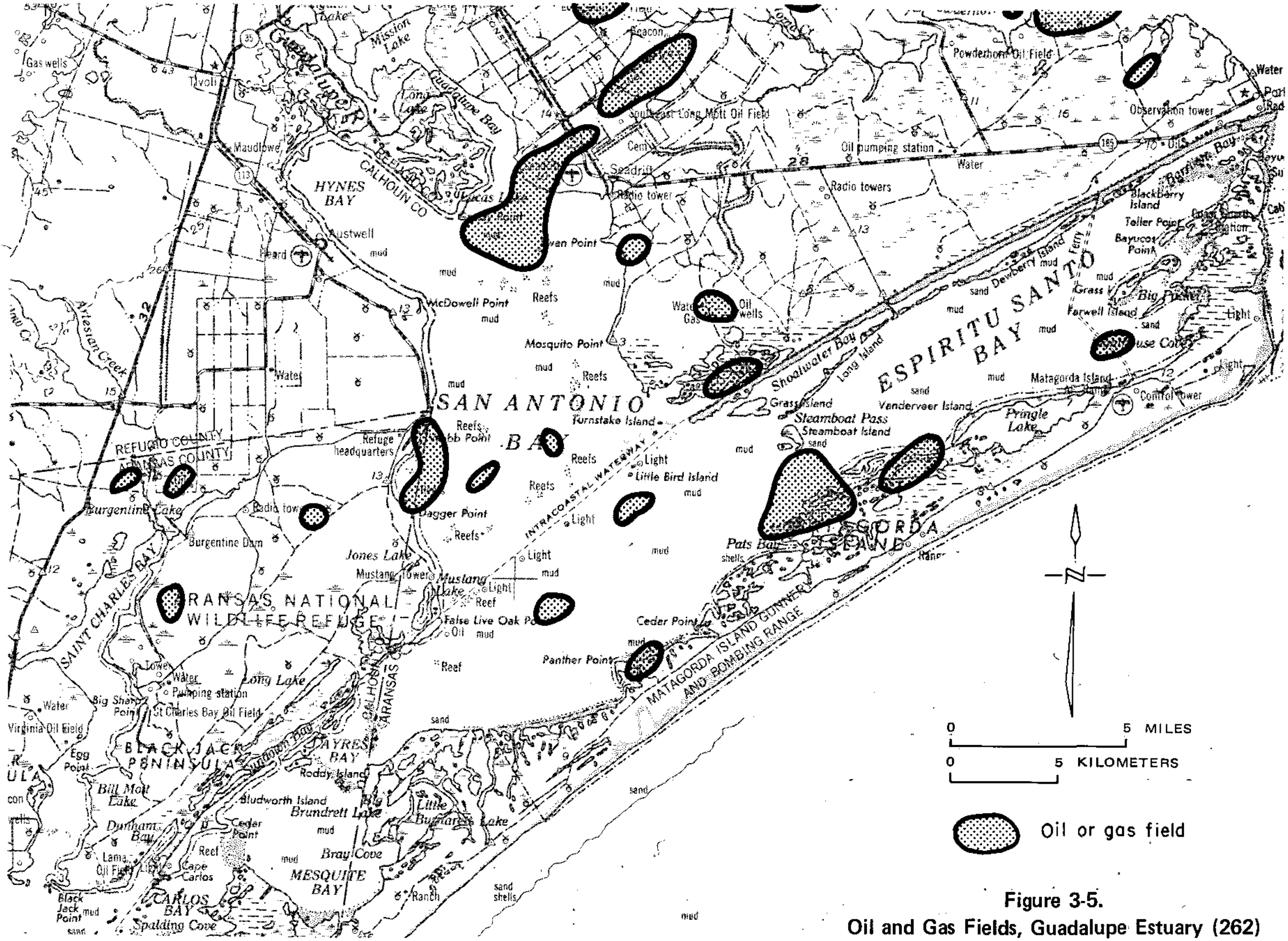

Figure 3-5.
Oil and Gas Fields, Guadalupe Estuary (262)

Shell resources are finite, and at present rates of consumption they will be depleted in the near future. Substitute materials will then have to be imported, either from inland sources or by ocean barge from more distant locations.

Groundwater Resources. Groundwater resources in the area of the Guadalupe estuary occur in a thick sedimentary sequence of interbedded gravel, sand, silt and clay. The stratigraphic units included in this sequence are the Jackson Group; the Catahoula, Oakville, and Goliad Formations of Tertiary Age; and the Willis, Lissie, and Beaumont Formations of Quaternary Age. These ancient sedimentary units are variable in composition and thickness and were deposited by the same natural processes that are now active in shaping the coastline. Thick layers of sand and gravel representing ancient river channel deposits grade laterally into silt and clay beds which were deposited by the overbank flooding of ancient rivers. Individual beds of predominantly sand and clay interfinger with each other and generally are hydrologically connected laterally and vertically. Because of this interconnection, groundwater can move from one bed to another and from one formation to another. Thus, the entire sequence of sediment, with the exception of the Jackson Group, functions as a single aquifer, which is referred to as the Gulf Coast Aquifer.

Near the Guadalupe estuary, the fresh (up to 1,000 mg/l total dissolved solids) to slightly saline (1,000 to 3,000 mg/l total dissolved solids) portion of the aquifer extends to a maximum depth of about 1,800 feet (550 m). The most productive part of the aquifer is from 200 to 800 feet (61 to 244 m) thick (237).

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 (266).

The Guadalupe estuary lies in the Coastal Prairie land resource area (326), a nearly level, slightly dissected plain with poorly-developed drainage. The native vegetation consists of coarse grasses with a narrow fringe of trees along the streams. Much of the area is now covered by improved pasture grasses. Marshes are confined to narrow strips along the coast characterized by sedge and salt-tolerant coarse grasses (330). Soils are dark, neutral to slightly acid, clay loams and clays, changing gradually with depth to light, calcareous clay.

Land use in the area is dominated by agricultural and ranching activities (Figure 3-6) (328, 231). Rice is the principal irrigated crop even though other crops may receive supplemental irrigation water in dry years. Results of studies on irrigation return flow quantities (331) show that 30 to 40 percent of the water applied for rice irrigation returns as surface flow to the drainage system. Crops such as grain sorghum, corn and cotton are dryland crops produced in the area. Forested areas, primarily oak, are prevalent.

The Aransas National Wildlife Refuge, managed by the U.S. Fish and Wildlife Service, is the only non-privately owned recreational site in the immediate vicinity of the Guadalupe estuary (Figure 3-7) (330). Archeological sites within the area indicate aborginal utilization of the region from the Paleo-Indian through the Neo-American periods (322).

The Guadalupe estuary system is a significant resource base of the commercial fishing industry in Texas. Since 1962, the average annual commercial catch (all species) in this estuarine system has exceeded 2.4 million pounds (1.1 million kg), ranking as the third most productive resource base for commercial fisheries of the Texas Gulf Coast. Shellfish, particularly shrimp, comprise the major portion of the commercial bay landings, accounting for approximately 90 percent of the total harvest weight. The remaining portion of the annual commercial bay catch is distributed among the finfish species, with black drum, red drum, seatrout and flounder being the major commercial species.

Natural resources of the bays and adjoining inland areas provide a wide variety of recreational opportunities for the people of Texas, as well as visitors from other states. Water-oriented recreational activities such as fishing, boating, skiing and swimming are amply available to the recreationists, with approximately 96,000 surface acres (39,000 ha) of bay waters available for recreational use. The fishing resources of the Guadalupe estuary include many fish species preferred by sport fishermen. Sports creel studies conducted by the Texas Parks and Wildlife Department (252) indicate that an estimated 380,700 fish (all species) totaling approximately 416,000 pounds (188,700 kg) were harvested from this estuary during the year 1975 through 1976. Species composition of the sport harvest was dominated by seatrout (73 percent) and red drum (10 percent) of the total number of fish harvested. Other preferred species include black drum, flounder, sheepshead, croaker, sand trout, and gafftopsail.

Inland areas and marshes contiguous to the Guadalupe estuary provide terrestrial and aquatic habitat for many species of wildlife including the endangered American alligator, the whooping crane, Atlantic Ridley turtle, brown pelican, and leatherback turtle. Wildlife resources of the area enhance the recreational opportunities, including sightseeing, nature studies and esthetic benefits accruing to naturalists and environmentalists alike. In addition, approximately 19,800 acres (8,019 ha) of marshland are available to outdoor sportsmen for hunting opportunities. These marsh areas support large populations of migratory game birds, such as geese and ducks.

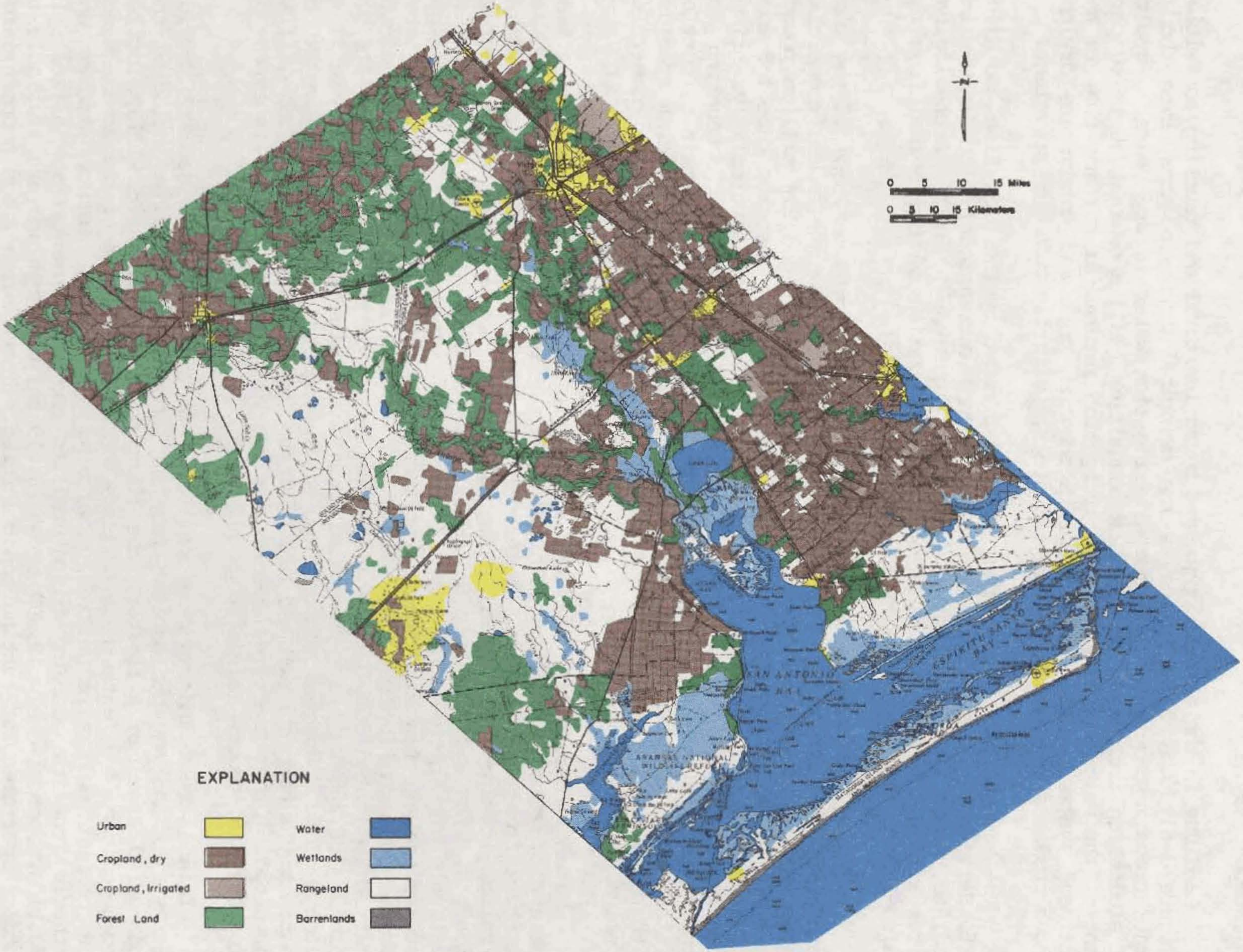

Figure 3-6. Land Use/Land Cover, Guadalupe Estuary (231)

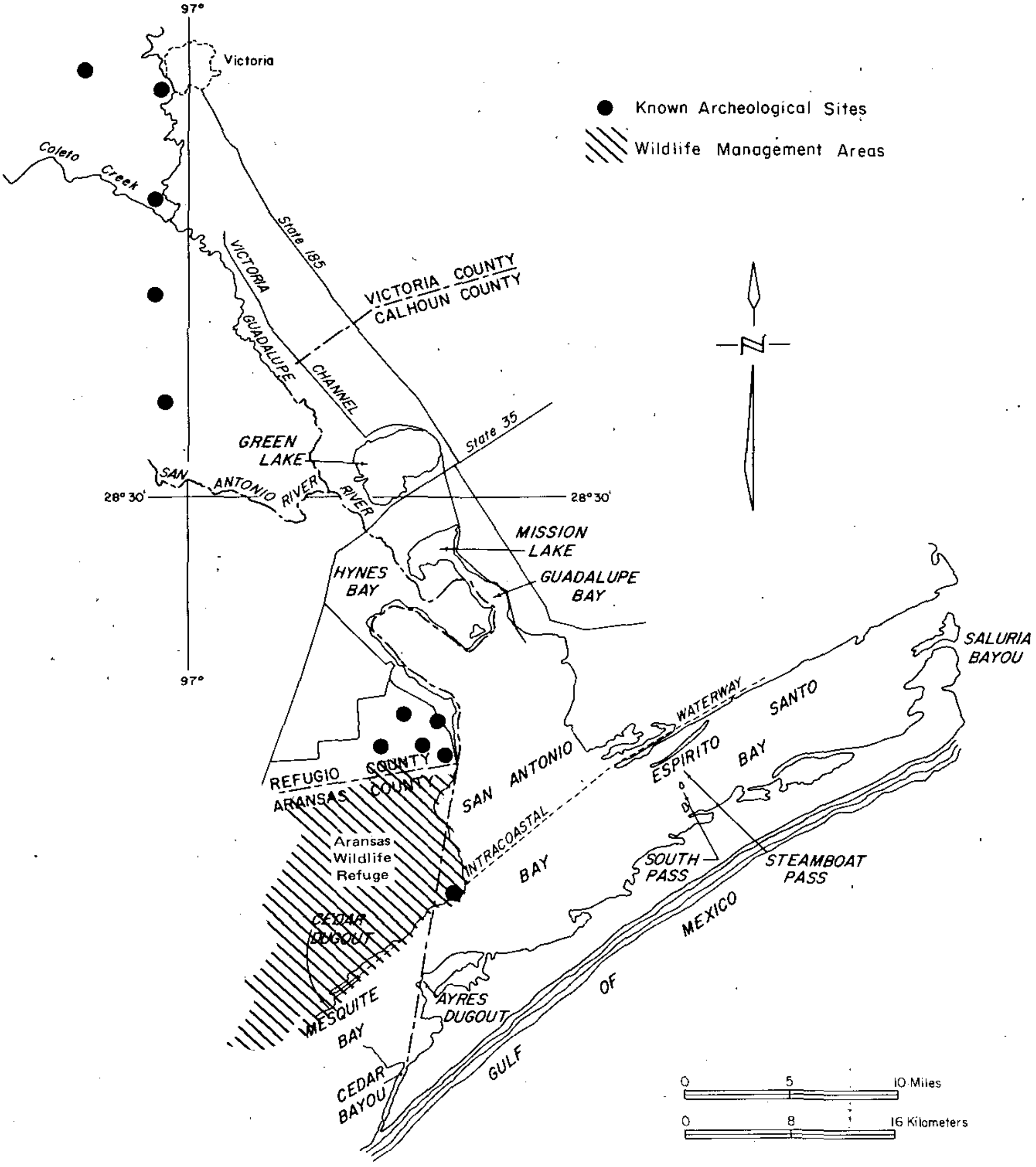

Figure 3-7. Natural Resources, Guadalupe Estuary (330)

Base by U.S. Geological Survey, 1956

Data Collection Program

The Texas Department of Water Resources realized during its planning activities that, with the exception of data from the earlier Galveston Bay Study, very little data were available on the estuaries of Texas. Several limited research programs were underway; however, these were largely independent of one another. The data collected under any one program were not comprehensive, and since sampling and measurement of environmental and ecological parameters under different programs were not accomplished simultaneously, the resulting data could not be reliably correlated. In some estuaries, virtually no data had been collected.

A program was therefore initiated by the Department, in cooperation with other agencies, to collect the data considered essential for analyses of the physical and water quality characteristics and ecosystems of Texas' bays and estuaries. To begin this program, the Department consulted with the U. S. Geological Survey and initiated a reconnaissance-level investigation program in September 1967. Specifically, the initial objectives of the program were to define: (1) the occurrence, source and distribution of nutrients; (2) the current patterns, directions, and rates of water movement; (3) the 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 local, State, and Federal agencies interested in Texas estuarine systems and their management. Principally, through this cooperative program with the U.S. Geological Survey, the Department has continued the collection of 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 Guadalupe estuary during November 16-20, 1970 and August 6-9, 1973. Tidal amplitudes were measured simultaneously at numerous locations throughout the estuary (Figure 3-9). Tidal flow measurements were made at several different bay cross-sections (A,B,C,D,E, and H of Figure 3-9). In addition, conductivity data were collected at many of the sampling stations shown in Figure 3-8. 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 Guadalupe estuary is reflected in the direct and indirect linkages of bay-supported resources to the economies of Aransas, Calhoun, Refugio,

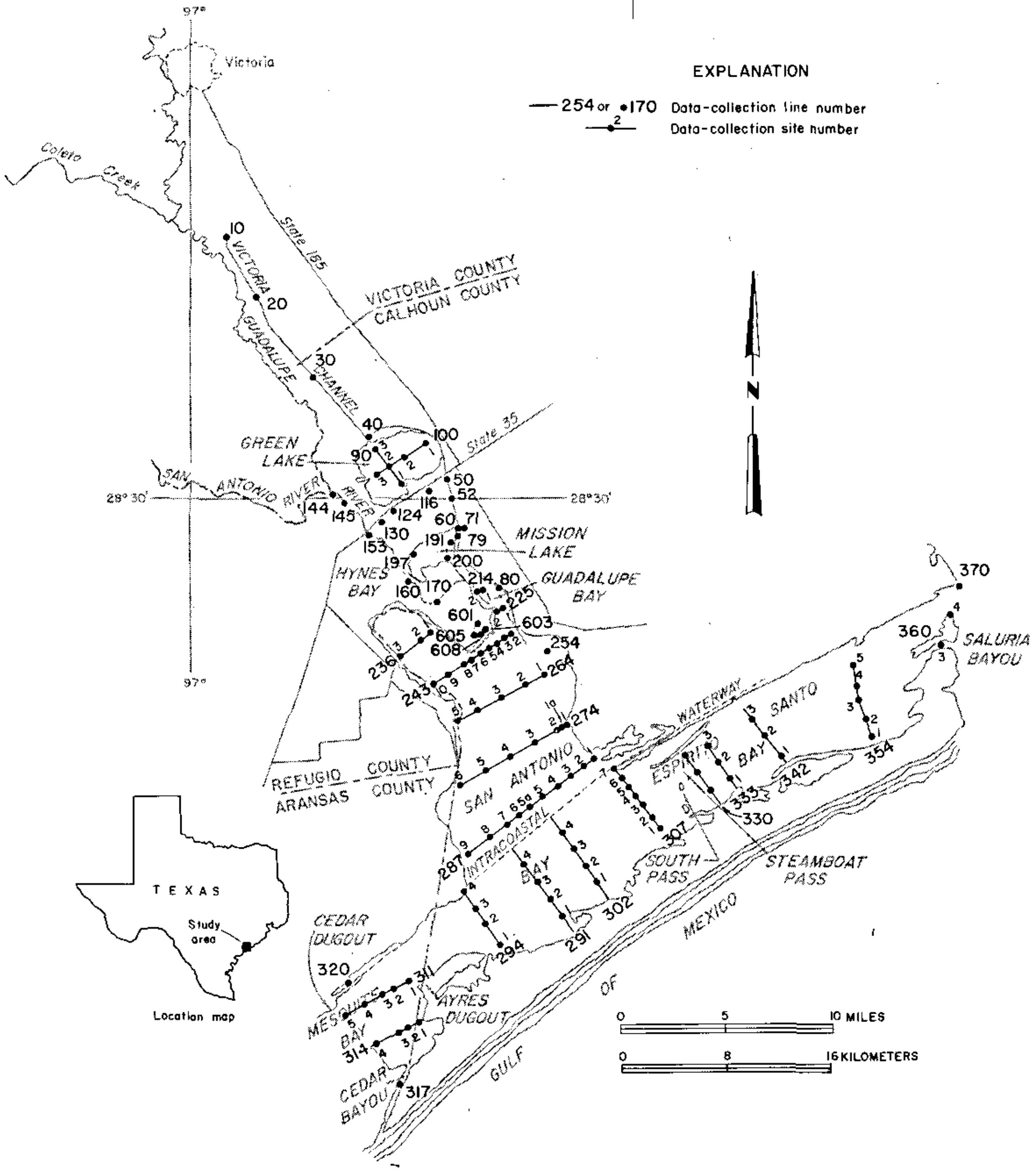

Figure 3-8. Data Collection Sites in the Guadalupe Estuary

Base by U.S. Geological Survey, 1956

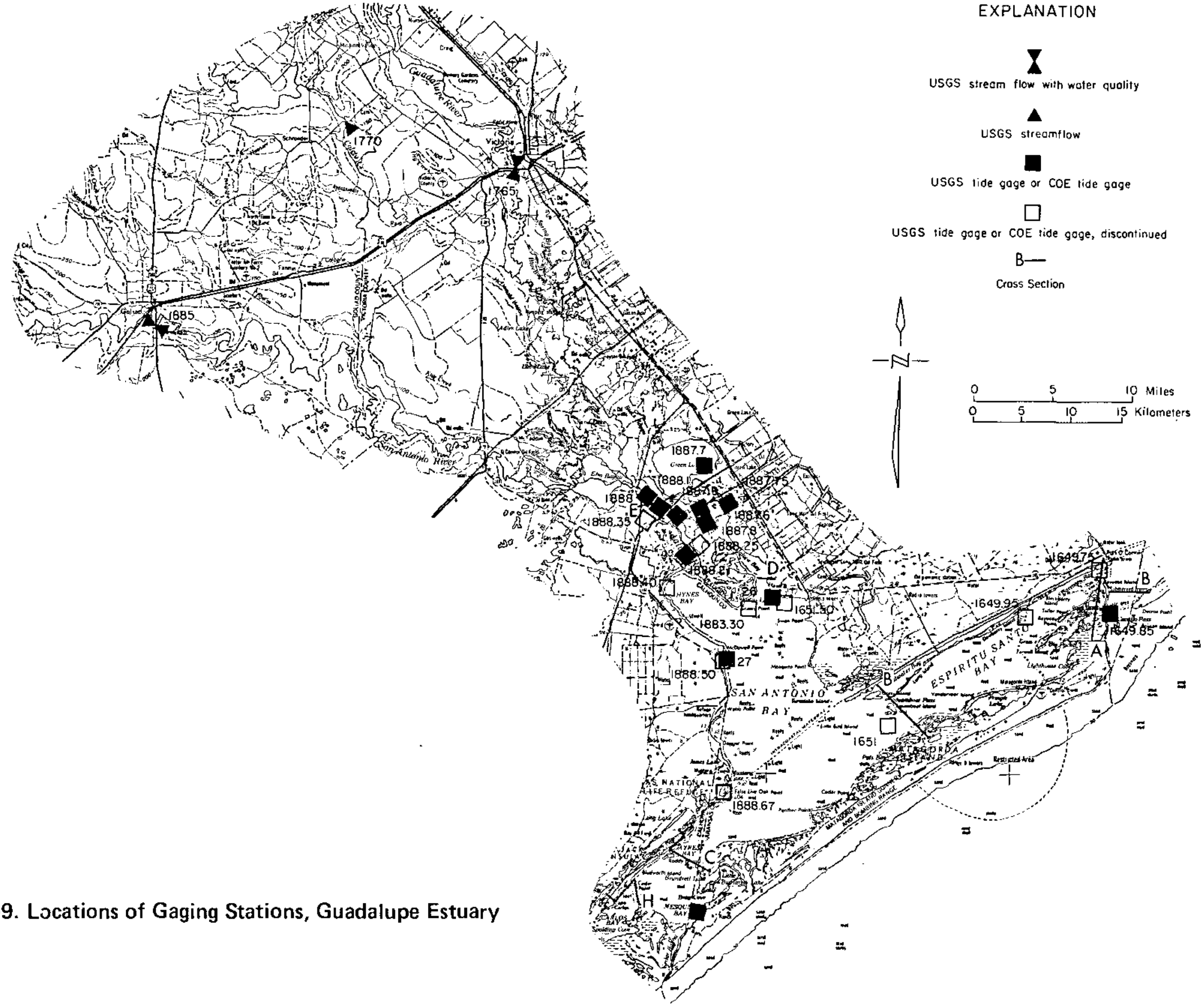

Figure 3-9. Locations of Gaging Stations, Guadalupe Estuary

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

Station Number	Station Description	Period of Record	Operating Entity	Type of Record
	Tide Gages			
22A	Saluria Bayou, Old Coast Guard Station	1964-69	COE	Continuous Recording
26	San Antonio Bay, Victoria Channel Marker #28	1966-	COE	Continuous Recording
27	San Antonio Bay, Hoppers Landing	1969-	COE	Continuous Recording
1649.75	Intracoastal Waterway at Port O'Connor	1970-71	USGS	Continuous Recording
1649.85	Pass Cavallo nr. Port O'Connor	1971-	USGS	Continuous Recording
1649.95	Espiritu Santo Bay nr. Port O'Connor	1966-	USGS	Continuous Recording
1651.00	San Antonio Bay (S. Pass) nr. Seadrift	1971-76	USGS	Continuous Recording
1651.55	San Antonio Bay nr. Seadrift	1966-	USGS	Continuous Recording
1887.60	Guadalupe Delta at Goff Bayou nr. Long Mott	1974-76	USGS	Continuous Recording
1887.70	Green Lake nr. Long Mott	1975-	USGS	Continuous Recording
1887.75	Aligator Slide Lake nr. Long Mott	1975-	USGS	Continuous Recording
1887.80	Mission Lake at Mamie Bayou nr. Long Mott	1975-76	USGS	Continuous Recording
1887.90	Schwing's Bayou nr. Tivoli	1975-	USGS	Continuous Recording
1888.00	Guadalupe River nr. Tivoli	1965-	USGS	Continuous Recording
1888.10	Guadalupe River at Hwy. 35 nr. Tivoli	1975-	USGS	Continuous Recording

(continued)

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

Station Number	Station Description	Period of Record	Operating Entity	Type of Record
1888.20	Guadalupe River nr. Traylor Cut nr. Tivoli	1974-	USGS	Continuous Recording
1888.25	Traylor Cut nr. Tivoli	1974-	USGS	Continuous Recording
1888.30	Lucas Lake nr. Seadrift	1975-	USGS	Continuous Recording
1888.35	Townsend Bayou nr. Austwell	1975-	USGS	Continuous Recording
1888.40	Guadalupe Delta at Townsend Bayou nr. Austwell	1974-	USGS	Continuous Recording
1888.50	San Antonio Bay nr. Austwell	1969-	USGS	Continuous Recording
1888.67	San Antonio Bay (Mus. Lake) nr. Austwell	1971-76	USGS	Continuous Recording
1888.75	Mesquite Bay (CED BA) nr. Fulton	1971-	USGS	Continuous Recording
	Stream Gages			
1765.00	Guadalupe River at Victoria	1934-	USGS	Continuous Recording
1770.00	Coleto Creek nr. Schroeder	1930-1933 & 1952-	USGS	Continuous Recording
1885.00	San Antonio River at Goliad	1924-1929 & 1939-	USGS	Continuous Recording

and Victoria Counties. Trends in population, employment, earnings by industry sector, and personal income levels are presented here for the four counties.

Population. The population of the four county study area experienced an annual growth of 1.1 percent between 1970 and 1975, lower than the statewide figure of 1.7 percent for the same period. Only Aransas County had annual growth (3.49 percent) higher than the statewide average, while Calhoun and Refugio Counties both had slight annual declines in population (-0.03 and -0.84 percent, respectively). Victoria County's population grew in this period (1.5 percent annually) but at a rate lower than the statewide average. In 1975, the population of the four-county area was 95,200 with Victoria County accounting for 61 percent of the projected total.

Population forecasts for the period 1975 to 2030 project an increase in the population of the study area of 1.5 percent per annum up to the year 2030. Victoria County is projectd to remain the most populated, accounting for 64 percent of the study area population in the year 2030. Aransas County, however, has the highest projected growth rate, growing by 2.6 percent per annum from 1970 (9.9 percent of the study area population) to 2030 (19 percent of the study area population). Details of population estimates for the four-county area are presented in Table 3-3.

Income. Regional personal real income is projected to grow at approximately the same annual rate (4.6 percent) as statewide personal real income during the period 1970-2030 (Table 3-4). Regional personal income is projected to quadruple in the period 1970 to 2000, and to be 15 times the 1970 amount (in constant dollars) by the year 2030.

Employment. In 1970, an estimated 31,507 persons were employed in the study area, with over half of these (60 percent) working in Victoria County. Although Aransas County had the lowest study area employment in 1970 (9 percent of the regional total), it was projected to grow steadily to 2030 at a rate of 3.0 percent higher than the statewide average (1.9 percent). Refugio County, however, was projected to have a steady decline in employment, falling to 3.5 percent of the regional total by 2030 (Table 3-5).

The four county area employment is projected to increase by 1.6 percent annually from 1970 to 2030, bringing total employment to 79,747. During this period, however, the region's share of total state employment should fall from 0.76 percent to 0.63 percent.

Almost eighty percent of the region's employed labor force is distributed among eight major industrial sectors (Table 3-6). More workers are involved in wholesale and retail trade than any other sector.

Industry. The "basic" industries in the area, are manufacturing, agriculture-forestry-fisheries, and mining. These sectors account for over 25 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 42 percent of the region's workers. The service sectors provide goods and services to the

Table 3-3. Population Estimates and Projections, Area Surrounding Guadalupe Estuary, 1970-2030 (234).

County	1970	1975	1980	1990	2000	2010	2020	2030	1970-2000 Annual % Change	1970-2030 Annual % Change
Aransas	8,902	10,500	12,400	16,200	20,600	26,000	33,000	42,200	2.8	2.6
Annual % Change	3.4	3.4	2.7	2.4	2.4	2.4	2.5			
Calhoun	17,831	17,800	18,100	18,800	19,800	21,600	24,700	29,900	.35	.87
Annual % Change	.03	.33	.38	.52	.87	1.4	1.9			
Refugio	9,494	9,100	8,900	8,300	7,900	7,600	7,500	7,500	-.61	-.39
Annual % Change	.84	-.44	-.70	-.49	-.39	-.13	0.0			
Victoria	53,766	57,800	63,200	74,400	86,400	100,000	117,700	140,200	1.6	1.6
Annual % Change	1.5	1.8	1.6	1.5	1.5	1.6	1.8			
Area Total	89,993	95,200	102,600	117,700	134,700	155,200	182,900	219,800	1.4	1.5
Annual % Change	1.1	1.5	1.4	1.4	1.4	1.7	1.9			
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. Total Personal Income Estimates and Projections, Area Surrounding Guadalupe Estuary, 1970-2030 (233)

County	1970		1975		1980		1990		2000		2010		2020		2030	1970-2000 Annual % Change	1970-2030 Annual % Change
									(Thousands of 1967 Dollars)								
Aransas	26,874		37,730		56,704		97,651		162,510		265,247		434,968		718,399	6.2	5.6
Annual % Change		7.0		8.5		5.6		5.2		5.0		5.1		5.1			
Calhoun	53,384		66,154		85,297		115,972		158,786		222,604		327,210		508,468	3.7	3.8
Annual % Change		4.4		5.2		3.1		3.2		3.4		3.9		4.5			
Refugio	24,761		28,143		35,494		44,839		57,306		73,181		95,772		126,893	2.8	2.8
Annual % Change		2.6		4.8		2.4		2.5		2.5		2.7		2.9			
Victoria	145,510		199,576		278,555		434,998		665,377		1,003,164		1,537,283		2,382,589	5.2	4.8
Annual % Change		6.5		6.9		4.6		4.3		4.2		4.4		4.5			
Area Total	250,529		331,603		456,050		693,460		1,043,979		1,564,196		2,395,233		3,736,349	4.9	4.6
Annual % Change		5.8		6.6		4.3		4.2		4.1		4.4		4.5			
State Total	35,846,152		44,951,363		62,557,602		95,505,267		145,751,088		221,114,166		337,452,588		517,720,460	4.8	4.6
Annual % Change		4.6		6.8		4.3		4.3		4.3		4.3		4.4			

Table 3-5. Employment Estimates and Projections, Area Surrounding Guadalupe Estuary, 1970-2030 (228)

County	1970	1980	1990	2000	2010	2020	2030	1970-2000 Annual % Change	1970-2030 Annual % Change
Aransas	2,845	4,123	5,456	7,689	10,507	14,372	19,690	3.4	3.3
Annual % Change	3.8	2.8	3.5	3.2	3.2	3.2			
Calhoun	5,835	6,736	8,067	9,695	11,521	13,660	16,186	1.7	1.7
Annual % Change	1.4	1.8	1.9	1.7	1.7	1.7			
Refugio	3,471	3,694	3,421	3,333	3,187	3,010	2,828	-.14	-.34
Annual % Change	.62	-.76	-.26	-.45	-.57	-.62			
Victoria	19,356	23,417	26,039	29,381	32,787	36,658	41,043	1.4	1.3
Annual % Change	1.9	1.1	1.2	1.1	1.1	1.1			
Area Total	31,507	37,970	42,984	50,098	58,002	67,700	79,747	1.6	1.6
Annual % Change	1.9	1.2	1.5	1.5	1.6	1.7			
State Total	4,141,529	5,464,942	6,359,709	7,626,875	8,996,254	10,674,866	12,735,365	2.1	1.9
Annual % Change	2.8	1.5	1.8	1.7	1.7	1.8			

Table 3-6. Employment by Industrial Sector, Area Surrounding Guadalupe Estuary, 1970 (228)

	1970					
Sector	Calhoun	Aransas	Refugio	Victoria	Total	Percent of Total Employment of Study Area
Wholesale and Retail Trade	1,020	721	815	4,466	7,022	22.2
Manufacturing	1,589	295	198	3,196	5,278	16.8
Professional Services	877	305	490	3,251	4,923	15.6
Construction	758	273	257	1,567	2,855	9.1
Agriculture, Forestry, and Fisheries	521	217	369	863	1,970	6.3
Mining	80	129	441	980	1,630	5.2
Civilian Government	198	132	124	604	1,058	3.4
Amusement and Recreation	31	35	7	169	242	.8
All Other	761	738	770	4,260	6,529	20.7
Total	5,835	2,845	3,471	19,356	31,507	100.0

basic industries as well as the general public and are, in varying degrees, dependent upon them.

The most important basic sector, in terms of total earnings, is manufacturing (Table 3-7). Most of the manufacturing activity is concentrated in the production of primary metals (mainly aluminum), chemicals, and allied products.

The mineral wealth of the area is also an important factor in its economy. Crude oil production in 1977 exceeded 39 million barrels, or approximately four percent of the state total (259). Ninety percent of regional crude oil production is from Refugio County. Natural gas production (gas well and casinghead gas) in 1977 was over 210 billion cubic feet, or almost 3 percent of the state total. These mineral products supply raw materials for the manufacturing, petroleum refining, and petrochemical industries.

The four county area had over $29 million in crop production in 1977. Major regional crops were cotton, corn, and grain sorghum, with rice being produced primarily in Calhoun County. Livestock and livestock product receipts in 1977 were over $19 million, for a regional agricultural output of over $49 million in that year. Over 60 percent of the regional livestock production was from Victoria County (224). In addition, the bay-supported commercial fishing industry provides fish and shellfish seafoods to local and regional markets.

Total earnings for the region (Table 3-8) are expected to increase at a rate approximately equal to that for the State in the next fifty years, with Aransas County forecasted to grow the fastest and Calhoun County the slowest.

Summary. The four county area possesses 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 co-exist in the bay environment.

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

Economic Importance of Sport and Commercial Fishing

Introduction. Concurrent with the biological and hydrological studies of the Guadalupe 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

Table 3-7. Earnings by Industrial Sector, Area Surrounding Guadalupe Estuary, 1970 (227)

	1970					
Sector	Calhoun	Aransas	Refugio	Victoria	Area Total	Percent of Total Earnings in Study Area
	(Thousands of 1967 Dollars)					
Wholesale and Retail Trade	7,957	3,761	3,002	21,357	36,077	18.5
Manufacturing	26,162	2,250	1,053	25,215	54,680	28.0
Professional Services	4,398	933	1,058	9,994	16,383	8.4
Construction	5,999	1,431	951	7,602	15,983	8.2
Agriculture, Forestry, and Fisheries	5,884	1,898	2,279	5,976	16,037	8.2
Mining	815	1,015	2,451	6,119	10,400	5.3
Civilian Government	4,126	2,078	1,378	7,716	15,298	7.8
Amusement and Recreation	140	118	17	469	744	.38
All Other	5,520	2,953	2,316	18,633	29,422	15.1
County Totals	61,001	16,437	14,505	103,081	195,024	100.0

Table 3-8. Total Earnings Estimates and Projections, Area Surrounding Guadalupe Estuary, 1970-2030 (227)

County	1970	1975	1980	1990	2000	2010	2020	2030	1970-2000 Annual % Change	1970-2030 Annual % Change
				(Thousands of 1967 Dollars)						
Aransas	16,437	19,863	30,666	55,854	98,695	171,233	302,628	534,660	6.2	6.0
Annual % Change	3.9	9.1	6.2	5.9	5.7	5.9	5.9			
Calhoun	61,001	73,658	91,250	114,728	145,698	189,419	261,517	378,421	2.9	3.1
Annual % Change	3.8	4.4	2.3	2.4	2.7	3.3	3.8			
Refugio	14,505	14,517	18,843	25,269	34,418	46,894	66,387	94,438	2.9	3.2
Annual % Change	.02	5.4	3.0	3.1	3.1	3.5	3.6			
Victoria	103,081	143,340	200,041	312,845	480,674	727,820	1,134,509	1,773,213	5.3	4.9
Annual % Change	6.8	6.9	4.6	4.4	4.2	4.5	4.6			
Area Total	195,024	251,378	340,800	508,696	759,485	1,135,366	1,765,041	2,780,732	4.6	4.5
Annual % Change	5.2	6.3	4.1	4.1	4.1	4.5	4.7			
State Total	28,497,186	34,484,956	47,585,986	71,697,242	108,467,269	163,384,822	251,140,204	385,307,112	4.6	4.4
Annual % Change	3.9	6.7	4.2	4.2	4.2	4.4	4.4			

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 Guadalupe estuary. The surveys included: (1) personal interviews; (2) roving counts; and (3) motor vehicle license plate counts (252). Personal interviews of a sample of sport fishing parties on a randomly selected sample of weekend days were conducted at major access points to the Guadalupe 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 for the personal interview sample and fishermen counts conducted during the period September 1, 1976 through August 31, 1977 were used in this analysis. A motor vehicle license plate sample survey was conducted during the summer of 1977 to obtain additional information on sport fishing visitation patterns by county of origin.

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

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

$$T = Z + W$$

where:

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

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

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

where:

Z = Estimated number of boat parties fishing in the Guadalupe estuary for the period September 1, 1976 through August 31, 1977.
z_k = Estimated number of boat parties fishing in the Guadalupe 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 Guadalupe estuary for the period September 1, 1976 through August 31, 1977.
w_k = Estimated number of wade-bank parties fishing in the Guadalupe estuary during the kth calendar quarter of the study period.

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

For boat fishing:

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

where:

z_k = Estimated number of boat fishing parties on weekdays in quarter k,
B_k = Estimated proportion of trailers for which there were boat parties fishing in the study area in quarter k, on weekdays,
H_k = Number of hours subject to being surveyed per weekday in quarter k (14 hours per day in fall, 12 hours per day in winter, 14 hours per day in spring, and 15 hours per day in summer),
r = Sample boat sites within the study area (10 boat sites for the Guadalupe estuary),
D_k = Weekdays in quarter k (m = 64 in fall, spring, and winter, m = 67 in summer),
x_{ij}= Number of trailers counted per hour on weekdays at site i on day j, in quarter k,

N_{ik}= Number of times site i was surveyed on weekdays during quarter k, and
$\bar{A}_k$ = Average number of hours fished per boat party on weekdays in quarter k.

No data were collected for wade-bank fishing in this study period; therefore, the estimate of wade-bank parties was based on the relation of wade-bank to boat fishing as observed in a 1975 study of San Antonio Bay (252).

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

Sport Fishing Visitation Estimates. Results from the visitation estimation equations indicate that more than 50 thousand fishing parties visited the Guadalupe estuary during the period September 1, 1976 through August 31, 1977 (Table 3-9). Seasonal visitation as a percentage of annual visitation ranged from a high of more than 42 percent for the summer quarter to a low of approximately 15 percent during the winter quarter. The distribution of fishing parties by strata indicates that boat fishing accounted for about 93 percent of annual visitation followed by wade-bank fishing with approximately seven percent (Table 3-9).

Sport Fishing Visitation Patterns. Although the personal interview information included the county of residence of the interviewee, the number of interviews (423 in all) was too small to estimate a general visitation pattern to the estuary system. Thus, an intensive sample survey was undertaken in the summer of 1977 to observe, in conjunction with the roving count, the motor vehicle license plate numbers of fishing parties. From the license plate numbers, the vehicle's registration county, presumably the fishing party's county of residence, could be determined. In this way, the effective sample size was increased.

The results of the survey show that over 60 percent of fishermen at Guadalupe estuary came from the following six counties — Victoria (30.8 percent of the summer 1977 visitation), Harris (10.8 percent), Calhoun (7.0 percent), Lavaca (5.9 percent), DeWitt (4.3 percent), and Bexar (3.8 percent). A more general visitation pattern distinction of "local" and "nonlocal" was also made. "Local," for the purposes of this study, includes counties within approximately 60 miles of the estuary area. For the Guadalupe estuary, these counties are Aransas, Calhoun, Goliad, Jackson, Refugio, and Victoria. "Nonlocal" comprises all other Texas counties and out-of-state visitors.

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

Table 3-9. Estimated Seasonal Sport Fishing Visitation to Guadalupe Estuary, 1976-1977 a/

Season b/	Boat	Wade-Bank	Total - All Strata
	thousands of parties		
Fall	11.0 (2.66)	1.3 — c/	12.2 —
Winter	6.9 (2.43)	.5 —	7.4 —
Spring	8.7 (2.53)	.4 —	9.2 —
Summer	20.1 (2.72)	1.3 —	21.4 —
Total All Seasons	46.7 (2.63)	3.5 —	50.2 —

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

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

c/ Wade-bank fishermen/party data not available.

interview data to remove the bias toward local data and provide a more accurate reflection of year-round visitation patterns (Table 3-10).

Sport Fishing Direct Expenditures. During the interview, a question was asked of the party head for total expected cost of the trip for the entire group, including food, lodging, and gasoline. The personal interview survey sample of fishing party expenditure data was grouped by origin (local or nonlocal). The average cost per party for the various fishing types and origins (Table 3-11) was applied to the adjusted visitation distribution estimates (Table 3-10) and visitation estimation by type (Table 3-9) to obtain an estimate of total sport fishing expenditures (Table 3-12). Nearly 43 percent of estimated $2.1 million expenditures were made during the summer and 15 percent were made during the winter quarter (Table 3-12).

Sport Fishing Economic Impact Analysis. Sport fishing expenditures exert an effect upon the economies of the local regions where fishing occurs and upon the entire State because of transportation expenses, sport fishing equipment sales, and service sector supply and demand linkages directly and indirectly associated with fishing expenses. The direct, or initial, business effects are the actual expenditures for goods and services purchased by sport fishing parties. For this analysis, the expenditures for transportation, food, lodging, equipment, and other materials and services purchased were classified by economic sector. Specifically, the expenditures that vary with size of party, duration of trip, and distance traveled, i.e., variable expenditures, were classified into: recreation (including marinas, boat rental fees, and boat fuel); fisheries (bait); eating and drinking establishments; lodging services; and travel (gasoline and auto service stations). Equipment expenditures for boat insurance, boats, motors, trailers, and fishing tackle are not available. Thus, this analysis is an understatement of the total business associated with sport fishing in the Guadalupe 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 purchased materials and services. The total amount of successive rounds of purchases is known as the indirect effect. The total business effects of sales of equipment, supplies, and services to fishing parties upon the regional and state economies include the direct and indirect incomes resulting from the direct fishing business. Each economic sector pays wages, salaries and other forms of income to employees, owners and stockholders who in turn spend a portion of these incomes on goods and services. In this study, the Texas Input-Output model (236) and regional input-output tables (240) were used to calculate the impact throughout the economy.

The expenditure data collected by personal interviews of a sample of fishing parties at the Guadalupe estuary (Table 3-12) 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

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

Table 3-10. Estimated Seasonal Sport Fishing Visitation Patterns at Guadalupe Estuary, 1976-1977

Visitation	Fall	Winter	Spring	Summer	Total-Annual
			thousands of parties		
Local	6.1	2.8	3.0	8.3	20.2
Nonlocal	6.2	4.7	6.1	13.0	30.0
Total Visitation	12.3	7.5	9.1	21.3	50.2

Table 3-11. Estimated Average Cost per Sport Fishing Party by Type and Origin, Guadalupe Estuary, 1976-1977

Average Cost per Party	Boat	Wade-Bank	Pier a/	Weighted Average
		1976 dollars		
Local	24.41	12.31	—	23.17
Nonlocal	53.99	51.62	—	53.87

a/ No data collected in this time period.

Table 3-12. Estimated Sport Fishing Expenditures by Season and Fishing Party Type, Guadalupe Estuary, 1976-1977

Season a/	Boat	Wade-Bank	Pier b/	Total	Percent
			thousands of 1976 dollars		
Fall	431.2	41.6	—	472.8	22.7
Winter	299.8	14.7	—	314.6	15.1
Spring	390.3	10.6	—	400.9	19.2
Summer	861.2	33.7	—	894.8	43.0
Total	1982.5	100.6	—	2083.0	100.00

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

b/ No data collected in this time period.

industries in the West Gulf of Mexico region (Mississippi delta to Mexican border) (385). To account for different origins and types of fishing parties, variable expenditures were analyzed for each of the four types of fishing parties: local boat parties; local wade-bank parties; nonlocal wade-bank parties; and nonlocal boat parties. Variable expenditures, except for travel, were classified as having been made within the local region, since that is the site at which the service is produced. For the travel sector, it was assumed that one-half of the expenditures occurred within the local area and one-half occurred elsewhere in the state en route to the study area.

The results of the survey show that variable sport fishing expenditures in the local area of the Guadalupe estuary were over $1.93 million. In addition, there were an estimated $146 thousand spent outside the region within Texas (Table 3-13). Most of the expenditure impact, over 92 percent, accrued to the region. However, when the total impacts are calculated, the regional gross impact of over $3.4 million accounted for less than half (49 percent) of the gross dollar value statewide (Table 3-14). 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 $1.1 million from the sport fishing business in the area (Table 3-14). Statewide, the income impact amounted to over $1.9 million, annually.

The input-output analysis estimated a total of 125 full time job equivalents directly related to sport fishing in the Guadalupe estuary region in 1976 through 1977. Statewide, an additional 13 full time job equivalents were estimated to be directly related to the expenditures for sport fishing. The total employment impact to the state economy was 232 full time job equivalents (Table 3-14).

Revenues to state and local governments (including schools) are positively impacted by the increased business activity and gross dollar flows from sport fishing business. The total statewide state tax revenues amounted to over $71 thousand, with $33.3 thousand collected in the local region. Most of the state revenues were received from the rest of the State and not from the surrounding estuarine region. However, the total tax revenue impacts for local jurisdictions were concentrated within the region where an estimated $65.9 thousand resulted from direct, indirect and induced sport fishing expenditures (Table 3-14). In addition, local governments outside the Guadalupe estuary region collected an estimated $49 thousand in taxes on travel expenditures by fishing parties in 1976 through 1977.

The data show that sport fishing in the Guadalupe estuary region results in a larger economic impact in areas outside the region than within the region, except for regional local tax revenues. However, data necessary to analyze the affects of the sport fishing equipment business were not available. Thus, the annual statewide gross output impact of over $6.7 million represents a contribution to the State's economy from only the variable expenditures by sport fishermen in the estuary region and does not include the effects of purchases of sport fishing equipment.

Table 3-13. Estimated Sport Fishing Variables Expenditures by Sector, Guadalupe Estuary, 1976-1977

	Bait	Travel	Food	Lodging	Recreation a/	Total
	thousands of 1976 dollars					
Total	393.1	377.7	421.2	128.1	762.9	2,083.0 b/

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a/ Marinas, boat fuel, and boat rental.
b/ Adjusted for travel expenditures outside the study area 2,083.0 - 146.2 . Expenditures in the region = $1,936.8 thousand.

Table 3-14. Direct and Total[a/] Economic Impact from Sport Fishing Expenditures, Guadalupe Estuary, 1976-1977 b/

	Direct c/		Total	
	Regional	State	Regional	State d/
Output (thousands)	$1,936.8	$2,083.0	$ 3,485.9	$ 6,783.4
Employment (Man-Years)	125	138	161	232
Income (thousands)	714.3	787.2	1,071.3	1,959.5
State Tax Revenues (thousands)	e/	20.7	33.3	71.9
Local Tax Revenues (thousands)	e/	32.5	65.9	115.3

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

Economic Impact of Commercial Fishing. The analysis of the commercial fishing industry in the Guadalupe estuary was somewhat limited by the availability of estuary-specific data. Estimates made of this estuary's total contribution to commercial fisheries harvests were based on the fisheries inshore-offshore harvest distributions. However, the specific markets into which the fish catch were marketed were 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 538,700 pounds (244,863 kg) of finfish and 12,411,800 pounds (5,641,727 kg) of shellfish for the period 1972 through 1976. Using 1976 dockside finfish and shellfish prices ($0.357 per lb. and $1.456 per lb., respectively), the direct commercial value of fish attributed to the estuary was estimated at $18.26 million (1976 dollars) (362). Shrimp, blue crab, and oysters constituted approximately 98 percent of this value.

The Texas economy-wide total business resulting from commercial fish catch attributed to the Guadalupe estuary was estimated using the 1972 Texas Input-Output Model fisheries sector multipliers. Total value of the catch was $18.26 million, direct employment in the fisheries sector was 665, and direct salaries to fisheries employees was $6.1 million (Table 3-15).

Gross Texas business resulting from fishing, processing, and marketing the catch attributed to the estuary in 1976 was estimated at $56.89 million. Statewide employment associated with this fishery business was estimated at 665 full time equivalent jobs in the direct fishing activity and an additional 401 full time equivalent jobs in the indirect supporting and marketing activities. Gross personal income in Texas attributed to the estuarine fishing and supporting sectors was estimated at $15.64 million, state taxes at $576.9 thousand, and taxes paid to local units of governments throughout Texas, as a result of this fishery business, at $717.8 thousand in 1976 (Table 3-15).

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 affects 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 $1.93 million. In addition, there was an estimated $146.2 thousand spent outside the region, within Texas.

Table 3-15. Direct and Total a/ Economic Impact of Commercial Fishing in the Guadalupe Estuary, 1976

	Fishing Sector	Total	
		Regional	State
Output (1000's 1976 $)	18,263.9	30,592.0	56,892.0
Employment (Man-Years)	665	1,066	1,413
Income (1000's 1976 $)	6,102.0	10,526.0	15,645.5
State Tax Revenues (1000's 1976 $)	69.4	244.7	516.9
Local Tax Revenues (1000's 1976 $)	82.2	493.1	717.8

a/ Total = direct, indirect and induced.

Over 36 percent of the direct expenditures by sport fishermen in the region resulted in increased personal incomes for regional households directly affected by the sport fishing industry. Statewide, the income impact amounted to over $1.95 million, annually. In addition, the total employment impact to the State economy was 232 full-time job equivalents.

Revenues to State and local government (including schools) were positively impacted by the increased business activity and gross dollar flows from the sport fishing industry. The total statewide State tax revenues amounted to over $71 thousand. Except for regional local tax revenues, sport fishing resulted in a larger economic impact in areas outside the region than locally.

Estimates were made of the inshore-offshore commercial fisheries catch associated with the Guadalupe estuary. The average annual commercial fisheries contribution was estimated at 12,950,500 pounds of finfish and shellfish for the period 1972 through 1976. The total value of the catch was $18.26 million, direct employment in the commercial fisheries sector was 665, and direct salaries to employees was $6.10 million.

CHAPTER IV

HYDROLOGY

Introduction

Detailed studies of the hydrology of areas draining to the Guadalupe 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 Guadalupe estuary, the Guadalupe and San Antonio Basins. Additionally, small coastal basins, including a portion of the Lavaca-Guadalupe Coastal Basin and the San Antonio-Nueces Coastal Basin, contribute to the estuary. An earlier section of this report (Chapter III, "Influence of Contributory Basins") describes upstream reservoirs in the major basins. The present section deals with aspects of the quality and quantity of freshwater inflow from a historical perspective.

Freshwater Inflows

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

Gaged Inflows from the Guadalupe and San Antonio Basins

The Guadalupe and San Antonio Basins have a total gaged drainage area of 9,447 square miles (24,580 km^2). This inflow enters the estuary through the Guadalupe delta at the western edge of Mission Lake and Guadalupe Bay. Gaged contributions of the Guadalupe and San Antonio River Basins to the estuary have averaged 1,808,000 acre-feet/year (2,221 million m^3/yr) over the period 1941 through 1976 (Table 4-1). Gaged yields from the Guadalupe Basin and San Antonio Basin (1941 through 1976) have averaged 412 acre-feet per square mile (1,962 m^3/ha) and 124 acre-feet per square mile (590 m^3/ha), respectively. Gaged Guadalupe and San Antonio Basin inflows have accounted for 80 percent of the combined inflow1/ and 67 percent of the total freshwater inflow2/ to the Guadalupe estuary over the 1941 through 1976 period (Table 4-2).

Ungaged Runoff Contributions

Ungaged drainage areas contributory to the Guadalupe estuary include some 762 square miles (1,983 km^2) in the Lavaca-Guadalupe Coastal Basin, the San

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

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

Table 4-1. Monthly Freshwater Inflow, Guadalupe Estuary (1941-1976) a/

thousands of acre-feet

MONTH	GAGED GUADU. INFLOW	SAN. AN. INFLOW	TOTAL GAGED INFLOW	UNGAGED INFLOW	RETURN FLOWS	DIVERSIONS	COMBINED INFLOW	PRECIPITATION ON BAY	TOTAL FRESHWATER INFLOW	BAY EVAPORATION LOSSES	FRESHWATER INFLOW BALANCE
AVERAGE OVER ALL YEARS											
JANUARY	97	32	129	21	0	0	150	26	176	28	148
FEBRUARY	107	33	140	35	0	0	176	29	205	28	177
MARCH	96	24	120	24	0	0	144	18	163	38	124
APRIL	121	36	157	35	0	0	193	29	222	45	177
MAY	190	66	256	46	0	0	303	43	347	58	288
JUNE	142	45	188	42	0	0	230	39	269	71	198
JULY	81	35	116	30	0	0	147	31	179	85	93
AUGUST	52	24	76	30	0	0	107	50	158	87	71
SEPTEMBER	113	71	184	63	0	0	248	67	316	69	246
OCTOBER	130	57	188	62	0	0	250	48	299	59	239
NOVEMBER	99	33	132	31	0	0	164	29	193	43	149
DECEMBER	87	26	114	35	0	0	149	31	180	33	147
TOTALS	1315	482	1800	454	0	0	2261	440	2707	644	2057
MONTHLY AVERAGE	110	40	150	38	0	0	188	37	226	54	171

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

Table 4-2. Annual Freshwater Inflow, Guadalupe Estuary (1941-1976) a/b/

YEAR	GAGED GUADA. INFLOW	SAN. AN. INFLOW	TOTAL GAGED INFLOW	UNGAGED INFLOW	RETURN FLOWS	DIVERSIONS	COMBINED INFLOW	PRECIPITATION ON BAY	TOTAL FRESHWATER INFLOW	BAY EVAPORATION LOSSES	FRESHWATER INFLOW BALANCE
1941	2683	765	3448	843	0	0	4291	582	4873	519	4354
1942	1600	903	2503	618	0	0	3121	451	3572	532	3040
1943	706	302	1008	278	0	0	1286	335	1621	578	1043
1944	1388	373	1761	619	0	0	2380	466	2846	554	2292
1945	1401	350	1751	370	0	0	2121	458	2579	554	2025
1946	1919	1034	2953	585	0	0	3538	563	4101	542	3559
1947	1144	317	1461	251	0	0	1712	403	2115	553	1562
1948	480	219	699	252	0	0	951	356	1307	567	740
1949	1108	480	1588	491	0	0	2079	587	2666	545	2121
1950	559	170	729	67	0	0	796	226	1022	612	410
1951	402	225	627	265	0	0	892	351	1243	636	607
1952	831	341	1172	310	0	0	1482	366	1848	614	1234
1953	797	254	1051	259	0	0	1310	438	1748	636	1112
1954	234	88	322	51	0	0	373	239	612	659	-47
1955	268	118	386	107	0	0	493	313	806	774	32
1956	124	111	235	41	0	0	276	244	520	763	-243
1957	2356	780	3136	804	0	0	3940	479	4419	682	3737
1958	2161	760	2941	668	0	0	3609	472	4081	695	3386
1959	1150	315	1465	513	0	0	1978	519	2497	648	1849
1960	2309	544	2853	1011	0	0	3864	676	4540	636	3904
1961	1859	503	2362	548	0	0	2910	509	3419	624	2795
1962	548	212	760	170	0	0	930	349	1279	693	586
1963	371	146	517	41	0	0	558	225	783	707	76
1964	479	223	702	219	0	0	921	335	1256	661	595
1965	1599	516	2115	360	0	0	2475	352	2827	705	2122
1966	919	222	1141	603	0	0	1744	457	2201	613	1588
1967	1454	957	2411	1251	0	0	3662	596	4258	692	3566
1968	2140	756	2896	737	0	0	3633	577	4210	706	3504
1969	1433	375	1808	427	0	0	2235	420	2655	764	1891
1970	1227	347	1574	495	0	0	2069	460	2529	707	1822
1971	834	404	1238	721	0	0	1959	552	2511	763	1748
1972	1677	622	2299	438	0	0	2737	519	3256	690	2566
1973	2993	1591	4584	449	0	0	5033	515	5548	676	4872
1974	1658	565	2223	543	0	0	2766	618	3384	676	2708
1975	2228	764	2992	456	0	0	3448	369	3817	654	3163
1976	2479	894	3373	693	0	0	4066	598	4664	714	3950
TOTAL	47518	17566	65084	16554	0	0	81638	15975	97613	23344	74269
AVERAGE	1320	488	1808	460	0	0	2266	444	2711	648	2063
MEDIAN	1307	374	1669	452	0	0	2100	457	2617	656	1958
PERCENT	48.7 +	18.1 =	66.7 +	17.0 +	.0 −	.0 =	83.7 +	16.4 =	100.0 :	24.0	
PERCENT	58.3 +	21.6 =	79.8 +	20.3 +	.0 −	.0 =	100.0 :	19.6			

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a/ Units are thousands of acre-feet.

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

Antonio-Nueces Coastal Basin, the San Antonio River Basin, and the Guadalupe River Basin. To facilitate the study of inflow contributions, the ungaged drainage contributing to the Guadalupe estuary was divided into six subbasins (Figure 4-1). Using a Thiessen network (336), the weighted daily precipitation was determined for each subbasin. 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 total inflow to the estuary reconstructed from daily inflow records. These records were collected by the Guadalupe-Blanco River Authority for the 1967 through 1976 period. 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 for the 1941 through 1976 period (Table 4-3).

During the period 1941 through 1976, ungaged runoff averaged 460,000 acre-feet/year (0.57 billion m^3/yr) and runoff yield averaged 603 acre-feet/mi^2 (2,872 m^3/ha). Ungaged inflow accounted for 20 percent of the combined inflow and 17 percent of the total freshwater inflow to the Guadalupe 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. Return flows from the Union Carbide plant near Seadrift enter the Victoria Barge Canal, but have an insignificant effect on inflow to the estuary.

Diversions

Diversions were accounted for in the reconstruction of daily total inflow to the estuary in order to obtain ungaged contributions.

Combined Inflow

A category of "combined inflow" was obtained by aggregating gaged Guadalupe River and San Antonio River contributions, and ungaged runoff. Over the period 1941 through 1976, combined inflow averaged 2,268,000 acre-feet/year (2.80 billion m^3/yr) (Table 4-2). Combined inflow accounted for 84 percent of the total freshwater inflow to the Guadalupe estuary over the 1941 through 1976 period. Average monthly distributions of combined inflow are shown in Figure 4-2.

Precipitation on the Estuary

Direct precipitation on the 138,720 acre (56,162 ha) surface area (363) of the Guadalupe estuary was calculated using Thiessen-weighted precipitation techniques (336). Over the 1941 through 1976 period, annual mean precipita-

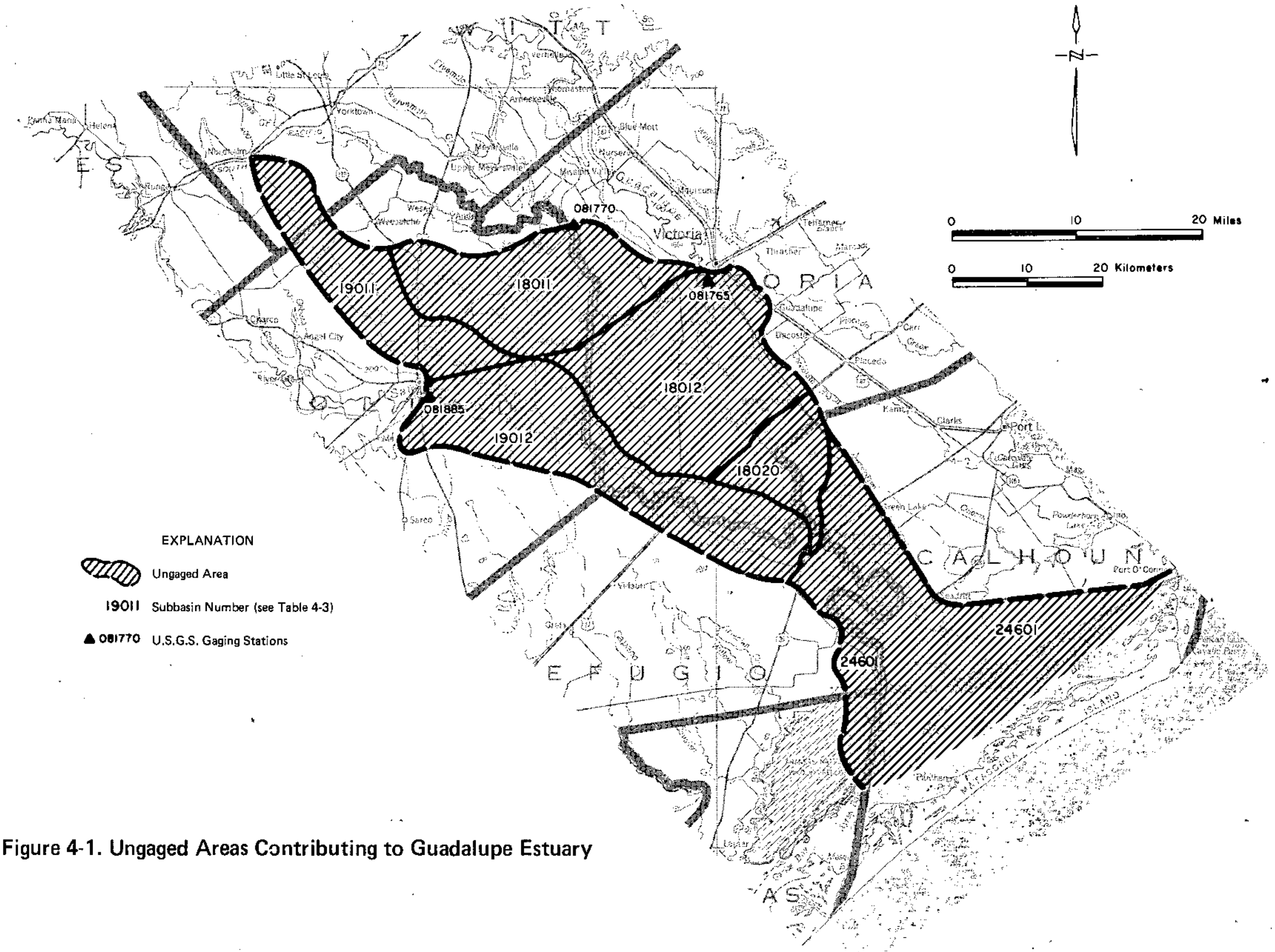

Figure 4-1. Ungaged Areas Contributing to Guadalupe Estuary

Table 4-3. Runoff from Ungaged Areas, Guadalupe Estuary

Subbasin Description	Drainage Area (mi^2)	Weighted Precipitation		Average Runoff ac-ft/mi^2 (1941-1976)	Average Curve Number c/ / Beta x10^{-6} d/	Explained Variation (%)		Gaged	
		NWS a/ Station No.	Weight b/ Factor			Annual r^2	Monthly r^2	USGS Station No.	Period of Record mth/yr
18011 Confluence Upper Above Hwy. 59	146	3618 9363	.40 .60	466	85/43.5	—	—	—	—
18012 Confluence Lower Below Hwy. 59	157	3618 9363 0437	.02 .96 .02	524	85/41.0	—	—	—	—
18020 Coleto	78	0437 9364	.92 .08	631	85/41.2	—	—	—	—
19011 Fannin Upper Above Hwy. 59	98	3618 7836 9953	.64 .16 .20	460	85/41.9	—	—	—	—
19012 Fannin Lower Below Hwy. 59	161	3618 9363 0437	.41 .24 .35	469	85/44.9	—	—	—	—
24601 Coastal	122	0437 7186	.60 .40	620	85/44.0	—	—	—	—
Coleto Creek Near Victoria	514	—	—	111	—	—	—	081775	1/32-12/52
Coleto Creek Near Schroeder	365	—	—	198	—	—	—	081770	10/52-
Guadalupe River At Victoria	5,161	—	—	243	—	—	—	081765	11/34-
San Antonio River At Goliad	3,921	—	—	124	—	—	—	081885	2/39-

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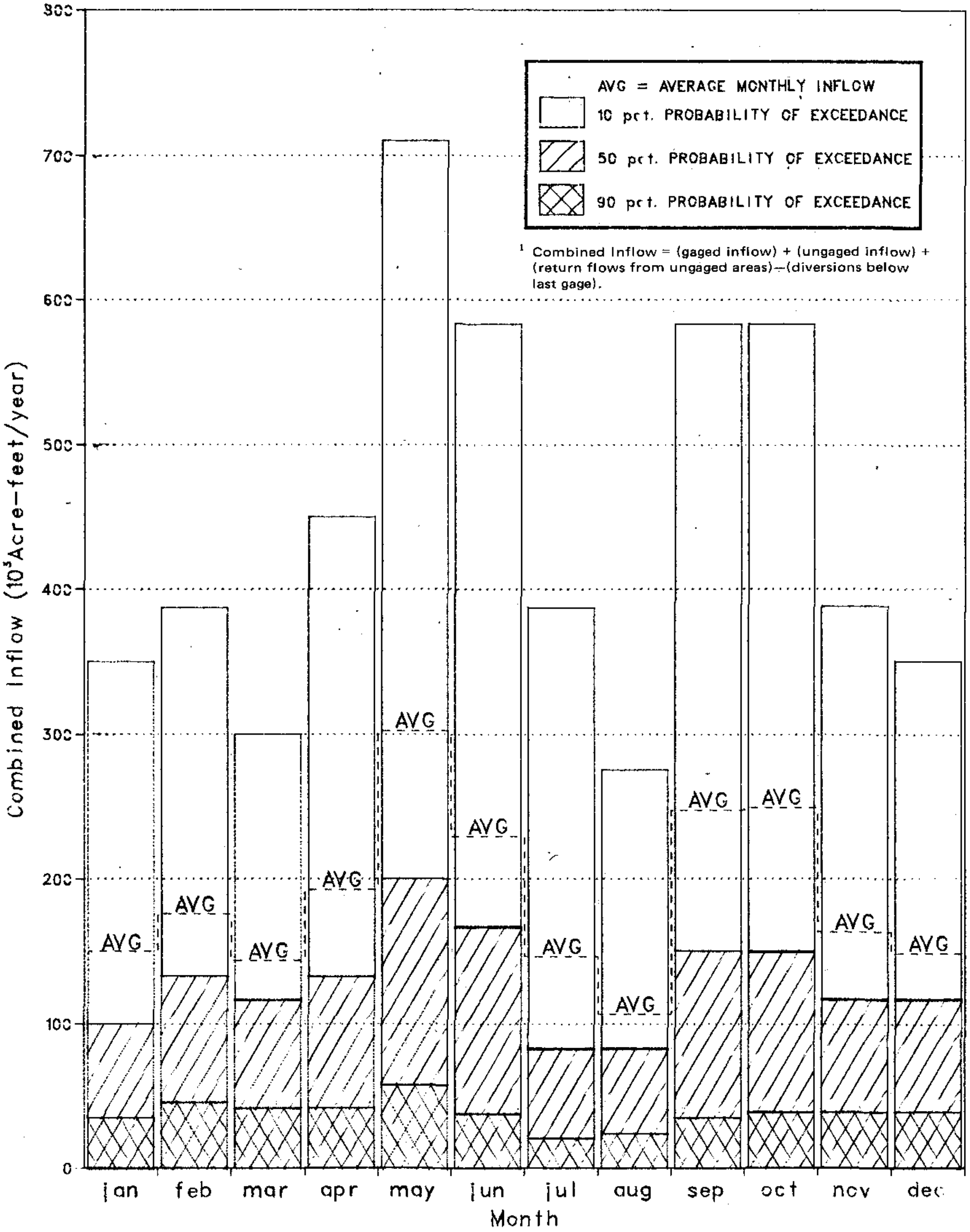
a/ National Weather Service.
b/ Percentage of area of influence expressed as a factor (336)
c/ An assigned parameter for a particular hydrologic soil-cover complex (327)
d/ Soil moisture depletion coefficient (327)



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

Figure 4-2. Monthly Distribution of Combined Inflow, Guadalupe Estuary, 1941-1976 tion amounted to 444,000 acre-feet/year (0.55 billion m^3/year), or 16 percent of the total freshwater inflow to the Guadalupe estuary over the period 1941 through 1976 (Table 4-2).

Total Freshwater Inflow

Total freshwater inflow includes gaged Guadalupe and San Antonio River contributions, ungaged runoff, and direct precipitation on the estuary. For the 1941 through 1976 period, average annual freshwater inflow amounted to 2,771,000 acre-feet (3.35 billion m^3). Average monthly distributions of total freshwater inflow are shown in Figure 4-3.

Bay Evaporation Losses

Gross surface evaporation rates for the estuary were calculated from Texas Department of Water Resources pan evaporation data (329). Since the reduction in evaporation due to estuarine salinity is never in excess of a few percent (over an extended period of time), salinity effects were neglected in the estimation of evaporation rates. Over the period 1941 through 1976, mean evaporation over the 138,720 acre (56,162 ha) estuary surface averaged 648,000 acre-feet/year (0.80 billion m^3/yr). When compared to total freshwater inflow, evaporation on the estuary's surface was about 24 percent of total inflow over the 1941 through 1976 period.

Freshwater Inflow Balance

A freshwater inflow balance for the period of 1941 through 1976 is shown in Table 4-2. A negative number in some years indicates evaporation exceeding total freshwater inflow (during periods of extreme drought). For the 1941 through 1976 period, the mean freshwater inflow balance amounted to 2,063,000 acre-feet/year (2.55 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 4-3 for combined inflow and total freshwater inflow, respectively.

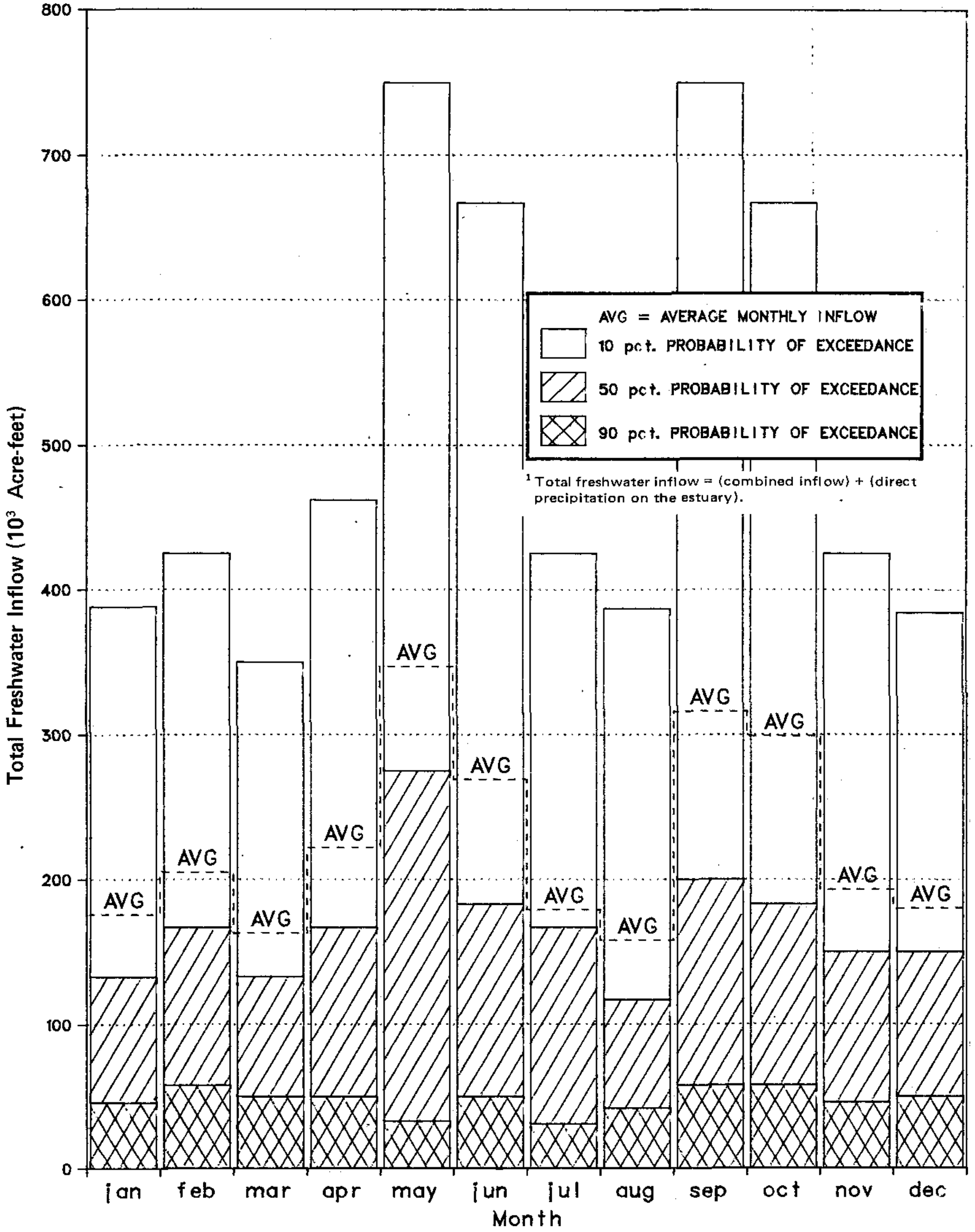


Figure 4-3. Monthly Distribution of Total Freshwater Inflow,[1] Guadalupe Estuary, 1941-1976

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

Month	Gaged Guadalupe Basin Inflow			Gaged San Antonio Basin Inflow			Ungaged Inflow			Combined Inflow			Precipitation on Bay			Total Freshwater Inflow			Bay Evaporation Losses		
	10%	50%	90%	10%	50%	90%	10%	50%	90%	10%	50%	90%	10%	50%	90%	10%	50%	90%	10%	50%	90%
January	200	75	21	56	22	8	75	5	2	350	100	35	58	20	7	388	133	46	39	31	20
February	223	80	28	60	26	9	100	18	2	387	133	46	83	20	5	425	167	58	39	31	24
March	195	75	25	43	23	10	83	8	1	300	117	42	46	12	3	350	133	50	46	42	35
April	280	77	26	75	29	9	92	13	1	450	133	42	75	18	5	462	167	50	58	46	39
May	444	125	30	165	38	11	150	20	2	710	200	58	100	35	12	750	275	83	75	58	50
June	380	87	22	110	27	7	167	18	3	583	167	38	100	27	5	667	183	50	92	75	58
July	205	50	15	69	17	5	100	5	1	387	83	21	92	17	2	425	167	31	117	92	67
August	115	40	14	50	18	5	100	9	1	275	83	24	117	39	10	387	117	42	117	92	75
September	265	60	15	134	36	8	200	24	2	583	150	35	150	50	12	750	200	58	83	75	58
October	275	70	15	117	35	8	200	24	1	583	150	39	133	39	8	667	183	58	75	58	50
November	210	60	15	75	24	8	92	15	1	388	117	39	75	20	5	425	150	46	58	46	39
December	177	65	25	50	24	9	117	12	1	350	117	39	75	24	8	387	150	50	42	35	27

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a/ Units are thousands of acre-feet.

b/ Exceedance frequencies indicate the probability that the corresponding monthly inflow will be exceeded during the given month.

c/ Computed values based on 1941 through 1976 hydrological period.

Quality of Gaged Inflows

Only two USGS gaging stations monitor the quality of inflows to the Guadalupe estuary: Station No. 08176500 (Guadalupe River at Victoria) and Station No. 08188500 (San Antonio River at Goliad). The range of water quality parameters that were experienced in the 1977 water year are tabulated in Figure 4-4. During the period, nine to 12 samples were available for most parameters.

Student's t-tests were performed on the data to determine if any statistical differences (two-tailed test) were evident in the sample means. It was found that for some parameters the difference between the mean values recorded was not statistically significant. However, statistically highly significant differences between parameter means ($\alpha = 0.01$) were found for silica, sodium, sulfate, dissolved solids, total ammonia nitrogen, nitrate nitrogen, total organic nitrogen, and chloride. Statistically significant differences between parameter means ($\alpha = 0.05$) were found for calcium, fluoride and total phosphorus. As a result, concentrations of silica, sodium, sulfate, dissolved solids, ammonia nitrogen, nitrate nitrogen, organic nitrogen, and chloride flowing to the bay from the San Antonio Basin are shown to be higher than those found in the Guadalupe Basin inflows. Higher nutrient concentrations in the San Antonio River can generally be attributed to upstream municipal return flows, including the predominant influence of the City of San Antonio.

In general, the water quality of flows draining to the Guadalupe estuary has been good. No parameters were found in violation of Texas stream standards, although one "total lead" sample from the San Antonio River was in violation of the EPA drinking water standard (0.05 mg/l).

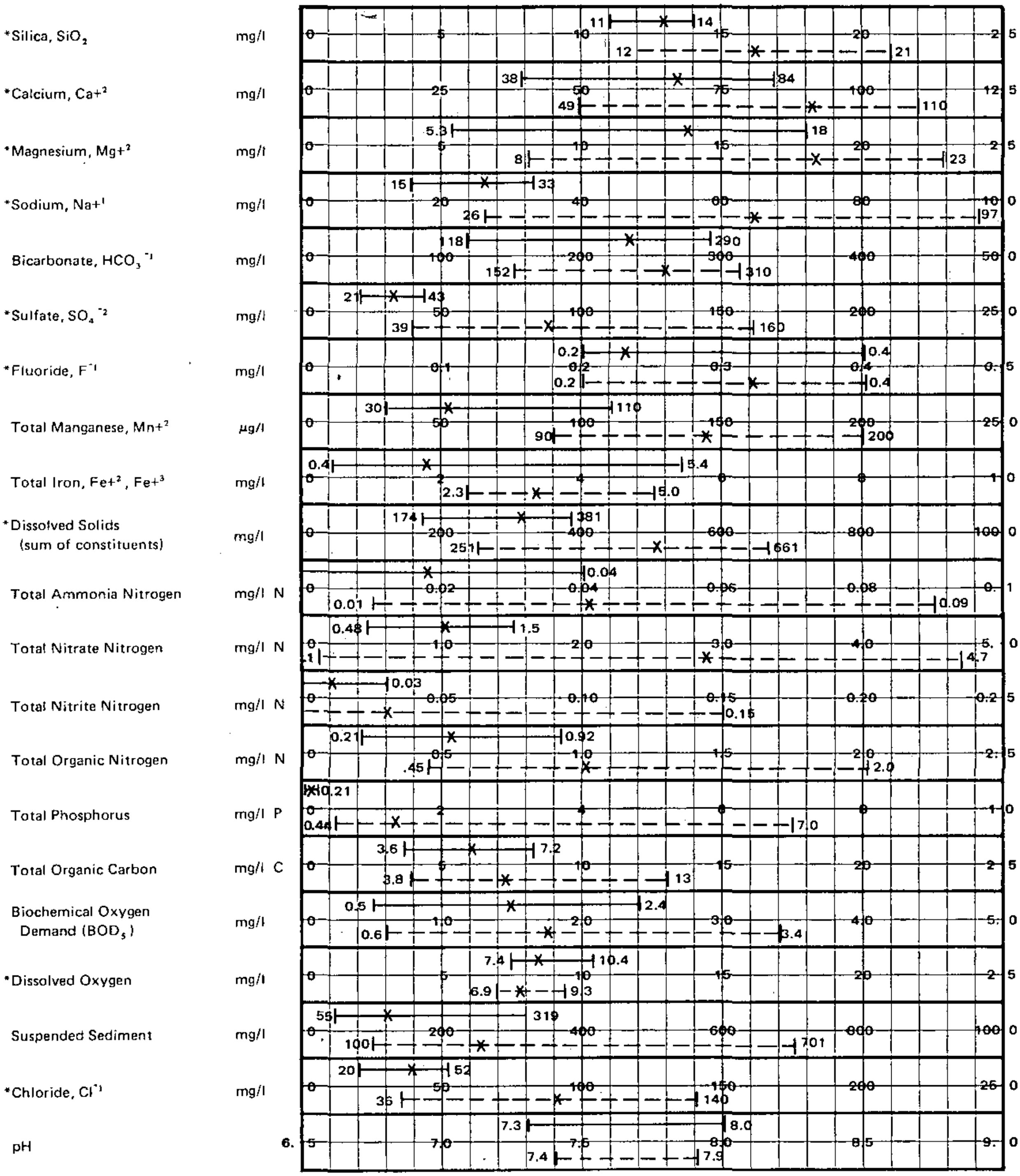
Quality of Estuarine Waters

Nutrient Concentrations in the Guadalupe Estuary

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

Available data can be used to determine general 1968 through 1977 concentrations of nitrogen and phosphorus in the Guadalupe estuary. Temporal variation of nitrogen and phosphorus are based on regional averages for each month for the various portions of the estuary. The estuary was sectioned into five major regions for the analysis: (G1) Hynes, Guadalupe, and upper San Antonio Bays, (G2) middle San Antonio Bay, (G3) lower San Antonio Bay, (G4) Espiritu Santo Bay, and (G5) Ayres and Mesquite Bays (Figure 4-5). Only sample sites located away from major population or industrial centers in open bay waters were considered, since nutrient concentrations near these locales might bias resultant concentrations in open waters.

Freshwater discharges from the San Antonio and Guadalupe Rivers and contributions from the deltaic marshes have been the major source of nutrients



1 |———| 5 Range of values reported at USGS Station 08176500, Guadalupe River at Victoria, Texas.

2 |– – – – –| 6 Range of values reported at USGS Station 08188500, San Antonio River at Goliad, Texas.

——x—— Mean of reported values.

*Dissolved fraction only.

Figure 4-4. Range of Values for Water Quality Parameters, Gaged Inflow to Guadalupe Estuary, October 1975-September 1976 (384)

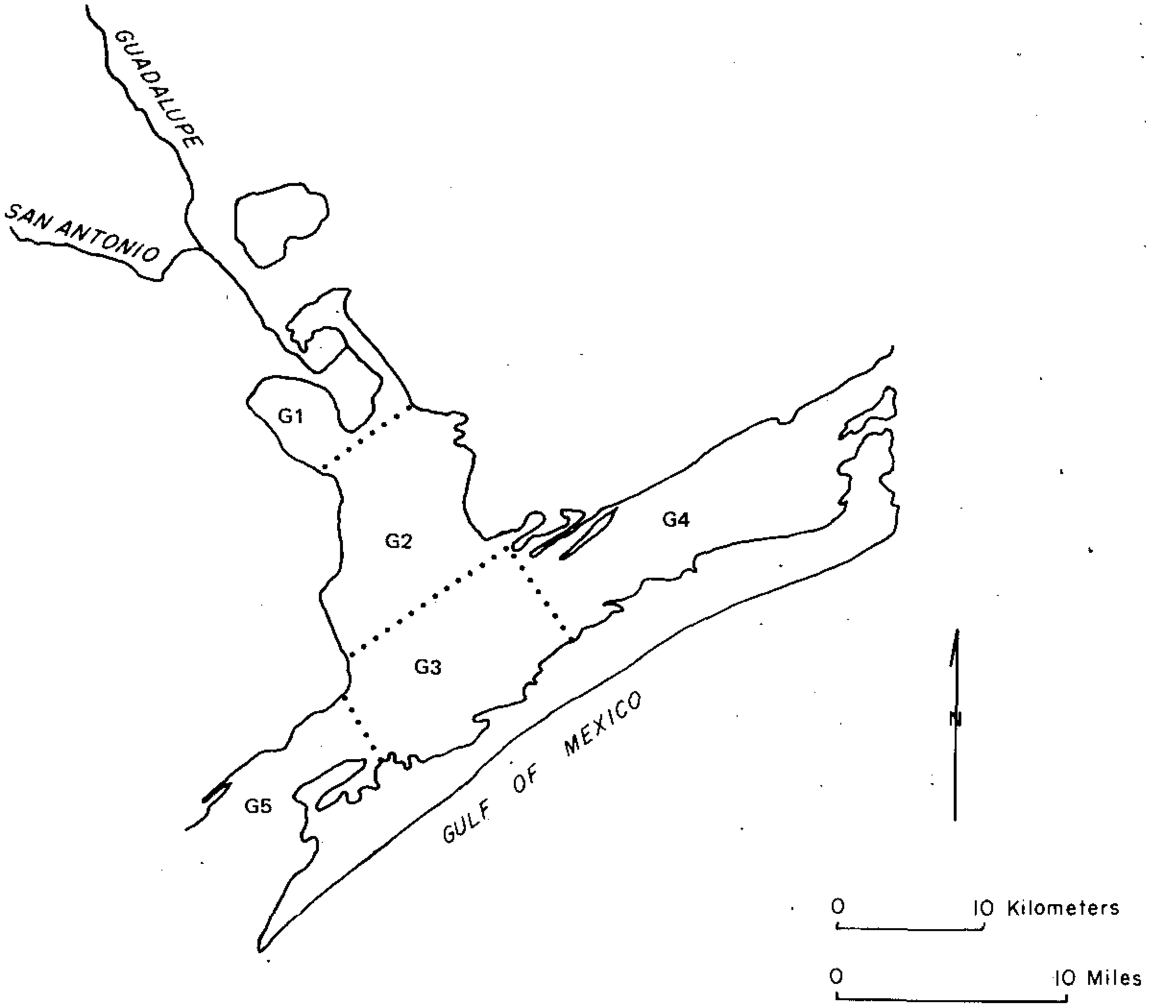


Figure 4-5. Segmentation of the Guadalupe Estuary

for the Guadalupe estuary. The concentrations of nutrients in the bay would, therefore, be expected to exhibit a decreasing gradient with distance from the Guadalupe delta.

Ammonia, nitrite, and nitrate nitrogen were summed for each sample station and month to arrive at total available nitrogen concentrations. Average monthly concentrations for nitrogen and phosphorus were taken for the study period. Subsequent average nutrient isolines and spatial representations are shown for nitrogen and for phosphorus (Figures 4-6 to 4-17) for each month of the year, 1968 through 1977. Nitrogen and phosphorus concentrations have been typically an order of magnitude higher in the upper reaches of the bay. Concentrations of total available nitrogen have ranged from 0.01 mg/l to 2.77 mg/l, whereas, phosphorus levels have ranged from 0.01 mg/l to 0.62 mg/l. Both nitrogen and phosphorus have shown a definite gradient from upper San Antonio to lower San Antonio Bay, while concentrations of these constituents in Espiritu Santo, Ayres and Mesquite Bays have been relatively uniform.

Total phosphorus in the estuary has appeared relatively constant except for the months of December and January (Figure 4-18). Variations in the distribution throughout the estuary could be due to changing flow patterns and biological activity.

Except for the month of May, total available nitrogen has shown a general decreasing trend from the high values normally found in winter months of December and January (Figure 4-19). The total available nitrogen response has followed closely that observed in Guadalupe, Hynes, and upper San Antonio Bays.

Heavy Metals

Samples of the bottom sediments in the Guadalupe estuary are available for the period of record (1970 to 1978) at 16 data collection sites shown in Figure 4-20. Sampling efforts have been conducted by the USGS and the Texas Department of Water Resources in cooperation with other interested agencies. Heavy metals detected have included arsenic (As), barium (Ba), boron (B), cadmium (Cd), cobalt (Co), chromium (Cr), copper (Cu), lead (Pb), manganese (Mn), mercury (Hg), nickel (Ni), silver (Ag), zinc (Zn), and iron (Fe).

Statistical analyses were not possible due to the limited number of samples throughout the period of record. The range of values found for heavy metals in Guadalupe, San Antonio, Hynes, Mesquite, and Espiritu Santo Bays are listed in Table 4-5.

Accumulation of metals in bottom deposits may not be detectable in overlying water samples, yet still exert an influence from time to time. Wind and tide induced water movements, ship traffic and dredging activities are some physical processes that can cause mixing of materials from the sediment into the water. Chemical changes resulting from seasonal temperature fluctuations, oxygenation, and respiration, can influence the rate of movement and distribution of dissolved substances between water and sediment. Microorganisms living on the bottom (benthos) also play an important role in the circulation of metals by taking them up from the sediment, sometimes converting them to more toxic forms. Heavy metals in sediment and water may pose a threat to edible shellfish such as oysters and crabs as these organisms generally con-

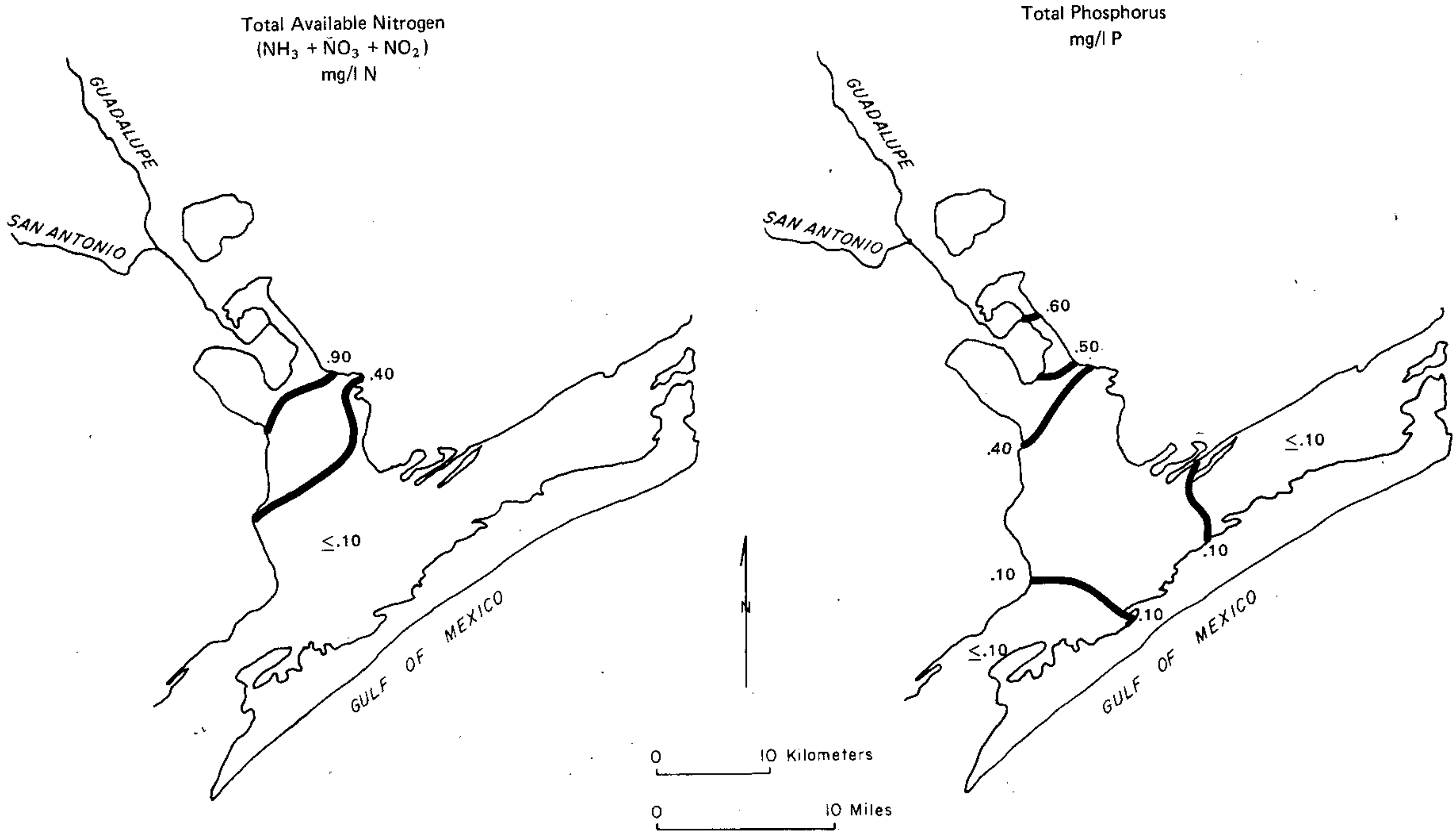


Figure 4-6. Average Monthly Concentrations of Total Nitrogen and Phosphorus, January 1968-1977

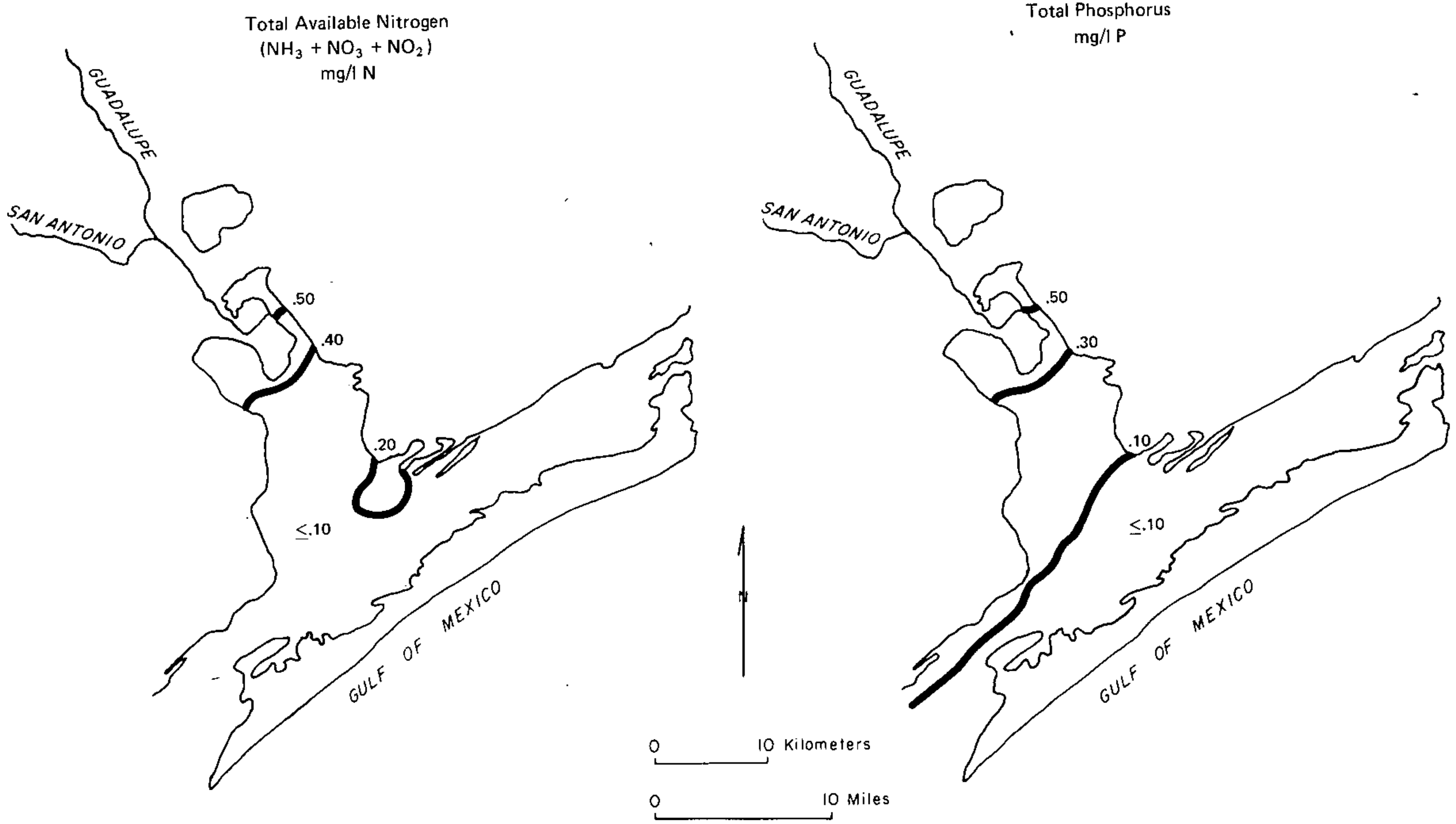
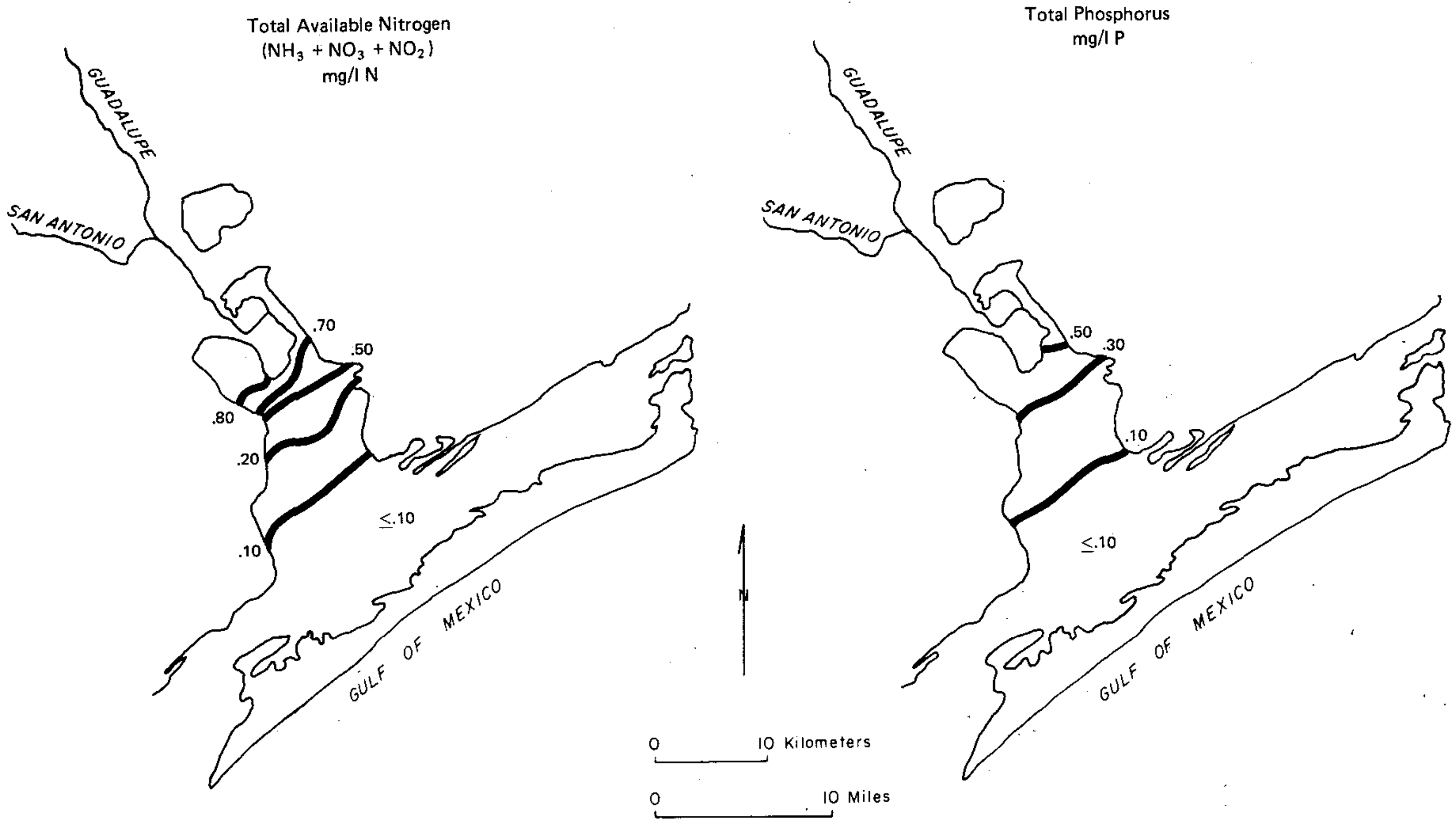
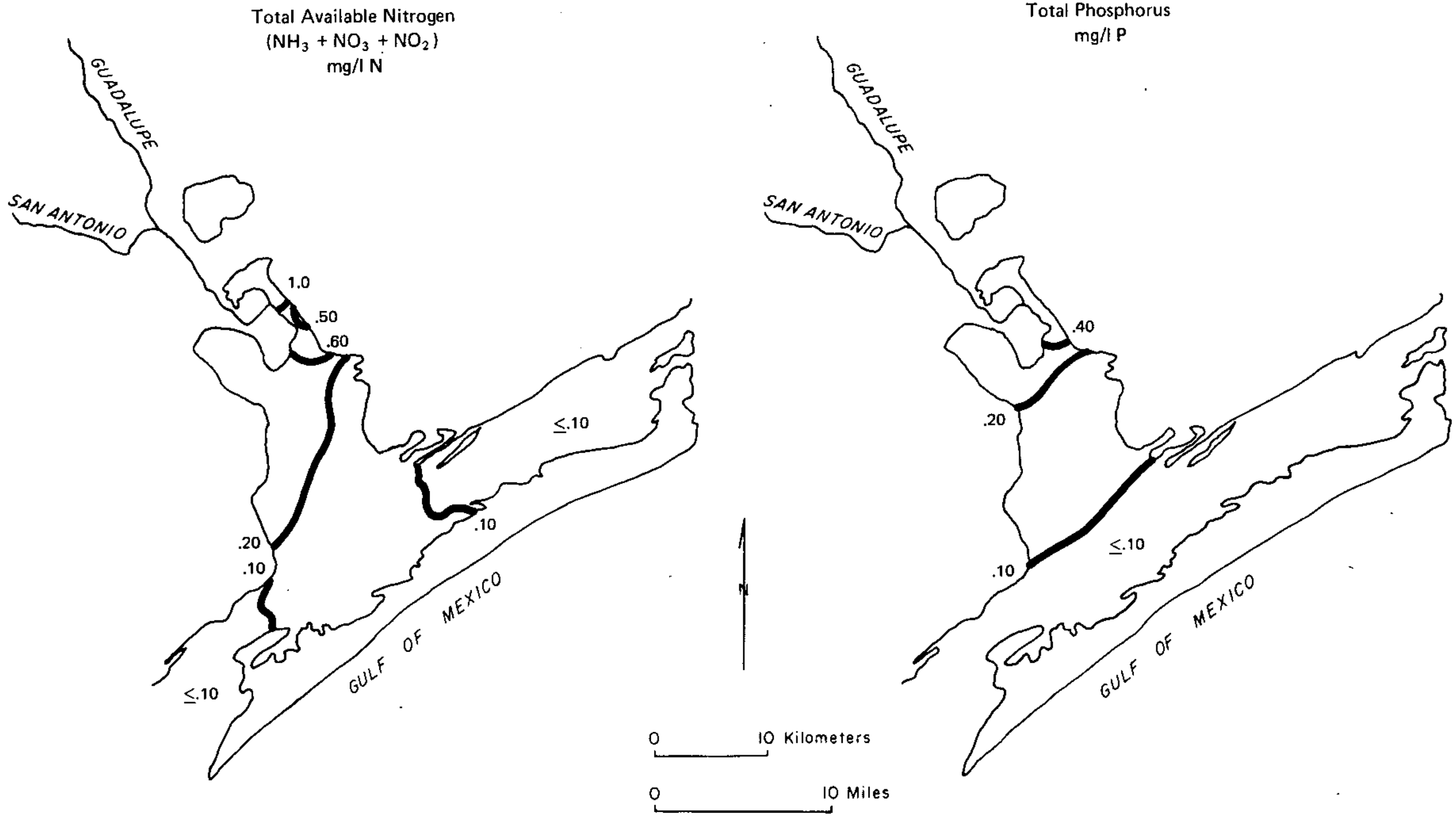


Figure 4-7. Average Monthly Concentrations of Total Nitrogen and Phosphorus, February 1968-1977


Total Available Nitrogen
($NH_3 + NO_3 + NO_2$)
mg/l N

Total Phosphorus
mg/l P

Figure 4-8. Average Monthly Concentrations of Total Nitrogen and Phosphorus, March 1968-1977



Total Available Nitrogen (NH_3 + NO_3 + NO_2) mg/l N

Total Phosphorus mg/l P

Figure 4-9. Average Monthly Concentrations of Total Nitrogen and Phosphorus, April 1968-1977

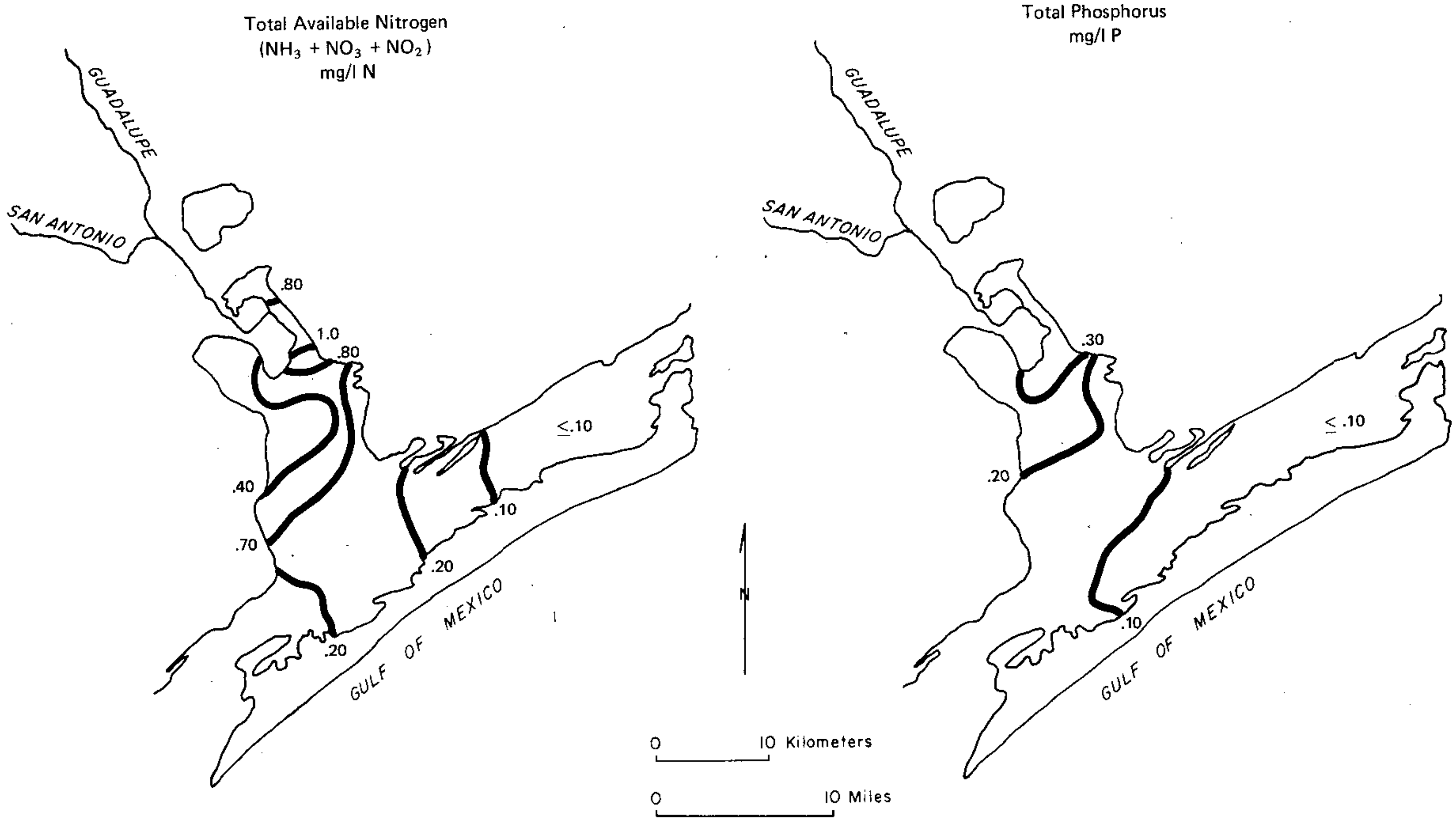
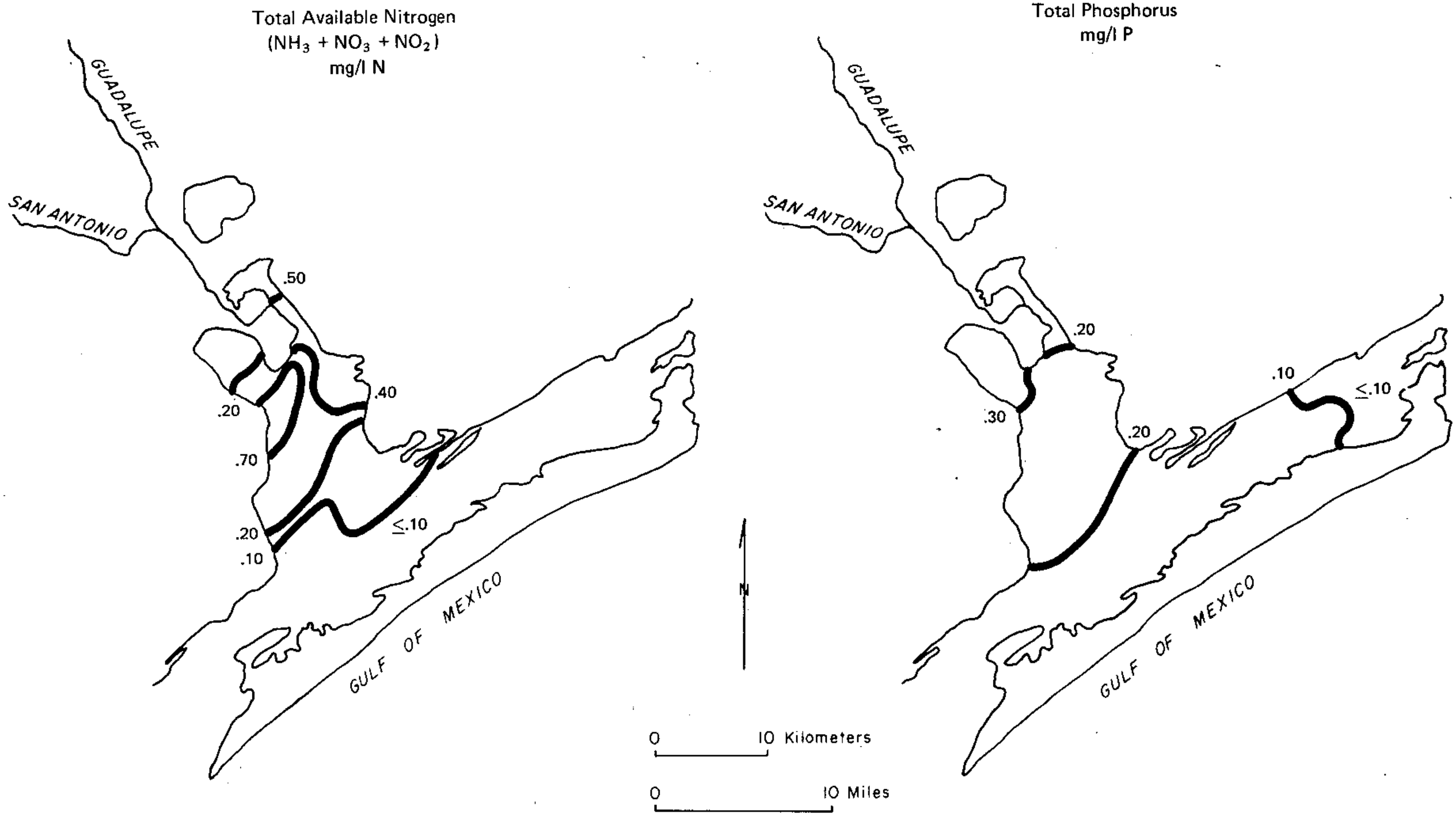


Figure 4-10. Average Monthly Concentrations of Total Nitrogen and Phosphorus, May 1968-1977


Total Available Nitrogen ($NH_3 + NO_3 + NO_2$) mg/l N

Total Phosphorus mg/l P

Figure 4-11. Average Monthly Concentrations of Total Nitrogen and Phosphorus, June 1968-1977

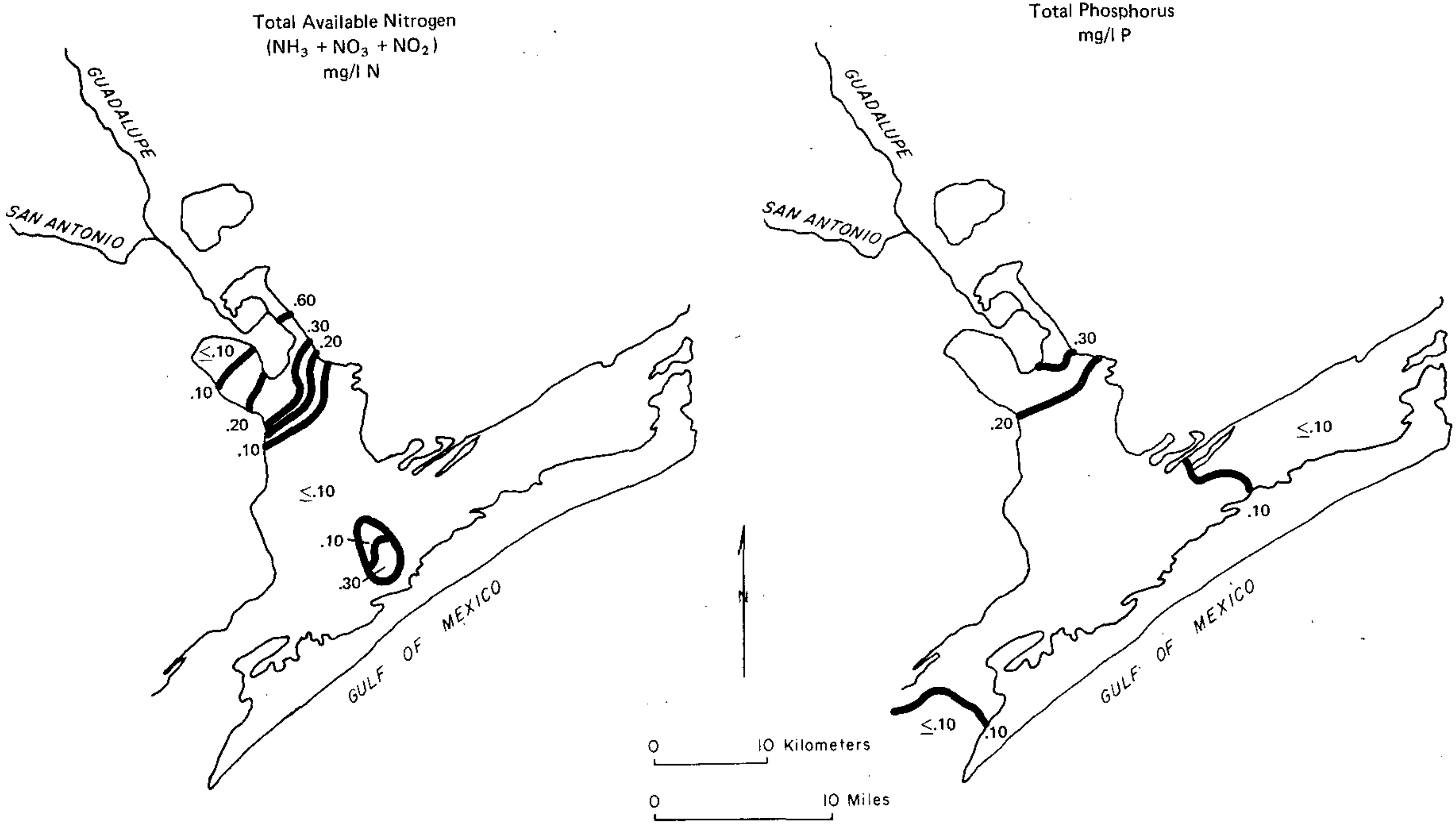


Figure 4-12. Average Monthly Concentrations of Total Nitrogen and Phosphorus, July 1968-1977

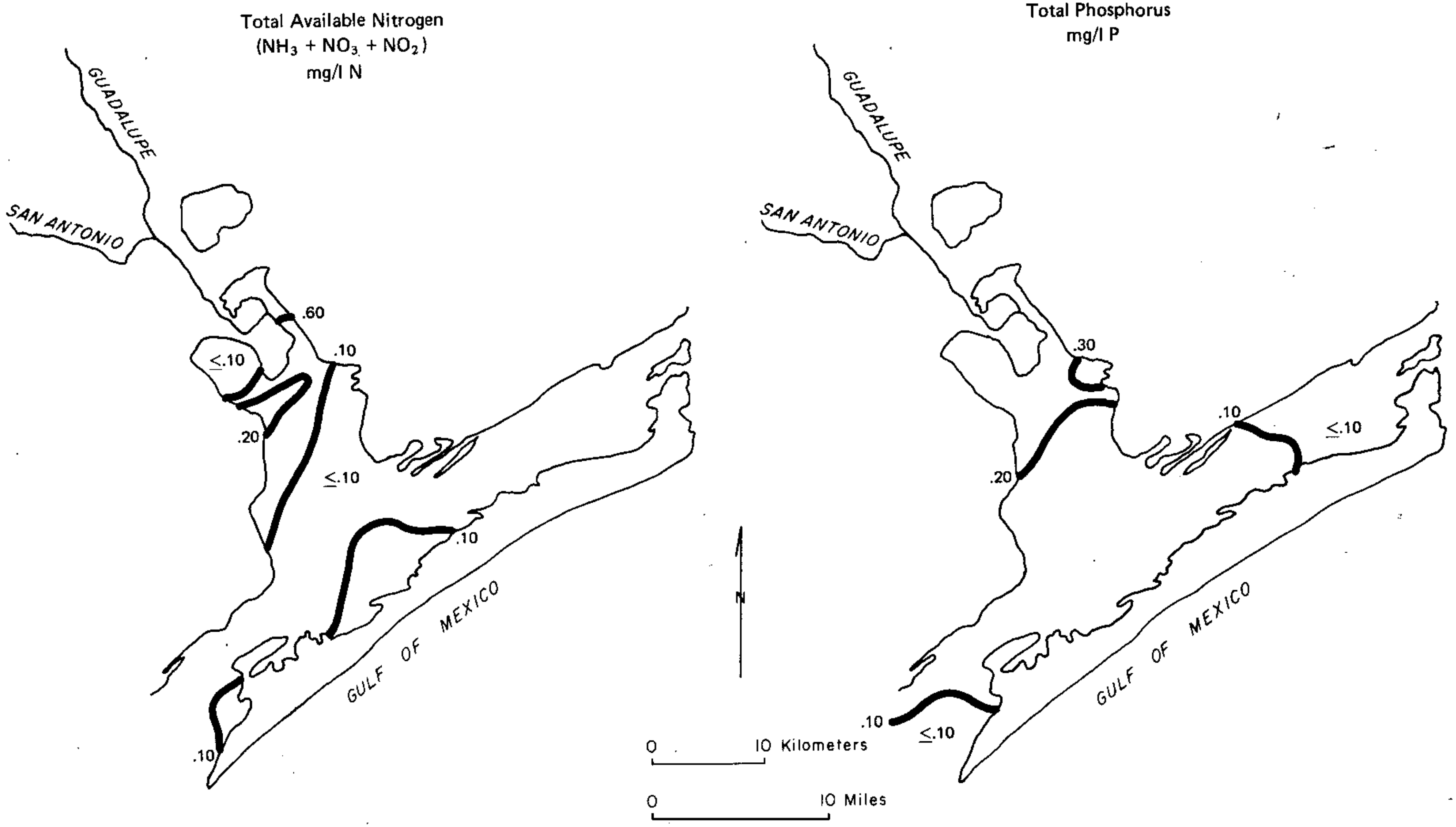
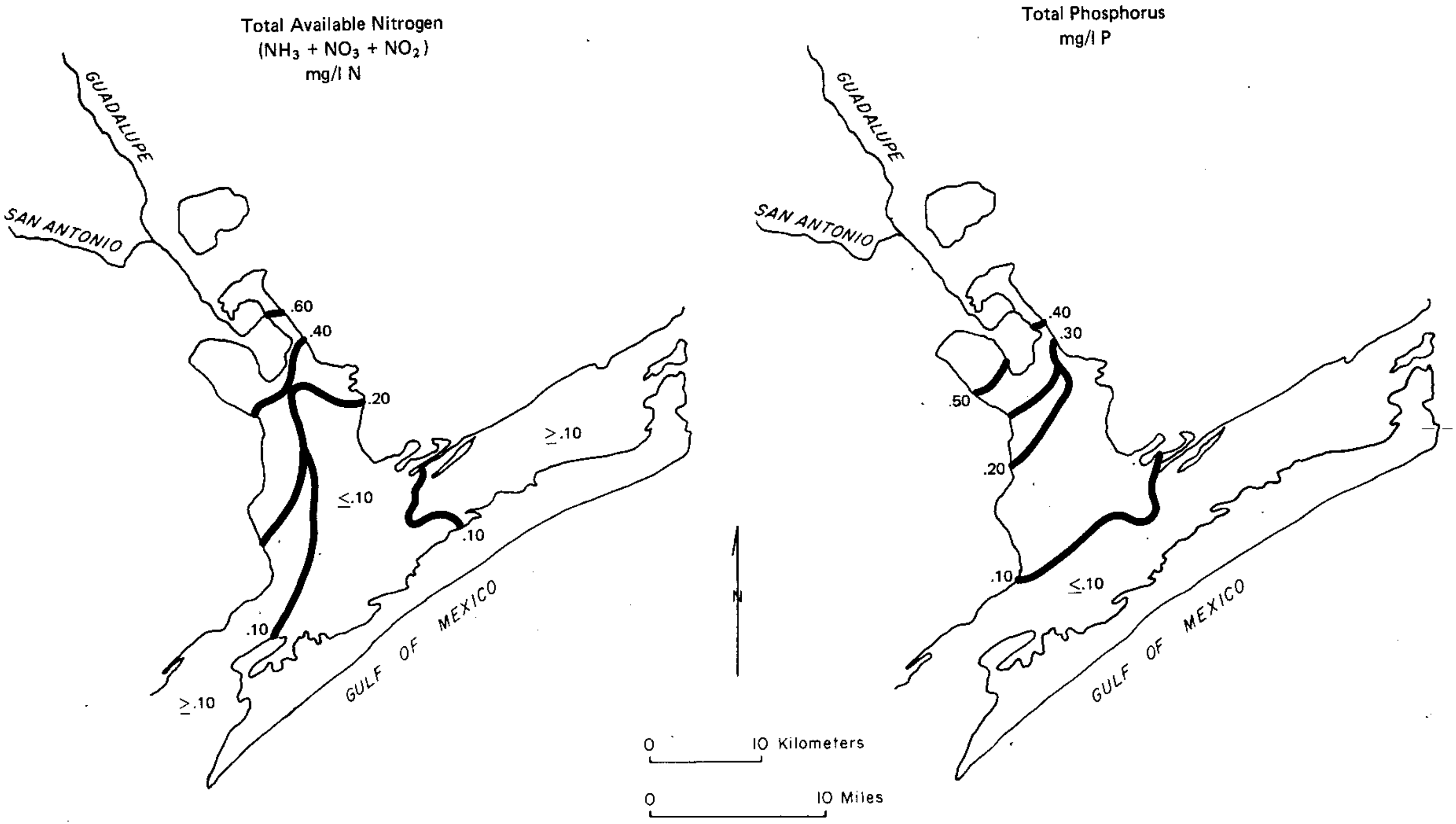


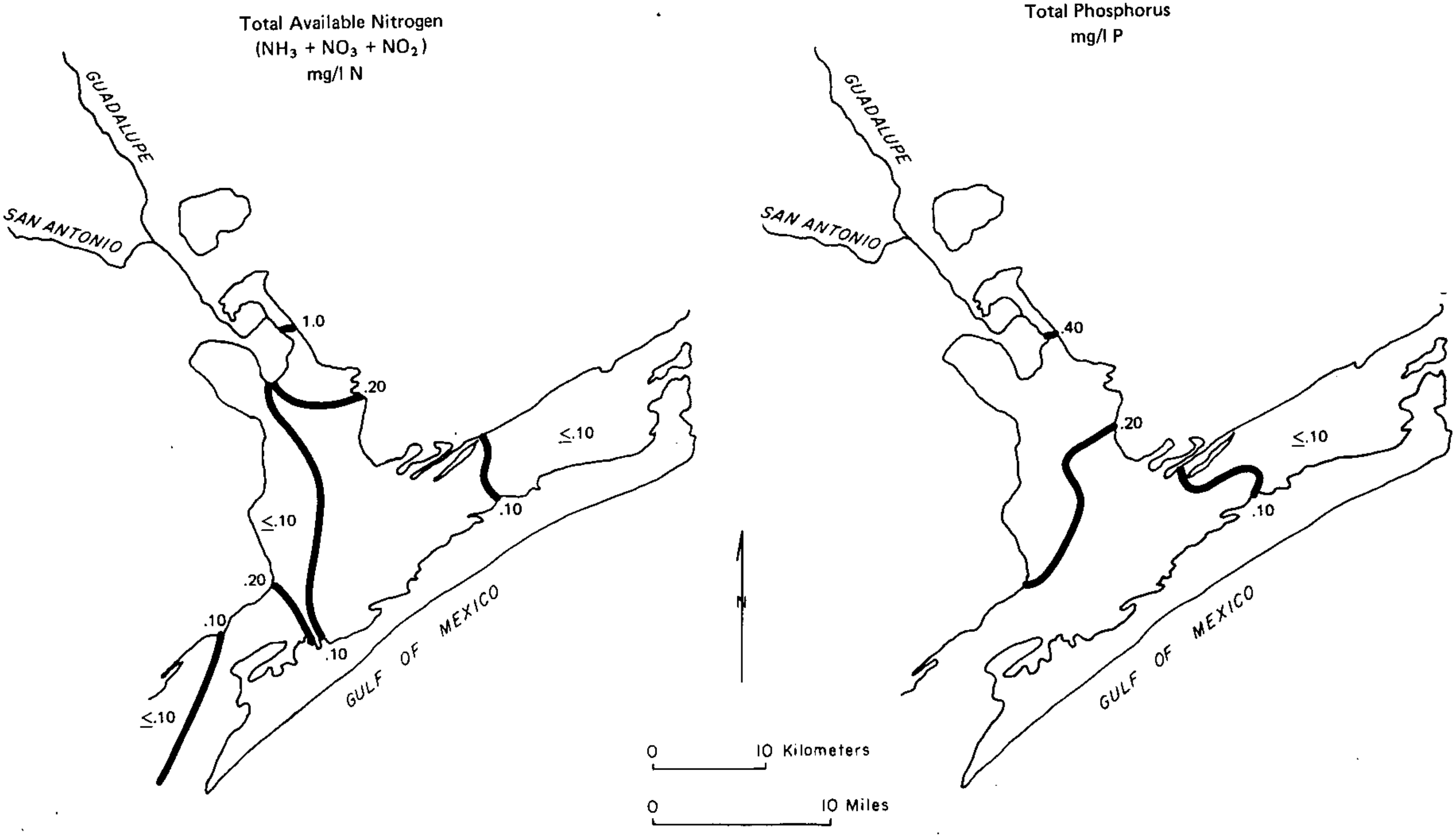
Figure 4-13. Average Monthly Concentrations of Total Nitrogen and Phosphorus, August 1968-1977



Total Available Nitrogen
($NH_3 + NO_3 + NO_2$)
mg/l N

Total Phosphorus
mg/l P

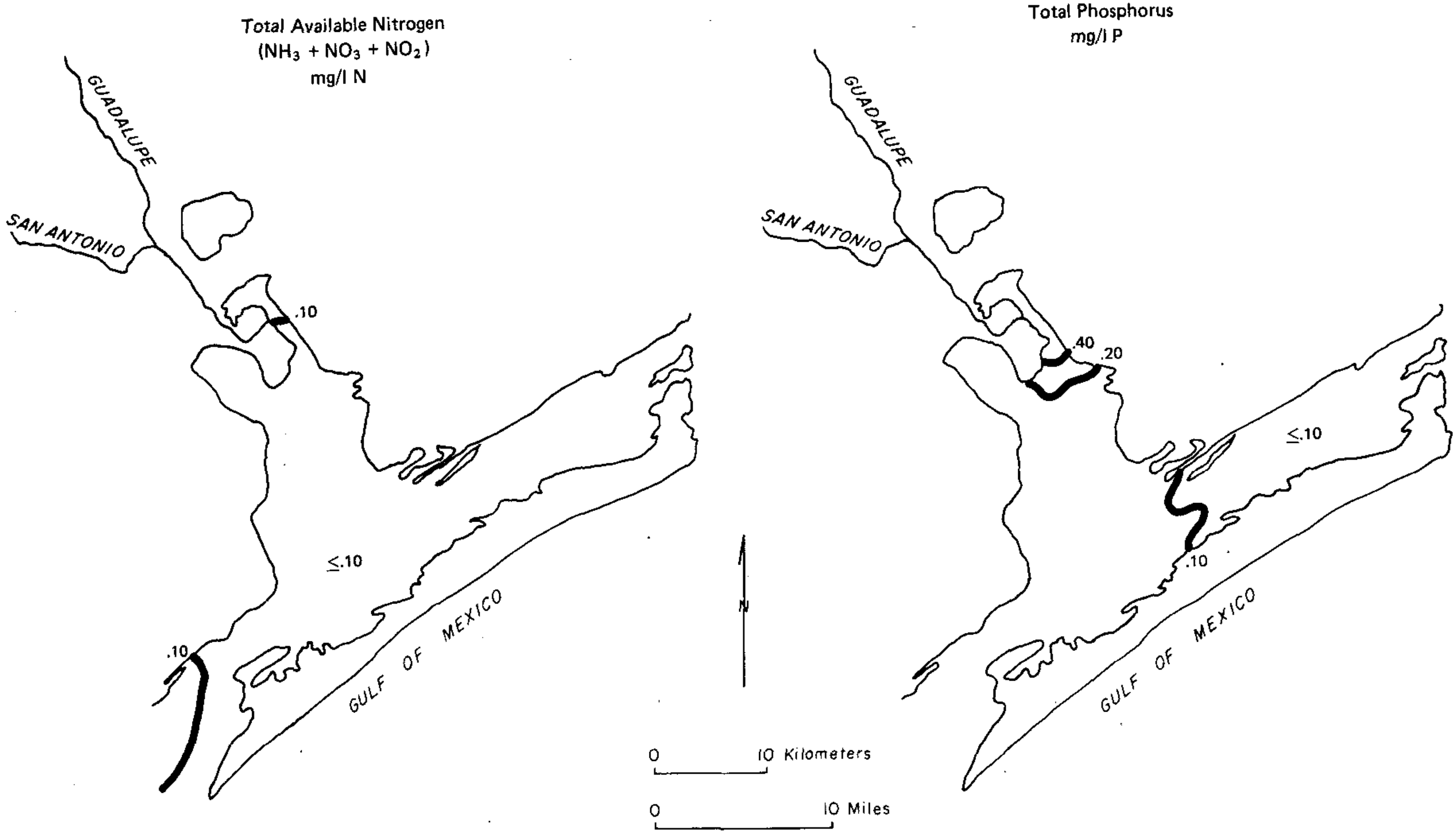
Figure 4-14. Average Monthly Concentrations of Total Nitrogen and Phosphorus, September 1968-1977



Total Available Nitrogen ($NH_3 + NO_3 + NO_2$) mg/l N

Total Phosphorus mg/l P

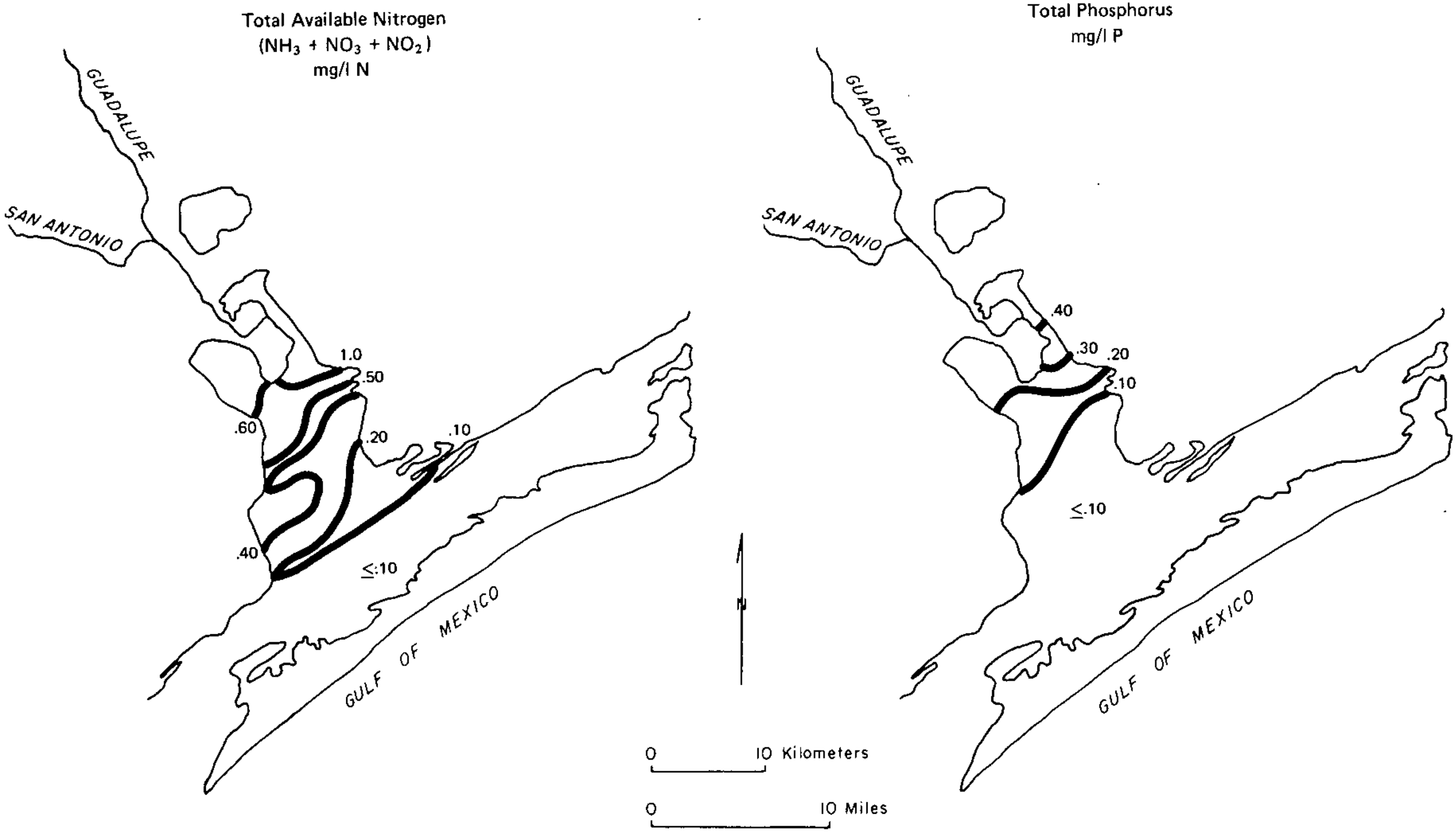
Figure 4-15. Average Monthly Concentrations of Total Nitrogen and Phosphorus, October 1968-1977



Total Available Nitrogen ($NH_3 + NO_3 + NO_2$) mg/l N

Total Phosphorus mg/l P

Figure 4-16. Average Monthly Concentrations of Total Nitrogen and Phosphorus, November 1968-1977



Total Available Nitrogen

($NH_3 + NO_3 + NO_2$)

mg/l N

Total Phosphorus

mg/l P

Figure 4-17. Average Monthly Concentrations of Total Nitrogen and Phosphorus, December 1968-1977

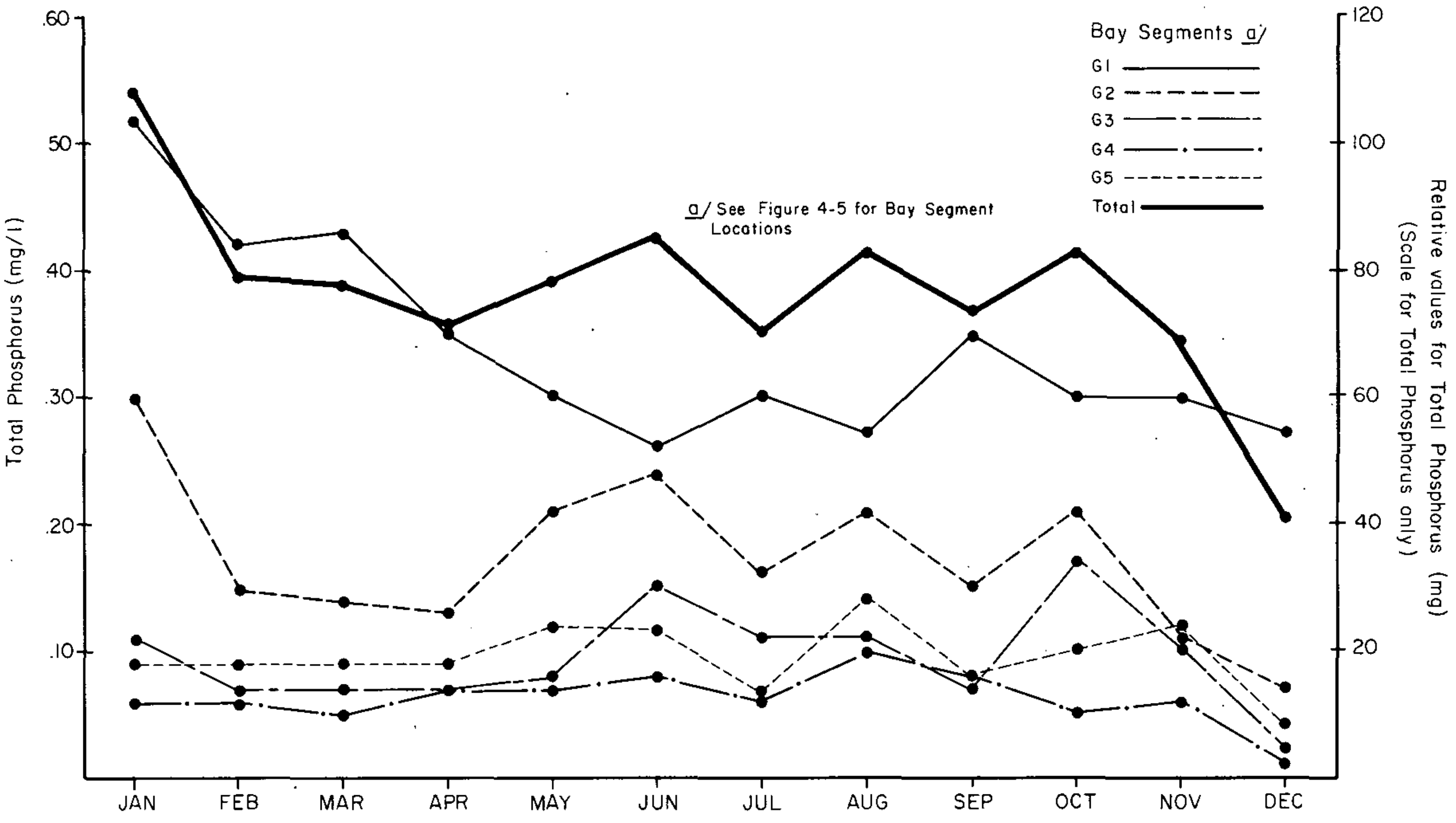


Figure 4-18. Average Monthly Phosphorus Concentrations for the Five Segments of the Guadalupe Estuary

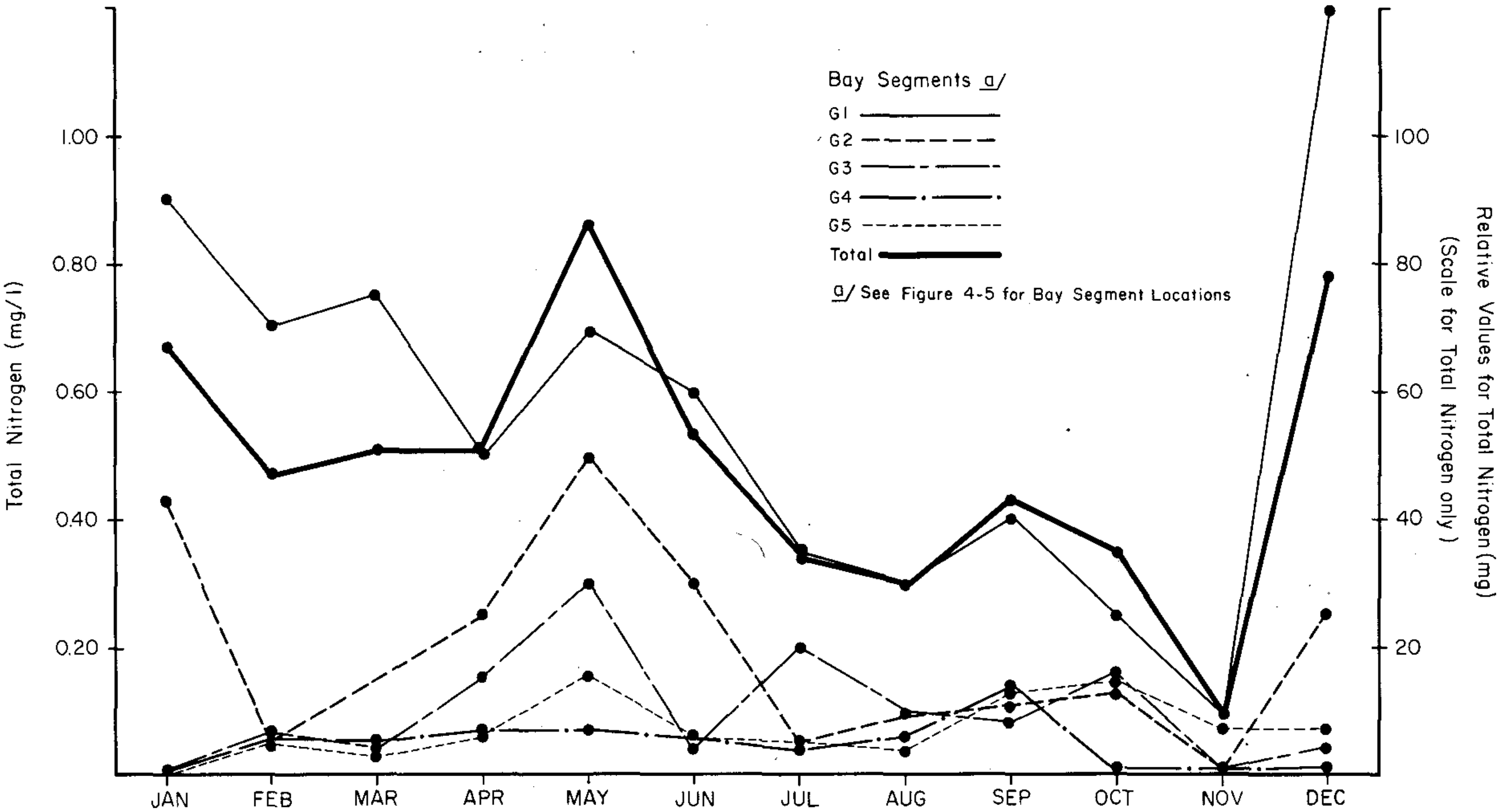


Figure 4-19. Average Monthly Nitrogen Concentrations for the Five Segments of the Guadalupe Estuary

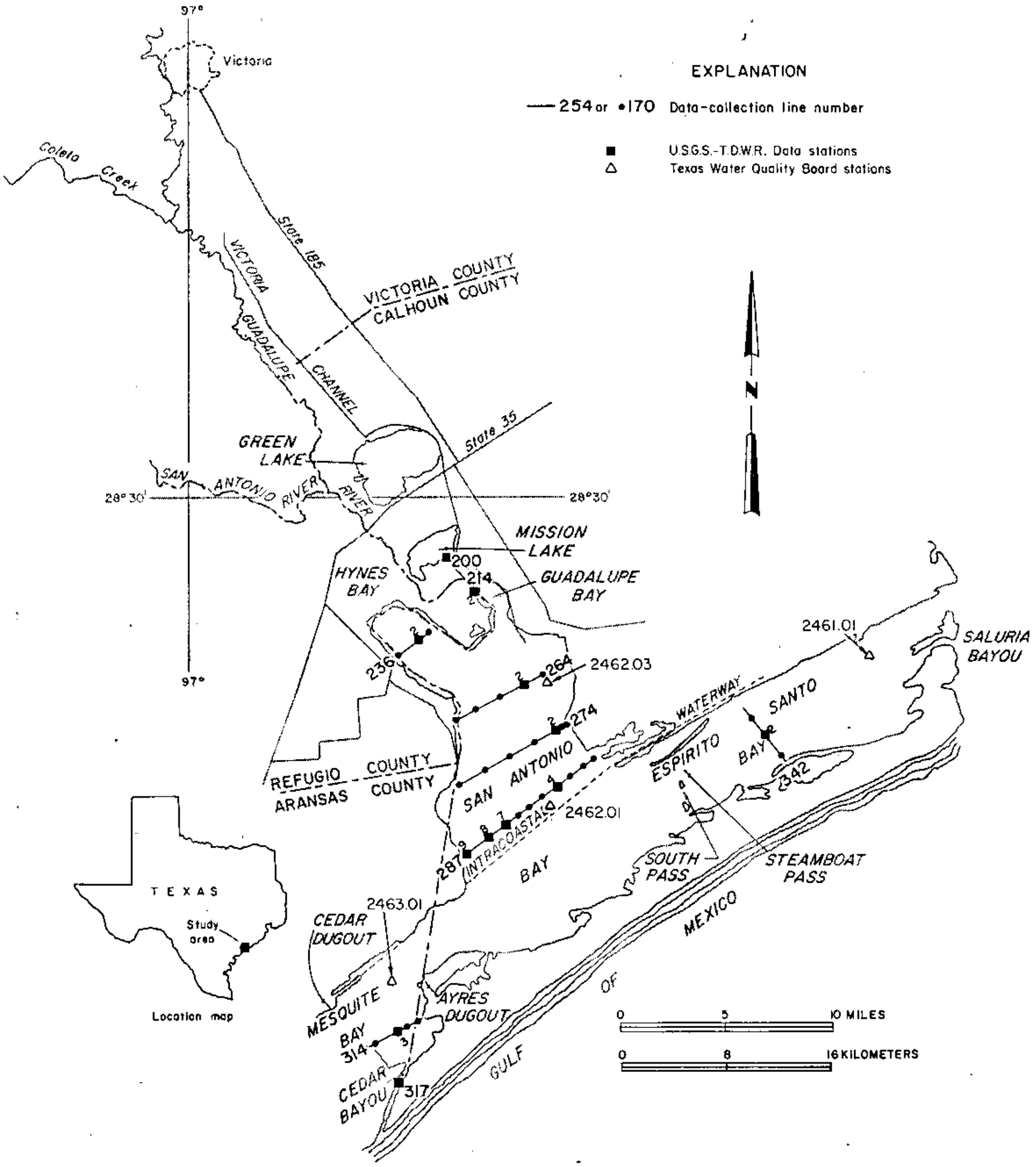


Figure 4-20. Heavy Metals Data-Collection Sites in the Guadalupe Estuary

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

Station Location b/ & USGS Station Number / Parameter	Guadalupe Bay	San Antonio Bay				Hynes Bay	Mesquite Bay	Espiritu Santo Bay	Dredge Criteria
	200 & 214	264.2 & 2462.03	274.2	287.4 & 2462.01	287.7 287.8 & 287.9	236	314.3 & 2463.01	342.2 2461.01	
	Units are mg/kg								
Arsenic	2.0-3.2	0.002-3.4	2.4-5.0+	0.002-3.6	0.3-3.0	2.3	1.0-4.5	0.02-3.0	5
Barium	—	3.5*	—	43.0-106.0*	—	—	80-83*	25.0-250.0*	—
Boron	—	0.002*	—	0.002-8.70*	—	—	1.0-16.0*	0.4-22.0*	—
Cadmium	0.0-<10.0+	0.002-0.300	1.8-<10.0+	0.002-17.0*+	0.0-2.1	0.5	0.0-23.0*+	<10.0-17.0+	2
Chromium	—	1.6-18.0*	—	1.4-110.0*+	—	—	1.7-12.0*	2.0-10.0*	100
Cobalt	2.2-16.0	3.2-7.2	<10.0-19.0	—	0.7-33	18.0	3.1	<10.0	—
Copper	3.9-<10.0	1.7-8.1	4.6-<10.0	0.23-15.0*	0.4-4.8	3.5	1.0-7.5	1.5-<10.0	50
Iron	8,900-13,000	1200-8200	13,000	—	820-16,000.0	6,700	11,000	—	—
Lead	2.2-12.0	0.26-11.0*	—	5.3-16.0*	—	9.6	<0.2-9.4	1.5-12.0	50
Manganese	150-290	12.0-300.0*	—	26.2-337.0*	—	140.0	71-220	61.0-240.0	—
Mercury	—	0.02-4.7*+	—	0.02-1.8*+	—	—	0.01-4.0*+	6.0*+	1
Nickel	—	0.78-15.0*	—	0.002-25.0*	—	—	0.02-14.0*	4.5-9.0*	50
Silver	—	0.002-3.1*	—	0.002-<1.0*	—	—	0.2-0.5*	<0.07-<1.0*	—
Zinc	20.0-51.0	4.0-46.0	20.0-34.0	0.36-128.0*+	3-47	19.0	0.6-32.0	16.0-160.0+	75

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a/ Includes data from ref. (237).
b/ See Figure 4-20 for data collection sites.
* Includes only Texas Water Quality Board data.
\+ Denotes at least one sample in violation of EPA's dredge spoil criteria.

centrate certain metals in their bodies when feeding in polluted areas. Reduction in productivity in the area may be the result of toxic effects of heavy metals upon organisms, and may have an ultimate effect on man if he is exposed to heavy metals through edible fish and shellfish. Areas of the Guadalupe estuary have occasionally exceeded the U.S. EPA criteria for metals in the sediments (prior to dredging) for the following contituents (Table 4-5): arsenic, cadmium, chromium, mercury, and zinc.

Herbicides and Pesticides

Samples of the bottom sediments in the Guadalupe estuary have been collected at 17 data collection sites shown in Figure 4-21 for the period 1969 to 1975 as part of the USGS-TDWR cooperative program. The data were analyzed for herbicide and pesticide concentrations (Table 4-6). The parameters detected included aldrin, DDD, DDE, DDT, dieldrin, endrin, heptachlor, heptachlorexpoxide, and silvex. Only DDD, DDE, DDT, dieldrin, and silvex were detected at levels above or equal to the detection limit of 0.1 μg/kg. Statistical analyses were not possible due to the limited number of samples available.

Summary

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

Freshwater inflows in terms of annual and monthly average values over the 1941 through 1976 period varied widely from the mean as a result of recurrent drought and flood conditions. On the average, total freshwater inflow to the estuary (1941-1976) consisted of 2,771,000 acre-feet (3.35 billion m^3).

In general, the water quality of gaged inflows to the Guadalupe estuary has been good. No parameters were found in violation of existing Texas stream standards, although one "total lead" sample from the San Antonio River was in violation of federal drinking water 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 Guadalupe estuary have occasionally exceeded the U. S. Environmental Protection Agency criteria for metals in sediments (prior to dredging) for arsenic, cadmium, chromium, mercury and zinc. Bottom sediments collected and analyzed for herbicides and pesticides showed DDD, DDE, DDT, dieldrin and silvex occurring in local areas in concentrations equal to or greater than the analytical detection limit during the period 1969 to 1975.

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

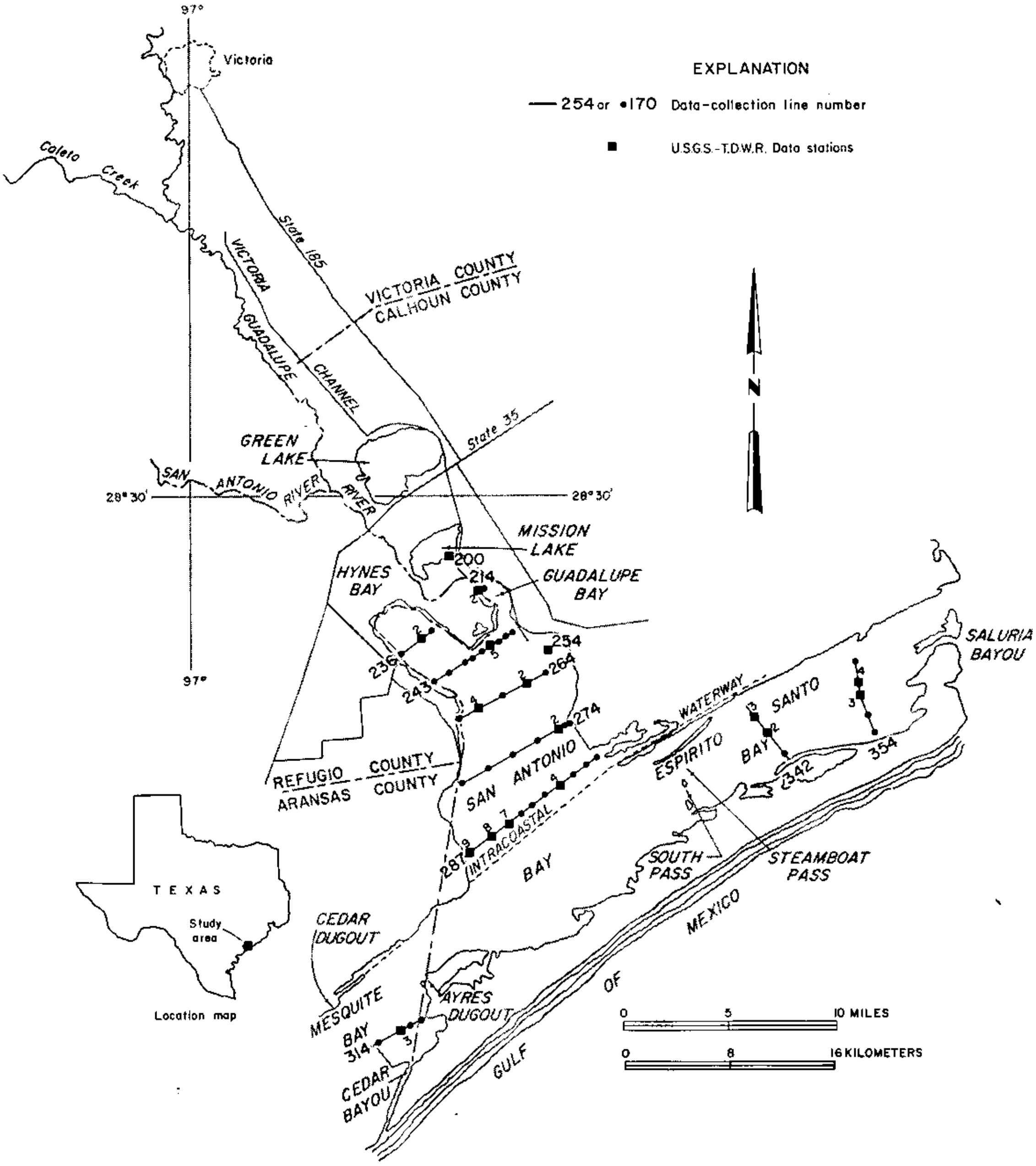

Figure 4-21. Pesticide Data-Collection Sites in the Guadalupe Estuary

Base by U.S. Geological Survey, 1956

Table 4-6. Range of Pesticide Concentrations in Sediment, Guadalupe Estuary, 1969-1975 (384) a/

Sampling Station / Parameter	Guadalupe Bay	San Antonio Bay					Espiritu Santo Bay	Hynes Bay
	200 & 214	243.5	254	264.2	274.2	287.7 & 287.9	354.3	236
	Units are µg/kg							
DDD	<0.1-2.9	<0.2 0.4	—	<0.1-1.0	<0.1-1.8	—	0.5	<0.1-2.4
DDE	0.5-2.6	1.10	0.4	<0.1-0.70	—	—	—	0.4-1.8
DDT	<0.1-3.0	—	—	—	—	—	—	—
Dieldrin	<0.1-0.64	—	—	—	—	—	—	—
Silvex	<0.3-<0.7	—	—	—	<0.70	<1.20	<0.3	—

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a/ See Figure 4-21 for data collection sites.

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 significant influences on the circulation and transport patterns within the estuarine system.

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

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

Description of the Estuarine Mathematical Models

Description of Modeling Process

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

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

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

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

Mathematical Model Development

The mathematical tidal hydrodynamic and conservative transport models for the Guadalupe estuary have been developed by Masch (149). These models are designed to simulate the tidal and circulation patterns and salinity distributions in a shallow, irregular, non-stratified estuary. The two models are sequential (Figure 5-1) in that the tidal hydrodynamic model computes temporal histories of tidal amplitudes and flow. These are then used as input to the conservative transport model to compute vertically averaged salinities (or any conservative material) under the influence of various source salinities, evaporation, and rainfall. Both of these models have "stand alone" capabilities although it must be recognized that the transport model ordinarily cannot be operated unless the tidally generated convective inputs are available.

Hydrodynamic Model.

Under the assumption that the bays are vertically well-mixed, and the tidally generated convection in either of the two area-wise coordinate directions can be presented with vertically integrated velocities, the mathematical characterization of the tidal hydrodynamics in a bay system requires the simultaneous solution of the two-dimensional dynamic equations of motion and the unsteady continuity equation. In summary, the equations of

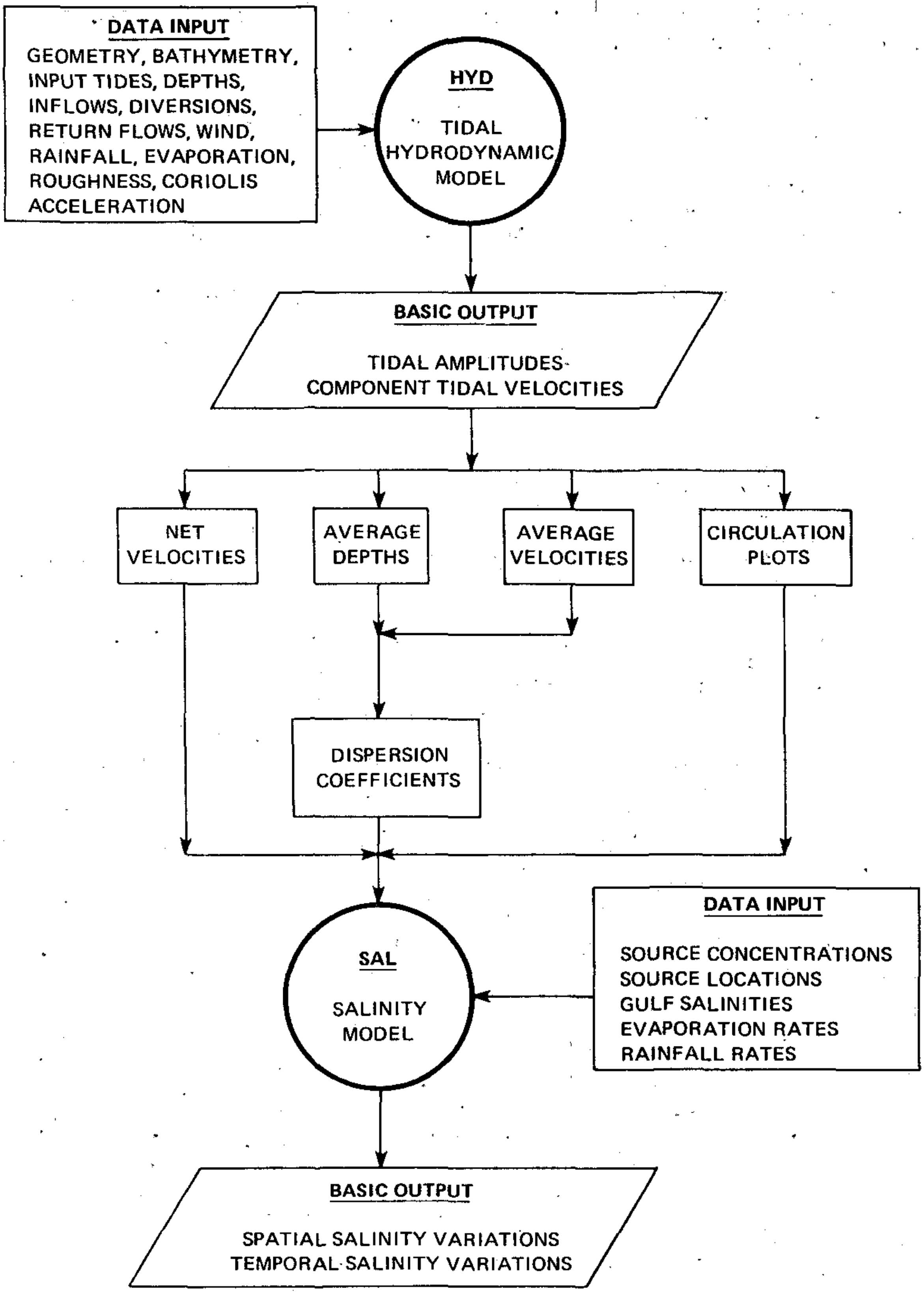

Figure 5-1. Relationship Between Tidal Hydrodynamic and Salinity Models (149)

motion neglect the Bernoulli terms but include wind stresses and the Coriolis acceleration, and can be written as:

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

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

The equation of continuity for unsteady flow can be expressed as

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

where

x,y = horizontal Cartesian coordinates
t = time
q_x, q_y = vertically integrated x and y components of flow per unit width, respectively (x and y taken in the plane of the surface area)
g = acceleration due to gravity
h = water surface elevation with respect to mean sea level (msl) as datum
d = total water depth (h-z)
z = bottom elevation with respect to msl
q = $(q_x^2 + q_y^2)^{1/2}$ = magnitude of flow per unit width
f = dimensionless bed resistance coefficient from the Manning Equation
V_w = wind speed at a specified elevation above the water surface
Θ = angle between the wind velocity vector and the x-axis
K = dimensionless wind stress coefficient
Ω = Coriolis parameter = $2\omega\sin\Phi$
ω = angular velocity of the earth = 0.73×10^{-4} rad/sec
Φ = latitude = 28.1° for the Guadalupe estuary
r = rainfall intensity
e = evaporation rate.

The numerical solution utilized in the hydrodynamic model of the Guadalupe estuary involves an explicit computational scheme where equations [1], [2], and [3] are solved over a rectangular grid of square cells used to represent in a discretized fashion the physiography and various boundary conditions found in this bay system (Figure 5-2). This explicit formulation of the hydrodynamic model requires for stability a computational time step, $\Delta t < \Delta s/(2gd_{max})^{1/2}$, where Δs is the cell size and d_{max} is the maximum water depth encountered in the computational matrix. The numerical solutions of the basic equations and the programming techniques have been described previously (149).

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

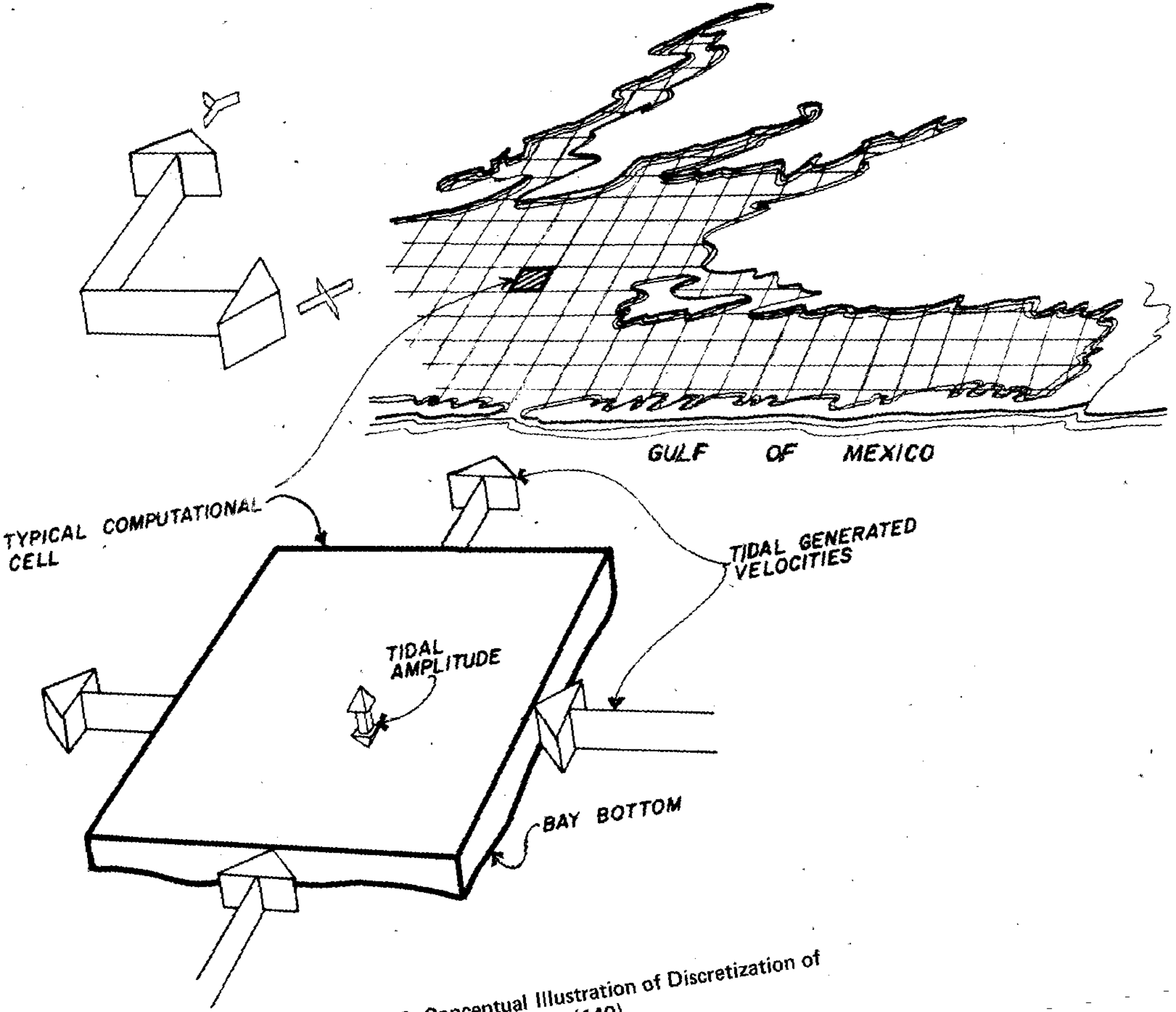

Figure 5-2. Conceptual Illustration of Discretization of a Bay (149)

Physical Data

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

Hydrologic - Hydraulic Data

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

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

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

where C is the tidally averaged salinity or TDS concentration; $\bar{q}_x$ and $\bar{q}_y$ are the net flows over a tidal cycle in the x and y directions, respectively; D_x and D_y are the corresponding dispersion coefficients evaluated at a scale representative of total tidal mixing; and $\bar{d}$ is the average depth over a tidal cycle. The term $K_e C\bar{d}$ is a first order reactive term included to represent the buildup of concentration due to evaporation from the bay surface, and K_e is a coefficient determined volumetrically in accordance with methods described by Masch (149, 150). The primary difference in the form of Equation [4] given above and that reported previously (149), is that Equation [4] is written in terms of net flows per foot of width rather than tidally averaged velocities.

The numerical technique employed in the salinity model involves an alternating direction implicit (ADI) solution of Equation [4] applied over the same grid configuration used in the tidal hydrodynamic model to determine the net flows and tidally averaged depths. Because of its implicit formulation the ADI solution scheme is unconditionally stable and there are no restrictions on the computational time step, Δt. However, to maintain accuracy and to minimize round-off and truncation errors, a condition corresponding to $\Delta t/\Delta s^2 \leqslant \frac{1}{2}$ was always maintained throughout this work. Details of the numerical solution of Equation [4] and programming techniques have also been previously described by Masch (149).

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

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

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

$$\frac{\partial Q}{\partial t} + \frac{\partial}{\partial x}\left(\frac{Q^2}{A}\right) + gA\frac{\partial H}{\partial x} + \frac{gn^2 Q|Q|}{2.2 \quad AR^{4/3}} = 0 \qquad [1]$$

and

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

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

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

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

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

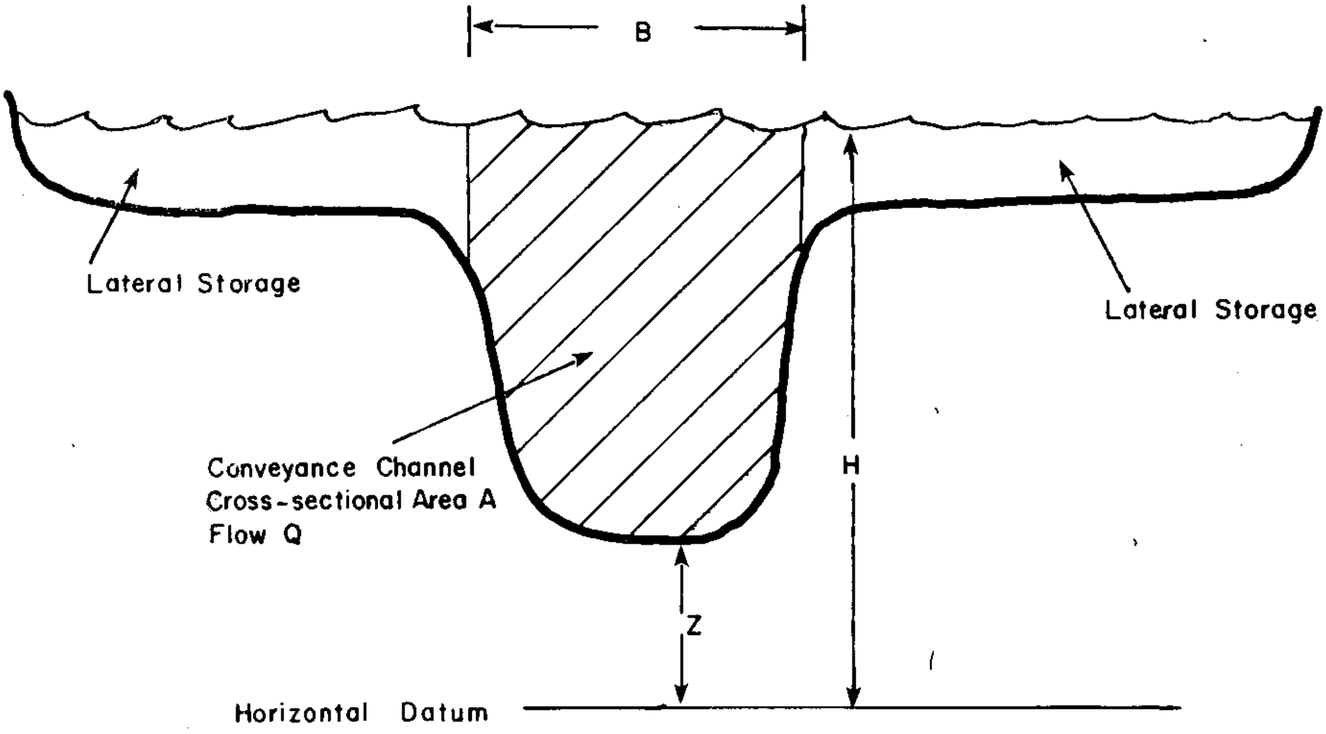

Figure 5-3. Definition of Variables in Cross Section (229)

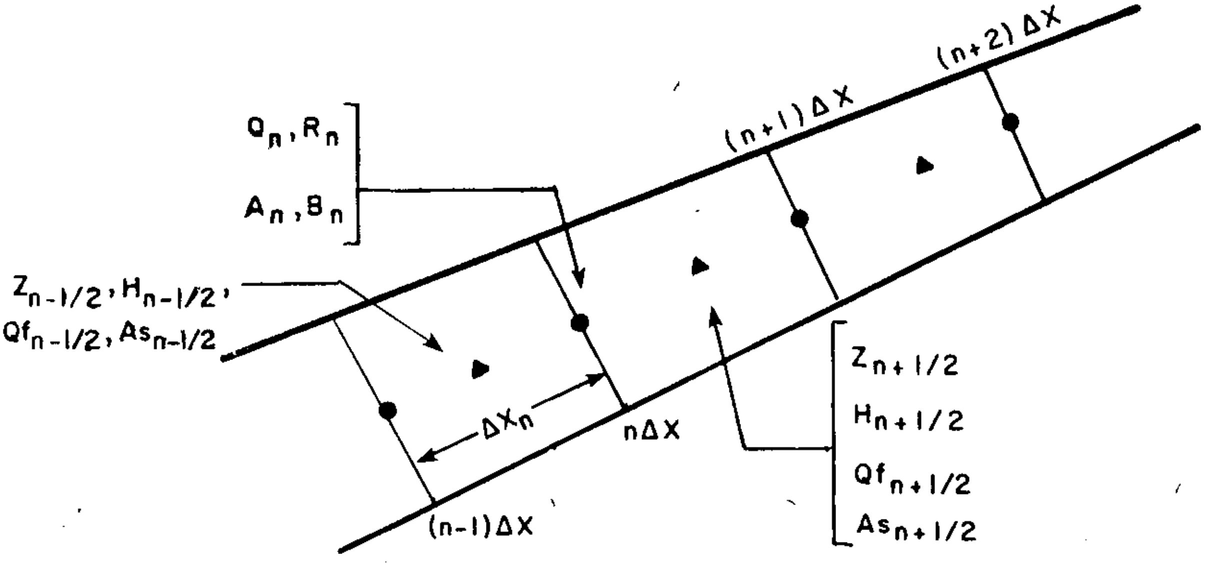

Figure 5-4. Definition of Finite-Difference Segmentation for Hydrodynamic Model (229)

MTDELT uses the one-dimensional mass continuity equation:

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

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

(3) Calibration and Validation of the Marsh Inundation Model. The hydrodynamic submodel, HYDELT, was calibrated and validated for the Guadalupe delta during nonflood conditions by Hauck, Ward and Huston (45). Results of flood simulations were not satisfactory for a variety of explained and unexplained reasons.

Guadalupe River Delta. The system boundaries and segmentation schematic utilized for the Guadalupe delta are presented in Figure 5-5. The upstream and downstream system boundaries were selected in accordance with model specifications, the availability of tide records for San Antonio Bay, and availability of flow data entering the delta from the Guadalupe River and Green Lake.

Ten continuously recording tide gages are located within the study area. These gages are located near Seadrift (08165100), at Lucas Lake (08188830), at Townsend Bayou near Austwell (08188835), at Townsend Bayou near Tivoli (08188840), at Traylor Cut near Tivoli (08188825), at the Guadalupe River near Traylor Cut (08188820), near Mission Lake at Mamie Bayou (08188780), at Goff Bayou (08188760), on the Guadalupe River at State Highway 35 (08188810), and on Schwings Bayou at State Highway 35 (08188790). In addition, the water stage is read daily for the Guadalupe River, Hog Bayou and Goff Bayou by the Guadalupe-Brazos River Authority (GBRA). From these records and stage-discharge relationships developed by the TDWR (237), it is possible to define daily flows for the ten channels flowing under State Highway 35. These ten channels are, from west to east, the Guadalupe River, Schwings Bayou, Schwings Relief, Hog Bayou, Hog Relief, Frenchman's Bayou, Shallow Water, Shallow Water #1, Shallow Water #2 and Goff Bayou.

Though the spatial distribution of tide gages indicates the availability of abundant data for model calibration and validation, the available period of record covers only from January 1975 to January 1976. Also, stream flow readings were recorded only once per day and only on week days; limiting temporal coverage.

The initial calibration simulations of the Guadalupe delta are performed for the "equilibrium" period (September 3-9, 1975). During this period the streamflow for the seven locations is nearly constant at 2,000 ft^3/sec (56.6 m^3/sec) on the Guadalupe River, 50 ft^3/sec (1.42 m^3/sec) on Frenchman's Bayou, 150 ft^3/sec (4.24 m^3/sec) on Hog Bayou and the four other input locations having no input (Figure 5-6). In every case the tidal amplitude and phase variations are simulated

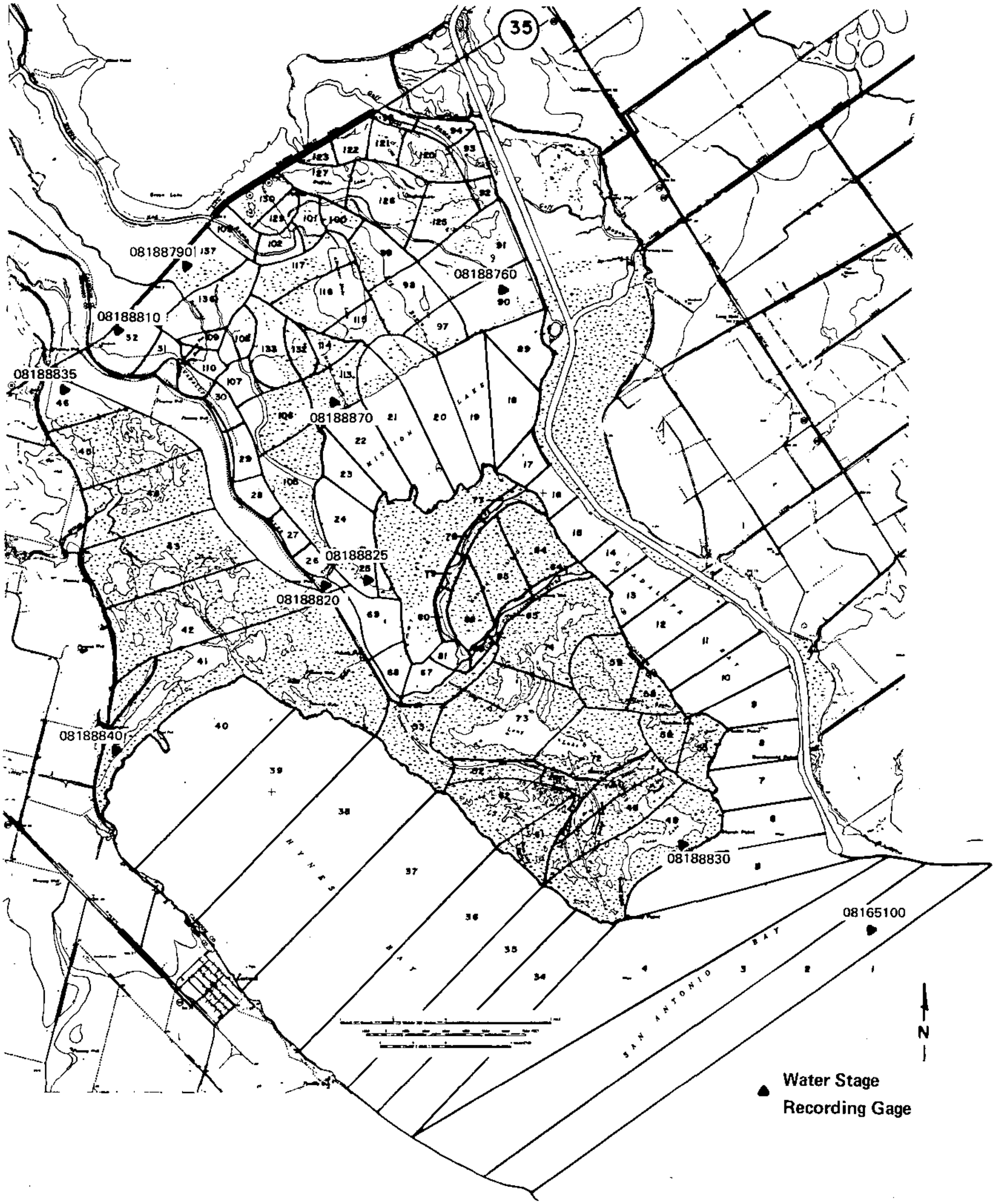

Figure 5-5. Deltaic Systems Boundaries of the Guadalupe Delta (45)

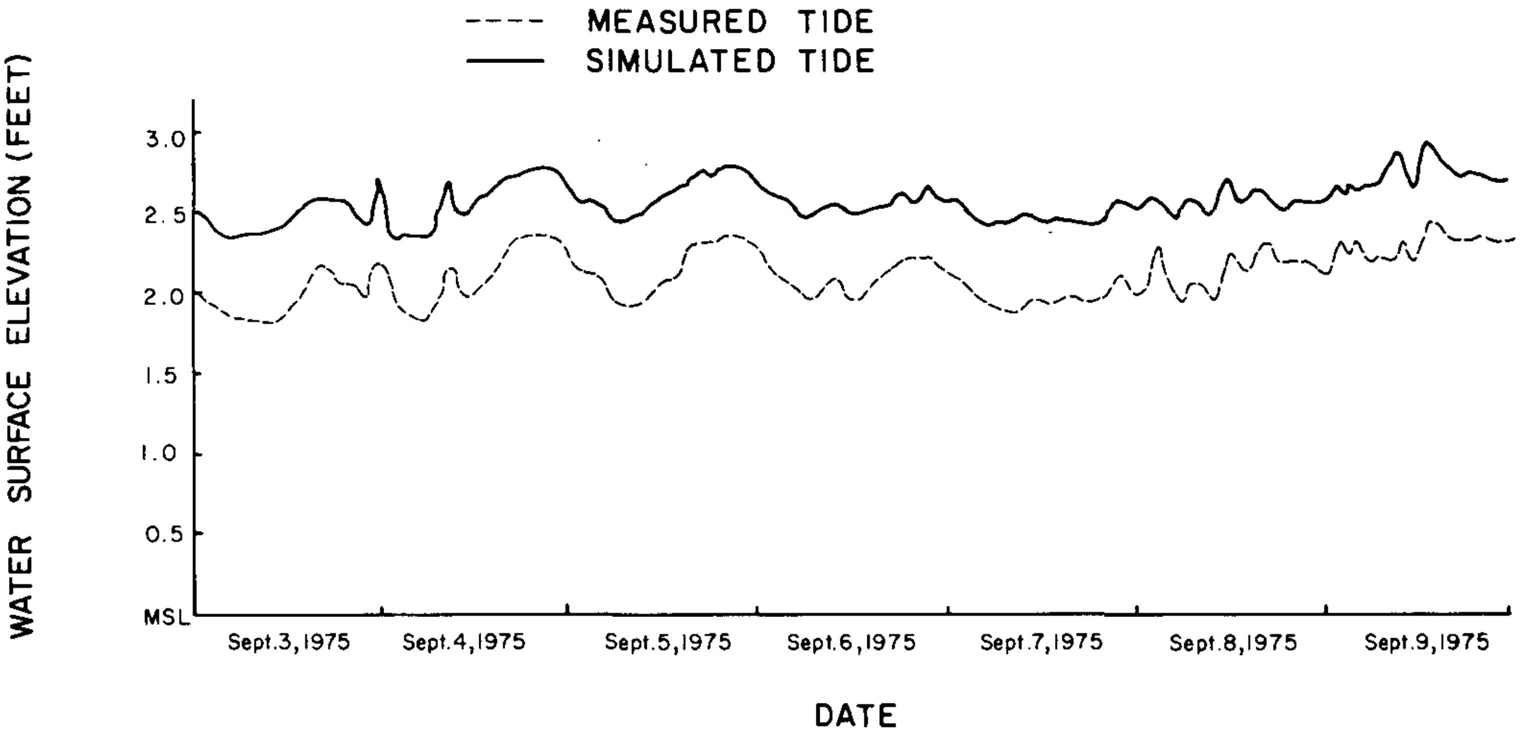

Figure 5-6. Comparison of Measured and Simulated Tidal Elevations at Section 22, Mamie Bayou Tide Gage, September 3-9, 1975 (45)

correctly; however, simulated tides are consistently displaced 0.5 ft. (0.15 m) below recorded tides.

A second equilibrium state test case was run for the period November 4-12, 1975. During this period flows were occurring at only two of the seven inflow points: the Guadalupe River at 1,750 ft^3/sec (49.6 m^3/sec) and Goff Bayou at 1,150 ft^3/sec (32.6 m^3/sec). The passage of a front accompanied by strong northerly winds occurred in the early morning of November 12, and the resulting drop in water surface elevations was apparent in the driving tide (Figure 5-7). The Mamie Bayou gage was again typical of the validation achieved for the steady-state case, with the persistent -0.5 ft. deviation between simulated and recorded tides.

In addition to tide elevation validation data, diurnal flow data have been collected at various locations throughout the delta during November 11-12, 1975 (229). Since the objective of the model is to simulate transport, these velocity data are preferable to elevation recordings. Comparisons of simulated and observed velocities as well as direction of flow are presented in Table 5-1. In nearly all cases, the simulated and observed velocities are within one order of magnitude, which is considered adequate for flow velocity validation. Simulation of one flood event covering the period May 27 through June 7, 1975 has been attempted with HYDELT on the Guadalupe delta; however, due to the lack of adequate temporal coverage of the event, validation simulations are less than adequate.

The HYDELT model may be considered calibrated and validated on the Guadalupe delta for steady-state flows of low to moderate magnitude.

Application of Mathematical Models, Guadalupe Estuary

Hydrodynamic and Mass Transport Models

The computational grid network used to describe the Guadalupe estuary is illustrated in Figure 5-8. The grid is superimposed on a map showing the general outline of the estuary. Included in the grid network are the locations of islands (solid lines), submerged reefs (dash lines), inflow points, and tidal excitation cells. The x-axis of the grid system is aligned approximately parallel to the coastline, and the y-axis extends far enough landward to cover the lower reaches of all freshwater sources to the bay. The cell size (one square nautical mile) was based on (1) the largest possible dimension that would provide sufficient accuracy, (2) the density of available field data, and (3) computer storage requirements and computational time. Similar reasoning was used in selection of the computational time step except that the maximum possible time step in the hydrodynamic model was constrained by the criterion for mathematical stability. In the indexing scheme shown in Figure 5-8, cells were numbered with the indices $1 < i < IMAX = 36$ and $1 < j < JMAX = 24$. With this arrangement, all model parameters such as water depths, flows in each coordinate direction, bottom friction, and salinity can be identified with each cell in the grid.

The basic data necessary for the development, verification and calibration of the mathematical models include Gulf tides, measured tides at discrete

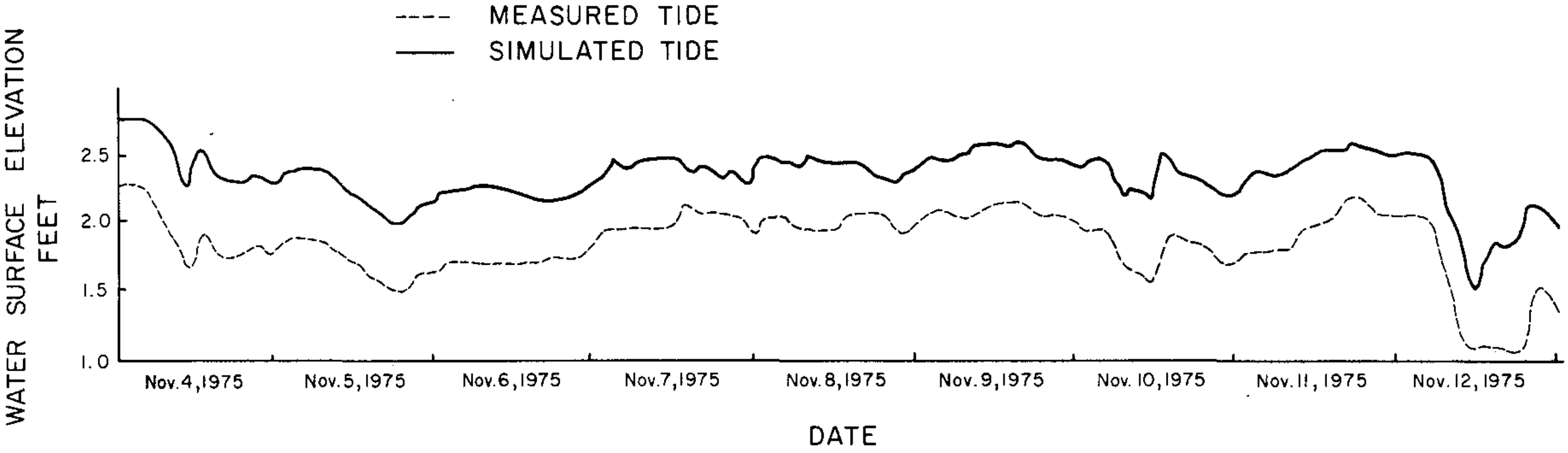

Figure 5-7. Comparison of Observed and Simulated Tidal Elevations at Section 22, Mamie Bayou Tide Gage, November 4-12, 1975 (45)

Table 5-1. Velocity Comparison on November 11-12, 1975

	Guadalupe Bay (Section 8)				Redfish Bayou (Section 58)			
	Recorded		Simulated		Recorded		Simulated	
Time	Velocity (ft/sec)	Direction	Velocity (ft/sec)	Direction	Velocity (ft/sec)	Direction	Velocity (ft/sec)	Direction
Nov 11 1200	.00	—	.05	Out	.44	In	.59	In
1500	.35	Out	.14	Out	.66	In	.37	In
1800	.28	Out	.14	Out	.41	In	.30	In
2100	.17	Out	.26	Out	.13	Out	.48	Out
Nov 12 0000	.17	Out	.15	Out	.18	In	.32	Out
0300	.28	Out	.19	Out	.15	Out	.07	In
0600	.86	Out	.59	Out	1.3	Out	.44	Out
0900	.93	Out	.63	Out	1.1	Out	1.1	Out
1200	.57	Out	.12	Out	.37	Out	1.7	Out

	Swan Lake Bayou (Section 61)				Schwings Bayou (Section 105)			
	Recorded		Simulated		Recorded		Simulated	
Time	Velocity (ft/sec)	Direction	Velocity (ft/sec)	Direction	Velocity (ft/sec)	Direction	Velocity (ft/sec)	Direction
Nov 11 1200	.86	In	.62	In	.28	Out	.04	Out
1500	.71	In	.43	In	.06	In	.08	Out
1800	.62	In	.24	In	.19	Out	.02	Out
2100	.22	Out	.47	Out	.26	Out	.49	Out
Nov 12 0000	.17	Out	.32	Out	.25	Out	.29	Out
0300	.24	Out	.22	Out	.26	Out	.26	Out
0600	2.4	Out	.75	Out	.43	Out	.45	Out
0900	1.6	Out	1.3	Out	.44	Out	.91	Out
1200	1.8	Out	1.4	Out	.44	Out	.48	Out

	Townsend Bayou (Section 40)				Varmum Bayou (Section 48)			
	Recorded		Simulated		Recorded		Simulated	
Time	Velocity (ft/sec)	Direction	Velocity (ft/sec)	Direction	Velocity (ft/sec)	Direction	Velocity (ft/sec)	Direction
Nov 11 1200	.47	In	1.0	In	.17	In	.56	In
1500	1.1	In	1.2	In	.21	In	.17	In
1800	.44	In	1.0	In	.15	In	.18	In
2100	.32	Out	.14	In	.09	Out	.30	Out
Nov 12 0000	.15	Out	.35	Out	.04	In	.07	In
0300	.24	Out	.71	Out	.25	Out	.14	Out
0600	.80	Out	1.6	Out	.87	Out	1.2	Out
0900	1.7	Out	2.7	Out	1.1	Out	1.6	Out
1200	.93	Out	3.0	Out	2.2	Out	1.6	Out

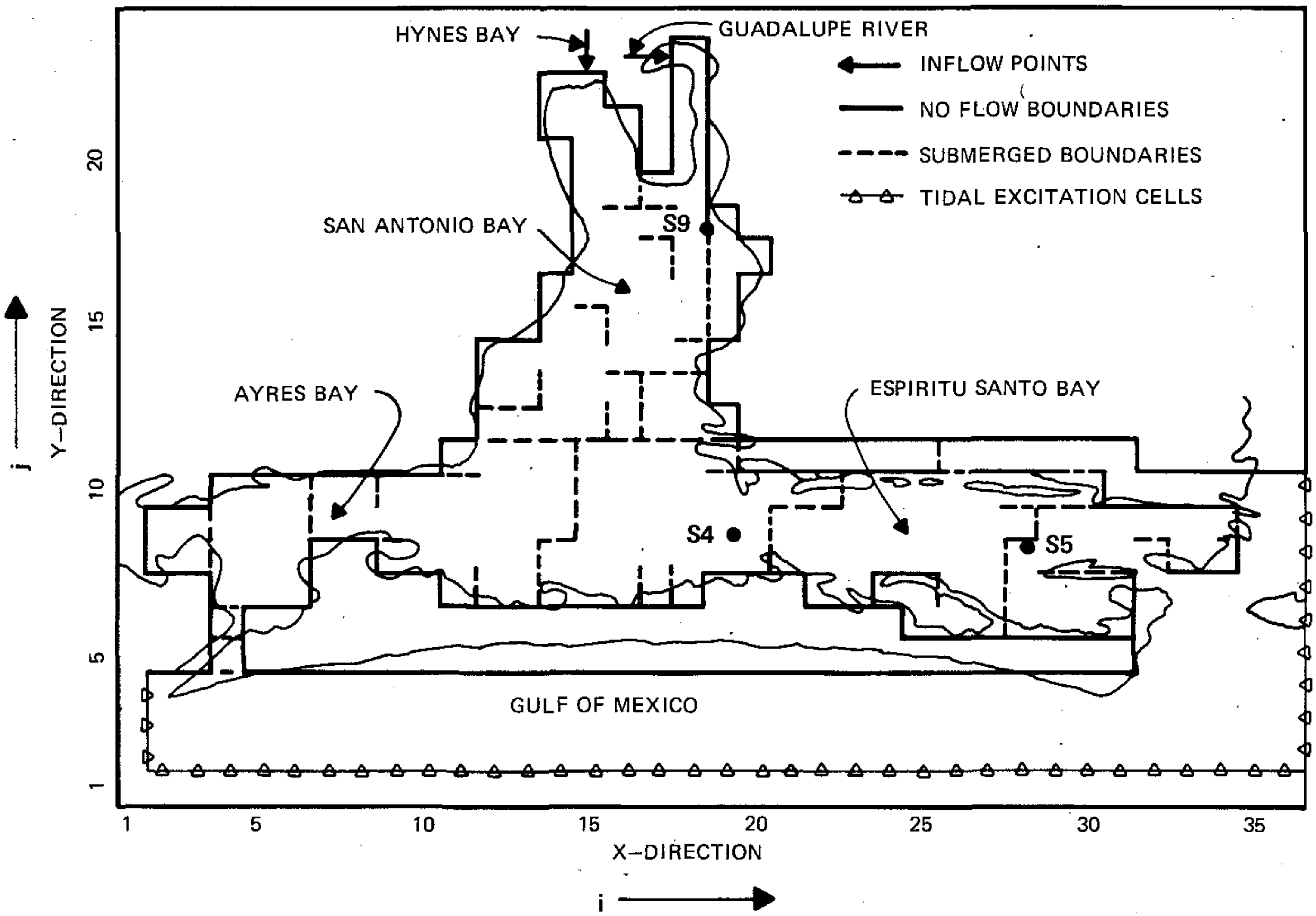

Figure 5-8. Schematic Computational Grid, Guadalupe Estuary (149)

points throughout each estuary, gaged freshwater inflows, estimate of ungaged and return flows, wind magnitude, direction and duration, evaporation, and measurements of conservative constitutents (chlorides, specific conductance or total dissolved solids, TDS) throughout the estuary and at each inflow source. Such a compilation of data for a specified period of time is referred to as a "data package." Through successive applications of the model to several independent data packages, the model is calibrated and verified. Data packages necessary for the calibration and verification of the estuary models were obtained through a cooperative program with the U. S. Geological Survey. Especially important were the two comprehensive data collection efforts conducted in the estuary during November 1970 and August 1973.

The initial calibration and verification of the Guadalupe estuary models was reported by Masch (149). A representative sample of the results of the final calibration of the models using data obtained during the August 1973 field study is presented in Figures 5-9 to 5-11 to demonstrate the ability of the models to simulate observed values of tidal amplitude, flow, and salinity throughout a tidal cycle at several locations in the estuary.

To test the model's abilities to simulate the salinity response of the estuary over an extended time period, an operation schedule was developed to calculate the variation in salinity distribution during 1968 through 1973. The six-year period was divided into 94 consecutive hydrologic sequences.1/ The minimum time period used as a hydrologic sequence was seven days. Seasonal averages were used for the meteorological and tidal inputs. The results of the model operation show reasonable agreement with observed data (Figures 5-12 to 5-17). Perfect agreement cannot be expected since the simulated results represent average salinity conditions for the time period covered by the hydrologic sequence while the measured data are an instantaneous response of the estuary to the specific tidal, freshwater inflow, and meteorological conditions present at the time of the measurement.

Marsh Inundation Model

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

Guadalupe River Delta. In the Guadalupe delta study estimates were made of the percentage of the delta surface area subject to inundation through the interaction of varying freshwater inflows and selected tides. Six Guadalupe delta flood events of varying magnitude and duration were selected from historical records obtained from the stage recorders located at the Guadalupe River near Tivoli (08188810) and Hog and Goff Bayous. Calculated inflow into the delta through the Guadalupe River and six additional channels that carry a varying volume of water into the delta depending upon the flood event are

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

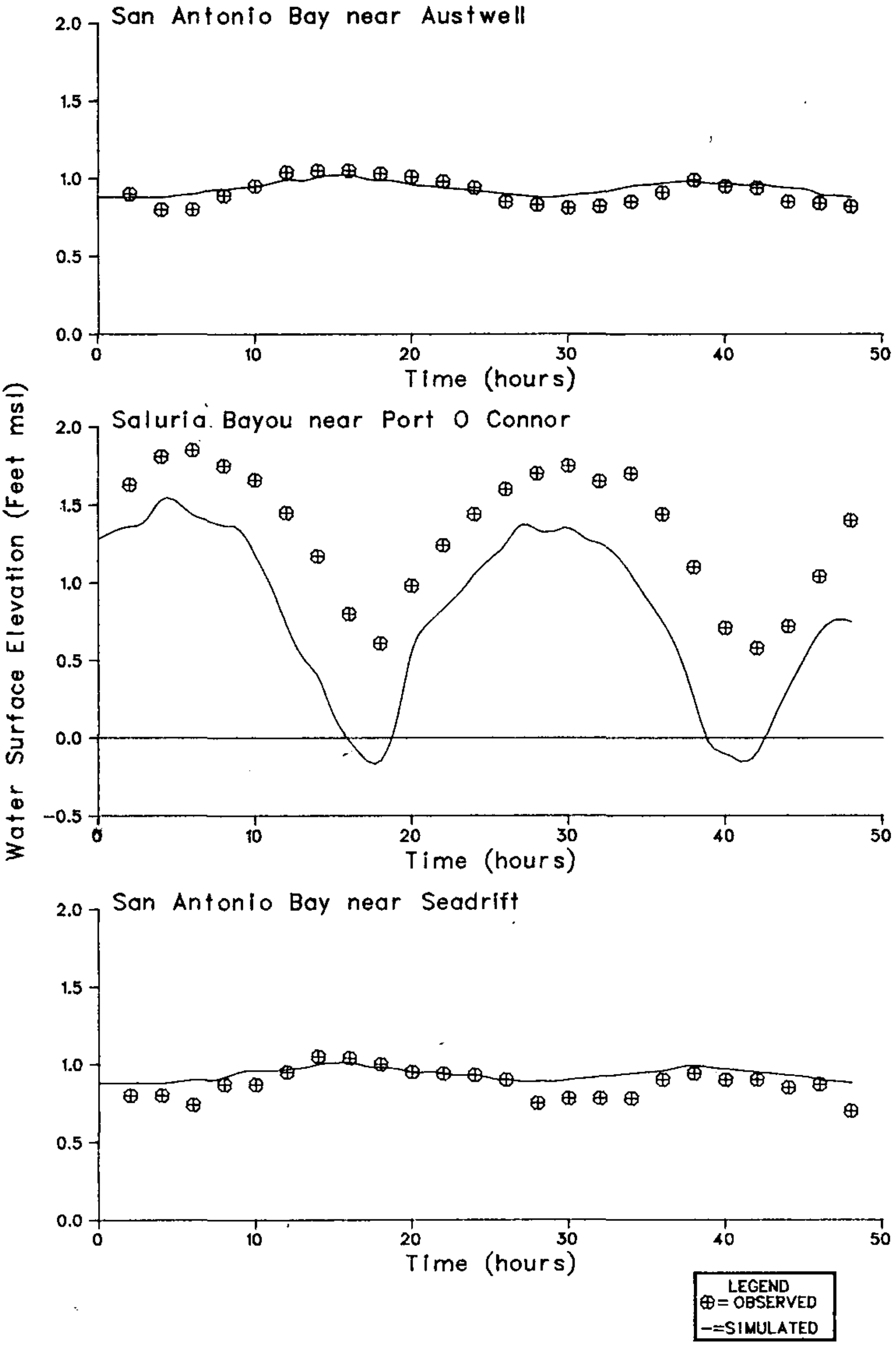

Figure 5-9. Comparison of Observed and Simulated Tidal Elevations, Guadalupe Estuary, August 8-9, 1973

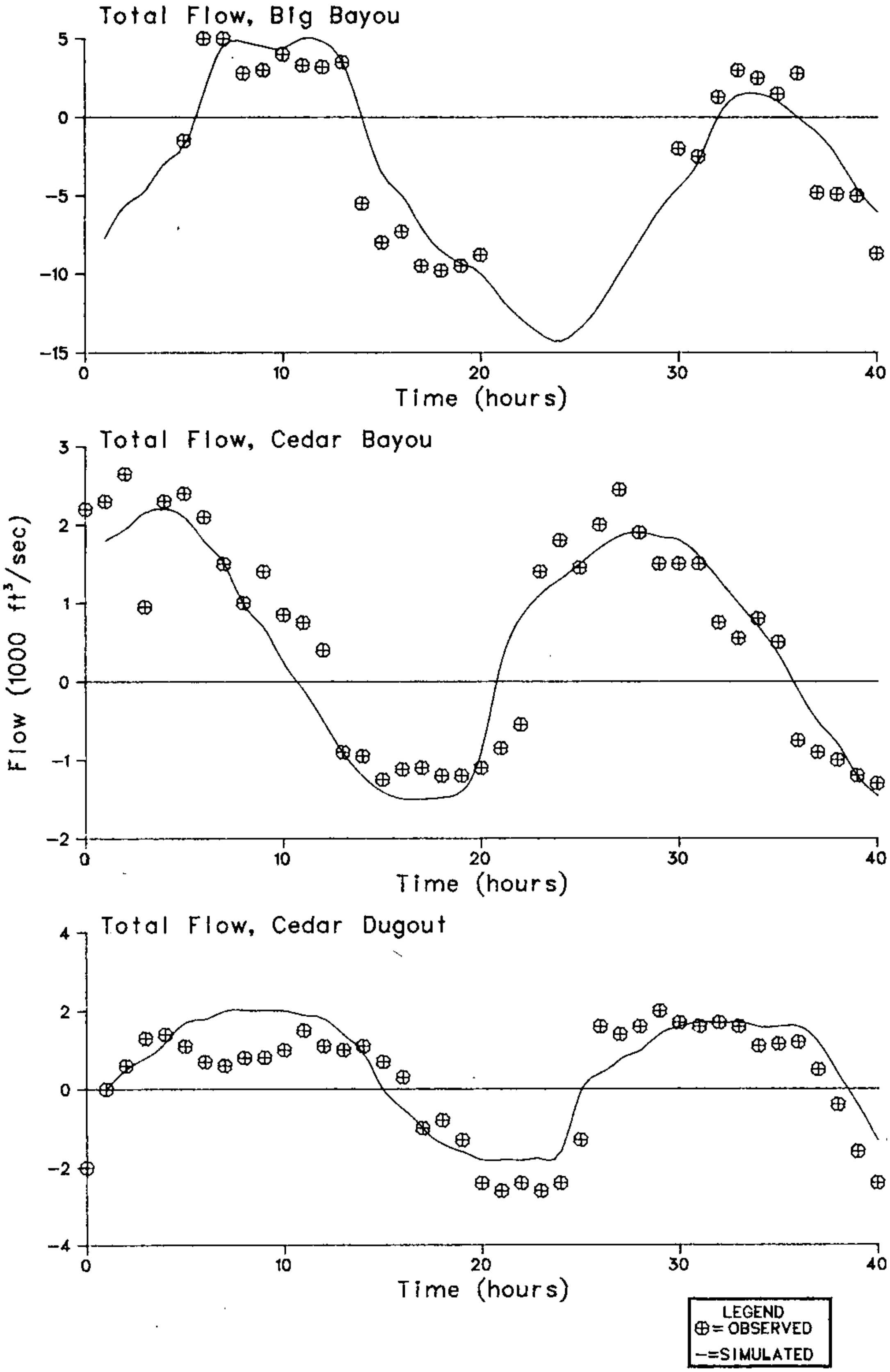

Figure 5-10. Comparison of Observed and Simulated Flows, Guadalupe Estuary, August 8-9, 1973

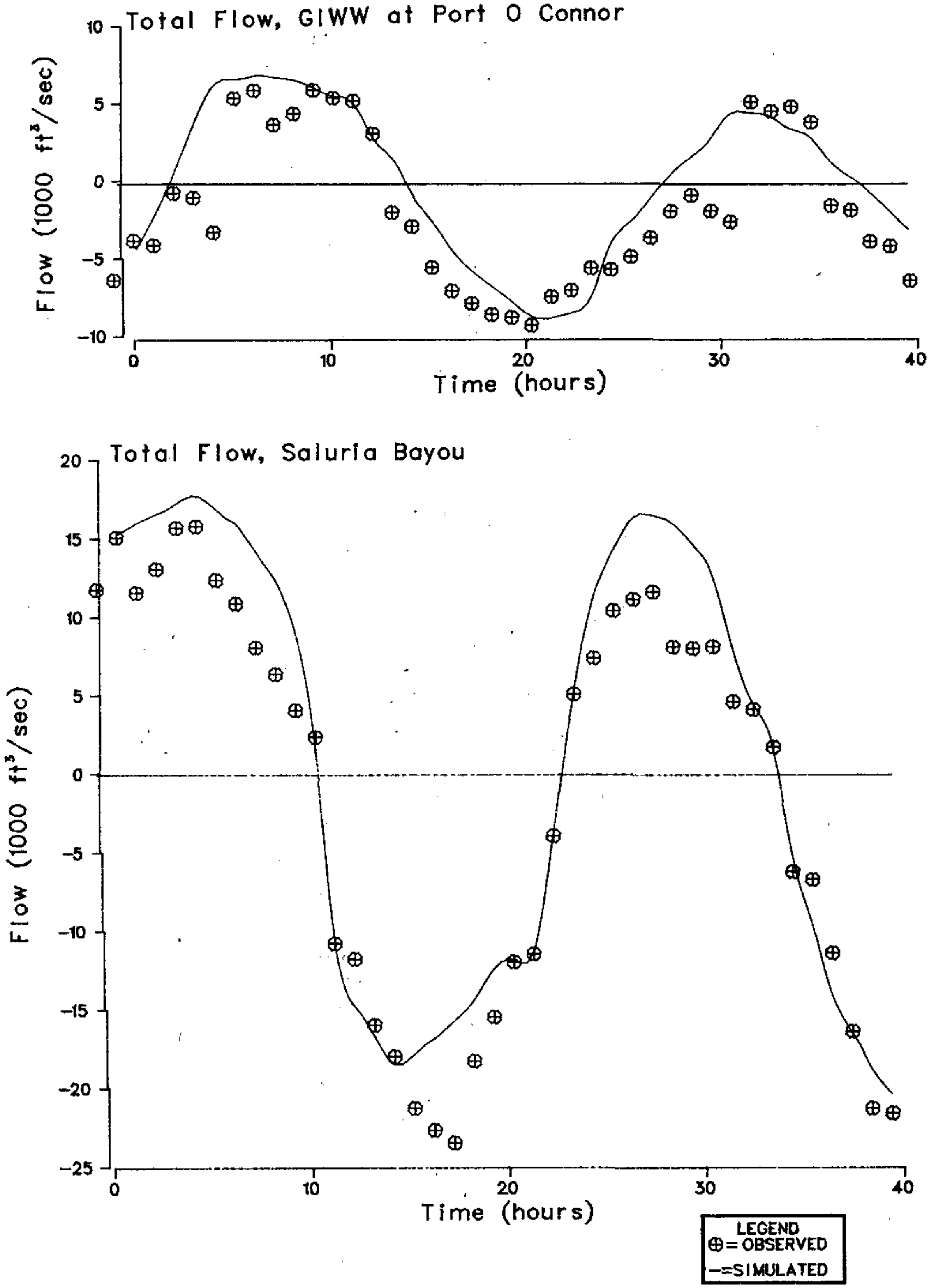

Figure 5-10. Comparison of Observed and Simulated Flows, Guadalupe Estuary, August 8-9, 1973--Continued

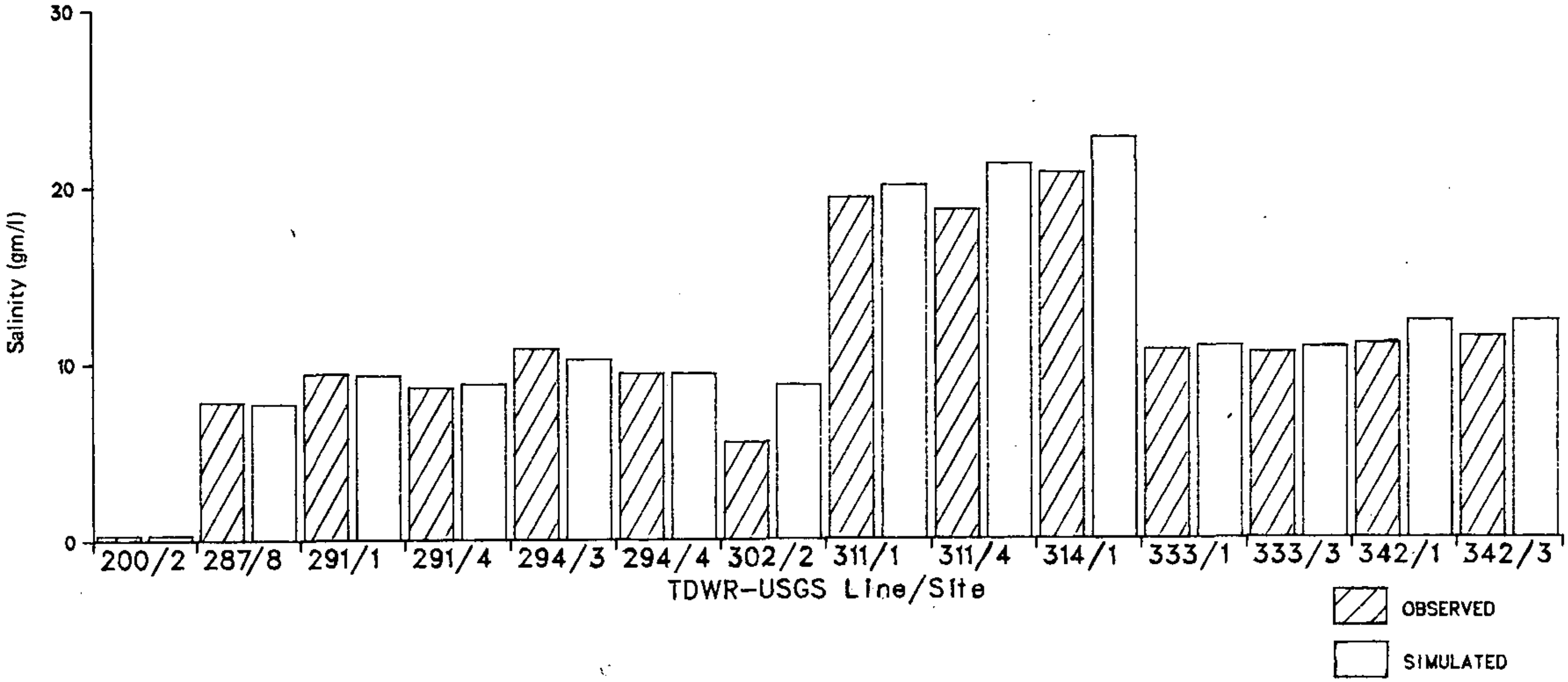

Figure 5-11. Comparison of Observed and Simulated Salinitites, Guadalupe Estuary, August 8-9, 1973

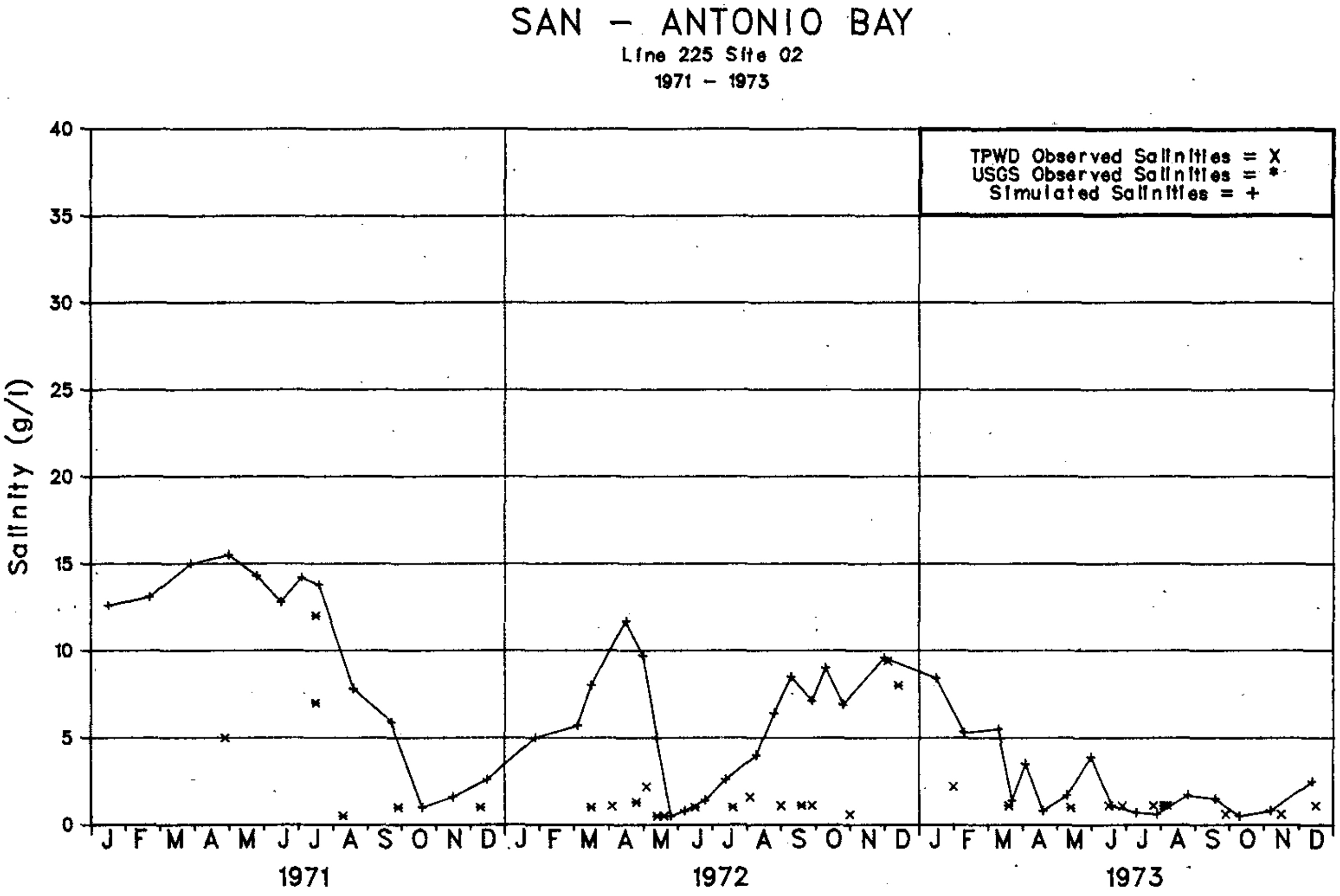

Figure 5-12. *Comparison* of Observed and Simulated Salinities, Guadalupe Estuary, Line 225, Site 02

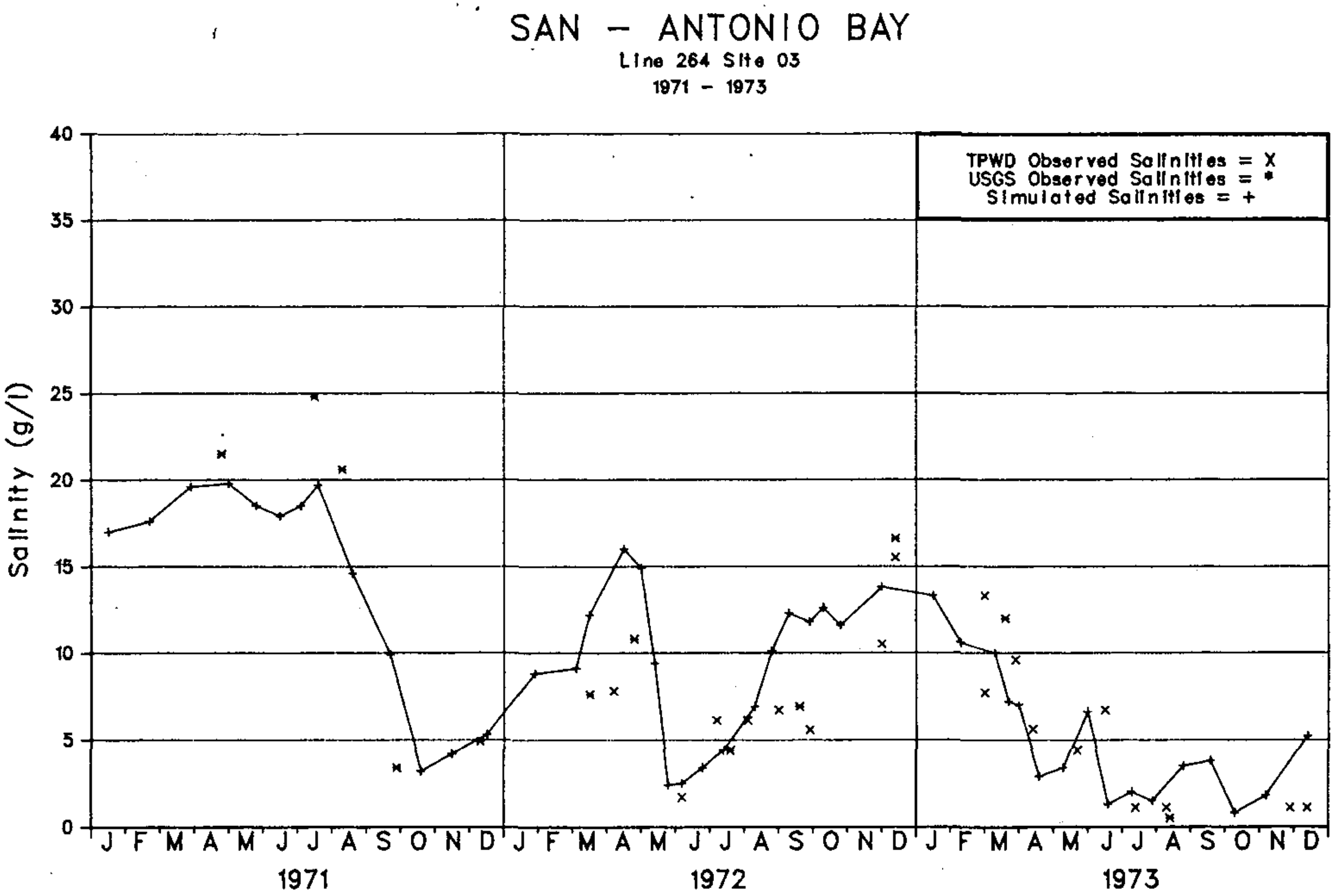

Figure 5-13. Comparison of Observed and Simulated Salinities, Guadalupe Estuary, Line 264, Site 03

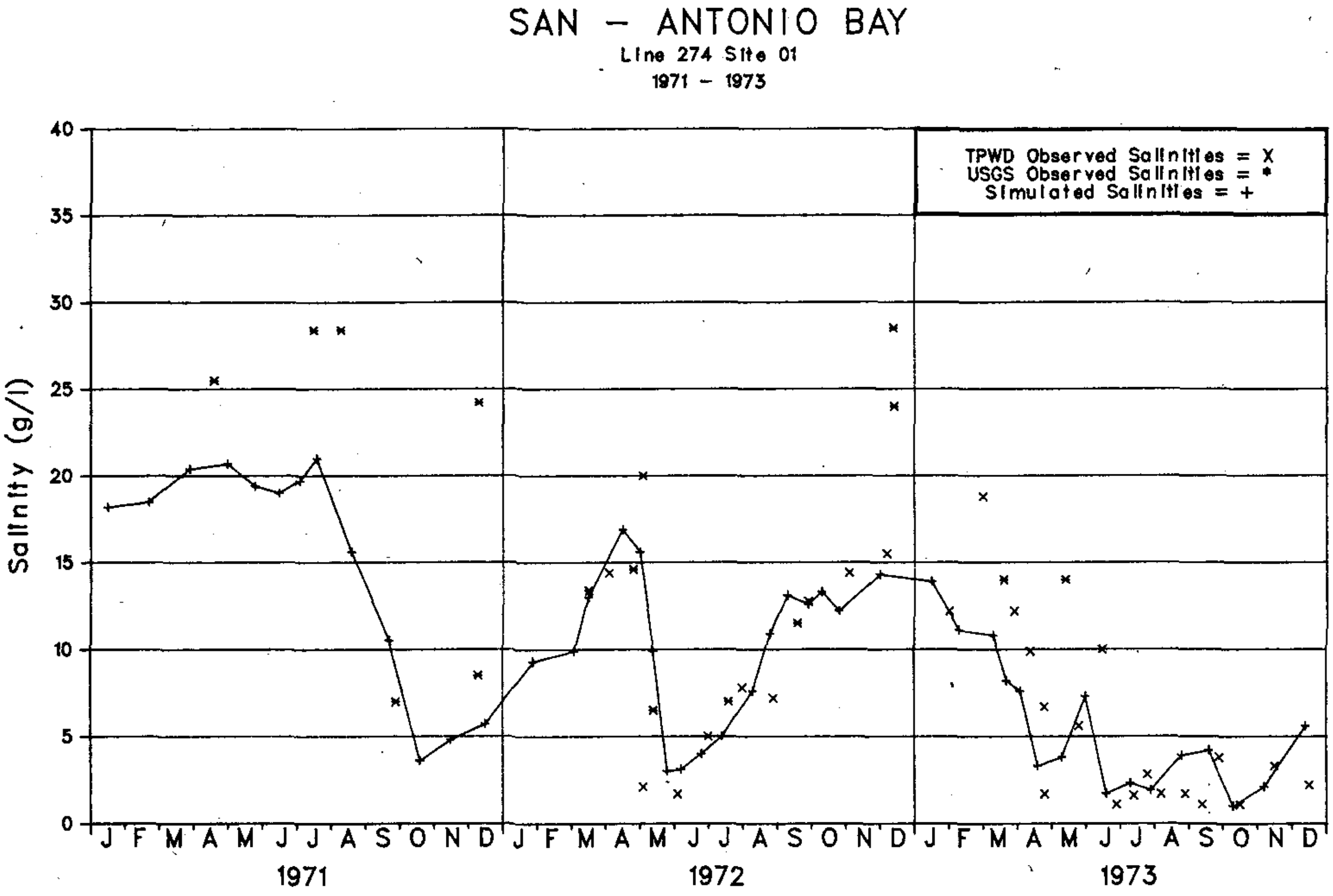

Figure 5-14. Comparison of Observed and Simulated Salinities, Guadalupe Estuary, Line 274, Site 01

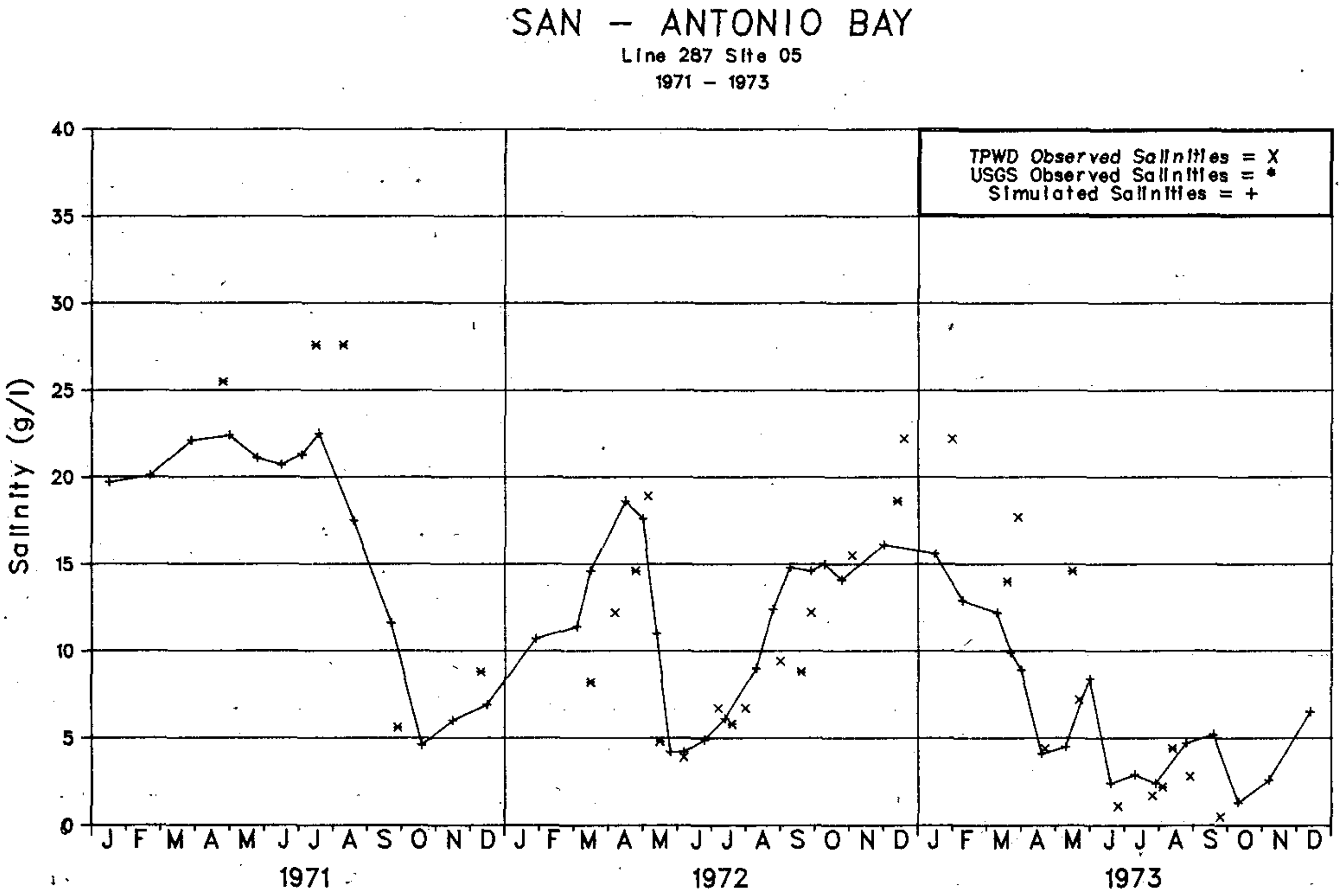

Figure 5-15. Comparison of Observed and Simulated Salinities, Guadalupe Estuary, Line 287, Site 05

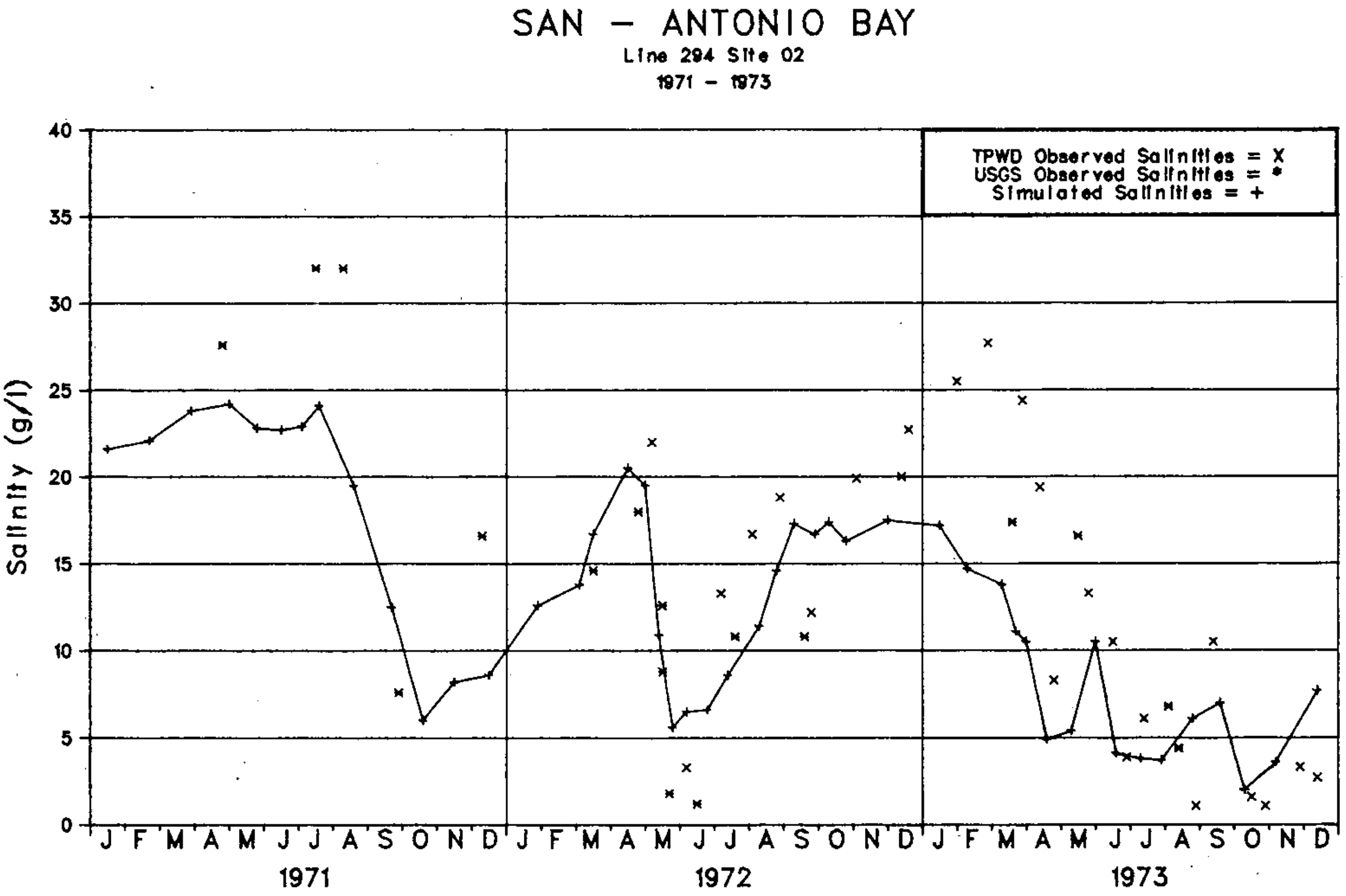

Figure 5-16. Comparison of Observed and Simulated Salinities, Guadalupe Estuary, Line 294, Site 02

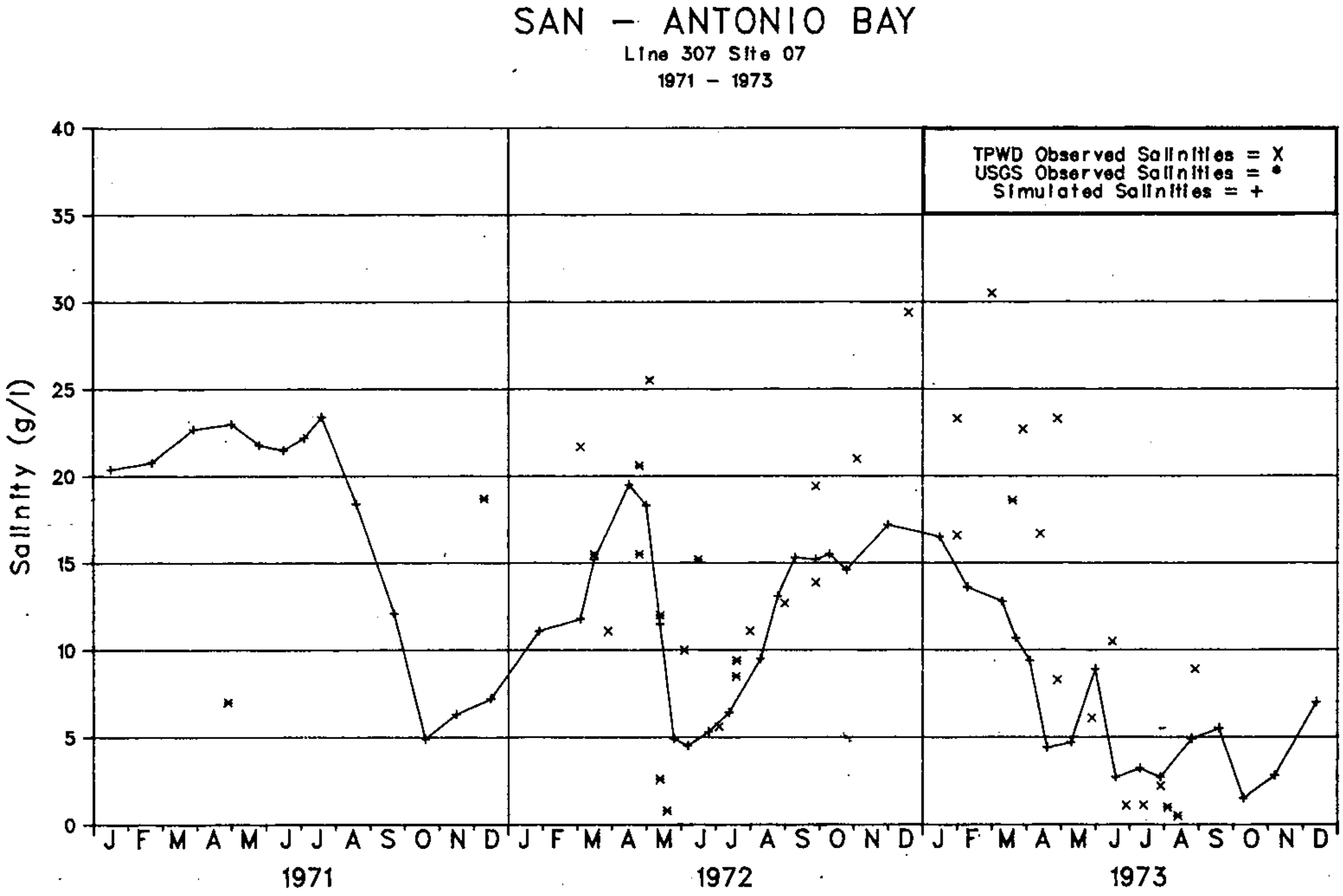

Figure 5-17. Comparison of Observed and Simulated Salinities, Guadalupe Estuary, Line 307, Site 07

shown in Table 5-2. In addition, two independent tide records from the San Antonio Bay near the Seadrift gage (08165100) were selected which correspond to average and normal tide conditions. Each of the six flood cases were simulated with both a high and normal driving tide in an effort to differentiate portions of the delta that would be inundated as a result of high flows, and to differentiate areas which would be inundated as a result of the interaction of high freshwater inflows and high tidal activity.

Driven by normal tides, inundation of the Guadalupe delta in the area below Mission Lake and between the two river arms, begins when the flood peak approaches 4,000 ft^3/sec (113.3 m^3/sec). The area above Mission Lake and below Highway 35 becomes inundated with flood peaks of approximately 7,000 ft^3/sec (198.2 m^3/sec); however, high tides will cause this same area to begin to inundate with flows of 4,000 ft^3/sec (113.3 m^3/sec). High tide simulations also show that the area in the vicinity of Lucas Lake and Long Lake is completely tidally dominated as this area is not influenced by any of the floods studied under normal tide conditions but floods with high tide - low flow conditions. In addition, most of the area directly above Hynes Bay and west of the Guadalupe River will inundate only with high tides.

High flows demonstrate little impact on the main river channel. Only the river channel in the immediate vicinity of the Guadalupe River at Highway 35 is ever subjected to inundation with flood peaks of less than 30,000 ft^3/sec (849.5 m^3/sec) (Figure 5-18).

As a result of these studies, curves were developed relating the percentage of marsh area inundated to a function of flow, for both normal and high tides. These results are presented in Figure 5-19.

Freshwater Inflow/Salinity Regression Analysis

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

The dominance of the effect of freshwater inflow on estuary salinity increases with an increase in proximity to freshwater inflow sources. The areal extent of the estuary influenced by freshwater inflow varies in proportion to the magnitude of freshwater inflow except during conditions of extreme drought. Regression analyses of measured salinities versus freshwater inflow are carried out to verify and quantify such a relationship. Salinity data from San Antonio Bay are correlated with the sum of gaged streamflows from San Antonio and Guadalupe Rivers.

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

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

Table 5-2. Hydrograph Peaks for Guadalupe Delta Simulation Model

Guadalupe River Maximum	Goff Bayou Maximum	Hog Bayou Maximum	Shallow Water Maximum	Frenchmans Bayou Maximum	Hog Relief Maximum	Schwings Bayou Maximum	Total
(in ft^3/sec)							
2,055	1,450	360	120	195	5	180	4,365
2,760	1,420	650	682	530	125	930	7,097
4,360	2,650	91	8	495	139	1,766	10,329
2,730	2,870	2,100	1,420	1,230	580	4,030	14,960
3,270	5,250	3,370	2,940	2,510	1,140	6,530	25,010
3,300	7,660	3,720	3,935	2,760	2,040	7,100	30,515

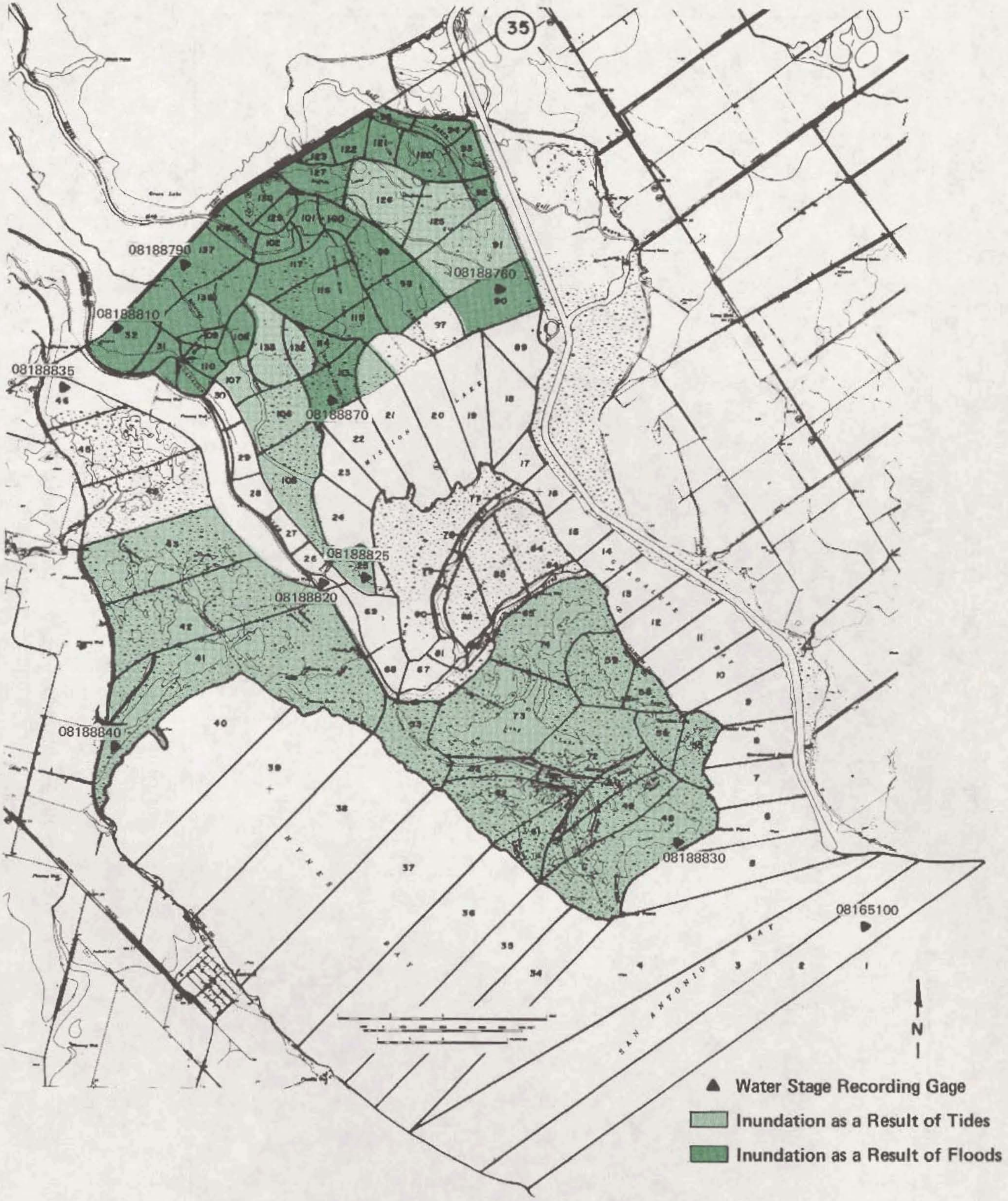

Figure 5-18. Guadalupe Delta System Showing Inundation Areas (45)

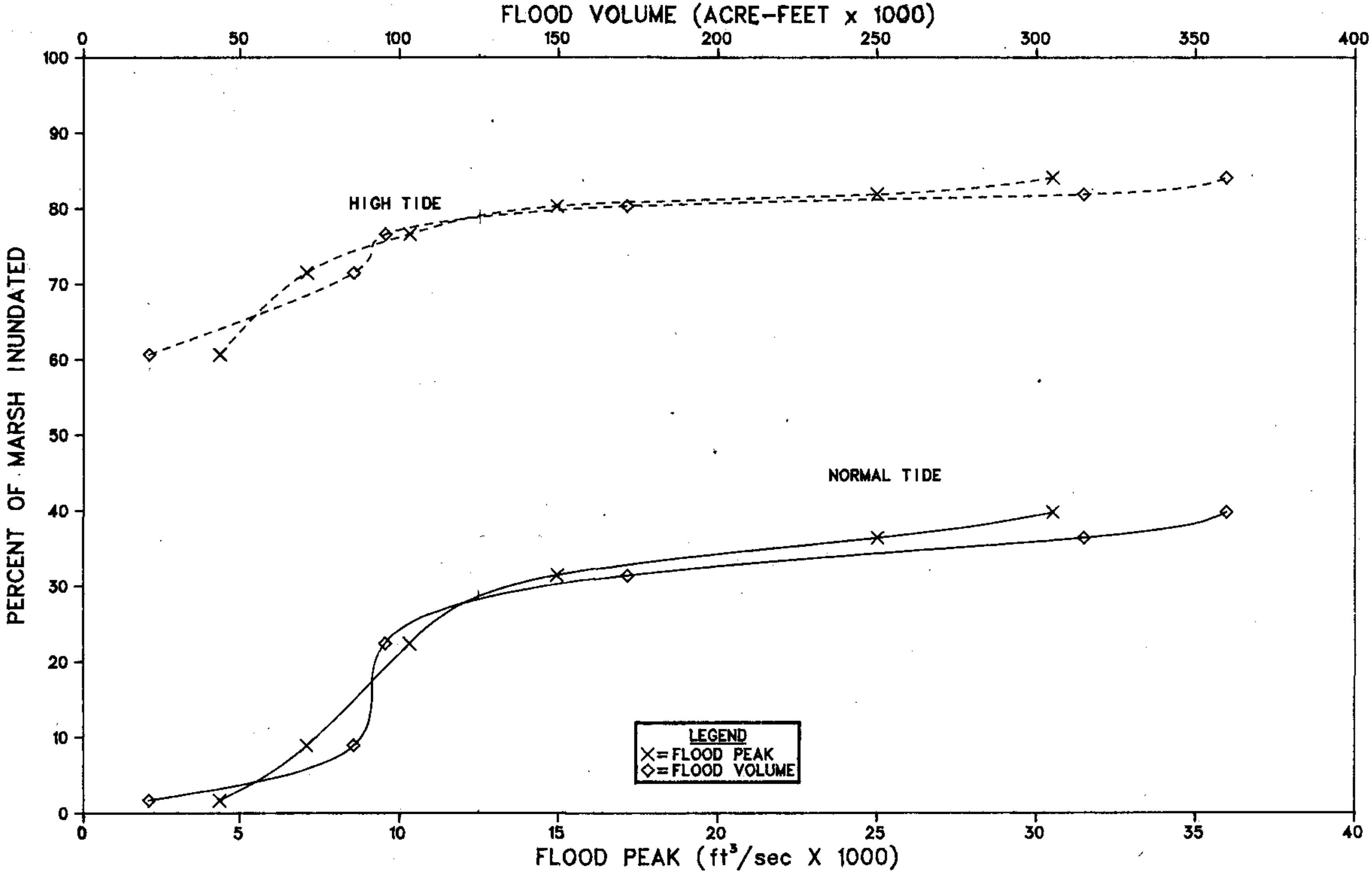

Figure 5-19. Simulated Guadalupe Delta Marsh Inundation,
High and Normal Tides

or

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

where S_t is the average salinity of the t-th day; Q_{t-k} or Q_{t-i} is gaged streamflow k or i days antecedent to the t-th day; b is a positive number between zero and one; n is an integer; and a_0, a_1 and a_2 are regression coefficients. The term $\sum_{i=1}^{n} Q_{t-i}$ in Equations [1] and [2] represents the antecedent inflow conditions, while Q_{t-k} represents the present inflow condition taking into consideration streamflow time lag between the gage and the estuary. The regression coefficients were determined using a step-wise multiple regression procedure (15).

The regression equations developed for San Antonio Bay use the salinities obtained by the Texas Department of Water Resources at statewide monitoring program station[1/] Nos. 2046.01 and 2046.03 and the sum of gaged streamflows recorded for the Guadalupe River near Goliad and the San Antonio River at Victoria (Table 5-3). The daily average salinity at station 2046.01 is related to the daily gaged streamflow by

$$S_t = -10.87 + 5892.2 \, (\sum_{i=1}^{26} Q_{t-i})^{-0.5} \qquad [3]$$

where S_t and Q_{t-i} are salinity and streamflow in ppt and ft^3/sec, respectively. The relationship is plotted in Figure 5-20. With a correlation coefficient (r) of 0.84 and an explained variation (r^2) of 70 percent, the regression is tested to be highly significant ($\alpha = .01$).

Average monthly salinity-inflow relationships were derived using equation [3] to generate daily salinities for the period of streamflow record, 1940 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. A frequency analysis indicates that both monthly salinities and monthly gaged flows have approximately log-normal distributions. Therefore, the random component has a normal distribution and can be expressed by ts_e (57), 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

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[1/] See Figure 3-9, station 2046.01 is located near line site 243-2, and 2046.03 at the intersection of line 302 and the Intracoastal Waterway.

Table 5-3. Description of Data for Regression Analysis

Bay	Salinity		Inflow		No. of Obs. for Regression
	Station	Period of Record	USGS Station	Period of Record	
San Antonio	TDWR Network 2462.01	Jul. 1969 to Jun. 1977	Guadalupe River at Victoria & San Antonio River near Goliad	Jan. 1940 to Sep. 1976	32
San Antonio	TDWR Network 2462.03	Sep. 1973 to Sep. 1976	—		13

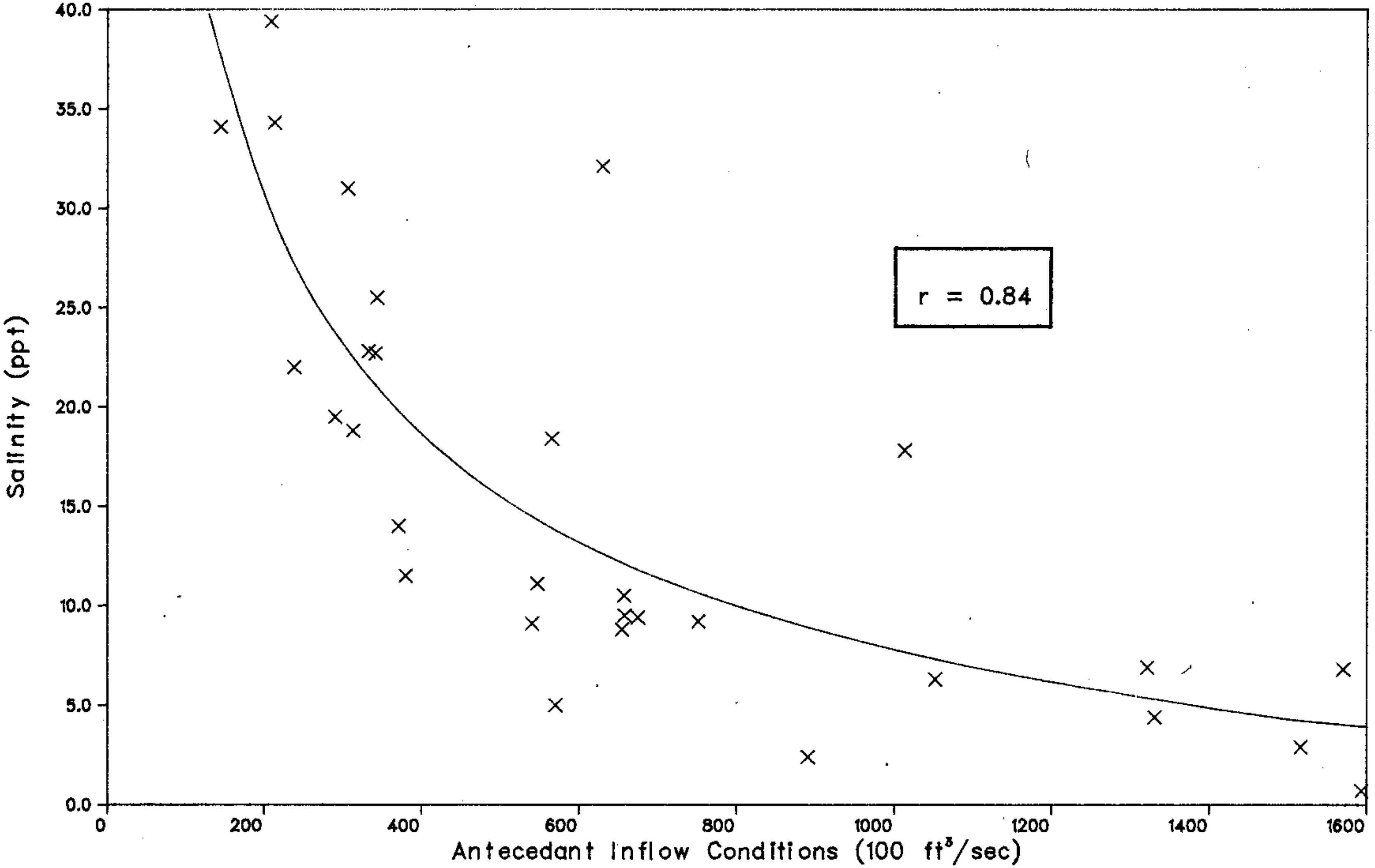

Figure 5-20. Daily Average Salinity Versus
Antecedent Inflow Conditions

the twelve months (r) ranged from 0.74 to 0.94, which are highly significant ($\alpha = .01$).

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

$$S_y = 5{,}113.5\ Q_y^{-0.779} \qquad [5]$$

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 5-21. The other statistics of equation [5] are listed in Table 5-4.

The spatial distribution of salinities was evaluated by correlating the average salinities measured at stations 2046.01 and 2046.03 (Table 5-3). Assuming a linear relation, the analysis yielded

$$S_{03} = 0.25 + 0.65\ S_{01} \qquad [6]$$

where S_{01} and S_{03} are salinities measured at 2046.01 and 2046.03 in ppt, respectively. The relation is highly significant ($\alpha = .01$) with $r^2 = 0.79$.

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

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

Summary

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

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

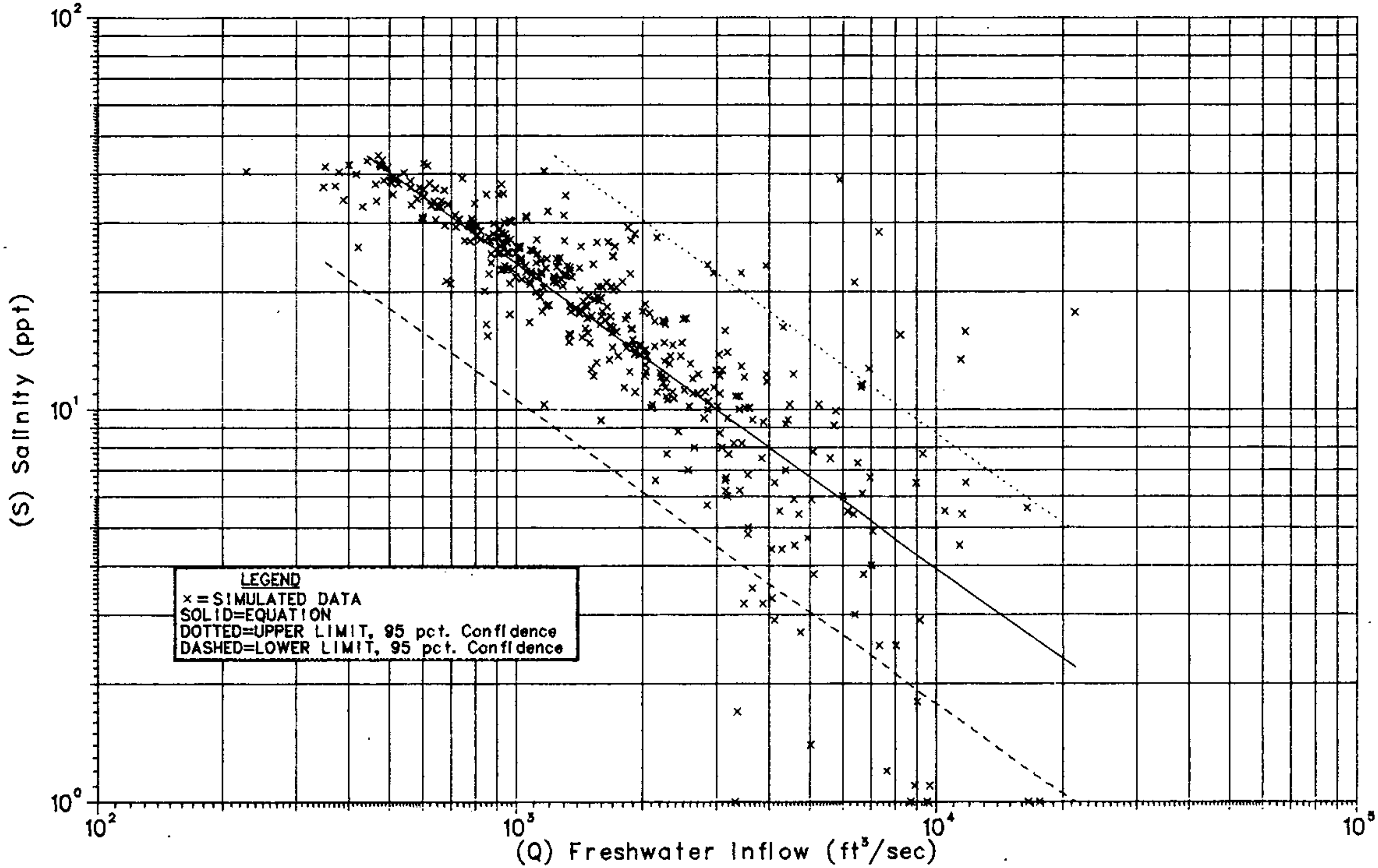

Figure 5-21. Average Monthly Salinity Versus Average Monthly Gaged Inflow, San Antonio Bay, 1940-1976

Table 5-4. Results of Salinity Regression Analysis, San Antonio Bay

Station	Class	Regression Equation (S in ppt and Q in ft^3/sec)		Correlation Coefficient r	Explained Variation r^2	Standard Error of Estimate s_e	F-test
TDWR 2462.01	Daily	$S_t = -10.87 + 5892.2 \left(\sum_{i=1}^{26} Q_{t-i}\right)^{-0.5}$		0.84	0.70	——	**
	Jan.	$S = 1337.9\ Q^{-0.580}$,	$350 \leq Q \leq 11500$	0.88	0.78	0.259	**
	Feb.	$S = 7668.0\ Q^{-0.821}$,	$330 \leq Q \leq 11500$	0.87	0.75	0.370	**
	Mar.	$S = 10104.7\ Q^{-0.880}$,	$470 \leq Q \leq 5100$	0.83	0.69	0.421	**
	Apr.	$S = 1941.8\ Q^{-0.631}$,	$400 \leq Q \leq 7000$	0.88	0.77	0.289	**
	May	$S = 19559.2\ Q^{-0.956}$,	$500 \leq Q \leq 16600$	0.79	0.63	0.722	**
	Jun.	$S = 4771.5\ Q^{-0.793}$,	$360 \leq Q \leq 11800$	0.83	0.69	0.551	**
	Jul.	$S = 9040.0\ Q^{-0.891}$,	$390 \leq Q \leq 10500$	0.94	0.88	0.340	**
	Aug.	$S = 2997.7\ Q^{-0.696}$,	$420 \leq Q \leq 4130$	0.87	0.76	0.318	**
	Sept.	$S = 635.7\ Q^{-0.460}$,	$320 \leq Q \leq 21400$	0.74	0.50	0.440	**
	Oct.	$S = 11999.6\ Q^{-0.900}$,	$500 \leq Q \leq 17700$	0.82	0.67	0.636	**
	Nov.	$S = 9667.4\ Q^{-0.879}$,	$450 \leq Q \leq 9530$	0.89	0.79	0.424	**
	Dec.	$S = 15268.8\ Q^{-0.929}$,	$530 \leq Q \leq 4240$	0.94	0.88	0.241	**
	All Months	$S = 5113.5\ Q^{-0.779}$,	$320 \leq Q \leq 21400$	0.83	0.69	0.483	**
2462.03 vs 2462.01	Spatial	$S_{03} = 0.25 + 0.65\ S_{01}$	——	0.89	0.78	2.579	**

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

to simulate the temporal and spatial behavior of circulation and salinity patterns in an estuary.

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

The marsh inundation model is applied to the Guadalupe River delta. The delta system is represented as a series of interconnected shallow channels which are subject to varying levels of inundation, depending upon the tidal and riverine flow rates. The representation of the Guadalupe River delta includes the non-tidally influenced flood plain of the Guadalupe River from the stream gages near State Highway 35 downstream to San Antonio Bay.

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

The numerical tidal hydrodynamic and salinity mass transport models were applied to the Guadalupe estuary, with the model representation of the system including Hynes Bay, San Antonio Bay, Ayres Bay, Espiritu Santo Bay, and a portion of the Gulf of Mexico adjacent to Matagorda Peninsula. The hydrodynamic and mass transport models were calibrated and verified for the estuary.

The extent of marsh inundation in the Guadalupe River delta was investigated utilizing the verified inundation model for this system. The surface area of the Guadalupe delta flooded was determined for six typical flood hydrographs under low, high and average tidal amplitudes.

Statistical analyses were undertaken to quantify the relationship between freshwater inflows from the Guadalupe and San Antonio Rivers and salinities from San Antonio Bay. A set of monthly predictive salinity equations was derived utilizing regression analyses. These equations predicted the mean monthly salinity as a function of the mean monthly freshwater inflow rate.

CHAPTER VI

NUTRIENT PROCESSES

Introduction

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

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

CNP ratios (carbon to nitrogen to phosphorus) vary from organism to organism. Generally, oceanic species have a reported CNP ratio of 106:16:1 (120). Nitrogen to phosphorus ratios for a variety of phytoplankton species are usually in the range of 10-12:1 (120). Carbon is normally required in the greatest quantity, followed by nitrogen and phosphorus. Carbon is rarely if ever limiting, however, due to the readily available supply of atmospheric carbon dioxide (CO_2) available and the ability of autotrophic organisms to use it in this form; therefore, nitrogen and phosphorus can be considered to be the two "critical" nutrients in most aquatic ecosystems.

The amount of nitrogen required in an aquatic ecosystem is generally greater than phosphorus, thus biological productivity is most likely to be nitrogen limited. This has been reported to be the case in a number of estuaries (388, 135, 188, 192, 111) including those in Texas (317, 318).

Nutrients can be brought into the estuary in either particulate or dissolved forms. Both forms may be composed of organic and inorganic components. Particulate nutrients may exist in the form of detritus from decaying vegetation, sewage and industrial water effluent or nutrients adsorbed onto silt, clay, and various mineral particles. In general, some form of mixing is necessary to keep particulate materials (especially the larger ones) in suspension. Mixing forces may be in the form of wind driven circulation, as in the shallow bays of the Texas coast, or 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 considerable exchange of seawater with bay water depending upon prevailing conditions, and some nutrients may enter from this source. Rainfall probably does not act as a major nutrient source, although soluble ammonia may be available in the atmosphere at times. On the Texas coast, the major source of nutrients is freshwater inflow from the rivers and streams that empty into the estuary. Inflows suspend and transport nutrients of natural and man-made origin.

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

Nutrient Loading

Attempts to determine the amount of nutrient loading from a riverine source to an estuary have been conducted by Smith and Stewart (197). The basic methodology includes a determination of mean annual flow magnitudes and mean annual concentrations of the nutrient species; simple multiplication is used to arrive at a loading in pounds (or kilograms) per year. The U.S. Geological Survey (USGS), in cooperation with the Texas Department of Water Resources, has maintained daily stream discharge records of the major rivers and tributaries that empty into Texas' bays and estuaries. Nutrient concentration and water quality data have been collected systematically for these rivers only since the late 1960's.

The major source of nutrients to the Guadalupe estuary is freshwater inflow contributed by the San Antonio and Guadalupe Rivers. Contribution of nutrients by local ungaged runoff is unknown, but thought to be significant when compared to the total nutrient input from gaged sources into San Antonio Bay. On the other hand, nutrient loading into the adjacent Mesquite and Espiritu Santo Bays comes from either local ungaged runoff and/or transport from adjacent bays and the Gulf of Mexico, as there are no significant sources of gaged freshwater directly feeding these areas. Inundation of salt marshes found in these bays is due primarily to tide and wind step phenomena. Locally rainfall may serve to flush some nutrients and detrital material into the bays but at present there are no quantitative data to use in determining the significance of this source.

Nutrient concentrations in the Guadalupe and San Antonio Rivers at Victoria and Goliad, respectively, were calculated from streamflow and water quality data provided by the USGS Water Resources Data for Texas, 1968 through 1973, and presented in an unpublished draft report prepared by staff of the Texas Department of Water Resources (237). A subsequent update of this information using 1974 through 1976 data from the USGS source was recently completed (237). The data were reduced and tabulated to a form comparable with the earlier report.

Nutrient concentrations (carbon, nitrogen, and phosphorus) from the 1968 through 1973 data are compared with concentrations observed during 1974 through 1976 (Tables 6-1 through 6-4). The 1968 through 1973 results show no apparent significant seasonal variation in carbon levels but a definite

Table 6-1. Carbon Levels a/ in the San Antonio and Guadalupe Rivers at the Goliad and Victoria Gages (mg/l)

Flow Range ft^3/sec	San Antonio River at Goliad 1968-73	San Antonio River at Goliad 1974-76	Guadalupe River at Victoria 1968-73	Guadalupe River at Victoria 1974-76
0-500	51	61.5	47	
500-1,000	44	53.7	45	53.4
1,000-5,000	35	48.5	40	49.9
5,000-10,000	25		33	48.4
10,000-Up	25		25	

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a/ As total C based on CO_3-C and HCO_3-C concentrations

Table 6-2. Inorganic Nitrogen Levels a/ in the San Antonio and Guadalupe Rivers at the Goliad and Victoria Gages (mg/l)

San Antonio River

Season or Months / Flow Range ft^3/sec	Jan-Mar Winter 68-73	Jan-Mar Winter 74-76	April-June Spring 68-73	April-June Spring 74-76	July-Sept Summer 68-73	July-Sept Summer 74-76	Oct-Dec Fall 68-73	Oct-Dec Fall 74-76
0-500	3.8	4.9	3.4	6.0	2.2	4.3	2.9	3.7
500-1,000	3.2	2.5	2.7	4.2	2.5	3.2	2.0	3.3
1,000-5,000	2.3	3.1	1.6	2.6	1.5	2.8	1.6	2.7
5,000-10,000	1.1		1.1		0.7		0.5	
10,000-up	0.9		0.9		0.4		0.4	

Guadalupe River

Season or Months / Flow Range ft^3/sec	Jan-April 68-73	Jan-April 74-76	May-Sept 68-73	May-Sept 74-76	Oct-Dec 68-73	Oct-Dec 74-76
0-500	2.0		0.6		0.6	
500-1,000	1.5	1.1	0.7	1.3	0.6	
1,000-5,000	0.9	1.1	0.9	1.1	0.6	0.9
5,000-10,000	0.5	0.6	0.8	0.8	0.6	
10,000-up	0.3		0.5		0.6	

a/ As total N based on NO_3-N, NO_2-N, and NH_3-N concentrations

Table 6-3. Organic Nitrogen Levels in San Antonio and Guadalupe Rivers at the Goliad and Victoria Gages (mg/l)

San Antonio River

Season or Months / Flow Range ft^3/sec	Jan-Mar Winter		April-June Spring		July-Sept Summer		Oct-Dec Fall	
	68-73	74-76	68-73	74-76	68-73	74-76	68-73	74-76
0-500	0.4	0.6	0.4	0.8	0.5	1.0	0.4	1.0
500-1,000	0.4	0.7	0.5	0.6	0.6	1.0	0.4	1.1
1,000-5,000	0.4	0.6	0.6	1.2	0.9	1.1	0.6	1.6
5,000-10,000	0.4		0.7		1.2		0.7	
10,000-up	0.4		0.8		1.2		0.8	

Guadalupe River

Season or Months / Flow Range ft^3/sec	Jan-Mar Winter		April-June Spring		July-Sept Summer		Oct-Dec Fall	
	68-73	74-76	68-73	74-76	68-73	74-76	68-73	74-76
0-500	0.2		0.2		0.3		0.2	
500-1,000	0.2	0.2	0.2	0.4	0.3		0.2	0.5
1,000-5,000	0.2	0.3	0.3	0.4	0.5	0.5	0.3	0.4
5,000-10,000	0.4	0.2	0.4	0.4	0.5	0.4	0.3	
10,000-up	0.5		0.8		0.6		0.4	

Table 6-4. Total Phosphorus Levels in the San Antonio and Guadalupe Rivers at the Goliad and Victoria Gages (mg/l)

San Antonio River

Season or Months / Flow Range ft^3/sec	Jan-Mar Winter		April-June Spring		July-Sept Summer		Oct-Dec Fall	
	68-73	74-76	68-73	74-76	68-73	74-76	68-73	74-76
0-500	2.0	2.7	1.7	2.0	1.2	2.7	1.4	1.6
500-1,000	2.0	1.5	1.2	1.3	1.2	1.3	0.7	1.7
1,000-5,000	1.0	0.6	0.6	0.6	1.0	1.1	0.7	1.1
5,000-10,000	0.9		0.6		0.5		0.7	
10,000-up	0.9		0.6		0.5		0.7	

Guadalupe River

Season or Months / Flow Range ft^3/sec	Jan-Mar Winter		April-June Spring		July-Sept Summer		Oct-Dec Fall	
	68-73 a/	74-76	68-73	74-76	68-73	74-76	68-73	74-76
0-500								
500-1,000		0.1		0.1				
1,000-5,000		0.1		0.1		0.1		0.1
5,000-10,000		0.2		0.1		0.0		0.1
10,000-up								

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a/ 1968-1973 data for the Guadalupe at Victoria were not presented in this form in the San Antonio Bay Report relationship exists between inorganic carbon concentrations and streamflow. Inorganic carbon occurs in an equilibrium state as carbonate or bicarbonate ions and carbon dioxide in accordance with the equation:

$$CO_2 + H_2O \rightleftarrows H_2CO_3 \rightleftarrows H^+ + HCO_3^- \rightleftarrows 2H^+ + CO_3^{-2}$$

This equilibrium is dependent on pH. The carbonic acid (H_2CO_3) form predominates at pH levels less than 4.5. The carbonate (CO_3^{-2}) form is not found unless pH levels are greater than 8.3. Since pH values in both the Guadalupe and San Antonio Rivers are usually between 7.0 and 8.0, bicarbonate (HCO_3) is the dominant species. As streamflow increases, inorganic carbon concentrations decrease. Most inorganic carbon can be attributed to the groundwater contribution that either originates or flows through the limestone aquifers in and around the Edwards Plateau. This is a principal source of the dissolved bicarbonate ion. At low river flows, a greater percentage of the water is contributed by the aquifers. At higher flows, resulting from increased rainfall and surface runoff, the percentage of total flow contributed by the aquifers decreases. As the bicarbonate ion contributed by groundwater is diluted, the inorganic carbon concentrations decrease. Inorganic carbon concentrations range from 8.4 to 15.4 mg/l higher during 1974 through 1976 than in 1968 through 1973 (Table 6-1).

There is a scarcity of total organic carbon data collected by the USGS. Available data show total organic carbon (TOC) concentrations generally less than 10-12 ppm. Steed (201) has attempted to identify the sources of particulate and dissolved organic carbon in the Guadalupe and San Antonio Rivers as well as San Antonio Bay. He notes that particulate organic carbon (POC) concentrations in the Guadalupe River roughly follow patterns of river discharge; that is, POC concentrations are generally higher at peak river discharges. The same pattern occurs for POC concentrations in the San Antonio River. Dissolved organic carbon (DOC) concentrations are similar to POC concentrations in the Guadalupe River but roughly half the observed POC concentrations in the San Antonio River. The San Antonio River has higher POC and DOC concentrations than the Guadalupe but the total organic carbon (TOC) contributed is less since the Guadalupe River contributed 96.8 percent of the total river discharge to San Antonio Bay during the study. Below the confluence of the two rivers and Elm Bayou the POC concentrations range from 1.33 to 8.0 mg/l, averaging 3.77 mg/l. DOC concentrations rage from 1.28 to 6.9 mg/l, averaging 2.95 mg/l during the study period. Based on the combined river discharge rates of gaged freshwater inflows from the Guadalupe and San Antonio River basins, DOC and POC loadings to San Antonio Bay are 20.67 million kg/yr (56,630 kg/d) and 26.84 million kg/yr (73,534 kg/d), respectively. By combining the DOC and POC concentrations reported by Steed (201), the total TOC values are comparable to those few data points available from the USGS.

Organic carbon does not, as a rule, stimulate primary productivity. Under certain conditions it can be used in conjunction with other data such as chlorophyll a concentrations as an indicator of the amount of primary productivity occurring in an ecosystem. Atmospheric or dissolved carbon dioxide (CO_2) is the main source of carbon fixed and converted to vegetative biomass by photosynthetic processes responsible for primary production.

Analysis of USGS water quality data showed that inorganic nitrogen levels were lowest in summer and fall and highest in the winter months during the 1968 through 1973 period (Table 6-2). A similar trend, not as distinct, was noted for the 1974 through 1976 data. The data also showed a decrease in concentrations during higher flows, probably due to increased dilution of nitrogen sources, although absolute quantities contributed are larger during high inflow events.

Organic nitrogen contributions are similar for the two periods, 1968 through 1973 and 1974 through 1976 (Table 6-3). If a trend exists, it is for increased concentrations with increased streamflow. This can be attributed to organic nitrogen of detrital origin being introduced into the system during periods of high runoff.

Both inorganic and organic nitrogen concentrations are higher in the San Antonio River than in the Guadalupe River. Nitrogen inputs into the San Antonio River are largely from municipal and industrial wastewater discharges originating in the Bexar County area.

Total phosphorus concentrations exhibit trends similar to inorganic nitrogen. From 1974 through 1976, San Antonio River concentrations are similar in magnitude to those of the 1968 through 1973 period (Table 6-4). Further, phosphorus concentrations for the San Antonio River are an order of magnitude higher during the 1974 through 1976 period than those in the Guadalupe River.

Data reduction and computation reveal that the mean monthly discharge of the Guadalupe River measured at Victoria averages 73 percent of the total measured discharge from the Guadalupe and San Antonio Rivers (Tables 6-5 through 6-7). Even though the Guadalupe River contributes the majority of the flow, the San Antonio River contributes the larger percentage of the total amounts of inorganic nitrogen and total phosphorus (Table 6-8). These are nutrients of great concern as they directly stimulate biological productivity. The contributions of organic nitrogen, as discussed earlier, are dependent on available detritus and runoff necessary to introduce it into the system. Carbon loading, since it is based on bicarbonate ion concentrations, more nearly reflects the relative percentages of water contributed from each watershed. Total nutrient loading data are presented in Table 6-9 to give an illustration of the potential amount of nutrients that can be contributed by the watershed of each contributing river basin. However, one is cautioned that the data of Table 6-9 are taken from an apparent small sample of the time series data.

Childress et al. (245) found nitrite (NO_2) and nitrate (NO_3) concentrations in the Guadalupe River at the State Highway 35 bridge to be similar to concentrations reported in the USGS data. They reported a much larger range of nutrient contributions in kg/d than the 1968 through 1976 analysis of nitrogen contributions presented in Table 6-9. This increase in total nitrogen loading could be attributed to greater river discharges reported over the September 1971 to May 1974 study period. Total phosphorus concentrations reported by Childress et al. (245) were also similar to USGS values in Table 6-4. Like nitrogen, total phosphorus loading was greater than that given in Table 6-9 due to larger river flow volumes discharged to the estuary. The study also noted the phenomenon of highest N and P concentrations during

Table 6-5. Discharge Data, Guadalupe River at Victoria (ft^3/sec)

Water Year	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept
1968	2,270	2,213	1,114	7,130	2,348	1,869	2,907	4,991	6,178	1,669	962	1,649
1969	838	943	2,048	934	3,326	2,982	3,671	3,255	1,535	862	708	842
1970	1,353	1,225	1,532	1,797	1,864	2,814	1,921	3,433	2,757	1,204	853	798
1971	1,052	731	695	671	613	583	430	367	378	323	1,570	2,914
1972	1,453	1,448	2,026	1,446	1,583	1,056	756	12,230	2,789	1,648	1,343	971
1973	933	878	837	1,128	1,635	2,531	5,174	2,253	7,511	4,277	2,721	2,189
					Measured Discharge on Sample Collection Date							
1974	7,400	2,860	2,030	3,800	1,680	1,390	1,140	1,630	1,130	773	835	2,260
1975	1,230	3,600	2,890	1,900	5,300	2,050	1,650	2,900	6,200	3,120	1,840	1,390
1976	920	910	873	1,070	800	940	3,820	3,950	2,040	2,720	1,640	1,390
					1968-73 Maximum and Minimum Daily Discharges							
Maximum	10,500	9,020	9,320	41,000	10,700	12,300	13,800	24,600	31,900	6,360	5,300	9,240
Minimum	639	656	612	631	582	470	389	337	178	169	213	690

Table 6-6. Discharge Data, San Antonio River at Goliad (ft^3/sec)

Water Year	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept
1968	1,052	969	385	4,309	1,014	647	678	2,063	843	538	292	854
1969	315	317	584	360	990	577	709	1,333	574	170	232	334
1970	383	250	355	458	471	696	350	1,134	1,296	233	234	221
1971	272	204	203	237	208	194	174	137	225	143	1,285	961
1972	1,402	913	795	536	451	354	556	4,235	1,073	517	521	517
1973	610	464	396	442	618	521	1,792	597	4,253	4,723	1,400	2,244
Measured Discharge on Sample Collection Date												
1974	3,940	1,520	979	806	635	749	502	561	379	244	474	1,170
1975	550	858	680	650	1,350	700	620	780	1,250	871	483	517
1976	378	375	382	405	316	305	1,120	969	516	1,260	454	1,030
1968-73 Maximum and Minimum Daily Discharges												
Maximum	5,010	4,980	2,230	24,900	6,160	2,550	5,510	12,700	13,700	14,700	4,910	5,540
Minimum	208	175	185	197	179	119	104	90	89	53	54	145

Table 6-7. Percent Total Flow Contribution of the Guadalupe and San Antonio Rivers

	Guadalupe River at Victoria	San Antonio River at Goliad
1968-73 Average % mean discharge	73%	27%
1968-73 Range of % discharge	48-88%	12-52%
1974-76 Average % discharge	73%	27%
1974-76 Range of discharge	70-77%	23-30%

Table 6-8. Percent Total Contribution of Nutrients from the San Antonio and Guadalupe Rivers, 1974-1976

	Guadalupe River at Victoria	San Antonio River at Goliad
Average Percent Contributions of Nutrients		
Inorganic Nitrogen	44%	56%
Organic Nitrogen	53%	47%
Total Phosphorus	18%	82%
Inorganic Carbon	71%	29%
Range of Percent Contributions of Nutrients		
Inorganic Nitrogen	39-49%	51-61%
Organic Nitrogen	46-51%	39-54%
Total Phosphorus	17-19%	81-83%
Inorganic Carbon	66-75%	25-34%

Table 6-9. 1974-1976 Nutrient Contributions by the Guadalupe and San Antonio Rivers (kg/d)

	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept
Guadalupe River												
1974												
Inorg N	770	635	416	668	390	304	183	270	176	103	120	266
Org N	202	68	42	448	20	81	37	192	100	22	120	177
Total P	189	44	31	214	26	19	20	42	35	8	14	54
Carbon	63,700	29,600	19,500	15,800	16,200	13,800	11,100	12,500	10,100	6,100	7,100	15,500
1975												
Inorg N	223	485	508	360	678	350	434	450	836	511	314	216
Org N	82	221	207	146	317	102	130	282	444	276	94	107
Total P	27	98	54	15	54	7	37	40	32	48	19	17
Carbon	11,700	25,900	24,400	19,500	42,000	18,800	15,200	24,600	51,200	23,800	16,000	12,600
1976												
Inorg N	159	202	134	243	182	210	665	566	251	427	249	197
Org N	46	39	19	62	44	55	561	371	91	246	76	81
Total P	8	12	7	9	12	16	117	88	49	56	14	10
Carbon	8,809	8,977	8,731	10,135	7,783	8,423	28,491	27,842	17,652	19,637	13,883	11,956
San Antonio River												
1974												
Inorg N	1,036	825	710	619	463	658	296	407	281	180	292	583
Org N	363	153	62	61	55	87	63	115	63	32	105	399
Total P	336	187	134	165	130	217	154	201	175	79	138	340
Carbon	35,707	16,240	11,044	8,845	6,947	8,015	5,560	5,649	4,023	2,549	5,218	9,904
1975												
Inorg N	433	546	560	473	588	339	491	415	376	477	317	290
Org N	94	88	78	83	277	66	92	146	198	97	80	141
Total P	169	220	209	155	148	99	201	84	126	178	173	194
Carbon	5,688	7,717	7,079	6,390	11,244	7,001	6,158	6,909	10,326	8,414	5,317	4,200
1976												
Inorg N	336	315	316	370	370	296	732	361	138	759	219	313
Org N	46	46	29	55	25	63	249	199	88	387	64	165
Total P	219	147	163	104	119	120	306	116	82	237	57	93
Carbon	3,987	3,930	4,081	4,133	3,290	3,082	8,544	6,962	4,712	8,795	4,316	5,537

periods of lowest flow as was observed to occur in the USGS data from 1968 through 1976.

Marsh Vegetative Production

An estuarine marsh is a complex living system which provides (1) detrital materials (small decaying particles of plant tissue) that are a basic food source for the estuary, (2) "nursery" habitats for the young of economically important estuarine-dependent fisheries species, (3) maintenance of water 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 (162, 163). 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 (295, 393, 33, 180, 297, 291, 342, 9). 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 (38, 37, 208, 164, 401, 140, 139, 34, 175, 41, 118, 203, 90, 91, 96). Recent research has demonstrated a correlation between the area of intertidal salt marsh vegetation with the commercial harvests of penaeid shrimp (339). 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 (66). 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 wetland habitats. Deltaic marshes at the headwaters of an estuary generally exhibit a dendritic pattern of drainage channels and are especially important because they form a vital link between an inflowing river and its resulting estuary. 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 (288, 177, 171, 161, 88, 195).

Major contributing marshes to the Guadalupe estuary include the wetland areas of the Guadalupe River delta. The delta has been delineated into fourteen hydrological units with a combined area of 11,942 acres (4,833 hectares) (50). Dominant marsh plants include the vascular macrophytes Spartina spartinae, S. patens, Scirpus maritimus, Distichlis spicata, Monanthocloe littoralis, Borrichia frutescens, and Phragmites communis. Above-ground net production (ash-free dry weight) is estimated at 120.4 million pounds (54,624 metric tons) per year and annual net productivity (ash-free dry weight) averages 10,084 pounds per acre (1,130.3 g/m^2). Approximately 73 percent of the annual production occurs during the spring and summer quarters, and about

61 percent of the annual biomass losses occur during the summer and fall quarters. In addition, inundated areas of the Guadalupe delta exhibit net production (ash-free dry weight) from periphytes (organisms attached to surfaces of plants and other objects) that range from 1.64 lbs/acre/day (0.148 g/m^2/day) in December to 2.91 lbs/acre/day (0.326 g/m^2/day) in April, with an overall average of 2.27 lbs/acre/day (0.254 g/m^2/day) (49).

Although high productivity of the marshes results in large amounts of biogenic detritus for potential transport to the estuary's aquatic habitats (bays), actual detrital transport is dependent upon the episodic nature of the marsh inundation/dewatering process. The vast majority of primary production in the higher, irregularly-flooded vegetative zones may go into peak production and not be exported out of the marsh (27); however, it has been estimated that the lower, frequently-flushed vegetative zone characterized by Spartina alterniflora exports about 45 percent of its net production to estuarine waters (208).

In many coastal areas the production and nutritive contribution of emergent vascular plants to the estuarine ecosystem is supplemented or even largely replaced by vast submerged seagrass beds. This is particularly true for south Texas estuaries. An established seagrass community is highly productive, provides valuable habitat (food and cover) to economically important estuarine-dependent fish and shellfish, and stabilizes the bottom of the estuary (158, 114). In the Guadalupe estuary, areal estimates of submerged vegetation range from 12,269 acres (4,965 ha) to 16,350 acres (6,616 ha) (245, 363). The average standing crop of submerged vegetation from 1971 to 1974 has been estimated at 521 lbs/acre (584 kg/ha) in northern San Antonio Bay, 1,514 lbs/acre (1,697 kg/ha) in southern San Antonio and Mesquite Bay areas, 1,866 lbs/acre (2,092 kg/ha) in Espiritu Santo Bay, and 2,594 lbs/acre (2,908 kg/ha) in the Pass Cavallo area, with peak standing crops in all four areas occurring in spring (April-June) (245). Seagrass species present in the Guadalupe estuary are Halodule beaudettei (dominant), Ruppia maritima, and Halophila engelmanni.

Marsh Nutrient Cycling

Functions of Delta Marshes in Nutrient Processes

Deltaic and other brackish and salt marshes are known to be sites of biological productivity. Emergent macrophytes and blue-green algal mats serve to trap nutrients and sediment as flow velocities decrease. These nutrients are incorporated into the plant biomass during growth periods and are sloughed off and exported to the bay as detrital material during seasons of plant senescence and/or periods of inundation and increased flows into the open bay.

Studies by Armstrong et al. (267), Dawson and Armstrong (271), Armstrong and Brown (270), and Armstrong and Gordon (268, 269) have been conducted to determine the role of the plants and deltaic sediments in nutrient exchange processes. Carbon, nitrogen, and phosphorus exchange rates tend to follow seasonal patterns. In most cases these patterns seem to be similar from species to species (Figures 6-1 through 6-7). The rates also appear to be similar to those rates observed from similar plant types in other Texas

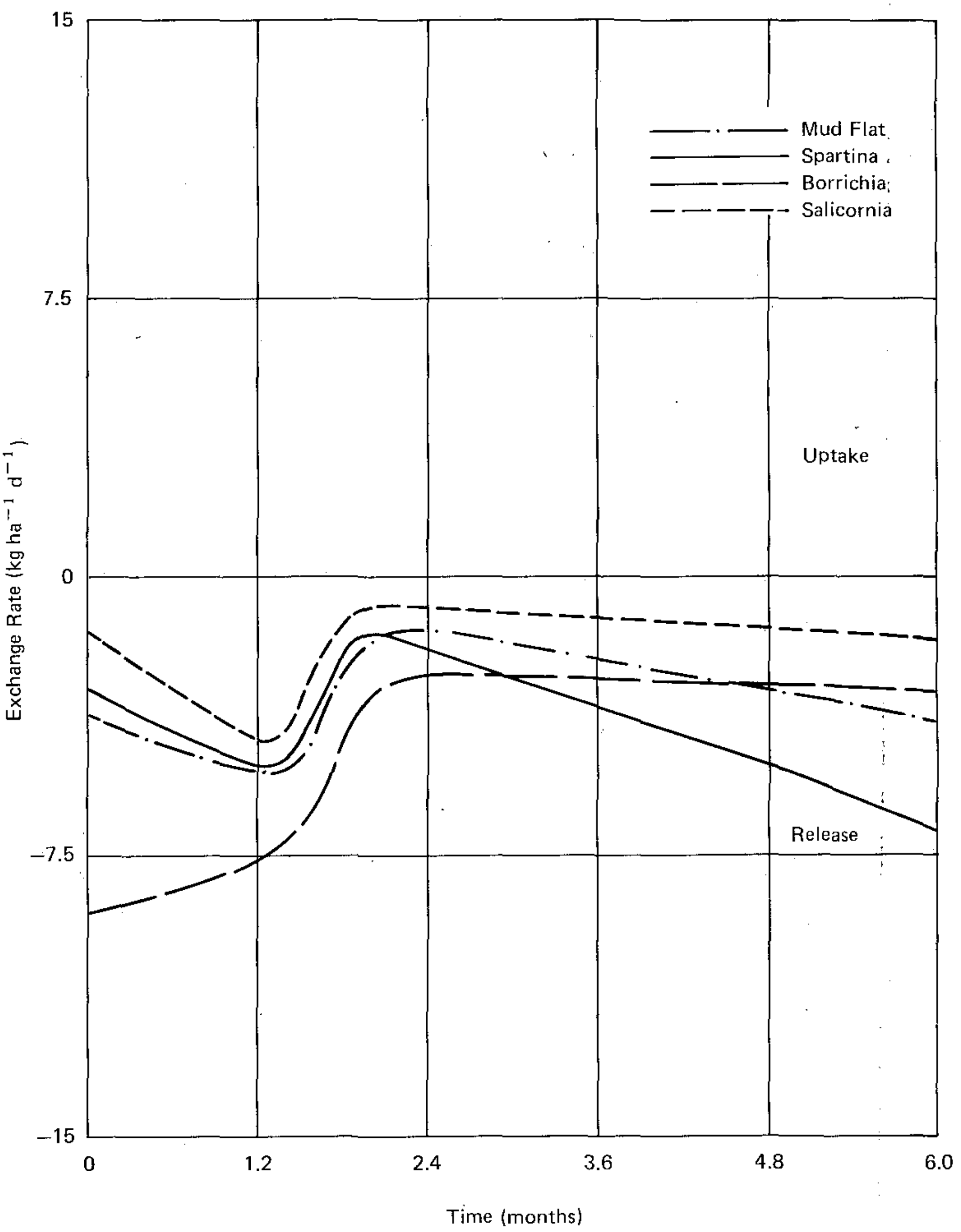

Figure 6-1. Exchange Rates for Total Organic Carbon in Guadalupe Estuary (271)

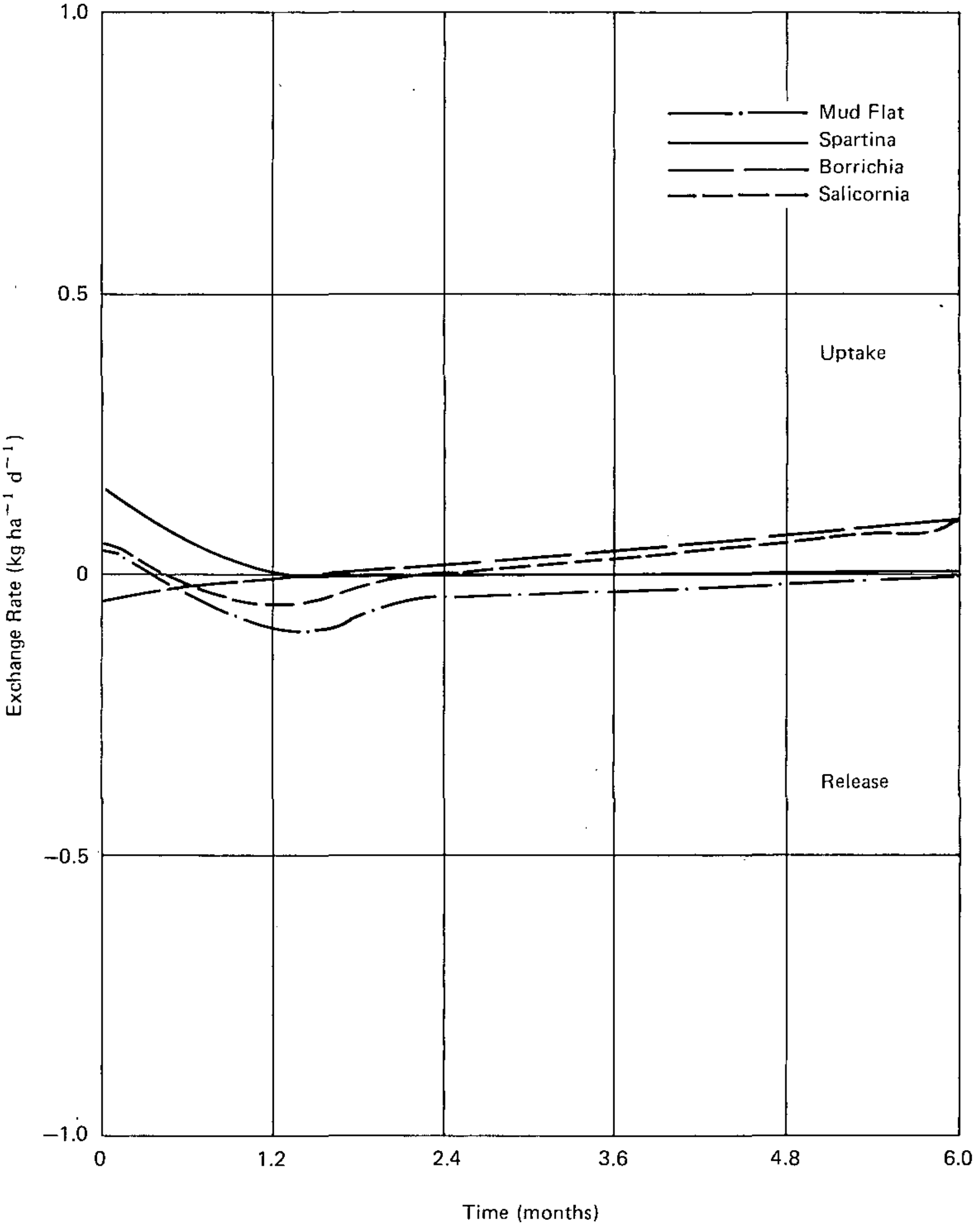

Figure 6-2. Exchange Rates for Unfiltered Total Kjeldahl Nitrogen in Guadalupe Estuary (271)

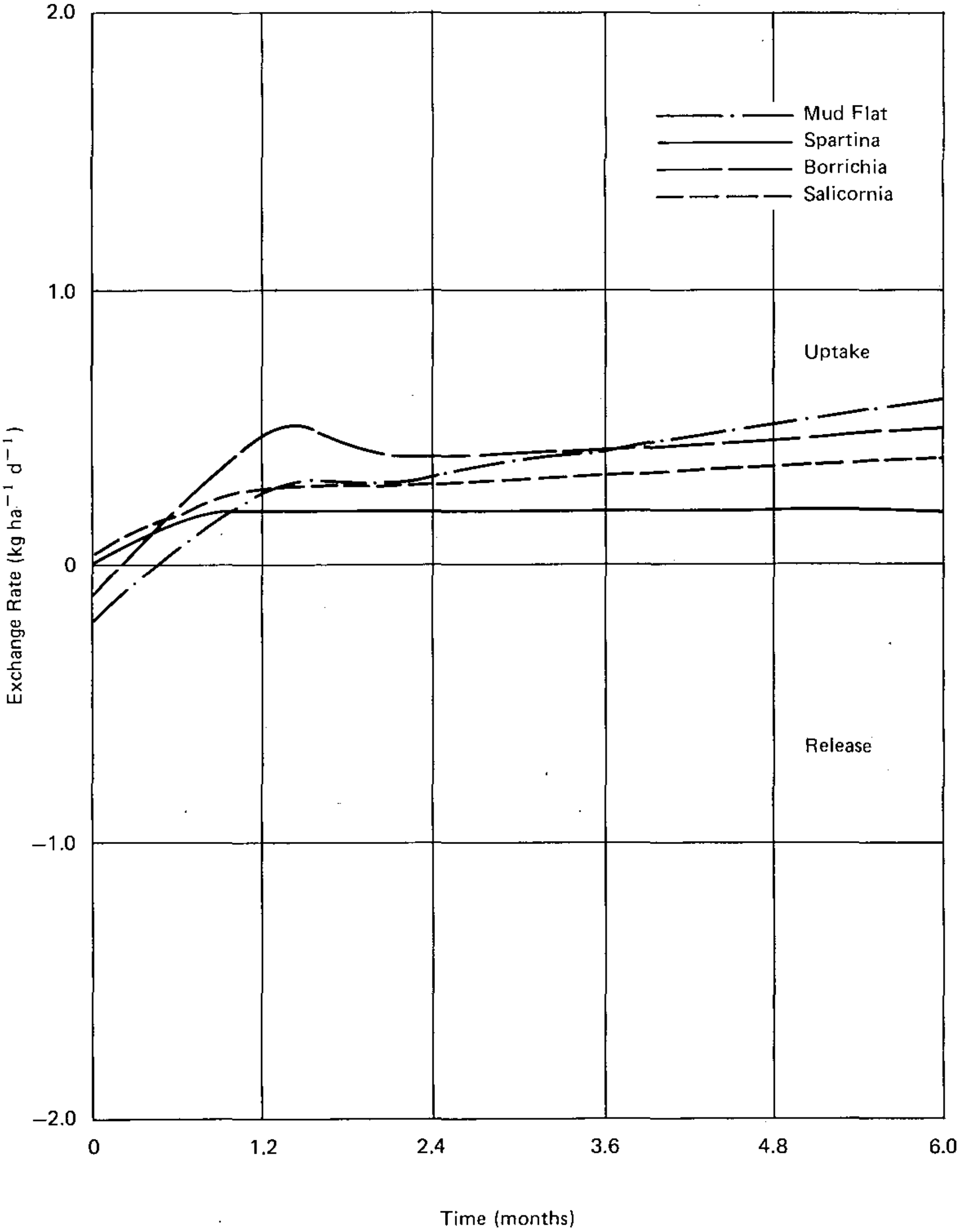

Figure 6-3. Exchange Rates for Ammonia Nitrogen in Guadalupe Estuary (271)

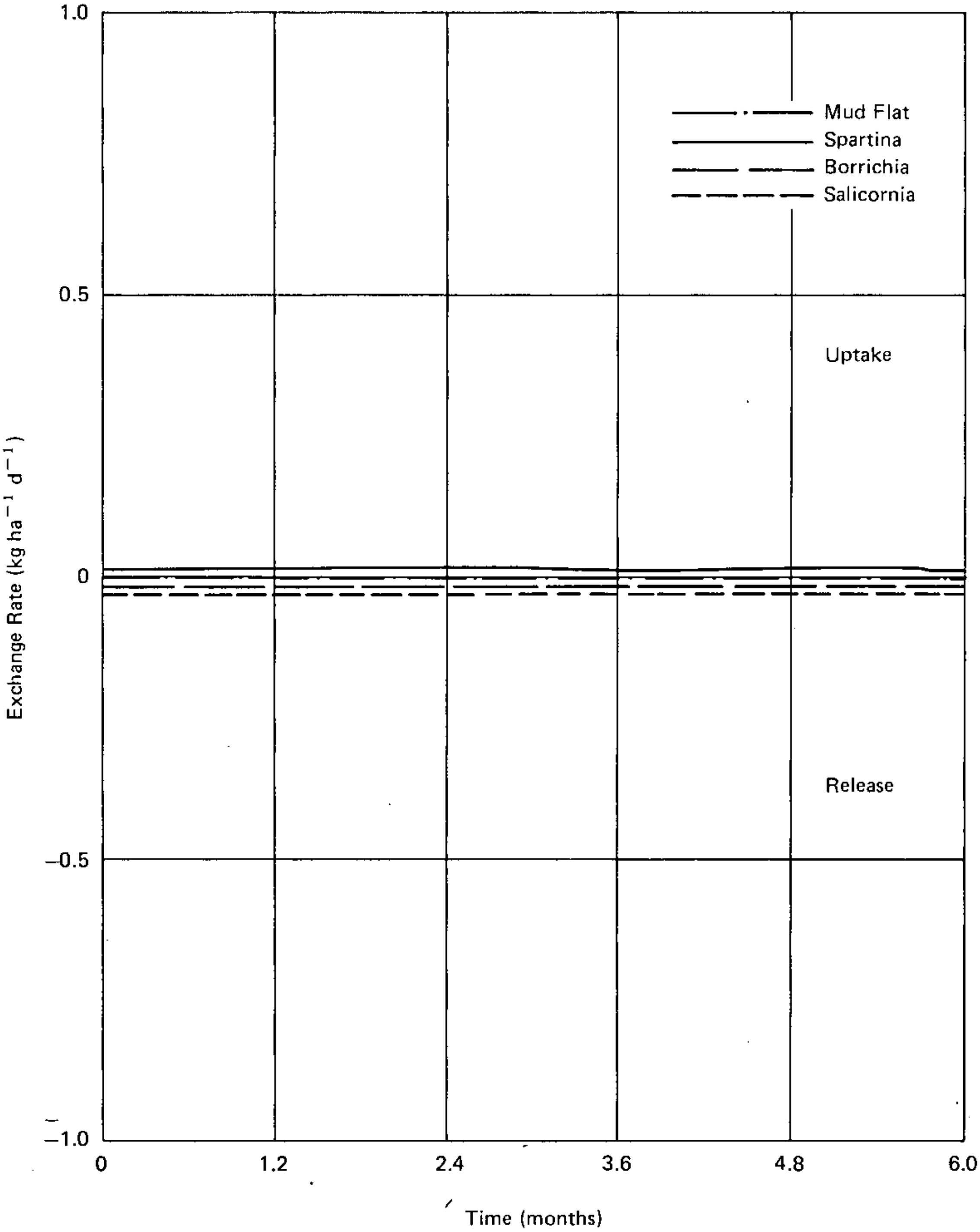

Figure 6-4. Exchange Rates for Nitrite Nitrogen in Guadalupe Estuary (271)

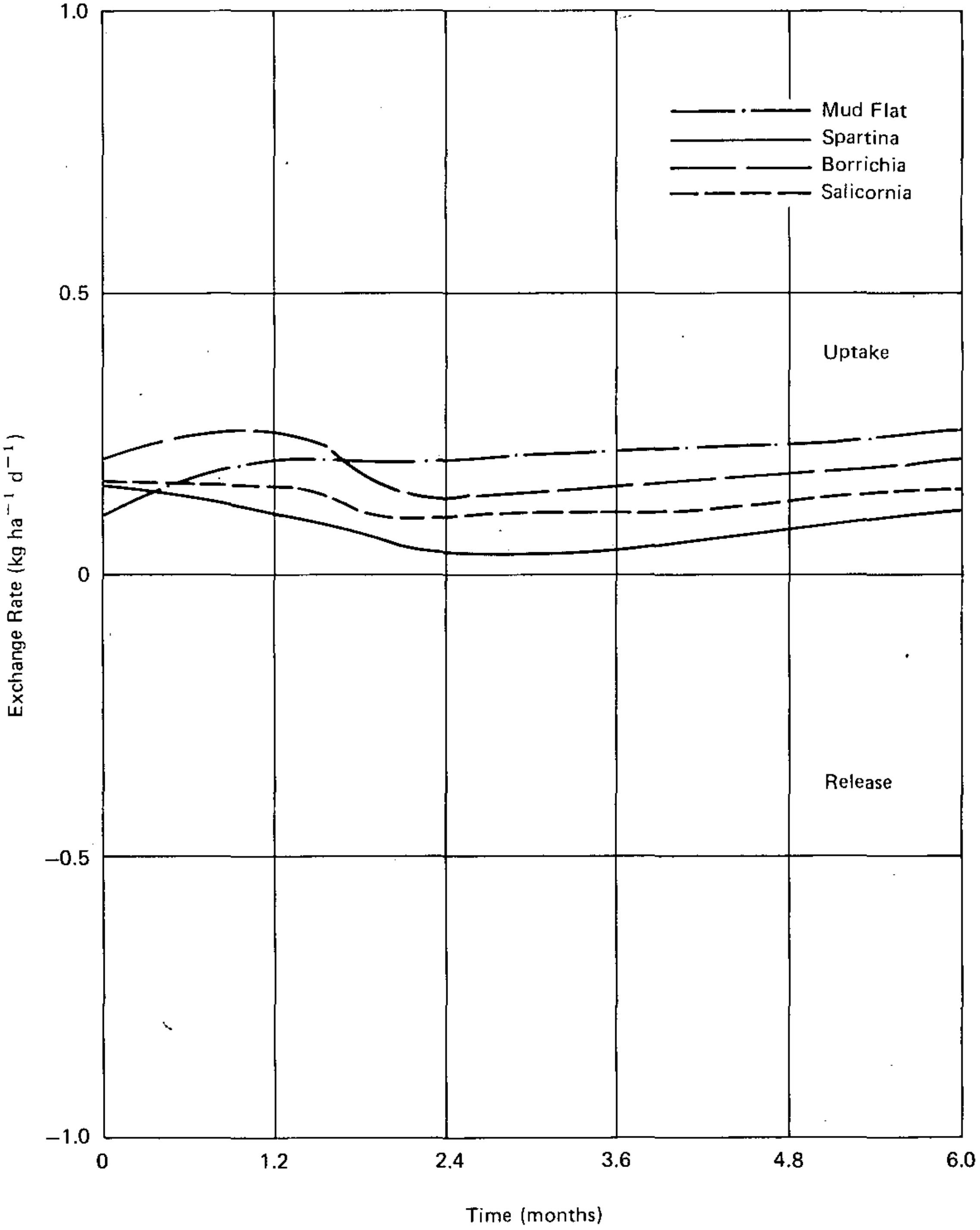

Figure 6-5. Exchange Rates for Nitrate Nitrogen in Guadalupe Estuary (271)

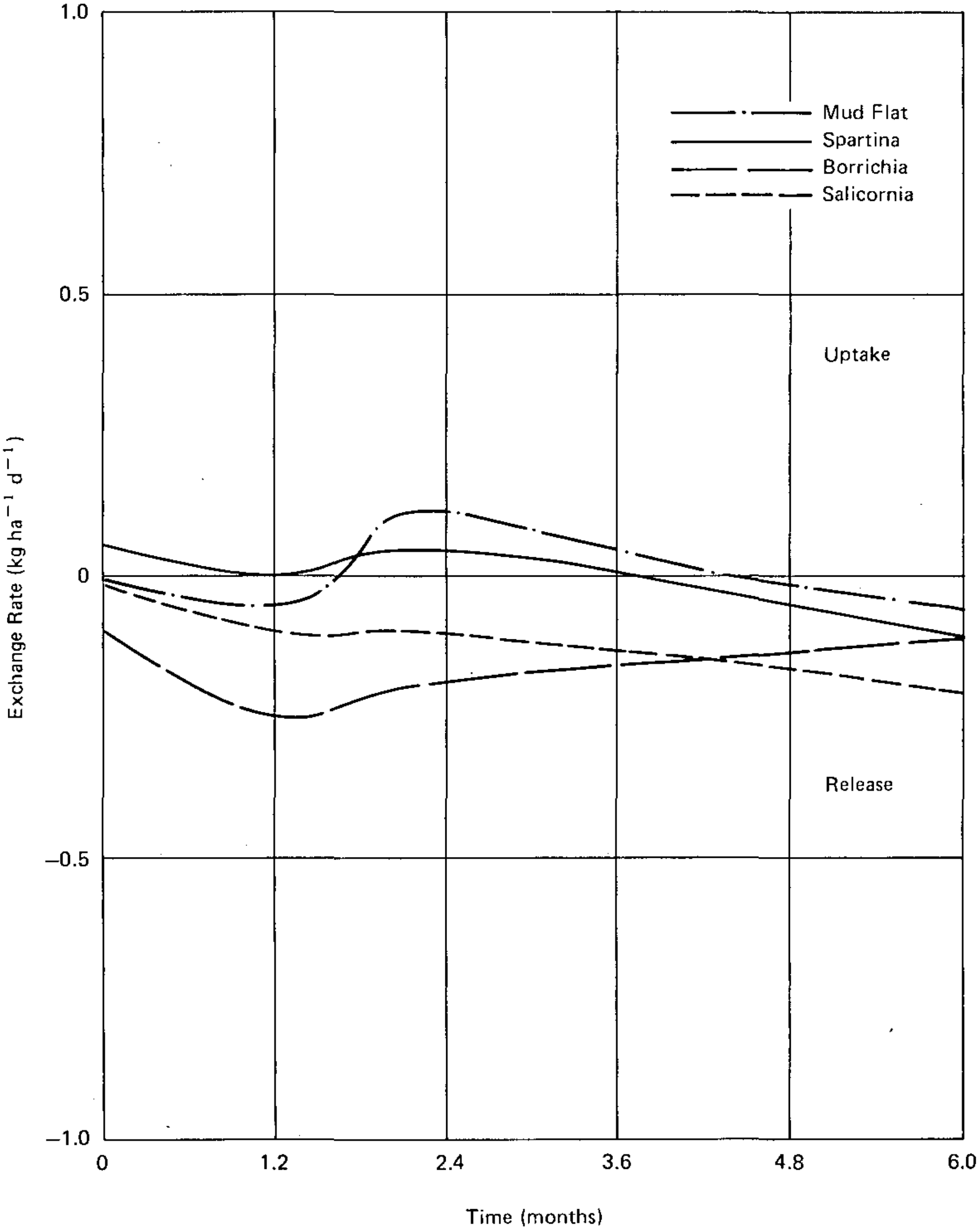

Figure 6-6. Exchange Rates for Unfiltered Total Phosphorus in Guadalupe Estuary (271)

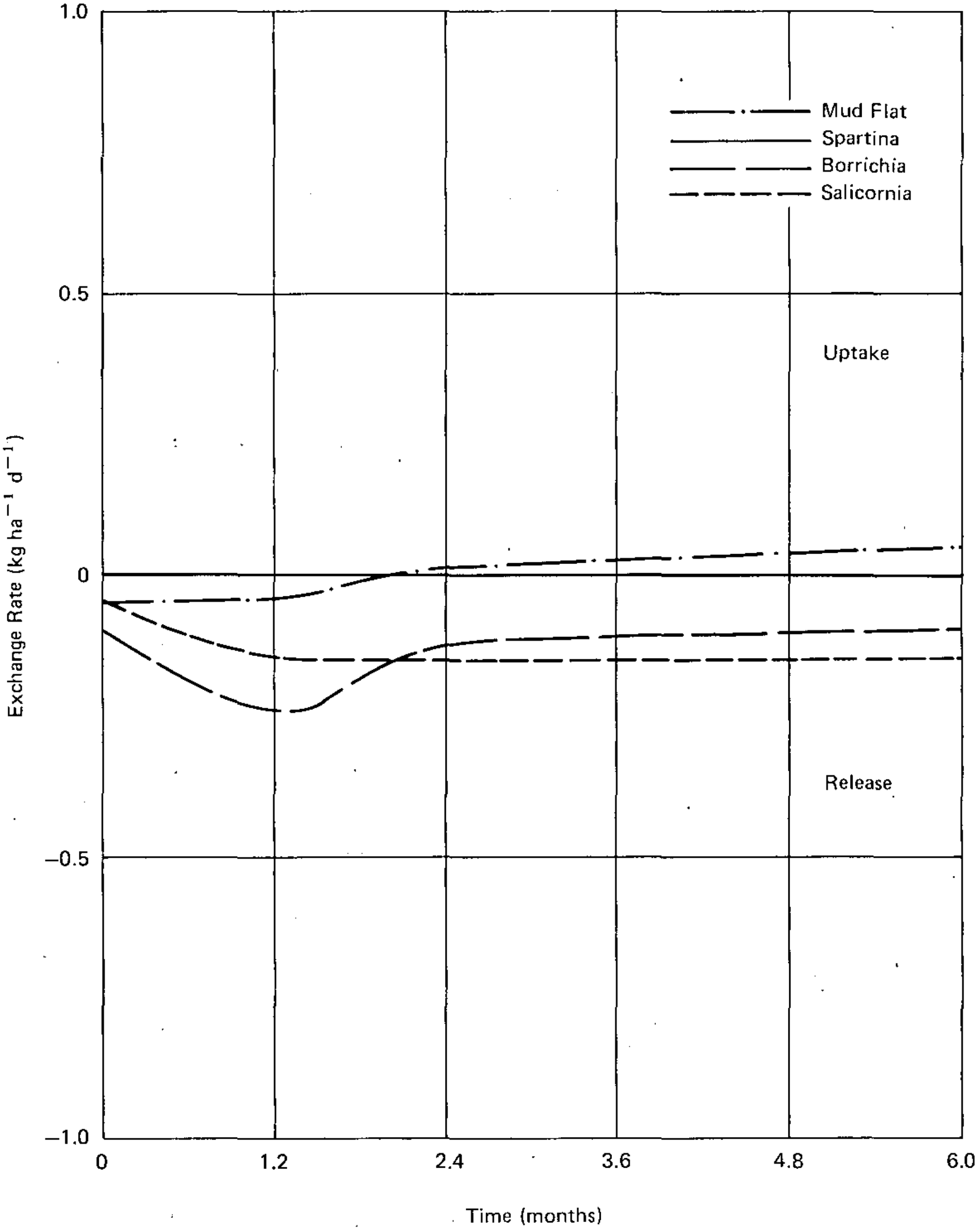

Figure 6-7. Exchange Rates for Ortho-Phosphorus in Guadalupe Estuary (271)

marshes. The order of magnitude of exchange rates appears to be very similar among the species for uptake or release of total organic carbon and nitrogen and phosphorus nutrients. Deltaic marshes are releasing total organic carbon year-round, with highest export rates occurring during winter and summer. Total phosphorus is generally exported with the greatest rates also occurring in later winter and summer. Nitrate nitrogen and ammonia nitrogen are continually absorbed while nitrite nitrogen and total Kjeldahl nitrogen are neither taken up nor released in sizable amounts. This general uptake of nitrogen tends to support the contention of Davis, Smith and Bishop (317) and Davis (316) that San Antonio Bay waters are nitrogen limited.

Using C, N, and P exchange rates observed from a linear marsh model containing a representative cross-section of marsh vegetation (269), an export of 11,000 to 17,000 kg/d TOC and up to 50 kg/d total phosphorus from the Guadalupe deltaic marshes can be expected during periods of continuous inundation. There is evidence that following a prolonged period of drying a sudden inundation event over the delta marshes will result in a short period of high nutrient release (271). This period, which may last for one or two days, is subsequently followed by a period where release rates decrease rapidly until they begin to approach a seasonal equilibrium. Therefore, during periods of high river discharges and/or extremely high tides that immediately follow prolonged dry periods, the contribution of C, N, and P from the deltaic marshes to the estuarine waters can be expected to increase dramatically.

Nutrient Contributions of the Guadalupe River Delta Marshes

The marshes of the Guadalupe River delta are subject to periodic inundation1/ and dewatering. Studies were conducted using a mathematical hydrodynamic model of the Guadalupe River delta (45). Given a normal tide range of 1.8 - 2.2 feet above mean sea level (0.55 - 0.67 meters), the model predicts less than two percent of the delta area will be inundated at discharges as great as 4,000 ft^3/sec (113 m^3/sec) and less than 10 percent of the delta will be inundated at discharges up to 7,000 ft^3/sec (198 m^3/sec) (Table 6-10). The largest rate of increase for areal extent of inundation occurs at discharges between 7,000 and 10,000 ft^3/sec (198-283 m^3/sec). A discharge of this latter magnitude can result in 22.4 percent of the delta being inundated.

Similar magnitude discharges and a high tide (2.3 - 3.1 ft above mean sea level) (0.70 - 0.94 m) result in 61 percent areal extent of deltaic inundation at 4,000 ft^3/sec (113 m^3/sec) and 76.6 percent inundation at 10,000 ft^3/sec (283 m^3/sec). The nature of the delta topography is such that as river discharges increase to 30,000 ft^3/sec (850 m^3/sec), the model predicts inundation of only 40 percent of the deltaic area with normal tides and 84 percent at high tide conditions.

Results of nutrient exchange studies conducted in the Guadalupe River delta marshes by Armstrong and Gordon (269) demonstrate that organic carbon is

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1/ Inundation is here defined as a layer of water at least 0.5 feet (0.15 m) deep remaining for a period of at least 48 consecutive hours. The duration of such a state is a function of river discharge, wind and tides.

Table 6-10. Guadalupe Delta Inundation Study

Peak Discharge (ft^3/sec)	Flood Duration (d)	Flood Volume (ac-ft)	Total Discharge (ft^3/sec	Inundation a/ Percent Norm	Percent High	Acres Norm	Acres High	Hectares Norm	Hectares High
4,000	8	21,000	10,700	1.7	60.7	233.6	7,983.9	94.5	3,231.0
7,000	20	85,750	43,300	8.9	71.5	1,170.6	9,404.4	473.7	3,805.8
10,000	19	95,630	48,300	22.4	76.6	2,946.3	10,075.2	1,192.3	4,077.3
15,000	14	171,500	86,590	31.4	80.3	4,130.0	10,561.9	1,671.4	4,274.3
25,000	15	314,900	159,000	36.4	81.9	4,787.7	10,772.3	1,937.5	4,359.4
30,000	19	359,700	181,650	39.8	84.1	5,234.9	11,061.7	2,118.5	4,476.5

a/ Inundation of 0.5 feet for 48 consecutive hours.
Total marsh area subject to inundation = 13,153 Acres.

consistently exported at rates[1/] ranging from 2.95 to 4.44 kg/ha/d. It is likely that export rates during an inundation event following a prolonged dry period will be higher for at least 24 hours as suggested by Dawson and Armstrong (271). Export rates of greater than 12 kg/ha/d as were measured in the Lavaca River delta marshes (267) are likely during the first hours of inundation.

Calculations have been made to determine the contribution of TOC from the Guadalupe River delta that might be expected during flood events of various magnitudes and durations as predicted by the Guadalupe delta inundation model (Tables 6-11 and 6-12). To arrive at the figures four assumptions have been made: (1) these marshes function as do those of the Lavaca River delta and upon inundation the release rate of TOC is of similar magnitude to that measured in the Lavaca River delta, (2) this maximum rate of release (12.6 kg/ha/d) (267) occurs simultaneously with the occurrance of the inundation event, (3) a 24-hour period is required for these rates to decline from an initial high value to a lower steady state condition of 3.75 kg/ha/d (mean of seasonal rates of TOC export reported by Armstrong and Gordon (269), and (4) the decrease in this rate occurs as a linear algebraic function. After the initial 24 hours of the inundation event, the TOC export rate is considered to be relatively constant throughout the remainder of the event.

Wetlands Processes

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

In pursuit of this goal, the Texas Department of Water Resources has funded aerial photographic studies with the Texas A&M Remote Sensing Center to provide baseline characterization of key coastal wetlands in Texas in order to comparatively evaluate the various components of the marsh systems. The following description of the Guadalupe River delta is a by-product of seasonal aerial photographic studies conducted during the 1976 growing season (220).

The lower Guadalupe River and its extensive deltaic marshes function in a relatively undisturbed fashion. Except on the eastern edge, where construction of the Victoria Channel has cut off a portion of Goff Bayou, and at various sites where there are now pastures and cultivated areas, the Guadalupe deltaic marsh is in a relatively natural state. The bulk of the river's outflow now passes through Traylor Cut into Mission Lake, rather than through the North and South Guadalupe River branches. The North Guadalupe is heavily infested with water hyacinth, further restricting the already reduced flow. This diversion of flow could affect the continued development and maintenance

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[1/] These rates were measured after several days of acclimation to a steady-state seasonal condition.

Table 6-11. Export of Total Organic Carbon (TOC) from the Guadalupe River Delta during Flood Events and Normal Tides a/

Guadalupe (ft^3/sec) River Discharges		4,000	7,000	10,000	15,000	25,000	30,000
Area of Delta Inundation (ha)		95	474	1,192	1,671	1,938	2,119
Inundation Hour No.	TOC Exchange Rate (kg/ha/d)	kg TOC					
1	12.5	50	247	621	870	1,009	1,104
2	12.1	48	239	601	842	977	1,068
3	11.7	46	231	581	815	945	1,033
4	11.3	45	223	561	787	912	998
5	10.9	43	215	541	759	880	962
6	10.4	41	205	517	724	840	918
7	10.0	40	198	497	696	808	883
8	9.6	38	190	477	668	775	848
9	9.2	36	182	457	641	743	812
10	8.9	35	176	442	620	719	786
11	8.5	34	168	422	592	686	750
12	8.1	32	160	402	564	654	715
13	7.7	30	152	382	536	622	680
14	7.3	29	144	363	508	589	645
15	6.9	27	136	343	480	557	609
16	6.5	26	128	323	453	525	574
17	6.1	24	120	303	425	493	539
18	5.7	23	113	283	397	460	503
19	5.3	21	105	263	369	428	468
20	4.9	19	97	243	341	396	433
21	4.5	18	89	224	313	363	397
22	4.1	16	81	204	285	331	362
23	3.7	15	73	184	258	299	327
24	3.7	15	73	184	258	299	327
		Total TOC Exported during 1st day (kg)					
		751	3,745	9,418	13,201	15,310	16,741
		TOC Export following 1st day (kg/d)					
		352	1,754	4,410	6,183	7,171	7,840
25- ∞	3.7						

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a/ Range 1.8 - 2.2 feet above mean sea level

Table 6-12. Export of Total Organic Carbon (TOC) from the Guadalupe River Delta during Flood Events and High Tides a/

Guadalupe (ft^3/sec) River Discharges		4,000	7,000	10,000	15,000	25,000	30,000
Area of Delta Inundation (ha)		3,231	3,806	4,077	4,274	4,359	4,477
Inundation Hour No.	TOC Exchange Rate (kg/ha/d)	kg TOC					
1	12.5	1,683	1,982	2,123	2,226	2,270	2,332
2	12.1	1,629	1,919	2,055	2,155	2,198	2,257
3	11.7	1,575	1,855	1,988	2,084	2,125	2,183
4	11.3	1,521	1,792	1,920	2,012	2,052	2,108
5	10.9	1,467	1,729	1,852	1,941	1,980	2,033
6	10.4	1,400	1,649	1,767	1,852	1,889	1,940
7	10.0	1,346	1,586	1,699	1,781	1,816	1,865
8	9.6	1,292	1,522	1,631	1,710	1,744	1,791
9	9.2	1,239	1,459	1,563	1,638	1,671	1,716
10	8.9	1,198	1,411	1,512	1,585	1,616	1,660
11	8.5	1,144	1,348	1,444	1,514	1,544	1,586
12	8.1	1,090	1,285	1,376	1,442	1,471	1,511
13	7.7	1,037	1,221	1,308	1,371	1,399	1,436
14	7.3	983	1,158	1,240	1,300	1,326	1,362
15	6.9	929	1,094	1,172	1,229	1,253	1,287
16	6.5	875	1,031	1,104	1,158	1,181	1,213
17	6.1	821	967	1,036	1,086	1,108	1,138
18	5.7	767	904	968	1,015	1,035	1,063
19	5.3	714	840	900	944	963	987
20	4.9	660	777	832	873	890	914
21	4.5	606	714	764	801	817	839
22	4.1	552	650	696	730	745	765
23	3.7	498	587	629	659	672	690
24	3.7	498	587	629	659	672	690
		Total TOC Exported during 1st day (kg)					
		25,524	30,067	32,208	33,765	34,437	35,366
		TOC Exported following 1st day (kg/d)					
25–∞	3.7	11,955	14,082	15,085	15,814	16,128	16,565

a/ Range 2.3 – 3.1 feet above mean sea level of the lower deltaic marsh, depriving that area of much of the overflow which it would otherwise receive.

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

Summary

The marshes of the Guadalupe River delta are subject to periodic inundation during periods of increased river flows. An initial period occurs exhibiting high rates of organic carbon and organic nitrogen export (both particulate and dissolved). After this initial pulse of material is flushed out, the steady state exchange rates appear to be slightly greater than those observed in the Lavaca River delta marshes. Pulses of increased freshwater discharge and the resulting deltaic inundation appear to be important mechanisms contributing to increased nutrient transport from the marshes to the estuary.

Aerial photographic studies of the Guadalupe River delta have provided an insight into on-going wetland processes. These deltaic marshes function in a relatively undisturbed fashion. The bayous provide the necessary outlets for overflow and, at the same time, serve to duct water throughout the marsh system. Although the Guadalupe deltaic system is in a relatively "natural" state, the long-range condition of the wetlands environment will be considerably affected by the kinds of decisions which are made over the next few years with regard to water, power, navigational development, oil and gas production, and expansion of agricultural and cattle-raising activities.

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 Guadalupe estuary. In order to describe the "health" of an estuarine ecosystem, the food-web and its trophic levels (e.g., primary and secondary bay production) must be monitored for a long enough period to establish seasonality, distribution of production, and community composition. Ecological variables which were studied and are discussed herein include the abundance (counts per unit volume or area), distribution, and species composition of the phytoplankton, zooplankton, and the benthic invertebrates.

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

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

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

Data presented in this report for each of the lower food chain categories (i.e., phytoplankton, zooplankton, and benthos) were obtained from a Texas Parks and Wildlife study (248) conducted under interagency contract with the

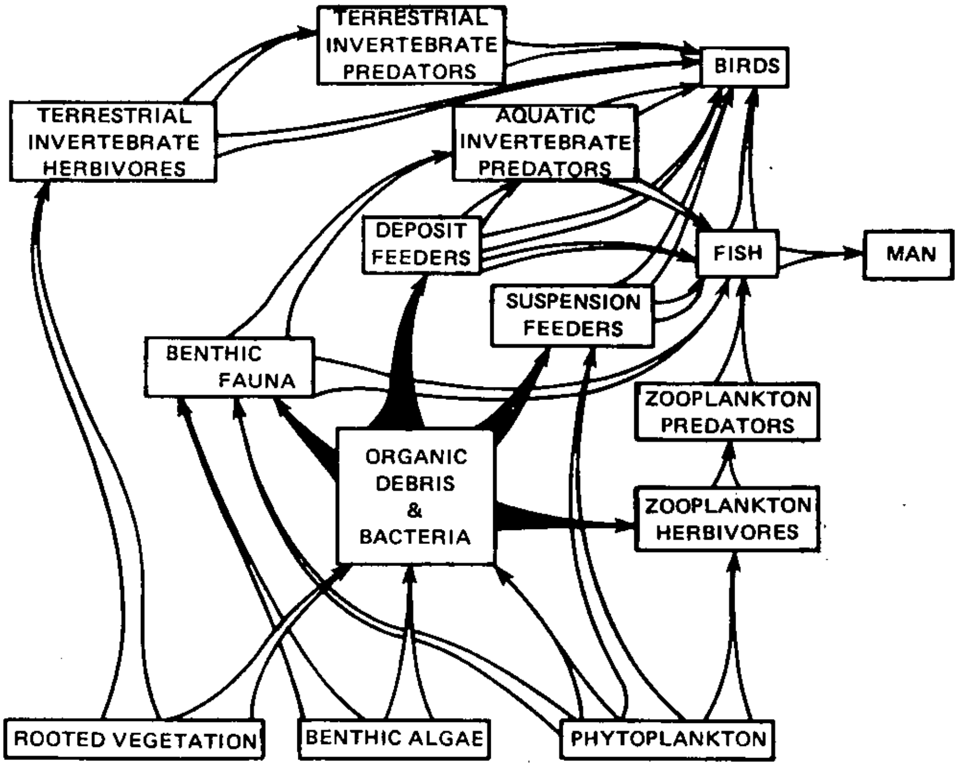


Figure 7-1. Estuarine Food-Web Relationships Between Important Ecological Groups (65)

Texas Department of Water Resources. The objectives of the study were: (1) to determine standing crops and species composition of the phytoplankton, zooplankton, benthos and nekton assemblages of the San Antonio Bay system; and (2) to determine how freshwater inflows and water quality of the San Antonio Bay system affect these assemblages.

Hydrological parameters were monitored on a monthly basis at 25 sites from March through October 1972 (Figure 7-2). From November 1972 through July 1973, monthly hydrological samples were collected from 21 of the original sites. Hydrological measurements were taken on a monthly basis at 11 sites and on a semi-monthly basis at 8 sites, from August 1973 through July 1974. Salinity, dissolved oxygen, water temperature, turbidity, and pH were determined for each sample.

Phytoplankton samples were collected twice a month from 10 line-sites throughout the San Antonio Bay system from October 1973 through July 1974. Chlorophyll a measurements were determined for 16 sites twice monthly from January through July 1974.

Zooplankton samples were collected from 12 sites on a monthly basis during the first six months of the study; during the following 11 months, samples were collected from 15 sites once a month and from 8 sites twice a month. The change to a semi-monthly sampling schedule was made to obtain more data during a greater variety of river flow conditions. Benthos samples were collected from 21 sites from April 1972 through July 1974.

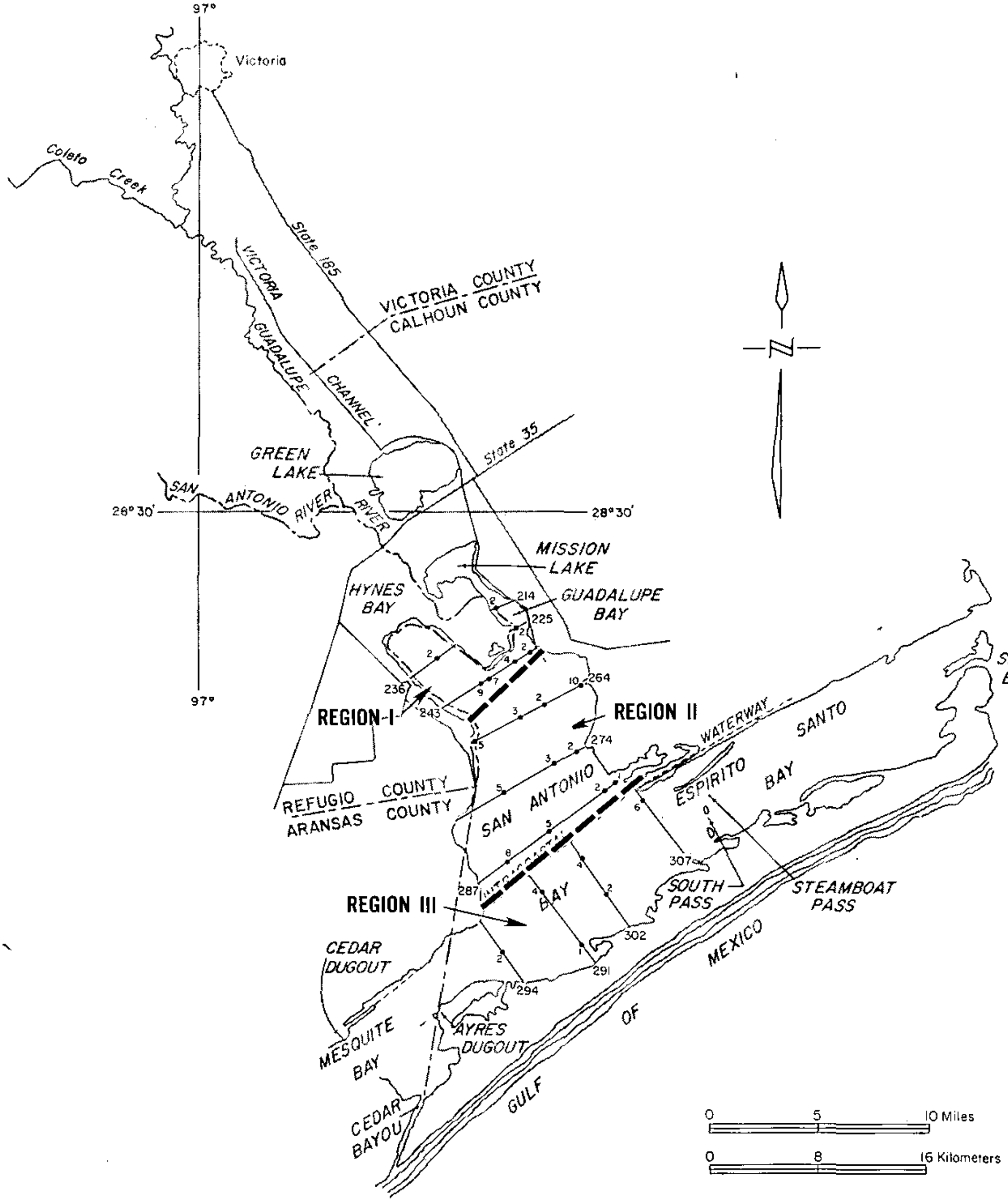
For convenience in data handling, the study area was divided into three regions (Figure 7-2). Sites 214-2, 225-2, 236-2, 243-2, 243-4, 243-7, and 243-9, including Guadalupe and Hynes Bays, comprised Region I. Region II, middle San Antonio Bay, included sites 264-2, 264-3, 264-5, 264-10, 274-1, 274-2, 274-3, 274-5, 287-1, 287-2, 287-5, and 287-8. Region III, Espiritu Santo Bay and the lower portion of San Antonio Bay south of the Intracoastal Waterway, included sites 291-1, 291-4, 294-2, 302-2, 302-4, and 307-6.

Phytoplankton

Data Collection

According to Matthews et al. (248), six divisions represented by a minimum of 60 taxa were collected in the San Antonio Bay system from October 1973 through July 1974: Chrysophyta - golden-brown algae (24 taxa); Chlorophyta - green algae (16 taxa); Pyrrophyta - dinoflagellates (8 taxa); Cyanophyta - blue-green algae (6 taxa); Euglenophyta - euglenoids (4 taxa); and Cryptophyta (2 taxa). The dominant numerical division in San Antonio Bay was Cryptophyta (e.g., phytoflagellates and Chroomonas sp.), followed by Chlorophyta, Chrysophyta, Cyanophyta, Euglenophyta, and Pyrrophyta, respectively (Figure 7-3). It may be of interest to note that many of the species collected, especially the Chlorophyta, were considered to be freshwater forms.

Phytoplankton concentrations in a single sample from the San Antonio Bay study ranged from 252,480,000 cells/l at site 274-5 in February 1974 to 50,000 cells/l at site 243-9 in October 1973. The highest mean standing crop for the study was 20,270,000 cells/l which occurred at Region II site 274-5; the low-



Base by U.S. Geological Survey, 1956

Figure 7-2. San Antonio Bay, Hydrologic and Biologic Sample Sites and Regional Divisions (248)

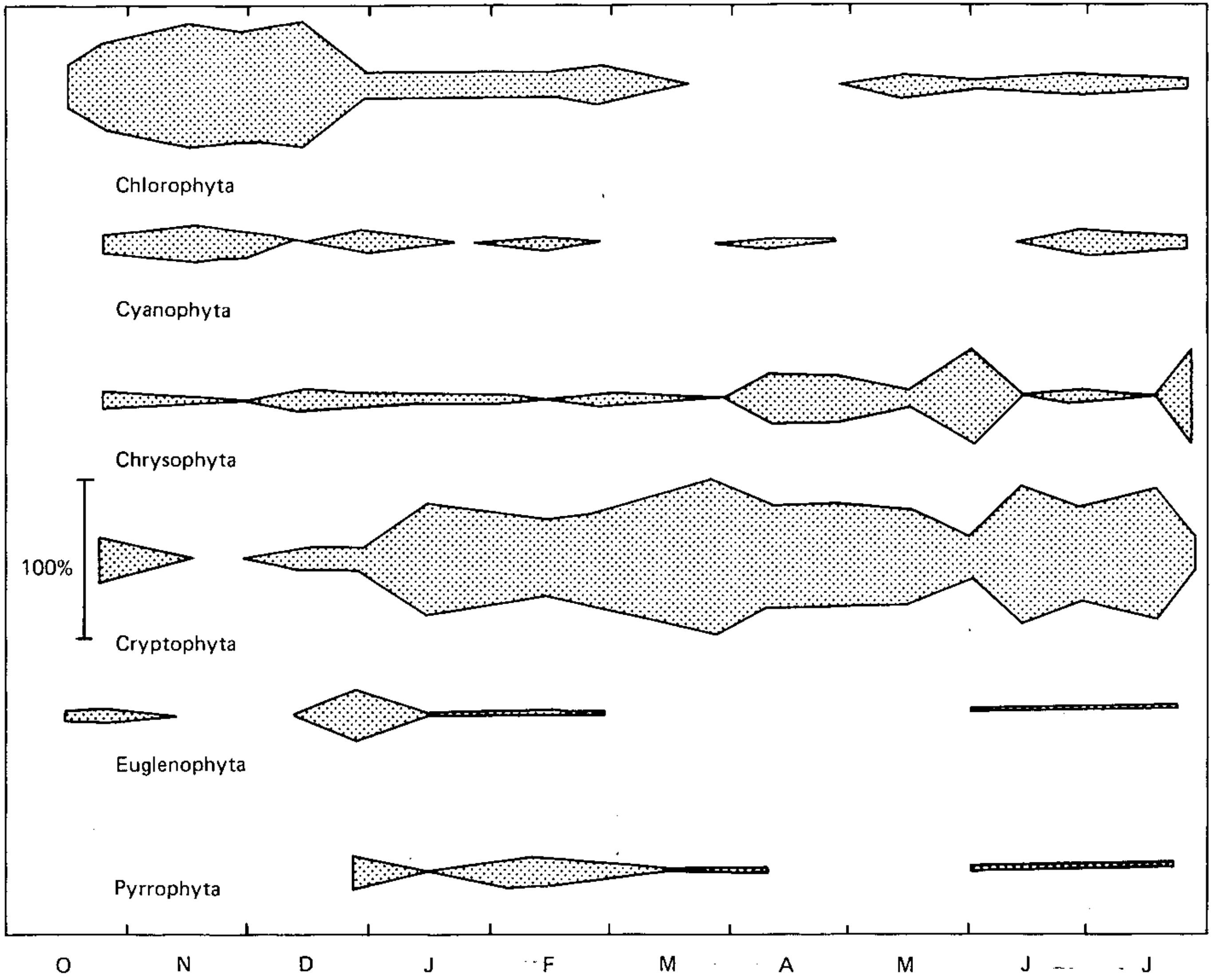


Figure 7-3. San Antonio Bay, Percentage Composition of Six Phytoplankton Divisions Present in Semi-Monthly Samples, 1973-1974

est mean standing crop was 4,080,000 cells/l occurring at site 274-2, also in Region II. Spring and summer months of 1974 (February-March and June) produced the highest phytoplankton densities (Figure 7-4). Mean monthly densities ranged from 363,000 cells/l in October 1973 in Region I to 38,074,000 cells/l in February 1974 also in Region I.

The average percent composition by biomass of the more prominent plankton species is shown by region for the San Antonio Bay system (Table 7-1). The group of unidentified chlamydomonoids (green algae) was ubiquitous throughout the study period. The second most abundant species, Ankistrodesmus convoluta, also a green algae, was prominent in late winter samples. Chroomonas sp. maintained relatively high populations throughout the study period but reached maximum densities in late winter, as did Chlorella sp. and Westella botryoides.

Results of Analyses

San Antonio Bay phytoplankton densitites observed during the TPWD study were high in comparison to other marine areas and estuaries of Texas. Mean standing crop for the study period was 8,875,000 cells/l. Moseley et al. (20) stated that phytoplankton densities of 730,000 cells/l occurred in Cox Bay, while Espey, Huston and Associates (47) reported phytoplankton densities of 133,000 cells/l from Sabine Lake.

Seasonally, phytoplankton densities and chlorophyll a measurements appeared to fluctuate independently of one another (Figure 7-5). Peaks in mean monthly phytoplankton crops occurred in February, March, and June 1974; lowest numbers occurred in January and April 1974. Mean monthly chlorophyll a measurements were fairly consistent throughout the study period with one peak occurring in February.

The green and blue-green algae collected are representative of typical forms found in freshwater reservoirs in 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.

Correlation analyses of river inflow versus phytoplankton counts per liter performed by the TPWD were not statistically significant ($\alpha > 0.05$). Freshwater inflows from river sources act to import freshwater phytoplankton species into the estuarine system. This input may be substantial as evidenced by the high average phytoplankton densites for Regions I and II, as compared to Region III. Although river flows function to lower salinities and to transport nutrients, detritus, and dissolved organic materials into the bay, the rate of river flow through an estuary can have contrasting effects. More nutrients and freshwater plankton may be imported to the system with increased flow rates thus increasing standing crops and primary production. At very high flow rates or flood conditions, however, the high turbidities, salinity changes, and flushing out of indigenous populations may depress phytoplankton abundance and productivity. Comparing the average monthly gaged and ungaged flows into the San Antonio Bay system to monthly phytoplankton densities during the study period, peak phytoplankton populations occurred after moderate pulses of flow (Figure 7-6).

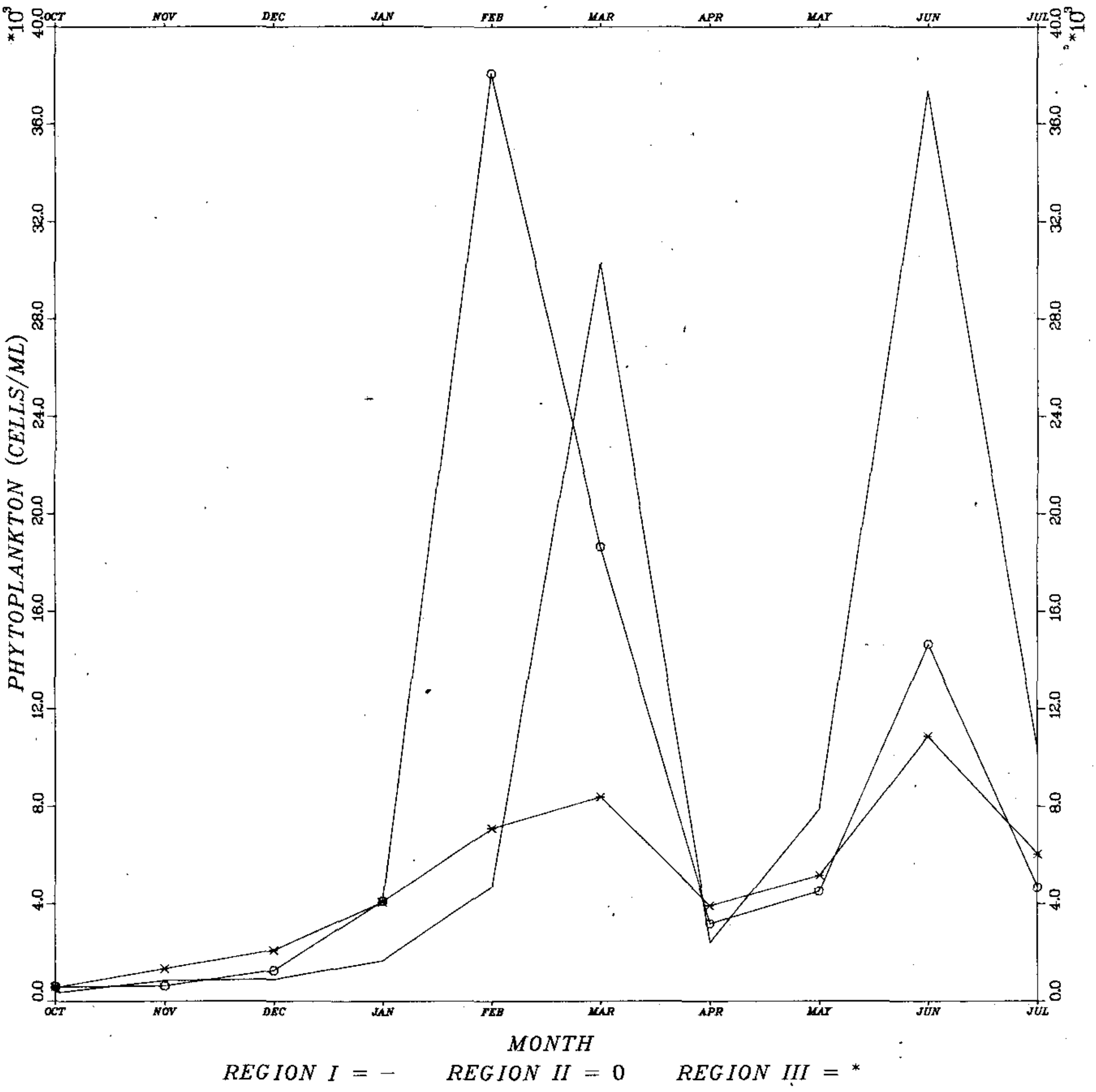


Figure 7-4. Mean Monthly Phytoplankton Densities in San Antonio Bay, October 1973-July 1974

Table 7-1. Percent Composition by Biomass of Dominant Phytoplankton Species in the San Antonio Bay System, October 1973 - July 1974

Region a/	Species	Percent Composition b/
Region I	Chlamydomonoid	37.5
	Chlorella sp.	17.1
	Chroomonas sp.	8.9
	Ankistrodesmus convoluta	8.6
	Westella botryoides	5.6
	Navicula sp.	4.4
		82.1
Region II	Chlamydomonoid	31.8
	Ankistrodesmus convoluta	18.0
	Chroomonas sp.	12.4
	Chlorella sp.	8.3
	Westella botryoides	5.5
	Navicula sp.	4.3
		80.3
Region III	*Ankistrodesmus convoluta*	21.6
	Chroomonas sp.	14.4
	Eutreptia sp.	14.2
	Amphidinium sp.	9.6
	Merismopedia sp.	8.5
	Chlamydomonoid	8.4
		76.7
All Regions	Chlamydomonoid	22.9
	Ankistrodesmus convoluta	17.9
	Chroomonas sp.	12.7
	Chlorella sp.	7.5
	Eutreptia sp.	6.1
	Westella botryoides	5.9
		73.0

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a/ Refer to Figure 7-2 for location of Regions I, II and III.
b/ Total Phytoplankton Biomass = 100%

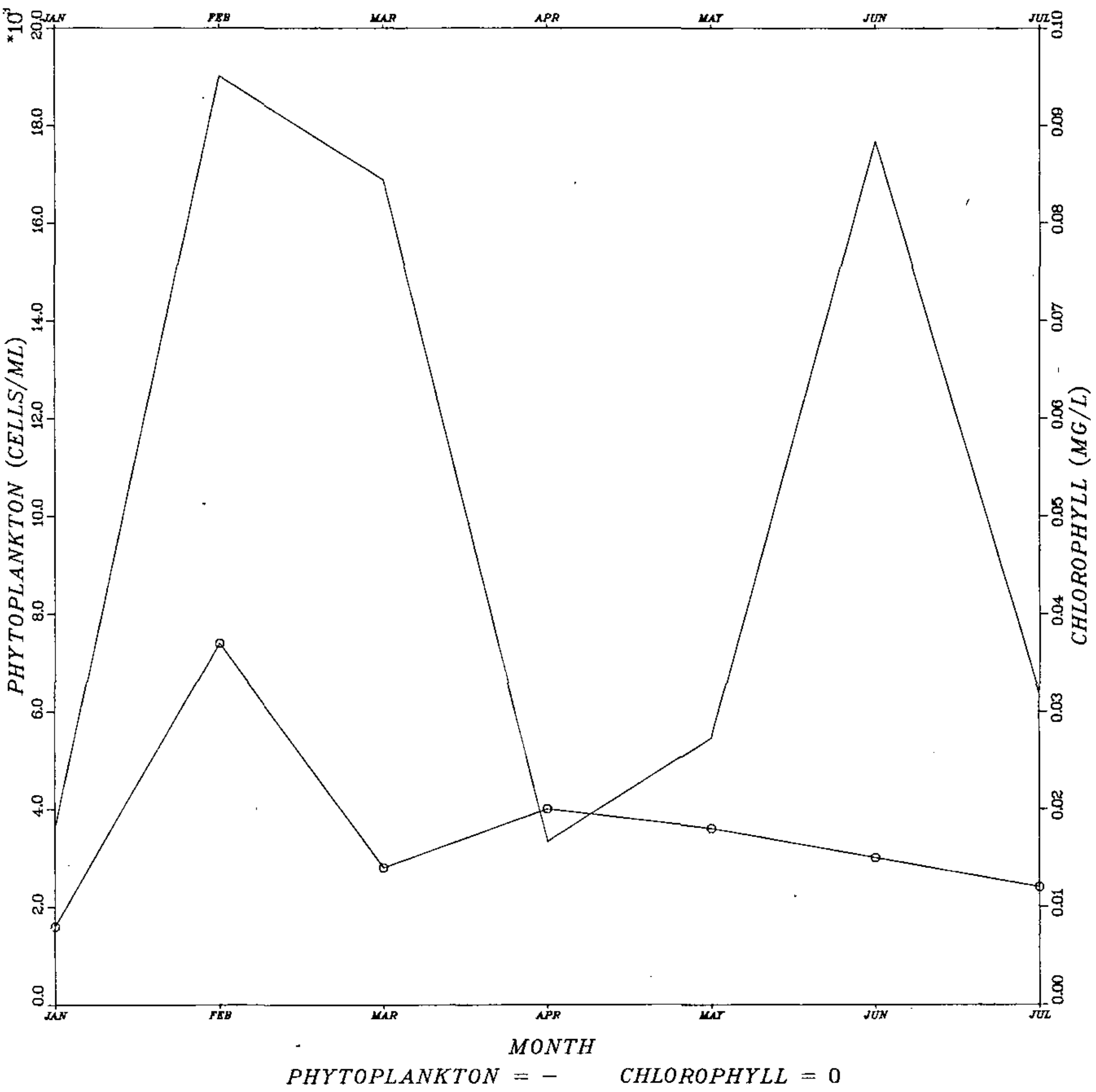

Figure 7-5. Mean Monthly Phytoplankton Densities Versus Chlorophyll a Concentrations in San Antonio Bay, January 1974-July 1974

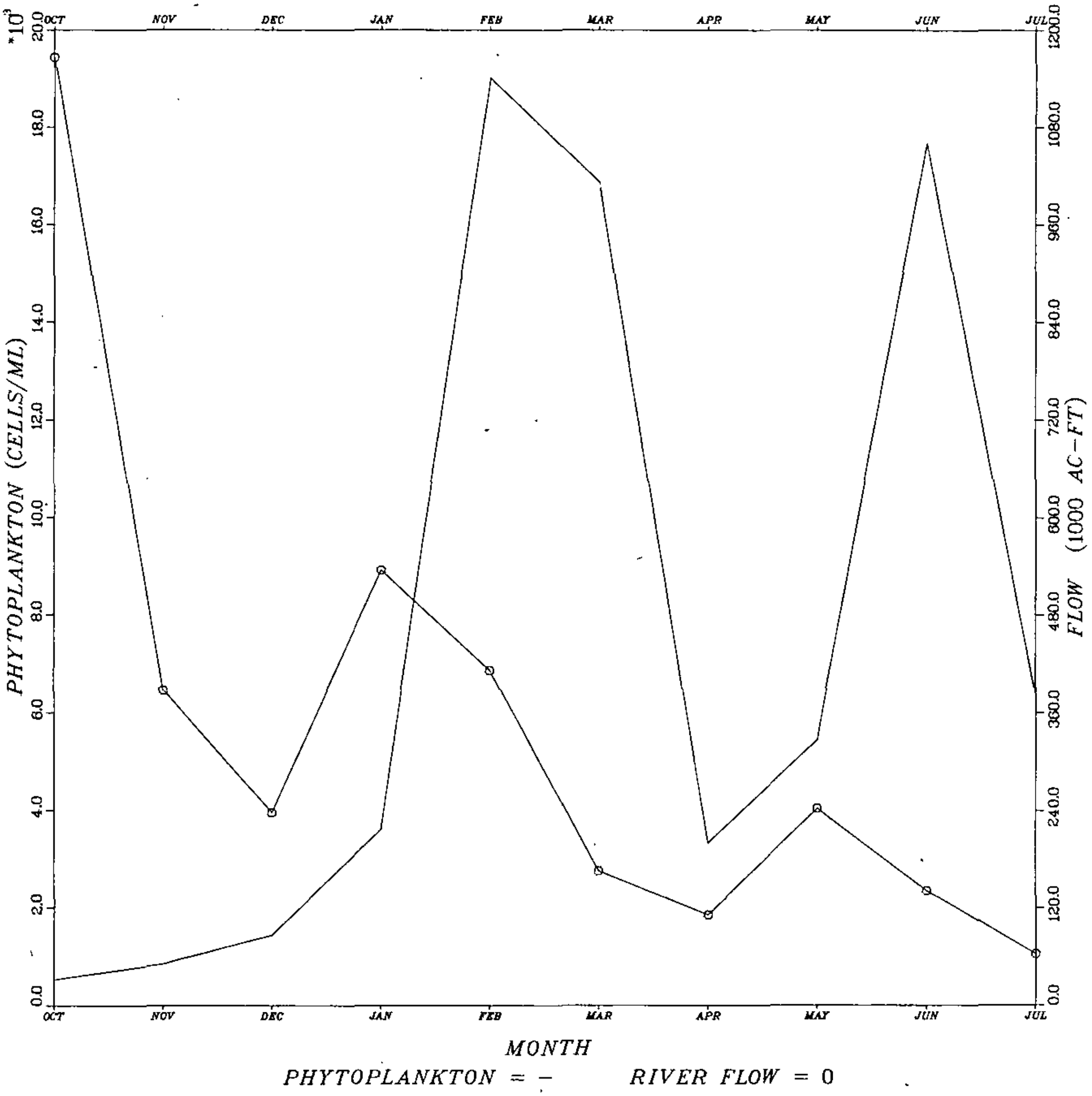

Figure 7-6. Mean Monthly Phytoplankton Densities Versus Combined River Inflow in San Antonio Bay, October 1973-July 1974

Phytoplankton species vary markedly in ability to withstand changes in salinity. Accurate halobion classification of most species found in San Antonio Bay is impossible due to insufficient culture experimentation on salinity optima and tolerances. Chu (22) notes that although cell division can continue in freshwater for most estuarine species, most freshwater species cannot grow in salinities exceeding 2.0 ppt. Foerster (58) finds, however, that many freshwater species can resume growth after exposure to seawater if placed in a freshwater medium.

Estuarine plankton are divided by Perkins (174) into three components: "(1) autochthonous populations, the permanent residents; (2) temporary autochthonous populations, introduced from an outside area by water movements, are capable of limited proliferation only and are dependent upon reinforcement from the parent populations; and (3) allochthonous populations, recently introduced from freshwater or the open sea, are unable to propagate and have a limited survival potential." The San Antonio Bay system supports a phytoplankton population derived from the entire range described above. The Euglenophyta (e.g., Euglena sp. and Trachelomonas sp.) are representative of the permanent autochthonous populations. Temporary autochthonous species include diatoms, e.g., Skeletonema costatum and Chaetoceros spp., and dinoflagellates. The allochthonous element is difficult to define but is probably represented by diatoms and green algae derived from fresh and marine environments.

The seasonal changes in salinities and temperature in the San Antonio Bay study appeared to relate only weakly with phytoplankton standing crops. This implies, perhaps, that there are a combination of primary seasonal controlling factors of San Antonio Bay phytoplankton. Although typical phytoplankton populations appear to be primarily influenced by temperature, salinity, and availability of nutrients, each species' presence and density is governed by physical, chemical, and biological parameters operating simultaneously.

Zooplankton

Data Collection

According to Matthews et al. (248), a total of 162 zooplankton taxa representing 12 phyla were identified from 415 samples collected during the 29-month study. The most prominent phylum was the Arthropoda, which accounted for 67 percent (109 taxa) of the species identified. The chordates and rotifers each accounted for 6 percent (9 taxa); the protozoans, cnidarians, and annelids each for 5 percent (8 taxa); platyhelminthes for 2 percent (4 taxa); and ctenophores, nematodes, and ectoprocts each for one percent. The freshwater zooplankton assemblages included such organisms as the cyclopoid copepods of the genus Cyclops and cladoceran water fleas of the genus Daphnia. The brackish or estuarine species were commonly represented by calanoid copepods Acartia tonsa, Paracalanus crassirostris, and Pseudodiaptomus coronatus, or the cyclopoid copepod Oithona brevicornis. Marine species from the neritic Gulf waters were represented by calanoid copepods Centropages hamatus and Labidocera aestiva, the bioluminescent dinoflagellate Noctiluca scintillans, and the chordate larvacean genus Oikopleura.

Average zooplankton standing crops (reported in individuals/m^3) in Region I ranged from 400 to 25,000 during 1972 (beginning in March), from 140 to 14,000 in 1973, and from 100 to 17,000 in 1974 (through August). Ranges for the identical periods in Region II were 6,200 to 21,000, 100 to 47,000, and 1,000 to 34,000. Region III averages for the identical periods ranged from 4,000 to 20,000, from 250 to 60,000 and from 300 to 38,000, respectively. Observed trends in zooplankton populations were similar in Regions II and III.

Zooplankton populations illustrated greater seasonal fluctuations than phytoplankton. Peaks in standing crops occurred during the early spring of each year of the study (Figure 7-7). Averages, showing tremendous variation over short periods of time — up to two orders of magnitude — became evident when the semi-monthly sampling schedule was started. The mean monthly density for all stations ranged from 820 individuals/m^3 in June 1973 to 46,296 individuals/m^3 in February 1973.

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

1. Acartia tonsa - calanoid copepod.
2. Immature barnacles - barnacle nauplii and barnacle cyprids.
3. Immature copepods - naupliar larvae and copepodities.
4. Gastropod veligers.
5. Other copepods - all Copepoda with the exception of Acartia sp., such as Cyclops sp., Oithona sp., and Paracalanus sp.
6. Others - protozoans, acoel worms, polychaetes, rotifers, and ectoprocts.

The overall mean percentage composition by biomass for these groups in the San Antonio Bay system during the study period is shown in Table 7-2. The predominance of the copepod, Acartia tonsa, and the barnacle nauplii was evident in all three regions (Table 7-3). These two groups comprised over 80 percent of the biomass of each region for the entire study period.

Results of Analyses

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

Many zooplankton species found in the San Antonio Bay estuarine system are widely distributed along the coasts of the United States, while others may even have a worldwide distribution. For example, Green (65) reports that Acartia tonsa may be found in the Central Baltic Sea area; Centropages hamatus has been collected in British waters and in the Gulf of Bothnia in the Baltic Sea; and Brachionus quadridentata is also known from points as distant as the Aral Sea of Russia.

Other zooplankton studies conducted in estuaries and bays along the Gulf of Mexico have produced similar results to the TPWD San Antonio Bay study. Gilmore et al. (200) has reported that naupliar larvae and calanoid copepods were the dominant zooplankton forms in the Lavaca Bay estuarine system. This

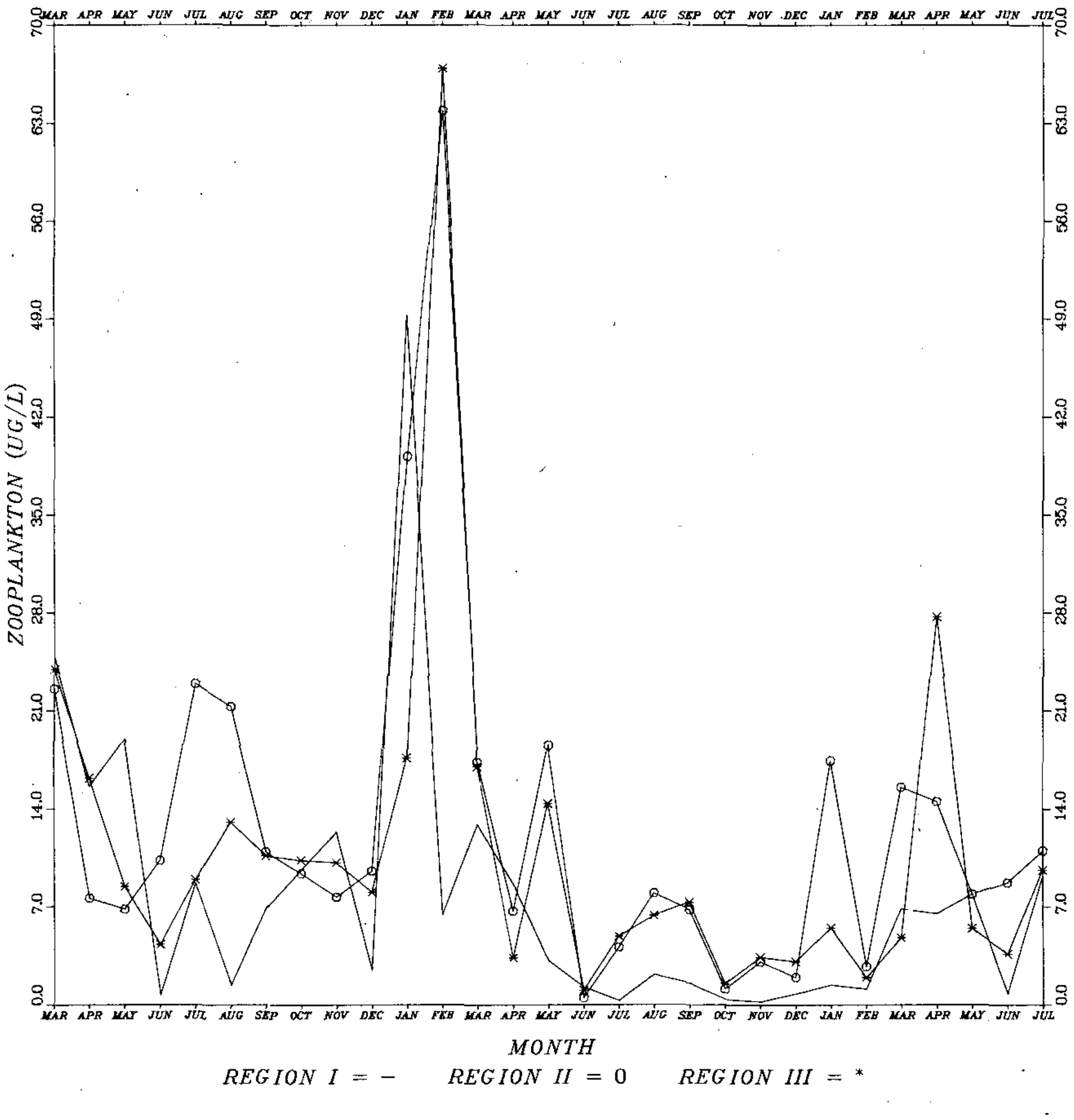

Figure 7-7. Mean Monthly Zooplankton Densities in San Antonio Bay, March 1972-July 1974

Table 7-2. Mean Percentage Representation by Biomass of the Zooplankton in the San Antonio Bay System, March 1972 - July 1974

Zooplankton	Region I a/	Region II	Region III
	(percent)		
Acartia tonsa	70.0	52.0	50.1
Immature barnacles	11.4	45.4	45.8
Immature copepods	3.3	0.9	1.7
Gastropod veligers	5.2	0.5	0.5
Other copepods	4.5	0.4	0.2
Others	5.6	0.8	1.7
Total Zooplankton	100.0	100.0	100.0

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

Table 7-3. Percent Composition by Biomass of Dominant Zooplankton Species in the San Antonio Bay System, March 1972 - July 1974

Region a/	Species	Percent Composition b/
Region I	*Acartia tonsa*	70.0
	Barnacle nauplii	11.3
	Gastropod veligers	5.2
	Copepod nauplii	3.0
	Cyclops sp.	2.2
	Acoel worm	2.0
		93.7
Region II	*Acartia tonsa*	52.0
	Barnacle nauplii	45.0
	Copepod nauplii	0.9
	Barnacle cypris	0.8
	Gastropod veligers	0.5
	Diaptomus sp.	0.2
		99.4
Region III	*Acartia tonsa*	50.1
	Barnacle nauplii	45.3
	Copepod nauplii	1.7
	Gastropod veligers	0.5
	Cyphonautes larvae	0.5
	Barnacle cypris	0.4
		98.5
All Regions	*Acartia tonsa*	54.5
	Barnacle nauplii	38.9
	Copepod nauplii	1.5
	Gastropod veligers	1.3
	Barnacle cypris	0.6
	Cyclops sp.	0.5
		97.3

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

study is in agreement with zooplankton studies in Sabine Lake (336, 47) and Nueces, Corpus Christi, Copano, and Aransas Bays (281).

Maximum and minimum total mean monthly densities in San Antonio Bay were also similar to results from the studies mentioned above (Table 7-4).

Zooplankton densities in San Antonio Bay are compared with combined (gaged and ungaged) river inflow in Figure 7-8. High flow rates in May-June 1972, June-July 1973, October 1973, and January-February 1974 were accompanied by low zooplankton standing crops. Conversely, zooplankton blooms in December 1972-January 1973 and April 1974 occurred during periods of low flow. However, no statistical correlations were discovered between these parameters.

Freshwater inflow can influence zooplankton in several ways. Estuarine zooplankton standing crop composition can be altered by importation of freshwater species. Inflow can also transport zooplankton food resources into the system in the form of phytoplankton and detritus; however, zooplankton communities may also be adversely affected by increased river inflows. Sudden shifts in salinity and flushing out of autochthonous populations can decrease zooplankton populations. Perkins (174) reports that the primary factor influencing the composition and abundance of estuarine zooplankton is development rate versus flushing time. For example, Holland et al. (281) stated that freshwater inflow/salinity changes had a direct effect on the standing crop of brackish-marine zooplankton and freshwater zooplankton in adjacent estuarine systems of the Corpus Christi Bay complex. In all cases the result was the same, a decrease in the standing crop of brackish-marine zooplankton and an increase in freshwater zooplankton whenever inflows were great and salinities depressed. Saltwater intrusions, on the other hand, act to (1) import marine zooplankton into the system; (2) import marine phytoplankton as a food source; and (3) increase salinity.

The impact of freshwater inflow on zooplankton diversity and standing crops was evident in the three bay regions of the San Antonio estuarine system. According to the TPWD study (248), diversity in Region I, closest to the river's mouth, was directly related to the rate of river flow; diversity changes were closely allied with the presence or absence of freshwater taxa. Region II, middle San Antonio Bay, represented an area of considerable mixing of water masses and zooplankton. The effects of river inflow in this region were not as pronounced as in Region I but were still strong. The zooplankton community of Region II consisted mainly of brackish water species and species preferring more saline waters. Floods tended to decrease the average diversity per site in this area.

In conclusion, Matthews et al. (248) states that heavy flooding reduced both the diversity and standing crop of the zooplankton assemblage of San Antonio Bay. The recuperation period was short, however, and populations increased rapidly throughout most of the bay when salinities returned to their seasonal norms.

The dominant zooplankton of the system, Acartia tonsa, was nearly ubiquitous throughout the salinity/temperature ranges (Table 7-5). The lowest catches occurred under extreme conditions such as low salinity/low temperature and high salinity/high temperature. Acartia tonsa has an extremely wide range of salinity tolerance. Populations of this copepod have been collected at salinities from 10-80 ppt in the Laguna Madre by Hedgpeth (95) and at

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

System	Minimum	Maximum
Nueces Bay (281)	832 (Oct. 1973)	8,027,855 (Feb. 1974)
Corpus Christi Bay (281)	1,722 (Dec. 1972)	53,657,037 (Mar. 1973)
Copano Bay (281)	1,296 (Sept. 1974)	53,536 (Feb. 1973)
Aransas Bay (281)	2,497 (Dec. 1972)	3,008,679 (Feb. 1974)
Sabine Lake (47)	381 (Apr. 1975)	20,042 (Oct. 1974)
Lavaca Bay (250)	1,980 (Oct. 1973)	27,846 (Feb. 1974)
San Antonio Bay (248)	820 (June 1973)	46,296 (Feb. 1973)

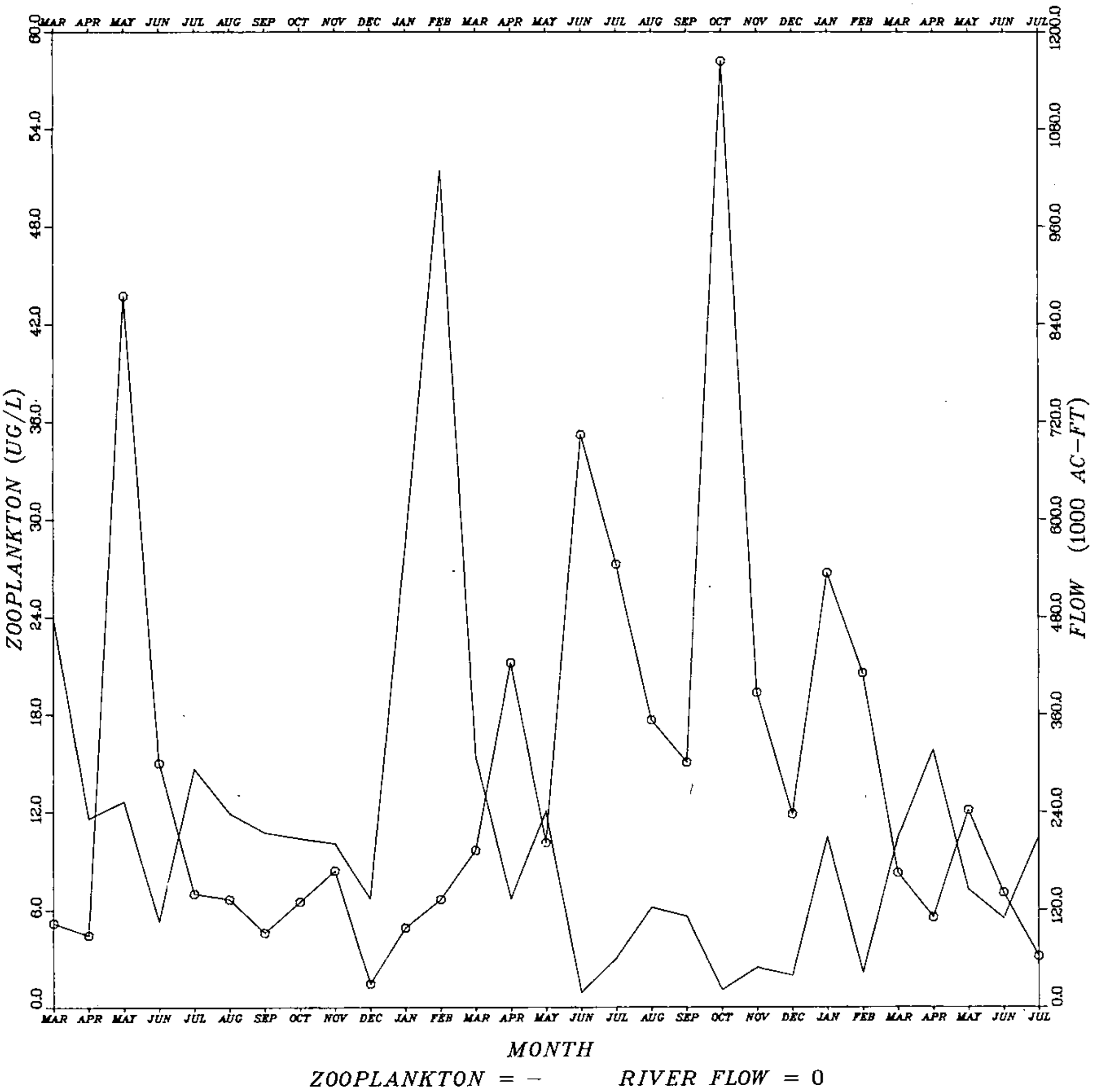

Figure 7-8. Mean Monthly Zooplankton Densities Versus Combined River Inflow in San Antonio Bay, March 1972-July 1974

Table 7-5. Distribution of Acartia tonsa by Salinity and Temperature Ranges, San Antonio Bay, March 1972 - July 1974

Salinity (ppt)		Water Temperature (Degrees Centigrade)											
		0.- 3.	3.- 6.	6.- 9.	9.- 12.	12.- 15.	15.- 18.	18.- 21.	21.- 24.	24.- 27.	27.- 30.	30.- 33.	33.- 36.
0.-4.	Samples				1	9	24	18	13	41	47	9	1
	Occurrences				1	8	23	14	11	33	38	8	1
	Avg. Catch a/				3	716	1429	68	992	1561	2398	2294	2601
4.-8.	Samples					8	16	5	5	9	21	2	
	Occurrences					6	16	2	5	9	20	2	
	Avg. Catch					357	4891	1502	15332	15491	13275	10611	
8.-12.	Samples			3		1	8	10	2	11	11	3	
	Occurrences			3		1	3	8	2	10	11	3	
	Avg. Catch			4907		11660	997	7593	2982	6558	10584	21834	
12.-16.	Samples			1	1		5	4	5	3	11	4	1
	Occurrences			1	1		5	4	4	2	11	4	1
	Avg. Catch			2188	2545		4356	2873	4490	3672	8630	13910	4501
16.-20.	Samples			1	4	2	1	8	6	3		1	1
	Occurrences			1	4	2	1	5	6	3		1	1
	Avg. Catch			1280	3918	3823	957	4469	3351	3624		5580	7180
20.-24.	Samples				3	1	1	5	2	3			
	Occurrences				3	1	1	5	1	3			
	Avg. Catch				1593	1473	2932	3087	1477	3413			
24.-28.	Samples			1	3	2	5	1	2	1			
	Occurrences			1	3	2	5	1	1	1			
	Avg. Catch			2408	1436	2531	5993	4416	2465	2414			
28.-32.	Samples			1		1	2		1				
	Occurrences			1		1	2		1				
	Avg. Catch			5751		2330	2950		7784				
32.-36.	Samples												
	Occurrences												
	Avg. Catch												
36.-40.	Samples												
	Occurrences												
	Avg. Catch												

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

salinities less than 2 ppt to over 30 ppt in Louisiana estuaries by Gillespie (141). Greatest densities of the second most prominent zooplankton, the meroplanktonic barnacle nauplii, occurred in the cool, higher salinity waters of the winter, which corresponds to the period of peak spawning activity of the barnacle (Table 7-6).

Seasonal abundances of zooplankton and phytoplankton in San Antonio Bay are illustrated in Figure 7-9. Relationships between zooplankton and phytoplankton communities (predator/prey) are difficult to establish. Peak zooplankton densities occurred in January and March-April while phytoplankton populations were depressed. From the limited data available it is not possible to determine if a correlation exists between these populations.

Because the species in an area can vary in density and species predominance as well as fluctuate seasonally during the year, reliable conclusions on the plankton populations of an area can only be drawn on the basis of long-term investigations with regular catches.

Benthos

Data Collection

According to Matthews et al. (248), a total of 70,254 organisms representing 128 species in 8 phyla were identified from 454 benthic samples collected during the 28-month TPWD study. Of this total, 24,754 (35 percent) organisms representing 31 species were collected from Region I; 36,586 (52 percent) organisms representing 69 species were collected from Region II; and from Region III, the highest salinity area, only 8,914 (12 percent) organisms representing 92 species were collected. The most prominent phyla was the Mollusca which accounted for 42 percent (54 taxa) of the species identified, followed by the Arthropoda with 28 percent (36 taxa), and the Annelida with 23 percent (30 taxa). The chordates accounted for 3 percent (4 taxa), and the platyhelminthes, nematodes, nemertines, and echinoderms each for one percent (one taxon).

The mean number of benthos (reported in organisms/m^2) ranged from 450 (September 1972) to 6,550 (June 1973) in Region I, from 270 (October 1973) to 7,350 (May 1973) in Region II, and from 120 (August 1973) to 2,030 (July 1974). The average density for the entire study period was 169 organisms/m^2. Regions I and II were 3 to 4 times as productive as Region III. The mean monthly density for all stations ranged from 59.25 organisms/m^2 in January 1974 to 521.43 organisms/m^2 in May 1973.

Benthic populations varied seasonally with high spring/summer and low fall/winter standing crops (Figure 7-10). The largest number of species occurred in the lower, more saline areas of Region III and the smallest number in the upper, low salinity areas of Region I.

Molluscan gastropods and bivalves were most prominent in the low salinity waters of the upper bay, while the annelids appeared to prefer the more saline waters of Region III. Biomass values for the other groups were similar from region to region (Table 7-7).

Table 7-6. Distribution of Barnacle Nauplii by Salinity and Temperature Ranges, San Antonio Bay, March 1972 - July 1974

		Water Temperature (Degrees Centigrade)											
Salinity (ppt)		0.- 3.	3.- 6.	6.- 9.	9.- 12.	12.- 15.	15.- 18.	18.- 21.	21.- 24.	24.- 27.	27.- 30.	30.- 33.	33.- 36.
0.-4.	Samples				1	9	24	18	13	41	47	19	1
	Occurrences				0	9	21	8	18	16	17	2	1
	Avg. Catch a/				0	248	1009	154	120	477	36	85	7
4.-8.	Samples					8	16	5	5	9	21	2	
	Occurrences					6	16	2	5	9	19	2	
	Avg. Catch					1652	8520	688	2710	2024	1031	89	
8.-12.	Samples			3		1	8	10	2	11	11	3	
	Occurrences			3		1	3	8	2	9	11	3	
	Avg. Catch			3973		23200	443	5508	3788	2707	1973	662	
12.-16.	Samples			1	1		5	4	5	3	11	4	1
	Occurrences			1	1		5	4	4	2	11	4	1
	Avg. Catch			1837	4845		4536	6190	4181	1218	564	2738	1913
16.-20.	Samples			1	4	2	1	8	6	3		1	1
	Occurrences			1	4	2	1	5	6	3		1	1
	Avg. Catch			10290	17360	29330	38	4111	2602	687		209	265
20.-24.	Samples				3	1	1	5	2	3			
	Occurrences				3	1	1	5	1	3			
	Avg. Catch				5577	14860	70540	10482	810	1099			
24.-28.	Samples			1	3	2	5	1	2	1			
	Occurrences			1	3	2	5	1	1	1			
	Avg. Catch			2187	1471	49090	34600	119	394	4752			
28.-32.	Samples			1		1	2		1				
	Occurrences			1		1	2		1				
	Avg. Catch			11050		86920	59094		6269				
32.-36.	Samples												
	Occurrences												
	Avg. Catch												
36.-40.	Samples												
	Occurrences												
	Avg. Catch												

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

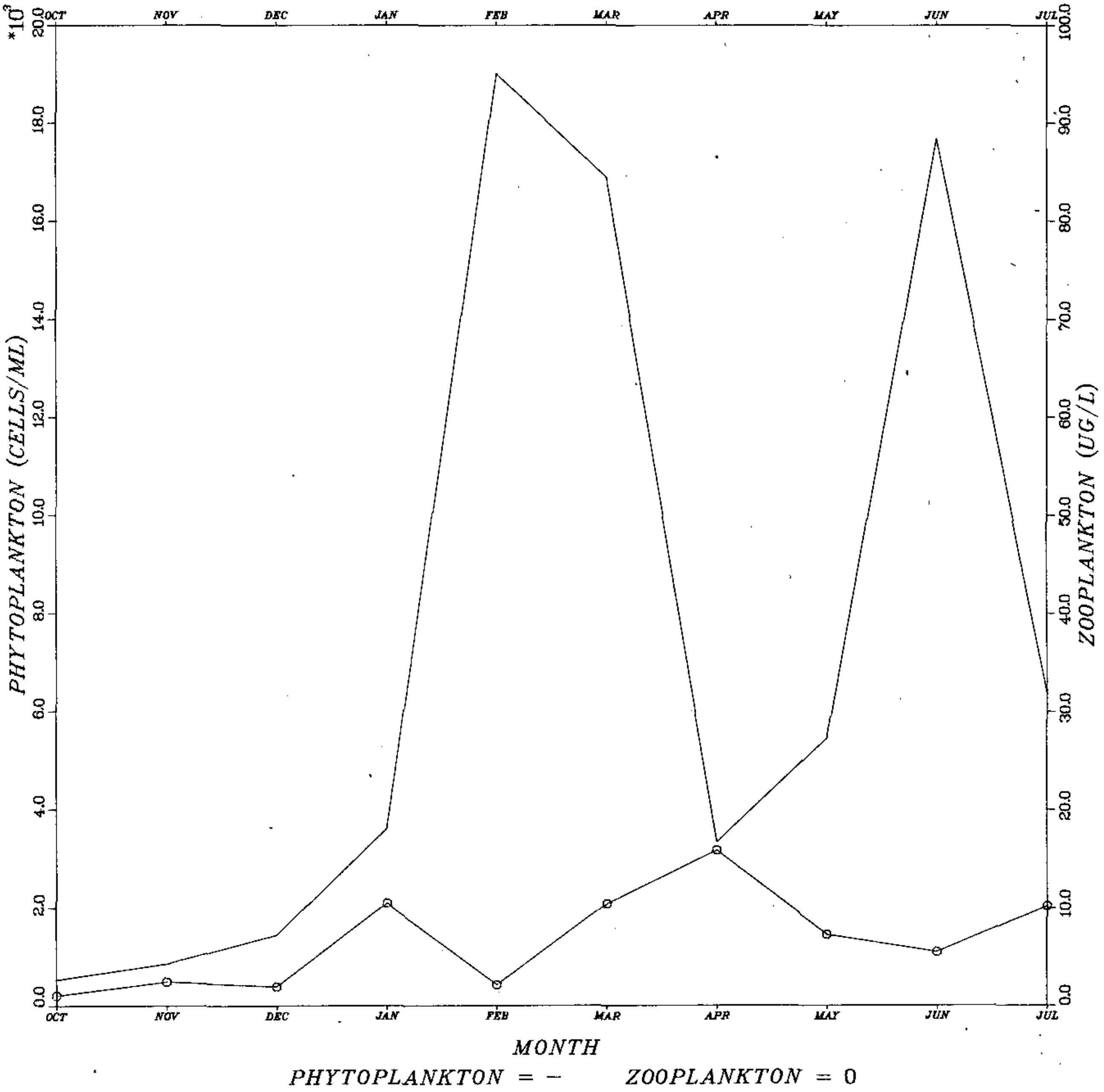

Figure 7-9. Mean Monthly Phytoplankton and Zooplankton Densities in San Antonio Bay, October 1973-July 1974

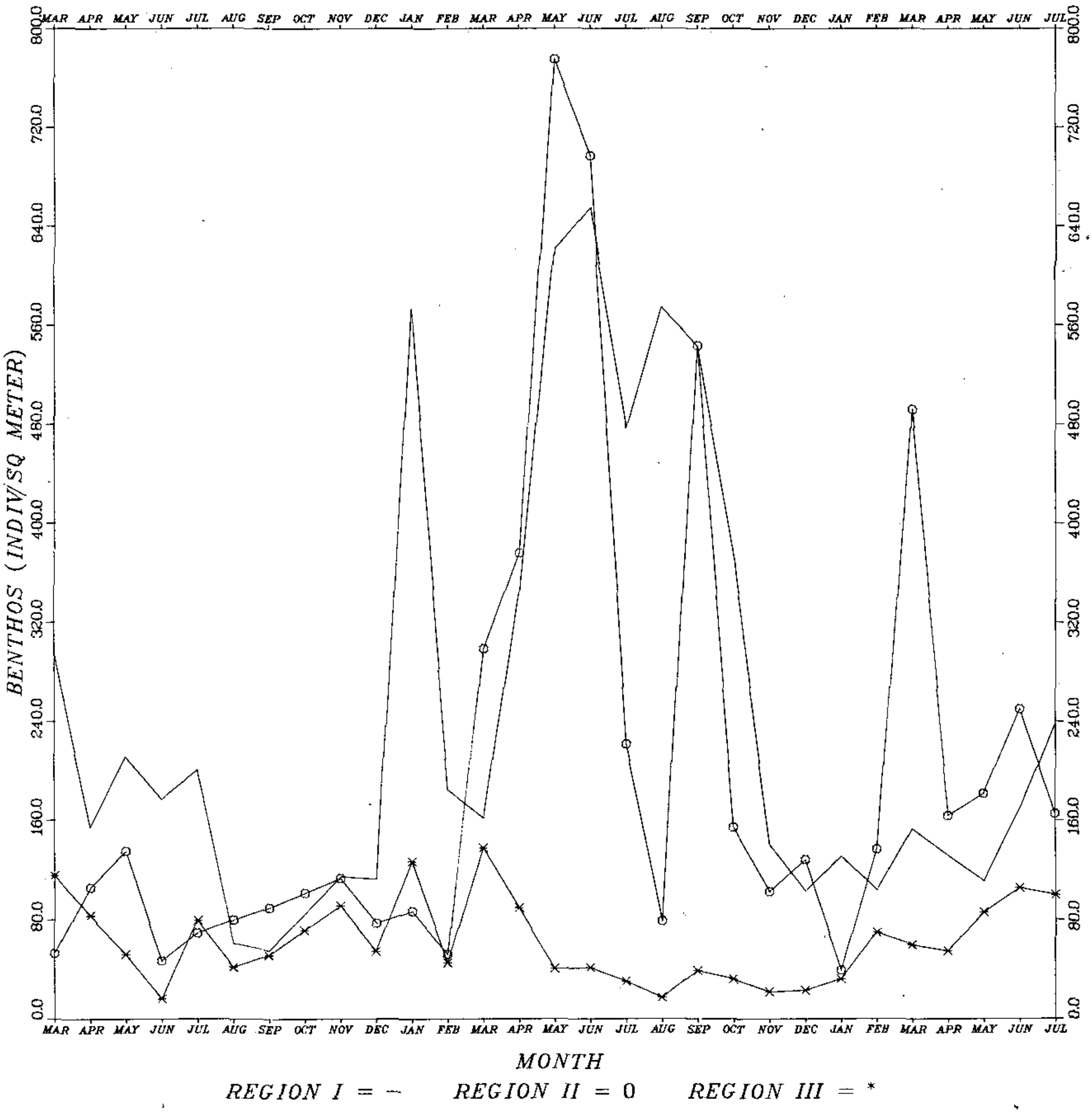

Figure 7-10. Mean Monthly Benthos Densities in San Antonio Bay, March 1972-July 1974

Table 7-7. Mean Percentage Representation by Biomass of Benthos in the San Antonio Bay System, March 1972 - July 1974

Zooplankton	Region I [a]	Region II	Region III
		(percent)	
Molluscan gastropods	52.4	48.1	3.6
Molluscan bivalves	31.5	13.4	17.6
Annelids (polychaetes and oligochaetes)	10.3	37.6	76.9
Arthropod crustaceans	3.3	0.1	0.1
Nemertines	0.2	0.6	1.6
Insect larvae	2.0	0.1	0.1
Others	0.3	0.1	0.1
Total Benthic Biomass	100.0	100.0	100.0

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[a] Refer to Figure 7-2 for locations of Regions I, II, and III.

The six most prominent taxa in each region and for the entire bay system are shown in Table 7-8. It is apparent from these tables that the molluscan gastropod *Littoridina sphinctostoma* was most abundant and nearly ubiquitous throughout the system, followed by the polychaete worm *Mediomastus californiesnsis* and the molluscan pelecypod *Rangia cuneata*. Certain species like *Littoridina sphictostoma*, *Rangia cuneata*, and *Hypaniola gunneri floridus* attained the highest numbers in the upper, low salinity regions, while species such as *Mediomastus californiensis* and *Streblospio beneditci* seemed to prefer the higher salinity waters of the lower bay. Although the lowest number of species were taken from Regions I and II, these lower salinity areas clearly had the largest benthic biomass.

Mudshell dredging and silt movement produced by dredging operations strongly affected stations 264-3, 274-3, 274-5, 287-5, and 287-8 in Region II. Dredging operations produced a bottom substrate unfavorable for benthic organisms.

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 (65).

Benthos diversity generally decreases with distance upstream in an estuary. From a minimum, at a salinity of 5.0 ppt, species numbers increase seaward to a maximumn at about 35 ppt, the normal salinity of sea water, and decline once more with increasing salinity. Taxa diversity in Lavaca Bay declined from the high salinity lower bay to the low salinity upper bay and riverine areas (250). Diversities were highest during late winter and early spring when sustained freshwater inflows were low. Matthews et al. (248) found that the number of benthic species in the San Antonio Bay system decreased with increased freshwater inflow; however, the total benthic standing crop was greater due to increases in the gastropod *Littoridina sphinctostoma*, the pelecypod *Rangia cuneata*, the polychaete *Hypaniola gunneri*, and chironomid larvae populations.

Harper (211), studying the distribution of benthic organisms in undredged control areas of San Antonio Bay, also found increases in benthic populations associated with decreased salinity. This was attributed to increased inflow of water-borne nutrients since benthic organisms like *Rangia cuneata* and *Littoridina sphinctostoma* are known to spawn in response to increased nutrients and rapid decreases in salinity.

Catch distributions based on temperature and salinity of the two most prominent taxa in San Antonio Bay, *Littoridina sphinctostoma* and *Mediomastus californiesnsis*, indicated that seasonal variations showed mainly high spring/summer and low fall/winter populations (Tables 7-9 and 7-10). Benthic standing crops were generally variable from month to month at all stations.

Table 7-8. Percent Composition by Biomass of Dominant Benthic Species in the San Antonio Bay System, March 1972 - July 1974

Region a/	Species	Percent Composition b/
Region I	*Littoridina sphinctostoma*	51.2
	Rangia cuneata	28.2
	Hypaniola gunneri	4.8
	Mediomastus californiensis	3.8
	Corophium louisianum	2.4
	Chironomid larvae	1.9
		92.3
Region II	*Littoridina sphinctostoma*	46.0
	Mediomastus californiensis	25.2
	Rangia cuneata	10.7
	Streblospio benedicti	4.8
	Parandalia fauveli	3.8
	Littoridina sp. B	2.1
		92.6
Region III	*Mediomastus californiensis*	47.8
	Parandalia fauveli	14.4
	Mulina lateralis	11.3
	Streblospio benedicti	8.5
	Macoma mitchelli	5.0
	Glycinde solitaria	3.8
		90.8
All Regions	*Littoridina spinctostoma*	43.7
	Mediomastus californiensis	18.2
	Rangia cuneata	17.3
	Parandalia fauveli	3.4
	Streblospio benedicti	3.4
	Mulina lateralis	2.0
		88.0

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

Table 7-9. Distribution of <u>Littoridina</u> <u>sphinctostoma</u> by Salinity and Temperature Ranges, San Antonio Bay, March 1972 - July 1974

Salinity (ppt)		Water Temperature (Degrees Centigrade)											
		0.- 3.	3.- 6.	6.- 9.	9.- 12.	12.- 15.	15.- 18.	18.- 21.	21.- 24.	24.- 27.	27.- 30.	30.- 33.	33.- 36.
0.-4.	Samples				4	8	41	37	26	41	68	12	
	Occurrences				2	4	20	16	18	23	43	8	
	Avg. Catch a/				89	11	78	71	72	30	147	134	
4.-8.	Samples			1	1	1	17	15	12	20	46	6	1
	Occurrences			1	0	0	8	9	10	15	14	2	1
	Avg. Catch			28	0	0	52	73	106	76	80	83	124
8.-12.	Samples			2		4	7	10	10	15	23	3	
	Occurrences			2		2	3	3	5	5	4	0	
	Avg. Catch			197		107	8	12	32	288	1	0	
12.-16.	Samples			4	3	1	8	7	9	9	15	6	
	Occurrences			3	0	1	5	3	4	2	1	0	
	Avg. Catch			17	0	38	61	6	7	1	1	0	
16.-20.	Samples			3	5	3	5	8	8	15	1	4	
	Occurrences			0	2	2	2	0	1	3	0	0	
	Avg. Catch			0	2	90	3	0	1	18	0	0	
20.-24.	Samples			2	4	1	1	3	8	6	1		
	Occurrences			0	0	0	1	1	0	2	0		
	Avg. Catch			0	0	0	9	4	0	1	0		
24.-28.	Samples			2	5	2	6	5	3	2	1		
	Occurrences			0	0	0	1	0	1	0	0		
	Avg. Catch			0	0	0	2	0	16	0	0		
28.-32.	Samples			2		1	3		1				
	Occurrences			0		4	0		0				
	Avg. Catch			0		4	0		0				
32.-36.	Samples												
	Occurrences												
	Avg. Catch												
36.-40.	Samples												
	Occurrences												
	Avg. Catch												

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

Table 7-10. Distribution of Mediomastus californiensis by Salinity and Temperature Ranges, San Antonio Bay, March 1972 - July 1974

Salinity (ppt)		Water Temperature (Degrees Centigrade)											
		0.- 3.	3.- 6.	6.- 9.	9.- 12.	12.- 15.	15.- 18.	18.- 21.	21.- 24.	24.- 27.	27.- 30.	30.- 33.	33.- 36.
0.-4.	Samples				4	8	41	37	26	41	68	12	
	Occurrences				3	3	13	11	7	23	32	5	
	Avg. Catch a/				12	2	4	4	10	14	13	14	
4.-8.	Samples			1	1	1	17	15	12	20	46	6	1
	Occurrences			1	0	0	10	6	7	16	32	2	0
	Avg. Catch			10	0	0	15	10	34	49	29	3	0
8.-12.	Samples			2		4	7	10	10	15	23	3	
	Occurrences			1		3	4	9	8	11	15	1	
	Avg. Catch			3		30	9	73	40	23	20	23	
12.-16.	Samples			4	3	1	8	7	9	9	15	6	
	Occurrences			3	3	0	4	7	4	9	13	4	
	Avg. Catch			44	10	0	10	288	30	64	33	28	
16.-20.	Samples			3	5	3	5	8	8	15	1	4	
	Occurrences			1	4	2	2	8	5	12	1	1	
	Avg. Catch			2	15	4	10	15	30	47	32	5	
20.-24.	Samples			2	4	1	1	3	8	6	1		
	Occurrences			1	3	0	0	2	8	5	1		
	Avg. Catch			10	34	0	0	47	19	30	36		
24.-28.	Samples			2	5	2	6	5	3	2	1		
	Occurrences			2	3	0	1	3	2	1	1		
	Avg. Catch			20	7	0	9	3	9	21	45		
28.-32.	Samples			2		1	3		1				
	Occurrences			2		1	0		1				
	Avg. Catch			12		3	0		28				
32.-36.	Samples												
	Occurrences												
	Avg. Catch												
36.-40.	Samples												
	Occurrences												
	Avg. Catch												

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

Summary

The community composition, distribution, density, and seasonality of the phytoplankton, zooplankton, and benthic invertebrates of the Guadalupe estuary have been used by the Texas Parks and Wildlife Department 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).

Six phytoplankton divisions represented by a minimum of 60 taxa were collected from the Guadalupe estuary. Standing crops were not significantly related to salinity or river inflow.

A total of 162 zooplankton taxa representing 12 phyla were identified. The calanoid copepod *Acartia tonsa* was the dominant organism. Species diversity and standing crops were reduced by heavy flooding; the recuperation period was short, however, and these parameters increased rapidly when salinities returned to their seasonal norms.

Seasonal variations in benthic inveterbrate populations were exhibited through high spring/summer and low fall/winter standing crops. Increased freshwater inflows generally were associated with lowered species numbers, although the total benthic standing crop was greater due to increases in the gastropod *Littoridina sphinctostoma*, the pelecypod *Rangia cuneata*, the polychaete *Hypaniola gunneri*, and chironomid larvae populations.

The phytoplankton, zooplankton, and benthic assemblages in any body of water respond to a seasonal combination of physical, chemical, and biological controlling factors. Thus, it is difficult to single out the influence of any one of these factors on the entire community. Most estuarine organisms can be classified by salinity tolerance as oligohaline, mesohaline, polyhaline, or euryhaline. That is, there is always an assemblage of species which will be capable of maintaining high standing crops, regardless of the salinity (as long as it is relatively stable) and provided that other physical-chemical requirements for that particular assemblage are met. If freshwater inflow is decreased, either partially or totally, the community composition will shift toward the neritic or marine 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

During the five year period, 1972 through 1976, commercial landings of finfish and shellfish in Texas averaged 97.3 million pounds (44.2 million kg) annually (358-362). Approximately 75 percent of the harvest was taken offshore in the Gulf of Mexico and the remainder was taken inshore in the bays and estuaries. Computed on the basis of the two general fisheries components, the finfish harvest distribution was approximately 28 percent offshore and 72 percent inshore, while the shellfish harvest was of an opposite distribution with about 21 percent inshore and 79 percent offshore. Specifically, the offshore harvests accounted for about six percent of the total Texas red drum (redfish) landings, 17 percent of spotted seatrout landings, 60 percent of white shrimp landings, and 95 percent of brown and pink shrimp landings.

Virtually all (97.5 percent) of the coastal fisheries species are considered estuarine-dependent (79). The Guadalupe estuary is the third largest estuarine ecosystem on the Texas coast and ranks third overall of eight Texas estuarine areas for inshore commercial harvest of seafood organisms. With respect to commercial bay landings from the five year period, 1972 through 1976, bays of the Guadalupe estuary contributed an average 7.1 percent of finfish landings and 13.8 percent of shellfish landings. By comparison, the largest Texas estuary, the Trinity-San Jacinto estuary, contributed an average 11.0 percent of finfish and 45.4 percent of shellfish bay landings during the same period (226).

Based on the five year inshore-offshore commercial landings distribution, the average contribution of the Guadalupe estuary to total Texas commercial landings is estimated at 538,700 pounds (244,400 kg) of finfish and 12,411,800 pounds (5.6 million kg) of shellfish annually. In addition, the commercial finfish harvest has been estimated to account for approximately 53.7 percent of the total finfish harvest in the estuary, with the remainder (46.3 percent) going to the sport or recreational catch of finfish (252). Thus, an additional 464,500 pounds (210,700 kg) of sport finfish harvest can be computed which raises the estimated average annual finfish harvest contribution from the estuary (both inshore and offshore) to 1,003,200 pounds (455,100 kg). The average harvest contribution of all fisheries species (finfish and shellfish) dependent on the estuary is therefore estimated at 13.4 million pounds (6.1 million kg) annually.

Previous research has described the general ecology, utilization, and management of the coastal fisheries (257, 311, 157, 155, 74, 190, 186), and has provided information on Texas tidal waters (295, 300, 363, 176) and the relationship of freshwater inflow to estuarine productivity (381). In addition, prior studies of the Guadalupe estuary have dealt with aspects of organic carbon transport (201), nutrient biogeochemical cycling (271), water quality standards (246), and the effects of seasonal freshwater inflows on hydrological and biological parameters (245). Multivariate equational models of fisheries production as a function of the effects of seasonal freshwater inflows have not been previously constructed.

Data and Statistical Methods

Direct analysis of absolute fisheries biomass fluctuations as a function of freshwater inflow is not possible. Accurate biomass estimation requires either considerable experimental calibration of current sampling methods (119) 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 (35). 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 (119).

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 (98, 82, 81, 340, 206, 205). Therefore, commercial harvest can be useful as a relative indicator of fisheries abundance, especially if the harvest is not critically limited below the production available for harvest on a long-term basis (i.e., the surplus production) by market conditions. Similarly, annual harvest fluctuations can provide relative estimates of the fisheries biomass fluctuations occurring from year to year. In Texas, commercial harvest data are available from the Texas Landings publications (365-371, 355-362) which report inshore harvests from the bays and offshore harvests from the Gulf of Mexico. Since the offshore harvests represent collective fisheries production from the region's estuaries, it is the inshore harvests reported by estuarine area that provide fisheries data related to a particular estuary.

Commercial inshore harvests from bays of the Guadalupe estuary are tabulated for several important fisheries components (Table 8-1). By using harvest data since 1962, data inconsistencies with earlier years and problems of rapidly increasing harvest effort as the commercial fisheries developed in Texas are avoided. For example, landings data for the penaeid shrimp fishery are better than for most of the fisheries components because of the high demand for this seafood. Nevertheless, landings data from the turn of the century to the late 1940's are incomplete and report only the white shrimp harvest. Exploitation of the brown shrimp began in 1947 with night trawling in offshore waters and rapidly increased throughout the 1950's; however, separation of the two species in the fisheries statistics was not begun until after 1957. Therefore, since reporting procedures were not fully standardized until the early 1960's, and since earlier harvest records were inconsistent, the fisheries analysis utilizes the more reliable records available from 1962 to 1976. This 15-year interval includes both wet and dry climatic cycles and is sufficient in length to identify positive and negative fisheries responses to seasonal inflow, as well as quantify the seasonal freshwater inflow needs of the fisheries components.

The finfish component of the fisheries harvest is specific for the combined harvests of croaker (mostly *Micropogon undulatus* Linnaeus), black drum (*Pogonis cromis* Linnaeus), red drum or redfish (*Sciaenops ocellata* Linnaeus), flounder (*Paralichthys* spp.; mostly *P. lethostigma* Jordan and Gilbert), sea catfish (*Arius felis* Linnaeus), spotted seatrout (*Cynoscion nebulosus* Cuvier),

Table 8-1. Commercial Fisheries Harvests in the Guadalupe Estuary a/, 1962-1976 (365-371, 355-362)

Year	Commercial Fisheries Harvest (thousands of pounds)								
	Shellfish b/	White Shrimp	Brown & Pink Shrimp	Blue Crab	Bay Oyster	Finfish c/	Red Drum	Spotted Seatrout	Black Drum
1962	1,292.4	602.3	314.7	170.9	204.5	257.1	61.9	40.4	131.0
1963	1,767.6	359.1	90.1	984.9	333.5	189.3	35.1	20.5	103.4
1964	2,399.7	1,379.7	98.5	639.9	281.6	154.1	26.5	16.9	71.8
1965	2,560.0	1,415.0	329.5	693.0	122.5	79.4	24.4	12.2	14.9
1966	1,179.0	485.5	181.1	362.7	149.7	240.8	82.9	94.6	47.7
1967	1,813.8	832.1	453.5	276.1	252.1	286.3	86.5	94.3	70.9
1968	1,839.5	1,203.2	—	472.5	163.8	161.2	31.8	81.2	14.8
1969	2,636.7	887.7	210.9	1,484.0	54.1	84.7	33.7	19.2	17.2
1970	2,060.3	1,121.6	185.2	531.7	221.8	209.0	110.6	39.0	40.1
1971	1,726.4	493.9	254.7	582.8	395.0	248.6	96.8	76.0	44.6
1972	2,444.4	959.1	91.8	995.5	398.0	156.5	55.5	49.0	28.0
1973	2,515.3	867.5	654.3	859.0	134.5	250.0	78.1	85.3	52.7
1974	2,203.3	815.3	67.1	1,124.3	196.6	421.9	168.6	103.8	109.7
1975	2,940.2	771.9	502.2	1,539.1	124.0	442.8	179.2	114.0	92.0
1976	3,053.2	412.1	221.5	2,140.4	279.2	373.4	144.5	114.8	55.8
Mean d/	2,162.1	840.4	261.1	857.1	220.7	237.0	81.1	64.1	59.6
±S.E.	±143.9	±86.5	±46.6	±139.2	±26.4	±28.3	±13.2	±9.7	±9.4

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

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% confidence limits about the mean and sheepshead (Archosargus probatocephalus Walbaum). Similarly, the shellfish component refers to the blue crab (Callinectes sapidus Rathbun), American oyster (Crassostrea virginica Gmelin), white shrimp (Penaeus setiferus Linnaeus), and brown and pink shrimp (Penaeus aztecus Ives and P. duorarum Burkenroad; mostly P. aztecus). Other fisheries components are given as a single species or species group of interest.

Freshwater inflow to the estuary is discussed in Chapter IV and is tabulated here on the basis of two analytical categories: (1) freshwater inflow at Guadalupe delta (FINGD) contributed to the estuary (Table 8-2), and (2) combined freshwater inflow (FINC) from all river and coastal drainage basins contributed to the estuary (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 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 Guadalupe estuary fisheries components was performed utilizing the University of California biomedical (BMD) computer program for the stepwise multiple regression procedure (15). This statistical procedure computes a sequence of multiple linear regression equations in a stepwise manner. At each step, the next variable which makes the greatest reduction in the sum of squares error term is added to the equation. Consequently, the best significant equation is developed as the equation of highest multiple correlation coefficient (r), greatest statistical significant (F value), and lowest error sum of squares. A typical form of the harvest regression equation can be given as follows:

$$H_t = a_0 + a_1 Q_{1,t-b_1} + a_2 Q_{2,t-b_2} + a_3 Q_{3,t-b_3} + a_4 Q_{4,t-b_4} + a_5 Q_{5,t-b_5} + a_6 Q_{6,t-b_6} + e$$

where a_0 is the intercept harvest value, $a_1 \ldots a_6$ are partial regression coefficients, e is the normally distributed error term with a mean of zero, and the regression variables are:

Table 8-2. Seasonal Freshwater Inflow Volumes at Guadalupe Delta Contributed to Guadalupe 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.	Annual Jan.-Dec.
1959	488.1	551.1	207.0	386.0	218.0	1,850.2
1960	366.9	567.9	467.0	1,244.0	1,021.0	3,666.8
1961	960.0	780.0	411.0	326.0 a/	291.0	2,768.0
1962	204.9	305.1	73.0	146.0	161.0	890.0
1963	195.9	129.0	40.0	50.0 b/	126.0	540.9
1964	282.0	156.0	109.0	195.0	144.0	886.0
1965	683.1	950.1	135.0	218.0	440.0	2,426.2
1966	414.0	675.0	200.0	198.0	138.0	1,625.0
1967	195.9	171.9	91.0	2,602.0 c/	448.0	3,508.8
1968	1,188.9	1,290.9	387.0	332.0	298.0	3,496.8
1969	711.0	887.1	130.0	185.0	256.0	2,169.1
1970	585.9	870.0	190.0 d/	204.0	117.0	1,966.9
1971	150.9	144.0	221.0	829.0 e/	485.0	1,829.9
1972	411.0	1,443.9	274.0	246.0	246.0	2,620.9
1973	423.0	1,430.1	909.0	1,537.0 f/	625.0	4,924.1
1974	656.1	497.1	196.0	554.0	708.0	2,611.2
1975	840.9	1,575.0	487.0	266.0	234.0	3,402.9
1976	261.9	1,434.9	375.0	541.0	1,298.0	3,910.8
Mean	501.1	770.0	272.3	558.8	403.0	2,505.3
± S.E. g/	±68.8	±117.6	±49.5	±152.0	±77.2	±275.5

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

Table 8-3. Seasonal Volumes of Combined Freshwater Inflow a/ Contributed to Guadalupe 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.	Annual Jan.-Dec.
1959	519.9	564.0	240.0	433.0	221.0	1,977.9
1960	393.9	599.1	498.0	1,294.0	1,079.0	3,863.1
1961	1,008.9	822.9	427.0	354.0 b/	297.0	2,909.8
1962	207.9	318.9	75.0	152.0	176.0	929.8
1963	201.9	132.0	42.0	52.0 c/	130.0	557.9
1964	291.0	162.0	111.0	206.0	151.0	921.0
1965	693.9	957.9	137.0	225.0	461.0	2,474.8
1966	450.9	744.9	204.0	204.0	140.0	1,743.8
1967	198.0	195.9	107.0	2,713.0 d/	448.0	3,661.9
1968	1,215.0	1,379.1	397.0	344.0	298.0	3,633.1
1969	720.9	923.1	130.0	186.0	275.0	2,235.0
1970	606.9	884.1	196.0 e/	265.0	117.0	2,069.0
1971	150.9	147.9	226.0	905.0 f/	529.0	1,958.8
1972	432.9	1,470.0	283.0	288.0	263.0	2,736.9
1973	423.9	1,464.9	910.0	1,609.0 g/	625.0	5,032.8
1974	660.0	558.9	200.0	573.0	774.0	2,765.9
1975	845.1	1,581.0	501.0	287.0	234.0	3,448.1
1976	261.9	1,452.0	446.0	553.0	1,353.0	4,065.9
Mean	515.8	797.7	285.0	591.3	420.6	2,610.3
± S.E h/	±70.5	±119.1	±50.5	±158.1	±81.3	±282.7

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a/ Includes flow from all contributing river and coastal drainage basins (see Chapter IV).

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 erros provide approximately 95 percent confidence limits about the mean.

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

$Q_{1,t-b_1}$ = winter season (January-March) mean monthly freshwater inflow in thousands of acre-feet at year $t-b_1$, where b_1 is a positive integer (Table 8-4),

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

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

$Q_{6,t-b_6}$ = annual (January-December) mean monthly freshwater inflow in thousands of acre-feet at year $t-b_6$, where b_6 is a positive integer (Table 8-4).

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 the curves and the double log transformed regression equation is rewritten as follows:

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

where the variables are the same as defined above.

In practice, the time series for the dependent variable (H) is the aforementioned inclusive period 1962 through 1976, giving 15 annual harvest observations for the regression analysis. The independent variables ($Q_1 \ldots Q_6$) also result in 15 observations each; however, the time series is not necessarily concomitant with that of harvest and varies because of consideration of species life history aspects involved in the analysis of each fisheries component. Thus, the data alignment between dependent/independent variates in the fisheries analysis was 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 (70, 151). Early articulation of this idea was put forth by the Norwegian fishery

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

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

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a/ includes blue crab, bay oyster, and white, brown, and pink shrimp

b/ includes croaker, black drum, red drum, flounder, sea catfish, spotted seatrout, and sheepshead scientist Johan Hjort in 1914 (101) 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 (184). Based on the equations alone, definite statements about the true ecological relationships among the variables cannot be made because of the inherent noncausal nature of statistical regression and correlation (70, 183). However, the hypothesis that freshwater inflow is a primary factor influencing the estuary and its production of estuarine-dependent fisheries is well-founded and reasonable considering the substantial volume of previous scientific research demonstrating inflow effects on nutrient cycling, salinity gradients, and the metabolic stresses and areal distributions of estuarine organisms.

Fisheries Analysis Results

Shellfish

Analysis of the multi-species shellfish fisheries component results in two weakly significant equations (Table 8-5). Statistical information given for each regression equation includes: (1) level of statistical significance (α value); (2) multiple coefficient of determination (r^2 value); (3) standard error of the estimate for the dependent variable, inshore harvest; (4) standard error of the regression coefficient associated with each independent variable, seasonal freshwater inflow; and (5) upper bounds, lower bounds, and means of the variables entering the equation. The best significant equation (first equation of Table 8-5) explains only 43 percent of the observed variation in inshore shellfish harvest and is significant (α = 5.0%) for correlation of the harvests to spring (Q_2) and late fall (Q_5) seasonal freshwater inflows at Guadalupe delta (FINGD).

The estimated effect of a correlating seasonal inflow on harvest is computed by holding all other correlating seasonal inflows in the best significant equation constant at their respective mean values, while varying the seasonal inflow of interest from its lower to upper observed bounds. Repeating this process for each correlating seasonal inflow in the best significant equation and plotting the results permits illustration of the individual seasonal inflow effects on the estimate of inshore commercial shellfish harvest (Figure 8-1). For example, Panel A of Figure 8-1 shows the annual harvest is estimated to increase from about 1.6 million pounds to 2.8 million pounds as the inflow at Guadalupe delta during the April-June (Q_2) seasonal interval increases from its observed lower bounds of 43.0 thousand acre-feet per month to its observed upper bounds of 525.0 thousand acre-feet per month. Thus, the positive (+) sign on the regression coefficient (a_2) for the correlating Q_2 inflow term in the best significant equation is illustrated as a line of positive slope relating increasing spring season inflow at Guadalupe delta to an increasing estimate of annual shellfish harvest. It is noted that this line can be shifted upward or downward in a parallel manner from that which has been graphed by holding the other correlating seasonal inflow (i.e., Q_5) in the best significant equation at a specified level of interest other than its mean observed value. For instance, if the negatively correlating November-December (Q_5) inflow is specified at some level lower than its mean of 157.2 thousand acre-feet per month, then the estimated harvest response to

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

Guadalupe Estuary Shellfish Harvest = f (seasonal FINGD b/)
Significant Equation (α = 5.0%, r^2 = 43%, S.E. Est. = ±453.0)

$$H_{sf} = 1767.4 + \underset{(0.8)}{2.3}\,(Q_2) - \underset{(1.5)}{1.4}\,(Q_5)$$

	H_{sf}	Q_2	Q_5
upper bounds	3053.2	525.0	354.0
lower bounds	1179.0	43.0	58.5
mean	2162.1	265.8	157.2

Guadalupe Estuary Shellfish Harvest = f (seasonal FINC c/)
Significant Equation (α = 2.5%, r^2 = 37%, S.E. Est. = ±459.5

$$H_{sf} = 1654.3 + \underset{(0.7)}{1.8}\,(Q_2)$$

	H_{sf}	Q_2
upper bounds	3053.2	527.0
lower bounds	1179.0	44.0
mean	2162.1	274.9

---

where: H_{sf} = inshore commercial shellfish 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
Q_6= January-December

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

April-June (Q_2) inflow would be similar to that shown in Panel A (Figure 8-1) and would have the identical positive slope; however, the computed line would be shifted upward and parallel to that which is graphed. Analogous circumstances exist for each of the harvest responses illustrated, but to facilitate comparisons only the seasonal inflow of interest in each panel graph is varied, while all others in the best significant equations are held constant at their respective values.

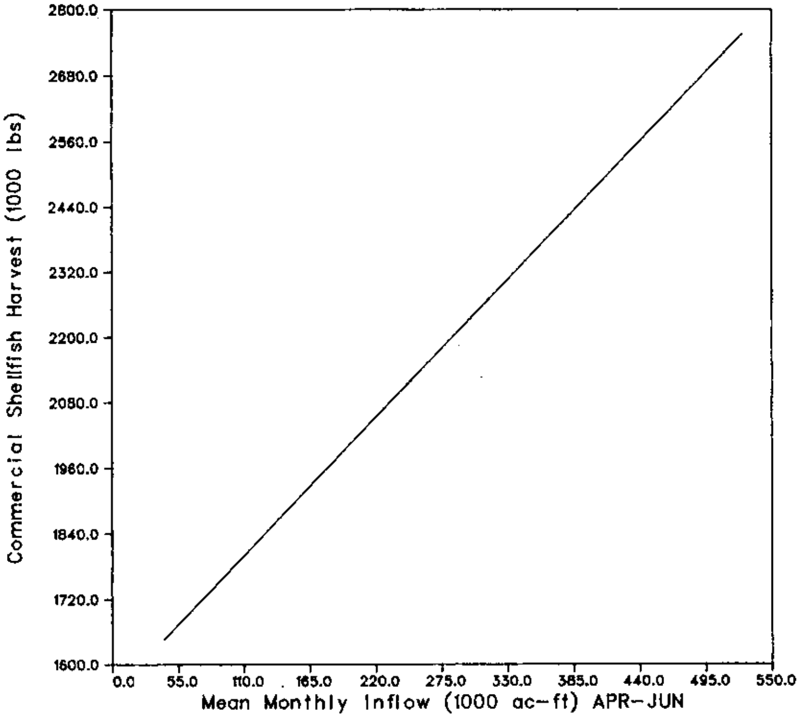
Panel B (Figure 8-1) exhibits the weakly negative response of inshore shellfish harvest to late fall season freshwater inflow at Guadalupe delta. The estimate of harvest decreases 18.0 percent (from about 2.3 million to about 1.9 million pounds annually) as the November-December (Q_5) inflow increases from its observed lower bounds of 58.5 thousand acre-feet per month to its observed upper bounds of 354.0 thousand acre-feet per month.

Considered together, Panels A and B in Figure 8-1 illustrate a strong positive statistical response of inshore commercial shellfish harvest to spring season (Q_2) inflow and a weaker, more variable negative response to late fall (Q_5) inflow over the observed ranges of these seasonal inflows at Guadalupe delta. Based on the statistical regression model described by the best significant equation, maximization of shellfish harvest can be achieved by increasing spring inflow and diminishing late fall inflow at Guadalupe delta.

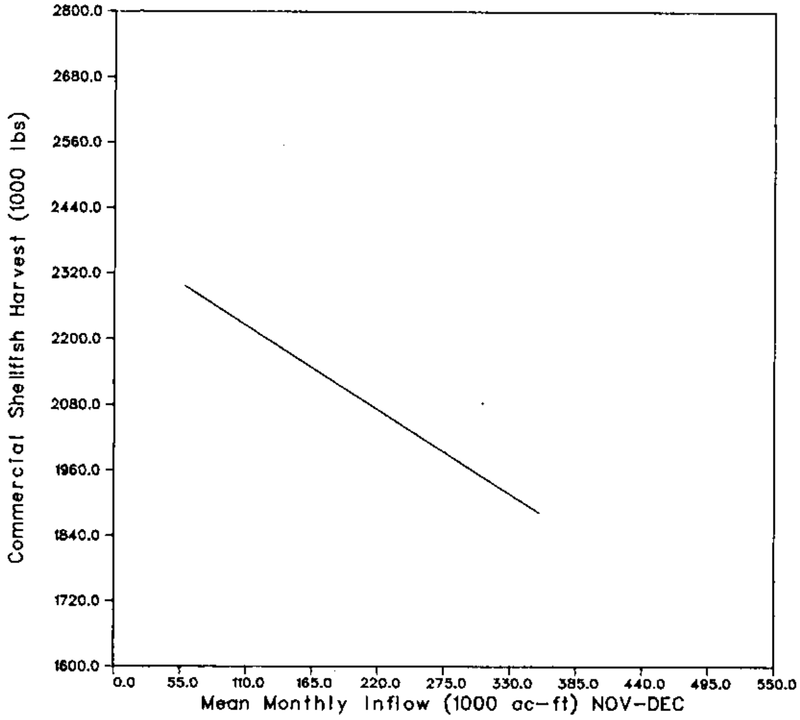
All Penaeid Shrimp

Analysis of the fisheries component for all penaeid shrimp (i.e., white, brown, and pink shrimp) yields a significant equation for both of the freshwater inflow categories (Table 8-6). The best significant equation (first equation, Table 8-6) accounts for 63 percent of the observed harvest variation and is significant (α = 2.5%) for correlation of inshore penaeid shrimp harvests to winter (Q_1), autumn (Q_4), and annual (Q_6) inflows at Guadalupe delta (FINGD).

The effect of each of the correlating inflow terms in the best significant equation is illustrated by using the previously discussed procedure of holding all other correlating inflows in the equation constant at their respective mean values, while varying the inflow of interest over its observed range and computing the estimated harvest response (Figure 8-2). The estimate of harvest increases 2.3 times (from about 0.7 to 1.6 million pounds annually) as January-March (Q_1) inflow increases from the observed lower bounds of 50.3 thousand acre-feet per month to the observed upper bounds of 280.3 thousand acre-feet per month (Panel A, Figure 8-2). Thus, the penaeid shrimp fisheries component is shown to have a positive relationship with winter season inflow at Guadalupe delta. Another positive response to autumn inflow results in the estimate of inshore harvest increasing from about 0.9 to 1.6 million pounds annually as September-October (Q_4) inflow increases over the observed range of 25.0 to 1,301.0 thousand acre-feet per month (Panel B, Figure 8-2). The estimate of harvest decreases 59.8 percent (from about 1.4 to 0.6 million pounds annually) as the one-year antecedent annual inflow (Q_6) increases over the observed range of 45.1 to 410.3 acre-feet per month (Panel C, Figure 8-2), indicating a negative relationship of harvest to high inflow from the year prior to harvest. Maximization of penaeid shrimp harvest is therefore statistically related to increasing winter (Q_1) and autumn



A. regression coefficient (slope of line) = +2.3, standard error = ±0.8



B. regression coefficient (slope) =−1.4, standard error = ±1.5

Figure 8-1. Inshore Commercial Shellfish Harvest as a Function of Each Seasonal Inflow at Guadalupe Delta, Where all Other Seasonal Inflows in the Multiple Regression Equation are Held Constant at Their Mean Values

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

Guadalupe Estuary All Shrimp Harvest = f (seasonal FINGD b/)
Significant Equation ($\alpha = 2.5\%$, $r^2 = 63\%$, S.E.Est. - ±263.1)

$$H_{as} = 796.9 + \underset{(1.1)}{4.0}\,(Q_1) + \underset{(0.2)}{0.5}\,(Q_4) - \underset{(0.8)}{2.3}\,(Q_6)$$

	H_{as}	Q_1	Q_4	Q_6
upper bounds	1744.5	280.3	1301.0	410.3
lower bounds	449.2	50.3	25.0	45.1
mean	1075.6	143.2	277.5	191.4

Guadalupe Estuary All Shrimp Harvest = f (seasonal FINC c/)
Significant Equation ($\alpha = 2.5\%$, $r^2 = 62\%$, S.E.Est. = ± 266.7

$$H_{as} = 784.4 + \underset{(1.1)}{3.9}\,(Q_1) + \underset{(0.2)}{0.5}\,(Q_4) - \underset{(0.8)}{2.2}\,(Q_6)$$

	H_{as}	Q_1	Q_4	Q_6
upper bounds	1744.5	281.7	1356.5	419.4
lower bounds	449.2	50.3	26.0	46.5
mean	1075.6	146.3	293.5	198.9

---

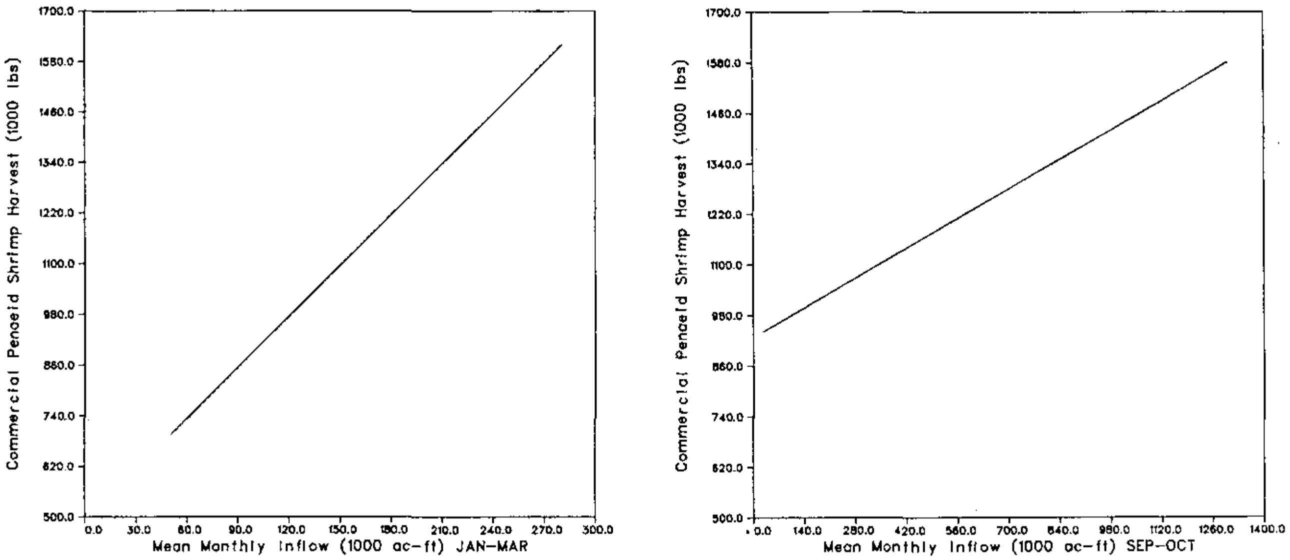
where: H_{as} = inshore commercial penaeid shrimp harvest, in thousands of pounds;
Q = mean monthly freshwater inflow, in thousands of acre-feet:

Q_1 = January-March
Q_2 = April-June
Q_3 = July-August
Q_4= September-October
Q_5= November-December
Q_6= January-December

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

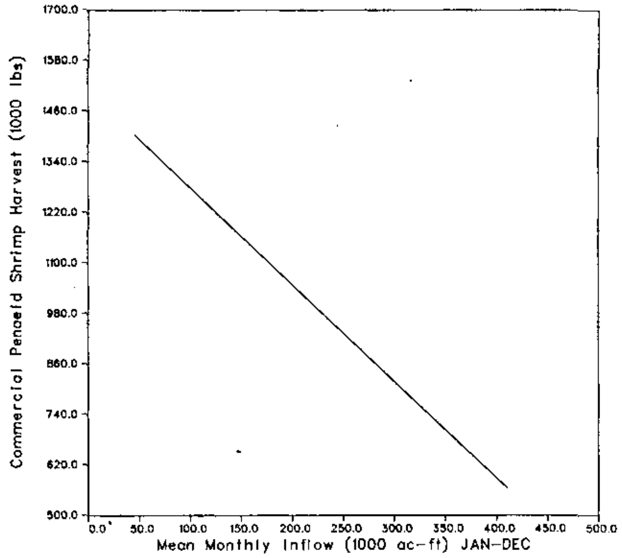
b/ FINGD = freshwater inflow at Guadalupe Delta

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



A. regression coefficient (slope) = +4.0, standard error = ±1.1

B. regression coefficient (slope) = +0.5, standard error = ±0.2



C. regression coefficient (slope) = -2.3, standard error = ±0.8

Figure 8-2. Inshore Commercial Penaeid Shrimp Harvest as a Function of Each Seasonal Inflow at Guadalupe Delta, Where all Other Seasonal Inflows in the Multiple Regression Equation are Held Constant at Their Mean Values

(Q_4) season inflows, while diminishing the annual (Q_6) inflow at Guadalupe delta.

White Shrimp

Analysis of the white shrimp fisheries component involves logarithmic transformation of the regression variables to natural logarithms (ln) and results in two highly significant equations (Table 8-7). The best significant equation (second equation, Table 8-7) explains 74 percent of the observed harvest variation and is highly significant (α = 1.0%) for correlation of natural log transformed inshore white shrimp harvests to natural log transformed winter (Q_1), summer (Q_3), autumn (Q_4), and one-year antecedent annual (Q_6) freshwater inflows to the estuary from all contributing river and coastal drainage basins (FINC).

The effects of each correlating inflow on the estimate of harvest are computed similar to previous examples, however, illustrations of the effects are graphed in non-transformed units to show the curvilinearity of harvest responses (Figure 8-3). The estimate of harvest increases 4.2 times (from about 0.4 to 1.6 million pounds annually) as January-March (Q_1) inflow increases over the observed range of 50.3 to 405.0 thousand acre-feet per month (Panel A, Figure 8-3). A weakly negative response to July-August (Q_3) inflow results in the estimate of annual harvest declining 38.9 percent (Panel B, Figure 8-3), while increasing September-October (Q_4) inflow increases the estimate of annual harvest 2.8 times its minimum value (Panel C, Figure 8-3). The response to increasing one-year antecedent annual inflow (Q_6) is negative and the estimate of annual harvest declines 60.6 percent (Panel D, Figure 8-3). Consequently, maximization of white shrimp harvest is statistically related to increasing winter (Q_1) and autumn (Q_4) inflows and decreasing summer (Q_3) and annual (Q_6) inflows to the estuary from all contributing river and coastal drainage basins.

Brown and Pink Shrimp

Analysis of the brown and pink shrimp fisheries component yields two highly significant equations (Table 8-8). The best significant equation (first equation, Table 8-8) accounts for 62 percent of the observed harvest variation and is highly significant (α = 0.5%) for correlation of inshore brown and pink shrimp harvests to summer (Q_3) and autumn (Q_4) inflows at Guadalupe delta (FINGD). Responses to both seasonal inflows are positive, and increasing July-August (Q_3) and September-October (Q_4) inflows to the upper bounds of their observed ranges increases the estimates of annual harvest 3.0 and 2.3 times their minimum values, respectively (Panels A and B, Figure 8-4). Therefore, maximization of brown and pink shrimp harvest is statistically related to increasing summer and autumn season inflows at Guadalupe delta. It is noted that the strong, positive harvest response to summer inflow is in apparent conflict with the weak, negative response of white shrimp harvest to summer inflow.

Blue Crab

No statistically significant equations were obtained from analysis of the blue crab fisheries component.

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

Guadalupe Estuary White Shrimp Harvest = f (seasonal FINGD b/)
Highly Significant Natural Log Equation (α = 1.0%, r^2 = 72%, S.E.Est. = ± 0.2692

$$\ln H_{ws} = 4.9531 + \underset{(0.1504)}{0.6809 (\ln Q_1)} - \underset{(0.1334)}{0.1299 (\ln Q_3)} + \underset{(0.0957)}{0.2328 (\ln Q_4)}$$

$$- \underset{(0.1422)}{0.4335 (\ln Q_6)}$$

	$\ln H_{ws}$	$\ln Q_1$	$\ln Q_3$	$\ln Q_4$	$\ln Q_6$
upper bounds	7.2549	5.9822	6.1192	7.1709	6.0169
lower bounds	5.8836	3.9180	2.9957	3.2189	3.8089
mean	6.6526	4.8990	4.5519	5.0939	5.1457

Guadalupe Estuary White Shrimp Harvest = f (seasonal FINC c/)
Highly Significant Natural Log Equation (α = 1.0%, r^2 = 74%, S.E.Est. = ± 0.2618)

$$\ln H_{ws} = 4.8394 + \underset{(0.1442)}{0.6889 (\ln Q_1)} - \underset{(0.1325)}{0.1602 (\ln Q_3)} + \underset{(0.0965)}{0.2627 (\ln Q_4)}$$

$$- \underset{(0.1389)}{0.4232 (\ln Q_6)}$$

	$\ln H_{ws}$	$\ln Q_1$	$\ln Q_3$	$\ln Q_4$	$\ln Q_6$
upper bounds	7.2549	6.0039	6.1203	7.2127	6.0388
lower bounds	5.8836	3.9180	3.0445	3.2581	3.8395
mean	6.6526	4.9206	4.5935	5.1581	5.1869

---

where:

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

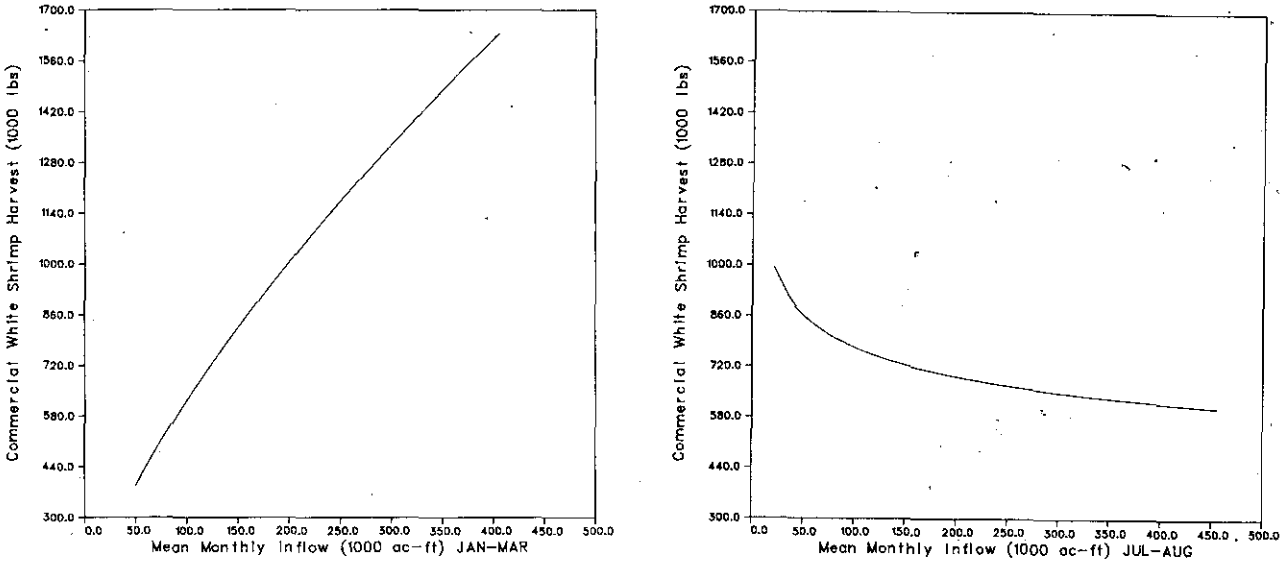
$\ln Q$ = natural log, mean monthly freshwater inflow, in thousands of acre-feet:

Q_1 = January-March
Q_2 = April-June
Q_3 = July-August
Q_4 = September-October
Q_5 = November-December
Q_6 = January-December

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

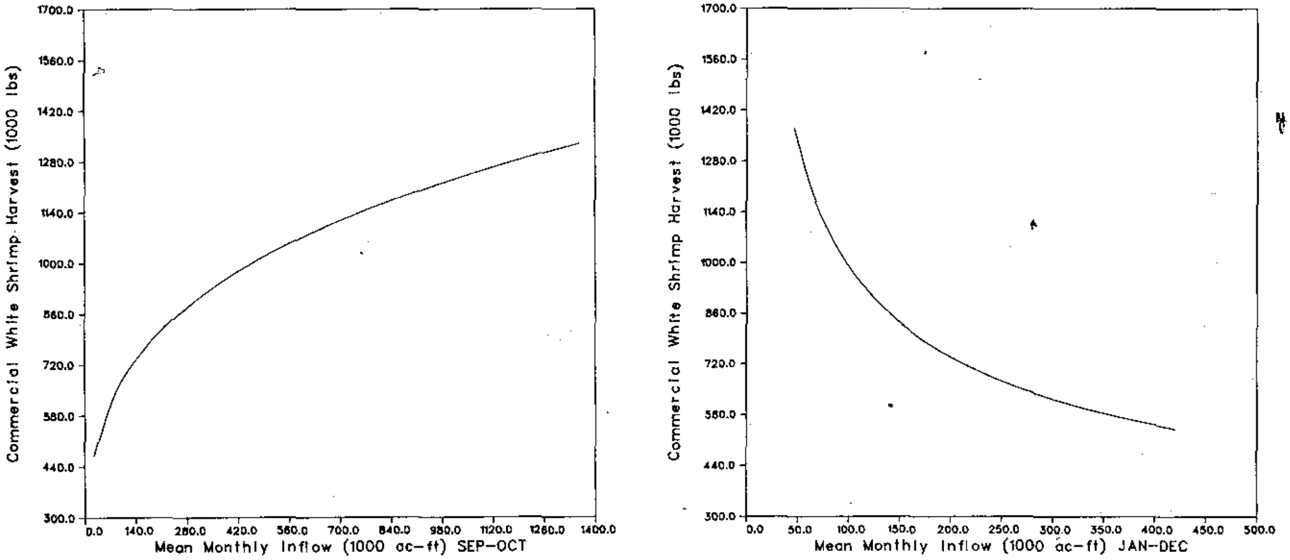
b/ FINGD = freshwater Inflow at Guadalupe Delta

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



A. regression coefficient = +0.6809,
standard error = ±0.1504

B. regression coefficient = −0.1299,
standard error = ±0.1334



C. regression coefficient = +0.2328,
standard error = ±0.0957

D. regression coefficient = +0.4335,
standard error = ±0.1422

Figure 8-3. Inshore Commercial White Shrimp Harvest as a Function of Each Seasonal Inflow From Combined River and Coastal Drainage Basins, Where all Other Seasonal Inflows in the Multiple Regression Equation are Held Constant at Their Mean Values

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

Guadalupe Estuary Brown and Pink Shrimp Harvest = f (seasonal FINGD b/)
Highly Significant Equation ($\alpha = 0.5\%$, $r^2 = 62\%$, S.E.Est. = ± 117.1)

$$H_{bps} = 98.5 + \underset{(0.3)}{0.8}\,(Q_3) + \underset{(0.1)}{0.2}\,(Q_4)$$

	H_{bps}	Q_3	Q_4
upper bounds	654.3	454.5	1301.0
lower bounds	67.1	20.0	25.0
mean	261.1	122.5	277.5

Guadalupe Estuary Brown and Pink Shrimp Harvest = f (seasonal FINC c/)
Highly Significant Equation ($\alpha = 1.0\%$, $r^2 = 60\%$, S.E.Est. = ± 119.4)

$$H_{bps} = 97.7 + \underset{(0.3)}{0.8}\,(Q_3) + \underset{(0.1)}{0.2}\,(Q_4$$

	H_{bps}	Q_3	Q_4
upper bounds	654.3	455.0	1356.5
lower bounds	67.1	21.0	26.0
mean	261.1	127.4	293.5

---

where

H_{bps} = inshore commercial brown and pink shrimp harvest, in thousands of pounds;

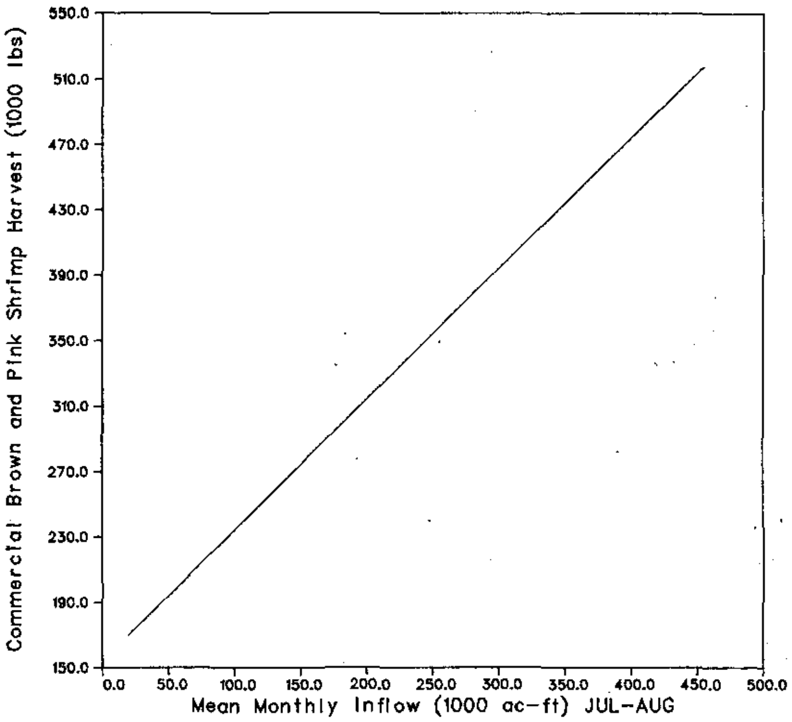
Q = mean monthly freshwater inflow, in thousands of acre-feet:

Q_1 = January-March
Q_2 = April-June
Q_3 = July-August
Q_4 = September-October
Q_5 = November-December
Q_6 = January-December

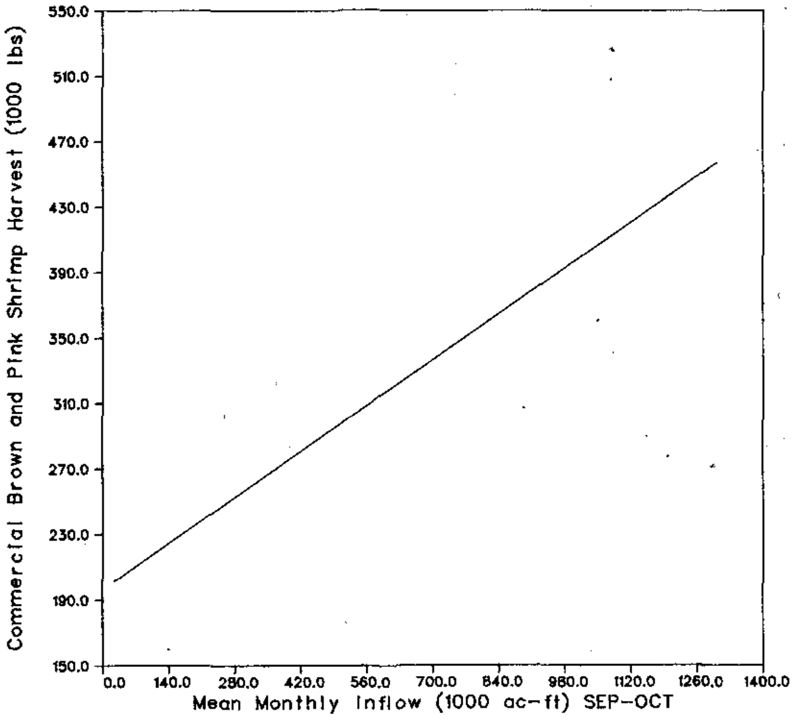
a/ Standard error of each regression coefficient is shown in parentheses beneath the coefficients of the regression equations

b/ FINGD = freshwater inflow at Guadalupe Delta

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



A. regression coefficient (slope) = +0.8, standard error = ±0.3,



B. regression coefficient (slope) = +0.2, standard error = ±0.1

Figure 8-4. Inshore Commercial Brown and Pink Shrimp Harvest as a Function of Each Seasonal Inflow at Guadalupe Delta, Where all Other Seasonal Inflow in the Multiple Regression Equation are Held Constant at Their Mean Values

Bay Oyster

No statistically significant equations were obtained from analysis of the bay oyster fisheries component.

Finfish

Analysis of the multi-species finfish component also involves logarithmic transformation of the regression variables to natural logarithms (ln) and results in two very highly significant equations (Table 8-9). The best significant equation (first equation, Table 8-9) explains 88 percent of the observed harvest variation and is very highly significant (α = 0.1%) for correlation of inshore finfish harvests to all seasonal inflows (Q_1 through Q_5) at Guadalupe delta (FINGD). The curvilinear effects of each of the correlating seasonal inflows on harvest are negative for increasing January-March (Q_1) inflow (Panel A, Figure 8-5), strongly positive for increasing April-June (Q_2) inflow (Panel B, Figure 8-5), negative for increasing July-August (Q_3) inflow (Panel C, Figure 8-5), negative for increasing September-October (Q_4) inflow (Panel D, Figure 8-5), and strongly positive for increasing November-December (Q_5) inflow (Panel E, Figure 8-5). In particular, the estimate of annual harvest increases about 8.6 times (from 50.0 to 430.0 thousand pounds) as spring season (Q_2) inflow increases over the observed range of 65.6 to 389.1 thousand acre-feet per month. Taken together, the results indicate that maximization of inshore commercial finfish harvest is statistically related to increasing spring and late fall season inflows, while diminishing winter, summer, and autumn season inflows at Guadalupe delta. However, all three shrimp components previously analyzed exhibit positive responses to autumn inflow, and additional conflicts are noted with winter and summer season inflows.

Spotted Seatrout

Analysis of the spotted seatrout fisheries component yields two very highly significant equations (Table 8-10) following natural log transformation of the regression variables. The best significant equation (first equation, Table 8-10) explains 93 percent of the observed harvest variation and is very highly significant (α = 0.1%) for correlation of inshore commercial spotted seatrout harvests to all seasonal inflows (Q_1 through Q_5) at Guadalupe delta (FINGD).

The curvilinear effects on harvest of each of the correlating seasonal inflows in the best significant equation are negative for increasing January-March (Q_1) inflow (Panel A, Figure 8-6), strongly positive for increasing April-June (Q_2) inflow (Panel B, Figure 8-6), strongly negative for increasing July-August (Q_3) inflow (Panel C, Figure 8-6), negative for increasing September-October (Q_4) inflow (Panel D, Figure 8-6), and positive for increasing November-December (Q_5) inflow (Panel E, Figure 8-6). Similar to results from the finfish component, the greatest effect on spotted seatrout harvest is from increasing spring season inflow. Here, the estimate of harvest increases about 210 times its minimum value (from 1.4 to 294.1 thousand pounds annually) as April-June inflow increases 5.9 times over the observed range of 65.6 to 389.1 thousand acre-feet per month. In addition, the estimate of annual harvest experiences a severe decline of 97 percent (from 355.2

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

Guadalupe Estuary Finfish Harvest = f (seasonal FINGD b/)
Very Highly Significant Natural Log Equation ($\alpha = 0.1\%$, $r^2 = 88\%$, S.E.Est. = ± 0.2201)

$$\ln H_{ff} = \underset{}{-0.3223} - \underset{(0.2370)}{0.4839} (\ln Q_1) + \underset{(0.2669)}{1.2087} (\ln Q_2) - \underset{(0.2636)}{0.3126} (\ln Q_3)$$

$$-\underset{(0.1375)}{0.6352} (\ln Q_4) + \underset{(0.3623)}{1.2937} (\ln Q_5)$$

	$\ln H_{ff}$	$\ln Q_1$	$\ln Q_2$	$\ln Q_3$	$\ln Q_4$	$\ln Q_5$
upper bounds	6.0931	5.6211	5.9639	5.5810	6.2577	5.5728
lower bounds	4.3745	4.3290	4.1831	3.6109	4.1769	4.2743
mean	5.3574	5.0744	5.3791	4.7064	5.4177	5.0595

Guadalupe Estuary Finfish Harvest = f (seasonal FINC c/)
Very Highly Significant Natural Log Equation ($\alpha = 0.1\%$, $r^2 = 88\%$, S.E.Est. = ± 0.2208)

$$\ln H_{ff} = -0.3477 - \underset{(0.2394)}{0.4911} (\ln Q_1) + \underset{(0.2679)}{1.2381} (\ln Q_2) - \underset{(0.2654)}{0.3001} (\ln Q_3)$$

$$-\underset{(0.1361)}{0.6419} (\ln Q_4) + \underset{(0.3526)}{1.2625} (\ln Q_5)$$

	$\ln H_{ff}$	$\ln Q_1$	$\ln Q_2$	$\ln Q_3$	$\ln Q_4$	$\ln Q_5$
upper bounds	6.0931	5.6438	5.9928	5.5929	6.2980	5.6240
lower bounds	4.3745	4.3550	4.2210	3.6376	4.2244	4.3329
mean	5.3574	5.1048	5.4202	4.7373	5.4799	5.1014

where:

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

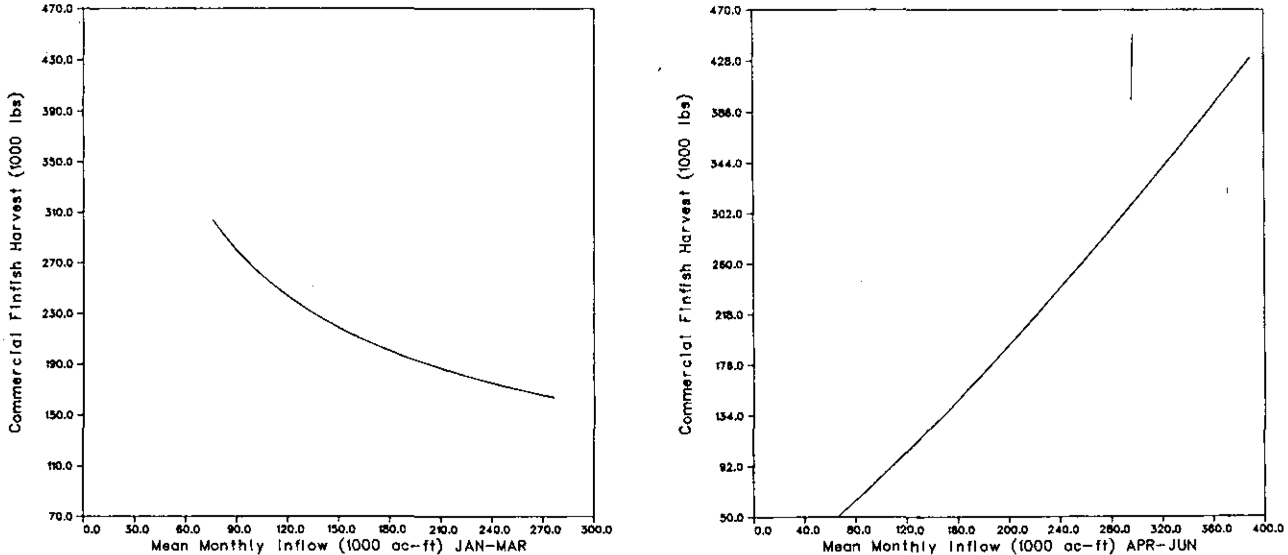
$\ln Q$ = natural log, mean monthly freshwater inflow, in thousands of acre-feet:

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

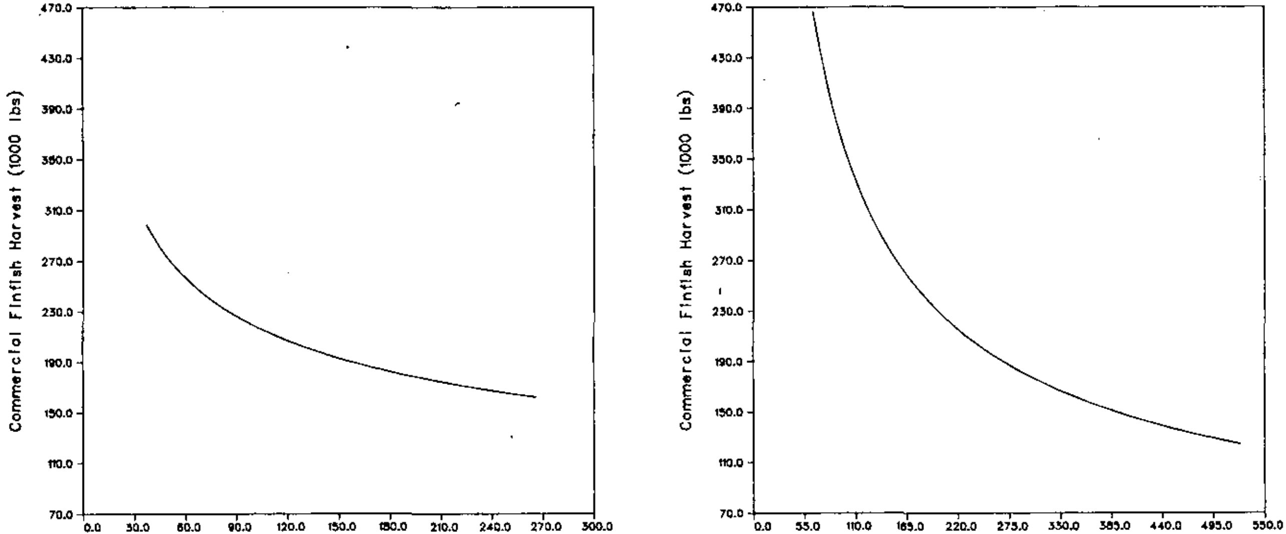
b/ FINGD = freshwater inflow at Guadalupe Delta

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



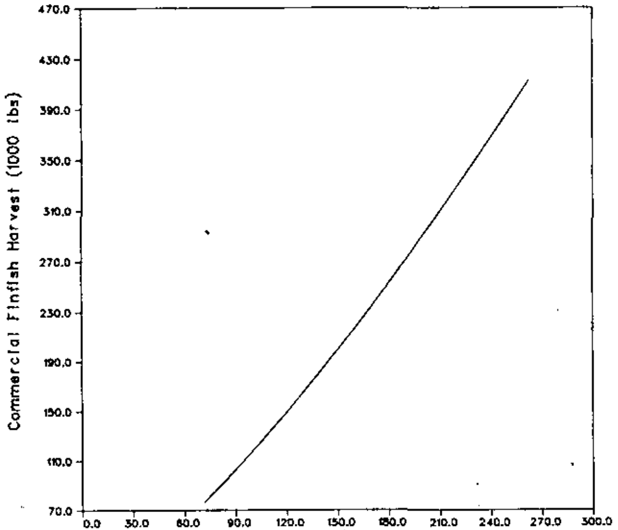
A. regression coefficient =-0.4839,
standard error = ±0.2370

B. regression coefficient = +1.2087,
standard error = ±0.2669



C. regression coefficient =-0.3126,
standard error = ±0.2636

D. regression coefficient =-0.6352,
standard error = ±0.1375



E. regression coefficient = +1.2937,
standard error = ±0.3623

Figure 8-5. Inshore Commercial Finfish Harvest as a Function of Each Seasonal Inflow at Guadalupe Delta, Where all Other Seasonal Inflows in the Multiple Regression Equation are Held Constant at Their Mean Values

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

Guadalupe Estuary Spotted Seatrout Harvest = f (seasonal FINGD b/)
Very Highly Significant Natural Log Equation (α = 0.1%, r^2 = 93%, S.E.Est. = ± 0.2547)

$$\ln H_{ss} = -4.5501 - \underset{(0.2742)}{1.1015} (\ln Q_1) + \underset{(0.3089)}{2.9982} (\ln Q_2) - \underset{(0.3050)}{1.7728} (\ln Q_3)$$

$$- \underset{(0.1591)}{0.7879} (\ln Q_4) + \underset{(0.4192)}{2.0861} (\ln Q_5)$$

	$\ln H_{ss}$	$\ln Q_1$	$\ln Q_2$	$\ln Q_3$	$\ln Q_4$	$\ln Q_5$
upper bounds	4.7432	5.6211	5.9639	5.5810	6.2577	5.5728
lower bounds	2.5014	4.3290	4.1831	3.6109	4.1769	4.2743
mean	3.9300	5.0744	5.3791	4.7064	5.4177	5.0595

Guadalupe Estuary Spotted Seatrout Harvest = f (seasonal FINC c/)
Very Highly Significant Natural Log Equation (α = 0.1%, r^2 = 92%, S.E.Est. = ± 0.2697)

$$\ln H_{ss} = -4.6657 - \underset{(0.2925)}{1.0928} (\ln Q_1) + \underset{(0.3273)}{2.9924} (\ln Q_2) - \underset{(0.3242)}{1.7614} (\ln Q_3)$$

$$- \underset{(0.1663)}{0.7971} (\ln Q_4) + \underset{(0.4307)}{2.0911} (\ln Q_5)$$

	$\ln H_{ss}$	$\ln Q_1$	$\ln Q_2$	$\ln Q_3$	$\ln Q_4$	$\ln Q_5$
upper bounds	4.7432	5.6438	5.9928	5.5929	6.2980	5.6240
lower bounds	2.5014	4.3550	4.2210	3.6376	4.2244	4.3329
mean	3.9300	5.1048	5.4202	4.7373	5.4799	5.1014

---

where:

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

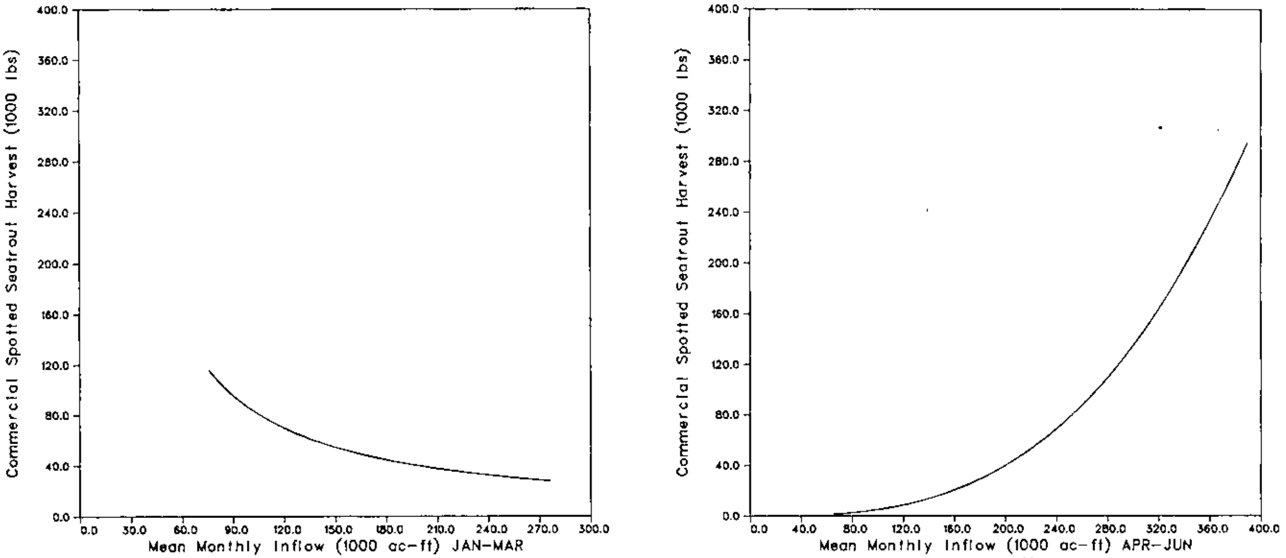
$\ln Q$ = natural log, mean monthly freshwater inflow, in thousands of acre-feet:

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

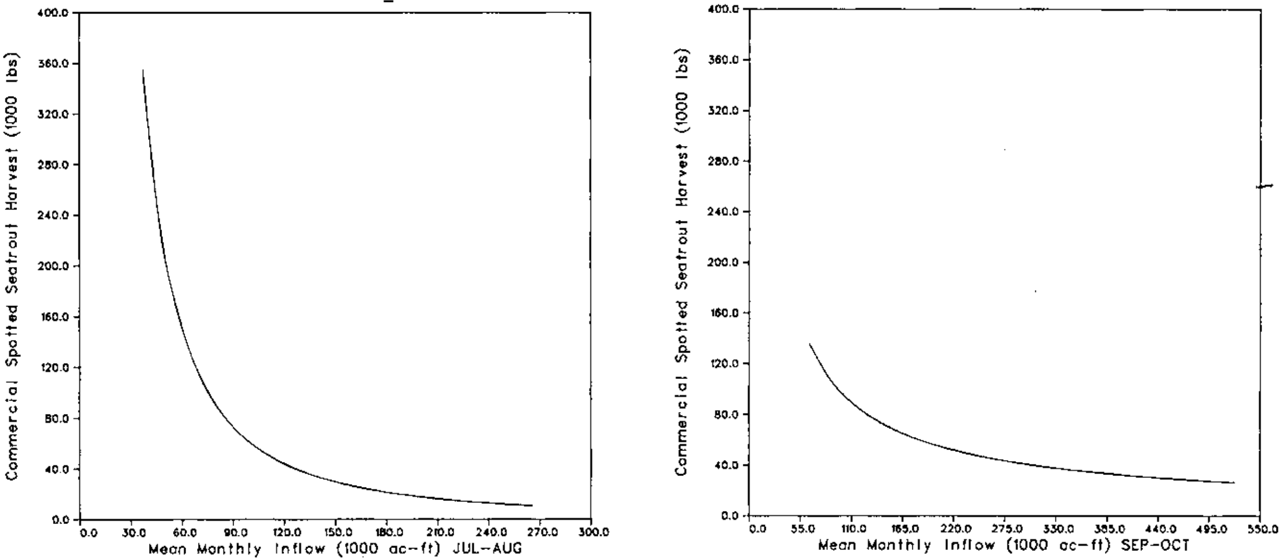
b/ FINGD = freshwater inflow at Guadalupe Delta

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



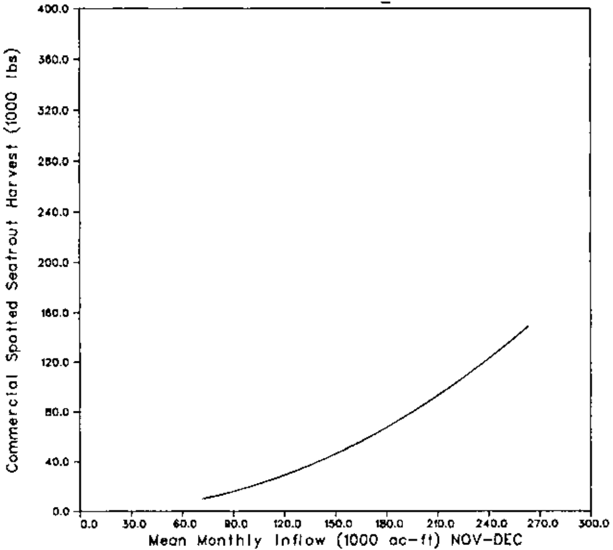
A. regression coefficient = -1.1015, standard error = ±0.2742

B. regression coefficient = +2.9982, standard error = ±0.3089



C. regression coefficient = -1.7728, standard error = ±0.3050

D. regression coefficient = -0.7879, standard error = ±0.1591



E. regression coefficient = +2.0861, standard error = ±0.4192

Figure 8-6. Inshore Commercial Spotted Seatrout Harvest as a Function of Each Seasonal Inflow at Guadalupe Delta, Where all Other Seasonal Inflows in the Multiple Regression Equation are Held Constant at Their Mean Values to 10.8 thousand pounds) as summer (July-August) inflow increases from 37.0 to 265.3 thousand acre-feet per month. Based on the regression model described by the best significant equation, maximization of inshore commercial spotted seatrout harvest is statistically related to increasing spring and late fall season inflows and decreasing winter, summer, and autumn season inflows at Guadalupe delta.

Red Drum

Natural log transformation of the regression variables in the analysis of the red drum fisheries component results in two significant logarithmic equations (Table 8-11). The best significant equation (second equation, Table 8-11) accounts for 77 percent of the observed harvest variation and is highly significant ($\alpha = 1.0\%$) for correlation of inshore red drum harvests to all seasonal inflows (Q_1 through Q_5) to the estuary from all contributing river and coastal drainage basins (FINC).

The curvilinear harvest effects of each of the correlating seasonal inflows in the best significant equation are negative for increasing January-March (Q_1) inflow (Panel A, Figure 8-7), strongly positive for increasing April-June (Q_2) inflow (Panel B, Figure 8-7), negative for increasing July-August (Q_3) inflow (Panel C, Figure 8-7), negative for increasing September-October (Q_4) inflow (Panel D, Figure 8-7), and positive for increasing November-December (Q_5) inflow (Panel E, Figure 8-7). Again, the strong positive effect of spring season inflow is noted with the estimate of harvest increasing 32.5 times (from 6.3 to 204.7 thousand pounds annually) as April-June inflow increases 5.9 times over the observed range of 68.1 to 400.5 thousand acre-feet per month. Similar to the previous analysis of finfish and spotted seatrout components, maximization of inshore red drum harvest is statistically related to increasing spring and late fall season inflows, while diminishing winter, summer, and autumn season inflows to the estuary from all contributing river and coastal drainage basins.

Black Drum

Analysis of the black drum fisheries component also involves natural log transformation of the regression variables and results in two highly significant equations (Table 8-12). The best significant equation (second equation, Table 8-12) explains 76 percent of the observed harvest variation and is highly significant ($\alpha = 0.5\%$) for correlation of inshore black drum harvests to summer (Q_3), autumn (Q_4), and late fall (Q_5) season inflows to the estuary from all contributing river and coastal drainage basins (FINC).

The curvilinear harvest effects of each of the correlating seasonal inflows in the best significant equation are positive for increasing July-August (Q_3) inflow (Panel A, Figure 8-8), strongly negative for increasing September-October (Q_4) inflow (Panel B, Figure 8-8), and positive for increasing November-December (Q_5) inflow (Panel C, Figure 8-8). In particular, the estimate of harvest decreases 84.5 percent (from 149.7 to 23.2 thousand pounds annually) as autumn (September-October) inflow increases over the observed range of 68.3 to 543.5 thousand acre-feet per month. Maximization of inshore black drum harvest is thus statistically related to decreasing autumn season inflow and increasing summer and late fall season inflows to the estuary from all contributing river and coastal drainage basins.

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

Guadalupe Estuary Red Drum Harvest = f (seasonal FINGD b/)
Significant Natural Log Equation ($\alpha = 2.5\%$, $r^2 = 76\%$, S.E.Est. = $\pm$ 0.4061)

$$\ln H_{rd} = -2.2414 \underset{(0.4373)}{- 0.6486} (\ln Q_1) \underset{(0.4925)}{+ 1.8957} (\ln Q_2) \underset{(0.4863)}{- 0.4963} (\ln Q_3)$$

$$\underset{(0.2537)}{-0.5449} (\ln Q_4) \underset{(0.6685)}{+ 0.9527} (\ln Q_5)$$

	$\ln H_{rd}$	$\ln Q_1$	$\ln Q_2$	$\ln Q_3$	$\ln Q_4$	$\ln Q_5$
upper bounds	5.1885	5.6211	5.9639	5.5810	6.2577	5.5728
lower bounds	3.1946	4.3290	4.1831	3.6109	4.1769	4.2743
mean	4.1968	5.0744	5.3791	4.7064	5.4177	5.0595

Guadalupe Estuary Red Drum Harvest = f (seasonal FINC c/)
Highly Significant Natural Log Equation ($\alpha = 1.0\%$, $r^2 = 77\%$, S.E.Est. = $\pm$ 0.3992)

$$\ln H_{rd} = -2.2508 \underset{(0.4328)}{- 0.7121} (\ln Q_1) \underset{(0.4845)}{+ 1.9642} (\ln Q_2) \underset{(0.4798)}{- 0.5185} (\ln Q_3)$$

$$\underset{(0.2461)}{-0.5816} (\ln Q_4) \underset{(0.6375)}{+ 0.9958} (\ln Q_5)$$

	$\ln H_{rd}$	$\ln Q_1$	$\ln Q_2$	$\ln Q_3$	$\ln Q_4$	$\ln Q_5$
upper bounds	5.1885	5.6438	5.9928	5.5929	6.2980	5.6240
lower bounds	3.1946	4.3550	4.2210	3.6376	4.2244	4.3329
mean	4.1968	5.1048	5.4202	4.7373	5.4799	5.1014

---

where:

$\ln H_{rd}$ = natural log, inshore commercial red drum harvest, in thousands of pounds;

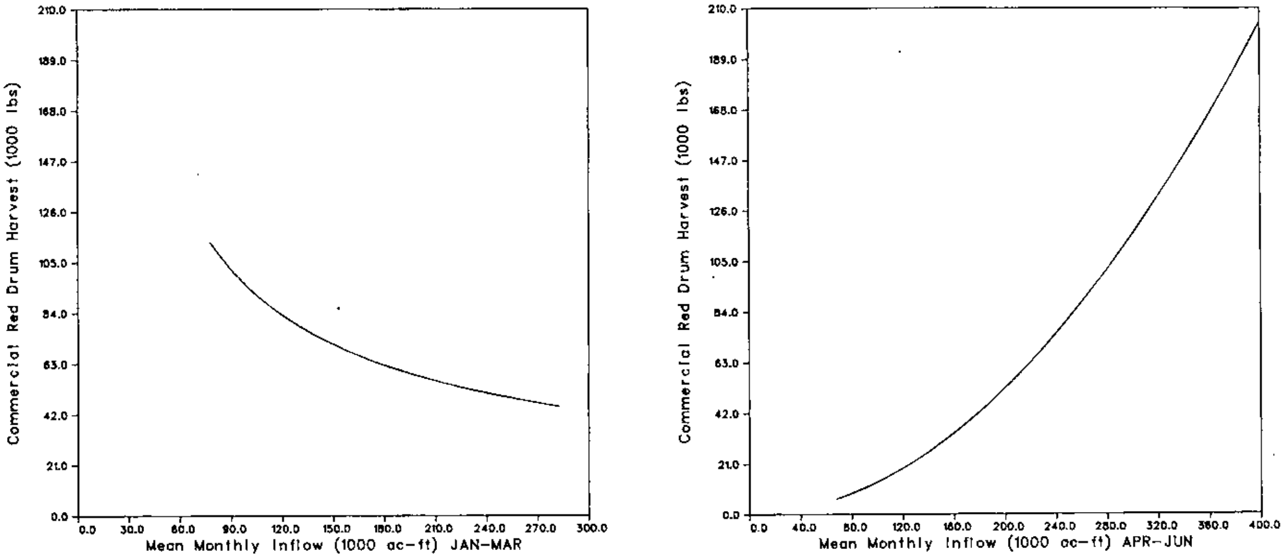
$\ln Q$ = natural log, mean monthly freshwater inflow, in thousands of acre-feet;

Q_1 = January-March
Q_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

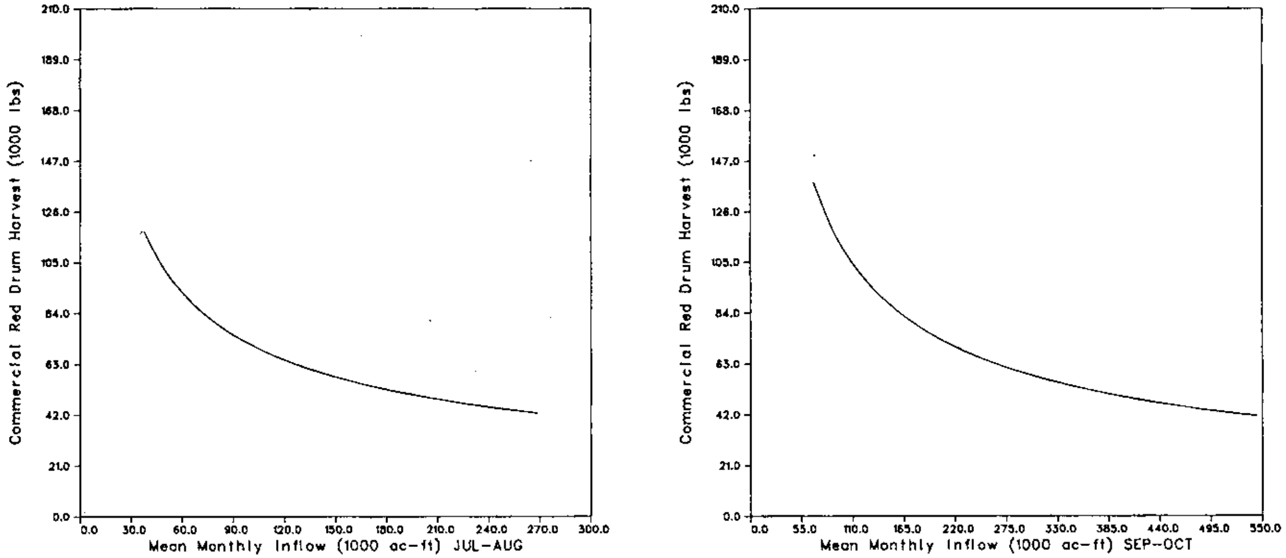
b/ FINGD = freshwater inflow at Guadalupe Delta

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



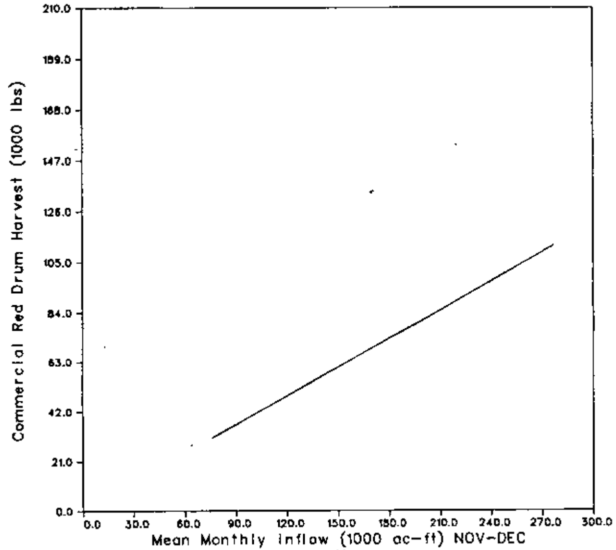
A. regression coefficient =-0.7121, standard error = ±0.4328

B. regression coefficient = +1.9642, standard error = ±0.4845



C. regression coefficient =-0.5185, standard error = ±0.4798

D. regression coefficient =-0.5816, standard error = ±0.2461



E. regression coefficient = +0.9958, standard error = ±0.6375

Figure 8-7. Inshore Commercial Red Drum Harvest as a Function of Each Seasonal Inflow From Combined River and Coastal Drainage Basins, Where all Other Seasonal Inflows in the Multiple Regression Equation are Held Constant at Their Mean Values

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

Guadalupe Estuary Black Drum Harvest = f (seasonal FINGD b/)
Highly Significant Natural Log Equation (α = 0.5%, r^2 = 75%, S.E.Est. = ± 0.4006)

$$\ln H_{bd} = -1.8548 + \underset{(0.3632)}{0.7372 (\ln Q_3)} - \underset{(0.2331)}{0.9250 (\ln Q_4)} + \underset{(0.6361)}{1.4380 (\ln Q_5)}$$

	$\ln H_{bd}$	$\ln Q_3$	$\ln Q_4$	$\ln Q_5$
upper bounds	4.8752	5.5810	6.2577	5.5728
lower bounds	2.6946	3.6109	4.1769	4.2743
mean	3.8788	4.7064	5.4177	5.0595

Guadalupe Estuary Black Drum Harvest = f (seasonal FINC c/)
Highly Significant Natural Log Equation (α = 0.5%, r^2 = 76%, S.E.Est. = ± 0.3984)

$$\ln H_{bd} = -1.6231 + \underset{(0.3679)}{0.8243 (\ln Q_3)} - \underset{(0.2248)}{0.9000 (\ln Q_4)} + \underset{(0.6083)}{1.2798 (\ln Q_5)}$$

	$\ln H_{bd}$	$\ln Q_3$	$\ln Q_4$	$\ln Q_5$
upper bounds	4.8752	5.5929	6.2980	5.6240
lower bounds	2.6946	3.6376	4.2244	4.3329
mean	3.8788	4.7373	5.4799	5.1014

---

where:

$\ln H_{bd}$ = natural log, inshore commercial black drum harvest, in thousands of pounds;

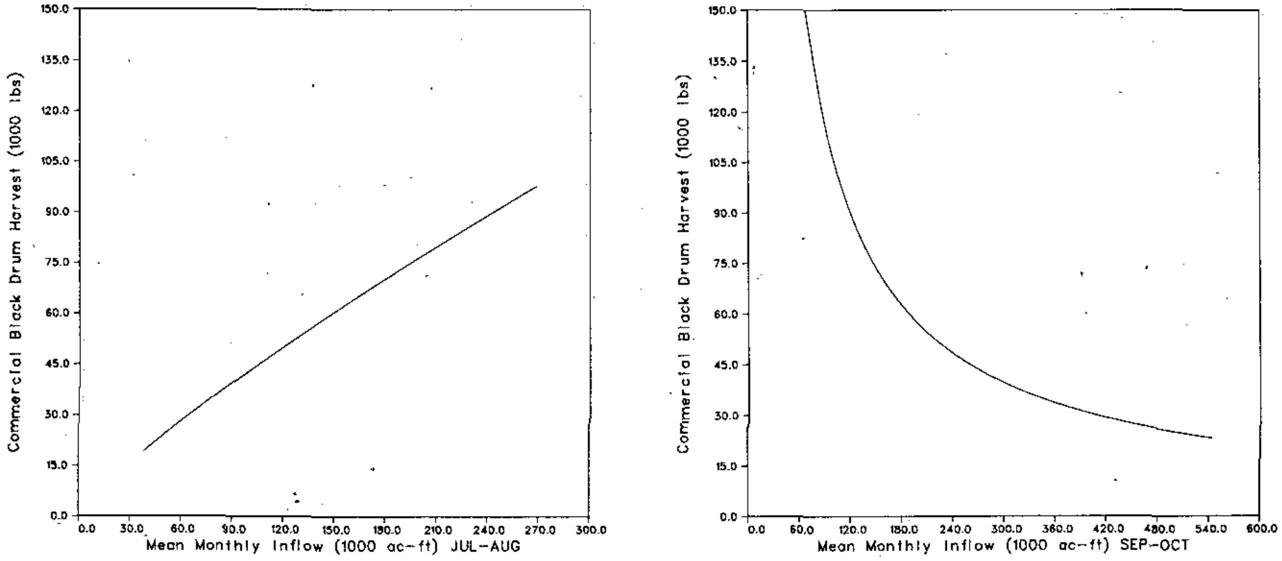
$\ln Q$ = natural log, mean monthly freshwater inflow, in thousands of acre-feet:

Q_1 = 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

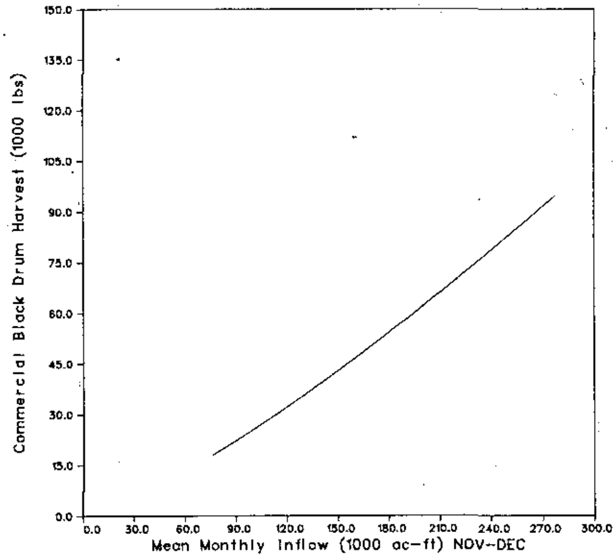
b/ FINGD = freshwater inflow at Guadalupe Delta

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



A. regression coefficient = +0.8243,
standard error = ±0.3679

B. regression coefficient = -0.9000,
standard error = +0.2248



C. regression coefficient = +1.2798,
standard error = ±0.6083

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

Fisheries Component Summary

The fisheries analysis involves ten fisheries components and two freshwater inflow source categories in the analytical design, allowing a maximum 20 potentially significant equations. The analysis results in 16 regression equations of statistical significance and is thus successful for 80 percent of the correlations attempted. Although each of the inflow categories can potentially produce ten significant equations, the analysis yields eight equations with freshwater inflow at Guadalupe delta (FINGD) and also eight equations with combined inflow (FINC) to the estuary from all contributing river and coastal drainage basins. Seasonal inflow needs are similar for fisheries components when the signs (positive or negative) on the regression coefficients in the harvest equations are the same for a season of interest (Table 8-13). Therefore, the seasonal inflow needs of the fisheries components can reinforce each other. However, where seasonal inflow needs are of opposite signs, the fisheries components become competitive in terms of inflow management. Altogether, these results support the hypothesis that seasonal freshwater inflow has a significant impact on the estuary's fisheries, and by ecological implication, on the "health" of the ecosystem.

Freshwater Inflow Effects

Introduction

The hydrologic importance of both tidal inlets and freshwater inflow for ecological preservation of estuaries has been recognized (130, 276). 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 (28, 167, 276, 137, 134, 168). 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 (130, 326), Mississippi, and Louisiana (56).

Perhaps the most direct and most apparent effects of freshwater inflow occur as a result of changes associated with estuarine salinity conditions. In addition, the concentration of salts can interact with other environmental factors to stimulate species-specific biotic responses (4) which may be reflected in physiological adaptation to the estuarine environment (115, 116, 391, 392), in species distribution patterns and community diversity (85, 75, 61, 87, 24, 121), and ultimately in species evolution (112). Previous research emphasizing Texas estuarine-dependent species has dealt with several aspects of the inflow/salinity relationship including environmental limits (309), tolerance to hypersaline waters (79, 95, 7), and rapid recovery of typical estuarine community species at the end of a severe drought (104). In addition, salinity changes resulting from man's development of the estuary and its contributing river and coastal drainage basins have been reviewed relevant to many Texas estuarine-dependent species (83, 343), and their diseases and symbionts (170).

While plants provide the estuary's primary production, most secondary production comes from the invertebrate bay fauna. For the invertebrates, inflow/salinity effects have a demonstrated physiological basis (8, 337, 117, 125, 335) and are effective at modifying species distribution (284, 296, 172).

Table 8-13. Positive (+) and Negative (-) Correlation of Fisheries Components to Seasonal Freshwater Inflow Categories

Fisheries Components	Winter Inflow (Jan.-Mar.) Q_1	Spring Inflow (Apr.-Jun.) Q_2	Summer Inflow (Jul.-Aug.) Q_3	Autumn Inflow (Sep.-Oct.) Q_4	Late Fall Inflow (Nov.-Dec.) Q_5	Annual Inflow (Jan.-Dec.) Q_6	Explained Variation r^2 (%)	Significance Level α (%)
Shellfish								
FINGD a/		+			-		43	5.0
FINC b/		+					37	2.5
All Shrimp								
FINGD	+			+		-	63	2.5
FINC	+			+		-	62	2.5
White Shrimp								
FINGD	+		-	+		-	72	1.0
FINC	+		-	+		-	74	1.0
Brown and Pink Shrimp								
FINGD			+	+			62	0.5
FINC			+	+			60	1.0
Finfish								
FINGD	-	+	-	-	+		88	0.1
FINC	-	+	-	-	+		88	0.1
Spotted Seatrout								
FINGD	-	+	-	-	+		93	0.1
FINC	-	+	-	-	+		92	0.1
Red Drum								
FINGD	-	+	-	-	+		76	2.5
FINC	-	+	-	-	+		77	1.0
Black Drum								
FINGD			+	-	+		75	0.5
FINC			+	-	+		76	0.5
Summary:								
FINGD	(+) = 2 (-) = 3	(+) = 4 (-) = 0	(+) = 2 (-) = 4	(+) = 3 (-) = 4	(+) = 4 (-) = 1	(+) = 2 (-) = 0		
FINC	(+) = 2 (-) = 3	(+) = 4 (-) = 0	(+) = 2 (-) = 4	(+) = 3 (-) = 4	(+) = 4 (-) = 0	(+) = 2 (-) = 0		

---

a/ FINGD = freshwater inflow at Guadalupe delta

b/ FINC = freshwater inflow to estuary from all contributing river and coastal drainage basins

The brackish water clam (Rangia cuneata) has been suggested as an indicator of ecological effects associated with salinity changes because of its sensitivity (210); however, the focus of invertebrate management is generally on the economically important mollusc (e.g., oyster) and crustacean (e.g., shrimp and crab) members of the invertebrate group (138).

Shrimp

The Gulf of Mexico shrimp fishery is the most valuable fishery in the United States (67) and the Gulf estuaries play a crucial role in the production of this renewable resource (69, 122). Commercial shrimp species are from the crustacean family Penaeidae. White shrimp (Penaeus setiferus Linnaeus, 1767) and brown shrimp (P. aztecus Ives, 1891) predominate in Texas harvests, although the pink shrimp (P. duorarum Burkenroad, 1939) also occurs in small numbers. Synopses of species life history and biological information are available for the white shrimp (129), brown shrimp (26), pink shrimp (30), and for all species in the genus Penaeus (382). Other information especially important for management of this fisheries resource comes from research on shrimp spawning and early larval stages (348, 301, 317, 380), seasonal migration behavior (339, 29, 251), utilization of estuarine nursery habitats (75), and major environmental factors influencing species population dynamics and production (212, 89, 144, 143, 32, 133). Species-specific response to inflow/salinity conditions in the estuary are fundamentally physiological (5, 12, 219, 216, 124, 345), and therefore directly influence not only growth and survival of the postlarval shrimp (407, 408, 406, 390), but the distribution of the bay shrimp populationns as well (307, 86, 287).

Results of the fisheries analysis (i.e., shellfish, all penaeid shrimp, white shrimp, and brown and pink shrimp fisheries components) support the importance of freshwater inflow to shrimp production and provide quantified data on the responses of commercial inshore harvests from the Guadalupe estuary to seasonal fluctuations of the two analyzed inflow categories (i.e., FINGD and FINC). In general, the associated harvest responses are positive for winter (January-March), spring (April-June), and autumn (September-October) season inflows and negative for late fall (November-December) and one-year antecedent annual (January-December) inflows. In addition, white shrimp relate weakly negative to summer (July-August) inflow, while brown and pink shrimp relate strongly positive to inflow in the same season.

Blue Crab

Another major crustacean fishery species is the estuarine-dependent blue crab (Callinectes sapidus Rathbun, 1896). Previous research has described blue crab taxonomy (244, 285), life history (350, 243), migration behavior (291, 105, 251), and responses to environmental factors such as salinity (191, 31, 213, 123) and storm water runoff (127). Although analysis of the blue crab fisheries component did not produce any statistically significant harvest equations, the life history and migrational information indicates that young crabs are most abundant in the low salinity estuarine "nursery" areas from summer through fall. Therefore, it is probable that adequate freshwater inflow during this interval is most important to good growth and survival of the blue crab stocks.

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 (375, 395), as well as geographic variation of its populations (193). The effects of inflow/salinity are particularly important and have stimulated considerable research covering a wide range of subjects including effects on oyster distribution (303, 142, 43), gametogenesis (development of viable eggs and sperm) and spawning (349, 13, 132, 185), eggs and larvae (6, 40, 376, 379, 97), respiration (310, 389), free amino acids which are protein building blocks (146), the effects on oyster reef growth and mortality (77, 292), abundance of faunal associates (77, 399) and reef diseases (218, 170).

Previous studies have described the Texas oyster fishery (252) and the State's major oyster producing areas (383, 258). Numerous oyster reefs have been recently inventoried in the Guadalupe estuary with most located in mid to upper San Antonio Bay areas (363). Classified "polluted areas" are closed to harvest by the Texas Department of Health under authority of Section 76.202, Parks and Wildlife Code, until such time as sampling indicates a return of healthy estuarine conditions. Currently, the areas closed include Mission Lake, Hynes Bay, Guadalupe Bay, and the bay area near Seadrift, Texas. During the 1972 through 1976 period, oyster harvest from the Guadalupe estuary has averaged 225,700 pounds (102,400 kg) annually, accounting for about 8.6 percent of the average annual Texas oyster harvest at this time. By comparison, the Lavaca-Tres Palacios estuary contributed 8.7 percent and the Trinity-San Jacinto estuary contributed 81.8 percent of the average annual oyster harvest in Texas during the same period.

Extreme high or low inflow can drastically affect oyster mortality, especially when the duration of unfavorable conditions persists for several months. Although severe flooding in the spring (April-June) and autumn (September-October) seasons have been responsible for much oyster mortality in the upper portion of the Guadalupe estuary, dredging operations are also cited as a major environmental factor affecting the estuary's oyster production and the loss of many formerly productive reefs (245, 2). Analysis of the bay oyster fisheries component did not produce any statistically significant harvest equations; however, similar anlaysis of oyster harvest from adjacent estuaries (i.e, Lavaca-Tres Palacios and Mission-Aransas estuaries) indicates a positive relationship to late fall (November-December) and winter (January-March) season inflows and a negative response to increased summer (July-August) season inflow.

Finfish

Estuaries play a vital functional role in the life cycle and production of most coastal fish species (347, 109, 136, 247, 106). Environmental sensitivity of the estuarine-dependent fishes has allowed the use of species diversity indices as indicators of pollution (289). Although migration does occur across the boundary between riverine and estuarine habitats by both freshwater and estuarine-dependent marine fishes (166, 182), there is a predominance of young marine fishes found in this low salinity area (78).

In general, seasonal variations in estuarine fish abundance are related to life history and migrational behavior (88, 313, 312, 107, 291, 105, 251, 189, 286, 404, 257). The primary effects of inflow/salinity are physiological (103, 108, 126), and are particularly important for the survival of the early life stages (102), the metabolism (i.e., metabolic stresses) of adult bay populations (306, 308, 315, 280, 394)and juvenile rates of adaptability (281, 282). Low temperature extremes can also interact physiologically with salinity stress to produce dramatic fish mortality (72, 73, 76).

The importance of freshwater inflow to finfish of the Guadalupe estuary is strongly supported by the fisheries analysis. Harvest responses are positive to inflow from spring (April-June) and late fall (November-December) seasons and negative to winter (January-March), summer (July-August), and autumn (September-October) season inflows. However, this freshwater inflow regime appears to conflict with shrimp fisheries harvests which exhibit positive responses to winter and autumn season inflows.

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 (347, 217, 106). 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 (378). The greater restriction and estuarine-dependence of this species are reflected in its nearly exclusive utilization of estuarine habitats (68, 207, 62) and the increased genetic differences among populations in separate bays (398). Previous research has described spotted seatrout life history and seasonal abundance in Texas waters (351, 313, 238, 239, 312, 107, 105, 251), 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 (279, 280, 304, 394, 281, 282).

Analysis of spotted seatrout harvests in the Guadalupe estuary indicates a positive seasonal response to spring (April-June) and late fall (November-December) inflows and negative responses to inflows during winter (January-March), summer (July-August), and autumn (September-October) seasons. Results of the fisheries analysis strongly support the importance of seasonal freshwater inflow to production and harvest of the spotted seatrout.

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 (351, 313, 238, 239, 148, 314, 312, 107, 405, 251, 106, 105, 169). 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 (280, 394, 281, 282). Similar to results from the finfish and spotted seatrout fisheries components, analysis of the red drum component also shows that Guadalupe estuary harvests are positively related to increasing spring (April-June) and late fall (November-December) season inflows and negatively related to increasing winter (January-March), summer (July-August), and autumn (September-October) season inflows.

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 (313, 106, 251, 351, 314, 312, 347). In addition, the effects of inflow/salinity on the metabolism (i.e., metabolic stresses) of the species have been investigated at salt concentration varies from an optimum of about 20-25 ppt salinity (280, 394). The seasonal importance of freshwater inflow to the species' production and harvest are demonstrated by the fisheries analysis. Results indicate positive harvest responses to summer (July-August) and late fall (November-December) season inflows and a negative response to inflow during the autumn (September-October) season. The positive response to summer inflow is unique among fish species analyzed since the finfish, spotted seatrout, and red drum fisheries components all exhibit negative responses to increased summer inflow. This may be due to the summer presence of juvenile black drum in brackish estuarine "nursery" areas following the peak spawning period of February to May (313, 351, 314).

Harvest Response to Long- and Short-Term Inflow

The fisheries analysis spans the recent 1962 through 1976 short-term interval where more complete and compatible fisheries data exist; however, long-term inflow data are available for the estuary from 1941 to 1976 (see Chapter IV). Average (arithmetic mean) inflow conditions are computed and a frequency analysis (i.e., Log-Pearson Type III) of the long-term inflow data can yield information about the exceedance frequencies of seasonal inflow to the estuary, including the frequency (percent) at which short-term average (arithmetic and geometric mean) inflow conditions were exceeded in the long-term record (Table 8-14). Exceedance frequencies of the short-term seasonal inflows are all below the 50 percent frequency level and vary from 43 percent (spring, FINGD) to 28 percent (autumn, FINC). Since lower exceedance frequencies indicate higher inflow, the short-term inflows are indicated as comparatively "wetter" than the long-term temporal median inflows.

Although the central seasonal tendencies of the short-term record are given as average inflow conditions, the long-term central tendencies are expressed by both average inflow conditions and the 50 percent exceedance frequency inflows which reflect the temporal median inflows to the estuary from the freshwater source categories (92). When short-term and long-term average inflow conditions, as well as the long-term 50 percent frequency inflow conditions, are used separately as input to the previously developed fisheries regression equations, predicted harvest responses can be computed for comparison (Table 8-15). There are eight positive and eight negative harvest responses to long-term mean inflows, and two positive and 14 negative harvest responses to the 50 percent exceedance frequency inflows, for a total

Table 8-14. Comparison of Short-Term and Long-Term Seasonal Inflow, Including Inflow Exceedance Frequencies

Freshwater Inflow Category and Season	Short-Term Mean Seasonal Inflow a/ With Long-Term Exceedance Frequencies						Long-Term Seasonal Inflow b/			
	D_s		D_{s-1}		D_f					
	Inflow	(EF%) c/	Inflow	(EF%)	Inflow	(EF%)	Mean Inflow	10% EF Inflow	50% EF Inflow	90% EF Inflow
FINGD, Guadalupe Delta Inflow										
Q_1 (Jan. - March)	480.4	(36)	526.9	(32)	479.6	(36)	457	930	360	72
Q_2 (April - June)	797.3	(34)	753.7	(36)	650.5	(43)	704	1,500	540	75
Q_3 (July - Aug.)	254.5	(35)	256.9	(35)	221.3	(41)	240	510	170	18
Q_4 (Sept. - Oct.)	540.2	(27)	525.9	(28)	450.7	(36)	472	1,080	280	46
Q_5 (Nov. - Dec.)	314.5	(35)	314.5	(35)	315.0	(35)	301	620	210	36
Total	2,386.9		2,377.9		2,117.1		2,174	4,640	1,560	247
FINC, Combined Drainage Inflow										
Q_1 (Jan. - March)	490.7	(37)	540.5	(32)	494.4	(37)	468	948	363	75
Q_2 (April - June)	824.8	(33)	782.9	(36)	677.8	(42)	726	1,560	561	81
Q_3 (July - Aug.)	264.3	(36)	263.1	(36)	228.3	(42)	254	550	180	20
Q_4 (Sept. - Oct.)	570.8	(28)	557.5	(28)	479.6	(34)	498	1,100	310	54
Q_5 (Nov. - Dec.)	327.9	(34)	327.9	(34)	328.5	(34)	313	680	220	38
Total	2,478.5		2,471.9		2,208.6		2,259	4,838	1,634	268

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

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

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

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

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

c/ Long-term exceedance frequencies, in percent, of the short-term mean seasonal inflows.

Table 8-15. Estimated Average Inshore Harvest Responses from Fisheries Component Equations Using Short-Term Mean Inflow, Long-Term Mean Inflow and Long-Term 50 Percent Exceedance Frequency Inflow.

	Guadalupe Delta Inflow FINGD a/					Combined Inflow FINC b/				
Fisheries Component	Short-Term: Mean Inflow: Harvest d/	Long-Term Mean-Inflow Harvest	(Shift) e/	Long-Term 50%EF c/ Inflow Harvest	(Shift)	Short-Term Mean Inflow: Harvest	Long-Term Mean Inflow Harvest	(Shift)	Long-Term 50% EF Inflow Harvest	(Shift)
Shellfish	2,162.1	2,096.5	(-3.0)	2,034.4	(-5.9)	2,162.1	2,089.9	(-3.3)	1,990.9	(-7.9)
All Shrimp	1,075.6	1,107.3	(+2.9)	1,047.9	(-2.6)	1,075.6	1,103.0	(+2.6)	1,034.2	(-3.9)
White Shrimp	774.8	872.6	(+12.6)	793.3	(+2.4)	774.8	875.7	(+13.0)	786.6	(+1.5)
Brown & Pink Shrimp	261.1	241.7	(-7.4)	194.5	(-25.5)	261.1	249.1	(-4.6)	200.7	(-23.1)
Finfish	212.2	213.2	(+0.5)	169.2	(-20.3)	212.2	211.1	(-0.5)	167.9	(-20.9)
Spotted Seatrout	50.9	51.7	(+1.6)	39.9	(-21.6)	50.9	48.3	(-5.1)	37.7	(-25.9)
Red Drum	66.5	71.5	(+7.5)	56.5	(-15.0)	66.5	69.8	(+5.0)	55.9	(-15.9)
Black Drum	48.4	46.1	(-4.8)	34.5	(-28.7)	48.4	48.0	(-0.8)	35.3	(-27.1)

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a/ Freshwater inflow at Guadalupe Delta

b/ Combined freshwater inflow from all contributing river and coastal drainage basins

c/ EF = exceedance frequency

d/ Average inshore harvest, in thousands of pounds

e/ Shift in percent increase (+) or decrease (-) of harvest of 32 computed harvest responses (10 positive, 22 negative). The harvest responses are variable among the fisheries components and range from an estimated +13.0 percent shift in white shrimp harvest to an estimated -28.7 percent shift in black drum harvest, when compared to the harvest levels resulting from the observed short-term record. The results reflect not only differences in inflow quantity, but also differences in the seasonal distributions of inflow from the freshwater source categories. In addition, they suggest that fisheries harvests based on the long-term inflows would be somewhat lower overall than those resulting from the "wetter" 15-year experience of the recent short-term record unless management policies favored the specific seasonal inflow needs of preferred fisheries components. In actuality, it is difficult and in many cases impossible to maximize the harvests from more than one fisheries component at the same time because of competitive seasonal inflow needs among the species. Nevertheless, management scenarios for inflow can be developed that predict good harvest levels from several of the fisheries components simultaneously (see Chapter IX).

Summary

Virtually all of the Gulf fisheries species are estuarine-dependent. Commercial inshore harvests from bays of the Guadalupe estuary rank third in shellfish and sixth in finfish of eight major Texas estuarine areas. In addition, the sport or recreational finfish harvest is approximately equal to the commercial finfish harvest in the estuary. For the 1972 through 1976 interval, the average annual sport and commercial harvest of fish and shellfish dependent upon the estuary inshore and offshore components is estimated at 13.4 million pounds (6.1 million kg).

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

A time series analysis of the 1962 through 1976 commercial bay fisheries landings was successful for 80 percent of the correlations attempted between the harvests and the seasonal freshwater inflows to the Guadalupe estuary. The analysis of harvest as a function of the seasonal inflows results in 16 statistically significant regression equations. These equational models provide numerical estimates of the effects of variable seasonal inflows, contributed from the major freshwater sources, on the commercial harvests of seafood organisms from the estuary. The analysis also supports existing scientific information on the seasonal importance of freshwater inflow to the estuary. All harvest responses to spring (April-June) inflow are estimated to be positive for increased inflow in this season. In addition, harvest responses to late fall (November-December) inflow are all positive, except for the weakly negative response of the shellfish component. The harvest responses to winter (January-March) and autumn (September-October) inflows are split between shrimp and fish components, with shrimp relating positively and fish relating negatively to inflow in these seasons. Increased summer (July-August) inflow relates negatively to all fisheries components, except for black drum and brown and pink shrimp which exhibit positive correlations to summer inflow.

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

CHAPTER IX

ESTIMATED FRESHWATER INFLOW NEEDS

Introduction

In previous chapters, the various physical, chemical and biological factors affecting the Guadalupe 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.

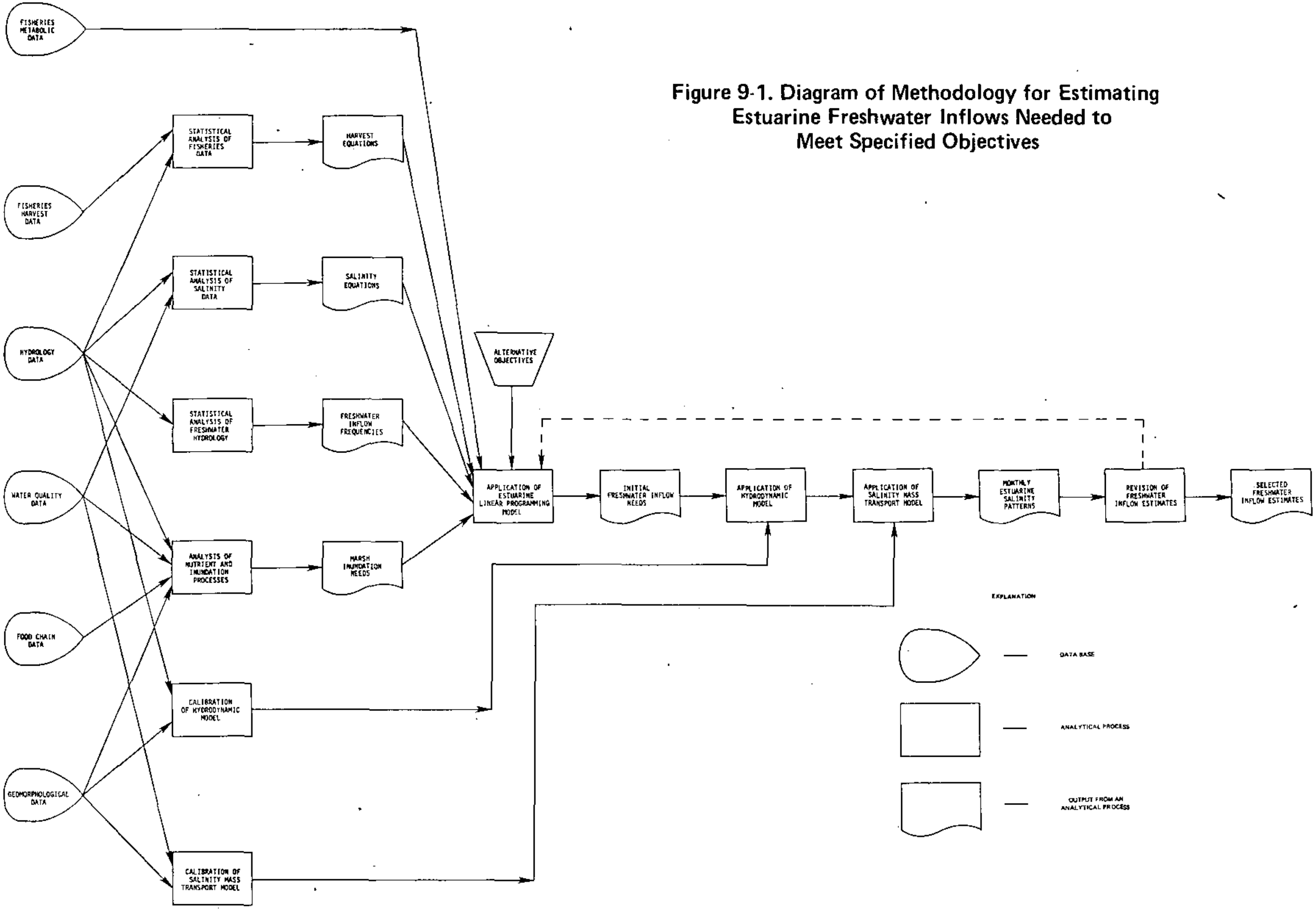
The methodology presented here incorporates major interacting elements described in previous chapters (Figure 9-1). The methodology includes the use of data bases and certain analytical processes described herein. Data for these analyses include six groups: (1) metabolic data for finfish and shellfish,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

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

Application of the Methodology to Compute Estimates of Freshwater Inflow Levels Needed to Meet Selected Objectives

The schematic indicated in Figure 9-1 shows the sequence of steps utilized in computing the freshwater inflow needs to achieve specified objectives as expressed in terms of salinity, marsh inundation, and productivity. The six data bases developed for the Guadalupe estuary provide the fundamental information of the system. These data were used in previous sections of the

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



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

The data bases and analytical processes utilized in this chapter have been described in detail in previous chapters (Figure 9-1). Only the procedures necessary to establish salinity bounds, estimate marsh inundation needs, and apply the Estuarine Linear Programming Model are presented in this chapter.

Salinity Bounds for Fish and Shellfish Species

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

Specific information on salinity limits, preferences and/or optima for selected fisheries species has been tabulated from the scientific literature and TDWR research data (Table 9-1). The optimum condition for most of these species lies between 25 percent and 75 percent seawater (8.8-26.3 ppt). Young fish and shellfish commonly utilize estuarine "nursery" habitats 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.

Salinity data, when combined with life cycle information, were to be 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 in the estuary, below the "null zone"[1/] in upper San Antonio Bay near the Guadalupe River

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[1/] Null Zone: The general area where the net landward flow creates the phenomenon of landward and seaward density currents being equal but opposite in effect. The nullification of net bottom flows in this area allows suspended materials to accumulate and has also been termed the entrapment zone, the critical area, the turbidity maxima, the nutrient trap, and the sediment trap (364, 93).

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

Species	Limits		Preference or Optimum (ppt)	Remarks	Reference
	Min. (ppt)	Max. (ppt)			
			19-30	maximum survival (80% contour plot) in lab of 2-day larvae at 19-30.5°C temperatures	379
			8-30.5	maximum survival (60% contour plot) in lab of 8-day larvae at temperatures > 21°C	379
			>33	maximum growth (100% contour plot) in lab of 8-day larvae at temperatures > 19°C	379
			18-35	optimum (80% contour plot) for both larval survival and growth at temperatures > 30°C	379
			15-22.5	optimum for juvenile growth and development	21
	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	307
			15-30	optimum range of salt content	254
	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)	375
		43.5-45		distribution limit in Redfish and Corpus Christi Bays (Tex.)	294
			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	43
	≤ 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.)	258
			15-30	best growth in reasonably stable salinity	170
	3			lower tolerance limit about 3 ppt	83
	8-10			lower limit of predator Thais haemastoma, a gastropod oyster drill or conch	83 307
	< 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	302
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	207
			> 30	spawning occurs in estuarine areas of higher salinity (La.)	189
		≤ 60	< 45	"young" collected up to about 60 ppt in Laguna Madre (Tex.); no spawning if salinity > 45 ppt	289
		< 55	15-35	absent above 55 ppt in Baffin and Alazan Bays (Tex.); most abundant range 15-35 ppt	288
	2.3	34.9	5-20	field distribution in Copano and Aransas Bays (Tex.); over 80% collected in 5-20 ppt	313
	< 5	77		field distribution in bays and lagoons at northwestern Gulf of Mexico (Tex.)	95
	10	45	20	operational limits; optimum metabolic condition at 20-28°C temperatures	304

Species	Limits		(ppt)	Remarks	Reference
	Min. (ppt)	(ppt)			
Pogonias cromis (black drum)	2.1	32.4	< 15	field distribution in Copano and Aransas Bays (Tex.); greater abundance below 15 ppt	313
	0	> 50	20-40	field distribution (Tex.); range of preference (most abundant in 30-35 ppt); young mature in 3-5 years	314
			< 50	populations in Laguna Madre (Tex.) severely limited by >50 ppt	289
	5-10	40-45	20-25	operational limits; range of optimum metabolic condition at 20-28°C temperatures	280
	2.6	34.9	<15	field distribution in Copano and Aransas Bays (Tex.); most abundant range 10.0-15.0 ppt	313
	<5	77		field distribution in bays and lagoons of northwestern Gulf of Mexico (Tex.)	95
	0	80		field distribution (Tex.); usual range in Laguna Madre 25-50 ppt	314
	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	280

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

Species	Limits		Preference or Optimum (ppt)	Remarks	Reference
	Min. (ppt)	Max. (ppt)			
Penaeus setiferus (white shrimp)	< 2	> 40		range at which 80% of 8-50 mm (postlarvae to juvenile) shrimp survive; 48 hr. acclimation	410
			5-15	increased growth at this range (and >25°C) more than two times tissue production of postlarvae at 25-35 ppt	409
			28.0	median salinity average of postlarval distribution (May-July) in laboratory gradient tanks	216
			21.0	median salinity average of postlarval distribution (Aug.-Nov.) in laboratory gradient tanks	216
		47.96		field collection of small white shrimp (23-76 mm) in Laguna Madre de Tamaulipas (Mexico)	99
	0.42			lower distribution limit in Grand and White Lakes (La.); young shrimp 140 more abundant at 0.7-0.8 ppt	87
			27.6-28.3	isosmotic salinity conditions for shrimp ≥ 100 mm length; osmoregulation below 27.6 ppt better than brown shrimp	154
	1	34	1-20	field distribution in Caminada Bay (La.) and range for 91.1% of juveniles collected	32
	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	307
	2.9	45.3		field distribution in Mesquite Bay (Tex.)	104
	2	45		field distribution in bays and lagoons of northwestern Gulf of Mexico (Tex.)	95
			< 10	preference based on population distributions	86
	0	38		optimum catch over entire salinity range with 20-38°C temperatures	309
Penaeus aztecus (brown shrimp)	2	40		range of equal postlarval growth over 23-25°C temperature; survival 90-100% in laboratory	410
	< 10			marked reduction in postlarval tolerance at low (7-15°C) temperatures to low (5 ppt) salinity	408
			15-35	range of increased postlarval growth at temperatures >25°C; decreased growth below 15 ppt	409
	< 5	> 40		range at which 80% of 10-15 mm postlarvae survive; 12 hr. acclimation	409
			> 15	appeared to enhance survival and growth of postlarvae in Barataria Bay (La.)	200
			> 15	commercial catches poor in years when postlarvae were present in Louisiana bays with < 15 ppt	145
			29.9	median salinity average of postlarval distribution (March-April) in laboratory gradient tank	216
			20.6	median salinity average of postlarval distribution (May-July) in laboratory gradient tank	216
			10.0-19.9	range at which juveniles were more abundant based on population distributions	86
	0.2	30	10-30	field distribution in Caminada Bay (La.) and range for 91.8% of juveniles collected	32
			< 17	preference of juvenile (70 mm) shrimp in laboratory at >26°C temperature	345
			15-25	optimal range for subadult (95 mm) shrimp in laboratory at <25°C temperature	345
			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	390
			27.6-28.3	isosmotic salinity conditions for shrimp > 100 mm length; osmoregulation above 28.3 ppt better than white shrimp	154
	2.1	36.6	15.0-19.9	field distribution in Copano and Aransas Bays (Tex.) and range of greater abundance	307
		69.0		field collection in Laguna Madre (Tex.)	289
	0.8			lower distribution limit in Grand and White Lakes (La.)	87
	0.22			field collection in St. Lucie Estuary (Fla.)	71
	5	70		field distribution in bays and lagoons of northwestern Gulf of Mexico (Tex.)	95
	0.1			field collection (North Carolina)	402
			5	acclimation at low (5 ppt) salinity provides near-optimum resistance to high temperatures and 5-25 ppt salinities in laboratory tests	400
	9	40		no optimum salinity established with 20-35°C temperatures	309
Callinectes sapidus (blue crab)	22.9	32.4	≥ 30.0	range for capture of egg-bearing females near Aransas Pass (Tex.)	307
			23-28	optimum range for hatching of eggs (Virginia)	191
			> 20	occurrence of spawning and early development	243
			< 1.9	peak abundance of juvenile blue crabs in Texas bays (1965)	243
	< 1.0		2-21	lethal limit at optimum (29°C) temperature and range of little effect on juvenile growth and survival	213
	0			observed freshwater populations in Louisiana	84
	2.0	37.2	10.0-20.0	field distribution in Copano and Aransas Bays (Tex.) and range of greater abundance	307
		117		field collection in Laguna Madre de Tamaulipas (Mexico); high salinity briefly tolerated	99
		45		blue crabs observed leaving upper Laguna Madre (Tex.) area as salinity increased	249
	2	60		field distribution in bays and lagoons of northwestern Gulf of Mexico (Tex.)	95
			24.2	salinity for widest thermal tolerance zone in adult blue crab	63
	0	40	0-27	optimum range with 10-35°C temperatures	309
			10-30	range of no effect on metabolic consumption of oxygen (respiration)	123
Crassostrea virginica (American bay oyster)	< 6			gametogenesis inhibited by prolonged low salinity exposure; up to 3-4 months required to regain normal gonadal activity after salinity increases towards the optimum	13
	5-7.5			normal gonadal development near 7.5 ppt; however, oysters with previously ripe gonads spawn when subjected to low (5 ppt) salinities	131
			20-21	larval spat setting requirement in Galveston Bay (Tex.)	349
	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	117

delta. The limits are expressed as mean (average) monthly salinities for general limits of viability. From the indicated location, salinities generally increase toward the Gulf inlets (Brown Cedar Cut and Pass Cavallo via Saluria Bayou) and eventually attain seawater concentration (35 ppt). The salinity gradient 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 cycle to the natural freshwater inflow.

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 severe flood or drought, salinity regimes may be so altered from normal conditions that motile species commonly residing in the estuary may be forced to migrate to other areas where environmental conditions are more suitable. Generally, however, the estuarine-dependent species will remain during normal periodic salinity fluctuations. Should the normal salinity conditions be altered for prolonged periods due to natural or man-made causes, the diversity, distribution and productivity of species within an estuary will be restricted.

The median monthly salinities in Table 9-2 are a measure of the normal monthly salinities of the estuary. The median monthly salinity is that value for which one-half of the observed average monthly salinities exceed the median and one-half are less. The median monthly salinity thus reflects the "expected" salinity in the estuary. Median monthly salinities have been computed for the area in upper San Antonio Bay for which the monthly salinity regression equations were developed (Table 9-2).

Marsh Inundation Needs

The periodic inundation of deltaic marshes serves to maintain shallow protected habitats for postlarval and juvenile stages of several important estuarine species, provides a suitable fluid medium for nutrient exchange processes, and acts as a transport mechanism to move detrital materials (food) from the deltaic marsh into the open estuary. The areal extent of deltaic marsh inundation is a function of the channel capacity, discharge rate and volume, wind direction, and tidal stage.

Historically, the discharge rates of Texas' rivers have fluctuated on a seasonal basis. Monthly freshwater inflows usually peak in the spring and early fall, reflecting the increased rainfall and surface runoff that normally occurs during these months. The cyclic periods of high and low freshwater discharge have influenced the evolution of estuarine dependent organisms,

Table 9-2. Salinity Characteristics of Upper San Antonio Bay

Month	Salinity in Upper San Antonio Bay a/ (ppt)		
	Upper b/ Viability Limit	Lower b/ Viability Limit	Meadian Historic Salinity
January	20	10	13
February	20	10	12
March	20	10	12
April	15	5	13
May	15	1	10
June	15	1	9
July	20	10	11
August	20	10	17
September	15	5	13
October	15	5	13
November	20	10	13
December	20	10	14

a/ Represented by the average of TDWR network sites 2462.03 and 2462.01 (Figure 3-8).

b/ These values represent the limits of long-term viable species activity, at a control point in the estuary and not individual organism survival limits.

especially the early life stages which are dependent upon marsh inundation and nutrient processes for biological productivity.

The Guadalupe River delta, the only major river delta in the Guadalupe estuary, is subject to periodic inundation[1/] by freshwater due to discharge from the Guadalupe River system. The areal extent of deltaic inundation is a function of wind, tide, and discharge rate and volume. If high tides are present, the area of the 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 a management procedure, it is necessary to determine both the periodicity and magnitude of historical flood events for the delta. If what has happened naturally in the past has been sufficient to maintain the productivity of the estuary, incorporation of historical patterns into a management plan will most likely provide inundation sufficient to maintain productivity in the future.

Historical deltaic inundation was computed through the use of a hydrodynamic model for Guadalupe delta (45). A series of peak discharges ranging from 4,000 to 30,000 ft^3/sec (113 to 850 m^3/sec) (for normal and high tidal regimes) were used in the analysis and the areal extent of deltaic inundation was determined for each tide/discharge scenario. With normal tides (1.8 feet to 2.2 feet [0.55 - 0.67 m] above MSL), a peak discharge of 4,000 ft^3/sec (113 m^3/sec) was sufficient to begin inundation of the delta. During high tides (range 2.3 feet to 3.1 feet [0.70 - 0.94 m] above MSL), the model predicted that a 4,000 ft^3/sec (113 m^3/sec) peak discharge from the Guadalupe River system would result in inundation of 61 percent of the delta.

Since historical tide stages are unknown for a large portion of the period of record, a daily peak discharge of 4,000 ft^3/sec (113 m^3/sec) or greater was considered a potential inundation event. This figure was selected on the basis of model predictions showing inundation beginning to occur for normal tides as freshwater inflow to the delta approaches 4,000 ft^3/sec (113 m^3/sec).

Daily gaged discharge data for the period of record (1941-1976) were examined to arrive at monthly and seasonal distributions of discharge events with peak flows of 4,000 ft^3/sec (113 m^3/sec) or greater (Table 9-3). It was apparent that more inundation events have occurred in the spring months of April, May, and June than during any other seasonal period. The data suggest that inundation events in the Guadalupe delta have occurred more often in the spring and fall than in winter and summer. According to biological evidence, spring inundation events are necessary for (1) adequate physical wetting of the marsh plant communities, (2) nutrient exchange and biogeochemical cycling of carbon, nitrogen and phosphorus, (3) transport of detrital food materials,

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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 (0.15 m) for a period not less than 48 hours. These values are based upon TDWR supported research (271, 275). 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 and drying.

Table 9-3. Peak Gaged Discharge for Discrete Flood Events Greater Than 4,000 ft^3/sec in the Guadalupe River Delta, 1941-1976

Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
					ft^3/sec						
19,740	90,200	17,260	35,680	58,100	62,000	92,900	23,010	247,000	85,800	47,000	29,210
18,740	25,050	15,335	35,130	66,590	59,140	28,200	14,990	57,150	55,800	44,073	21,423
15,810	17,827	15,202	34,090	49,930	39,540	20,390	11,370	54,395	41,650	31,500	12,967
13,200	17,160	9,87	27,259	38,920	30,850	15,570	9,755	43,730	36,950	23,057	11,754
12,528	15,920	9,573	26,510	29,320	21,710	14,524	9,077	36,530	30,639	20,120	10,880
12,250	15,138	7,402	18,507	28,530	21,180	13,636	7,910	19,700	30,020	14,544	10,381
11,530	11,080	6,785	14,200	24,330	20,220	10,157	7,857	18,040	20,620	14,250	9,920
9,732	9,130	6,173	14,100	20,590	18,064	7,920	6,859	15,204	15,260	14,103	9,494
8,600	8,528	6,096	12,398	19,714	17,183	7,360	5,921	14,946	13,449	14,048	8,794
8,502	6,672	5,077	10,974	18,004	14,606	5,777	4,483	13,370	13,383	13,100	6,860
7,550	6,219	4,289	10,548	16,570	14,051	5,077	4,023	10,120	10,003	9,277	6,833
6,165	5,892	4,263	10,368	14,918	13,053	4,874		9,827	9,360	7,760	5,259
5,620	5,754		10,057	14,250	12,930	4,458		9,516	8,928	6,688	4,765
	5,489		8,730	13,640	11,151	4,034		8,680	7,398	6,674	4,623
	5,381		7,375	12,850	10,150			6,300	5,570	6,151	4,277
	4,849		6,365	12,780	8,749			5,970	4,930	5,742	
	4,737		6,228	12,430	7,912			5,777	4,662		
	4,285		4,428	12,170	7,532			5,334	4,519		
			4,265	11,460	6,436			5,285	4,411		
				11,425	5,595			4,567			
				11,350	5,537						
				11,254	5,265						
				11,240	4,836						
				10,900	4,624						
				10,488							
				10,142							
				9,894							
				8,872							
				8,594							
				7,707							
				6,508							
				6,426							
				4,944							
				4,530							

Median peak flood discharge
April-June 12,500 ft^3/sec
September-December = 12,500 ft^3/sec

and (4) reduction of salinity to suit the preferences of young, estuarine-dependent organisms utilizing the "nursery" habitats of the marsh and adjacent shallow water areas. Although fewer juveniles inhabit the nursery areas during the tropical storm dominated fall season, the sporadic inundation events of that season also provide similar maintenance benefits to the estuary.

If historical inundation events (peak daily flows greater than 4,000 ft^3/sec [113 m^3/sec]) are grouped into those that occur during the spring (April, May, and June), those that occur during the late fall and early winter (September, October, November, and December), and the total that occurs during the year, it is evident that an average of five inundation events have occurred per year in the Guadalupe delta over the period of record (Table 9-4). In order to maintain the historical inundation frequency, the Guadalupe River delta would need to receive a median of five flood events per year greater than 4,000 ft^3/sec (113 m^3/sec).

Ideally, inundation events should occur at times which would provide the most benefit to estuarine organisms. The importance of at least one spring and one fall event has been discussed previously. Since low salinities and shallow habitat (for protection of the young) are primary requisites during the spring, any inundation events occurring during this period will provide the greatest benefit to the organisms. An inundation event in April and subsequent events in May and June would be expected to extend favorable habitat conditions for larvae and juvenile stages of estuarine-dependent organisms. The April-June and September-December median daily peak discharges over the period of record have been 12,500 ft^3/sec (354 m^3/sec).

The typical flood hydrograph for the contributing basins associates flood volume of 125,000 acre-feet (15 million m^3), with the above peak discharge. The percent of marsh inundated as computed by the delta hydrodynamic model, will vary with wind direction and tide stage. With a normal tide (range 1.8 feet to 2.2 feet [0.55 - 0.67 m] above MSL) and peak discharges of the above mentioned magnitudes, the model predicts that only about 28-30 percent of the delta area will be inundated. Under a "high tide" (range 2.3 to 3.1 feet [0.70 - 0.94 m] above MSL) similar peak discharges will result in inundation of 78-80 percent of the Guadalupe delta.

Estuarine Linear Programming Model Description

The combination of desired objectives and environmental and physical constraints relating the effects 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 Guadalupe River Basin and San Antonio River Basin.1/ A Linear Programming (36) optimization procedure is used to determine the monthly freshwater inflows from the Guadalupe and San Antonio River Basins needed to meet specified

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1/ Additional freshwater inflows are contributed to the estuary from the San Antonio-Nueces and Lavaca-Guadalupe Coastal Basins; however, the individual monthly inflows from these sources are taken to be fixed at their historical monthly average inflow over the period 1941 through 1976.

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

Number of Events per Period	Number of Occurrences over Period of Record					
	Spring		Fall		Total Annual	
(x)	Freq.(f) a/	f*x b/	Freq.(f)	f*x	Freq.(f)	f*x
0	6	0	10	0	1	0
1	9	9	6	6	1	1
2	10	20	10	20	6	12
3	4	12	4	12	4	12
4	2	8	4	16	4	16
5	2	10	1	5	2	10
6	3	18	1	6	4	24
7					2	14
8					4	32
9					2	18
10					2	20
11					2	22
12					0	0
13					2	26
Σf*x		77		65		207
Number of Years = 36						
Mean Number Inundation events per year		2.2		1.8		5.75
Median Number Inundation events per year		2		2		5

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a/ Frequency (f) is the number of seasons or years in which the number of flood events greater than 4,000 ft^3/sec equals x.

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

salinity, marsh inundation and commercial bay fisheries levels. The quantifications of salinity and commercial fisheries harvest as functions of freshwater inflow are represented by the statistical regression equations given in Chapter V and VIII, respectively. The harvest equation utilized for a given species is the best significant regression equation accounting for the most variance in the data (i.e., having the largest r^2 value and having the smallest standard error for the harvest estimate).

Specification of Objectives. The criteria or objectives in this optimization formulation can be any desired estuarine condition. One objective of interest is to determine the least annual inflow to the estuary while meeting the constraints on salinity regimes and marsh inundation. Another alternative could be to compute the estimated quantity of freshwater inflow to maximize the commercial harvests in the estuary. This harvest could be either for an individual species of aquatic organism, a weighted sum of the harvests of a group of the commercially important species (e.g., shellfish), or other combinations.

Computational 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 bay fisheries harvest,
(2) statistical regression equations relating mean monthly salinities to mean monthly freshwater inflows,
(3) upper and lower limits on the monthly inflows used in computing the salinity regression relationships, and
(4) upper and lower viability limits on allowable monthly salinities (Table 9-2).

Alternative Estuarine Objectives

Three alternative objectives are considered, as follows:

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

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

Alternative III, Shrimp Harvest Enhancement
Objective: maximize the total annual commercial harvest of shrimp in the estuary while observing salinity viability limits, marsh inundation needs, and utilizing an annual combined inflow no greater than the average 1941 through 1976 historical annual

combined inflow. In addition, it is required that the projected commercial harvest of the all shellfish component be no less than the average 1962 through 1976 historical harvest.

The objective and constraints for the listed alternatives are indicated in Table 9-5. The three specified objectives are not the only possible options for the Guadalupe estuary; however, they provide a range of alternatives: survival or subsistence (Alternative I), maintenance of bay harvest levels (Alternative II), and shrimp bay harvest enhancement (Alternative III).

Alternative I: Subsistence. The objective of Alternative I (Subsistence) is to minimize total annual combined inflow while meeting specified bounds on salinity (Table 9-2) in upper San Antonio Bay and satisfying marsh inundation needs for the Guadalupe delta.1/ The upper salinity bound for each month is the minimum of the upper viability limit and the historical median salinity. Optimal monthly inflows to the estuary needed to meet the objective have been determined by the Estuarine Linear Programming Model. The estimated annual combined inflow need amounts to approximately 1.6 million acre-feet, with 1.49 million acre-feet from the Guadalupe River Basin (including the San Antonio River Basin), and 83.0 thousand acre-feet from the San Antonio-Nueces and Lavaca-Guadalupe Coastal Basins (Table 9-6).

Monthly freshwater inflow needs generated by the Estuarine Linear Programming Model for Alternative I provide salinities in upper San Antonio Bay which closely approximate those for the required upper bounds during most months of the year (Figure 9-2). Guadalupe River Basin inflows during the months of June and October provide lower salinities as a consequence of meeting marsh inundation requirements.

Comparison between the mean 1941 through 1976 historical combined inflows and the estimated freshwater inflow needs from the Guadalupe River Basin are made for each month (Figure 9-3). The estimated monthly freshwater inflow needs are less than the mean monthly 1941 through 1976 inflows except for the month of September2/. The distribution of the freshwater inflow needs between the Guadalupe Basin and the coastal basins is illustrated in Table 9-6. Note the relative insignificance of the inflow from the coastal basins.

Implementation of Alternative I for the Guadalupe estuary under the inflow regime indicated in Table 9-6 would result in moderate to severe projected decreases in commercial bay fisheries harvests from average historical levels observed during the 1962 through 1976 period (Figure 9-4). The finfish category would have a projected annual harvest of 103.7 thousand

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1/ Guadalupe delta inundation needs include inundation volumes of 125,000 acre-feet each month for the period April through June (peak daily discharge of 12,500 ft^3/sec at the Guadalupe delta) and in September and October.

2/ The inflow need is greater than average inflow as a result of the upper salinity limit in September being less than the median historical salinity for sample sites in San Antonio Bay where the salinity was evaluated (Table 9-2).

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

	Alternatives		
	I	II	III
Criteria:			
. Maximize Annual Harvest of Shrimp			x
. Least Possible Annual Combined Inflow	x	x	
Constraints:			
. Annual Inflow from the Guadalupe River Basin is no greater than its Average Annual Historical Value (1941-1976)		x	x
. Predicted Annual Spotted Seatrout and Red Drum Commercial Harvests no less than their Average Annual Values (1962-1976)		x	
. Predicted Annual Commercial Shellfish Harvest no less than the Average Harvest (1962-1976)			x
. Predicted Annual Shrimp, and Shellfish Commercial Harvests no less than their Average Harvests (1962-1976)		x	
. Upper and Lower Limits on Seasonal Inflows to Insure Validity of Predictive Harvest Equations	x	x	x
. Upper and Lower Limits on Mean Monthly Salinity	x	x	x
. Upper and Lower Limits on Monthly Inflows to Insure Validity of Predictive Salinity Equations	x	x	x
. Lower Limits on Mean Monthly Guadalupe River Basin Inflow for Marsh Inundation of the Guadalupe Delta	x	x	x

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

Period	Guadalupe River Basin		Total Inflow From Coastal Basins	Combined Inflow c/
	Estuary Inflow Need from the Basin	Estuary Inflow Need from Gaged Portion of the Basin b/		
	Thousands of Acre-Feet			
January	102.2	86.4	4.0	106.2
February	115.8	96.2	6.0	121.8
March	97.0	80.3	3.0	100.0
April	160.4	134.1	6.0	166.4
May	165.1	138.1	8.0	173.1
June	125.0	104.0	8.0	133.0
July	70.4	57.6	6.0	76.4
August	97.5	80.6	7.0	104.5
September	247.1	207.8	14.0	261.1
October	125.0	104.0	10.0	135.0
November	93.1	76.9	5.0	98.1
December	92.6	76.5	6.0	98.6
Annual	1,491.2	1,240.7	83.0	1,574.2

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a/ All inflows are mean monthly values.

b/ These values computed using regression equations relating monthly river basin inflow to the estuary with monthly gaged flows at USGS Stations at Goliad and Victoria on the Guadalupe River, and Coleto Creek near Schroeder.

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

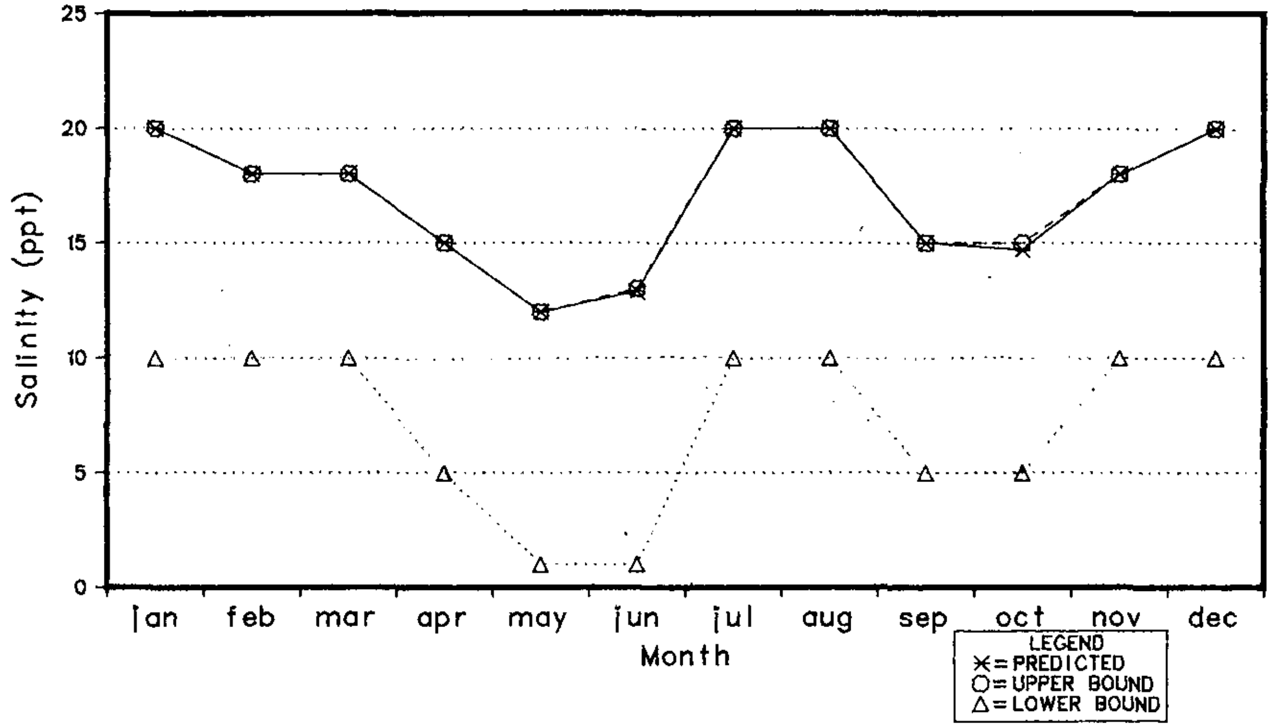

Figure 9-2. Average Monthly Salinities in Upper San Antonio Bay Under Alternative I

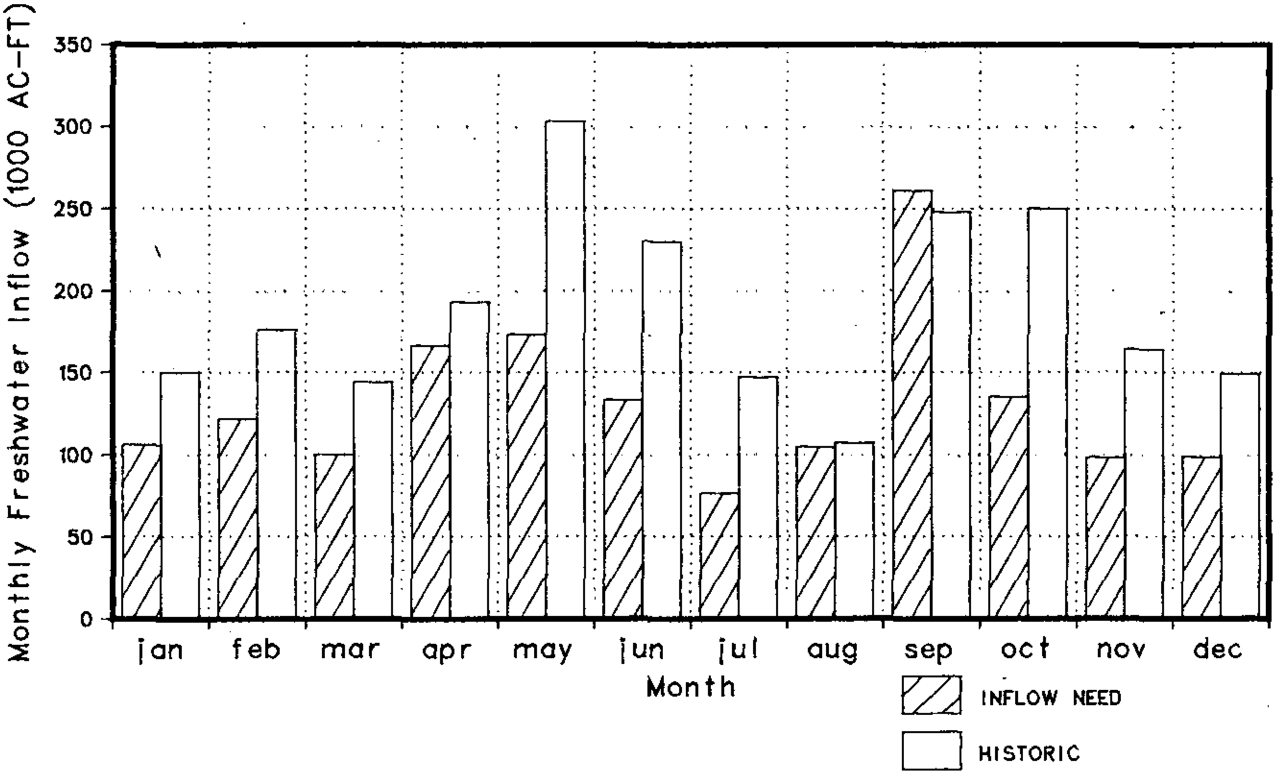

Figure 9-3. Comparison Between Mean Historical Freshwater Inflow and Inflow Needs Under Alternative I From the Guadalupe River Basin for the Guadalupe Estuary

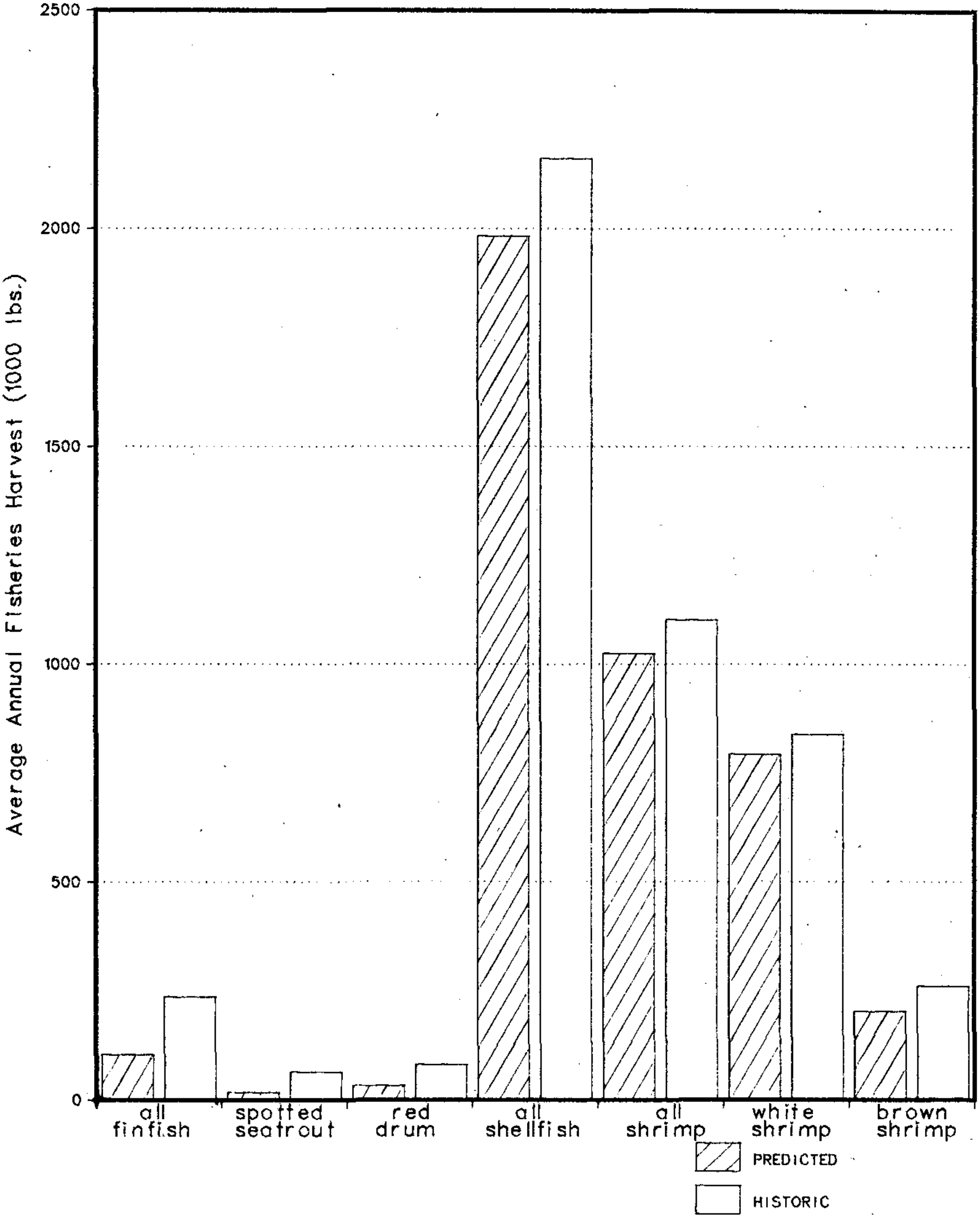

Figure 9-4. Comparison Between Guadalupe Estuary Historical Fisheries Harvests and Predicted Harvests Under Alternative I

pounds, or a 56 percent decrease from the average (mean historical levels); total shellfish harvest, an eight percent reduction; and shrimp, a predicted seven percent decline in harvest.

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 predicted annual commercial bay harvests of red drum, seatrout, shrimp, and total shellfish at levels no less than mean 1962 through 1976 historical values; satisfying marsh inundation needs; and meeting viability limits for salinity.

The optimal set of monthly freshwater inflow needs derived by the Estuarine Linear Programming Model for Alternative II (Table 9-7) amounts to almost 2.02 million acre-feet annually, of which 1.937 million acre-feet are contributed by the Guadalupe River system and 83 thousand acre-feet from the coastal basins. The yearly volume needed from the Guadalupe River Basin is 11 percent less than the average historical inflow from the basin over the period 1941 through 1976.

Monthly freshwater inflow needs generated for Alternative II provide salinities (Figure 9-5) which are predicted to be lower in upper San Antonio Bay in certain months than under Alternative I. Predicted salinities are lower than those for Alternative I during the critical spring months (April, May, and June) of fisheries productivity, as additional inflow during that period is supplied under Alternative II.

The Estuarine LP Model does not specify unique monthly inflows from the Guadalupe River Basin except in the months of July through October. The inflows for the seasons covered by the remaining months could be distributed on a monthly basis in any desired manner, consistent with the minimum inflow needed in each month for salinity maintenance and marsh inundation (Table 9-6). This is possible since the inflow variables in the fisheries equations represent seasonal inflows. It was decided to distribute the inflows for the winter (January-March), spring (April-May), and fall (November and December) seasons to individual months based upon the historical (1941-1976) average inflow distribution within each monthly grouping (see Chapter IV), while observing monthly salinity and inundation needs.

Comparisons between the mean historical combined inflows and estimated freshwater inflow needs for this alternative were made for the Guadalupe River Basin (Figure 9-6). The average 1941 through 1976 historical inflows from the Guadalupe River Basin are generally greater for each month than the freshwater inflow needs under this alternative. The exceptions are the months of April, May, June and September. Freshwater inflow needs in the spring season (April, May and June) are approximately equal to the average historical inflows in these months. Inflow needs in the summer (July and August) and autumn (September and October) seasons are near the minimum values necessary to satisfy the upper biological viability bounds for salinity.

Implementation of Alternative II for the Guadalupe estuary under the inflow regime indicated in Table 9-7 is projected to result in commercial fisheries harvests equal to or greater than the average historical levels observed during the 1962 through 1976 period, with the exception of the total

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

Period	Guadalupe River Basin		Total Inflow From Coastal Basins	Combined Inflow c/
	Estuary Inflow Need from the Basin	Estuary Inflow Need from Gaged Portion of the Basin b/		
	Thousands of Acre-Feet			
January	139.5 d/	116.4	4.0	143.5
February	163.7 d/	136.9	6.0	169.7
March	133.9 d/	111.6	3.0	136.9
April	193.4 e/	162.2	6.0	199.4
May	303.5 e/	255.8	8.0	311.5
June	230.3 e/	193.5	8.0	238.3
July	70.4	57.6	6.0	76.4
August	97.5	80.6	7.0	104.5
September	247.1	207.8	14.0	261.1
October	125.0	104.0	10.0	135.0
November	121.9 f/	101.4	5.0	126.9
December	110.7 f/	91.9	6.0	116.7
Annual	1,936.9	1,619.7	83.0	2,019.9

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a/ All inflows are mean monthly values.

b/ These values computed using regression equations relating monthly river basin inflow to the estuary with monthly gaged flows at USGS Stations at Goliad and Victoria on the Guadalupe River, and Coleto Creek near Schroeder.

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

d/ Total seasonal freshwater inflow need distributed according to Guadalupe River Basin (1941-1976) average monthly inflow distribution in the season (January, February and March).

e/ Total seasonal freshwater inflow need distributed according to Guadalupe River Basin (1941-1976) average monthly inflow distribution in the season (April, May and June).

f/ Total seasonal freshwater inflow need distributed according to Guadalupe River Basin (1941-1976) average monthly inflow distribution in the season (November and December).

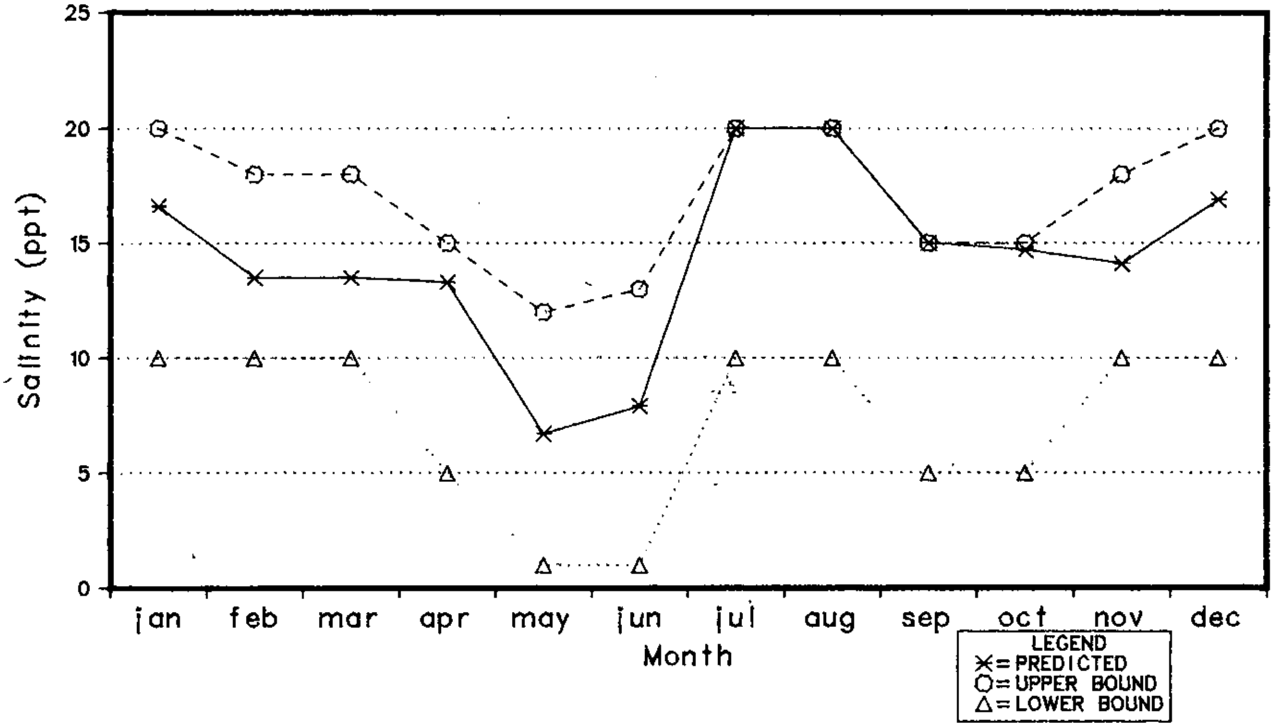

Figure 9-5. Average Monthly Salinities in Upper San Antonio Bay Under Alternative II

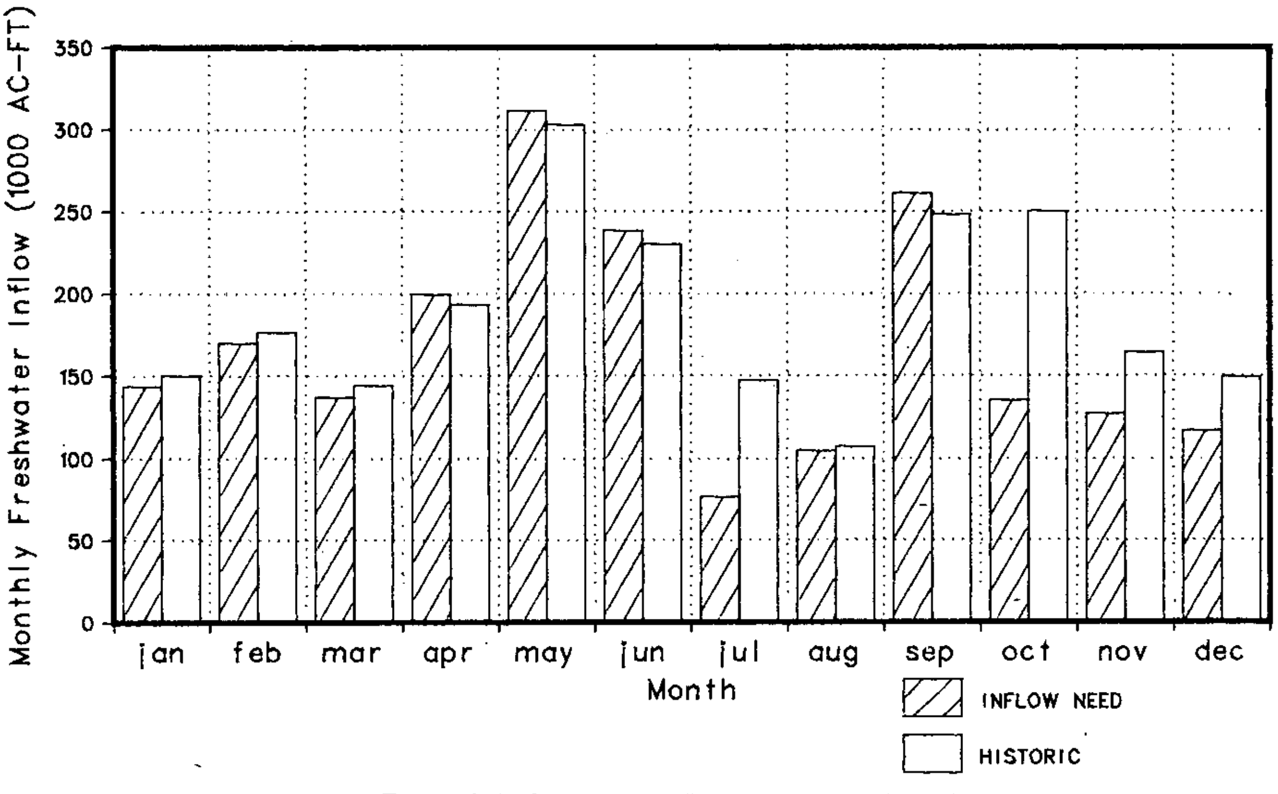

Figure 9-6. Comparison Between Mean Historical Freshwater Inflow and Inflow Needs Under Alternative II for the Guadalupe Estuary

finfish and brown and pink shrimp harvests (Figure 9-7). Under these inflow conditions, total finfish harvest is projected to be 11 percent less than the historical average, while the brown and pink shrimp harvest is estimated to decrease by 22 percent.

Alternative III: Shrimp Harvest Enhancement. The objective of Alternative III (Shrimp Harvest Enhancement) is to maximize the total annual estuarine commercial bay harvest of shrimp, while observing salinity viability limits and marsh inundation needs, utilizing annual Guadalupe River Basin inflows at a level no greater than the average 1941 through 1976 historical annual inflow, and not allowing the total shellfish harvest to be less than the 1962 through 1976 historical annual average.

The Estuarine Linear Programming Model was utilized to determine an optimal set of monthly river basin inflows to meet the stated objective (Table 9-8). The annual combined inflow[1/] from freshwater sources needed to maximize the shellfish harvest was estimated at 2.26 million acre-feet (the constraining 1941 through 1976 historical annual average inflow). The total annual contribution from the Guadalupe River Basin was estimated at almost 2.18 million acre-feet. The remaining annual freshwater contribution of 82 thousand acre-feet is the historical average inflow from the San Antonio-Nueces and Lavaca-Guadalupe Coastal Basins. As with Alternative II, seasonal inflow needs were distributed monthly on the basis of the historical inflow distribution, as indicated in Table 9-8.

Monthly freshwater inflow needs generated for Alternative III provide monthly salinities which are lower for the months of January, February and March in upper San Antonio Bay than those under Alternative II (Figure 9-8). In the summer and fall months, however, upper San Antonio Bay salinities are about the same as those under Alternative I.

Comparisons between mean historical combined inflows and estimated freshwater inflow needs under Alternative III were made for the Guadalupe Basin (Figure 9-9). The average historical inflows from the basin were higher than the freshwater inflow needs under Alternative III for the spring, summer, and fall months, and lower than the estimated needs for the winter (January, February and March).

Implementation of Alternative III for the Guadalupe estuary under the inflow regime indicated in Table 9-8 would result in a projected 34 percent increase in total shrimp harvest above the mean 1962 through 1976 historical level (Figure 9-10). Changes in individual shrimp categories under Alternative III give a projected 47 percent increase in white shrimp harvested, and 22 percent decrease in brown and pink shrimp harvested. The total shellfish harvest is projected to equal the average annual 1962 through 1976 harvest. In the finfish categories, projected commercial harvest changes from historic 1962 through 1976 conditions include a 54 percent decrease in total finfish harvest, a 66 percent increase in spotted seatrout, and a 52 percent decrease in red drum.

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

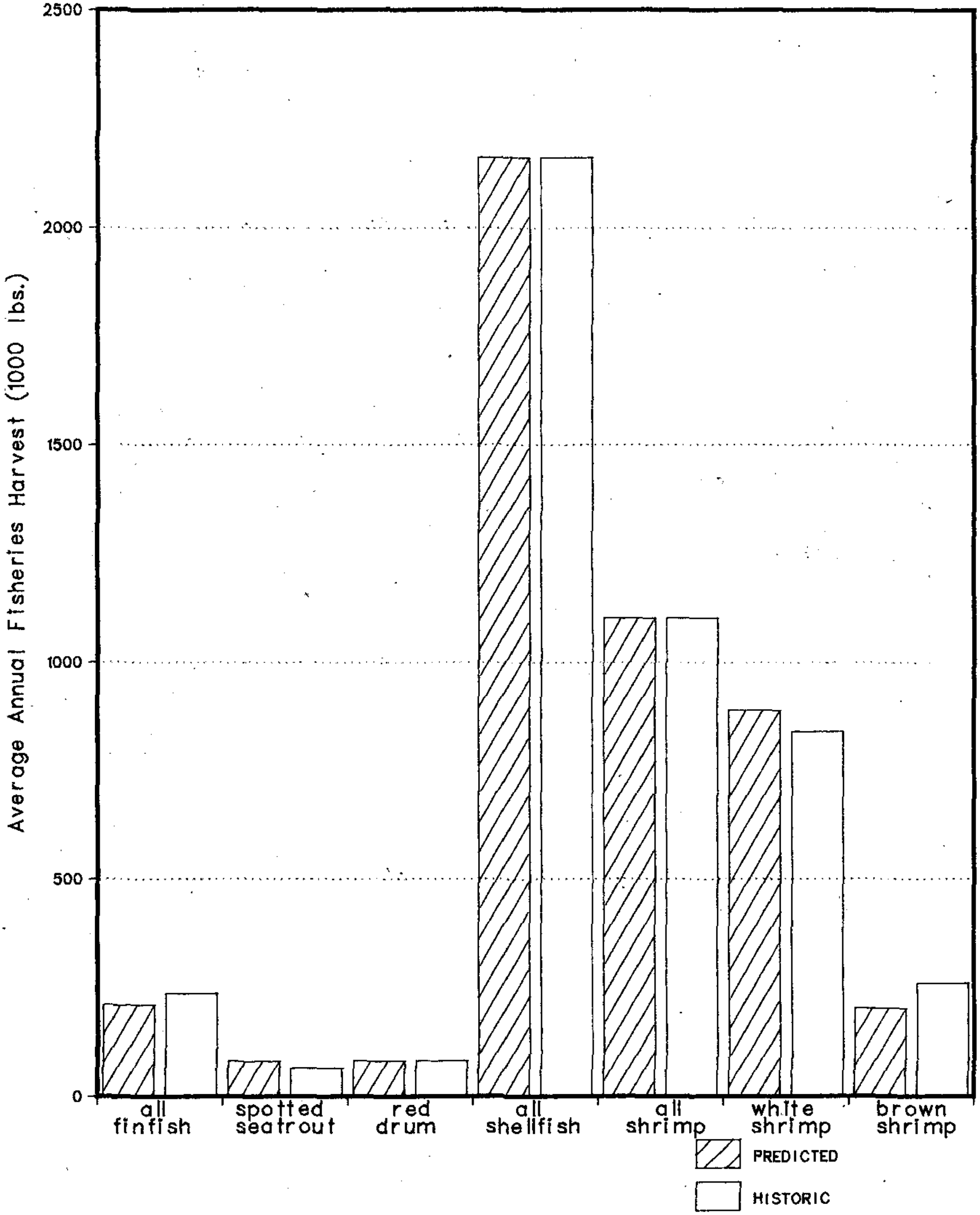

Figure 9-7. Comparison Between Guadalupe Estuary Historical Fisheries Harvests and Predicted Harvests Under Alternative II

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

Period	Guadalupe River Basin		Total Inflow From Coastal Basins	Combined Inflow c/
	Estuary Inflow Need from the Basin	Estuary Inflow Need from Gaged Portion of the Basin b/		
	Thousands of Acre-Feet			
January	331.6	279.6	4.0	335.6
February	234.1	196.8	6.0	240.1
March	186.8	156.5	3.0	189.8
April	182.0 d/	152.4	6.0	188.0
May	285.6 d/	240.6	8.0	293.6
June	216.8 d/	182.1	8.0	224.8
July	70.4	57.6	6.0	76.4
August	97.5	80.6	7.0	104.5
September	247.1 e/	207.8	14.0	261.1
October	141.6 e/	118.1	10.0	151.6
November	93.1	76.9	5.0	98.1
December	92.6	76.5	6.0	98.6
Annual	2,179.2	1,825.5	83.0	2,262.2

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a/ All inflows are mean monthly values.

b/ These values computed using regression equations relating monthly river basin inflow to the estuary with monthly gaged flows at USGS Stations at Goliad and Victoria on the Guadalupe River, and Coleto Creek near Schroeder.

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

d/ Total seasonal freshwater inflow need distributed according to Guadalupe River Basin (1941-1976) average monthly inflow distribution in the season (April, May and June).

e/ Total seasonal freshwater inflow need distributed as closely as possible to Guadalupe River Basin (1941-1976) average monthly inflow distribution in the season (September and October).

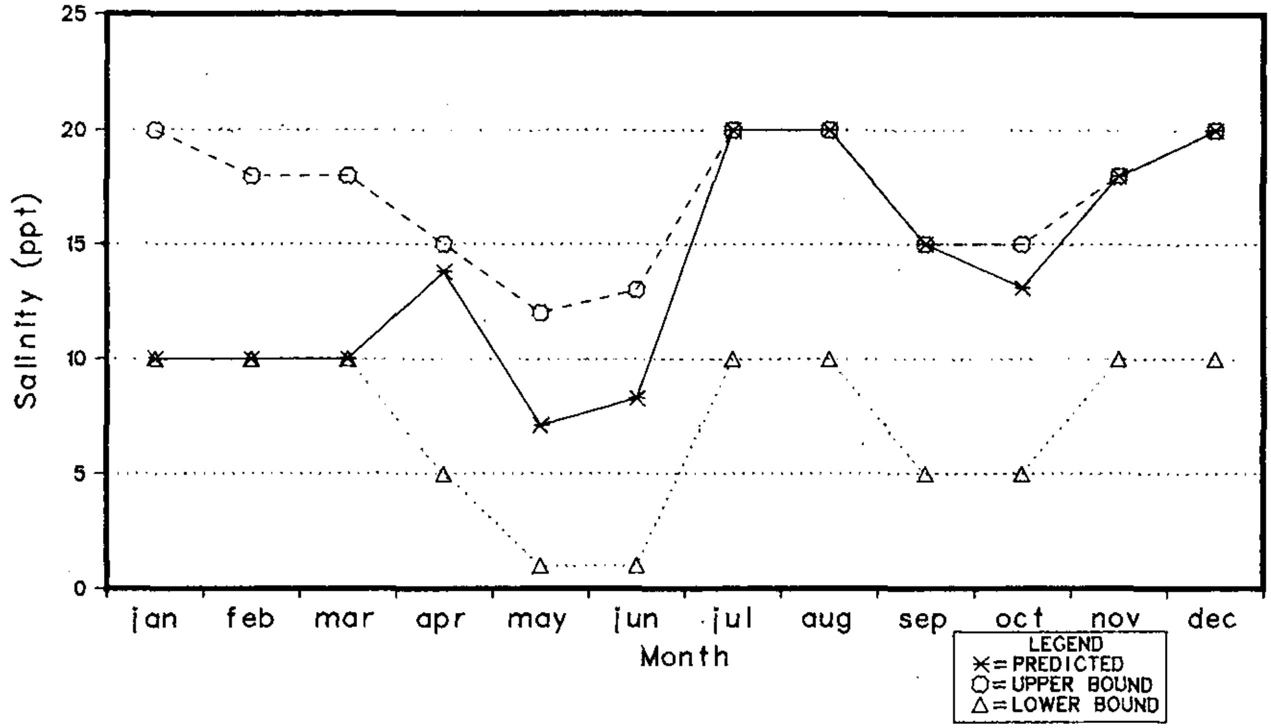

Figure 9-8. Average Monthly Salinities in Upper San Antonio Bay Under Alternative III

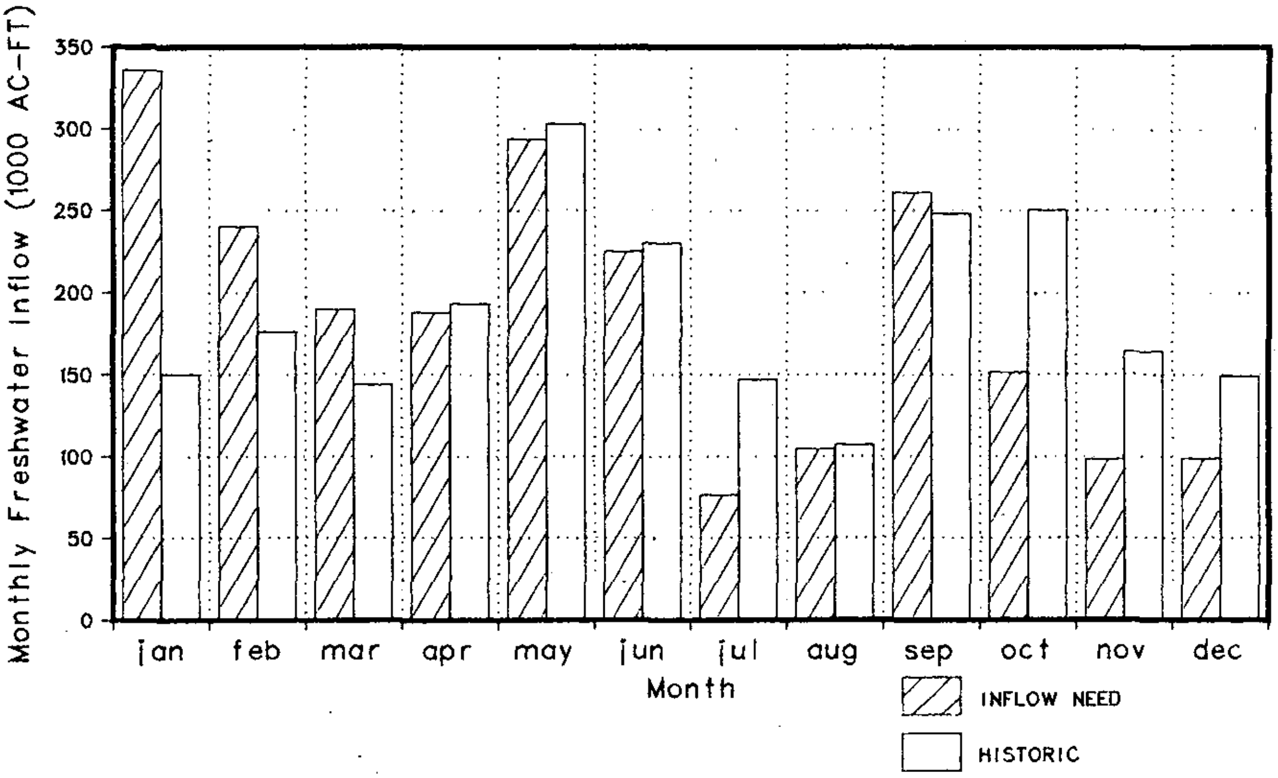

Figure 9-9. Comparison Between Mean Historical Freshwater Inflow and Inflow Needs Under Alternative III for the Guadalupe Estuary

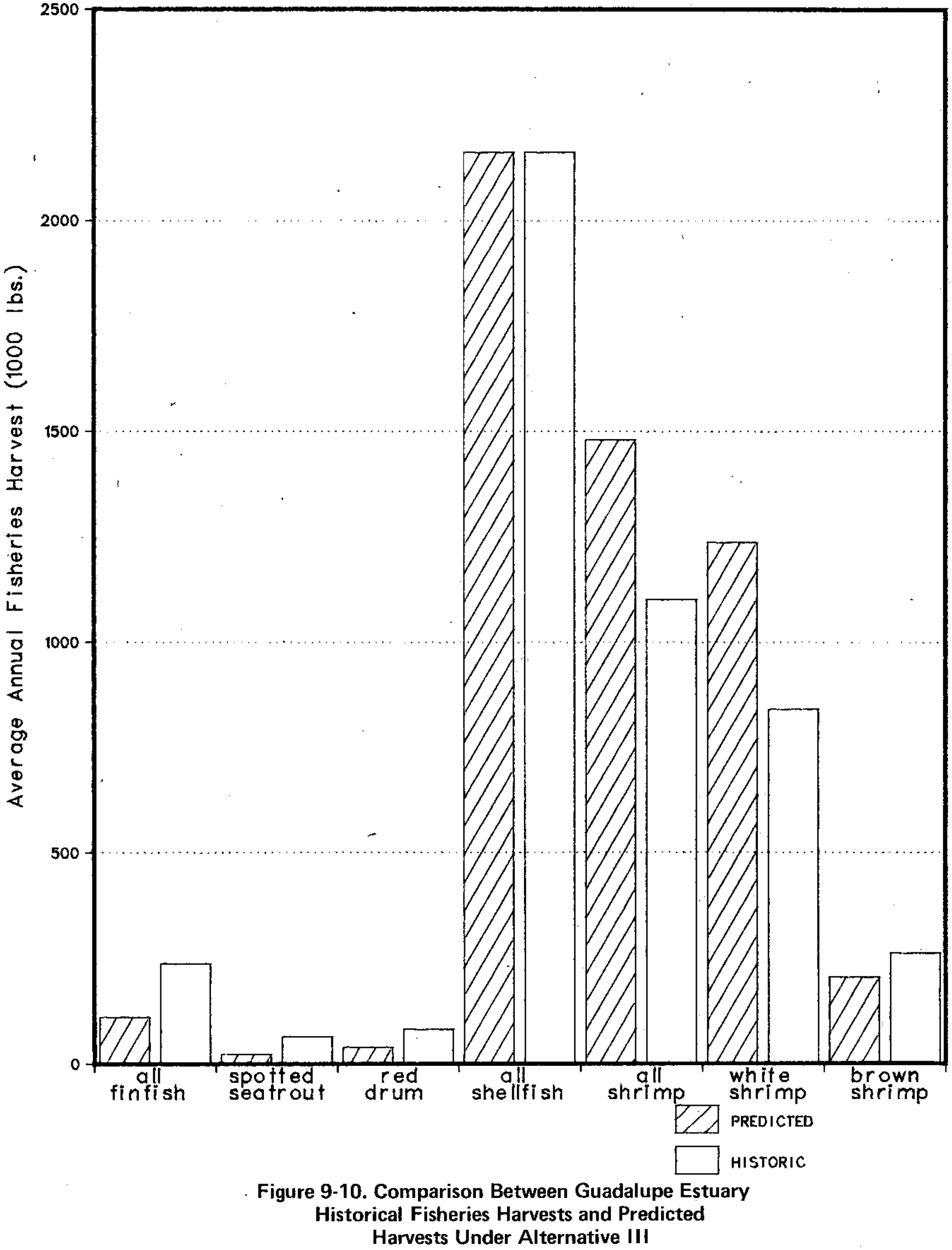

Figure 9-10. Comparison Between Guadalupe Estuary Historical Fisheries Harvests and Predicted Harvests Under Alternative III

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 one point in the Guadalupe estuary near the major source of freshwater inflow. To determine circulation and salinity patterns throughout the estuary it is necessary to apply the tidal hydrodynamic and salinity mass transport models (described in Chapter V) using the estimates of monthly freshwater inflow needs obtained from the Estuarine Linear Programming Model. If the circulation patterns and salinity gradients predicted by the hydrodynamic and transport models are acceptable, then the tentative monthly freshwater inflow needs may be accepted. Should the estuarine conditions not be satisfactory, then the constraints upon the Linear Programming Model must be modified, and the model again used to compute new estimates.

Salinity patterns in 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 San Antonio Bay should not exceed 25 parts per thousand (ppt) in any month under the projected freshwater inflow needs. The lowest annual inflow to the estuary from any of the three alternatives considered here is provided by Alternative I; thus, if the salinity conditions across the estuary meet the 25 ppt criteria under Alternative I, monthly freshwater inflows under Alternatives II and III should also satisfy the condition (since they specify higher inflows). A lower limit on the salinity in the center of San Antonio Bay was not evaluated since it was not anticipated that the monthly inflows under the three alternatives would give salinities lower than 10 ppt.

Simulation of Mean Monthly Circulation and Salinity Patterns in the Guadalupe Estuary. The estimated monthly freshwater inflow needs to the Guadalupe estuary under Alternative I were used as input conditions to the tidal hydrodynamic model, along with typical tidal and meteorological conditions for each month, to simulate average circulation patterns in the Guadalupe 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 36 X 24 computational matrix representing the Guadalupe 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 be best illustrated in the form of vector plots, wherein each vector (or arrow) represents the net flow through a computational cell. The orientation of the vector represents the direction of flow, and the length of the vector represents the magnitude of flow.

The tidal amplitudes and flows calculated by the tidal hydrodynamics model are used as input to operate the salinity transport model to simulate the salinity distributions in the Guadalupe estuary for each of the mean monthly periods. The resultant salinity distributions are illustrated in the form of salinity contour plots wherein lines of uniform salinity are shown in increments of five parts per thousand (ppt).

Simulated Flow Patterns. The simulated steady-state flows in the estuary are given in Figures 9-11 through 9-22 for each of the twelve months. The magnitude and direction of net flow in each computational "cell" is indicated by an arrow or vector. The magnitude of flow is indicated by the length of each vector, with one inch corresponding to approximately 40,000 ft^3/sec (570 m^3/sec).

Examination of the vector plots for each of the numerical simulations using average monthly inflows revealed that the circulation patterns in the Guadalupe estuary could be divided into two groups based upon similarities: (1) the months of November, December, and January and (2) the other months of the year. This breakdown of the circulation patterns into winter and non-winter periods facilitates the following discussion of the simulated monthly hydrodynamic conditions.

(1) Simulated November, December and January Circulation Patterns. The flow circulations and salinities in the Guadalupe estuary were simulated for historical average meteorological conditions and estimated freshwater inflow needs for Alternative I for the months of November, December and January. The predominant wind speed and direction of 10 miles per hour (mph) (4.5 m/sec) from the north-northeast varied only slightly among these winter months.

Examination of the simulated circulation patterns in the bays for these three months (Figures 9-21, 9-22 and 9-11) indicates that the predominant net water circulation under these simulated conditions is from Carlos Bay in the Mission-Aransas estuary into Mesquite Bay of the Guadalupe estuary and continuing northeastward through San Antonio and Espiritu Santo Bays into the Lavaca-Tres Palacios estuary.

The circulation patterns in the middle and upper portions of San Antonio Bay have several circular net currents which dominate the circulation pattern. The flow from the Guadalupe River appears to be the dominant factor inducing these currents in the upper portion of San Antonio Bay.

Several simulated secondary currents in the lower San Antonio and Espiritu Santo Bays result in flow along the northern shore of Mustang Island being directed in a southwesterly direction.

The major exchange points between the Guadalupe estuary and the Mission-Aransas estuary, the Lavaca-Tres Palacios estuary, and the Gulf of Mexico were evaluated for net flow volume and direction during these months. The primary exchange points were from the Mission-Aransas estuary into Mesquite Bay and from Espiritu Santo Bay into the Lavaca-Tres Palacios estuary. Net exchange directly into the Guadalupe estuary from the Gulf of Mexico was relatively small although substantial instantaneous flows did occur.

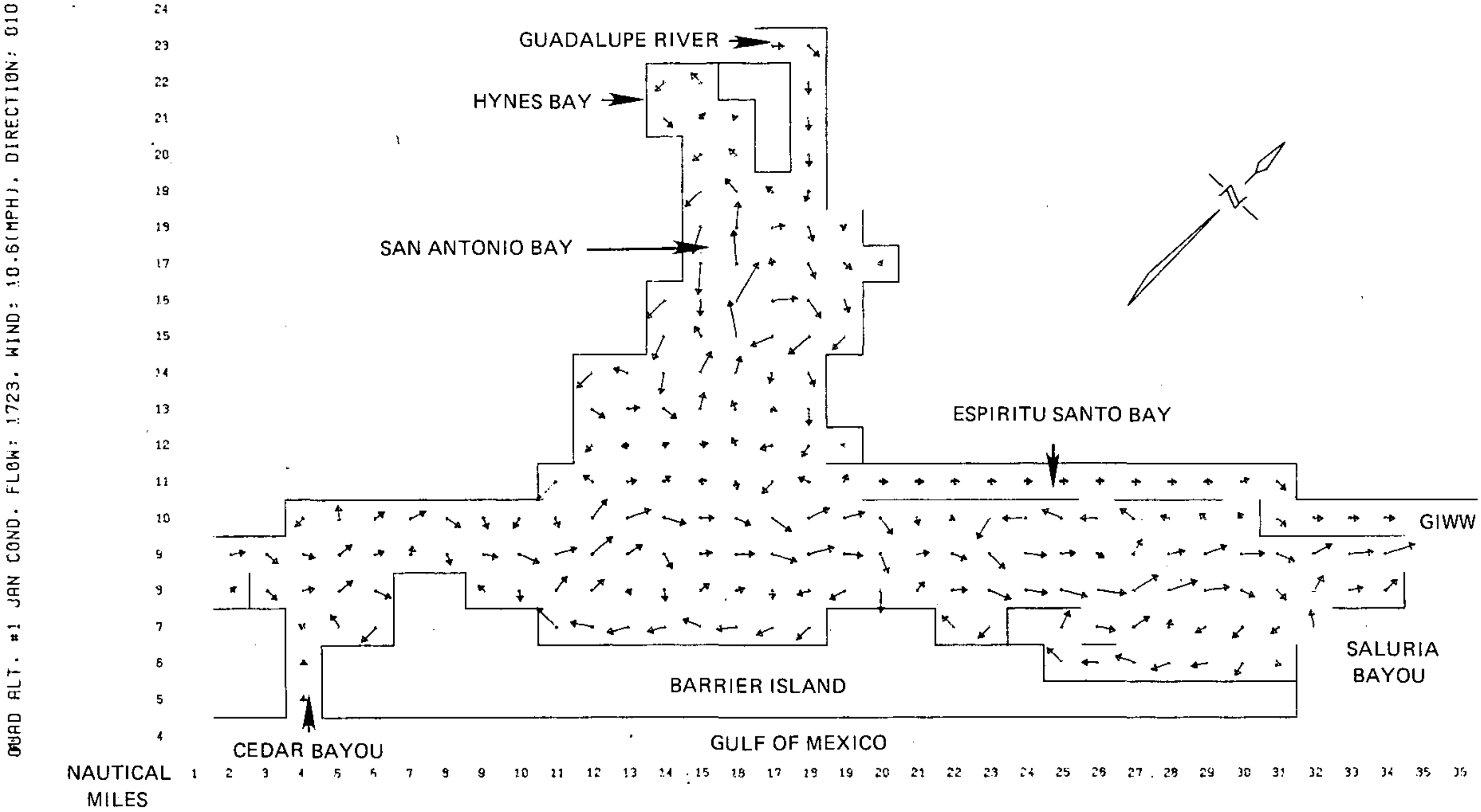

Figure 9-11. Simulated Net Steady-State Flows in the Guadalupe Estuary Under January Freshwater Inflow Needs, Alternative I

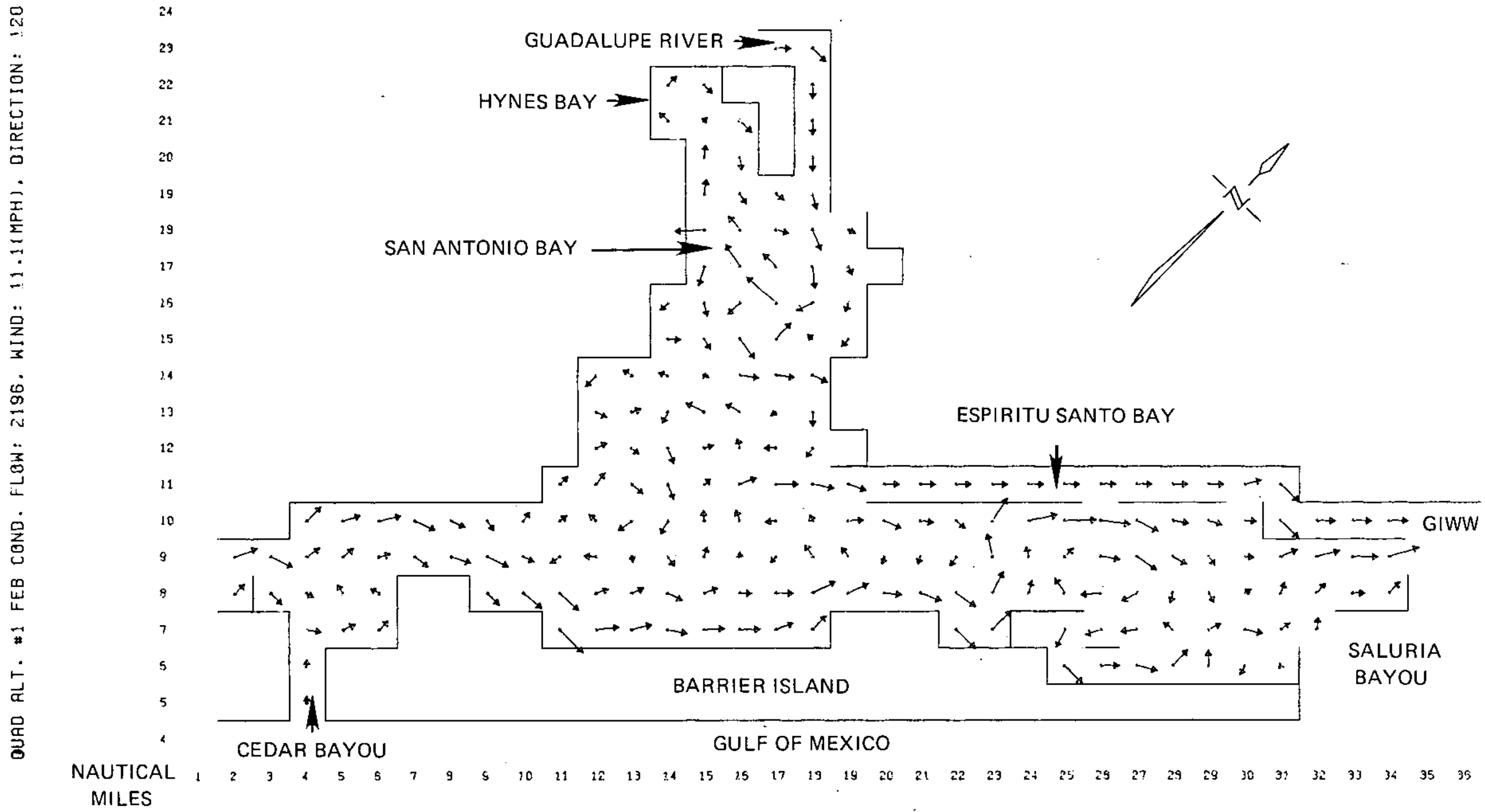

Figure 9-12. Simulated Net Steady-State Flows in the Guadalupe Estuary Under February Freshwater Inflow Needs, Alternative I

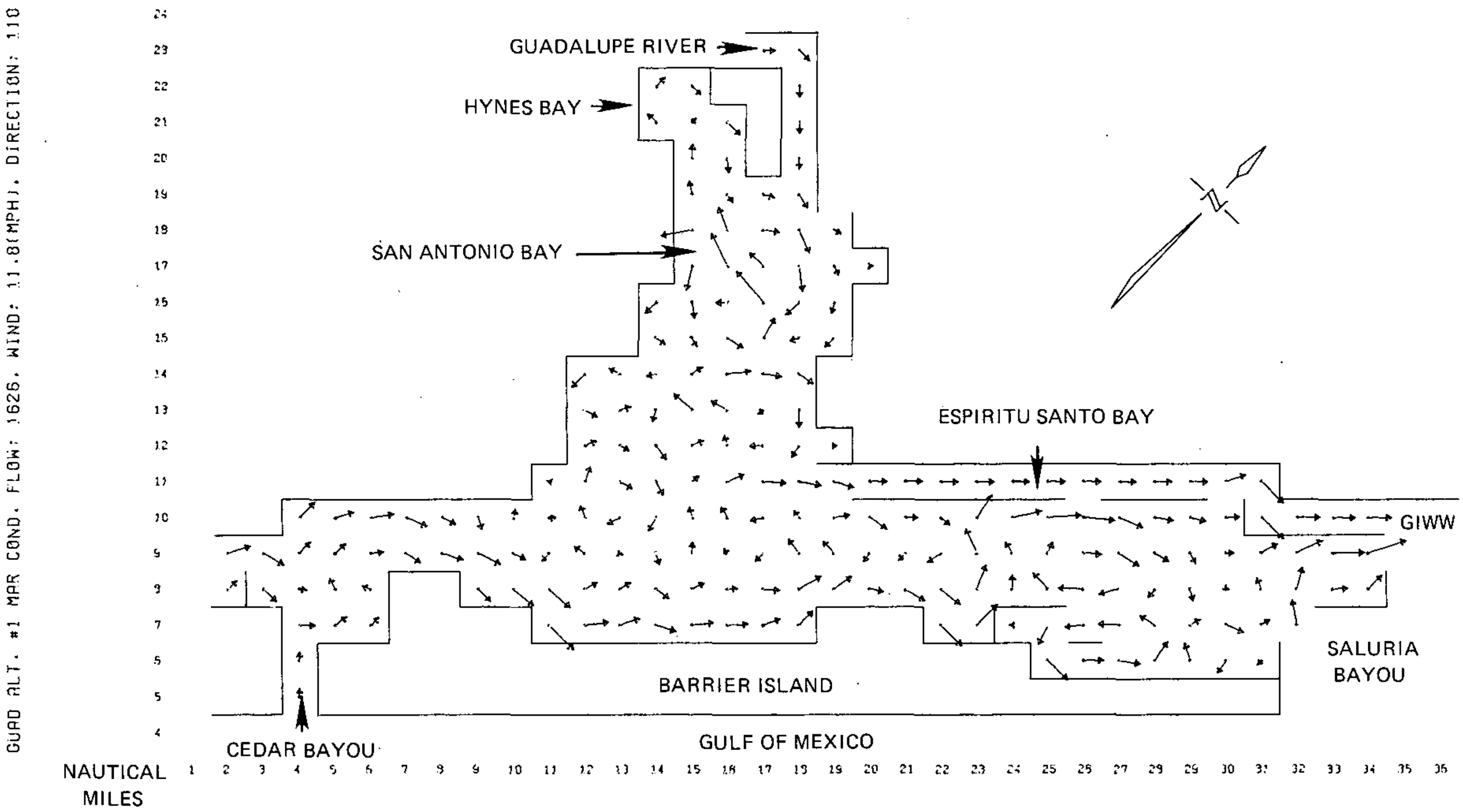

Figure 9-13. Simulated Net Steady-State Flows in the Guadalupe Estuary Under March Freshwater Inflow Needs, Alternative I

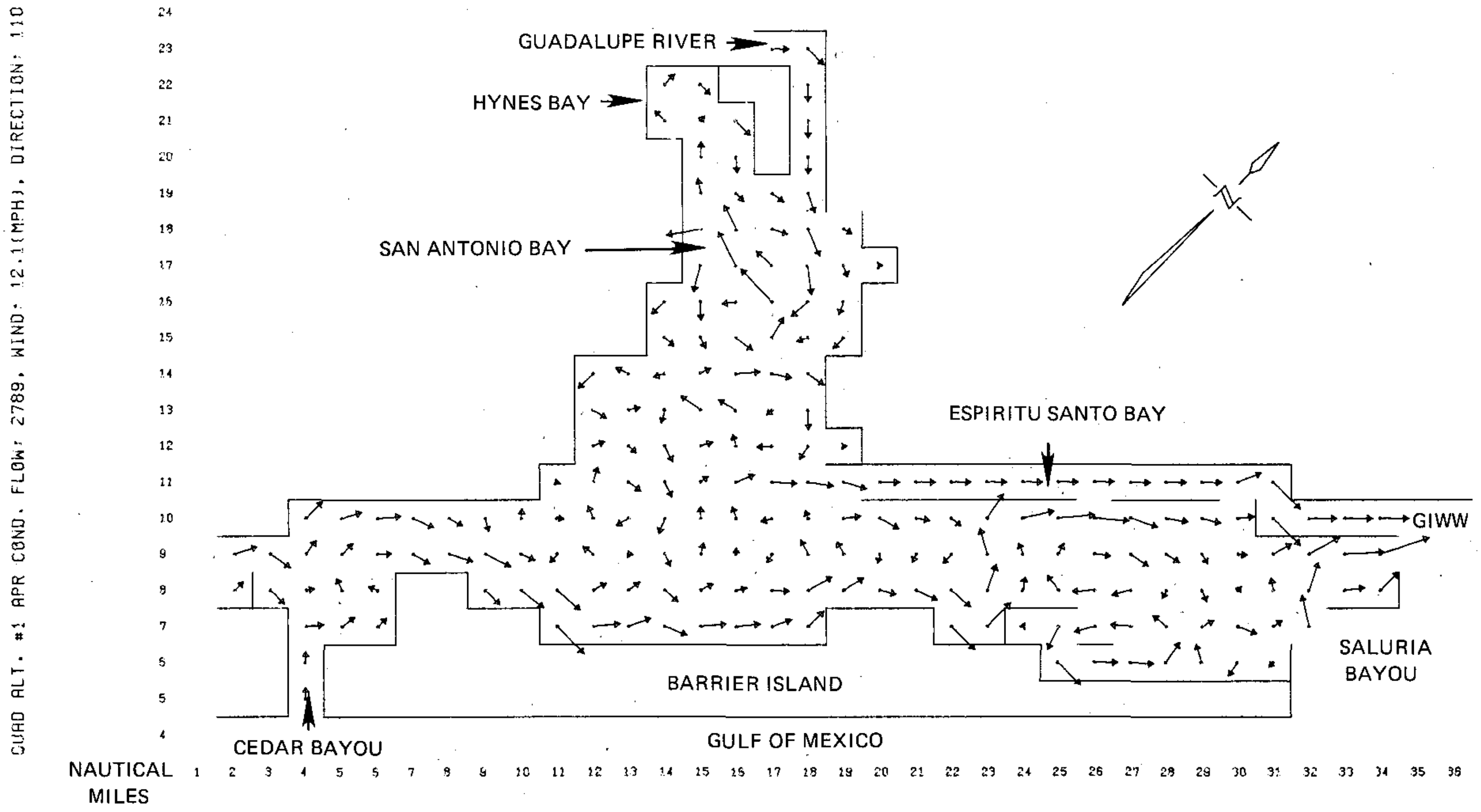

Figure 9-14. Simulated Net Steady-State Flows in the Guadalupe Estuary Under April Freshwater Inflow Needs, Alternative I

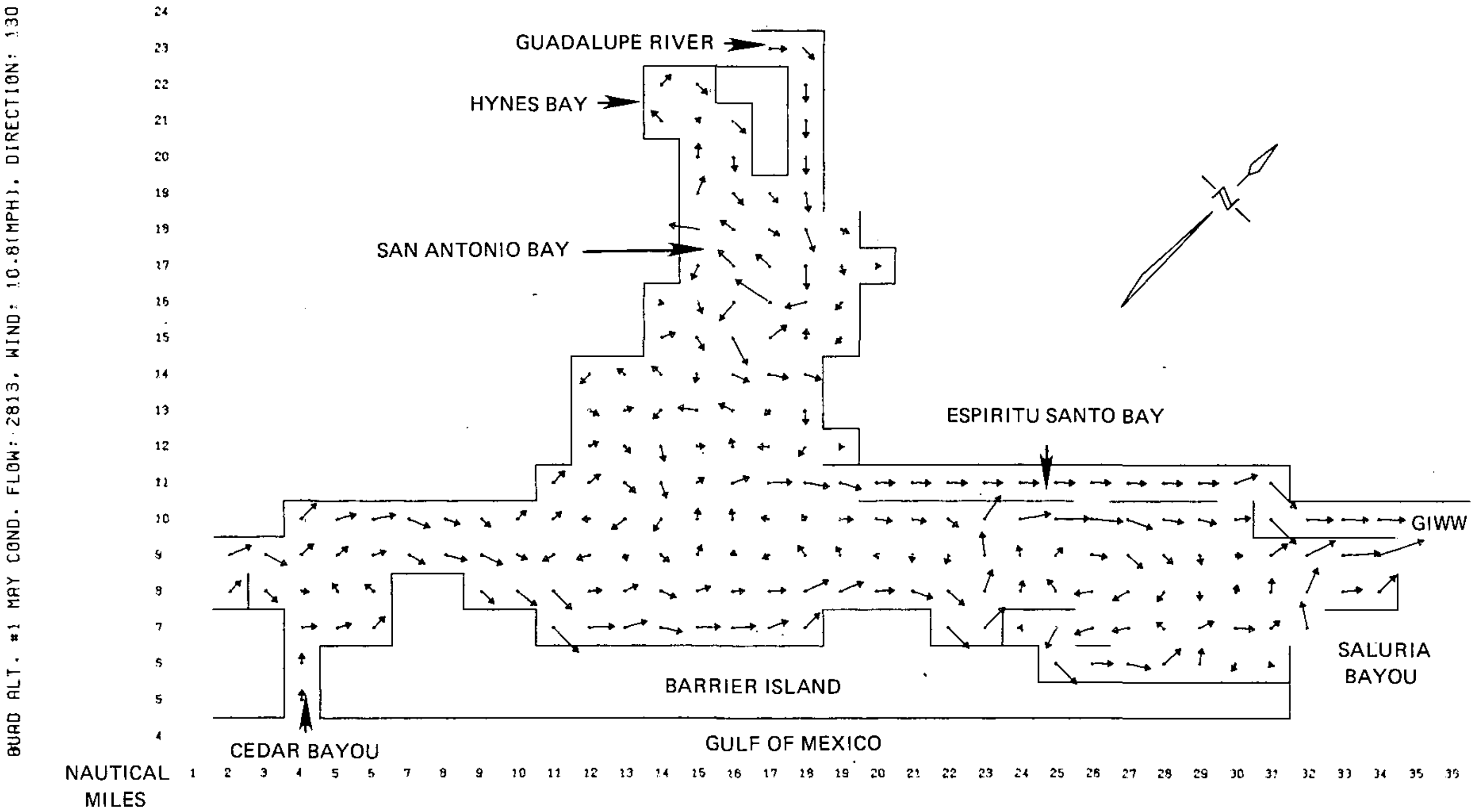

Figure 9-15. Simulated Net Steady-State Flows in the Guadalupe Estuary Under May Freshwater Inflow Needs, Alternative I

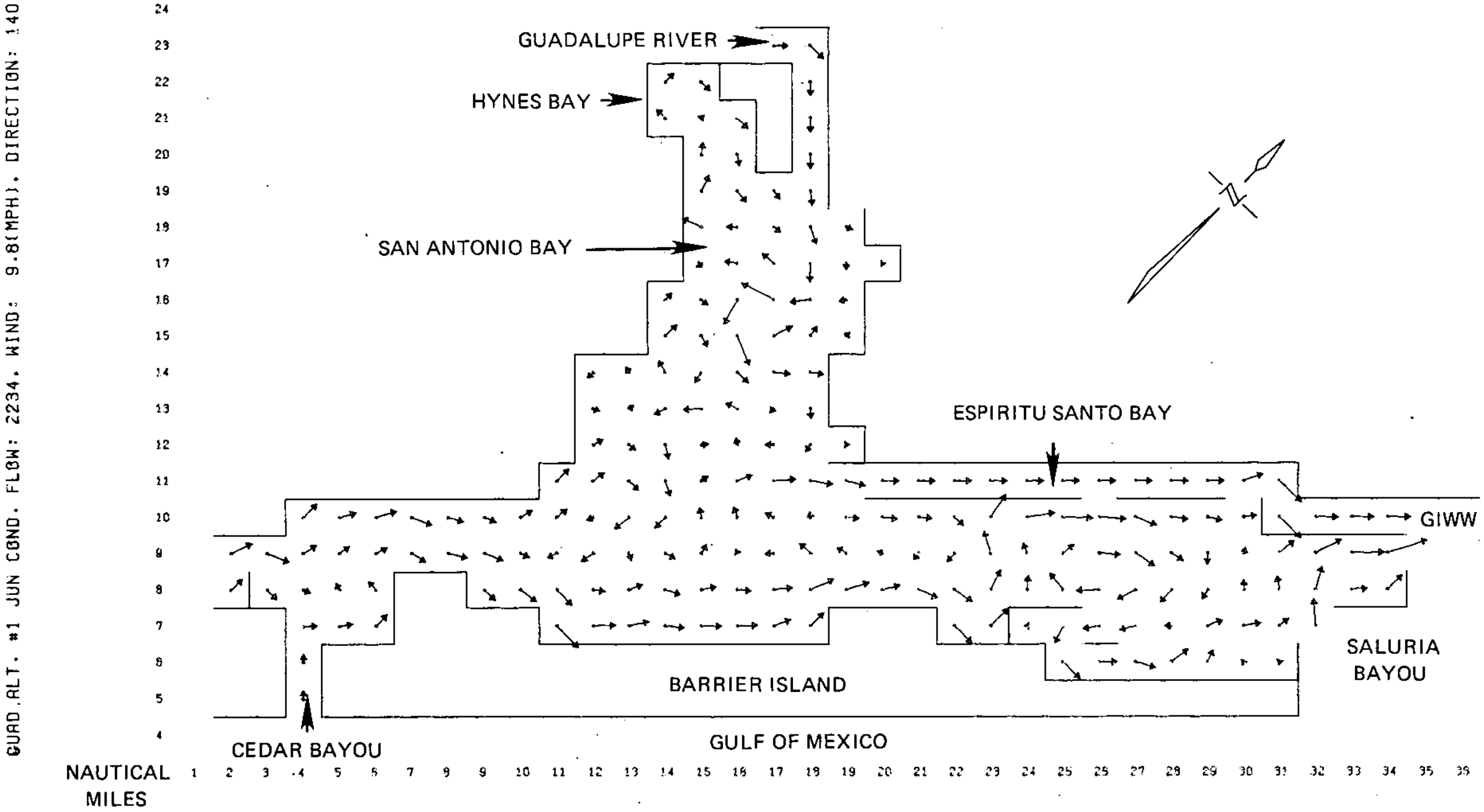

Figure 9-16. Simulated Net Steady-State Flows in the Guadalupe Estuary Under June Freshwater Inflow Needs, Alternative I

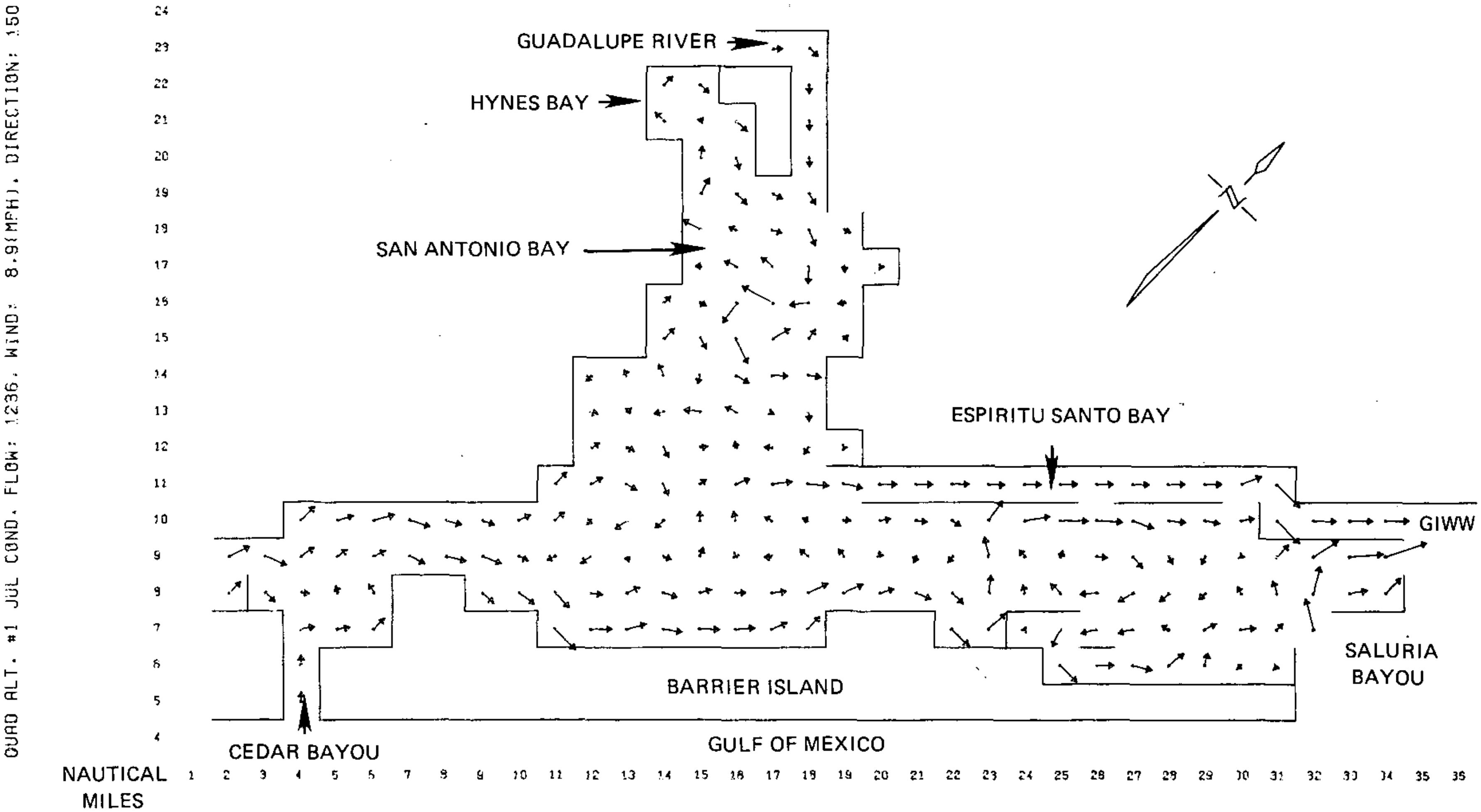

Figure 9-17. Simulated Net Steady-State Flows in the Guadalupe Estuary Under July Freshwater Inflow Needs, Alternative I

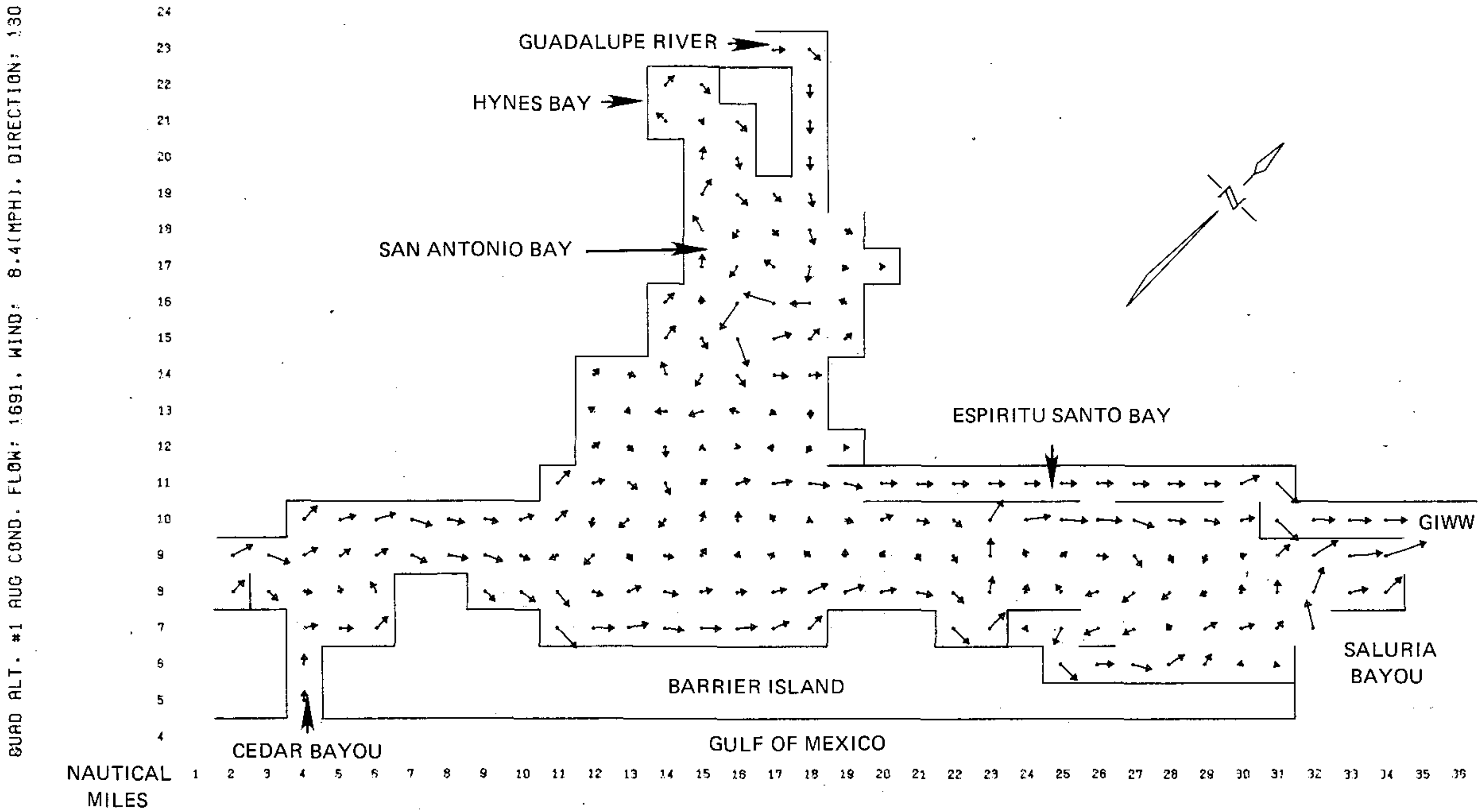

Figure 9-18. Simulated Net Steady-State Flows in the Guadalupe Estuary Under August Freshwater Inflow Needs, Alternative I

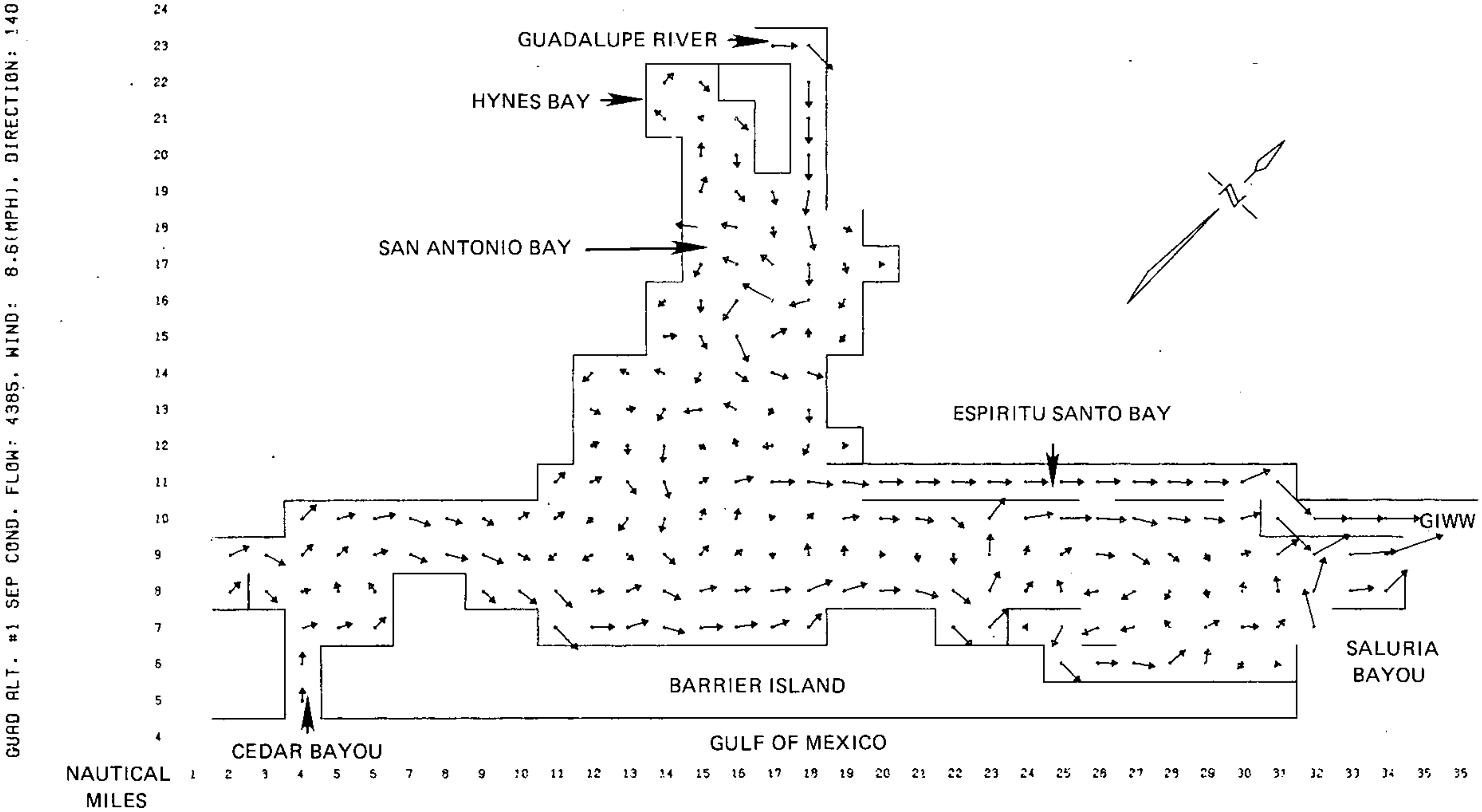

Figure 9-19. Simulated Net Steady-State Flows in the Guadalupe Estuary Under September Freshwater Inflow Needs, Alternative I

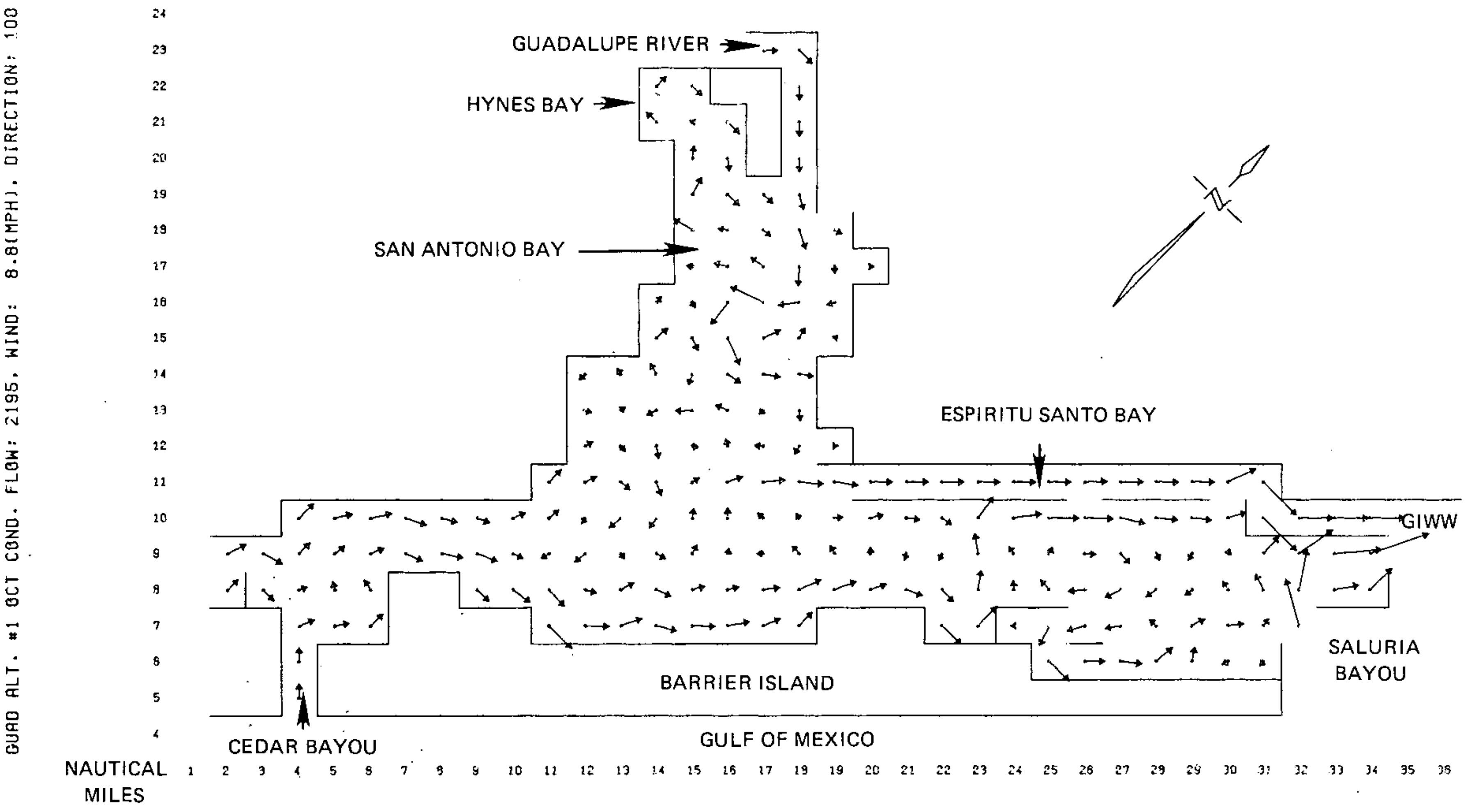

Figure 9-20. Simulated Net Steady-State Flows in the Guadalupe Estuary Under October Freshwater Inflow Needs, Alternative I

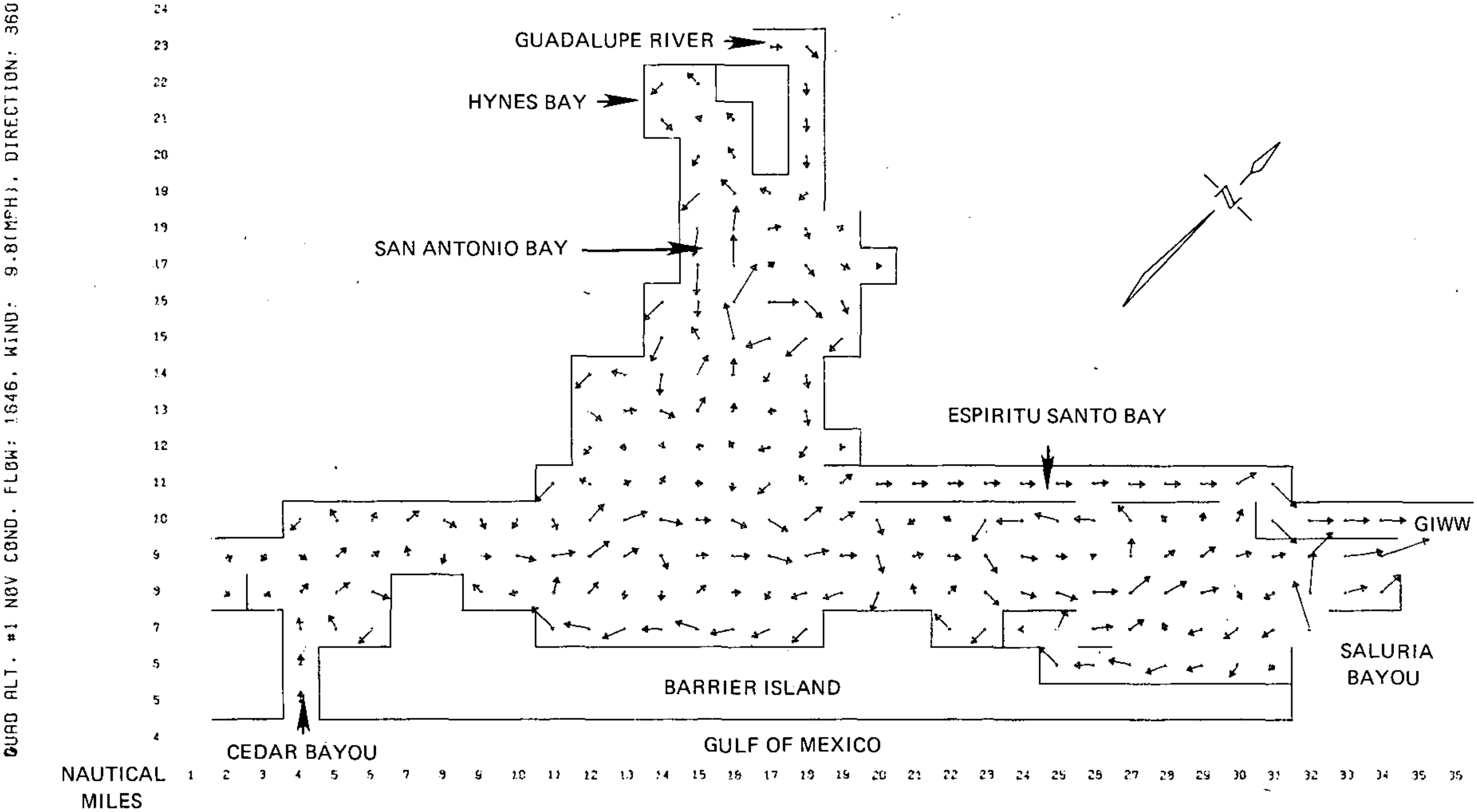

Figure 9-21. Simulated Net Steady-State Flows in the Guadalupe Estuary Under November Freshwater Inflow Needs, Alternative I

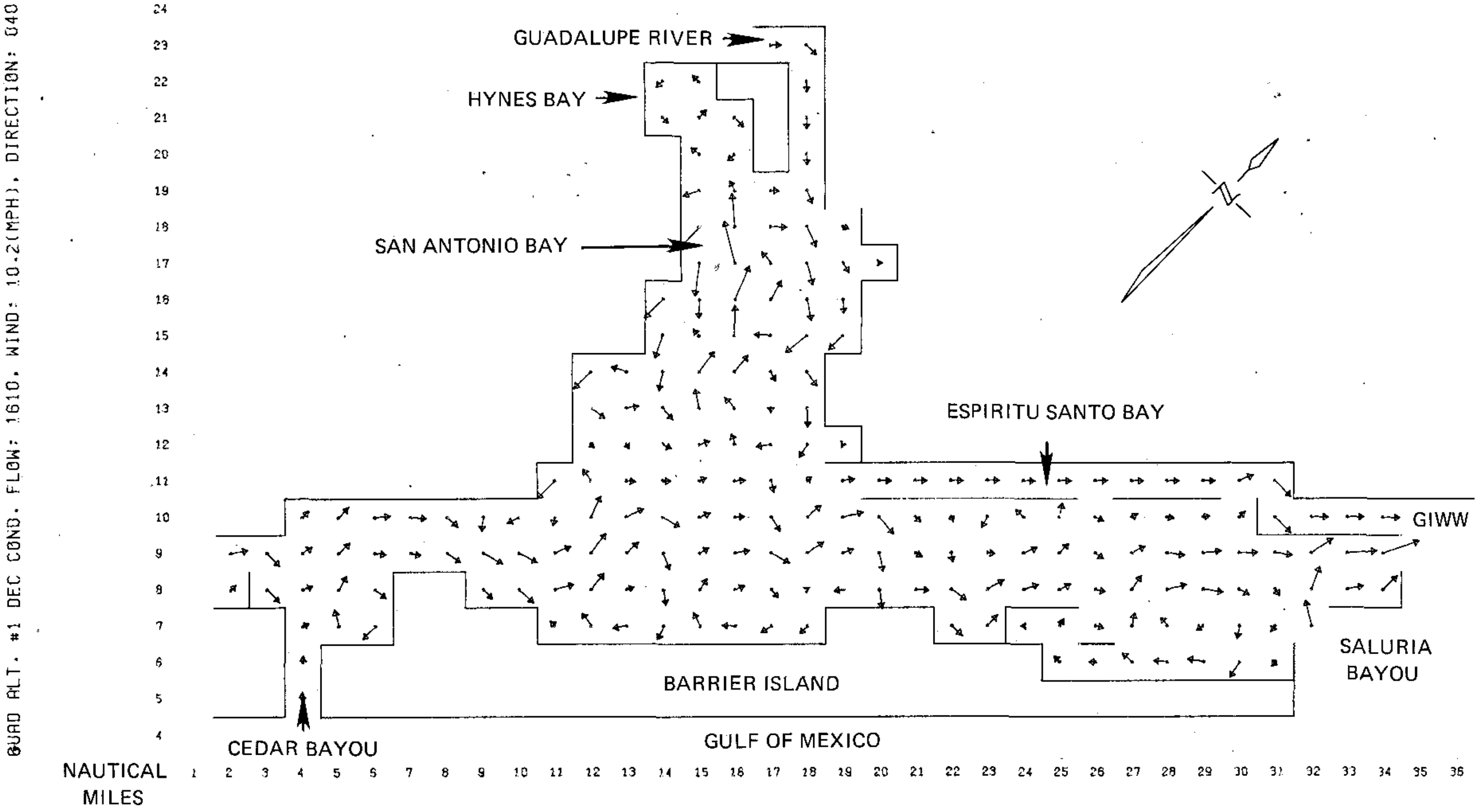

Figure 9-22. Simulated Net Steady-State Flows in the Guadalupe Estuary Under December Freshwater Inflow Needs, Alternative I

(2) Simulated Non-Winter Circulation Patterns. Simulation of the tidal hydrodynamic conditions in the Guadalupe estuary indicated that net flow patterns specified under the monthly freshwater inflow needs of Alternative I were similar for all months except November, December and January (Figures 12 through 20). Similarities occurred even though the historical mean wind speed and direction varied from month-to-month. In April, wind speed averaged 12.8 mph (5.7 m/sec) from the south-southeast, while in August, it averaged 8.1 mph (3.6 m/sec) from the southeast. Wind direction throughout the period March through November was predominantly from the east and southeast.

Predominant net circulation patterns as simulated for these months indicate flow from Mesquite Bay in the southeast, through the lower portion of San Antonio Bay adjacent to the northern coast of Mustang Island, into Espiritu Santo Bay, then along the intracoastal waterway and the northern shore of Espiritu Santo Bay, and finally out of the Guadalupe estuary through the passes leading to the Lavaca-Tres Palacios estuary. The second most significant current pattern simulated showed movement from the mouth of the Guadalupe River into the main portion of San Antonio Bay, then toward the intracoastal waterway, where it joins the current moving from Mesquite Bay.

Several circular current patterns are evident in the simulation for these months. The most significant is located in eastern Espiritu Santo Bay. The current is clockwise in direction and appears to exchange flow with the primary current moving from Mesquite Bay. Other evident circular currents are found in Hynes Bay and the northern portion of San Antonio Bay.

The simulation indicates net flow into the estuary at each of the exchange points with the Gulf of Mexico (Cedar Bayou and Pass Cavallo via Saluria Bayou) and at Cedar Dugout. Simulated net flows out of Guadalupe estuary are found at the passes connecting the Guadalupe and Lavaca-Tres Palacios estuaries, the Intracoastal Waterway channel, and Big Bayou.

Simulated Salinity Patterns. The results of the monthly hydrodynamic simulations were used to provide the basic flow circulation information to execute the salinity transport model for the Guadalupe estuary. The application of the salinity model was undertaken for each of the monthly freshwater inflow needs of Alternative I.

Simulated monthly salinities in the Guadalupe estuary (Figures 9-23 through 9-34) can be divided into two monthly groups having similar characteristics: (1) January, February, March, July, August, November and December; and (2) April, May, June, September and October. The pattern of salinities evident in each of these groupings is discussed in the following paragraphs.

(1) Simulated January, February, March, July, August, November and December Salinity Patterns. The salinities simulated by the numerical mass transport model for the months of January, February, March, July, August, November, and December, range from below 10 parts per thousand (ppt) to over 30 ppt in the Guadalupe estuary (Figures 9-23 to 9-25, 9-29, 9-30, 9-33), and 9-34). Mesquite Bay has simulated salinities of between 25 and 30 ppt in an area adjacent to Cedar Bayou. The salinities decrease from Mesquite Bay into San Antonio Bay, where concentrations in the lower portion of the latter bay were between 20 and 25 ppt. Simulated salinities in Hynes and upper San

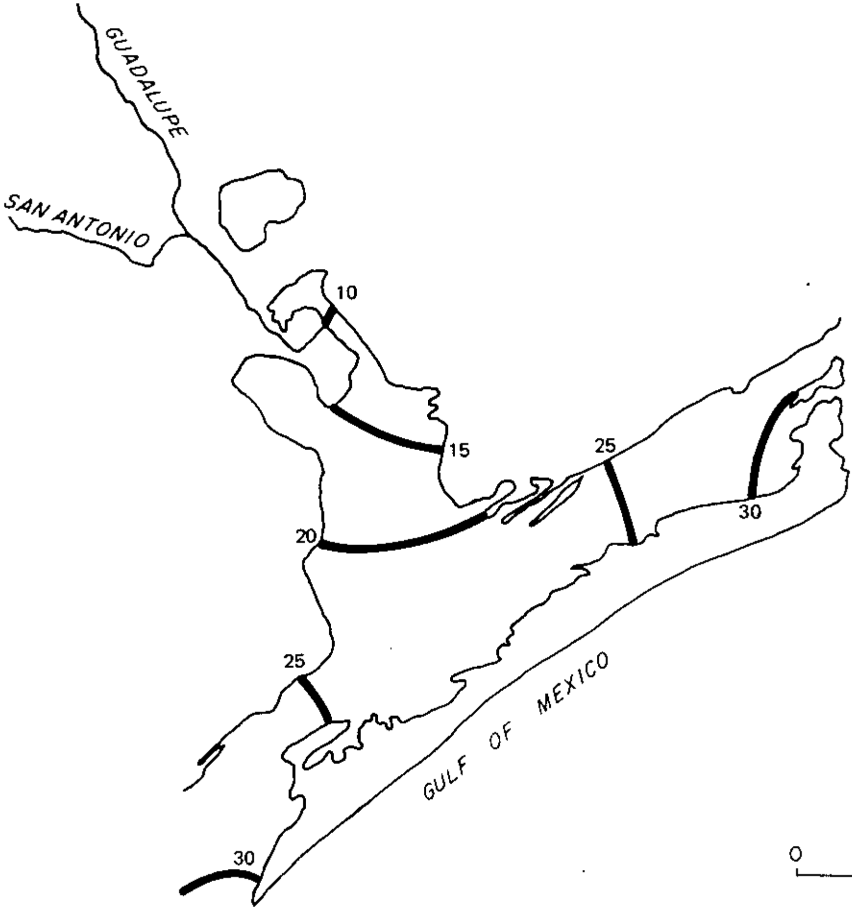

Figure 9-23. Simulated Salinities in The Guadalupe Estuary Under January Freshwater Inflow Needs, Alternative I (ppt)

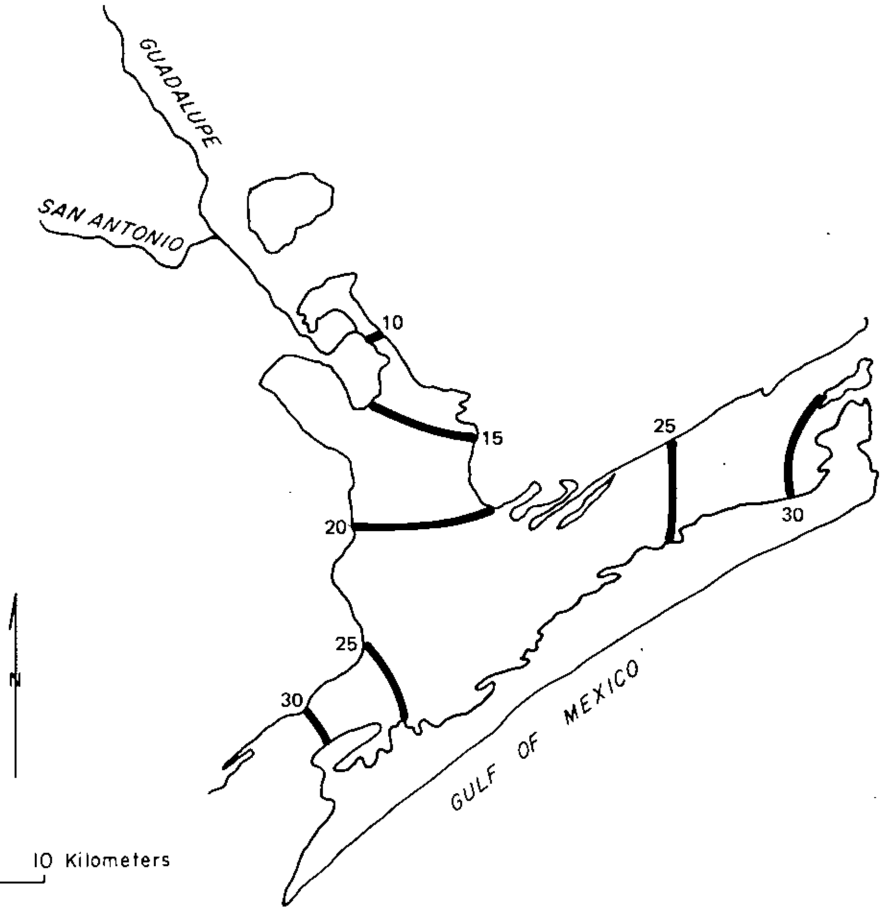

Figure 9-24. Simulated Salinities in the Guadalupe Estuary Under February Freshwater Inflow Needs, Alternative I (ppt)

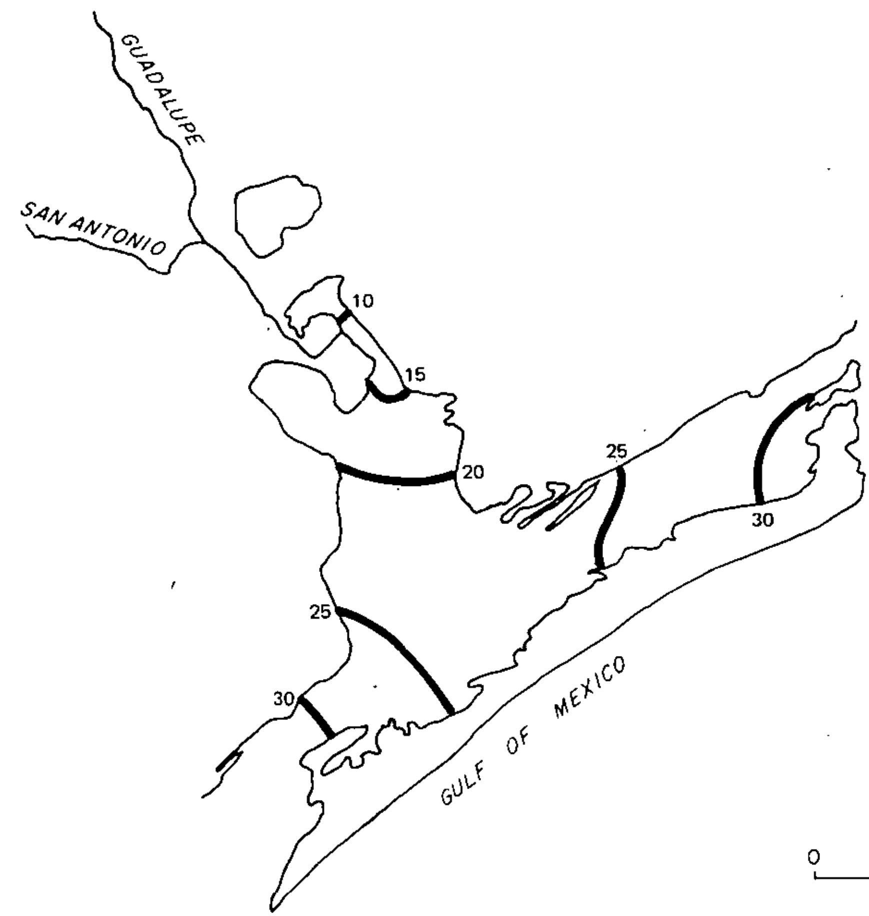

Figure 9-25. Simulated Salinities in The Guadalupe Estuary Under March Freshwater Inflow Needs, Alternative I (ppt)

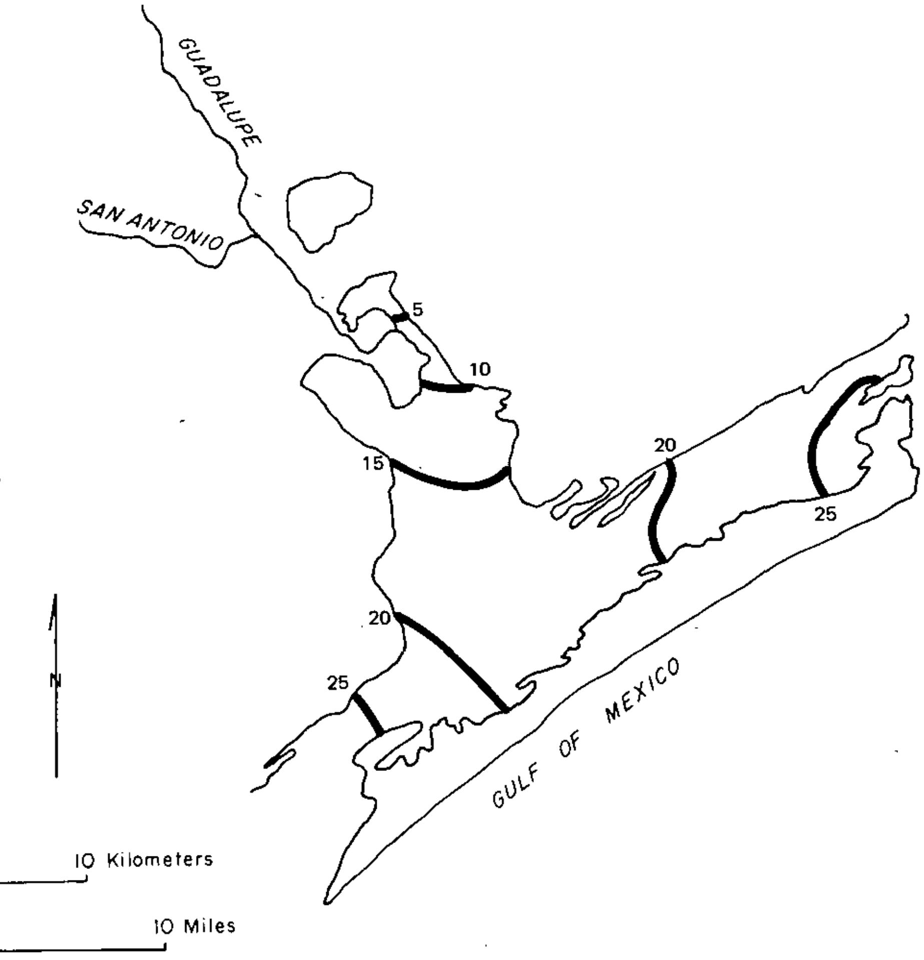

Figure 9-26. Simulated Salinities in The Guadalupe Estuary Under April Freshwater Inflow Needs Alternative I (ppt)

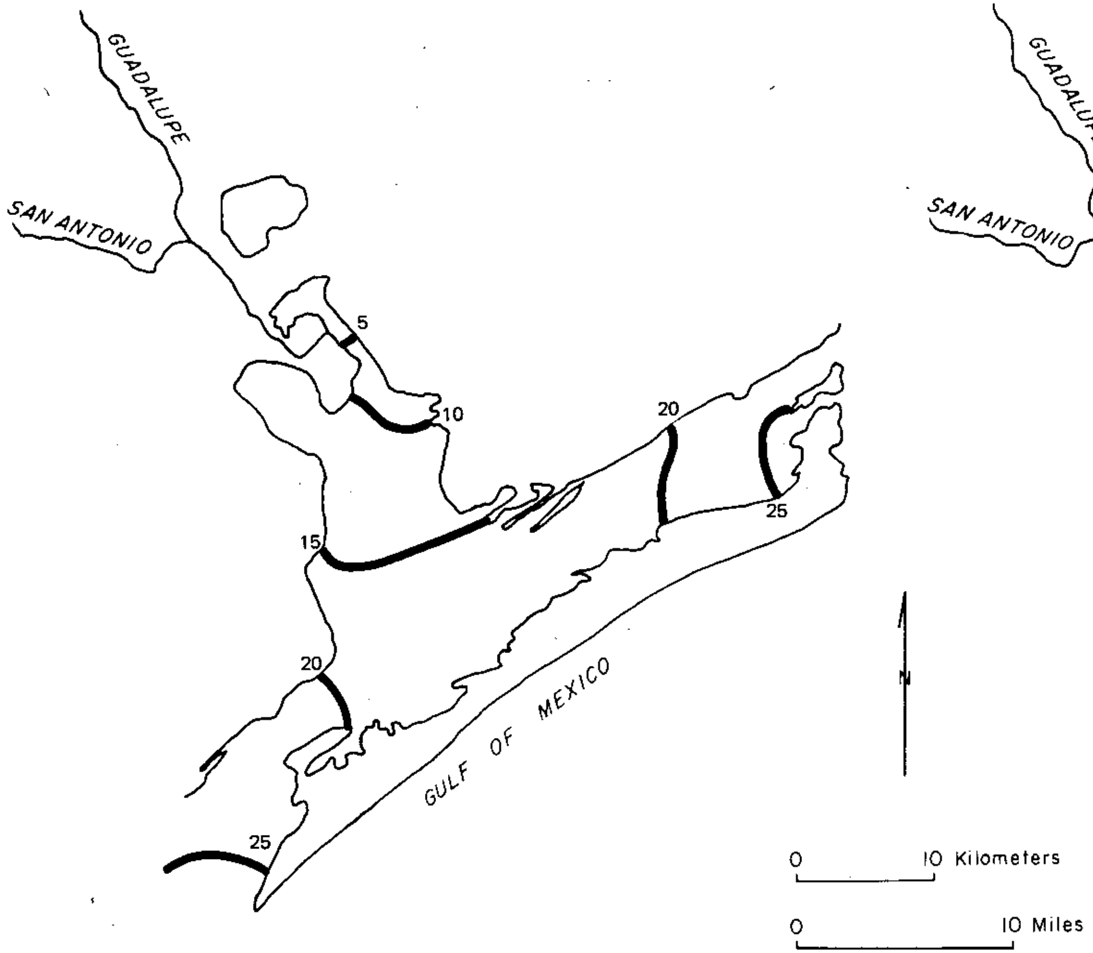

Figure 9-27. Simulated Salinities in The Guadalupe Estuary Under May Freshwater Inflow Needs, Alternative I (ppt)

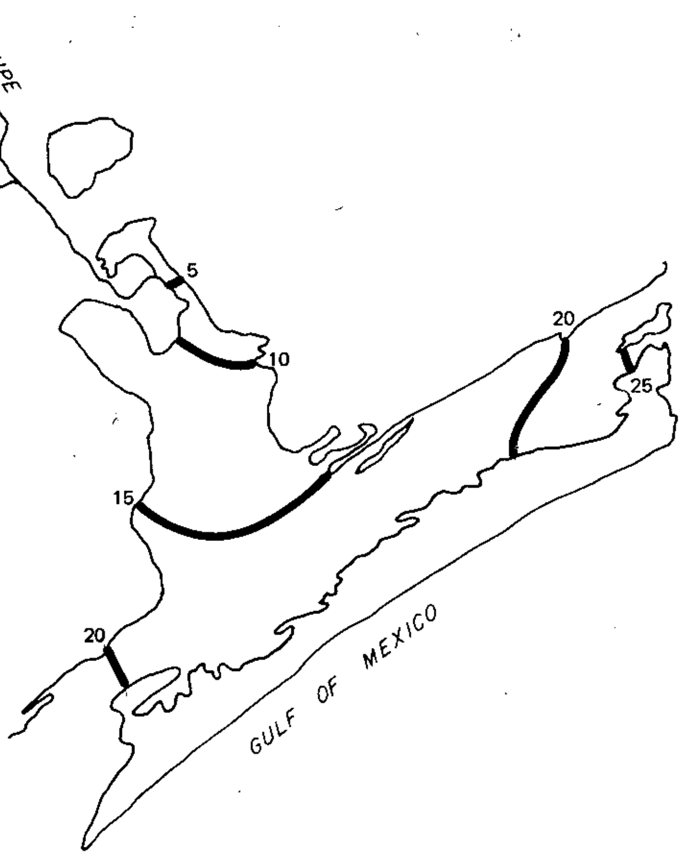

Figure 9-28. Simulated Salinities in The Guadalupe Estuary Under June Freshwater Inflow Needs Alternative I (ppt)

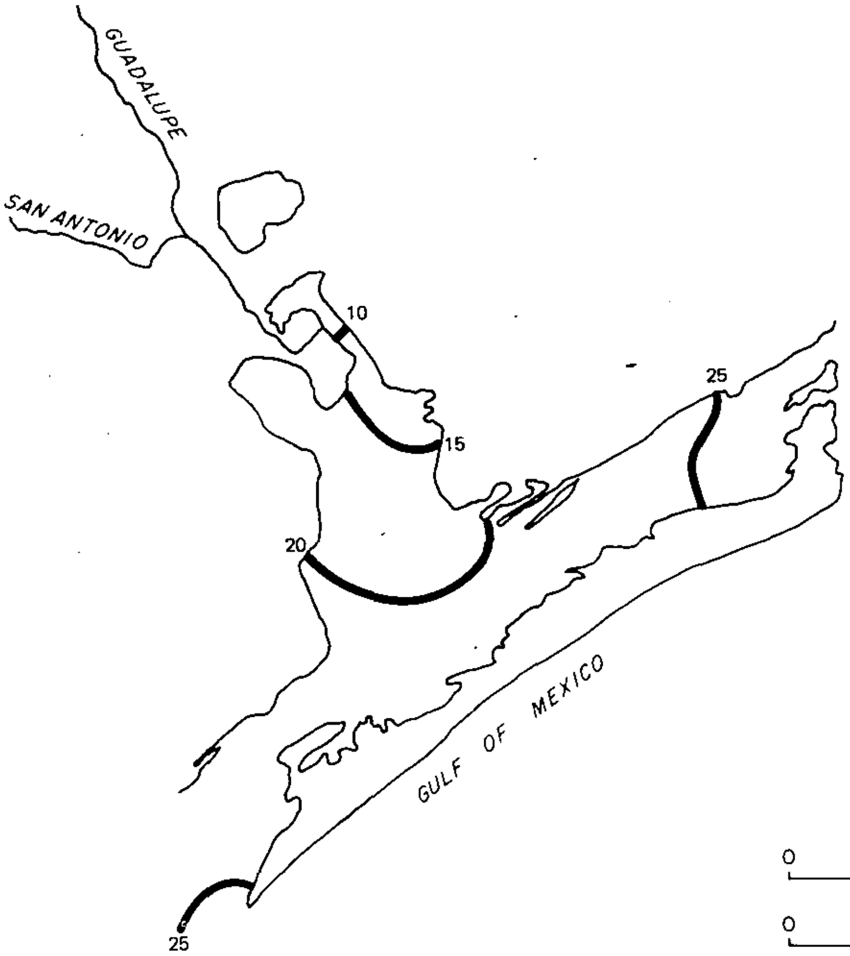

Figure 9-29. Simulated Salinities in The Guadalupe Estuary Under July Freshwater Inflow Needs, Alternative I (ppt)

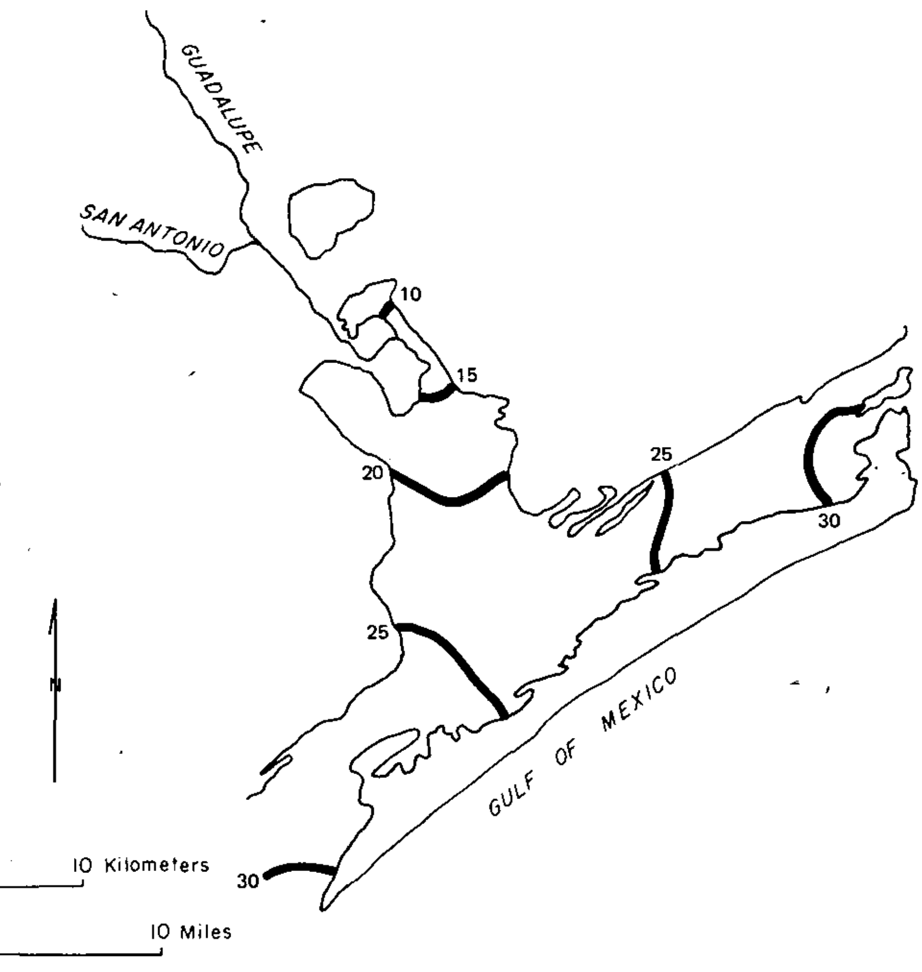

Figure 9-30. Simulated Salinities in The Guadalupe Estuary Under August Freshwater Inflow Needs Alternative I (ppt)

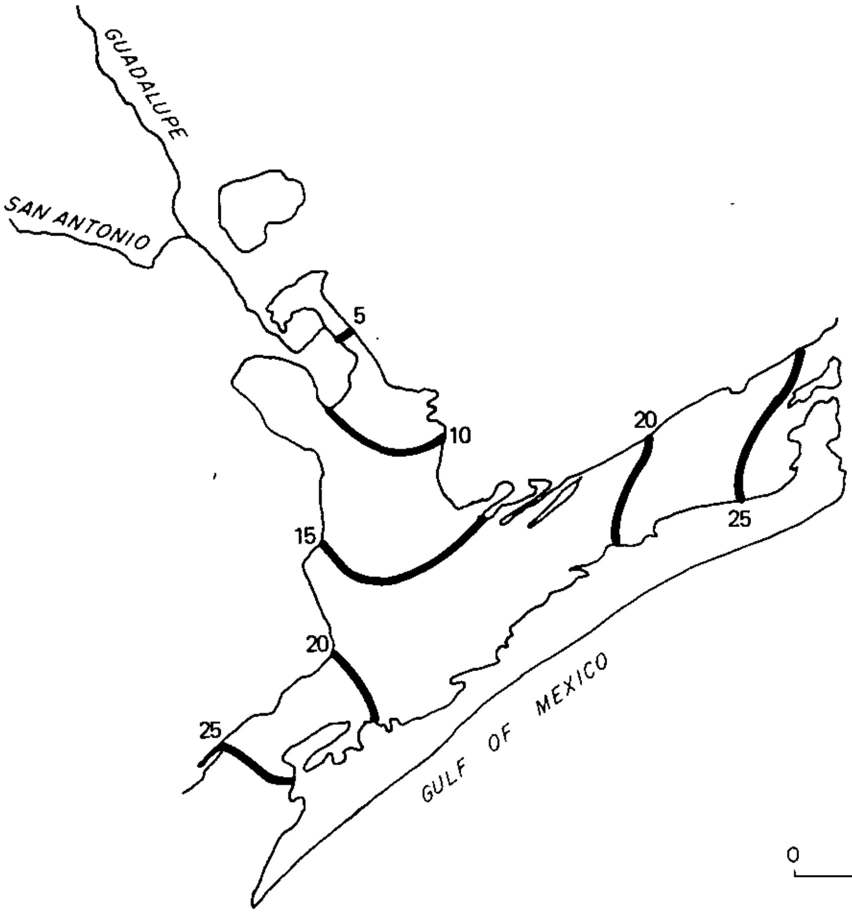

Figure 9-31. Simulated Salinities in The Guadalupe Estuary Under September Freshwater Inflow Needs, Alternative I (ppt)

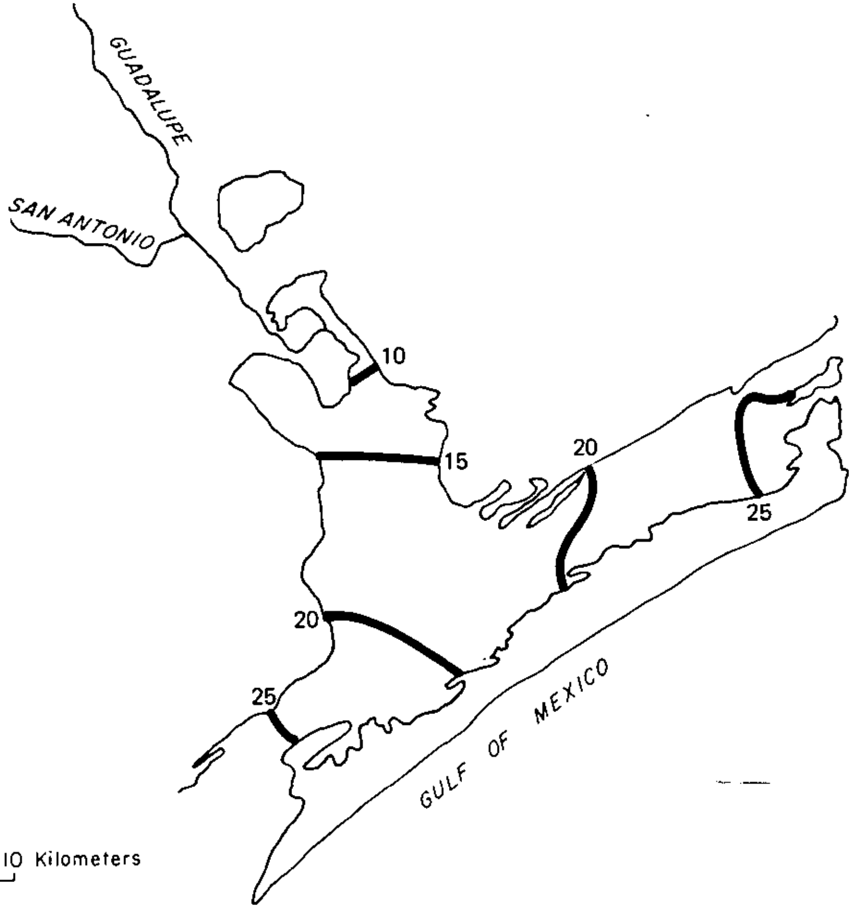

Figure 9-32. Simulated Salinities in the Guadalupe Estuary Under October Freshwater Inflow Needs Alternative I (ppt)

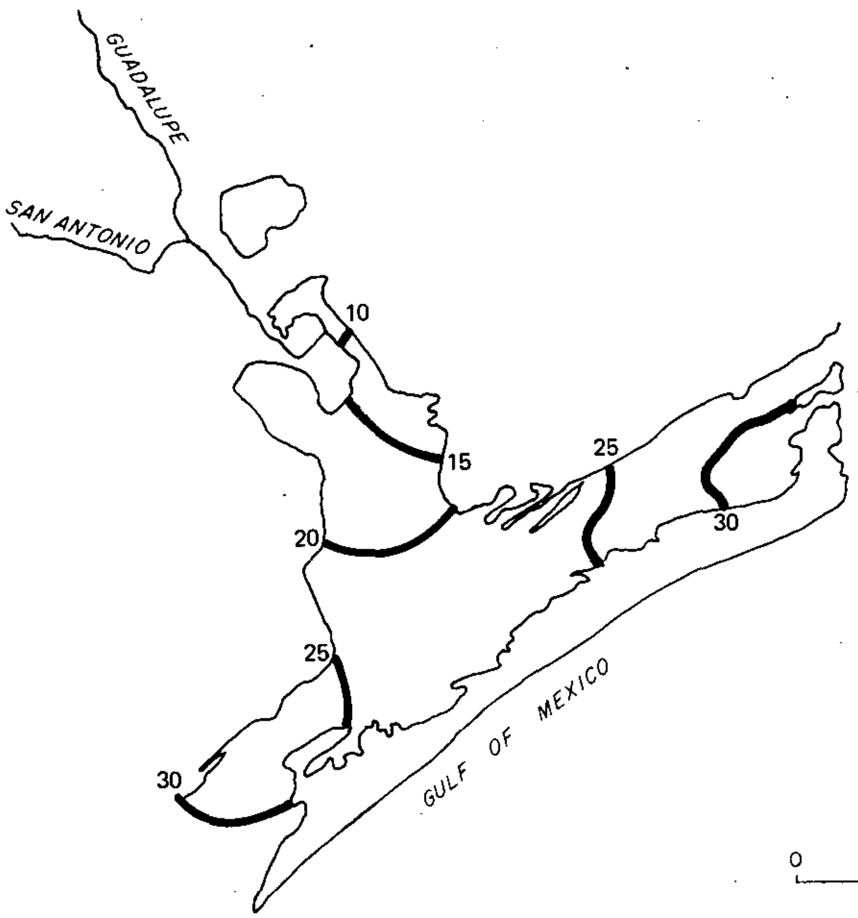

Figure 9-33. Simulated Salinities in The Guadalupe Estuary Under November Freshwater Inflow Needs, Alternative I (ppt)

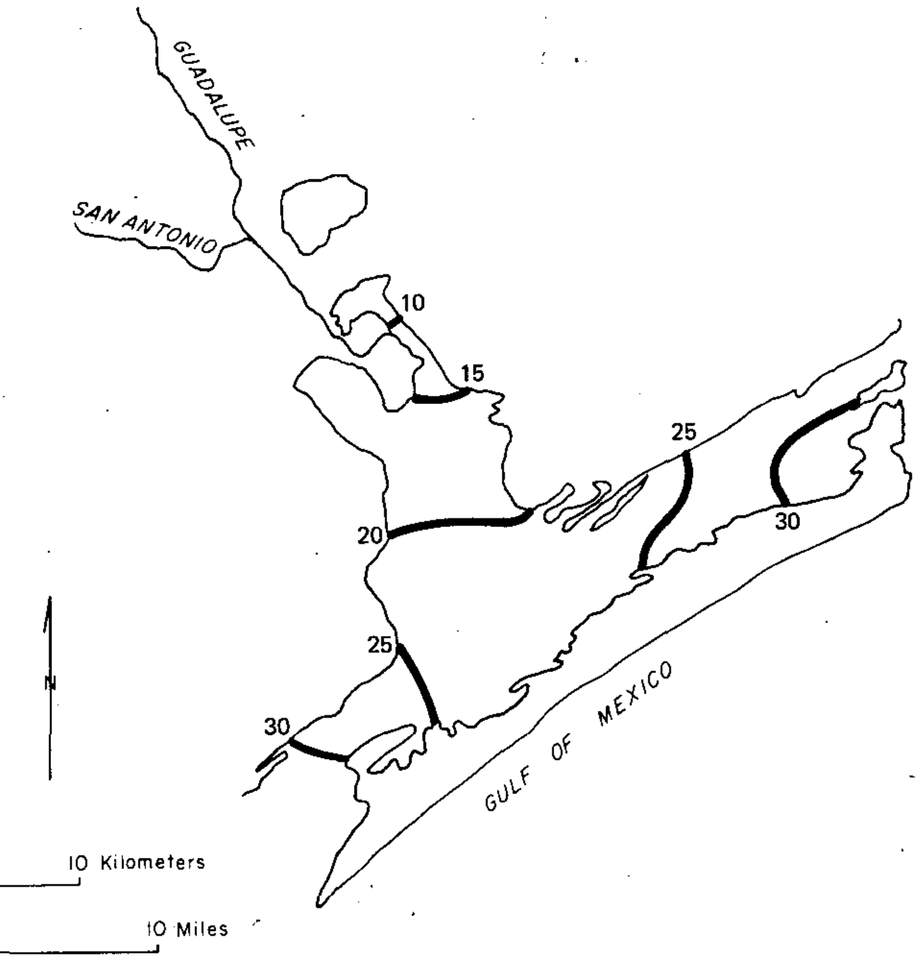

Figure 9-34. Simulated Salinities in the Guadalupe Estuary Under December Freshwater Inflow Needs, Alternative I (ppt)

Antonio Bay are between 15 and 20 ppt, with Guadalupe Bay and Mission Lake concentrations of less than 10 parts per thousand. Salinities increased from San Antonio Bay into Espiritu Santo Bay where they ranged from 20 ppt at the western end of the bay to over 30 ppt at the extreme eastern end near Saluria Bayou having concentrations less than 10 ppt. Salinities increase from San Antonio Bay into Espiritu Santo Bay where they ranged from 20 ppt at the western end of the bay to over 30 ppt at the extreme eastern end near Saluria Bayou.

(2) Simulated April, May, June, September and October Salinity Patterns.

Simulated salinities throughout the Guadalupe estuary showed definite similarities for the months of April, May, June, September and October (Figures 9-26 to 9-28, 9-31, and 9-32). In all of these months Mesquite Bay generally has simulated salinities above 25 ppt. Lower salinities occur in San Antonio Bay, with the lower half of the bay having concentrations of between 15 and 20 ppt, whereas the upper portion of the bay has salinities less than 15 ppt. The simulated salinity in Hynes Bay is between 10 and 15 ppt. The area in San Antonio Bay immediately adjacent to Guadalupe Bay has simulated salinities of less than 10 ppt, with the salinity in Guadalupe Bay and Mission Lake at less than 5 ppt. The simulated salinities in Espiritu Santo Bay vary from 15 to 20 ppt in areas adjacent to San Antonio Bay to over 25 ppt at the flow exchange points with the Lavaca-Tres Palacios estuary.

In all of the monthly simulations, the salinities in the middle portion of San Antonio Bay were simulated at under 25 ppt; thus, further refinements of the estimated monthly freshwater inflow needs for the three alternatives were not considered necessary.

Interpretation of the Physical Significance of the Estimated Freshwater Inflow

The monthly freshwater inflow estimated in this report for the Guadalupe estuary from the Guadalupe River Basin represents the best statistical estimate of monthly inflows satisfying selected specified objectives for the major estuarine factors of marsh inundation, salinity distribution, and fisheries harvests. These estimates cover a range of potential factors and illustrate the complexity of the estuarine system.

Freshwater inflows approximately equal to the estimated needs may give estuarine responses which are indistinguishable, on a statistical basis, from the desired conditions. Confidence limits can be obtained for changes in estuarine conditions, such as salinity, using statistical techniques. It is not clear, however, as to the proper technique for determining confidence bounds on the actual monthly inflow estimates for those months where the individual confidence limits on the inflow needs for salinity, harvest and inundation must be combined into a single confidence interval.

A wide variability of freshwater inflow occurs in Texas estuaries from year-to-year, through drought and flood cycles. The monthly freshwater inflow levels received by the estuary fluctuate about the average inflow due to natural hydrologic variability. Such fluctuations are expected to continue to exist for practically any average level of inflow that might occur or that might be specified. It is not likely that sufficient control can be exerted to completely regulate the inflow extremes. In fact, to do so may be detrimental to the process of natural selection. However, some provision may be needed to prevent an increase in the frequency of periods of low flow. Such a provision could specify minimum monthly inflows required to keep salinities below the upper viability limits indicated for the key species of the estuary (Table 9-1).

Summary

A methodology is presented which combines the analysis of the component physical, chemical and biological elements of the Guadalupe estuary into a sequence of steps which result in estimates of the freshwater inflow needs for the estuary based upon specified salinity, marsh inundation and commercial bay fisheries harvest objectives.

Monthly salinity limits are established at locations in the estuary below the "null zone" and near the inflow point of the Guadalupe River Basin. These upper and lower limits on monthly salinity provide a range within which viable metabolic activity can be maintained and normal historical salinity conditions can be observed.

Marsh inundation needs for the flushing of nutrients from riverine marshes into the open bays are specified for the Guadalupe River delta. The delta is frequently submerged by floods from the San Antonio and Guadalupe Rivers. Based upon historical conditions and gaged inflow records, freshwater inflow needs for marsh inundation are specified at 125 thousand acre-feet in April, May, June, October and September. These volumes correspond to flood events with peak daily flow rates of 12,500 ft^3/sec.

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

The monthly freshwater inflow needs for the Guadalupe estuary were estimated for each of the following three alternatives.

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

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

Alternative III (Shrimp Harvest Enhancement): maximization of the total annual bay harvest of shrimp while observing salinity viability limits and marsh inundation needs, providing for a total shellfish harvest no less than the annual historical 1962 through 1976 average harvest, and utilizing an annual Guadalupe River inflow no greater than the average historical inflow for the period 1941 through 1976.

Under Alternative I (Subsistence), the Guadalupe system, which has functioned as both a commercial shellfish and finfish producing system in the past, can continue to be an important fisheries producing estuary with substantially less freshwater inflow, but at the expense of significantly reduced estimated fisheries harvests. Freshwater inflows totaling 1.6 million acre-feet annually are predicted to satisfy the basic salinity gradient and marsh inundation needs, but with resulting decreases in annual commercial bay finfish harvest of 43 percent and shellfish harvest of nine percent, from average annual values for the period 1962 through 1976.

Under Alternative II (Maintenance of Fisheries Harvests), the predicted annual commercial harvests of red drum, spotted seatrout, shrimp, and total shellfish are required to be at least as great as 1962 through 1976 historical average levels, as well as to meet salinity bounds and inundation needs. To satisfy these criteria, annual freshwater inflows of 2.02 million acre-feet are needed.

Under Alternative III (Shrimp Harvest Enhancement), the Guadalupe estuary annually needs an estimated 2.26 million acre-feet distributed in a specified seasonal manner. The objective maximizes the total annual predicted commercial bay harvest of shrimp, under the conditions that the predicted total shellfish harvest is at least as great as the 1962 through 1976 historical average while the average 1941 through 1976 annual inflow to the estuary is available. This objective is achieved with a 34 percent increase in total shrimp harvest, with an estimated loss of 54 percent in the total commercial finfish harvest (including a 52 percent decline in the commercial harvest of red drum and a 66 percent decline in commercial seatrout harvest).

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

The net circulation patterns simulated by the tidal hydrodynamic model indicate that the dominate net circulation pattern in the Guadalupe estuary is a net movement of water from Mesquite Bay through San Antonio Bay and Espiritu Santo Bay into the Lavaca-Tres Palacios estuary. Simulated water movements in the upper and middle portions of San Antonio Bay were dominated by internal currents induced by freshwater inflows from the Guadalupe River. Simulated flows in Espiritu Santo Bay are governed by a major internal circulation current which moves with a clockwise rotation.

The simulated salinities in the Guadalupe estuary for the Alternative I monthly freshwater inflow needs vary over a wide range monthly. Salinities throughout the estuary are generally lowest in the month of June, with average simulated salinities of less than 25 parts per thousand (ppt) over the entire estuary. The highest levels of simulated salinities occur during the month of

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

August, when salinities in Mesquite Bay near Cedar Bayou exceed 30 ppt. The simulated salinities in upper San Antonio Bay are generally less than 15 ppt throughout the year. The major portion of San Antonio Bay has simulated salinities no greater than 20 to 25 ppt; however, during the high freshwater inflow months of May and June, the salinities in the bay are between 10 and 20 ppt. Since the middle portion of San Antonio Bay has simulated salinities in all months below the target maximum allowable concentration of 25 ppt, the freshwater inflow needs established by the Estuarine Linear Programming Model are adequate to sustain desired salinity gradients throughout the estuary.

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

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

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Project Supervision - Administrative Staff

Executive Directors Office – Seth C. Burnitt
Planning and Development Division – Herbert W. Grubb, Director
– William A. White, Assistant Director
Engineering and Environmental and Systems Section – Quentin W. Martin, Chief
Economics, Water Requirements and Uses Section – Jim Hull, Acting Chief

Report Preparation

Editing:	Charles Chandler Jan Knox Leon Byrd	Drafting:	Nancy Kelly Leroy Killough
Typing:	Zelphia Severn Jean Hobbs	Computer Graphics:	Roger Wolff
Proofing:	Leon Byrd Jan Knox Charles Chandler	Other Technical Assistance:	Nick Carter Wiley Haydon Norman Merryman

Chapter Authors:

Chapter I – Summary
Numerous Contributors

Chapter II – Concepts and Methods
Quentin Martin
Gary Powell

Chapter III – Description of the Estuary and the Surrounding Area
Leon Byrd
Jan Knox
Butch Bloodworth
Anita Locy
Charles Gilliam

Chapter IV – Hydrology
Gary Laneman
Charles Chandler
Alan Goldstein
Stuart Madsen

Chapter V – Circulation and Salinity
Gordon Thorn
Michael Sullivan
George Chang
Norman Merryman

Chapter VI – Nutrient Processes
Alan Goldstein
Sandra Belaire
Gary Powell

Chapter VII – Primary and Secondary Production
Sandra Belaire

Chapter VIII – Fisheries
Gary Powell

Chapter IX – Estimated Freshwater Inflow Needs
Quentin Martin
Alan Goldstein
Gary Powell
Gordon Thorn

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