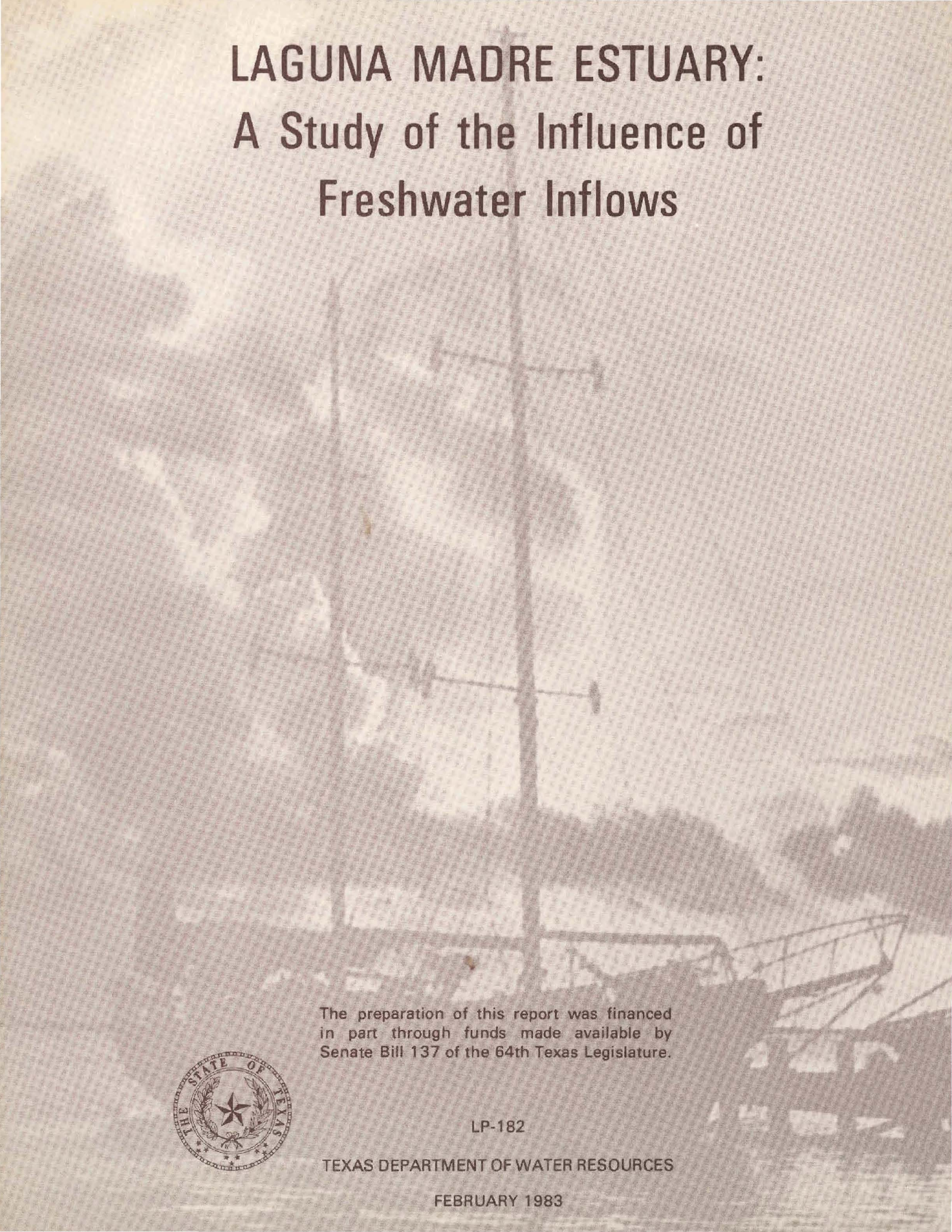
LAGUNA MADRE ESTUARY: A Study of the Influence of Freshwater Inflows



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TEXAS DEPARTMENT OF WATER RESOURCES

FEBRUARY 1983

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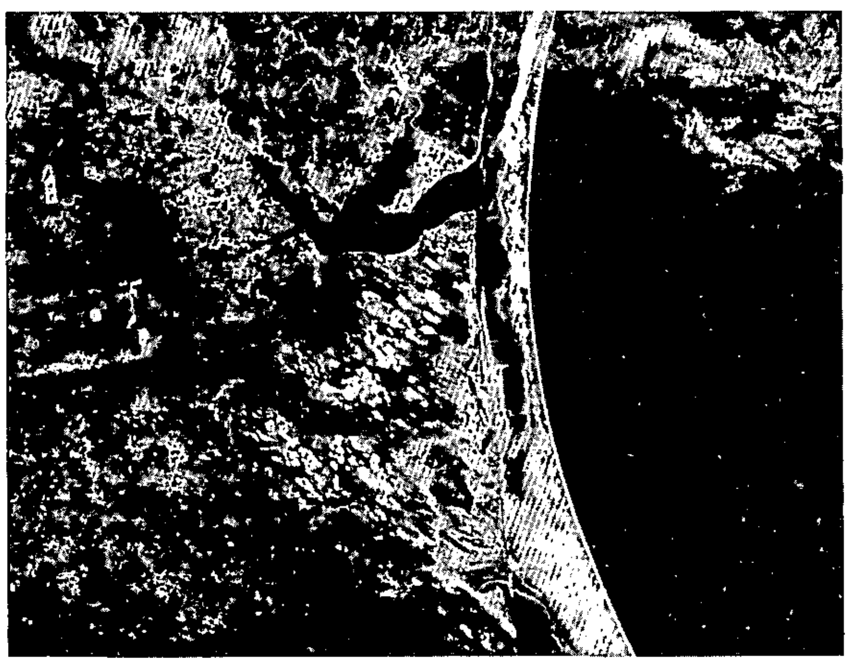

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PREFACE

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. Seven major estuaries on the Texas coast are part of the series, including (1) the Laguna Madre estuary, (2) the Nueces estuary, (3) the Mission-Aransas estuary, (4) the Guadalupe estuary, (5) the Lavaca-Tres Palacios estuary, (6) the Trinity-San Jacinto estuary, and (7) 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.

ABSTRACT

The Laguna Madre is one of three oceanic, hypersaline, lagoonal areas known in the world. The most divergent estuarine region in Texas, the Laguna Madre has a water surface area of less than 440 square miles (1,140 km^2) under mean low tidal conditions. Contributions of freshwater from the surrounding river and coastal drainage basins are generally modest, with combined inflows estimated to average only 689 thousand acre-feet (849 million m^3) per year over the 1941 through 1976 historical period. During the 1972 through 1976 interval, the average annual sport and commercial harvest of fish and shellfish seafoods is estimated at 7.3 million pounds (3.3 million kg; 12 percent shellfish). At this level of fishing activity, the total annual economic impact is estimated to be $39.7 million in 1976 dollars. Major estuarine-dependent species harvested include the black drum, red drum (redfish), spotted seatrout, and brown shrimp.

Freshwater inflows to Texas bays and estuaries are a vital factor in maintaining estuarine productivity, as well as a significant contributor to the near-shore (neretic) productivity of the Gulf of Mexico. It is assumed that the importance of freshwater flow to the Laguna Madre can be analyzed through effects on key indicators such as water quality, circulation and salinity patterns, and fisheries production. For the fisheries species, variations in productivity are indicated to be affected by the seasonal quantities and sources of freshwater inflow through ecological interactions involving salinity (osmoregulation), nutrients (biogeochemical cycling), food (prey) production, and habitat availability.

Determining estimates of the freshwater inflow needs of the Laguna Madre requires utilization of sophisticated mathematical and analytical techniques in order to integrate the large number of relationships and constraints involved. Freshwater need estimates were computed using an Estuarine Mathematical Programming Model. The model calculates the monthly freshwater flows from the Baffin Bay drainage area, and those of the Arroyo Colorado and North Floodway, which best achieve the specified objectives. The objectives could be varied to produce almost any desired estuarine condition, but three long-term (multi-year average) alternative need levels were selected for estimation. Alternative I, the ecosystem subsistence level, has the objectives of minimizing the annual combined freshwater inflow while meeting monthly salinity viability limits that provide an opportunity for survival, growth, and reproduction of the estuarine-dependent organisms. The Alternative I freshwater inflow need is estimated to be an average 344 thousand acre-feet (424 million m^3) per year. Alternative II, the level for maintenance of the fisheries, is calculated to average 578 thousand acre-feet (713 million m^3) annually, and has the same objectives as Alternative I, plus provides sufficient inflows to give predicted fisheries harvests at no less than their average historic levels. Alternative III, the level of inflow necessary for fisheries harvest enhancement, is estimated at an annual average of 602 thousand acre-feet (743 million m^3) and also has the same basic objectives of Alternative I, but additionally includes maximizing the fish harvest in upper Laguna Madre and the shrimp harvest in Gulf Area No. 21 offshore of the lower Laguna Madre without causing the lower Laguna Madre fish harvest to fall below its historical average.

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CHAPTER I

SUMMARY

Concepts and Methods

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

Simplifying assumptions must be made in order to estimate freshwater inflow requirements necessary to maintain Texas estuarine ecosystems. A basic premise used 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 Laguna Madre estuary includes Arroyo Colorado, Laguna Madre, and Baffin Bay. Laguna Madre estuary is divided into upper (northern) and lower (southern) parts by a "land bridge" of sand dunes some 60 miles south of the city of Corpus Christi. About 10,442 square miles (27,045 km^2) of Texas, consisting of the Nueces-Rio Grande Coastal Basin, drain into the estuary, although a large portion is essentially non-contributing to this estuary (Figure 4-1).

Little or no marsh development occurs in the upper reaches of Baffin Bay. This area is occupied by extensive wind-tidal flats. Mainland shorelines in Baffin Bay and upper Laguna Madre are generally in a state of erosion; whereas the barrier island shoreline of Laguna Madre and most of the mainland shoreline of lower Laguna Madre is depositional.

Land use in the drainage area is dominated by agricultural and ranching activities. Cotton, grain sorghum, fruits, and vegetables are the principal irrigated crops.

The Laguna Madre estuary supports a significant portion of the commercial fishing industry in Texas. The average annual commercial (estuarine and gulf) fisheries harvest dependent upon the Laguna Madre estuary was 4.8 million pounds (2.2 million kg) of finfish and shellfish during the 1972-1976 interval. Finfish, particularly red drum, black drum, and seatrout, constitute the majority of these commercial landings, accounting for 86 percent of the total harvest weight.

Fishing resources of the Laguna Madre estuary included many of the fish species preferred by sport fishermen. The method of input-output anaysis was used to calculate the economic impact of sport fisheries activities. The results show that sport fishing expenditures (excluding fishing tackle and equipment) in the local area exceed $8.68 million per year. In addition, there was an estimated $1.04 million per year spent outside the region, but within Texas, as a result of the sport fishing activity around this estuary.

Hydrology

Sources of freshwater inflow to the Laguna Madre estuary include gaged inflow from the contributing rivers and streams; ungaged runoff; return flows from municipal, industrial and agricultural sources; and direct 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, the total freshwater inflow (excluding direct precipitation) to the Laguna Madre estuary (1941-1976) consisted of 690 thousand acre-feet (851 million m^3) annually, of which an estimated 330 thousand acre-feet (411 million m^3) was contributed from gaged drainage areas.

Water quality of gaged inflows varies significantly due to the intermittent nature of stream flow and the phenomenon of the first flush during a major rain.

Studies of past water quality in and around the estuary have pinpointed the occurrence of heavy metals in sediment samples as a significant concern. Locally, bottom sediment samples have exceeded the U.S. Environmental Protection Agency criteria for metals in sediments (prior to dredging) for arsenic, cadmium, mercury and zinc. Bottom sediments collected and analyzed during the period 1969 through 1979 for herbicides and pesticides showed DDD, DDE, and lindane occurring in some local areas in concentrations equal to or greater than the analytical detection limit of the laboratory test procedures used.

Circulation and Salinity

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

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

Statistical analyses were also undertaken to quantify the relationship between freshwater inflows from the contributing drainage area and salinities at selected points in Baffin Bay and lower Laguna Madre. Utilizing gaged daily river flows and observed salinities, a set of monthly predictive salinity equations were derived utilizing regression analyses for two areas of the estuary: (1) a point in the western end of Baffin Bay and (2) at the intersection of the Intracoastal Waterway and the Arroyo Colorado. These equations enable the prediction of the mean monthly salinity as a function of the mean monthly freshwater inflow rate.

Nutrient Processes

The factors controlling nutrient dynamics in Laguna Madre involve both the cycling and regeneration processes within the animal and plant communities, and nutrient inflows to the estuary via terrestrial drainages. The rates of nutrient loading from the river and coastal drainages of the Laguna Madre are variable, depending on local weather events and tropical storms. The aridity of the region is reflected in the low levels of nutrient input commonly asssociated with low freshwater inflows. Therefore, cycling of nutrients within the seagrass communities becomes particularly important in this estuary. Specifically, the seagrass beds demonstrate nitrogen fixation, recovery of nutrients from the sediments, and transfer of nutrients to economically valuable species through both detrital and herbivorous (grazing) food chains.

Limited data on nutrients within the system and an incomplete understanding of transfer rates within the community have hindered a more thorough analysis, but from the data available it appears that the dynamics of nutrients within seagrass beds is very important to the estuarine system.

Primary and Secondary Bay Production

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

Extreme fluctuations in salinity, in response to fluctuations in fresh and salt water inflows, are cited as a major factor in the low diversity of some groups of organisms in Laguna Madre. This has resulted in shorter food chains and a high rate of transfer of solar energy through these food chains to species of commercial importance. Variation in salinity also affects the productivity of Laguna Madre through (a) limitations of mangroves, (b) succession from one species of seagrass to another, (c) succession in types of phytoplankton and zooplankton species from euryhaline to marine forms, and (d) limitation on distributions of benthic algae and invertebrates.

Thus changes in the overall salinity regime of Laguna Madre would primarily result in a succession in species types among the various communities. This would change some aspects of the food webs present, though with changes occurring at so many places in the biologic framework it would be hard to predict overall effects of salinity changes on the productivity of the total system.

Fisheries

Virtually all of the coastal fisheries species in the Gulf of Mexico are estuarine-dependent. Commercial inshore harvests (1962-1976) from lower Laguna Madre rank first in finfish and eighth in shellfish, while upper Laguna Madre ranks second in finfish and seventh in shellfish harvests of eight major Texas estuarine areas. In addition, the sport or recreational finfish harvest is approximately 1.5 times larger than the estuary's commercial finfish harvest. For the 1972 through 1976 interval, the average annual sport and commercial harvest of fish and shellfish dependent upon the Laguna Madre estuary is estimated at 7.3 million pounds (3.3 million kg; 12 percent shellfish).

Although a large portion of the fisheries production in each Texas estuary is harvested offshore in collective association with fisheries production from other regional estuaries, inshore bay and lagoon harvests can be 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. The effects of freshwater inflow on lower Laguna Madre are also reflected in the offshore harvests of the penaeid shrimp fishery. Therefore, the fisheries species can be viewed as integrators of their environment's conditions and their harvests used as relative ecological indicators, insofar as they reflect the general productivity and "health" of an estuarine ecosystem.

A time series analysis of Laguna Madre's commercial inshore (bay and lagoon) fisheries landings (1962 through 1976) and the commercial penaeid shrimp harvests (including Offshore Gulf Area No. 21, 1959 through 1976) produces 19 statistical regression equations that estimate harvest as a function of seasonal freshwater inflows to the Laguna Madre estuary. These statistical relationships provide numerical estimates of the effects of variable seasonal inflows contributed from the major freshwater sources on the commercial harvests of seafood organisms dependent upon the estuary. The analysis also supports existing scientific information on the seasonal importance of freshwater inflow to the estuaries.

There are 13 significant harvest relationships to winter (January-March) inflow obtained from the analysis and eight (62 percent) of these are positive harvest responses associated with larger winter inflows, especially increased inflow to lower Laguna Madre. Negative harvest responses to winter inflow result from the brown and pink shrimp fisheries component in upper Laguna Madre, and lower Laguna Madre's shellfish, bay oyster, and black drum fisheries components. Positive fisheries harvest responses to upper Laguna Madre spring (April-June) inflow account for half of the ten significant harvest relationships to this season's inflow. Eleven (79 percent) of the 14 significant harvest responses to summer (July-August) inflow are positive. Exceptions include the negative harvest response of penaeid shrimp to upper Laguna Madre inflow, and the negative harvest responses of white shrimp and red drum to lower Laguna Madre inflow during this season. Harvest responses to the tropical storm dominated autumn (September-October) season inflows are negative only for the black drum fisheries component, which is in particular contrast to the strong positive relationships exhibited by the red drum component. All of the eight significant harvest responses to late fall (November-December) inflow are negative, except for the single positive response of inshore penaeid shrimp harvests to this season's upper Laguna Madre 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. These other factors, however, are largely beyond human control, whereas freshwater inflow can be restricted by man's activities so that fish and wildlife resources are adversely affected.

Estimated Freshwater Inflow Needs

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

Monthly mean salinity limits are established at locations in the estuary near the freshwater inflow points to Baffin Bay and lower Laguna Madre. These upper and lower limits on monthly salinity provide a range within which viable metabolic activity of the resident organisms can be maintained and the median monthly (1941-1976) historical salinity conditions are not exceeded.

The river deltas in Laguna Madre are limited in areal extent and relatively insignificant nutrient sources compared to the vast seagrass beds within the estuary. As a result, no inflow requirements for riverine marsh inundation are specified for Laguna Madre.

Evaluation of Estuarine Alternatives

Estimates of the freshwater inflow needs for Laguna Madre estuary were computed by representing the interactions among freshwater inflows, estuarine salinity, and fisheries harvests within an Estuarine Mathematical Programming Model. The model computes the monthly freshwater inflows from the Baffin Bay drainage area, and the Arroyo Colorado and North Floodway which best achieve a specified objective.

The monthly freshwater inflow needs for Laguna Madre estuary were estimated for each of three alternatives. These alternatives are intended to demonstrate the method of estimating freshwater inflows and are by no means the only alternatives possible. Gulf Offshore Area No. 21 mentioned below refers to the area extending approximately 30 miles offshore and bounded by latitudes 26°N, 27°N, longitude 96°30'W, and Padre Island.

Alternative I (Subsistence): minimization of annual combined freshwater inflow to the estuary while meeting salinity viability limits;

Alternative II (Maintenance of Fisheries Harvests): minimization of annual combined inflow to the estuary while providing freshwater inflow sufficient to give predicted annual commercial bay harvests separately for both the upper (including Baffin Bay) and lower (including Gulf Offshore Area No. 21) portions of the estuary for red drum, seatrout, black drum, white shrimp, brown and pink shrimp and bay oysters at levels no less than their mean historical 1962 through 1976 values and meeting viability limits for salinity; and

Alternative III (Harvest Enhancement): maximization of the total annual commercial bay harvest of all finfish in upper Laguna Madre and of all shrimp in Gulf Offshore Area No. 21 while meeting salinity limits and utilizing annual combined inflow to the estuary at a level no greater than the average annual historical inflow over the 1941 through 1976 period. A further constraint is that the predicted total annual commercial finfish harvest in lower Laguna Madre be no less than the mean 1962 through 1976 historical harvest.

Under Alternative I (Subsistence), the Laguna Madre system, which has functioned as both a commercial shellfish and finfish producing system in the past, can continue to be an important fisheries producing estuary with substantially less freshwater inflow. Freshwater inflows totaling 344 thousand acre-feet (424 million m^3) annually are predicted to satisfy the basic salinity gradient, with a resulting predicted increase in commercial finfish bay harvests of 9 percent and a 12 percent decrease in shrimp harvest (including shrimp from Gulf Offshore Area No. 21) from the average annual harvest for the period 1962 through 1976 (Figure 1-1). This annual inflow is approximately 50 percent of the 1941 through 1976 historical average inflow.

Under Alternative II (Maintenance of Fisheries Harvests), the predicted annual commercial bay harvests of red drum, spotted seatrout, black drum, white shrimp, brown and pink shrimp, and bay oyster are predicted to be at least as great as their historical 1962 through 1976 average levels. The salinity limits are also satisfied. The estimated total annual freshwater inflow need is 578 thousand acre-feet (713 million m^3), or 84 percent of the average annual inflow over the period 1941 through 1976 (Figure 1-1). The combined predicted annual finfish and shellfish commercial harvest is 11.2 million pounds (5.1 million kg), or five percent higher than the 1962 through 1976 annual average.

Under Alternative III (Harvest Enhancement), the combined annual freshwater inflow need is computed at 602 thousand acre-feet (743 million m^3), distributed in a seasonally unique manner, to achieve the objective of maximizing the total annual predicted commercial bay harvest of finfish in upper Laguna Madre and shrimp in Gulf Offshore Area No. 21 (Figure 1-1). This inflow regime is 87 percent of the 1941 through 1976 average annual inflow. This objective is achieved with a predicted 40 percent increase in the annual finfish bay harvest, above average historic 1962 through 1976 levels, and an estimated gain of approximately 19 percent in total commercial shrimp harvest. The total predicted annual commercial fisheries harvest is 23 percent greater than the 1962 through 1976 average.

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

Significance of Freshwater Inflow Need Estimates

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

Freshwater inflows to Texas estuaries vary widely both seasonally and yearly. Consequently, large fluctuations in inflows will continue regardless of any freshwater inflow maintenance criteria that may be established. Some provision should be made, however, in any estuarine management program to prevent an increase (over historical levels) in the frequency of low inflows detrimental to the ecosystem and its resident aquatic organisms.

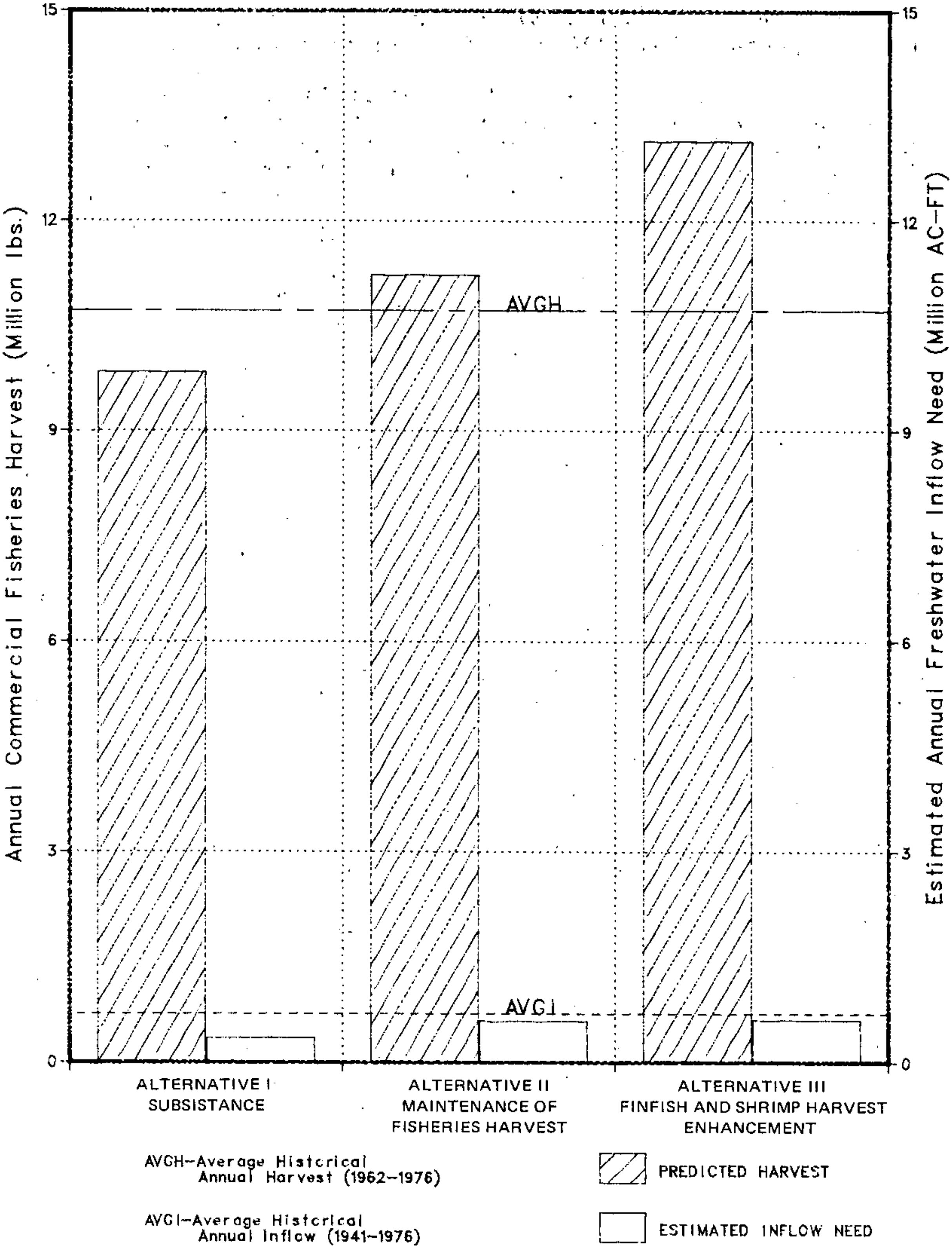


Figure 1-1. Predicted Annual Commercial Fisheries Harvest and Estimated Inflow Needs Under Three Alternatives for the Laguna Madre Estuary

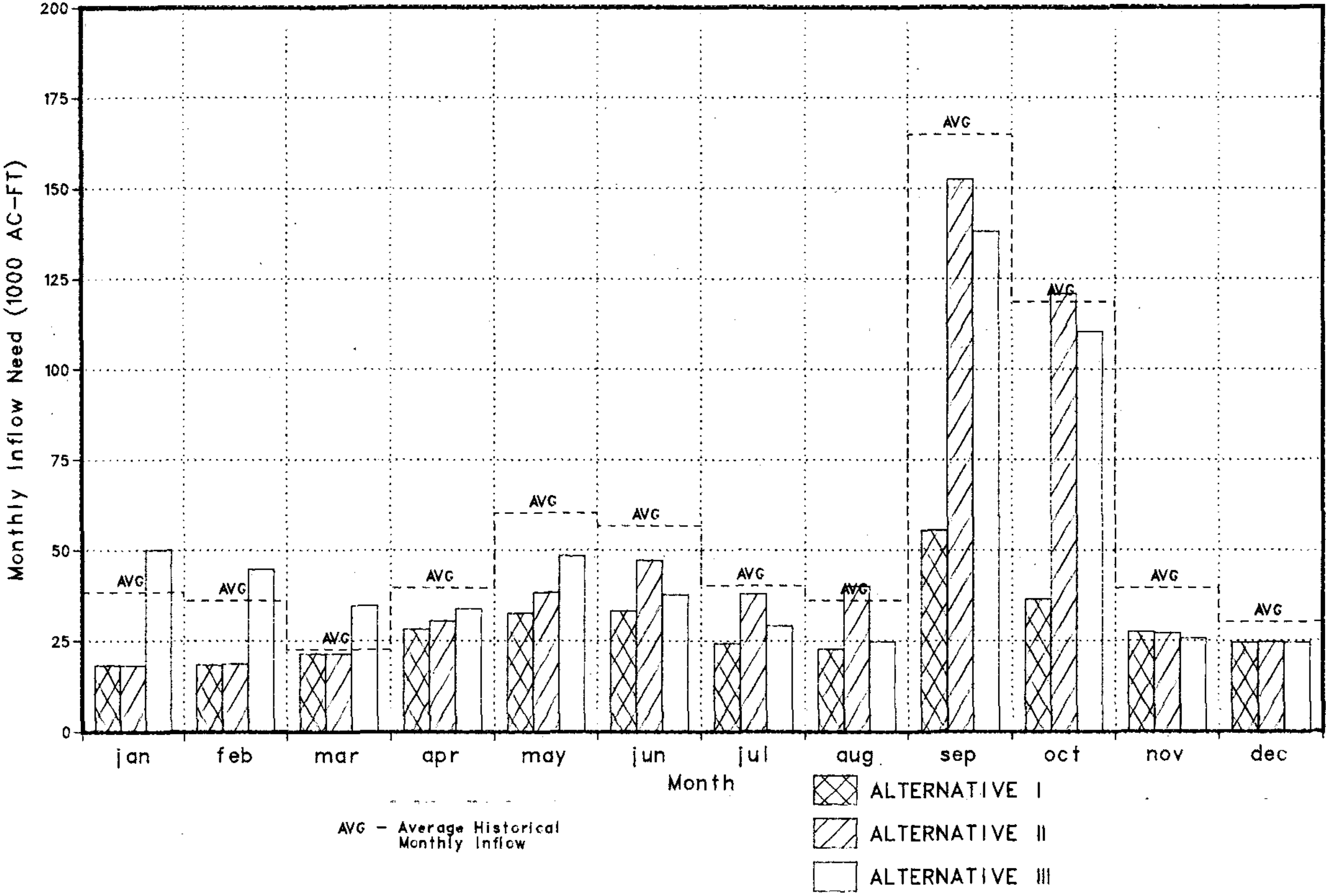


Figure 1-2. Estimated Monthly Freshwater Inflow Needs for the Laguna Madre Estuary Under Alternatives I, II, III

CHAPTER II

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

Scope of Study

Senate Bill 137 (64th Texas Legislature) mandates a comprehensive study of environmental variables, especially freshwater inflow, which affect Texas estuarine ecosystems. This report presents the results of the studies of the Laguna Madre 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 (181). 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 Laguna Madre 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 a coastal region of the state from the tidally affected reaches of terrestial inflow sources to the Gulf of Mexico. Shallow bays, tidal marshes, bayous, creeks and other bodies of water behind barrier islands are included under this definition. Estuarine systems contain sub-systems (e.g., individuals bays), lesser but recognizable units with characteristic chemical, physical and biological regimes. Primary, secondary, and tertiary bays, although interrelated, all require study for proper understanding and management of the complete system.

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

Texas has about 373 miles (600 kilometers) of open-ocean or Gulf shoreline and 1,419 miles (2,290 kilometers) of bay shoreline, along which are located seven major estuarine systems and three smaller estuaries (Figure 2-1). Eleven major river basins, ten with headwaters originating within the boundaries of the state, have estuaries of major or secondary importance. These estuarine systems have a total open-water surface area of more than 1.5 million acres (607,000 hectares) with more than 1.1 million acres (445,000 hectares) of adjacent marshlands and tidal flats (359). Physical characteristics of the Laguna Madre 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 Laguna Madre 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

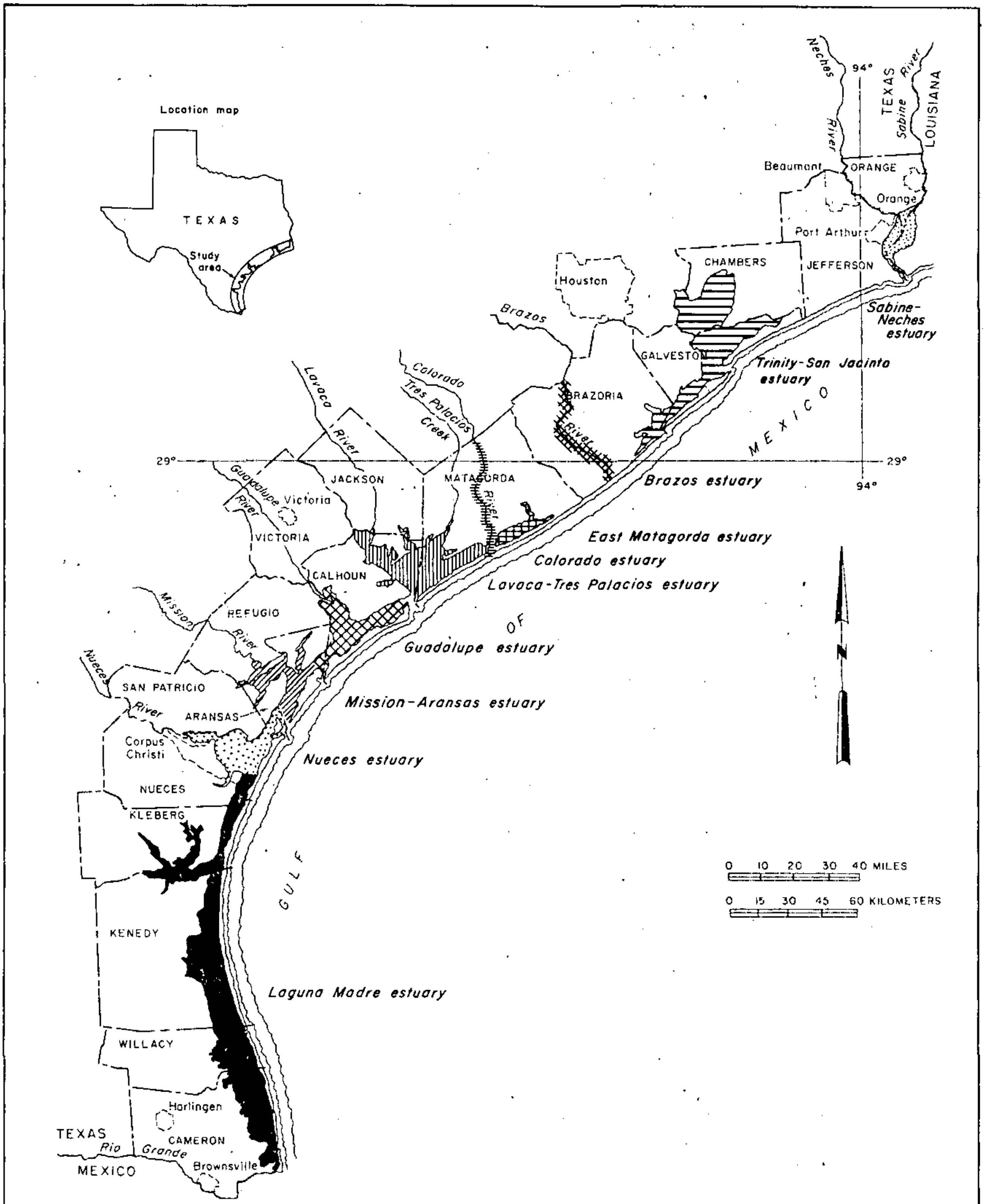


Figure 2-1. Locations of Texas Estuaries

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

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

Biological Characteristics

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

Salinity, temperature, and catastrophic events (e.g., hurricanes) are factors that largely control and influence species composition in these ecosystems. While the number of species generally remains low, numbers of organisms within a species fluctuate with the seasons and with hydrologic cycles (421, 422, 72). 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 Laguna Madre 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 (45, 48, 103, 149, 172, 215). 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),

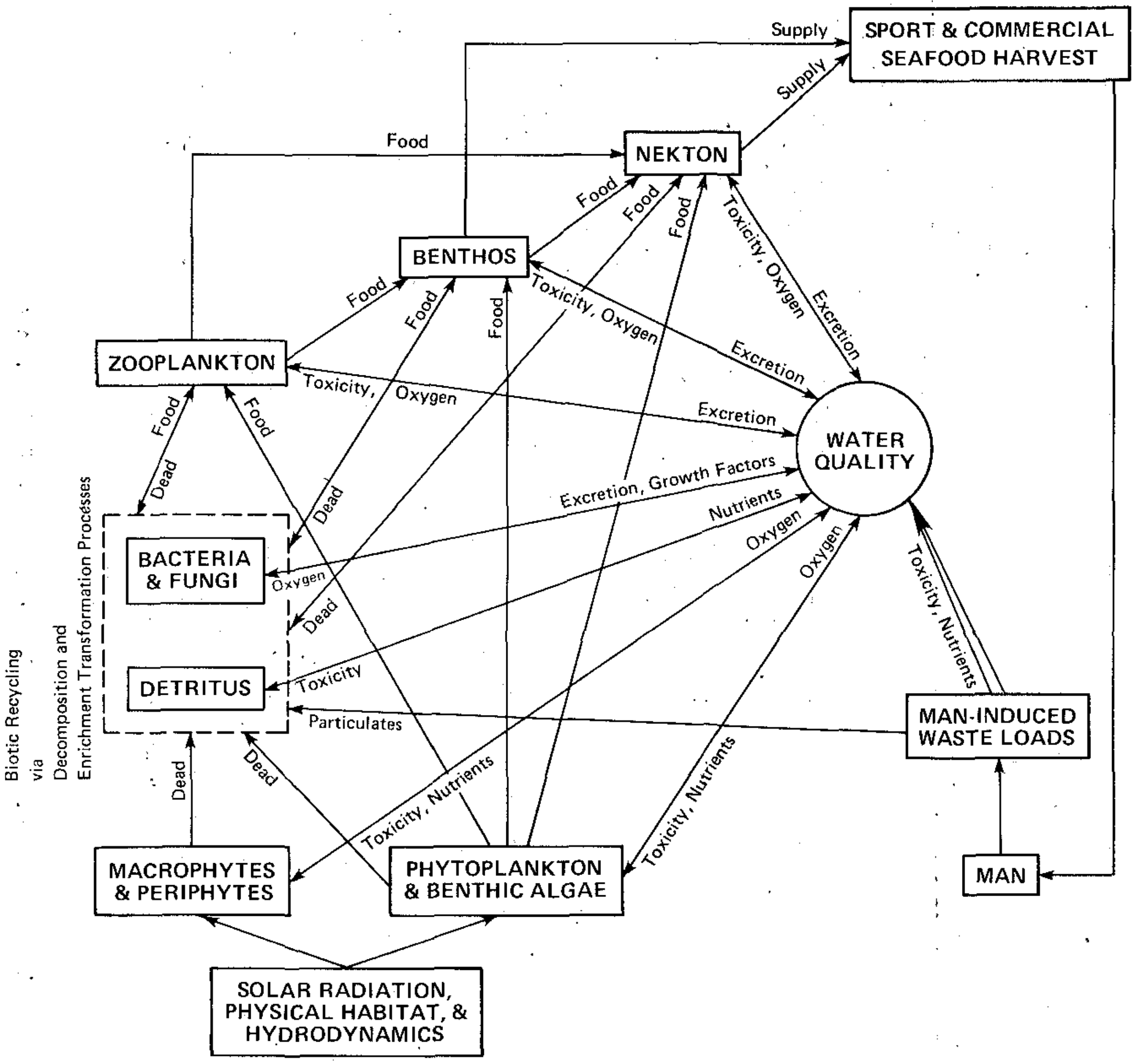


Figure 2-2. Component Schematic Diagram of a Generalized Texas Estuarine Ecosystem

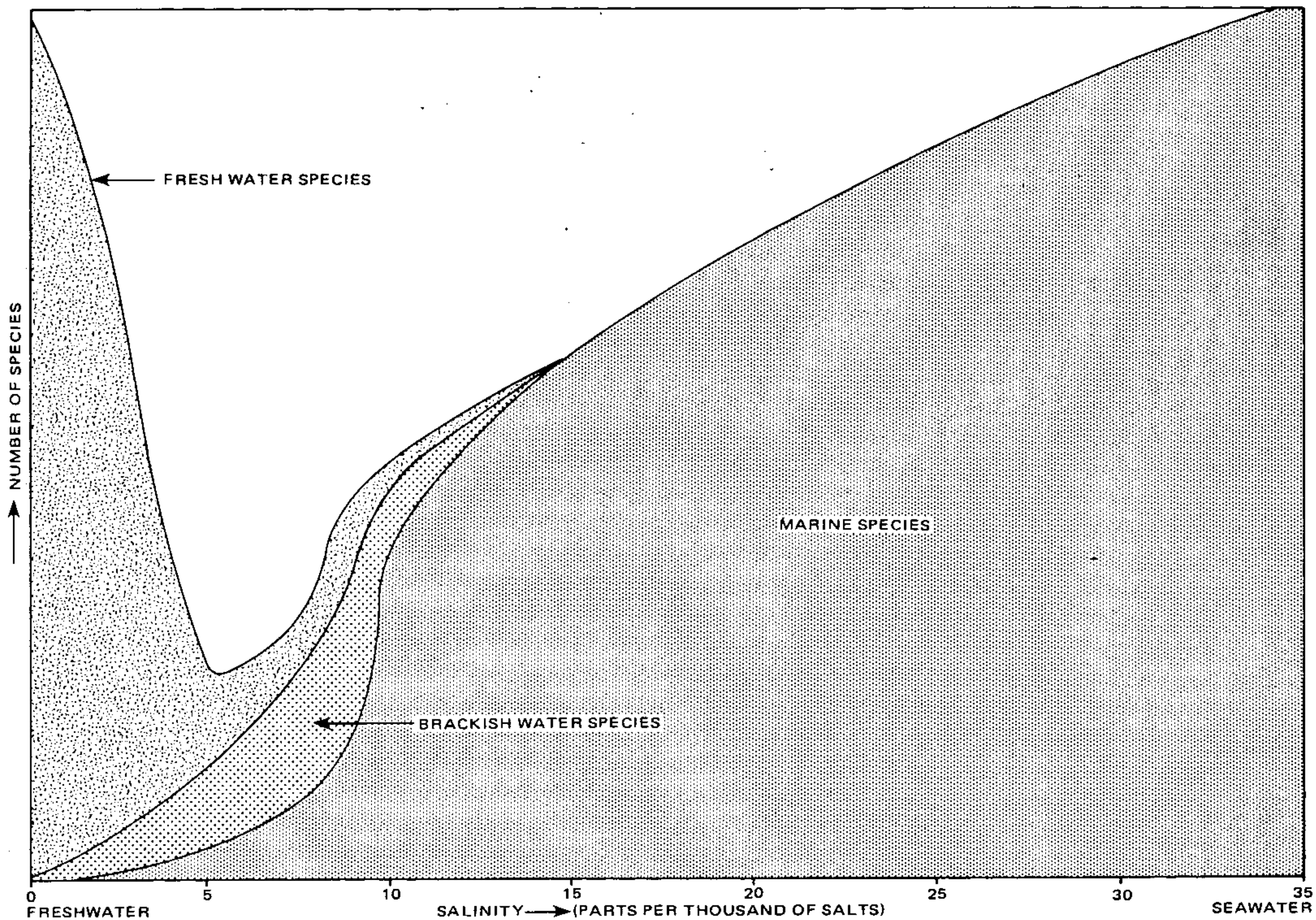


Figure 2-3. Species Composition of Estuarine Environments (192)

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 (197). 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 (124, 400), and/or for protection against predators and parasites (129, 180). Juvenile forms use the shallow "nursery" areas during early growth (81, 84), migrating back to the Gulf of Mexico in their adult or subadult life stage.

For high ecosystem productivity to occur, the timing of freshwater inflow, inundation (irrigation) of marshes, and nutrient stimulation (fertilization) of estuarine plants must coincide with the subtropical climatic regime of the Gulf region. Nature's seasons provide environmental cues, such as increases or decreases in salinity and temperature, that enable estuarine-dependent species to reproduce and grow successfully in the coastal environments. These species have adapted their life cycles to the natural schedule of seasonal events in the ecosystem and also to reduce competition and predation. Coincidence of seasonal events, such as spring rains, inundation of marshes and increased nutrient cycling is made more complex by both antecedent events and ambient conditions. For example, winter inundation and nutrient stimulation of marshes may not be as beneficial to the estuarine system as similar events in the spring because low winter temperatures do not support high biological activity. Consequently, the growth and survival of many economically important seafood species will be limited if antecedent events and ambient conditions are unfavorable and far from the seasonal optimum. Further, the entire ecosystem can lose productivity through disruption of energy flow and become altered by slight, but chronic stresses (424).

Virtually all (97.5%) of the Gulf fisheries species are considered estuarine-dependent (86); however, the seasonal aspects of their life cycles are quite different. Some species, such as the redfish, spawn in the fall an the young are particularly dependent on migration to and utilization of the "nursery" habitats during this season. Others, such as the penaeid shrimp, spawn primarily in the spring and early summer, and their young move inshore to shallow, low salinity estuarine areas for growth and development at this

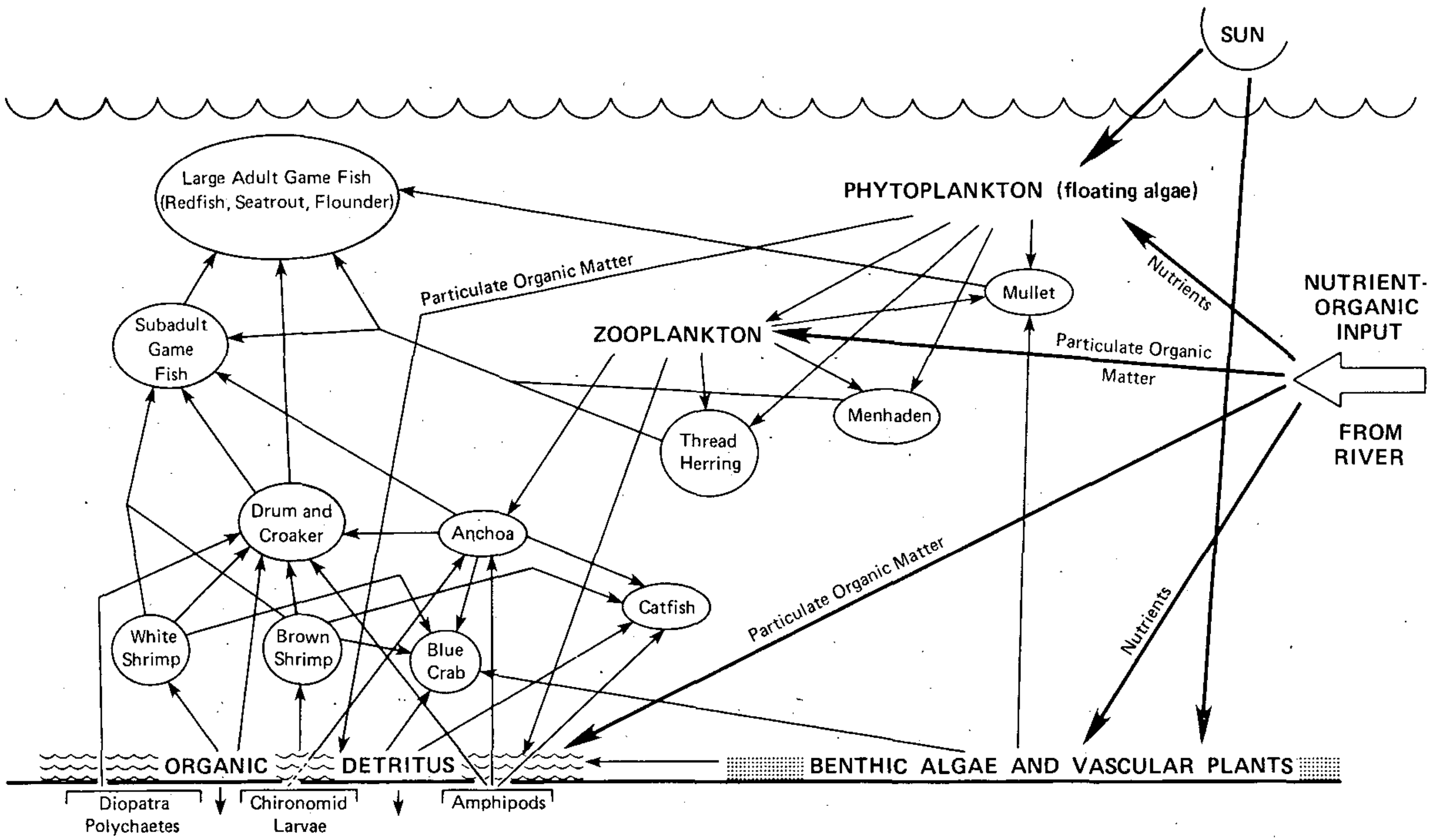


Figure 2-4. Simplified Trophic Relationships in a Texas Estuary [After WRE (417)]

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 (425).

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 (426). Throughout the world, only tropical rain forests, coral reefs, and some algal beds produce more abundantly per unit of area (172, 299).

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 (41, 103, 148). Because of high plant productivities an estuarine marsh can assimilate, if necessary, substantial volumes of nutrient-rich municipal and industrial wastes (397, 427) and incorporate them into the yield of organic material which supports higher trophic level production, such as fishery species. Such high food density areas serve as "nursery" habitats for many economically important estuarine-dependent species, as well as provide food and cover for a variety of water fowl and mammals. Delta marshes may serve other beneficial functions acting as a temporary floodwater storage area and/or aiding in erosion control by absorbing potentially destructive wave energy.

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

Summary

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

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

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

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

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

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

Evaluation of Individual Estuarine Systems

Introduction

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

Mathematical Modeling

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

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

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

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

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

The mathematical models being developed to evaluate the hydrodynamics and salinity of the Laguna Madre estuary are described in detail in Chapter V.

Key Indicators of Estuarine Conditions

The large number of complex interactions of physical, chemical, and biological parameters make it difficult to completely define the interrelationships of an estuarine ecosystem. Major environmental factors and identifiable biological populations can be used, however, as "key indicators" to understand and demonstrate the response of higher food chain organisms, such as shellfish and finfish, to major changes in the ecosystem (172). 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.

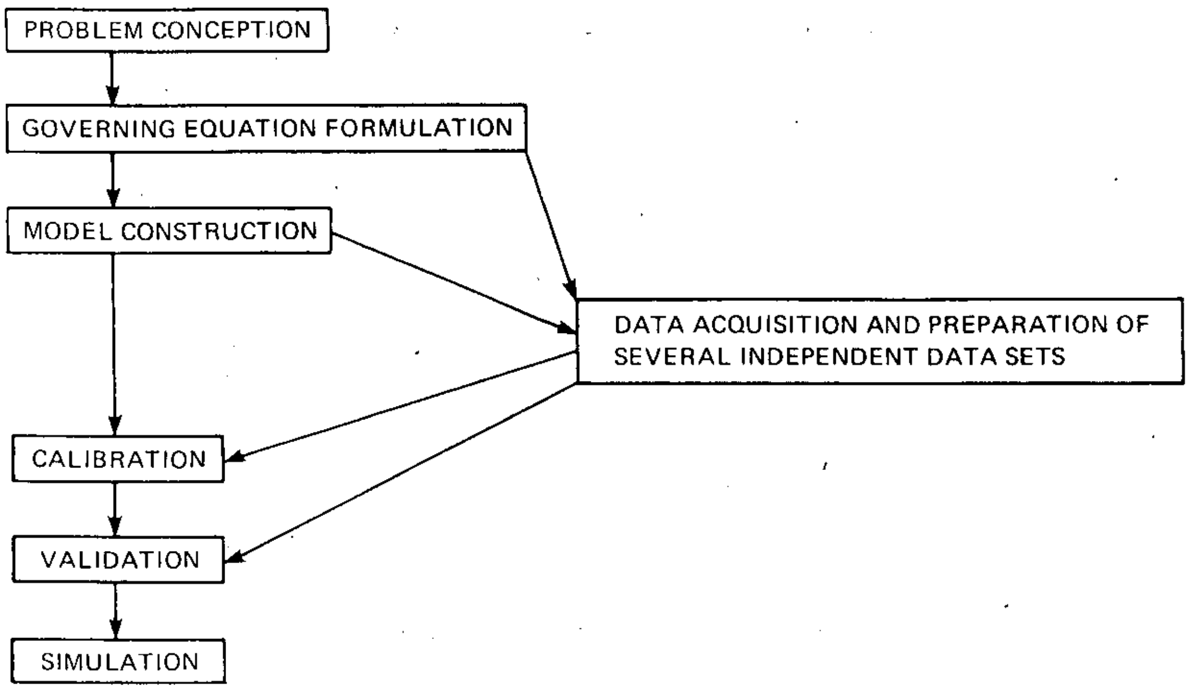


Figure 2-5. Flow Diagram of Model Development

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

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

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

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

(2) Critical Period. An understanding of the concept of "critical period" is necessary in order to understand the importance of freshwater inflow to texas estuarine systems (108, 158). There are basically two types of critical periods that must be considered--long term and seasonal. The first, or more general type, is that resulting from extended years of drought with extreme low freshwater inflow, creating stressful or lethal conditions in the estuary. A second type of critical period occurs on a seasonal basis, whereby lowered freshwater inflow affects the growth and maturation of delta marsh habitats, the utilization of "nursery" areas by juvenile fish and shellfish, and the transport of sediment and nutritive substrate materials (especially detritus) to the estuary.

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

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

(3) Circulation. The movement of waters within an estuary largely determines the distribution of biotic and abiotic constituents in the system. To study the movement of estuarine waters under varying conditions, tidal hydrodynamic mathematical models have been developed and applied to individual texas estuaries (156). Each model computes velocities and water surface elevations at node points of a computational grid superimposed on an estuary. Estuarine characteristics along any given vertical line (the water column) are assumed to be homogeneous.

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

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

(4) Salinity. A knowledge of the distribution of salinities over time at points throughout the estuary is vital to the understanding of environmental conditions within the system. To better assess the variations in salinities, a salinity transport mathematical model has been developed (157, 156) to simulate the salinity changes in response to dispersion, molecular diffusion and tidal hydrodynamics. This model is a companion model to the hydrodynamic model described previously.

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

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

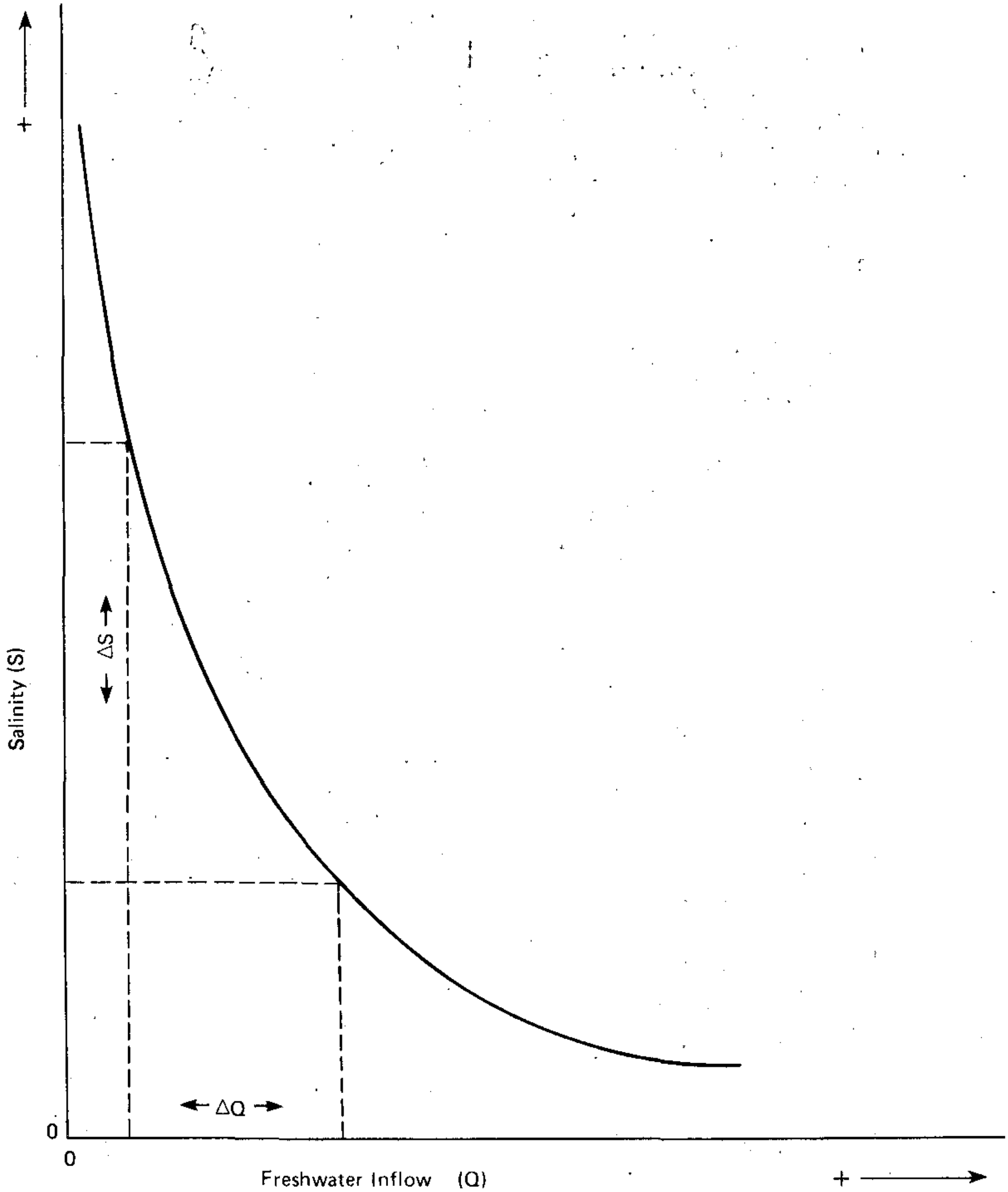


Figure 2-6. Typical Variation of Freshwater Inflow Versus Salinity in a Texas Estuary

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 quality 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 (41, 148). 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.

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

Dr. Eugene Odum has remarked that "ecologists constantly employ such organisms as indicators in exploring new situations or evaluating large areas" (172). 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

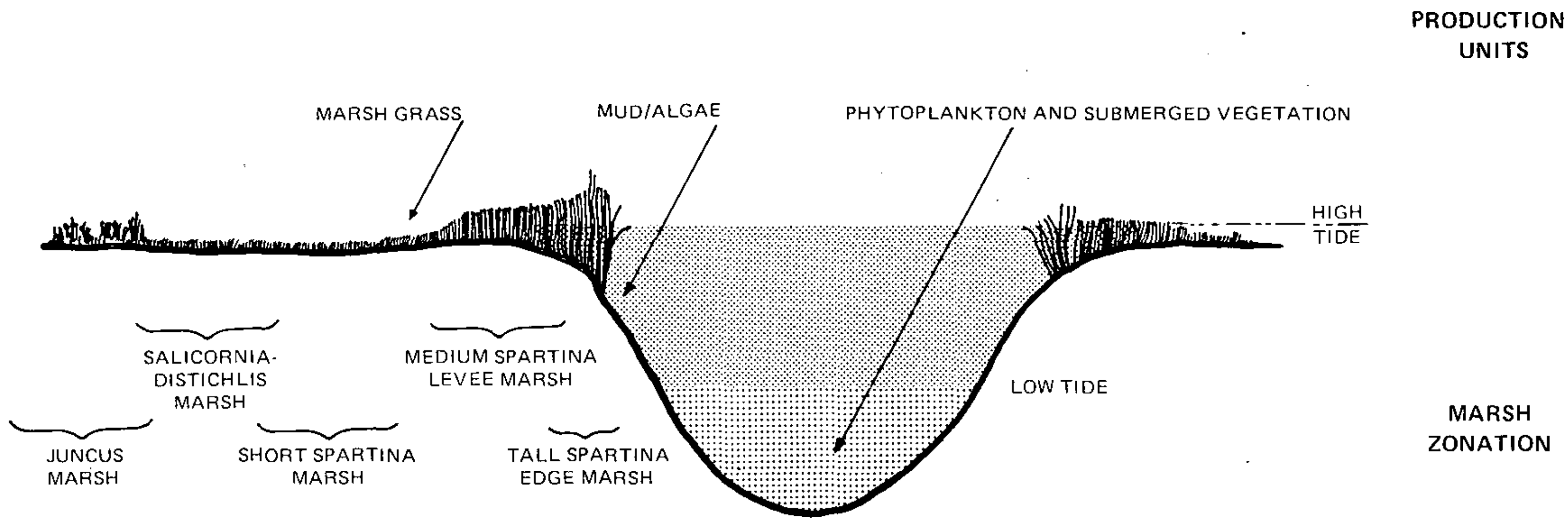


Figure 2-7. Zonation of a Salt Marsh in a Texas Estuary (236)

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 (236, 417). The model was formulated to provide a systematic means of predicting the response of estuarine biotic and abiotic constituents to environmental changes. Ecological modeling techniques involve the use of mathematical relationships, based on scientific evidence, to predict changes in estuarine constituents.

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

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

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

(2) Statistical Models. An investigation of the effects of freshwater inflow on an estuary necessitates the use of existing information on the system's hydrology and biology. In most cases, numerical analysis of this information allows the demonstration of statistical relationships between freshwater inflow and dependent environmental variables such as fishery production. The use of linear regression analysis allows the development of a variety of descriptive and predictive relationships between seasonal freshwater inflows and commercial harvest of finfish and shellfish. The specific regression equations for estimating harvest of spotted seatrout, red drum, black drum, white shrimp, brown and pink shrimp, blue crab, and bay oysters as

a function of the reported quantities of seasonal freshwater inflow are computed using data from each estuarine system (Chapter VIII). These regression equations can be used to compute estimates of the estuarine productivity, in terms of harvested fisheries biomass, as a function of freshwater inflows. However, there are variations in the historical harvest data which were not explained by variations in seasonal freshwater inflow. These variations may be due to other factors such as temperature, predation and disease.

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

(3) Finfish Metabolic Stress Analysis. The health of organisms in an estuarine ecosystem is dependent upon a number of factors. Wohlschlag (276, 277, 278, 279) and Wakeman (404) have reported on the stress of salinity changes upon the metabolic activities of several Texas estuarine fish species. For example, Wakeman (404) measured the maximum sustained swimming speeds of four estuarine fish species (i.e., spotted seatrout, sheepshead, and black and red drum) at 28 degrees Celsius over a range of salinities (10-40 parts per thousand, ppt) normally encountered in the estuary. All of these species are of commercial and recreational importance; therefore, results of these metabolic research studies are valuable in the planning and management of the texas estuarine systems and their production of renewable fish resources. Salinity ranges and salinity optima have also been determined for several other estuarine-dependent fish and shellfish species (including shrimp, crabs, and oysters), and are presented in Chapter IX.

Analyzing the Estuarine Complex

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

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

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

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

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

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

The constraints listed above are incorporated into a special mathematical programming (MP) 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 generalized reduced gradient algorithm (133) for the solution of nonlinear programs. A nonlinear program may be used to reach an optimum solution to a problem where a desired nonlinear objective is maximized (or minimized) subject to satisfying a set of linear constraints.

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

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

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

seasonal schedule of inflows needed by the estuary to meet the specified objectives is thus derived.

A process for synthesis of estimated freshwater inflow needs for the Laguna Madre 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 83 percent complete. Although the adjudication program is being accelerated, several years will be required to complete the remaining unadjudicated basins. Final judgments have been rendered by the appropriate District Courts and certificates of adjudication have been issued in portions of the Rio Grande, Colorado, San Antonio and Guadalupe Basins.

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

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

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

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

(2) Elimination of Water Pollutants. The presence of toxic pollutants in freshwater inflows can have a detrimental effect upon productivity of an estuarine ecosystem by suppressing biological activity. Historically, pollutants have been discharged into rivers and streams and have contaminated the coastal estuaries. Imposition of wastewater discharge and streamflow water quality standards by State and Federal governmental agencies 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 Laguna Madre estuary, but other ongoing studies by the Department of Water Resources do address such problems.

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

Summary

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

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

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

CHAPTER III

DESCRIPTION OF THE ESTUARY AND THE SURROUNDING AREA

Physical Characteristics

Introduction

The Laguna Madre estuary consisting of parts of Arroyo Colorado, upper and lower Laguna Madre, and Baffin Bay (Figure 3-1) has an approximate surface area of 640 square miles (1,660 km^2), as compared to about 600 square miles (1,554 km^2) for the Trinity-San Jacinto estuary. The mean low water surface area of Laguna Madre is 439 square miles (1,137 km^2) versus 547 square miles (1,417 km^2) for Trinity-San Jacinto estuary. Therefore, the Laguna Madre estuary is only 80% as large as the Galveston system, based on surface water area. The estuary is shallow with a mean depth of less than four feet (1.2 km) except in parts of Arroyo Colorado, the Intracoastal Waterway, Brazos Santiago Pass, and the Brownsville and Port Mansfield channels.

The upper portion of Laguna Madre lies in the humid, subtropical climatic region. The lower Laguna Madre is a tropical to subtropical steppe. Prevailing winds are southeasterly throughout the year and the warm tropical air from the Gulf of Mexico is responsible for mild winter temperatures and hot, humid summer weather.

Some of the heavier rainfall occurrences during late summer and early fall are associated with tropical disturbances.

Influence of Contributory Basins

Drainage areas within the State of Texas contributing inflow to the Laguna Madre estuary include the Rio Grande Basin and the Nueces-Rio Grande Coastal Basin. The northern part of the coastal basin is drained by a network of coastal streams into Baffin Bay, whereas, the southern part is drained principally by Arroyo Colorado. The Rio Grande originates in the State of Colorado, flows through New Mexico, and becomes the international border between the United States and Mexico just above El Paso, Texas (Figure 3-2).

The total drainage area of the Rio Grande Basin is 335,500 square miles, (868,945 km^2) however, the runoff contributing area is only about one half of the total or about 176,300 square miles (456,617 km^2). Of this total contributing area about 147,000 square miles (380,730 km^2) is downstream of the New Mexico-Texas State line with 59,700 square miles (154,623 km^2) originating in Texas and the remainder in Mexico. Amounts and rates of runoff vary widely throughout the Rio Grande Basin. Reservoirs, numerous diversions, and substantial return flows modify the flow of the main stem throughout its length. Upstream development has progressively reduced the flow of the Rio Grande as it enters Texas.

The Nueces-Rio Grande Coastal Basin has a total drainage area of 10,442 square miles (27,045 km^2), of which a large portion is non-contributory,

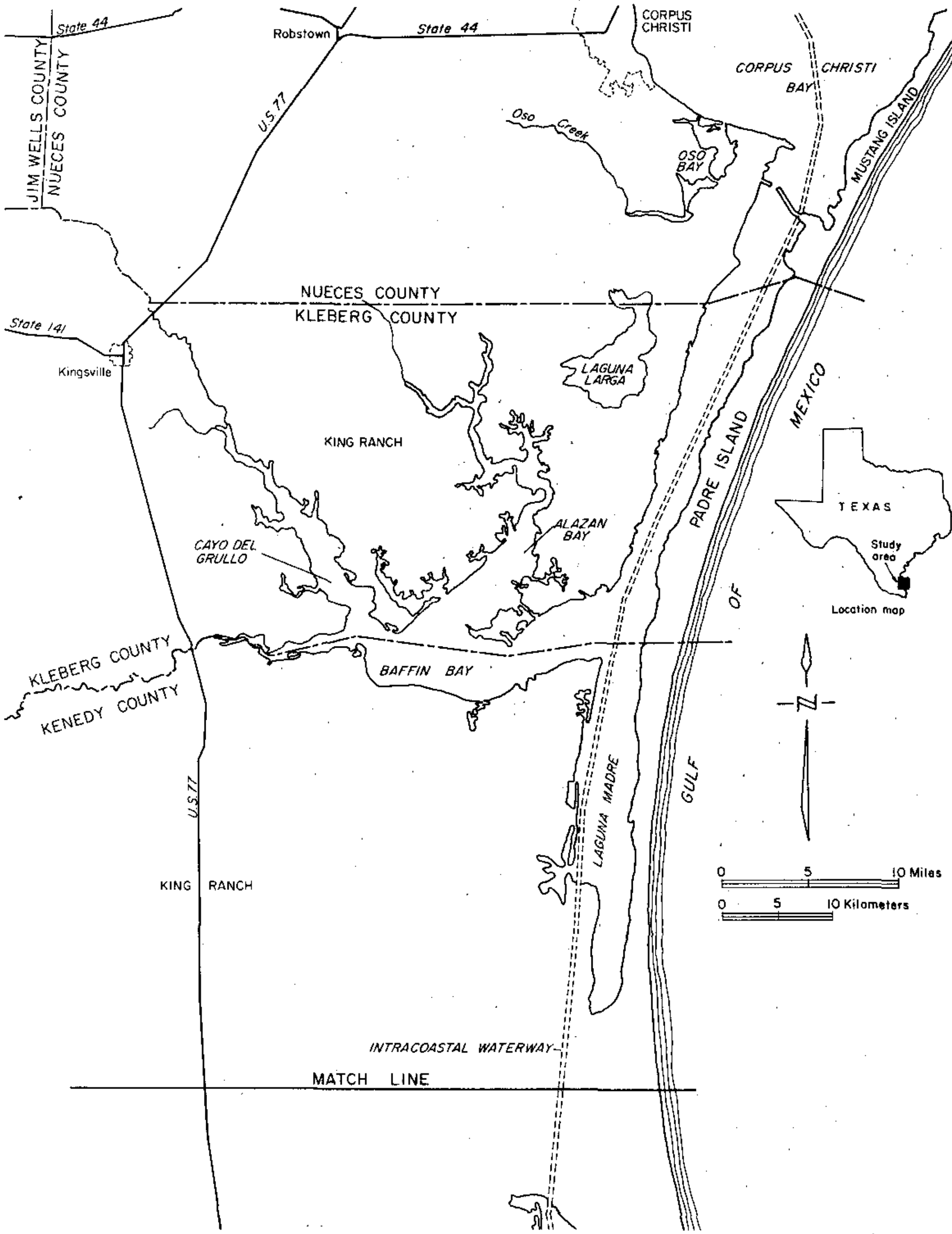


Figure 3-1. Laguna Madre Estuary (cont'd)

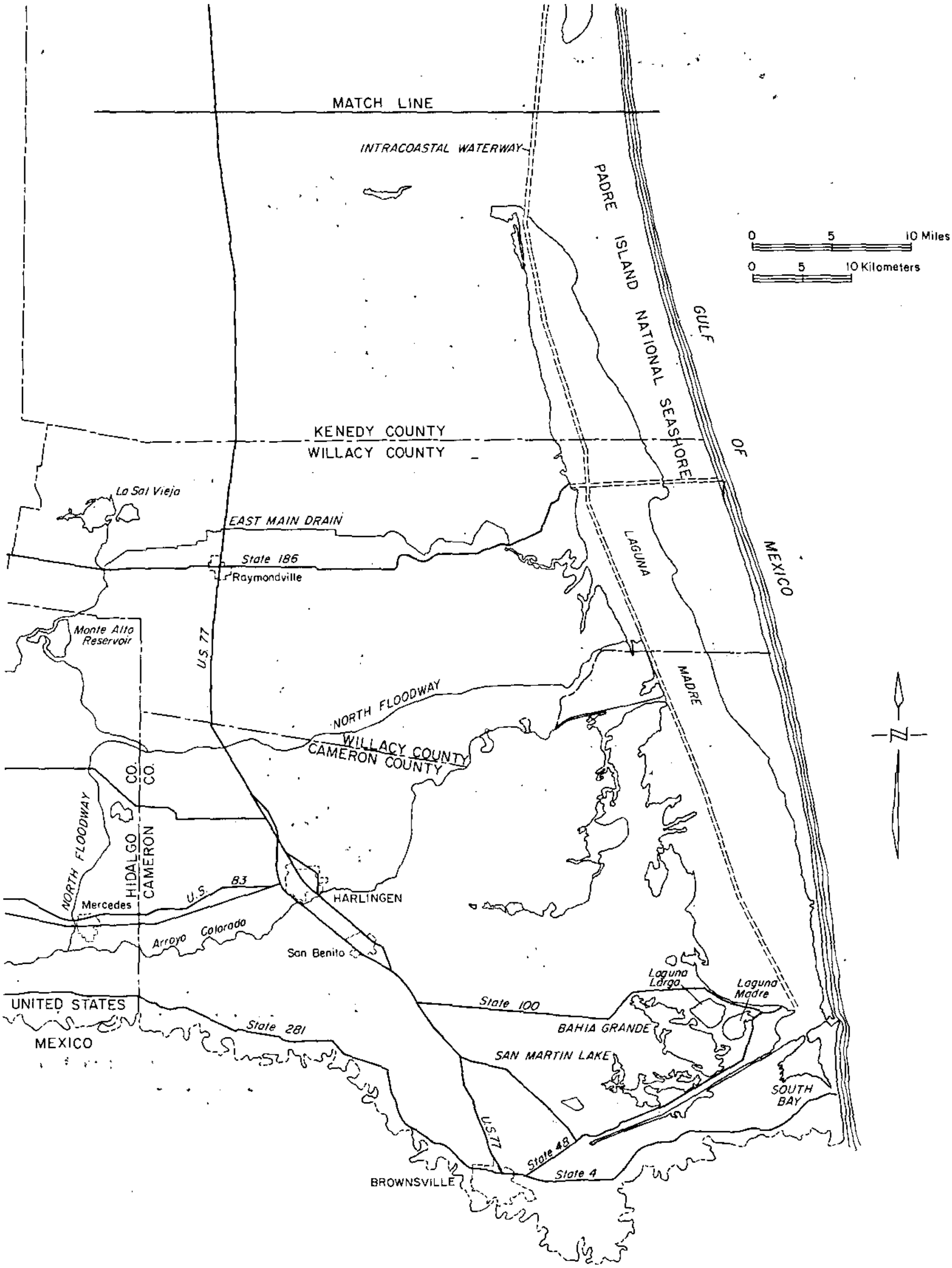


Figure 3-1. Laguna Madre Estuary (continued)

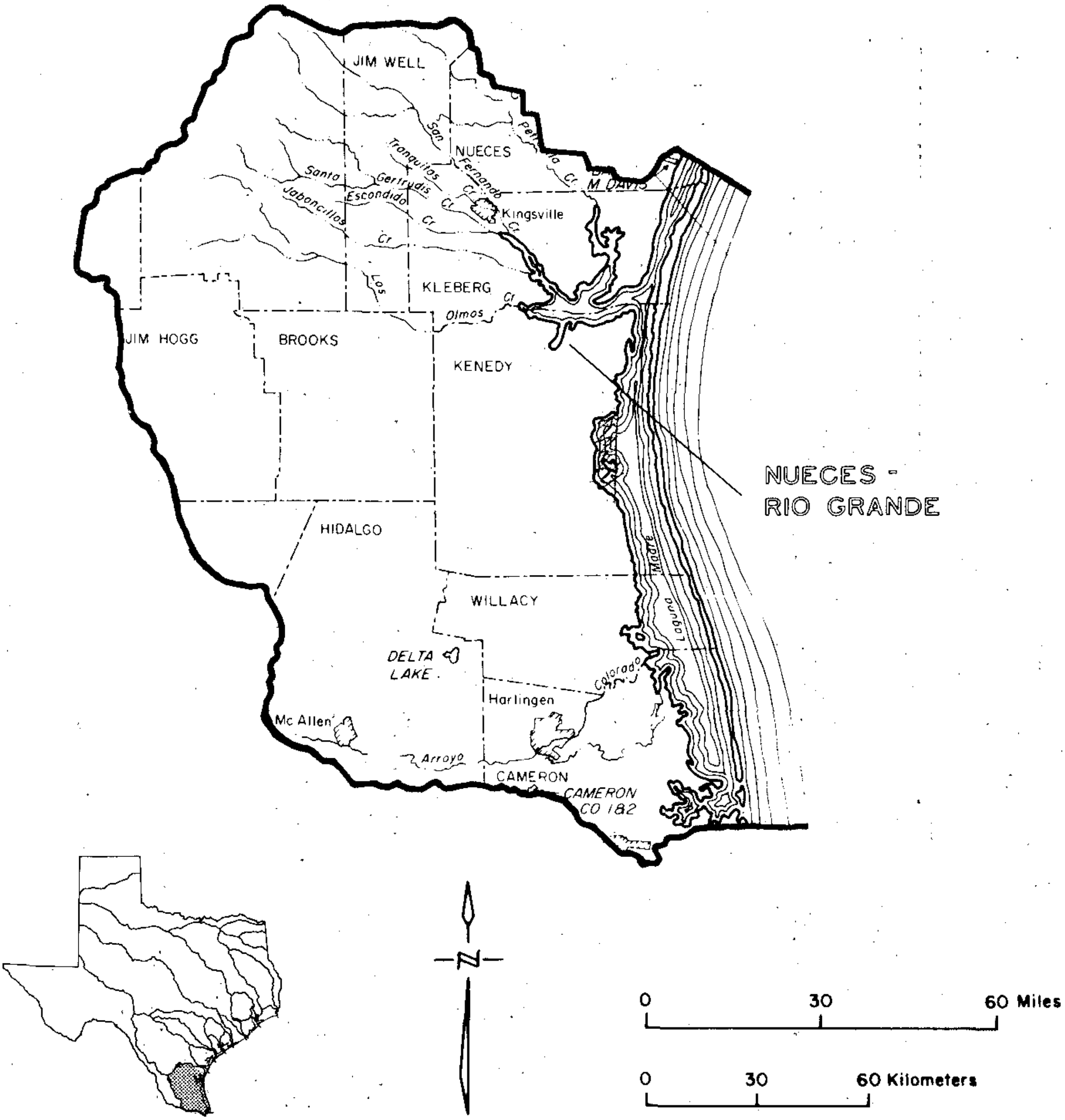


Figure 3-2. Basins Contributing to the Laguna Madre Estuary Under Alternatives I, II, III

and is characterized by flat terrain and narrow stream channels that flood frequently. Most streams are intermittent except in tidally affected reaches.

Large scale control of the Rio Grande began with the completion of International Falcon Dam in 1953. Other major reservoir development in or bordering Texas is shown on Table 3-1.

Geological Resources

Sedimentation and Erosion. The combined discharge of the Olmos, Santa Gertrudas, San Fernando, and Petronila Creeks into Baffin Bay is less than the discharge into any other Texas bay system. These ephemeral streams carry small amounts of sediment into the upper reaches of Baffin Bay resulting in little or no marsh development. Instead, extensive wind-tidal flats occupy the upper reaches of Baffin Bay. Moderate quantities of sandy bedload are transported onto and across the wind-tidal flats into the bay (Figure 3-3).

Relatively small amounts of sediment are deposited in lower Laguna Madre from the Arroyo Colorado or the North Floodway due to the low gradient of these channels and the fact that they carry mainly storm runoff and irrigation return flows. Because it discharges directly into the Gulf of Mexico, the Rio Grande has no effect on salinity or sedimentation within the Laguna Madre estuary.

The southeasterly winds, along with occasional hurricanes, transport sand across Padre Island to form large back island dune fields. These large dunes, in turn, supply sediment to Laguna Madre or to broad wind-tidal flats in the area. Lack of vegetation on central Padre Island accelerates the transport of sediment across the barrier island.

Shoreline and vegetation changes within the estuaries and in other areas of the Texas Gulf Coast are the result of natural processes (267, 269). Shorelines are either in a state of erosion, accretion, or are stabilized either naturally or artificially. Erosion produces a net loss in land, accretion produces a net gain in land, and equilibrium conditions produce no net change in land area.

Within Baffin Bay shorelines are generally in a state of erosion, as is the mainland shoreline of upper Laguna Madre. The barrier island shoreline of both upper and lower Laguna Madre is totally depositional. Most of the mainland shore of lower Laguna Madre is depositional with portions either in a state of equilibrium or erosion (Figure 3-4 and 3-5). Gulfward of the barrier island the shoreline is in a state of erosion from Brazos Santiago Pass to Yarborough Pass. The gulfward shoreline of Little Shell Beach is in a state of equilibrium for about ten miles where it becomes depositional.

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

Table 3-1. Reservoirs of Contributing Basins, Laguna Madre Estuary

Reservoir Name	Type of Use(s) a/	Year Dam Completed	Surface Area Acres b/	Pool Elevation Ft. (MSL)	Pool Storage c/ 1000 Ac-Ft	Flood Control Storage 1000 Ac-Ft	Total Storage 1000 Ac-Ft
San Estaban	R	1911	762	-	4,451		4,451
Red Bluff	W.S., H.E.	1936	11,700	2,841.7	310,000		310,000
Balmorhea	W.S.	1917	573	3,187.0	6,340		6,350
Amistad	W.S., R, H.E.	1968	64,900	1,117.0	3,505,400	1,744,300	5,249,700
Casa Blanca	W.S.	1949	1,656	465.0	20,000		20,000
Falcon	W.S., R, H.E.	1953	86,843	301.1	2,667,588	509,505	3,177,093

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
I.R. - Irrigation only
b/ At conservation pool elevation
c/ Includes sediment storage

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)

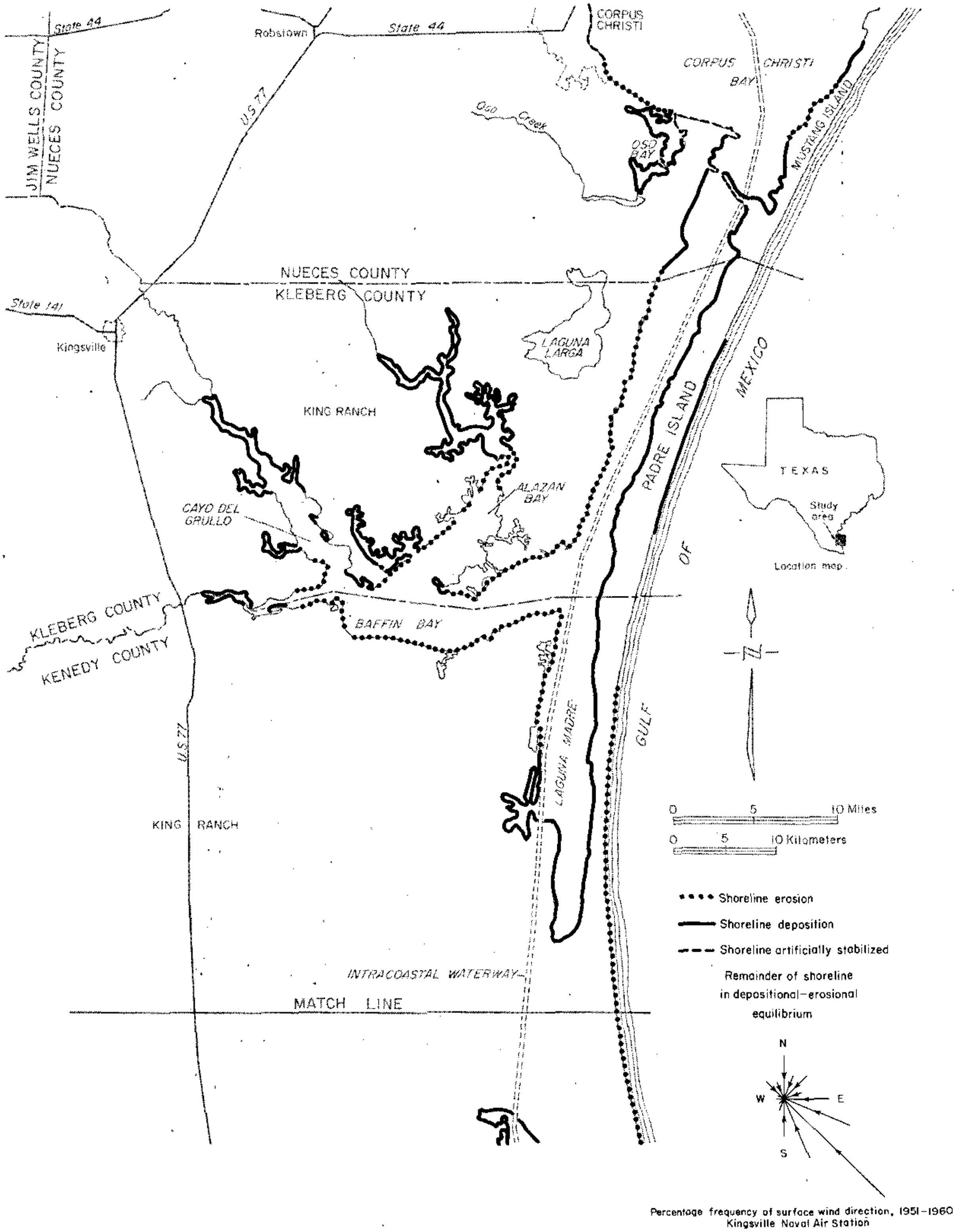


Figure 3-4. Shoreline Physical Processes, Upper Laguna Madre Estuary (266)

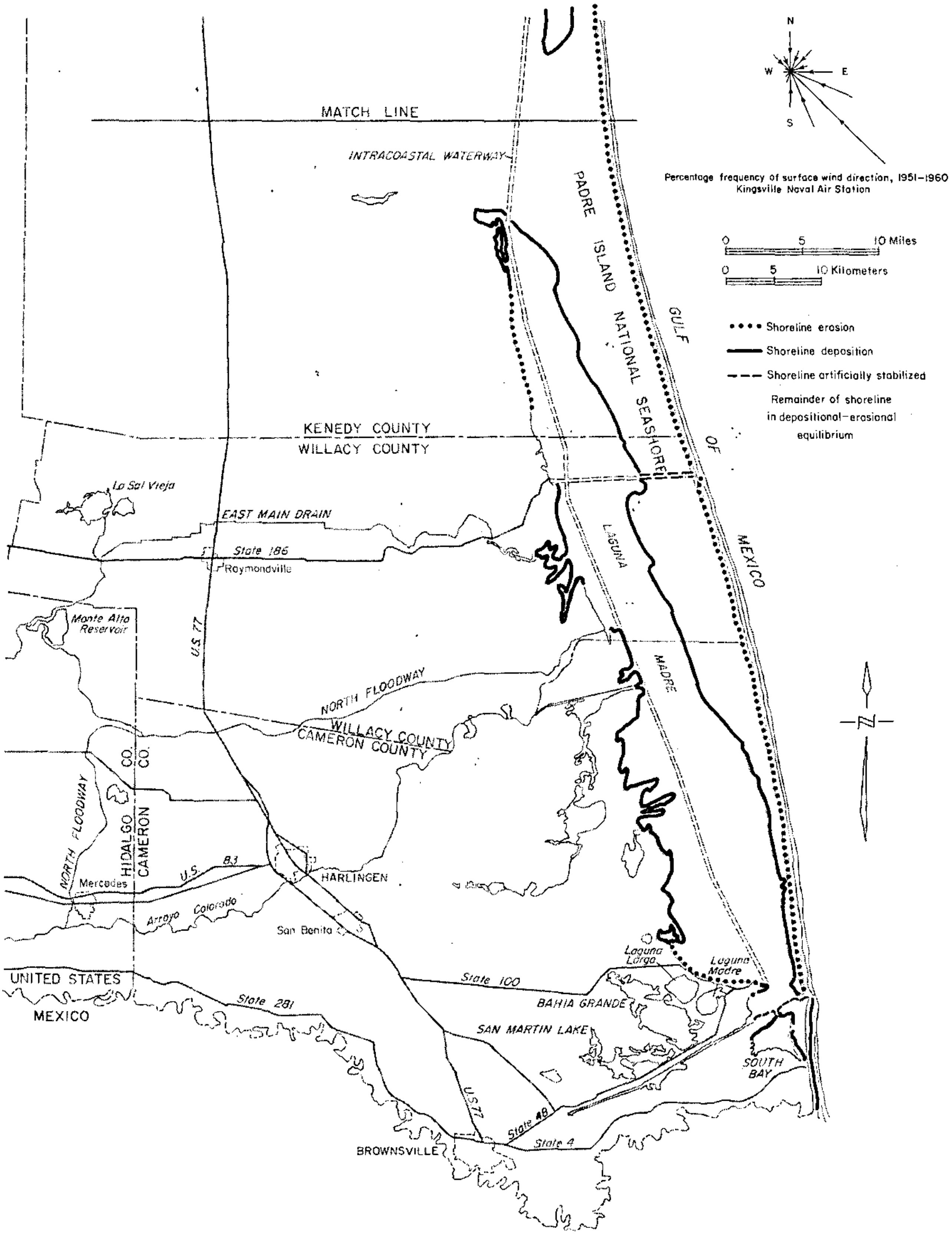


Figure 3-5. Shoreline Physical Processes, Lower Laguna Madre Estuary (266)

is blowing. Wind can also generate waves and longshore currents (190, 100, 300).

The seasonal threat of wind and water damage associated with tropical cyclones occurring in the Gulf of Mexico exists each year from June through October. Wind damage from hurricanes and associated tornadoes can be costly, but the most severe losses occur from the flooding brought by heavy rains and high storm tides along the coast. Gulf and mainland shorelines may be drastically altered during the approach, landfall, and inland passage of hurricanes (100, 328). Storm surge flooding and attendant breaking waves erode Gulf shorelines from a few tens to a few hundreds of feet. Washovers along the barrier islands and peninsulas are common, and saltwater flooding may be extensive along the mainland shorelines.

Flooding of rivers and small streams normally corresponds either with spring thunderstorms or with the summer hurricane season. Rivers generally flood as a result of regional rainfall, but flooding along smaller streams may be activated by local thunderstorms (267). Some effects of flooding include: (1) overbank flooding into marsh areas of the floodplain and onto delta plains; (2) progradation of bayhead and oceanic deltas; (3) flushing of bays and estuaries; and (4) reduction of salinities.

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

There are several oil and gas fields within the area surrounding Laguna Madre estuary. The production of oil, natural gas, and natural gas liquids plays a prominent role in the total economy of the area. In addition to the direct value of these minerals, oil and gas production supports major industries within the area and elsewhere in the coastal zone by providing readily available fuels and raw materials. Oil and natural gas constitute the main economic base of the area, even though agriculture (mainly ranching) is the major current land use in the area (Figure 3-8).

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

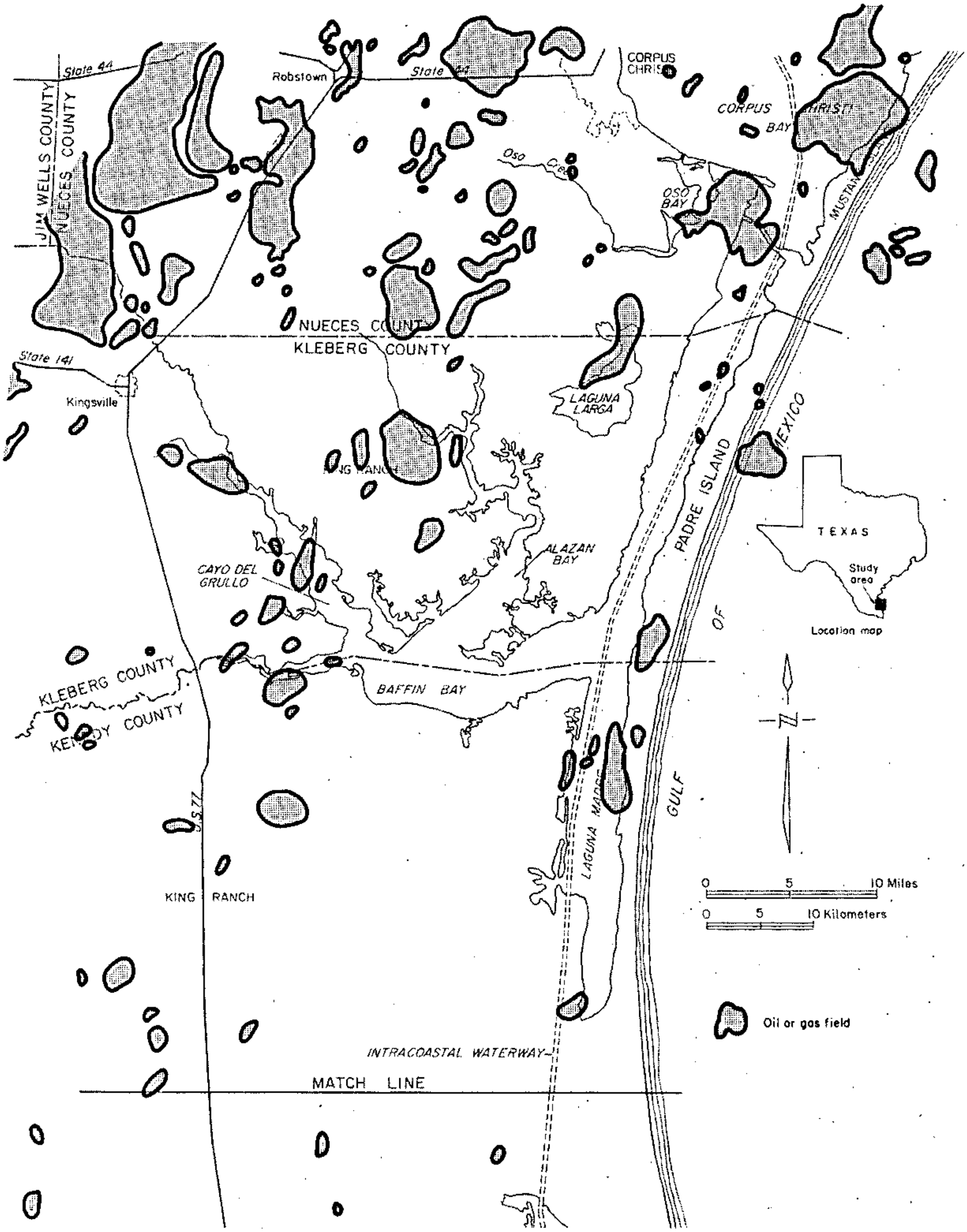


Figure 3-6. Oil and Gas Fields, Upper Laguna Madre Estuary (266)

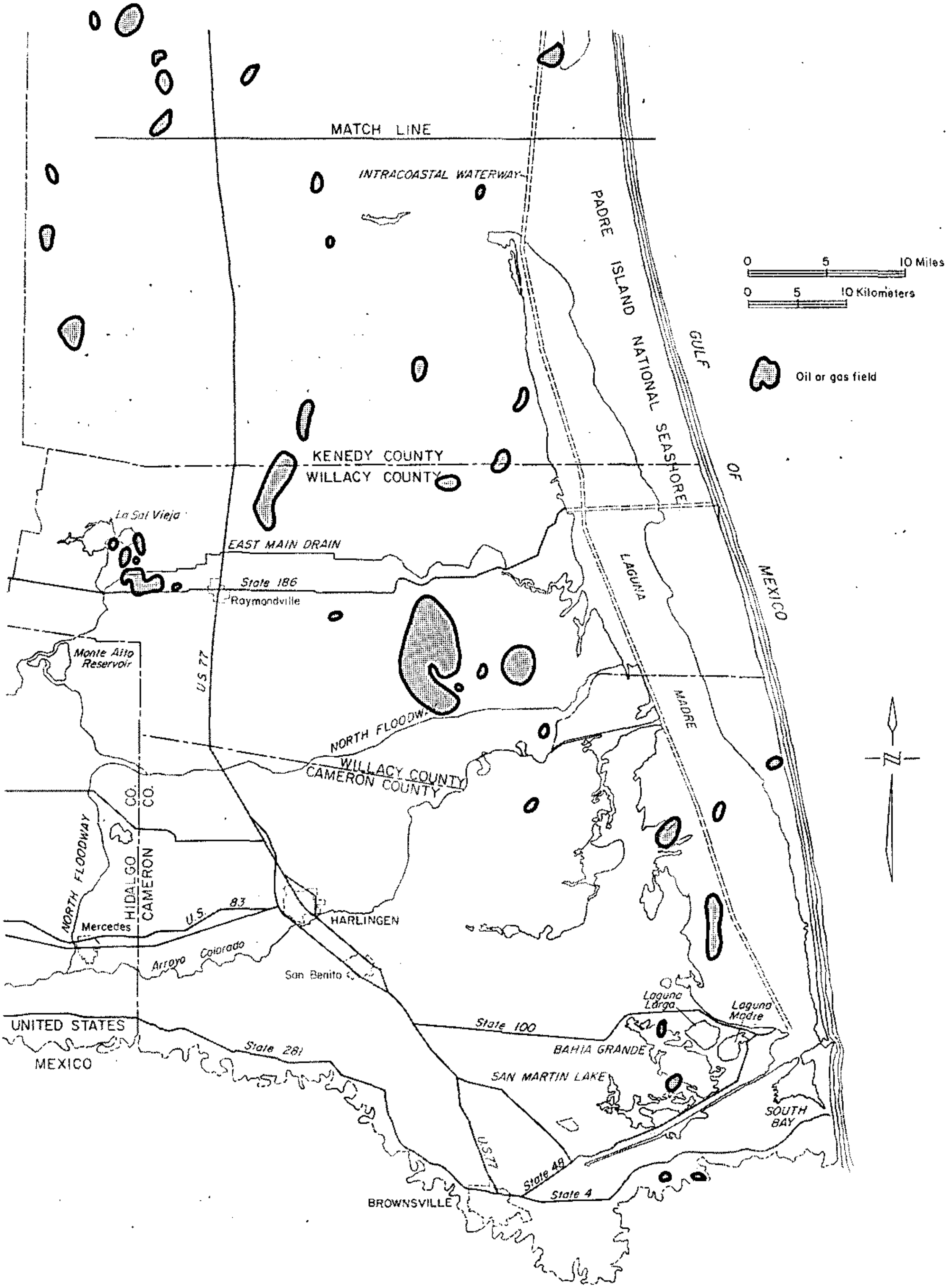


Figure 3-7. Oil and Gas Fields, Lower Laguna Madre Estuary (266)

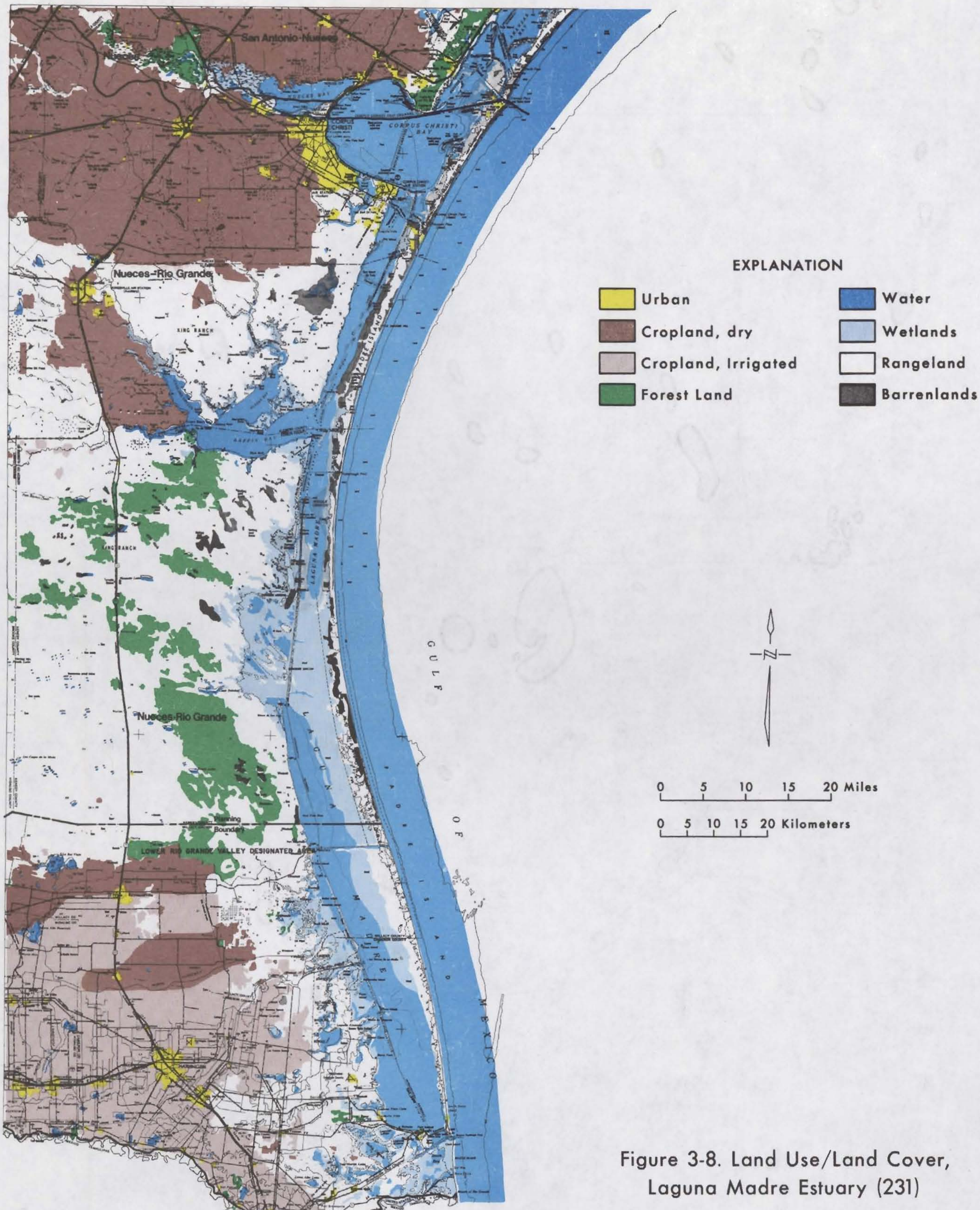


Figure 3-8. Land Use/Land Cover, Laguna Madre Estuary (231)

Near the Laguna Madre estuary this fresh (up to 1,000 mg/l total dissolved solids) to slightly saline (1,000 to 3,000 mg/l total dissolved solids) portion of the aquifer extends to a maximum depth of about 2,500 feet (760 m). The most productive part of the aquifer is from 200 to 600 feet (60 to 180 m) thick (238).

The quality of water in the aquifer varies widely, but generally is 1,000 to 1,500 mg/l total dissolved solids. In the area adjacent to the Gulf, saline water overlies usable fresh water. 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 (270).

The Laguna Madre estuary lies in the West Gulf Coast land resource area (328), an undulating to rolling, moderately dissected, brush covered plain. Native vegetation consists of thorny shrubs, mesquite, and tall and short grasses. Soils vary from calcareous to neutral. Saline and sodic soils are extensive along the coast.

Land use in the area is dominated by agricultural and ranching activities (Figure 3-8). Cotton, grain sorghum, fruits, and vegetables are the principal irrigated crops.

The Padre National Seashore, managed by the U.S. Department of Interior, and the Olmito Fish Hatchery and the Las Palomas Wildlife Management Area, controlled by the State of Texas, occur in the immediate vicinity of the Laguna Madre estuary (Figure 3-9) (330). More than 300 known archeological sites and 10 National Register sites occur in the area. Archeological surveys indicate occupation by aboriginal cultures during the Archaic and Neo-American periods (326). In addition, there are five State parks of recreational, historic, and scenic significance in the area (262, 263).

Natural resources of the bay system and adjoining inland areas provide a wide variety of recreational opportunities for the people of Texas as well as visitors from other states. Inland areas and marshes adjacent to the estuaries provide terrestrial and aquatic habitat for many species of wildlife such as the endangered Kemp ridley turtle, jaguarundi, and Mexican wolf. Wildlife resources of the area enhance the recreation opportunities for sightseeing and nature studies, which esthetic benefits accruing to both naturalists and environments.

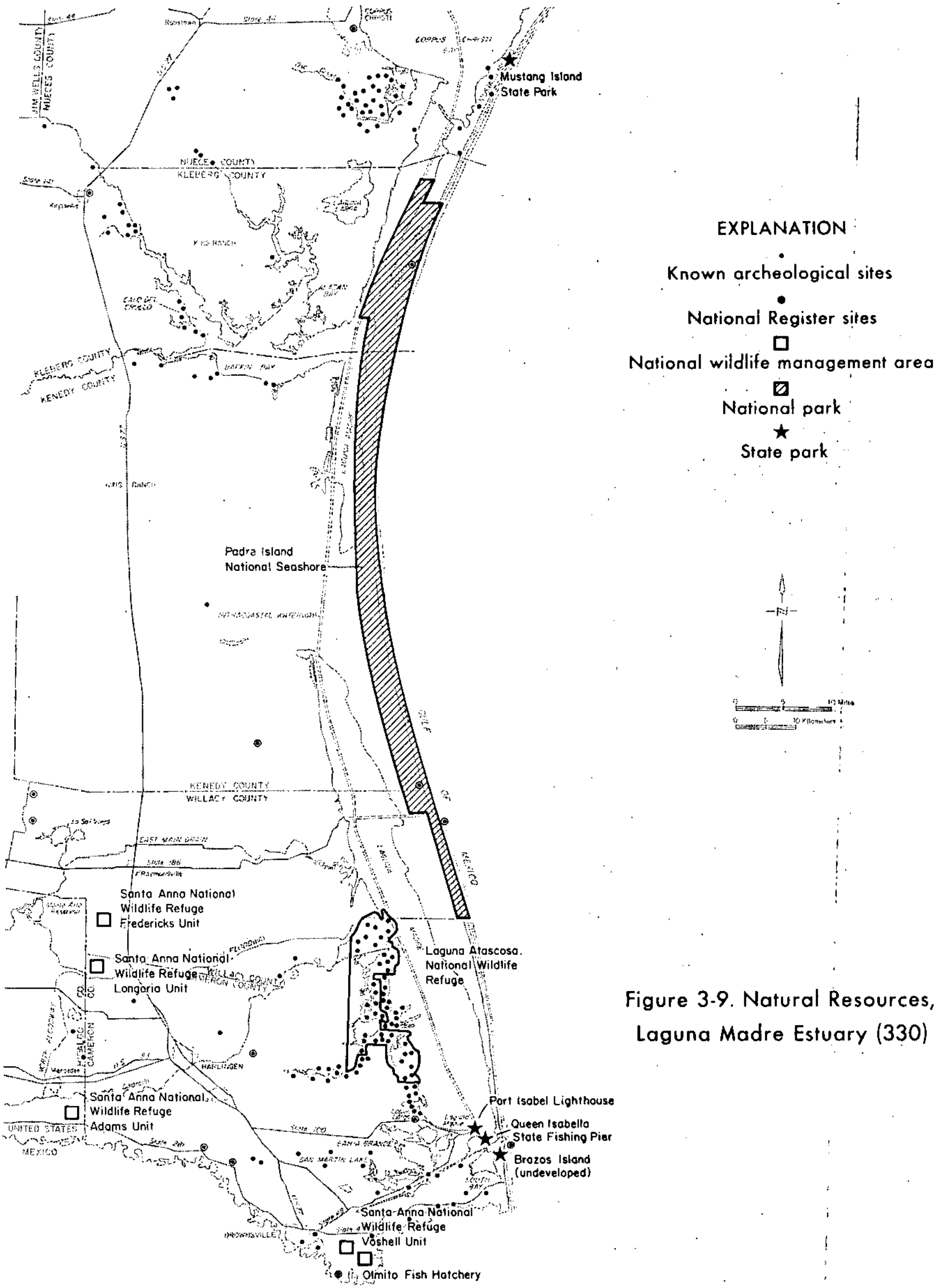


Figure 3-9. Natural Resources, Laguna Madre Estuary (330)

Data Collection Program

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

A program was therefore initiated by the Department, in cooperation with other agencies, to collect the data considered essential for analyses of the physical and water quality characteristics and ecosystems of Texas' bays and estuaries. To begin this program, the Department consulted with the U. S. Geological Survey and initiated a reconnaissance-level investigation program in September, 1967. Specifically, the initial objectives of the program were to define: (1) the occurrence, source and distribution of nutrients; (2) current patterns, directions, and rates of water movement; (3) physical, organic, and inorganic water quality characteristics; and (4) the occurrence, quantity, and dispersion patterns of water (fresh and Gulf) entering the estuarine system. To avoid duplication of work and to promote coordination, discussions were held with other State, Federal and local agencies having interests in Texas estuarine systems and their management. Principally through this cooperative program with the U. S. Geological Survey, the Department has continued to collect data in all estuarine systems of the Texas Coast (Figure 3-10 and 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 Laguna Madre estuary on July 15-18, 1980. Tidal amplitudes were measured simultaneously at numerous locations throughout the estuary (Figure 3-11). Tidal flow measurements were made at several different bay cross-sections. In addition, conductivity data were collected at many of the sampling stations shown in Figures 3-10. Studies of past and present freshwater inflows to Texas' estuaries have used all available sources of information on the physical, chemical, and biological characteristics of these estuarine systems in an effort to define the relationship between freshwater and nutrient inflows and estuarine environments.

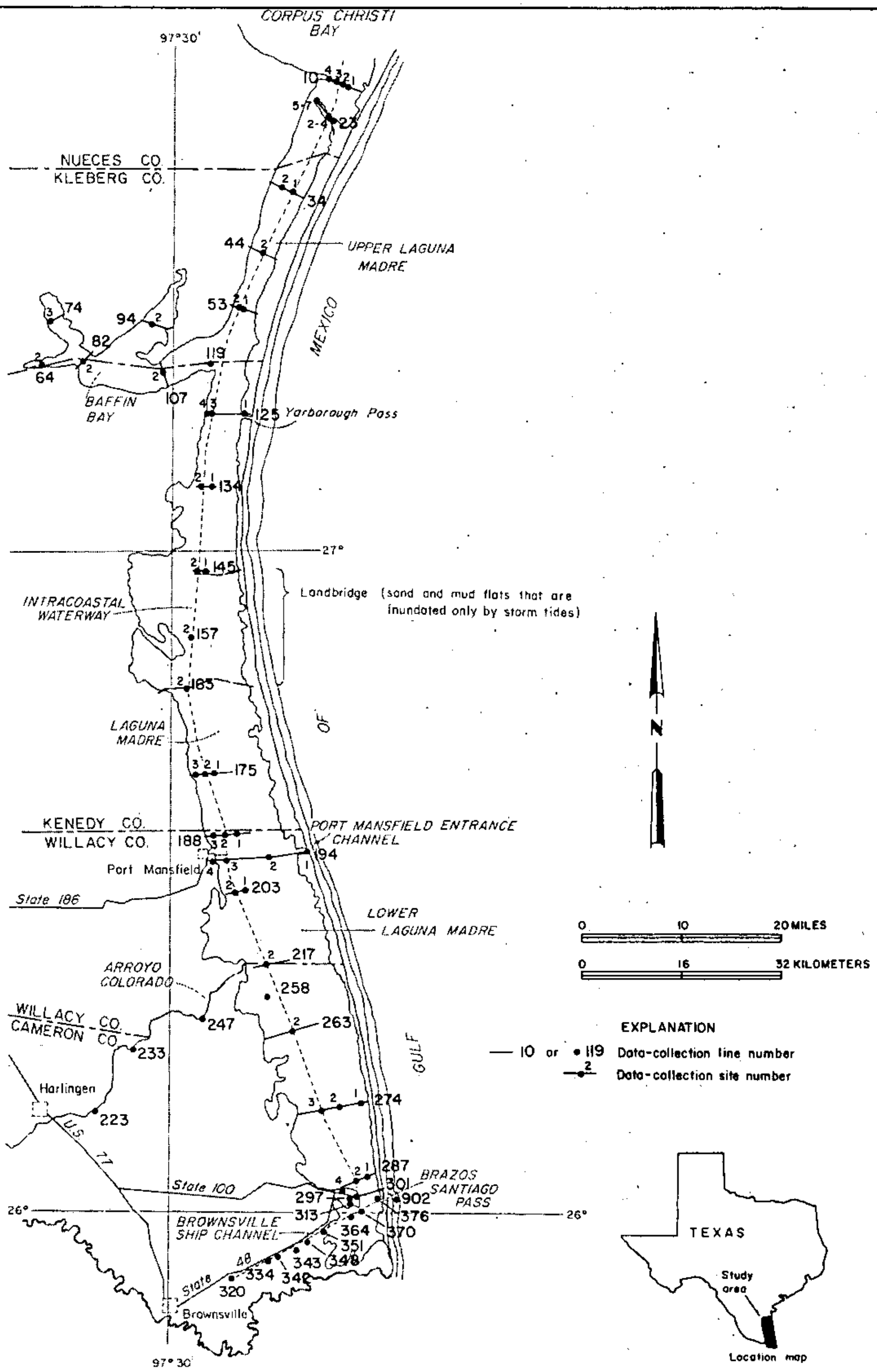


Figure 3-10. Data Collection Sites in the Laguna Madre Estuary

Table 3-2. Laguna Madre Estuary Gaging Stations

Station Number	Station Description	Period of Record	Operating Entity	Type of Record
E	Raymondville Drain nr. Port Mansfield	1977–	TDWR[a/]	Continuous
F	Trickle Ditch nr. Willamar	1978–	TDWR	Continuous
G	North Floodway nr. Sebastian	1940–	IBWC[b/]	Flood Flows Only
H	Arroyo Colorado Floodway, South of Harlingen	1958–	IBWC	Flood Flows Only
I	Cayo Atascosa, at Wildlife Refuge, nr. Rio Hondo	1978–	TDWR	Continuous
44	Laguna Madre GIWW #73 – Wildlife Refuge	1970–	COE[c/]	Continuous
45	Laguna Madre Small Boat Harbor Channel, Port Isabel	1974–	COE	Continuous
45A	Laguna Madre GIWW Marker #125 – Port Isabel	1970–74	COE	Continuous
J	Laguna Madre at Old Port Isabel Causeway	1981–	TDWR	Continuous
46	Brazos-Santiago Pass, N. Jetty, Gulfside Padre Island	1968–	COE	Continuous
211530	Laguna Madre nr. Corpus Christi	1976–	USGS[d/]	Continuous
40	North Laguna Madre Kennedy Memorial Hwy., GIWW Marker #21	1971–75	COE	Continuous
41	Baffin Bay Laguna Salado	1971–	COE*	Continuous
42	Baffin Bay GIWW Marker #115 nr. Pt. of Rocks	1971–75	COE	Continuous
W # 1	Baffin Bay, Adjacent to Leo Kaufer Co. Park	1980–	TDWR	Continuous
A	Baffin Bay nr. C.M. #8	1980–	TDWR	Continuous
B	Laguna Madre, Land Cut, North	1980–	TDWR	Continuous
W # 2	Southeast Point Island at S. End of Land Cut	1981–	TDWR	Continuous
C	Laguna Madre, Land Cut, South	1978–	TDWR	Continuous
D	Port Mansfield	--	NOAA[e/]	Continuous
43	Port Mansfield Entrance Channel, N. Jetty, Gulfside Padre Island	1965–	COE	Continuous

a/ Texas Department of Water Resources
b/ International Boundary and Water Commission
c/ Corps of Engineers
d/ U. S. Geological Survey
e/ National Oceanic and Atmospheric Administration
* COE property, operated by TDWR, 1980

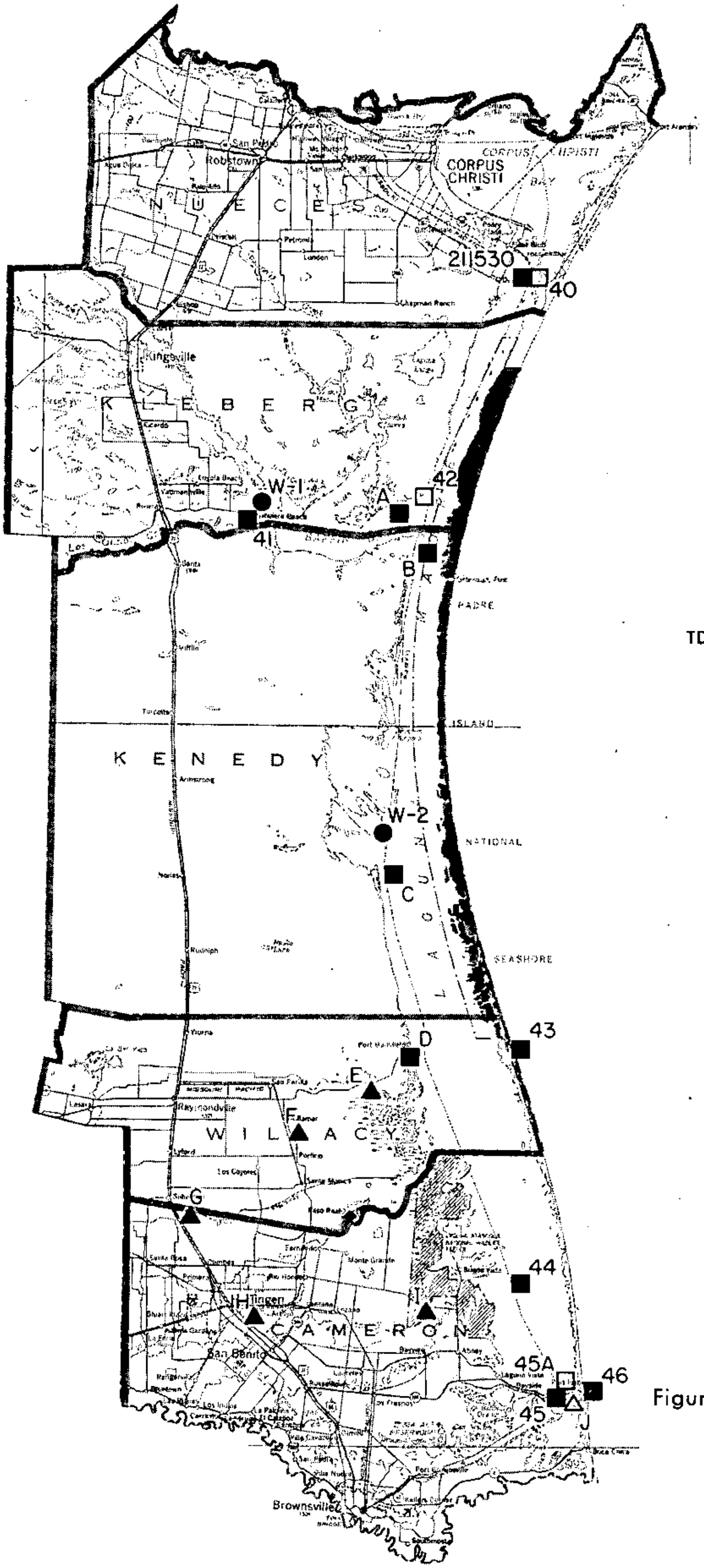


Figure 3-11. Locations of Gaging Stations, Laguna Madre Estuary

Economic Characteristics

Socioeconomic Assessment of Adjacent Counties

The economic significance of the natural and man-made resources associated with the Laguna Madre estuary is reflected in the direct and indirect linkages of bay-supported resources to the economies of Nueces, Jim Wells, Kleberg, Brooks, Kenedy, Hidalgo, Willacy and Cameron Counties. Trends in population, employment, and earnings are presented below for the four county study area (Cameron, Kenedy, Kleberg, and Willacy).

Population. The population of the four-county study area experienced an annual growth of 3.1 percent between 1970 and 1975, which is well above the statewide figure of 1.7 percent for the same period. Only Kenedy County had annual growth (-2.3 percent) lower than the statewide average, while Cameron, Kleberg, and Willacy Counties had annual changes of +3.9, +2.1, and +1.8 percent, respectively.

In 1975, the population of the four-county area was 219,000. Cameron County, which includes the City of Brownsville, accounted for 76 percent of the total. Population forecasts for the period 1975 to 2030 indicate that the population of the study area can be expected to increase 3.1 percent per annum to the year 2030. Cameron County is projected to remain the most populated, growth to 85 percent of the study area population in 2030. Details of future population estimates for the four-county area are presented in Table 3-3.

Employment. In 1970, an estimated 54,300 persons were employed in the study area, and almost 75 percent of these worked in Cameron County.

About 80 percent of the region's employed labor force is distributed among eight major industrial sectors (Table 3-4). Workers employed by wholesale and retail trade establishments, the largest employment sector, account for more than 23 percent of the area's labor force.

Industry. The "basic" industries in the area are manufacturing, agriculture-forestry-fisheries, construction, and mining. These sectors account for 31 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 almost 50 percent of the region's workers. The service sectors provide goods and services to the basic industries as well as the general public and are, in varying degrees, dependent upon them.

The most significant basic sector, in terms of total earnings, is manufacturing (Table 3-5). The major portion of manufacturing activity is centered in the Brownsville metropolitan area.

The Port of Brownsville is another important factor in the regional economy. In 1975, it was the tenth largest port in Texas, in terms of tonnage handled. It functions as a maritime harbor as well as an inland harbor with access via the Intracoastal Canal to ports on the Mississippi River. In addition to providing basic low-cost transportation for raw materials and

Table 3-3. Population Estimates and Projections, Laguna Madre Estuary, 1970-2030 (234)

County	1970	1975	1980	1990	2000	2010	2020	2030	1970-2000 Annual % Change	1970-2030 Annual % Change
Cameron	140,368	168,100	199,400	248,900	306,700	376,400	452,400	530,000		
Annual % Change		3.9	3.7	2.5	2.3	2.3	2.0	1.7	3.9	4.6
Kenedy	678	600	600	500	400	300	300	300		
Annual % Change		-2.3	0.0	-1.7	-2.0	-2.5	0.0	0.0	-1.4	-.9
Kleberg	33,166	33,300	33,800	34,900	36,000	41,200	49,500	62,800		
Annual % Change		2.1	.3	.7	.3	1.5	2.0	2.7	.3	1.5
Willacy	15,570	17,000	18,200	19,000	21,100	23,700	26,700	30,000		
Annual % Change		1.8	1.4	.9	.6	1.2	1.3	1.2	1.2	1.6
Area Total	189,782	219,000	252,000	304,200	364,200	441,600	528,900	623,100		
Annual % Change		3.1	3.0	2.6	2.0	2.1	2.0	1.8	3.1	3.8
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		
Annual % Change		1.7	1.9	1.5	1.6	1.7	1.7	1.8	1.6	1.7

Table 3-4. Employment by Industrial Sector, Laguna Madre, 1970 (229)

Sector	1970					
	Cameron	Kenedy	Kleberg	Willacy	Area Total	Percent of Total Employment in Study Area
Wholesale and Retail Trade	10,129	13	1,866	966	12,974	23.9
Manufacturing	4,579	9	844	106	5,538	10.2
Professional Services	7,194	41	2,578	789	10,602	19.5
Construction	2,817	-	935	160	3,912	7.2
Agriculture, Forestry, and Fisheries	4,730	179	639	1,446	6,994	12.9
Mining	103	-	416	63	582	1.1
Civilian Government	2,211	12	722	97	3,042	5.6
Amusement and Recreation	336	-	60	11	407	.7
All Other	8,079	44	1,596	530	10,249	18.9
Total	40,178	298	9,656	4,168	54,300	100.0

Table 3-5. Earnings by Industrial Sector, Area Surrounding Laguna Madre Estuary, 1970 (228)

Sector	1970					
	Cameron	Kenedy	Kleberg	Willacy	Area Total	Percent of Total Earnings in Study Area
	(thousands of 1967 dollars)					
Wholesale and Retail Trade	44,541	35	7,521	4,094	56,191	20.6
Manufacturing	23,582	29	6,991	552	31,154	11.5
Professional Services	18,639	64	6,094	1,970	26,767	9.8
Construction	10,316	-	3,785	565	14,666	5.4
Agriculture, Forestry, and Fisheries	26,353	799	4,319	7,765	39,236	14.4
Mining	616	-	2,530	363	3,509	1.3
Civilian Government	47,495	96	8,782	2,008	58,381	21.5
Amusement and Recreation	1,056	-	156	33	1,245	.5
All Other	32,696	83	5,992	2,149	40,920	15.0
Total	205,294	1,106	46,170	19,499	272,069	100.0

finished products, it is also an important source of direct and indirect employment in the area.

The mineral wealth of the area is also an important factor in its economy. Crude oil production in 1977 exceeded four million barrels. Annually, Kleberg County produces about two-thirds of the regional crude oil production. Regional natural gas production (gas well and casinghead gas) in 1977 was over 538 billion cubic feet.

Agriculture. The four-county area had over $136 million in receipts from crop production in 1977. Major regional crops are cotton, grain sorghum, and fruits. Livestock and livestock product receipts in 1977 were over $38 million, for a total regional agricultural output of over $174 million in that year.

Summary. The four-county area possesses abundant natural and man-made resources. Examination of projected trends in population, employment, industrial composition, and earnings provides an estimate of the future course of the area's economy. The future well-being of the regional economy will depend on the extent to which the diverse economic activities of manufacturing, agriculture, tourism, fishing, and oil and gas mining are able to coexist in the bay environment.

The economic outlook for the study area is somewhat uncertain due to the limited growth potential of the agricultural, oil and gas, and commercial fisheries industries which currently play an important role in the economy. In view of this situation, water-oriented outdoor recreation potential will contribute to economic progress for the area and will tend to increase 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 Laguna Madre estuary, analyses have been performed to compute estimates of the quantities of sport and commercial fishing and the economic impacts of these fisheries upon the local and state economies. The sport fishing estimates are based upon data obtained through surveys of a sample of fishing parties and upon the analytic methods presented below. The commercial fishing estimates were based on data from published statistical series about the industry.

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

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

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

The estimated number of fishing parties at the Laguna Madre estuary for the study period is stated as follows:

$$T = Z + W + P$$

where:

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

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

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

where:

Z = Estimated number of boat parties fishing in the Laguna Madre estuary for the period September 1, 1976 through August 31, 1977.

z_k = Estimated number of boat parties fishing in the Laguna Madre 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 Laguna Madre estuary for the period September 1, 1976 through August 31, 1977.

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

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

where:

P = Estimated number of pier parties fishing in the Laguna Madre estuary for the period September 1, 1976 through August 31, 1977.

p_k = Estimated number of pier parties fishing in the Laguna Madre estuary during the kth calendar quarter of the study.

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

For boat fishing:

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

where:

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

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

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

r = Sample boat sites within the study area,

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

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

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

A_k = Average number of hours fished per boat party on weekend days in quarter k.

No data were collected for wade-bank and pier fishing in this study period; therefore, the estimate of wade-bank and pier parties was based on the relation of wade-bank and pier fishing to boat fishing as observed in the year-long studies of Corpus Christi and Aransas Bays (258,259).

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 180 thousand fishing parties annually visit the Laguna Madre estuary (Table 3-6). Seasonal visitation as a percentage of annual visitation ranged from a high of more than 41 percent for the summer quarter to a low of approximately 12 percent during the winter quarter. The distribution of fishing parties by strata indicates that wade-bank fishing accounted for about 38 percent of annual visitation followed by boat fishing with approximately 37 percent (Table 3-6).

Sport Fishing Visitation Patterns. Although the personal interview information included the county of residence of the interviewee, the number of interviews (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 90 percent of fishermen at the Laguna Madre estuary came from the following seven counties -- Cameron (20.1 percent of the summer 1977 visitation), Bexar (17.4 percent), Hidalgo (17.2 percent), Nueces (13.4 percent), Harris (11.7 percent), Dallas (5.5 percent) and Willacy (4.9 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 Laguna Madre estuary, these counties are Nueces, Jim Wells, Kleberg, Kenedy, Brooks, Willacy, Cameron and Hidalgo. "Non-local" comprises all other Texas counties and out-of-state visitors.

Since it is expected that the proportions of local and nonlocal bay sport fishermen vary from season to season, an attempt was made to estimate this pattern for seasons other than the summer period. The only information available on visitation patterns for all seasons was the sample of personal interview data which, in addition to the small number of observations, was

Table 3-6. Estimated Seasonal Sport Fishing Visitation to the Laguna Madre Estuary, 1976-1977 a/

Season b/	Boat	Wade-Bank c/	Pier d/	Total - All Strata
		(thousands of parties)		
Fall	10.7 (2.59)	15.1 (2.26)	10.8 (2.29)	36.6
Winter	4.0 (2.26)	14.5 (1.98)	2.3 (2.37)	20.8
Spring	12.1 (2.48)	15.1 (2.52)	21.3 (2.10)	48.5
Summer	16.9 (2.57)	24.4 (2.23)	32.9 (2.35)	74.2
Total All Seasons	43.7 (2.52)	69.1 (2.25)	67.3 (2.26)	180.1

a/ The figures in parenthesis indicate the weighted average number of fishermen per party for the respective fishing type and quarter for the two estuarine systems.
b/ Fall = September, October and November
Winter = December, January and February
Spring = March, April and May
Summer = June, July and August
c/ Wade-bank fishermen/party data obtained from (258,259)
d/ Pier fishermen/party (258,259)

felt to be biased toward local parties. Thus, the summer license survey visitation pattern was compared to the summer interview pattern, for the purpose of computing an adjustment factor. This was applied to the remaining quarters of interview data to remove the bias toward local data and provide a more accurate reflection of year-round visitation patterns (Table 3-7).

Sport Fishing Direct Expenditures. During the interview, a question was asked of the party head for total expected cost of the trip for the entire group, including food, lodging, and gasoline. The personal interview survey sample of fishing party expenditure data was grouped by origin (local or nonlocal). As previously mentioned, no data were collected for wade-bank and pier parties during this study period; therefore, the relationship between average cost per boat party and wade-bank and pier parties from the 1975-1976 study of Corpus Christi Bay (259) was used to estimate average cost per party for the two strata. The average cost per party for the various fishing types and origins (Table 3-8) was applied to the adjusted visitation distribution estimates (Table 3-7) and visitation estimation by type (Table 3-6) to obtain an estimate of total sport fishing expenditures (Table 3-9). More than 40 percent of the estimated $9.72 million expenditures was made during the summer and 27.4 percent was made during the spring quarter (Table 3-9).

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

Indirect impacts are the dollar values of goods and services that are used to supply the sectors which have made direct sales to fishing parties. Each directly affected sector has supplying sectors from which it purchases materials and services. The total amount of these successive rounds of purchases is known as the indirect effect. The total business effects of sales of equipment, supplies, and services to fishing parties upon the regional and state economies include the direct and indirect incomes resulting from the direct fishing business. Each economic sector pays wages, salaries and other forms of income to employees, owners and stockholders who in turn spend a portion of these incomes on goods and services. In this study, the method used to calculate this total impact is input-output analysis, using the Texas Input-Output Model (237) and regional input-output tables derived from the state model (241). 1/

1/ Input-output relationships were estimated for Nueces, Kleberg, Jim Wells, Kenedy, Brooks, Willacy, Hidalgo, and Cameron Counties.

Table 3-7. Estimated Seasonal Sport Fishing Visitation Patterns at Laguna Madre Estuary, 1976-1977

Visitation	Fall	Winter	Spring	Summer	Total-Annual
			(thousands of parties)		
Local	13.4	8.6	21.6	27.3	70.9
Nonlocal	23.2	12.2	26.9	46.9	109.2
Total Visitation	36.6	20.8	48.5	74.2	180.1

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

Average Cost per party	Boat	Wade-Bank	Pier	Weighted Average
		(1976 dollars)		
Local	26.12	18.96	22.40	21.98
Nonlocal	87.11	70.60	71.14	74.78

Table 3-9. Estimated Sport Fishing Expenditures by Season and Fishing Party Type, Laguna Madre Estuary, 1976-1977

Season a/	Boat	Wade-Bank	Pier	Total	Percent
			(thousands of 1976 dollars)		
Fall	648.9	752.9	505.5	1,907.3	19.6
Winter	285.1	782.2	125.5	1,192.8	12.2
Spring	818.7	763.9	1,079.7	2,662.3	27.4
Summer	994.5	1,160.6	1,810.7	3,965.8	40.8
Total	2,747.2	2,695.7	1,710.7	9,728.2	100.0

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

The expenditure data collected by personal interviews of a sample of fishing parties at the Laguna Madre estuary (Table 3-9) indicated only the magnitude of variable expenditures by sport fishermen. To estimate the sectoral distribution of all expenditures, the interview data were supplemented with data from estimated retail sales in 1975 by marine sport fishing related industries in the West Gulf of Mexico region (Mississippi delta to Mexican border) (388). 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 Laguna Madre estuary were over $8.68 million. In addition, there was an estimated $1.04 million spent outside the region, within Texas (Table 3-10). Most of the expenditure impact, over 89 percent, accrues to the region. However, when the total impacts are calculated, the regional gross impact of over $19.15 million accounts for more than 61 percent of the gross dollar value statewide (Table 3-11). This spreading of impact results from business and industry market linkages among regional establishments and suppliers throughout the State.

Approximately 35 percent of the direct expenditures by sport fishermen in the region results in increased personal incomes for regional households directly affected by the sport fishing industry. From these data it is estimated that regional households received an increased annual income of over $5.6 million from the sport fishing business in the area (Table 3-11). Statewide, the income impact amounted to over $8.8 million, annually.

The input-output analysis estimated a total of 520 full time job equivalents directly related to sport fishing in the Laguna Madre estuary region in 1976 through 1977. Statewide, an additional 91 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 1038 full time job equivalents (Table 3-11).

Revenues to state and local governments (including schools) are positively impacted by the increased business activity and gross dollar flows from sport fishing business. The total statewide State tax revenues amounted to over $319.7 thousand, with $216.5 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 $334.6 thousand resulted from direct, indirect and induced sport fishing expenditures (Table 3-11). In addition, local governments outside the Laguna Madre estuary region collected an estimated $154 thousand in taxes on travel expenditures by fishing parties in 1976 through 1977.

The data show that sport fishing in the Laguna Madre estuary region results in a larger economic impact in areas outside the region than within

Table 3-10. Estimated Sport Fishing Variable Expenditures by Sector, Laguna Madre, Estuary, 1976-1977

	Bait	Travel	Food	Lodging	Recreation a/	Total
Total	2,582.8	2,480.8	841.2	2,766.3	1,057.1	9,728.2 b/

a/ Marinas, boat fuel, and boat rental
b/ Adjusted for travel expenditures outside the study area 9,728.2 - 1,042.1. Expenditures in the region = $8,686.1 thousand

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

	Direct c/		Total	
	Regional	State	Regional	State d/
Output (thousands)	$8,686.1	$9,728.2	$19,151.3	$31,378.5
Employment (Man-Years)	520	611	734	1,038
Income (thousands)	3,056.6	3,576.5	5,657.9	8,888.7
State Tax Revenues (thousands)	e/	72.5	216.5	319.7
Local Tax Revenues (thousands)	e/	102.5	334.6	488.6

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

the region. However, data necessary to analyze the effects of the sport fishing equipment business were not available. Thus, the annual statewide gross output impact of over $31.37 million represents a contribution to the State's economy from only the variable expenditures by sport fishermen in the estuarine region and does not include the effects of purchases of sport fishing equipment.

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

The average annual commercial fishing contribution of the estuary was estimated at 3,910,200 pounds (1.8 million kg) of finfish and 874,100 pounds (396,500 kg) of shellfish for the period 1972 through 1976. Using 1976 dockside finfish and shellfish prices ($.357 per lb. and $1.456 per lb., respectively), the direct commercial value of fish attributed to the estuary was estimated at $2.67 million (1976 dollars) (358). Red Drum, Black Drum, and Seatrout constituted approximately 86 percent of this value.

The Texas economy-wide total business resulting from commercial fish catch attributed to the Laguna Madre estuary was estimated using the 1972 Texas Input-Output Model fisheries sector multipliers. Total value of the catch was $2.67 million (1976 dollars), direct employment in the fisheries sector was 97, and direct salaries to fisheries employees was $891 thousand (Table 3-12).

Gross Texas business resulting from fishing, processing, and marketing the catch attributed to the estuary was estimated at $8.3 million. Indirect supporting and marketing activities provided an additional 97 full time job equivalents regionally and an additional 50 full time job equivalents statewide. Gross personal income in Texas attributed to the estuarine fishing and supporting sectors was estimated at $2.3 million, State taxes at $75.5 thousand, and taxes paid to local units of government throughout Texas, as a result of this fishery business, at $104.9 thousand in 1976 (Table 3-12).

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

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

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

	Fishing Sector	Total: Regional	Total: State
Output (1000's 1976$)	$2,668.6	5,596.1	8,312.7
Employment (Man-Years)	97	147	207
Income (1000's 1976 $)	891.6	1,871.4	2,286.0
State Tax Revenues (1000's 1976 $)	10.1	65.3	75.5
Local Tax Revenues (1000's 1976 $)	12.0	81.1	104.9

a/ Total = direct, indirect, and induced 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 $8.68 million. In addition, there was an estimated $1.04 million spent outside the region, within Texas.

Approximately 35 percent of the direct expenditures by sport fishermen in the region resulted in increased personal incomes for regional households directly affected by the sport fishing industry. Statewide, the income impact amounted to over $8.8 million, annually. In addition, the total employment impact to the State economy was 1038 full-time job equivalents.

Revenues to State and local government (including schools) were positively impacted by the increased activity and gross dollar flows from the sport fishing industry. The total statewide State tax revenues amounted to more than $319 thousand.

Estimates were made of the total (inshore-offshore) commercial fisheries harvest dependent upon the Laguna Madre estuary. The average commercial fisheries contribution was estimated at 4.8 million pounds of finfish and shellfish for the period of 1972 through 1976. The total value of the catch was $2.67 million (1976 dollars), direct employment in the commercial fisheries sector was 97, and direct salaries to fisheries employees was $891 thousand.

CHAPTER IV

HYDROLOGY

Introduction

Detailed studies of the hydrology of areas draining to the Laguna Madre estuary were necessary to estimate historical freshwater inflows from contributory areas, only a portion of which are gaged. Of all Texas basins, only the Nueces-Rio Grande Coastal Basin contributes inflow to the Laguna Madre estuary. The Rio Grande is separated from the estuary by a coastal land mass and does not contribute to freshwater inflow. 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 Laguna Madre estuary consist of (1) gaged inflow from the Nueces-Rio Grande Coastal Basin (2) ungaged runoff, (3) return flows from 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 in order to arrive at a freshwater inflow balance.

Gaged Inflow, Laguna Madre Estuary

The Nueces-Rio Grande Coastal Basin has a total gaged drainage area of 1,347 square miles (3,504 km^2). This inflow enters Laguna Madre estuary from San Fernando Creek and Los Olmos Creek (into Baffin Bay) and from the North Floodway and the Arroyo Colorado (into the lower Laguna Madre). Gaged contributions have averaged 335,000 acre-feet/year (411 million m^3/yr) over the period 1941 through 1976 (Table 4-1). Gage yields from the Nueces-Rio Grande Coastal Basin (1941 through 1976) have averaged 249 acre-feet per square mile (1186 m^3/ha). Gaged flows have accounted for 49 percent of the combined inflow 1/ and 17 percent of the total freshwater inflow 2/ (Table 4-2).

Ungaged Runoff Contributions

Ungaged drainage areas contributory to the Laguna Madre estuary include some 2,686 square miles (6,995 km^2) in Nueces-Rio Grande Coastal Basin. To facilitate the study of inflow contributions, the ungaged drainage contributing to the Laguna Madre estuary was divided into eleven subbasins which contribute flow into Baffin Bay and six subbasins contributing flow into lower

1/ Combined inflow = (total Baffin Bay inflow) + (total lower Laguna Madre Inflow)

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

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

MONTH	GAGED BAFFIN BAY	UNGAGED BAFFIN BAY	TOTAL BAFFIN BAY	GAGED LOWER LAGUNA	UNGAGED LOWER LAGUNA	UNGAGED IRRIGATION RETURN	TOTAL LOWER LAGUNA	COMBINED LAGUNA MADRE	PRECIPITATION ON BAY	TOTAL FRESHWATER INFLOW	BAY EVAPORATION LOSSES	FRESHWATER INFLOW BALANCE
						thousands of acre-feet						
AVERAGE OVER ALL YEARS												
JANUARY	0	6	6	16	11	3	31	37	74	111	122	-11
FEBRUARY	0	5	5	17	7	1	27	35	75	110	127	-17
MARCH	0	1	1	13	3	4	21	22	45	67	169	-102
APRIL	0	6	6	20	8	4	33	39	83	122	196	-76
MAY	0	17	17	21	16	4	44	61	126	187	240	-53
JUNE	0	8	8	22	20	5	48	56	125	181	291	-110
JULY	3	11	14	17	5	3	26	40	73	113	360	-247
AUGUST	0	4	4	19	9	2	31	35	121	156	369	-213
SEPTEMBER	10	41	51	60	46	3	113	164	266	432	293	139
OCTOBER	3	21	24	59	27	6	93	117	153	270	251	19
NOVEMBER	0	1	1	29	6	2	38	39	79	118	192	-74
DECEMBER	0	6	6	16	4	3	24	30	72	102	141	-39
TOTALS	16	130	146	309	166	40	529	675	1294	1969	2753	-784
Monthly Average	1	11	12	26	14	3	44	56	108	164	229	-64

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

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

MONTH	GAGED BAFFIN BAY INFLOW	UNGAGED BAFFIN BAY INFLOW	TOTAL BAFFIN BAY INFLOW	GAGED LOWER LAGUNA MADRE INFLOW	UNGAGED LOWER LAGUNA MADRE	UNGAGED IRRIGATION RETURN INFLOWS	TOTAL LOWER LAGUNA MADRE	COMBINED LAGUNA MADRE INFLOW	PRECIPITATION ON BAY	TOTAL FRESHWATER INFLOW	BAY EVAPORATION LOSSES	FRESHWATER INFLOW BALANCE
1941	16	469	485	195	679	14	888	1373	2128	3501	2165	1336
1942	103	187	290	97	75	32	204	494	1267	1761	2240	-479
1943	0	42	42	93	115	54	262	304	1392	1696	2669	-973
1944	0	17	17	297	261	29	587	604	1219	1823	2312	-489
1945	0	13	13	93	108	43	244	257	1238	1495	2666	-1173
1946	49	64	113	116	177	43	336	449	1475	1924	2286	-362
1947	5	68	73	129	51	47	227	300	1354	1654	2328	-674
1948	0	26	26	244	151	47	442	468	1036	1504	2670	-1166
1949	4	29	33	206	79	53	338	371	1658	2029	2288	-259
1950	0	5	5	165	51	53	269	274	668	942	2717	-1775
1951	124	221	345	149	34	56	239	584	1055	1639	2758	-1119
1952	0	1	1	41	24	57	122	123	849	972	2637	-1665
1953	11	55	66	234	53	82	369	435	1015	1450	2616	-1166
1954	0	0	0	506	22	57	585	585	794	1379	2758	-1379
1955	30	83	113	364	243	53	660	773	1024	1797	3656	-1859
1956	0	50	50	148	40	62	250	300	1055	1355	3274	-1919
1957	13	75	88	218	84	47	349	437	1152	1589	3047	-1458
1958	55	522	577	1886	399	40	2325	2902	1882	4784	2773	2011
1959	0	32	32	284	142	23	449	481	1390	1871	2453	-582
1960	14	363	377	358	121	40	519	896	1672	2568	2537	31
1961	0	73	73	300	174	44	518	591	1211	1802	2396	-594
1962	2	3	5	120	0	53	181	186	909	1095	2967	-1872
1963	0	0	0	291	71	43	405	405	908	1313	2894	-1581
1964	1	2	3	180	22	47	249	252	815	1067	2906	-1839
1965	8	37	45	141	47	67	255	300	1336	1636	2901	-1265
1966	11	103	114	321	310	19	650	764	1038	1802	2682	-880
1967	93	725	818	1071	588	58	1717	2535	2025	4560	3142	1418
1968	3	93	96	207	280	33	520	616	1502	2118	3200	-1082
1969	2	5	7	168	37	57	262	269	942	1211	3065	-1654
1970	3	71	74	178	222	57	457	531	1373	1904	2932	-1026
1971	167	280	447	472	233	53	758	1205	1447	2652	3021	-369
1972	7	146	153	293	142	31	466	619	1643	2262	2741	-479
1973	17	541	558	393	344	37	774	1332	1742	3074	2704	370
1974	13	35	48	347	90	53	496	544	1017	1561	3074	-1513
1975	1	96	97	367	275	48	690	787	1548	2335	2967	-632
1976	19	347	366	648	421	25	1094	1460	2021	3481	2844	637
TOTAL	771	4879	5650	11320	6179	1657	19156	24806	46800	71606	99288	-27682
Average	21	136	157	314	172	46	532	689	1300	1989	2758	-766
Median	4	66	73	226	118	47	445	512	1252	1779	2749	-1000
Percent c/	1.1 +	6.9 =	7.9	15.8 +	8.7 +	2.4 =	26.8	34.7 +	65.4 =	100.0 :	138.7	
Percent d/	3.1 +	19.8 =	22.8	45.6 +	25.0 +	6.7 =	77.3	100.0 :	188.7			

a/ Units are thousands of acre-feet
b/ Rounding errors may result in small differences between Table 4-1 and Table 4-2
c/ Total freshwater inflow to the Laguna Madre estuary = 100 percent
d/ Combined freshwater inflow to the Laguna Madre estuary = 100 percent

Laguna Madre (Figure 4-1). Using a Thiessen network (335), 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 two gaged subbasins located within the contributing drainage area and adjacent drainage areas (329). Statistical correlations between annual and monthly gaged and simulated runoff were used to determine the "goodness of fit" of the calibration procedure. The calibrated model was then applied to the ungaged runoff (Table 4-3).

During the period 1941 through 1976, ungaged runoff to the Laguna Madre estuary averaged 136,000 acre-feet/year (168 million m^3/yr) for the upper Laguna Madre and 172,000 acre-feet/year (213 million m^3/yr.) for the lower Laguna Madre. Runoff yield averaged 68 acre-feet/mi^2 (324 m^3/ha) and 254 acre-feet/mi^2 (1209 m^3/ha) respectively from ungaged drainage areas. Total ungaged inflow accounted for 44.8 percent of the combined inflow and 15.6 percent of the total freshwater inflow to the Laguna Madre 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 and were considered insignificant. Irrigation return flows in ungaged areas were also calculated using agency data. Average return flows over the 1941 through 1976 period were approximately 46,000 acre-feet per year (56.8 million m^3). Estimated ungaged return flows accounted for seven percent of the combined inflow and two percent of the total freshwater inflow to the Laguna Madre estuary (Table 4-2) over the 1941 through 1976 period.

Combined Inflow

A category termed "combined inflow" is obtained by aggregating gaged inflow contributions, ungaged runoff, and estimated ungaged return flows. Over the period 1941 through 1976, combined inflows have averaged 689,000 acre-feet per year (851 million m^3/yr.) (Table 4-2). Combined inflow accounts for 35 percent of the total freshwater inflow to the Laguna Madre estuary over the 1941 through 1976 period. Average monthly distribution of combined inflow are shown in Figure 4-2. Wide variations in monthly combined inflow have occurred throughout the period of record (Figure 4-3).

Precipitation on the Estuary

Direct precipitation on the 566,400 acre (214,545 hectare) surface area (231) of Laguna Madre estuary was calculated using Thiessen-weighted precipitation techniques (335). Over the 1941 through 1976 period, annual mean precipitation amounted to 1,300,000 acre-feet per year (1.61 billion m^3/yr.). Direct precipitation accounted for 65 percent of the total freshwater inflow to the Laguna Madre estuary (Table 4-2) over the period 1941 through 1976.

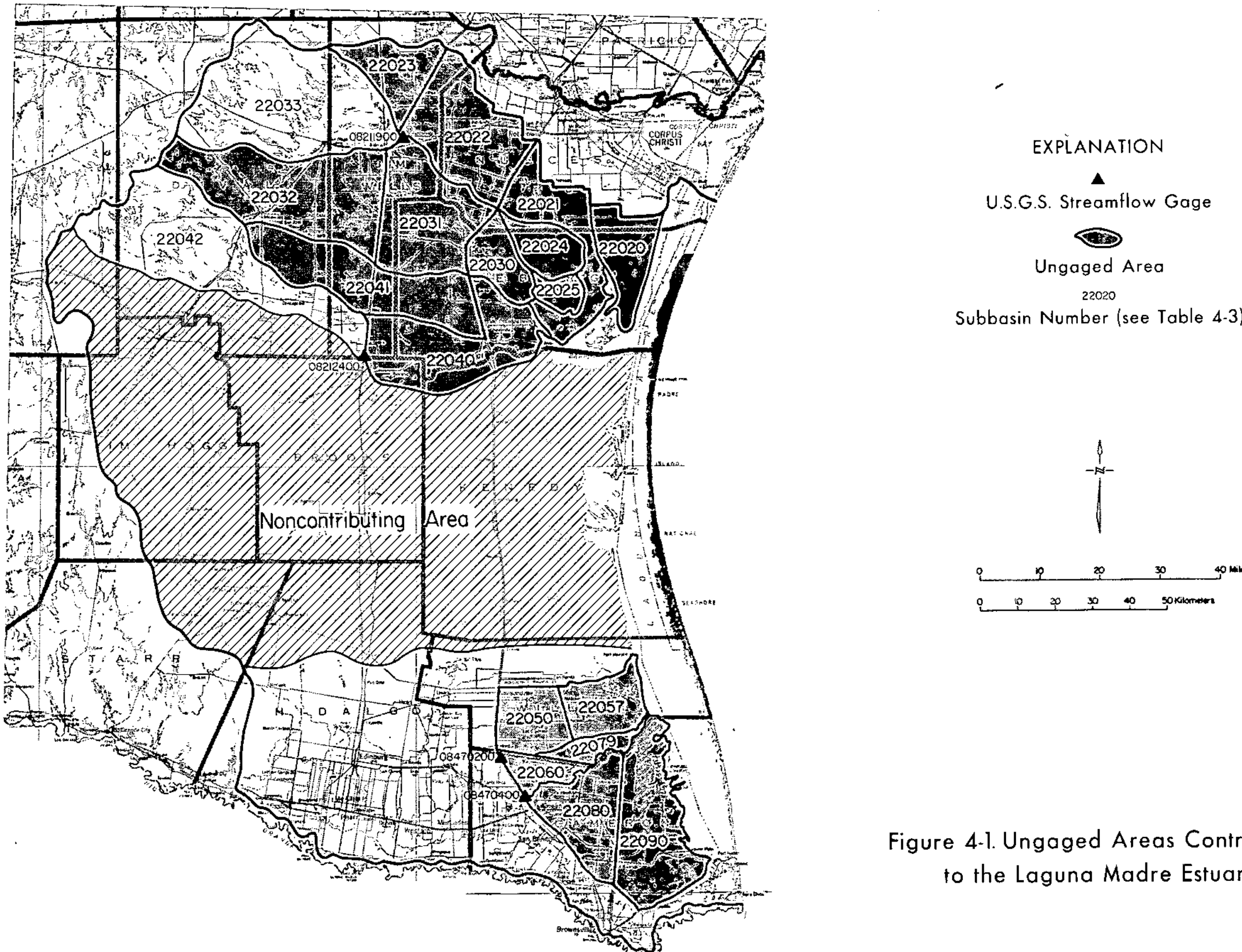


Figure 4-1. Ungaged Areas Contributing to the Laguna Madre Estuary

Table 4-3. Runoff from Ungaged Areas, Laguna Madre Estuary

Subbasin Description	Drainage Area (mi^2)	Weighted Precipitation: NWS a/ Station No.	Weighted Precipitation: Weight b/ Factor	Average Runoff ac-ft/mi^2 (1941-1976)	Average Curve Number c/ / Beta $x10^{-6}$ d/	Explained Variation %: Annual r^2	Explained Variation %: Monthly r^2	Gaged: USGS Station No.	Gaged: Period of Record
22020 Laguna Largo Coastal	134	1651	1.00	75	56 / 99.6				
22021 Petronila Creek Lower	191	1651	1.00	106	60 / 80.7				
22022 Petronila Creek Middle	228	7677	1.00	48	55 / 105.2				
22023 Petronila Creek Upper	91	0144	1.00	53	50 / 140.2				
22024 Chiltipin Creek	84	4810	1.00	150	65 / 57.8				
22025 Kleberg Point Coastal	89	1651	1.00	106	60 / 80.7				
22030 San Fernando Creek Lower	64	4810	1.00	98	60 / 72.8				
22031 San Fernando Creek Middle	274	4810	1.00	61	55 / 95.4				
22032 San Fernando Creek Upper	434	0144	1.00	35	45 / 230.0				
22033 San Fernando Creek above Alice	507	0144	1.00	45	45.48 / 253.0	.88	.81	08211900	1965-76
22040 Los Olmos Creek Lower	255	4810	1.00	99	60 / 72.8				
22041 Los Olmos Creek Upper	162	3063	1.00	25	40 / 487.6				
22042 Los Olmos Creek at Falfurrias	480	3063	1.00	16	34.62 / 13,994.0	.63	.59	08212400	1967-76
22050 Raymondville	122	7458	1.00	238	75 / 47.7				
22057 Port Mansfield Coastal	102	7184	1.00	255	75 / 44.1				
22060 Sebastian	97	3943	1.00	261	75 / 45.8				
22079 Arroyo City Coastal	64	7184	1.00	255	75 / 44.1				
22080 Harlingen	181	3943	1.00	261	75 / 45.8				
22090 Port Isabel	114	7179	1.00	242	75 / 46.6				
North Floodway near Sebastian	354.4			*				08470200	1941-76
Arroyo Colorado at Harlingen	199.2			*				08470400	1941-52 1965-76

* Representative average annual runoff not available because of Rio Grande flood diversions
a/ National Weather Service
b/ Percentage of area of influence expressed as a factor (335)
c/ An assigned parameter for a particular hydrologic soil-cover complex (329)
d/ Soil moisture depletion coefficient (329)

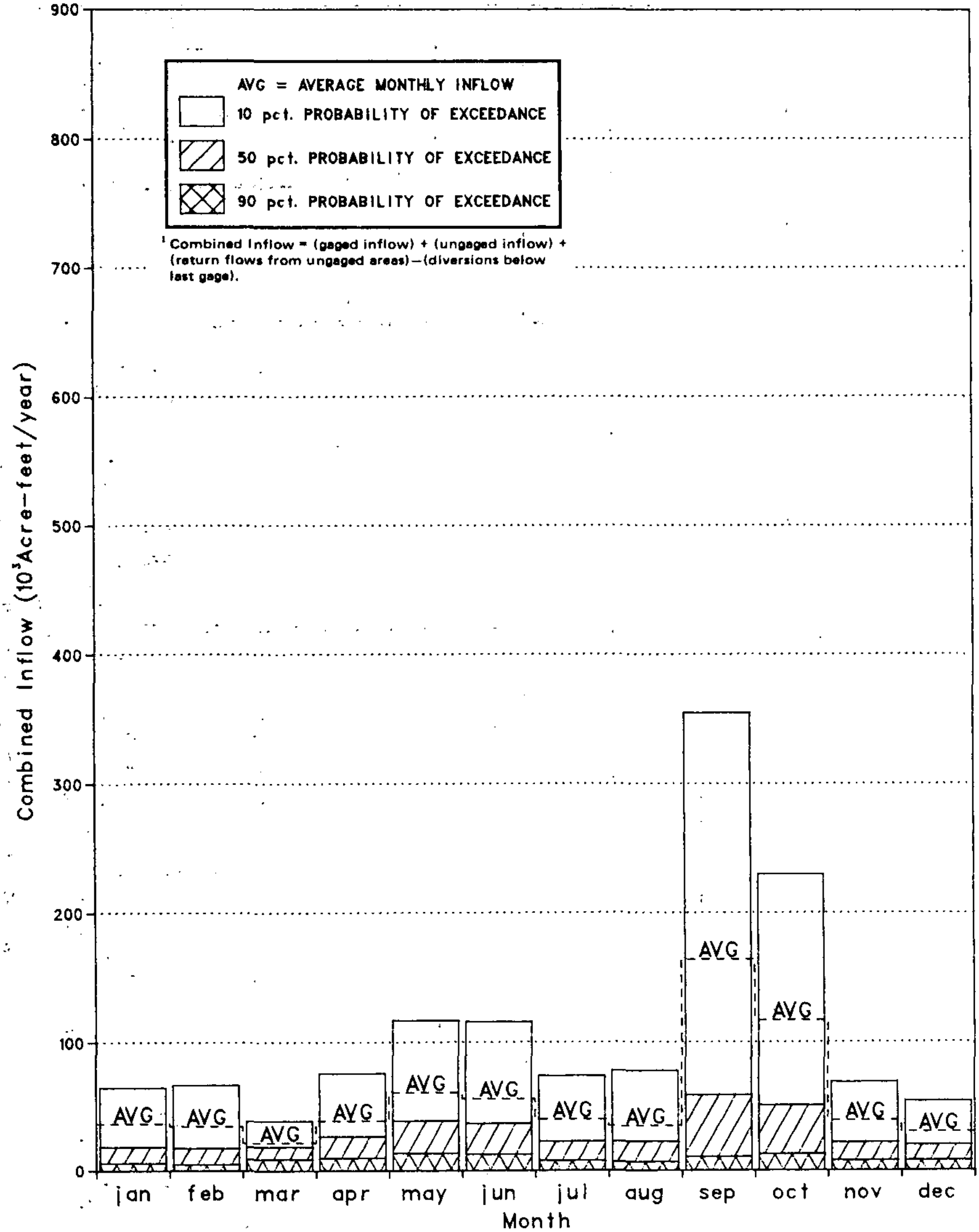


Figure 4-2. Monthly Distribution of Combined Inflow,[1] Laguna Madre Estuary, 1941-1976

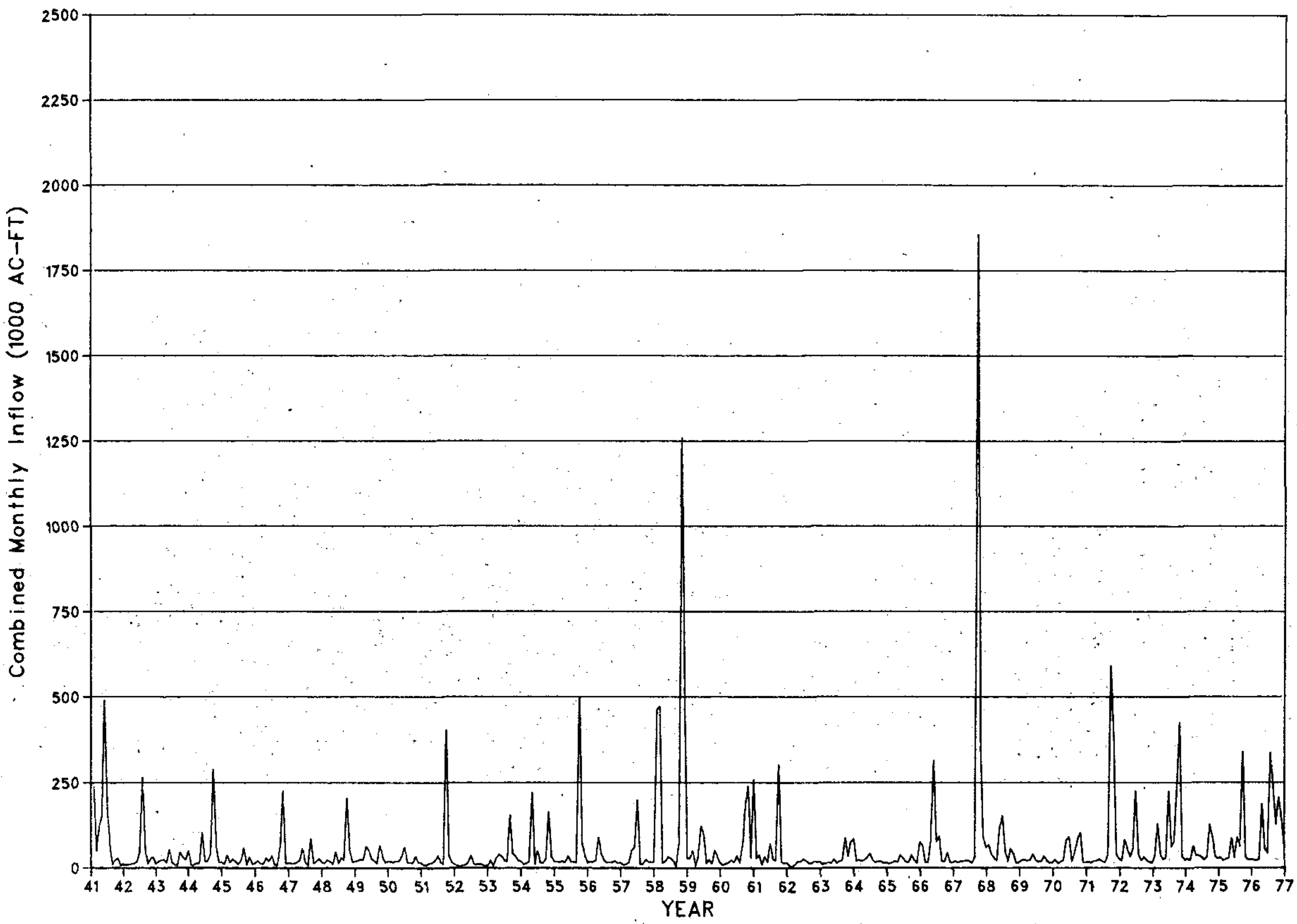


Figure 4-3. Combined Monthly Inflow to the Laguna Madre Estuary, 1941-1976

Total Freshwater Inflow

Total freshwater inflow includes gaged contributions, ungaged runoff, return flows from ungaged areas and direct precipitation on the estuary. For the 1941 through 1976 period, average annual freshwater inflow amounted to 1,989,000 acre-feet (2.45 billion m^3). Average monthly distributions of total freshwater inflow are shown in Figure 4-4.

Bay Evaporation Losses

Gross surface evaporation rates for the estuary were calculated from Texas Department of Water Resources pan evaporation data (317). Since the reduction in evaporation due to estuarine salinity is never in excess of a few percent (over an extended period of time), salinity effects were neglected. The estimation of evaporation over the 566,400 acre (214,545 hectare) estuary surface averaged 2,758,000 acre-feet per year (3.41 billion m^3/yr.). When compared to total freshwater inflow, evaporation on the estuary's surface was about 139 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. Negative numbers indicate evaporation exceeding total freshwater inflow (during periods of extreme drought). For the 1941 through 1976 period, the mean freshwater inflow balance amounted to -768,000 acre-feet per year (-.95 billion m^3/yr.).

Variations in Inflow Components Through Drought and Flood Cycles

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

Quality of Gaged Inflows, Laguna Madre Estuary

There are four USGS gaging stations which monitor inflow to the Laguna Madre estuary, although only one of these collects any water quality data. This station, on Los Almos Creek (USGS No. 08212400) which drains into Baffin Bay, was generally found unsuitable for statistical purposes because of the distant inland location of the station itself, the intermittent nature of the

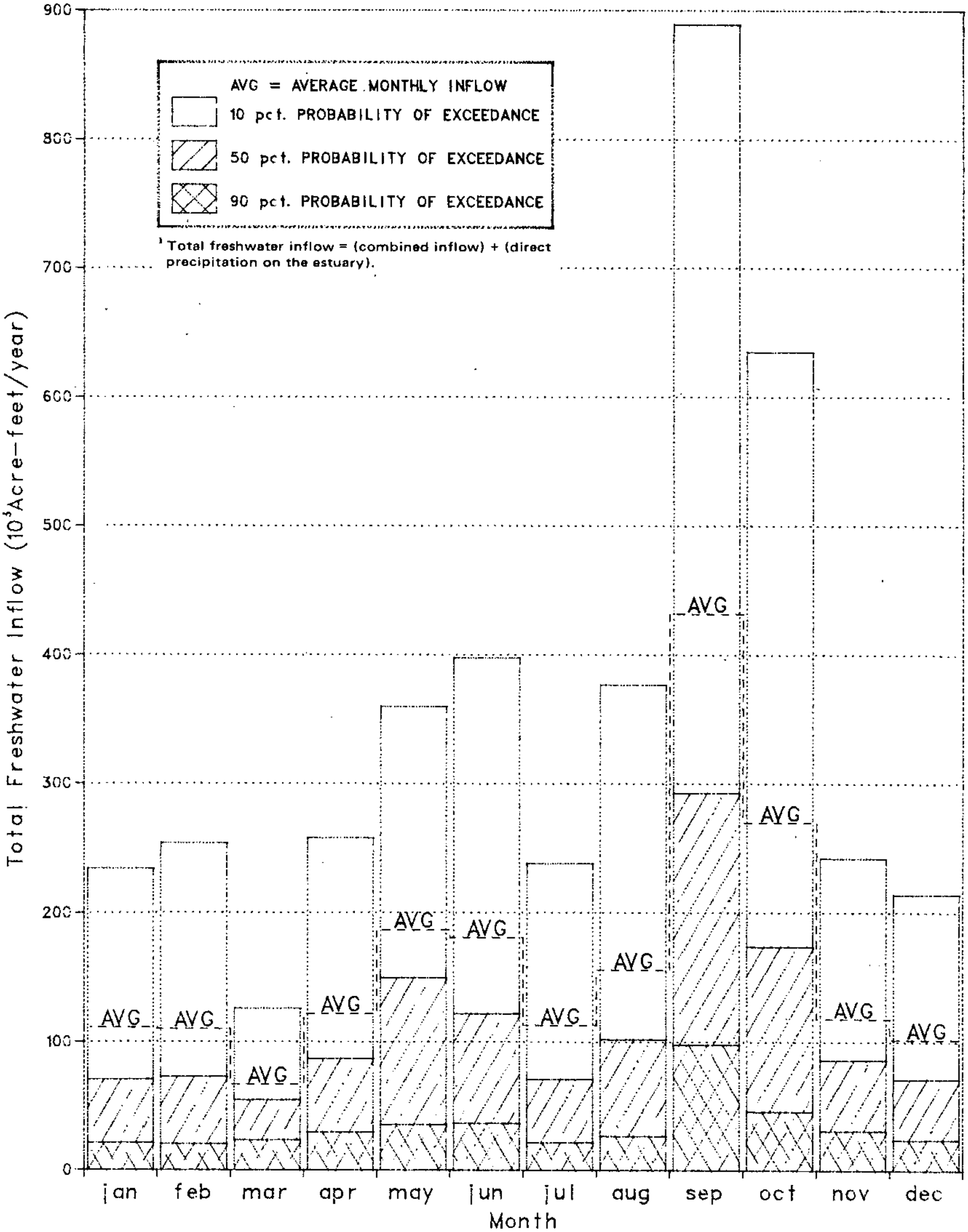


Figure 4-4. Monthly Distribution of Total Freshwater Inflow,[1] Laguna Madre Estuary, 1941-1976

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

Month	Gaged Baffin Bay Inflow			Ungaged Baffin Bay Inflow			Total Baffin Bay Inflow			Gaged Lower Laguna Madre Inflow			Ungaged Lower Laguna Madre Inflow			Ungaged Irrigation Return Inflow			Total Lower Laguna Madre Inflow			Combined Laguna Madre Inflow			Precipitation on Bay			Total Freshwater Inflow			Bay Evaporation Losses		
	10%	50%	90%	10%	50%	90%	10%	50%	90%	10%	50%	90%	10%	50%	90%	10%	50%	90%	10%	50%	90%	10%	50%	90%	10%	50%	90%	10%	50%	90%	10%	50%	90%
January	0	0	0	4	0	0	4	0	0	31	11	4	25	0	0	5	3	2	56	18	7	65	19	6	178	46	11	234	71	22	159	120	90
February	0	0	0	17	0	0	17	0	0	34	11	3	20	0	0	3	2	1	52	15	5	67	18	5	249	47	6	254	73	21	168	124	91
March	0	0	0	3	0	0	4	0	0	23	12	6	5	0	0	7	4	3	35	18	9	39	19	9	121	31	6	126	55	24	213	167	129
April	2	0	0	16	0	0	18	0	0	36	14	6	22	1	0	7	5	3	61	24	10	76	27	10	224	52	11	258	87	30	240	197	160
May	3	0	0	45	0	0	47	0	0	39	17	7	48	6	0	6	4	3	80	33	14	117	39	14	257	103	40	360	150	63	285	239	200
June	2	0	0	21	0	0	23	0	0	47	17	5	61	5	0	8	5	3	100	34	12	116	37	13	316	77	18	398	122	37	355	288	233
July	2	0	0	20	0	0	23	0	0	33	13	5	15	0	0	5	3	2	47	20	9	74	23	8	193	41	7	238	71	22	436	357	290
August	3	0	0	14	0	0	15	0	0	34	12	4	30	1	0	4	2	1	64	19	6	78	23	7	331	17	14	377	102	27	449	365	296
September	22	0	0	90	2	0	110	2	0	126	25	6	142	13	0	6	4	2	248	48	10	355	59	11	548	212	79	889	293	98	346	291	244
October	9	0	0	49	0	0	62	0	0	103	20	4	75	10	0	9	6	4	170	44	13	230	51	13	390	113	25	635	174	46	309	249	199
November	0	0	0	3	0	0	4	0	0	47	14	5	20	2	0	4	2	1	65	21	7	69	22	8	186	53	15	242	86	31	241	188	148
December	0	0	0	4	0	0	4	0	0	28	14	7	14	0	0	5	3	2	42	19	9	54	20	8	180	45	10	214	71	24	185	138	103

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.

flow in the stream, and the infrequency with which data was actually collected.

The Texas Department of Water Resources maintains five water quality monitoring stations for monitoring stream segments as part of the statewide monitoring program within the Laguna Madre drainage area. Streamflow data are not collected, however, at these points and these stations fall within ungaged drainage areas. Even if stream gaging data were taken at these locations, the intermittent nature of the streams and the infrequency of stream quality data collection would generally portend very little usefulness to analyses of the data at these sites.

Notwithstanding these somewhat unfavorable conditions for data analyses, a few preliminary findings can be made from the data that have been collected at the five TDWR sites.

Water quality varies significantly over a wide range due to the intermittent nature of the stream flow and the phenomenon of the first flush during a major rain, in which large amounts of foreign matter are washed into the stream from the surrounding countryside. Much of the study area is located on sandy soil with high permeability and low runoff potential; thus much of the area is noncontributory. Drainage ways are not well developed because the land is flat with little natural relief. Vegetation in the area is generally scrub brush and grasses which is used for cattle grazing, the rest of the region is used for various agricultural activities. Oil field operations have taken place in some parts of the area in the past and these operations have increased the salinity of drainage ways to some extent because brine from these operations was often disposed of in surface leach pits. Much of this salt still remains in the soil.

The general quality of water draining into the Laguna Madre estuary is believed to be good, although there is little basis in the existing data to prove this point. The intermittent nature of the streams and the first flush phenomenon dictate that sampling times and locations be selected with care and results be analyzed with a full knowledge of the condition of the stream at the time the sample was collected.

Quality of Estuarine Waters

Nutrient Concentrations in the Laguna Madre Estuary

Historical concentrations of carbon, nitrogen, and phosphorus (CNP) 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 the frequency of sampling. Concurrent with the cooperative efforts of these two agencies, additional nutrient data were also made available through contract work performed by Espey, Huston and Associates, Inc. (Austin, Texas) in 1977 and 1980.

Laguna Madre estuary was divided into thirteen distinct segments: (1) the northern end of upper Laguna Madre; (2) Baffin Bay (inclusive); (3) the southern end of upper Laguna Madre; (4) "Land Bridge" region of Laguna Madre; (5) the northern end of lower Laguna Madre above Port Mansfield; (6) lower Laguna Madre at Port Mansfield; (7) lower Laguna Madre at Arroyo Colorado; (8) lower Laguna Madre below Arroyo Colorado; (9) South Bay; (10) Baffin Bay (proper); (11) Laguna Salada; (12) Cayo del Grullo; and (13) Alazan Bay. These are the segments considered in the nutrient analysis study of the Laguna Madre estuary (Figure 4-5).

Freshwater inflow to the upper portion of the Laguna Madre is by means of numerous intermittent streams that enter Baffin Bay; these streams are dry except during periods of substantial precipitation (332). In the lower portion, freshwater input is mainly via channelized floodways that carry overflow from the Rio Grande basin and the Nueces-Rio Grande coastal basin. These include Raymondville Drain, the existing Willacy County Ditch (Existing Ditch) dredged by the U.S. Corps of Engineers, the North Floodway, and the Arroyo Colorado. These drainage outfalls also carry local runoff, effluents, and agricultural drainage. The Arroyo Colorado, in particular, carries a substantial amount of treated sewage.

Data samples were available from four sources: (1) the USGS-TDWR and statewide monitoring network data stations for the period 1968-1977 (historical data); (2) published records from the July, 1977 Field Data Survey by Espey, Huston and Associates, Inc. (1977 Field Survey Data) for the Environmental Effects Assessement of a major drainage improvement project proposed jointly by Hidalgo County Drainage District No. 1 and Willacy County Drainage District No. 1; (3) unpublished records from the 1979-1980 Field Data Survey at USGS-TDWR line sites by the U.S. Geological Survey (1979-1980 Field Survey Data); and (4) unpublished records from a July, 1980 Laguna Madre Inflow Study by the Texas Department of Water Resources (1980 Field Survey Data). Sampling sites for these four data sources are shown in Figures 4-5 and 4-6.

Sampling sites used by Espey, Huston and Associates, Inc. in the July, 1977 Field Data Survey were selected to provide a broad coverage of the Lower Rio Grande Valley area in the general vicinity of the proposed Hidalgo-Willacy County Stormwater Disposal Channel. Sampling stations used in the July, 1980 Laguna Madre Inflow Study were located at major exchange points of flow into and out of Laguna Madre estuary. The USGS-TDWR and statewide monitoring stations that fell within a segment location and had data available were used for determining the mean concentrations of nutrient parameters for that segment.

Parameters considered were total nitrogen, total phosphorus, total organic carbon, and total Kjeldahl nitrogen (i.e., free ammonia plus organic nitrogen compounds). Ammonia nitrogen, nitrite nitrogen, and nitrate nitrogen were summed for each sample station in each segment or for each exchange point to arrive at total available nitrogen concentrations. Ammonia nitrogen and organic nitrogen were summed for each sample station in each segment or for each exchange point to arrive at total Kjeldahl nitrogen concentrations.

A limited number of seasonal samples for each water quality parameter made seasonal comparisons infeasible. Thus, the historical data and the 1979-1980 Field Survey Data were summed in each segment location for each parameter, respectively, and then averaged to arrive at a mean sample value for the combined years of 1968-1977, and 1979-1980, respectively (Tables 4-5 and 4-7). For the 1980 Field Survey Data, nutrient samples for each parameter were collected approximately every two hours over a two-day period at the

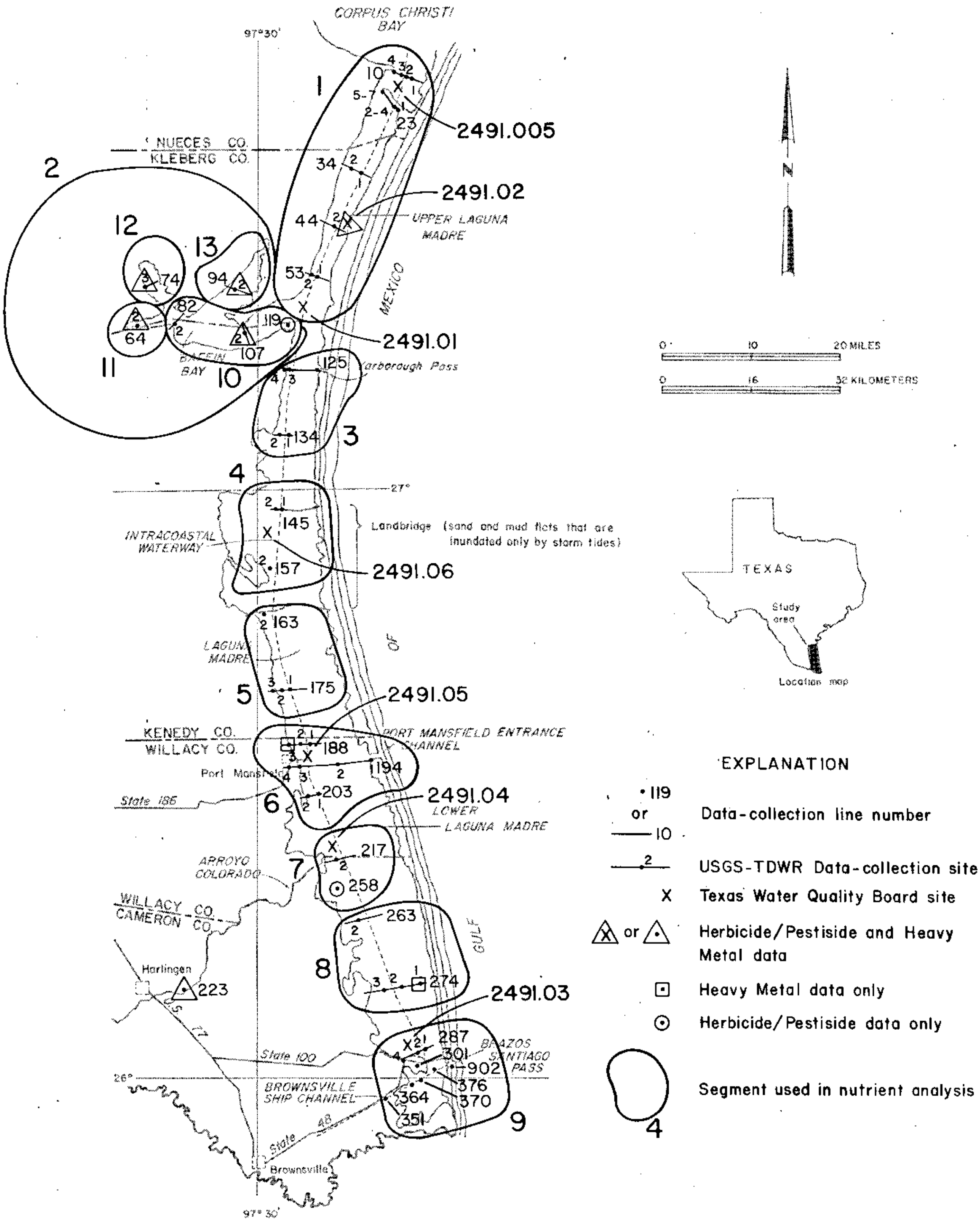


Figure 4-5. Data Collection Sites in the Laguna Madre Estuary

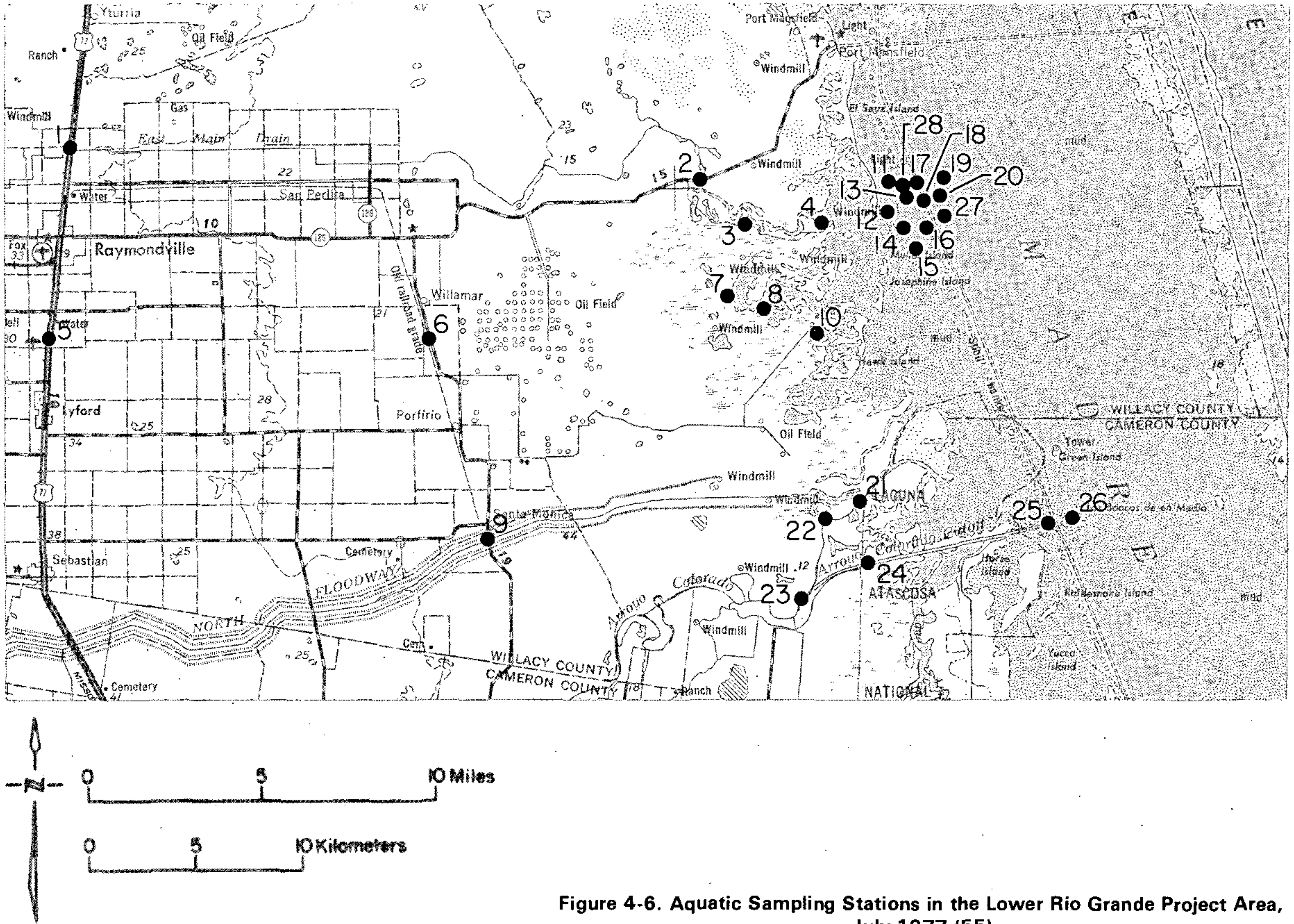


Figure 4-6. Aquatic Sampling Stations in the Lower Rio Grande Project Area, July 1977 (55)

Table 4-5. 1968-1977 Historical Data Survey at USGS-TDWR and Statewide Monitoring Network Data Stations a/

Total Nitrogen				Total Phosphorus				Total Organic Carbon				Total Kjeldahl Nitrogen			
Segment Numbers c/	No. of Samples	$\bar{X}$ (mean) mg/l	σ^2 (variance) mg^2/l^2	Segment Numbers	No. of Samples	$\bar{X}$ (mean) mg/l	σ^2 (variance) mg^2/l^2	Segment Numbers	No. of Samples	$\bar{X}$ (mean) mg/l	σ^2 (variance) mg^2/l^2	Segment Numbers	No. of Samples	$\bar{X}$ (mean) mg/l	σ^2 (variance) mg^2/l^2
7	40	0.490	0.6937	12	11	0.231	0.0141	11	3	24.00	79.00	10	15	0.436	0.4752
1	94	0.189	0.1217	2	42	0.169	0.0103	13	3	19.00	109.00	13	7	0.322	0.1779
6	65	0.183	0.0552	13	7	0.151	0.0049	12	7	17.86	49.14	2	42	0.312	0.2997
10	15	0.153	0.0246	11	9	0.149	0.0072	2	20	16.10	66.91	7	40	0.287	0.5198
12	11	0.152	0.0245	10	15	0.143	0.0091	1	49	12.63	45.74	8	26	0.255	0.1635
4	30	0.137	0.0145	7	40	0.136	0.0127	3	9	10.24	18.83	6	65	0.245	0.1122
9	62	0.129	0.0306	3	14	0.075	0.0028	10	7	9.83	4.64	12	11	0.238	0.2235
2	42	0.126	0.0190	8	26	0.071	0.0037	4	16	8.17	12.94	11	9	0.191	0.2014
13	7	0.120	0.0119	9	61	0.069	0.0088	6	25	7.97	9.93	3	14	0.153	0.0658
3	14	0.114	0.0129	6	64	0.067	0.0038	8	14	7.39	17.97	4	31	0.141	0.0441
8	26	0.105	0.0097	5	13	0.060	0.0045	7	18	7.14	6.12	1	94	0.132	0.0376
5	13	0.069	0.0066	1	93	0.049	0.0018	9	23	5.63	11.12	9	62	0.116	0.0247
11	9	0.052	0.0042	4	29	0.045	0.0010	5b/	-	-	-	5	13	0.106	0.0559

a/ Includes data from reference (235,238)
b/ Data not available for this segment location
c/ See Figure 4-5 for segment location

following exchange points of both upper and lower Laguna Madre Estuary: JFK Causeway, Baffin Bay, the north end of the Land Bridge, the south end of the Land Bridge, Mansfield Entrance Channel, Raymondville Drain, North Floodway, Arroyo Colorado, Brazos Santiago Pass, Brownsville Ship Channel, and the South Bay Pass. These samples were summed and then averaged to arrive at a mean sample value for each parameter at each of the above exchange points (Table 4-6). For the 1977 Field Survey Data, average total nitrogen and total phosphorus concentrations by geographic area were used as reported by Espey, Huston and Associates, Inc. (Table 4-8).

Methodology

The test for significant differences among all possible combinations of means is necessarily defined as an a posteriori test (i.e., tests of comparisons among all possible pairs of means suggest themselves after the results are known). Thus, two sample t-tests, for testing the differences among mean concentrations of a parameter for all possible parings of segments which had available data, are not statistically valid because (1) all tests would not be independent, and (2) it would be virtually impossible to assign an overall level of significance to this kind of procedure since the probablity of error for any particular test of some subset, such as a test of differences among three or between two means, is necessarily less than α, the probability of making a type I statistical error (170).

Statistical multiple-comparison methods prevent the effective error rate, α from becoming too small when comparing differences among subsets of the original means. One such method used in the following analysis is the Student-Newman-Keuls (SNK) procedure which tests differences among a set of means only if the set is contained within a larger set that was found to be significant. Therefore, this type of procedure provides a consistent method of testing all possible comparisons between means (208).

An underlying assumption for any analysis of variance is the homogeneity of variances which was determined in this analysis using the F-max test. Consequently, when the mean concentrations of a parameter were homoscedastic (i.e., had equal variances), the SKN procedure was used for testing significant differences among mean concentrations for all possible pairings of segment locations which had data available for that parameter. However, when the mean concentrations of a parameter were heteroscedastic (i.e., had unequal variances), the SNK procedure could not be applied, and therefore an approximate test of equality of means based on the assumption of variance heterogeneity was used to test if the relative differences among the mean concentrations for that parameter were significant (208).

When comparing the historical data with the 1979-1980 Field Survey Data, either a two-sample t-test when the mean sample concentrations were homoscedastic, or a modified two-sample t-test when the mean sample concentrations were heteroscedastic, was used for determining if the mean concentrations of the historical data and of the 1979-1980 Field Survey Data were significantly different for a given segment location (208).

Table 4-6. 1980 Field Data Survey at Exchange Points a/

Total Nitrogen

Exchange Point Locations	No. of Samples	$\overline{X}$ (mean) mg/l	σ^2 (variance) mg^2/l^2
North Floodway	14	2.51	0.0143
Raymondville Drain	14	0.81	0.055
Arroyo Colorado	13	0.61	0.0033
No. Land Bridge	14	0.074	0.00027
JFK Causeway	27	0.048	0.00084
So. Land Bridge	13	0.046	0.00027
Baffin Bay	13	0.04	0.0
Mansfield Entrance Channel	13	0.04	0.0
Brazos Santiago	13	0.04	0.0
South Bay Pass	13	0.04	0.0000071
Brownsville Ship Channel	14	0.04	0.000027

Total Phosphorus

Exchange Point Locations	No. of Samples	$\overline{X}$ (mean) mg/l	σ^2 (variance) mg^2/l^2
North Floodway	14	0.23	0.0025
Arroyo Colorado	13	0.21	0.00042
Raymondville Drain	14	0.20	0.0048
Baffin Bay	13	0.10	0.0006
No. Land Bridge	14	0.086	0.00064
JFK Causeway	27	0.068	0.00059
South Bay Pass	13	0.05	0.00089
Brownsville Ship Channel	14	0.05	0.0011
So. Land Bridge	13	0.049	0.00064
Mansfield Ent. Channel	13	0.042	0.00011
Brazos Santiago	13	0.03	0.000052

Total Organic Carbon

Exchange Point Locations	No. of Samples	$\overline{X}$ (mean) mg/l	σ^2 (variance) mg^2/l^2
Raymondville Drain	14	9.60	1.67
Baffin Bay	13	8.00	0.923
JFK Causeway	27	7.96	1.37
No. Land Bridge	14	7.43	2.53
Arroyo Colorado	13	7.40	1.31
North Floodway	14	6.90	0.209
So. Land Bridge	13	5.50	0.249
Mansfield Entrance Channel	13	3.80	1.67
South Bay Pass	13	3.20	4.64
Brazos Santiago	13	2.40	0.852
Brownsville Ship Channel	14	2.30	0.204

Total Kjeldahl Nitrogen

Exchange Point Locations	No. of Samples	$\overline{X}$ (mean) mg/l	σ^2 (variance) mg^2/l^2
Raymondville Drain	14	3.1	0.372
Arroyo Colorado	13	2.6	0.734
North Floodway	14	2.1	0.163
Baffin Bay	13	1.6	0.027
JFK Causeway	27	1.2	0.039
No. Land Bridge	14	1.1	0.018
So. Land Bridge	13	0.95	0.010
Mansfield Entrance Channel	13	0.77	0.022
Brownsville Ship Channel	14	0.61	0.007
South Bay Pass	11	0.60	0.007
Brazos Santiago	13	0.52	0.021

a/ Includes data from reference (57)

Table 4-7. 1979-1980 Field Data Survey at USGS-TDWR Line Sites [a]

Total Nitrogen				Total Phosphorus				Total Organic Carbon				Total Kjeldahl Nitrogen			
Segment Numbers [c]	No. of Samples	$\overline{X}$ (mean) mg/l	σ^2 (variance) mg^2/l^2	Segment Numbers	No. of Samples	$\overline{X}$ (mean) mg/l	σ^2 (variance) mg^2/l^2	Segment Numbers	No. of Samples	$\overline{X}$ (mean) mg/l	σ^2 (variance) mg^2/l^2	Segment Numbers	No. of Samples	$\overline{X}$ (mean) mg/l	σ^2 (variance) mg^2/l^2
7	2	0.16	0.0144	10	3	0.073	0.00016	10	3	10.90	39.62	10	3	1.47	0.042
3	6	0.12	0.0007	8	5	0.052	0.00014	3	6	8.33	1.402	3	6	1.25	0.113
10	3	0.097	0.00082	1	17	0.051	0.0018	1	17	7.97	8.473	4	3	1.01	0.017
6	7	0.084	0.0019	9	8	0.043	0.00094	6	7	7.20	1.594	1	17	0.893	0.103
1	17	0.080	0.00081	6	7	0.041	0.000041	8	4	5.33	4.782	6	7	0.804	0.009
4	3	0.067	0.00016	4	3	0.037	0.000089	4	3	4.67	7.39	8	5	0.654	0.0313
8	5	0.058	0.00086	3	6	0.033	0.000089	9	7	2.53	0.388	9	8	0.409	0.081
9	8	0.048	0.00082	2[b]	-	-	-	2[b]	-	-	-	2[b]	-	-	-
2[b]	-	-	-	5[b]	-	-	-	5[b]	-	-	-	5[b]	-	-	-
5[b]	-	-	-	7[b]	-	-	-	7[b]	-	-	-	7[b]	-	-	-
11[b]	-	-	-	11[b]	-	-	-	11[b]	-	-	-	11[b]	-	-	-
12[b]	-	-	-	12[b]	-	-	-	12[b]	-	-	-	12[b]	-	-	-
13[b]	-	-	-	13[b]	-	-	-	13[b]	-	-	-	13[b]	-	-	-

a/ Includes data from reference (238)
b/ Data not available for these segment locations
c/ See Figure 4-5 for segment location

Table 4-8. Summary of Average Nutrient Concentrations (mg/l) in Water Samples by Geographic Area [a]

Area	NH_3-N	NO_3-N	NO_2-N	TN-N	Total PO_4-P
Arroyo Colorado	0.88	0.03	2.80	3.71	6.28
Existing Ditch[c]	0.79	0.367	4.56	5.72	4.06
Raymondville Drain	0.58	0.237	8.70	9.50	2.77
Offshore, Arroyo Colorado	0.35	0.006	ND[b]	0.356	3.70
Offshore, Existing Ditch	0.34	0.156	0.30	0.796	1.87

a/ Reference (55)
b/ ND not detectable
c/ Existing Ditch refers to small drainage ditch through the El Sauz Ranch

Results and Conclusions

Total Nitrogen. The differences among the total nitrogen mean concentrations for the historical data were significant at the 5% level even though the variances of the mean concentrations were highly heterogeneous at the 5% significance level. Similar total nitrogen results were obtained for the 1980 Field Survey Data collected at the estuary's exchange points except that the differences among mean values were highly significant at the 5% level.

Based on the results for the historical data, segment 7 experienced at least 2.5 times higher mean concentrations of total nitrogen than all other segment locations (Table 4-5). In addition, the 1980 Field Survey Data show that the Raymondville Drain, North Floodway, and Arroyo Colorado experienced at least 8 times higher mean concentrations of total nitrogen than all other exchange points sampled (Table 4-6). The July 1977 Field Survey Data, though limited to Hidalgo and Willacy Counties and the general region of lower Laguna Madre bordering Willacy County, tends to support the above results. The 1977 data suggest that high concentrations of nitrogeneous wastes were being introduced into the study area with greater loading observed at inland and deltaic stations (i.e., stations 3, 4, 6, 7, 8, 9, 10, 22, and 23) than at the offshore stations (Figure 4-6). Average nitrogen concentrations by geographic area indicate that the Arroyo Colorado and the Sauz Ranch drainage ditch had generally higher mean nitrogen levels, except for nitrites, than Raymondville Drain (Table 4-8).

The variances of the total nitrogen mean concentrations for the 1979-1980 Field Survey Data were not heterogeneous at the 5% significance level. The following results were obtained using the SNK procedure: (1) segment 3 had higher significant (5% level) mean concentrations of total nitrogen than segment 9, and (2) segment 7 had higher significant (5% level) mean concentrations of total nitrogen than segments 8 and 9. No other pair-wise comparisons of segments gave significant results. Also, the 1979-1980 Field Survey Data show that segment 7 had a higher mean concentration of total nitrogen than all other segments for which data were available (Table 4-7).

Even though there is no evidence of a temporal trend for average total nitrogen concentrations in the Laguna Madre; segments 1, 4, 6, and 9 did experience higher significant (5% level) mean concentrations of total nitrogen during the historical period from 1968 to 1977, than during the Field Survey of 1979-1980 (Table 4-9).

Total Phosphorus. The differences among the total phosphorus mean concentrations were highly signficant at the 5% level for the historical data and the 1980 Field Survey Data even though the variances of the mean concentrations for the historical data and the 1980 Field Survey Data were highly heterogenous at the 5% significance level.

Based on the results from the analysis of the historical data, segment 2 and segment 7 experienced at least 1.5 times higher mean concentrations of total phosphorus than all other segment locations (Table 4-5). Further, 1980 Field Survey Data indicate that the North Floodway, Arroyo Colorado, Raymondville Drain, and Baffin Bay exchange points experienced at least 10% higher mean concentrations of total phosphorus than all other exchange points sampled (Table 4-6).

Table 4-9. Comparison of Historical Mean Nutrient Concentrations with 1979-1980 Field Data Mean Nutrient Concentrations a/

Parameters / Segment Numbers b/	Total Nitrogen		Total Phosphorus		Total Organic Carbon		Total Kjeldahl Nitrogen	
	Mean (# Samples) 1968-1977	Mean (# Samples) 1979-1980	Mean (# Samples) 1969-1977	Mean (# Samples) 1979-1980	Mean (# Samples) 1968-1977	Mean (# Samples) 1979-1980	Mean (# Samples) 1968-1977	Mean (# Samples) 1979-1980
1	0.189* (94)	0.08 (17)	0.049 (93)	0.051 (17)	12.63* (49)	7.97 (17)	0.132 (94)	0.893* (17)
3	0.114 (14)	0.12 (6)	0.075* (14)	0.033 (6)	10.24 (9)	8.33 (6)	0.153 (14)	1.25* (6)
4	0.137* (30)	0.067 (3)	0.0454 (29)	0.0367 (3)	8.17 (16)	4.67 (3)	0.141 (31)	1.01* (3)
6	0.183* (65)	0.084 (7)	0.0665* (64)	0.041 (7)	7.97 (25)	7.20 (7)	0.245 (65)	0.804* (7)
7	0.490 (40)	0.16 (2)	-	-	-	-	-	-
8	0.105 (26)	0.058 (5)	0.0710 (26)	0.052 (5)	7.39 (14)	5.33 (4)	0.255 (26)	0.654 (5)
9	0.129* (62)	0.048 (8)	0.0687 (61)	0.0425 (8)	5.63* (23)	2.53 (7)	0.116 (62)	0.409* (8)
10	0.153 (15)	0.097 (3)	0.143* (15)	0.073 (3)	9.83 (7)	10.90 (3)	0.436 (15)	1.47* (3)

a/ Includes data from reference (235,238)
b/ See *Figure* 4-5 for segment location
* Significantly higher mean concentration (at 5% level) for given segment location

Only for the 1979-1980 Field Survey Data were the differences among the mean concentrations not significant at the 5% level, yet segment 10 had a higher mean concentration of total phosphorus than all other segments for which data were available (Table 4-7).

The July 1977 Field Survey Data, though limited to Hidalgo and Willacy Counties and the general region of lower Laguna Madre bordering Willacy County, suggest that high concentrations of phosphorus-bearing wastes were being introduced into the study area with greater loading observed at the inland and deltaic stations (i.e., stations 3, 4, 6, 7, 8, 9, 10, 22, and 23) than at the offshore stations (Figure 4-6). Average phosphorus concentrations by geographic area showed that Arroyo Colorado and Sauz Ranch drainage ditch had higher mean phosphorus levels than Raymondville Drain (Table 4-8).

Even though there is no evidence of a temporal trend for average total phosphorus concentrations in Laguna Madre, segments 3, 6, and 10 did experience higher significant (5% level) mean concentrations of total phosphorus during the historical period from 1968 to 1977, than during the Field Survey of 1979-1980 (Table 4-9).

Total Organic Carbon. The variances of total organic carbon mean concentrations for the historical data and the 1979-1980 Field Survey Data were homogeneous at the 5% significance level. The following results were obtained from historical data using the SNK procedure: (1) segments 1 and 2 had higher significant (5% level) mean concentrations of total organic carbon than segments 4, 6, 7, 8, and 9; and (2) segments 11, 12, and 13 all within the inclusive Baffin Bay segment 2, had higher significant (5% level) mean concentrations of total organic carbon than all other segments except for segments 1 and 3 of upper Laguna Madre. No other pair- wise comparison of segments gave statistically significant results (segment 5 omitted because of insufficient data).

In addition, the historical data show that segments 1 and 2 experienced higher mean concentrations of total organic carbon than all other segments except for segments 11, 12, and 13 (Table 4-5).

For the 1979-1980 Field Survey Data, the SNK procedure demonstrated that segments 1, 3, 6, and 10 had higher signficant (5% level) mean concentrations of total organic carbon than segment 9. No other pair-wise comparisons of segments for which data were available were statistically significant (segments 2, 5, 7, 11, 12, and 13 did not have data available). Also, the 1979-1980 Field Survey Data indicate that segment 10 had a higher mean concentration of total organic carbon than all other segments for which data were available (Table 4-7).

For the 1980 Field Survey Data, the differences among the total organic carbon mean concentrations were signficant at the 5% level even though the variances of the mean concentrations were found to be highly heterogenous at the 5% level. Thus, Baffin Bay and JFK Causeway exchange points experienced higher mean concentrations of total organic carbon than all other exchange points, except for Raymondville Drain (Table 4-6).

Even though there is no evidence of a temporal trend for average total organic carbon concentrations in Laguna Madre, the analysis does show that segments 1 and 9 experienced higher signficant (5% level) mean concentrations of total organic carbon during the historical period from 1968 to 1977, than during the Field Survey of 1979-1980 (Table 4-9).

Total Kjeldahl Nitrogen. The differences among the total Kjeldahl nitrogen mean concentrations for the historical data were highly significant at the 5% level even though the variances of the mean concentrations were found to be highly heterogeneous at the 5% significance level. Similar results were obtained for the 1980 Field Survey Data collected at the estuary's exchange points.

Based on the results for the historical data (Table 4-5), segment 10 experienced a higher mean concentration of total Kjeldahl nitrogen than all other segments (at least 1.5 times higher than segment 7). In addition, the 1980 Field Survey Data show that (with exception of Raymondville Drain, North Floodway, and Arroyo Colorado exchange points) the Baffin Bay exchange point experienced at least 1.3 times higher mean concentration of total Kjeldahl nitrogen than all other exchange points sampled (Table 4-6).

The variances of the total Kjeldahl nitrogen mean concentrations for the 1979-1980 Field Survey Data were not found to be heterogenous at the 5% significance level. Therefore, the following results were obtained using the SNK procedure: (1) segments 10 and 3 had higher significant (5% level) mean concentrations of total Kjeldahl nitrogen than segments 1, 6, 8, and 9; and (2) segments 1, 4, and 6 had higher significant (5% level) mean concentrations of total Kjeldahl nitrogen than segment 9. No other pair-wise comparisons of segments, for which data were available, were found to be statistically significant. In addition, the 1979-1980 Field Survey Data indicate that segment 10 had a higher mean concentration of total Kjeldahl nitrogen than all other segments (total Kjeldahl nitrogen data were not available for segments 2, 5, 7, 11, 12, and 13) (Table 4-8).

Even though the evidence does not support a temporal trend for average total Kjeldahl nitrogen concentrations in Laguna Madre estuary, segments 1, 3, 4, 6, 9, and 10 did experience higher significant (5% level) mean concentrations of total Kjeldahl nitrogen during the 1979-1980 Field Survey than during the historical period from 1968 to 1977 (Table 4-9).

Heavy Metals

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

Samples of bottom sediments in the Laguna Madre estuary and the Arroyo Colorado were collected by the Texas Department of Water Resources at only one data collection site for the period 1973 to 1978 and by the cooperative efforts of the U.S. Geological Survey and the Texas Department of Water Resources at seven data collection sites for the period 1972 to 1978 (Figure 4-5). The heavy metals detected included arsenic (As), cadmium (Cd), chromium (Cr), cobalt (Co), lead (Pb), manganese (Mn), mercury (Hg), nickel (Ni), silver (Ag), and zinc (Zn).

Statistical analyses were not possible due to the limited number of samples for the test period from 1972 to 1978. The number of samples and the range of values for heavy metals detected at the northern end of upper Laguna Madre, Baffin Bay (inclusive), lower Laguna Madre at Port Mansfield, lower Laguna Madre below Arroyo Colorado, and the Arroyo Colorado are listed in Table 4-10.

Accumulation of metals in bottom deposits may not be detectable in overlying water samples, yet still exert an influence from time to time. Wind and tide induced water movements, ship traffic and dredging activities are some physical processes that can cause mixing of materials from the sediment into the water. Chemical changes resulting from seasonal temperature fluctuations, oxygenation, and respiration, can influence the rate of movement and distribution of dissolved substances between water and sediment. Microorganisms living on the bottom (benthos) also play an important role in the circulation of metals by taking them up from the sediment, sometimes converting them to more toxic forms. Heavy metals in sediment and water may pose a threat to fish and shellfish as these organisms generally concentrate certain toxic metals in their bodies when feeding in polluted areas. Reduction of productivity in the area may be the result of toxic effects of heavy metals upon organisms, and may have an ultimate effect on man if he is exposed to heavy metals through edible fish and shellfish. Sediment samples from some areas of the Laguna Madre estuary and the Arroyo Colorado exceed the U.S. Environmental Protection Agency criteria for metals in the sediments (prior to dredging). The following constituents have been found in violation of these standards in at least one sample: arsenic, cadmium, mercury, and zinc (Table 4-10).

Herbicides and Pesticides

Samples of the bottom sediments in the Laguna Madre estuary and the Arroyo Colorado have been collected by the Texas Department of Water Resources at only one data collection site for the period 1969 to 1979 and by the cooperative efforts of the U.S. Geological Survey and the Texas Department of Water Resources at 8 data collection sites for the period 1969 to 1975 (Figure 4-5). The data were analyzed for herbicide and pesticide concentrations (Table 4-11). The parameters detected included aldrin, DDD, DDE, DDT, dieldrin, endrin, heptachlor, heptachlor epoxide, lindane, and silvex. Only DDD, DDE, and lindane were detected at levels above or equal to the detection limit of 0.2 µg/kg (USGS-TDWR cooperative program). Statistical analyses were not possible due to the limited number of samples available.

Table 4-10. Ranges of Concentrations for Metals in Sediment Compared to USEPA (1974) Dredge Criteria a/

Segment Location b/ & Station Number / Parameter	Segment #1 (Northern End of Laguna Madre) 2491.02	Segment #2 (Baffin Bay Inclusive) 64.2, 74.3, 94.2, 107.2	Segment #6 (Port Mansfield) 188.3	Segment #8 (Below Arroyo Colorado) 274.1	Arroyo Colorado 233.2	Dredge Criteria
			(units mg/kg)			
Arsenic	1.0 - 4.3 (4) c/	0.8 - 4.9 (6)	0.0 (1)	3.0 (1)	5.0* (1)	5
Cadmium	0.2 - 2.0* (4)	0.0 - <10.0* (6)	<10.0* (1)	<10.0* (1)	--	2
Chromium	3.9 - 34.0 (5)	--	--	--	--	100
Cobalt	--	2.1 - 11.0 (6)	<10.0 (1)	<10.0 (1)	1.7 - 7.4 (2)	--
Lead	4.3 - 26.0 (5)	3.0 - 16.0 (6)	<10.0 (1)	<10.0 (1)	2.0 - 8.8 (2)	50
Manganese	52.0 - 360.0 (5)	50.0 - 300.0 (6)	80.0 (1)	290.0 (1)	320.0 - 500.0 (2)	--
Mercury	0.04 - 5.0* (3)	--	--	--	--	1
Nickel	5.1 - 16.0 (5)	--	--	--	--	50
Silver	0.2 - 3.5 (5)	--	--	--	--	--
Zinc	14.0 - 74.0 (3)	18.0 - 50.0 (6)	80.0* (1)	30.0 (1)	56.0 - 57.0 (2)	75

a/ Includes data from references (53,235)
b/ See Figure 4-5 for segment and station location
c/ Number of samples for a parameter
* Denotes at least one sample in violation of EPA's dredge spoil criteria

Table 4-11. Range of Pesticide Concentrations in Sediment, Laguna Madre Estuary, 1969-1975 a/

Segment b/ Location & Station Number / Parameter	Segment #7 Mouth of (Arroyo Colorado) 258.2 c/	Segment #10 (Baffin Bay) 107.2, 119.3 d/	Segment #11 (Laguna Salada) 64.2 e/	Segment #12 (Cayo del Grullo) 74.2, 74.3 d/	Segment #13 (Alazan Bay) 94.2 f/	Arroyo Colorado 223.2 e/
			(units µg/kg)			
DDD	--	--	0.1 - 2.2 (3) g/	--	--	1.1 - 10.0 (3)
DDE	0.80 - 0.84 (2)	0.1 - 0.40 (3)	0.5 - 5.4 (3)	0.1 - 1.30 (5)	0.7 - 5.7 (2)	5.1 - 39.0 (3)
Lindane	--	--	0.1 - <2.0 (3)	0.1 - <2.0 (5)	0.1 - <2.0 (2)	0.1 - <2.0 (4)

a/ Includes data from reference (53)
b/ See Figure 4-5 for segment and station location
c/ Data collected at station from 1969-1970
d/ Data collected at station(s) from 1969-1975
e/ Data collected at station from 1969-1973
f/ Data collected at station from 1972-1973
g/ Number of samples per parameter for given station #

CHAPTER V

CIRCULATION AND SALINITY

Introduction

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

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

The following sections of Chapter V will address the hydrodynamic and mass transport models currently being developed to evaluate the circulation and salinity patterns of the Laguna Madre 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.

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

Mathematical Model Development

The mathematical tidal hydrodynamic and conservative transport models for a typical Texas estuary have been developed by Masch (156). These models are designed to simulate the tidal and circulation patterns and salinity distributions in a shallow, irregular, non-stratified estuary. The two models are sequential (Figure 5-1) in that the tidal hydrodynamic model computes temporal histories of tidal amplitudes and flows. These are then used as input to the conservative transport model to compute vertically averaged salinities (or any conservative material) under the influence of various source salinities, evaporation, and rainfall. Both of these models have "stand alone" capabilities although it must be recognized that the transport model ordinarily cannot be operated unless the tidally generated convective inputs are available.

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

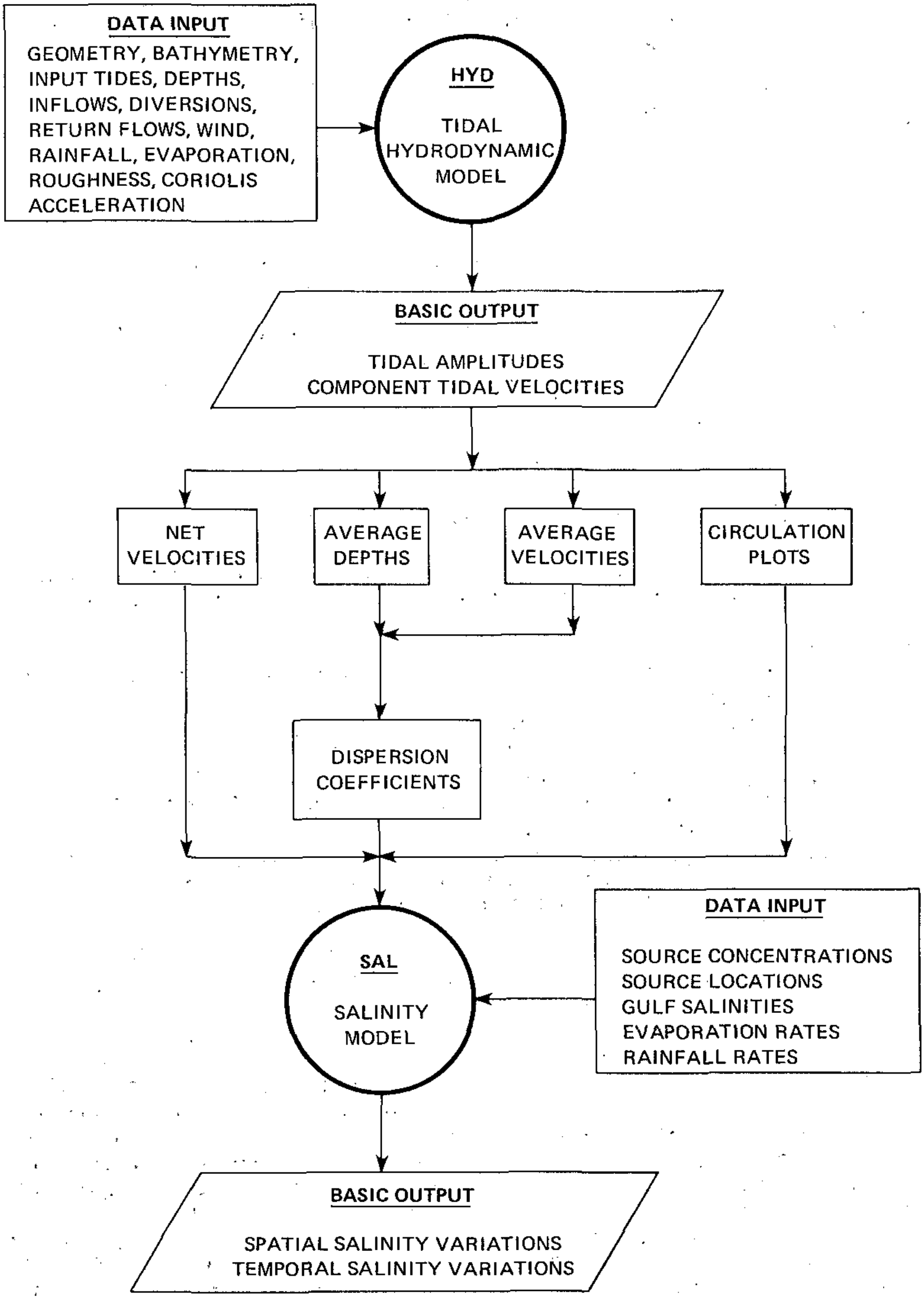


Figure 5-1. Relationship Between Tidal Hydrodynamic and Salinity Models (156)

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 = $(qx^2 + qy^2)^{\frac{1}{2}}$ = 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 for the Laguna Madre estuary
- r = rainfall intensity
- e = evaporation rate.

The numerical solution utilized in the hydrodynamic model of the Laguna Madre 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 the bay system (Figure 5-2). This explicit formulation of the hydrodynamic model requires for stability a computational time step, $\Delta t < \Delta s/(2gd_{max})^{\frac{1}{2}}$, 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 (156).

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

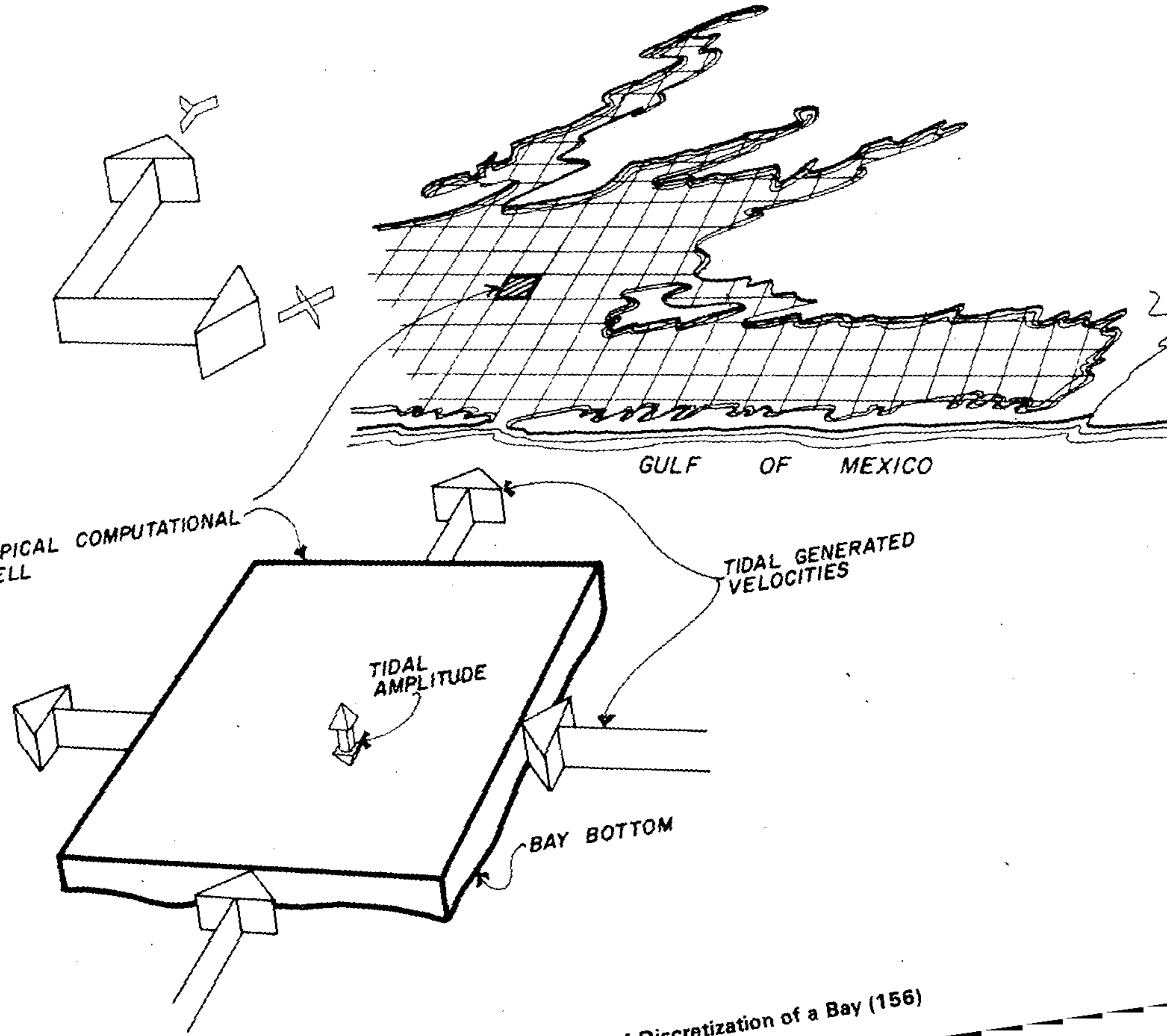


Figure 5-2. Conceptual Illustration of Discretization of a Bay (156)

Physical Data

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

Hydrologic - Hydraulic Data

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

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

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

where C is the tidally averaged salinity or TDS concentration; $\bar{q}_x$ and $\bar{q}_y$ are the net flows over a tidal cycle in the x and y directions, respectively; D_x and D_y are the corresponding dispersion coefficients evaluated at a scale representative of total tidal mixing; and $\bar{d}$ is the average depth over a tidal cycle. The term $K_e C\bar{d}$ is a first order reactive term included to represent the buildup of concentration due to evaporation from the bay surface, and K_e is a coefficient determined volumetrically in accordance with methods described by Masch (156). The primary difference in the form of Equation [4] given above and that reported previously (156), 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 $\Delta t / \bar{s}^2 \leqslant \frac{1}{2}$ was always maintained throughout this work. Details of the numerical solution of Equation [4] and programming techniques have also been previously described by Masch (156).

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

Application of Mathematical Models, Laguna Madre Estuary

Hydrodynamic and Mass Transport Models

The computational grid network used to describe the Laguna Madre estuary has been developed. The basic data necessary for the development, verification and calibration of the mathematical models have been obtained. However, due to problems with the data and the uniqueness of the system being modelled, the models have not been satisfactorily calibrated for use in this study. At such time that the models have been calibrated and verified, their application will be included in the study.

Freshwater Inflow/Salinity Regression Analysis

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

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

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

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

or

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

where S_t is the average salinity of the t-th day; Q_{t-k} or Q_{t-i} is gaged streamflow k or i days antecedent to the t-th day; b is a positive number between zero and one; n is an integer; and a_0, a_1 and a_2 are regression coefficients. The term $\sum_{i=1}^{n} Q_{t-i}$ in equations [1] and [2] represents the antecedent inflow conditions, while Q_{t-k} represents the conditions taking into consideration streamflow time lag between the gage and the inflow estuary. The regression coefficients were determined using a step-wise multiple regression procedure (20).

The regression equations developed for Baffin Bay use the salinities obtained by the Texas Department of Water Resources (TDWR) and United States Geological Survey (USGS) cooperative data collection programs at line 82, site 2 and the sum of the gaged streamflows recorded for Los Olmos Creek near Falfurrias and San Fernando Creek at Alice (Table 5-1). The daily average salinity is related to the daily gaged streamflow by the equation

$$S_t = 1241.3 \left(\sum_{i=1}^{60} Q_{t-i} \right)^{-0.7148} \qquad [3]$$

where S_t and Q_{t-i} are salinity and streamflow in ppt and ft^3/sec, respectively. With a correlation coefficient (r) of 0.91 and an explained variation (r^2) of 83 percent, the regression is tested to be highly significant ($\alpha = .01$).

Monthly salinity-inflow relationships were derived using equation [3] to generate daily salinities for the period of streamflow record, 1969 through 1978. The computed daily salinity values were averaged monthly over the study period, and the averages were related to the monthly average flows by the geometric equation

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

where S_m and Q_m are monthly average salinity and gaged flow in ppt and ft^3/sec, respectively, C_0 and C_1 are regression coefficients, and (ts_e) is a random component. The frequency analyses for Baffin Bay and Lower Laguna-Madre estuary indicate that both monthly salinities and monthly gaged streamflows are approximately log-normal distributed. Therefore, the random component has a normal distribution and can be expressed by ts_e (62), 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 Upper Baffin Bay (Table 5-2) for the twelve months (r) ranged from 0.66 to 0.99, which are highly significant ($\alpha = .01$) except for the months of June and July.

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

$$S_y = 84.1 \;\; Q_y^{-0.5835} \qquad [5]$$

where S_y and Q_y are, respectively, the mean monthly average salinity and the sum of the mean flow in the current and antecedent months. The equation and the 95 percent confidence limits of S_y versus Q_y are plotted in Figure 5-3. The other statistics of equation [5] are listed in Table 5-2.

The analysis for Lower Laguna Madre estuary in uses salinities obtained by the Texas Department of Water Resources and U. S. Geological Survey cooperative data collection programs at line 217, sites 2 and TDWR Station No. 2491.04 at the intersection of the Intracoastal Waterway and the Arroyo Colorado, and the sum of the gaged streamflows recorded for the North Floodway near Sebastian and the Arroyo Colorado at Harlingen (Table 5-1). Using the

Table 5-1. Description of Data for Regression Analysis

Bay	Salinity: Station Line-Site	Salinity: Period of Record	Inflow: USGS Station	Inflow: Period of Record	Number of Observations for Regression
Baffin	TDWR-USGS 58-2	Aug. 1968 to Jun. 1975	Los Olmos Creek near Falfurrias	Jan. 1967 to Dec. 1978	12
			San Fernando Creek at Alice	Jan. 1965 Dec. 1978	
Lower Laguna Madre	TDWR-USGS 217-2	Sept. 1969 to Sept. 1979	North Floodway near Sebastine	Jan. 1965 to Jan. 1980	42
	TDWR 2491.04		Arroyo Colorado at Harlingen	Oct. 1968 Jan. 1980	

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

Station a/	Class	Regression Equation b/ (S_t in ppt and Q_t in ft^3/sec)	Correlation Coefficient r	Explained Variation r^2	Standard Error of Estimate s_e	F-test
TDWR-USGS line-site 82-2	Daily	$S_t = 1241.3 \left(\sum_{i=1}^{60} Q_{t-i}\right)^{-.7148}$	0.91	0.83	0.530	**
	Jan.	$S = 133.6\ Q^{-0.8607},\ 2 \leq Q \leq 22$	0.99	0.99	0.063	**
	Feb.	$S = 118.1\ Q^{-0.7577},\ 2 \leq Q \leq 13$	0.97	0.93	0.092	**
	Mar.	$S = 72.4\ Q^{-0.4596},\ 2 \leq Q \leq 60$	0.88	0.77	0.257	**
	Apr.	$S = 106.9\ Q^{-0.7043},\ 2 \leq Q \leq 60$	0.96	0.93	0.177	**
	May	$S = 75.3\ Q^{-0.4098},\ 4 \leq Q \leq 63$	0.93	0.87	0.152	**
	Jun.	$S = 59.1\ Q^{-0.4213},\ 4 \leq Q \leq 92$	0.66	0.43	0.481	*
	Jul.	$S = 46.6\ Q^{-0.4179},\ 6 \leq Q \leq 228$	0.73	0.54	0.432	*
	Aug.	$S = 65.1\ Q^{-0.5398},\ 4 \leq Q \leq 226$	0.89	0.79	0.398	**
	Sep.	$S = 69.2\ Q^{-0.4617},\ 4 \leq Q \leq 1{,}912$	0.85	0.72	0.510	**
	Oct.	$S = 91.2\ Q^{-0.6441},\ 4 \leq Q \leq 2{,}644$	0.99	0.97	0.212	**
	Nov.	$S = 85.0\ Q^{-0.6966},\ 2 \leq Q \leq 860$	0.98	0.95	0.294	**
	Dec.	$S = 138.5\ Q^{-0.9427},\ 2 \leq Q \leq 36$	0.95	0.90	0.280	**
	All Months	$S = 84.1\ Q^{-0.5835},\ 2 \leq Q \leq 2{,}644$	0.90	0.81	0.395	**

a/ See Figure 3-11.
b/ S is the mean monthly salinity in ppt and Q is the sum of mean monthly gaged inflows for the current and antecedent months in ft^3/sec.
* Indicates a statistical significance level of $\alpha = 0.05$ (significant).
** Indicates a statistical significance level of $\alpha = 0.01$ (highly significant).

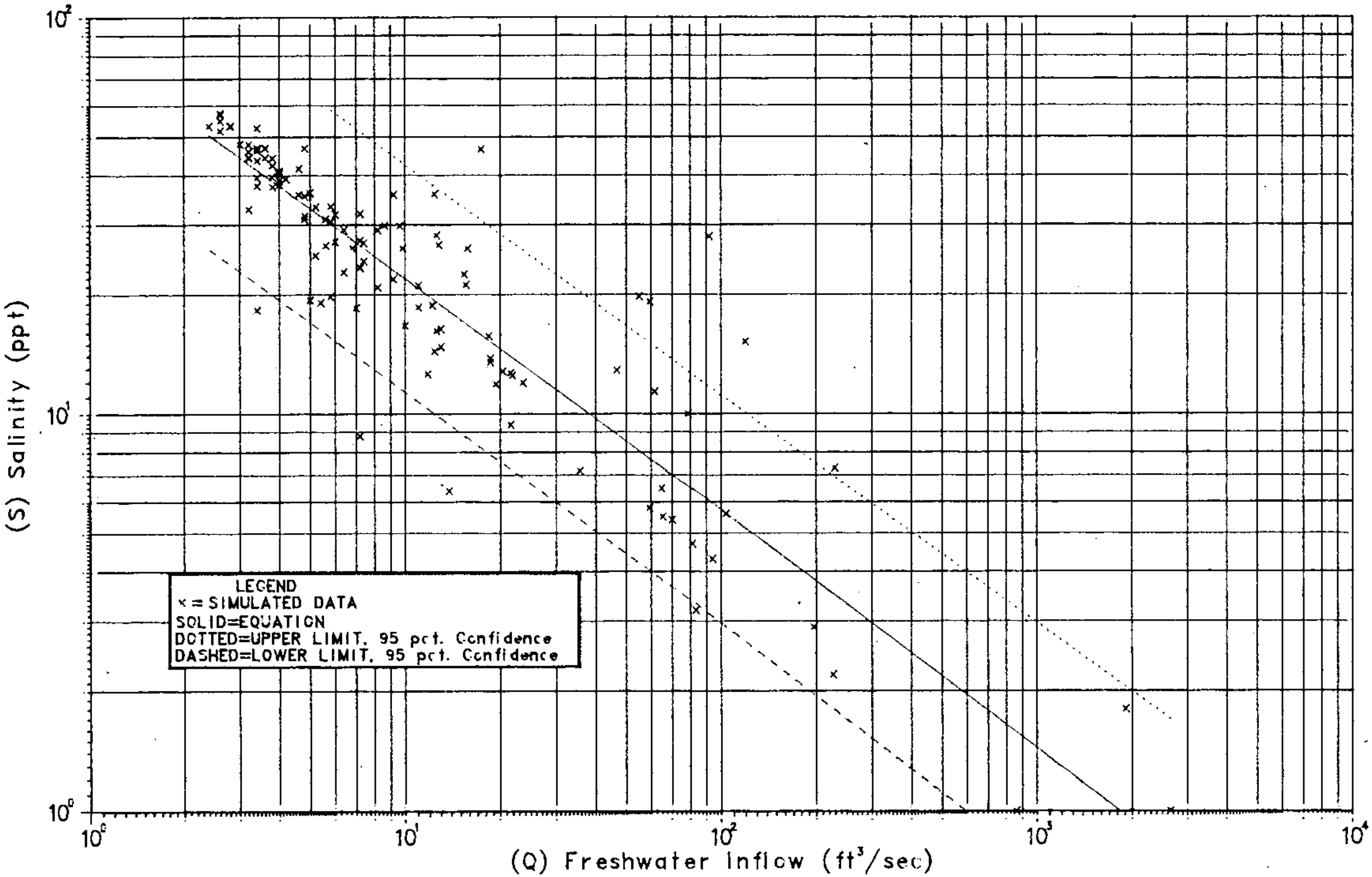


Figure 5-3. Average Monthly Salinity Versus Average Monthly Gaged Inflow, Baffin Bay, 1940-1976

averages of salinities measured at the line site, the analysis yields the relationship

$$S_t = 922.97\, Q_{t-2}^{-0.5935} \qquad [6]$$

with a highly significant correlation coefficient of 0.73.

Using equation [6] to generate mean daily salinity for the period of streamflow record, 1970 through 1979, the relationships between computed mean monthly salinities and mean monthly streamflows are determined (Table 5-3). The average condition of the relationships can be fitted to the equation

$$S_y = 305.9\, Q_y^{-0.3978} \qquad [7]$$

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 5-4. The other statistics of equation [7] are listed in Table 5-3.

The above freshwater inflow-salinity relationships can be used to provide preliminary estimates of the response of the estuary to proposed freshwater inflow regimes. Such a technique allows a quick screening of the inflow regimes that have the least desirable impacts on salinity 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. Physical data collected in this estuary are being utilized to calibrate and verify the models for the Laguna Madre estuary.

Statistical analyses were undertaken to quantify the relationship between freshwater inflows from the contributing drainage area and salinities at selected points in Baffin Bay and lower Laguna Madre. Utilizing gaged daily river flows and observed salinities, a set of monthly predictive salinity

Table 5-3. Results of Salinity Regression Analysis, Lower Laguna Madre

Station a/	Class	Regression Equation b/ (S_t ppt and Q_t on ft³/sec)	Correlation Coefficient r	Explained Variation r^2	Standard Error of Estimate s_e	F-test
TDWR-USGS line-site 217-2	Daily	$S_t = 922.97\ Q_{t-2}^{-.05935}$	0.73	0.53	0.432	
TDWR Station 2491.0900	Jan.	$S = 583.6\ Q^{-0.5114},\ 222 \leq Q \leq 526$	0.97	0.93	0.033	**
	Feb.	$S = 219.2\ Q^{-0.3395},\ 179 \leq Q \leq 697$	0.77	0.59	0.098	**
	Mar.	$S = 604.8\ Q^{-0.5168},\ 180 \leq Q \leq 545$	0.96	0.92	0.049	**
	Apr.	$S = 665.9\ Q^{-0.5297},\ 196 \leq Q \leq 695$	0.97	0.94	0.048	**
	May	$S = 770.8\ Q^{-0.5559},\ 208 \leq Q \leq 498$	0.95	0.91	0.045	**
	Jun.	$S = 232.5\ Q^{-0.3483},\ 255 \leq Q \leq 1{,}344$	0.89	0.79	0.095	**
	Jul.	$S = 352.4\ Q^{-0.4216},\ 180 \leq Q \leq 1{,}140$	0.97	0.93	0.062	**
	Aug.	$S = 185.4\ Q^{-0.2995},\ 128 \leq Q \leq 3{,}551$	0.91	0.82	0.119	**
	Sep.	$S = 317.5\ Q^{-0.3946},\ 329 \leq Q \leq 1{,}504$	0.76	0.58	0.154	**
	Oct.	$S = 390.8\ Q^{-0.4386},\ 289 \leq Q \leq 3{,}889$	0.98	0.96	0.074	*
	Nov.	$S = 713.6\ Q^{-0.5493},\ 219 \leq Q \leq 927$	0.99	0.99	0.024	**
	Dec.	$S = 945.3\ Q^{-0.5970},\ 210 \leq Q \leq 623$	0.99	0.99	0.007	**
	All Months	$S = 305.9\ Q^{-0.3978},\ 128 \leq Q \leq 3{,}889$	0.92	0.84	0.097	**

a/ See Figure 3-12.
b/ S is the mean monthly salinity in ppt and Q is the mean monthly gaged inflow in ft³/sec.
* Indicates a statistical significance level of $\alpha = 0.05$ (significant).
** Indicates a statistical significance level of $\alpha = 0.01$ (highly significant).

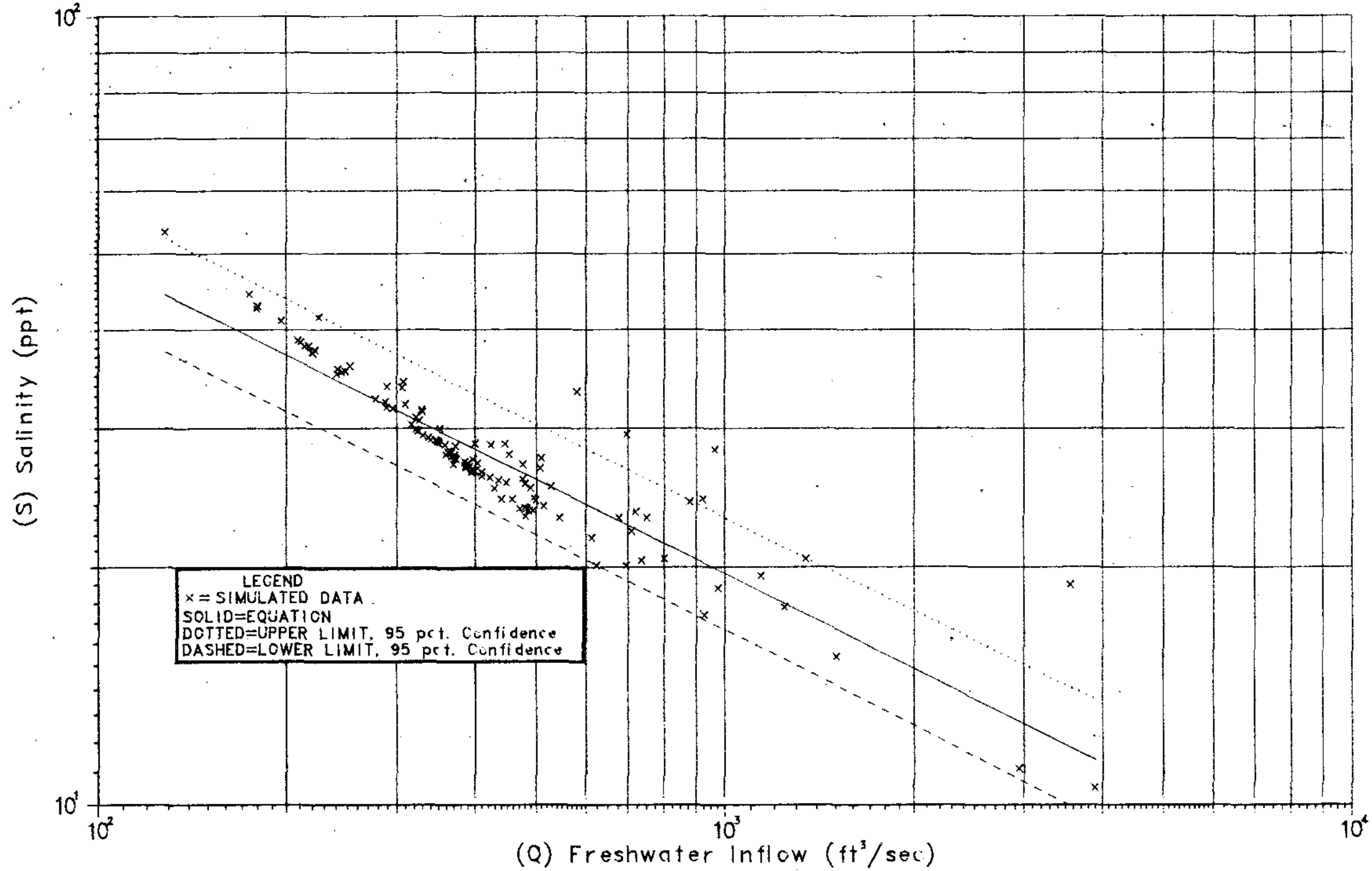


Figure 5-4. Average Monthly Salinity Versus Average Monthly Gaged Inflow, Lower Laguna Madre Estuary, 1941-1976

equations were derived utilizing regression analyses for two areas of the estuary: (1) a point in the western end of Baffin Bay and (2) at the intersection of the Intracoastal Waterway and the Arroyo Colorado. These equations enable the prediction of the mean monthly salinity as a function of the mean monthly freshwater inflow rate.

CHAPTER VI

NUTRIENT PROCESSES

Introduction

Biological productivity is related to a variety of physical and chemical conditions that include adequate nutrient concentrations and favorable conditions of temperature, salinity, and pH, as well as a sufficient energy source (e.g., sunlight and tides) to drive the natural processes. Although biological productivity in the Laguna Madre may be reflected in the production and harvest of economically important fisheries (fish and shellfish) species, it ultimately depends on the extent of plant production in these shallow estuarine waters and the tropho-dynamics (feeding relationships) of the ecosystem's food web. Utilizing the sun's energy, plants combine inorganic nutrient compounds into organic compounds and substances that form plant tissues; through a food web of prey and predators, these organic substances are incorporated into the tissues of higher organisms, including man.

A number of factors can limit the productivity of an estuary like the Laguna Madre. Turbidity of waters limits the input of solar energy; temperature and salinity limits the rate at which organisms can survive and grow. These factors can represent the major constraints capable of reducing the productivity of the system. However, within the bounds imposed by seasonal variation in salinity, temperature, and light, variations in the concentrations of nutrients are most often the crucial factors controlling production. In addition, from the standpoint of man's effects on estuaries, investigation of nutrients frequently shows the most direct linkage between man's activities and production.

Organic matter is composed primarily of carbon, hydrogen, oxygen, nitrogen, and phosphorus with lesser amounts of silicon, sodium, calcium, potassium, manganese, chlorine, sulfur, and other elements in trace amounts. In the majority of ecosystems, these elements are available in quantities necessary to support an active level of biological production. A deficiency of any one, may be sufficient to limit biological productivity. In most cases, nutrients required in the largest amounts are quickly depleted from the surrounding medium. Their concentrations can consequently be considered among the most important factors relating to biological productivity. The ratios of the three most important elements--carbon, nitrogen, and phosphorus--to lesser ones are such that a deficiency of any one of the three will act as a limiting factor regulating the level of productivity in the system.

Carbon to nitrogen to phosphorus (CNP) ratios vary from organism to organism. Carbon is normally required in the greatest quantity followed by nitrogen and phosphorus. Generally, oceanic species have a reported value of 106:16:1 (127). Nitrogen to phosphorus ratios for a variety of phytoplankton species are usually in the range of 10-21:1 (127). These two elements are considered to be the "critical" nutrients in aquatic ecosystems since carbon is rarely, if ever, limiting due to the readily available supply of atmospheric carbon dioxide (CO_2) and the ability of autotrophic organisms to use this form. The amount of nitrogen required in an aquatic ecosystem is generally greater than phosphorus, thus biological productivity is most likely to be nitrogen-limited. This has been reported to be the case in a number of estuaries (397, 398, 144, 199, 119, 203) including those in Texas (324, 325).

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

Since the rate of biological production can often be related to the rate of supply (chemical availability) of these nutrients, much of this chapter focuses on the inputs of nitrogen and phosphorus and processes which affect their supply. Sources of nutrient loading to Laguna Madre are considered first, followed by a discussion of nutrient cycling within the ecosystem and pathways of nutrient loss.

Nutrient Loading

The major sources of nutrient loading to Laguna Madre are from inland drainage and, for the lower Laguna, through Brazos Santiago Pass from the Gulf. Gulf water usually has lower nutrient concentrations than do the bay and estuary waters so is not considered a major contributor of nutrients. During prolonged droughts in the area, however, portions of Laguna Madre may be dominated by seawater input (see Chapter IV). Input from drainages involves river and creek flows plus storm water runoff. River water input includes contributions from (a) municipal return flows (sewage treatment plant discharge plus storm water runoff), (b) industrial return flows (discharges plus storm water runoff), and (c) agricultural sources (irrigation return flows plus storm-water runoff from fields).

Gulf Exchange

There is little data available on the amount of nutrients entering Laguna Madre from the Gulf of Mexico; however, there is some information on the nutrient concentrations of Gulf water off the South Texas Coast. Seasonal oceanographic cruises for a recent federal Bureau of Land Management study (311) of the Gulf's continental shelf found generally low surface water nitrate (NO_3) concentrations ranging from less than 0.1 micro moles (μm) in the fall to 4.0 μm in the spring (normal maximum concentrations were near 0.5 μm). Phosphate (PO_4) in the Gulf's surface waters ranged from 0.04 μm to 0.66 μm, with the lowest concentrations occurring in the spring season and the highest in the fall near the end of the warm growing seasons.

River Inputs

Attempts to determine the amount of nutrient loading from a riverine source to an estuary have been conducted by Smith and Stewart (207). 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. However, nutrient concentrations and other water quality data have only been systematically collected for these rivers only since the late 1960's.

The relatively infrequent data on nutrient concentrations and flows into Laguna Madre are summarized in Table 6-1 as monthly ranges of nutrient input. Maximum and minimum levels are given instead of average nutrient concentrations, and lack of sufficient data makes even these measures not consistently adequate. Inflows from the contributing drainage basins can be calculated as either arithmetic means or as 50% exceedance frequency (E.F.) flows (see Chapter IV). The latter is perhaps more biologically meaningful as a measure of the central tendency; both are used in the table. Nutrient data for this table come from the Texas Statewide Water Quality Monitoring Network for San Fernando Creek, Petronila Creek, and the Arroyo Colorado; and from U.S. Geological Survey monitoring stations on Los Olmos Creek. Flow rate data are from Tables 4-1 and 4-4. The nutrient compounds reported as ammonia, nitrate, total phosphate, and total organic carbon are not the only nutrients which could be considered, but they were commonly measured and do provide the most important contributions to productivity.

The large differences between average (arithmetic mean) and 50% E.F. inflows illustrate that in the arid drainages of Laguna Madre most flows are the result of locally heavy, sporadic rains and flooding associated with tropical storms, particularly in late summer and fall. Attempts were made to correlate stream nutrient load with flow rates. This effort failed to provide equations to predict how flood surges would alter nutrient loading. In streams swollen with heavy rains, nutrient loads from some sources (municipal waste, for instance) would be diluted, but increased loads of suspended solids might mean an overall greater nutrient loading. Lack of information on nutrient concentration in flood waters limits the understanding of nutrient input into a system like Laguna Madre, where sporadic downpours provide the major freshwater inflows, while much of the day-to-day nutrient requirements may be supplied by natural nutrient regeneration and cycling processes.

In both upper and lower Laguna Madre, the maximum recorded levels of nutrient loading vary by at least one order of magnitude (a factor of ten), over the seasons. This is because of the nonuniform distribution of freshwater inflows over the year. Flows are locally higher during the tropical storm dominated autumn season, but otherwise the rates of nutrient loading do not follow a definite seasonal pattern which might explain the observed seasonal pattern of productivity.

A further summary of nutrient loading into Laguna Madre is given in Table 6-2, where yearly loadings calculated for average and 50% E.F. flows are shown. These figures should be considered only as very crude estimates of the nutrient loading. In recognition of the variability of inflows, and thus the potential error in estimations of nutrients brought into the system, caution should be exercised in using these figures for comparisons with other estuaries or projections of productivity.

Nitrogen Fixation

Nitrogen fixation is the conversion of atmospheric, gaseous nitrogen (N_2) into nitrogenous compounds which can be used by plants in the synthesis

Table 6-1. Nutrient Loading in the Laguna Madre Estuary From Freshwater Inflows a/

		UPPER LAGUNA MADRE								LOWER LAGUNA MADRE							
		AVERAGE FLOWS				50% E.F. FLOWS				AVERAGE FLOWS				50% E.F. FLOWS			
		NH_3	NO_3	T PO_4	TOC	NH_3	NO_3	T PO_4	TOC	NH_3	NO_3	T PO_4	TOC*	NH_3	NO_3	T PO_4	TOC*
		thousands of kilograms															
JAN	MIN	.296	.222	.592	81.4	0	0	0	0	-	-	-	-	-	-	-	-
	MAX	14.8	49.6	139.	-	0	0	0	-	-	-	-	-	-	-	-	-
FEB	MIN	.986	.296	1.18	83.8	0	0	0	0	6.66	1.33*	33.3*	199.	3.69	.739	18.5	133.
	MAX	30.6	21.9	46.4	-	0	0	0	-	26.6*	123.	59.9	666.	14.8	68.4	33.3	443.
MAR	MIN	.123	.037	.185	-	0	0	0	-	7.77	25.9*	25.9*	129.	6.66	22.2	22.2	111.
	MAX	.247	.469	.789	-	0	0	0	-	25.9*	82.9	59.6	181.	22.2	71.0	51.0	155.
APR	MIN	.369	.222	.444	81.4	0	0	0	0	2.85*	68.8*	58.6*	285.	3.50	84.5	72.0	207.
	MAX	11.1	13.3	94.7	140.	0	0	0	0	-	-	-	448.	-	-	-	325.
MAY	MIN	1.05	.629	14.0	252.	0	0	0	0	-	-	-	-	-	-	-	-
	MAX	6.71	69.2	236.	-	0	0	0	-	-	-	-	-	-	-	-	-
JUN	MIN	1.48	.395	1.97	148.	0	0	0	0	1.18*	2.37*	14.2*	59.2	.838	1.68	10.1	41.9
	MAX	9.86	32.6	18.4	-	0	0	0	-	23.7*	36.7*	39.7*	533.	16.8	25.9	28.1	377.
JUL	MIN	1.73	.518	1.55	173.	0	0	0	0	35.3	64.1	83.4	-	27.1	49.3	64.1	-
	MAX	114.	6.90	943.	-	0	0	0	-	-	-	-	-	-	-	-	-
AUG	MIN	.345	.049	10.9	46.4	0	0	0	0	3.82*	.764*	23.3*	420.	2.34	.469	14.3	258.
	MAX	.493	1.09	57.2	73.9	0	0	0	0	-	2.29*	27.9*	-	-	1.41	17.1	-
SEP	MIN	3.14	1.87	11.3	1195	.123	.074	.444	46.9	4.18*	1.39*	47.4*	418.	1.78	.592	20.1	178.
	MAX	48.4	490.	503.	-	1.89	19.2	19.7	-	69.7*	71.1*	222.	1115.	29.6	30.2	94.1	473.
OCT	MIN	.888	.888	3.55	207.	0	0	0	0	11.5	86.0*	76.8*	803.	5.43	40.7	36.3	379.
	MAX	23.7	154.	28500	355.	0	0	0	0	-	172.	101.	1490.	-	81.4	47.7	705.
NOV	MIN	.062	.037	.111	9.86	0	0	0	0	4.69*	30.9*	56.2*	328.	2.59	17.1	31.1	181.
	MAX	.123	1.85	2.96	-	0	0	0	-	9.37*	46.9*	-	-	5.18	25.9	-	-
DEC	MIN	.739	.888	3.11	-	0	0	0	-	8.88	32.6*	23.7*	88.8	7.03	25.8	18.7	70.3
	MAX	1.85	39.2	62.8	-	0	0	0	-	23.7	94.7	51.8	296.	18.7	74.9	40.9	234.

a/ Monthly minimum and maximum nutrient mass was computed using average and 50% exceedance frequency flows
* From tidally influenced station

Table 6-2: Yearly Nutrient Loading in the Laguna Madre Estuary From Freshwater Inflows

Nutrients	Upper Laguna Madre		Lower Laguna Madre	
	Mean Inflows a/	50% EF b/	Mean Inflows	50% EF
	(thousands of kilograms)			
Ammonia-Nitrogen	27.90	.472	185	135
Nitrate-Nitrogen	9.78	.165	386	281
Total Phosphate	211.00	3.570	513	374
Total Organic Carbon	1,993.00	33.700	4,008	2,923

a/ Based on arithmetic mean monthly inflows
b/ Based on monthly 50 percent exceedance frequency (EF) inflows

of organic molecules. It represents a mechanism of nutrient input to the Laguna Madre which could be of considerable importance. Organisms capable of fixing nitrogen include species of bluegreen algae and some bacteria. These organisms are known to occur on the sediment surface (49, 71), as part of the epiphyte community on seagrass leaves (70), within sediments (71) and within algal mats (21), which characterize shallow flats of Laguna Madre.

Goering and Parker (70) estimated that rates of N-fixation by epiphytes might be 12.6 mg N/m^2 surface/hr in the summertime in Redfish Bay. Carpenter et al. (21) estimated algal mat N-fixation may reach 100 N_g/cm^2/hr (1.0 mg/m^2/hr). Given the broad areas of seagrass and algal mat within the lagoon, (see Chapter VII) these rates result in a significant contribution, on the order of 400 kg/hr-4800 kg/hr input of nitrogen over the length of Laguna Madre during the productive season.

Other Nutrient Sources

Rain contributes some nutrients and minerals important in some ecological systems. Loder and Gilbert (139) estimated that a New Hampshire estuary received 2% of phosphates from rain. In Laguna Madre, however, the effects of rain through washing in nutrients from land would be by far the more important source.

Drift algae may also represent a source of nutrient import into Laguna Madre from the Gulf (191). Sargassum and other plants are carried in on currents and may die in the hypersaline conditions of the lagoon, feeding the detritus food chain.

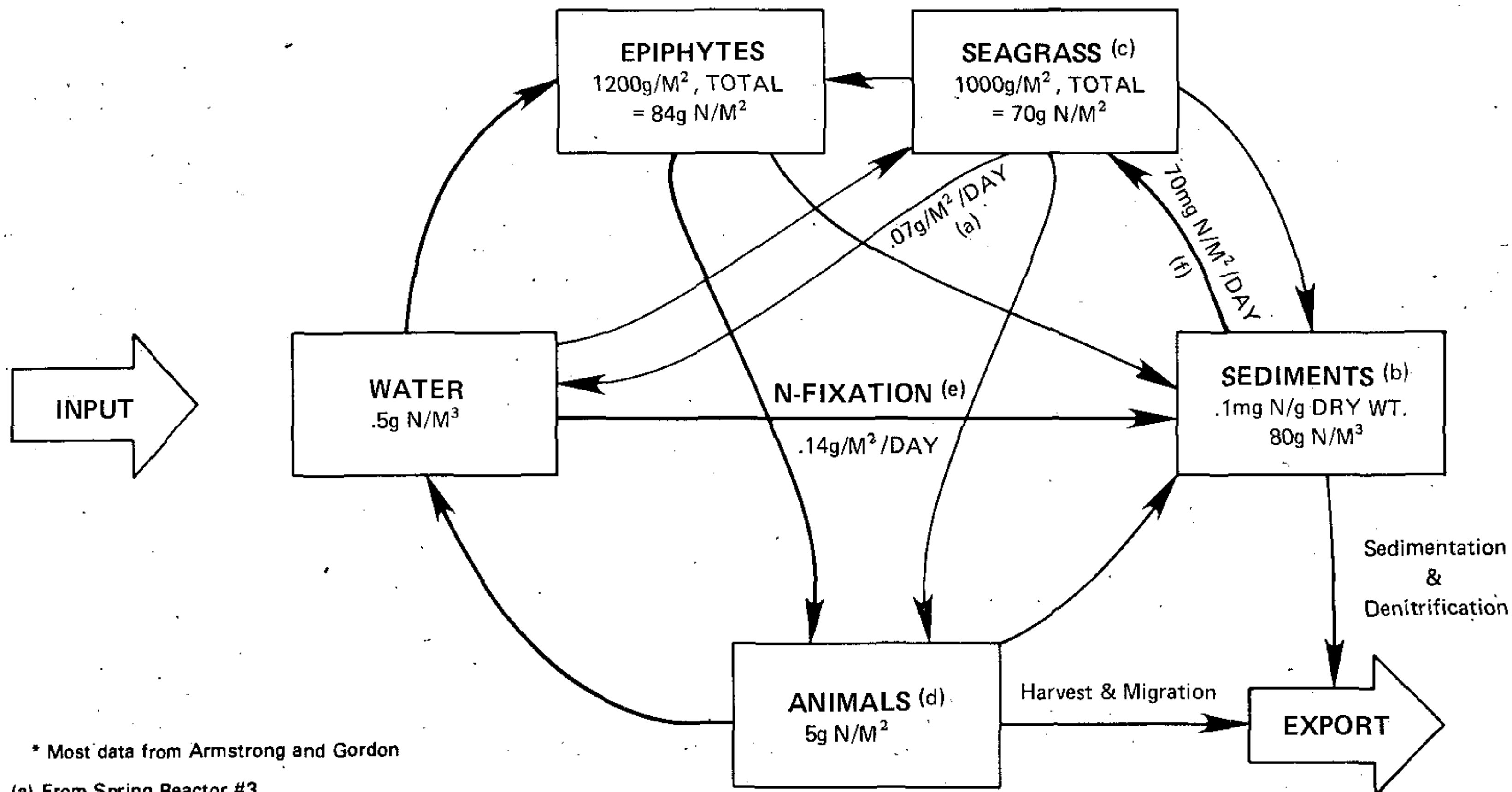
Nutrient Cycling

Estuarine productivity depends not only on nutrient loadings, but also on the ways and rates at which nutrients are cycled within the biogeochemical systems of the estuary. The communities within Laguna Madre can be seen to contribute to nutrient processing in different but complementary ways.

Seagrasses

Figure 6-1 is a model for discussion of the nutrient processes involving seagrasses. This diagram represents the nitrogen cycle within the seagrass community, based mostly on data gathered by Armstrong and Gordon (273). The diagram is much simplified, which in part reflects an incomplete understanding of the processes and organisms involved.

The amount of nutrients tied up in plant tissue can be calculated from estimates of the amount of seagrass present. Much of the nitrogen seagrasses use in new growth comes from the sediments (168), but some seagrass species may also be able to take up nitrogen compounds from the water. Nessmith (171) suggests that the amount of nitrogen present in sediment may not usually be sufficient for growth; and the discrepancy may be made up by removal of nitrogen from the overlying water column or by nitrogen fixation. Seagrasses may secrete certain organic substances and otherwise maintain environmental conditions within the sediments favorable to the growth of bacteria and algae capable of converting nitrogen compounds into those easily used by the seagrass (187). Plants and surrounding sediments may lose some nutrients to



* Most data from Armstrong and Gordon

(a) From Spring Reactor #3

(b) Top 10cm for M² plot, assuming 20% H_2O (Table 3-2 of 273)

(c) Assume from 273 that dry weight of seagrass is 20% wet weight

(d) Odum (176)

(e) Gotto et al. (71)

(f) Assume leaf productivity value at 7mg N/g leaf.
2g dry weight = 10g wet weight

Figure 6-1. Nitrogen Cycling in a *Thalassia* Seagrass Bed.*

the water by simple diffusion processes. Further, even in healthly plants some leaves and roots die and are decomposed--transferring nutrients to other organisms. Another source of nutrient loss is the direct grazing of various fish and bird species, although the cycling of nutrients brings back nitrogen to the seagrasses from the excretory products of these animals. Nitrogen and other elements are lost to the system through (1) man's harvest of fish and shellfish; (2) migration of animals (mostly fish and macrocrustaceans) from the bays to the Gulf; (3) loss within deeper layers of sediments; (4) conversion of nitrogen compounds by some forms of bacteria to nitrogen gas (N_2), which is then lost to the atmosphere; and (5) through tidal exchange with Gulf waters.

In a way, the seagrass beds act as a storage battery of nutrients and energy. Seagrasses grow during warmer months and most species then reach senescence and die during the winter season. The nutrients and energy contained within the dead blades and stems are then slowly released (through a decomposition process and the detrital food chain) to the rest of the system in time for a period of rapid growth in the following spring and summer.

The cycle of phosphorus differs from the nitrogen cycle primarily in that phosphorus becomes lost to the system in sediments more readily, as it often forms insoluable compounds in the aquatic environment. Cycles of other nutrient compounds can also be of importance, but less is known about their fluxes and limits in Laguna Madre.

Armstrong and Gordon (273) conducted a study of nutrient processing by seagrasses which provides some information on the rates of exchanges of nutrients between seagrasses and the rest of the estuary. Table 6-3 summarizes the shifts between nutrient release and uptake depending on the state of growth of the plants used, Thallasia testudinum and Halodule wrightii.

The rate studies conducted with seagrasses maintained at low, cool temperatures (10°C) involved healthy plants, although the growth rates were far below what may be expected in early summer in Laguna Madre. The plants involved in warm temperature laboratory tests at 30°C did not grow, however, but started to die; therefore, information from these plants represents decomposition processes. The complementarity in processes is easiest seen in the filtered total Kjeldahl and filtered organic nitrogen data where uptake accompanies growth, but nitrogen compounds are rapidly lost (i.e., exported) during decomposition. Rates of uptake are low, near zero, and are measures approaching the limitations of instrumentation, so less certainity can be placed on comparisons in which rates are very low.

In both seagrass species, plant growth reduces the biological oxygen demand (BOD) of the water, whereas plant decay increases the BOD. Differences in the dynamics of total organic carbon between the two species may be a function of other organisms present in the experimental chambers or they may represent real differences in the way the two species decompose. From the data, it appears that decomposition of Thallasia results in a lower rate of release of organic carbon, while Halodule releases organic carbon at a fast rate during decomposition. In many instances, the uptake rates for the seagrasses are small compared to the release rates. This may reflect, in part, an uptake of nutrients from the sediments by the plants, then a release of these nutrients to the surrounding waters during seagrass decomposition.

Table 6-3. Nutrient Exchange Rates for Two Seagrass Species During Low Growth (10°C) and Decline (30°C) Periods (273)

Nutrient \ Seagrass Species	*Thalassia testudinum*		*Halodule wrightii*	
	Low Growth	Decline	Low Growth	Decline
	(kg/ha/d)			
Total Suspended Solids x 10	-3.170	7.65	-2.70	0.804
Biological Oxygen Demand	0.252	-6.56	0.014	-6.58
Total Organic Carbon	-0.842	1.69	-0.424	-12.65
Particulate Total Kjeldahl Nitrogen	-0.022	0.107	0.011	0.19
Filtered Total Kjeldahl Nitrogen	0.089	-1.40	0.024	-0.92
Filtered Organic Nitrogen	0.089	-1.40	0.024	-0.92
Ammonia - Nitrogen	0.038	-0.934	-0.004	-0.28
Nitrite - Nitrogen	-0.004	0.011	0.002	-0.21
Nitrate - Nitrogen	-0.090	0.071	-0.093	0.02
Particulate Total Phosphate	-0.001	-0.695	-0.004	0.02
Filtered Total Phosphate	0.017	0.034	0.010	-0.02
Ortho Phosphate	0.005	-0.003	-0.001	0.03

Plankton

Nutrient cycling within the plankton community is extremely rapid, with nutrients quickly removed by phytoplankton, phytoplankton incorporated into herbivorous zooplankton, and nutrients released via zooplankton excretions. The time a nutrient molecule spends in anyone phase of the cycle can be very short, possibly averaging only minutes in some phases, so the small quantity of nutrients observed to be dissolved in the water belies a large primary productivity. In addition to plankton, Pomeroy, et al (188) has suggested that in trubid estuaries, colloidal clay may play a role in buffering nutrient concentrations. Clay particles may adsorb nutrients, releasing them only when concentrations are very low.

Benthos

In Texas estuaries, benthic organisms play a major role as intermediates in the transfer of nutrients and energy from primary producers (plants) to larger organisms. This can be seen in an analysis of diets of common coastal fish and bird species. The crustaceans, worms and molluscs which inhabit the grass and mud/sand flats are major constituents of the diets of croaker, drum, seatrout, and most wading birds (380). For example, the small clam Mulinia lateralis, very abundant in shallow waters of Laguna Madre, filters plankton and other material from the waters. This species is a major food source for the black drum (Pogonias cromis) and the productivity of this fishery species has been directly linked to the cycling of energy from plankton to fish through these benthic clams.

Small shrimp, such as the grass shrimp (Paleomonetes sp.), small snails, and polycheate worms are part of the detrital nutrient cycle. Bacteria and fungi attack dead seagrass leaves and actually increase the nutritive value of these particles by increasing their protein content (40). When larger organisms consume these enriched particles, some of the nutrients are excreted and thus made available to the planktonic food web, while the remaining nutrients are incorporated into benthic organisms, which are preyed upon by higher consumers in the trophic system of the estuary.

Birds and Fish

Higher order consumers such as birds and large fish play a role in conversion of nutrients stored in other organisms to forms available for primary productivity through their respiration and excretion. The Texas Colonial Waterbird Survey documents local concentrations of birds along Laguna Madre (260). Bowman et al. (16) estimated that some of these birds, particularly the larger fish eating birds, consume up to 1 lb fish/bird/day. Some of the consumption is lost as excretion products which could be a locally important source of nutrients for primary production. A variety of species of waterfowl over-winter in the Laguna Madre. Cornelieus (35) estimates that the Redhead duck population consumes 4% of the shoal grass standing crop during its stay in lower Laguna Madre. Excretory products from these birds contribute to nutrient concentrations.

Similarly, fish feeding on benthic organisms provide a recognized mechanism for transferring nutrients from the sediments to Laguna Madre waters through respiration and excretion of metabolic waste products.

Summary

The factors controlling nutrient dynamics in Laguna Madre involve both the cycling and regeneration processes within the animal and plant communities, and nutrient inflows to the estuary via terrestrial drainages. The rates of nutrient loading from the river and coastal drainages of Laguna Madre are variable, depending on local weather events and tropical storms. The aridity of the region is reflected in the low levels of nutrient input commonly associated with low freshwater inflows. Therefore, cycling of nutrients within the seagrass communities becomes particularly important in this estuary. Specifically, the seagrass beds demonstrate nitrogen fixation, recovery of nutrients from the sediments, and transfer of nutrients to economically valuable species through both detrital and herbivorous (grazing) food chains.

Limited data on nutrients within the system and an incomplete understanding of transfer rates within the community have hindered a more thorough analysis, but from the data available it appears that the dynamics of nutrients within seagrass beds is very important to the estuarine system.

CHAPTER VII

PRIMARY AND SECONDARY BAY PRODUCTION

Introduction

In order to understand the variations in Laguna Madre fisheries and the general "health" of this estuary, the changes in lower trophic levels of the biological system (i.e., primary and secondary producers) must be monitored and studied. By routinely monitoring these organisms over a number of years, we can understand the seasonality of production, distribution of production, and the sensitivity of the biological community to environmental changes.

In Laguna Madre, the groups of plants and animals which comprise the food web are the primary producers--planktonic algae, submerged attached algae, submerged flowering plants; secondary producers--zooplankton, benthic invertebrates; and fish which may function at several trophic levels (Figure 7-1). Fish and shellfish are discussed in chapter VIII. This chapter discusses the distribution and seasonality of production in lower trophic levels.

The Laguna Madre is a system more dependent on primary production within its waters than on material imported from the land via rivers. Basically, this primary production depends on the numbers and kinds of photosynthetic organisms which use the sun's energy to fix carbon from carbon dioxide and to incorporate it in organic material.

The phytoplankton (free-floating plant cells) form a portion of the base of this 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.

Aquatic macrophytes such as seagrass and algae also contribute to the productivity of the estuary in a major way. These submerged plants are a source of food energy to the estuary both during their growth season and then through their detritus as they die back in unfavorable seasons.

Though the Laguna Madre ecosystem combines the contributions of all food web elements, in this chapter the elements--phytoplankton, zooplankton, other aquatic plants, and benthic invertebrates--are dealt with separately.

Data Collection

Information on plankton and benthic organisms comes from recent studies of Laguna Madre. Hildebrand and King (23) conducted an environmental survey of the marine ecosystems in upper Laguna Madre in the vicinity of the Barney Davis Power Station at the base of Encinal Peninsula (near Flour Bluff). The study, which began in July 1972 and ended in June 1978, was divided into three 2-year periods--one, before the generation of electricity; two, after the first 325 megawatt generator went on line; and three with two 325 megawatt units in operation. Phytoplankton, zooplankton and benthos collections were made from eleven stations established in upper Laguna Madre (Figure 7-2).

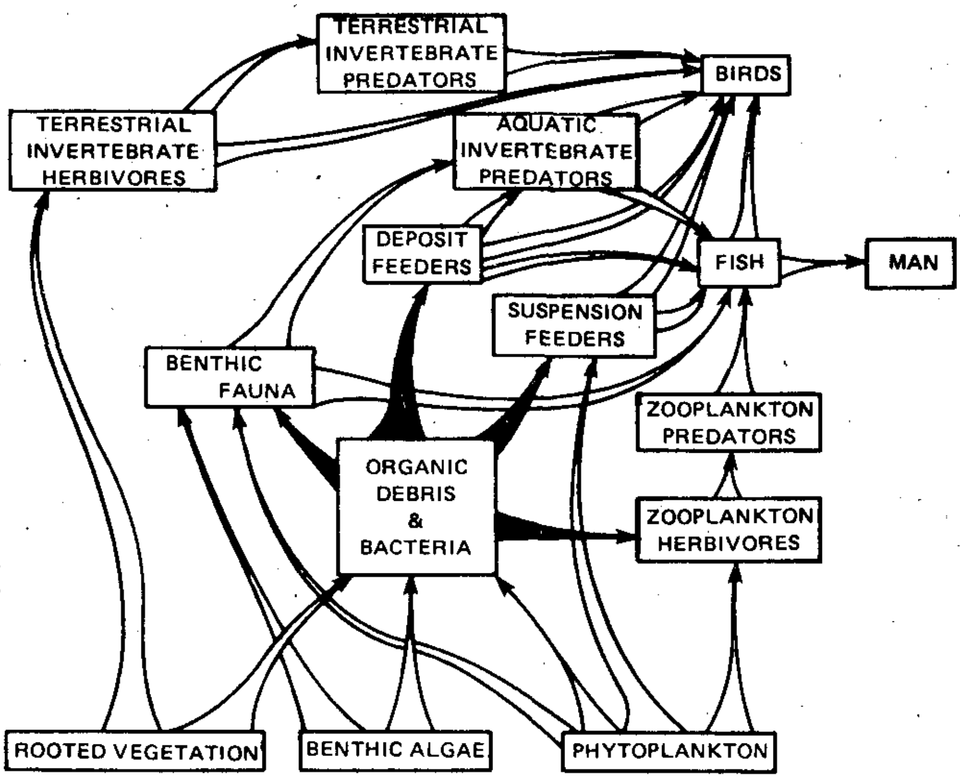


Figure 7-1. Estuarine Food-Web Relationships Between Important Ecological Groups (72)

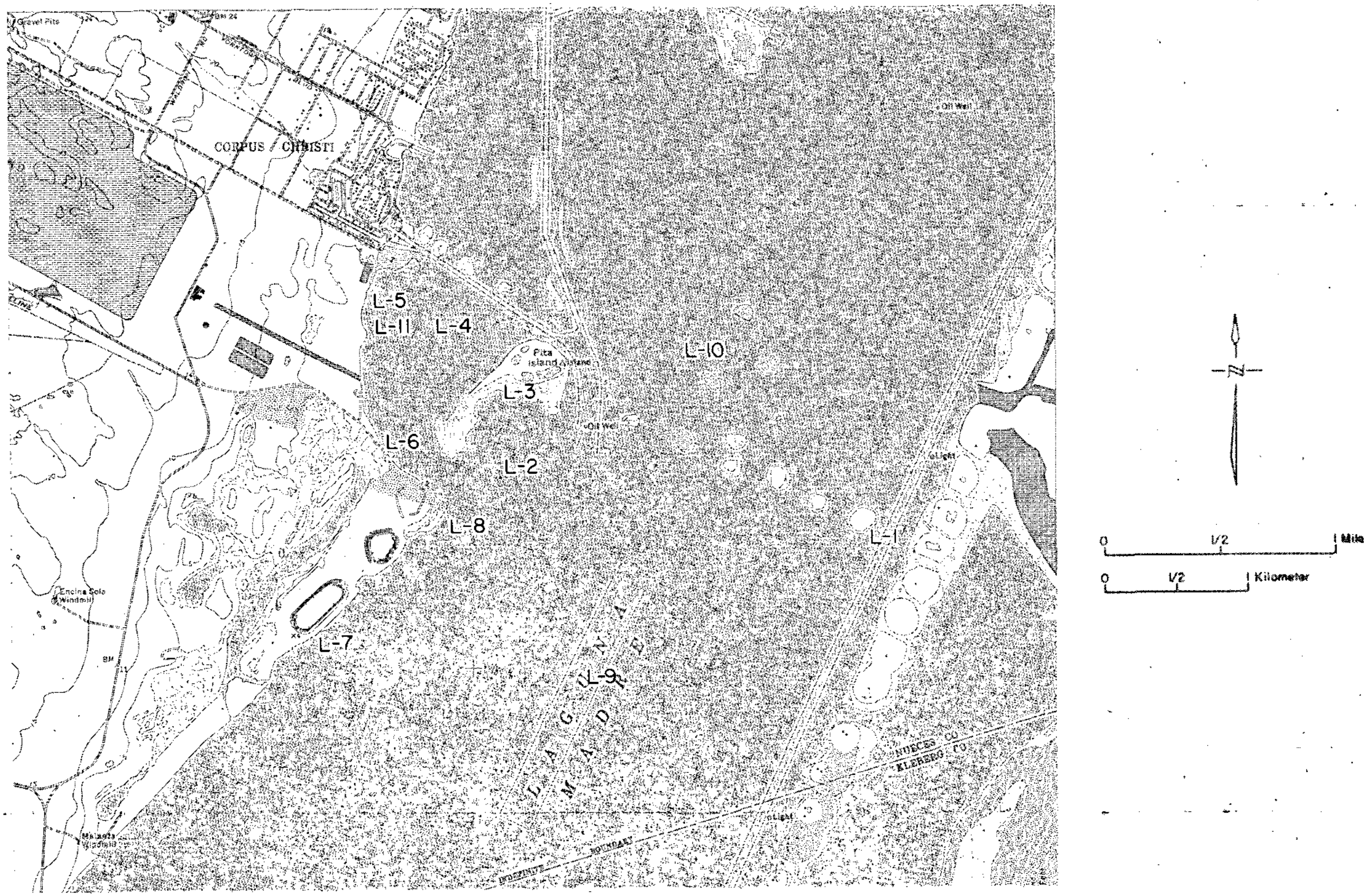


Figure 7-2. Biological Sampling Locations in Upper Laguna Madre (23)

Espey, Huston and Associates, Inc. (55) conducted an aquatic biota survey of lower Laguna Madre based on available literature and field studies performed July 12-16, 1977. Phytoplankton and zooplankton samples were collected from 13 sites; benthic macroinvertebrates were collected from 15 sites. Stations were located to give a broad coverage of lower Laguna Madre in the general vicinity of a proposed drainage canal in Willacy and Hidalgo Counties. In addition, transects were established along the Raymondville Drain, Existing Ditch through the El Sauz Ranch, North Floodway, Arroyo Colorado, and Arroyo Colorado Cutoff. Sampling stations are described in Table 7-1 (55).

Phytoplankton

Upper Laguna Madre

Hildebrand and King (23) obtained samples of only the large phytoplankton in upper Laguna Madre due to the collection method they employed. Even so, a total of 135 phytoplankton species were identified from the area, including 115 diatoms and 20 dinoflagellates.

The lowest number of phytoplankton species was collected during the first year of the study (64 species). The number remained fairly constant (75-80 species) until the Barney Davis Power Station reached full capacity and the number collected fell to 67 species. Densities were greatest during the winter months and lowest in the spring and summer months except for occasional moderate blooms of diatoms (Figure 7-3 and 7-4). The greater winter concentrations were perhaps due to favorable temperature and rainfall conditions.

Phytoplankton blooms generally occurred from December through March during the study. Major blooms were most often characterized by four diatom species: *Chaetoceros affinis*, *Thalassionema nitzschoides*, *Asterionella japonica*, and *Skeletonema costatum*. Salinity was the apparent controlling factor of phytoplankton blooms (i.e., blooms generally occurred after a salinity change, but never in salinities exceeding 40 ppt).

The most numerically dominant diatom genera during the entire study were *Chaetoceros*, *Nitzschia*, *Thalassionema*, and *Thalassiothrix*; the dominant dinoflagellate genera were *Ceratium* and *Noctiluca*. *Ceratium* was collected throughout the study. *Noctiluca* catches, however, were greatest during the initial collection period, and declined to a low during the later stages of the study; peak catches were recorded during the winter months.

Species diversity was relatively constant in upper Laguna Madre throughout the study (Figure 7-5). *Rhizosolenia alata*, a single species which composed 99 percent of the sample, was responsible for the severe decline of diversity in May 1977.

Lower Laguna Madre

Seventy (70) phytoplankton species representing 7 divisions were collected during the Espey, Huston and Associates survey (55). The Chlorophyta

Table 7-1. Descriptions of Aquatic Sampling Stations in the Lower Rio Grande Basin Project Area, 12-16 July 1977

Station/Drainage Area	Location	Description	Substrate	Depth (meters)	Surface Salinity (ppt)
Raymondville Drain					
Station 1	Intersection with US 77	Channel adjacent to bridge; approximately 12 m wide	soft mud	1.0 1.0	4.8 4.8
2	Intersection with TX 186	Channel adjacent to bridge; approximately 12 m wide	soft mud	0.8 0.8	7.1 7.1
3	SE of Station 2	Shallow area, 200 m wide; turbid, virtually no emergent vegetation	silt and mud	0.2	7.9
4	Mouth of East Main Drain	Shallow area, 300 m wide; turbid, virtually no emergent vegetation	soft mud and silt	0.2	8.3
Existing Ditch in Project Area					
Station 5	Intersection with US 77 Approximately 6 km S of Raymondville and 300 m N of the Loop 56 Intersection with US 77	Pothole, 3 m wide Stagnant area near culvert opening on east side of US 77	deep soft mud	1.6	10.1
6	Intersection of FM 1420, approximately 0.8 km south of Willimar	Pool, 8 m wide, near culvert, on east side of FM 1420. Pronounced flow towards east	soft mud	1.5	3.7
7	Laguna Madre, at mouth of ditch in project area	Shallow flat	firm sand and mud bottom	0.2	21.1
8	Laguna Madre, approximately 1.6 km E-SE of ditch mouth	Shallow flat	firm sand and mud bottom	0.2	18.8
North Floodway:					
Station 9	Intersection of FM 1420	Steeply channelized canal, 16 m wide, with pronounced flow to east	very soft, deep mud	2.3	3.7
Isolated Falt:					
Station 10	Located between mouth of existing ditch and south of North Floodway, approximately 75 m from shore	Shallow embayment with no direct source of freshwater input	hard, shallow crust with underlying soft mud	0.2	62.0

(Continued)

Table 7-1. Descriptions of Aquatic Sampling Stations in the Lower Rio Grande Basin Project Area, 12-16 July 1977 (Cont'd.)

Station/Drainage Area	Location	Description	Substrate	Depth (meters)	Surface Salinity (ppt)
Laguna Madre near Project Area--W Side of Intercoastal Spoil Banks					
Station 11				0.8	28.5
12				0.6	21.0
13				0.5	34.0
14		Open areas with little aquatic vegetation at locations sampled although seagrass patches and red algal mats were observed		0.6	--
15			soft mud	0.9	34.0
16				0.3	33.0
28				0.1-0.5	--
Laguna Madre near Project Area--Intercoastal Canal					
Station 17	In Mid-channel Adjacent to Buoy 297	Open area	soft mud	3.0-4.0	36.1
18	In Mid-channel Adjacent to Buoy 299	Open area	soft mud	3.0-4.0	36.2
27	West Edge of Canal Adjacent to Buoy 301	Open area	soft mud	1.5-3.0	35.0
Laguna Madre near Project Area--On E side of Intercoastal Canal Spoil Banks					
Station 19	Approximately 0.5 km East of Buoy 297	Open area	firm mud	0.6-1.1	31.0
20	Approximately 0.5 km East-Northeast of Buoy 299	Open area	firm mud	0.7-1.1	35.9

(Continued)

Table 7-1. Descriptions of Aquatic Sampling Stations in the Lower Rio Grande Basin Project Area, 12-16 July 1977 (Cont'd.)

Station/Drainage Area	Location	Description	Substrate	Depth (meters)	Surface Salinity (ppt)
Arroyo Colorado Northern Branch Station 21	Approximately 4 km downstream from fork with Arroyo Colorado cutoff	Shallow area with negligible flow, approximately 25 m wide	mud and sand	0.30	--
22	Approximately 100 m southwest of Station 21, in mid-channel	Shallow area with negligible flow, approximately 30 m wide.	mud and sand	0.46	10.0
Arroyo Colorado Cutoff Station 23	12 m from north shore, approximately 200 m west of fork between northern branch and cutoff	Open area, approximately 50 m wide	soft mud and silt	3.5	14.0
24	Mid-channel near east end of Arroyo Hondo City and approximately 3 km east of Station 23	Open area, approximately 50 m wide	unknown	5.0	16.0
25	Mouth of Arroyo, Colorado cutoff	Turbid delta area	shell and gray-black silt	0.5	19.0
26	East side of Intracoastal Canal spoil banks, near mouth of Arroyo Colorado cutoff	Turbid; approximately 100 m from spoil banks	silt, sand and rooted vegetation	0.3	24.0

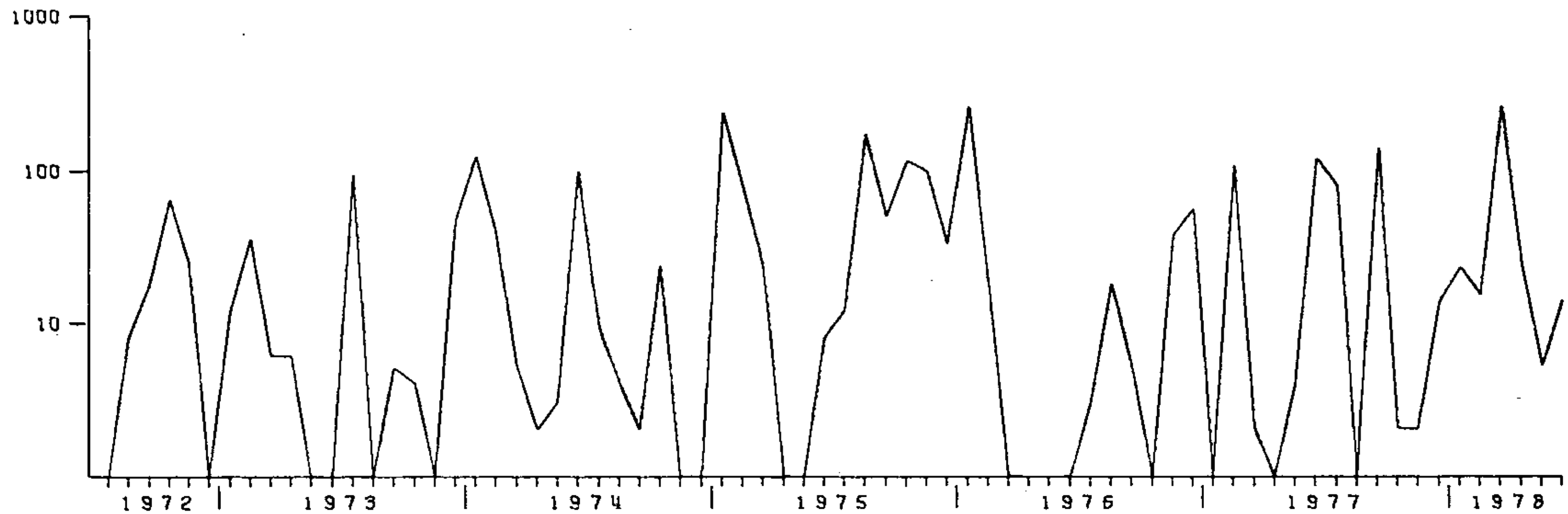


Figure 7-3. Dinoflagellate Densities (cells/liter) in the Upper Laguna Madre (23)

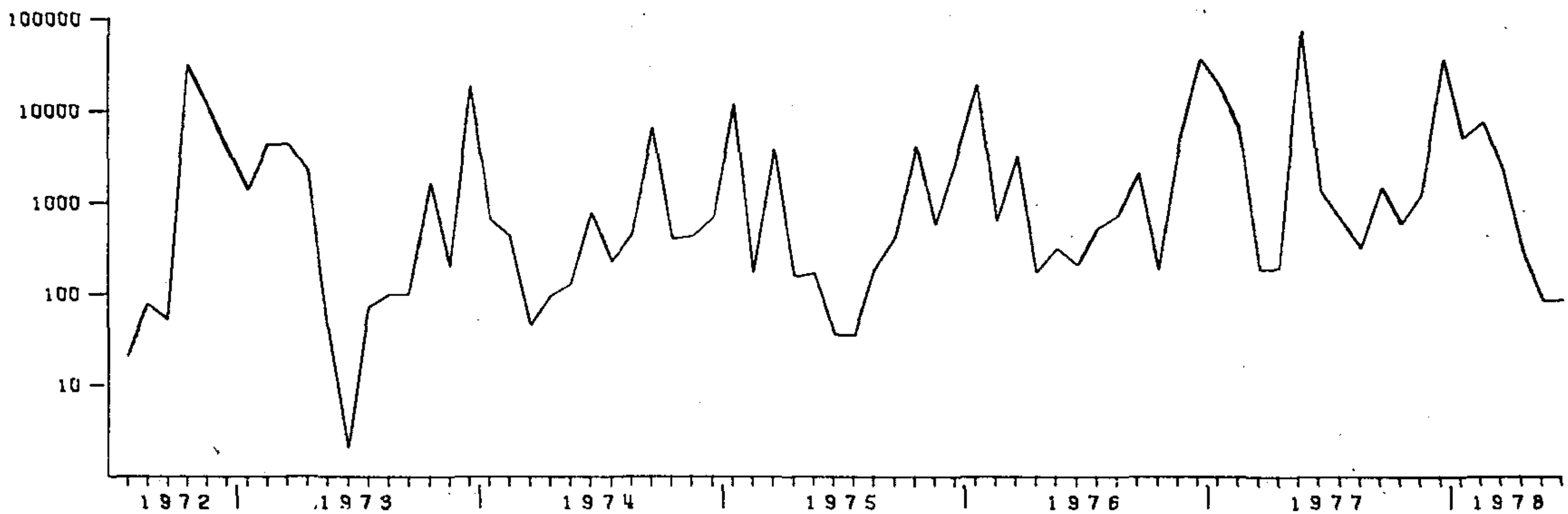


Figure 7-4. Diatom Densities (cells/liter) in Upper Laguna Madre (23)

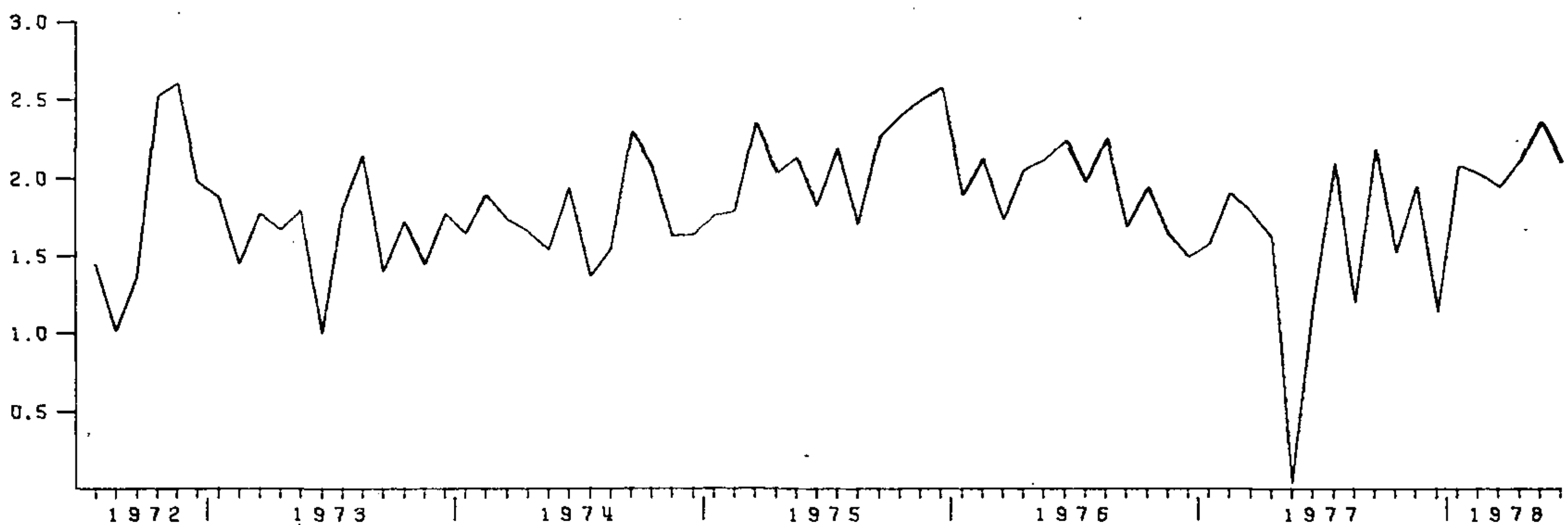


Figure 7-5. Average Species Diversities in Upper Laguna Madre (23)

(green algae) and Bacillariophyta (diatoma) were the most taxonomically abundant divisions, comprising approximately 70% of the species collected. The diatoms were the most numerically abundant group, comprising 90 percent of the total number of organisms collected; the euglenoids were least abundant, comprising less than 1 percent. A summary of phytoplankton occurrence is presented in Table 7-2.

In general, phytoplankton populations were greatest in the drainage systems and shallow inland bays where salinities ranged from 3.7 to 21.1 ppt. These areas were characterized by high densities of various freshwater and brackish diatom species, particularly Nitzschia palea, N. silicula, and N. triblionella. Although green and blue-green algae were also present, their densities were relatively low compared to the diatoms. The Arroyo Colorado was an exception to the pattern, with the diatom population being replaced by high numbers of various flagellated forms. These flagellate populations virtually disappeared, however, in the mixing zone at the mouth of the drainage (station 25).

In contrast, depauperate phytoplankton populations were discovered in the hypersaline bay area (station 10) and the open Laguna Madre where salinities exceeded 30 ppt. Densities in these areas ranged only from 23,000 to 181,000 cells/liter (stations 12, 18, 20, 25). At the mouth of the Arroyo Colorado, salinities of 19 ppt were accompanied by reduced phytoplankton populations typical of the open Laguna Madre areas. For comparison purposes, EH&A found phytoplankton densities of 171,000 cells/liter in Trinity Bay (58). Moseley et al. (24) state that phytoplankton densities of 730,000 cells/liter occurred in Cox Bay, while Espey, Huston and Associates (54) reported densities of 133,000 cells/liter in Sabine Lake. Standing crops in the Nueces and Mission-Aransas estuaries observed by Holland et al. (280) ranged from 55,000 cells/liter in Copano Bay to 790,000 cells/liter in Nueces Bay.

Phytoplankton abundance did not appear to correlate with levels of macronutrients nor available light (as determined by secchi disk visibility). In the drainage systems, the pond-like brackish environments created by low-flow conditions and the availability of nutrients facilitated great phytoplankton densities, despite the relatively high turbidities occurring in these areas. The open waters of the Laguna Madre, in contrast, produced sparse phytoplankton populations even though ample nutrient concentrations existed. This is perhaps due to the dominance of macrophyte production in this area as compared to phytoplankton. Odum and Hoskins (284) reported that phytoplankton production in upper Laguna Madre and Redfish Bay near Port Aransas, where seagrasses comprise a substantial portion of the aquatic community, may constitute as little as 5 percent of the overall primary production. This appears to be the case also in lower Laguna Madre.

Discussion

Estuarine plankton were divided by Perkins (184) into three components: (1) autochthonous populations, the permanent residents; (2) temporary autochthonous populations, introduced from an outside area by water movements (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 (unable to propagate and have a limited survival potential). Results indicate that the Laguna Madre system

Table 7-2. Summary of Phytoplankton Occurrence (no./ml) in the Lower Rio Grande Basin Project Area, 12-16 July 1977

Station	Salinity (ppt)	Greens	Euglenoids	Diatoms	Dinoflagellates	Blue-Greens	Others	Total Density	No. of Taxa	Diversity (H) a/
3	7.9	340	0	137,072	0	2,040	0	139,452	17	1.45
4	8.3	340	0	100,680	340	0	0	101,360	11	1.36
6	3.7	364	46	4,808	23	433	0	5,674	24	1.75
7	21.1	0	0	23,468	0	3,741	0	27,209	10	1.58
8	18.8	1,020	0	98,299	0	1,360	408	100,679	8	0.40
9	3.7	6,734	544	25,578	0	3,537	0	36,801	35	2.30
10	60.4	0	0	23	0	0	0	23	1	(0) b/
12 c/	33.0	0	0	23	0	0	0	23	1	(0)
12 d/	30.5	0	0	158	0	0	0	158	3	(1.08)
18 c/	35.0	0	0	23	0	0	0	23	1	(0)
18 d/	37.0	0	0	181	0	0	0	181	1	(0)
20 c/	35.5	0	0	68	0	0	0	68	2	(0.64)
20 d/	32.0	0	0	46	0	0	0	46	2	(1.34)
22	10.0	749	91	1,224	91	590	953	3,698	23	2.31
23	14.0	2,154	0	0	13,061	181	2,177	17,573	7	1.11
25	19.0	0	0	23	0	0	23	46	2	(0.69)

a/ Calculated as $-\sum_{i=1}^{n} P_i \ln P_i$

b/ Sample size with densities too low for adequate diversity determination

c/ Sample taken between 0100 and 0300 hours on 13 July 1977

d/ Sample taken between 1130 and 1200 hours on 13 July 1977 supports a phytoplankton population based on allochthonous or temporary autochthonous components due to the harsh, fluctuating environment.

Freshwater inflows may act to import freshwater phytoplankton species into the system. This input may be substantial as evidenced by the high phytoplankton densities in the drainage systems of lower Laguna Madre compared to the open water stations (55). Freshwater inflows function to lower salinities and to transport nutrients, detritus, and dissolved organic materials into the system. More nutrients and freshwater plankton may be imported to the system with increased flow rates, thereby increasing standing crops and primary production. However, very high flow rates (flood conditions), the effect of high turbidities, salinity changes, and flushing out of indigenous populations may actually depress phytoplankton abundance and productivity.

Phytoplankton species vary markedly in their ability to withstand changes in salinity. Accurate halobion classification of most species found in the Laguna Madre is impossible at the present, due to insufficient culture experimentation on salinity optima and tolerances. Chu (26) noted that although cell division can continue in freshwater for most estuarine species, most freshwater species cannot grow in salinities exceeding 2 ppt. Foerster (64) found, however, that many freshwater species can resume growth after exposure to seawater if placed in a freshwater medium.

Zooplankton

Upper Laguna Madre

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).

Hildebrand and King (23) found zooplankton populations in upper Laguna Madre were erratic throughout the six year study. Mean monthly densities showed tremendous variation--up to two orders of magnitude--over short periods of time. Densities ranged from an average of 27,000 organisms/month (1973-74) to 118,000 organisms/month (1975-76). In general, peak densities occurred during the spring months.

The zooplankton population in upper Laguna Madre was dominated by copepods. Approximately 70 copepod species were identified from collections in upper Laguna Madre and Oso Bay. Copepod populations were generally greatest during the fall and spring months of the year. Because of their dominance, the copepods are an important group to monitor, since their disappearance could greatly disturb the macroscopic consumers in the region. The calanoid copepod *Acartia tonsa* was the dominant species in the zooplankton community, comprising approximately 50 percent of the total organisms identified each year. Other major genera of calanoid copepods included *Pseudodiaptomus* and *Centropages*; populations of these zooplankters followed the same seasonal pattern as *Acartia tonsa*, with peaks in the fall and spring and a decline in winter. The cyclopoid copepods, commonly represented by Oithona and Saphirella, were only about one-tenth as abundant as the calanoid copepods.

The meroplankton, dominated by trochophore larvae, bivalve larvae, gastropod veligers, and barnacle nauplii, contributed heavily to springtime zooplankton peaks. The polychaetous annelids were also a consistent meroplanktonic group during the study and made a major contribution to the diversity of species. The barnacle nauplii, which formed a major component of the zooplankton community, were ubiquitous throughout the study; populations generally increased steadily to a springtime peak and then decreased through early summer.

The chaetognaths, represented by Sagitta spp., averaged less than 1 percent of the total number of zooplankton. These voracious carnivores, however, form an important link in the energy conversion of microzooplankton into food for fish.

Lower Laguna Madre

A total of 47 zooplankton species representing 12 phyla were collected from the Espey, Huston and Associates study (55) in lower Laguna Madre. The most taxonomically prominent phylum was Arthropoda which accounted for 40 percent of the organisms identified. Numerically, the rotifers accounted for almost half of the organisms collected. The freshwater zooplankton assemblages included such organisms as the cyclopoid copepods of the genus Cyclops and rotifers, including Asplancha and Brachionus. The brackish or estuarine species were commonly represented by the calanoid copepod Acartia or the cyclopoid copepod Oithona. Greatest densities were recorded in the isolated flat off the mouth of the North Floodway at station 10; lowest densities occurred in the open Laguna Madre waters (stations 12, 18, and 20) and the Arroyo Colorado Cutoff (station 25) (Table 7-3).

The drainage systems with the brackish, plankton-rich waters were dominated by moderate numbers of the rotifer Brachionus plicatilis. This rotifer species was also present in extremely high numbers from station 10. The open Laguna Madre areas exhibited low to moderate populations of foraminifera, barnacle nauplii, crab zoea, larval polychaetes, and immature copepods, with virtually no Brachionus plicatilis; moderate densities of adult copepods (e.g. Oithona plumifera, Saphirella sp., Macrosetella sp. and Acartia tonsa) were observed. The zooplankton populations collected in the mixing zone of the Arroyo Colorado Cutoff water with the open Laguna Madre were a mixture of both systems: (1) the euryhaline rotifer, Brachionus plicatilis, common in the brackish, inland drainage areas, was present in moderate densities; (2) densities of the foraminiferan Elphidium were similar to those of the open Laguna Madre; and (3) the copepod taxa found in Laguna Madre waters were conspicuously absent.

It is interesting to note that the copepod Acartia tonsa was not present in large numbers in lower Laguna Madre. This species was a dominant zooplankton form in the Sabine-Neches, Trinity-San Jacinto, Lavaca-Tres Palacios, Guadalupe, Nueces and Mission-Aransas estuaries, as shown in previous studies (338, 58, 54, 251, 256, 280).

Table 7-3. Summary of Zooplankton (no./l) Collected in the Lower Rio Grande Basin Project Area 12-16 July 1977

Station	Salinity (ppt)	Rotifers	Gastrotrichs	Copepods	Barnacles	Zoea	Tintinnids	Foraminiferans	Others	Total Density	No. of Taxa	Diversity (H) a/
3	7.9	180.0	0	1.9	0	0	0	5.6	1.9	189.4	6	0.767
4	8.3	45.0	0	57.4	0.8	0	0	2.5	6.6	111.5	10	1.502
6	3.7	501.2	1.3	76.4	0	0	0	0	0	578.8	7	0.624
7	21.1	190.0	110.0	390.0	0	0	0	0	1,000.0	1,690.0	9	1.695
8	18.8	800.0	537.5	150.0	12.5	0	62.5	0	12.5	1,575.0	9	1.319
9	3.7	474.9	0	5.0	0	0	0	0	2.4	482.3	11	0.546
10	60.4	6,896.5	5,316.1	1,449.3	287.4	0	299.9	0	0	14,249.2	8	1.171
12 b/	33.0	0	0	20.6	38.8	0	0.6	29.3	1.2	90.5	9	1.491
12 c/	30.5	0.2	0.2	23.3	0	0.5	0.2	1.5	0.2	26.1	12	1.719
18 b/	35.0	0	0	44.4	18.8	0.6	0	13.1	0.6	77.5	9	1.764
18 c/	37.0	0	0	23.8	14.5	0.5	0	0	25.2	64.0	12	1.733
20 b/	35.5	0.2	0	14.5	10.8	0	0.2	0	7.6	33.3	12	1.861
20 c/	32.0	0	0	28.0	17.5	1.0	0.5	7.5	2.0	56.6	12	2.045
22	10.0	113.0	0	1.0	1.0	0	1.0	5.0	3.0	124.0	8	0.447
23	14.0	24.0	0	1.0	0	0	0	0.2	0	25.8	5	1.023
25	19.0	26.5	1.0	16.5	0	0	1.0	11.0	3.0	59.0	11	1.497

a/ Calculated as $-\sum_{i=1}^{n} P_i \ln P_i$

b/ Sample taken between 0100 and 0300 hours on 13 July 1977

c/ Sample taken between 1130 and 1200 hours on 13 July 1977

Maximum and minimum densities in lower Laguna Madre were moderate to high compared to results mentioned from the above studies (Table 7-4).

Discussion

Many zooplankton species found in Laguna Madre are widely distributed along the coasts of the United States, while others may even have a worldwide distribution. For example, Green (72) reports that Acartia tonsa may be found in the Central Baltic Sea area; 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 Texas coast have produced similar results to the Laguna Madre study. As previously mentioned, the calanoid copepod Acartia tonsa was the dominant zooplankton in upper Laguna Madre. This agrees with other studies of Sabine Lake (58, 338), Lavaca Bay (256), San Antonio Bay (251), and the Nueces and Mission-Aransas estuaries (280).

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

Freshwater inflows can influence zooplankton in several ways. Estuarine zooplankton standing crop composition can be altered by importation of freshwater species. Inflows can also transport zooplankton food resources into the system in the form of phytoplankton and detritus. However, zooplankton communities may also be adversely affected by increased river inflows. Sudden shifts in salinity and flushing out of autochthonous populations can decrease zooplankton standing crops. Indeed, Perkins (184) reported that the primary factor influencing the composition and abundance of estuarine zooplankton is development rate versus flushing time. Saltwater intrusions, on the other hand, act to (1) import marine zooplankton into the system, (2) import marine phytoplankton as a food source, and (3) increase salinity.

Shifts in zooplankton composition and abundance resulting from altered freshwater inflows are an area of concern. Inadequate data on the seasonal patterns of zooplankton in the Laguna Madre, however, precludes any analysis. Previous studies (55) have indicated that periods of heavy freshwater inflows result in decreased zooplankton populations. Espey, Huston and Associates concluded that zooplankton populations in lower Laguna Madre drainage systems could be temporarily reduced due to the flushing effects and salinity drops occurring during flood conditions.

Marsh Vegetative Production

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

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

System	Minimum	Maximum
Sabine Lake (62)	381 (Apr. 1975)	20,042 (Oct. 1974)
Trinity Bay (74)	1,235 (Dec. 1975)	190,560 (Apr. 1976)
Lavaca Bay (272)	1,980 (Oct. 1973)	27,846 (Feb. 1974)
San Antonio Bay (271)	820 (Jun. 1973)	46,296 (Feb. 1973)
Nueces Bay (295)	832 (Oct. 1973)	8,027,855 (Feb. 1974)
Corpus Christi Bay (295)	1,722 (Dec. 1972)	53,657,037 (Mar. 1973)
Copano Bay (295)	1,296 (Sep. 1974)	53,536 (Feb. 1973)
Aransas Bay (295)	2,497 (Dec. 1972)	3,008,679 (Feb. 1974)
Lower Laguna Madre (55)	33,000 (Jul. 1977)	90,500 (Jul. 1977)

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 (173, 172). United States estuarine marshes of the Atlantic and Gulf coasts are no exception, since the inhabiting rooted vascular plants have adapted advantageously to the environment and are known to exhibit high biomass production (299, 403, 39, 192, 301, 294, 343, 14). As a result, the marshes are large-scale contributors to estuarine productivity, poviding a major source of particulate (detrital) substrate and nutrients to the microbial transformation processes at the base of the food-web which enrich the protein levels and food value for consuming organisms (44, 45, 215, 174, 409, 149, 148, 41, 185, 48, 125, 211, 96, 97, 103). Recent research has demonstrated a correlation between the area of salt marsh vegetation and the commercial harvests of penaeid shrimp (341). For Texas estuaries, the statistical relationship indicates at least 30.0 pounds of shrimp harvested (heads-off weight) per acre of intertidal marsh (33.6 kg/ha).

The area of salt marsh in Laguna Madre is severely restricted. Other than marsh associated with mangroves in the South Bay, the only marsh areas lie along the upper arms of Baffin Bay, inclusive of Alazan Bay, Cayo del Grullo, and Laguna Salado. This is chiefly a marginal fringe of plants associated with salt marsh production. No data has been found on the contribution of this marshy fringe to the bay's productivity, but since the salt marsh in other Texas estuaries is so important it should not be ignored.

Seagrass Productivity

Seagrass beds constitute a major biological feature of Laguna Madre and dominate the primary productivity. Recent reviews of the literature on seagrasses are found in Nessmith (171), Merkord (169), and McRoy and Helfferich (167). The seagrasses are submerged aquatic flowering plants common in many estuaries worldwide. Kikuchi and Peres (121) summarize the general importance of seagrass beds to the estuaries and coastal marine community. Briefly, the categories are (a) as a site for epiphytic algal productivity, (b) as a physical shelter for organisms from wave action and high light intensity, (c) as an aid to sedimentation of suspended particles, (d) for production (contributing oxygen to the water) and (e) as a food resource.

Through these mechanisms, seagrass beds, or meadows, are considered to be nurseries for fish and shellfish. Thus the distribution and productivity of these plants are important in evaluating the Laguna Madre ecosystem.

Table 7-5 lists the species of seagrasses important in Laguna Madre together with their salinity and temperature tolerances. Thallasia testudinum (turtle grass), has long wide blades. It is important throughout the Caribean and does best under strong marine influence -- as near the Brazos Santiago Pass in lower Laguna Madre. The other common species are smaller plants with narrower leaves. Ruppia maritima (widgeon grass) generally grows in the shallowest waters, Halodule wrightii appears in the upper intertidal zone, Thalassia prefers constant submersion, and Syringodium filifome (manatee grass) appears to require constant submersion (171).

Table 7-5. Salinity and Temperature Tolerances of Some Seagrass Species

Species	Salinity Tolerance (ppt)	Salinity Preference (ppt)	Temperature Tolerance
Thallasia testudinum	<60 (168) 10 - 50 (165)	20 - 35 (187) 28 - 32 (168)	7-32°C (187)
Ruppia maritima	0 - 30 (168)	<28 (168)	
Halophila engelmanni	13 - 50 (168)	<37 (168)	
Syringodium filiforme	3.5 - 40 (168) 10 - 50 (165)		
Halodule wrightii	10 - 60 (187) <72 (168)		7-32°C (187)

Upper Laguna Madre contains large beds of Halodule with associated Halophila engelmanii and Ruppia. In lower Laguna Madre Syringodium filiforme is most important, with increasing Thallassia near Port Isabel.

Seagrass meadows are one of the most productive systems in capturing the sun's energy and producing biomass. McRoy and McMillan (168) provide a recent review of data on the productivity of seagrass communities. Thallasia beds may fix an average of 9 g C/m^2/day and consist of a standing stock of 8 kg dry weight/m^2. Other species have smaller leaves but may attain 500 g dry weight/m^2 during optimal conditions. McRoy and McMillan estimate that subtropical Thallasia beds may yield an annual production of 1000 g C/m^2. Less data is available for other species represented in Texas bays. Production is highly seasonal, highest during June or July and almost nothing during the winter months. Seagrasses die back to their rhizomes in the fall or beginning during hot summer months. Combinations of high temperature and low salinity can also cause a die back of seagrass populations (187). Consumer species such as mullet and shrimp migrate into and out of the seagrass meadows in response to this cycle of productivity.

Seagrass productivity fuels the rest of the ecological system through three routes: (1) directly, (2) through seagrass detritus, and (3) through the epiphytes and epifauna growing on the leaves.

Relatively few species utilize the living seagrass leaves though pinfish have been observed to pluck them (171). Wintering ducks also use these seagrasses directly as food. Cornelius (35) estimated that 4 to 5 percent of the fall standing crop of Halodule in lower Laguna Madre was consumed by wintering Redhead ducks.

For the invertebrates and fish of the estuary, however, seagrass detritus is far more important than the living plants. Each year dead leaves break away from the plants to form huge mats, driven by winds onto the shore. Leaves also wash around in the water column, or are buried in sediments. Hildebrand and King (23) mention that the large mats of dead leaves accumulating in the fall are broken up and dispersed during the winter. The decomposition of this detritus provides the main fuel for the spring and summer productivity of Laguna Madre estuary. The dead seagrass represents a pool of nutrients released slowly during winter with low bacterial growth rates and released more rapidly as spring temperatures increase.

The contribution of the seagrass meadows to Laguna Madre lies not only in primary production, but also in the productivity of the epifauna and flora of seagrass leaves. Pulich (191) estimated that epiphyte growth in upper Laguna Madre could amount to 12 g/m^2 in a bed where seagrass leaves totaled 200 g/m^2. Much of the grazing of herbivores within these meadows is on the epiphytes and not on the grass tissue itself. The data of Fry and Parker (65) support this. Analysis of $^{13}C/^{14}C$ ratios in producers, consumers and predators strongly suggests that much of the carbon that finds its way up through the trophic chain originates in the seagrass beds, probably in the epiphytes.

Pulich (191) demonstrated that salinity and nutrients potentially limit the growth of epiphytes on seagrass. Epiphytic growth is less in the more saline upper Laguna Madre than in Corpus Christi Bay, for instance. Thus, factors which effect long term salinity change within Laguna Madre would influence also the food chain dependent on seagrass epiphytes.

Algal Mat Productivity

The large portion of Laguna Madre which is very shallow (less than 10 cm water). Periodically exposed sand and mud flats, primarily on the landward side, are sites for another community which contributes to productivity. The flats can be seasonally covered with a thin algal mat, 1-3 cm thick, composed mostly of the filamentous blue-green algae Lyngbya convervoides (13). Birke (13) describes the structure of this natural community and the functions of its elements. Briefly, the mat consists of an overlying photosynthetic zone, a heterotrophic mid-zone, and a bottom layer which grades into the sediment and where there are strong reducing potentials. In the water above the mat live aquatic insects, crustaceans, and fish (including silversides, pupfish, and the Gulf Killifish). Within and beneath the mat are found marine worms and amphipods. Small mussels, important in the diet of the black drum, may live beneath the mat.

The chlorophyll a content and productivity of the algal mat is very high. Sollins (209) found net productivity to be .55-.76g $O_2/m^2/d$. From the data of Sorensen and Conover a mat could have a weekly increase in biomass of 1.04 grams/gram of mat/week (g/grm mat/week) during warm months (1 grm mat = 4 cm^2). This would give a potential productivity of 5.2 kg/m^2/week. However, much of this productivity is not realized due to fluctuations in the environment; some is lost within the community to grazers and decomposition of lower layers, and some production may wash away.

Significant exportation of productivity from this community to other areas would be associated with wind events and winter breakup of the mats. This could mean significant output to the detrital pool.

Other input from this community to the Laguna system flows through the fish and benthos associated with this community. No information is available on amounts, but this could be significant for winter waterfowl and other bird species, as well as major commercial fish species.

Little direct information exists on the effects of inundation on this community or on the system as a whole through this community. The elements of the community have the capacity to withstand both highly saline and freshwater conditions; many can survive dry periods in dormant stages. Therefore, a rise in water level may transform a flaky crust on the mud surface into a highly productive community within hours. Flooding, or storm conditions, or high wind and rain, may act to transport materials from the flats to other portions of the estuary. This would greatly fuel the detrital based productivity, a vital segment in the food chain, and important in shrimp and black drum production.

Mangrove Productivity

In Laguna Madre the black mangrove occurs in scattered patches along Padre Island and in the South Bay region as a more extensive growth. Sherrod (206) discusses the present and past distribution of this mangrove (Avicennia germinalis) along the Texas Gulf Coast.

In Texas, black mangroves grow as woody shrubs which have been suggested as representing the tropical equivalent of saltmarsh vegetation (266). Mangroves stand in water so that their leaf fall contributes detritus to the system. Since mangroves are very productive, this leaf fall can amount to a substantial biomass input, fueling detrital food chains in the estuary. The pathways of this detrital energy input in the system are discussed by Odum and Heald (178).

The black mangrove can survive freshwater conditions indefinitely, but withstand hypersaline conditions (100-180 ppt) for only a few days (206). Thus it has been historically limited in its distribution within Laguna Madre by the hypersalinity associated with extended droughts.

Discussion

Table 7-6 summarizes the contribution of the major primary producers to Laguna Madre. Areal extent of some communities is based on environmental mapping from remote sensing data (266). Areal coverage of seagrass epiphytes is based on the assumption that all seagrass leaves have a similar cover of epiphytes in all areas. The areal coverage of plankton is taken as the area where depths exceed 4 ft; the areal coverage of algal mats is assumed to be the total area of very shallow or exposed sand and mud flats. These latter two areas are probably potential maximal areas.

From this table one can estimate the relative energy input from each of these natural communities to the Laguna Madre trophic system. The data can be converted to biomass productivity per square mile and multiplied by the areal coverage of each community. The productivity, in millions of kilograms carbon fixed per day over the entire Laguna Madre is the following, by group:

Phytoplankton	.048
Seagrasses	1.50
Algal mats	.94
Epiphytes	.18

These figures are only estimates, and would only apply during the season of favorable growth. The figures illustrate, however, the great relative importance of seagrass meadows in Laguna Madre. Combining seagrass and their epiphytic productivities, 63 percent of energy entering the ecosystem comes in through the seagrass community.

From year to year, and over longer periods, variation in environmental factors, particularly flood events and droughts, will alter the balance of contributions from these community types. Changes in other trophic levels in the biologic community would probably be associated with these variations in productivity.

Benthos

Upper Laguna Madre

Hildebrand and King (23) found that the polychetes were the most abundant and varied class in the bottom sediments of upper Laguna Madre. The

Table 7-6. Primary Productivity in the Laguna Madre Estuary

Species Group	Coverage Area (sq. mi.)	Biomass/Area	Productivity Rate
Phytoplankton	105 (266)	4.4 g dry-wt/m^3 a/	4.24 g C/m^2/day b/, e/
Seagrasses	129 c/ (169)	300 - 800 g dry-wt/m^2 (191) 6.2 - 570 g dry-wt/m^2 (169)	.9 - 9.0 g C/m^2/day (168)
Algal Mats	114 (266)	270 - 640 g/m^2 (13)	.27 - .38 g C/m^2/day e/ (13)
Mangroves	1.09 - 1.25 (206)	--	--
Epiphytes	129 d/	3.5 - 10.7 g dry-wt/m^2 (187)	200 g C/m^2/yr (187)

a/ Estimated using plankton counts (Table 7-2, Station 8), approximate biovolumes (183), and dry weight conversion (136)
b/ Baffin Bay only (293)
c/ Excluding sparce shoalgrass
d/ Assuming epiphytes cover same area as seagrasses
e/ Uses conversion factor from (136) to change units of production from g O_2 to g C

Capitellidae, Ampharetidae, and Spionidae were the dominant families in terms of numbers of individuals and species collected. The ampharetid Melinna maculata was the dominant polychaete.

Only two species of snails, Bittium varium and Cerithium variabile, were common; these gastropod species were confined to submerged meadows. Mulinia lateralis (dwarf surf clam) and Anomalocardia cuneimeris (paper clam) were the most abundant bivalves. Simmons (289) and Parker (182) both reported on the abundance of Mulinia lateralis in Laguna Madre. This species is apparently able to tolerate fluctuating environmental conditions, evidenced by the occurrence of large populations in both low salinity and hypersaline waters. This clam is often referred to as "drum shell" by commercial fishermen because of its importance in the diet of the black drum. Densities of Anomalocardia cunemeris, also eaten in large numbers by black drum, as high as 2000 organisms/ft^2 were reported by Parker (182). Hildebrand and King (23), however, did not locate any large beds and only on the large shell ridge at station L-8 was it considered common.

In general, the greatest numbers of species and individuals were collected in the winter and spring months. The polychaetes were the most varied group, followed by the molluscs. The grass flats had relatively few species but were nevertheless more diverse than any other shallow water community in the area. It is apparent that in the harsh, erratically fluctuating environment of Laguna Madre, where floods and droughts can eliminate entire populations of certain species, the strategy of survival is a very high reproductive rate. This is illustrated in the zooplankton section where large numbers of larvae of benthic animals in meroplankton were reported.

The Texas Department of Water Resources (332) has monitored benthic diversity at two stations in upper Laguna Madre, near the mouth of Baffin Bay and at Marker 59 in the Intracoastal Waterway (ICWW) between Padre Island and the mainland. Diversity values have generally been greater at the protected ICWW station even though water quality at the two stations is similar. It appears, therefore, that some other factor is exerting control over the benthic communities.

Lower Laguna Madre

Parker (182) found that a distinct physiographic and biological environment exists in Laguna Madre due to the high salinities, high summer water temperatures (30° - 35°C), and the minimal water exchange with either Corpus Christi Bay or the Gulf of Mexico. As a result, several researchers (350, 297, 287, 289, 182) have reported that the macro-invertebrate populations in lower Laguna Madre differ from the oyster shell and brackish-water organism-dominated assemblages found in less saline bays. In fact, lower Laguna Madre has been divided into two major areas on the basis of benthic fauna (182). The extreme southern end of Laguna Madre, subject to the influence of the Gulf of Mexico water exchange through Brazos Santiago Pass, exhibits fairly stable marine conditions. The diversity of species is great although the total number of individuals per species is small.

The area extending from the inlet northward to the land bridge is also characterized by fairly stable physical conditions. These conditions, however, are at the upper limit of tolerance for most species of marine invertebrates; species diversity is therefore sharply reduced but the number of individuals per species is high. Two characteristic pelecypods of this environment include Amygdalum papyria and Laevicardium mortoni. The distribution and composition of the benthic macroinvertebrate populations is apparently related to the abundance of marine vegetation in the area. Tables 7-7 and 7-8 exhibit the characteristic benthic species of each area (350).

Espey, Huston and Associates (55) found that the substrate composition was responsible for the distribution of the benthic communities in lower Laguna Madre (i.e., greater diversities occurred in areas with variable substrates). Diversities were also affected to an extent by nutrient availability. Organisms collected ranged from ubiquitous adults to juvenile forms inhabiting various salinity waters during life stages. Areas receiving increased freshwater inflows (i.e., Raymondville Drain, Existing Ditch, and Arroyo Colorado) generally exhibited increased diversities. The open waters of Laguna Madre were characterized by relatively constant diversities and a variety of organisms.

Discussion

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 (72).

Benthos diversity generally decreases with distance moved upstream in an estuary. From a minimum, at a salinity of 5.0 ppt, species numbers gradually increase seaward to a maximum about 35 ppt, the normal salinity of seawater, and decline once more with increasing salinity (101). This was found to be true in Lavaca and San Antonio Bays where benthic diversities declined from the high salinity lower bays to the low salinity upper bays and riverine areas. Diversities were highest during late winter and early spring when sustained freshwater inflows were low (251, 256). Espey, Huston and Associates (55) found that increased freshwater inflows in lower Laguna Madre, especially in the drainage systems, were accompanied by increased benthos diversities.

Harper (217) studied the distribution of benthic organisms in undredged control areas of San Antonio Bay and found an almost logarithmic decrease in benthic populations with increased salinity. Holland et al. (280) also found this to be true in Nueces Bay where an inverse relationship was discovered between salinity and standing crop. Gilmore et al. (256) reported that benthic populations in Lavaca Bay were not significantly related to freshwater inflows; significant relationships were discovered, however, with such hydrological parameters as bottom salinity, turbidity, total carbon, organic nitrogen and nitrate.

Table 7-7. Characteristic Mollusks of the Northern Portion of the Lower Laguna Madre (350)

Gastropods

Bittium varium (Pheiffer, 1840)
Harminoea succinea (Conrad, 1846)
Mitrella lunata (Say, 1826)
Truncatella pulchella (Pheiffer, 1839)

Pelecypods

Amygdalum papyria (Conrad, 1846)
Brachidontes citrinus (Roding, 1798)
Laevicardium mortoni (Conrad, 1830)
Macoma brevifrons (Say, 1834)
Mactra fragilis (Gmelin, 1790)
Pseudocyrena floridana (Conrad, 1846)
Tagelus divisus (Spengler, 1794)
Tellina tampaensis (Conrad, 1866)

Table 7-8. Characteristic Benthic Species of the Extreme End of the Lower Laguna Madre (350)

Gastropods

Anachis avara semiplicata (Stearns, 1873)
Bulla striata (Bruguiere, 1792)
Crepidula glauca convexa (Say, 1822)
Littorina nebulosa (Lamarck, 1822)
Nassarius vibex (Say, 1822)
Neritina virginea (Linne, 1758)
Turbonilla interrupta (Totten, 1835)

Pelecypods

Abra aequalis (Say, 1822)
Aequipecten irradians amplicostatus (Dall, 1898)
Anadara transversa (Say, 1822)
Anomia simplex (d'Orbigny, 1842)
Atrina seminuda (Lamarck, 1819)
Chione cancellata (Linne, 1767)
Cyrtopleura costata (Linne, 1758)
Macoma tenta (Say, 1834)
Ostrea equestris (Say, 1834)

Echinoderms

Lytechinus variegatus (Lamarck, 1816)
Ophiothrix angulatus (Say, 1825)

Crustaceans

Crangon heterochelis (Say)
Seopenope texana sayi (Stimpson)
Portunus gibbesi (Stimpson)

Summary

This chapter discusses the community composition, distribution. abundance, and seasonality of phytoplankton, zooplankton, aquatic macrophytes, and benthic invertebrates of Laguna Madre. The estuarine communities were typical in that they were composed of a mixture of endemic species (i.e., species restricted to the estuarine zone) and marine species plus several species with the osmoregulatory capabilities for penetrating from the freshwater environment.

Extreme fluctuations in salinity, in response to fluctuations in fresh and salt water inflows, are cited as a major factor in the low diversity of some groups of organisms in Laguna Madre (34). This has resulted in shorter food chains and a high rate of transfer of solar energy through these food chains to species of commercial importance (34). Variation in salinity also affects the productivity of Laguna Madre through (a) limitations of mangroves, (b) succession from one species of seagrass to another, (c) succession in types of phytoplankton and zooplankton species from euryhaline to marine forms, and (d) limitation on distributions of benthic algae and invertebrates.

Thus changes in the overall salinity regime of Laguna Madre would primarily result in a succession in species types among the various communities. This would change some aspects of the food webs present, though with changes occurring at so many places in the biologic framework it would be hard to predict overall effects of salinity changes on the productivity of the total system.

CHAPTER VIII

FISHERIES

Introduction

Virtually all (97.5 percent) of the coastal fisheries species are considered estuarine-dependent (86). 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 (354-358). Approximately 75 percent of the harvest was taken offshore in the Gulf of Mexico, and the remainder was taken inshore in the bays and estuaries. Computed on the basis of two general fisheries components, the finfish harvest distribution was approximately 28 percent offshore and 72 percent inshore, while the shellfish harvest was of an opposite distribution with about 21 percent inshore and 79 percent offshore. Specifically, the offshore harvests accounted for about six percent of the total Texas red drum (redfish) landings, 17 percent of spotted seatrout landings, 60 percent of white shrimp landings, and 95 percent of brown and pink shrimp landings.

With respect to the 1972 through 1976 commercial Texas bay (inshore) landings, Baffin Bay and the upper Laguna Madre area contributed an average 21.4 percent of finfish landings and 0.6 percent of shellfish landings, while the central and lower Laguna Madre contributed an average 30.5 percent of finfish landings and 0.4 percent of shellfish landings. Thus, the combined inshore areas of the Laguna Madre estuary have contributed over half (51.9 percent) of the finfish landings and about one percent of the shellfish landings in Texas bays. By comparison, the largest Texas estuary, the Trinity-San Jacinto estuary, contributed an average 11.0 percent of commercial finfish landings and nearly half (45.4 percent) of commercial shellfish landings from Texas bays during the same period (225).

Based on the five year inshore-offshore commercial landings distribution, the average contribution of the Laguna Madre estuary to total Texas commercial landings is estimated at 3,910,200 pounds (1,773,600 kg) of fish and 874,100 pounds (396,500 kg) of shellfish annually. In addition, the commercial fish harvest is estimated to account for approximately 60.4 percent of the total fish harvest in the estuary, with the remainder (39.6 percent) going to the sport or recreational catch (258, 259). Thus, an additional 2,563,600 pounds (1,162,800 kg) of sport catch can be computed which raises the estimated average annual fish harvest contribution from the estuary (both inshore and offshore) to 6,473,800 pounds (2,936,500 kg). The average harvest contribution of all fisheries species (fish and shellfish) dependent on the estuary is therefore estimated at 7,347,900 pounds (3,333,000 kg) annually.

Previous research has described the general ecology, utilization, and management of the coastal fisheries (316, 264, 162, 161, 80, 201, 197), and has provided information on Texas tidal waters (296, 302, 359, 186) and the relationship of freshwater inflow to estuarine productivity (385). The Laguna Madre of Texas and Mexico (Tamaulipas) is one of three oceanic, hypersaline (salinity > 45 ppt), lagoon areas in the world (322). Prior studies relevant to this system include extensive historical and ecological surveys (102, 287, 289, 106, 288, 246, 34, 31, 56, 191), research on fish ecology and the area fisheries (5, 117, 60, 381, 291, 322, 337, 66, 250, 242, 258, 259, 252, 253, 248, 254, 247, 50), shrimp and other invertebrates (297, 182, 295, 298, 85, 245), seagrass beds and other vegetation (46, 116, 275, 28, 163, 416, 169), community metabolism (284, 286, 293, 33), water quality (224, 321, 327, 331, 332, 230), and sediments and shorelines (198, 6, 160, 268, 418). It is of interest to note that Hellier (291) estimated the maximum summer biomass of fish and macroinvertebrates (e.g., shrimp and crabs) at 337 pounds per acre (37.8 g/m^2) and the minimum winter biomass at 18 pounds per acre (2.0 g/m^2) in an ecologically homogeneous 27,000 acre (109 km^2) study area in upper Laguna Madre dominated by seagrass beds and their rich biotic communities. Indeed, seagrass communities are among the most favorable habitats known for many of the fish species, supplying both food and cover to a myriad of inhabiting organisms (310, 411, 2, 4, 3, 52, 17, 121, 61, 187). Thus, it is not surprising that Hellier measured the annual net growth rate of four dominant fishes at 57 percent and conservatively estimated the total annual fish production at 137 pounds per acre (15.4 g/m^2). It was also reported that photosynthesis (the primary production of food) peaked annually in the spring and that the migration and growth of the fish stocks was generally in phase (i.e., seasonally coincident) with photosynthesis (291, 293). Similarly, Dokken (50) found that larval and postlarval fishes had their greatest diversity and abundance in Alazan bay (associated with upper Laguna Madre) during the spring (April-June), which was the only season when the sciaenids (croakers, drums, and seatrouts) were collected in substantial numbers. Therefore, while information does exist on seasonal ecology of Laguna Madre, multivariate equational models of fisheries production from several important species, as a function of the effects of seasonal freshwater inflows, have not been previously constructed for this estuary.

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 (126) 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 (42). 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 (126).

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 (105, 89, 88, 340, 213, 212). 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 (361-367, 351-358) which report inshore harvests from the various bays and offshore harvests from the Gulf of Mexico. Since the offshore harvests represent collective fisheries production from the region's estuaries, it is the inshore harvests reported by estuarine area that provide fisheries data related to a particular estuary. In addition, the shrimp fishery is partitioned into shrimp fishing grid zones in the Gulf Coast Shrimp Data publications (368-377, 389-396), which report the quantity and value of the commercial catch by species and the effort (number of fishing trips) in each area of capture at each trawling depth. Although it has been suggested that penaeid shrimp may not be produced in large numbers in the estuarine areas south of Nueces estuary (85), Gunter (312) was among the first to show that the shrimp go south on the Texas coast during the fall and winter, eventually drifting into Mexican waters, with some returning north the following spring and summer as the seasonal regime of the Gulf's thermal gradient geographically expands and contracts over the annual cycle. Harvest data from the inshore (bay) and offshore (Gulf) areas may therefore be useful in analyzing the relationships between seasonal freshwater inflows and the region's penaeid shrimp stocks.

Commercial inshore landings of several important fisheries components are tabulated for fishing areas in Baffin bay and upper Laguna Madre (Table 8-1), and those in the central and lower Laguna Madre, including South Bay (Table 8-2). In addition, the commercial harvests and fishing effort for penaeid shrimp are tabulated for the inshore areas of upper Laguna Madre and the offshore area (Gulf Area No. 21, an area extending approximately 30 miles offshore and bounded by latitudes 26°N, 27°N, longitude 96°30'W, and Padre Island) associated with lower Laguna Madre (Table 8-3). By using harvest data after the 1950's, 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 late 1950's, and since earlier harvest records are inconsistent, the shrimp analysis utilizes the more reliable records available from 1959 to 1976. This 18-year interval includes both wet and dry climate cycles and is sufficient in length to identify positive and negative fisheries responses to seasonal inflow, as well as quantify the seasonal freshwater inflow needs of the fisheries components. Analysis of the inshore landings of fish, crabs and oysters covers the 15-year interval from 1962 to 1976 because the State's statistical data collection program for these marine products was not improved until the early 1960's, and complete field coverage was not available until the mid-1960's (265).

The finfish component of the fisheries harvest is specific for the combined harvests of croaker (mostly Micropogonias undulatus Linnaeus), black drum (Pogonias cromis Linnaeus), red drum or redfish (Sciaenops ocellatus Linnaeus), flounders (Paralichthys spp.; mostly P. lethostigma Jordan and Gilbert), sea catfish (Arius felis Linnaeus), spotted seatrout (Cynoscion nebulosus Cuvier), and sheepshead (Archosargus probatocephalus Walbaum). Similarly, the shellfish component refers to the blue crab (Callinectes sapidus Rathbun), American oyster (Crassostrea virginica Gmelin), white shrimp (Penaeus setiferus Linnaeus), and brown and pink shrimp (Penaeus aztecus Ives and P. duorarum Burkenroad; mostly P. aztecus). Other fisheries components are given as a single species or species group of interest.

Freshwater inflow to the estuary is discussed in Chapter IV and is tabulated here on the basis of three analytical categories: (1) freshwater inflow to Baffin Bay and upper Laguna Madre (Table 8-4), (2) freshwater inflow to

Table 8-1. Commercial Fisheries Harvests in Baffin Bay and Upper Laguna Madre a/, 1962-1976 (361-367, 351-358)

Year	Commercial Fisheries Harvests (thousands of pounds)							
	Shellfish b/	White Shrimp	Brown & Pink Shrimp	Blue Crab	Finfish c/	Spotted Seatrout	Red Drum	Black Drum
1962	11.3	11.3	-	-	462.9	121.0	152.0	181.8
1963	-	-	-	-	631.6	123.3	128.2	373.1
1964	2.8	-	2.8	-	540.8	134.4	52.8	351.3
1965	-	-	-	-	579.9	95.7	70.8	369.4
1966	-	-	-	-	500.3	70.2	87.2	302.2
1967	-	-	-	-	849.4	215.0	185.3	413.5
1968	200.3	41.3	34.9	124.1	650.6	227.6	167.6	227.3
1969	556.6	1.5	26.6	528.5	721.8	193.4	254.3	254.8
1970	4.7	-	-	4.7	980.2	225.8	393.1	336.1
1971	0.2	-	-	0.2	1,530.0	377.5	545.4	547.9
1972	4.1	-	-	4.1	1,073.6	272.9	244.3	493.5
1973	449.2	45.5	402.8	1.0	842.4	209.2	238.2	356.3
1974	2.0	-	-	2.0	1,326.6	331.5	398.7	498.0
1975	66.6	0.9	56.8	8.9	1,197.7	393.1	416.9	310.1
1976	61.1	14.5	45.8	0.8	1,325.3	304.4	321.7	612.2
Mean d/	123.5	19.2	95.0	74.9	880.9	219.7	243.8	375.2
± S.E.	±59.7	±8.0	±62.0	±58.3	±88.2	±26.0	±37.5	±31.0
(N) e/	(11)	(6)	(6)	(9)	(15)	(15)	(15)	(15)

a/ area ranks second in finfish and seventh in shellfish commercial harvests of the eight major Texas estuarine areas
b/ multi-species fisheries component includes blue crab, and white, brown, and pink shrimp harvests; no bay oyster harvests reported
c/ multi-species fisheries component includes croaker, black drum, red drum, flounder, sea catfish, spotted seatrout, and sheepshead harvests
d/ Standard error of mean; two standard errors provide approximately 95 percent confidence limits about the mean
e/ N = number of observations (years)

Table 8-2. Commercial Fisheries Harvests in Central and Lower Laguna Madre a/, 1962-1976 (361-367, 351-358)

Year	Commercial Fisheries Harvests (thousands of pounds)						
	Shellfish b/	Blue Crab	Bay Oyster	Finfish c/	Spotted Seatrout	Red Drum	Black Drum
1962	15.7	-	15.7	1,277.3	185.9	273.8	803.2
1963	16.5	-	16.5	1,130.4	282.7	336.4	503.8
1964	14.2	-	14.2	1,286.6	319.9	231.6	673.4
1965	5.6	-	5.6	1,478.8	357.3	250.2	790.8
1966	2.0	-	2.0	1,202.2	428.4	313.8	421.5
1967	2.1	-	2.1	782.7	270.1	264.4	210.8
1968	2.6	-	2.6	1,161.7	486.0	417.3	195.3
1969	1.1	-	1.1	965.9	353.0	428.4	144.6
1970	3.0	-	3.0	986.9	233.8	593.6	127.8
1971	3.0	-	3.0	1,370.1	316.5	773.3	226.0
1972	1.2	-	1.2	1,272.1	347.3	594.0	280.5
1973	12.1	11.6	0.5	1,378.8	390.9	695.8	252.4
1974	16.0	12.7	3.3	1,564.9	492.8	668.0	320.0
1975	10.6	3.5	7.1	1,693.5	457.4	828.1	317.5
1976	303.6	299.0	4.6	2,288.6	504.1	729.9	932.6
Mean	27.3	81.7	5.5	1,322.7	361.7	493.2	413.3
± S.E. d/	±19.8	±72.5	±1.4	±91.9	±25.2	±54.9	±68.3
(N) e/	(15)	(4)	(15)	(15)	(15)	(15)	(15)

a/ area ranks first in finfish and eighth in shellfish commercial harvests of the eight major Texas estuarine areas

b/ multi-species fisheries component includes blue crab and bay oyster harvests; no white, brown, or pink shrimp harvests reported

c/ multi-species fisheries component includes croaker, black drum, red drum, flounder, sea catfish, spotted seatrout, and sheepshead harvests

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

e/ N = number of observations (years)

Table 8-3. Commercial Penaeid Shrimp Harvests in Laguna Madre a/ and Offshore Gulf Area No. 21 b/, 1959-1976 (368-377, 389-396)

Year	White Shrimp c/				Brown and Pink Shrimp d/				All Penaeid Shrimp e/			
	Baffin Bay and Upper Laguna Madre		Gulf Area No. 21		Baffin Bay and Upper Laguna Madre		Gulf Area No. 21		Baffin Bay and Upper Laguna Madre		Gulf Area No. 21	
	Harvest f/	Effort g/	Harvest	Effort	Harvest	Effort	Harvest	Effort	Harvest	Effort	Harvest	Effort
1959	-	-	20.3	2,730.6	12.7	2.0	8,891.3	3,301.4	12.7	2.0	8,911.9	3,301.4
1960	0.6	2.0	58.4	2,673.9	-	-	6,003.8	3,400.7	0.6	2.0	6,062.4	3,400.7
1961	0.1	1.0	180.5	1,849.3	-	-	4,498.1	2,508.9	0.1	1.0	4,680.4	2,508.9
1962	11.3	84.0	61.1	1,063.5	-	-	3,084.8	1,870.3	11.3	84.0	3,146.1	1,870.3
1963	-	-	9.3	977.1	-	-	6,253.3	2,388.9	-	-	6,263.0	2,388.9
1964	-	-	60.5	931.1	2.8	6.0	3,794.1	1,912.2	2.8	6.0	3,855.0	1,912.2
1965	0.7	2.0	32.5	889.1	-	-	5,611.9	2,485.1	0.7	2.0	5,645.9	2,485.1
1966	-	-	12.6	1,652.9	-	-	7,063.8	2,960.7	-	-	7,076.4	2,960.7
1967	-	-	212.5	1,763.9	0.2	1.0	15,364.9	4,488.1	0.2	1.0	15,580.2	4,488.1
1968	41.3	280.0	405.5	2,332.6	34.9	200.0	9,874.5	4,402.2	76.2	280.0	10,288.7	4,402.2
1969	1.5	178.0	460.9	3,396.3	26.6	187.0	10,528.4	5,295.6	28.1	187.0	10,990.6	5,295.6
1970	-	-	396.3	2,882.9	-	-	11,715.8	4,021.5	-	-	12,112.7	4,021.5
1971	2.5	45.0	275.7	2,562.9	1.6	45.0	6,912.5	3,890.5	4.1	45.0	7,188.3	3,890.5
1972	12.2	125.0	203.3	1,781.5	1.6	125.0	7,640.6	3,581.9	13.8	125.0	7,849.0	3,581.9
1973	45.4	2,253.0	389.6	3,289.1	402.8	2,253.0	11,260.3	5,071.1	448.2	2,253.0	11,651.8	5,071.1
1974	-	-	238.3	1,062.1	-	-	8,859.5	3,515.3	-	-	9,098.2	3,515.3
1975	0.9	6.6	122.8	1,173.1	56.8	6.6	10,007.1	2,612.1	57.7	6.6	10,130.2	2,612.1
1976	14.5	369.0	66.0	1,825.5	56.0	369.0	9,897.8	3,448.2	70.5	369.0	9,970.3	3,448.2
Mean	11.9	304.1	178.1	1,935.4	59.6	319.5	8,181.3	3,397.5	51.9	240.3	8,361.2	3,397.5
± S.E. h/	±5.0	±198.4	±36.1	±197.0	±38.8	±218.2	±737.0	±237.6	±31.3	±158.0	±757.6	±237.6
(N) i/	(11)	(11)	(18)	(18)	(10)	(10)	(18)	(18)	(14)	(14)	(18)	(18)

a/ harvest in upper Laguna Madre areas only; no harvest reported in lower Laguna Madre areas
b/ shrimp fishing grid Area No. 21 directly offshore of lower Laguna Madre
c/ white shrimp harvest and fishing effort at depths ≤ 20 fathoms
d/ brown and pink shrimp harvest and fishing effort at all depths recorded
e/ white, brown, and pink shrimp harvest and fishing effort at all depths recorded
f/ whole shrimp harvest weight in thousands of pounds estimated by tail weight X 1.54 (white shrimp), X 1.61 (brown shrimp), and X 1.60 (pink shrimp)
g/ effort in number of fishing trips by shrimp vessels
h/ Standard error of mean; two standard errors provide approximately 95 percent confidence limits about the mean
i/ N = number of observations (years)

Table 8-4. Seasonal Volumes of Freshwater Inflow Contributed to Baffin Bay and Upper Laguna Madre, 1959-1976

Year	Seasonal Freshwater Inflow (thousands of acre-feet)				
	Winter Jan.-March	Spring April-June	Summer July-Aug.	Autumn Sept.-Oct.	Late Fall Nov.-Dec.
1959	7.0	12.0	5.0	8.0	0.0
1960	0.0	5.0	0.0	152.0	220.0
1961	47.0	2.0	10.0	14.0 a/	0.0
1962	0.0	4.0	0.0	0.0	1.0
1963	0.0	0.0	0.0	0.0 b/	0.0
1964	0.0	0.0	0.0	0.0	0.0
1965	2.0	37.0	0.0	6.0	0.0
1966	0.0	114.0	0.0	0.0	0.0
1967	0.0	0.0	2.0	815.0 c/	1.0
1968	1.0	79.0	15.0	1.0	0.0
1969	1.0	1.0	3.0	1.0	1.0
1970	0.0	39.0	28.0 d/	7.0	0.0
1971	0.0	0.0	27.0	418.0 e/	2.0
1972	65.0	73.0	12.0	3.0	0.0
1973	0.0	105.0	3.0	450.0 f/	0.0
1974	32.0	10.0	5.0	1.0	0.0
1975	2.0	51.0	10.0	34.0	0.0
1976	0.0	84.0	182.0	70.0	30.0
Mean	8.7	34.2	16.9	110.0	14.2
± S.E. g/	±4.5	±9.5	±9.9	±52.8	±12.2

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

lower Laguna Madre (Table 8-5), and (3) combined freshwater inflow to the Laguna Madre estuary from all contributing river and coastal drainage basins (Table 8-6). 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 structual model can be constructed that represents the full spectrum of natural relationships. As a result, an alternative analytical procedure must be used which provides a functional model; that is, a procedure which permits estimation of harvest as a unique function of inflow. In this case, the aim is a mathematical description of relations among the variables as historically observed. Statistical regression procedures are most common and generally involve empirically fitting curves by a mathematical least squares criterion to an observed set of data, such as inflow and harvest records. Although functional model relationships do not necessarily have unambiguous, biologically interpretable meaning, they are useful when they adequately describe the relations among natural phenomena. Even after sufficient scientific knowledge is acquired to construct a preferable structural model, it may not actually be a markedly better predictor than a functional model. Thus, scientists often employ functional models to describe natural phenomena while recognizing that the relational equations may not or do not represent the true and as yet unclear workings of nature.

A time-series analysis of the fisheries components from the Laguna Madre estuary was performed utilizing the University of California biomedical (BMD) computer program for the stepwise multiple regression procedure (20). This statistical procedure computes a sequence of multiple linear regression equations in a stepwise manner. At each step, the next variable which makes the greatest reduction in the sum of squares error term is added to the equation. Consequently, the best significant equation is developed as the equation of highest multiple correlation coefficient (r), greatest statistical significance (F value), and lowest error sum of squares. A typical form of the harvest regression equation can be given as follows:

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

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

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

E_t = annual fishing effort of shrimp fishery in number of fishing trips at time 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 8-7);

Table 8-5. Seasonal Volumes of Freshwater Inflow Contributed to Lower Laguna Madre, 1959-1976

Year	Seasonal Freshwater Inflow (thousands of acre-feet)				
	Winter Jan.-March	Spring April-June	Summer July-Aug.	Autumn Sept.-Oct.	Late Fall Nov.-Dec.
1959	78.0	238.0	33.0	55.0	45.0
1960	36.0	69.0	83.0	262.0	69.0
1961	29.0	119.0	36.0	305.0 a/	29.0
1962	20.0	59.0	33.0	34.0	35.0
1963	36.0	50.0	39.0	119.0 b/	161.0
1964	61.0	93.0	32.0	36.0	27.0
1965	42.0	42.0	32.0	52.0	87.0
1966	96.0	349.0	113.0	62.0	30.0
1967	54.0	61.0	43.0	1,410.0 c/	149.0
1968	133.0	210.0	53.0	95.0	29.0
1969	65.0	82.0	33.0	53.0	29.0
1970	54.0	157.0	38.0 d/	175.0	33.0
1971	53.0	65.0	29.0	549.0 e/	62.0
1972	92.0	240.0	48.0	54.0	32.0
1973	200.0	171.0	138.0	209.0 f/	56.0
1974	81.0	94.0	50.0	211.0	60.0
1975	75.0	93.0	140.0	336.0	46.0
1976	69.0	199.0	387.0	263.0	176.0
Mean	70.8	132.8	75.6	237.8	64.2
± S.E. g/	±10.0	±20.1	±20.2	±76.2	±11.4

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 8-6. Seasonal Volumes of Combined Freshwater Inflow a/ Contributed to Laguna Madre Estuary, 1959-1976

Year	Seasonal Freshwater Inflow (thousands of acre-feet)				
	Winter Jan.-March	Spring April-June	Summer July-Aug.	Autumn Sept.-Oct.	Late Fall Nov.-Dec.
1959	85.0	250.0	38.0	63.0	45.0
1960	36.0	74.0	83.0	414.0	289.0
1961	76.0	121.0	46.0	319.0 b/	29.0
1962	20.0	63.0	33.0	34.0	36.0
1963	36.0	50.0	39.0	119.0 c/	161.0
1964	61.0	93.0	35.0	36.0	27.0
1965	44.0	79.0	32.0	58.0	87.0
1966	96.0	463.0	113.0	62.0	30.0
1967	54.0	61.0	45.0	2,225.0 d/	150.0
1968	134.0	289.0	68.0	96.0	29.0
1969	66.0	83.0	36.0	54.0	30.0
1970	54.0	196.0	66.0 e/	182.0	33.0
1971	53.0	65.0	56.0	967.0 f/	64.0
1972	157.0	313.0	60.0	57.0	32.0
1973	200.0	276.0	141.0	659.0 g/	56.0
1974	113.0	104.0	55.0	212.0	60.0
1975	77.0	144.0	150.0	370.0	46.0
1976	69.0	283.0	569.0	333.0	206.0
Mean	79.5	167.1	92.5	347.8	78.3
± S.E. h/	±10.9	±27.9	±29.3	±125.1	±17.5

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 errors provide approximately 95 percent confidence limits about the mean

Table 8-7. Time Series Alignments of Dependent/Independent Data Variates for Fisheries Regression Analysis

H_t Fisheries Component	Q_1 (Jan.-Mar.)	Q_2 (April-June)	Q_3 (July-Aug.)	Q_4 (Sept.-Oct.)	Q_5 (Nov.-Dec.)
Shellfish a/ (Inshore, 1962-1976)	t-0 c/ (1962-1976)	t-0 (1962-1976)	t-0 (1962-1976)	t-0 (1962-1976)	t-1 (1961-1975)
All Penaeid Shrimp White Shrimp Brown & Pink Shrimp (Inshore & Offshore, 1959-1976)	t-0 (1959-1976)	t-0 (1959-1976)	t-0 (1959-1976)	t-0 (1959-1976)	t-1 (1958-1975)
Blue Crab Bay Oyster (Inshore, 1962-1976)	t-1 d/ (1961-1975)	t-1 (1961-1975)	t-1 (1961-1975)	t-1 (1961-1975)	t-1 (1961-1975)
Finfish b/ Spotted Seatrout Red Drum Black Drum (Inshore, 1962-1976)	$\frac{\sum_{b=1}^{3}(t-b)}{3}$ e/ (1959-1975)	$\frac{\sum_{b=1}^{3}(t-b)}{3}$ (1959-1975)	$\frac{\sum_{b=1}^{3}(t-b)}{3}$ (1959-1975)	$\frac{\sum_{b=1}^{3}(t-b)}{3}$ (1959-1975)	$\frac{\sum_{b=1}^{3}(t-b)}{3}$ (1959-1975)

a/ Multi-species component includes blue crab, bay oyster, and white, brown and pink shrimp

b/ Multi-species component includes croaker, black drum, red drum, flounder, sea catfish, spotted seatrout, and sheepshead

c/ Inflow same year as harvest

d/ Inflow 1-year antecedent to harvest

e/ Running average inflow from three antecedent years before harvest

$Q_{2,t-b_2}$ = 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 8-7);

$Q_{3,t-b_3}$ = 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 8-7);

$Q_{4,t-b_4}$ = 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 8-7);

$Q_{5,t-b_5}$ = 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 8-7).

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:

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

where the variables are the same as defined above.

In practice, the time series for the dependent harvest variable (H) is the aforementioned inclusive period 1962 through 1976 for the fish, crab and oyster components, and 1959 through 1976 for the shrimp fishery components. These intervals provide 15 and 18 annual harvest observations, respectively. For the multiple regression analyses, the independent variables (e.g., $Q_1 \ldots Q_5$) contain a number of observations equal to their associated dependent harvest variable; however, the time series is not necessarily concomitant with that of harvest and varys because of consideration of species life history aspects involved in the analysis of each different fisheries component. Depending upon the specific fisheries component being analyzed, the time factor (t-b) of the independent variables can be the same year as harvest (t-0), one-year antecedent to harvest (t-1), or a running average of three antecedent years before harvest

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

Thus, the data alignment between dependent/independent variates in the fisheries analysis is appropriately chosen to take into account the probable lagged effect, in time, of freshwater inflow upon production and subsequent harvest of a particular fisheries component (Table 8-7). 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 (76, 158). Early articulation of this idea was put forth by the Norwegian fishery scientist Johan Hjort in 1914 (108) 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 the 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 (195). Based on the equations alone, definite statements about the true ecological relationships among the variables cannot be made because of the inherent non-causal nature of statistical regression and correlation (76, 194). 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 only one significant regression equation (Table 8-8). 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 shellfish equation explains about 90 percent of the observed harvest variation in lower Laguna Madre and is very highly significant ($\alpha = 0.1\%$) for correlation of the harvests to winter (Q_1) and summer (Q_3) season freshwater inflow to lower Laguna Madre (FINLL).

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 equation and plotting the results permits illustration of the effects of individual seasonal inflows on the estimate of harvest from lower Laguna Madre (Figure 8-1). For example, Panel A of Figure 8-1 shows the estimate of annual harvest declining to zero as inflow during the January-March (Q_1) seasonal interval increases from its observed lower bounds of 6.7 thousand acre-feet per month to its observed upper bounds of 66.7 thousand acre-feet per month. Thus, the negative (-) sign on the regression coefficient (a_1) for the correlating Q_1 inflow term is illustrated as a line of negative slope relating increasing winter season inflow to a decreasing 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_3) in the equation at specified levels of interest other than its observed mean value. For instance, if the positively correlating July-August (Q_3) inflow is specified at some level higher than its mean of 40.3 thousand acre-feet per month, then the estimated harvest response to

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

Upper Laguna Madre Shellfish Harvest = f (seasonal FINUL b/)
(no significant equation)

Lower Laguna Madre Shellfish Harvest = f (seasonal FINLL c/)
Very Highly Significant Equation ($\alpha = 0.1\%$, $r^2 = 90\%$, S.E. Est. = $\pm$ 25.9)

$$H_{sf} = -1.00 - \underset{(0.49)}{1.45}\,(Q_1) + \underset{(0.15)}{1.61}\,(Q_3)$$

	H_{sf}	Q_1	Q_3
upper bounds	303.6	66.7	195.5
lower bounds	1.1	6.7	14.5
mean	27.3	25.1	40.3

Laguna Madre Estuary Shellfish Harvest = f (seasonal $FINC_{lm}$ d/)
(no significant equation)

---

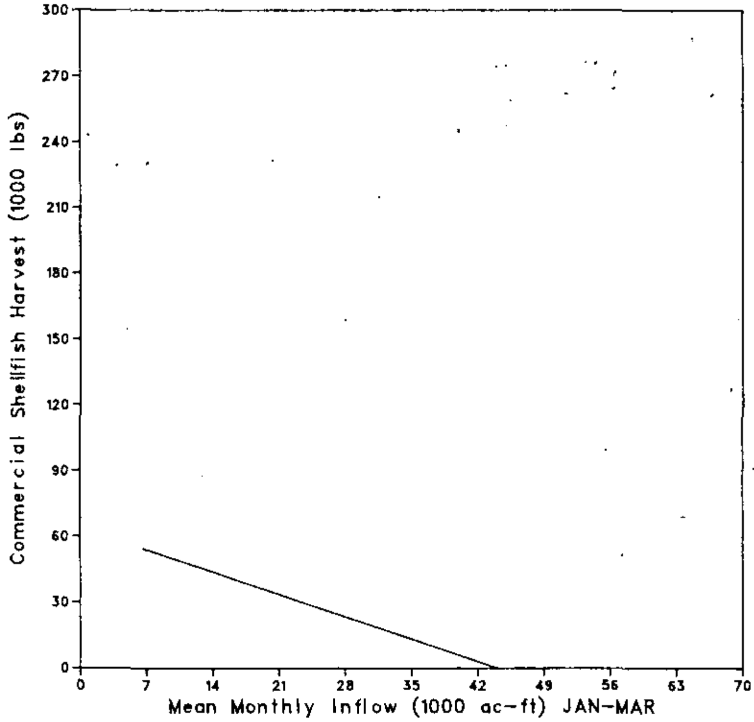
where:

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

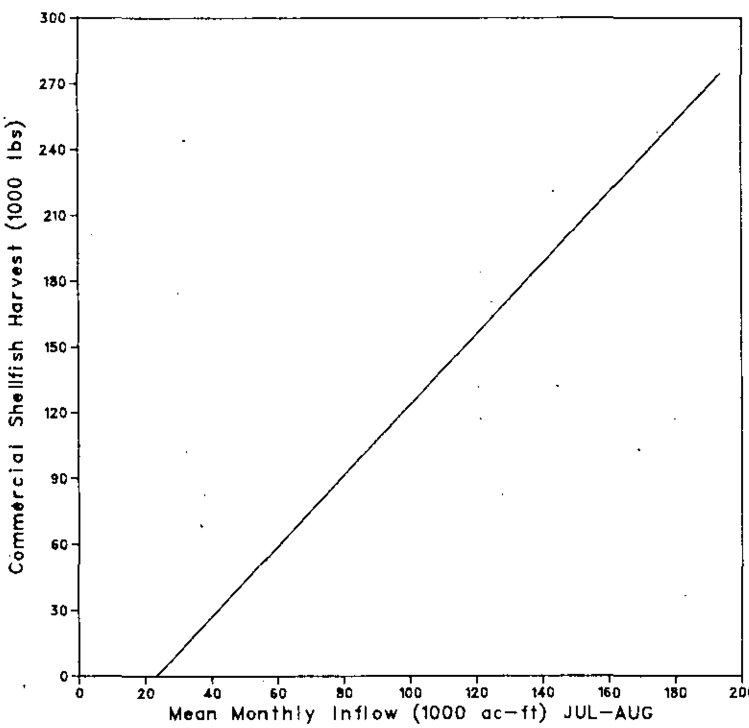
Q = mean monthly freshwater inflow, in thousands of acre-feet;

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

a/ Standard error of each coefficient is shown in parentheses beneath the coefficients of the regression equations
b/ FINUL = freshwater inflow to Upper Laguna Madre
c/ FINLL = freshwater inflow to Lower Laguna Madre
d/ $FINC_{lm}$ = combined freshwater inflow to Laguna Madre Estuary from all contributing river and coastal drainage basins



A. regression coefficient (slope) = -1.45, standard error = ±0.49



B. regression coefficient = +1.61 , standard error = +0.15

Figure 8-1. Lower Laguna Madre Commercial Shellfish Harvest as a Function of Each Seasonal Inflow from Contributing River and Coastal Drainage Basins, Where all Other Seasonal Inflows in the Multiple Regression Equation are Held Constant at their Mean Values.

January-March (Q_1) inflow would be very similar to that shown in Panel A (Figure 8-1) and would have the identical negative 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 mean values.

Panel B (Figure 8-1) exhibits the positive response of the inshore shellfish harvest of lower Laguna Madre to summer season freshwater inflows. The estimate of harvest increases to 274.1 thousand pounds annually as the July-August (Q_3) inflow increases from its lower observed bounds of 14.5 thousand acre-feet per month to its upper observed bounds of 195.5 thousand acre-feet per month.

Considered together, Panels A and B in Figure 8-1 illustrate a strong negative harvest response to winter (Q_1) inflow and a strong positive response to summer (Q_3) inflow, over the observed ranges of these seasonal inflows to lower Laguna Madre. Based on the statistical regression model described by the harvest equation, maximization of the lower Laguna Madre shellfish harvest (mostly oysters and crabs) can be achieved by decreasing winter inflow and increasing summer inflow to the estuary.

All Penaeid Shrimp

Analysis of the fisheries component for all penaeid shrimp (i.e., white, brown and pink shrimp) yields two very highly significant equations (Table 8-9). The offshore harvest equation (second equation, Table 8-9) estimates the largest shrimp harvest and involves transformation of the regression variables to natural logarithms. It accounts for 80 percent of the observed variation in Gulf Area No. 21 (offshore lower Laguna Madre) shrimp harvest and is very highly significant ($\alpha = 0.1\%$) for correlation of the natural log (ln) transformed harvests to natural log transformed fishing efforts (E_o) and winter (Q_1) and autumn (Q_4) freshwater inflows to lower Laguna Madre (FINLL).

The effect of each correlating term in the harvest equation is again illustrated by using the previously discussed procedure of holding all other correlating variables in the equation constant at their respective mean values, while increasing the variable of interest over its observed range and computing the estimated harvest response. Results are plotted in non-transformed units to show the curvilinear effects of each correlating variable on the offshore shrimp harvest (Figure 8-2). As might be anticipated, the estimate of harvest increases 2.2 times its minimum value (from about 5.0 to 11.3 million pounds annually) as offshore effort (E_o) increases from its observed lower bounds of about 1.9 thousand annual vessel fishing trips to its observed upper bounds of almost 5.3 thousand annual vessel fishing trips (Panel A, Figure 8-2). This increasing harvest trend with higher fishing effort would only exist to the point of over fishing, which may be near present levels. In contrast to the previous analysis of the shellfish component, increasing winter (Q_1) inflow over its observed range results in a 64 percent increase (from about 6.1 to 10.0 million pounds annually) in the offshore shrimp harvest (Panel B, Figure 8-2). The shrimp harvest estimate also increases 53 percent (from about 6.6 to 10.1 million pounds annually) in

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

Upper Laguna Madre All Shrimp Harvest = f (E_i + seasonal FINUL b/)
Very Highly Significant Equation ($\alpha = 0.1\%$, $r^2 = 99\%$, S.E. Est. = $\pm$ 14.4)

$$H_{as} = 0.28 + \underset{(0.01)}{0.17}\,(E_i) - \underset{(0.85)}{2.13}\,(Q_1) + \underset{(0.58)}{1.69}\,(Q_2) - \underset{(0.21)}{0.43}\,(Q_3) + \underset{(0.19)}{0.31}\,(Q_5)$$

	H_{as}	E_i	Q_1	Q_2	Q_3	Q_5
upper bounds	448.2	2,253.0	21.7	35.0	91.0	110.0
lower bounds	0.1	1.0	0.0	0.0	0.0	0.0
mean (n = 14)	51.9	240.3	3.0	10.8	9.7	8.5

Laguna Madre Offshore All Shrimp Harvest = f (E_O + seasonal FINLL c/)
Very Highly Significant Natural Log Equation ($\alpha = 0.1\%$, $r^2 = 80\%$, $\bar{S}$.E. Est. = $\pm$ 0.2079)

$$\ln OH_{as} = 1.5464 + \underset{(0.2351)}{0.7758}\,(\ln E_o) + \underset{(0.1210)}{0.2155}\,(\ln Q_1) + \underset{(0.0558)}{0.1142}\,(\ln Q_4)$$

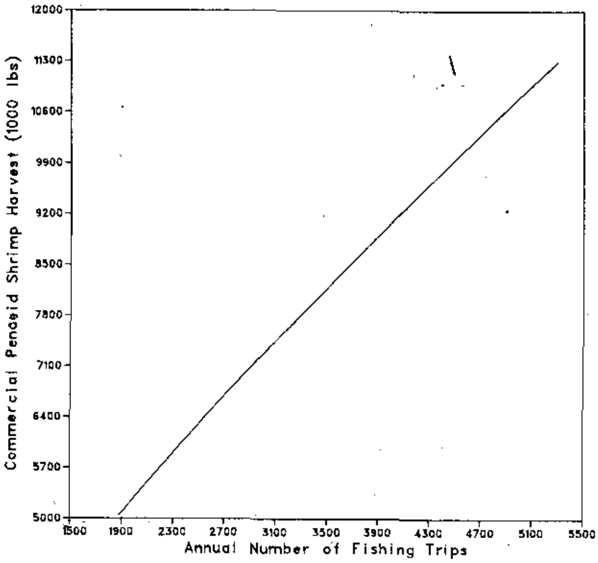
	$\ln OH_{as}$	$\ln E_o$	$\ln Q_4$	$\ln Q_1$
upper bounds	9.6538	8.5746	6.5582	4.1997
lower bounds	8.0539	7.5339	2.8332	1.8971
mean (n = 18)	8.9539	8.0874	4.2282	3.0169

where:

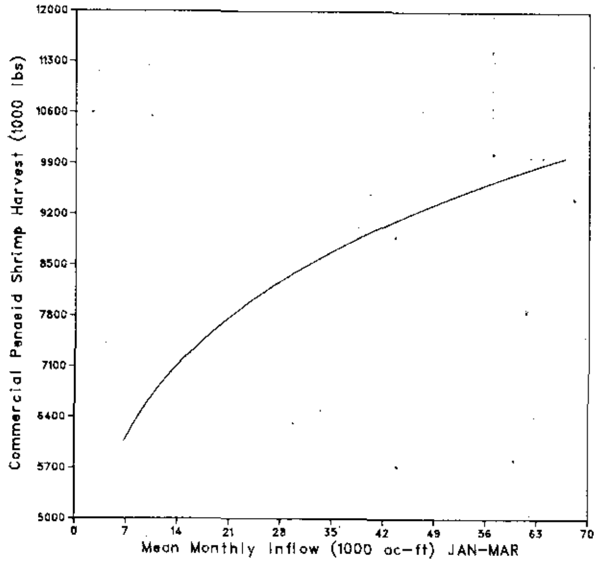
H_{as} = inshore commercial penaeid shrimp harvest, in thousands of pounds;
$\ln OH_{as}$ = natural log, offshore (Gulf Area No. 21) commercial penaeid shrimp harvest, in thousands of pounds;
E_i = inshore harvest effort, in number of fishing trips;
$\ln E_o$ = natural log, offshore (Gulf Area No. 21) harvest effort, in number of fishing trips;
Q = mean monthly freshwater inflow, in thousands of acre-feet;
ln Q = natural log of Q:

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

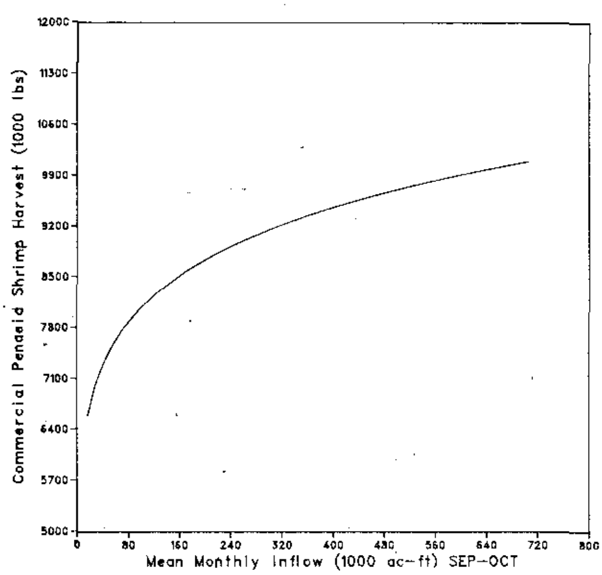
a/ Standard error of each regression coefficient is shown in parentheses beneath the coefficients of the regression equations
b/ FINUL = freshwater inflow to Upper Laguna Madre
c/ FINLL = freshwater inflow to Lower Laguna Madre



A. regression coefficient = +0.7758, standard error = ±0.2351



B. regression coefficient = +0.2155, standard error = ±0.1210



C. regression coefficient = +0.1142, standard error = ±0.0558

Figure 8-2. Offshore Area No. 21 Commercial Penaeid Shrimp Harvest as a Function of Fishing Effort and Each Seasonal Inflow to Lower Laguna Madre, Where all Other Variables than the Variable of Interest in the Natural Log Multiple Regression Equation are Held Constant at their Mean Values.

response to increasing autumn (Q_4) inflow over its observed range (Panel C, Figure 8-2). Maximization of the offshore penaeid shrimp harvests in Gulf Area No. 21 is therefore statistically related to high fishing effort and increased volumes of freshwater inflow to lower Laguna Madre during winter (January-March) and autumn (September-October).

White Shrimp

Analysis of the white shrimp fisheries component also results in two significant harvest equations (Table 8-10). The offshore harvest equation (second equation, Table 8-10) estimates the larger harvest of white shrimp, explains 70 percent of the annual harvest variation, and is highly significant ($\alpha = 0.5\%$) for the correlation of harvest to offshore fishing effort (E_O) and winter (Q_1), summer (Q_3), and late fall (Q_5) freshwater inflows to lower Laguna Madre (FINLL). The estimate of harvest increases 4.9 times its minimum value (from about 71.6 to 347.3 thousand pounds annually) as fishing effort increases over its observed range (Panel A, Figure 8-3). A positive response of white shrimp harvest to winter (Q_1) inflow results in harvest increasing 192 percent (from about 121.2 to 353.4 thousand pounds annually) as the seasonal inflow increases to its observed upper bounds of 66.7 thousand acre-feet per month (Panel B, Figure 8-3). White shrimp harvest responds negatively to high summer (Q_3) and late fall (Q_5) freshwater inflows and declines severely as these seasonal inflows are increased over their respective observed ranges (Panels C and D, Figure 8-3). Consequently, maximization of the offshore white shrimp harvest in Gulf Area No. 21 is statistically related to high fishing effort, increased winter (January-March) inflow, and reduced seasonal inflow in late fall (November-December) to lower Laguna Madre.

Brown and Pink Shrimp

Analysis of the brown and pink shrimp fisheries component yields two very highly significant ($\alpha = 0.1\%$) harvest equations (Table 8-11). The offshore harvest equation (second equation, Table 8-11) accounts for the larger shrimp harvest, involves natural log (ln) transformation of the variables, and explains 78 percent of the harvest variation as a function of offshore fishing effort (E_O) and winter (Q_1) and autumn (Q_4) season inflows to lower Laguna Madre (FINLL). The typically strong positive relationship of fishing effort results in the harvest estimate increasing 2.2 times its minimum value (from about 5.0 to 10.1 million pounds annually) as the number of fishing trips into Gulf Area No. 21 by shrimp vessels is increased over its observed range (Panel A, Figure 8-4). Similar to the previous offshore shrimp analyses, brown and pink shrimp harvest increases 66 percent (from about 5.9 to 9.8 million pounds annually) in response to increased winter (Q_1) inflow (Panel B, Figure 8-4). In addition, the estimate of harvest also increases 54 percent in response to increasing autumn (Q_1) inflow over its observed range (Panel C, Figure 8-4). Therefore, maximization of the offshore brown and pink shrimp harvest is also statistically related to high fishing effort and increased winter (January-March) and autumn (September-October) season inflows to lower Laguna Madre.

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

Upper Laguna Madre Shrimp Harvest = f (E_i + seasonal FINUL b/)
Very Highly Significant Natural Log Equation ($\alpha = 0.1\%$, $r^2 = 88\%$, S.E. Est. = $\pm$ 0.7640)

$$\ln H_{ws} = -1.5168 + \underset{(0.1010)}{0.6394} (\ln E_i) + \underset{(0.1223)}{0.2415} (\ln Q_2)$$

	$\ln H_{ws}$	$\ln E_i$	$\ln Q_2$
upper bounds	3.8155	7.7200	3.5553
lower bounds	-2.3026	0.0000	-2.3026
mean (n = 11)	1.1985	3.7080	1.4261

Laguna Madre Offshore White Shrimp Harvest = f (E_O + seasonal FINLL c/)
Highly Significant Equation ($\alpha = 0.5\%$, $r^2 = 70\%$, S.E. Est. = $\pm$ 95.2)

$$OH_{ws} = -27.26 + \underset{(0.03)}{0.11} (E_o) + \underset{(1.87)}{3.87} (Q_1) - \underset{(0.56)}{1.14} (Q_3) - \underset{(0.41)}{1.13} (Q_5)$$

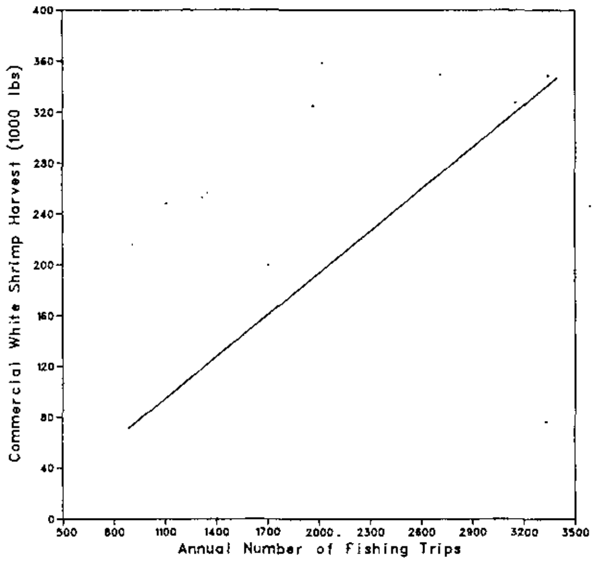
	OH_{ws}	E_o	Q_1	Q_3	Q_5
upper bounds	460.9	3,396.3	66.7	193.5	262.0
lower bounds	9.3	889.1	6.7	14.5	13.5
mean (n = 18)	178.1	1,935.4	23.6	37.8	41.8

where:

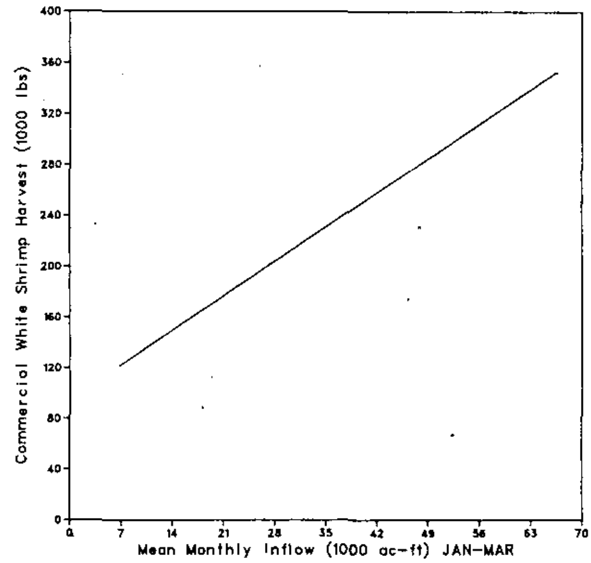
$\ln H_{as}$ = natural log, inshore commercial white shrimp harvest, in thousands of pounds;
OH_{ws} = offshore (Gulf Area No. 21, depth $\leq$ 20 fathoms) commercial white shrimp harvest, in thousands of pounds;
$\ln E_i$ = natural log, inshore harvest effort, in number of fishing trips;
E_o = offshore (Gulf Area No. 21, depth $\leq$ 20 fathoms) fishing effort, in number of fishing trips;
Q = mean monthly freshwater inflow, in thousands of acre-feet;
ln Q = natural log of Q:

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

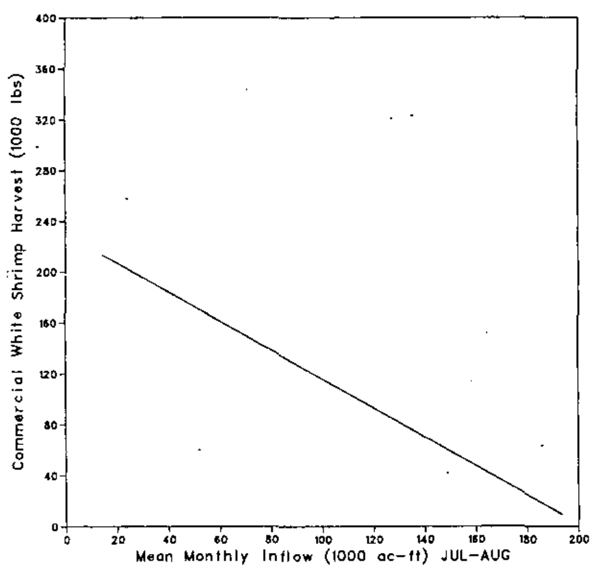
a/ Standard error of each regression coefficient is shown in parentheses beneath the coefficients of the regression equations
b/ FINUL = freshwater inflow to Upper Laguna Madre
c/ FINLL = freshwater inflow to Lower Laguna Madre



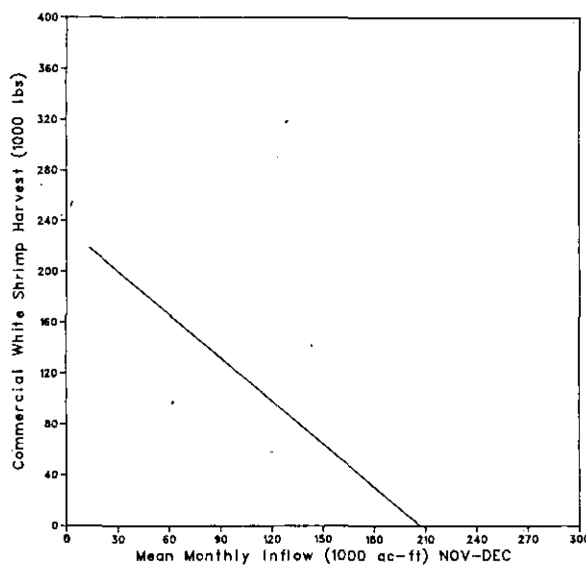
A. regression coefficient (slope) = +0.11, standard error = ±0.03;



B. regression coefficient = +3.87, standard error = ±1.87



C. regression coefficient -1.14 , standard error = ±0.56



D. regression coefficient = -1.13, standard error = ±0.41

Figure 8-3. Offshore Area No. 21 Commercial White Shrimp Harvest as a Function of Fishing Effort and Each Seasonal Inflow to Lower Laguna Madre, Where all Other Variables than the Variable of Interest in the Multiple Regression Equation are Held Constant at their Mean Values.

Table 8-11. Equations of Statistical Significance Relating the Brown and Pink Shrimp Fisheries Component to Freshwater Inflow Categories a/

Upper Laguna Madre Brown and Pink Shrimp Harvest = f (E_i + seasonal FINUL b/)
Very Highly Significant Equation ($\alpha = 0.1\%$, $r^2 = 98\%$, S.E. Est. = $\pm$ 21.4)

$$H_{bps} = 7.03 + \underset{(0.01)}{0.17}(E_i) - \underset{(1.06)}{1.16}(Q_1)$$

	H_{bps}	E_i	Q_1
upper bounds	402.8	2,253.0	21.7
lower bounds	0.2	1.0	0.0
mean (n = 10)	59.6	319.5	2.5

Laguna Madre Offshore Brown and Pink Shrimp Harvest = f (E_o + seasonal FINLL c/)
Very Highly Significant Natural Log Equation ($\alpha = 0.1\%$, $r^2 = 78\%$, S.E. Est. = $\pm$ 0.2151)

$$\ln OH_{bps} = 1.7612 + \underset{(0.2432)}{0.7436}(\ln E_o) + \underset{(0.1252)}{0.2212}(\ln Q_1) + \underset{(0.0577)}{0.1160}(\ln Q_4)$$

	$\ln OH_{bps}$	$\ln E_o$	$\ln Q_1$	$\ln Q_4$
upper bounds	9.6398	8.5746	4.1997	6.5582
lower bounds	8.0342	7.5339	1.8971	2.8332
mean (n = 18)	8.9331	8.0874	3.0169	4.2282

where:

H_{bps} = inshore commercial brown and pink shrimp harvest, in thousands of pounds;
$\ln OH_{bps}$ = natural log, offshore (Gulf Area No. 21) brown and pink shrimp harvest, in thousands of pounds;
E_i = inshore harvest effort, in number of fishing trips;
$\ln E_o$ = natural log, offshore (Gulf Area No. 21) harvest effort, in number of fishing trips;
Q = mean monthly freshwater inflow, in thousands of acre-feet;
ln Q = natural log of Q:

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

a/ Standard error of each regression coefficient is shown in parentheses beneath the coefficients of the regression equations
b/ FINUL = freshwater inflow to Upper Laguna Madre
c/ FINLL = freshwater inflow to Lower Laguna Madre

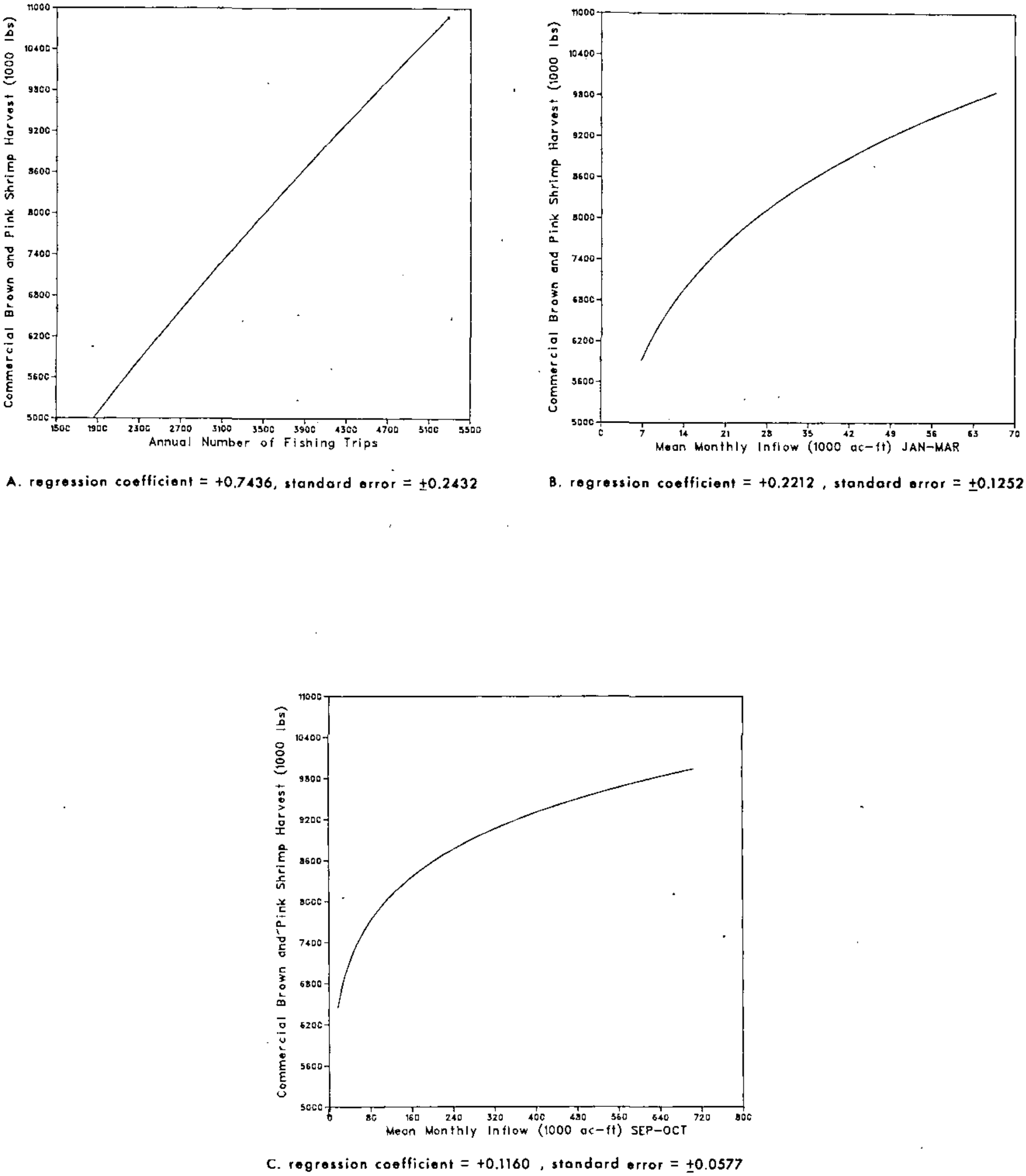


Figure 8-4. Offshore Area No. 21 Commercial Brown and Pink Shrimp Harvest as a Function of Fishing Effort and Each Seasonal Inflow to Lower Laguna Madre, Where all Other Variables than the Variable of Interest in the Natural Log Multiple Regression Equation are Held Constant at their Mean Values.

Blue Crab

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

Bay Oyster

Analysis of the bay oyster harvest in lower Laguna Madre results in a significant regression equation (Table 8-12). The harvest equation accounts for only 49 percent of the harvest variation and is significant (α = 2.5%) for correlation of natural log (ln) transformed oyster harvests to one-year antecedent, natural log transformed, winter (Q_1) and summer (Q_3) season freshwater inflows to lower Laguna Madre (FINLL). In contrast to the positive responses of the offshore *penaeid shrimp* harvests to winter (Q_1) inflow, the estimate of oyster harvest declines 98% (from about 21.6 thousand pounds to 500 pounds annually) as winter inflow is increased over its observed range (Panel A, Figure 8-5). A positive relationship to summer (Q_3) inflow increases the oyster harvest estimate from about 2.1 to 9.4 thousand pounds annually (Panel B, Figure 8-5). As a result, maximization of the oyster harvest is statistically related to decreasing winter (January-March) inflow and increasing summer (July-August) inflow to lower Laguna Madre. However, this inflow regime appears to conflict with the seasonal needs of penaeid shrimp, and to a lesser extent with the needs of such finfish as the redfish and spotted seatrout.

Finfish

Analysis of the multi-species finfish component of the commercial fisheries landings in Laguna Madre estuary gives a significant equation for each of the three freshwater inflow categories (Table 8-13). The best significant equation (third equation, Table 8-13) involves logarithmic transformation of the regression variables, explains 89 percent of the observed harvest variation, and is very highly significant (α = 0.1%) for correlation of the estuary's finfish harvests to winter (Q_1), spring (Q_2), summer (Q_3), and late fall (Q_5) freshwater inflows contributed to the Laguna Madre estuary from its combined river and coastal drainage basins ($FINC_{lm}$).

The curvilinear harvest responses estimated for each of the correlating seasonal inflows are computed and graphed as before. The estimate of finfish harvest increases 73 percent in response to increasing winter (January-March) inflow (Panel A, Figure 8-6). Another positive response to summer (July-August) inflow increases the harvest estimate 77 percent (Panel C, Figure 8-6). The two negative responses to increasing spring (April-June) and late fall (November-December) freshwater inflows result in the harvest estimates declining 53 and 37 percent, respectively (Panels B and D, Figure 8-6). Therefore, the regression model of finfish harvest described by the best significant equation indicates that harvest maximization is statistically related to increasing winter and summer season inflows, while diminishing spring and late fall season inflows contributed to the combined Laguna Madre estuary. Nevertheless, it should be noted that another finfish harvest equation which is specific for only the upper Laguna Madre (first equation, Table 8-13) exhibits positive harvest relationships with both spring and summer freshwater inflows to this area, responses similar to those reported by Powell (226) for the nearby Nueces estuary finfish harvest. Therefore,

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

Lower Laguna Madre Bay Oyster Harvest = f (seasonal FINLL b/)
Significant Natural Log Equation (α = 2.5%, r^2 = 49%, S.E. Est. = $\pm$ 0.7813)

$$\ln H_{bo} = 3.1180 - \underset{(0.4788)}{1.6071} (\ln Q_1) + \underset{(0.5195)}{0.9400} (\ln Q_3)$$

	$\ln H_{bo}$	$\ln Q_1$	$\ln Q_3$
upper bounds	2.8034	4.1997	4.2485
lower bounds	-0.6931	1.8971	2.6741
mean	1.2524	3.0284	3.1927

where:

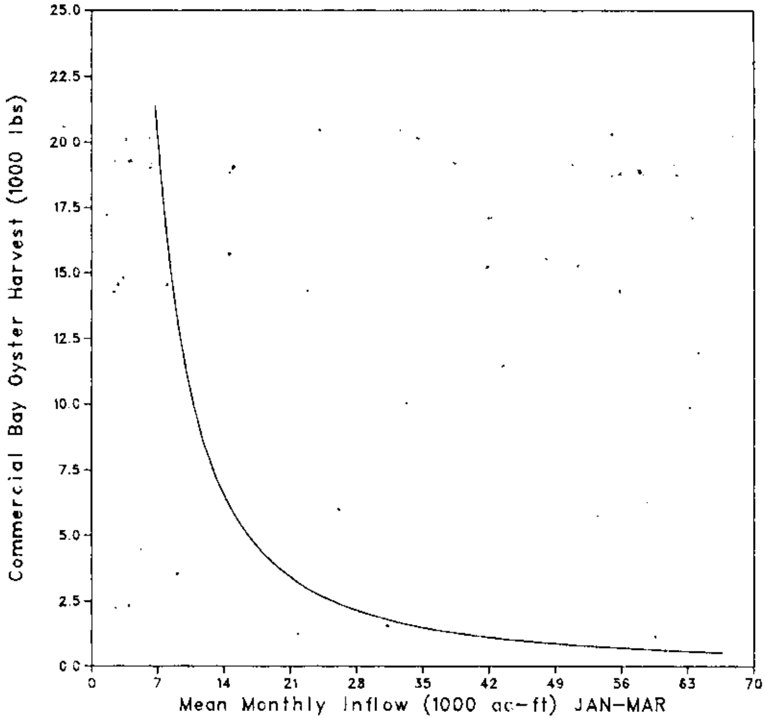
$\ln H_{bo}$ = natural log, commercial bay oyster harvest, in thousands of pounds;

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

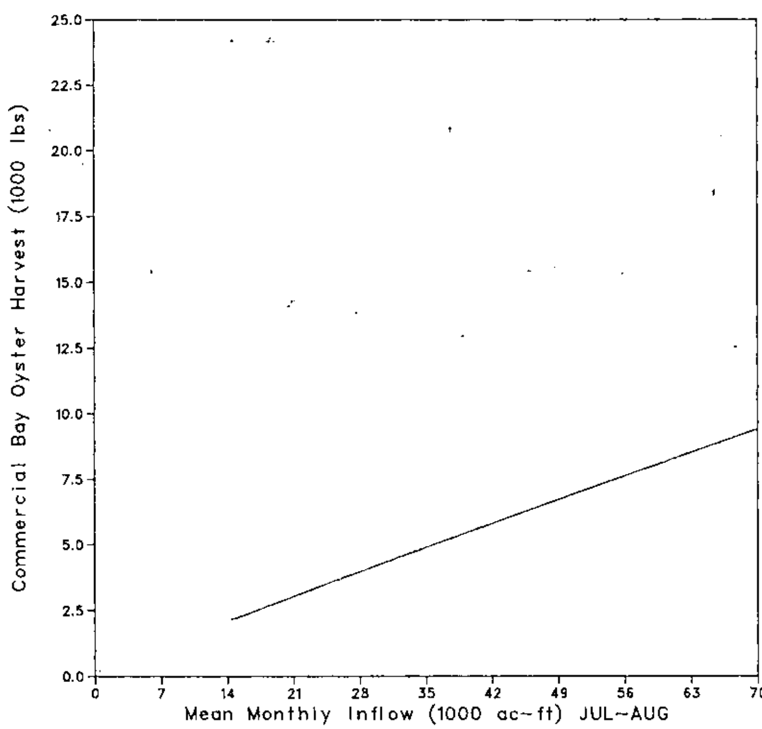
Q_1 = January-March
Q_2 = April-June
Q_3 = July-August
Q_4 = September-October
Q_5 = November-December

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

b/ FINLL = freshwater inflow to Lower Laguna Madre



A. regression coefficient = -1.6071, standard error = ± 0.4788



B. regression coefficient (slope) = +0.9400, standard error ± 0.5195

Figure 8-5. Lower Laguna Madre Commercial Oyster Harvest as a Function of Each Seasonal Inflow from Contributing River and Coastal Drainage Basins, Where all Other Seasonal Inflows in the Natural Log Multiple Regression Equation are Held Constant at their Mean Values.

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

Upper Laguna Madre Finfish Harvest = f (seasonal FINUL b/)
Highly Significant Natural Log Equation (α = 0.5%, r^2 = 69%, S.E. Est. = ± 0.2418)

$$\ln H_{ff} = 6.3054 + 0.1091 (\ln Q_2) + 0.1842 (\ln Q_3) - 0.0582 (\ln Q_5)$$
$$(0.0581) \qquad (0.0615) \qquad (0.0384)$$

	$\ln H_{ff}$	$\ln Q_2$	$\ln Q_3$	$\ln Q_5$
upper bounds	7.3330	3.0655	2.4129	3.6064
lower bounds	6.1375	-0.8110	-1.0987	-2.3026
mean	6.7110	1.8379	0.7981	-0.9966

Lower Laguna Madre Finfish Harvest = f (seasonal FINLL c/)
Significant Equation (α = 2.5%, r^2 = 68%, S.E. Est. = ± 236.8)

$$H_{ff} = 1535.02 + 18.98 (Q_1) - 19.70 (Q_2) + 16.82 (Q_3)$$
$$(10.73) \qquad (6.05) \qquad (9.13)$$
$$- 9.52 (Q_5)$$
$$(7.39)$$

	H_{ff}	Q_1	Q_2	Q_3	Q_5
upper bounds	2,288.6	41.4	68.9	54.7	45.8
lower bounds	782.7	9.4	20.6	16.7	15.2
mean	1,322.7	23.6	42.6	27.1	29.2

Laguna Madre Estuary Finfish Harvest = f (seasonal $FINC_{lm}$ d/)
Very Highly Significant Natural Log Equation (α = 0.1%, r^2 = 89%, S.E. Est. = ± 0.0990)

$$\ln H_{ff} = 8.0730 + 0.3950 (\ln Q_1) - 0.5478 (\ln Q_2) + 0.4822 (\ln Q_3)$$
$$(0.1504) \qquad (0.1072) \qquad (0.1775)$$
$$- 0.3372 (\ln Q_5)$$
$$(0.0812)$$

	$\ln H_{ff}$	$\ln Q_1$	$\ln Q_2$	$\ln Q_3$	$\ln Q_5$
upper bounds	8.1925	3.9555	4.5035	4.0547	4.1026
lower bounds	7.3976	2.5649	3.1307	2.8717	2.7300
mean	7.6668	3.1974	3.8884	3.3762	3.4608

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

where:

H_{ff} = inshore commercial finfish harvest, in thousands of pounds;

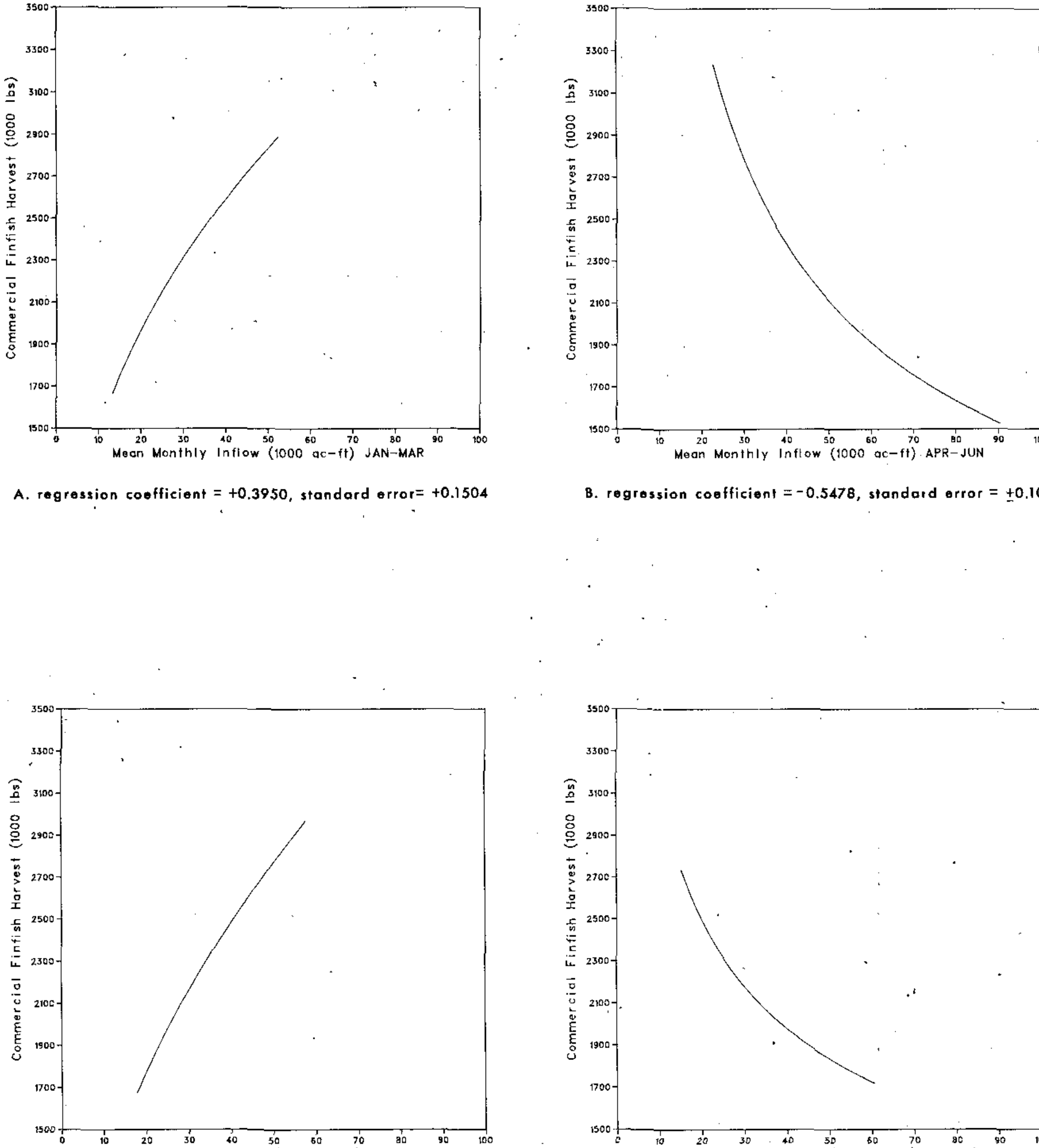
$\ln H_{ff}$ = natural log of H_{ff};

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

$\ln Q$ = natural log of Q:

Q_1 = 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/ FINUL = freshwater inflow to Upper Laguna Madre
c/ FINLL = freshwater inflow to Lower Laguna Madre
d/ $FINC_{lm}$ = combined freshwater inflow to Laguna Madre Estuary from all contributing river and coastal drainage basins



A. regression coefficient = +0.3950, standard error= +0.1504

B. regression coefficient = -0.5478, standard error = ±0.1072

C. regression coefficient = +0.4822, standard error = ±0.1775

D. regression coefficient = -0.3372, standard error = ±0.0812

Figure 8-6. Laguna Madre Estuary Commercial Finfish Harvest as a Function of Each Seasonal Inflow from Combined River and Coastal Drainage Basins, Where all Other Seasonal Inflows in the Natural Log Multiple Regression Equation are Held Constant at their Mean Values.

finfish in upper Laguna Madre appear to have seasonal inflow needs similar to those in the Nueces estuary, while the lower Laguna Madre finfish needs are unique and probably differ in some seasons (e.g., late fall and winter) because of the area's more southerly location in the sub-tropical zone and consequent warmer temperatures.

Spotted Seatrout

Analysis of the spotted seatrout fisheries component also yields a significant regression equation for each of the three freshwater inflow categories (Table 8-14). The best significant equation (third equation, Table 8-14) accounts for 73 percent of the observed harvest variation and is highly significant ($\alpha = 0.5\%$) for correlation of the estuary's commercial spotted seatrout harvests to winter (Q_1), summer (Q_3), and late fall (Q_5) freshwater inflows contributed to the Laguna Madre estuary from its combined river and coastal drainage basins ($FINC_{lm}$).

The harvest response to winter (January-March) is again positive with a 36 percent increase in the annual harvest estimate as the seasonal inflow increases to its upper observed bounds (Panel A, Figure 8-7). Another positive response to summer (July-August) inflow results in the harvest estimate increasing 37 percent (Panel B, Figure 8-7). The estimate of harvest also declines 31 percent in response to increasing late fall (November-December) freshwater inflow (Panel C, Figure 8-7). For the three correlating inflows, harvest responses are similar to those found with the general finfish component and indicate that maximization of the estuary's spotted seatrout harvest is related to increasing winter and summer inflows, and decreasing late fall freshwater inflows to the Laguna Madre estuary.

Red Drum

Analysis of the red drum fisheries component additionally results in three significant regression equations (Table 8-15). The best significant equation (second equation, Table 8-15) involves logarithmic (ln) transformation of the variables, explains 90 percent of the observed harvest variation, and is very highly significant ($\alpha = 0.1\%$) for correlation of the lower Laguna Madre redfish harvests to the seasonal inflows (Q_1 through Q_5) of lower Laguna Madre (FINLL).

Curvilinear harvest responses are similar to those of the finfish and spotted seatrout fisheries components, exhibiting a strong positive response to winter (January-March) inflow (Panel A, Figure 8-8), a negative response to spring (April-June) inflow (Panel B, Figure 8-8), a weak negative response to summer (July-August) inflow (Panel C, Figure 8-8), another positive response to autumn (September-October) inflow (Panel D, Figure 8-8), and a strong negative response to late fall (November-December) inflow (Panel E, Figure 8-8). The greatest changes in the lower Laguna Madre red drum harvest occurred as the estimate increased 4.3 times its minimum value in response to increasing winter inflow (Panel A) and declined 55 percent and 53 percent, respectively, as late fall inflow (Panel E) and spring inflow (Panel B) were increased over their observed ranges (Figure 8-8). The equational harvest model indicates that maximization of red drum production is related to

Table 8-14: Equation of Statistical Significance Relating the Spotted Seatrout Fisheries Component to Freshwater Inflow Categories a/

Upper Laguna Madre Spotted Seatrout Harvest = f (seasonal FINUL b/)
Very Highly Significant Natural Log Equation (α = 0.1%, r^2 = 69%, S.E. Est. = $\pm$ 0.3087)

$$\ln H_{ss} = 4.6950 + 0.2401 (\ln Q_2) + 0.1790 (\ln Q_3)$$
$$(0.0650) \qquad (0.0750)$$

	$\ln H_{ss}$	$\ln Q_2$	$\ln Q_3$
upper bounds	5.9741	3.0655	2.4129
lower bounds	4.2513	-0.8110	-1.0987
mean	5.2792	1.8379	0.7981

Lower Laguna Madre Spotted Seatrout Harvest = f (seasonal FINLL c/)
Significant Equation (α = 5.0%, r^2 = 27%. S.E. Est. = $\pm$ 86.4)

$$H_{ss} = 232.43 + 4.77 (Q_3)$$
$$(2.16)$$

	H_{ss}	Q_3
upper bounds	504.1	54.7
lower bounds	185.9	16.7
mean	361.7	27.1

Laguna Madre Estuary Spotted Seatrout Harvest = f (seasonal $FINC_{lm}$ d/)
Highly Significant Equation (α = 0.5%, r^2 = 73%, S.E. Est. = $\pm$ 96.6)

$$H_{ss} = 462.64 + 4.73 (Q_1) + 4.77 (Q_3) - 4.52 (Q_5)$$
$$(4.52) \qquad (4.70) \qquad (2.23)$$

	H_{ss}	Q_1	Q_3	Q_5
upper bounds	850.5	52.2	57.7	60.5
lower bounds	306.9	13.0	17.7	15.3
mean	581.4	26.8	30.8	34.2

Table 8-14. Equation of Statistical Significance Relating the Spotted Seatrout Fisheries Component to Freshwater Inflow Categories a/ (cond't.)

where:

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

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

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

$\ln Q$ = natural log of Q:

Q_1 = January-March

Q_2 = April-June

Q_3 = July-August

Q_4 = September-October

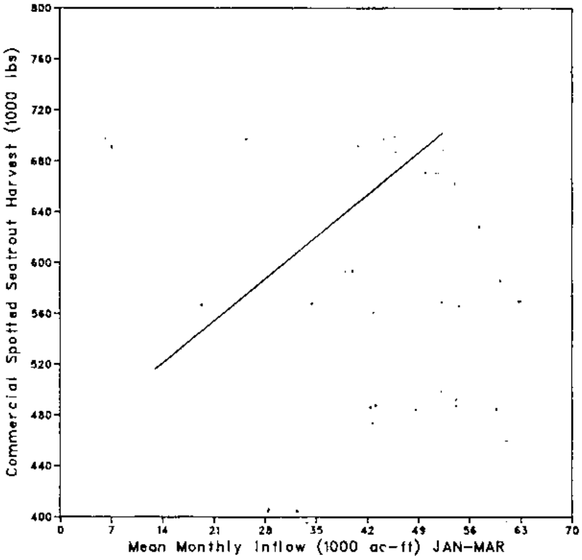
Q_5 = November-December

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

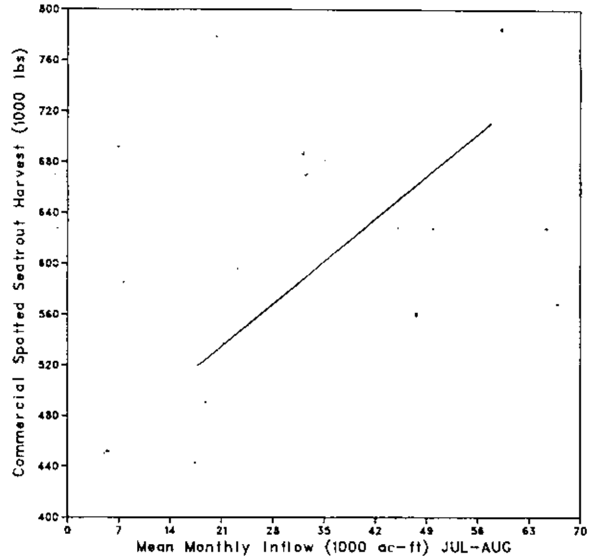
b/ FINUL = freshwater inflow to Upper Laguna Madre

c/ FINLL = freshwater inflow to Lower Laguna Madre

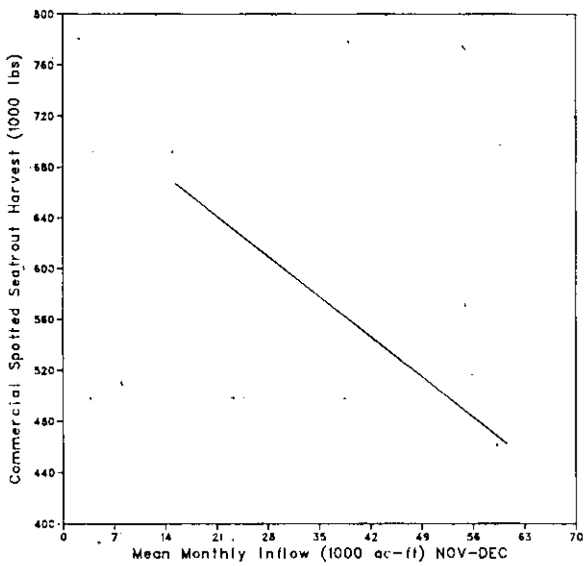
d/ $FINC_{lm}$ = combined freshwater inflow to Laguna Madre Estuary from all contributing river and coastal drainage basins



A. regression coefficient (slope) = +4.73, standard error = ±4.52



B. regression coefficient (slope) = +4.77, standard error = ±4.70



C. regression coefficient (slope) = -4.52, standard error = ±2.23

Figure 8-7. Laguna Madre Estuary Commercial Spotted Seatrout 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 8-15. Equations of Statistical Significance Relating the Red Drum Fisheries Component to Freshwater Inflow Categories a/

Upper Laguna Madre Red Drum Harvest = f (seasonal FINUL b/)
Very Highly Significant Natural Log Equation (α = 0.1%, $\bar{r}^2$ = 83%, S.E. Est. = ± 0.3108)

$$\ln H_{rd} = 4.4424 + \underset{(0.0654)}{0.3527} (\ln Q_2) + \underset{(0.0755)}{0.2625} (\ln Q_3)$$

	ln H_{rd}	ln Q_2	ln Q_3
upper bounds	6.3015	3.0655	2.4129
lower bounds	3.9665	-0.8110	-1.0987
mean	5.3000	1.8379	0.7981

Lower Laguna Madre Red Drum Harvest = f (seasonal FINLL c/)
Very Highly Significant Natural Log Equation (α = 0.1%, $\bar{r}^2$ = 90%, S.E. Est. = ± 0.1793)

$$\ln H_{rd} = 7.3810 + \underset{(0.1616)}{0.9799} (\ln Q_1) - \underset{(0.2226)}{0.6277} (\ln Q_2) - \underset{(0.1882)}{0.2231} (\ln Q_3)$$

$$+ \underset{(0.0751)}{0.2498} (\ln Q_4) - \underset{(0.1776)}{0.7127} (\ln Q_5)$$

	ln H_{rd}	ln Q_1	ln Q_2	ln Q_3	ln Q_4	ln Q_5
upper bounds	6.7191	3.7244	4.2325	4.0013	5.5652	3.8250
lower bounds	5.4450	2.2454	3.0231	2.8134	3.2189	2.7191
mean	6.1069	3.0615	3.6924	3.2363	4.5522	3.3274

Laguna Madre Estuary Red Drum Harvest = f (seasonal $FINC_{lm}$ d/)
Very Highly Significant Natural Log Equation (α = 0.1%, $\bar{r}^2$ = 85%, S.E. Est. = ± 0.2219)

$$\ln H_{rd} = 6.0829 + \underset{(0.2027)}{0.5235} (\ln Q_1) + \underset{(0.0814)}{0.1662} (\ln Q_4) - \underset{(0.1914)}{0.6000} (\ln Q_5)$$

	ln H_{rd}	ln Q_1	ln Q_4	ln Q_5
upper bounds	7.1844	3.9555	5.9844	4.1026
lower bounds	5.6504	2.5649	3.2581	2.7300
mean	6.4884	3.1974	4.8628	3.4608

Table 8-15. Equations of Statistical Significance Relating the Red Drum Fisheries Component to Freshwater Inflow Categories a/ (con'd.)

where:

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

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

Q_1 = January-March — Q_4 = September-October

Q_2 = April-June — Q_5 = November-December

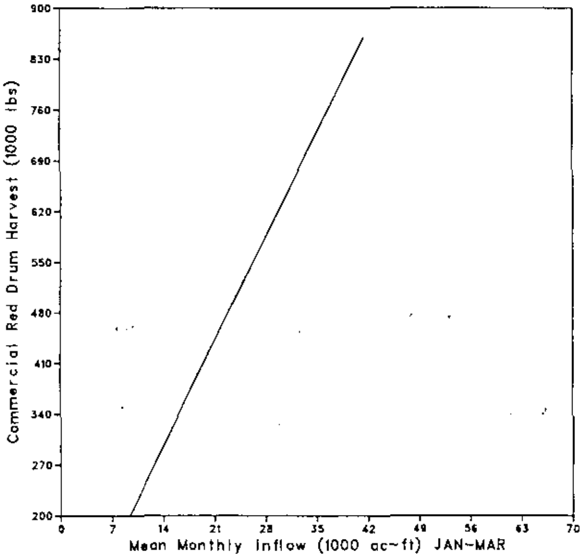
Q_3 = July-August

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

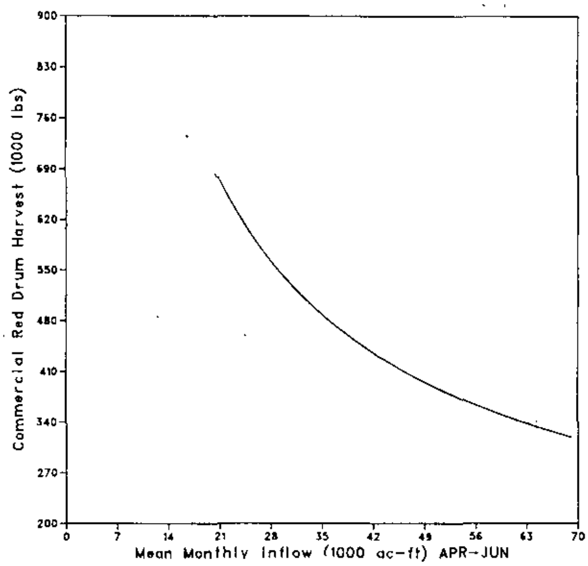
b/ FINUL = freshwater inflow to Upper Laguna Madre

c/ FINLL = freshwater inflow to Lower Laguna Madre

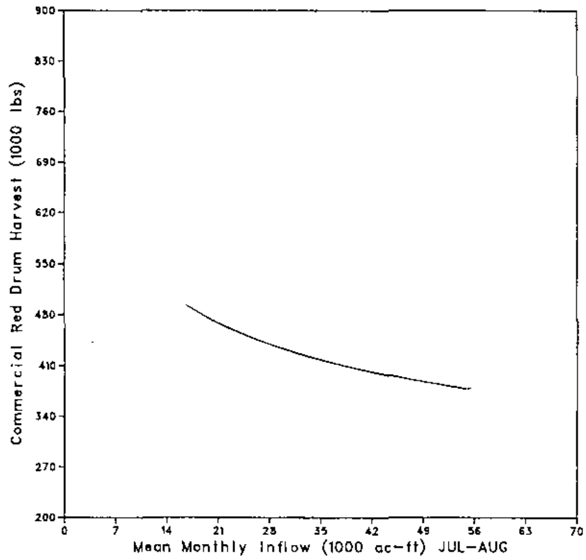
d/ $FINC_{lm}$ = combined freshwater inflow to Laguna Madre Estuary from all contributing river and coastal drainage basins



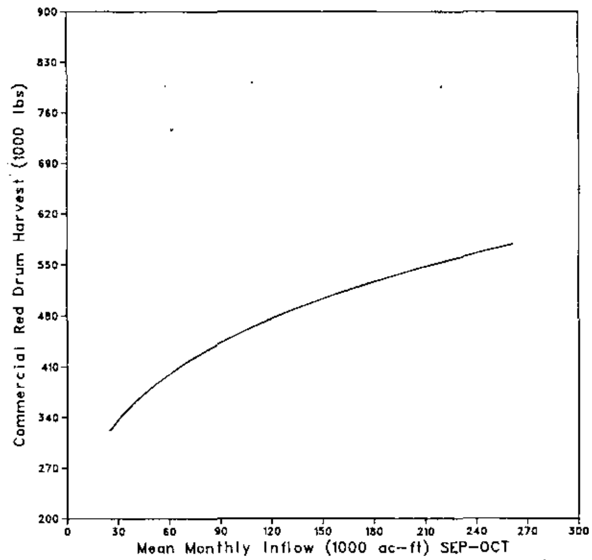
A. regression coefficient = +0.9799, standard error = $\pm$0.1616



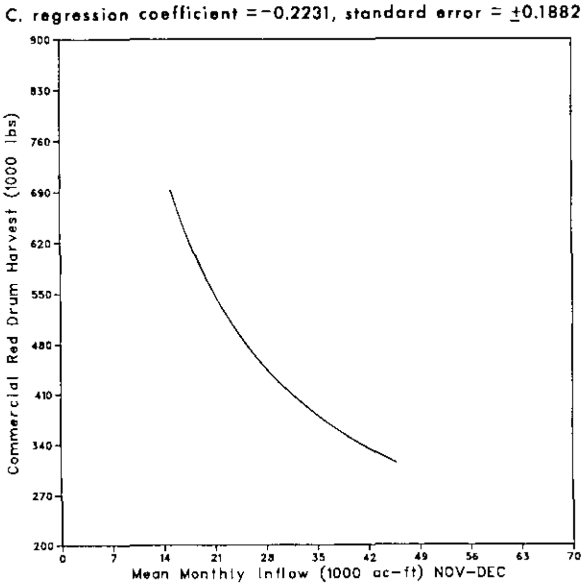
B. regression coefficient = -0.6277, standard error = $\pm$0.2226



C. regression coefficient = -0.2231, standard error = $\pm$0.1882



D. regression coefficient = +0.2498 , standard error = $\pm$0.0751



E. regression coefficient = -0.7127, standard error = $\pm$0.1776

Figure 8-8. Lower Laguna Madre Estuary Commercial Red Drum Harvest as a Function of Each Seasonal Inflow from Contributing River and Coastal Drainage Basins, Where all Other Seasonal Inflows in the Natural Log Multiple Regression Equation are Held Constant at their Mean Values.

increased winter and autumn inflows, with diminished seasonal inflows to lower Laguna Madre during spring, summer and late fall.

Black Drum

Only two significant regression equations are obtained from analysis of the black drum fisheries component (Table 8-16). The best significant equation (second equation, Table 8-16) accounts for 82 percent of the harvest variation and is very highly significant ($\alpha = 0.1\%$) for correlation of black drum harvests to spring (Q_2), summer (Q_3), and autumn (Q_4) freshwater inflows contributed to the Laguna Madre estuary from its combined river and coastal drainage basins ($FINC_{1m}$).

The seasonal inflow information is again similar to the previously discussed finfish, spotted seatrout, and red drum fisheries components, especially with regard to spring and summer inflows, but there are important species differences. The black drum harvest responses are strongly negative to spring (April-June) inflow (Panel A, Figure 8-9), strongly positive to summer (July-August) inflow (Panel B, Figure 8-9), and also negative to autumn (September-October) inflow (Panel C, Figure 8-9). It is noted that the estimate of harvest declines 74 percent as spring inflow increases (Panel A), and increases 3.7 times the minimum harvest estimate as summer inflow increases (Panel B). Maximization of black drum harvest is therefore statistically related to increased summer inflow and decreased spring and autumn season inflows to the Laguna Madre estuary.

Fisheries Component Summary

The fisheries analysis involves 10 fisheries components and three freshwater inflow source categories in the analytical design, allowing a maximum 30 potentially significant equations. The analysis results in 19 regression equations of statistical significance. Although each inflow category can potentially produce 10 significant equations, the analysis yields six equations with freshwater inflow to upper Laguna Madre (FINUL), nine equations with freshwater inflow to lower Laguna Madre (FINLL), and four equations with combined freshwater inflows to the Laguna Madre estuary from all contributing river and coastal drainage basins ($FINC_{1m}$).

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 8-17). Therefore, the seasonal inflow needs of the fisheries components can reinforce each other. However, where seasonal inflow needs are of opposite signs, the fisheries components become competitive in terms of inflow management. Altogether, these results support the hypothesis that seasonal freshwater inflow has a significant impact on the estuary's fisheries, and by ecological implication, on the "health" of the ecosystem.

Table 8-16. Equations of Statistical Significance Relating the Black Drum Fisheries Component to Freshwater Inflow Categories a/

Upper Laguna Madre Black Drum Harvest = f (seasonal FINUL b/)
(no significant equation)

Lower Laguna Madre Black Drum Harvest = f (seasonal FINLL c/)
Significant Equation (α = 2.5%, r^2 = 64%, S.E. Est. = ± 187.0)

$$H_{bd} = 624.45 - \underset{(8.40)}{12.04}\,(Q_1) - \underset{(4.95)}{9.15}\,(Q_2) + \underset{(7.15)}{21.06}\,(Q_3) - \underset{(0.69)}{0.90}\,(Q_4)$$

	H_{bd}	Q_1	Q_2	Q_3	Q_4
upper bounds	932.6	41.4	68.9	54.7	261.2
lower bounds	127.8	9.4	20.6	16.7	25.0
mean	413.3	23.6	42.6	27.1	120.0

Laguna Madre Estuary Black Drum Harvest = f (seasonal $FINC_{lm}$ d/)
Very Highly Significant Equation (α = 0.1%, r^2 = 82%, S.E. Est. = ± 145.5)

$$H_{bd} = 775.96 - \underset{(2.64)}{13.11}\,(Q_2) + \underset{(4.91)}{28.21}\,(Q_3) - \underset{(0.34)}{0.87}\,(Q_4)$$

	H_{bd}	Q_2	Q_3	Q_4
upper bounds	1,544.8	90.3	57.7	397.2
lower bounds	399.4	22.9	17.7	26.0
mean	788.5	53.4	30.8	181.0

where:

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

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

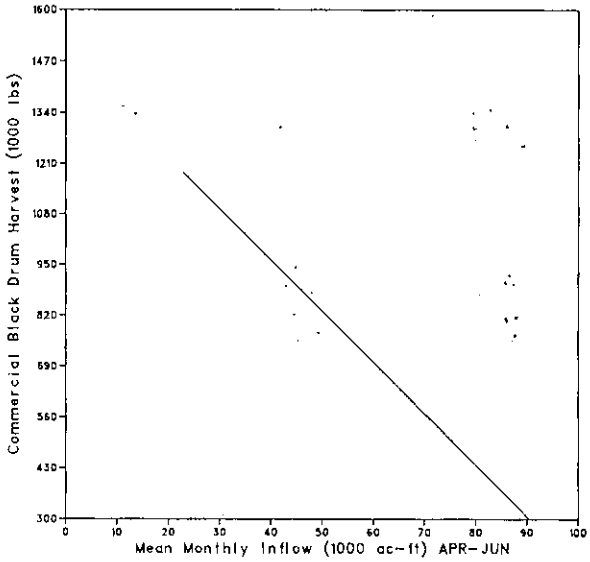
Q_1 = January-March
Q_2 = April-June
Q_3 = July-August
Q_4 = September-October
Q_5 = November-December

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

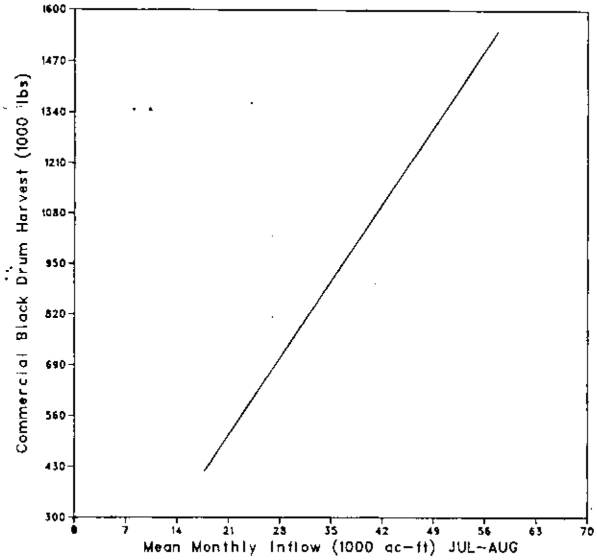
b/ FINUL = freshwater inflow to Upper Laguna Madre

c/ FINLL = freshwater inflow to Lower Laguna Madre

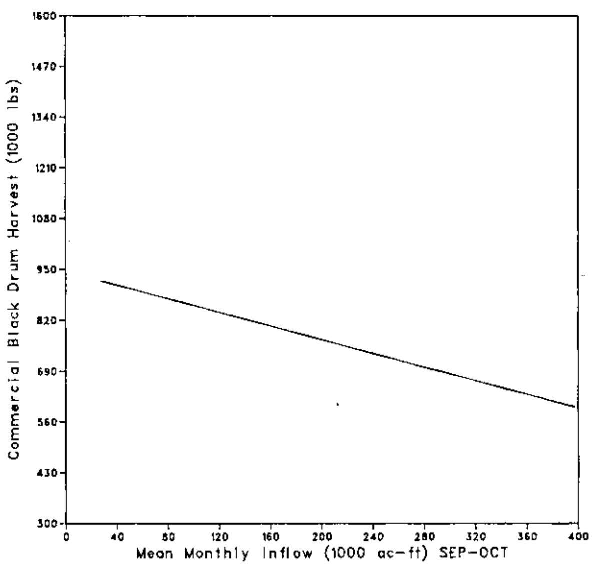
d/ $FINC_{lm}$ = combined freshwater inflow to Laguna Madre Estuary from all contributing river and coastal drainage basins



A. regression coefficient (slope) = -13.11, standard error = ±2.64



B. regression coefficient (slope) = +28.21, standard error = ±4.91



C. regression coefficient (slope) = -0.87, standard error = ±0.34

Figure 8-9. Laguna Madre Estuary 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.

Table 8-17. Positive (+) and Negative (-) Correlation of Fisheries Components to Seasonal Freshwater Inflow Categories

Fisheries Component	Winter Inflow Q_1 (Jan.-Mar.)	Spring Inflow Q_2 (April-June)	Summer Inflow Q_3 (July-Aug.)	Autumn Inflow Q_4 (Sept.-Oct.)	Late Fall Inflow Q_5 (Nov.-Dec.)	Explained Variation r^2 (%)	Significance Level α (%)
Shellfish							
FINUL[a]							
FINLL[b]	-		+			90	0.1
$FINC_{1m}$[c]							
All Shrimp							
FINUL	-	+	-		+	99 d/	0.1
FINLL	+			+		80 e/	0.1
$FINC_{1m}$							
White Shrimp							
FINUL		+				88 d/	0.1
FINLL	+		-		-	70 e/	0.5
$FINC_{1m}$							
Brown and Pink Shrimp							
FINUL	-					98 d/	0.1
FINLL	+			+		78 e/	0.1
$FINC_{1m}$							
Bay Oyster							
FINUL							
FINLL	-		+			49	2.5
$FINC_{1m}$							

(Continued)

Table 8-17. (Continued)

Finfish							
FINUL		+	+		−	69	0.5
FINLL	+	−	+		−	68	2.5
$FINC_{lm}$	+	−	+		−	89	0.1
Spotted Seatrout							
FINUL		+	+			69	0.1
FINLL			+			27	5.0
$FINC_{lm}$	+		+		−	73	0.5
Red Drum							
FINUL		+	+			83	0.1
FINLL	+	−	−	+	−	90	0.1
$FINC_{lm}$	+			+	−	85	0.1
Black Drum							
FINUL							
FINLL	−	−	+	−		64	2.5
$FINC_{lm}$		−	+	−		82	0.1
Summary:							
FINLL	(+) = 0 (−) = 2	(+) = 5 (−) = 0	(+) = 3 (−) = 1	(+) = 0 (−) = 0	(+) = 1 (−) = 1		
FINLL	(+) = 5 (−) = 3	(+) = 0 (−) = 3	(+) = 5 (−) = 2	(+) = 3 (−) = 1	(+) = 0 (−) = 3		
$FINC_{lm}$	(+) = 3 (−) = 0	(+) = 0 (−) = 2	(+) = 3 (−) = 0	(+) = 1 (−) = 1	(+) = 0 (−) = 3		

a/ Freshwater inflow to upper Laguna Madre
b/ Freshwater inflow to lower Laguna Madre
c/ Combined freshwater inflow to Laguan Madre estuary from all contributing river and coastal drainage basins
d/ Equation includes inshore fishing effort term (+ E_i)
e/ Equation includes offshore fishing effort term (+ E_o)

Freshwater Inflow Effects

Introduction

The hydrologic importance of both tidal inlets and freshwater inflow for ecological preservation of estuaries has been recognized (138, 274). Many scientists have pointed to the deleterious effects of reduction and/or alteration of an estuary's freshwater inflow regime (30, 177, 146, 143, 179), especially since the diminution of freshwater inflow to an estuary can decrease nutrient cycling in contiguous wetlands and may also result in unfavorable bay salinity conditions. Consequently, the addition of supplemental freshwater inflow for purposes of ecological maintenance and maximization of seafood production has been recommended for the Gulf estuaries of Texas (138, 328), Mississippi and Louisiana (59).

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 (7), which may be reflected in physiological adaptation to the estuarine environment (123, 122, 401, 402), in species distribution patterns and community diversity (92, 81, 87, 67, 94, 27, 128), and ultimately in species evolution (120). Previous research emphasizing Texas estuarine-dependent species has dealt with several aspects of the inflow/salinity relationship including environmental limits (314), tolerance to hypersaline waters (86, 101, 11), and rapid recovery of typical estuarine community species at the end of a severe drought (111). In addition, salinity changes resulting from man's development of an estuary and its contributing river and coastal drainage basins have been reviewed relevant to effects on many of the common estuarine-dependent species (90, 342), and their diseases and symbionts (180).

While plants provide an estuary's primary production, most secondary production comes from the invertebrate bay fauna. For the invertebrates, inflow/salinity effects have a demonstrated physiological basis (12, 336, 124, 132, 334) and are effective at modifying species distribution (281, 297, 181). The brackish water clam (Rangia cuneata) has been suggested as an indicator of ecological effects associated with salinity changes because of its sensitivity (216); 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 (147).

Shrimp

The Gulf of Mexico shrimp fishery is the most valuable fishery in the United States (73) and the Gulf estuaries play a crucial role in the production of this renewable resource (75, 129). 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 populations. Synopses of species life history and biological information are available for the white shrimp (137), brown shrimp (29), pink shrimp (36), and other species in the genus Penaeus (386). Information especially important for management of this fishery resource comes from research on shrimp spawning and early larval stages (346, 303, 323, 384), seasonal migration behavior

(339, 32, 257), utilization of estuarine nursery habitats (81), and major environmental factors influencing species population dynamics and production (218, 95, 152, 151, 38, 142). Species-specific responses to inflow/salinity conditions in the estuary are fundamentally physiological (8, 18, 223, 220, 131, 344), and therefore directly influence not only growth and survival of the postlarval shrimp (415, 413, 414, 400), but the distribution of the bay shrimp populations as well (309, 93, 285).

Results of the fisheries analyses and development of equational harvest models for the all penaeid shrimp, white shrimp, and brown and pink shrimp components strongly support the importance of freshwater inflow to shrimp production. In addition, the analyses provide quantified information on the responses of commercial harvests from inshore areas of upper Laguna Madre (includes Baffin Bay), and commercial harvests offshore of lower Laguna Madre, to the seasonal fluctuations of the associated freshwater inflows (i.e., FINUL and FINLL inflow categories). Equational harvest models indicate notable seasonal dichotomies among the species, and also within the same species over inshore versus offshore harvest areas. For example, although inshore brown and pink shrimp from upper Laguna Madre show a strong negative harvest response to winter (January-March) inflow, inshore white shrimp from the same area exhibit only a strong positive response to spring (April-June) inflow (see Table 8-17). These seasonal differences between the two shrimp fishery components can be associated with the earlier reproduction (i.e., late winter spawning) of adult brown shrimp and migration of the young produced into inshore "nursery" areas at this time. By comparison, the same life history events occur for the white shrimp later in the spring. The brown shrimp's sensitivity to concomitant low temperature and low salinity is revealed by its negative harvest response to high winter inflow. Since upper Laguna Madre is adjacent and directly connected to the Nueces estuary, the similarities of these inshore shrimp harvest responses to those reported for the Nueces estuary (226) are not unexpected. However, inshore-offshore differences between harvest responses of the same species are often more puzzling. For instance, the previously discussed negative inshore harvest response of brown and pink shrimp to upper Laguna Madre winter inflow is contrasted with the positive offshore harvest response of the same fisheries component to lower Laguna Madre winter inflow. Here again, the solution may involve temperature, but in the context of the region's geography. This explanation arises because the lower Laguna Madre's warmer, more sub-tropical location on the South Texas coast may allow the productive benefits of winter freshwater inflows to be realized by the penaeid shrimp stocks without the high probability of stressful or even lethal conditions that can result from the simultaneous low salinities and low winter temperatures typical of more northerly estuarine areas. This interpretation is supported by the finding that penaeid shrimp harvests directly offshore of the Trinity-San Jacinto estuary in the northwestern Gulf of Mexico are negatively related to high winter inflows to the estuary (227). In general, it is noted that the large penaeid shrimp harvests offshore of the lower Laguna Madre are positively related to most seasonal inflows (FINLL category), significantly to winter and autumn inflows. The exceptions are the negative responses to late fall inflow, which were significant only for the white shrimp, and also the white shrimp's negative harvest response to summer inflow.

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, 282), life history (348, 243), migration behavior (290, 112, 257), and responses to environmental factors such as salinity (202, 37, 219, 130) and storm water runoff (135). The Laguna Madre blue crab harvest data were not consistent and produced an incomplete time-series record over the 1962-1976 interval; therefore, the seasonal importance of freshwater inflow to the species could not be statistically demonstrated by the fisheries analysis. Nevertheless, the harvests appeared to be positively related to summer inflow and negatively related to cool season (i.e., late fall and winter) inflows.

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 (378, 405), as well as geographic variation of its populations (204). The effects of inflow/salinity are important to the oyster reef and have stimulated considerable research covering a wide range of subjects, including effects on oyster distribution (305, 150, 51), gametogenesis (development of viable eggs and sperm) and spawning (347, 19, 141, 196), eggs and larvae (9, 47, 379, 383, 104), respiration (315, 399), free amino-acids which are protein building blocks (154), and the effects on oyster reef growth and mortality (83, 295), reef diseases (222, 180), and abundance of faunal associates (83, 407).

Previous studies have described the Texas oyster fishery (261) and the State's major oyster producing areas (387, 265). The only oyster reefs inventoried in the Laguna Madre estuary are in the lower portion of the estuary (359). Classified "polluted areas" are closed by the Texas Department of Health under authority of Section 76.202, Parks and Wildlife Code, until such time as sampling indicates a return of healthy estuarine conditions. Currently, the areas closed in lower Laguna Madre include virtually all shoreline areas near Port Isabel and South Padre Island, as well as subdivision channels and harbor areas. Commercial oyster harvests were only made in lower Laguna Madre. The results of the fisheries analysis indicates that these oyster harvests are negatively related to winter inflow and positively related to summer inflow.

Finfish

Estuaries play a vital functional role in the life cycle and production of most coastal fish species (345, 118, 145, 249, 113). Environmental sensitivity of the estuarine-dependent fishes has allowed the use of species diversity indices as indicators of pollution (292). Although migration does occur across the boundary between riverine and estuarine habitats by both freshwater and estuarine-dependent marine fishes (175, 193), there is a predominance of young marine fishes found in this low salinity area (84).

In general, seasonal variations in estuarine fish abundance are related to life history and migrational behavior (91, 318, 317, 114, 290, 112, 257, 200, 264, 283, 423). The primary effects of inflow/salinity are physiological (110, 115, 134), and are particularly important for the survival of the early life stages (109), the metabolism (i.e., metabolic stresses) of adult bay populations (308, 313, 320, 277, 404), and juvenile rates of adaptability (278, 279). Low temperature extremes can also interact physiologically with salinity stress to produce dramatic fish mortality (78, 79, 82).

Results of the fisheries analysis for the multi-species finfish component indicate uniformly positive harvest responses to winter and summer inflows to Laguna Madre, and consistently negative responses to late fall inflows to the estuary. Although finfish harvests are positively related to spring inflow to upper Laguna Madre, similar to responses found in the adjacent Nueces estuary (226), finfish respond to lower Laguna Madre inflow in the same season with an opposite negative harvest reaction. It is of interest to note that the Laguna Madre estuary, especially the lower portion, is the first ranked finfish production area on the Texas coast.

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 (345, 221, 113). 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 (382). The greater restriction and estuarine-dependence of this species are reflected in its nearly exclusive utilization of estuarine habitats (74, 214, 68) and the increased genetic differences between populations in separate bays (406). Previous research has described spotted seatrout life history and seasonal abundance in Texas waters (349, 318, 239, 240, 317, 114, 112, 257), 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 (276, 277, 306, 404, 278, 279).

Harvest responses to seasonal Laguna Madre inflows are similar to those obtained in the analysis of the multi-species finfish component. Thus, spotted seatrout harvests are positively related to winter and summer inflows, and negatively related to late fall inflow. Again, only the harvests in upper Laguna Madre are positively related to spring inflow, which is in concert with the spotted seatrout responses to spring inflows in the adjacent Coastal Bend area of Nueces estuary (226).

Red Drum

Another important sciaenid species is the red drum or redfish (Sciaenops ocellata Linnaeus). Prior studies have reported on the general biology, food (prey) items, and seasonal distribution of the red drum (349, 318, 239, 240, 419, 420, 319, 317, 114, 412, 112, 257, 113). 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 (277, 404, 278, 279). Similar to results from the finfish and spotted seatrout fisheries components, analysis of the red drum component also shows positive harvest responses to winter inflow and negative responses to late fall inflow. However, red drum harvests exhibit a negative response to lower Laguna Madre summer (July-August) inflows that is unique among the fishes analyzed, and is shared only by the white shrimp's offshore harvest response. In addition, red drum harvests are positively related to inflows during the tropical storm dominated autumn season (September-October), a time of increased reproductive activity for the species.

Black Drum

The black drum (Pogonias cromis Linnaeus) is also a sciaenid species of commercial and recreational interest. The general biology and life history of the black drum, including behavioral migrations and seasonal distributions, have been reported previously (318, 113, 257, 349, 319, 317, 345). In addition, the effects of inflow/salinity on the metabolism (i.e., metabolic stresses) of this broadly tolerant (euryhaline) species have been investigated as salt concentrations varies from an optimum of about 20-25 ppt salinity (277, 404). The seasonal importance of freshwater inflow to black drum harvests in the Laguna Madre estuary is similar to that found in the adjacent Nueces estuary where harvests were negatively related to winter and autumn inflows, and positively related to summer inflow (226). However, in the Laguna Madre, especially the lower portion, black drum harvests are also negatively related to spring inflow.

Harvest Response to Long and Short Term Inflow

The inshore fisheries analysis (except shrimp components) spans the 1962 through 1976 short-term interval where more complete and compatible fisheries harvest data exist. The penaeid shrimp fishery (inshore and offshore) analysis is slightly expanded to include the 1959 through 1975 data interval. However, long-term inflow data are available for the estuary from 1941 to 1976, inclusively (see Chapter IV). Average (arithmetic and geometric mean) inflow conditions can be computed, and a frequency analysis (i.e., Log-Pearson Type III) of the long-term data can yield information about the exceedance frequencies of seasonal inflows to the estuary, including the frequency (percent) at which short-term average inflows were exceeded in the long-term record (Table 8-18). Short-term inflow exceedance frequencies for the three freshwater inflow categories (i.e., FINUL, FINLL, and $FINC_{lm}$) vary both above and below the median level of 50 percent exceedance frequency, but only about four percent of the seasonal inflows are equal to or exceed this level. Since lower exceedance frequencies indicate higher inflow, the short-term data bases are indicated as generally "wetter" than the long-term temporal median inflows.

Although the central seasonal tendencies of the short-term record are given as average (arithmetic and geometric mean) inflow conditions, the long-term central tendencies are expressed by both average inflow conditions and the 50 percent frequency inflows which reflect the temporal median inflows to the estuary from the freshwater source categories (98). When short-term and long-term average inflow conditions, as well as the long-term 50 percent

Table 8-18. Comparison of Short-Term and Long-Term Seasonal Inflow Volumes, Including Inflow Exceedance Frequencies

Freshwater Inflows Category and Season	Short-Term Mean Seasonal Inflow a/ With Long-Term Exceedance Frequencies: D_1 Inflow	D_1 (EF%) c/	D_2 Inflow	D_2 (EF%)	D_3 Inflow	D_3 (EF%)	Long-Term Seasonal Inflow b/: Arithmetic Mean Inflow	Geometric Mean Inflow	10% EF Inflow	50% EF Inflow	90% EF Inflow
FINUL d/											
Q_1 (Jan.-March)	6.9	(50)	8.7	(46)	2.7	(64)	15	2	29	0	0
Q_2 (April-June)	39.8	(32)	34.2	(36)	18.8	(49)	31	7	104	6	0
Q_3 (July-Aug.)	19.3	(28)	16.9	(30)	4.4	(42)	18	4	40	2	0
Q_4 (Sept.-Oct.)	120.4	(19)	110.0	(21)	34.3	(41)	75	9	200	8	0
Q_5 (Nov.-Dec.)	0.3	(38)	13.3	(9)	0.7	(28)	7	2	10	0	0
Total	186.7		183.1		60.9		146	24	383	16	0
FINLL e/											
Q_1 (Jan.-March)	75.4	(31)	61.3	(40)	70.9	(33)	79	57	143	56	24
Q_2 (April-June)	131.0	(33)	110.5	(43)	127.8	(35)	125	104	227	103	48
Q_3 (July-Aug.)	80.5	(17)	55.1	(32)	54.2	(33)	57	43	106	42	18
Q_4 (Sept.-Oct.)	243.9	(22)	137.2	(39)	239.9	(22)	206	108	443	106	27
Q_5 (Nov.-Dec.)	57.7	(30)	55.3	(32)	58.4	(30)	62	43	112	42	17
Total	588.5		419.4		551.2		529	355	1,031	349	134
$FINC_{lm}$ f/											
Q_1 (Jan.-March)	82.3	(31)	68.5	(38)	73.4	(35)	94	63	172	61	24
Q_2 (April-June)	170.8	(29)	132.7	(41)	146.5	(36)	156	122	298	120	51
Q_3 (July-Aug.)	99.9	(19)	64.6	(36)	58.5	(40)	75	52	147	51	19
Q_4 (Sept.-Oct.)	364.3	(19)	165.5	(41)	258.8	(28)	281	132	630	130	28
Q_5 (Nov.-Dec.)	58.0	(34)	60.3	(32)	63.7	(30)	69	46	130	45	17
Total	775.3		491.6		600.9		675	415	1,377	407	139

a/ Short-term inflow data bases, with seasonal volumes in thousands of acre-feet:
- D_1 = inflow from November 1961 to October 1976 used in analysis of shellfish
- D_2 = inflow from November 1958 to October 1976, natural log transformed except FINUL category, and used in analysis of penaeid shrimp
- D_3 = 3-year running average inflow from January 1959 to December 1975, natural log transformed except FINLL category, and used in analysis of finfish

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

c/ Long-term exceedance frequencies, in percent, of the short-term mean seasonal inflows

d/ Freshwater inflow to upper Laguna Madre

e/ Freshwater inflow to lower Laguna Madre

f/ Combined freshwater to Laguna Madre estuary from all contributing river and coastal drainage basins frequency inflow conditions, are used separately as input to the previously developed fisheries regression equations, predicted harvest responses can be computed for comparison (Table 8-19). It is noted that substitution involves using arithmetic mean seasonal inflows as input to the linear equations and geometric mean seasonal inflows as input to the natural log (ln) equations.

There are 10 positive and nine negative shifts of the harvest estimates in response to the long-term average inflows, and eight positive and 11 negative harvest shifts in response to the 50 percent frequency inflows, for a total of 38 computed harvest responses (18 positive and 20 negative). The harvest responses are variable among the fisheries components and range from an estimated +30.6 percent in black drum harvest ($FINC_{lm}$ inflow category) to an estimated -79.1 percent shift in shellfish harvest (FINLL), when compared to the fisheries harvest levels resulting from the observed short-term interval. The results reflect not only differences in inflow quantity, but also differences in the seasonal distributions of inflow from the freshwater source categories. Shellfish equational models (i.e., shellfish, penaeid shrimp, and bay oyster fisheries components) yield five positive and 11 negative harvest shifts in response to input of the long-term seasonal inflows. In opposite, equational models for the fishes (i.e., finfish, spotted seatrout, and red and black drum fisheries components) give 13 positive and nine negative harvest shifts. It is also noted that 61 percent of the positive harvest shifts are in response to long-term lower Laguna Madre (FINLL) inflows, while 55 percent of the negative shifts are in response to long-term upper Laguna Madre (FINUL) inflows. Therefore, the results suggest that overall there are no net benefits associated with fisheries based on the long-term inflows, especially since increased fish harvests are offset by decreased shellfish harvests.

While management policies could favor the specific seasonal inflow needs of preferred fisheries components, it is in reality difficult and in many cases impossible to maximize the harvests from more than one fisheries component at the same time because of competitive seasonal inflow needs among the species. Nevertheless, management scenarios for inflow can be developed that predict good harvest levels from several of the fisheries components simultaneously (see Chapter IX).

Summary

Virtually all of the coastal fisheries species in the Gulf of Mexico are estuarine-dependent. Commercial inshore harvests (1962-1976) from lower Laguna Madre rank first in finfish and eighth in shellfish, while upper Laguna Madre ranks second in finfish and seventh in shellfish harvests of eight major Texas estuarine areas. In addition, the sport or recreational finfish harvest is approximately 1.5 times larger than the estuary's commercial finfish harvest. For the 1972 through 1976 interval, the average annual sport and commercial harvest of fish and shellfish dependent upon the Laguna Madre estuary is estimated at 7.3 million pounds (3.3 million kg; 12 percent shellfish).

Although a large portion of the fisheries production in each Texas estuary is harvested offshore in collective association with fisheries production from other regional estuaries, inshore bay and lagoon harvests can be useful as relative indicators of the year to year variations in an estuary's surplus production (i.e., that portion available for harvest). These varia-

Table 8-19. Estimated Average Harvest Responses from Fisheries Component Equations Using Short-Term Inflow, Long-Term Mean Inflow and Long-Term 50-Percent Exceedance Frequency Inflow.

Fisheries Component	Upper Laguna Madre Inflow FINUL a/					Lower Laguna Madre Inflow FINLL b/					Combined Estuary Inflow $FINC_{lm}$ c/				
	Short-Term Mean Inflow	Long-Term Mean Inflow		Long-Term 50% EF Inflow d/		Short-Term Mean Inflow	Long-Term Mean Inflow		Long-Term 50% EF Inflow		Short-Term Mean Inflow	Long-Term Mean Inflow		Long-Term 50% EF Inflow	
	Harvest e/	Harvest	(shift) f/	Harvest	(shift)	Harvest	Harvest	(shift)	Harvest	(shift)	Harvest	Harvest	(shift)	Harvest	(shift)
Shellfish						27.3	6.7	(-75.5)	5.7	(-79.1)					
Bay Oyster						3.5	3.6	(+ 2.9)	3.6	(+ 2.9)					
All Shrimp	51.9 g/	45.2	(-12.9)	44.1	(-15.0)	7,738.0 h/	7,410.6	(- 4.2)	7,366.6	(- 4.8)					
Brown and Pink Shrimp	59.6 g/	55.5	(- 6.9)	61.3	(+ 2.9)	7,578.7 h/	7,251.9	(- 4.3)	7,207.9	(- 4.9)					
White Shrimp	3.3 g/	2.9	(-12.1)	2.8	(-15.2)	178.1 h/	220.0	(+23.5)	210.2	(+18.0)					
Finfish	821.4	682.3	(-16.9)	675.2	(-17.8)	1,322.7	1,398.1	(+ 5.7)	1,366.4	(+ 3.3)	2,136.2	2,343.8	(+ 9.7)	2,330.7	(+ 9.1)
Spotted Seatrout	196.2	151.8	(-22.6)	129.2	(-34.1)	361.7	368.4	(+ 1.9)	332.6	(- 8.0)	581.4	633.8	(+ 9.0)	578.7	(-0.5)
Red Drum	200.3	137.4	(-31.4)	108.5	(-45.8)	448.9	476.2	(+ 6.1)	479.1	(+ 6.7)	657.5	659.7	(+ 0.3)	655.6	(- 0.3)
Black Drum						413.3	433.7	(+ 4.9)	480.1	(+16.2)	788.5	1,029.9	(+30.6)	914.4	(+16.0)

a/ Freshwater inflow to Upper Laguna Madre
b/ Freshwater inflow to Lower Laguna Madre
c/ Combined freshwater inflow to Laguna Madre Estuary from all contributing river and coastal drainage basins
d/ EF = exceedance frequency; 50% EF reflects the temporal median inflow to the estuary
e/ Average harvest, in thousands of pounds
f/ Shift in percent increase (+) or decrease (-) of harvest
g/ inshore (Upper Laguna Madre) shrimp harvest
h/ offshore (Gulf Area No. 21) shrimp harvest

tions are affected by the seasonal quantities and sources of freshwater inflow to an estuary through ecological interactions involving salinity, nutrients, food (prey) production, and habitat availability. The effects of freshwater inflow on lower Laguna Madre are also reflected in the offshore harvests of the penaeid shrimp fishery. Therefore, the fisheries species can be viewed as integrators of their environment's conditions and their harvests used as relative ecological indicators, insofar as they reflect the general productivity and "health" of an estuarine ecosystem.

A time series analysis of Laguna Madre's commercial inshore (bay and lagoon) fisheries landings (1962 through 1976) and the commercial penaeid shrimp harvests (including Offshore Gulf Area No. 21, 1959 through 1976) produces 19 statistical regression equations that estimate harvest as a function of seasonal freshwater inflows to the Laguna Madre estuary. 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 dependent upon the estuary. The analysis also supports existing scientific information on the seasonal importance of freshwater inflow to the estuaries.

There are 13 significant harvest relationships to winter (January-March) inflow obtained from the analysis and eight (62 percent) of these are positive harvest responses associated with larger winter inflows, especially increased inflow to lower Laguna Madre. Negative harvest responses to winter inflow result from the brown and pink shrimp fisheries component in upper Laguna Madre, and lower Laguna Madre's shellfish, bay oyster, and black drum fisheries components. Positive fisheries harvest responses to upper Laguna Madre spring (April-June) inflow account for half of the ten significant harvest relationships to this season's inflow. Eleven (79 percent) of the 14 significant harvest responses to summer (July-August) inflow are positive. Exceptions include the negative harvest response of penaeid shrimp to upper Laguna Madre inflow, and the negative harvest responses of white shrimp and red drum to lower Laguna Madre inflow during this season. Harvest responses to the tropical storm dominated autumn (September-October) season inflows are negative only for the black drum fisheries component, which is in particular contrast to the strong positive relationships exhibited by the red drum component. All of the eight significant harvest responses to late fall (November-December) inflow are negative, except for the single positive response of inshore penaeid shrimp harvests to this season's upper Laguna Madre 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. These other factors, however, are largely beyond human control, whereas freshwater inflow can be restricted by man's activities so that fish and wildlife resources are adversely affected.

CHAPTER IX

ESTIMATED FRESHWATER INFLOW NEEDS

Introduction

In previous chapters, the various physical, chemical and biological factors affecting the Laguna Madre 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 freshwater inflow needs for this estuary, based upon historical data.

Methodology for Estimating Selected Impacts of Freshwater Inflow Upon Estuarine Productivity

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

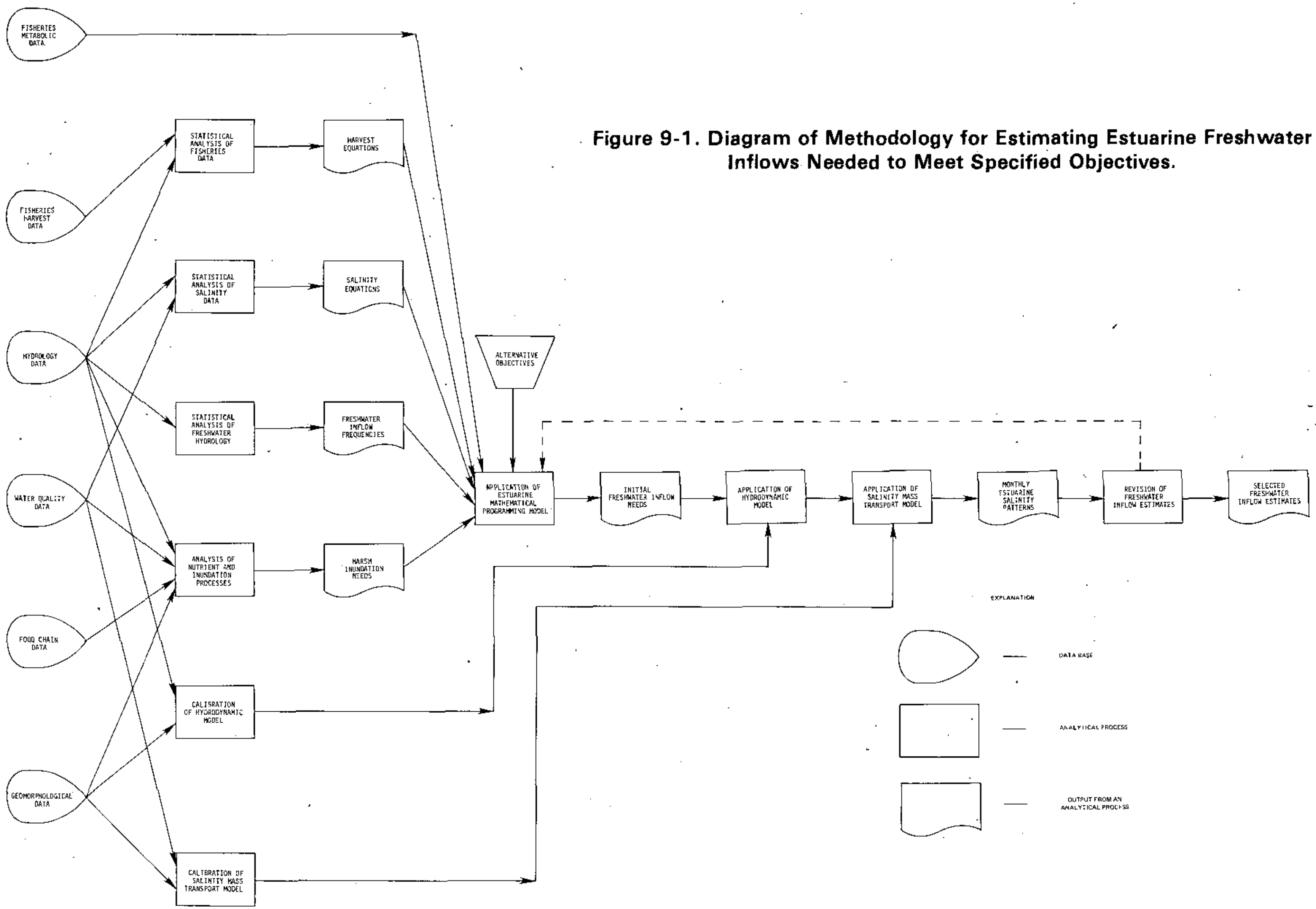
The methodology presented here incorporates major interacting elements described in previous chapters (Figure 9-1). The methodology includes the use of data bases and certain analytical processes described herein. Data for these analyses include six groups: (1) salinity data for finfish and shellfish,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

In this section data and results of previous sections, including (1) statistical analysis of relationships among freshwater inflow, commercial fisheries harvest, and estuarine salinity; (2) estimates of marsh freshwater inundation needs; (3) estimates of nutrient exchange; and (4) records of historical freshwater inflow, are used in an Estuarine Mathematical Programming Model to compute estimates of the monthly freshwater inflows needed to achieve specified objectives. The tidal hydrodynamic and salinity transport models for Laguna Madre require further development and will not be applied to compute salinity levels and circulation patterns throughout the estuary for a set of monthly freshwater inflow needs.

Application of the Methodology to Compute Estimates of Freshwater Inflow Levels Needed to Meet Selected Objectives

The schematic indicated in Figure 9-1 shows the sequence of steps utilized in computing the freshwater inflow needs to achieve specified objectives as expressed in terms of salinity, marsh inundation, and productivity. The six data bases developed for the Laguna Madre estuary provide the fundamental information of the system. These data were used in previous sections of these

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

The data bases and analytical processes utilized in this chapter have been described in detail in previous chapters. Only the procedures necessary to establish salinity bounds, estimate marsh inundation needs, and apply the Estuarine 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 and seagrass species has been tabulated from the scientific literature and Texas Department of Water Resources research data (Table 9-1). Optimum condition for most of the fisheries species lies between 25 percent and 75 percent seawater (8.8-26.3 ppt). Young fish and shellfish commonly utilize estuarine "nursery" habitats that are below 50 percent seawater (less than 17.5 ppt), while most adults seem to prefer salinities higher than 50 percent seawater. Similarly, the Laguna Madre's abundant seagrass species exhibit optimum growth and vigor at salinities near or exceeding 75 percent seawater. In general, and within the tolerance limits, it is the season, not salinity per se, that is more important to the fisheries species because of life cycle events such as spawning and migration. While the salinity limits for distribution of the species are ecologically informative, they are often physiologically too broad. Conditions encouraging good growth and reproduction are commonly restricted to a substantially narrower range of salinity than are simple survival needs.

Data on salinity effects, combined with life cycle information, are utilized to provide seasonal bounds on estuarine salinity within which fish, shellfish, and the seagrasses can survive, grow, and maintain viable populations (Table 9-2). Since universal consensus is not evident for precise saline viability limits, the salinity bounds are established subjectively based upon the available scientific information (Table 9-1). It is important to note that these limits are site specific and adjusted to two control points

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

Species	Limits Min. (ppt)	Limits Max. (ppt)	Preference or Optimum (ppt)	Remarks	Reference
Penaeus setiferus (white shrimp)					
	<2	>40		range at which 80% of 8-50 mm (postlarvae to juvenile) shrimp survive; 48 hr. acclimation	413
			5-15	increased growth at this range (and >25°C) more than two times tissue production of postlarvae at 25-35 ppt	413
			28.0	median salinity average of postlarval distribution (May-July) in laboratory gradient tanks	220
			21.0	median salinity average of postlarval distribution (Aug.-Nov.) in laboratory gradient tanks	220
		47.95		field collection of small white shrimp (23-76 mm) in Laguna Madre de Tamaulipas (Mexico)	106
	0.42			lower distribution limit in Grand and White Lakes (La.); young shrimp 140 times more abundant at 0.7-0.8ppt	94
			27.6-28.3	isosmotic salinity conditions for shrimp < 100 mm length; osmoregulation below 27.6 ppt better than brown shrimp	159
	1	34	1-20	field distribution in Caminada Bay (La.) and range for 91.1% of juveniles collected	38
	2.1	36.6	10.0-14.9	field distribution in Copano and Aransas Bays (Tex.) and range of greater abundance; common at < 4.9 ppt	309
	2.9	45.3		field distribution in Mesquite Bay (Tex.)	111
	2	45		field distribution in bays and lagoons of northwestern Gulf of Mexico (Tex.)	101
			<10	preference based on population distributions	93
	0	38		optimum catch over entire salinity range with 20-30°C temperatures	314
Penaeus aztecus (brown shrimp)					
	2	40		range of equal postlarval growth over 23-25°C temperature; survival 90-100% in laboratory	414
	<10			marked reduction in postlarval tolerance at low (7-15°C) temperatures to low (5 ppt) salinity	415
			15-35	range of increased postlarval growth at temperatures >25°C; decreased growth below 15 ppt	413
	<5	>40		range at which 80% of 10-15 mm postlarvae survive; 12 hr. acclimation	413
			>15	appeared to enhance survival and growth of postlarvae in Barataria Bay (La.)	210
			<15	commercial catches poor in years when postlarvae were present in Louisiana bays with < 15 ppt	153
			29.9	median salinity average of postlarval distribution (March-April) in laboratory gradient tank	220
			20.6	median salinity average of postlarval distribution (May-July) in laboratory gradient tank	220
			10.0-19.9	range at which juveniles were more abundant based on population distributions	93
	0.2	30	10-30	field distribution in Caminada Bay (La.) and range for 91.8% of juveniles collected	38
			>17	preference of juvenile (70 mm) shrimp in laboratory at >26°C temperature	344
			15-25	optimal range for subadult (95 mm) shrimp in laboratory at <25°C temperature	344
			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	400
			27.6-28.3	isosmotic salinity conditions for shrimp < 100 mm length; osmoregulation above 28.3 ppt better than white shrimp	159
	2.1	36.6	15.0-19.9	field distribution in Copano and Aransas Bays (Tex.) and range of greater abundance	309
		69.0		field collection in Laguna Madre (Tex.)	289
	0.8			lower distribution limit in Grand and White Lakes (La.)	94
	0.22			field collection in St. Lucie Estuary (Fla.)	77
	5	70		field distribution in bays and lagoons of northwestern Gulf of Mexico (Tex.)	101
	0.1			field collection (North Carolina)	410
			5	acclimation at low (5 ppt) salinity provides near-optimum resistance to high temperatures and 5-25 ppt salinities in laboratory tests	408
	4	40		no optimum salinity established with 20-35°C temperatures	314
Callinectes sapidus (blue crab)					
	22.9	32.4	± 30.0	range for capture of egg-bearing females near Aransas Pass (Tex.)	309
			23-28	optimum range for hatching of eggs (Virginia)	202
			>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	219
	0			observed freshwater populations in Louisiana	91
	2.5	37.2	10.?-20.5	field distribution in Copano and Aransas Bays (Tex.) and range of greater abundance	309
		117		field collection in Laguna Madre de Tamaulipas (Mexico); high salinity briefly tolerated	106
		45		blue crabs observed leaving upper Laguna Madre (Tex.) area as salinity increased	255
	2	60		field distribution in bays and lagoons of northwestern Gulf of Mexico (Tex.)	101
			24.2	salinity for widest thermal tolerance zone in adult blue crab	59
	0	40	0-27	optimum range with 10-35°C temperatures	314
			10-30	range of no effect on metabolic consumption of oxygen (respiration)	130
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	19
	5-7.5			normal gonadal development near 7.5 ppt; however, oysters with previously ripe gonads spawn when subjected to low (5 ppt) salinities	140
			20-21	larval spat setting requirement in Galveston Bay (Tex.)	347
	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	124

Species	Limits Min. (ppt)	Max.	Preference or Optimum (ppt)	Remarks	Reference
			19–30	maximum survival (80% contour plot) in lab of 2-day larvae at 19–30.5°C temperatures	383
			8–30.5	maximum survival (60% contour plot) in lab of 8-day larvae at temperatures > 21°C	383
			~33	maximum growth (100% contour plot) in lab of 8-day larvae at temperatures > 19°C	383
			18–35	optimum (80% contour plot) for both larval survival and growth at temperatures > 30°C	383
			15–22.5	optimum for juvenile growth and development	25
	1.5	39.0		early experimentally derived salinity limits	9
	0–2			oysters can survive freshwater (0ppt) for several days; increasing to about a month at 2 ppt salinity	309
			15–30	optimum range of salt content	261
	5	40	5–15	tolerance limits and optimum range for growth and survival; higher optimum (10–28 ppt) in cooler waters of northern latitudes (Chesapeake Bay)	378
		43.5–45		distribution limit in Redfish and Corpus Christi Bays (Tex.)	295
			15–20	ideal salinity conditions with lowest seasonal salinities in late summer and fall	1
	2–4	10–22	10.?–16.0	most productive reefs of Mississippi sound subject to 10.0–16.0 ppt average conditions	51
	~ 2			oysters can survive up to four weeks in low salinity at 20–27°C temperatures; mortality increases severely at higher temperatures in Galveston Bay (Tex.)	265
			15–30	best growth in reasonably stable salinity	180
	3			lower tolerance limit about 3 ppt	90
	8–10			lower limit of predator Thais haemastoma, a gastropod oyster drill or conch	90 309
	- 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	304
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	214
			> 30	spawning occurs in estuarine areas of higher salinity (La.)	200
		_ 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	287
	2.3	34.9	5–20	field distribution in Copano and Aransas Bays (Tex.); over 80% collected in 5–20 ppt	318
	- 5	77		field distribution in bays and lagoons at northwestern Gulf of Mexico (Tex.)	101
	10	45	20	operational limits; optimum metabolic condition at 20–28°C temperatures	306
Sciaenops ocellata (red drum)	2.1	32.4	< 15	field distribution in Copano and Aransas Bays (Tex.); greater abundance below 15 ppt	318
	0	> 50	20–40	field distribution (Tex.); range of preference (most abundant in 30–35 ppt); young mature in 3–5 years	319
			< 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	277

Species	Limits Min. (ppt)	Max. (ppt)	Preference or Optimum (ppt)	Remarks	Reference
Pogonias cromis (black drum)	2.6	34.9	<15	field distribution in Copano and Aransas Bays (Tex.); most abundant range 10.0–15.0 ppt	318
	<5	77		field distribution in bays and lagoons of northwestern Gulf of Mexico (Tex.)	101
	0	80		field distribution (Tex.); usual range in Laguna Madre 25–50 ppt	319
	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	277
Halodule wrightii (shoalgrass)	3.5	52.5		range of survival after six week test in laboratory	163
	< 5	80	23–37	plants transferred from 37 ppt to tap water and 5 ppt to conditions retained green tissue (leaves) for two weeks; plants retained green tissue in evaporated artificial seawater salinities up to 80 ppt; 23–37 ppt range of good survival for 13 weeks	165
		> 72		plant leaves showed continuous height increases to 72 ppt as salinity was increased during 55-day test	166
	10	60		salinity range reported for this adaptable tropical species which also tolerates 7–32°C temperatures in nothern Gulf of Mexico	187
Thalassia testudinum (turtlegrass)			28–32	flowering of Florida plants in laboratory	155
			37	flowering (staminate only) of plants from Pt. Isabel (Texas) observed in April following transplantation to 14 and 16 hour photoperiods in laboratory	165
		48	33–38	maximum field distribution in Florida; salinity range of common occurrence	63
		< 60		plant leaves showed no further height increases beyond 60 ppt as salinity was increased during 55-day test	166
	10	50		salinity range of green tissue survival for two weeks or more in laboratory; plants did not survive at 5 ppt salinity for more than a few days	165
			20–35	optimum salinity range reported for this restricted tropical species	63
Syringodium filiforme (manateegrass)		40		plant leaves showed height increases to 40 ppt as salinity was increased during 55-day test	166
		44		plants were rated not vigorous at 44 ppt salinity and died after three-week laboratory test at 52.5 ppt	163
	10	50		salinity range of green tissue survival for two weeks or more in laboratory; plants did not survive at 5 ppt and 60 ppt salinity	165
Halophila engelmanni			37	plants flowered profusely in March following transplantation to 14-hour photoperiod in laboratory	165
			25–36	plants observed flowering in Redfish Bay (Texas) from April to June at 25–29°C temperatures	164
	13–18	50	23–37	plants transferred from 37 ppt to 13 ppt and 18 ppt salinity retained some green tissue for at least a week; plants did not survive at 50 ppt past eight weeks; 23–37 ppt salinity range of good survival for 13 weeks	165
Ruppia maritima (widgeongrass)			< 28	flowering and seed formation reported to occur in Florida below 28 ppt salinity	15
		33.2	< 25	maximum field distribution in Florida; flowering and greatest plant occurrence in areas < 25 ppt salinity	63
	0		< 30	plants survived indefinitely in tap water; flowering in laboratory of Redfish Bay (Texas) plants observed in tap water and salinities < 30 ppt	165
		74	< 46	plants tolerated salinities up to 74 ppt for brief periods in laboratory; plant leaves showed height increases to 46 ppt as salinity was increased in outdoor tank during 55-day test	166

Table 9-2. Salinity Characteristics of Upper Baffin Bay and Lower Laguna Madre at the Arroyo Colorado and the Intracoastal Waterway (ICWW)

Month	Salinity in Upper Baffin Bay a/ (ppt)			Salinity at Arroyo Colorado and ICWW b/ (ppt)		
	Upper c/ Viability Limit	Lower c/ Viability Limit	Median d/ Historic Salinity	Upper c/ Viability Limit	Lower c/ Viability Limit	Median e/ Historic Salinity
January	45	20	33	45	15	42
February	45	20	35	45	15	38
March	45	15	29	45	15	40
April	35	10	28	35	10	38
May	35	10	28	35	10	34
June	35	10	17	35	10	33
July	45	10	14	45	10	37
August	45	10	14	45	10	39
September	35	10	15	35	10	29
October	35	10	13	35	10	31
November	40	15	14	40	15	36
December	45	15	24	45	15	37

a/ Represented by sampling site 2 on linesite 82 (Figure 3-10).
b/ Represented by the sampling site on linesite 217 (Figure 3-10).
c/ These values estimate the limits of long-term viable species activity at control points in the system, and not individual organism survival limits (Table 9-1).
d/ Based on the period 1969 through 1979. Insufficient data was available to estimate mean monthly salinities in years prior to 1969.
e/ Based on the period 1941 through 1976.

in the estuary below the "Null Zone"*: (1) in upper Baffin Bay near Laguna Salado and (2) in lower Laguna Madre near the mouth of the Arroyo Colorado. The limits are expressed as mean (average) monthly salinities for general limits of viability. From both locations, salinities generally increase towards the Gulf inlets (Brazos Santiago Pass and Aransas Pass) and eventually attain seawater concentration (35 ppt). The salinity gradient in the estuary is thus less distinct during seasonal low inflow (e.g., the summer), increasing steeply during seasons of higher freshwater inflow (e.g., the autumn). However, extreme low inflows which persist over several months can produce hypersaline conditions (salinities greater than seawater) in parts of the Laguna Madre estuary, a frequent occurrence as noted in Chapter V. Nevertheless, the estuarine-dependent species, particularly the finfish, have successfully adapted to this lagoonal regime of relatively high, stable salinities, and are today productively associated with local and state economies.

Although the fisheries species can generally tolerate salinities greater or less than the monthly specified viability range, foraging for food and production of body tissue (growth) becomes increasingly more difficult under extreme salinities, and may eventually cease altogether because body maintenance requirements consume an increasing amount of an organism's available energy under unfavorable conditions. High mortality and low production are expected during prolonged extremes of primary environmental factors such as salinity and temperature.

Monthly Salinity Conditions

The salinities within an estuarine system fluctuate with variations in freshwater inflow. During periods of flood or drought, salinity regimes may be so altered from normal conditions that motile species commonly residing in an estuary may migrate to other areas where the environmental conditions are more suitable. Generally, however, the estuarine-dependent species will remain in the system during normal periodic salinity fluctuations. Should the normal salinity conditions be altered for prolonged periods due to natural or man-made causes, the diversity, distribution and productivity of species within an estuary will be restricted.

The median monthly salinity is a measure of the normal monthly salinity condition at a point in an estuary. The median monthly salinity is that value for which one-half of the observed average monthly salinities exceed the value and one-half are less. The median monthly salinity thus reflects an "expected" salinity in the estuary and represents a numerical value exceeded 50 percent of the time. Median historic salinities have been computed for the two control points in upper Baffin Bay and near the mouth of the Arroyo Colorado (Table 9-2) for which the salinity regression equations were developed in Chapter V. These median monthly salinities are associated with the

* 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 (360, 99).

1969 through 1979 period for which daily gaged inflow data were available. The inflows into Laguna Madre are above average for this overall period (see Figure IV-6), but minor drought conditions also occurred during this time.

Marsh Inundation Needs

The periodic inundation of deltaic marshes serves to maintain shallow protected habitats for postlarval and juvenile stages of several important estuarine species, provides a suitable fluid medium for nutrient exchange processes, and acts as a transport mechanism to move detrital food materials from the deltaic marsh into the open estuary. The areal extent of deltaic marsh inundation is a function of the channel capacity, discharge rate and volume, wind direction, and tidal stage.

Generally, estuaries on the Texas coast are heavily dependent upon the cycling of nutrients through adjacent freshwater and brackish marsh systems along the periphery of their shorelines. However, the ecology of the Laguna Madre has been shown to be dominated by macrophytic organisms (i.e., rooted vascular plants), particularly varieties of seagrasses that proliferate in both the upper and lower portions of the estuary. Since nutrient transfers through a riverine delta are not a significant source of nutrients to Laguna Madre, it is not necessary to consider freshwater inundation of marshes adjacent to the Laguna Madre in the estimation of freshwater inflow needs.

Estuarine Mathematical Programming Model Description

The combination of specified objectives and environmental and physical constraints relating the interactions of freshwater inflows with selected estuarine indicators is termed the Estuarine Mathematical 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 contributing streams into Baffin Bay and into lower Laguna Madre. Linear Programming (43) and Nonlinear Programming (107) optimization procedures are used to compute the monthly freshwater inflows needed to meet specified salinity and commercial bay and offshore fisheries harvest levels. Particularly, the GRG2 computer program developed by Lasdon (133) is utilized extensively to determine the optimal inflow need estimates. The quantifications of salinity and commercial fisheries harvest as functions of seasonal freshwater inflow are represented by the statistical regression equations given in Chapters V and VIII, respectively.

Specification of Objectives. The criteria or objectives in this optimization formulation can be any desired estuarine condition. One objective of interest is to compute the minimum annual inflow to the estuary that meets the constraints on the salinity regime and marsh inundation. Another alternative could be to compute the estimated quantity of freshwater inflow to maximize the estimated commercial harvests in the estuary. This harvest could be either for an individual fisheries species, a weighted sum of the harvests of a group of the commercially important species (e.g., shellfish) or other combinations.

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

(1) upper and lower limits for the seasonal inflows used in the regression equations which estimate annual commercial bay fisheries harvests,

(2) statistical regression equations relating mean monthly salinities to mean monthly freshwater inflows,

(3) upper and lower limits on the monthly inflows used in computing the salinity regression relationships, and

(4) upper and lower viability limits on allowable monthly salinities (Table 9-2).

Alternative Estuarine Objectives

Three alternative objectives are considered as follows:

Alternative I, Subsistence
Objective: minimize annual combined inflow to the estuary while meeting salinity viability limits;

Alternative II, Maintenance of Fisheries Harvests
Objective: minimize annual combined inflow to the estuary while providing freshwater inflows sufficient to provide predicted combined annual commercial bay harvests separately for both the upper Laguna Madre (including Baffin Bay) and lower portions of the estuary (including Offshore Gulf Area 21, an area extending approximately 30 miles offshore and bounded by latitudes 26°N, 27°N, longitude 96°30'W, and Padre Island) for red drum, spotted seatrout, black drum, white shrimp, brown and pink shrimp, and bay oysters at levels no less than their mean 1962 through 1976 historical values, and meeting viability limits for salinity;

Alternative III, Harvest Enhancement
Objective: maximize the total annual commercial bay harvests of all finfish in upper Laguna Madre and of all shrimp offshore of lower Laguna Madre in Gulf Area 21, while observing salinity viability limits, utilizing annual combined inflows to each portion (i.e., upper and lower) of the estuary no greater than their average historical inflows over the 1941 through 1976 period, and maintaining the total annual commercial finfish harvest in lower Laguna Madre at no less than the mean 1962 through 1976 historical level.

The objectives and constraints for the listed alternatives are indicated in Table 9-3. The three specified objectives are not the only possible options for the Laguna Madre estuary; however, they provide a range of alternatives: survival or subsistence (Alternative I), maintenance of bay harvest levels (Alternative II), and harvest enhancement (Alternative III). An

Table 9-3. Criteria and System Performance Restrictions for the Selected Estuarine Alternatives

	Alternatives		
	I	II	III
Criteria:			
• Maximize Sum of Annual Upper Laguna Madre Finfish Harvest and Lower Laguna Madre Shrimp Harvest from Offshore Area 21			x
• Least Possible Annual Combined Inflow	x	x	
Constraints:			
• Annual Inflow from the Baffin Bay and Lower Laguna Madre drainage areas are each no greater than their Average Annual Historical Values (1941-1976)			x
• Predicted Annual Spotted Seatrout, Red Drum, and Black Drum Commercial Harvests in both Lower and Upper Laguna Madre no less than their Average Annual Values (1962-1976)		x	
• Predicted Annual Finfish Commercial Harvest in Lower Laguna Madre no less than the average Finfish Harvest (1962-1976)			x
• Predicted Annual White Shrimp, Brown and Pink Shrimp, and Bay Oyster Commercial Harvests are each no less than their Average Harvests (1962-1976)		x	
• Upper and Lower Limits on Seasonal Inflows to Insure Validity of Predictive Harvest Equations	x	x	x
• Upper and Lower Limits on Mean Monthly Salinity	x	x	x
• Upper and Lower Limits on Monthly Inflows to Insure Validity of Predictive Salinity Equations	x	x	x

additional enhancement alternative which could be evaluated is the maximization of the total finfish commercial harvest in the estuary.

Alternative I: Subsistence. The objective of Alternative I (Subsistence) is to minimize total annual freshwater inflows while meeting specified bounds on salinity in Baffin Bay and near the mouth of the Arroyo Colorado (Table 9-2). The upper salinity bound for each month at each of the two key locations is taken as the minimum of the monthly upper viability limit and the historic median monthly salinity (Table 9-2).

Optimal monthly inflows to the estuary needed to meet the objective are determined by the Estuarine Mathematical Programming Model. The estimated annual combined inflow[1/] need amounts to approximately 344.4 thousand acre-feet (424.8 million m^3), with 38.2 thousand acre-feet (47.1 million m^3) for Baffin Bay and upper Laguna Madre and 306.3 thousand acre-feet (377.8 million m^3) for lower Laguna Madre (Table 9-4). This annual inflow is approximately 50 percent of the mean historical total inflow to the estuary over the period 1941 through 1976.

Monthly freshwater inflow needs calculated by the Estuarine Programming Model for Alternative I provide salinities which closely approximate those for the required upper bounds during most months of the year (Figures 9-2 and 9-3). Baffin Bay salinities during the months of February, April, June, and December are lower than the maximum allowed as a consequence of the impact of the inflows in the months immediately previous upon the salinities in these months.

Comparisons between the mean historical combined inflows and the estimated freshwater inflow needs for upper and lower Laguna Madre (Figures 9-4 and 9-5) indicate that the estimated monthly freshwater inflow needs are less than the mean historical inflows except for the months of March and November in upper Laguna Madre. The distribution of the total estuarine freshwater inflow need between the upper and lower portions of estuary, illustrated in Figure 9-6, patterns the natural runoff contribution with the predominant inflow need in the lower estuary.

Implementation of Alternative I for the Laguna Madre estuary under the inflow regime indicated in Table 9-4 is projected to result in decreases in the majority of commercial fisheries harvest categories over the average historical levels in the 1962 through 1976 period (Figures 9-7, 9-8, and 9-9). The all-finfish category is predicted to have an annual harvest of almost 2.4 million pounds (1.1 million kg) for the entire estuary (Figure 9-9), or a 9 percent increase over the historic mean of 2.2 million pounds (997 thousand kg). Predictions, based upon independent harvest equations from Chapter VIII, for upper and lower Laguna Madre commercial finfish harvests are 765 thousand pounds (347 thousand kg) and 1.43 million pounds (649 thousand kg), respectively. Fisheries harvests in upper Laguna Madre are predicted to be below the 1962-1976 mean historic commercial catch for all species categories (Figure 9-7), under the Alternative I inflows. Commercial fisheries harvest

1/ Combined inflow does not include direct precipitation on the estuary's surface (see Chapter IV for definition).

Table 9-4. Freshwater Inflow Needs of the Laguna Madre Estuary under Alternative I a/

Month	Baffin Bay and Upper Laguna Madre b/		Lower Laguna Madre b/		Combined Inflow e/
	Total Inflow Needs	Inflow Need from Gaged Portion of the Basin c/	Total Inflow Needs	Inflow Need from Gaged Portion of the Basin d/	
	(Thousands of Acre-Feet)				
January	1.62	0.13	16.88	10.35	18.50
February	1.33	0.08	17.19	10.52	18.52
March	2.47	0.25	19.12	11.55	21.59
April	1.33	0.08	27.08	15.69	28.41
May	4.08	0.48	28.77	16.54	32.85
June	4.94	0.61	28.48	16.40	33.42
July	3.21	0.36	21.20	12.65	24.41
August	4.72	0.58	18.06	10.99	22.78
September	7.46	0.97	48.03	25.96	55.49
October	1.87	0.16	34.65	19.48	36.52
November	3.91	0.46	23.52	13.86	27.43
December	1.24	0.07	23.27	13.73	24.51
Annual	38.18	4.23	306.25	177.72	344.43

a/ All inflows are mean monthly values.

b/ The upper and lower portion of the estuary are separated by the "land cut".

c/ These values computed using regression equation relating monthly inflow to the estuary with the sum of the monthly gaged inflows at the USGS streamflow measuring stations on San Fernando Creek at Alice and on Los Almos Creek near Falfurrias.

d/ These values computed using regression equation relating monthly inflow the the estuary with monthly gaged inflows at the USGS streamflow measuring stations on the Arroyo Colorado at Harlingen and the North Floodway near Sebastian.

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

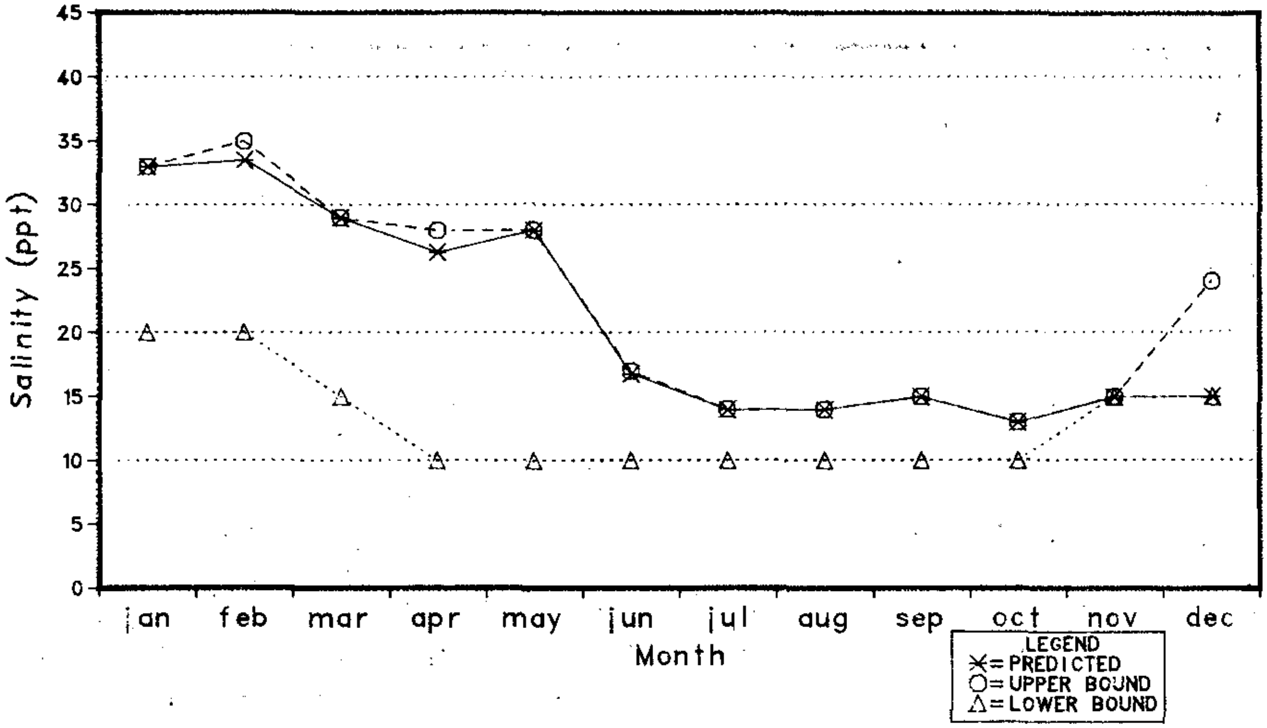


Figure 9-2. Average Monthly Salinities in Upper Baffin Bay Under Alternative I

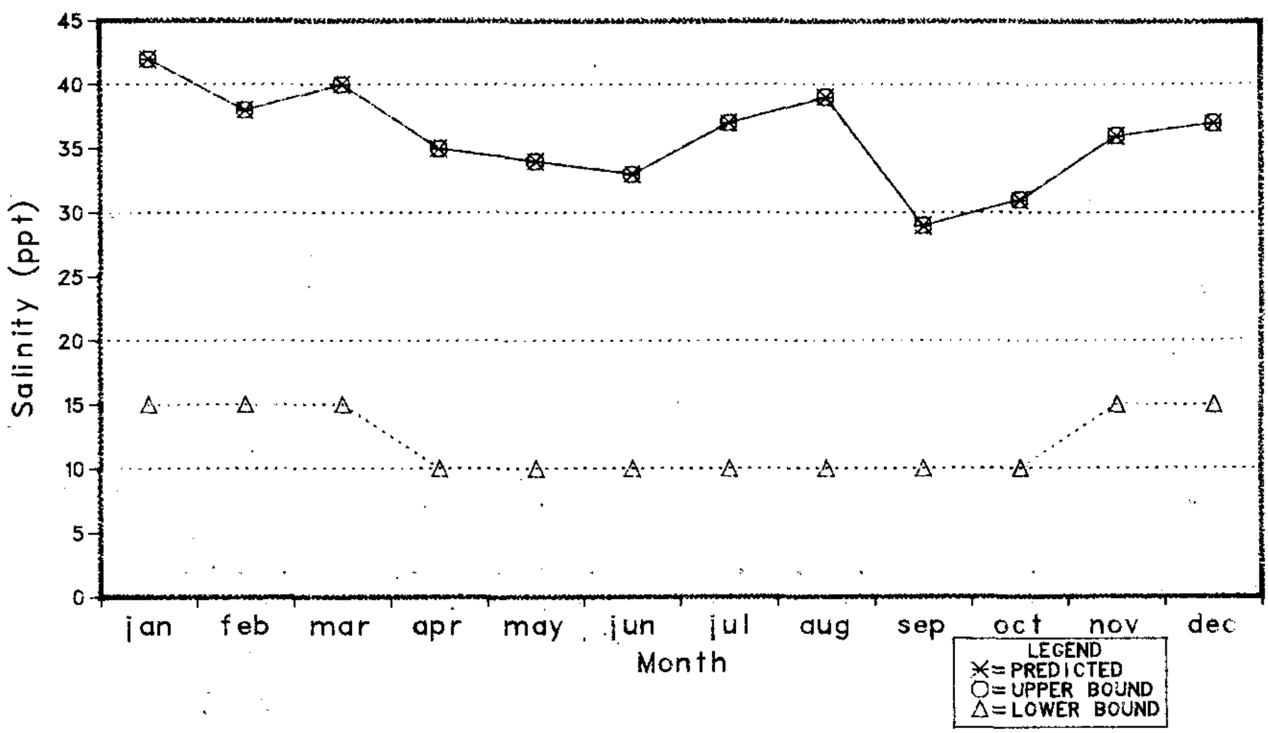


Figure 9-3. Average Monthly Salinities at Intersection of Intracoastal Waterway and Arroyo Colorado Under Alternative I

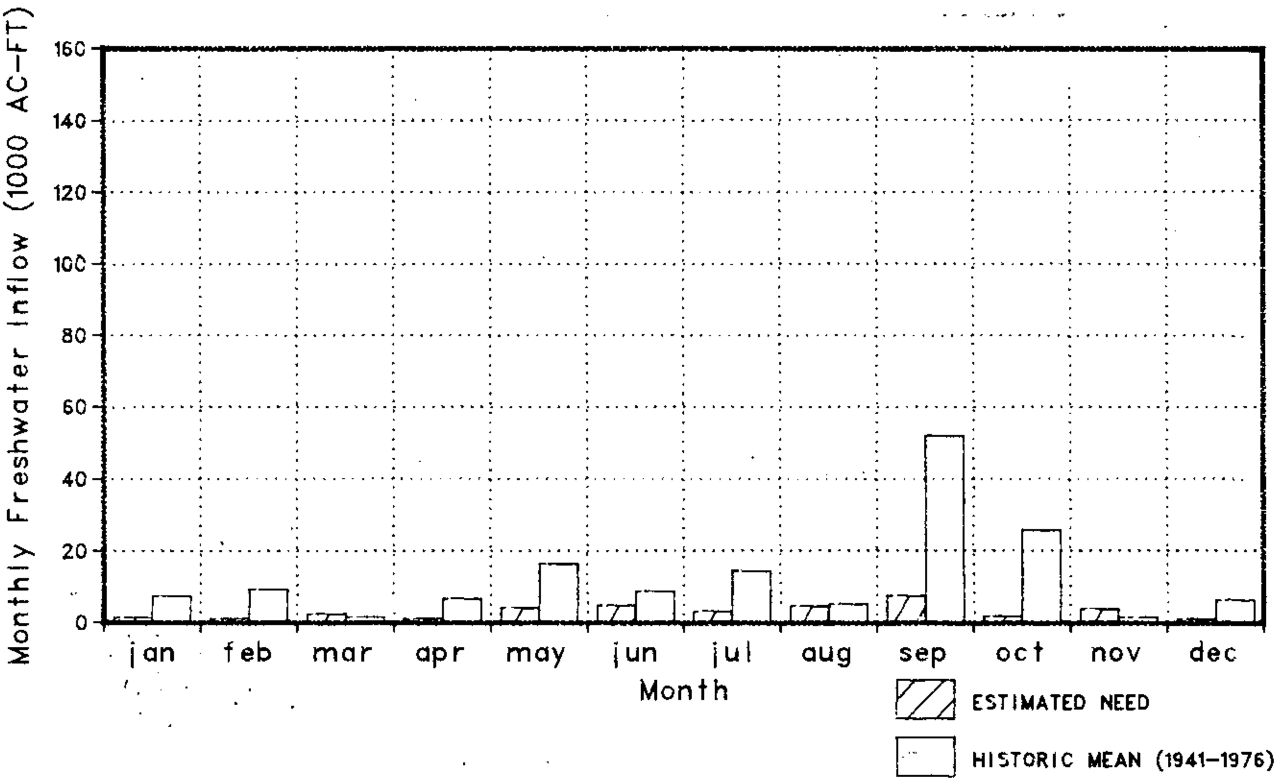


Figure 9-4. Comparison Between Mean Historical Freshwater Inflow and Inflow Needs for Baffin Bay and Upper Laguna Madre Under Alternative I

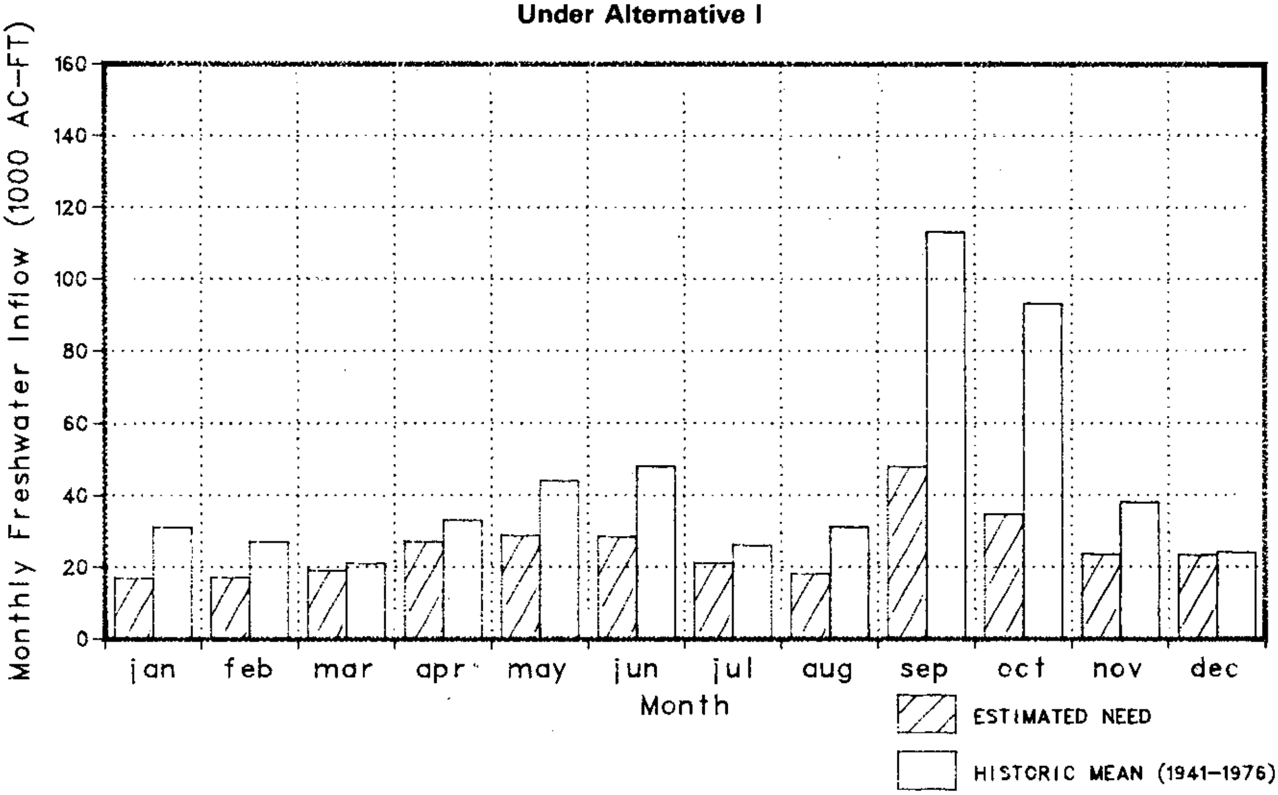


Figure 9-5. Comparison Between Mean Historical Freshwater Inflow and Inflow Needs for Lower Laguna Madre Under Alternative I

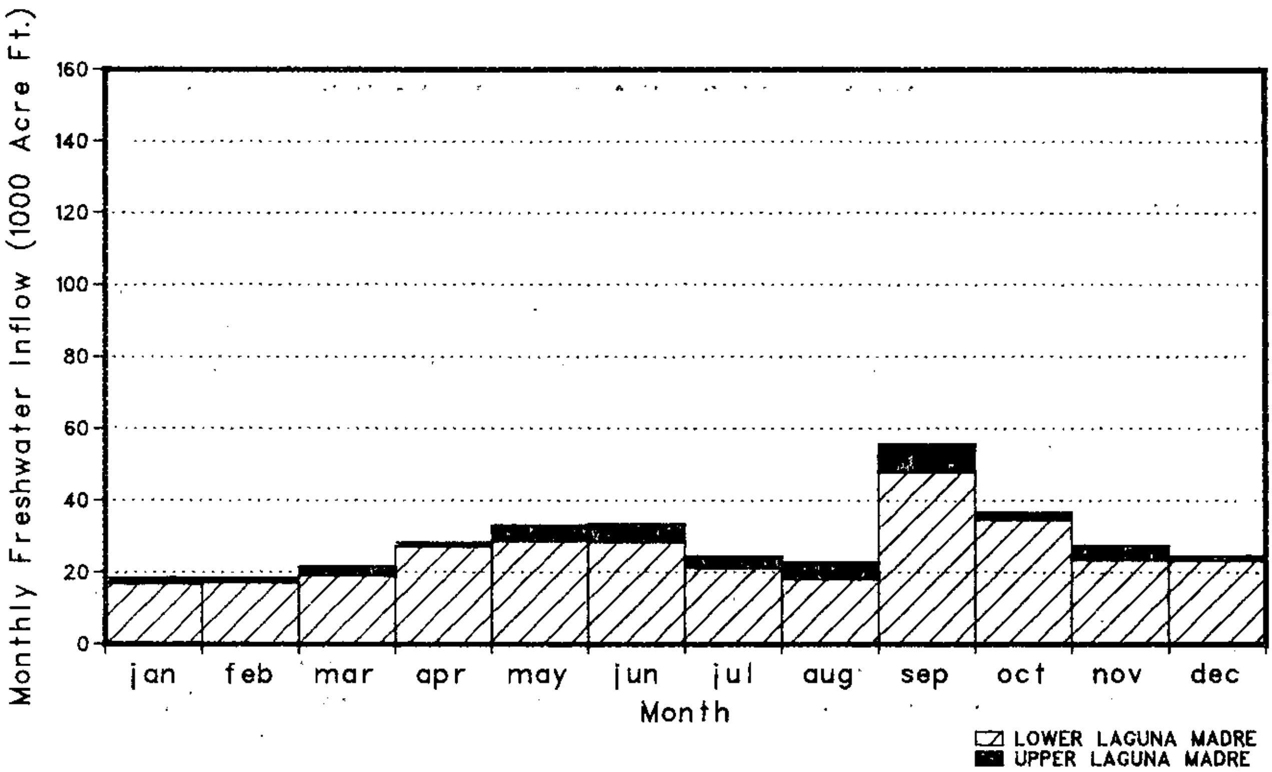


Figure 9-6. Estimated Freshwater Inflow Needs for the Laguna Madre Estuary Under Alternative I

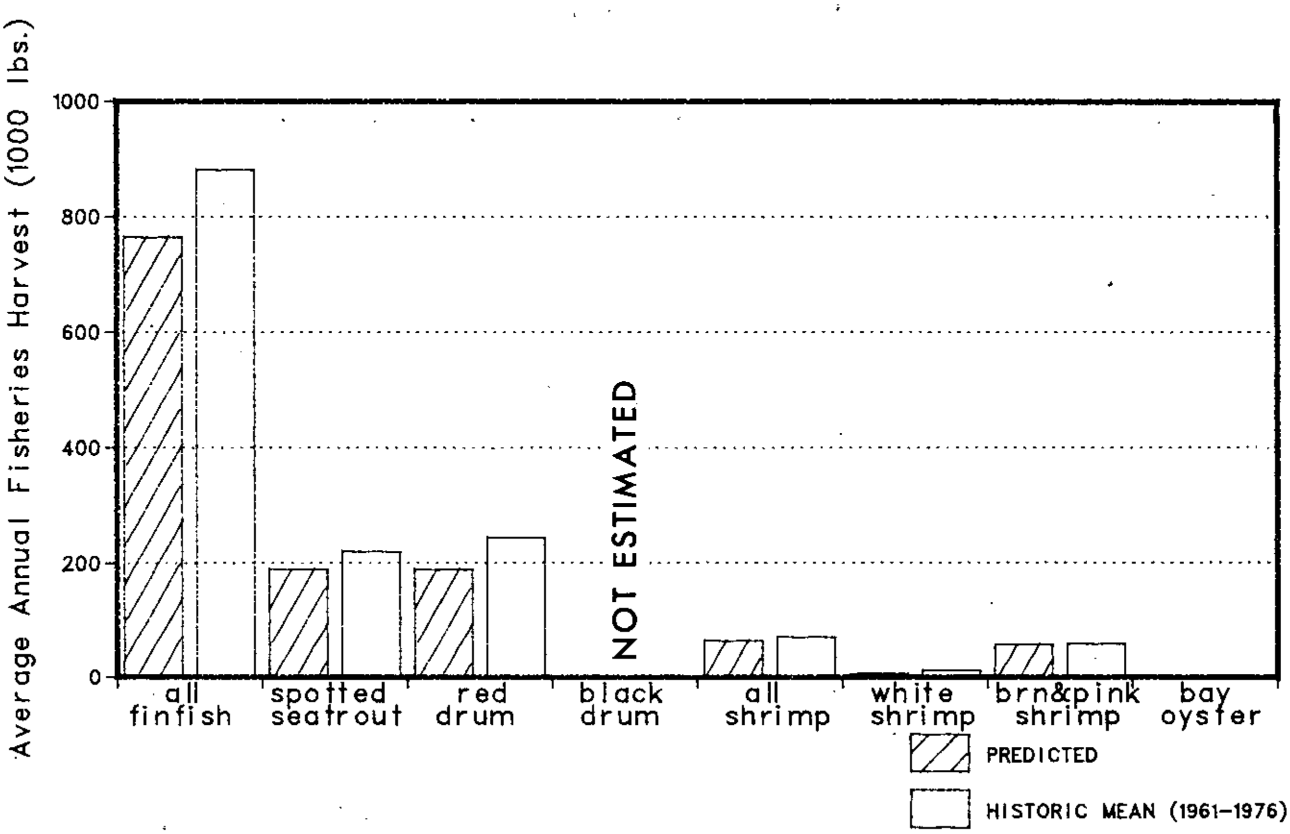


Figure 9-7. Comparison Between Upper Laguna Madre Historical Fisheries Harvest and Predicted Harvests Under Alternative I

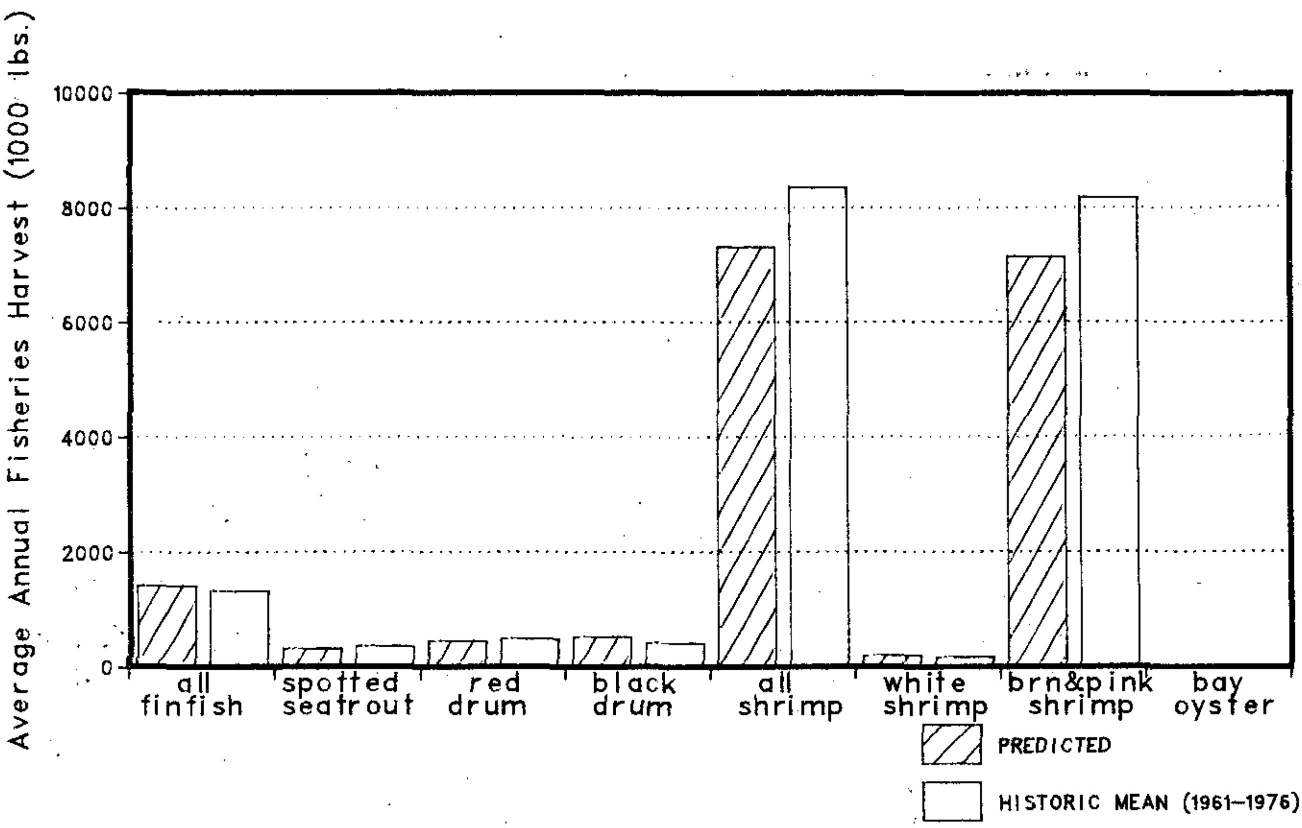


Figure 9-8. Comparison Between Lower Laguna Madre Historical Fisheries Harvests and Predicted Harvests Under Alternative I

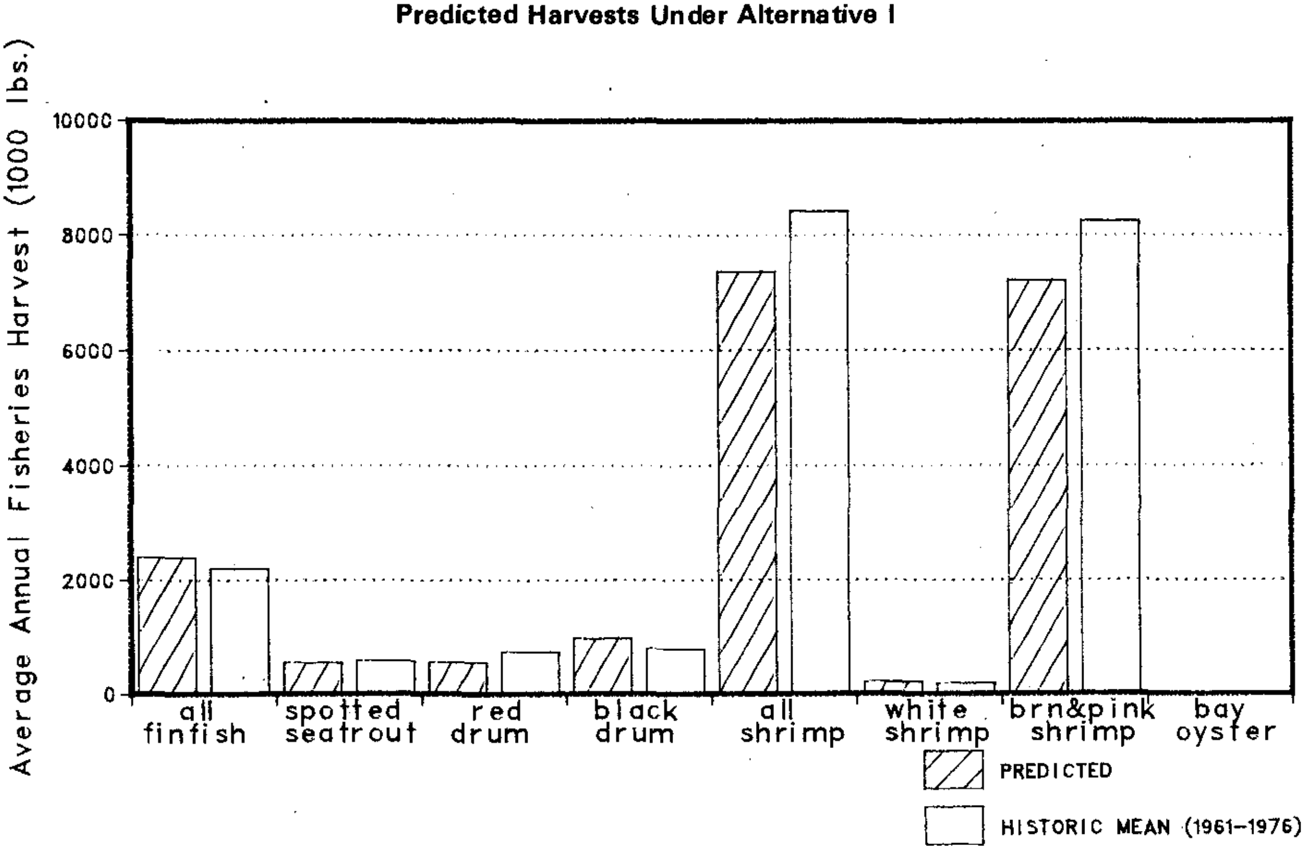


Figure 9-9. Comparison Between Laguna Madre Estuary Historical Fisheries Harvests and Predicted Harvests Under Alternative I

in lower Laguna Madre (Figure 9-8) are also estimated to be below average, with the combined estuarine and associated Offshore Area No. 21 shrimp harvest estimated at 7.32 million pounds (3.32 million kg), or about 12 percent below the average harvest.

Alternative II: Maintenance of Fisheries Harvest. The objective of Alternative II (Maintenance of Fisheries Harvests) is to minimize combined freshwater inflow to the estuary while providing inflows sufficient to generate predicted annual commercial harvests of red drum, black drum, seatrout, white shrimp, brown and pink shrimp, and bay oysters separately in both upper and lower Laguna Madre at levels no less than their mean 1962 through 1976 historical values and meet viability bounds for salinity (Figure 9-2).

The optimal set of monthly freshwater inflow needs derived by the Estuarine Programming Model for Alternative II (Table 9-5) amounts to 578.0 thousand acre-feet (713.0 million m^3) annually, of which 50.0 thousand acre-feet (61.7 million m^3) is contributed to the upper Laguna Madre. This annual volume to the estuary represents 84 percent of the combined average 1941 through 1976 historical freshwater inflow.

The Estuarine Programming Model does not specify unique monthly inflow needs for the upper or lower Laguna Madre in the spring (April, May and June) and summer (July and August), or for the lower portion of the estuary in the fall (September and October) season. The inflows in these seasons which are greater than the inflows needed in the individual months for salinity maintenance could be distributed on a monthly basis in any desired manner since the inflow variables in the fisheries equations represent seasonal inflows. It was decided to distribute the inflows in the above seasons to individual months based upon the historical (1941-1976) inflow distribution within each monthly grouping (see Chapter III), while observing monthly salinity needs.

Monthly freshwater inflow need estimates for Alternative II provide salinities in upper Baffin Bay (Figure 9-10) which are significantly lower during the months of April through August than those under Alternative I, but which continue to closely approximate the upper salinity bounds in the majority of the remaining months. The salinities predicted in June through October near the mouth of the Arroyo Colorado (Figure 9-11) are also considerably lower for Alternative II over Alternative I. Predicted salinities are lower for this alternative than those for Alternative I during critical seasons of fisheries productivity since additional inflow is supplied to increase fisheries harvests.

Comparisons between the mean historical 1941 through 1976 combined monthly inflows and estimated freshwater inflow needs for Alternative II were made for the upper and lower estuarine contributing areas (Figures 9-12 and 9-13). The average historical inflows from the upper areas around Baffin Bay are greater for each month than the freshwater inflow needs under this alternative, with the exception of March and November. In the lower estuary, larger monthly inflows than the historic mean are needed in July through October to increase the shrimp harvest and maintain desired salinities. The monthly distribution the combined estuarine inflow needs to achieve Alternative II (Maintenance of Fisheries Harvests) as indicated in Figure 9-14.

Table 9-5. Freshwater Inflow Needs of the Laguna Madre Estuary under Alternative II a/

Month	Baffin Bay and Upper Laguna Madre b/: Total Inflow Needs	Baffin Bay and Upper Laguna Madre b/: Inflow Need from Gaged Portion of the Basin c/	Lower Laguna Madre b/: Total Inflow Needs	Lower Laguna Madre b/: Inflow Need from Gaged Portion of the Basin d/	Combined Inflow e/
	Thousands of Acre-Feet				
January	1.33	.08	16.88	10.35	18.21
February	1.49	.11	17.19	10.52	18.68
March	2.30	.23	19.12	11.55	21.42
April	3.41 f/	.39	27.08 h/	15.69	30.49
May	9.66 f/	1.29	28.77 h/	16.54	38.43
June	4.54 f/	.55	42.65 h/	23.38	47.19
July	7.82 g/	1.02	30.17 i/	17.25	37.99
August	4.72 g/	.57	35.41 i/	19.86	40.13
September	7.46	.97	145.15 j/	68.59	152.61
October	2.16	.20	118.76 j/	57.50	120.92
November	3.62	.42	23.52	13.86	27.14
December	1.53	.11	23.27	13.73	24.80
Annual	50.04	5.94	527.97	278.83	578.01

a/ All inflows are mean monthly values.

b/ The upper and lower portion of the estuary are separated by the "land cut".

c/ These values computed using equation relating monthly inflow to the estuary with sum of the monthly gaged inflows at the USGS streamflow measuring stations on San Fernando Creek at Alice and on Los Almos Creek near Falfurrias.

d/ These values computed using regression equation relating monthly inflow to the estuary with monthly gaged inflows at the USGS streamflow measuring stations on the Arroyo Colorado at Harlingen and the North Floodway near Sebastian.

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

f/ Total seasonal freshwater inflow need distributed according to 1941-1976 average upper Laguna Madre monthly inflow distribution in the season (April, May and June).

g/ Total seasonal freshwater inflow need distributed as near as possible to 1941-1976 average upper Laguna Madre monthly inflow distribution in the season (July and August).

h/ Total seasonal freshwater inflow need distributed as near as possible to 1941-1976 average lower Laguna Madre monthly inflow distribution in the season (April, May and June).

i/ Total seasonal freshwater inflow need distributed according to 1941-1976 average lower Laguna Madre monthly inflow distribution in the season (July and August).

j/ Total seasonal freshwater inflow need distributed according to 1941-1976 average lower Laguna Madre monthly inflow distribution in the season (September and October).

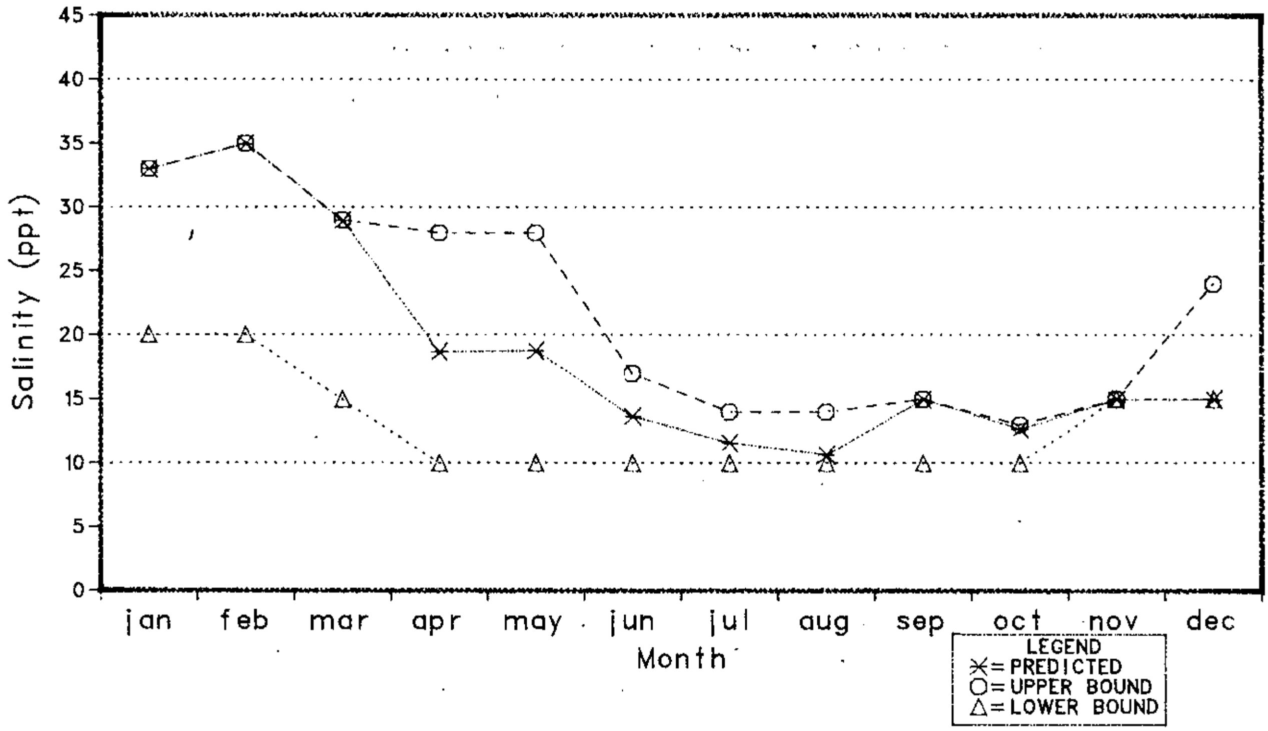


Figure 9-10. Average Monthly Salinity in Upper Baffin Bay Under Alternative II.

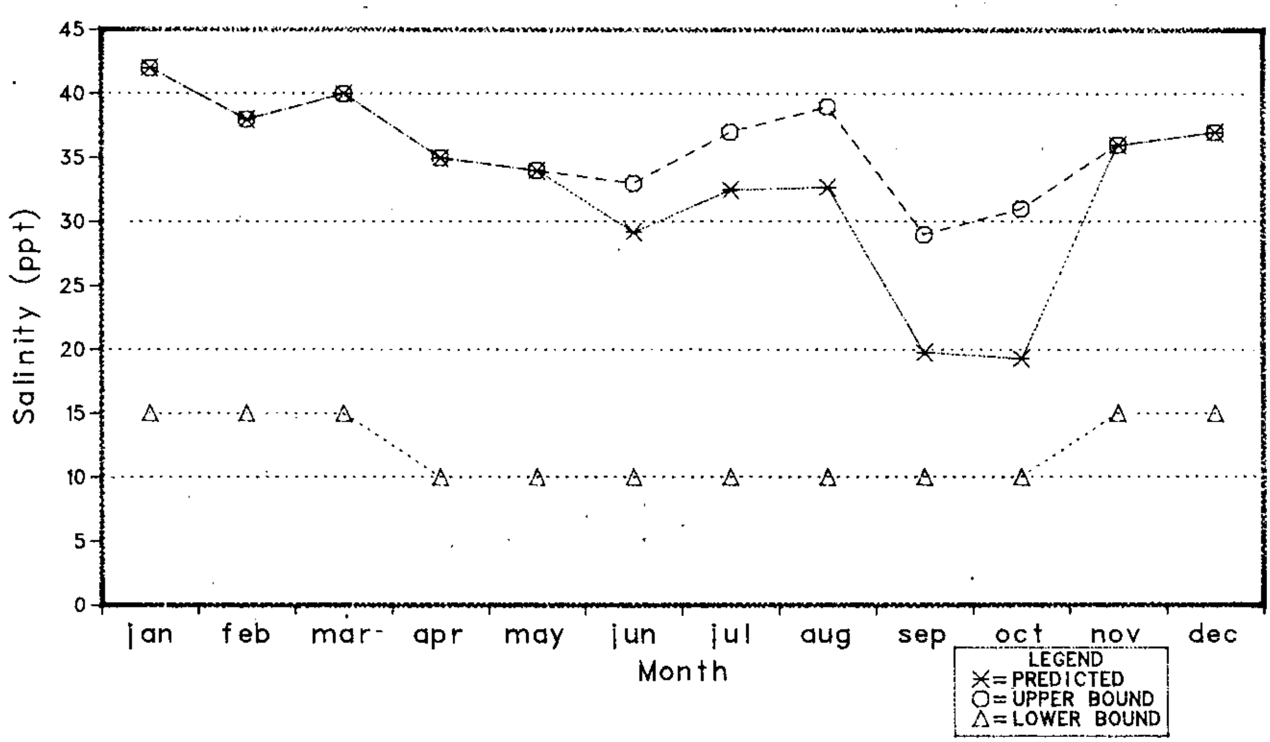


Figure 9-11. Average Monthly Salinities at Intersection of Intracoastal Waterway and Arroyo Colorado Under Alternative II

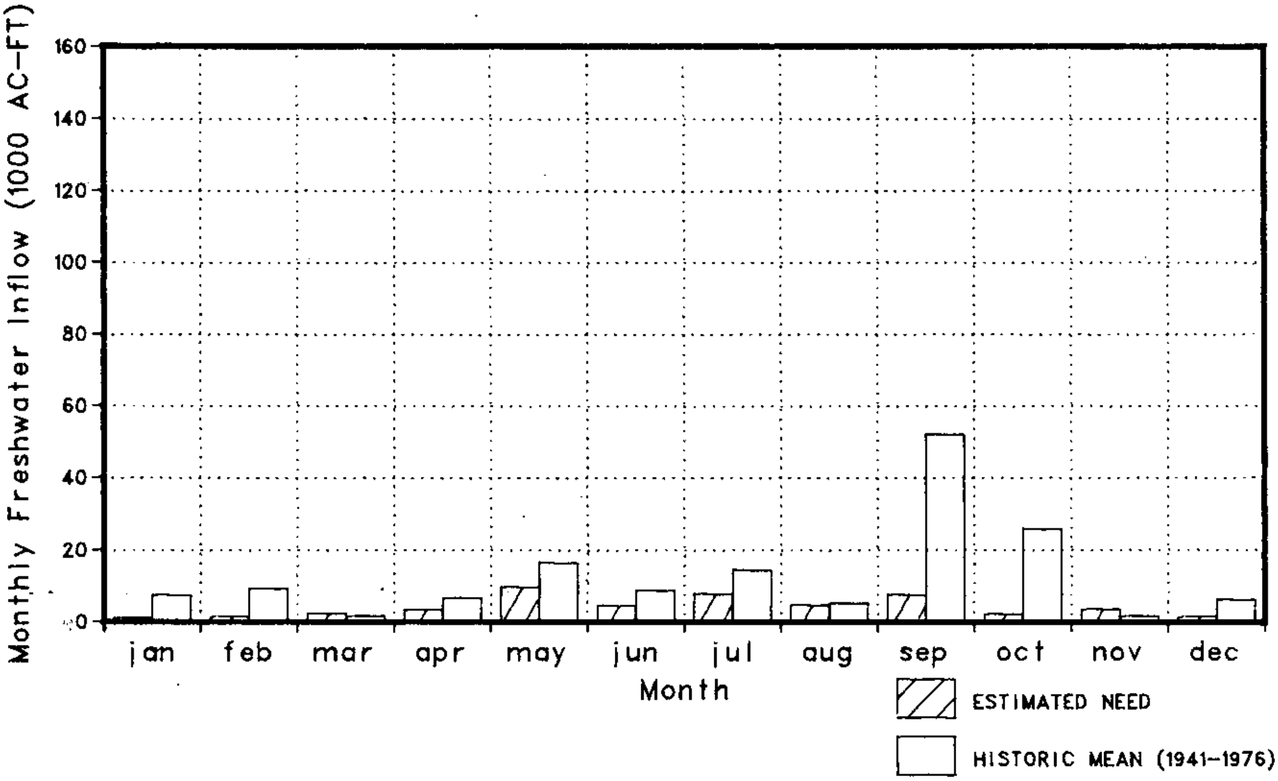


Figure 9-12. Comparison Between Mean Historical Freshwater Inflow and Inflow Needs for Upper Laguna Madre and Baffin Bay Under Alternative II

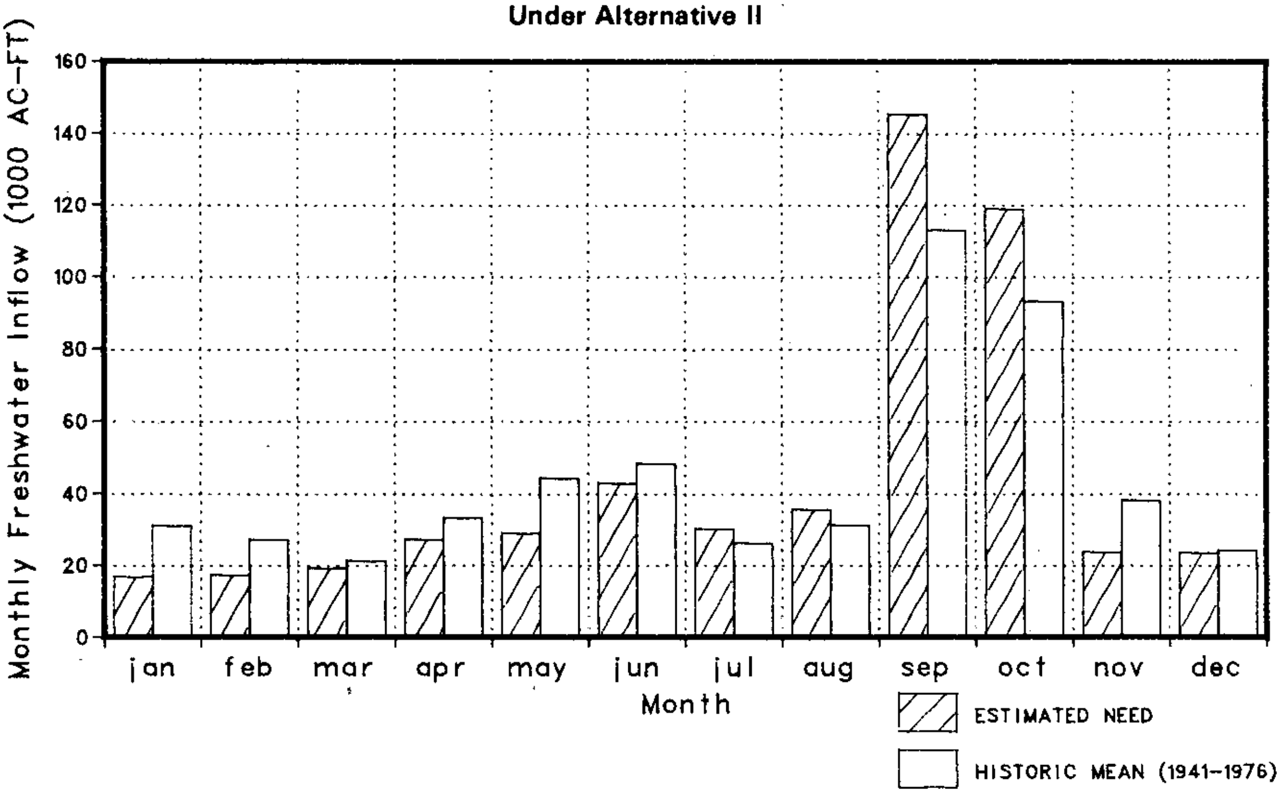


Figure 9-13. Comparison Between Mean Historical Freshwater Inflow and Inflow Needs for Lower Laguna Madre Under Alternative II

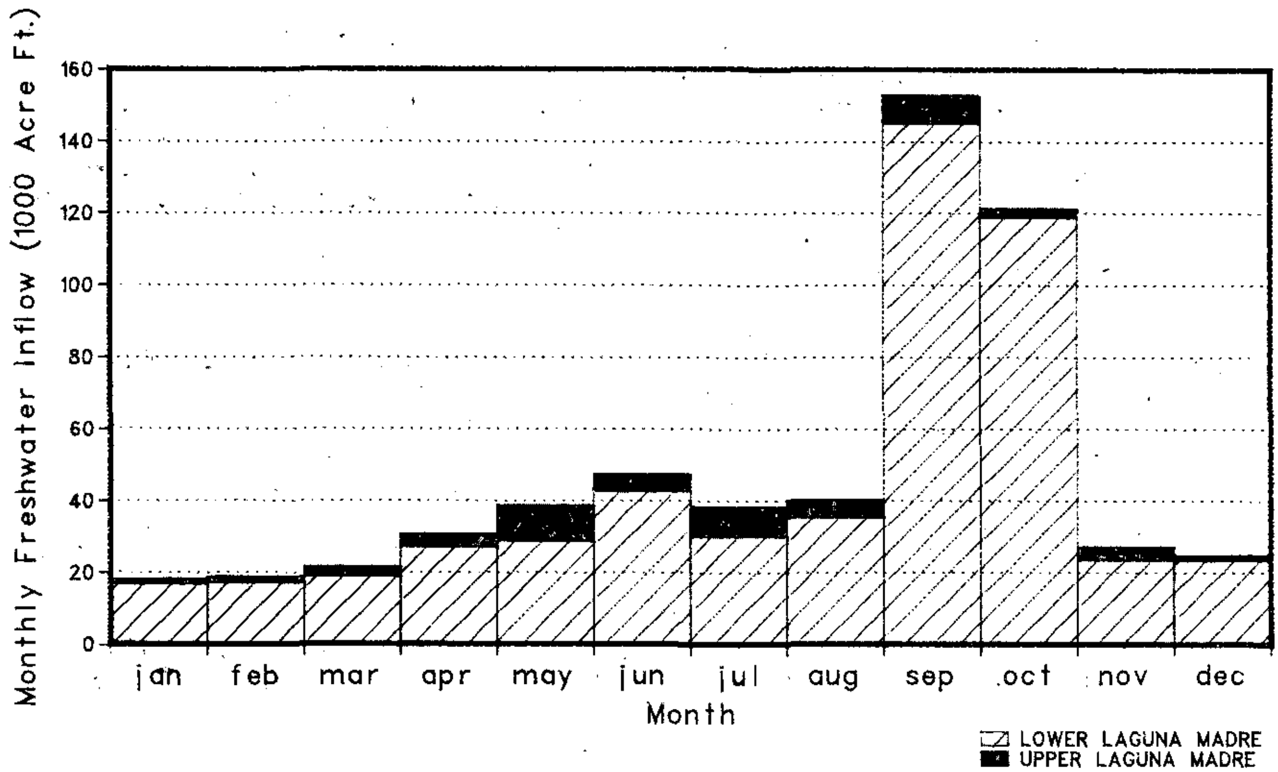


Figure 9-14. Estimated Freshwater Inflow Needs for the Laguna Madre Estuary Under Alternative II

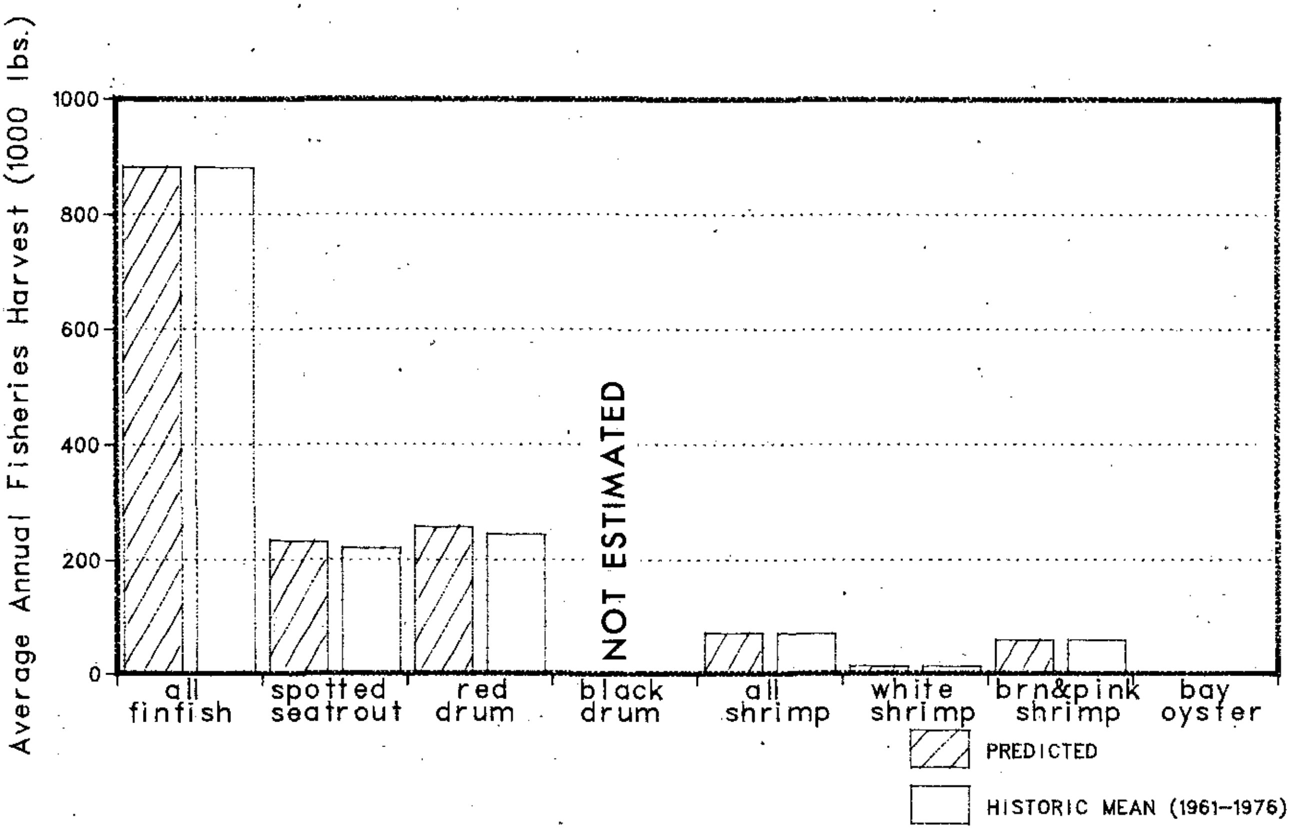


Figure 9-15. Comparison Between Upper Laguna Madre Historical Fisheries Harvests and Predicted Harvests Under Alternative II

Implementation of the inflow regime for Alternative II indicated in Table 9-5 is projected to result in commercial fisheries harvests at least as large as the average historical levels over the 1962 through 1976 period for all species harvest groups in both the upper (Figure 9-15) and lower (Figure 9-16) portions of the estuary. The total estuarine finfish harvest is projected to be 24 percent greater than the historical annual average (Figure 9-17), while the combined estuarine and offshore shrimp harvest is estimated to equal the mean historical 1962 through 1976 harvest.

<u>Alternative III: Harvest Enhancement</u>. The objective of Alternative III (Harvest Enhancement) is to maximize the annual estuarine commercial finfish harvest in upper Laguna Madre and the harvest of all shrimp offshore of lower Laguna Madre in Gulf Area No. 21, while observing salinity viability limits, utilizing annual freshwater inflows at levels no greater than their respective average historical 1941 through 1976 annual inflows, and maintaining the estimated annual commercial finfish harvest in lower Laguna Madre at a level no less than the mean 1962-1976 annual harvest.

The Estuarine Programming Model was utilized to determine an optimal set of monthly inflows to meet the stated objective (Table 9-6). The annual combined inflow from freshwater sources needed to maximize the finfish and shrimp harvests are estimated at approximately 602 thousand acre-feet (743 million m^3). The total annual contribution to the Baffin Bay area is estimated at about 70 thousand acre-feet (86 million m^3), while the corresponding lower Laguna Madre contribution is 532 thousand acre-feet (656 million m^3). As with Alternative II, seasonal inflow needs in excess on monthly salinity needs are distributed monthly on the basis of historical month inflow distribution, as indicated in Table 9-6, consistent with the minimum monthly salinity needs. The estimated annual inflow need is 88 percent of the 1941-1976 average annual inflow for the estuary, with the lower Laguna Madre need equal to 100 percent of the average inflow in that portion of the estuary.

Monthly freshwater inflow needs generated for Alternative III provide salinities which are lower in the majority of months for Baffin Bay (Figure 9-18) than those under Alternative II (Figures 9-10). The spring, summer and late fall months, in particular, for Baffin Bay have salinities considerably lower than those under Alternatives I or II. Salinities in lower Laguna Madre are markedly lower under Alternative III in the winter months, when inflows are required to maximize the offshore shrimp harvest, but are greater than those for Alternative II in June through October.

Comparisons between the mean historical 1941-1976 monthly inflows and the estimated freshwater inflow needs under Alternative III have been made for the upper and lower estuary (Figures 9-20 and 9-21). The average historical inflows for the Baffin Bay area are less than the freshwater inflow needs under Alternative III for the spring months (April, May and June), August and November, and higher than the estimated needs in the remaining months. Historical inflows to lower Laguna Madre are greater than the estimated monthly needs under Alternative III for all months except January, February, March, September and October. The monthly estuarine inflow needs are distributed to achieve Alternative III as indicated in Figure 9-22.

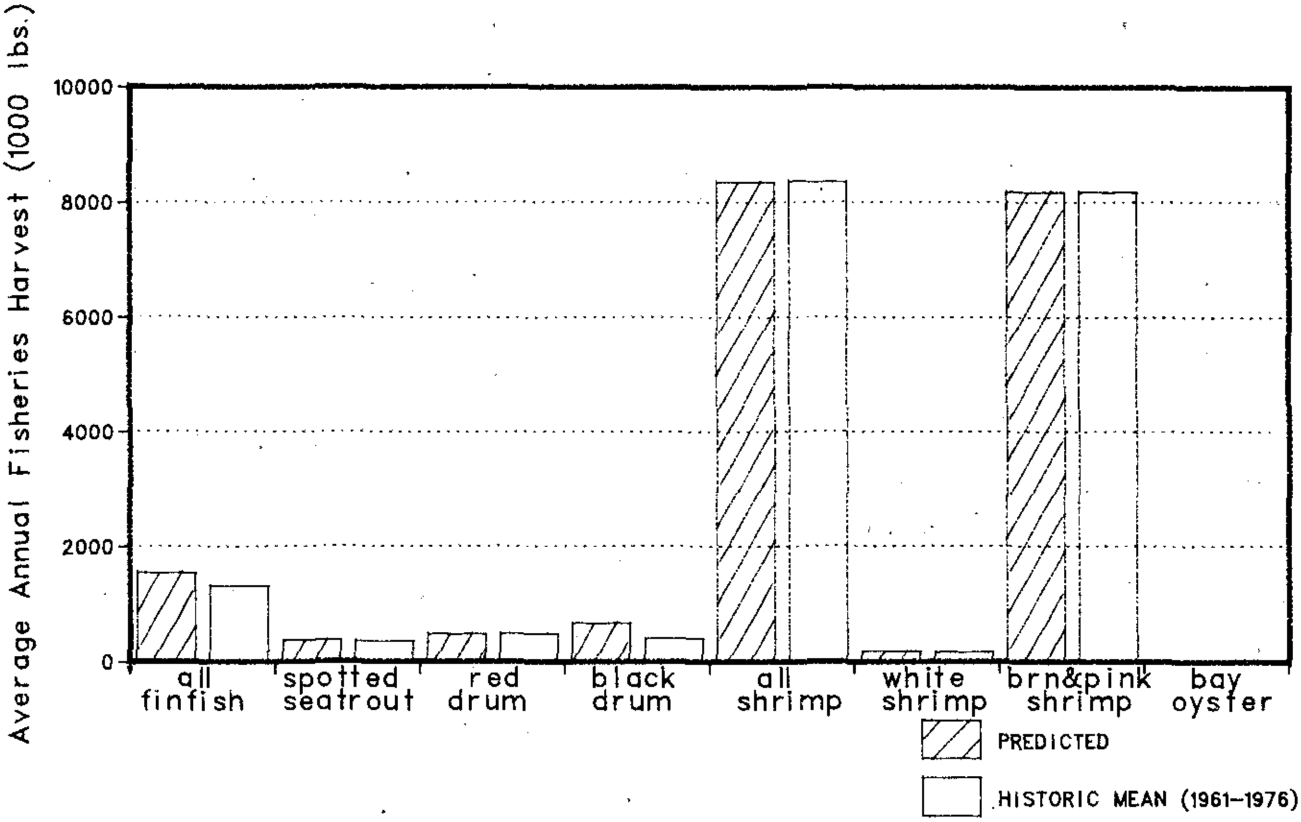


Figure 9-16. Comparison Between Lower Laguna Madre Historical Fisheries Harvests and Predicted Harvests Under Alternative II

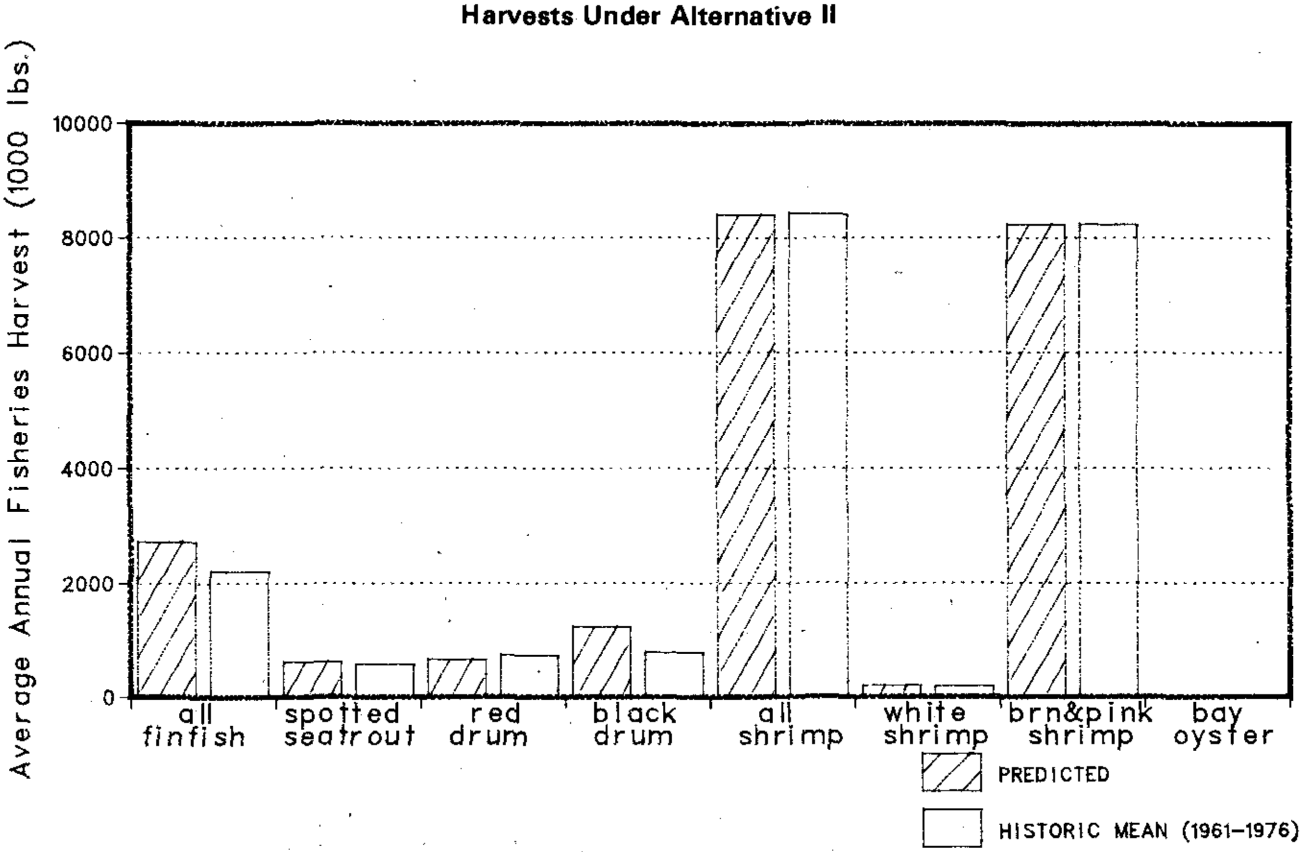


Figure 9-17. Comparison Between Laguna Madre Estuary Historical Fisheries Harvests and Predicted Harvests Under Alternative II

Table 9-6. Freshwater Inflow Needs of the Laguna Madre Estuary under Alternative III a/

Month	Baffin Bay and Upper Laguna Madre b/		Lower Laguna Madre b/		Combined Inflow e/
	Total Inflow Needs	Inflow Need from Gaged Portion of the Basin c/	Total Inflow Needs	Inflow Need from Gaged Portion of the Basin d/	
	Thousands of Acre-Feet				
January	1.62	.13	48.44 h/	26.15	50.06
February	2.55	.26	42.23 h/	23.18	44.78
March	1.25	.07	33.53 h/	18.93	34.78
April	6.80 f/	.88	27.08	15.69	33.88
May	19.68 f/	2.74	28.77	16.54	48.45
June	9.30 f/	1.24	28.48	16.40	37.78
July	8.02 g/	1.05	21.20	12.65	29.22
August	6.13 g/	.78	18.06	10.99	24.19
September	7.54	.98	130.58 i/	62.50	138.12
October	3.60	.41	106.84 i/	52.40	110.44
November	2.18	.21	23.52	13.86	25.70
December	1.24	.07	23.27	13.73	24.51
Annual	69.91	8.82	532.00	283.01	601.91

a/ All inflows are mean monthly values.

b/ The upper and lower portion of the estuary are separated by the "land cut".

c/ These values computed using regression equations relating monthly inflow to the estuary with the sum of the monthly gaged inflows at the USGS streamflow measuring stations on San Fernando Creek at Alice and on Los Almos Creek near Falfurrias.

d/ These values computed using regression equation relating monthly inflow the the estuary with monthly gaged inflows at the USGS streamflow measuring stations on the Arroyo Colorado at Harlingen and the North Floodway near Sebastian.

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

f/ Total seasonal freshwater inflow need distributed according to 1941-1976 average upper Laguna Madre monthly inflow distribution in the season (April, May and June).

g/ Total seasonal freshwater inflow need distributed as near as possible to 1941-1976 average upper Laguna Madre monthly inflow distribution in the season (July and August).

h/ Total seasonal freshwater inflow need distributed according to 1941-1976 average lower Laguna Madre monthly inflow distribution in the season (January, February and March). Seasonal inflow need is the maximum allowable for this season.

i/ Total seasonal freshwater inflow need distributed according to 1941-1976 average lower Laguna Madre monthly inflow distribution in the season (September and October).

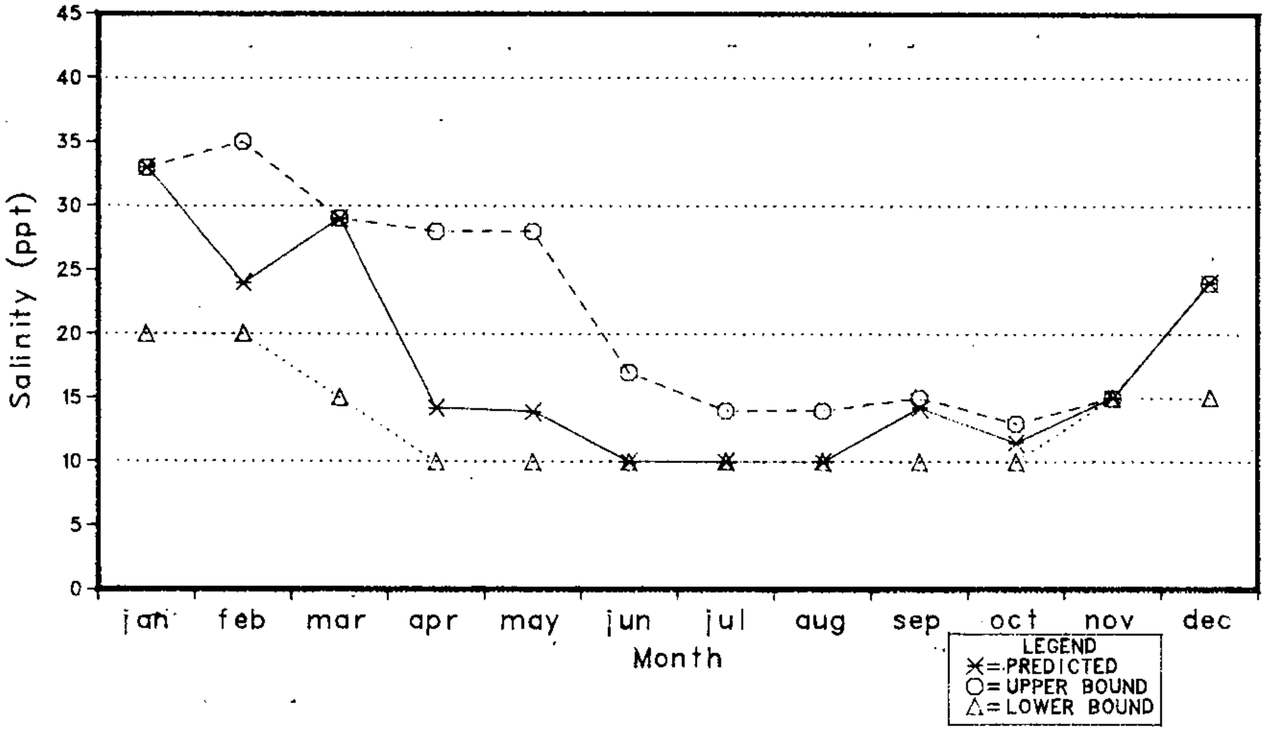


Figure 9-18. Average Monthly Salinity in Upper Baffin Bay Under Alternative III

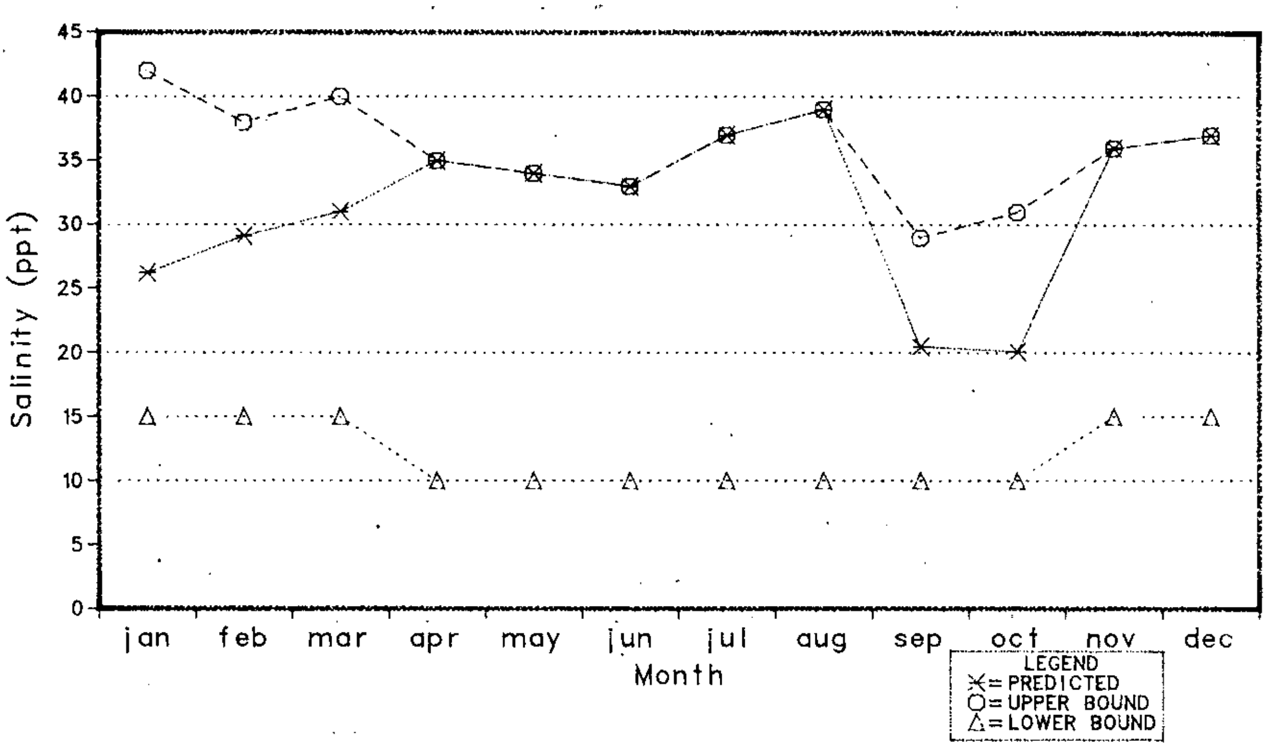


Figure 9-19. Average Monthly Salinities at Intersection of Intracoastal Waterway and Arroyo Colorado Under Alternative III

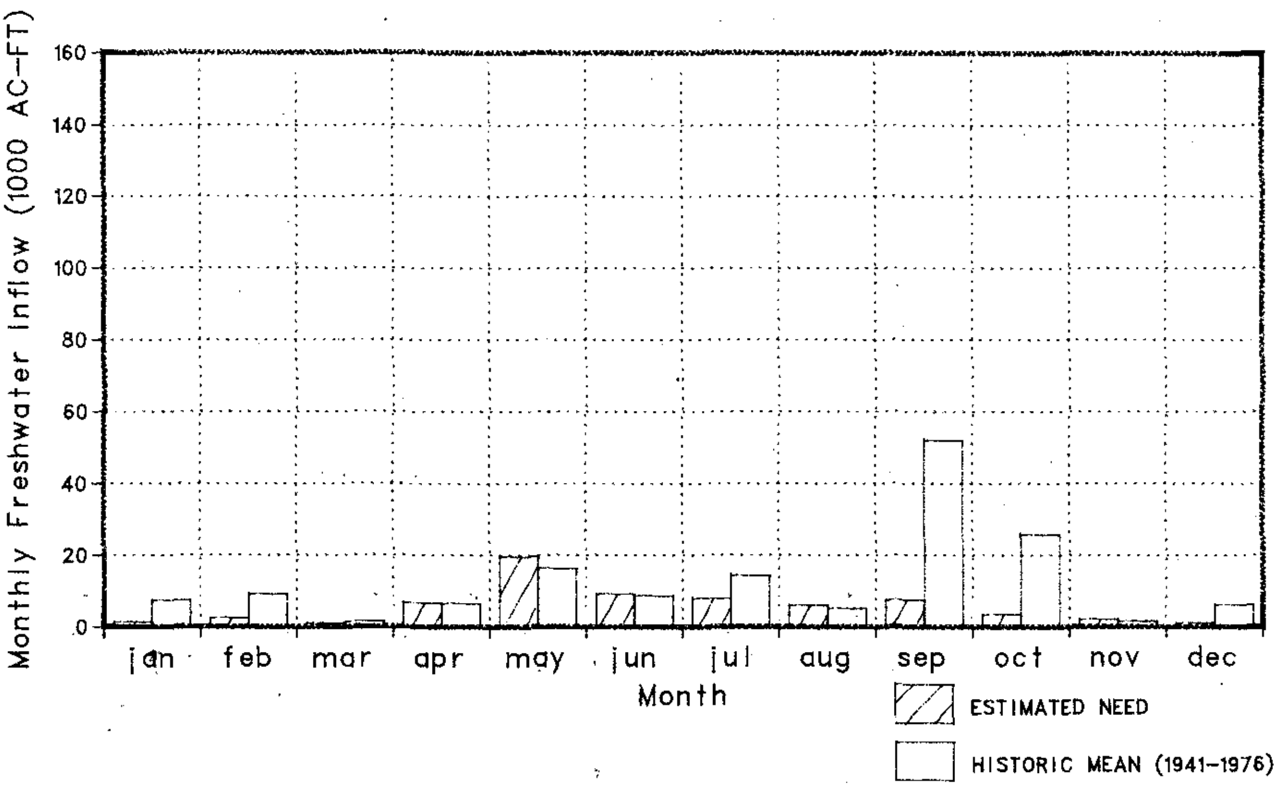


Figure 9-20. Comparison Between Mean Historical Freshwater Inflow and Inflow Needs for Upper Laguna Madre and Baffin Bay Under Alternative III

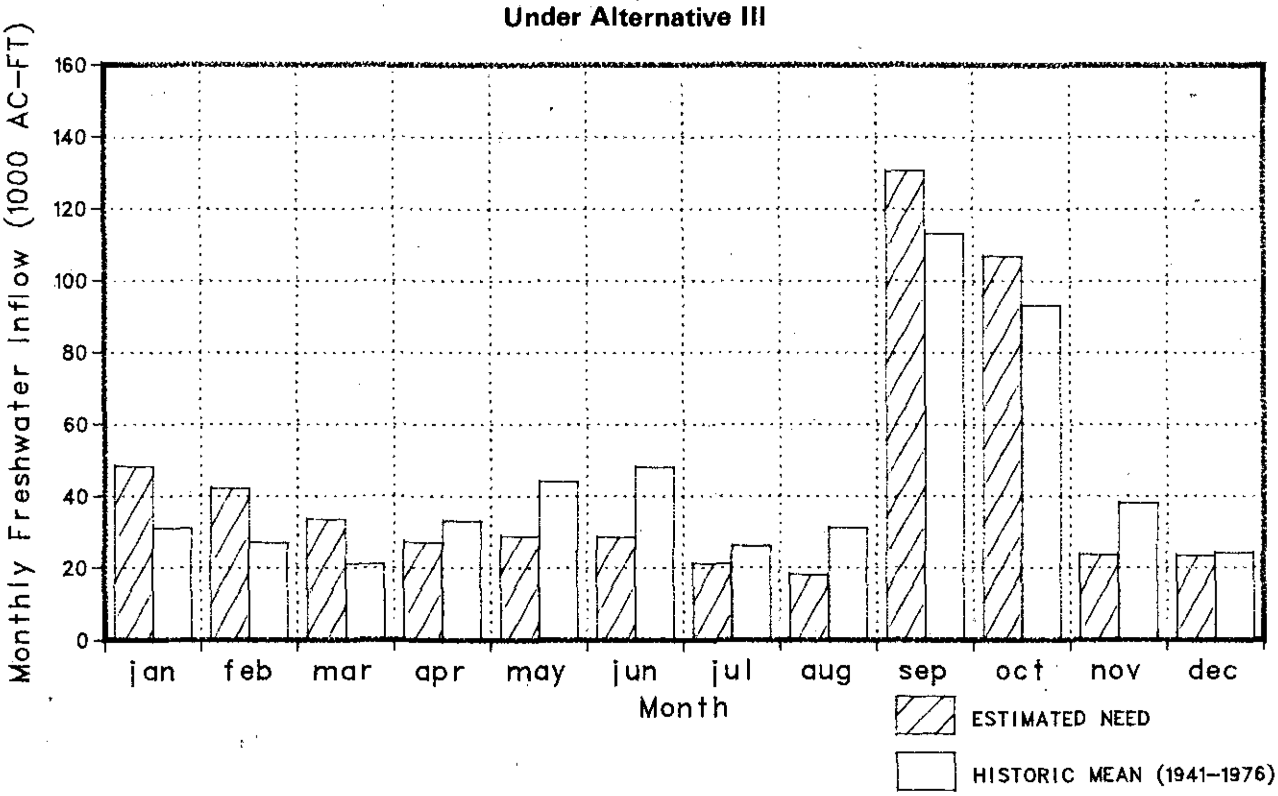


Figure 9-21. Comparison Between Mean Historical Freshwater Inflow and Inflow Needs for Lower Laguna Madre Under Alternative III

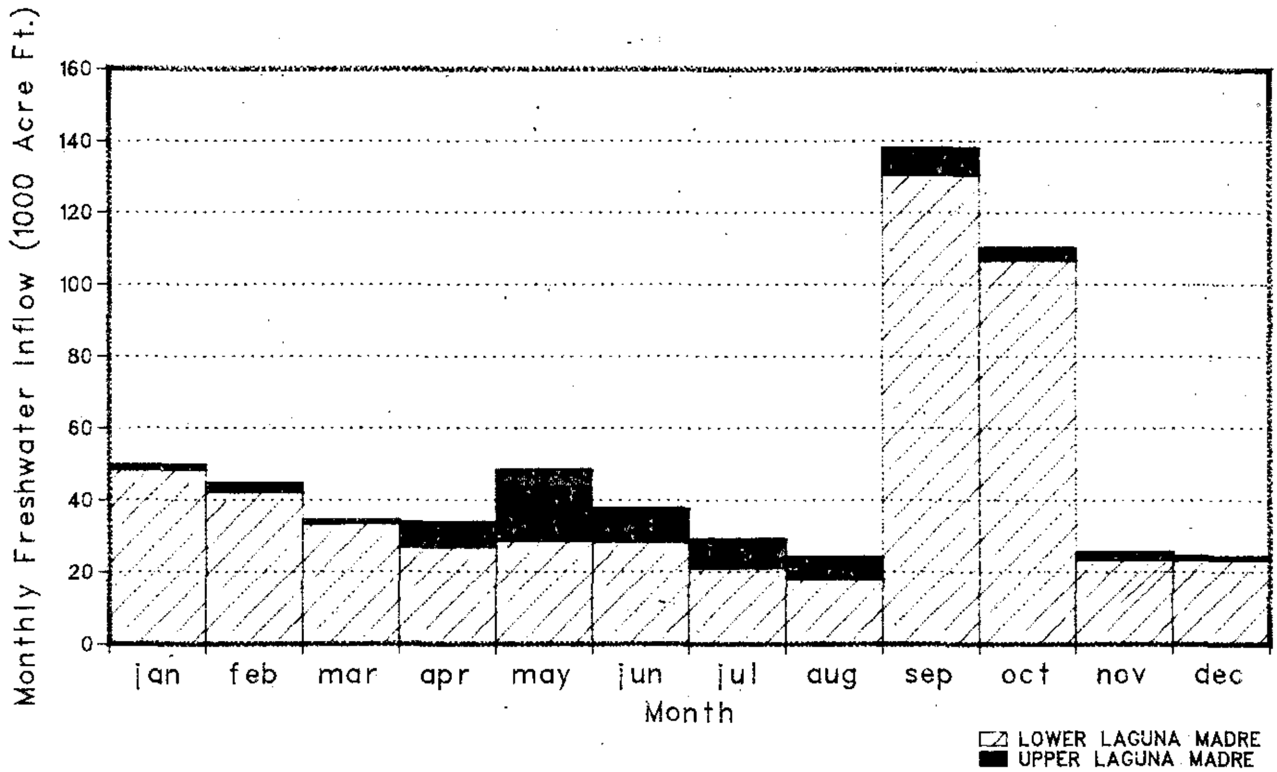


Figure 9-22. Estimated Freshwater Inflow Needs for the *Laguna Madre* Estuary Under Alternative III

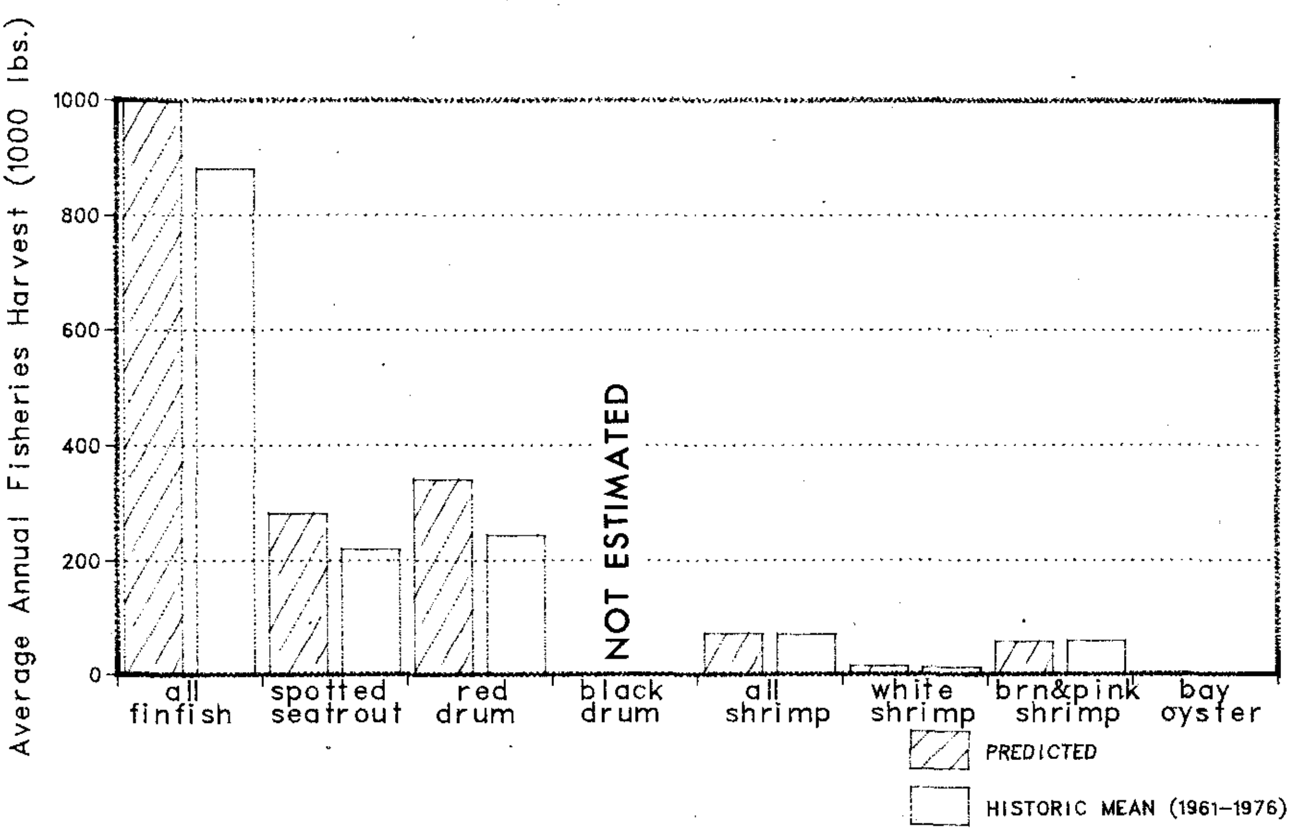


Figure 9-23. Comparison Between Upper Laguna Madre Historical Fisheries Harvests and Predicted Harvests Under Alternative III

According to this analysis, implementation of the Alternative III inflow regime indicated in Table 9-6 is projected to result in 997 thousand pounds (452 thousand kg) of annual commercial finfish harvest, in upper Laguna Madre, or a 13 percent increase above the mean 1962 through 1976 historical level (Figure 9-23). The annual shrimp harvest in Offshore Area No. 21 is predicted to be 9.92 million pounds (4.49 million kg), a 19 percent increase over the mean harvest (Figure 9-24). Projected increases above mean combined estuarine harvests for the 1962 though 1976 period in individual fishery harvest categories under Alternative III (Figure 9-25) include 17 percent in spotted seatrout, 37 percent in red drum, 14 percent in black drum, 19 percent in the all-shrimp harvest, 64 percent in white shrimp, and 19 percent in brown and pink shrimp. The estimated bay oyster harvest is projected to decline to .9 thousand pounds (.4 thousand kg) from an average of 5.5 thousand pounds (2.5 thousand kg).

Summary

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

Monthly salinity limits are established at two locations in the estuary below the "Null Zone" near the freshwater inflow points of Baffin Bay and lower Laguna Madre. These upper and lower limits on monthly salinity provide a range within which viable metabolic activity can be maintained and normal historical salinity conditions are observed.

The river deltas in Laguna Madre are limited in areal extent and relatively insignificant nutrient sources compared to the vast seagrass beds within the estuary. As a result, no inflow requirements for riverine marsh inundation are specified for Laguna Madre.

Estimates of the freshwater inflow needs for Laguna Madre estuary are computed by representing the interactions among freshwater inflows, estuarine salinity, and fisheries harvests within an Estuarine Mathematical Programming Model. The model computes the monthly freshwater inflows from the Baffin Bay drainage area and the Arroyo Colorado and North Floodway which best achieve a specified objective.

The monthly freshwater inflow needs for Laguna Madre estuary were estimated for each of three alternatives.

Alternative I (Subsistence): minimization of annual combined freshwater inflow to the estuary while meeting salinity viability limits;

Alternative II (Maintenance of Fisheries Harvests): minimization of annual combined inflow to the estuary while providing freshwater inflow sufficient to give predicted annual commercial bay harvests separately for both the upper Laguna Madre (including Baffin Bay) and lower portions of the estuary (including Offshore Area No. 21) for red drum, seatrout, black drum, white shrimp, brown and pink

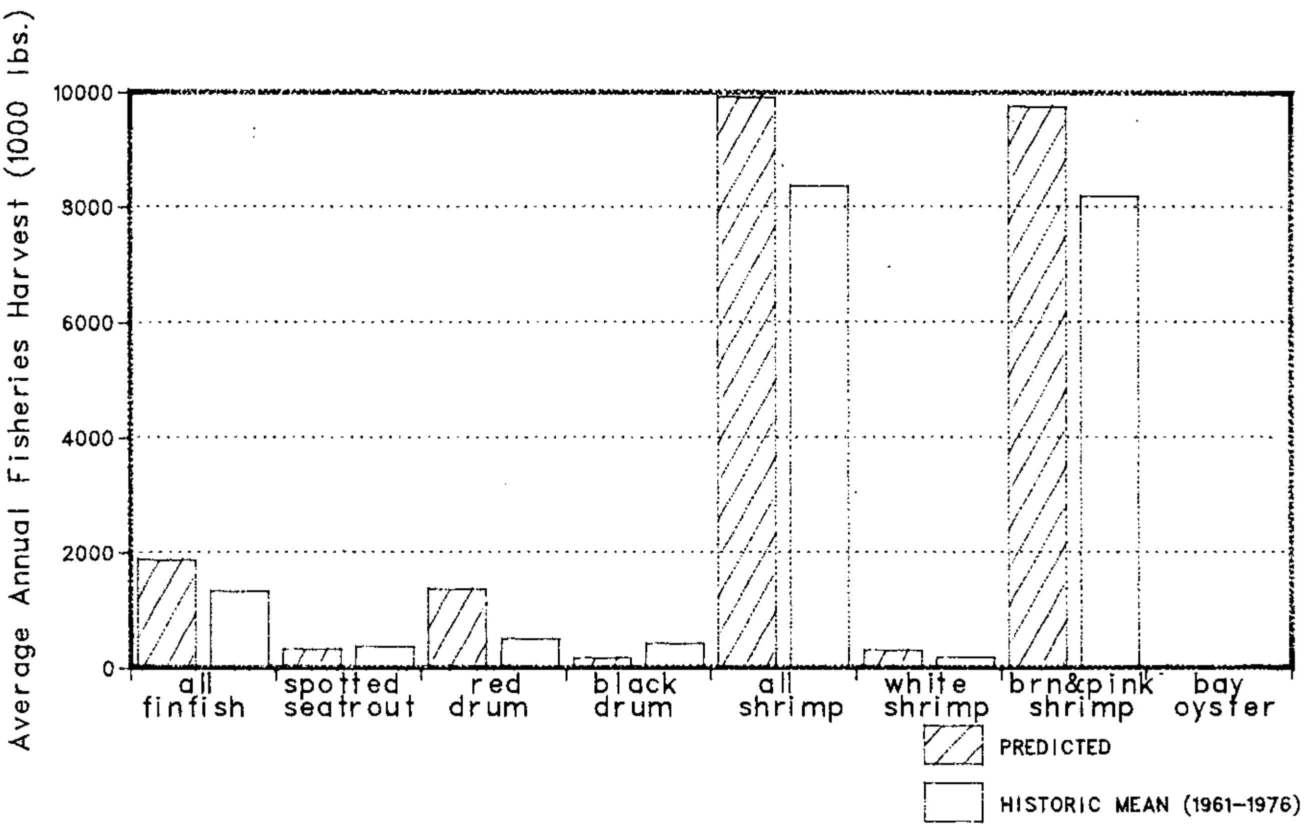


Figure 9-24. Comparison Between Lower Laguna Madre Historical Fisheries Harvests and Predicted Harvests Under Alternative III

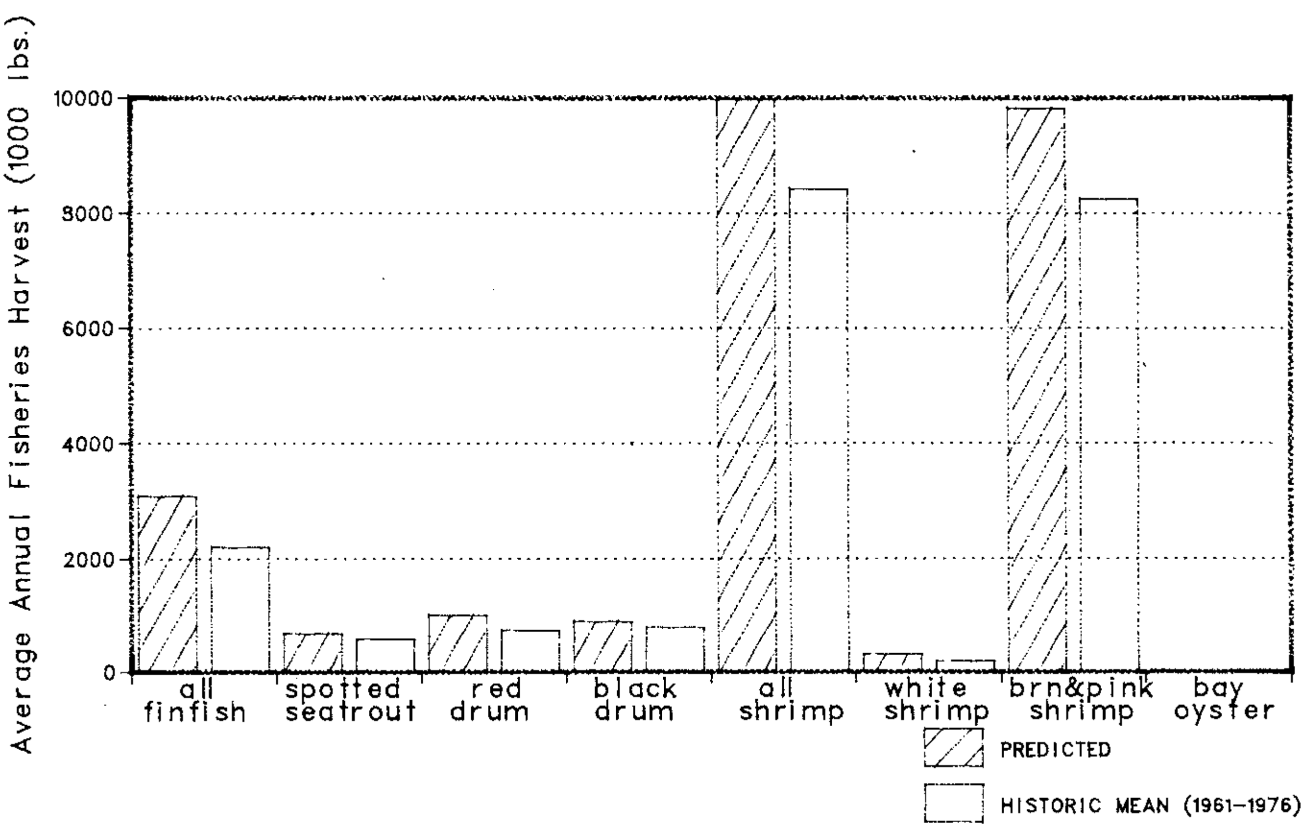


Figure 9-25. Comparison Between Laguna Madre Estuary Historical Fisheries Harvests and Predicted Harvests Under Alternative III

shrimp and bay oysters at levels no less than their mean historical 1962 through 1976 values and meeting viability limits for salinity; and

Alternative III (Harvest Enhancement): maximization of the total annual commercial bay harvest of all finfish in upper Laguna Madre and of all shrimp in Offshore Area No. 21 while meeting salinity limits and utilizing annual combined inflow to the estuary at a level no greater than the average annual historical inflow over the 1941 through 1976 period, and maintaining the total annual commercial finfish harvest in lower Laguna Madre at no less than the mean 1962 through 1976 historical level.

Under Alternative I (Subsistence), the Laguna Madre system, which has functioned as both a commercial shellfish and finfish producing system in the past, can continue to be an important fisheries producing estuary with substantially less freshwater inflow. Freshwater inflows totaling 344 thousand acre-feet (424 million m^3) annually are predicted to satisfy the basic salinity gradient, with a resulting predicted increase in commercial finfish bay harvests of 9 percent and a 12 percent decrease in shrimp harvest from the average annual harvests of 2.2 million pounds (997 thousand kg) and 8.4 million pounds (3.8 million kg), respectively, for the period 1962 through 1976. This annual inflow is approximately 50 percent of the 1941-1976 historical average inflow.

Under Alternative II (Maintenance of Fisheries Harvests), the predicted annual commercial bay harvests of red drum, spotted seatrout, black drum, white shrimp, brown and pink shrimp, and bay oyster are predicted to be at least as great as their historical 1962 through 1976 average levels. The salinity limits are also satisfied. The total annual freshwater inflow need is estimated at 578 thousand acre-feet (713 million m^3), or 84 percent of the 1941-1976 annual average inflow. The predicted total finfish and shellfish commercial harvests is 11.2 million pounds (5.1 million kg), compared to the 1962-1976 average catch of 10.6 million pounds (4.8 million kg).

Under Alternative III (Harvest Enhancement), the combined annual freshwater inflow need is computed at 602 thousand acre-feet (743 million m^3), distributed in a seasonally unique manner, to achieve the objective of maximizing the total annual predicted commercial bay harvest of finfish in upper Laguna Madre and shrimp in Offshore Area No. 21. This inflow regime is 87 percent of the 1941-1976 average annual inflow. This objective is achieved with a predicted 40 percent increase in the annual finfish bay harvest, above the average historic 1962 through 1976 catch of 2.2 million pounds (1.0 million kg), and an estimated gain of approximately 19 percent in total commercial shrimp harvest over the 1962-1976 harvest of 8.4 million pounds (3.8 million kg).

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

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

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