FRESHWATER INFLOW NEEDS OF THE MATAGORDA BAY SYSTEM

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EXECUTIVE SUMMARY

Introduction

The Matagorda Bay system is the second largest estuary on the Texas Gulf Coast covering approximately 352 square miles. The abundant production of finfish and shellfish make this environmentally sensitive area important not only as a ecological resource, but also as a source of economically significant commercial and sports fisheries. Many factors contribute to this high natural productivity, but the most significant is an ample source of freshwater. Freshwater inflows are vital to the continued health of the natural ecosystems in and around the Matagorda Bay system.

To determine the freshwater inflow needs of the Matagorda Bay system, the LCRA entered into a cooperative agreement with TPWD, TWDB and TNRCC in 1993. The LCRA agreed to adapt or modify existing methods for estimating freshwater inflow needs used by the TPWD and TWDB and apply those methods to compute alternative freshwater inflow needs for the estuary. The participating state agencies provided technical assistance and advice to the LCRA.

Methodology for Estimating Freshwater Inflow Needs

This method involved the synthesis of three components: (1) development of statistical relationships between freshwater inflows and key indicators of estuarine conditions, (2) computation of monthly and seasonal freshwater inflows to optimize estuarine conditions subject to specific constraints at key estuarine locations and (3) evaluation of estuarine-wide salinity conditions to ensure conditions remain within desired limits.

The first major component is the development of statistical relationships for the varied and complex interactions between freshwater inflows and important indicators of estuarine ecosystem conditions.

The key estuarine indicators considered are: salinity, species productivity, and nutrient inflows.

Statistical relationships were developed between seasonal freshwater inflows and biomass for nine finfish and shellfish species that are ecologically and economically important to the estuary. In general, most species demonstrated negative responses to freshwater inflows during winter months (November through February), and positive responses to freshwater inflows occurring from March through October.

The salinity conditions in upper Lavaca Bay and the eastern end of Matagorda Bay were found to be largely dependent on the freshwater inflows from the Lavaca and Colorado Rivers, respectively. These relationships were quantified into statistical relationships.

Similarly the nutrient inflows were related to total inflow to the estuary. A nutrient budget was prepared for the estuary which indicated that a minimum annual freshwater inflow of 1.7 million acre-feet was needed to replenish the estimated nutrient losses from the estuary.

The second essential process involves using the statistical functions noted above to compute optimal monthly and seasonal freshwater inflow needs. This is accomplished using the TWDB's Texas Estuarine Mathematical Programming (TXEMP) Model. TXEMP determines mathematically the best set of freshwater inflows needed to maximize specific conditions within the estuary while meeting a variety of limits on salinity, species productivity and nutrient inflows.

The third major component of the process of developing inflow needs is the simulation of the salinity conditions throughout the estuary using the TXBLEND estuarine hydrodynamic and salinity transport model developed by TWDB and modified by the LCRA. The simulated salinity is then compared to desired salinity ranges over broad areas of the estuary. If salinity is not within those ranges then constraints in TXEMP are modified to achieve the desired salinity.

Freshwater Inflow Needs

The freshwater inflow needs for the estuarine ecosystem associated with Matagorda Bay system were estimated for two levels of inflow needs: Target and Critical.

The Target inflow needs are the monthly and seasonal inflows that produced 98% of the maximum total normalized biomass for nine key estuarine finfish and shellfish species while maintaining certain salinity, population density and nutrient inflow conditions. The salinity condition requires that estimated salinity fall within predetermined monthly ranges preferred by most species. The productivity of any species must not be less than 80% of its historical average. Finally, the total inflow of nutrients are at least equal to the natural nutrient losses from the ecosystem. The 98 percent level of maximum biomass was selected for the target needs based on achieving the best tradeoff between productivity and freshwater inflows.

The Critical inflow needs were determined by finding the minimum the total annual inflow needed to keep salinity near the mouths of the Colorado and Lavaca Rivers at no more than 25 parts per thousand. These inflow needs are termed critical since they provide a fishery sanctuary habitat during droughts. From this sanctuary, the finfish and shellfish species, particularly oysters, could be expected to recover and repopulate the bay when more normal weather conditions returned.

The Target inflow need from all sources was calculated to be 2.0 million acre-feet per year (Table 1). Inflow needs from the Lavaca and Colorado Rivers were estimated at 346,200 and 1,033,100 acre-feet annually, respectively. The remaining contributing areas are estimated to provide an additional 620,700 acre-feet yearly.

The TXBLEND hydrodynamic and salinity transport model was used to simulate salinity conditions in the Matagorda Bay system with the Target inflow needs indicated in Table 1. The resulting simulated salinity regime was found to give acceptable salinity conditions throughout the estuary, thus the Target needs are anticipated to provide adequate salinity gradients within the Matagorda

Bay System.

A total annual freshwater inflow of about 287,400 thousand acre-feet was found to meet the Critical inflow needs (Table 2). Approximately 27,100 and 171,100 acre-feet yearly would be provided from the Lavaca and Colorado River basins, respectively, with the remaining annual inflow of 89,200 acre-feet coming from the other contributing drainage basins.

Table 1. Target Freshwater Inflow Needs (1000 Acre-Feet) for the Matagorda Bay System

Month	Colorado River Inflows	Lavaca River Inflows	Other Contributing Basin Inflows
January	44.1	14.8	35.4
February	45.3	14.5	40.3
March	129.1	33.9	32.9
April	150.7	57.3	44.1
May	162.2	60.1	76.3
June	159.3	58.8	71.4
July	107.0	28.0	59.6
August	59.4	16.0	24.8
September	38.8	21.9	90.6
October	47.4	16.0	78.2
November	44.4	12.8	35.4
December	45.2	12.2	31.7
Basin Total Inflow	1033.1	346.2	620.7
Total Inflow	2000.0		

Table 2. Critical Freshwater Inflow Needs (1000 Acre-Feet) for the Matagorda Bay System

Month	Colorado River Inflows	Lavaca River Inflows	Other Contributing Basin Inflows
January	14.26	2.26	5.08
February	14.26	2.26	5.08
March	14.26	2.26	4.45
April	14.26	2.26	6.14
May	14.26	2.26	10.70
June	14.26	2.26	10.70
July	14.26	2.26	8.92
August	14.26	2.26	3.57
September	14.26	2.26	13.38
October	14.26	2.26	11.59
November	14.26	2.26	5.00
December	14.26	2.26	4.46
Basin Total Inflow	171.1	27.1	89.2
Total Inflow	287.4		

ACKNOWLEDGMENTS

The LCRA expresses its appreciation to the Texas Water Development Board (TWDB), Texas Parks and Wildlife Department (TPWD), Texas Natural Resource Conservation Commission (TNRCC) and Lavaca-Navidad River Authority (LNRA) for their support during this study. Particularly, the members from these agencies that served on the study advisory committee provided valuable guidance and insight to the LCRA. The committee included Mr. Gary Powell (TWDB), Dr. Warren Pulich and Dr. Wen Lee (TPWD), Mr. Bruce Moulton (TNRCC), and Mr. Jack Nelson (LNRA). In addition, Dr. Junji Matsumoto, Mr. William Longley, Dr. David Brock, and Dr. Ruben Solis (TWDB) and Dr. Peter Eldridge (TPWD) made invaluable contributions to the technical analyses in this study.

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CHAPTER 1
INTRODUCTION

PURPOSE

The Matagorda Bay system is the second largest estuary on the Texas Gulf Coast. This estuary, also known as the Lavaca-Colorado estuary, covers approximately 352 square miles, and its largest single body of water is Matagorda Bay. Other major bays in the estuary are Lavaca, East Matagorda, Keller, Carancahua, and Tres Palacios (Figure 1). The abundant production of finfish and shellfish make this environmentally sensitive area important not only as a ecological resource, but also as a source of economically significant commercial and sports fisheries. Many factors contribute to this high natural productivity, but the most significant is an ample source of freshwater. Freshwater inflows are vital to the continued health of the natural ecosystems in and around the Matagorda Bay system.

The purpose of this report is to: (1) describe relationships between the volume and seasonal timing of freshwater inflows and important environmental conditions in the estuarine system and (2) estimate the needs for freshwater inflows to maintain and preserve its aquatic ecology.

BACKGROUND

Water management in Texas is becoming increasingly more complex as population and economic growth continues at a rapid pace and environmental needs for water are becoming fully recognized. The use of freshwater for municipal, industrial, agricultural, and other activities is often in direct conflict with estuarine freshwater inflow needs. This conflict has generated a major public controversy in Texas over the past several decades.

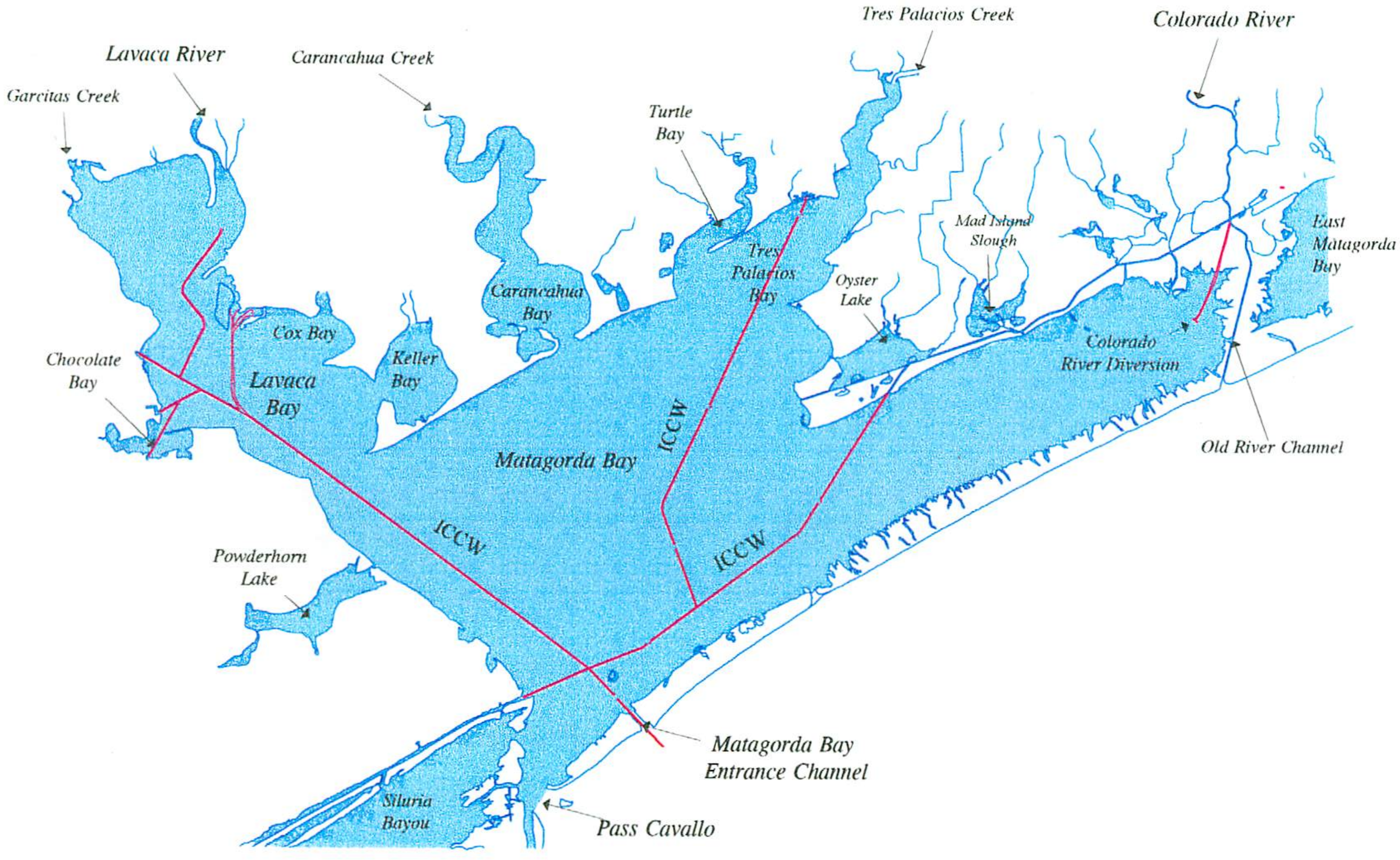

Figure 1. Major tributary streams, passes, and bays in the Lavaca-Colorado Estuary.

Presently, Texas law does not mandate specific freshwater inflow needs. However, the public policy of the State does call for "the maintenance of a proper ecological environment of the bays and estuaries of Texas and the health of related living marine resources" (SB137, 64th Legislature). Further, State statute requires that 5% of the firm yield of any reservoir within 200 river miles of the coast, that is constructed with State financial involvement be appropriated to instream uses and estuarine inflow releases. further, for water use permits within 200 river miles of the coast, the Texas Natural Resource Conservation Commission (TNRCC) must include conditions for maintaining beneficial estuarine inflows, to the extent practicable when all public interests are considered.

It is relatively easy to quantify the water needs for municipal, industrial, agricultural and other human uses of water. However, the influence of water on the complex interactions in aquatic ecologies found in streams, lakes and estuaries are not well quantified. To more fully understand the implications of changes in freshwater inflows to estuarine ecosystems, state and federal agencies began studies of Texas' estuarine in the 1960's.

In 1985, the Texas Legislature directed the Texas Parks and Wildlife Department (TPWD) and Texas Water Development Board (TWDB) to continue studies of the estuaries and determine sufficient information so that the need for freshwater inflows to the estuaries could be considered in the allocation of the state's water resources. These studies were to be completed by December 31, 1989. However, due to funding reductions, changes in priorities and other factors, they have been significantly delayed.

The LCRA was directly affected by the delay in completing these studies. Based on the findings of these studies, the LCRA was required by the TNRCC to submit amendments to the LCRA Water Management Plan to take into account freshwater inflow needs of the Lavaca-Colorado Estuary from the Colorado River. Thus establishing the freshwater inflow needs from the Colorado River is vital to the LCRA's management of its water rights in the Colorado River Basin for all beneficial purposes. The LCRA is conscious of its responsibilities in balancing water use all along the river so that the recipient bays and estuaries will have the benefits of adequate freshwater inflows and will continue to be productive in their natural role.

To expedite the state's freshwater inflow needs study of the Matagorda Bay system, the LCRA entered into a cooperative agreement with TPWD, TWDB and TNRCC in 1993. The LCRA agreed to adapt or modify existing methods used by the TPWD and TWDB and apply those methods to compute alternative freshwater inflow needs for the estuary. The participating state agencies would provide timely technical assistance to the LCRA from the other participating parties. The LCRA would also prepare a report on the methodology, data and results of the computation of alternative freshwater inflow needs.

Emphasis in the study was to be on the estuary west of the Colorado River in determining freshwater inflows from the Colorado and Lavaca Rivers and coastal basins. To the extent possible, the impact of freshwater inflows on the environmental conditions in East Matagorda Bay would be evaluated. Full analysis of East Matagorda Bay would be contingent on adequate external funding to allow the LCRA to contract for an evaluation of the hydrologic, salinity and biological data collected to date on the conditions in this bay.

The study agreement can be found in Appendix A.

ECONOMIC AND ECOLOGICAL VALUE

Bays and estuaries are critically important to the well-being of most marine shellfish and finfish species on the Texas coast and are vital to the state's commercial and sport fishing industry. Over 97% of the fishery species in the Gulf of Mexico are dependent upon estuaries during some portion of their life cycle. Many species are not permanent residents of the estuaries but migrate to them during different times of their lives. These migrations occur seasonally and are usually related to spawning cycles. Larval and juvenile organisms move from the ocean into estuarine marsh lands to find food and to seek the protection of lower salinity water. The young of many fishery species can tolerate lower salinity than their predators and parasites. When they mature to young adults, the individuals migrate back to the Gulf.

The life cycles of estuaries-dependent species require differing seasonal migratory patterns. Redfish, for example, spawn in the fall, and the young migrate into estuarine marshes shortly afterward to feed and grow. White shrimp, however, reproduce in the spring and again in the fall.

Estuaries are the permanent homes for many aquatic species that do not migrate. The most well-known of these is the bay oyster. The juveniles anchor upon natural reefs or other solid objects and remain on the same spot through their adult lives. This lack of mobility makes the bay oyster particularly susceptible to lethal changes in water conditions. Oysters cannot tolerate freshwater for more than a few days. On the other extreme, very salty water encourages parasites to attack the oysters, often destroying entire oyster reefs.

Many complicated interactions govern the biological productivity of Texas bays and estuaries other than the quantity of freshwater inflows. However, freshwater inflows and their associated nutrients and sediments are recognized by most estuarine biologists as one of the primary factors in estuarine productivity. Studies have demonstrated that these contributions from the freshwater inflows allow economically important fish and shellfish species to survive, grow, and reproduce abundantly.

Researchers have also discovered that periodic river floods inundate delta marshes, transport nutrients and other organic materials (food sources), and remove or limit many pollutants, parasites, bacteria, and viruses harmful to estuarine-dependent organisms. However, too much freshwater can stress or even severely damage these living coastal systems if their environment loses its marine character.

The economic importance of estuaries is shown in the value of estuary-dependent fish and shellfish. In 1981 the commercial harvest on the Texas estuaries totaled about 113 million pounds (over 90% shellfish) with a dockside landings value of $174.8 million. The total economic impact of this harvest is approximately $544.5 million, which reflects the gross business, personal income, and tax revenue values to the State's economy.

Estuaries also provide important recreational benefits. Sport fishermen catch between 4 and 10 million pounds annually with a direct and indirect economic impact to Texas of $709 million in 1979. Marsh wetlands surrounding the estuaries are vital habitats for migrating waterfowl. Many people annually enjoy sport hunting in these areas.

METHODOLOGY FOR DETERMINING FRESHWATER INFLOW NEEDS

The freshwater inflow needs are estimated following as closely as possible the process developed by the TWDB and TPWD in their study of the Guadalupe Estuary (Longley, ed., 1994). This process involves a number of separate functions (Figure 2). The first major element is the development of statistical relationships for the varied and complex interactions between freshwater inflows and important indicators of estuarine ecosystem conditions. The key estuarine indicators considered are salinity, species productivity, and nutrient inflows. These relationships are developed and described in later chapters of this report.

The second essential process involves using the statistical functions to compute optimal monthly and seasonal freshwater inflow needs. This is accomplished using the TWDB's Texas Estuarine Mathematical Programming (TXEMP) Model (Longley, ed., 1994). The TXEMP model estimates the freshwater inflow needs of an estuary by representing mathematically the varied and complex interactions between freshwater inflows and salinity, species productivity, and nutrient inflows. Sediment inflows are excluded due to a lack of data concerning the volume of sediment needed to balance erosion and subsidence in the Colorado and Lavaca River delta.

The third major component of the process of developing inflow needs is the simulation of the salinity conditions throughout the estuary using the TXBLEND model developed by TWDB and modified by the LCRA. The simulated salinity is then compared to desired salinity ranges over broad areas of the estuary. If salinity is not within those ranges then constraints in TXEMP are modified to achieve the desired salinity.

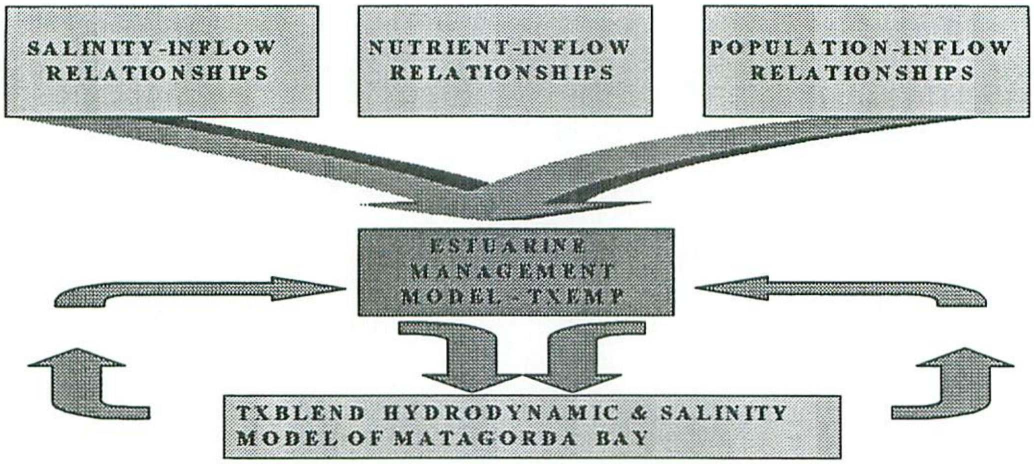

Figure 2. Process for Determining Freshwater Inflow Needs

CHAPTER 2

HYDROLOGIC CHARACTERISTICS OF THE MATAGORDA BAY SYSTEM

PURPOSE

This chapter describes the sources of inflow for the Lavaca-Colorado Estuary. The initial section discusses the measured sources of freshwater inflow. Sources of unmeasured freshwater inflows are next described and a mass balance of inflow for the estuary is given.

FRESHWATER INFLOWS

Gaged Inflows

The largest source of freshwater inflows to the Lavaca-Colorado estuary are the rivers and major coastal streams in the Colorado-Lavaca River basins and the adjacent coastal basins (Figure 1). Flows in these rivers and streams are generally measured at points sufficiently close to the estuary that these flows can be used to estimate the actual estuarine inflows from these sources.

The purpose of this analysis is to take recorded stream flows and estimate their contribution to the freshwater inflows to the estuary over the period 1941 through 1991. Previous studies by TWDB have estimated these inflows through 1987. The methods used in those studies are applied in this analysis to estimate the remainder of the historical period.

Data Sources

The United States Geological Survey (USGS) maintains an extensive network of stream gages across Texas. In addition to the stream gages, flows are also measured at the discharge structures

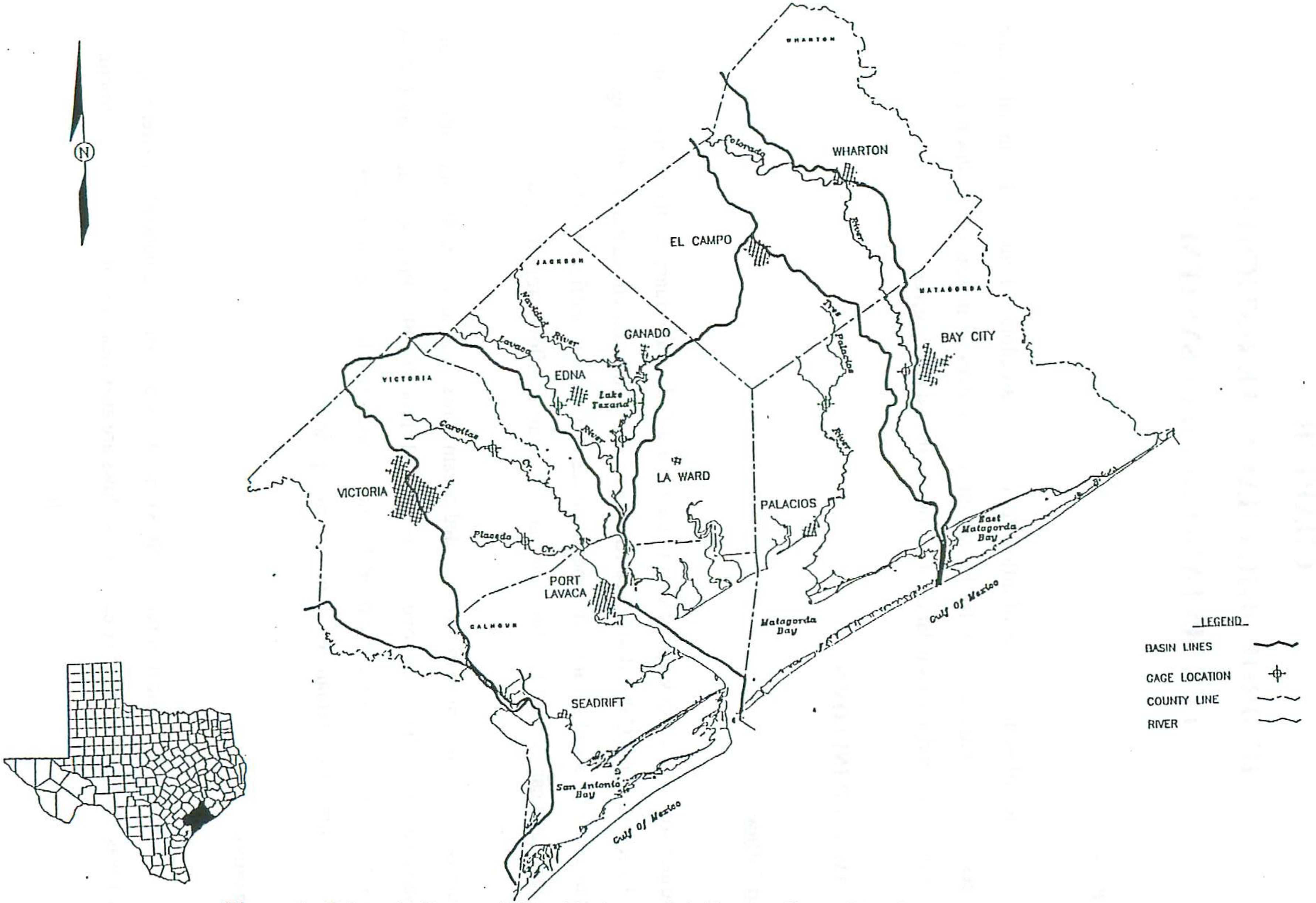

Figure 1. Colorado-Lavaca River Basins and Adjacent Coastal Basins

for Lake Texana. The location and duration of measured flows used in this analysis are shown in Table 1.

Estimation of Missing Data

The streamflow data in Table 1 can be translated into equivalent freshwater inflows for many of the locations. However, freshwater inflows to the estuary from the Colorado River must be estimated from the river flows. This is necessary since the complex geomorphology and hydrodynamics of the Colorado Delta from the mid 1930's until 1990 caused part of the river flows to move into the Gulf of Mexico rather than entering the estuary.

The Texas Department of Water Resources (TDWR) developed a method of estimating the inflows from the Colorado River (TDWR 1978). Using this method, TDWR determined inflows from 1941 through 1976 (TDWR 1980). TWDB staff also used this approach to extend the inflow record through 1987 (Solis, 1994). Monthly inflows calculated by TDWR and TWDB for the 1941-1987 period are used in this analysis.

The computer program developed to automate the estimate of Colorado River estuarine inflows was provided to LCRA by TWDB staff (Solis, 1994). This program was used to determine the monthly estuarine inflows from the Colorado River for the period 1988 though May 1990. In May 1990, the Corps of Engineers opened the diversion channel component of the Mouth of the Colorado River Project. This channel connects the junction of the Inter-Coastal Water Ways (ICWW) and the Colorado River directly with Matagorda Bay. From May 1990 through June 1992, water from the Colorado River could move into Matagorda Bay by means of both the new diversion channel and the existing Tiger Island Cut off of the former Colorado River channel through the Colorado River Delta.

In early July 1992, a barrier dam was completed which closed the former Colorado River channel at the junction of the river and the ICWW. For purposes of this analysis, all flow in the Colorado

River is considered to enter Matagorda Bay beginning in June 1990. Table 2 shows the annual measured and estimated gaged freshwater inflow contributions, by major drainage basin, for the 1941-1991.

TABLE 1. MEASURED STREAMFLOW LOCATIONS

River Basin	River or Stream	Location	USGS Stream Gage Number	Period of Record
Colorado	Colorado River	Wharton	08162000	Oct. 1938 - Present
		Bay City	08162500	April 1948 - Present
Colorado-Lavaca	Tres Palacios Creek	Midfield	08162600	June 1970 - Present
Lavaca	Lavaca River	Edna	08164000	Aug. 1938 - Present
	Navidad River	Ganado	08164500	May 1939 - April 1982
		Lake Texana Dam	-	May 1982 - Present
Lavaca-Guadalupe	Garcitas Creek	Inez	08164600	June 1970 - Present
	Placedo Creek	Placedo	08164800	June 1970 - Present

Ungaged Inflows

In 1980, the TDWR conducted a hydrologic analysis of watersheds contributing inflow to the

Lavaca-Colorado estuary from 1941 through 1976 (TDWR, 1980). One of the objectives of the TDWR's original study was to evaluate the volume of water entering the estuary system from ungaged sources. The TWDB, one of the successor agencies to the TDWR, subsequently updated that information for the period from 1977 through 1987. In this analysis we updated the monthly ungaged inflow estimates made by TDWR from January 1988 through December 1991 using similar methods.

Study Area

The study area of this analysis includes those watersheds which contribute inflow to the Lavaca-Colorado estuary downstream of existing gage locations. The study area is shown in Figure 1.1, and includes the following four basins

- Basin No. 14 - Colorado River Watershed: Colorado River watershed below gage at Bay City, Texas
- Basin No. 15 - Colorado-Lavaca Coastal Watershed: Colorado-Lavaca coastal watershed excluding the Tres Palacios River watershed above gage at Midfield, Texas.
- Basin No. 16 - Lavaca River Watershed: Lavaca River watershed excluding the Navidad River watershed above Lake Texana, and also excluding the Lavaca River watershed above gage at Edna, Texas.
- Basin No. 17 - Lavaca-Guadalupe Coastal Watershed: Lavaca-Guadalupe coastal watershed excluding the Placedo Creek watershed above gage at Placedo, Texas and also excluding the Garcitas Creek watershed above gage at Inez, Texas.

Method

Total combined inflow to the Lavaca-Colorado estuary is comprised of gaged inflow into the estuary, rainfall runoff from ungaged watersheds, diversions and return flows in the ungaged areas and direct precipitation and evaporative losses from the bay surface. This mass balance relationship is illustrated by the following equation.

$$Q_{total} = Q_m - Q_d + Q_r + Q_p - Q_{e+}Q_g$$

where Q_{total} = Total inflow to the Lavaca-Colorado Estuary; Q_m = Modeled estimates of runoff in ungaged area; Q_d = Municipal, Industrial and Irrigation diversions in ungaged area; Q_r = Return flows in ungaged area, including direct return flows in the form of municipal and industrial wastewater discharges, and return flows from agricultural use of both surface water and groundwater; Q_e = Gross evaporative losses from the bay surface; Q_p = Direct precipitation on the surface of the estuary; and Q_g = Gaged inflow into the estuary.

Each of these variables were estimated and summed to approximate the total inflow to the Lavaca-Colorado estuary system.

Runoff Estimates (Q_m)

TWDB supplied estimates of rainfall runoff from the ungaged areas. This was calculated by a water yield model which uses Thiessen-weighted daily precipitation, Soil Conservation Service's average curve numbers, and soil depletion index (Beta) to predict runoff from small watersheds (TDWR, 1980). This model was calibrated with seven gaged subbasins located within the contributing drainage area (TDWR, 1980). During 1941 through 1991, ungaged runoff averaged 963,400 acre-feet per year. Ungaged runoff ranged from a low of 30,900 acre-feet in 1956, to a high of 2,655,000 acre-feet in 1960.

Diversions (Q_d)

Monthly runoff estimates obtained from the rainfall runoff model were adjusted for municipal, irrigation and industrial surface water diversions in the ungaged areas. The diversion information was obtained from water use records from the TNRCC. Major surface water diverters in the ungaged watershed which were identified as part of this analysis are shown in Table 3 below. Diversions in the ungaged area during 1977 to 1991, averaged 27,400 acre-feet per year. Annual diversions during this period ranged from a low of 9,500 acre-feet in 1983, to a high of 66,200 acre-feet in 1988. It appears that no attempt was made to identify surface water diversions in the study area prior to 1977.

Table 3 Surface Water Diversion in Ungaged Watersheds

Basin No. 14 Colorado River Watershed	Basin No. 15 Colorado-Lavaca Costal Watershed	Basin No. 16 Lavaca River Watershed	Basin No. 17 Lavaca-Guadalupe Coastal Watershed
HL&P	Farmers Canal Company, W. Jenkins, Ocean Ventures Inc, Point Comfort Water Company and others	W. Kresta L. Thedford	None

Return Flows (Q_r)

Monthly rainfall runoff estimates were further adjusted to reflect return flows from municipal, industrial and agricultural activities. The return flows are comprised of both direct discharges and indirect discharges. Direct discharges are principally from municipal and industrial wastewater plants in the ungaged watersheds. Municipal and industrial return flows which were identified as part of this analysis are shown in Table 4 below.

Indirect discharges generally result as tailwater runs off from irrigated lands. The return flows from agricultural activities were estimated in several ways from basin to basin depending on the available data. For those basins with a significant amount of surface water irrigation, runoff was estimated to equal to 10 percent of the surface water diversion (Longley, 1994). This was the case in estimating return flows from the Lower Colorado River Authority's Bay City Pump Station No. 3 in Matagorda County and the Guadalupe-Blanco River Authority's Calhoun Canal Company in Calhoun County.

Table 4 Municipal and Industrial Return Flows in Ungaged Watersheds

Basin No. 14 Colorado River Watershed	Basin No. 15 Colorado-Lavaca Costal Watershed	Basin No. 16 Lavaca River Watershed	Basin No. 17 Lavaca-Guadalupe Coastal Watershed
HL&P, Hoechst Celanese, Matagorda Waste Disposal and Occidental Chemical	Formosa Plastics, Jackson County WCID #1, Laward, Markham MUD, Matagorda County WCID#5, Palacios and Tri-County Property	Edna and Jackson County WCID No. 2	Air Liquide American Corp,BP Chemicals, Carbide/Graphite Group, Port Lavaca, Seadrift, Texas Parks and Wildlife Dept, Union Carbide, Victoria County WCID#1 and Victoria County Airport.

Groundwater runoff from agricultural activities was estimated to be 0.33 acre-feet per irrigated acre which is 10 percent of a 3.3 acre-foot per acre application rate (Longley, 1994). This estimated unit runoff was multiplied by the number of acres of land identified as using groundwater for irrigation. The annual groundwater irrigation runoff estimates were then distributed to each of the months using the distribution factors in Table 5.

Irrigated acreage and irrigation sources were estimated from maps and other data provided by the Texas Agricultural Statistics Service (1994) and the TWDB 1994. Prior to 1977, uniform annual values were used as estimates for return flows. These values ranged from 69,000 to 96,000 acre-feet per year. Annual return flow estimates in the ungaged area during the period from 1977 to 1991 averaged 34,000 acre-feet per year. These estimates ranged from a low of 23,000 acre-feet in 1983, to a high of 41,500 acre-feet in 1977.

Table 5 Monthly Irrigation Distribution Factors

January	February	March	April	May	June
0%	0%	4%	9%	15%	21%
July	August	September	October	November	December
17%	15%	14%	5%	0%	0%

Precipitation and Evaporative Losses (Q_p) and (Q_e)

Direct precipitation and evaporative losses from the surface area of the Lavaca-Colorado estuary were calculated using Thiessen-weighted estimation techniques as generally described in LP-106 (TWDB, 1980). Monthly precipitation and evaporation data was obtained from the Texas Natural Resource Information System. Gage sites included Palacios Airport, Point Comfort, Port Lavaca, and Matagorda.

Inflow from direct precipitation during 1941 to 1991 averaged 852,700 acre-feet per year. During this period, direct precipitation ranged from a low of 423,500 acre-feet in 1988, to a high of 1,254,500 acre-feet in 1960. Evaporative losses during the same period ranged from a low of 939,000 acre-feet in 1941, to a high of 1,907,000 acre-feet in 1966, averaging 1,195,200 acre-feet per year.

ESTUARINE WATER BALANCE

The estimated annual water balance for the Lavaca-Colorado estuary is shown in Table 6. During

Table 6. Annual Water Balance (Acre-Feet/Year)

Year	Gaged	Modeled	Diversion	Return Flow	Combined Inflow	Evaporation	Precipitation	BALANCE
1941	4,701,867	1,955,491	0	69,000	6,726,358	939,000	1,159,536	6,946,894
1942	1,778,988	826,430	0	69,000	2,674,418	961,000	824,513	2,537,931
1943	1,397,351	331,222	0	69,000	1,797,573	1,043,000	686,745	1,441,318
1944	2,310,210	1,558,025	0	69,000	3,937,235	1,002,000	923,664	3,858,899
1945	2,132,091	931,623	0	69,000	3,132,714	1,001,000	796,336	2,928,050
1946	2,953,177	1,659,794	0	69,000	4,681,971	981,000	1,149,100	4,850,071
1947	1,553,615	415,969	0	69,000	2,038,584	993,000	732,668	1,778,252
1948	941,603	353,879	0	69,000	1,364,482	1,022,000	582,378	924,860
1949	1,612,723	1,474,939	0	69,000	3,156,662	983,000	1,211,721	3,385,383
1950	1,021,739	226,091	0	69,000	1,316,830	1,105,000	463,397	675,227
1951	559,782	209,633	0	69,000	838,415	1,148,000	744,150	434,565
1952	860,884	451,014	0	69,000	1,380,898	1,107,000	820,339	1,094,237
1953	1,029,038	789,423	0	69,000	1,887,461	1,147,000	896,528	1,636,989
1954	327,004	45,152	0	69,000	441,156	1,189,000	425,825	-322,019
1955	998,232	146,363	0	69,000	1,213,595	1,399,000	620,994	435,589
1956	337,626	30,879	0	69,000	437,505	1,379,000	485,315	-456,180
1957	4,266,048	1,458,663	0	69,000	5,793,711	1,232,000	1,025,944	5,587,655
1958	2,574,600	937,894	0	69,000	3,581,494	1,252,000	887,132	3,216,626
1959	2,575,104	1,432,275	0	69,000	4,076,379	1,170,000	1,021,770	3,928,149
1960	3,265,751	2,655,000	0	69,000	5,989,751	1,149,000	1,254,511	6,095,262
1961	3,653,248	1,998,967	0	69,000	5,721,215	1,129,000	1,076,044	5,668,259
1962	794,741	143,076	0	69,000	1,006,817	1,252,000	613,689	368,506
1963	503,098	60,192	0	69,000	632,290	1,275,000	512,451	-130,259
1964	517,479	482,267	0	69,000	1,068,746	1,192,000	771,286	648,032
1965	2,034,662	345,356	0	80,000	2,460,018	1,272,000	741,018	1,929,036
1966	1,282,664	1,089,073	0	80,000	2,451,737	1,907,000	881,916	1,426,653
1967	948,823	1,164,460	0	80,000	2,193,283	1,252,000	1,029,075	1,970,358
1968	3,294,120	1,855,972	0	80,000	5,230,092	1,272,000	1,074,999	5,033,091
1969	2,034,304	1,005,074	0	80,000	3,119,378	1,376,000	827,646	2,571,024
1970	2,323,506	1,615,713	0	84,000	4,023,219	1,275,000	944,537	3,692,756

Table 6. Annual Water Balance (Acre-Feet/Year)

1971	1,403,788	874,242	0	84,000	2,362,030	1,374,000	943,495	1,931,525
1972	1,553,103	1,030,710	0	84,000	2,667,813	1,246,000	1,026,989	2,448,802
1973	4,049,255	1,894,304	0	96,000	6,039,559	1,222,000	1,148,056	5,965,615
1974	2,995,426	1,112,508	0	96,000	4,203,934	1,220,000	1,060,387	4,044,321
1975	2,706,326	453,070	0	96,000	3,255,396	1,183,000	702,401	2,774,797
1976	2,275,274	685,340	0	96,000	3,056,614	1,290,000	993,591	2,760,205
1977	2,184,310	1,192,889	16,928	41,489	3,401,760	1,228,383	903,489	3,076,866
1978	1,360,841	731,754	13,371	36,550	2,115,774	1,153,055	769,447	1,732,166
1979	3,195,754	2,510,927	11,261	35,998	5,731,418	1,003,905	1,204,085	5,931,598
1980	1,032,773	561,317	16,566	37,558	1,615,082	1,259,268	611,999	967,813
1981	3,338,669	1,781,002	15,539	35,857	5,139,989	1,147,404	1,114,176	5,106,761
1982	1,989,624	974,733	17,442	31,813	2,978,728	1,190,344	714,350	2,502,734
1983	2,310,265	1,450,957	9,535	23,067	3,774,754	1,121,414	928,765	3,582,105
1984	1,027,480	670,037	19,983	30,863	1,708,397	1,285,444	781,577	1,204,530
1985	2,364,356	1,131,842	18,720	26,438	3,503,916	1,169,060	753,707	3,088,563
1986	2,089,074	969,213	18,382	27,921	3,067,826	1,214,256	897,056	2,750,626
1987	3,953,420	823,617	15,240	26,531	4,788,328	1,224,238	661,675	4,225,765
1988	534,680	96,146	66,184	40,880	605,522	1,279,900	423,503	-250,875
1989	708,568	332,587	65,414	38,760	1,014,500	1,190,637	682,425	506,288
1990	571,074	622,940	53,941	38,953	1,179,026	1,179,326	765,735	765,435
1991	3,765,498	1,583,413	52,072	37,281	5,334,121	1,370,616	1,217,113	5,180,617
Minimum	**327,004**	**30,879**	**0**	**23,067**	**437,505**	**939,000**	**423,503**	**-456,180**
Maximum	**4,701,867**	**2,655,000**	**66,184**	**96,000**	**6,726,358**	**1,907,000**	**1,254,511**	**6,946,894**
Average	**1,960,660**	**963,401**	**8,051**	**62,784**	**2,978,794**	**1,195,221**	**852,730**	**2,636,303**

Note: Combined Inflow = Gaged + Modeled - Diversion + Return Flow

Balance = Combined Inflow - Evaporation + Precipitation

1941 through 1991, the combined surface water inflows averaged 2,978,800 acre-feet per year. These inflows ranged from a low of 437,500 acre-feet in 1956, to a high of 6,726,400 acre-feet in 1941. During 1988-1991, the combined surface water inflows ranged from a low of 605,500 acre-feet to 5,334,100 acre-feet, averaging 2,033,300 acre-feet per year. During 1941-1991, ungaged inflows contributed 12 to 57 percent of total combined surface water inflows. On average during this period, ungaged inflows contributed 33 percent of the combined surface water inflows. During 1941-1991 the freshwater inflow balance of the estuary system varied from a low of -456,200 acre-feet in 1956, to a high of 6,946,900 acre-feet in 1941, averaging 2,636,300 acre-feet per year.

CONCLUSIONS AND COMMENTARY

The methods used by TDWR were reasonably reproducible in this study. As the results indicate, the estimates for 1988 through 1991 are fairly representative of the previous 46 year period. The 1988-1991 record did not produce any significant outliers. The most notable variance from the previous study relates to the diversion data. The diversions from 1988 through 1991 average 59,400 acre-feet per year. This compares with an average of 15,700 acre-feet per year between the years of 1977 and 1987. The variance is predominantly a result of including Houston Lighting and Power's South Texas Project's diversions in last four years of this analysis.

This analysis did not attempt to evaluate data by sub-watersheds as was done in previous studies. However, care was taken to identify where diversions and return flows occurred in relation to major watershed boundaries and existing streamflow gage locations. Therefore, the results of this analysis should reasonably match results of previous efforts.

In some instances, data was not available for portions of the 1988 through 1991. In these cases the missing data was estimated. Specifically, no water use data was available from 1990 and 1991 for certain permit holders. Linear regression was used to estimate total monthly diversions in each basin as a function of one or more of the larger diverters for whom data was available. Also, the data for evaporation and precipitation was sporadic over the entire period of record for most of the gage locations. Again, linear regression was used to project missing data for a particular gage as a function of neighboring gage data.

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CHAPTER 3

TXBLEND MODEL CALIBRATION

INTRODUCTION

This chapter describes the application of TWDB's TX-BLEND hydrodynamic and salinity transport models to describe the flow and salinity patterns in the estuary. The calibration of the models is given in detail, followed by verification using annual historical freshwater inflows, meteorological and Gulf of Mexico tidal conditions.

TxBLEND Model

TxBLEND is a computer model designed to simulate water circulation and salinity conditions in estuaries. The model is based on the finite element method, employs triangular elements with linear bias functions and simulates movement in two horizontal directions. Water circulation is simulated by solving the continuity equation and the momentum equation, jointly called the shallow water equations. Salinity condition is simulated by solving the mass transport equation or the convective-diffusion equation.

TxBLEND is an expanded version of the BLEND model to which additional input routines for tides, river inflows, winds, evaporation, salinity concentration, and some utility routines were added. BLEND is also an expanded version of a preceding model called FLEET (Gray, 1987), which is a two-dimensional finite element model that employs linear triangular elements and applies the explicit scheme to numerically solve the shallow water equations but not the convective-diffusion equation.

CALIBRATION DATA

To provide synoptic data for the calibration of the TxBLEND model to the Matagorda Bay estuary, an intensive survey was conducted from June 28 to July 3, 1993. The survey was conducted by the TWDB in conjunction with TPWD, TNRCC, USGS and LCRA.

Intensive Survey

Hourly water quality and velocity measurements were taken at 20 sites, listed in Table 1, distributed across the Matagorda Bay estuary. Locations of these sampling sites are shown in Figure 1. Figure 2 shows the depth profile of the Matagorda Bay. In addition to hourly measurements, flow and velocity data from two sites and salinity data from three sites from were collected with continuously using automated instruments. These automated instrument site id's and names are listed in Table 2. Continuous tide data was collected at five sites and weather data was collected at two sites. The continuous tidal and weather station site id's and names are also listed in Table 2.

Data Preparation

Tide Data

Tide data were collected at the five sites for approximately one month prior to the intensive survey and continued for about one month after the intensive survey. Figures 3 to 7 illustrate the raw tide data from the five gages. Two problems, common to most tide records, occurred with these data, there are missing data in the records and the elevation datum varies between gages.

A time series was constructed for each tidal record from each tide site. Most of the tidal locations were highly correlated to the Gulf driving tide. The Gulf tide was measured at station T1, which was in the old Colorado River channel near Gulf of Mexico. Multiple regressions, including a time offset to account for the phasing difference between stations, provided a method to reconstruct some of the data gaps at some stations. Unfortunately this method did not resolve all the gaps in all the tide records. The remaining data gaps were estimated and filled in by hand by estimating an apparently reasonable tidal pattern to fill the gap.

Table 1 Matagorda Bay Intensive Survey Sites

ID	Station Name	Latitude (N) (d,m,s)	Longitude (W) (d,m,s)
1	Matagorda Entrance Channel	28 25 44	96 19 51
2A	Pass Cavallo	28 23 52	96 23 56
2B	Saluria Bayou	28 24 03	96 24 36
3A	Big Bayou	28 25 39	96 24 26
3B	Port O'Connor	28 26 21	96 24 42
4C	Matagorda Channel (center)	28 33 36	96 30 51
4W	Matagorda Channel (west of)	28 33 29	96 31 03
4E	Matagorda Channel (east of)	28 33 47	96 30 37
5C	Lavaca Bay Causeway (center)	28 39 15	96 35 51
5W	Lavaca Bay Causeway (west of)	28 39 09	96 36 05
5E	Lavaca Bay Causeway (east of)	28 39 21	96 35 41
6A	Culver Cut	28 39 48	96 00 33
6B	Intercoastal Waterway near Culver Cut	28 39 51	96 00 53
7A	Colorado River above Matagorda	28 41 13	95 58 35
7B	Colorado River Diversion	28 40 24	95 58 37
8A	Intercoastal Waterway East of Matagorda	28 41 20	95 57 41
8B	Bypass Channel (Old River Channel)	28 40 50	95 58 23
9	Carancahua Pass	28 37 36	96 22 07
10	Palacios Channel Marker 52 (34)	28 38 14	96 15 38
11	Lavaca River near FM 616 Bridge	28 49 50	96 34 34

Table 2 Matagorda Bay Automated Monitor Sites

ID	Station Name	Latitude (N) (d,m,s)	Longitude (W) (d,m,s)
N1	South Palacios Point (Niskin Automated Flow)	28 03 15	96 03 40
T1	Colorado River (Tide Gage)	28 37 13	95 58 22
T2	Lavaca River (Tide Gage)	28 49 54	96 34 39
T3	Matagorda Bay (Tide Gage)	28 36 17	96 01 11
T4	Lavaca Bay at Magnolia Beach (Tide Gage)	28 33 52	96 32 50
T5	Big Bayou (Tide Gage)	28 25 22	96 24 52
DS1	Lavaca Causeway (Salinity Monitor)	28 39 16	96 35 37
DS2	Matagorda Bay (Salinity Monitor)	28 26 35	96 21 10
DS3	Magnolia Beach (Salinity Monitor)	28 33 52	96 32 50
W1	Lavaca Causeway (Weather Station)	28 38 26	96 36 35
W2	Matagorda Bay Range Tower (Weather Station)	28 27 02	96 21 12

Tide gages are rarely set to the same elevation datum, particularly temporary gages. To set the datum for the Gulf Boundary tide (T1), the record was searched for a period of time during which the change in tidal elevation was symmetrical around a constant elevation. This constant elevation was set to mean sea level for this simulation. Where possible, the tidal data for each of the other gages were shifted vertically and in time to be consistent with the Gulf boundary tide.

The tidal gages in the Lavaca River (T2) and Lavaca Bay (T4) presented a problem due to large inflows from Lake Texana during the week preceding the intensive survey. Figure 7 indicates that the Lavaca River rose approximately 8 feet during the week prior to the survey. Due to these large inflows and the relatively restricted exchange between Lavaca Bay and Matagorda Bay proper, there was a large amount of fresh water in Lavaca Bay and a resulting "tide set".

Water Quality Data

Hourly water quality data were taken at all stations listed in Table 1. Field parameters consisting of dissolved oxygen, pH, temperature, specific conductance, and, at some stations, salinity were obtained with field instruments. Some of the instruments read salinity and some do not. The instruments that read salinity do so by measuring specific conductance and temperature and internally calculating salinity. Salinity values were calculated for those stations without recorded salinity in a like fashion.

The water quality parameters were measured at each station at 20% of the station depth, 50% of the station depth and 80% of the station depth to obtain information concerning density stratification. Since TxBLEND is a horizontally two dimensional model and is, therefore, depth averaged, salinity measurements were averaged at each station at each hourly record to obtain a water column average salinity for use in the model calibration.

Velocity Measurements

Water velocity measurements were obtained at the same times as the water quality data and at the same depth intervals. In addition to velocity, current direction was recorded with each velocity measurement. For model purposes, a sign convention was adopted to denote current direction. the sign of the velocity scaler is positive if the current was headed toward Matagorda Bay proper and negative if the current was headed away from Matagorda Bay proper. Since TxBLEND is a horizontally two dimensional model and is, therefore, depth averaged, velocity measurements were averaged at each station at each hourly record to obtain a water column average velocity for use in the model calibration.

MODEL CALIBRATION

As previously mentioned, TxBLEND operates upon a mesh of triangular elements constructed from interconnected nodes. Figure 8 illustrates the model grid layout. The final schematic arrangement of the triangular elements that comprise the Matagorda Bay system is shown and major geographic features are identified.

The original model grid consisted of 2800 nodes interconnected to form 3200 triangular elements. After some initial calibration work, the grid density was increased in several areas to provide better spatial resolution of the calculated model predictions and to decrease the spatial calculational step. The final grid consists of 2489 nodes interconnected to form 4059 triangular elements. While decreasing the spatial step of the model slows the simulation by adding to the computational overhead it increases the stability of the calculations, particularly in areas that exhibit steep gradients in one of the modeled parameters. The model performs it's calculations at each node at each time step to simulate circulation and dissolved constituent movement through both space and time. To account for the vertical dimension, each node is associated with a depth at than location, gleaned from bathymetric maps.

The locations of the intensive survey within the model schematic are shown in Figure 9. The locations of both the continuous water quality monitors and tide gages utilized during the intensive surveys within the model schematic are shown in Figure 10. Model boundary locations are shown in Figure 11. There are two different kinds of boundary condition locations used within the model. Flow boundaries are locations where the time variable inflows are specified within the model input. There are flow boundaries specified for both the major inflows to the Matagorda Bay system, the Colorado River and the Lavaca River, and are shown in Figure 11 at the schematic headwaters for the reach of each river within the model grid. Tidal boundaries are locations at which time variable tidal elevations are specified within the model input. The Gulf of Mexico boundary accounts for the oceanic tidal input, which, in this model, is the dominant driving tide.

Hydrodynamic Calibration

The TxBLEND model was calibrated in two stages. The hydrodynamic portion of the model was calibrated first then the salinity transport portion was calibrated. To calibrate the hydrodynamic portion of the model, the simulation was run iteratively for the time period encompassing the intensive survey. During the iterative calibration runs, various parameters and the grid construct were adjusted in an effort to replicate tidal elevations, current velocities and current directions measured during the intensive survey.

The model tracks tidal elevations at sites T1, T3 and T5 well. It does not, however, track tidal elevations at sites T2 or T4. There are probably several reasons for this. Sites T2 and T4 are both in upper Lavaca Bay which, during the intensive survey, was affected by extremely large releases from Lake Texana the week preceding the survey. TxBLEND is an open bay model for shallow estuaries and those sites that are more open bay sites are tracked better by the model.

Figures 12 through 23 show predicted flow velocities versus observed flow velocities at those intensive survey sites where these data were generated. By the convention adopted here, a positive velocity is one that has a directional component oriented toward the main body of Matagorda Bay while a negative velocity has a directional component oriented away from the main body of Matagorda Bay. Therefore, the actual flow direction associated with the sign of the velocity differs for each sample site and depends upon the orientation of the site. In general, the predicted and observed velocities agree reasonably well.

Salinity Calibration

After the hydrodynamic calibration was finished, the boundary values and initial values for salinity were included in the model input and salinity model was calibrated in a fashion similar to the hydrodynamic model. Figures 24 through 35 show the predicted salinity versus the observed salinity at the intensive survey sites (note that missing salinity data are set to zero). The predicted salinities agree fairly well at the open bay sites, however, the more channelized sites (ICWW, passes, channels, etc.) do not agree particularly well. Again, TxBLEND is an open bay model and is best at what it was intended for.

During the week prior to the intensive survey, approximately 50,000 acre feet of fresh water was released down the Lavaca River, primarily from Lake Texana. This extreme release, in turn, depressed salinities particularly in Lavaca Bay but also in the entire Matagorda Bay system. Flows were moderately high in the Colorado River during this same time span. In addition, the near shore Gulf salinities were also affected. Near shore Gulf of Mexico salinities were closer to 15 to 20 ppt than to a normal 35 ppt oceanic salinity. Inspection of Figure 34 indicates that the incoming tide in the Old Colorado River channel peaked at approximately 15 ppt. This freshening of the Gulf of Mexico boundary to the model led to considerable operational problems. There were no measured salinities in the near shore Gulf of Mexico during the intensive survey, therefore the boundary salinities had to be estimated. Since the model, in common with most deterministic models, is sensitive to boundary conditions we feel that the model tracks salinity reasonably well, under the circumstances.

Calibration Conclusions

As a check on the overall reasonability of the model, velocities and salinities for the entire model grid were plotted during low water slack tide (7/2/88 @ 04:00 hrs.), incoming tide (7/2/84 @ 12:00 hrs.), high water slack tide (7/2/84 @ 18:00 hrs.), and outgoing tide (7/3/84 @ 00:00 hrs.) and . Figures 36 through 43 are sets of two plots for each of these tidal stages. The first plot in the series is a velocity vector plot (for example Figure 36). The flow direction is shown in these plots by the direction of an arrow originating at the node. The size of the arrow is proportional to magnitude of the flow velocity. The color of the arrow is also proportional to the magnitude of the flow velocity. The low velocities are depicted at the red end of the spectrum and the highest velocities are depicted at the blue end of the spectrum, with intermediate velocities being depicted in spectral order according to the magnitude of the vector scalar. The last plot in each set (for example Figure 37) is a color contour plot of salinity in parts per thousand. Each of these plots includes a color key that illustrates the variation in color coinciding with variation in salinity.

While the model has some trouble with upper Lavaca Bay, due to preceding exceptional inflow, and does not handle highly channelized areas particularly well, overall it does an acceptable job of simulating the Matagorda Bay system. The model works best in open bay shallow estuarine areas. Fortunately, the areas of concern for this study are of this type. Therefore, we feel the model is sufficiently accurate and calibrated for use as a predictive tool in this study.

MODEL VERIFICATION

As previously stated, the model appears to function acceptably and track the relatively short calibration period for which intensive field data were generated. However, that fact alone is no guarantee that the model is capable of accurately and stably simulating the longer time periods required to develop inflow requirements for Matagorda Bay. Incremental and additive small errors, particularly in mass or flow balance, might not manifest themselves to the point of detection during a short simulation but combine to prove longer simulations either unstable or inaccurate. A long term verification step was performed to address the potential long term stability problems and a long term mass balance calculation was performed to address potential mass balance problems.

Long Term Verification

Since the model will be used to verify salinity conditions resulting from various annual freshwater inflow management scenarios, it is appropriate to verify the model's ability to reliably simulate an entire year. The LCRA has been routinely sampling 17 sites in both East and West Matagorda Bay for the past several years. In addition, LCRA has maintained two continuous salinity monitors at two sites in West Matagorda Bay over the same period. Since these data were available in addition to the intensive survey data, the calendar year 1993 was chosen for a long term verification run.

The input deck was constructed from existing data and the entire year was simulated. Comparison of the results of the simulation versus the collected data indicates that the model generally reproduced the observed data. Figures 44 through 55 are color contour plots of the monthly average salinity profiles from the model simulation. Figures 56 and 57 are plots of daily average salinity versus measured data at the two stations where continuous salinity data were available. Both sites are well up into the estuary. The Lavaca Bay site is at the Lavaca Bay Causeway, well within the influence of the Lavaca River, while the site in the eastern arm of west Matagorda Bay is influenced by the Colorado River. Both sites reflect areas affected by freshwater inflow management and areas most difficult to accurately simulate. The model appears to predict long term salinity trends reasonably well.

Mass Balance Calculation

An auxiliary program was written to calculate the mass and flow balance for the TxBLEND model. The program reads the enormous output matrix that TxBLEND constructs and for each time step and calculates the mass of salt and volume of water crossing the boundaries of the control volume, West Matagorda Bay, in this case. In addition the change in volume of each element is calculated and summed to give the change in volume of the control volume. These figures are output to a spreadsheet that serves as a balance sheet for mass of salt and volume of water. If the change of volume is equal to the inflows minus the outflows, then the model flow balances. Similarly, if the change of mass of salt is equal to the mass flux in minus the mass flux out, then the model mass balances for salt. The results of theses calculations indicate that the model balances for both flow and mass, within an error ban of approximately 2 to 7 percent.

Wet Year / Dry Year Runs

Annual simulation runs were performed for a historically dry year (1984) and a historically wet year (1987) to corroborate the model's performance under more extreme conditions and to provide daily flow values for the Nutrient Budget analysis. The model provided reasonable simulations for both years. Figures 58 through 69 are color contour plots of the monthly average salinity profiles from the model simulation for 1984 and Figures 70 through 81 are color contour plots of the monthly average salinity profiles from the model simulation for 1987.

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Gary, William, Fast Linear Element Explicit in Time, Triangular Finite Element Model for Tidal Circulations, Users Manual, Department of Civil Engineering, University of Notre Dame, January 1987.

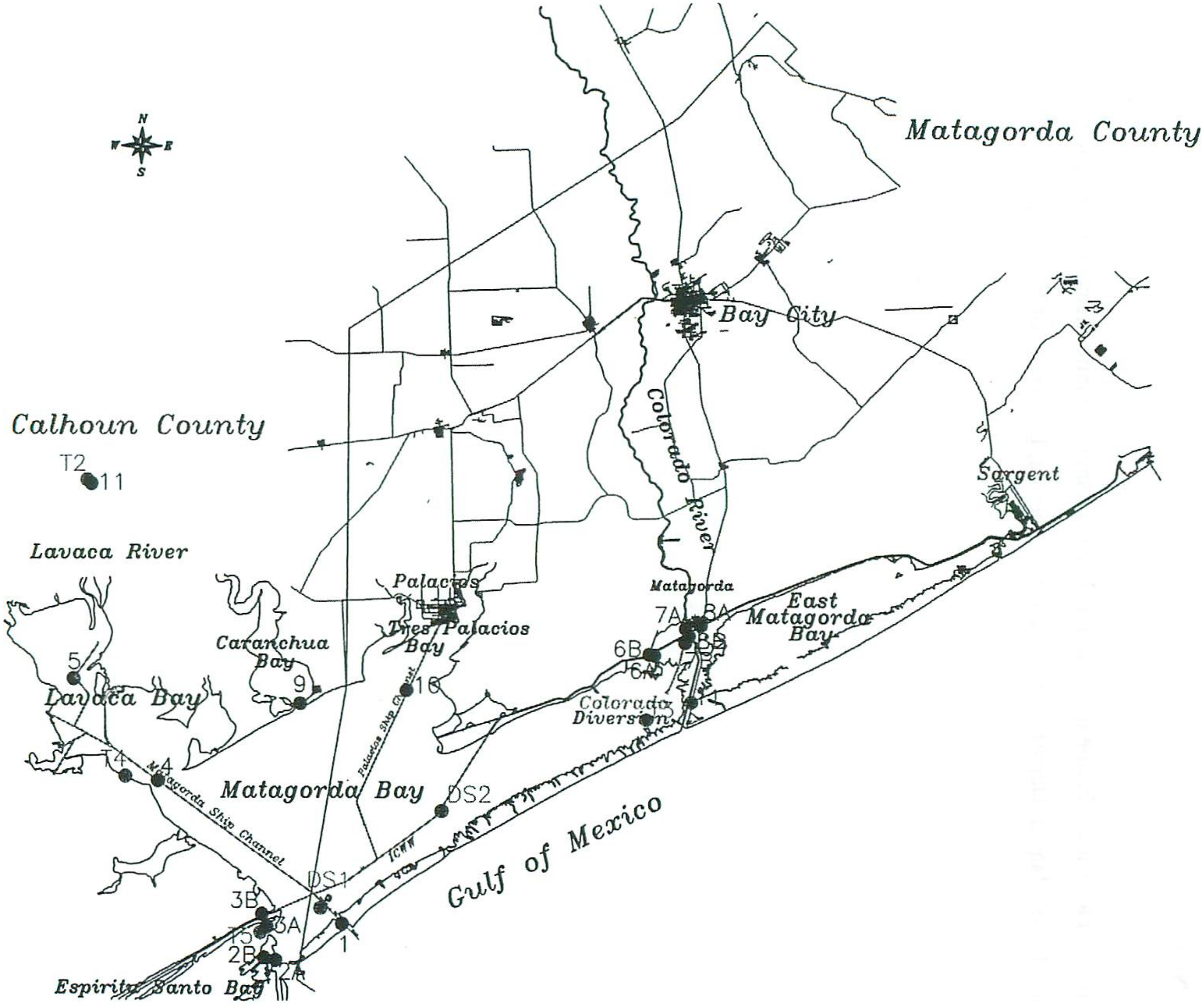


Figure 1. Matagorda Estuary Intensive Survey Sites

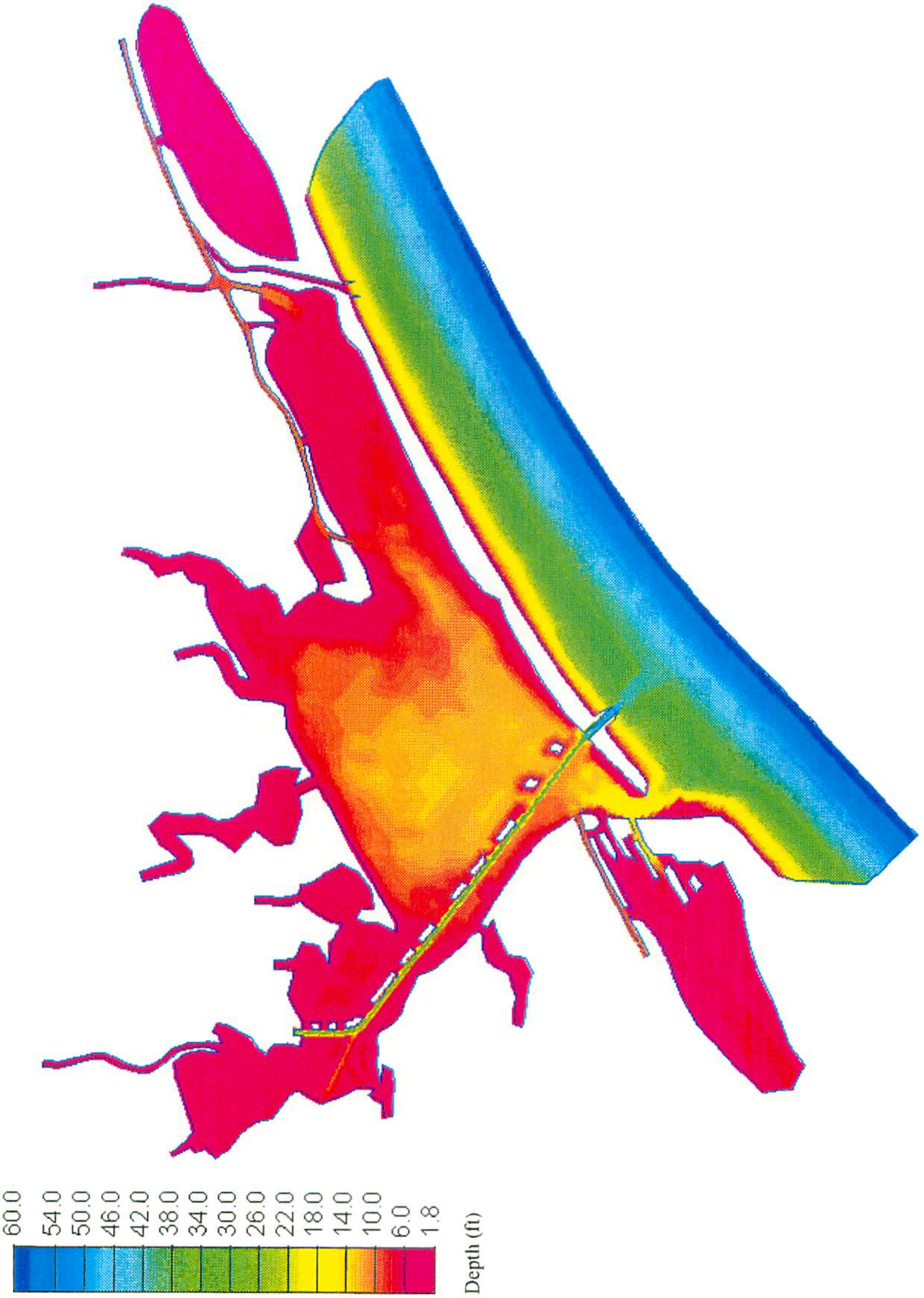


Figure 2 Matagorda Bay Depth Profile

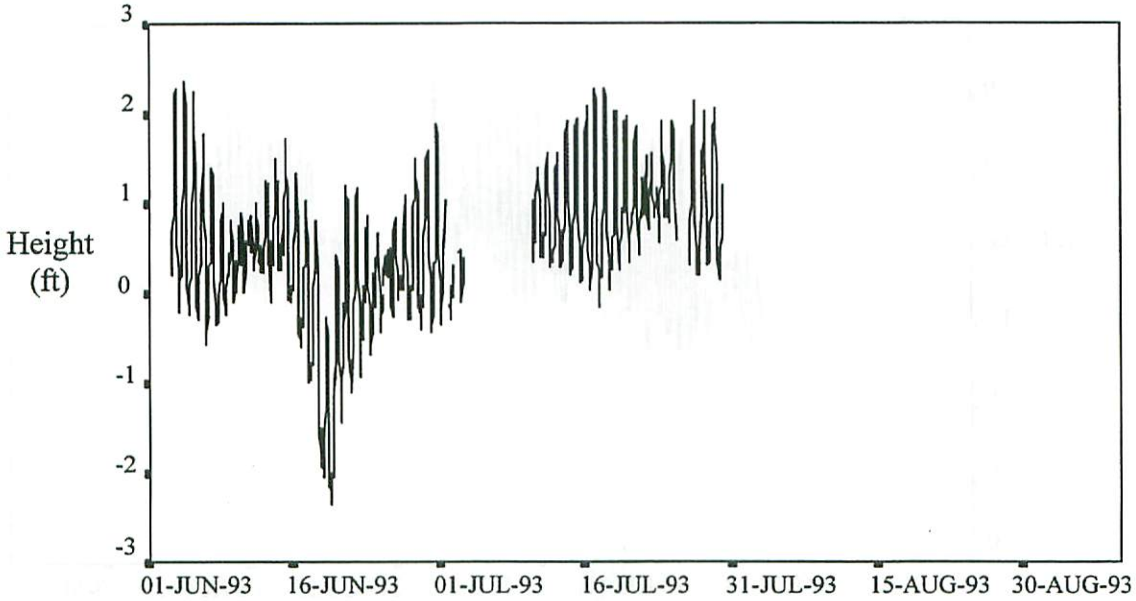


Figure 3 Raw Tide Record
Gulf Of Mexico (T1)

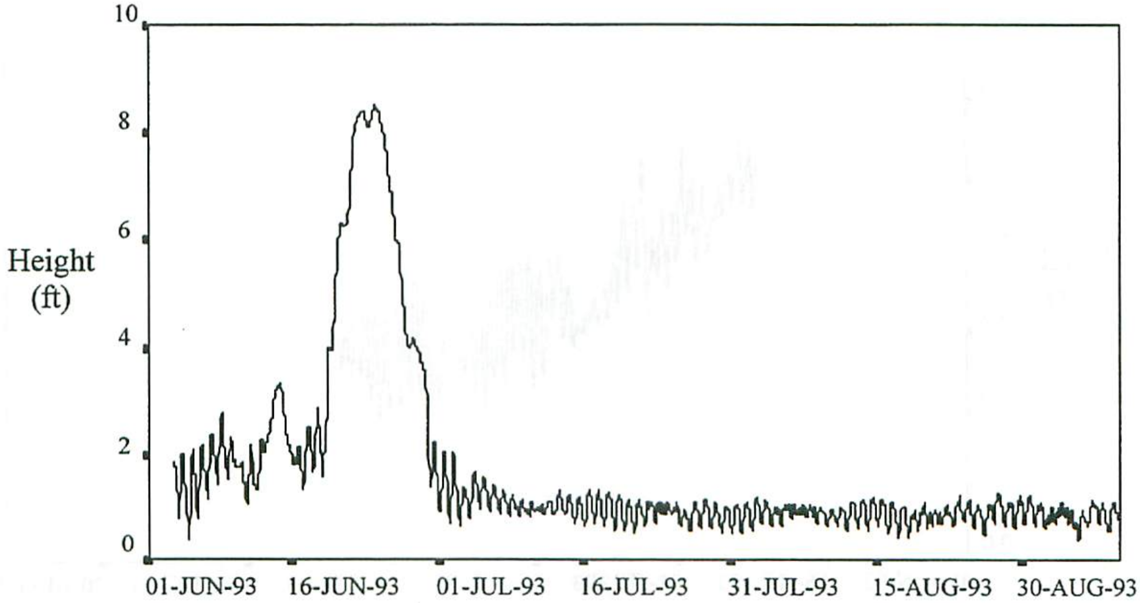


Figure 4 Raw Tide Record
Lavaca River (T2)

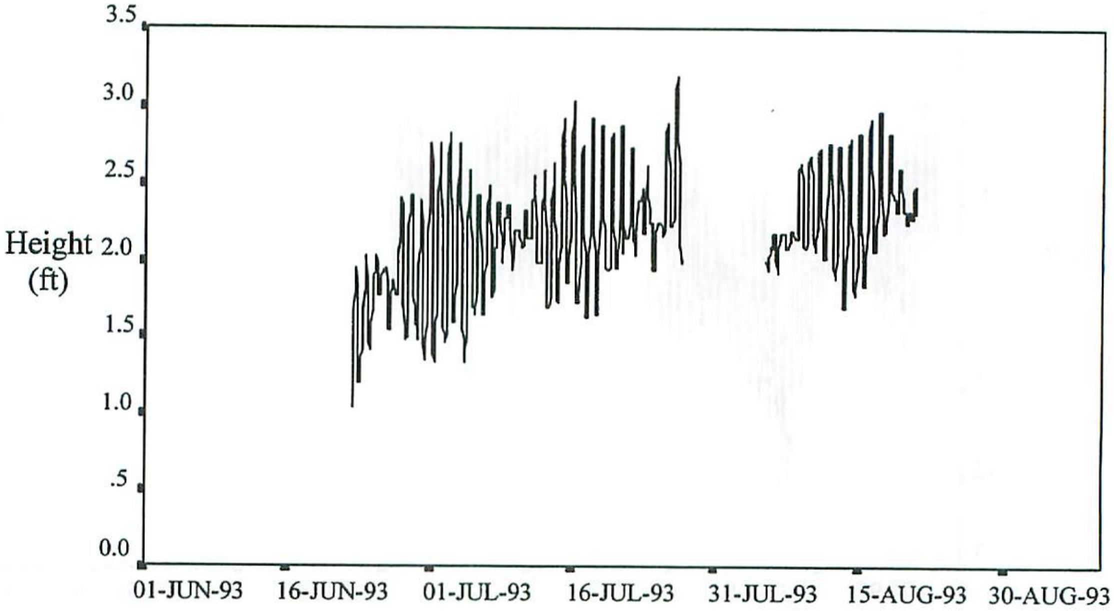


Figure 5 Raw Tide Record
Matagorda Bay (T3)

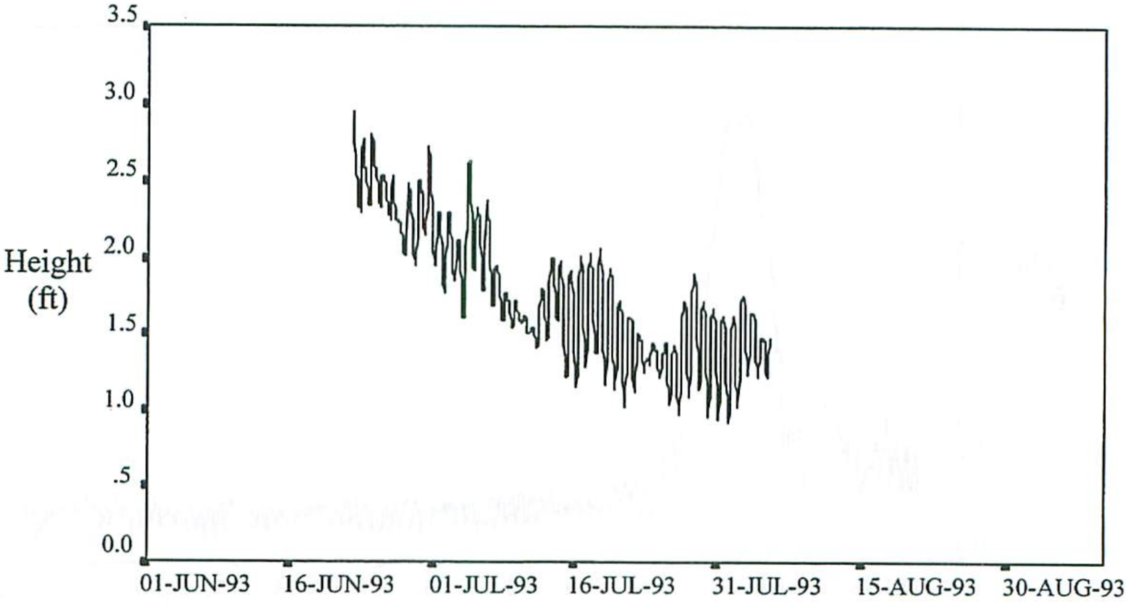


Figure 6 Raw Tide Record
Lavaca Bay at Magnolia Beach (T4)

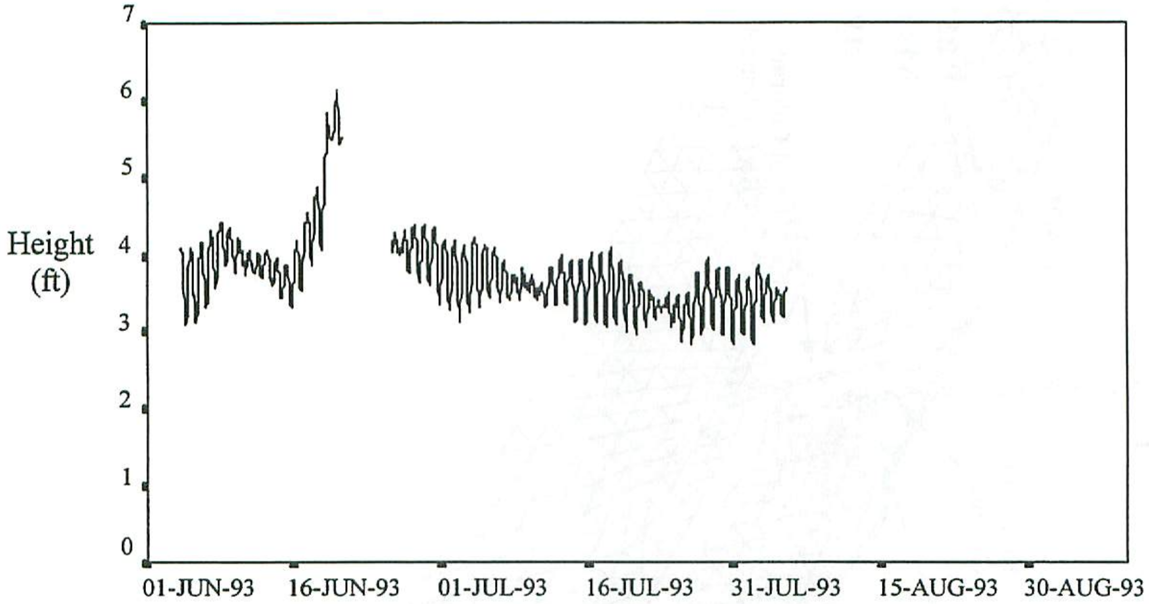


Figure 7 Raw Tide Record
Big Bayou (T5)

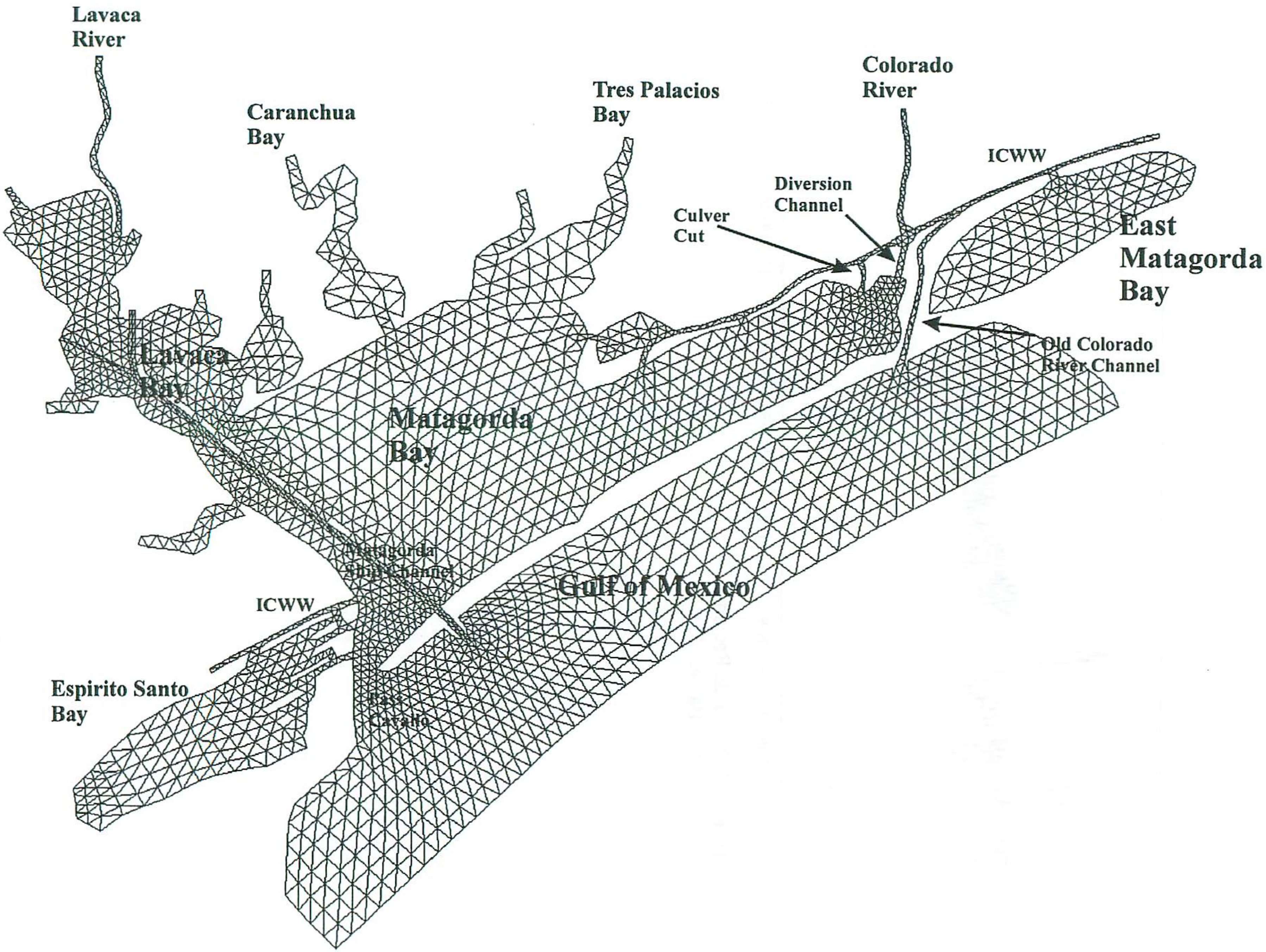


Figure 8 Model Grid Layout

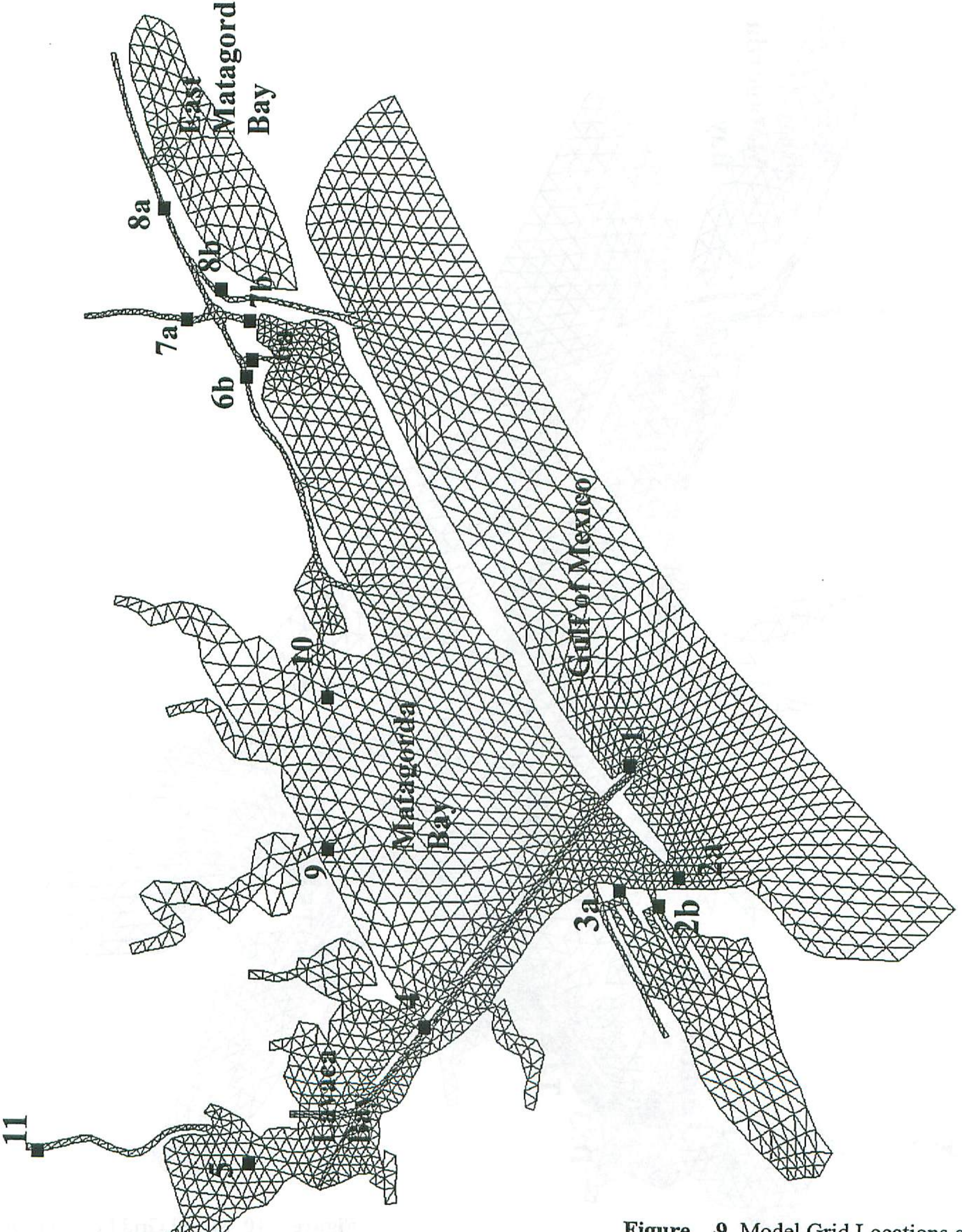


Figure 9 Model Grid Locations of Intensive Survey Sites (See Table 1)

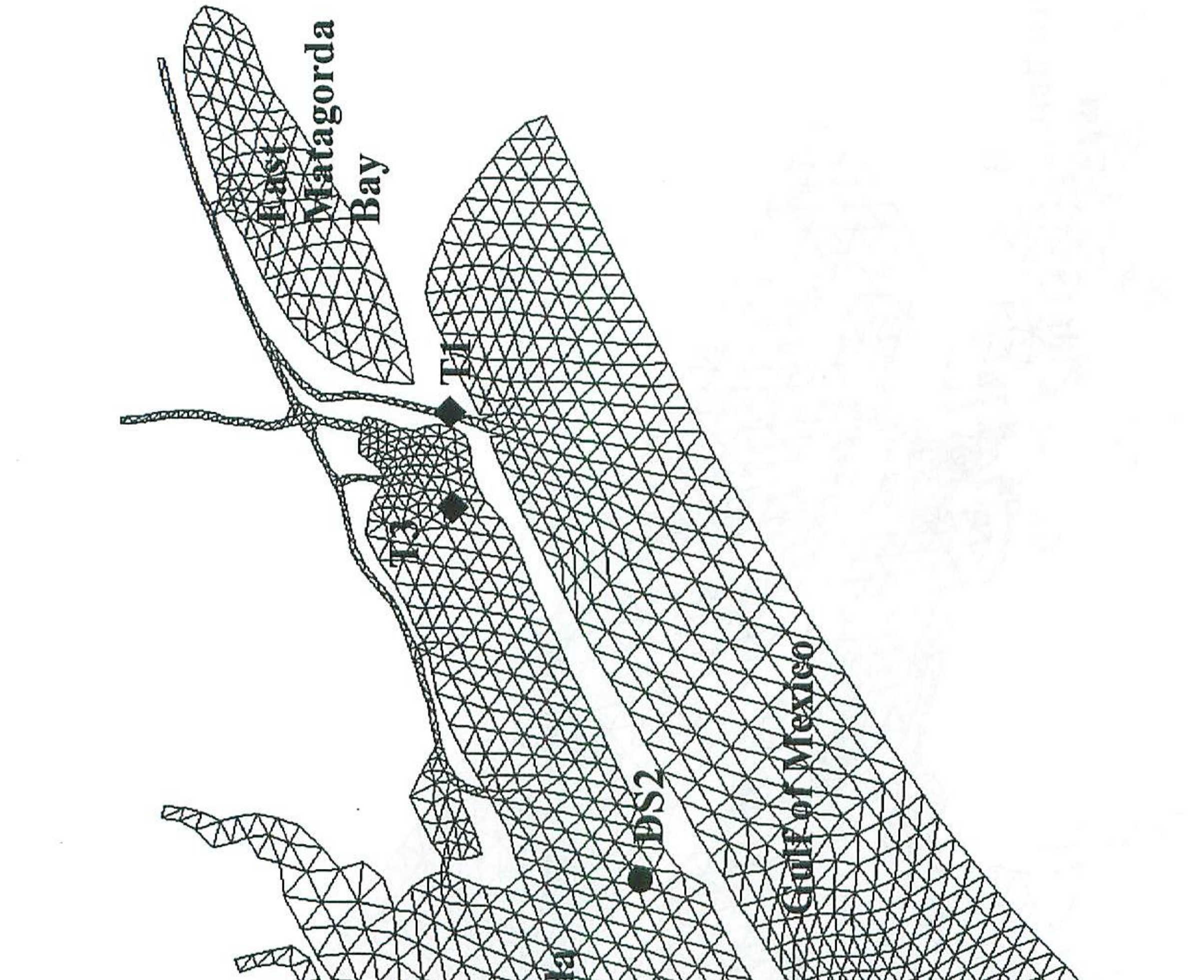


Figure 10 Model Grid Locations of Water Quality and Tide Monitors (See Table 2)

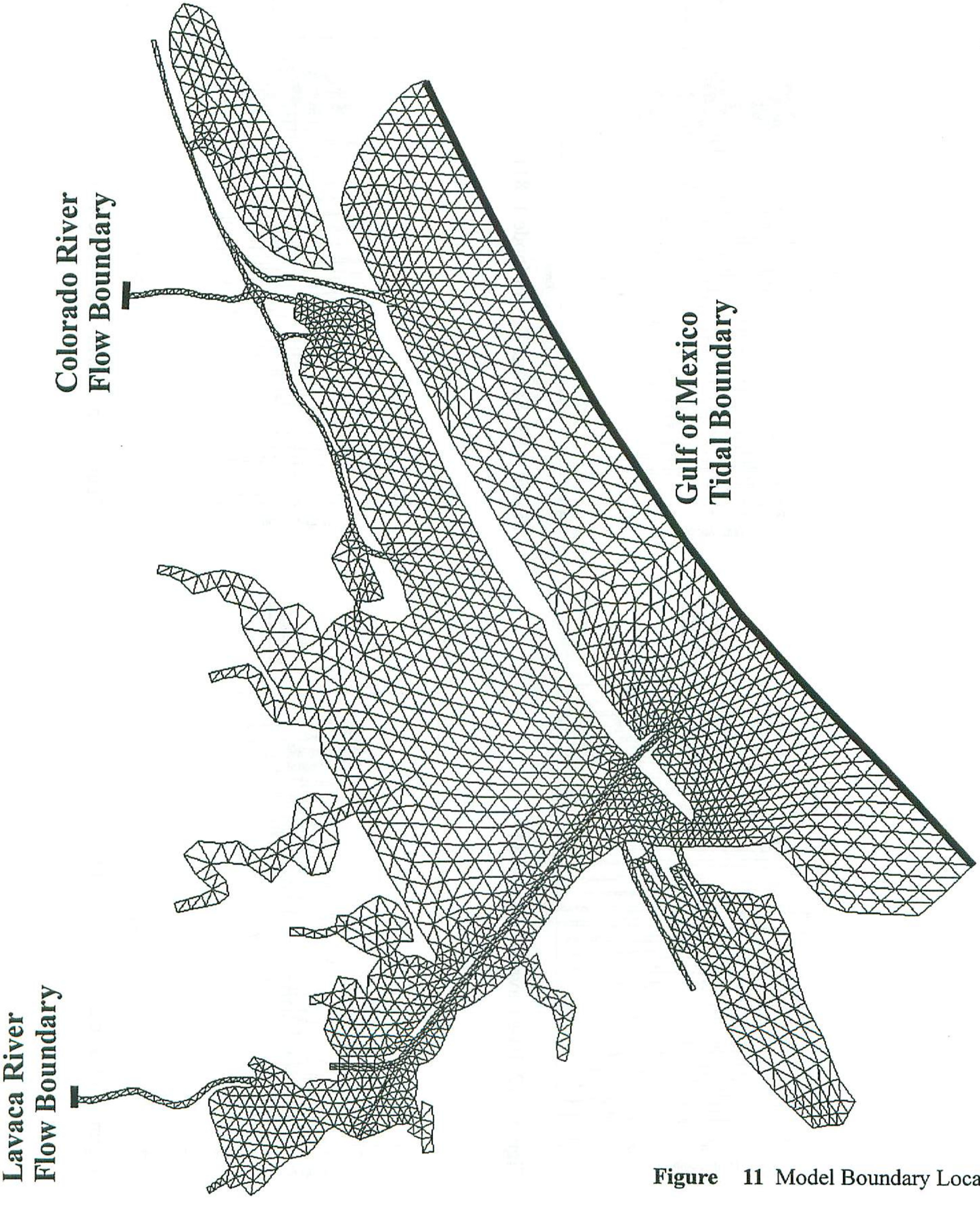


Figure 11 Model Boundary Locations

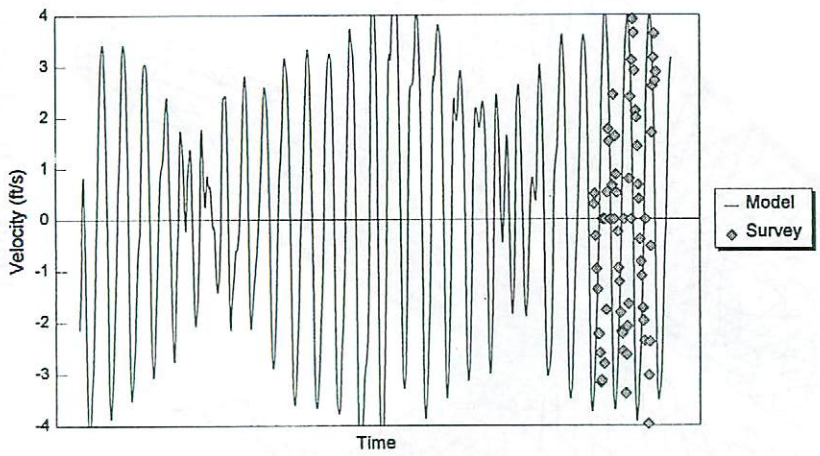


Figure 12 Pass Cavallo (node 1184)

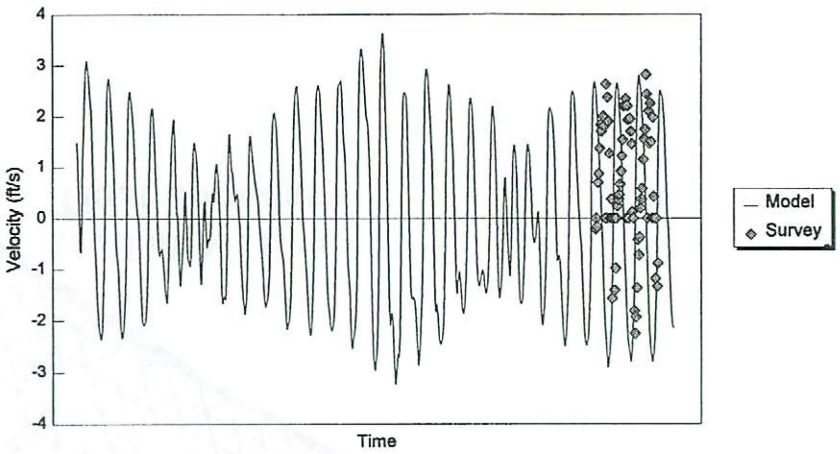


Figure 13 Saluria Bayou (node 1181)

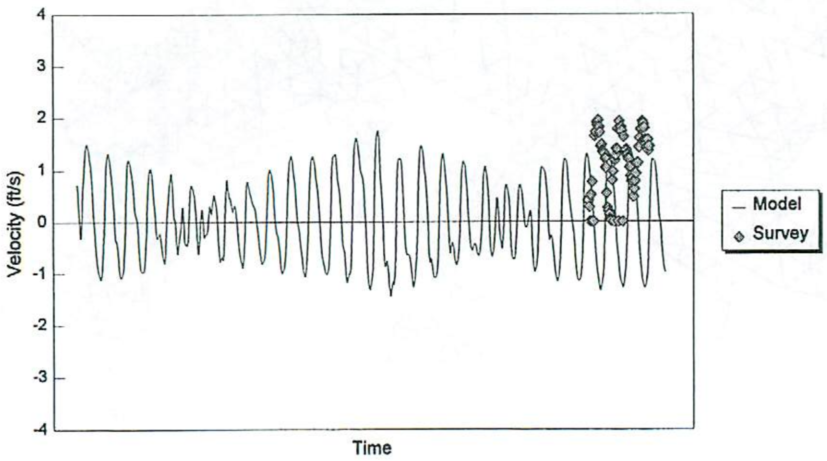


Figure 14 Big Bayou (node 1114)

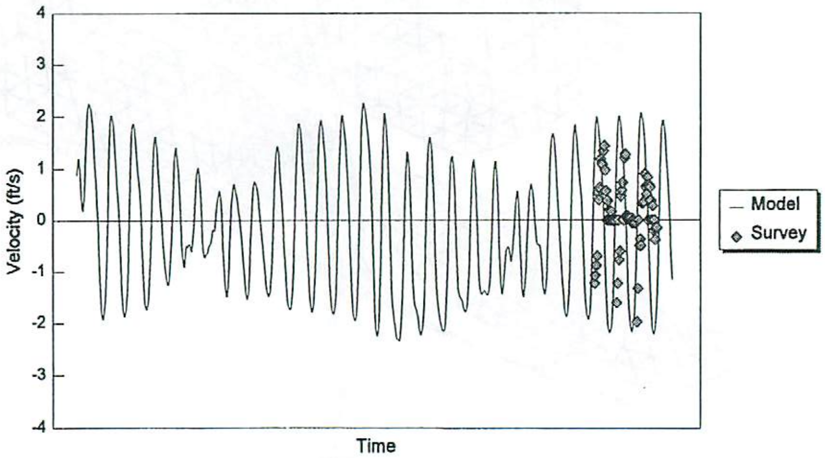


Figure 15 Indian Point (node 414)

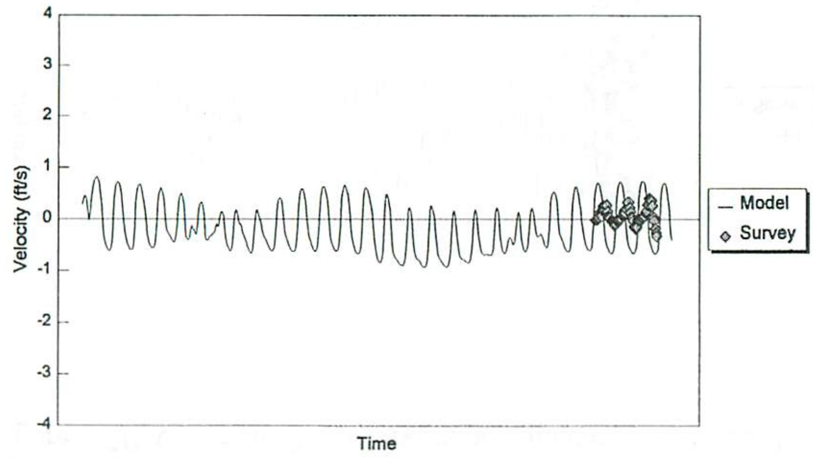


Figure 16 Port Lavaca Causeway (node 78)

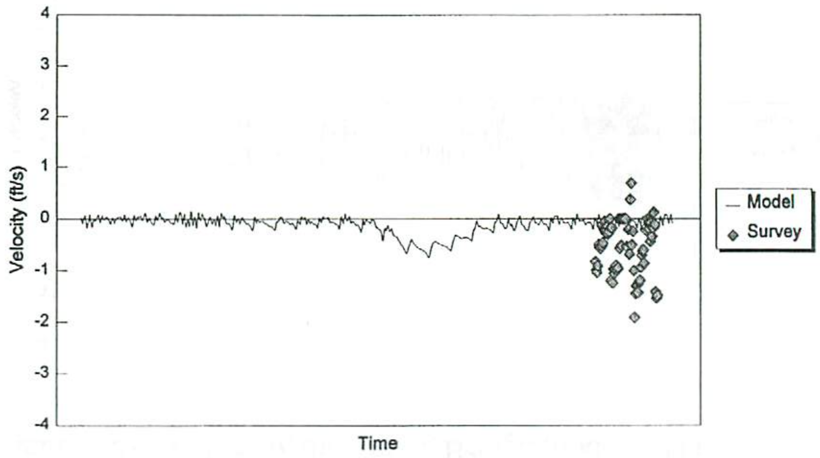


Figure 17 Culver Cut (node 2021)

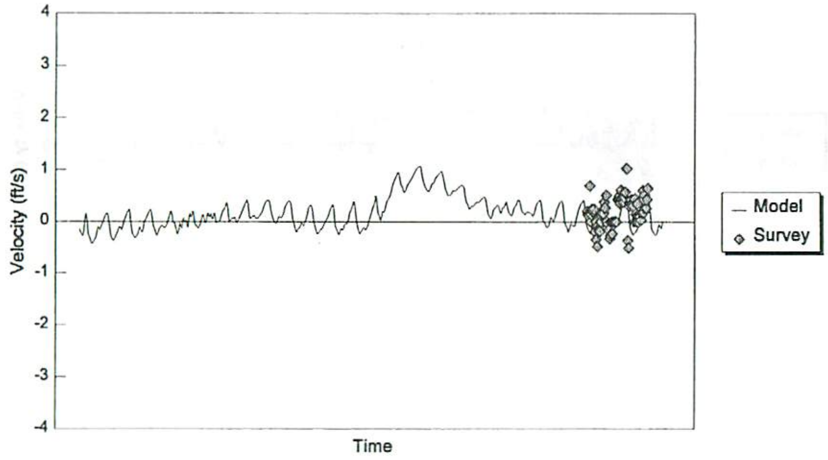


Figure 18 ICWW @ Culver Cut (node 1959)

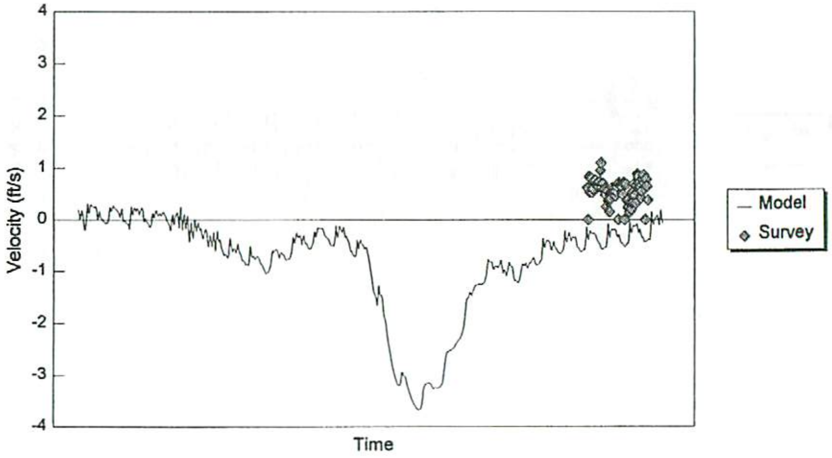


Figure 19 Colorado River (node 2172)

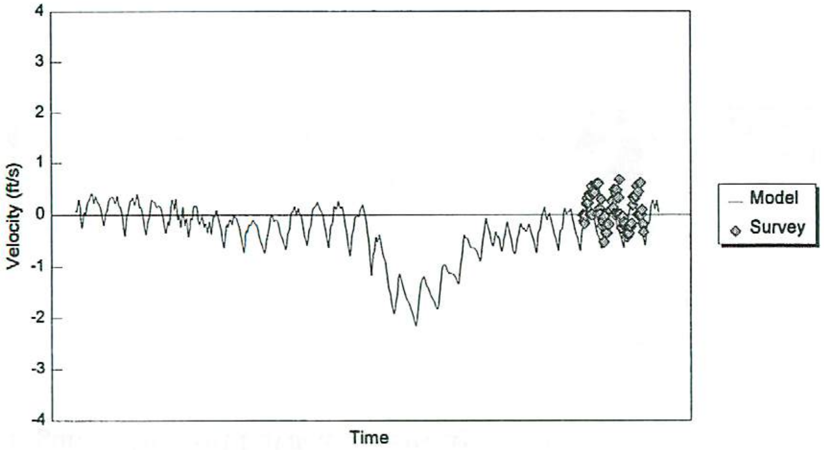


Figure 20 Colorado River Diversion Channel (node 2137)

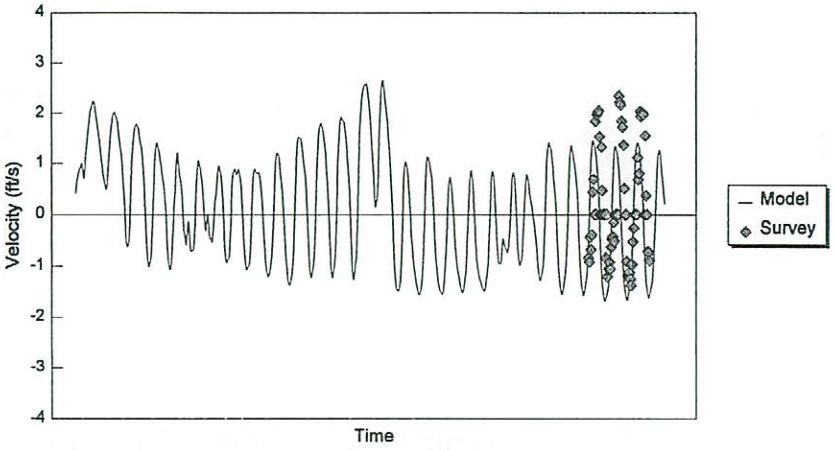


Figure 21 ICWW @ the Swing Bridge (node 2331)

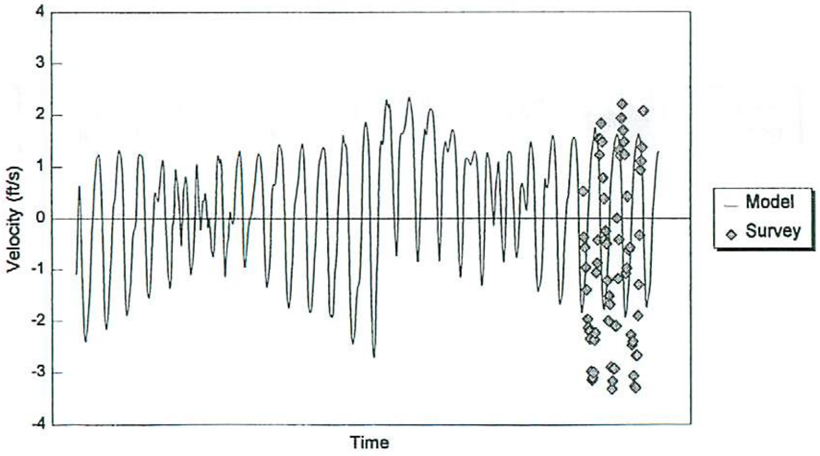


Figure 22 Old Colorado River Channel (node 2255)

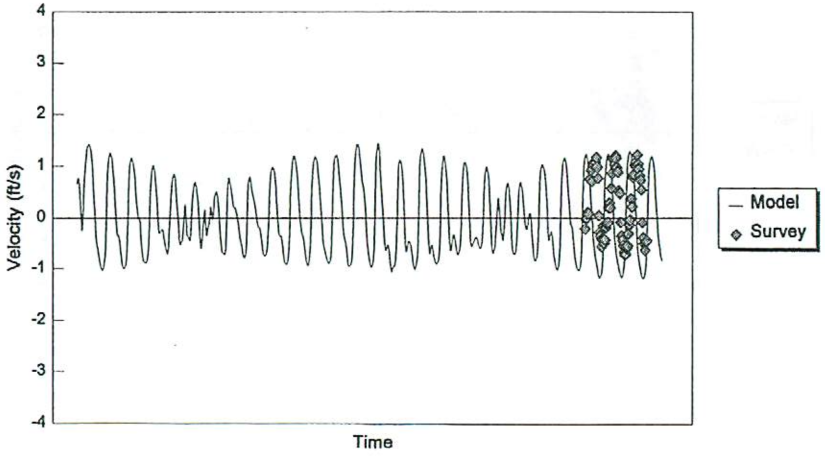


Figure 23 Carancahua Pass (node 597)

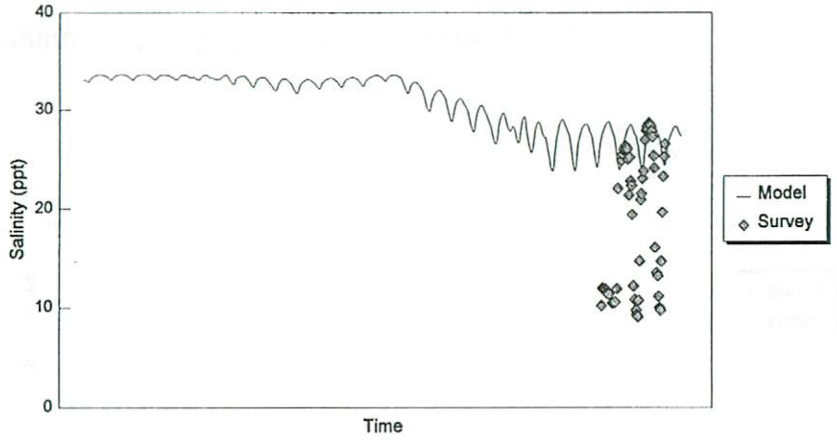


Figure 24 Pass Cavallo (node 1184)

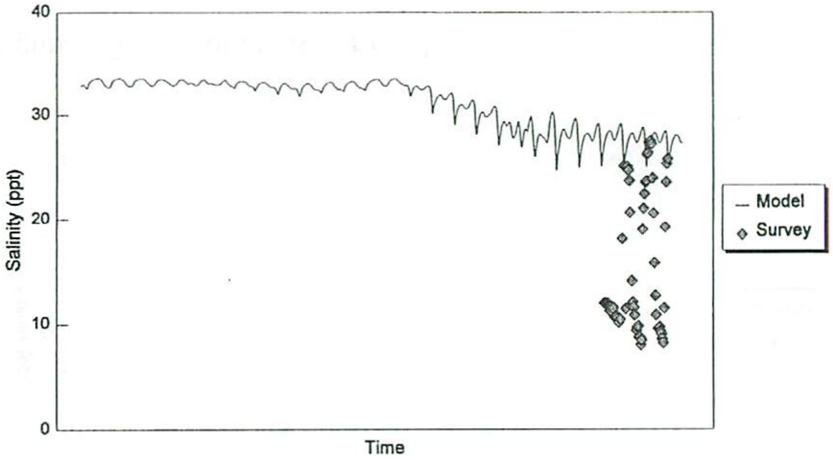


Figure 25 Saluria Bayou (node 1181)

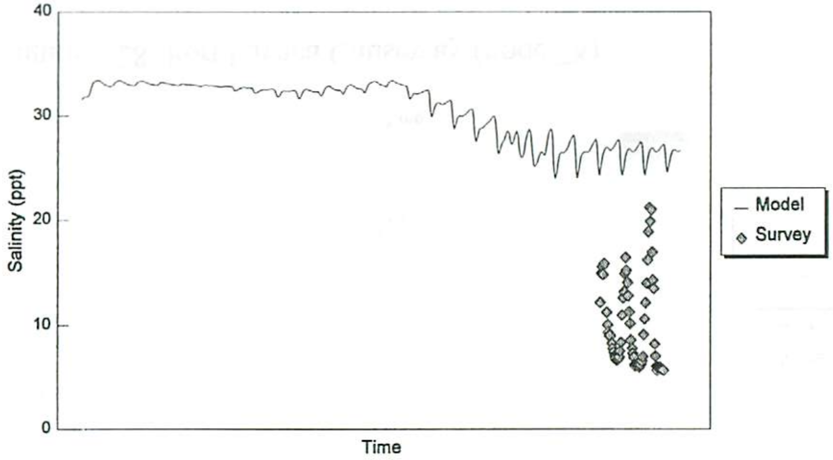


Figure 26 Big Bayou (node 1114)

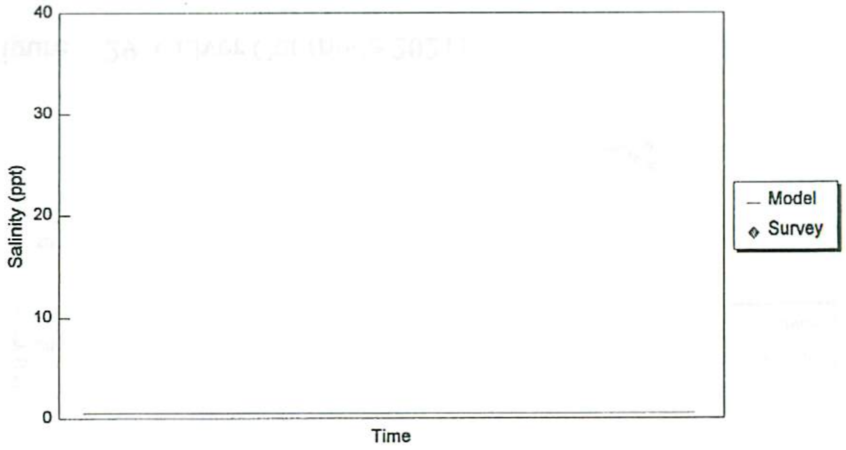


Figure 27 Lavaca River (node 442)

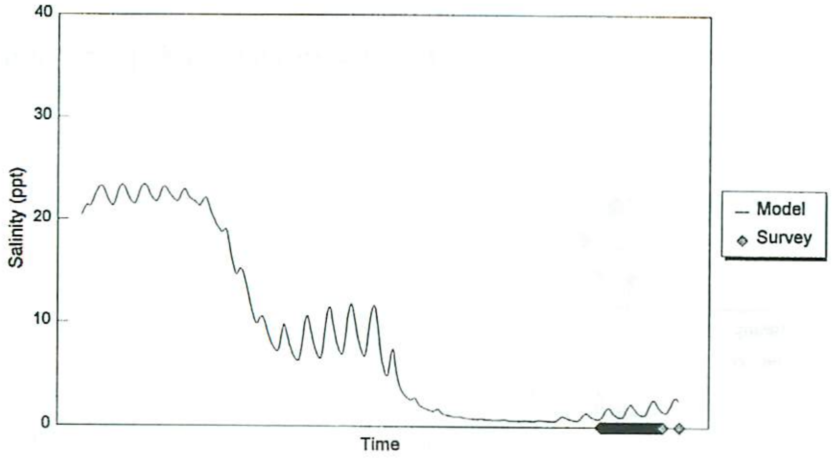


Figure 28 Port Lavaca Causeway (node 78)

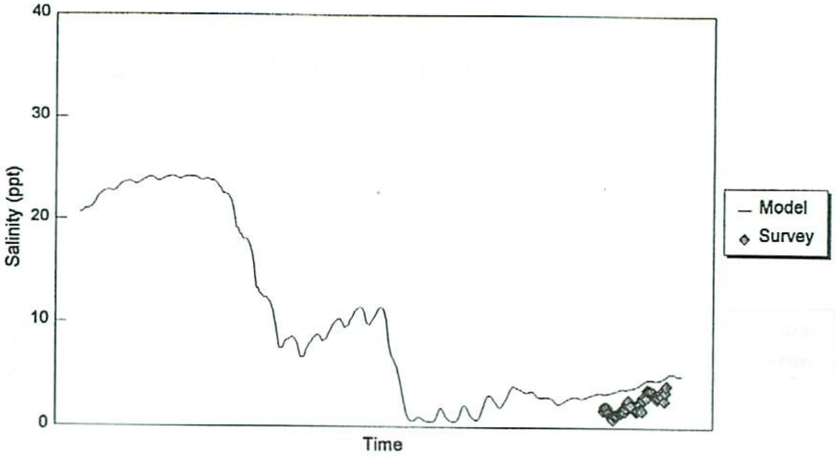


Figure 29 Culver Cut (node 2021)

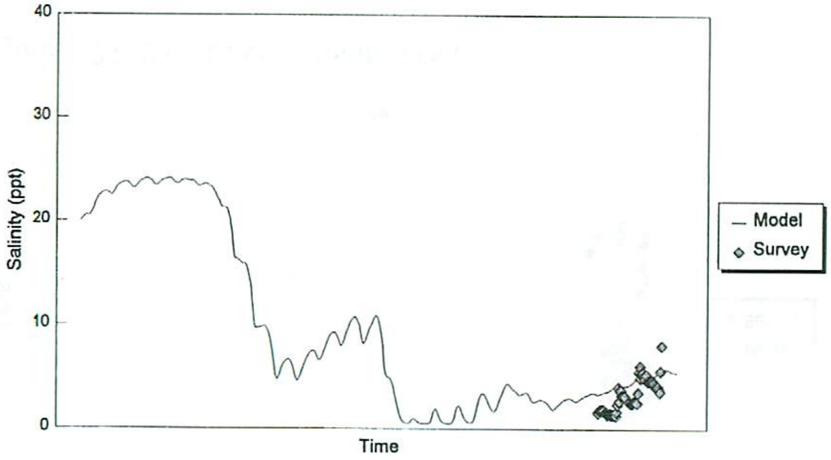


Figure 30 ICWW @ Culver Cut (node 1959)

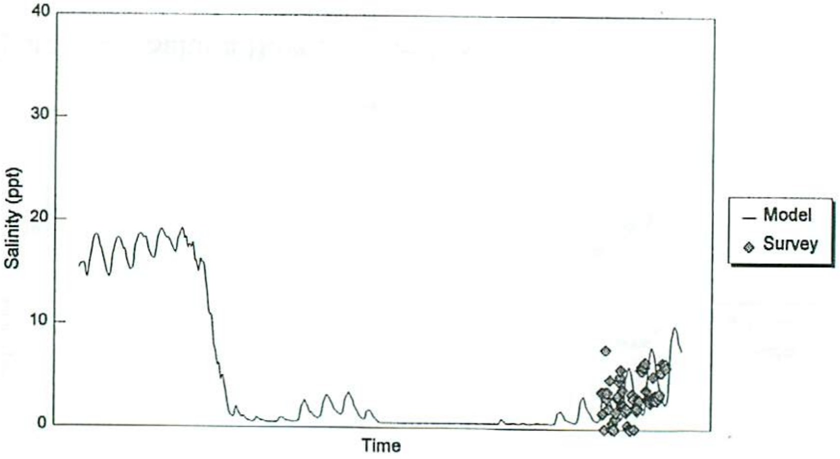


Figure 31 Colorado River (node 2172)

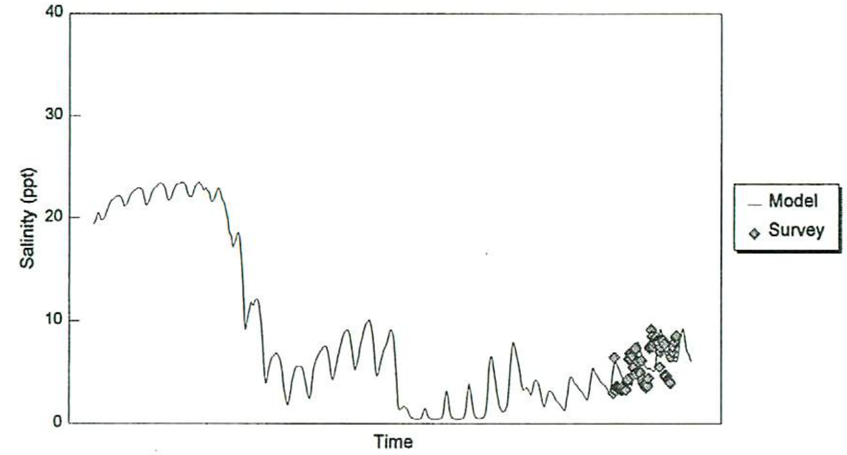


Figure ·32 Colorado Diversion Channel (node 2137)

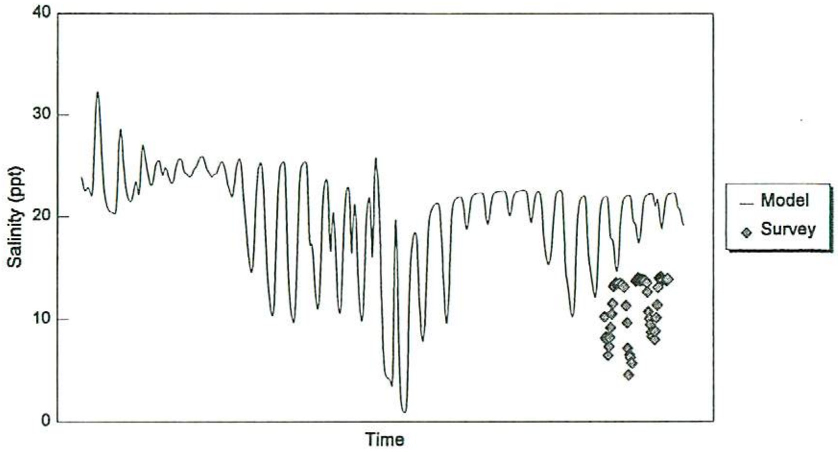


Figure 33 ICWW @ the Swing Bridge (node 2331)

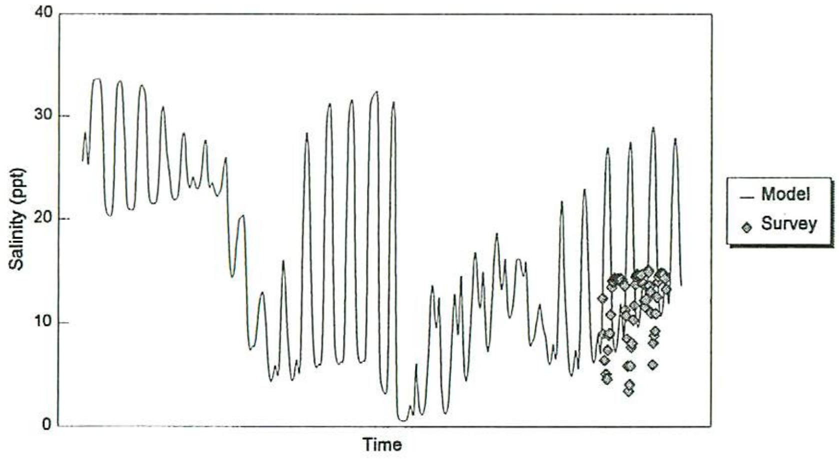


Figure 34 Old Colorado River Channel (node 2255)

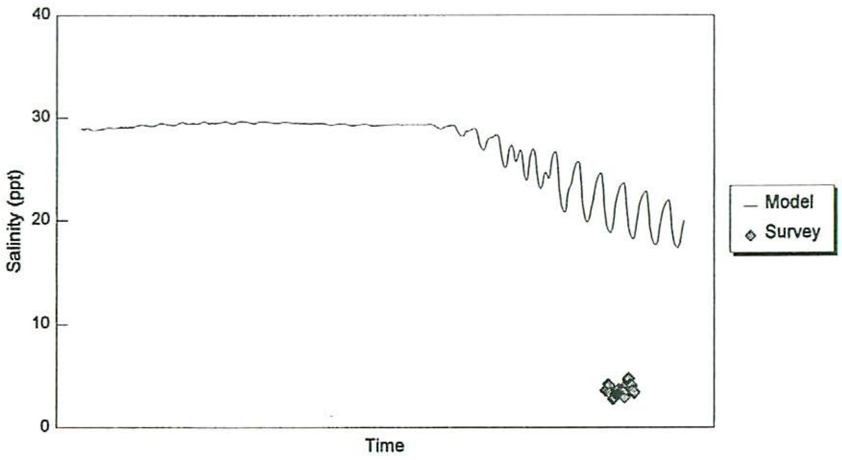


Figure ·35 Carancahua Pass (node 597

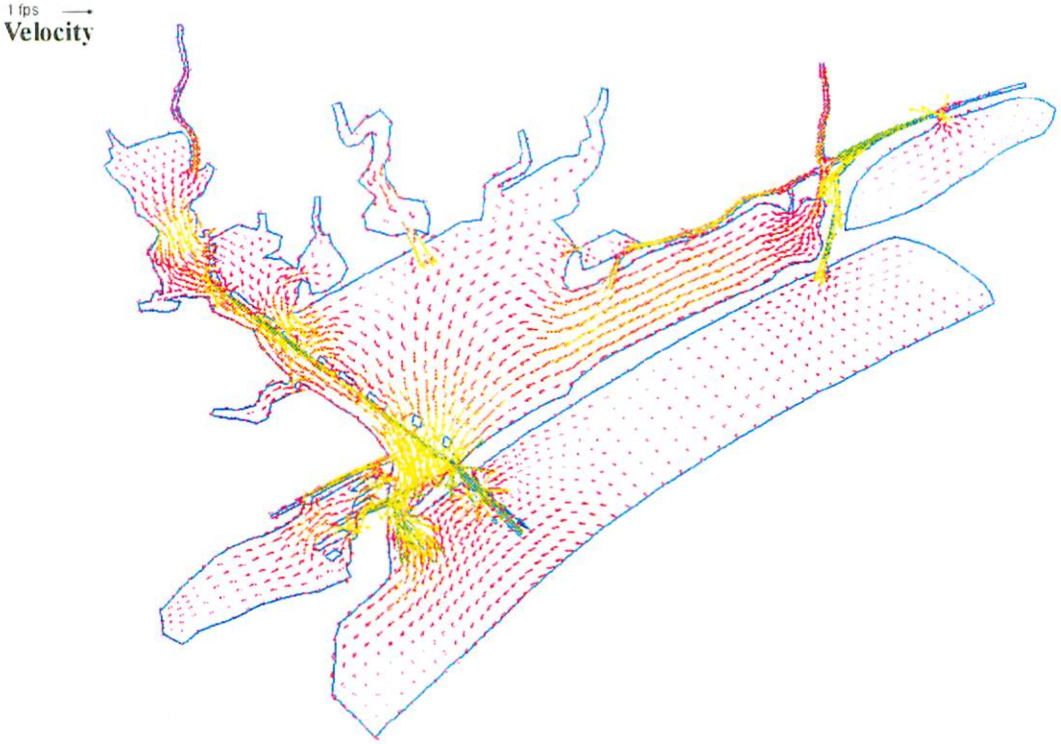


Figure 36 Low Water Slack Tidal Velocity Distribution
7/2/93 04:00 hrs

Figure 37 Low Water Slack Salinity Distribution
7/2/93 04:00 hrs

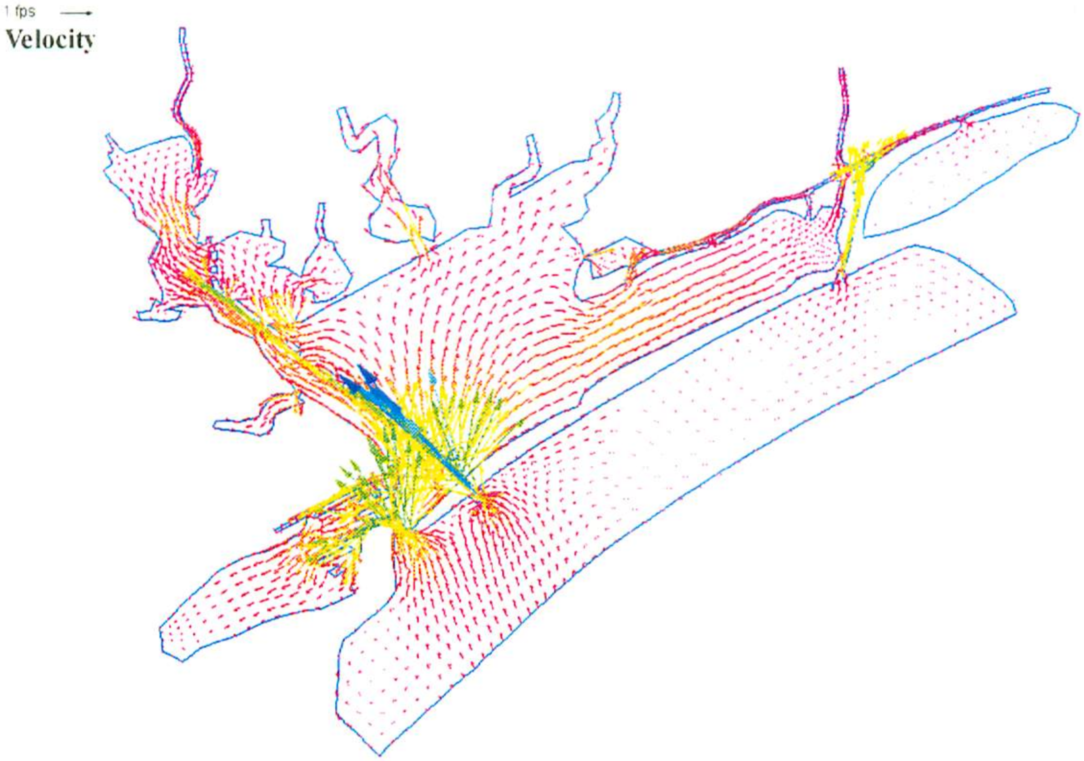


Figure 38 Incoming Tidal Velocity Distribution
7/2/93 12:00 hrs

Figure 39 Incoming Tide Salinity Distribution
7/2/93 12:00 hrs

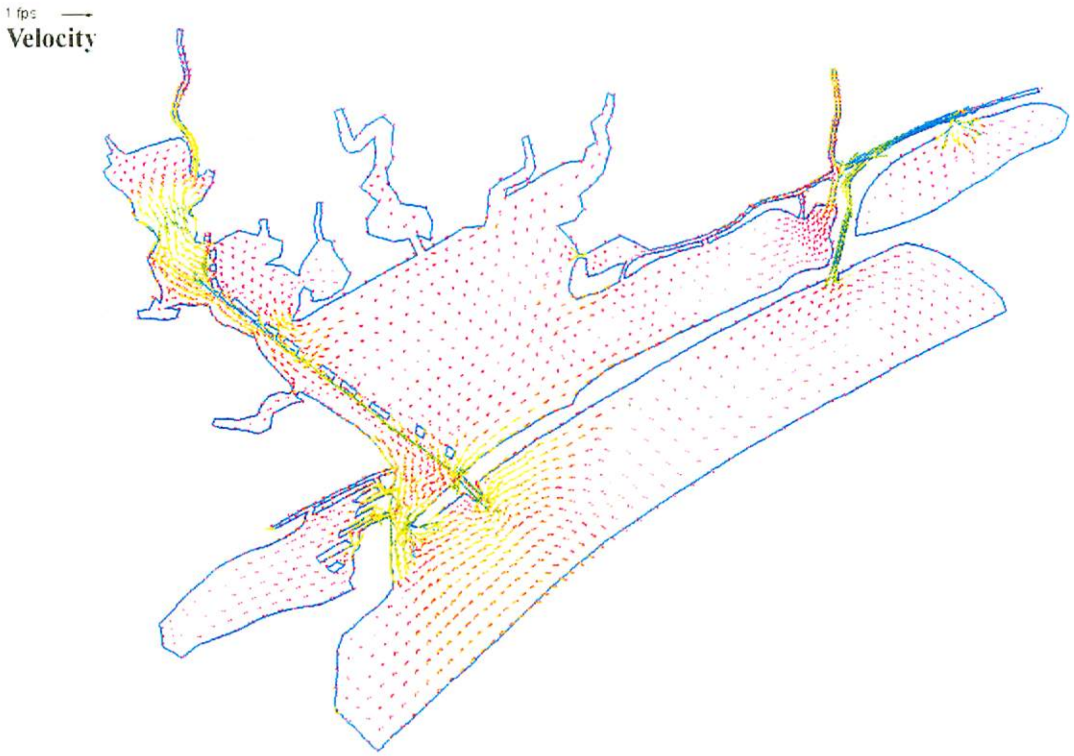


Figure 40 High Water Slack Tidal Velocity Distribution
7/2/93 18:00 hrs

Figure 41 High Water Slack Tide Salinity Distribution
7/2/93 18:00 hrs

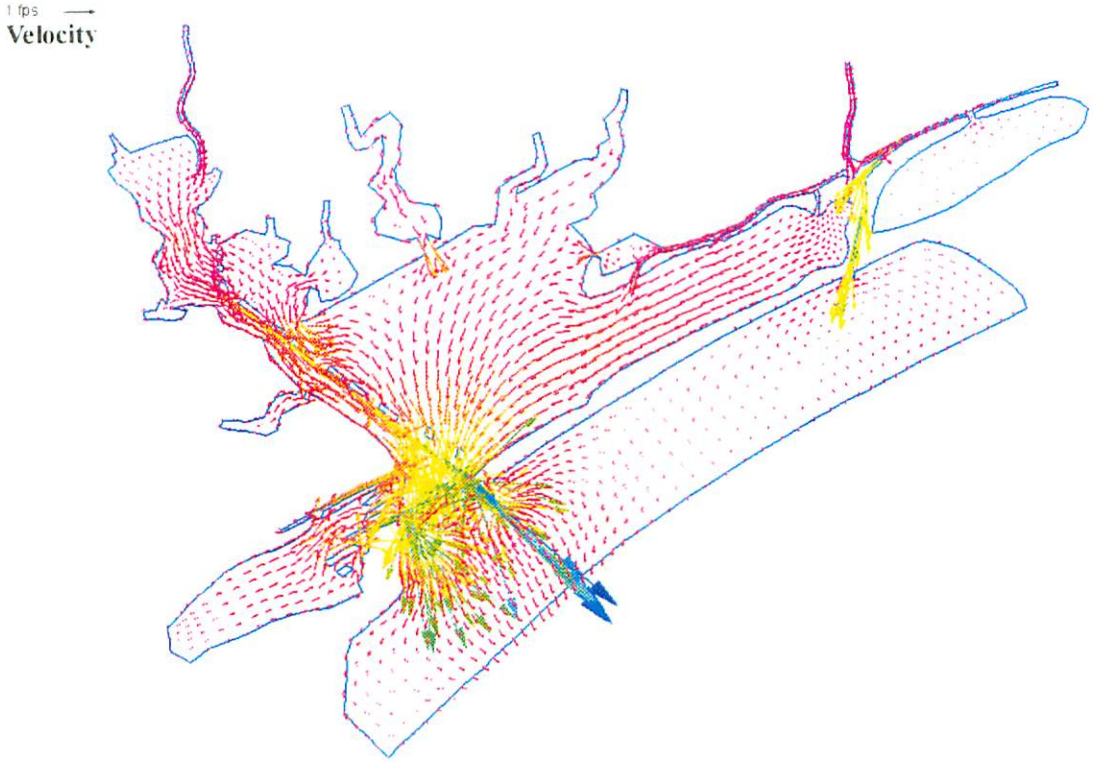


Figure 42 Outgoing Tidal Velocity Distribution
7/3/93 00:00 hrs

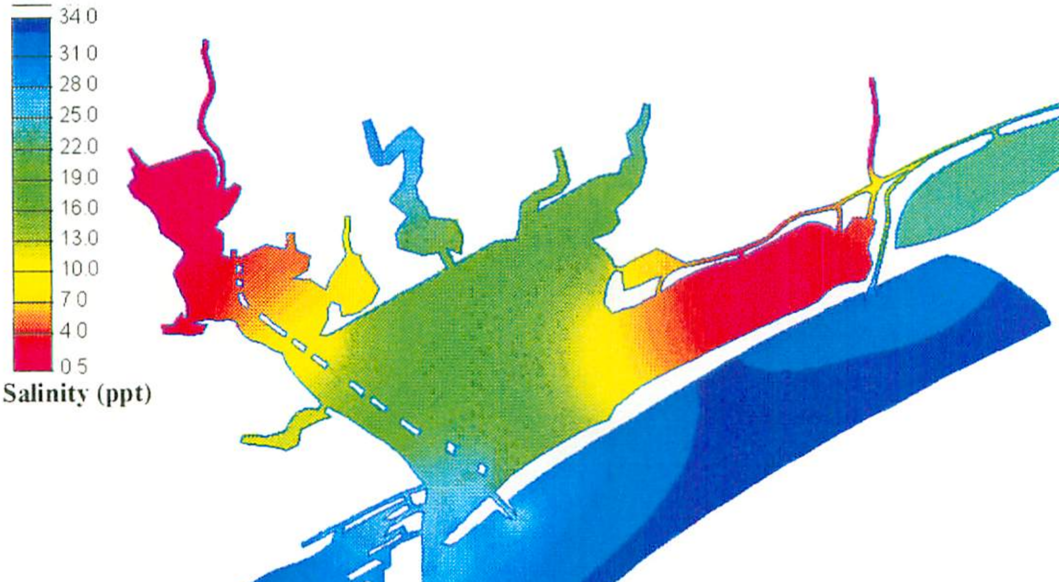


Figure 43 Outgoing Salinity Distribution
7/3/93 00:00 hrs

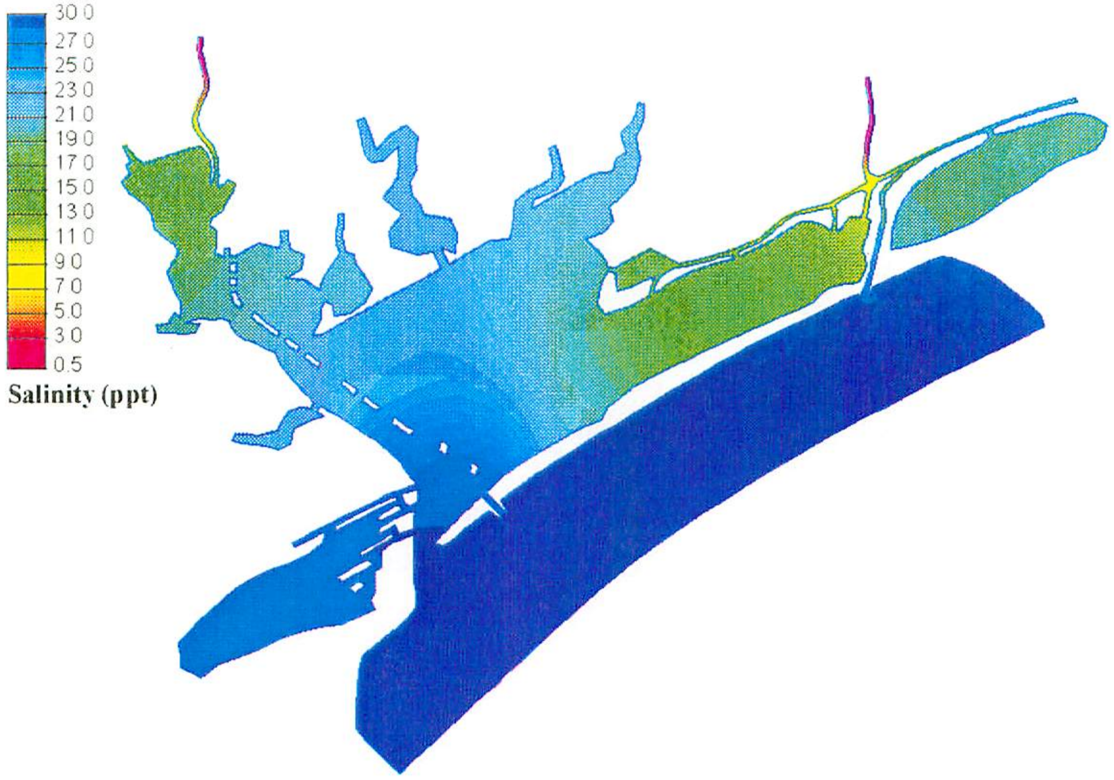


Figure 44 Salinity Distribution, Monthly Average
January, 1993

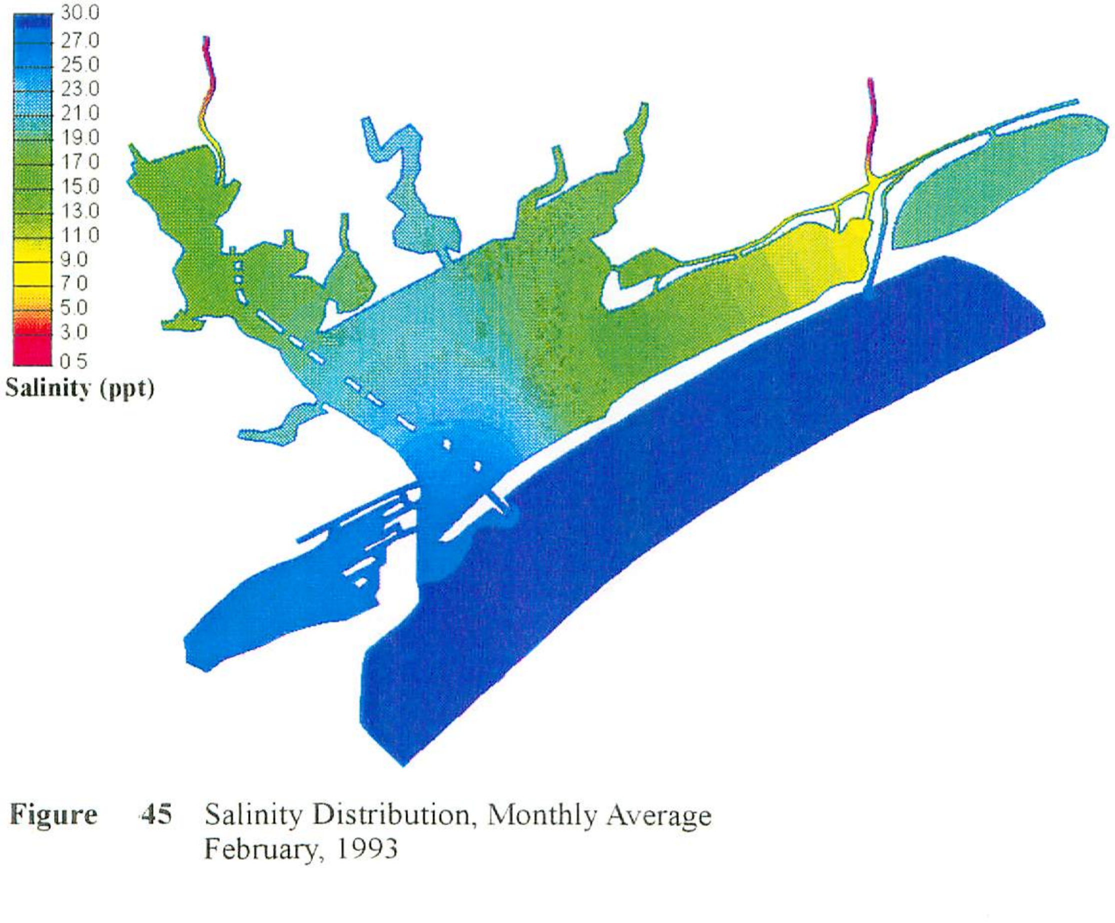


Figure 45 Salinity Distribution, Monthly Average
February, 1993

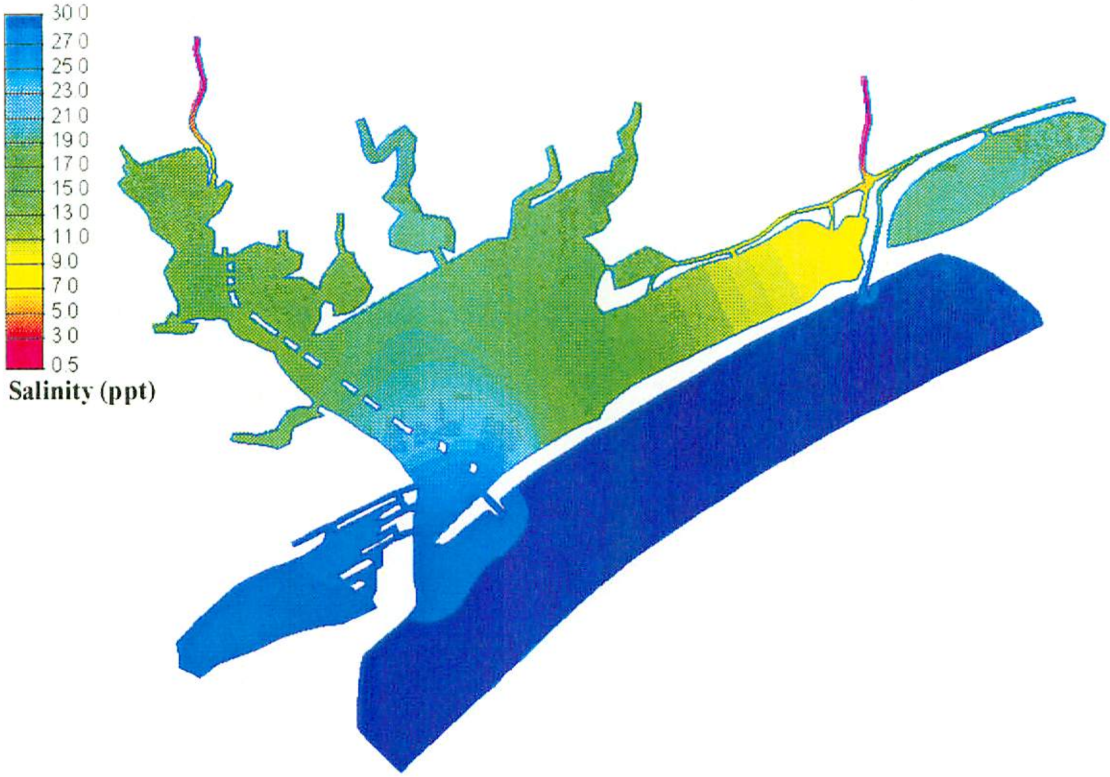


Figure 46 Salinity Distribution, Monthly Average
March, 1993

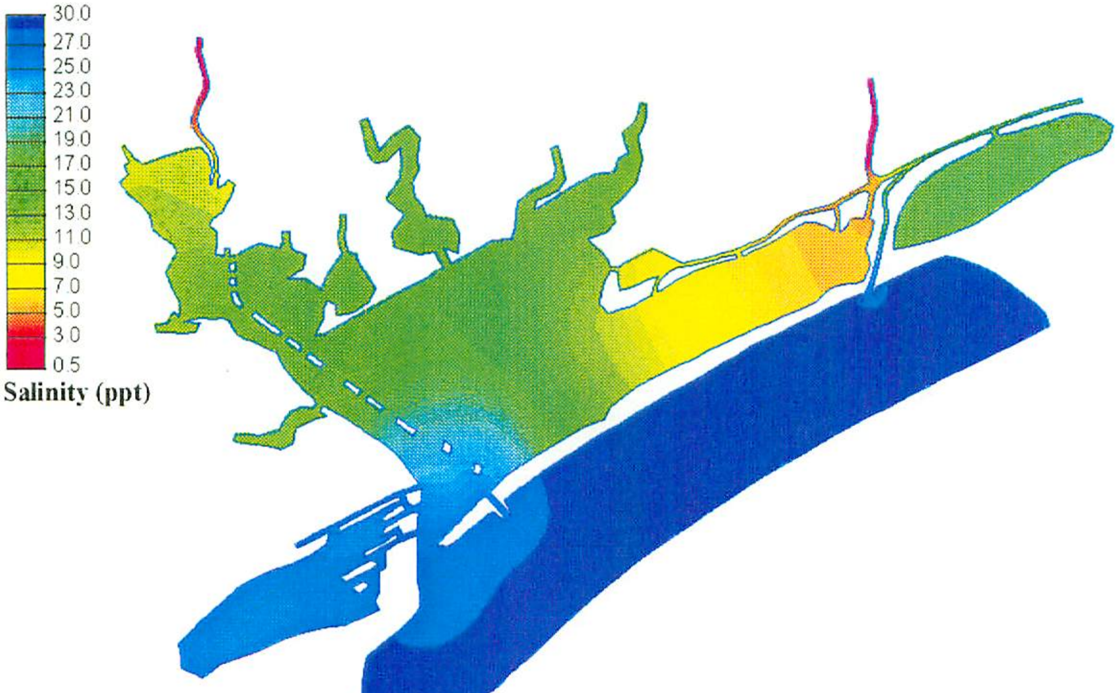


Figure 47 Salinity Distribution, Monthly Average
April, 1993

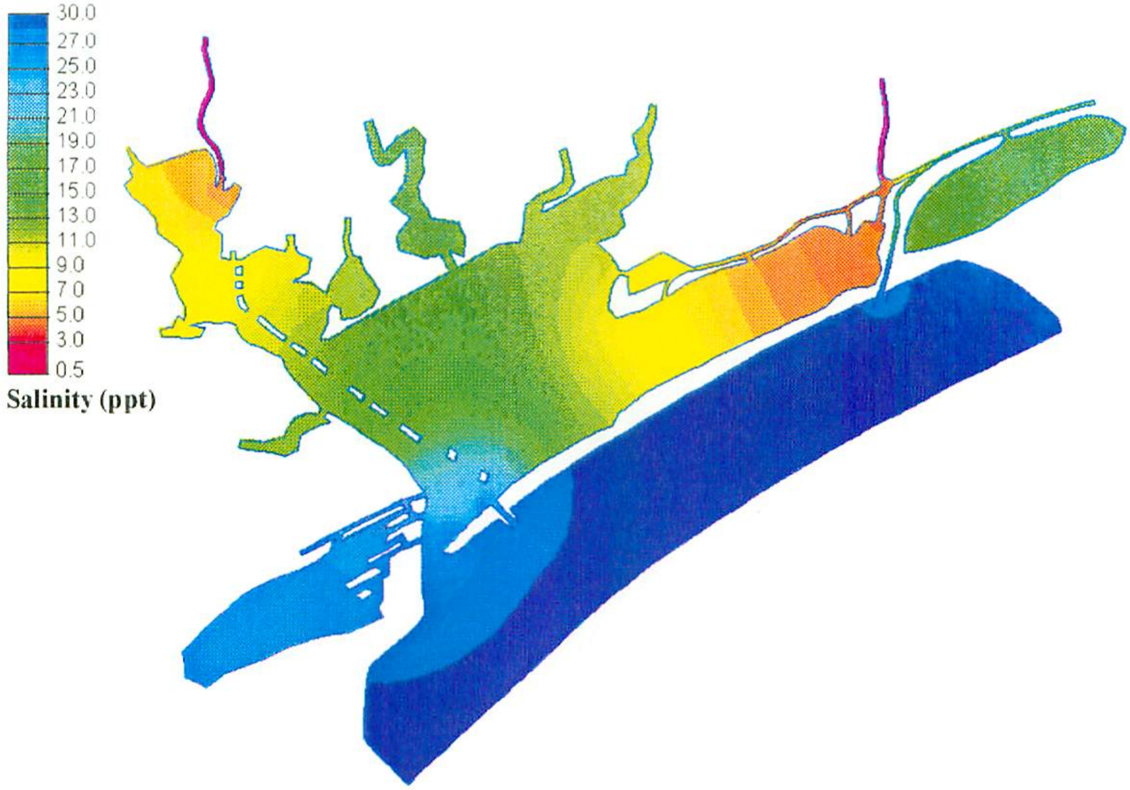


Figure 48 Salinity Distribution, Monthly Average
May, 1993

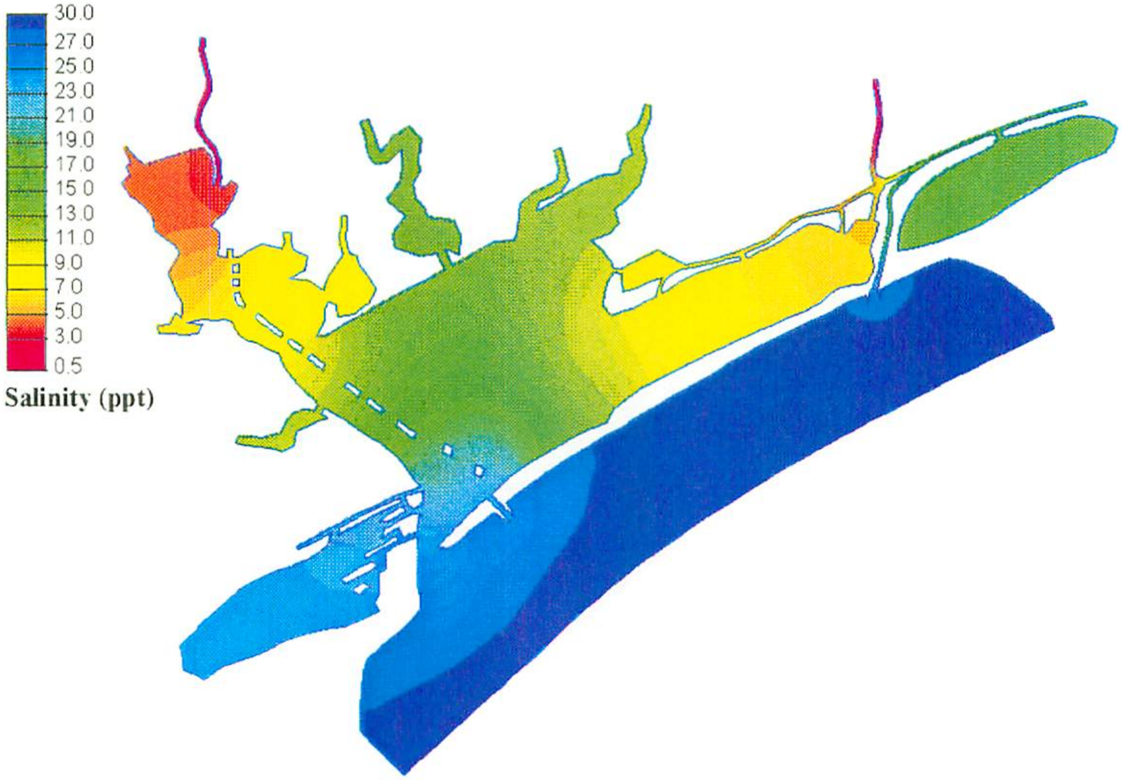


Figure 49 Salinity Distribution, Monthly Average
June, 1993

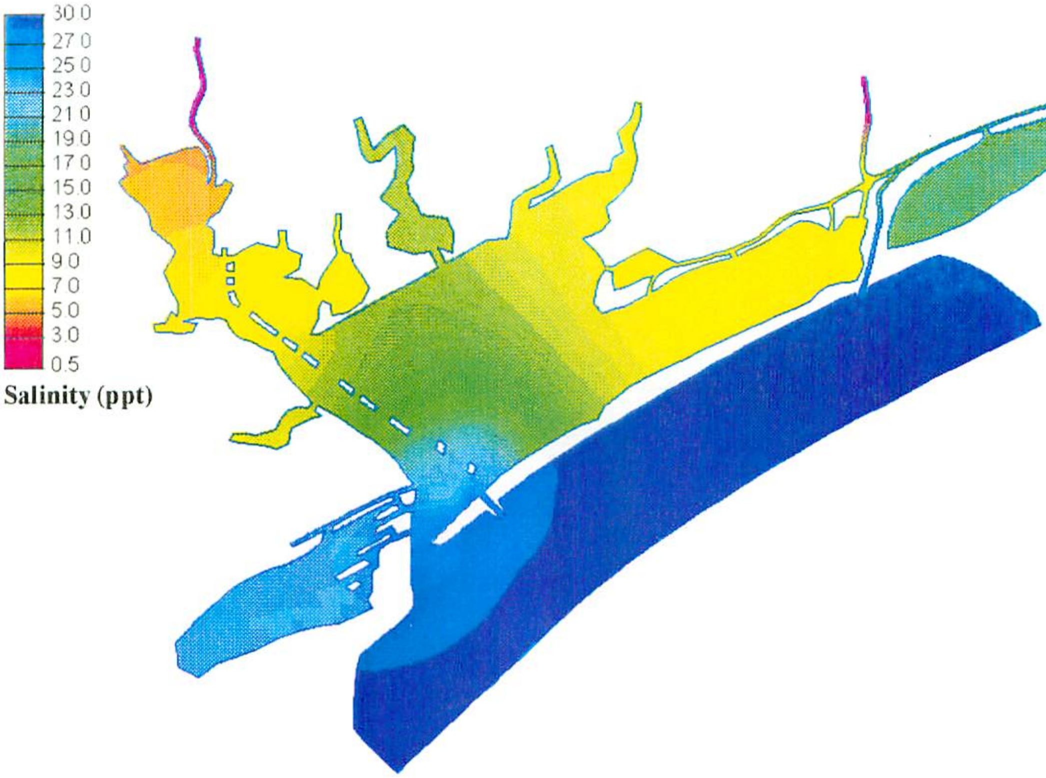


Figure 50 Salinity Distribution, Monthly Average July, 1993

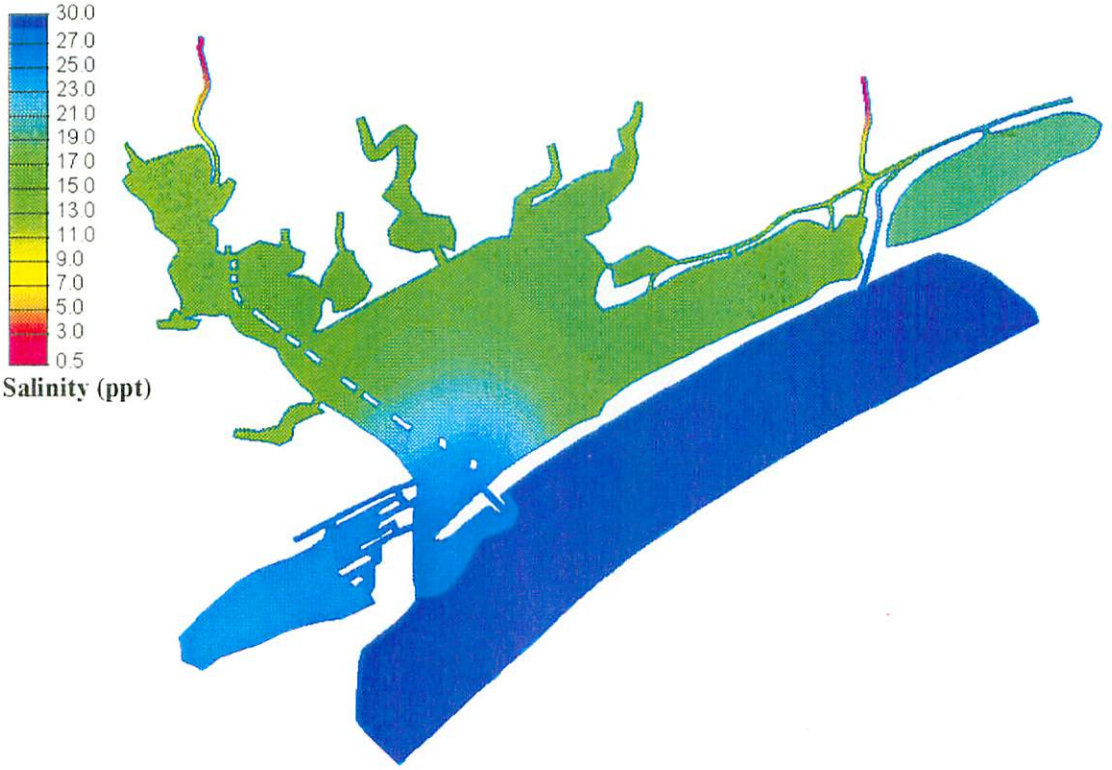


Figure 51 Salinity Distribution, Monthly Average August, 1993

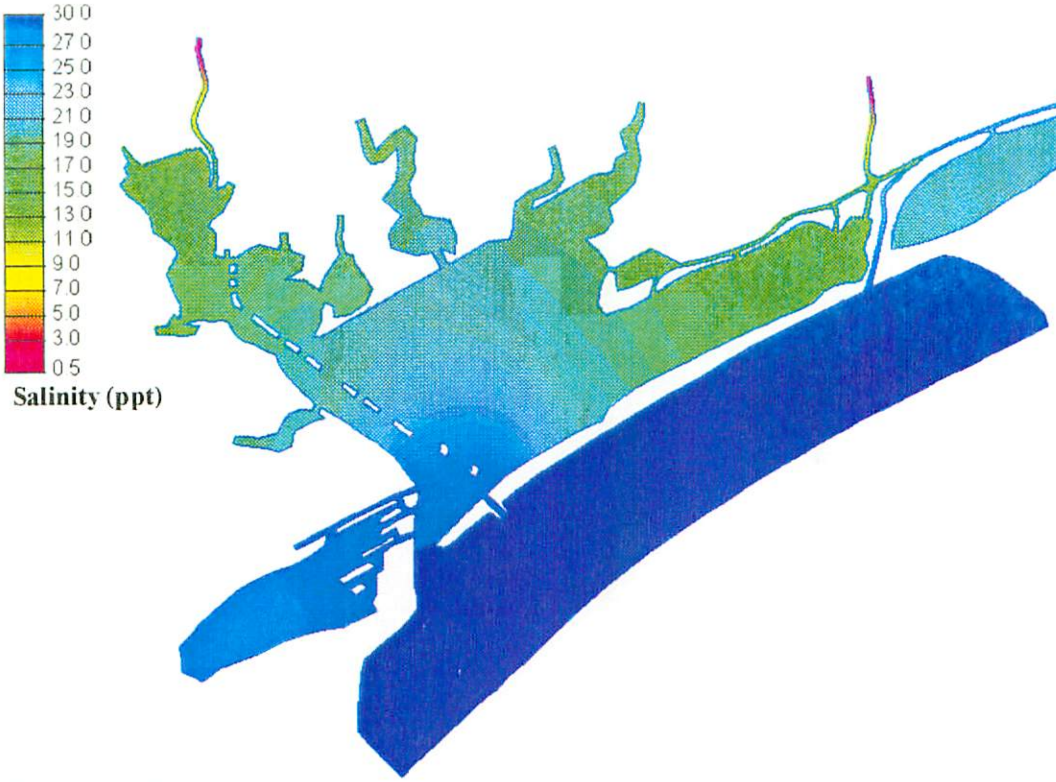


Figure 52 Salinity Distribution, Monthly Average September, 1993

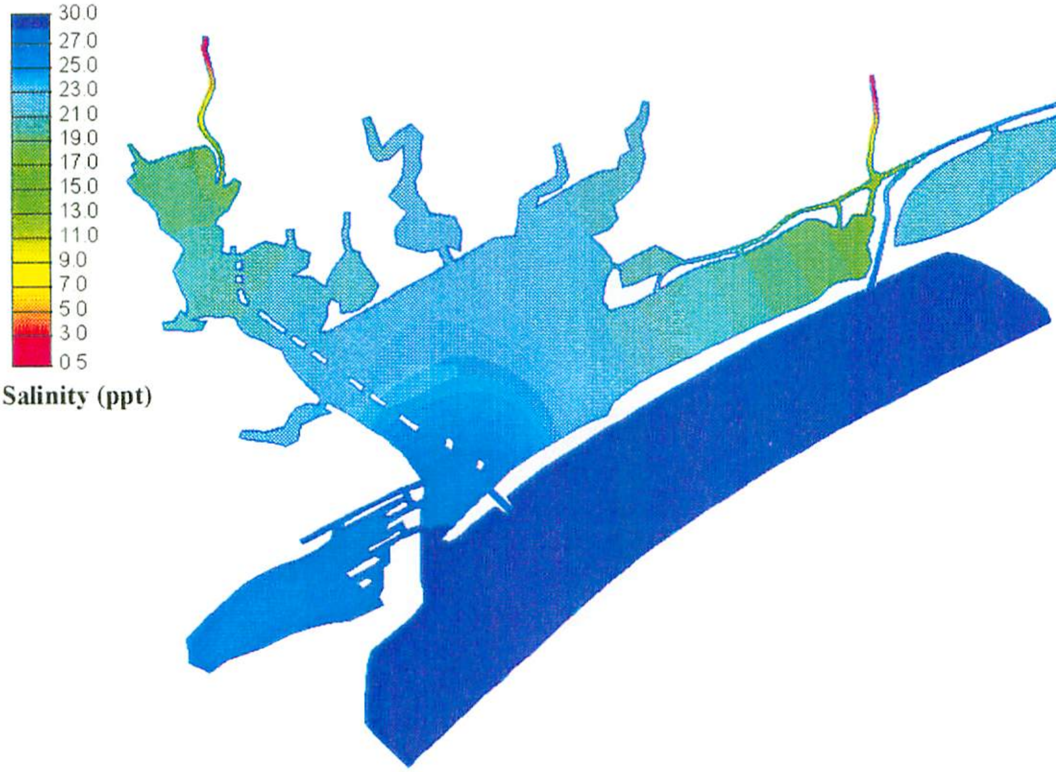


Figure 53 Salinity Distribution, Monthly Average October, 1993

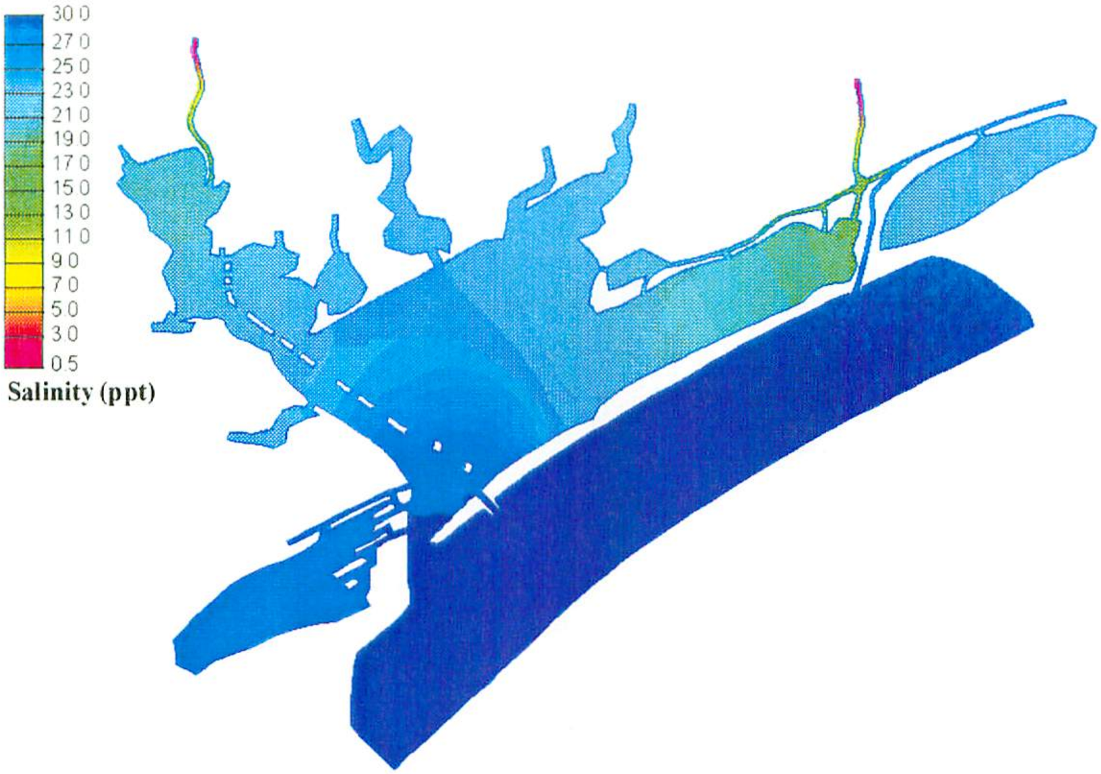


Figure 54 Salinity Distribution , Monthly Average
November, 1993

Figure 55 Salinity Distribution, Monthly Average
December, 1993

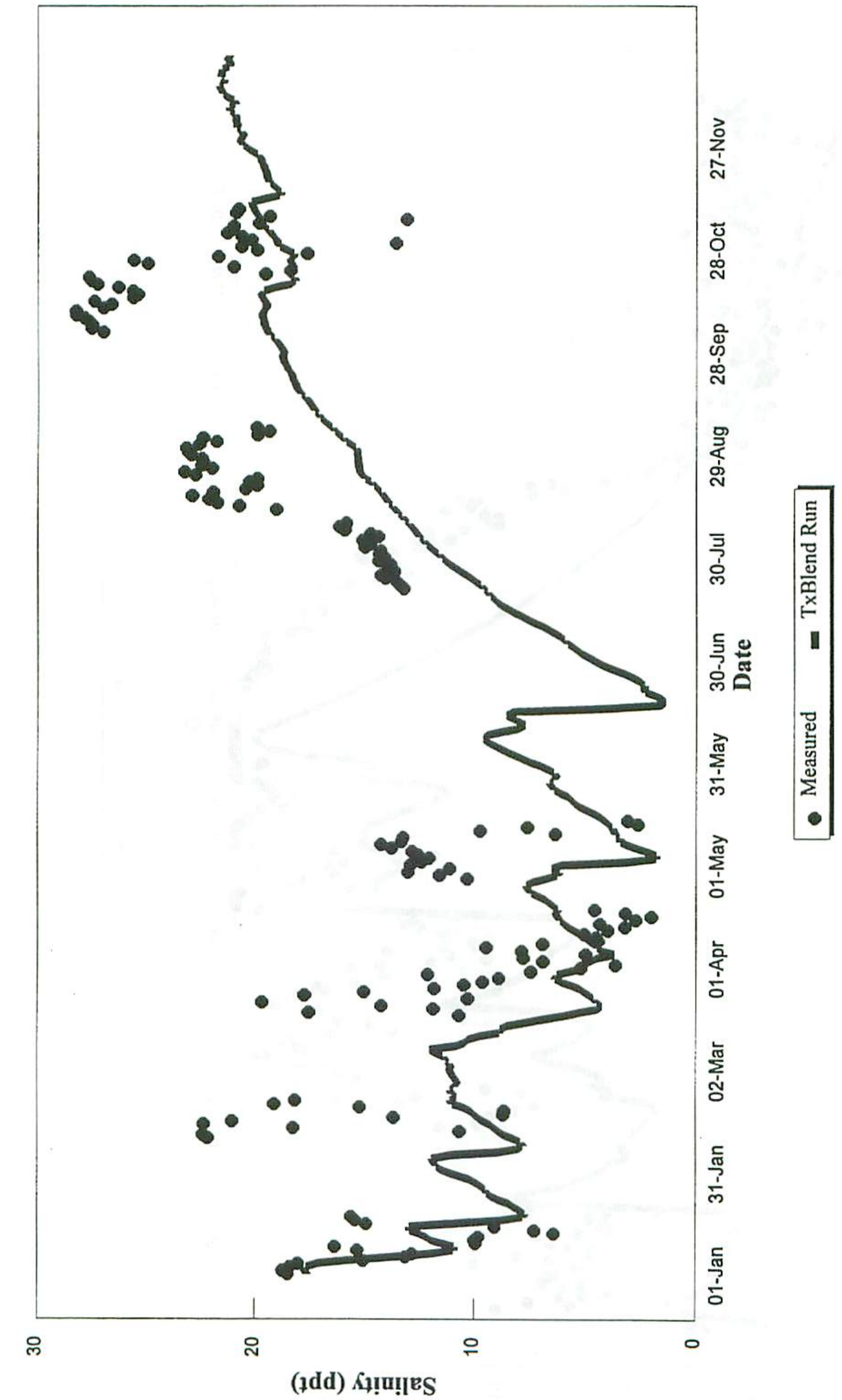


Figure 56 1993 Daily Average Salinity
Eastern Matagorda Bay (T3)

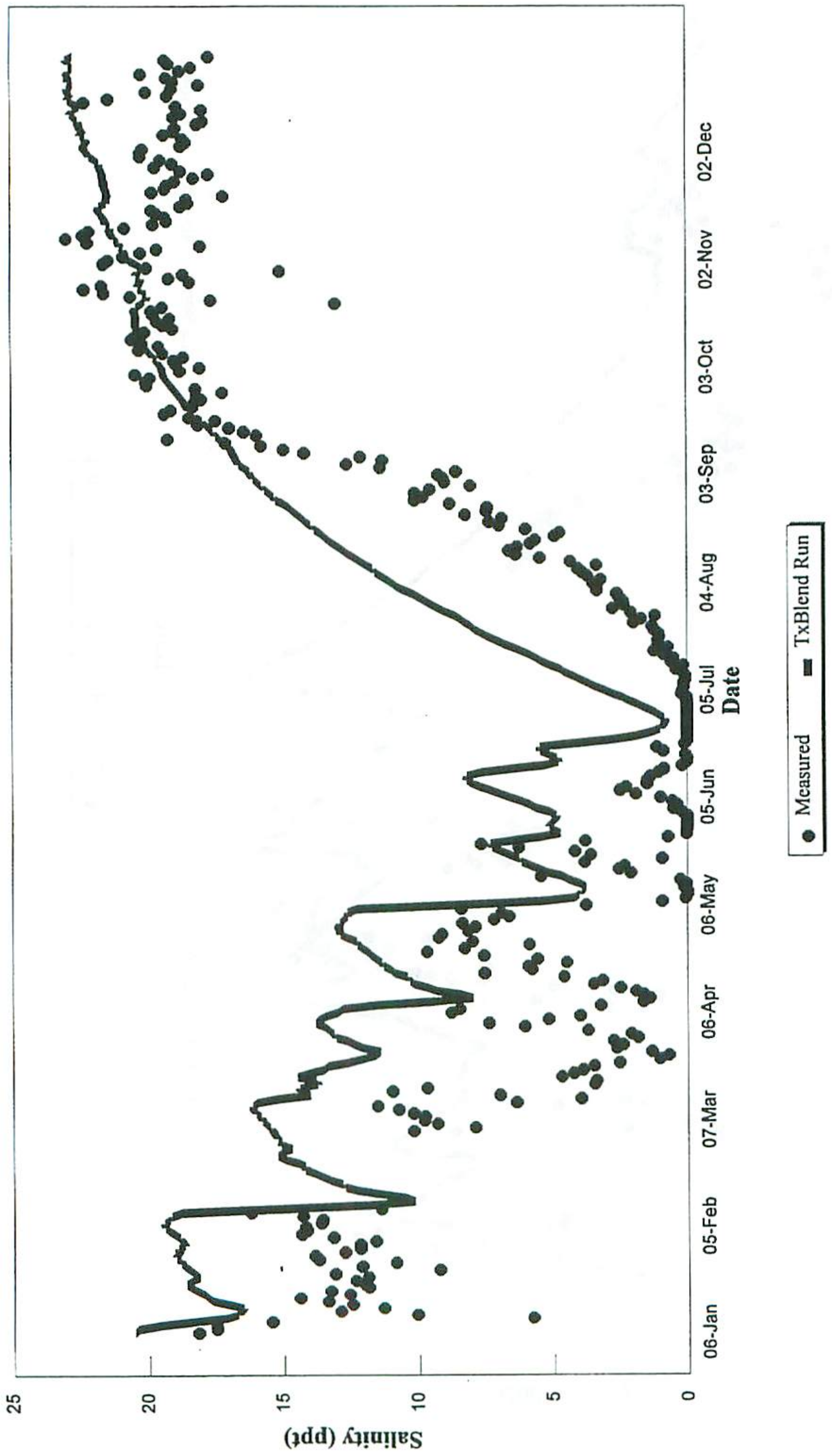


Figure 57 1993 Daily Average Salinity
Lavaca Bay Causeway

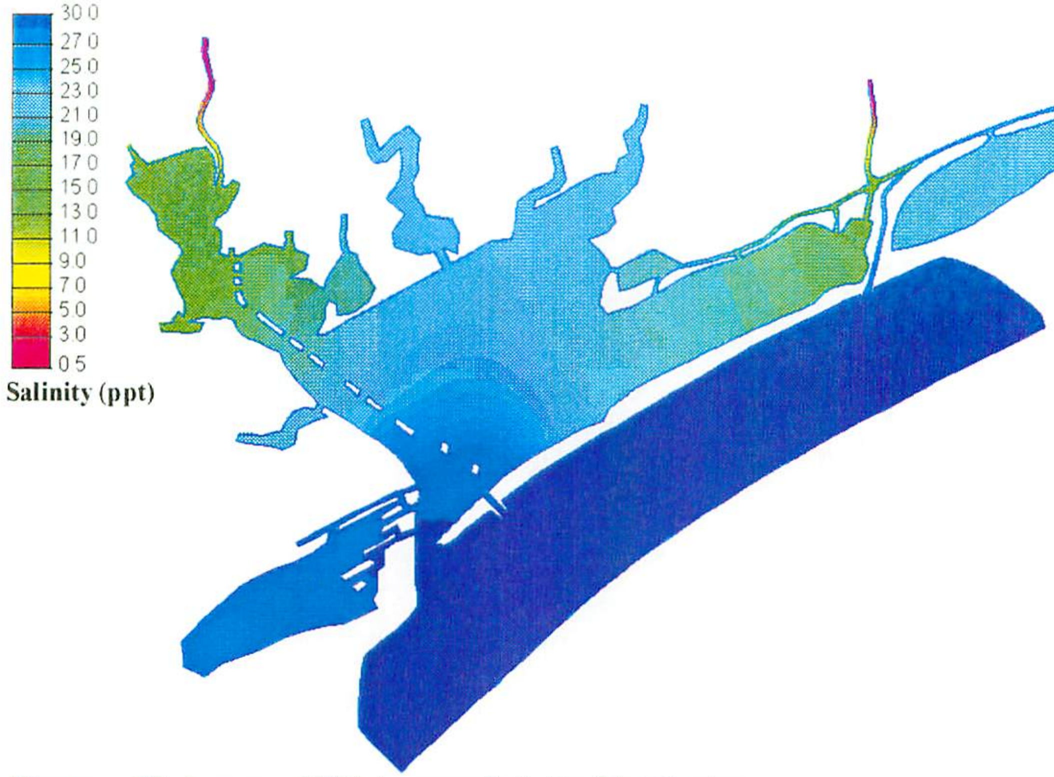


Figure 58 January, 1984 Average Salinity Distribution

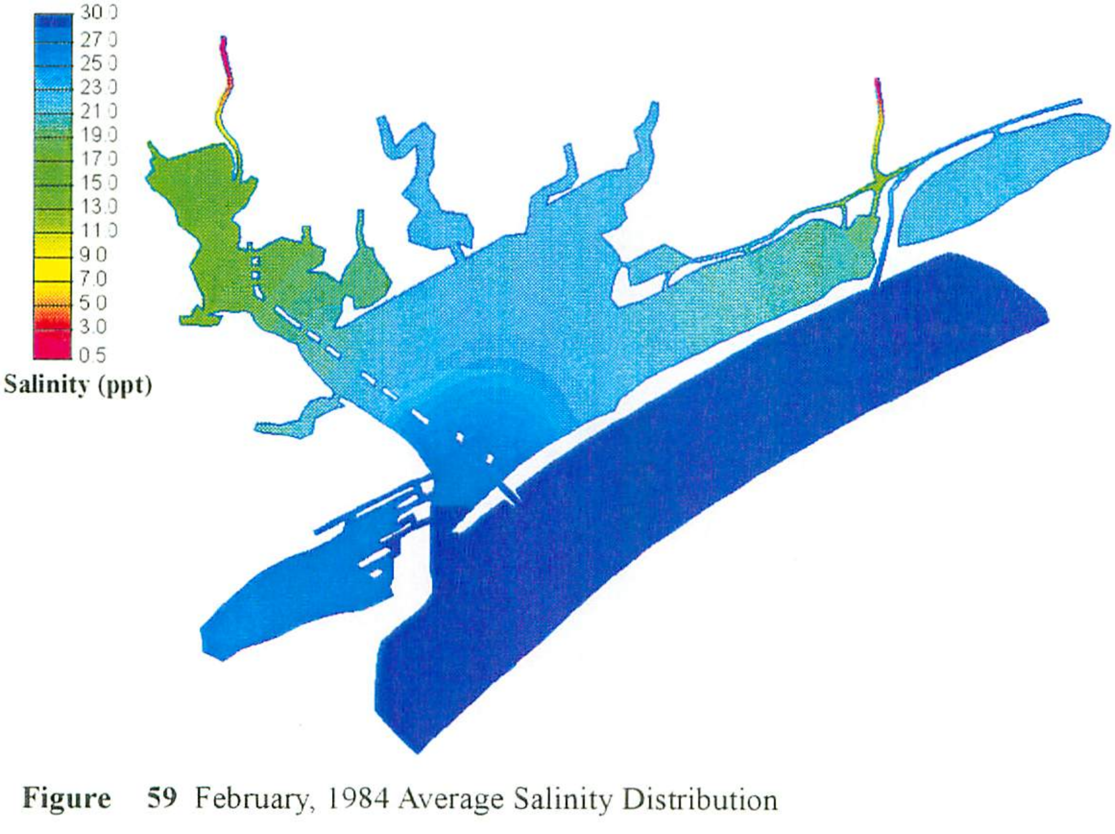


Figure 59 February, 1984 Average Salinity Distribution

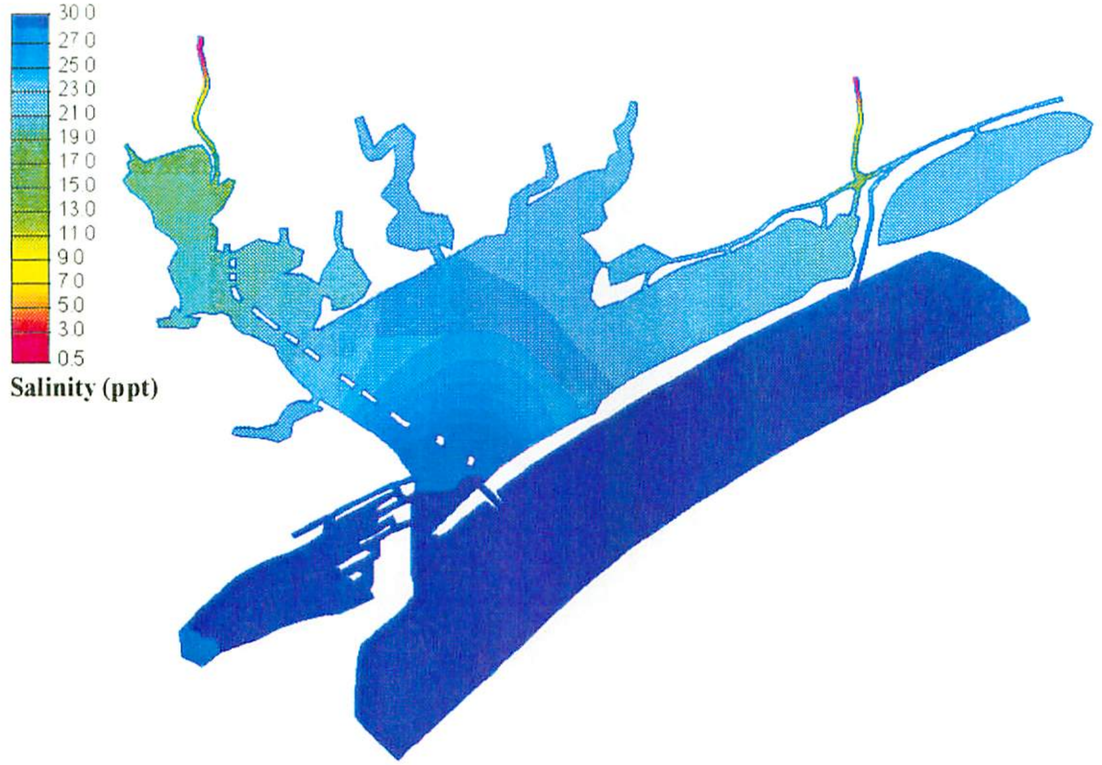


Figure 60 February, 1984 Average Salinity Distribution

Figure 61 April, 1984 Average Salinity Distribution

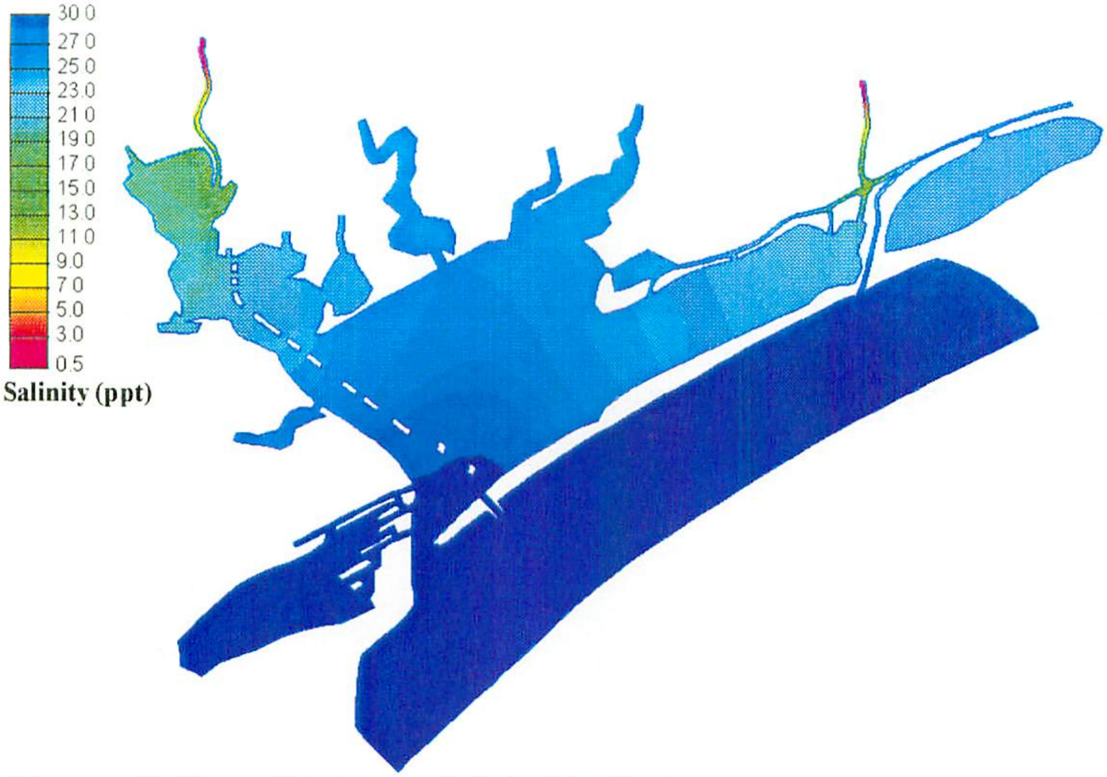


Figure 62 May, 1984 Average Salinity Distribution

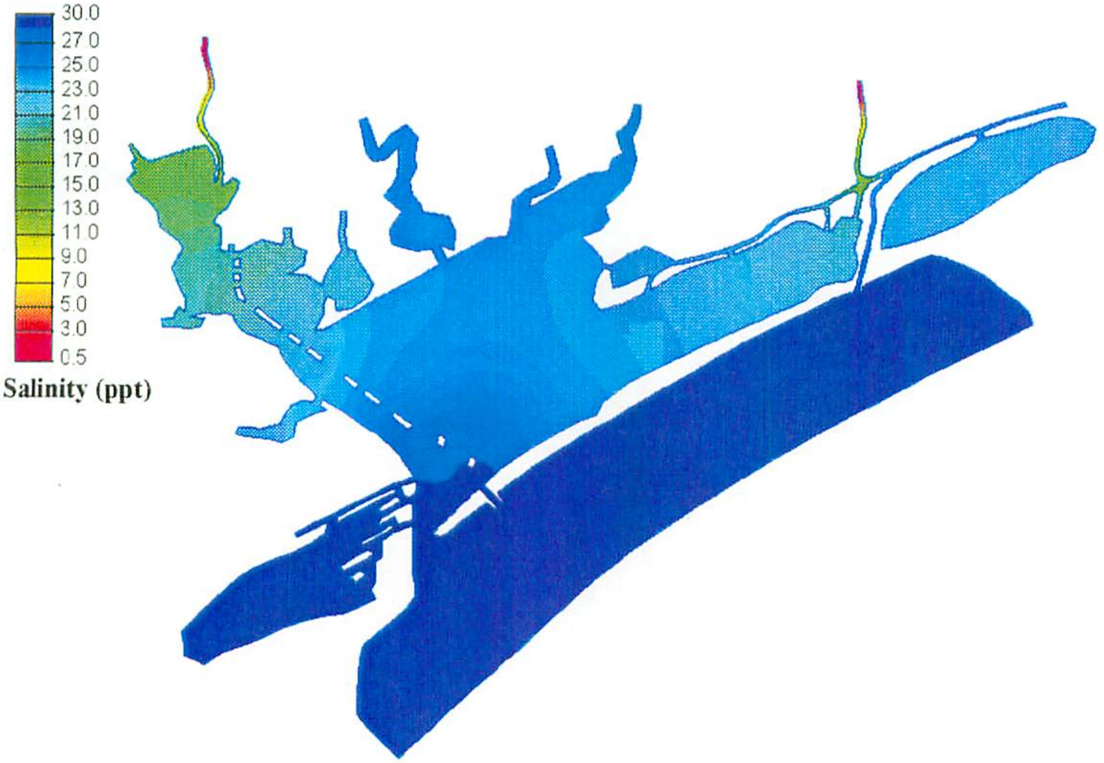


Figure 63 June, 1984 Average Salinity Distribution

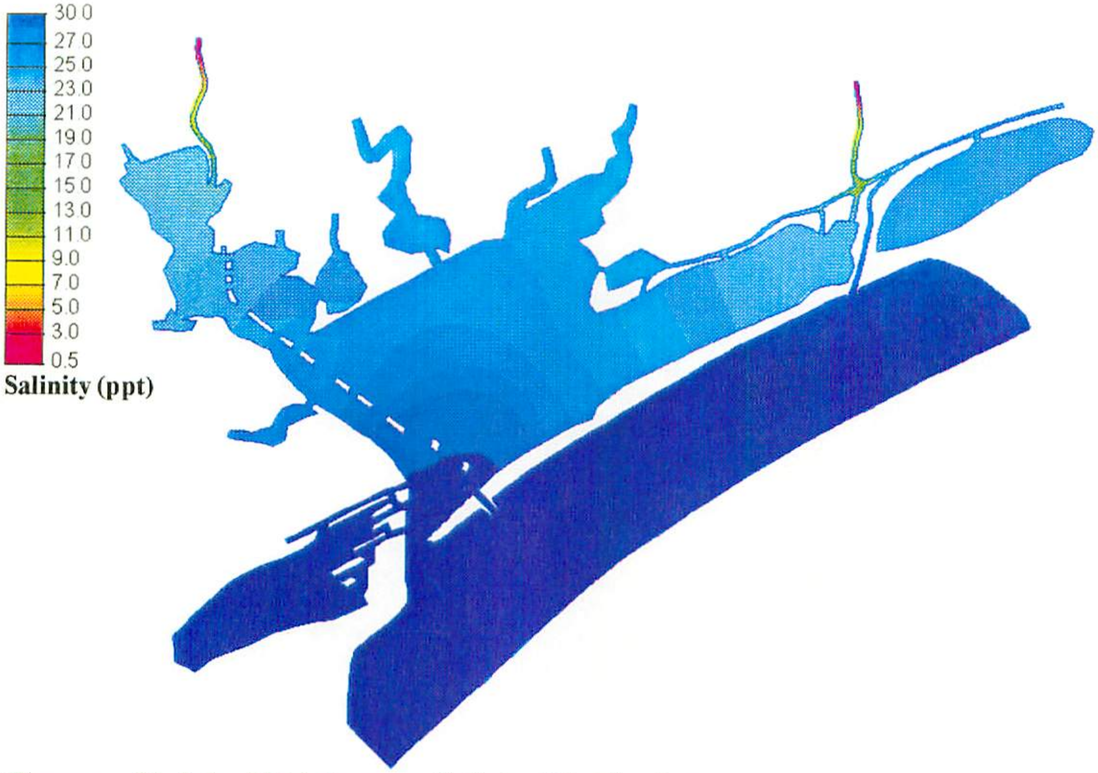


Figure 64 July, 1984 Average Salinity Distribution

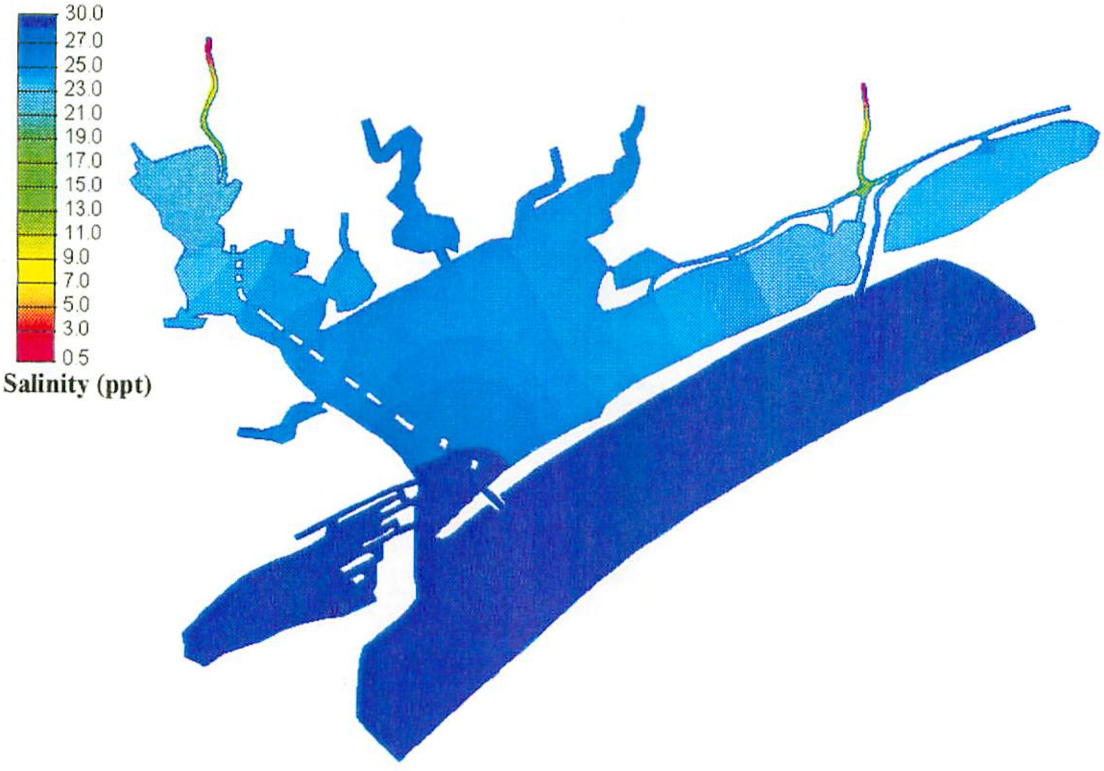


Figure 65 August, 1984 Average Salinity Distribution

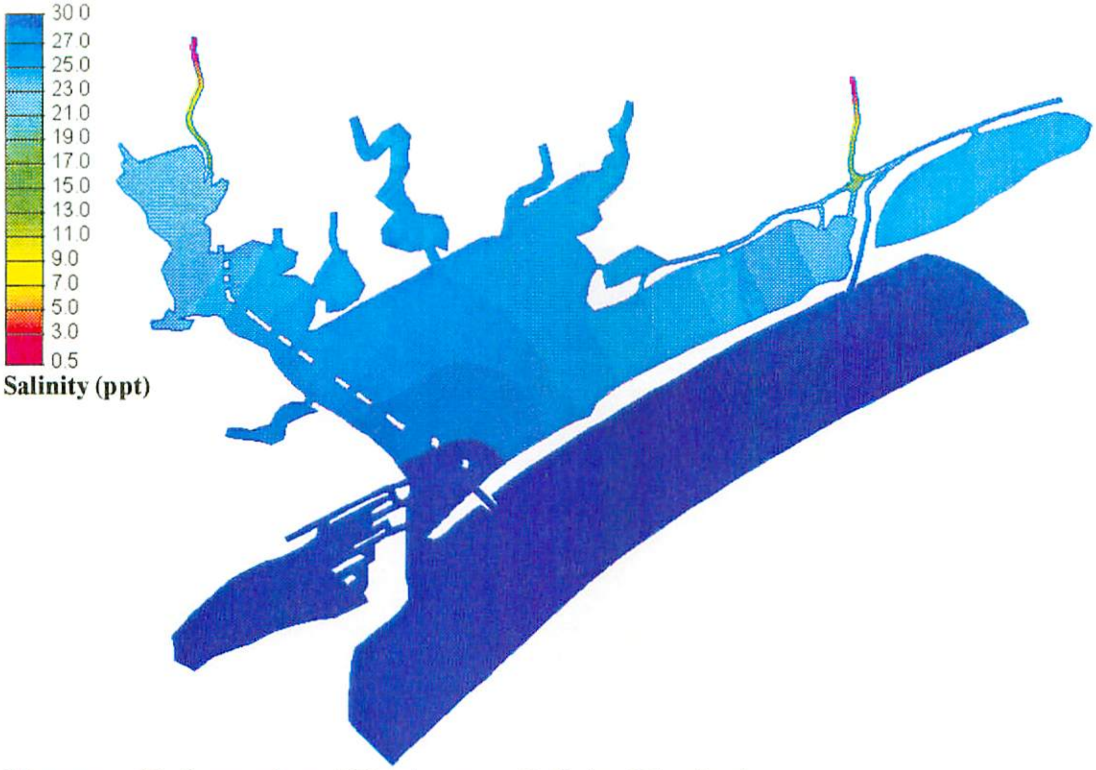


Figure 66 September, 1984 Average Salinity Distribution

Figure 67 October, 1984 Average Salinity Distribution

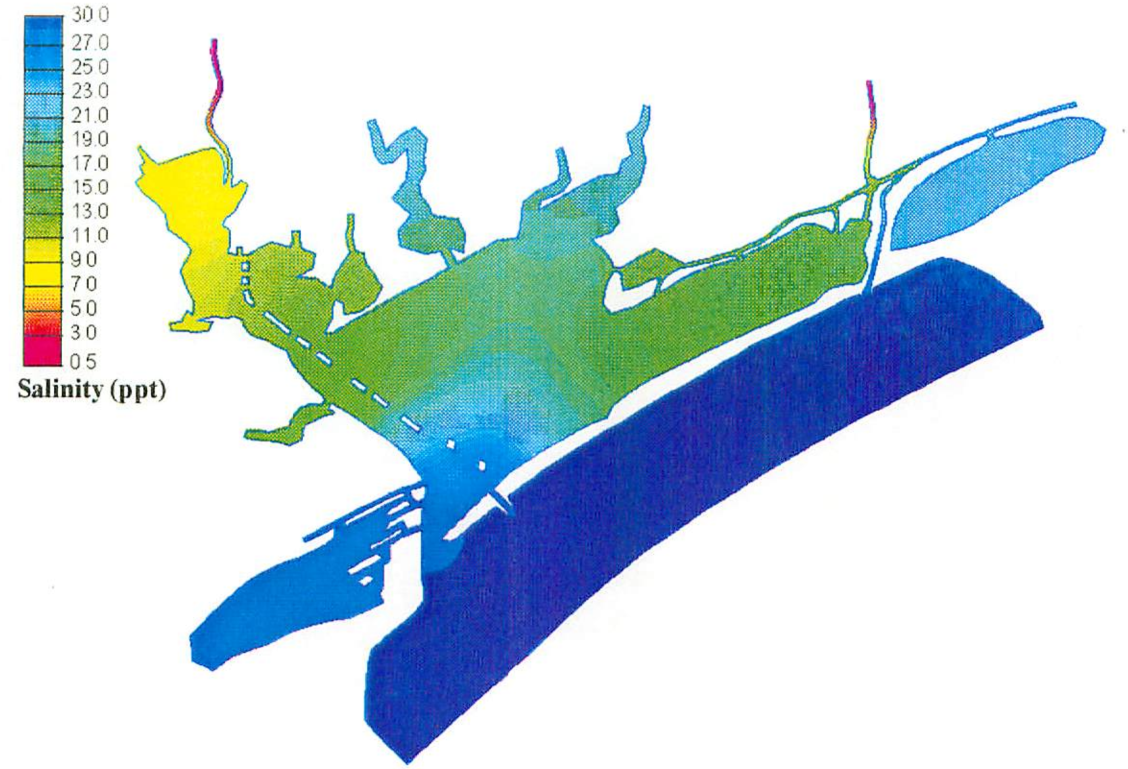


Figure 68 November, 1984 Average Salinity Distribution

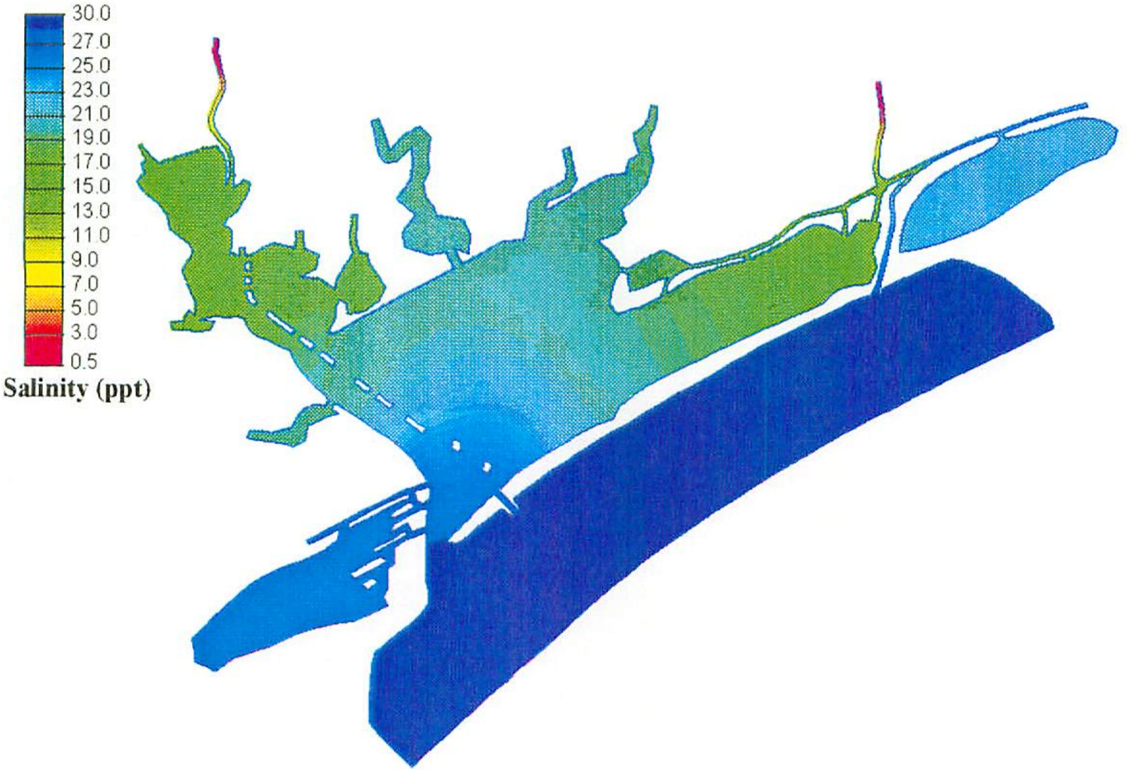


Figure 69 December, 1984 Average Salinity Distribution

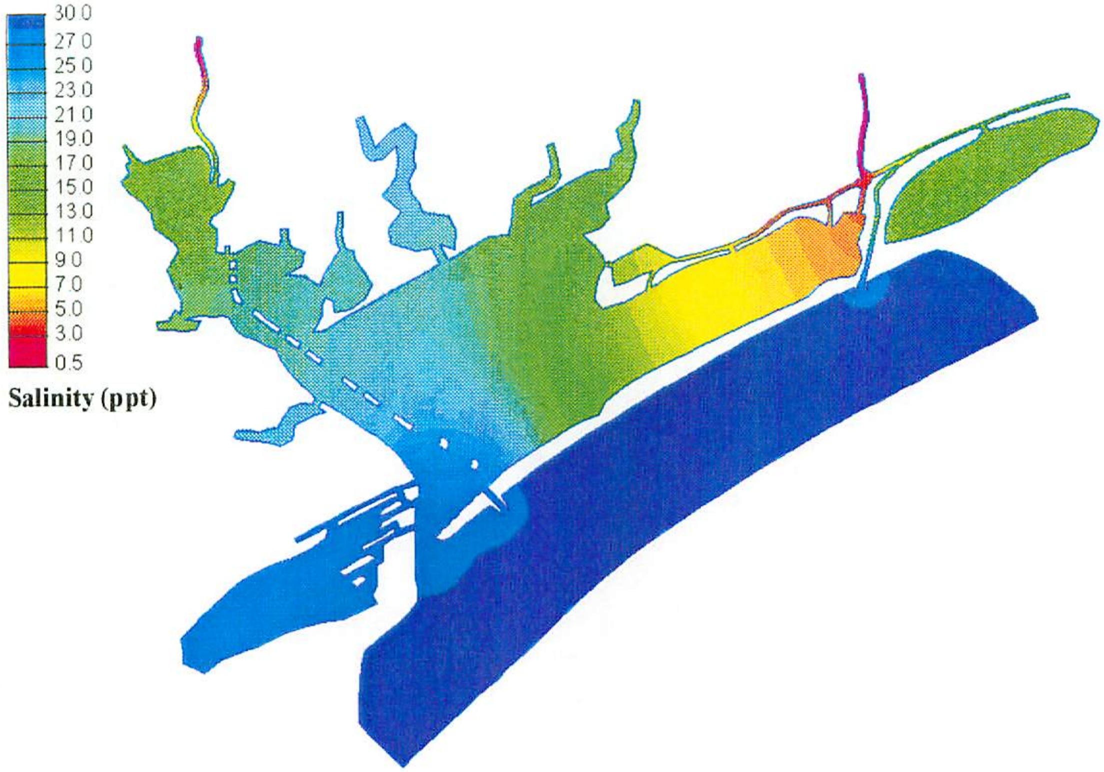


Figure 70 January, 1987 Average Salinity Distribution

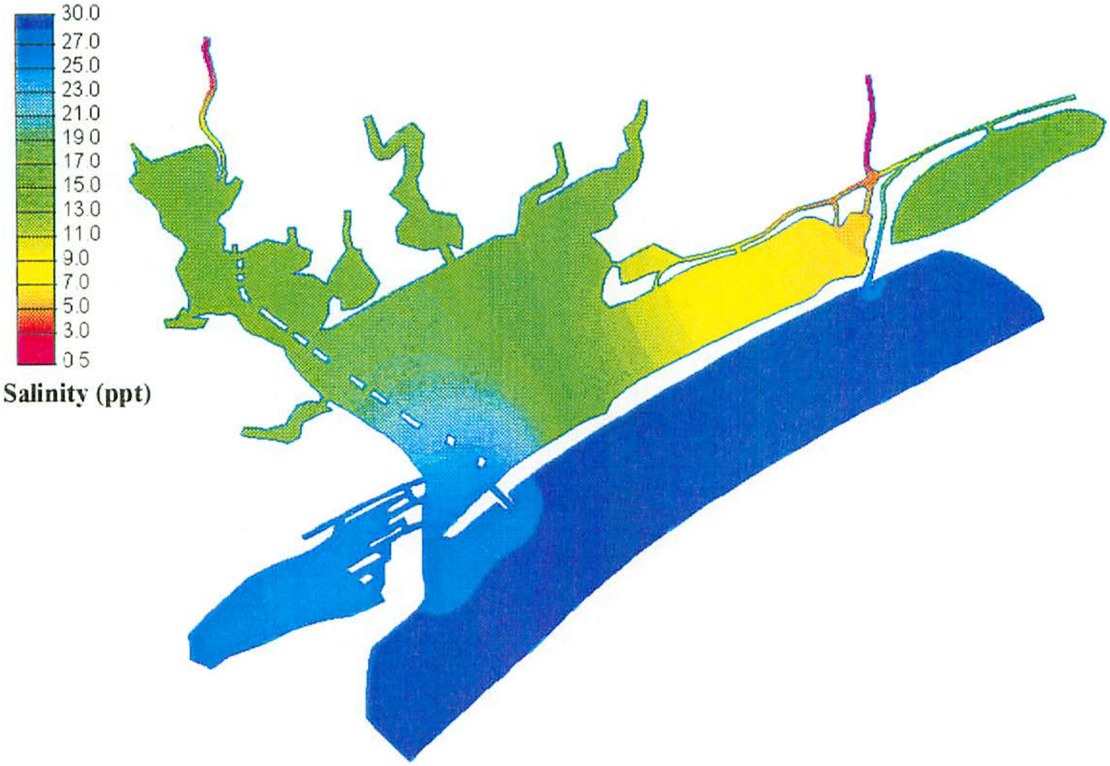


Figure 71 February, 1987 Average Salinity Distribution

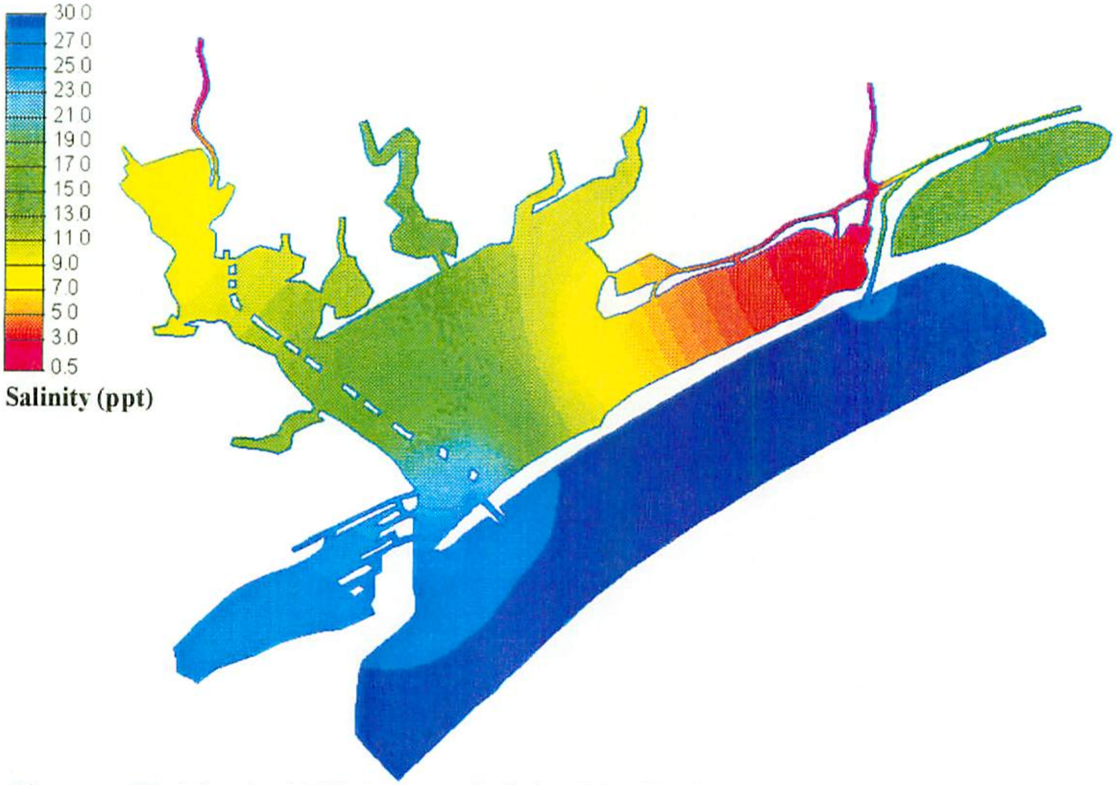


Figure 72 March, 1987 Average Salinity Distribution

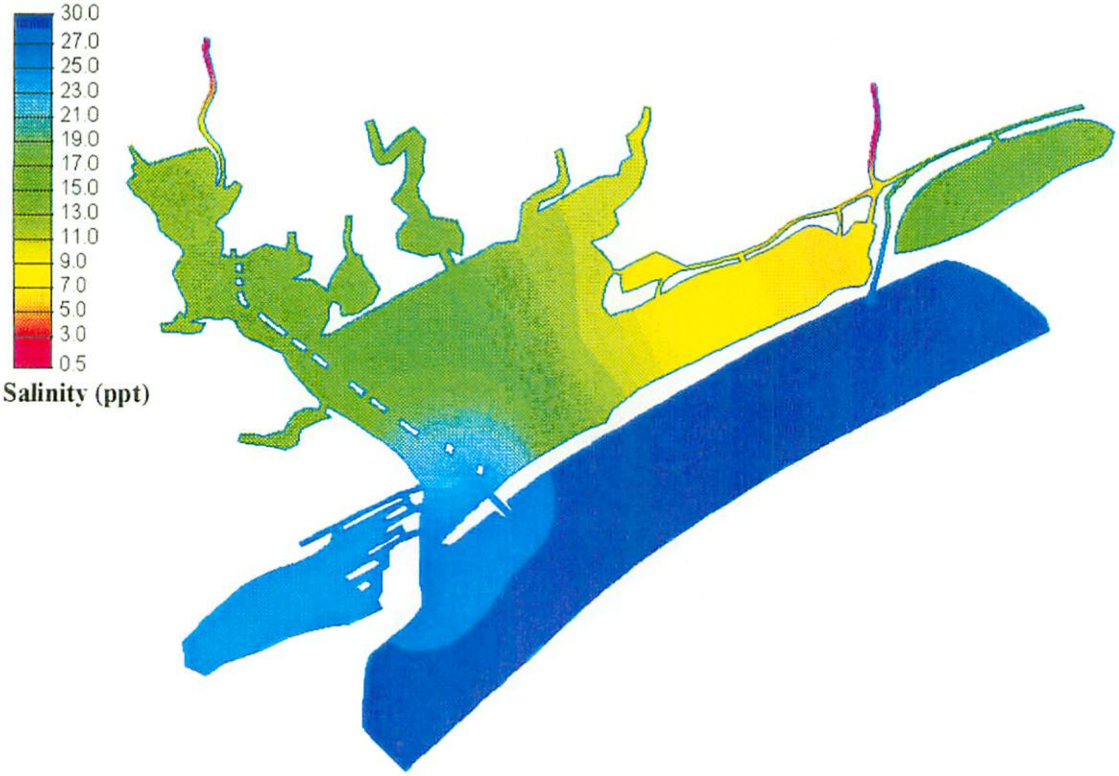


Figure 73 April, 1987 Average Salinity Distribution

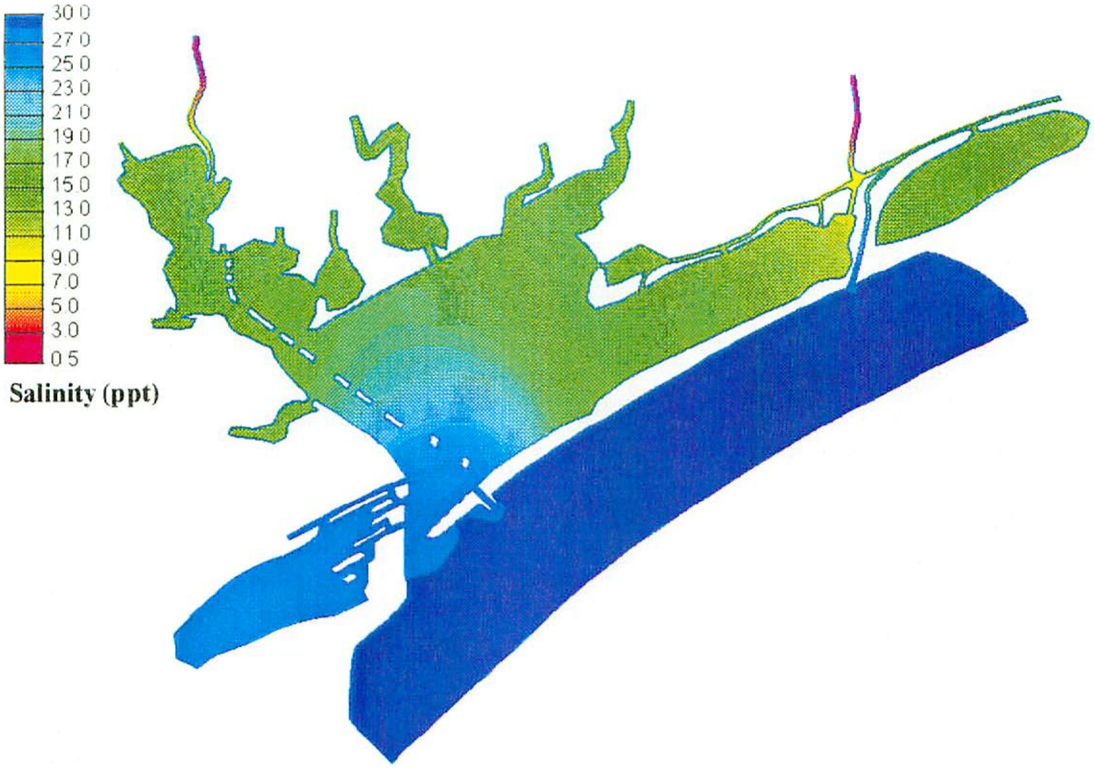


Figure **74** May, 1987 Average Salinity Distribution

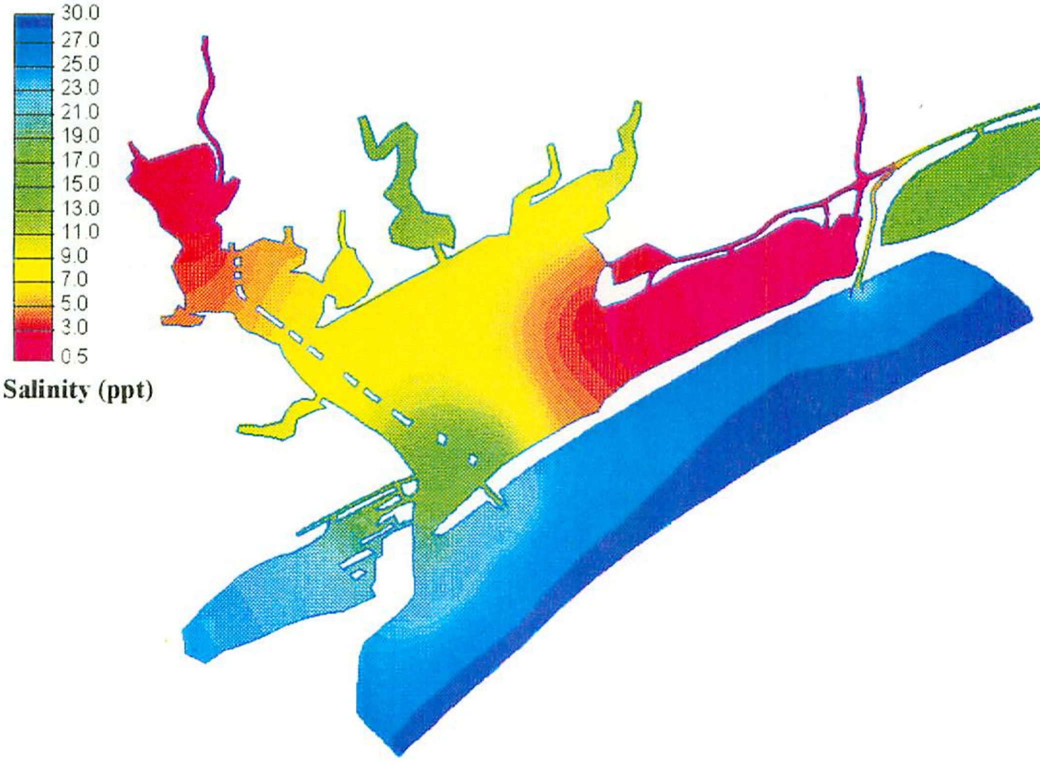


Figure **75** June, 1987 Average Salinity Distribution

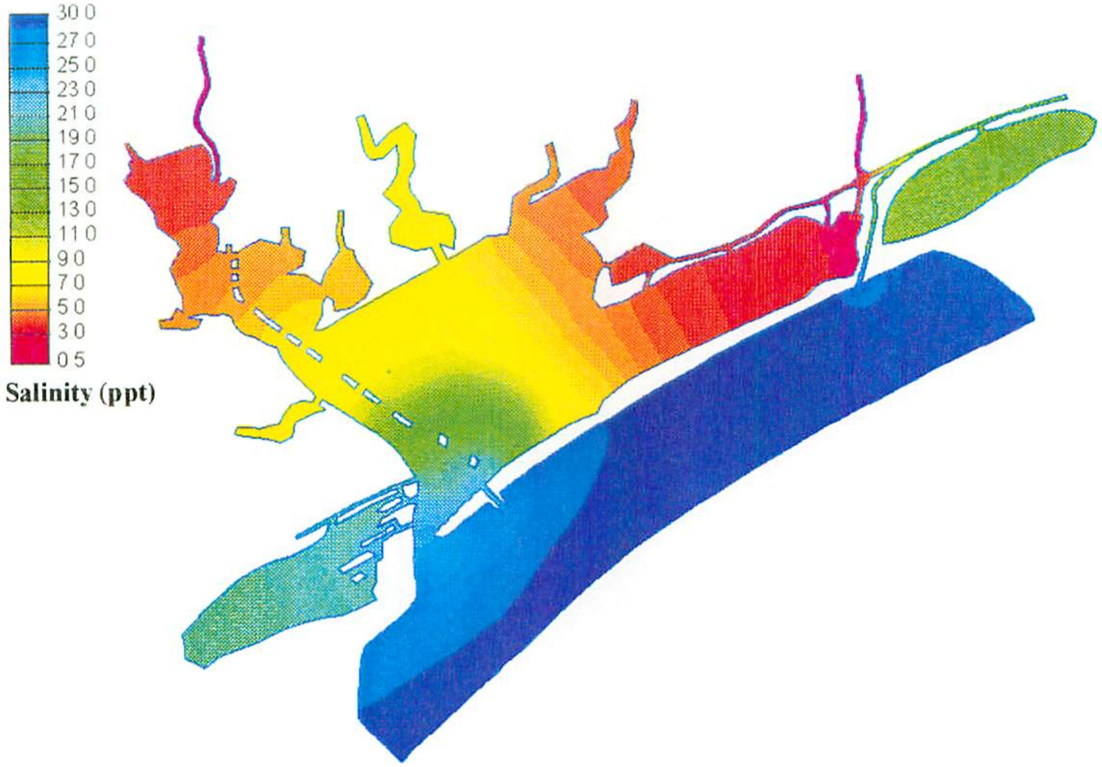


Figure **76** July, 1987 Average Salinity Distribution

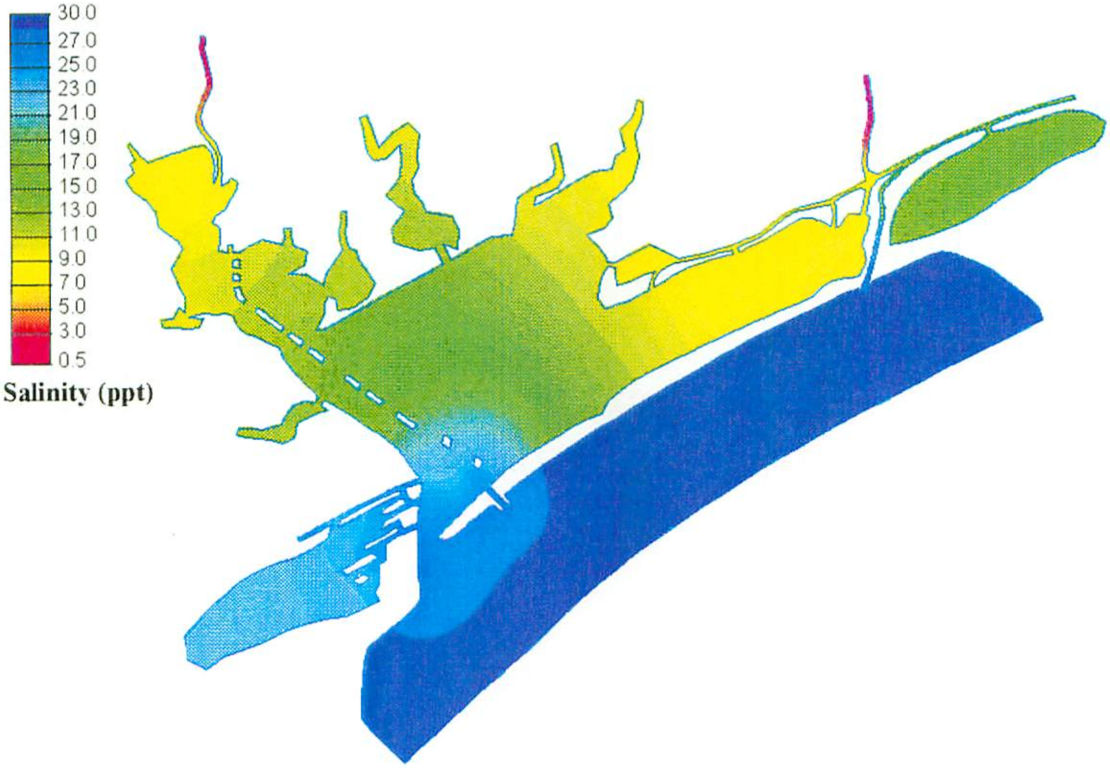


Figure 77 August, 1987 Average Salinity Distribution

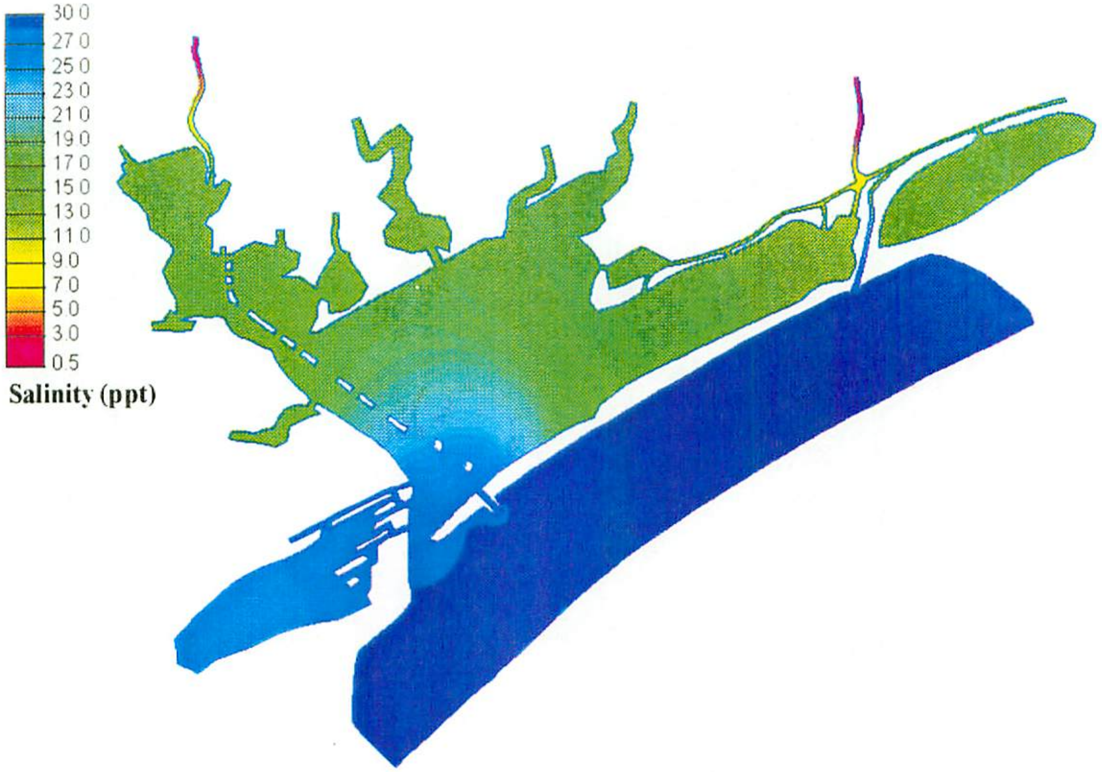


Figure 78 September, 1987 Average Salinity Distribution

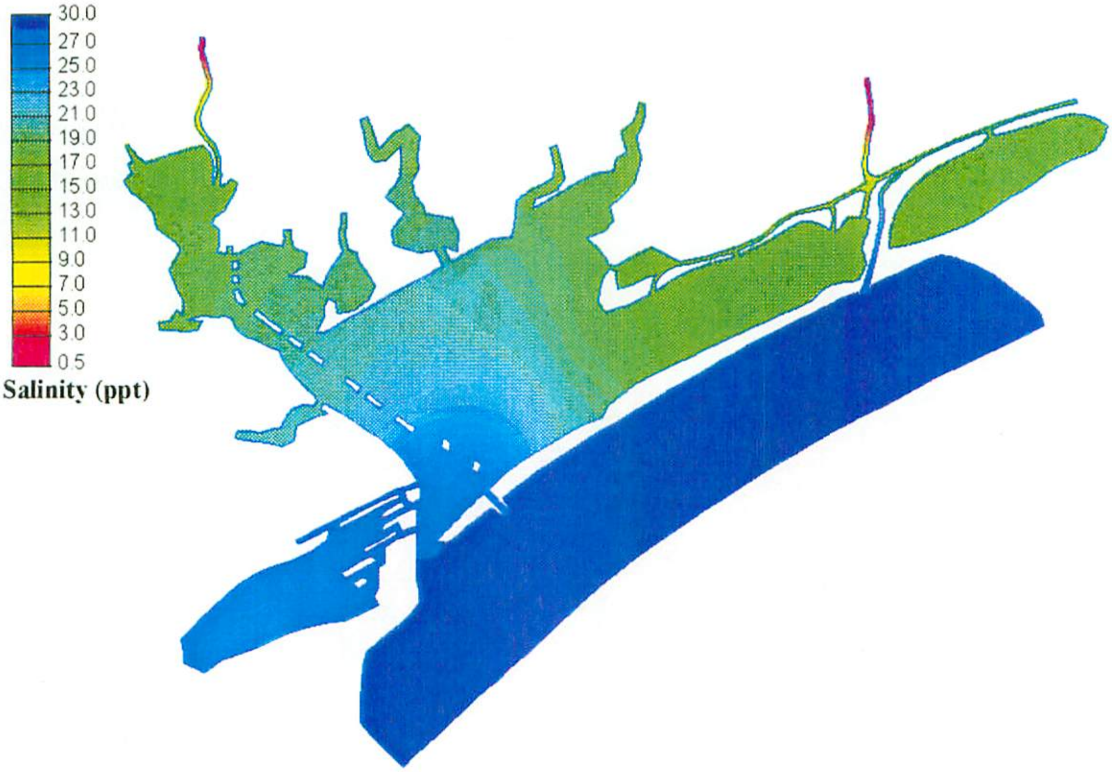


Figure 79 October, 1987 Average Salinity Distribution

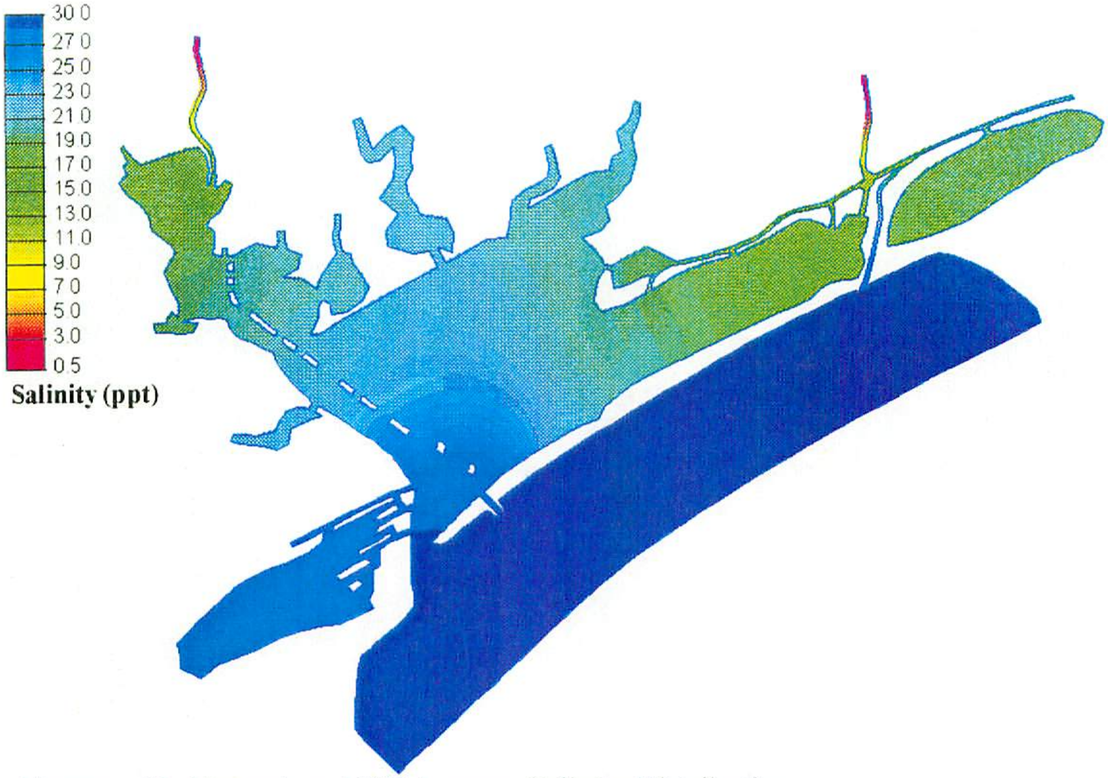


Figure 80 November, 1987 Average Salinity Distribution

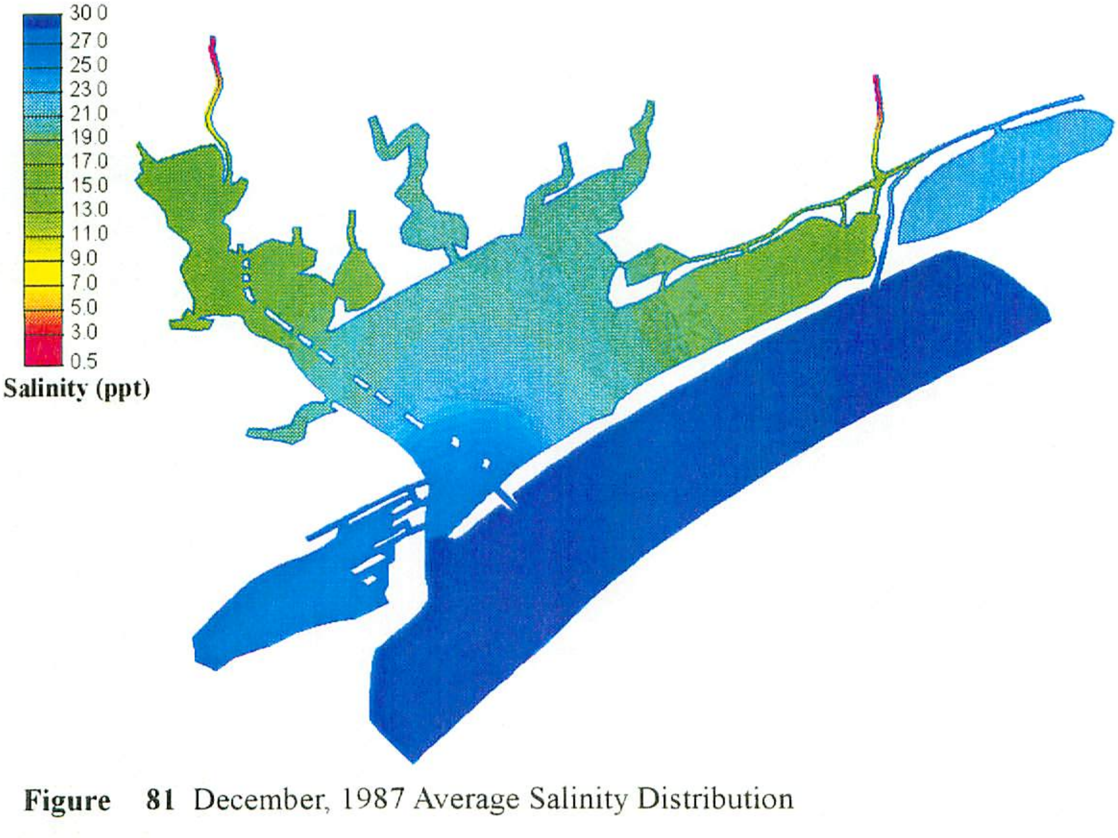


Figure 81 December, 1987 Average Salinity Distribution

CHAPTER 4

DEVELOPMENT OF SALINITY-INFLOW RELATIONSHIPS

INTRODUCTION

Purpose and Scope

The biological productivity of the Lavaca-Colorado Estuary is dependent in large degree on maintenance of a proper salinity gradient between fresh and marine waters. This gradient is preserved by maintaining appropriate quantities of freshwater inflows (Longley, et. al. 1994).

The purpose of this analysis is to determine the response of near-shore salinity in the Lavaca-Colorado Estuary to changes in the freshwater inflows from the Colorado and Lavaca Rivers. Of particular importance is the influence of the Colorado River on salinity in the eastern arm of Matagorda Bay.

The geomorphology of the Colorado River delta was radically altered by construction of the Mouth of the Colorado River Project by the U.S. Army Corps of Engineers. Completed in 1992, this project largely rerouted the flow of the Colorado River into Matagorda Bay by an artificial cut, called the Diversion Channel, in the river delta (Figure 1). The old river channel was dammed to prevent a direct outlet of the Colorado River into the Gulf of Mexico. Additionally, Tiger Island Cut, a major water exchange pass in the delta between the Gulf and Matagorda Bay, was artificially closed to prevent intrusion of Gulf waters directly into Matagorda Bay.

The analyses in this report rely on salinity and river flow data collected since December 1992 in eastern Matagorda Bay and data collected beginning in 1982 in Lavaca Bay. As additional data are collected, the predictive relationships developed in this report should be reviewed and revised.

Need for Study

The Corps' preliminary evaluation of salinity changes indicates that the eastern arm of Matagorda Bay has become significantly fresher as a result of the project (Bass, 1994). This change is largely due to the direct inflows from the Colorado River. However, prior to this analysis, predictive relationships between salinity in the bay and flow in the Colorado River had not been developed using data collected since the delta was altered. Clearly, such relationships are necessary to determine the impact of changes in freshwater inflows to the estuary's biological productivity. Without knowing how conditions in the estuary vary with changes in Colorado River flows, it is impossible to know how to balance the benefits of releasing freshwater to the estuary with the beneficial uses of the freshwater upstream in the LCRA service area.

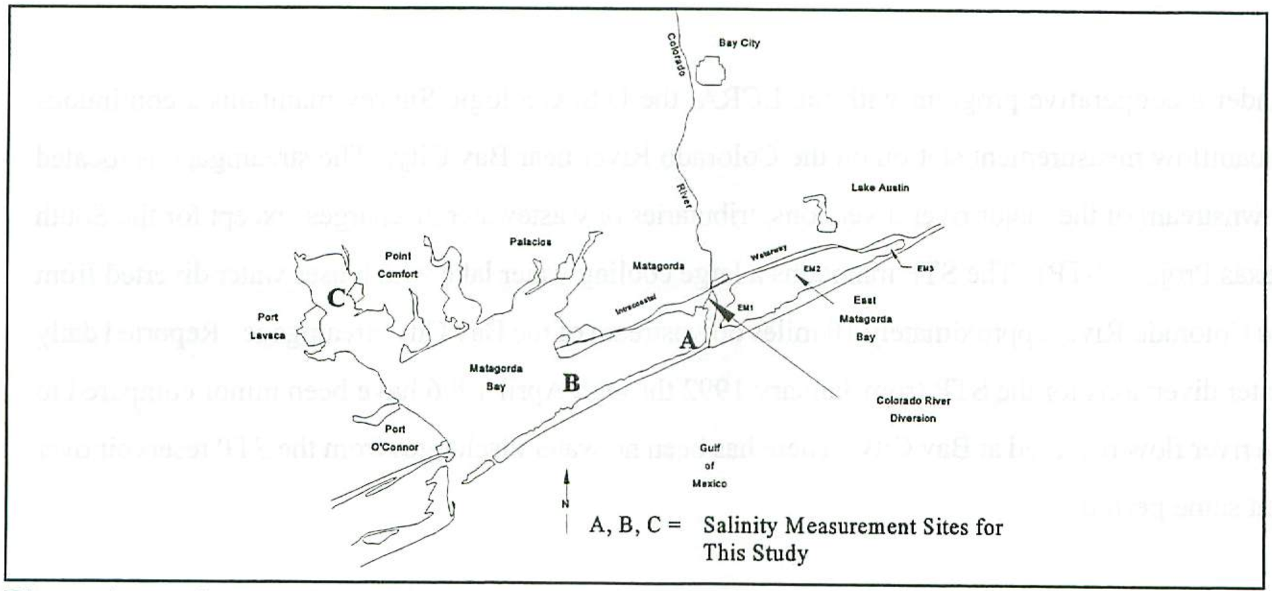
Expected Application of Results

The relationships between river flow and bay salinity will be used in the TWDB Texas Estuarine Mathematical Programming (TXEMP) model for this estuary. The TXEMP is an essential element in determining the appropriate volumes and timing of freshwater inflows to maintain and enhance the estuarine ecosystem.

DATA SOURCES

Salinity

In developing a reliable predictive relationship, it is essential that salinity be measured over a number of months and under a variety of hydrologic conditions. In late 1992, the LCRA installed two automatic measuring devices, termed datasondes, to provide hourly data collection of salinity, dissolved oxygen, pH, and other field parameters. The devices were located in eastern Matagorda Bay (Figure 1), with one near the mouth of the Colorado River Diversion Channel (A - tide gage site) and the other on the Intracoastal Waterway (ICWW) closer to Matagorda Bay proper (B - ship channel site).



A, B, C = Salinity Measurement Sites for This Study

Figure 1. **Lavaca-Colorado Estuary and Location of Salinity Measurement Stations Used in this Study**

Maintenance problems with the datasondes and their relocation for other studies prevented obtaining a continuous data record. The LCRA data record is by far the most complete at the tide gage site. The hourly salinity at that location was recorded over most of the period from December 22, 1992 through April 18, 1996.

In addition to the LCRA data, the U.S. Army Corps of Engineers made instantaneous salinity field measurements in the eastern arm of Matagorda Bay over 1992 and 1993 (Bass, 1994). The TWDB also maintains a continuous data collection program using a stationary datasonde in Lavaca Bay (site C in Figure 1). Further, TPWD and TNRCC have a periodic sampling program for field measurements at a number of stations in Matagorda Bay.

Daily River Inflows

Colorado River

Under a cooperative program with the LCRA, the U.S. Geologic Survey maintains a continuous streamflow measurement station on the Colorado River near Bay City. The streamgage is located downstream of the major river diversions, tributaries or wastewater discharges, except for the South Texas Project (STP). The STP maintains a large cooling water lake which uses water diverted from the Colorado River approximately 10 miles downstream of the Bay City streamgage. Reported daily water diversions for the STP from January 1992 through April 1996 have been minor compared to the river flow recorded at Bay City. There has been no water discharges from the STP reservoir over that same period.

The daily streamflow of the Colorado River at Bay City was taken from the U.S. Geologic Survey streamgage daily average flow records.

Lavaca River

Flows in the Lavaca River are measured on a continuous basis at the USGS streamgages on the Lavaca River at Edna and the Navidad River at Ganado, and at Palmetto Bend Dam on Lake Texana by the Lavaca-Navidad River Authority. There are no significant water diversions or discharges in the Lavaca River downstream of these measurement points.

COLORADO RIVER INFLUENCE ON ESTUARINE SALINITY

Introduction

As noted previously, the geomorphology of the Colorado River delta has been changed dramatically by the Corps of Engineers' Mouth of the Colorado River Project. Prior to these changes, the

Colorado River discharged primarily into Matagorda Bay through Parker Island Cut and Tiger Island Cut, with significant discharges during floods directly into the Gulf of Mexico.

East Matagorda Bay Salinity

Freshwater inflows into East Matagorda Bay occurred via cuts in the barrier islands along the ICWW on the northern edge of the bay. Even in times of flood, the Colorado River rarely overtopped its east bank within the delta and discharged directly into East Matagorda Bay.

The sources of freshwater were flows from the Colorado River moving east along the ICWW, local runoff in the Brazos-Colorado Coastal Basin, primarily in Matagorda County, and direct rainfall on the bay.

A study by Kimura (1993) of observed salinity in East Matagorda Bay concluded that local rainfall and ungaged runoff have a significantly greater influence on bay salinity than does the gaged flow of the Colorado River. The study examined historical salinity, rainfall and gaged Colorado River flows over the period 1980-1991. Rainfall was found to be twice as influential on bay salinity levels than Colorado River flows. With the change in the location of Colorado River outflows, there will be even less impact from the river on salinity in East Matagorda Bay.

Eastern Matagorda Bay Salinity

Statistical Analysis

Statistical analysis of the salinity recorded at the tide gage site and Colorado River inflows was undertaken to find if reasonable predictive relationships could be developed. Of course, bay salinity near the mouth of the Colorado River will respond to freshwater inflows from the river. However, there are a number of other factors influencing the salinity. These include bay currents, tidal inflows from the Gulf of Mexico, direct precipitation on the bay, evaporation, flow detention time in the bay, and other freshwater inflow sources, such as Tres Palacios River and other coastal streams.

The method of selecting appropriate predictive relationships was to use multiple regression. A variety of linear and nonlinear relationships were tested to discover patterns between daily Colorado River flows (1000 acre-feet) at Bay City (Q_t) (less diversions for the STP) and observed mean daily salinity (ppt) over consecutive seven day periods at the tidal gage site (S_t). The seven-day average salinity was used to be consistent with the methodology applied by TWDB and TPWD in their study of the San Antonio Bay system (Longley, et.al., 1994).

Daily Salinity-Inflow Relationship

Several statistical equations were found to reasonably reproduce observed daily variations in bay salinity. The relationship that best fit the observed daily salinity is

$$S_t = 36.63 - 3.18\ LN\left(\sum_{j=1}^{30} Q_{t-j}\right) - 1.19\ LN\left(\sum_{j=31}^{60} Q_{t-j}\right) \qquad (1)$$

where LN = natural logarithm operator. This equation is statistically very highly significant ($p<0.01$) and accounts for 53% of the observed variation in the recorded salinity. The standard error of the estimate is 3.3 parts per thousand (ppt), with the standard error of the coefficients at .36 for the first term and .37 for the second term.

Comparison of the predicted and observed salinity and Colorado River inflows is given in Figure 2. The predicted salinity generally matches observed values, but often fails to replicate the highest and lowest observed salinity, particularly the salinity values in excess of 25 ppt and less than 10 ppt.

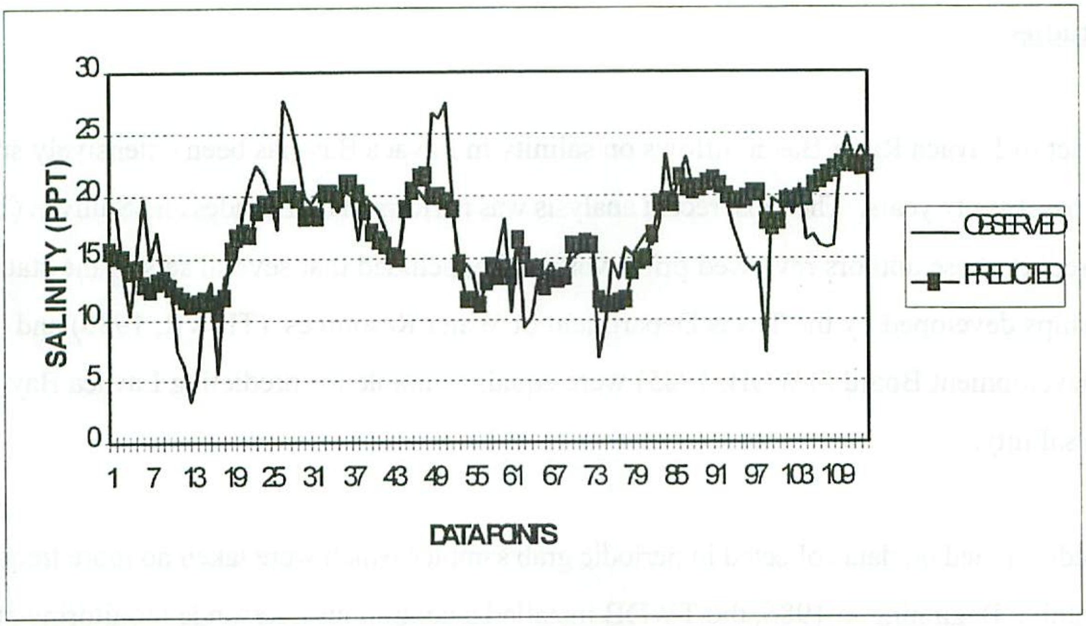


Figure 2. **Observed and Predicted Salinity for Eastern Matagorda Bay near Mouth of Colorado River**

As would be expected for sites close to the mouth of a major river, the estuary salinity can vary greatly over short periods of time.

To improve the salinity estimates, the data was categorized by four seasonal periods and the regression process repeated for each season. Except for the winter, all seasonal regression analyses resulted in improved predictive equations. However, the seasonal equations also failed to predict salinity matching the highest and lowest recorded values. Since the seasonal regression equations were not consistently better predictors, Eq. 1 was selected to represent the relationship between salinity at the tide gage site and Colorado River flows at Bay City.

LAVACA RIVER INFLUENCE ON ESTUARINE SALINITY

Prior Studies

The impact of Lavaca River Basin inflows on salinity in Lavaca Bay has been extensively studied over the past twenty years. The most recent analysis was performed by Brandes and Sullivan (1990). In their report, these authors reviewed prior work and concluded that several sets of the statistical relationships developed by the Texas Department of Water Resources (TDWR, 1980) and Texas Water Development Board (TWDB, 1985) were equally suitable for predicting Lavaca Bay mean monthly salinity.

These studies relied on data collected in periodic grab samples which were taken no more frequently than monthly. Beginning in 1986, the TWDB installed a continuous datasonde monitoring station in upper Lavaca Bay. This station collected hourly measurement of field parameters, including salinity. The abundance of additional salinity data warranted revision of the previous relationships developed for inflow and salinity.

Statistical Analysis

Statistical analysis of the mean daily salinity recorded at the datasonde and field sampling site and Lavaca River inflows was undertaken to find if reasonable predictive relationships could be developed. The method of selecting appropriate predictive relationships was to use multiple regression. The salinity data set from February 1968 through May 1993 was selected for use in this analysis since it covers all data available up to the diversion of the Colorado River directly into Matagorda Bay. The inflows to Lavaca Bay were taken as the daily discharge of the Lavaca River at Edna plus either the daily flow of the Navidad River at Ganado (for years prior to June 1982) or the daily releases from Lake Texana (beginning June 1982).

A variety of linear and nonlinear relationships were tested to discover patterns between mean daily inflows (Q_t) (1000 acre-feet) and observed mean daily salinity (S_t) (ppt). The datasonde data was averaged of seven day periods to provide the necessary salinity data. The salinity data used in the statistical analysis was provided by Dr. David Brock at the TWDB (Personal Communication, 1996). All equations examined were from the same general forms used in the analysis of Colorado River inflows and bay salinity.

Daily Salinity-Inflow Relationship

Several statistical equations were found to reasonably reproduce observed daily variations in bay salinity. The relationship that best fit the observed daily salinity is

$$S_t = 28.68 - 3.12\ LN(\sum_{j=1}^{30} Q_{t-j}) - 1.40\ LN(\sum_{j=31}^{60} Q_{t-j}) \qquad (2)$$

This equation is statistically very highly significant ($p<0.01$) and accounts for 71% of the observed variation in the recorded salinity. The standard error of the estimate is 5.04 parts per thousand (ppt), with the standard error of the coefficients at .13 for the first term and .14 for the second term.

Comparisons of the predicted and observed salinity and Lavaca River basin inflows are given in Figure 3. The predicted salinity generally matches observed values, and is able to replicate the full range of salinity conditions. Some seasonal variation was observed in the salinity estimations. However, there was no clear indication that seasonal equations would consistently improve the predictive power of Eq. 2. Therefore, no further statistical analysis were undertaken to develop season predictive equations.

RECOMMENDATION FOR CONTINUED EVALUATION OF SALINITY FOLLOWING COLORADO RIVER DELTA CHANGES

It has only been a relatively short time since the completion of the Mouth of the Colorado River Project. The limited record of salinity conditions since the redirection of the Colorado River directly into Matagorda Bay needs to be significantly extended to provide a more comprehensive database for estimating the response of salinity to freshwater inflows. Therefore it is recommended that salinity data continue to be collected at the datasonde sites in upper Lavaca Bay and eastern Matagorda Bay. Further, with collection of an additional three to five years of salinity data, the salinity-inflow relationships given in the chapter should be reevaluated to establish the most accurate predictive equations given the additional data.

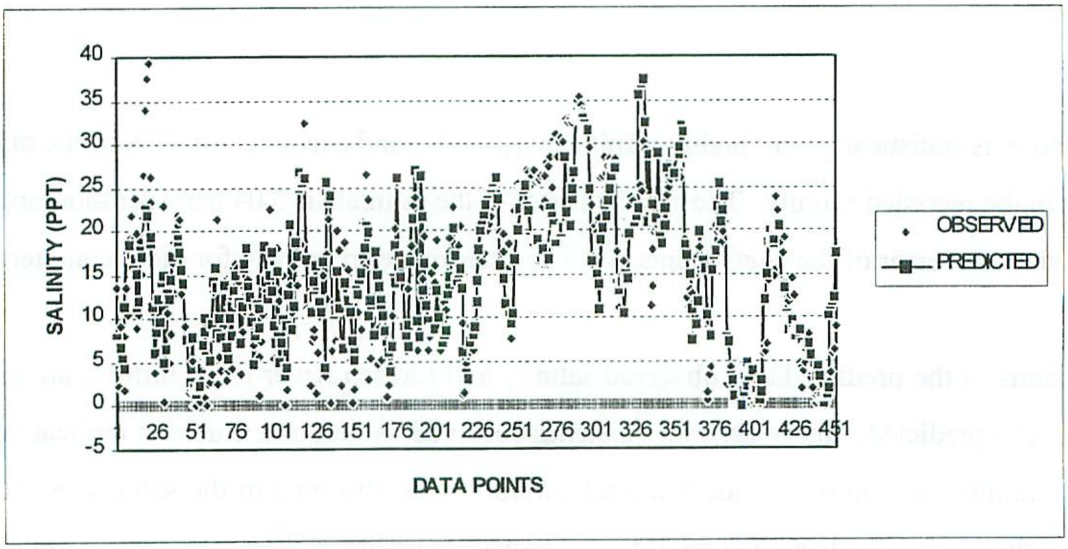


Figure 3. Observed and Predicted Salinity in Upper Lavaca Bay

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CHAPTER 5

NUTRIENT BALANCE AND REQUIREMENTS

INTRODUCTION

This chapter provides information on a nitrogen budget for the Lavaca-Colorado Estuary, Texas. The nutrient income to the Texas estuaries has become an important part of the freshwater inflow needs debate. To ensure that Texas estuaries will receive nutrient loads sufficient to maintain their fertility, the development of a nitrogen budget is a required section of the mandated freshwater inflow studies.

The dynamics of this system have changed in recent years due to the diversion of the Colorado River in 1991 and closing of Parker's Cut in 1992. The only two major sources of freshwater inflow to this estuary that can be managed are the Colorado River and the Navidad River. The freshwater inflow study will provide information for required flows from these two sources. This information will be used to determine management plans for these rivers.

Nitrogen is often considered the controlling nutrient in estuaries (Nixon, 1983; Nixon and Pilson, 1983). Ryther and Dunstan (1971) demonstrated that additions of nitrogen stimulated growth of marine algae. Dortsch and Whitledge (1992) found that algae growth will be limited when inorganic nitrogen concentrations are lower than 0.014 mg/l. In order to gain a broad understanding of the effects of nitrogen inputs upon the productivity of an estuary whole estuary ecosystem nutrient budgets have been developed by several scientists. Scott Nixon (1992) has taken these results and compared the inorganic nitrogen load with the amount of productivity for each system, and found that a pattern of increasing productivity with increasing inorganic nitrogen load does exist.

Nitrogen has been documented as being the limiting nutrient in the Lavaca-Colorado Estuary. To determine the range of yearly nitrogen loadings and losses to this estuary a nitrogen budget has been developed for a high inflow year and a low inflow year. Nitrogen budgets for the Lavaca-Colorado Estuary were determined for a low-inflow/dry year, 1984, and a high-inflow/wet year, 1987.

METHODS

Methods used in this study closely follow methods used by TWDB for the Guadalupe Estuary (Longley, 1994).

Total Nitrogen Inputs and Losses

Total nitrogen inputs and nitrogen losses are shown in Equations 1 and 2 respectively. See Table 1 for definitions of equation terms.

$$TNG = Nr*Qf + Ad + Ap + Wd + NF + Ng*Qni + Ng*Qavg*Ent \quad \ldots\ldots\ldots\ldots\ldots \quad (1)$$

$$TNL = Neb - Nee + Ne*Qno + Ne*Qavg*Ent + DN + Sed + FH + Esc \quad \ldots\ldots\ldots\ldots \quad (2)$$

Total nitrogen loadings from each source were calculated by multiplying daily flow by the nutrient concentration that is most representative for that day (Q*N). Nutrient concentration measurements were collected at various sites three to twelve times per year. Total nitrogen values reported in the data were used to represent nutrient concentrations from the date reported until the date that the next nitrogen value was reported. Inflow data for these time periods were also checked. If inflows changed significantly between the dates in which nitrogen values were reported, and if the nitrogen concentration values from the two sampling periods were different (greater than 0.05 mg/l), then the value that better represents the nitrogen concentration for flow conditions at that time period was used.

Nitrogen loadings were calculated for the Colorado River by using flow data collected by the USGS and water quality data collected by the LCRA at Bay City. Before the diversion was installed, part of the flow from the river went into the bay through Parker's Cut while some of the flow went directly into the Gulf of Mexico. Colorado River inflows to the bay through Parker's Cut (pre-diversion conditions) were determined using an equation developed by the TWDB. This equation predicts the percentage of the total daily river flow entering the bay through the cut and is dependent upon the total daily river flow measured at Bay City. A high percentage of river flow enters the bay during lower flow periods and as little as 60% of the river flow enters the bay during higher flow periods.

Nitrogen loadings were calculated for the Navidad River by using flow data collected by the USGS. Water quality data were not collected on the river or in Lake Texana in 1984 or 1987. The USGS began collecting quarterly data on Lake Texana in 1988. USGS data were reviewed to determine which years since 1988 had flows that were similar to 1984 and 1987. USGS data from Lake Texana, which were from similar inflow years after 1988, were used as representative nutrient concentrations for 1984 and 1987 for the Navidad River/Lake Texana inflow. Data from 1989 were used to represent the low inflow year, 1984, and data from 1991 were used to represent the high inflow year, 1987.

Lavaca River and Tres Palacios River nutrient loadings were calculated by using flow data collected by the USGS and water quality data collected by the TNRCC. Garcitas Creek and Placedo Creek nutrient loadings were calculated by using flow data and water quality data collected by the USGS.

Nitrogen loadings and losses from the ICWW east of the Colorado River and from Espiritu Santo Bay were not taken into account because the Hydrodynamic Model results from these areas were not calibrated, and therefore, not reliable. The net inputs and losses from each omitted site are probably no more than one to three percent of the total budget. However, flows into and out of Espiritu Santo Bay were subtracted from the flows into and out of Pass Cavallo to correct for gains and losses from this water body.

Results from the Hydrodynamic Model were used to determine the amount of water entering and leaving the bay through the Matagorda Ship Channel and Pass Cavallo. Net gains and losses from the Gulf passes determined using the following equations: sum(Qni*Ng) = net nutrient gain from the Gulf; sum(Qno*Ne) = net nutrient loss to the Gulf. See Table 1 for definitions of equation terms.

Near-shore Gulf nutrient concentration data is sparse. TWDB data collected on the gulf side of the Matagorda Entrance Channel reveal that nutrient values ranged from 0.35 to 1.1 mg/l from two sets of samples collected in 1980 and from 0.4 to 1.0 mg/l for two sets of samples collected in 1983. Total nitrogen concentrations used for net flow entering the bay from the Gulf were 0.45 mg/l during 1984 and 0.75 mg/l during 1987. Both concentrations were near one-half the interior primary bay water concentration. Total nitrogen values will be higher near the Gulf passes than further out in the Gulf due to influence of the bay water plume that is entering the Gulf at these passes. Off-shore concentrations are estimated to be approximately 0.1 mg/l.

Some measurements of DIN constituents have been collected in the Gulf of Mexico, but not total nitrogen. Nitrite/nitrate concentrations in the Gulf of Mexico (from LATEX cruise data) one mile from shore range from 0.002 to 0.020 mg/l less than 40 meters deep and 0.02 to 0.40 mg/l at depths greater than 40 meters (ammonia concentrations were not available).

Measurements of DIN were taken in the near coastal Gulf of Mexico (from TAMU Gyre cruises near Galveston, Texas) with averages of 0.004 mg/l in 1988, 0.01 mg/l in 1989 and 1990. All three years were years with low freshwater inflow to Texas bays.

Calculations of nutrients lost from the bay were determined using data collected by the TWDB for 1984 and 1987. Only four sets of measurements were taken in 1984 (which could contribute significantly to error in the budget results) and six sets of measurements in 1987.

An entrainment rate of 14% was used for nutrients entering and leaving the bay. This rate was determined by Dr. David Brock of TWDB by comparing hourly Total Dissolved Solids (TDS) concentration changes at a site near the Ship Entrance Channel on the bay-side (Brock, D.A., 1996). Entrainment was multiplied by the average of total flow entering and leaving the bay. (Ng*Qavg*Ent = nutrients entering the bay from the Gulf passes. Ne*Qavg*Ent = nutrients leaving the bay from the Gulf passes.)

Municipal and industrial permit files were reviewed from TNRCC to determine inflow from these sources and to attempt to determine nutrient concentrations of wastewater from each municipality and industry. Also, concentrations for nutrients in wastewater for industry "types" are placed in NCPDI discharge categories and given a representative concentration for a variety of pollutants. These values were found in "Point Source Discharges in Coastal Areas of Texas" (NOAA, 1990). Nutrient concentrations for specific wastewater sources (i.e., ALCOA, Formosa, Point Comfort WWTP) were multiplied by flows from these specific sources. Nutrient concentrations from wastewater from industry "types" (i.e., seafood houses, organic chemical companies) were multiplied by flows from the specific sources.

Nitrogen concentrations of precipitation were taken from data collected in 1984 and 1987 at Victoria, Texas by the National Atmospheric Deposition Program (NADP, 1993). Samples were collected quarterly. Precipitation falling directly on the bay in 1984 and 1987 were calculated by LCRA staff for the gaged and ungaged flow section of the freshwater inflow study. Dry deposition from air was determined for days with winds blowing off-shore. Dry deposition was not considered when winds were blowing on-shore because atmospheric nutrients over the Gulf would be much less than atmospheric nutrients at Victoria, Texas.

Ungaged flow nutrient loadings were calculated by using ungaged inflow data (Critendon, 1995) and by using the standard 1.53 mg/l total nitrogen concentration for runoff water from dry crop agricultural and open pasture lands (82% of land uses with 3% representing rice field flow that does not enter a portion of a gaged stream), and 0.83 mg/l for forests and wetlands (12% of land uses), and 3.4 mg/l for residential areas (6% of land uses). Nitrogen concentrations were taken from the report by Newell, et.al, "Characterization of Non-Point Sources and Loadings to Galveston Bay", 1992. During May, June, and July for each year the rice crop runoff nitrogen concentration average used was 4.0 mg/l. This value was taken from the study by G.N. McCauley, "Rice Irrigation Water Quality Demonstration Project - Colorado, Matagorda, and Wharton Counties", 1993. General concentrations used for runoff water from particular land uses could be a significant source of error in this budget.

Water column storage of nitrogen was calculated using nitrogen data from the TWDB and the average bay volume taken from the hydrodynamic model. Nitrogen values from open bay sites and from the mouths of Lavaca and Tres Palacios Bays were averaged for each representative time period (nitrogen measurements were taken five times in 1984 and six times in 1987). The difference between total storage from the first set of samples taken at the beginning of the year and the beginning of the next year represents the water column storage for that year. This value may be positive or negative. The nitrogen storage for 1984 and 1987 was negative, so it was placed in the losses category of the nitrogen budget. Whereas, the TDS storage for 1984 and 1987 was positive, so this gain was placed in the input category of the TDS budget.

Nitrogen fixation was calculated using a uniform rate of 0.37 gN/m2/yr for non-vegetated areas and 1.0 g/N/m2/yr for vegetated areas in the estuary (Howarth et al., 1989). Vegetated and non-vegetated bay bottom areas were determined by Diener (1975). A value for nitrogen stored in the sediments was not included in this budget due to lack of information of sediment process rates and depths of nitrogen recycling within a one year period.

Denitrification values determined for San Antonio Bay (Yoon and Benner, 1992) were used to represent the amount of denitrification occurring in the Matagorda Bay System. These calculations were adjusted by the ten year average of representative monthly water temperatures throughout the year.

Nutrient burial in the sediments were calculated using nutrient measurements at a 10 cm depth, which was considered to be below the active sediment layer. These sediment concentrations were determined by Dr. Paul Montagna (1994). Nutrient burial totals were calculated only for sediments with a high organic content (generally mud and clay sediments, but not sand). The distribution of sediments with high organic content were determined from data collected by the Bureau of Economic Geology (White et al., 1989). Burial rates were adjusted for yearly inflow.

Commercial and recreational harvest data collected by Texas Parks and Wildlife Dept. (TPWD) were used to determine nutrients lost from the fisheries (Boyd et al., 1995 and Quast et al., 1989 and Maddux et al., 1989). Escapement losses were determined by using calculations designed by Norman Boyd of TPWD (pers. comm., 1995). Standard ratios of weight to percent nutrients developed by S.W. Zison et al. (1978) were used.

Water Balance Error

Results from the Hydrodynamic Model were used to determine the amount of water entering and leaving the bay through the Matagorda Ship Channel and Pass Cavallo. The water balance of this result was a 0.7% water gain in 1984 and a 2.0% water loss in 1987. A correction for water balance error is provided using the following procedure. The average yearly total nitrogen concentration for the near-shore Gulf was multiplied by 0.7% of the 1984 water budget and then this value was subtracted from the 1984 nutrient budget. The average yearly total nitrogen concentration for the open bay was multiplied by 2.0% of the 1987 water budget and then added to the 1987 nutrient budget (See Table 2). The water balance error was not included in the final numbers used to determine recommended inflow needs.

Percentiles were determined using SPSS for the yearly freshwater inflows from gaged and ungaged sources from 1941 through 1991.

Total Dissolved Solids

Values for TDS were collected from the same sources as the nutrients and applied in the same manner as were nutrients where appropriate.

More data were available for near-shore TDS values than for near-shore nutrient values. Monthly salinity data, which were converted to TDS, were available from the TPWD for 1987 and for 1988 (which was used to represent conditions in 1984). This data was collected in the Gulf near Pass Cavallo.

RESULTS AND DISCUSSION

TDS Budget

A TDS budget was calculated to determine if the budget would balance using a conservative constituent. Using a conservative constituent to check the budget methodology eliminates many other pathways in the non-conservative constituents' cycle, which therefore presents a clearer view of the budget's validity.

TDS budget results are presented in Table 3. The TDS input/loss ratios for 1984 and 1987 revealed that the TDS budget is very close to balancing (96% - 98%). These results validate the approach used to determine the nutrient balance for sources and sinks included in both of the budgets. The close balance for TDS could be due to lower error in the calculations due monthly TDS data available in the Gulf near Pass Cavallo.

All Nitrogen Sources

A large portion of the estuary nutrients are entering (or re-entering) and leaving the estuary through the two Gulf passes, the Ship Entrance Channel and Pass Cavallo. Nitrogen loading and losses through these two passes overwhelm all other nitrogen sources and losses calculated (Figures 2 through 5). Unfortunately, nitrogen concentrations within the plume outside these passes are not known due to lack of data. Therefore, the calculated nitrogen load entering the bay from the Gulf through these passes should be viewed cautiously.

The DIN:TN loading estimate from freshwater sources for 1984 is 55% and for 1987 is 47%. The DIN:TN loading estimate from all sources for 1984 is 49%, and for 1987 is 34%. Concentrations of DIN (measured twice in 1980 and twice in 1983) on the gulf-side of the Matagorda Entrance Channel were similar to concentrations of DIN in the open bay (0.02 to 0.14 mg/l).

Total nitrogen concentration data collected outside the Ship Entrance Channel in 1980 and 1983 were used to estimate near-shore Gulf total nitrogen concentrations. The concentrations used were 0.45 mg/l in 1984 and 0.75 mg/l in 1987.

In 1984 the loading from the Gulf passes accounted for 69% of the nitrogen loading from all sources to the estuary leaving only 31% of nitrogen loading from direct sources (Figure 2). Direct sources refer to all freshwater inflow sources, wastewater discharges, and nitrogen fixation. In 1987 the loading from the Gulf passes accounted for 62% of the total loading to the estuary leaving 38% of nitrogen loading from direct sources (Figure 3). The Colorado River provides a large portion, 24%, of the total nitrogen load from all sources to the bay during the high inflow year (Figure 3) but only 5% of the total nitrogen load in the low inflow year (Figure 2).

Direct Sources of Nitrogen

The total nitrogen budget results are presented in Table 4, and Figures 1 through 5. Major nitrogen inputs from freshwater sources include the Colorado River, the Navidad River, ungaged flow, and precipitation (Figure 1).

The Colorado River inflow accounted for 16% of the nitrogen input from direct sources (freshwater sources, wastewater, and nitrogen fixation) in the dry year, and 63% in the wet year, assuming post-diversion conditions (in which all flow from the Colorado River entered the estuary). When assuming pre-diversion conditions (with the Colorado River emptying into the Gulf and a portion of the flow entering the bay at Parker's Cut), the Colorado River inflow accounted for 14% of the nitrogen input in the dry year, and 55% in the wet year.

The Lavaca-Navidad River System provided 11% to 12% of nutrients from direct sources in the dry year and 11% to 14% of the nutrient load in the wet year. Two values are presented for each year to represent nutrient input differences due to post-diversion and pre-diversion conditions.

Ungaged flows accounted for 30% - 31% of the nutrient load from direct sources in the dry year and 11% in the wet year. Precipitation accounts for 23% - 24% in the dry year and 7% - 8% in the wet year. Two values are presented for each year to represent nutrient input differences due to post-diversion and pre-diversion conditions (if greater than one percent differences occur).

Wastewater return flows provided only a minor portion of the nitrogen load to the entire Lavaca-Colorado Estuary. (However, these flows may have provided a large portion of the nitrogen load to Lavaca Bay.)

In both the dry and the wet years, the nitrogen budget results in a negative loss due to nitrogen losses being greater than nitrogen inputs. However, in reality, the nitrogen budget would be positive in wet years, which would provide a store of nitrogen in the water column and sediments. And, in reality, in very dry years, the budget would be negative.

Previous Studies

Nutrient loadings to the Lavaca-Colorado Estuary have been determined in other studies. A report by Ward and Armstrong (1982) for Matagorda Bay provides an average nitrogen loading value of 9537 million grams/year from all sources and 3580 million grams/year from freshwater sources.

These recent historical values are represented by data collected from 1968 through 1978. The 1968 through 1978 average values are 72% of all sources and 87% of direct sources from the present study's 1984 nitrogen budget (Table 5 and 6).

Another study (NOAA/EPA Team on Near Coastal Waters, 1989) reported that the nitrogen load to the estuary from freshwater sources was 13373 million grams/yr. About 60% of the estimated nitrogen load is from agricultural sources. Estimates of nutrient inputs from ocean influx were not included. This estimate from freshwater sources is similar to the high inflow year estimate from the present study (Table 5), but is significantly greater than the 7915 millions of grams/yr average estimate from the present study. From the NOAA study results, inference can be made that 12346 million grams/yr from freshwater sources will maintain total nitrogen concentrations of 1.0 mg/l in the estuary, which would be categorized in the upper limits of the medium loading range. The present study indicates that 12447 million grams/yr from all sources will maintain the total nitrogen concentration of 0.95 mg/l.

Nitrogen loading results from these three studies may vary so greatly due to low inflows to the system in the 1970's being relatively frequent, and low inflows to the system in the 1980's being relatively rare. The years of data used for each study to determine an average loading could greatly influence this result. The different approaches and different data sets available for each study also influenced the results of each study.

RECOMMENDATIONS FOR NITROGEN LOADING AND FRESHWATER INFLOWS

The results of this budget provide an overview of major loadings and losses to the Lavaca-Colorado Estuary. The budget process provided a better understanding of this system. The budget also provides the range of yearly nitrogen loadings under relatively low inflow and high inflow conditions. These ranges were used to provide a means of comparing nitrogen loads above and below levels that are considered productive for the estuary. These nutrient budget values were developed to estimate the limits of productivity for this estuary with respect to possible nitrogen limitation (Table 5) and to make comparisons with other estuaries. However, the paucity of data available for the Lavaca-Colorado Estuary and its coastal watershed limited the resolution of this analysis. Therefore, we could not use the nutrient budget alone to estimate nitrogen requirements for productivity needs. More data should be collected to fill in these gaps.

The following are recommended studies that should be undertaken to develop an improved nutrient budget for Matagorda Bay.

1) Nitrogen measurements should be taken at near-shore locations in the Gulf to determine near-shore concentrations, and locations and concentrations of the bay plume water. Nitrogen measurements (DIN and TKN) should continue to be taken at sites in the bay and at critical river and creek sites. The USGS water quality monitoring site at Midfield should be re-established. TNRCC monitors should begin to collect TKN data at present stations on rivers, creeks, and in the bay. Bottom water samples should be taken at critical sites in the bay, rivers and creeks.

2) Better estimates of ungaged flow nitrogen concentrations also need to be determined. Ungaged nitrogen concentrations could be determined by establishing monitoring sites on creeks that would be representative of the local watershed and that did not have a point source discharge located upstream of the sampling site.

3) Nitrogen loading associated with stream bed load should be studied. This could be a significant source of nutrients for the estuary.

4) Nitrogen dynamics in sediments of the Lavaca-Colorado Estuary should be studied to determine the storage capacity of nitrogen in the sediments, the flux if nitrogen in and out of the sediments, nitrogen fixation, denitrification, and permanent losses to the sediments. Uncertainty of the reliability of these values weakens the resolution of this analysis.

5) Nitrogen dry deposition data should be collected on Matagorda Bay rather than extrapolating

from data collected in Victoria, Texas by the NADP.

6) A total phosphorus budget also should be developed for this estuary.

Because of these limitations, the recommended nitrogen loading to this estuary was not taken directly from the nitrogen budget. The strategy for developing the budget was to determine nitrogen loadings that were above and below biologically productive levels, and then to target the recommended nitrogen load from the budget. Although this goal was not met from by developing the nitrogen budget, the nitrogen budget study has helped us develop a better understanding of the nitrogen sources and losses, their relative contribution to the system, areas where further study is needed, and the nitrogen dynamics of the Lavaca-Colorado Estuarine System.

Approaches Used for Determining Nitrogen Loading Requirements

Several approaches to determining nitrogen loading requirements were investigated, three are described in this report. The three approaches include the Trophic Status Approach, the Historical "Norm" Approach, and the Limiting DIN Concentration Approach.

The first approach taken to set a nitrogen loading requirement for the Lavaca-Colorado Estuary was based on information from the report, Marine Eutrophication Review (Hinga, etal., 1995) which cites a study by Nixon (1992). The yearly primary production (grams of carbon fixed per square meter per year) in an estuary can be used to determine the trophic status of that estuary. The trophic status of an estuary can be defined as the rate of organic carbon supply. According to the trophic index, oligotrophic waters produce less than or equal to 100 gC/m2/yr. Examples of oligotrophic systems include the North Pacific Gyre and the Sargasso Sea. Generally, when an average is made over a whole estuarine system, shallow coastal waters fix 150 - 400 gC/m2/yr (Nixon, 1981). Ward and Armstrong (1982) reported that primary production for the Lavaca-Colorado Estuary was 175 gC/m2/yr, which was within the mesotrophic range of 101-300 gC/m2/yr.

Primary productivity rates are important to consider when managing an estuary because the amount of algae produced in an estuary will affect the fisheries yield of that estuary. To illustrate the importance of primary productivity to fisheries yield a simple regression equation that relates fisheries yield (FY) to primary productivity is provided in a study by Nixon (1988), FY = 1.55ln*PP - 4.49. This equation predicts that the fisheries yield will equal approximately 40 Kg/hectare/yr when the primary productivity rate is 101 gC/m2/yr. If this relationship is as reliable as stated by the r^2 value of 0.84, then attempts to regulate primary productivity and nitrogen loading can be used to "manage" an estuary to maximize or maintain its fishery.

The nitrogen load to maintain primary productivity within the mesotrophic range base of 101 gC/m2/yr was the approach taken to establish minimum loading requirements.

The Redfield carbon to nitrogen molar ratio of 6.625 provides a rough indication of how much carbon would be fixed at a given rate of nitrogen input without any recycling of nitrogen in a system. This ratio was compared to fifteen marine systems and to the MERL 28-month eutrophication experiment with reasonable results (see Hinga, etal. 1995, results from Nixon, 1992 and Frithsen, etal., 1985). However, this ratio is based on dissolved inorganic nitrogen loading, whereas, the present study uses total nitrogen (TN) loading. In the present study the assumption was made that the organic nitrogen fraction of the total nitrogen load will be recycled to DIN and used by algae in the bay once before exiting the bay system.

From this ratio it was determined that 13359 million grams of nitrogen/yr (or 1.3 gN/m3/yr) from all sources and 1.71 million acre-feet of freshwater inflow/yr was needed to maintain primary productivity above the oligotrophic range at 101 gC/m2/yr (Table 5). This inflow volume would rank in the 28th percentile of inflows from the fifty year record (Table 7). The Lavaca-Colorado Estuary receives an average of 3.18 gN/m3/yr (Brock, in Longley, 1994) with a median inflow of 2.92 million acre-feet/year for the fifty year period of record..

Recommended inflow was determined using the following procedure. Divide the nitrogen load

(NL) calculated for 1984 by the freshwater inflow (Qf) for 1984 to give an average nitrogen load (NL_{avg}) for each acre-foot of freshwater inflow per year. (The 1984 values were used because the recommended nitrogen load was very close to the 1984 input values. Therefore, the recommended nitrogen load per acre-foot per year would be similar to the 1984 nitrogen load per acre-foot.) The average nitrogen load was then multiplied by the recommended nitrogen load (RNL) to give the recommended inflow (RQF)for pre- and post- diversion conditions.

Equations: $NL_{84}/Qf_{84} = NL_{avg}$ then $NL_{avg}*RNL = RQf$

Recommended inflow calculations:

13526 / 1.743453 = 7758, 7758 / 13559 = 1.72 million acre-feet/year for pre-diversion conditions

13649 / 1.743453 = 7829, 7829 / 13649 = 1.71 million acre-feet/year for post-diversion conditions

The second approach taken to set a nutrient loading requirement was to determine the recent historical "norm" nitrogen load to the bay. The recent historical time frame would represent the years with water quality and water quantity data in which pre-diversion conditions existed. Water quality data from 1977 through 1989 were reviewed. This period of record represented the range of possible inflows from the third lowest to the fifth highest freshwater inflows recorded for the fifty years period of record. Average total nitrogen and chlorophyll-a concentrations of 0.95 mg/l and 0.008 mg/l respectively, were determined from these data. An equation for a nitrogen load that would account for losses to the Gulf and bio-geochemical losses while maintaining a nitrogen concentration of 0.95 mg/l of nitrogen in bay waters throughout the year follows. This nitrogen load would require a load of 0.95 gN/m3/yr divided by 0.21, which is the hydraulic residence time of the bay (used to account for losses to the Gulf) plus the bio-geochemical losses total for 1984.

The result of the second approach was 12447 million grams of nitrogen/yr from all sources and 1.59 million acre-feet of freshwater inflow/yr.

The third approach involved in determining nitrogen loading requirements was to determine the nitrogen load threshold for limiting concentrations of dissolved inorganic nitrogen (DIN) for the Lavaca-Colorado Estuary. Nitrogen concentration data were reviewed to determine if limiting DIN concentrations have been reported in this system. Limiting concentrations of DIN for algae growth is 0.014 mg/l (Dortch and Whitledge, 1992). Limiting conditions were reported throughout the estuary in October 1980, when DIN concentrations reported were below detection limits. In 1980 the freshwater inflow volume was 1.56 million acre-feet with only 0.25 million acre-feet/year recorded for July, August, and September of 1980. From these results one could argue that 1.56 million acre-feet/yr is an insufficient volume of water to maintain nitrogen requirements. However, lower yearly inflows occurred in 1988 and 1989 without reports of limiting nitrogen conditions occurring in the estuary. As one would expect, factors other than freshwater inflow contribute to determining DIN (and TN) concentrations in the estuary.

The three approaches to determining a nitrogen load for the estuary reinforces that the nitrogen load requirements are fairly consistent for all three cases. Applying these approaches requires more data to assure that they are consistent with the dynamics of this bay system.

CONCLUSIONS

In conclusion, the recommended total nitrogen loading requirement for the Lavaca-Colorado Estuary is 13360 millions of grams/yr from 1.71 million acre-feet of freshwater inflow. The nitrogen load needed to maintain productivity at the mesotrophic range base (101 gC/m2/yr) was the approach used to determine this recommendation.

Nitrogen limitation was documented in 1980 with 1.56 million acre-feet, which could represent the threshold level of limitation. However, nitrogen limitation was not documented in 1988 or 1989, which were years with lower inflows.

The historical "norm" of 12450 million grams/yr of total nitrogen and 1.59 million acre-feet of freshwater inflow could be too low to consider as a recommended inflow because it is so near the possible threshold level for nitrogen limitation.

FUTURE STUDY NEEDS FOR THE LAVACA-COLORADO ESTUARY

The amount of inflow required to continue to maintain a healthy estuarine community is difficult to determine due to our limited understanding of the many interacting processes that occur in this system. A better understanding is needed of the nutrient concentrations and loadings per unit volume required to maintain a healthy algal population during critical periods for Finfish and shellfish nourishment.

Recommendations to improve the quantification of a nutrient budget and nutrient loading needs for the Lavaca-Colorado Estuary are described in the nutrient budget section of this report.

A relationship between nutrients, primary productivity, and secondary productivity should be developed to better understand the impact of nutrient loading upon the fisheries. Primary productivity measurements should continue to be taken at the two bay sites influenced by the Colorado River. Additional primary productivity measurement sites should be established to measure the influences of the Lavaca-Navidad River System.

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Table 1. Nutrient Budget Equations

Qf = daily Gaged + Ungaged inflows, 1000's m3
Qavg = average daily flow to and from Gulf
Qni = Net Inflow from the Gulf (when Qg > Qo) = sum (Qg-Qo)*Ng
Qno = Net Outflow to the Gulf (when Qo > Qg) = sum (Qg-Qo)*Ne
Ve = Volume of estuary
Ent = Entrainment rate = 0.14
Nr = TN concentration from freshwater sources, mg/l
Ne = TN concentration in the estuary, mg/l
Ng = TN concentrations from the Gulf, mg/l
Ad = Atmospheric Deposition when winds are blowing offshore, million grams
Ap = Atmospheric Precipitation (precip. TN conc. * precip.), million grams
Wd = Wastewater Discharge (flow discharge * TN conc. of discharge)
NF = Nitrogen Fixation, millions of grams
Neb = TN present in the estuary at the beginning of the year (Ve*Ne), million grams
Nee = TN present in the estuary at the end of the year (Ve*Ne), million grams
DN = Denitrification
Sed = Nitrogen buried in Sediments
FH = Fisheries Harvest
Esc = Escapement
TNG = Total Nitrogen Input, millions of grams
TNL = Total Nitrogen Loss, millions of grams
TNG = Nr*Qf + Ad + Ap + Wd + NF + Ng*Qni + Ng*Qavg*Ent
TNL = Neb - Nee + Ne*Qno + Ne*Qavg*Ent + DN + Sed + FH + Esc

Table 2. TDS Budget (Millions of Kilograms) for the Lavaca-Colorado Estuary

		1984		1987	
TDS Inputs					
	Colorado River	442		1520	
	Navidad River	55		78	
	Lavaca River	27		251	
	Tres Palacios River	94		65	
	Garcitas/Placedo Creeks	11		47	
	Wastewater Discharge	110		111	
	Ungaged Flow	316		483	
	Precipitation	1		1	
	Atmos. Dry Deposition	1		1	
	Ship Entrance Channel	89960		189437	
	Ship Ent. Ch., Entrained	264503		319329	
	Pass Cavallo	69611		128063	
	Water Column Storage	5211		12507	
TDS Losses					
	Ship Entrance Channel	114620		281884	
	Ship Ent. Ch., Entrained	250957		243873	
	Pass Cavallo	85172		218063	
	Pass Cavallo, Entrained	183814		179883	
			*Pre-Diversion		*Pre-Diversion
Total In		624052	623962	887184	886665
Total Out		634563		923703	
Total Loss/Total Input		0.98	0.98	0.96	0.96

* Adjusted for Colorado River TDS input prior to the construction of the Diversion Channel

	1984		1987	
Remaining	-10512		-36518	
Water Balance	-2817		119796	
In/Out with WB correction	0.98	0.98	1.09	1.09

Table 3. Total Nitrogen Budget (Millions of Grams) for the Lavaca-Colorado Estuary

	1984		1987	
Direct Inputs				
Colorado River	716	*592	8339	*5992
Navidad River	420		1021	
Lavaca River	68		465	
Tres Palacios River	190		207	
Garcitas/Placedo Creeks	28		137	
Wastewater Return	111		111	
Ungaged Flow	1290		1584	
Precipitation	951		875	
Atmos. Dry Deposition	330		596	
Nitrogen Fixation	487		487	
Subtotal	4591	4467	13822	11476
Water Exchanges In				
Ship Entrance Channel	1322		4239	
Ship Ent. Ch., Entrained	3880		7137	
Pass Cavallo	1017		2825	
Pass Cavallo, Entrained	2840		5263	
Subtotal	9059		19464	
Losses				
Water Column Storage	625		1897	
Water Exchanges Out				
Ship Entrance Channel	2674		14762	
Ship Ent. Ch., Entrained	6010		7187	
Pass Cavallo	2007		7227	
Pass Cavallo, Entrained	4398		5299	
Subtotal	15713		36372	
Bio-geochemical Losses				
Denitrification	2438		2438	
Burial in Sediments	60		410	
Fisheries Harvests	82		97	
Escapement	104		208	
Subtotal	2685		3153	
Total In	13649	13526	33286	30940
Total Out	18398		39525	
IN/OUT	0.74	0.74	0.84	0.78
*<u>Adjusted for Colorado River nitrogen input prior to the construction of the Diversion Channel</u>				
REMAINING	-4748	-4872	-6239	-8585
Water Balance Error	-44		5833	
Total In, adjusted for water balance error	13605	13482	39119	36773
In/Out with WB Correction	0.74	0.73	0.99	0.93

Table 4. Total Inflow and Total Nitrogen Inputs Needed for a Nutrient Balance in the Lavaca-Colorado Estuary.

Inflow (M ac-ft)	Nitrogen (MGY)	
1.74	13526	Nitrogen Balance in 1984.
4.74	30940	Nitrogen Balance in 1987.
1.60	12446	Maintain average nitrogen concentration (.95 g/m3/yr)* with pre-diversion conditions.
1.59	12446	Maintain average nitrogen concentration (.95 g/m3/yr)* with post-diversion conditions.
1.72	13359	Maintain baseline mesotrophic conditions (6.5 g/m2/yr or 1.3 g/m3/yr)** with pre-diversion conditions.
1.71	13359	Maintain baseline mesotrophic conditions (6.5 g/m2/yr or 1.3 g/m3/yr)** with post-diversion conditions.

*also accounting for hydraulic residence time and bio-geochemical losses

**also accounting for hydraulic residence time

Table 5. **Total Nitrogen and Inflow from Rivers, Creeks, and Ungaged Sources for the Lavaca-Colorado Estuary**

Inflow (M ac-ft)	Nitrogen (MGY)	
1.74	4467	Nitrogen Balance in 1984.
4.74	11476	Nitrogen Balance in 1987.

Table 6. **Fifty Year Period of Record Inflows from Rivers, Creeks, and Ungaged Sources for the Lavaca-Colorado Estuary.**

Inflow (M ac-ft)	Percentile	
1.56	27th	Inflow in 1980 when Nitrogen Conc. were Limiting.
1.59	27th	Inflow to Maintain Average Nitrogen Concentrations.
1.71	28th	Recommended Inflow to Maintain Mesotrophic Conditions.
1.74	31st	Inflow in 1984.
2.94	50th	Median Inflow.
4.74	82nd	Inflow in 1987.

Figure 1. Total Nitrogen Sources for the Lavaca-Colorado Estuary

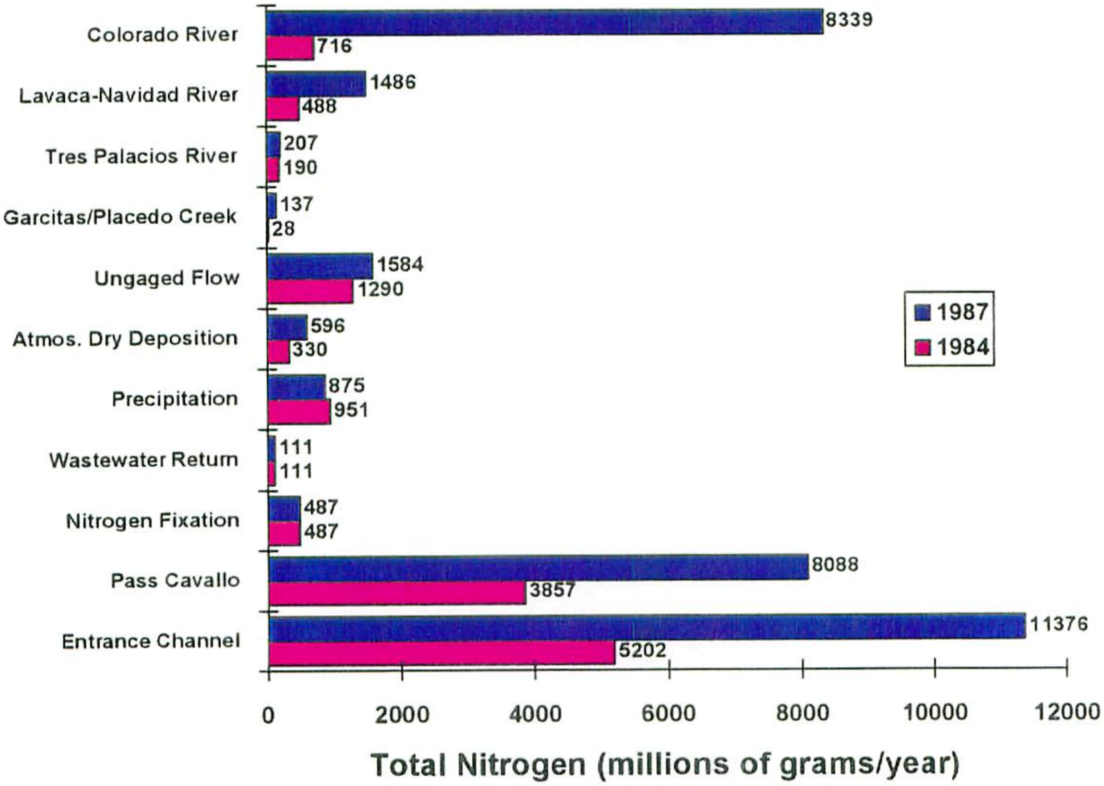


Figure 2. Total Nitrogen Contributions for the Lavaca-Colorado Estuary in 1984

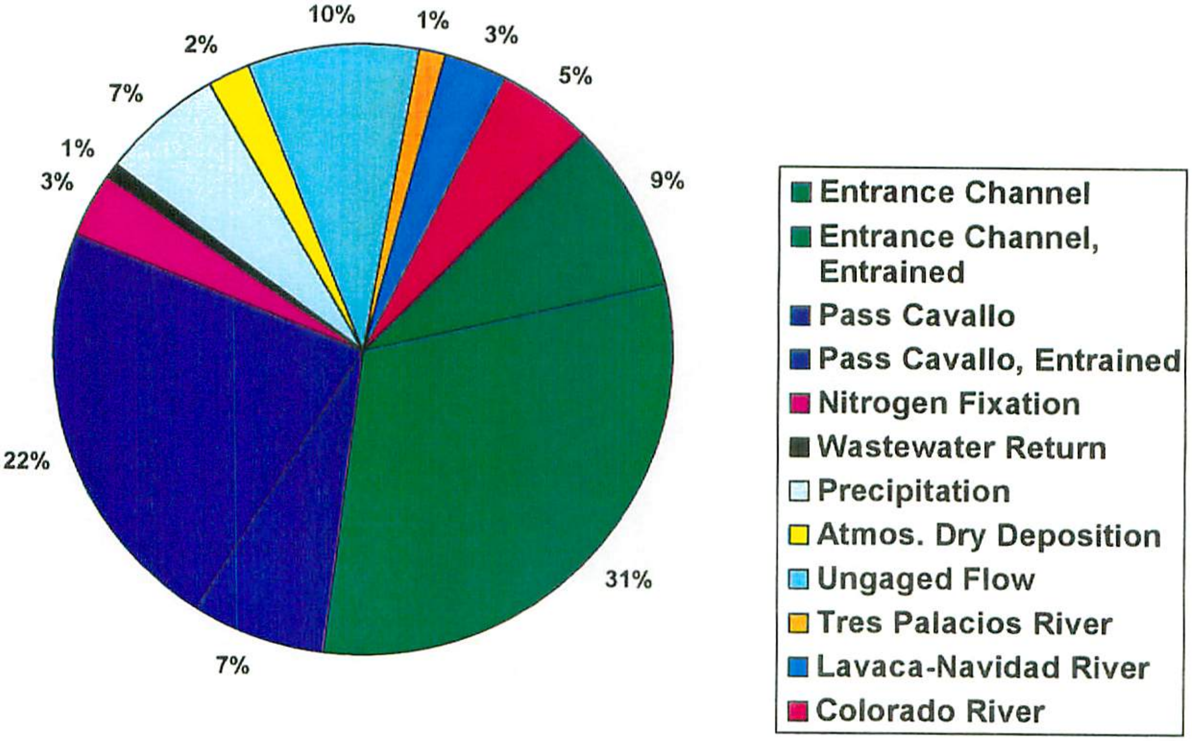


Figure 3. Total Nitrogen Contributions for the Lavaca-Colorado Estuary in 1987

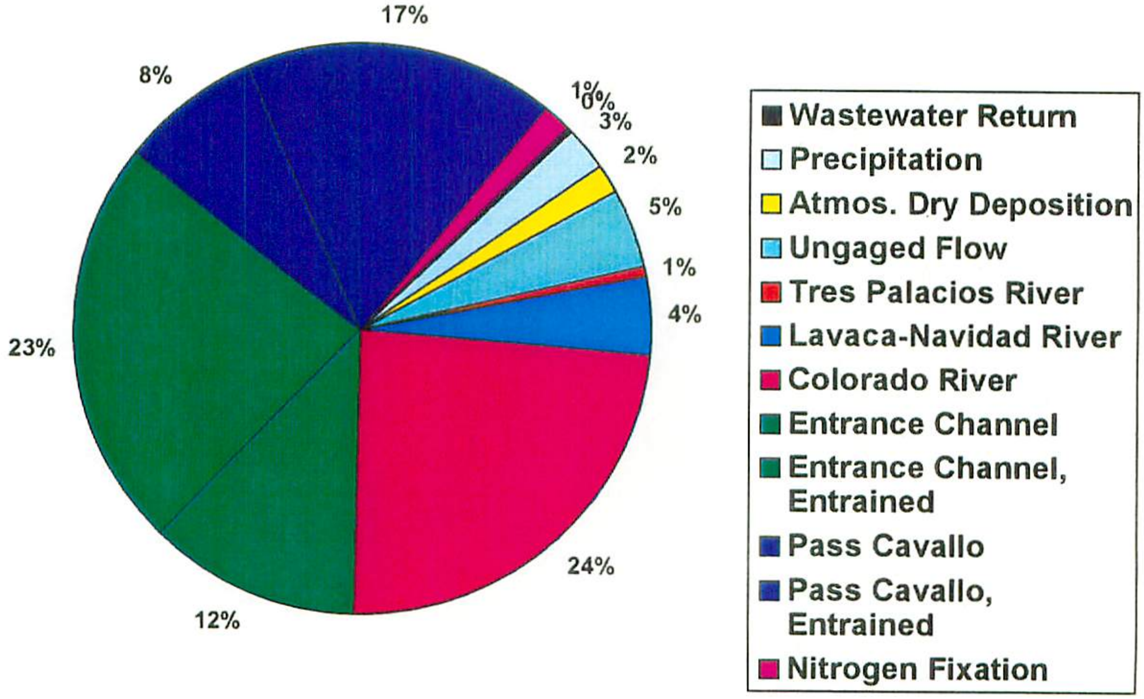


Figure 4. Total Nitrogen Losses for the Lavaca-Colorado Estuary

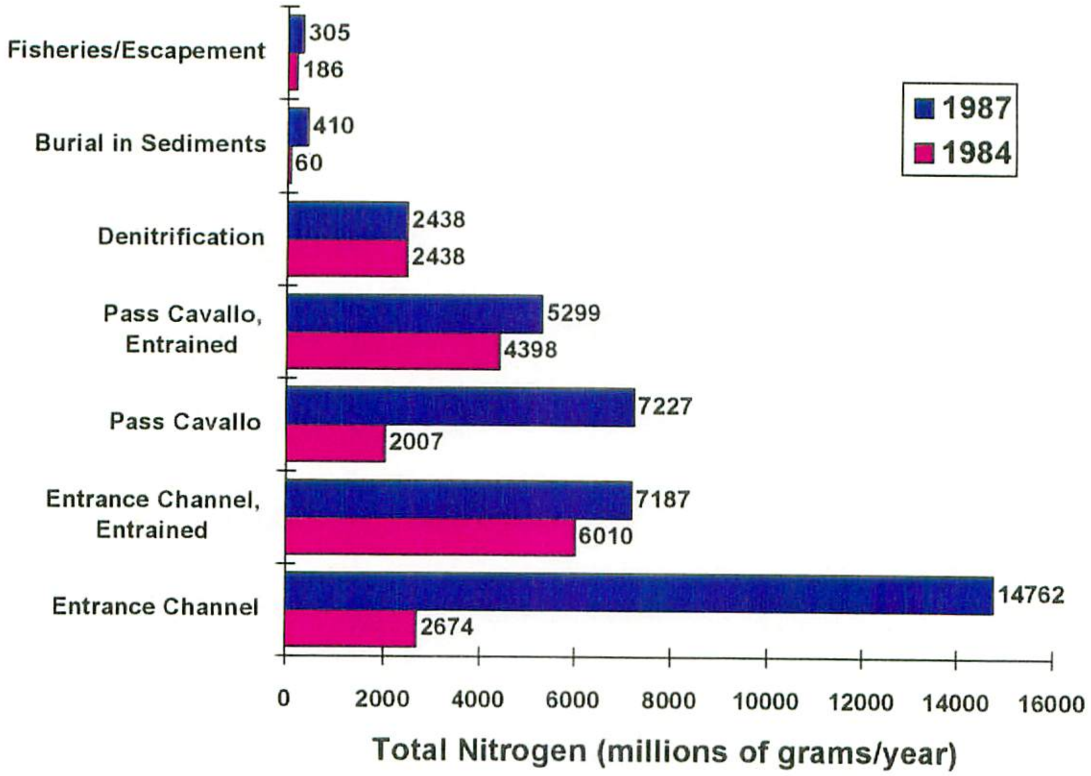
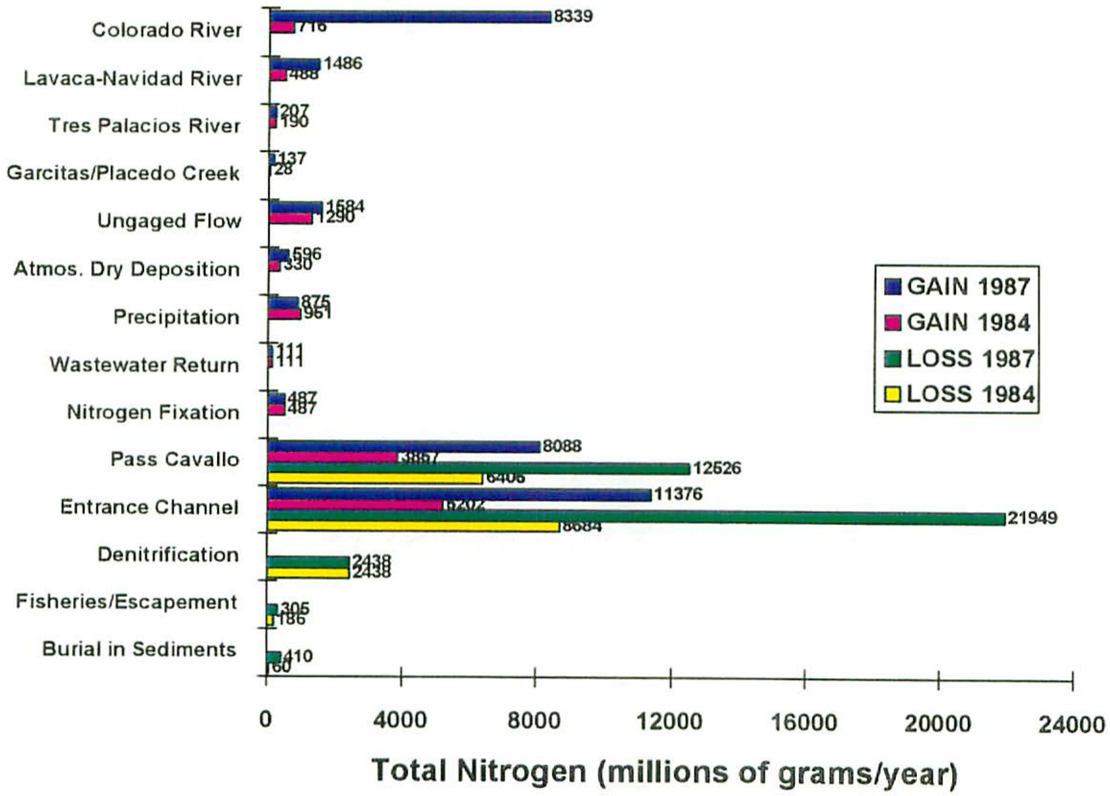


Figure 5. Total Nitrogen Sources and Losses for the Lavaca-Colorado Estuary



CHAPTER 6

BIOLOGICAL RELATIONSHIPS

INTRODUCTION

The Lavaca-Colorado Estuary, collectively know as the Matagorda Bay system, has a biologically and culturally rich history. Matagorda Bay and it's associated secondary bays is the second largest estuary on the Texas Coast with a combined area of more than 350 square miles. The estuary receives freshwater inflows from the Colorado River, with a drainage area of about 42,000 square miles at its northeast end, and from the Lavaca River (ca 2,800 mi^2 drainage area) at the north (upper) end of Lavaca Bay. Smaller tributary streams (e.g. Garcitas Creek, Tres Palacios Creek, and Carancahua Creek) contribute freshwater inflows from a combined watershed of about 4,700 square miles. With the exception of the Colorado River, all tributary streams flow directly into secondary embayments (Figure 1). Although the minor tributary streams have small drainages, they have a substantial localized influence on salinity characteristics within the bay, primarily because the coastal region receives substantially more rainfall per annum than much of the Colorado River's drainage, and secondarily since they receive much of the return flow from rice farms that are irrigated with surface water from the Colorado River and groundwater from the Gulf Coast aquifer.

From a historical perspective, freshwater inflow patterns into the Matagorda Bay system have been altered substantially over the years. From the 19th century until about 1929, the Colorado River flowed directly into Matagorda Bay at a point near the inshore end of the delta between Matagorda Bay and East Matagorda Bay, which formed a continuous open bay from Sargeant southwest to Port O'Connor. During this period, the Colorado River channel had been blocked by a series of floating rafts of logs and debris several miles long. The origin of these structures is uncertain, however their presence in the Colorado River between Bay City and Wharton was documented as early as 1824 by William Selkirk (Wadsworth 1941). The raft, which was about 2.4 miles long in 1824, had extended 47 miles upstream by 1926. During the early twentieth century, it was perceived that the rafts impeded flow in the river channel and were responsible for extensive flooding. In order to alleviate flooding along the river, the log rafts were removed from 1926 to 1930.

The removal of these log rafts had unexpected results. They had been in the river for at least a century, and all of the debris that had accumulated rapidly began to form a delta at the mouth of the Colorado River in Matagorda Bay. In 1934, a channel was cut through this delta across Matagorda Bay and into the Gulf of Mexico. Subsequently, the delta formed to the extent that East Matagorda Bay was isolated from Matagorda Bay, and the Colorado River flowed directly into the Gulf of Mexico. This diversion effectively removed the main source of freshwater inflows into Matagorda Bay; the impacts of this action on the ecology of Matagorda Bay will be discussed later. The Rivers and Harbors act of 1968 authorized the U. S. Army Corps of Engineers to construct and maintain a navigation channel in the lower Colorado River from the Gulf Intracoastal Waterway to the Gulf of Mexico. This project included a recommendation that the Colorado River be re-diverted into Matagorda Bay in order to "reduce maintenance costs in the navigation channel, reduce flooding, and to enhance fisheries and wildlife values of Matagorda Bay" (King 1989). This project was carried out, and the Colorado River was rediverted into Matagorda Bay in the fall of 1991 (Figure 1).

THE ESTUARINE COMMUNITY

The first major studies on the biological communities of Matagorda Bay were performed by H. F. Moore for the U. S. Department of Commerce and Labor (Bureau of Fisheries) in the early twentieth century (Moore 1907, 1915). Moore's work concentrated on the eastern oyster (*Crassotrea virginica*) and associated organisms since at the time, oysters supported a substantial seafood industry in the estuary. Subsequently, a number of studies have been performed in conjunction with various human impacts (e.g.. Mosely and Copeland 1973, Thonhoff 1980, Jones et al. 1986). Montagna (1994) evaluated the response of the meiobenthic community to freshwater inflows, particularly in regard to the recently completed Colorado River diversion. Much of the work on Texas bay systems, including the Colorado-Lavaca estuary, is summarized in Longley (1994).

The most notable feature of the estuarine community is its seasonally variable nature. Community structure changes noticeably over the year as different species migrate into and out of the estuary during different parts of their life cycle. Although these distributional patterns can be related to the seasonal nature of freshwater inflows, the underlying mechanism is probably the availability of appropriate food resources that result from nutrient loadings during inflow events (Montagna 1994). Seasonal salinity distributions remain important since the life stage of a particular species utilizing the estuary is generally adapted to be most physiologically efficient under salinity conditions that prevail when appropriate nutrient loadings are available (Longley 1994). Nutrient loadings to the Matagorda Bay system are the subject of a different chapter of this report (Gorham, In prep.).

Estuaries may be divided into several distinct regions, primarily on the basis of salinity characteristics and the associated flora and fauna. Green et al. (Chapter 7 *in* Longley 1994) delineated four different zones in the Guadalupe-San Antonio Estuary, each with distinctive wetland communities and faunal associations. The upper estuary (Zone I) is oligohaline and supports freshwater species capable of living in brackish conditions. This zone is directly impacted by freshwater inflows, consequently, salinity regimes are highly variable. Zone II (oligohaline to mesohaline) and Zone III (mesohaline to polyhaline), which are progressively more saline and more stable, represent intermediate conditions. Zone IV (polyhaline to euhaline), the lower bay contiguous with the Gulf of Mexico, is the most stable region. The Texas Parks and Wildlife Department have collected nearly 200 species of fishes and invertebrates from Matagorda Bay (Appendix A). These data indicate that Matagorda Bay, like other estuarine systems, supports a wide variety of species with substantially different ecological requirements. Although the areas delineated on Table 1 are not equivalent to the four salinity zones of Green et al.(1994), it should be noted that the characteristic species given for the more stable, higher salinity outer bay areas are similar to Green et al's (1994) Zone IV and the more variable, upper bay zones are similar to Green et al's (1994) Zone I. In this report, the salinity zone approach has been adopted but simplified to allow reasonable management application.

METHODS

Productivity-Inflow Relationships

Productivity-freshwater inflow relationships were developed for nine species of finfish and shellfish that are economically and/or ecologically important to the Lavaca-Colorado Estuary. Two data sets were examined and used; the Texas Parks and Wildlife Department's Coastal Fisheries Monitoring Data (bag seine subset) provided statistically better relationships for seven species: Blue Crab *(Callinectes sapidus)*, Brown Shrimp *(Panaeus aztecus)*, White Shrimp *(P. setiferus)*, Black Drum *(Pogonias chromis)*, Red Drum *(ocellatus)*, Gulf Menhaden *(Brevoortia patronus)*, and Striped Mullet *(Mugil cephalus)*, while annual Commercial Harvest Data from Matagorda Bay provided better relationships for the Eastern Oyster *(Crassotrea virginica)* and the Southern Flounder *(Paralichthys lethostigma)*.

Although annual commercial harvest data for finfish and shellfish species were available for a longer period of record (1962-1992) than TPWD monitoring data (1977-1992), it is recognized that the commercial harvest data contain numerous potential error sources. Differences among years in level of fishing effort, catch efficiency, consumer demand, harvest regulations, and economic factors (e.g. fuel prices) may contribute directly to unexplained variance in the data set. This is particularly evident for white and brown shrimp. Furthermore, since commercial harvest data are extracted from reports provided by commercial seafood dealers, it is assumed that all landings reported by seafood dealers on a given bay were actually harvested from that bay system. This is a questionable assumption since commercial fishing fleets have dramatically increased their capabilities to stay at sea and subsequently fish further from their home ports. The Texas Parks and Wildlife Department's data set provided only a fourteen year period of record, but it does eliminate many of the error sources present in the commercial harvest records since the data are collected in a systematic fashion. Commercial harvest data were considered preferable for oysters and flounder since neither of these species are effectively collected by seining.

Commercial Harvest data were converted to density (for oysters and southern flounder) by assuming an average harvestable weight per individual, then dividing the estimated total number of individuals by the area of Matagorda Bay. Since TPWD Monitoring bag seine data are collected by seining a standard area and reported as numbers of individuals per standard seine haul (Catch per Unit Effort, CPUE), these data were directly converted to density (individuals per hectare) by dividing the mean CPUE by the standard sample area (0.075 acres).

Regression equations were developed for each species by examining different combinations of bimonthly inflows (the independent variables) for each species and selecting the equation that provided the best statistical fit. Since the relationship between freshwater inflow and biological productivity is frequently indirect, productivity was lagged by one to three years depending on the life history of each species.

Distributional Patterns

The distribution of each species within the Lavaca-Colorado Estuary were examined with respect to seasonality and level of freshwater inflows using the Texas Parks and Wildlife Department's Coastal Fisheries Monitoring Data. Distributional maps were prepared for the each of the six bimonthly periods used to develop productivity-inflow relationships. Bag seine and trawl data were combined for those species where both were available; gill net data were treated separately for adult finfish since those data are not distributed evenly throughout the year and represent a substantially different size range of individuals. Gillnet data were divided into spring (April, May, June) and fall (September, October, November) subsets. For shellfish, average distributional patterns were plotted for wet and dry years, as determined by the median average annual bay salinity (22ppt) for the period of record.

RESULTS AND DISCUSSION

Seasonal Inflow-Productivity Relationships

The relationship between freshwater inflow and the productivity of estuarine species is complex. Freshwater inflow may effect the viability of the organisms while they are in the estuary, change predator-prey relationships or nutrient loading and subsequent food supplies. Consequently, freshwater inflows that effect the biological productivity of a species may not be coincident to that species presence in the estuary. In this study, several combinations of antecedent lag times were tried for each of the species of interest and the one that provided the best statistical relationship and could be explained on the basis of the species' life history was selected. Table 1 summarizes the seasonal inflow-productivity antecedent lag times used to develop the regression equations. In general, an antecedent lag time of one year provided the best statistical relationships for species with short life cycles (shellfish, gulf menhaden, and striped mullet) while a three year average antecedent lag provided the better fit for the larger, longer lived species (red drum, black drum, and southern flounder). Striped mullet and red drum was staggered by a season to account for fall spawning.

Significant seasonal inflow-productivity relationships were developed for nine species (Table 2). Five species responded negatively to freshwater inflows occurring in January and February while none exhibited significant positive responses for January-February inflows. Similarly, there were no positive responses for November-December inflows and two significant negative responses for November -December inflows. A combination of low salinities and low temperatures has been demonstrated to be detrimental to some finfish species, notably the Gulf Menhaden (Wetzel and Armstrong 1987).

Freshwater inflows occurring during the spring and summer produced generally positive relationships. Two species, the blue crab (*Callinectes sapidus*) and the eastern oyster (*Crassotrea virginica*), exhibited negative responses to March through June inflows. It should be noted that these two species also produced the weakest regression equations (Table 2).

The regression equation for the eastern oyster was developed from commercial harvest data and may not be a good representation of this organism's biological response to freshwater inflows. The Texas Department of Health bans the commercial harvest of oysters from estuarine areas with high fecal coliform bacteria levels. Since fecal coliform bacteria levels are usually elevated following high inflow events, commercial harvest records may not be a reasonable surrogate for biological productivity. This could result in a reduced harvest during high inflow periods due to legal restrictions instead of lower biological productivity.

Regression equations for the brown shrimp (*Penaeus aztecus*) and the white shrimp (*Penaeus setiferus*) are in agreement with the seasonal occurrence of these species in Matagorda Bay. Brown shrimp showed a positive response to freshwater inflows occurring in March and April; the months when juveniles are first appearing in the estuarine nursery areas. White shrimp showed positive responses to July through October inflows; this corresponds well to the seasonal presence of juvenile white shrimp in the bay.

It should be noted that, although the relationships among seasonal inflows and biological productivity seem to fit known seasonal and distributional patterns of most species, the balance of significant positive and negative responses do not track historical inflow patterns particularly well. The May-June flow period did not elicit significant positive responses for as many species as the March-April flow period even though May and June are historically high flow months. This is likely caused by the amount of interannual variation caused by high spring flows. It is likely that the early spring period (March-April) and summer to early fall flow period (July-October) are statistically more significant to brown and white shrimp, respectively, since they would benefit more from flows that occur during periods when there would be less competition from a closely related species.

Distribution and Abundance of Target Species

Blue Crab (*Callinectes sappidus*)

The blue crab spends much of its life in estuaries, occurring in all salinity zones at different times of the year. After mating in relatively low salinity waters, the female blue crab migrates from the bay into the Gulf of Mexico to spawn. Adult males remain in low salinity areas. Larvae return to the estuary and remain until maturation. Although immature blue crabs (< 50 mm) may be found year round, they are most abundant during March and April (Figure 2a-c). Migrational patterns are evident in seasonal distribution of this species. Young blue crabs (< 50 mm) are distributed throughout the bay during the winter months; then become concentrated in the upper bay and grow rapidly during the spring. The apparent dispersal of large blue crabs during the summer probably represents migration of adult females to the Gulf.

With the exception of hatching and early life stages when the eggs and larvae are in the Gulf, blue crabs are tolerant of a wide range of salinities. Growth rates of juveniles are optimal at intermediate salinities (10 to 20 ‰). Data from Matagorda Bay indicate that blue crabs tend to concentrate in low to intermediate salinities during the spring and summer. Juvenile blue crabs were present throughout the year, but peak abundance occurred during March and April.

Distribution and abundance of blue crabs varied substantially under different inflow conditions. Crabs were relatively abundant during wet years (Figure 3). During dry years, they were less abundant throughout the bay system, especially in the east arm of Matagorda Bay, and concentrated near the mouth of the Lavaca River, which is oligohaline as a result of consistent inflows from the Lavaca River.

Blue crabs from Matagorda Bay constitute about fifteen per cent of the total commercial harvest of this species from the Texas coast.

Brown Shrimp (*Penaeus aztecus*)

Brown shrimp are the one of the most commercially important species in Matagorda Bay. Landings of brown shrimp from Matagorda Bay account for about twenty five percent of the entire harvest on the Texas coast. Commercial harvest has increased nearly tenfold, from less than 300,000 pounds annually in 1960 to over 3,000,000 pounds annually in the late 1980's. This increase can generally be attributed to consumer demand, an increase in the local fishing fleet, and more efficient fishing techniques. Brown shrimp are commercially harvested from the Gulf of Mexico.

Adult brown shrimp generally occur in the Gulf of Mexico and spawn from September to May in offshore waters. Juveniles migrate to nursery grounds in estuaries and return to the Gulf as they mature (around 100-125mm). Brown shrimp are highly seasonal in Matagorda Bay (Figure 4a-c), with a peak in abundance during May and June. Like most estuarine species, brown shrimp are euryhaline and are found in a wide range of salinities. In Matagorda Bay, brown shrimp were found at a mean salinity of 23ppt during May and June.

Brown shrimp were more abundant during wet years, but were still present in substantial numbers during dry periods (Figure 5).

White Shrimp (*Penaeus setiferus*)

White shrimp spawn in near shore gulf waters from late spring through early fall and are abundant in Matagorda Bay from June through November (Figure 6a-c). Gunter et al (1964) indicated that white shrimp are most abundant in bays at salinities of less than 10 $^{0}/_{00}$; data from Matagorda Bay substantiate those findings. White shrimp and brown shrimp generally share nursery grounds in the bay, white shrimp juveniles are concentrated in the upper bays with lower salinities while brown shrimp tend to occur lower in the bay (Figures 4, 6). As they grow, white shrimp move down the bay into higher salinity waters of the open bay from January through April. White shrimp were concentrated in the uppermost areas of the bay near freshwater inflow sources during both wet and dry years (Figure 7), however, during dry years they were not common in the eastern part of the bay (Tres Palacios Bay and the eastern arm of Matagorda Bay).

Shrimp, principally *Penaeus setiferus and P. aztecus*, are presently the most commercially valuable finfish or shellfish harvested from Matagorda Bay and the contiguous Gulf of Mexico. Commercial harvest of white shrimp has not increased as dramatically over the last thirty years as brown shrimp. In the early 1960's, annual harvest of white shrimp from Matagorda Bay averaged in excess of 1,500,000 pounds; in the late 1980's commercial harvest had increased to about 3,000,000 pounds.

Eastern Oyster (*Crassotrea virginica*)

Around the turn of the century, the Matagorda Bay system was the most productive oyster fishery on the Texas coast, far out-producing all other bay systems in Texas. During surveys of the oyster beds in upper Matagorda Bay (Moore 1907) and Lavaca Bay (Moore and Danglade 1915), the Bureau of Fisheries reported Matagorda Bay as one of the most productive oyster bays in the country. In Matagorda Bay above Halfmoon Reef (Figure 8), there were more than 3,000 acres of natural oyster beds containing about 445,900 barrels of harvestable oysters, with an estimated sustainable yield of about 200,000 barrels per annum. Moore and Danglade (1915) noted that oyster populations in Lavaca Bay in 1913 were the most dense ever observed by the Bureau of Fisheries, with oyster beds covering about one sixth of the entire bay bottom. During this period, several large oyster houses operated on Lavaca Bay, exporting oysters to other parts of the country (King 1989).

The diversion of the river in 1934 directly to the Gulf of Mexico dramatically changed the freshwater inflow characteristics of Matagorda Bay, and resulted in the collapse of the commercial oyster fishery that was centered on the bay. Commercial harvest of oysters from Matagorda Bay accounted for less than one fifth of the total harvest from Texas bay systems from 1987-1991, and only about one fourth of the landings from Galveston Bay during that period.

Oysters are also among the most ecologically important organisms in the estuarine system. In addition to their direct role in recycling nutrients, their shell form reefs that provide physical habitat and nursery areas for other species (Zimmerman et al. 1989).

Unlike most other organisms, oysters are sessile molluscs that are restricted geographically to areas with hard substrates, such as existing oyster shell. Oysters spawn year round in Texas bays, with peak spawning in June and July, at temperatures above 20°C and at salinities above 10 °/$_{oo}$ (Hoffstetter, 1977, 1983). The larvae are free-floating for about ten days before the final larval stage (spat) settle on hard substrate. Spat settling has been reported to be most successful at salinities from 17°/$_{oo}$ to 24°/$_{oo}$ in Galveston Bay, Once the spat have set, they remain in the same place for their entire adult life. Juvenile and adults are capable of surviving a wide range of temperatures and salinities, but growth and survival is optimal with salinities fluctuating between 10°/$_{oo}$ and 30°/$_{oo}$. Fluctuating salinities help reduce fouling and predatory organisms. Predatory gastropods, principally the oyster drill (*Thais haemostoma*) and the conch species, *Busycon perversum*, cause substantial mortality at sustained high salinities (>25°/$_{oo}$). The black drum, *Pogonias cromis*, has also been reported to cause severe damage to oyster populations (Moore 1907). Additionally, high mortality of oysters have been attributed to two protozoan parasites, *Perkinsus marinus* (Dermo) and *Haplosporidium nelsoni* (MSX) when salinities remain above 15°/$_{oo}$ for extended periods.

B. D. King evaluated the condition of oyster populations in the eastern arm of Matagorda Bay in anticipation of the diversion of the Colorado River (King 1989). He noted that Halfmoon Reef, which was historically a highly productive reef, had high mortality of adult oysters and high incidents of predation. He noted only one successful spat set during his study; in July 1987 following a flood in the Colorado River the preceding month.

Oyster production in the eastern arm of Matagorda Bay is expected to increase dramatically as a result of the diversion of the Colorado River into the bay.

Since growth and survival of oysters is largely influenced by the salinity conditions over existing substrate, the location of existing oyster reefs may serve as a benchmark for determining appropriate salinity bounds within the Matagorda Bay system. Figure 8 shows the location of oyster reefs, towheads, and scattered oyster shell in Matagorda Bay as of spring 1995 (Jim Dailey, personal communication). Although oyster beds are temporally stable, there are some notable changes since Moore and his associates surveyed the oyster beds of Matagorda Bay in 1904 and 1913 (Moore 1907, Moore and Danglade 1915). Much of the dense oyster beds in Lavaca Bay have been either removed by commercial dredging operations following the collapse of the fishery, or have been covered with sediments. On the eastern end of the bay, Dog Island Reef, which was one of the largest (and economically important) oyster reefs in Matagorda Bay, is nearly covered by the delta that is rapidly forming at the mouth of the Colorado River diversion. Finally, the U.S. Army Corps of Engineers has placed three artificial reef complexes in the eastern arm of Matagorda Bay; an extension of Shell Island Reef, an extension of Mad Island Reef, and at a point between Mad Island Reef and Half Moon Reef (Figure 8).

Gulf Menhaden (*Brevoortia patronus*)

Gulf menhaden are one of the most abundant fish species on the gulf coast and are an ecologically important species in the Matagorda Bay system. The seasonal distribution of gulf menhaden in Matagorda Bay reflect their reported life history (Figures 9a-c). Adult menhaden spawn in the Gulf of Mexico from October to March. The juveniles migrate into the estuaries and are most abundant in low salinity waters (<15ppt). Migration from the estuary back to the Gulf of Mexico occurs in the fall. Menhaden first appear in seine hauls from Matagorda Bay in January-February, when they are predominately small juveniles (<50mm). During March and April, they are locally abundant in the low salinity conditions of the upper bays. They remain in the upper bays throughout the summer and early fall, then migrate back to the Gulf to spawn. Menhaden are virtually absent from the bay system in the late fall.

Striped Mullet (*Mugil cephalus*)

Striped mullet are present throughout the year in Matagorda Bay. Juvenile mullet (<50mm) are common in the winter (January-February), indicating a fall spawning season (Figures 10a-c). Seasonal distribution of striped mullet tended to agree with Rogers et al's (1984) observations in Georgia estuaries. Mullet moved away from freshwater inflow sources during the spring, then moved back into the upper bays during the summer and fall. Wetzel and Armstrong (1987) found a strong preference for freshwater inflow sources by adult mullet in Tres Palacios Bay.

Black Drum (*Pogonias cromis*)

Black drum (*Pogonias cromis*) juveniles were present in Matagorda Bay throughout the year, but only common from May through October (Figure 11a-c). It should be noted that black drum present in Matagorda Bay during March and April (Figure 11a) are mostly larger than 200mm and represent previous year classes. Black drum are winter spawners, and the current year's spawn first appears in numbers (50mm-150mm) in May. During the spring and summer, they are generally distributed around the bay, but congregate in the secondary bays during the fall. Adult black drum were sampled by the Texas Parks and Wildlife department during the Spring and Fall using gill nets. These data (Figure 12) indicate that adults are widely distributed in the bay and show little salinity preference.

Red Drum (*Sciaenops ocellata*)

Red Drum spawn from late summer to early winter (Longley 1994) in the Gulf of Mexico near shore. Juveniles migrate into bays after hatching; in Matagorda Bay juvenile redfish are abundant in the upper bays throughout the year; figures 13a-c indicate typical juvenile mortality throughout the year. Redfish also indicated a strong response to low salinity conditions in the estuary; relative abundance of juveniles in Matagorda Bay was noticeably higher during high flow years with lower than average salinities. Adult red drum were commonly collected in gill nets during the spring and fall (Figure 14). The apparent increase in abundance of adult red drum in the estuary during the fall is an artifact of collecting methodologies; note that the increase in numbers is predominately a result of the juvenile year class becoming large enough to be collected in gill nets during the fall.

Southern Flounder (*Paralichthys lethostigma*)

Flounder are common in Matagorda Bay except late fall and early winter when the adults migrate into the Gulf of Mexico to spawn (Figures 15a-c, Figure 16). Juvenile flounder migrate into low salinity areas of the upper bays during the winter and congregate in those areas through the spring. Southern flounder thrive under a wide range of salinity conditions; in Matagorda Bay adults tended to congregate in the upper arm of Matagorda Bay during the fall (Figure 16).

SALINITY PATTERNS IN MATAGORDA BAY

Historical salinity data for Matagorda Bay and it's secondary bays are shown in Figures 17a-c. The data are summarized in Table 3. While overall seasonal salinity distribution reflect typical rainfall patterns in the basin, there is substantial local variation. Lavaca Bay (upper and lower) and Carancahua Bay exhibited the lowest salinities in May and June, the typical high inflow months, and the highest salinities in November and December. Salinities were lowest in Tres Palacios Bay and Powderhorn Lake during July and August, which are typically low inflow months. Tres Palacios Bay receives substantial freshwater inflow as a result of return flows from rice fields during the summer.

Perhaps the most notable exception to the expected seasonal distribution is the east arm of Matagorda Bay. Salinity data indicated no significant drop in salinity during the spring high inflow months. This is due to the lack of direct freshwater inflows from the Colorado River and inflows of higher salinity water from Parker's Cut. The projected impact of the Colorado River diversion and the closure of Parker's Cut is the subject of another section of this report.

Given the changes in salinity regimes anticipated in the eastern arm of Matagorda Bay as a result of the diversion of the Colorado River, there are no recent biological data to support a direct delineation of salinity zones in that arm. There are, however, good historical data on oyster populations in Matagorda Bay around the turn of the century (Moore 1907, 1915), and the natural reefs that supported those fisheries are still present in the eastern arm of the bay. Consequently, the historical distribution of oysters were used as a baseline condition for the delineation of salinity zones in the eastern portion of the bay. Consequently, the historical distribution of oysters were used as a baseline condition for the delineation of salinity zones in the eastern portion of the bay (Figure 18). Zone IV represents relatively stable, outer bay salinities typically above 25ppt. Zones III and II are intermediate regions with salinities varying from 25 to 15 ppt in Zone III (optimal salinity conditions for oyster reproduction and survival) and 20 to 15ppt to near freshwater conditions near the river mouth (Zone I of Green et al. 1994). Using the TX-BLEND model we estimated monthly average salinity with target freshwater inflows. These estimated salinity zones for January through December are shown in Figures 19 through 30.

From a biological perspective, it should be noted that most of the species studied congregated in the nursery areas of the upper bays near the freshwater inflow sources as juveniles. The east arm of Matagorda Bay, which did not exhibit typical seasonal salinity patterns, did not support nursery areas equivalent to the upper Lavaca Bay or Carancahua Bay. This is particularly evident in the distribution of white shrimp, *Penaeus setiferus*, juveniles. White shrimp were uncommon in the eastern arm of Matagorda Bay during the period of peak abundance for juveniles (July through October). White shrimp collected the eastern arm of Matagorda Bay in November and December were larger than those in other parts of the bay and appeared to have migrated down bay from the nursery areas. Brown shrimp and blue crabs, which tended to be found lower in Lavaca Bay, Tres Palacios Bay, and Carancahua Bay, were also present in eastern Matagorda Bay. The only areas in east Matagorda Bay that consistently supported concentrations of juvenile finfish were around the major oyster reefs (Mad Island Reef, Shell Island Reef) where there is localized inflows from the Intercoastal Canal.

CONCLUSIONS AND RECOMMENDATIONS

The estuarine community of Matagorda Bay is comprised of a wide variety of organisms with differing responses to freshwater inflow conditions. The bay represents a temporally and spatially dynamic ecosystem; seasonal rainfall patterns provide generally predictable nutrient loadings into the bay system. Reproductive seasons of estuarine species are timed in such a manner as to allow juveniles to be in a position to exploit the resulting food resources. The amount of habitat available, its quality, and its position within the estuary is directly related to the timing and magnitude of the freshwater inflow events.

The relationship between productivity and seasonal freshwater inflows for the nine target species generally reflects the life history characteristics of the individual organisms. A notable exception is the eastern oyster, which is both ecologically and economically important in Matagorda Bay. It should be emphasized that oyster harvest data produced a biologically unsupportable regression equation, probably as a result of sampling bias resulting from closure of oyster beds during high inflow periods.

There are good information available on the communities of Matagorda Bay during the era when the Colorado River flowed directly into the bay (Moore 1907, Moore and Danglade 1915) and observations in those reports were relied on heavily for the following conclusions. Since the Colorado River was diverted into the upper arm of Matagorda only recently (1991), there is only a limited amount of data available on the biological communities of the estuary with the present inflow configuration. Additionally, the years where data are available (since 1992) have been wetter than average. The eastern arm of Matagorda Bay is directly effected by the diversion of the Colorado River into Matagorda Bay, and it is anticipated that this area will become substantially fresher and exhibit more typical seasonal fluctuations in freshwater inflows. Given the lack of direct information on the ecology of the eastern arm of Matagorda Bay under the current (post diversion) freshwater inflow patterns, it is assumed that freshwater inflow patterns and the resulting salinities should be similar to those observed in Lavaca Bay. Additionally, there is good information on the ecology of the eastern arm of Matagorda Bay prior to the formation of the delta and diversion of freshwater inflows directly to the Gulf of Mexico.

While many species are capable of moving within the estuary to exploit optimal physical, chemical, and biological conditions, oysters (*Crassotrea sp.*) are spatially confined to existing substrate, usually pre-existing oyster reefs. Given the historical and ecological importance of oysters in the Matagorda Bay system, salinity recommendations are made in order to provide optimal conditions over most reef systems during years of normal flow. In Lavaca Bay, productive oyster reefs are located at Galliniper Reef and Indian Point, at an average annual salinity of about 20ppt (Table 3), ranging from 16ppt to nearly 25ppt depending on the season. Average annual salinity in Upper Lavaca Bay has historically been 14ppt. In the eastern end of Matagorda Bay, equivalent, but more extensive oyster reefs are located at Mad Island and Half Moon Reef. Consequently, it is recommended that the mean annual salinities in the eastern arm of Matagorda Bay out to Halfmoon Reef be maintained to reflect the salinity patterns seen in Lavaca Bay down to Indian Point.

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Table 2. Regression equations and summary statistics relating seasonal freshwater inflows to abundance of finfish and shellfish in Matagorda Bay, Texas.

Species	Variable	S.E. coeff.	Maximum value	Minimum value	Mean value
Blue Crab (*Callinectes sappidus*) = f (seasonal total inflow) (n = 15, P = 0.0315, R = 0.73, Adj. R^2 = 0.41, S. E. Est. = ± 0.310875) $\ln H_{\text{Blue Crab}} = 2.20127 - 0.0007665(Q_{\text{Mar-Apr}}) - 0.0004912(Q_{\text{May-Jun}}) + 0.002197(Q_{\text{Jul-Aug}})$					
	$\ln H_{\text{Blue Crab}}$	-	2.68	1.14	2.06
	$Q_{\text{Mar-Apr}}$	0.000291	915	51	335
	$Q_{\text{May-Jun}}$	0.000190	1960	90	535
	$Q_{\text{Jul-Aug}}$	0.000888	428	68	171
Brown Shrimp (*Penaeus aztecus*) = f (seasonal total inflow) (n = 14, P = 0.0014, R = 0.82, Adj. R^2 = 0.61, S. E. Est. = ± 0.161476) $\ln H_{\text{Brown Shrimp}} = 5.2207 - 0.001145(Q_{\text{Jan-Feb}}) + 0.0004858(Q_{\text{Mar-Apr}})$					
	$\ln H_{\text{Brown Shrimp}}$	-	5.41	4.41	4.98
	$Q_{\text{Jan-Feb}}$	0.000248	828	66	352
	$Q_{\text{Mar-Apr}}$	0.000211	915	51	335
White Shrimp (*Penaeus setiferus*) = f (seasonal total inflow) (n = 14, P = 0.0058, R = 0.84, Adj. R^2 = 0.61, S. E. Est. = ± 127.872) $H_{\text{White Shrimp}} = 64.273 - 0.2188(Q_{\text{Jan-Feb}}) + 0.1313(Q_{\text{May-Jun}}) + 1.3199(Q_{\text{Jul-Aug}})$					
	$H_{\text{White Shrimp}}$	-	819.9	89.9	258.8
	$Q_{\text{Jan-Feb}}$	0.00014985	828	66	327
	$Q_{\text{May-Jun}}$	0.00010448	1221	90	434
	$Q_{\text{Jul-Aug}}$	0.00036508	428	68	158
Eastern Oyster (*Crassotrea virginica*) = f (seasonal total inflow) (n = 18, P = 0.033, R = 0.60, Adj. R^2 = .28, S. E. Est. = ± 173.307) $H_{\text{Eastern Oyster}} = 608.70 - 0.3646(Q_{\text{Mar-Apr}}) - 0.1915(Q_{\text{May-Jun}})$					
	$H_{\text{Eastern Oyster}}$	-	915.262	67.391	276.175
	$Q_{\text{Mar-Apr}}$	0.0001737	838	63	420
	$Q_{\text{May-Jun}}$	.00008769	1713	121	936

Species	Variable	S.E. coeff.	Maximum value	Minimum value	Mean value
Gulf Menhaden (*Brevoortia patronis*) = f (seasonal total inflow) (n = 15, P = 0.00399, R = 0.78, Adj. R^2 = 0.55, S. E. Est. = ±215.12) $H_{\text{Gulf Menhaden}} = 309.19 - 1.097(Q_{\text{Jan-Feb}}) + 1.194(Q_{\text{Mar-Apr}})$					
	$H_{\text{Gulf Menhaden}}$	-	1028.53	24.22	323.38
	$Q_{\text{Jan-Feb}}$	0.3302	828	66	352
	$Q_{\text{Mar-Apr}}$	0.2812	915	51	335
Striped Mullet (*Mugil cephalus*) = f (seasonal total inflow) (n = 14, P = 0.0033, R = 0.89, Adj. R^2 = 0.71, S. E. Est. = ± 15.23) $H_{\text{Striped Mullet}} = 20.489 - 0.07424(Q_{\text{Jan-Feb}}) + 0.04103(Q_{\text{May-Jun}}) + 0.1038(Q_{\text{Jul-Aug}}) - 0.07848(Q_{\text{Nov-Dec W}})$					
	$H_{\text{Striped Mullet}}$	-	111.6	2.9	14.34
	$Q_{\text{Jan-Feb}}$	0.0183	828	66	340
	$Q_{\text{May-Jun}}$	0.0187	1960328	90	534
	$Q_{\text{Jul-Aug}}$	0.0438	428171	68	176
	$Q_{\text{Nov-Dec W}}$	0.0200	896918	39	268
Black Drum (*Pogonias cromis*) = f (monthly total inflow) (n = 15, P =0.007, R = 0.75, Adj. R^2 = 0.49, S. E. Est. = ± 10.409) $H_{\text{Black Drum}} = 32.353 - 0.1272(Q_{\text{Mar}}) + 0.04708(Q_{\text{Apr}})$					
	$H_{\text{Black Drum}}$	-	46.68	1.89	23.42
	Q_{Mar}	0.04607	259	59	135
	Q_{Apr}	0.02530	365	52	176
Red Drum (*Sciaenops ocellata*) = f (seasonal total inflow) (n = 15, P = 0.0025, R = 0.85, Adj. R^2 = 0.64, S. E. Est. = ± 0.8823) $H_{\text{Red Drum}} = 10.166 + 0.004169(Q_{\text{Mar-Apr}}) + 0.002507(Q_{\text{may\_Jun}}) - 1.8736(Q_{\text{lnNov-Dec W}})$					
	$H_{\text{Red Drum}}$	-	6.18	0.55	2.40
	$Q_{\text{Mar-Apr}}$	0.0021	471	132	311
	$Q_{\text{May\_Jun}}$	0.0010	905	153	569
	$Q_{\text{lnNov-Dec W}}$	0.3623	6.47	3.78	5.60

Species	Variable	S.E. coeff.	Maximum value	Minimum value	Mean value
Southern Flounder (*Paralichthys lethostigma*) = f (seasonal total inflow) (n = 18, P = 0.000025, R = 0.87, Adj. $R^2 = 0.72$, S. E. Est. = ± 5.2374) $H_{\text{Southern Flounder}} = 21.025 - 0.05221(Q_{\text{Jan-Feb}}) + 0.04314(Q_{\text{Mar-Apr}})$					
	$H_{\text{Southern Flounder}}$	-	30.2	0.55	16.87
	$Q_{\text{Jan-Feb}}$	0.01071	730	271	441
	$Q_{\text{Mar-Apr}}$	0.00753	739	196	438

H = Biomass, Thousands Pounds
Q = Seasonal Freshwater Inflow, Thousands Acre-Feet
ln = Natural log

Note:

The following biomass conversion coefficients for the seven species caught by bag seine were estimated by TPWD using Coastal Fisheries Monitoring Data from the Matagorda Bay System between 1976 and 1996:

Common Name	Biomass Conversion (lbs/individual)
White Shrimp	0.0026
Brown Shrimp	0.0044
Blue Crab	0.00168
Black Drum	0.0210
Red Drum	0.00182
Gulf Menhaden	0.00144
Striped Mullet	0.0011

Table 3. Mean seasonal salinities in the Lavaca-Colorado Estuary.

Area	Mean Salinity (ppt)						
	JAN-FEB	MAR-APR	MAY-JUN	JUL-AUG	SEP-OCT	NOV-DEC	Annual Mean
Carancahua Bay	18.7	16.4	13.2	15.7	20.0	22.0	17.7
Upper Lavaca Bay	15.6	13.4	8.9	11.1	16.8	18.7	14.1
Lower Lavaca Bay	20.7	19.4	16.5	18.2	24.5	23.2	20.4
Palacios Bay	21.6	19.1	17.5	15.4	24.4	23.4	20.2
Powderhorn Lake	16.6	17.3	18.2	15.5	21.4	20.2	18.2
East Arm Matagorda Bay	18.0	18.7	18.7	23.3	26.8	23.8	21.6
Lower Matagorda Bay	23.6	24.6	22.8	26.6	28.8	27.1	25.6
Overall Mean Salinity	19.3	18.4	16.5	18.0	23.2	22.6	19.7

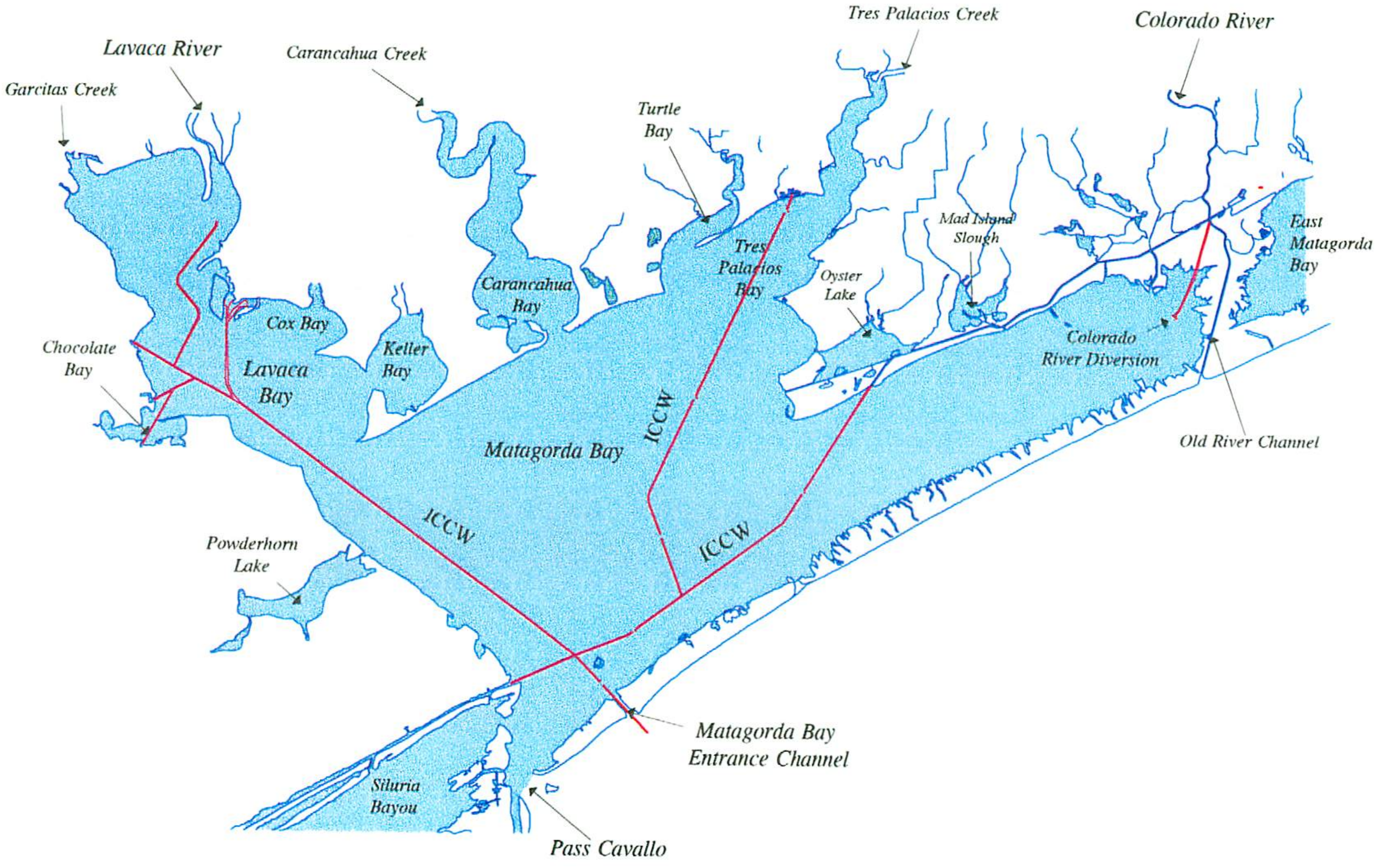


Figure 1. Major tributary streams, passes, and bays in the Lavaca-Colorado Estuary.

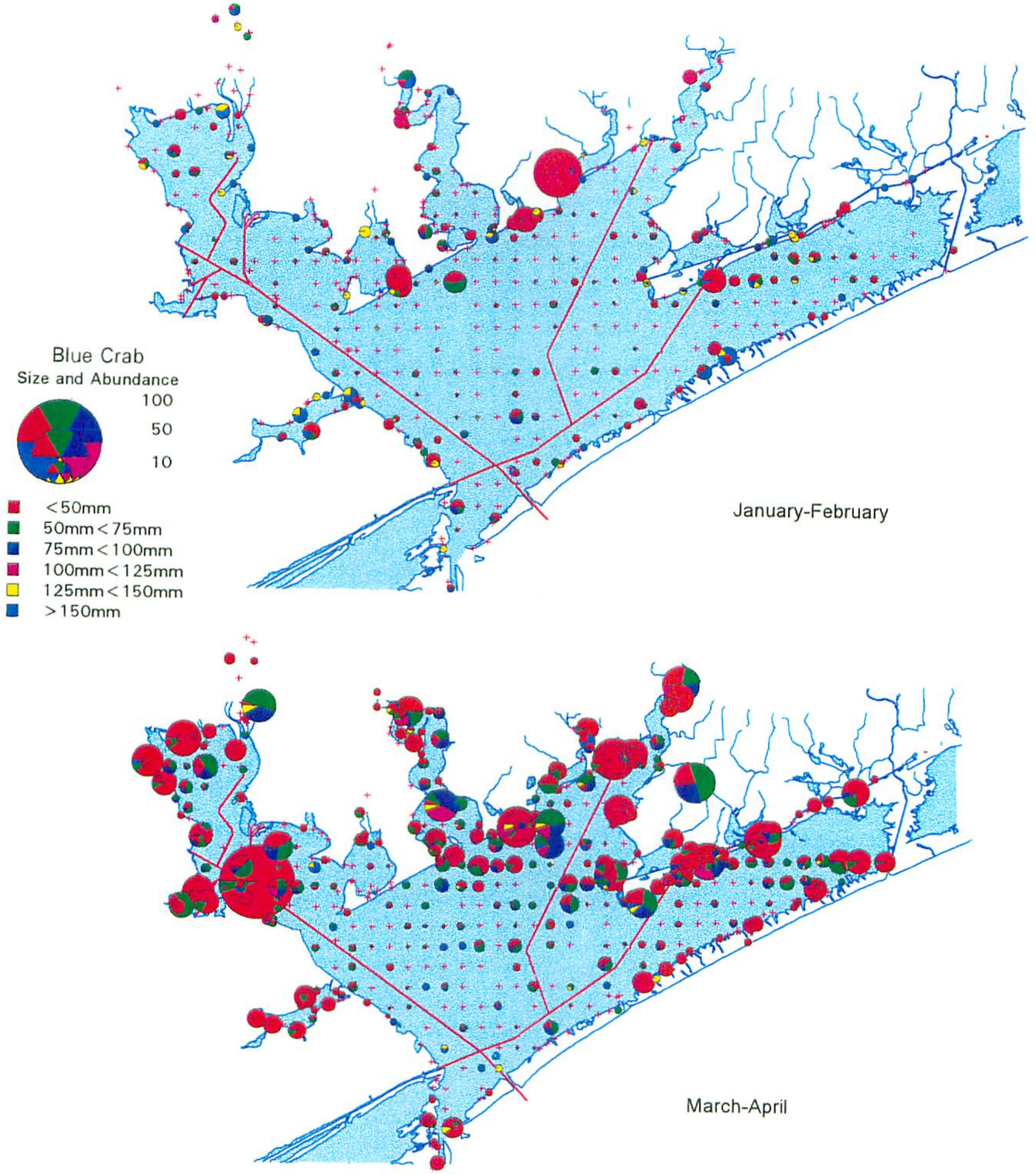


Figure 2a. Seasonal distribution and abundance of blue crabs in Matagorda Bay, Texas. January through April.

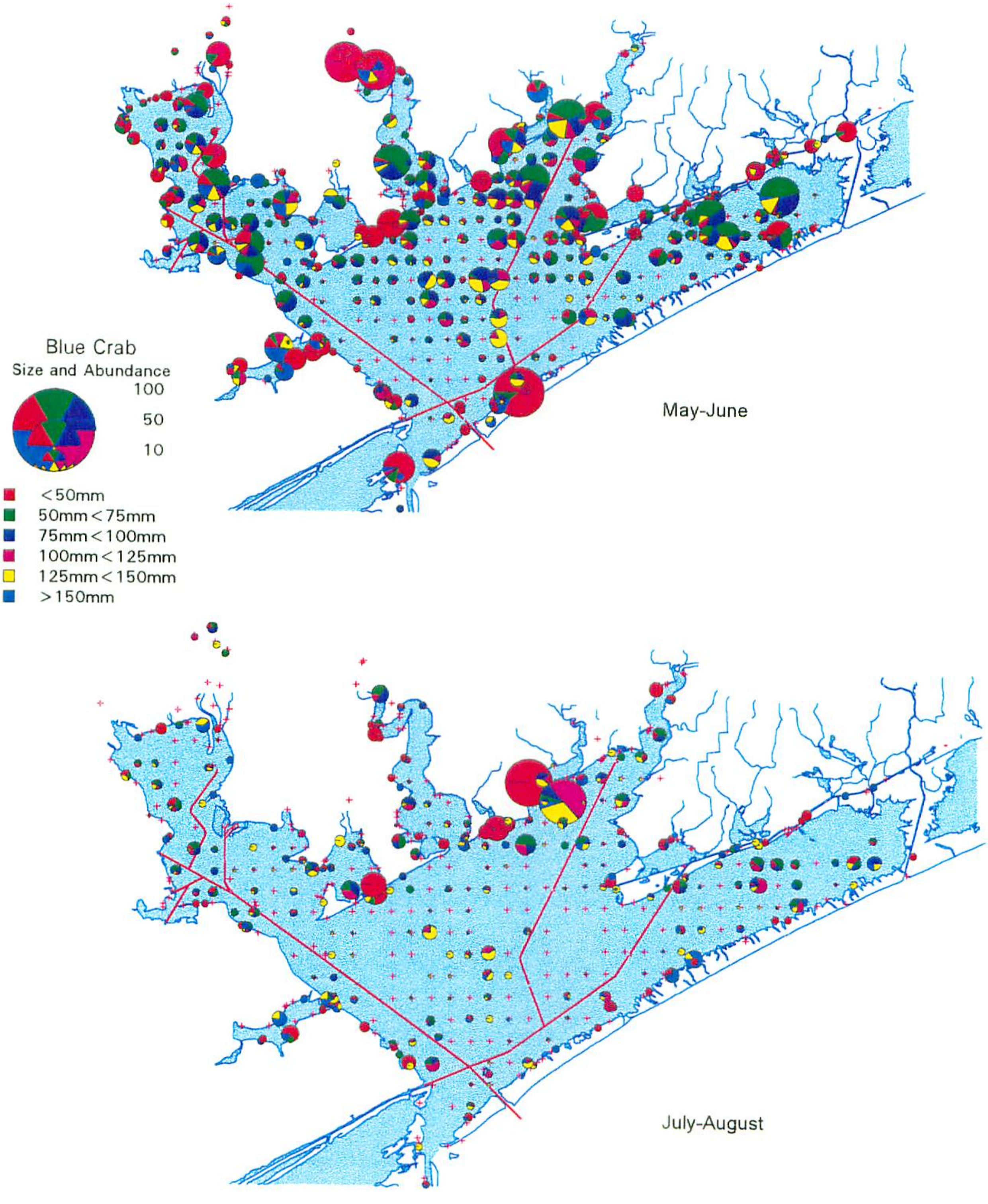


Figure 2b. Seasonal distribution and abundance of the blue crab in Matagorda Bay, Texas. May through July.

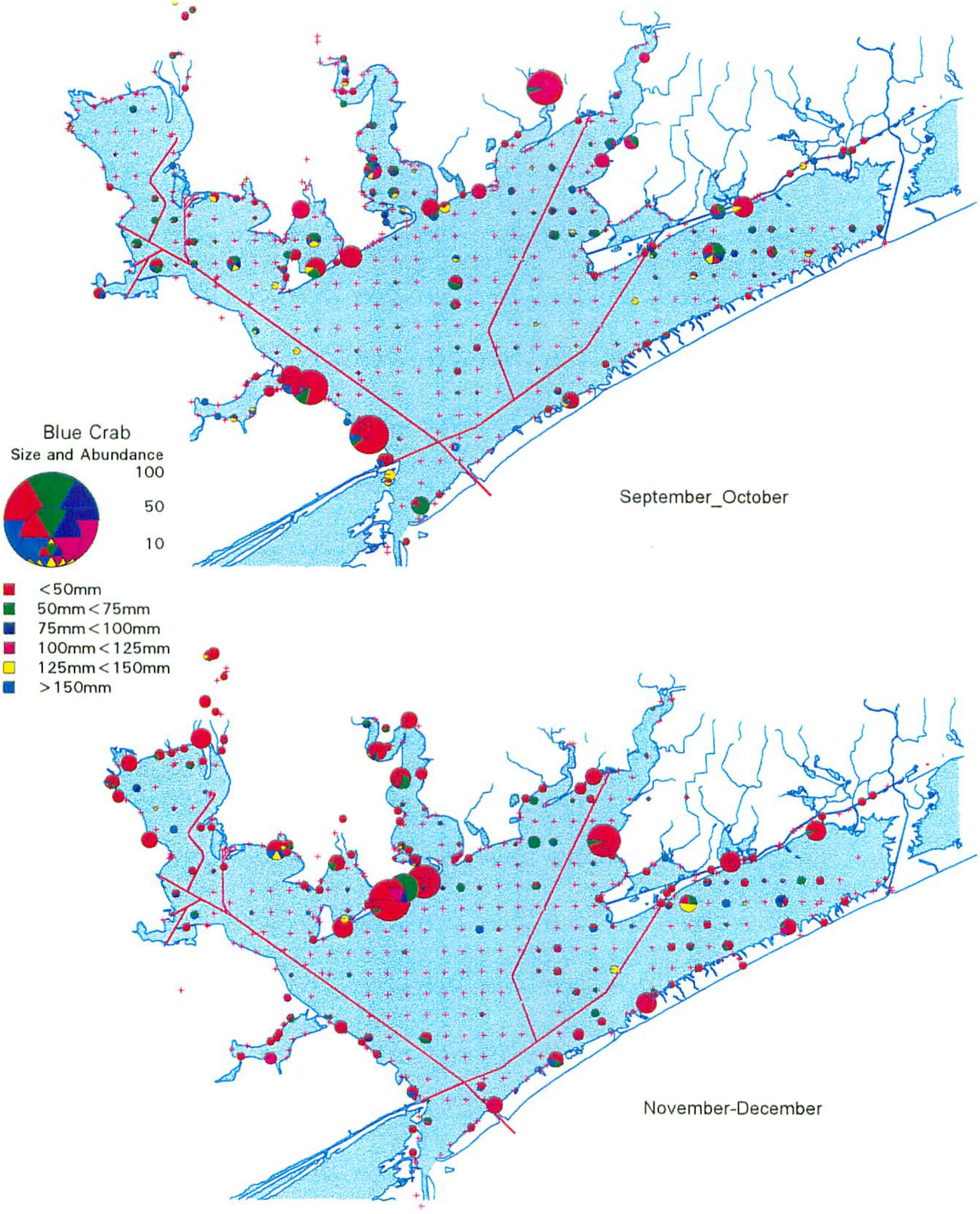


Figure 2c. Seasonal distribution and abundance of blue crabs in Matagorda Bay, Texas. September through December.

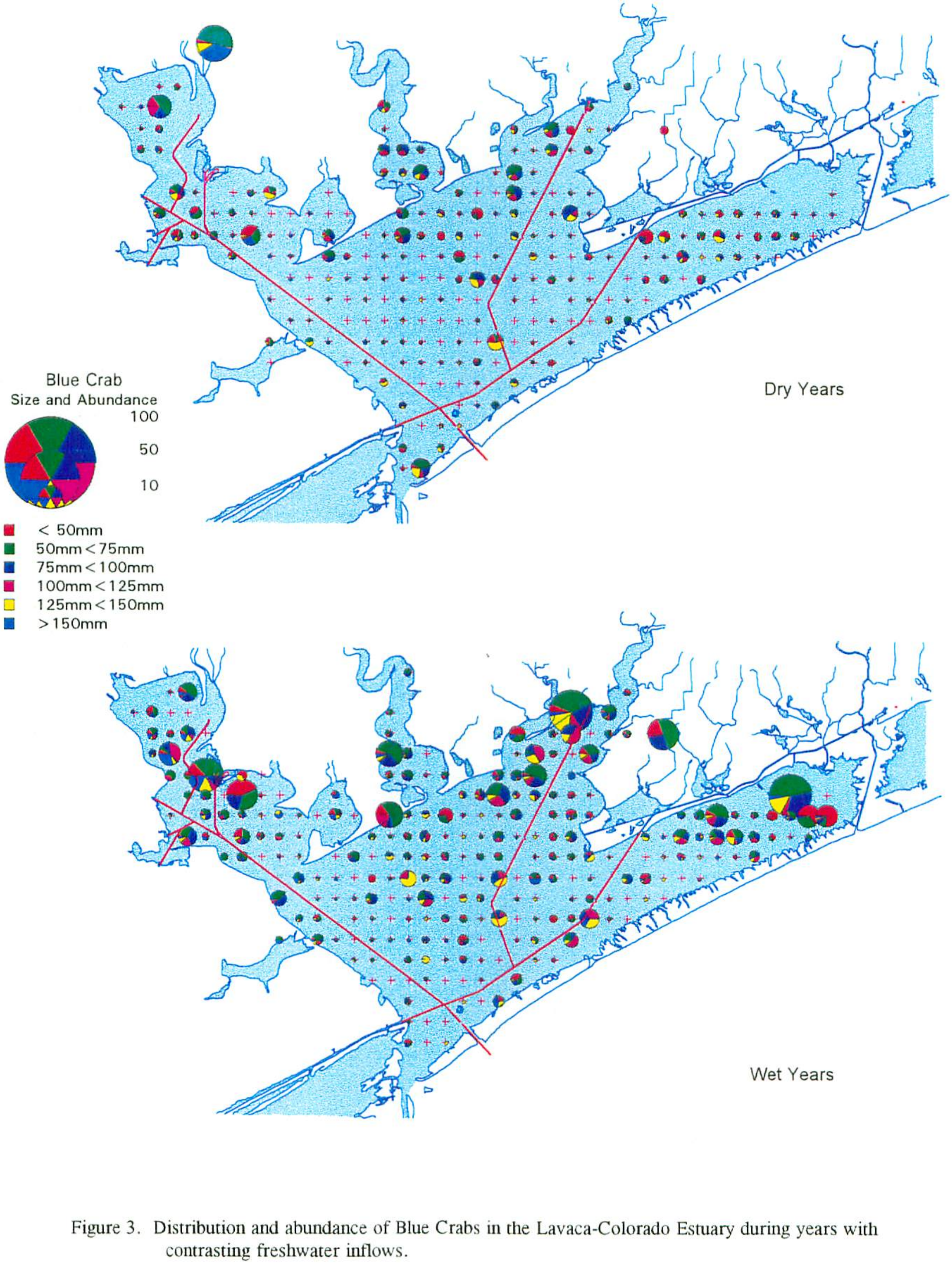


Figure 3. Distribution and abundance of Blue Crabs in the Lavaca-Colorado Estuary during years with contrasting freshwater inflows.

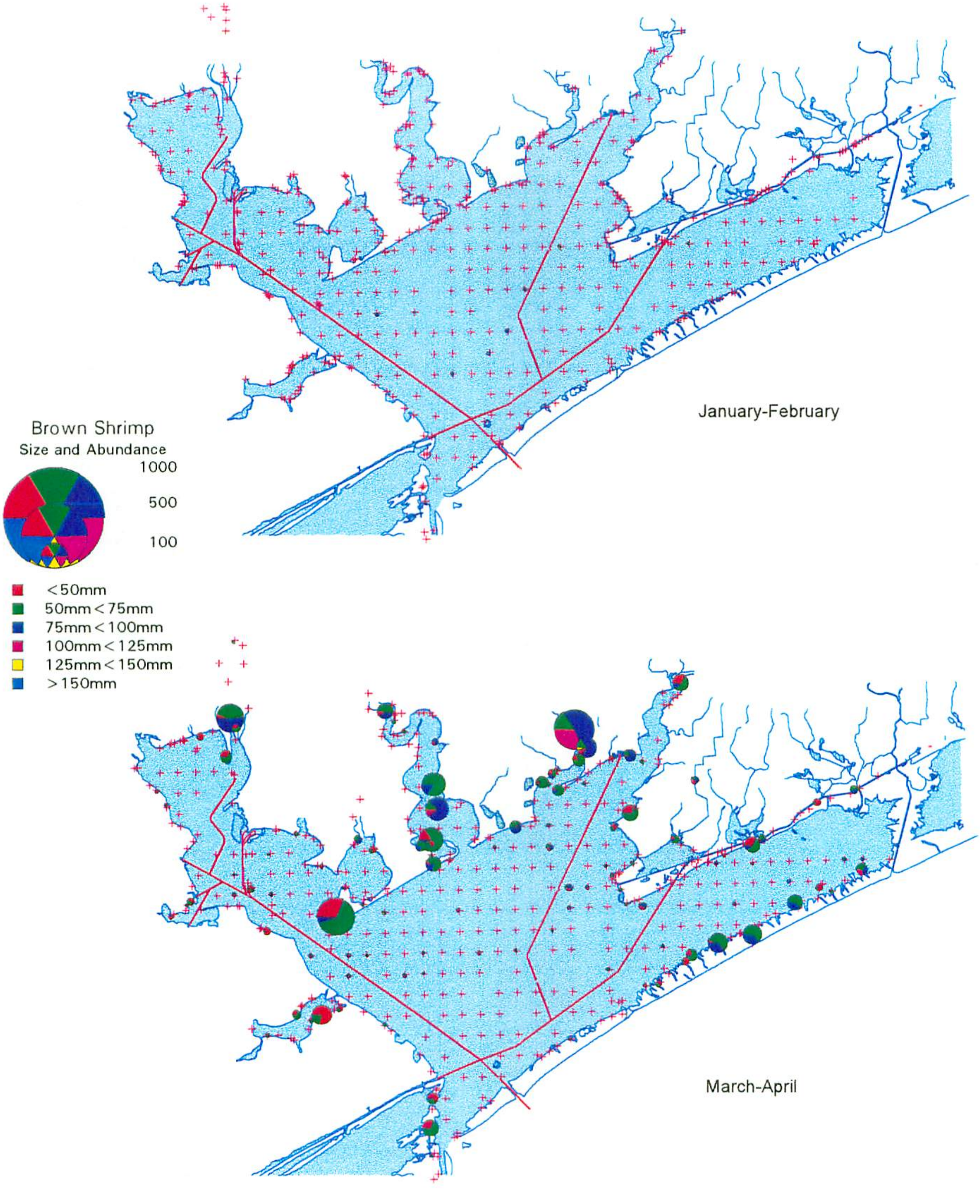


Figure 4a. Seasonal distribution and abundance of brown shrimp in Matagorda Bay, Texas. January through April.

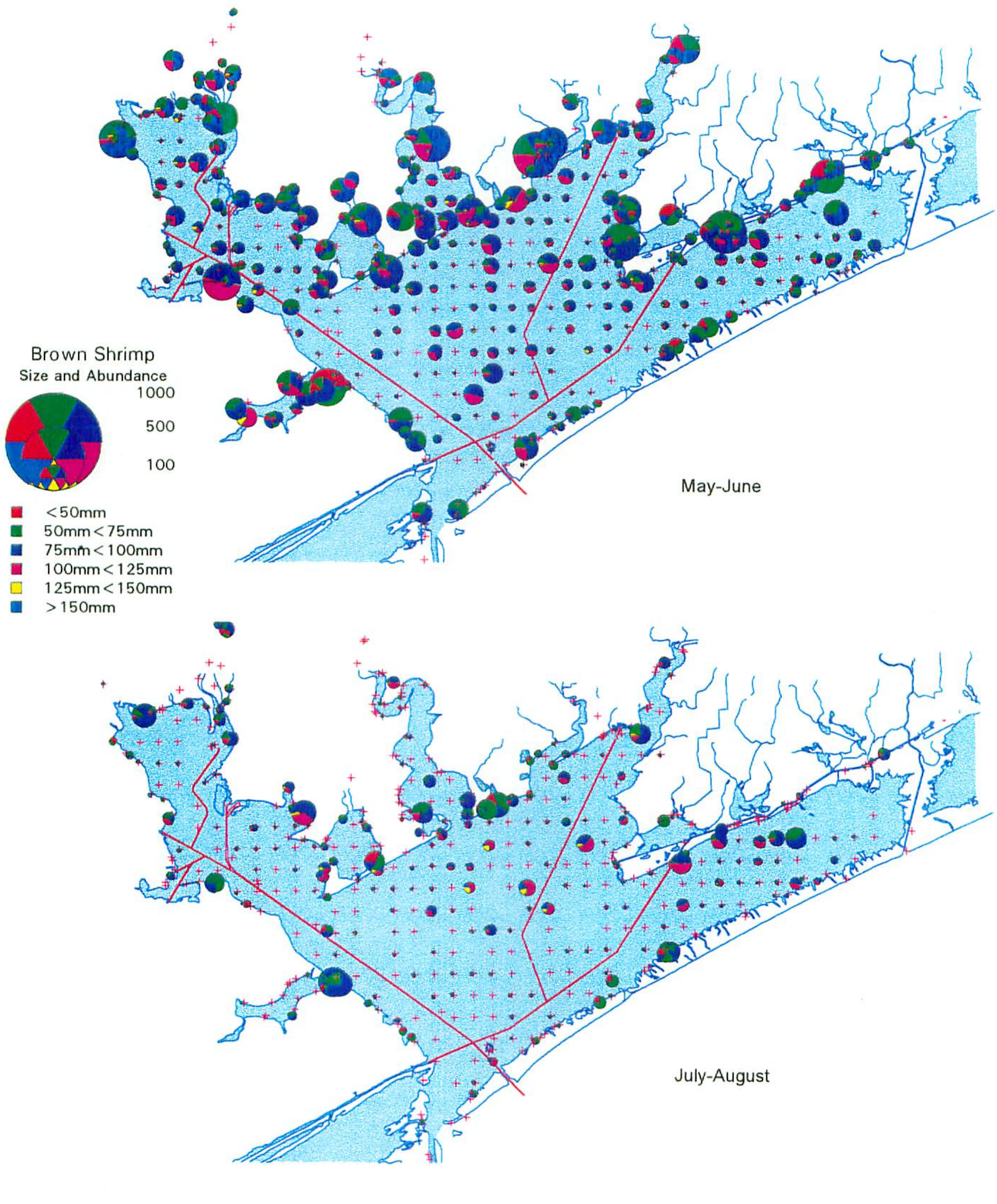


Figure 4b. Seasonal distribution and abundance of brown shrimp in Matagorda Bay, Texas. May through August.

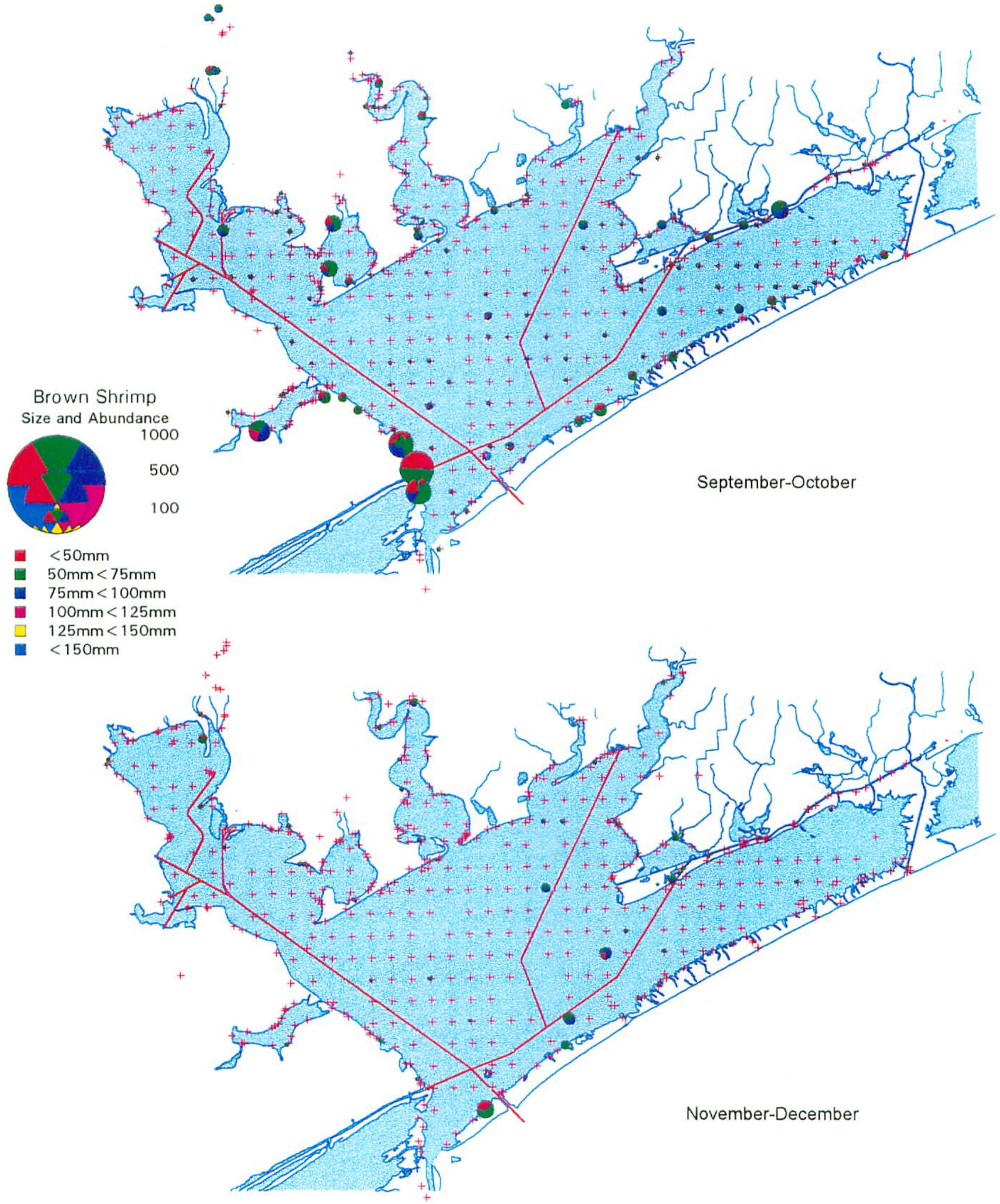


Figure 4c. Seasonal distribution and abundance of brown shrimp in Matagorda Bay, Texas. September-December.

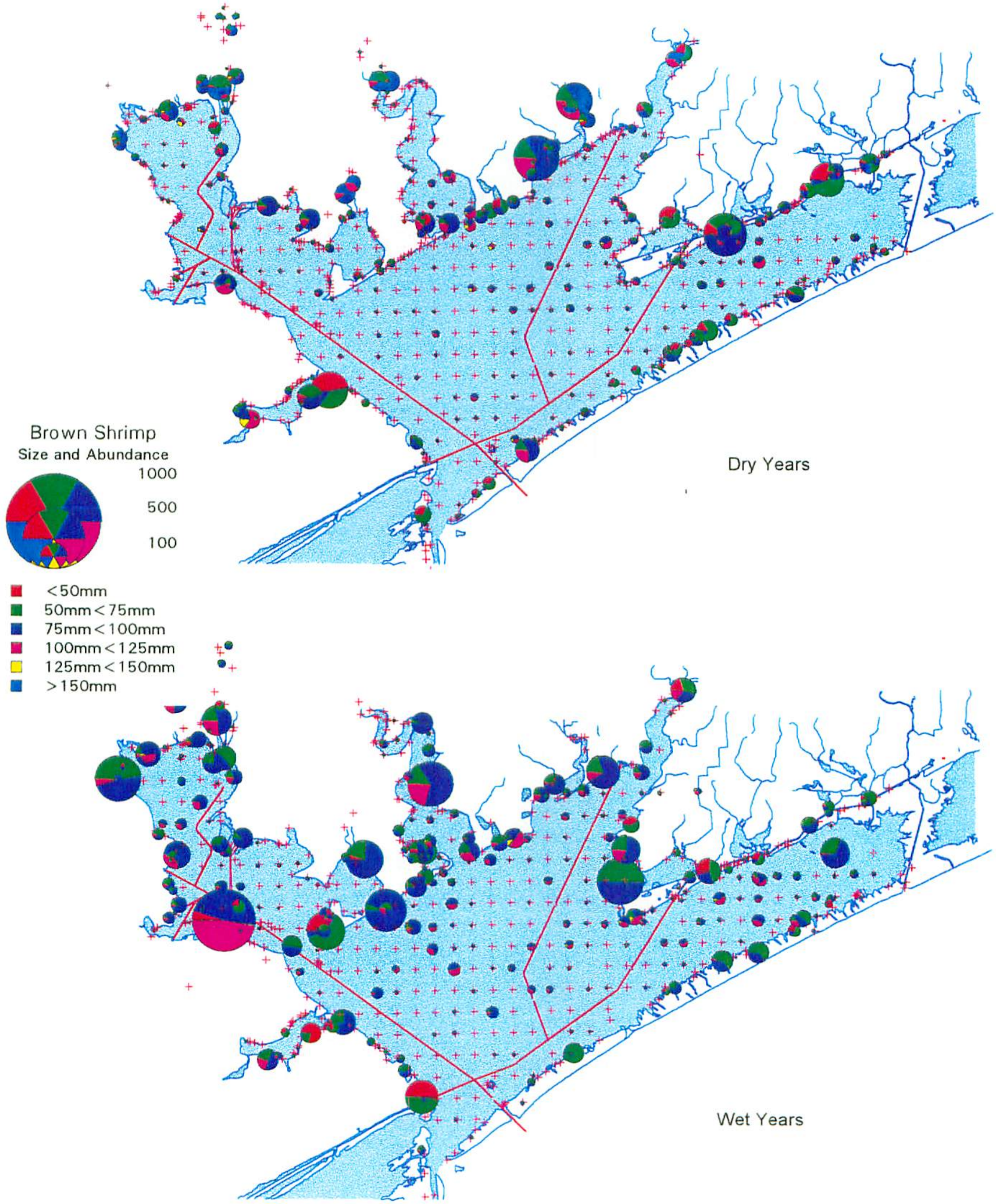


Figure 5. Distribution and abundance of brown shrimp in Matagorda Bay, Texas during years with contrasting freshwater inflows.

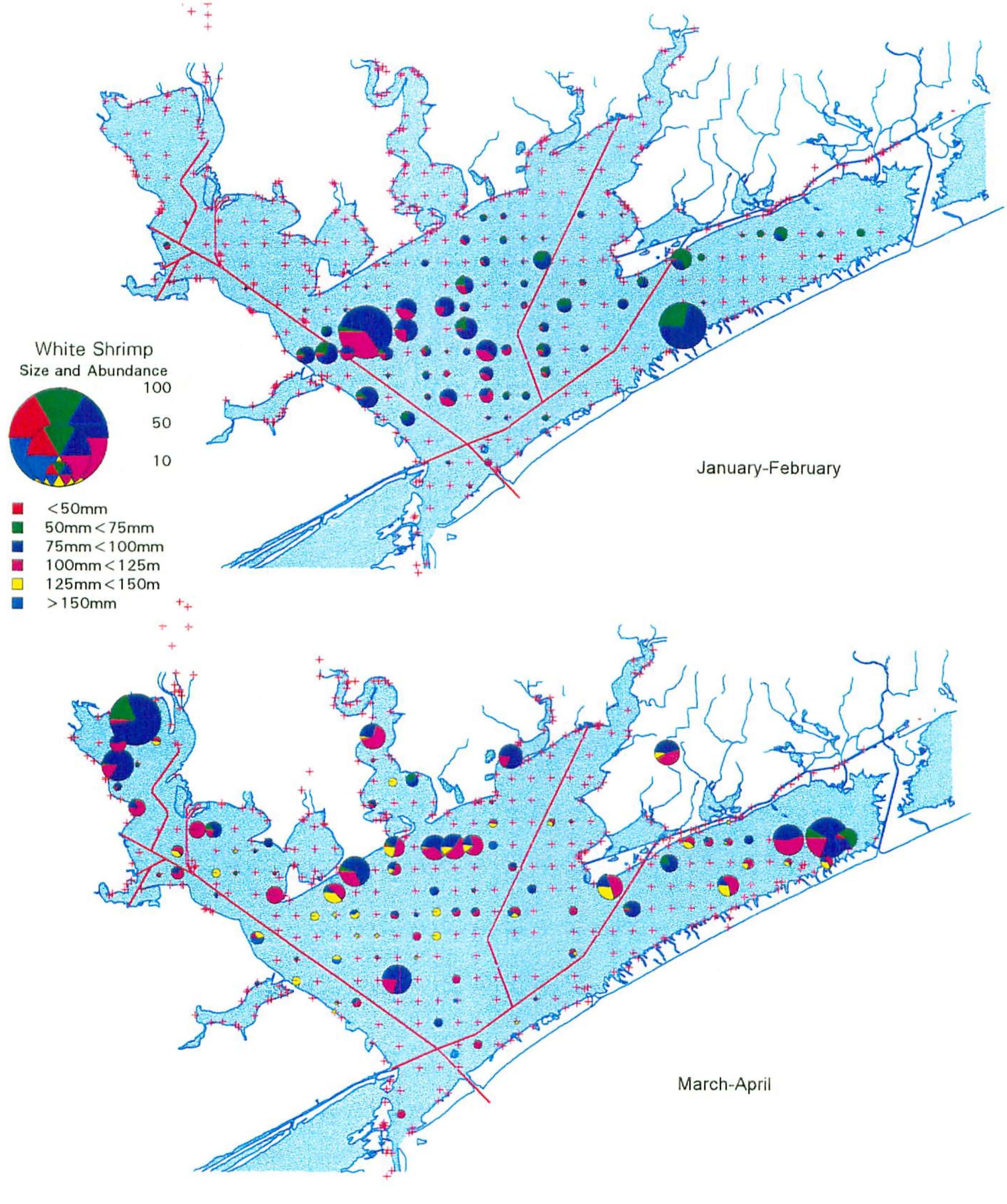


Figure 6a. Seasonal distribution and abundance of white shrimp in Matagorda Bay, Texas. January through April.

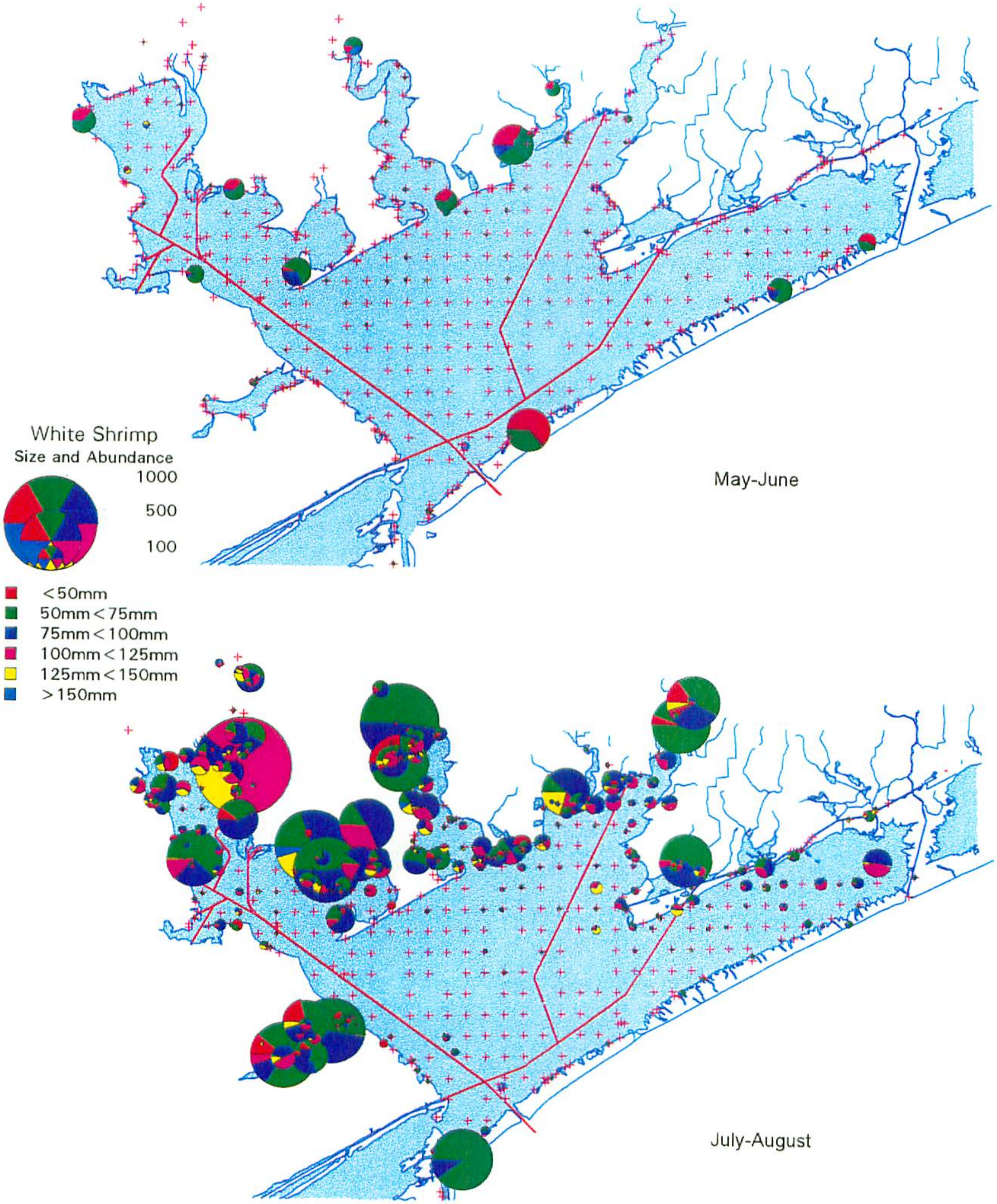


Figure 6b. Seasonal distribution and abundance of white shrimp in Matagorda Bay, Texas. May through August.

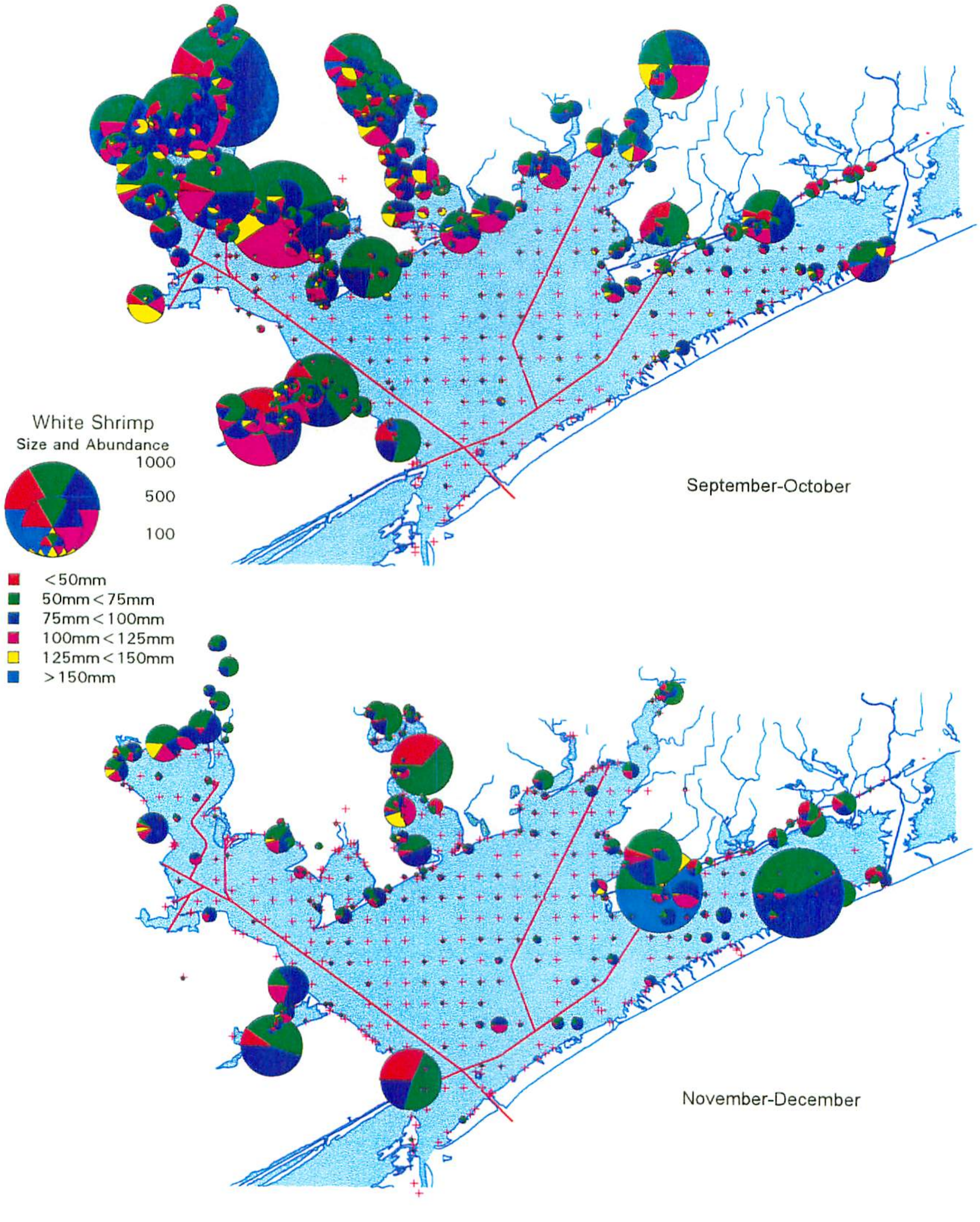


Figure 6c. Seasonal distribution and abundance of white shrimp in Matagorda Bay, Texas. September through December.

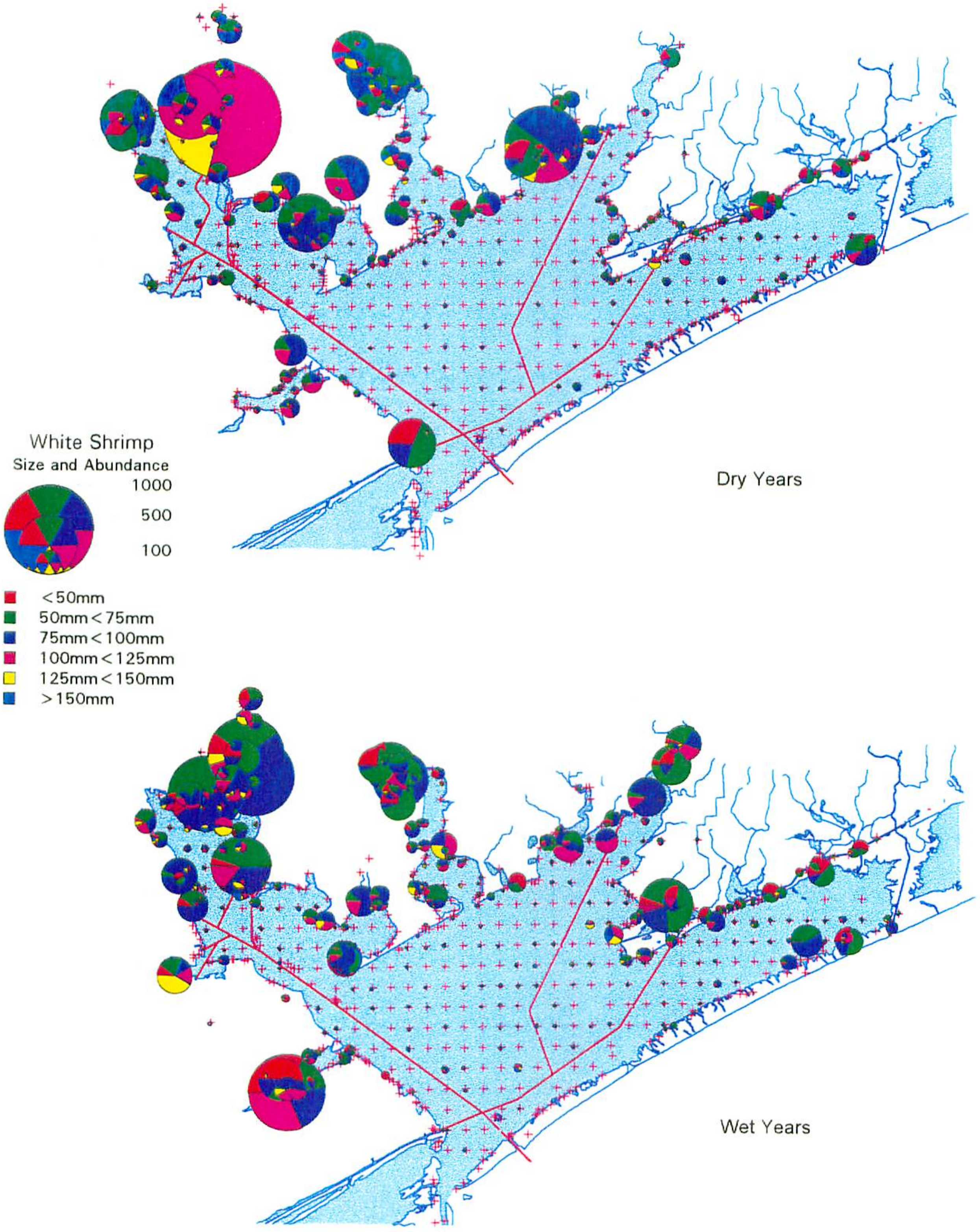


Figure 7. Distribution and abundance of white shrimp in Matagorda Bay, Texas during years with contrasting freshwater inflows.

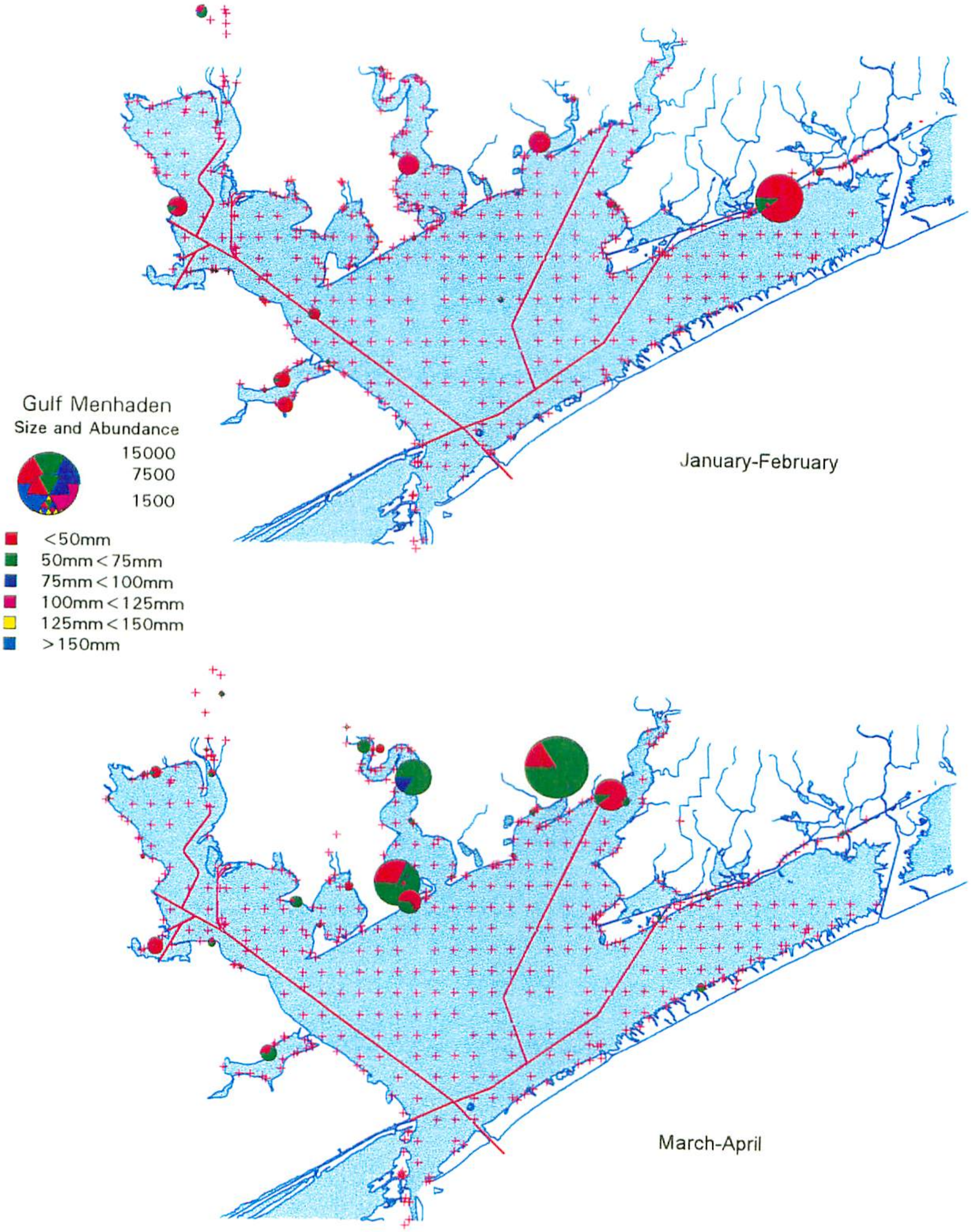


Figure 9a. Seasonal abundance and distribution of gulf menhaden in Matagorda Bay, Texas. January through April.

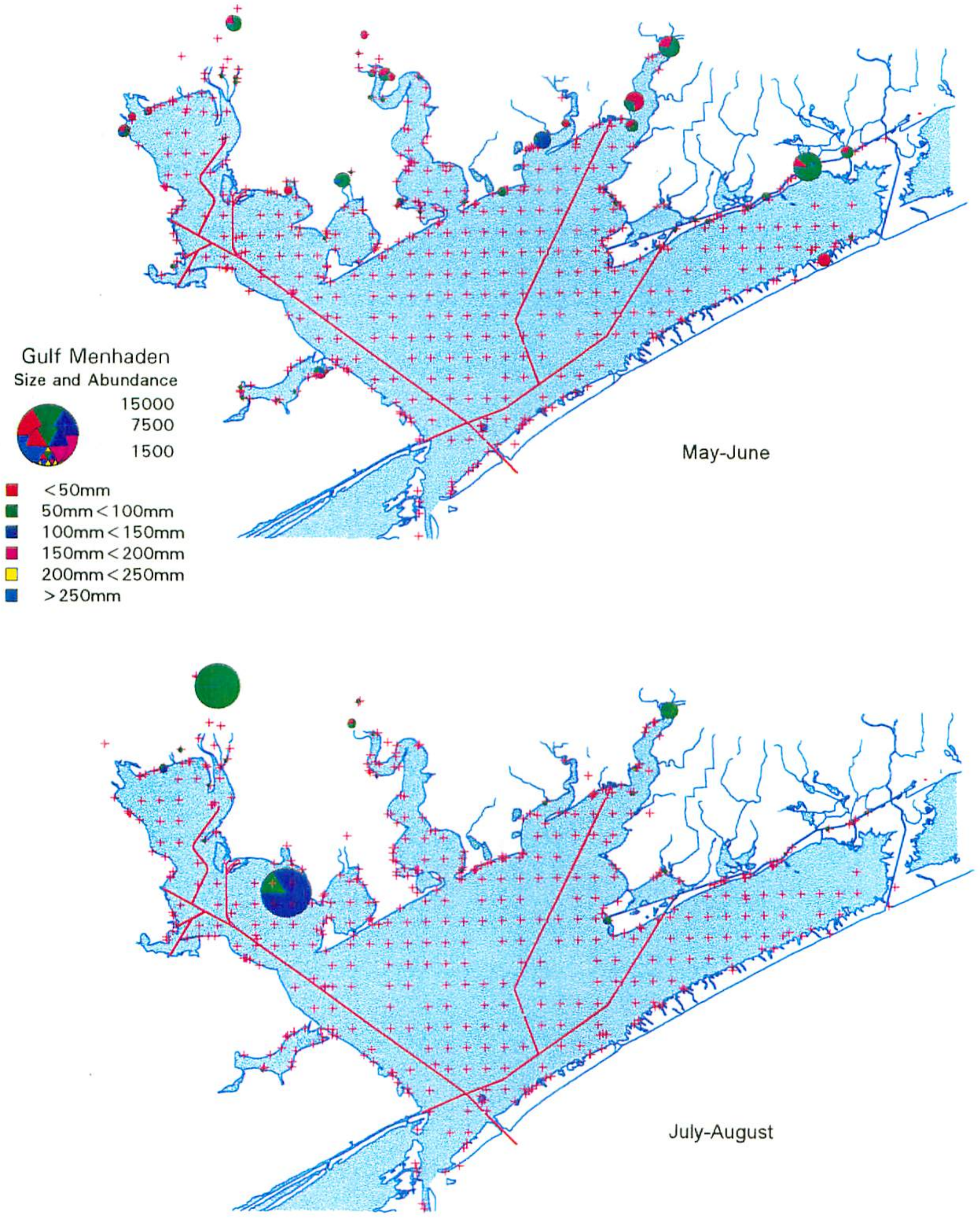


Figure 9b. Seasonal abundance and distribution of gulf menhaden in Matagorda Bay, Texas. May through August.

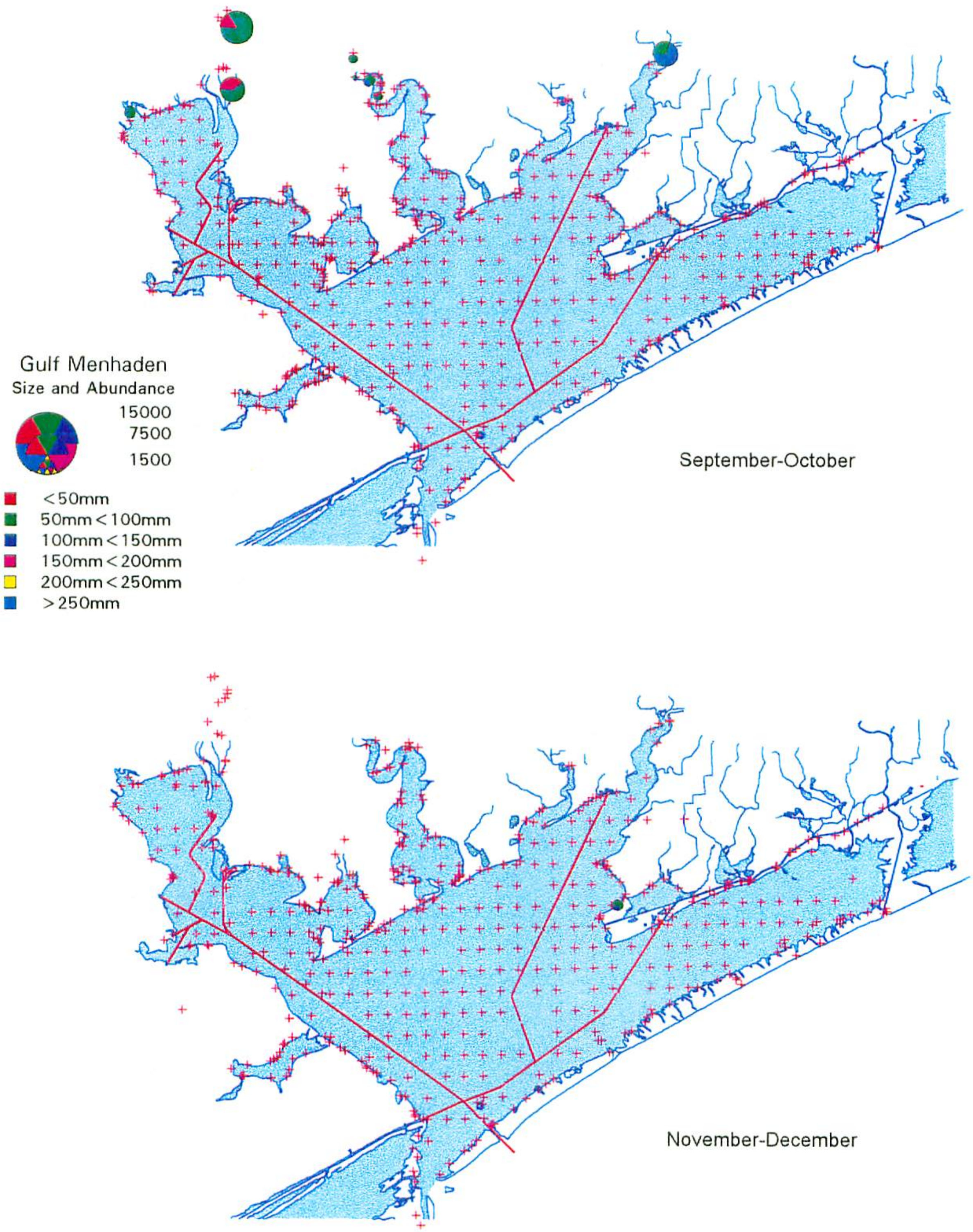


Figure 9c. Seasonal distribution and abundance of gulf menhaden in Matagorda Bay, Texas. September through December.

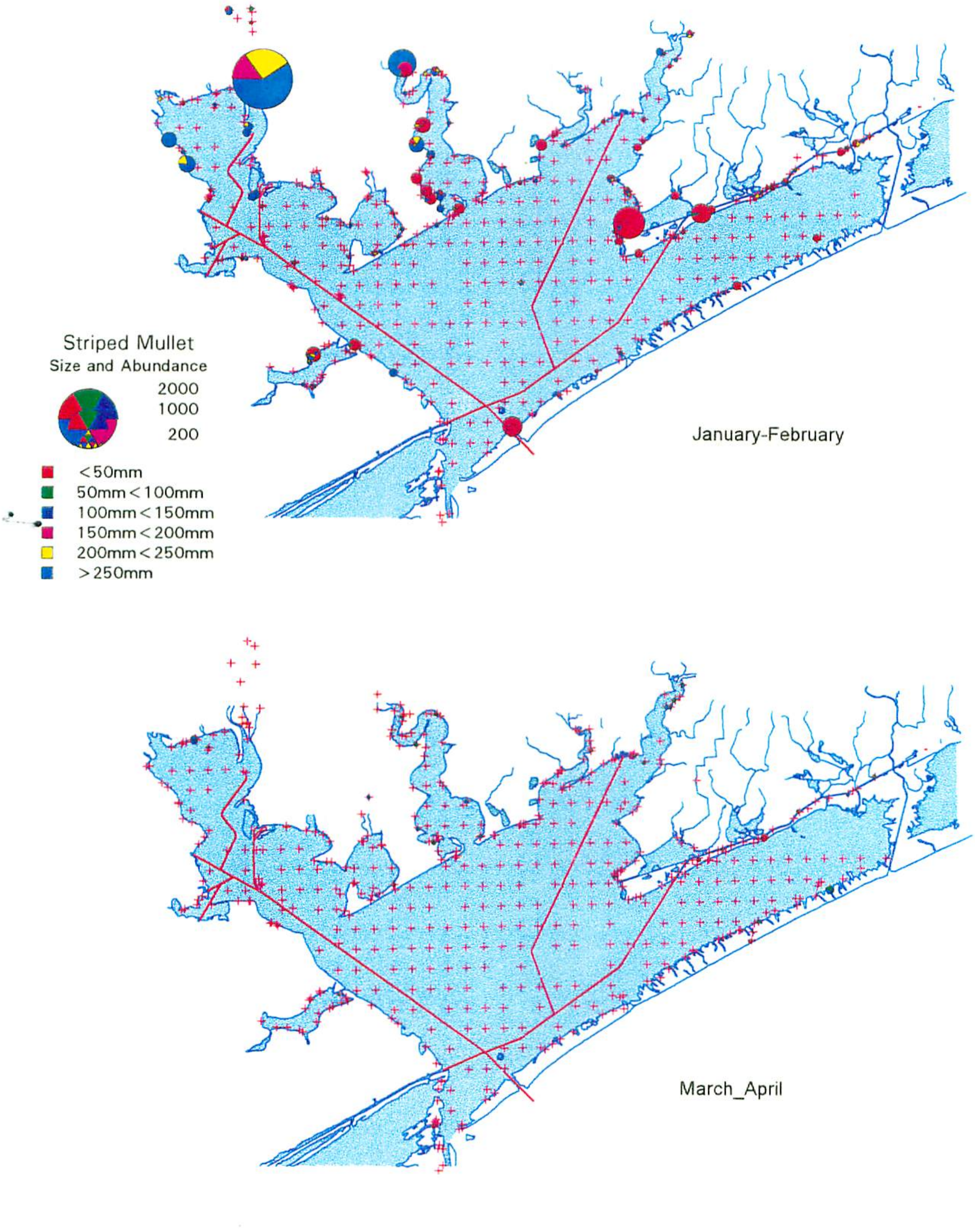


Figure 10a. Seasonal distribution and abundance of striped mullet in Matagorda Bay, Texas. January through April.

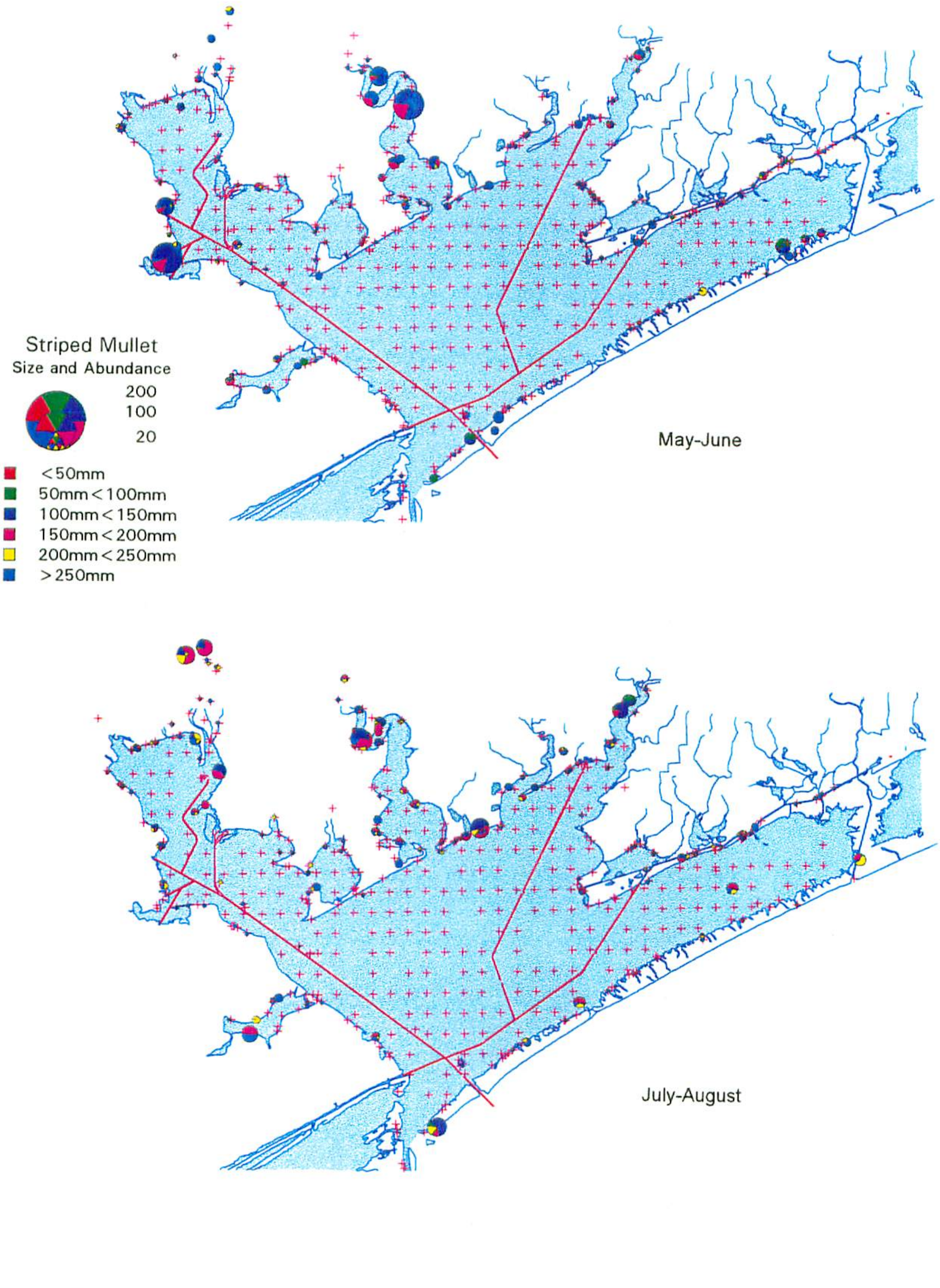


Figure 10b. Seasonal distribution and abundance of striped mullet in Matagorda bay, Texas. May through August.

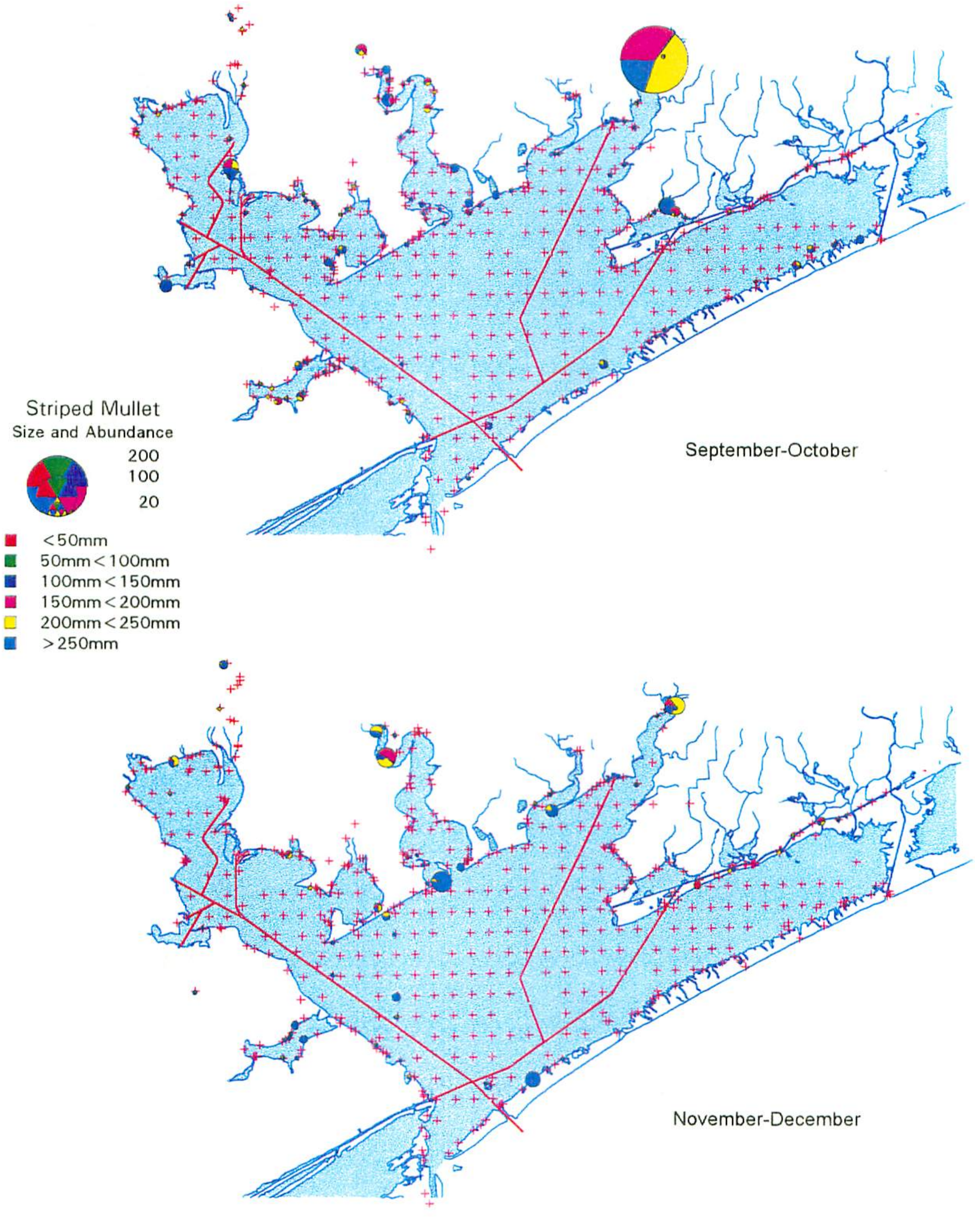


Figure 10c. Seasonal distribution and abundance of striped mullet in Matagorda Bay, Texas. September through December.

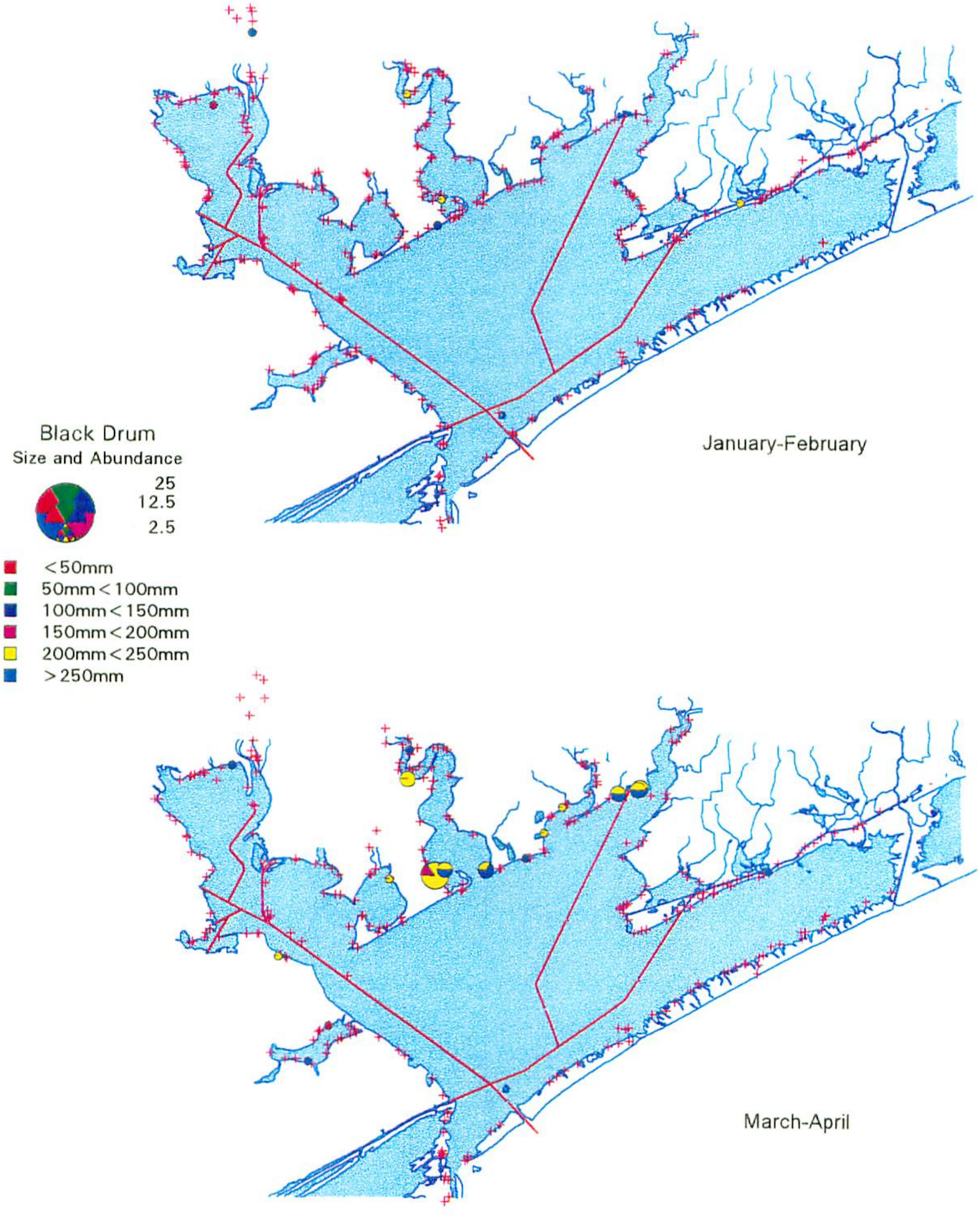


Figure 11a. Seasonal distribution and abundance of juvenile black drum in Matagorda Bay, Texas. January-April.

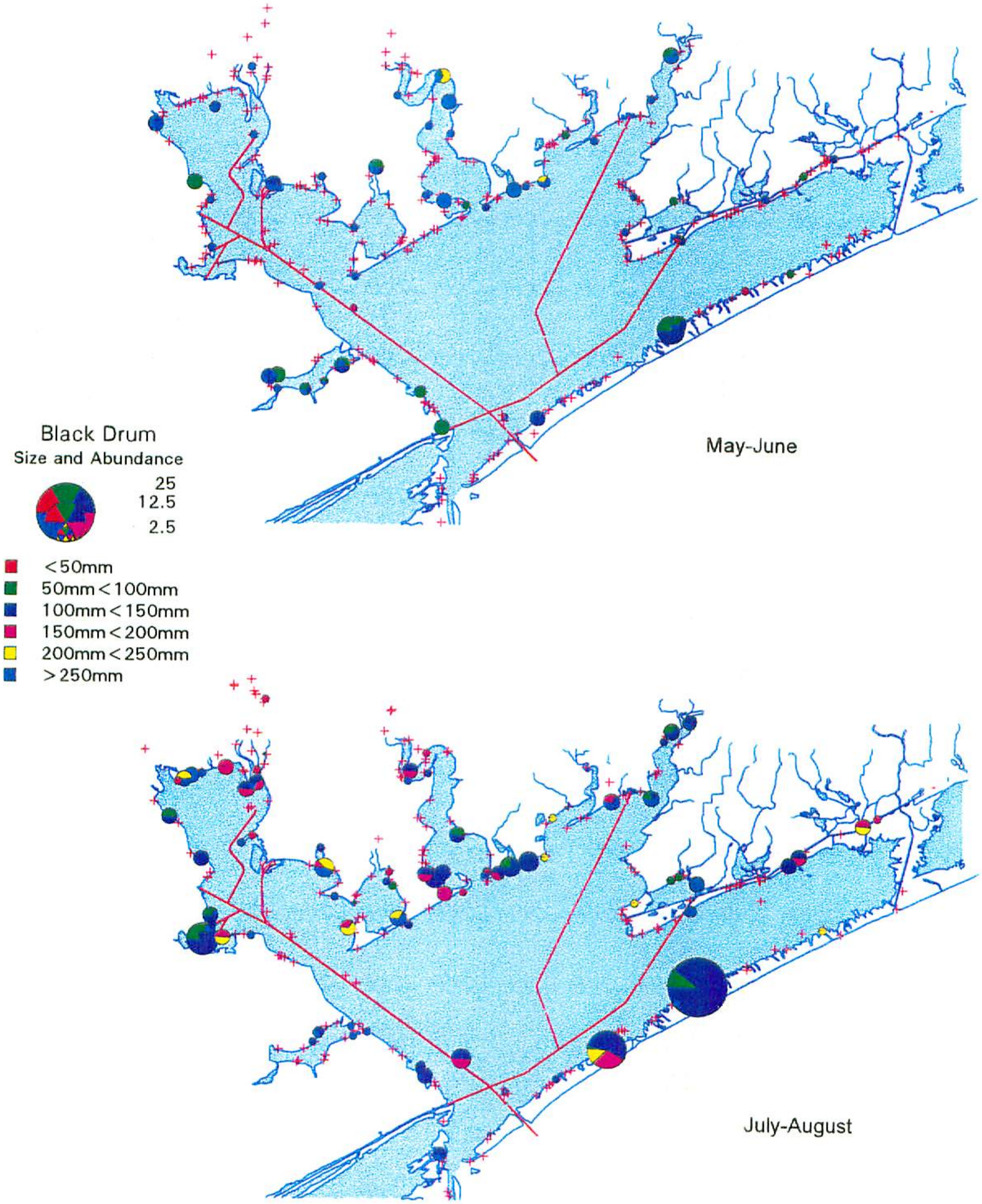


Figure 11b. Seasonal distribution and abundance of juvenile black drum in Matagorda Bay, Texas. May-August.

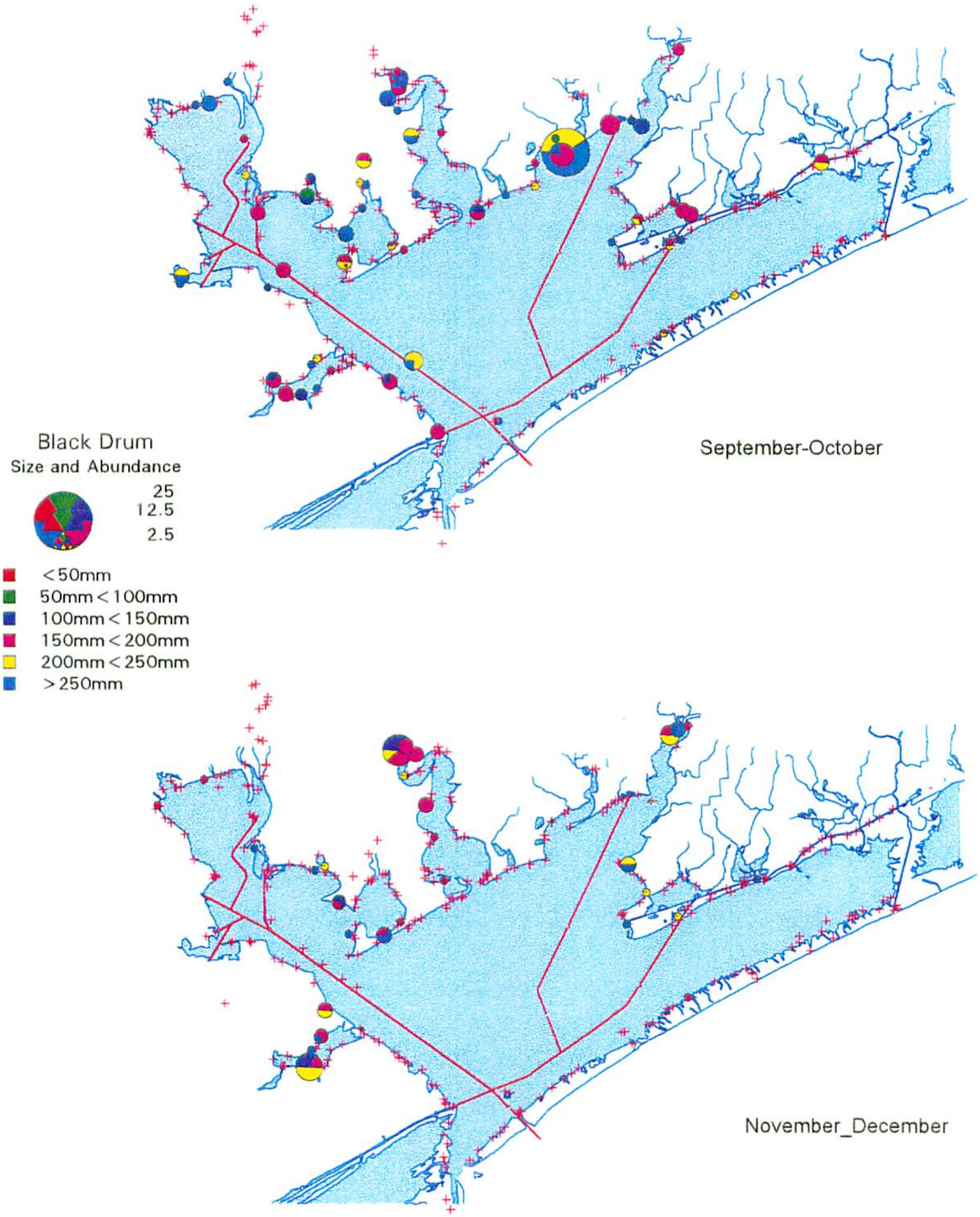


Figure 11c. Seasonal distribution and abundance of juvenile black drum in Matagorda Bay, Texas. September-December.

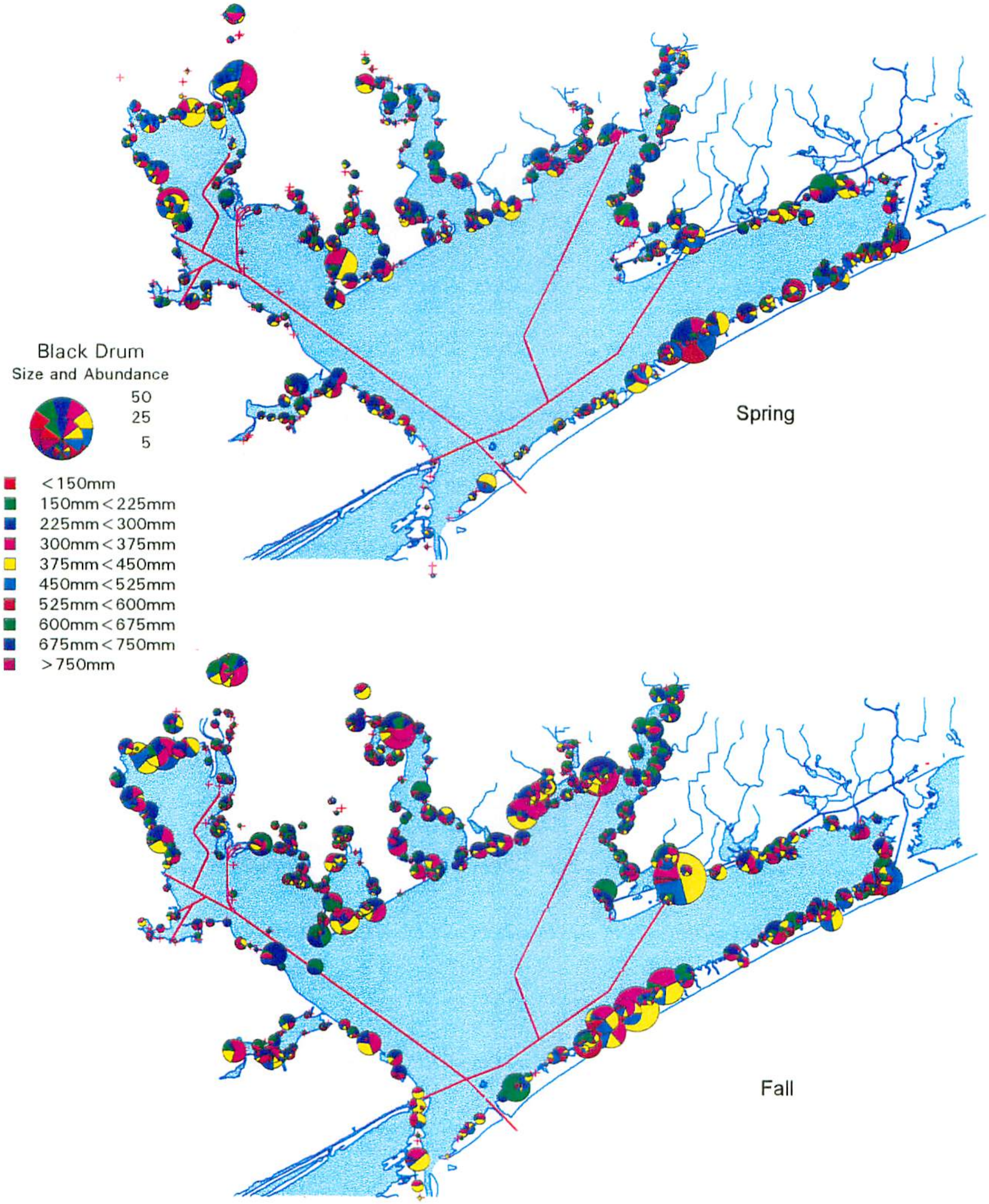


Figure 12. Distribution and abundance of adult black drum in Matagorda Bay, Texas. Spring and Fall.

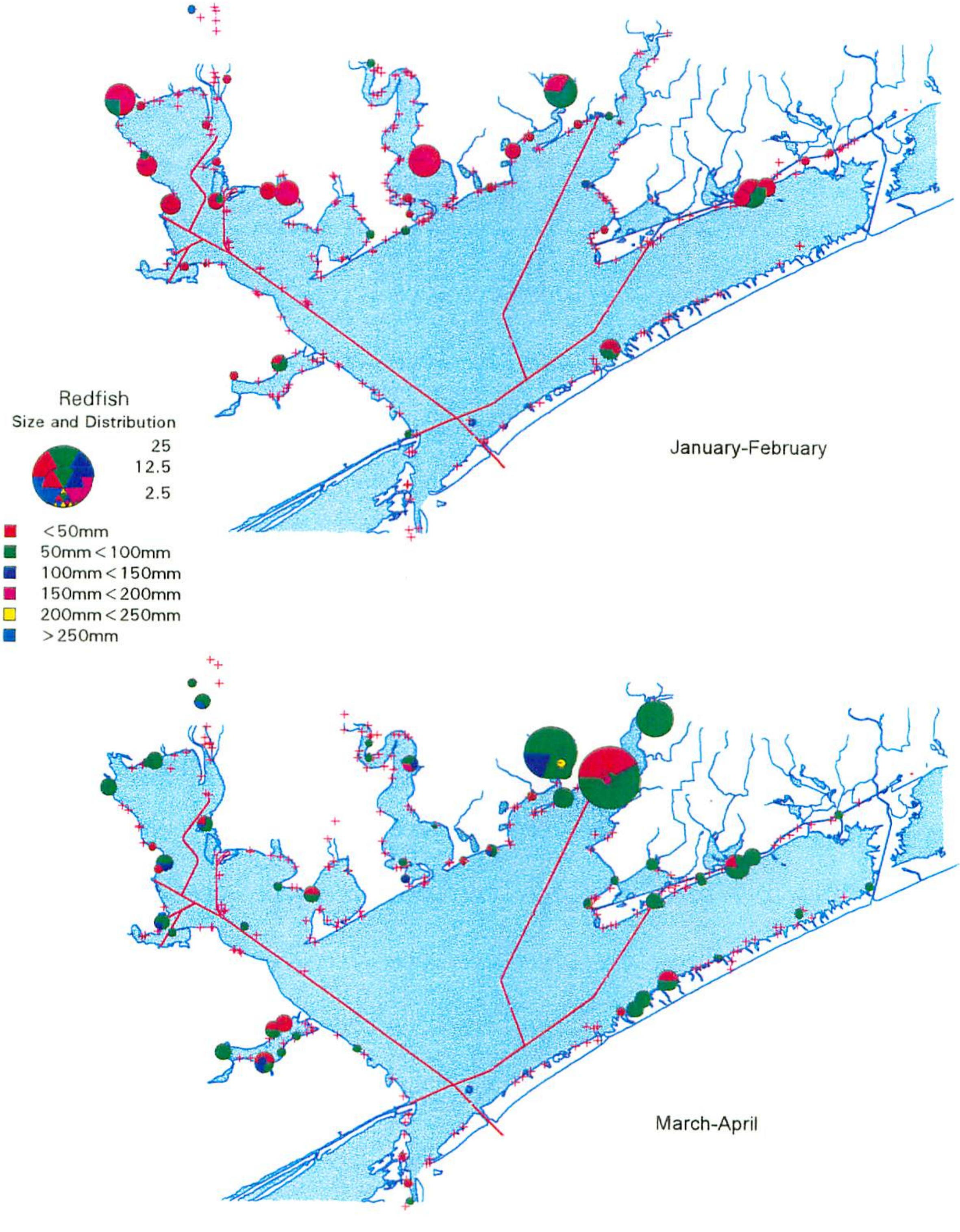


Figure 13a. Seasonal distribution and abundance of juvenile redrum in Matagorda bay, texas. January-April.

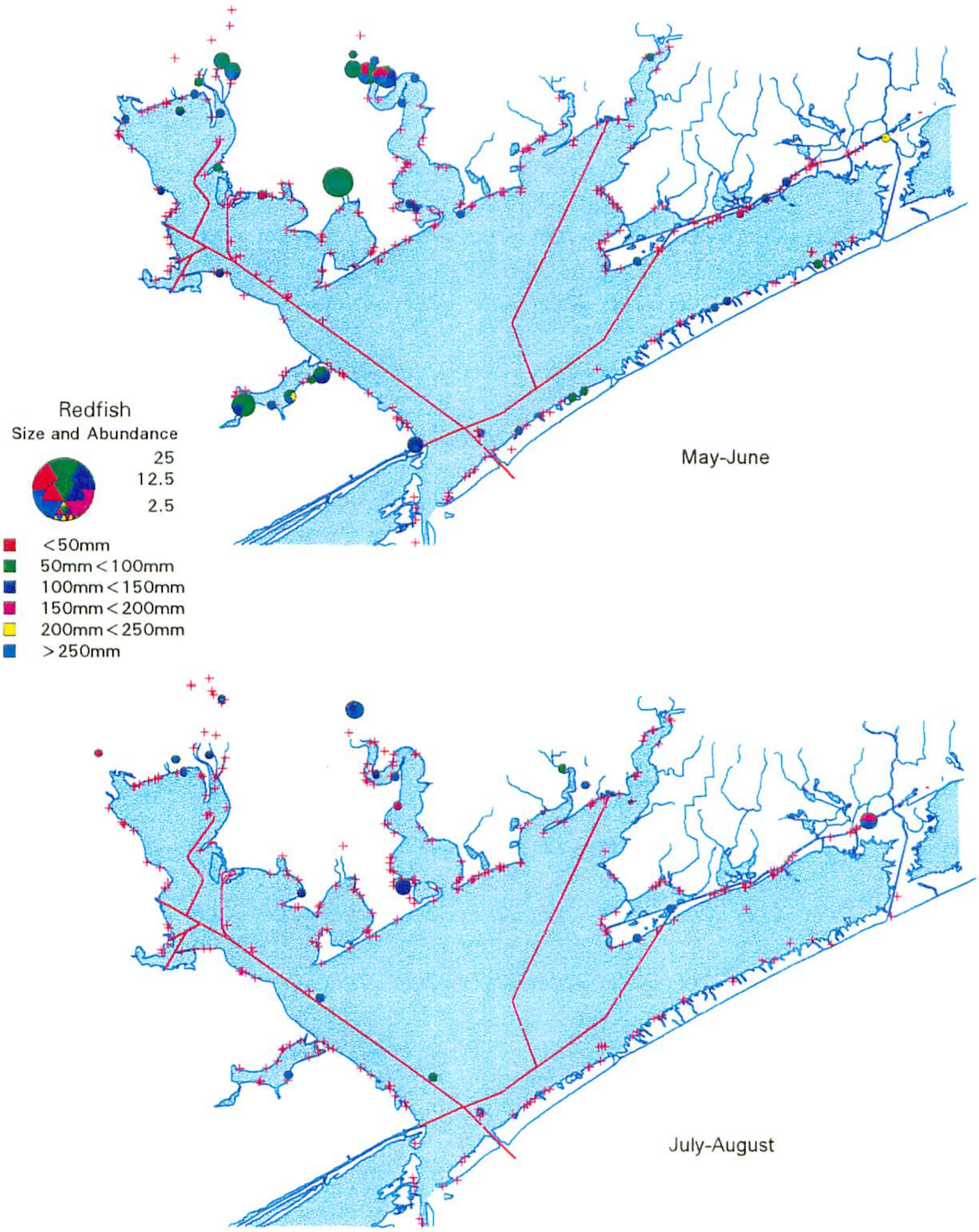


Figure 13b. Seasonal distribution and abundance of juvenile red drum in Matagorda Bay, Texas. May-August.

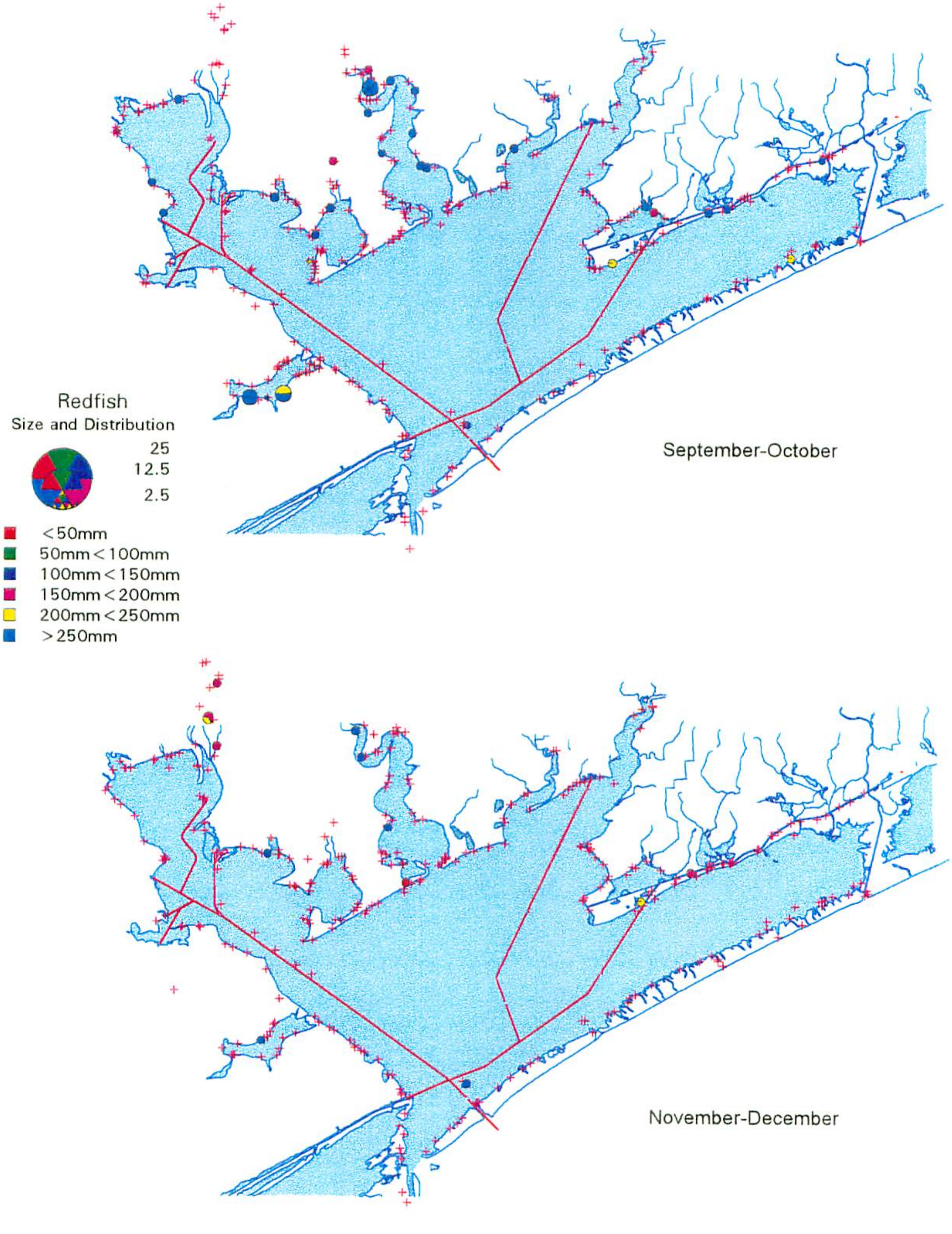


Figure 13c. Seasonal distribution and abundance of juvenile redfish in Matagorda Bay, Texas. September-December.

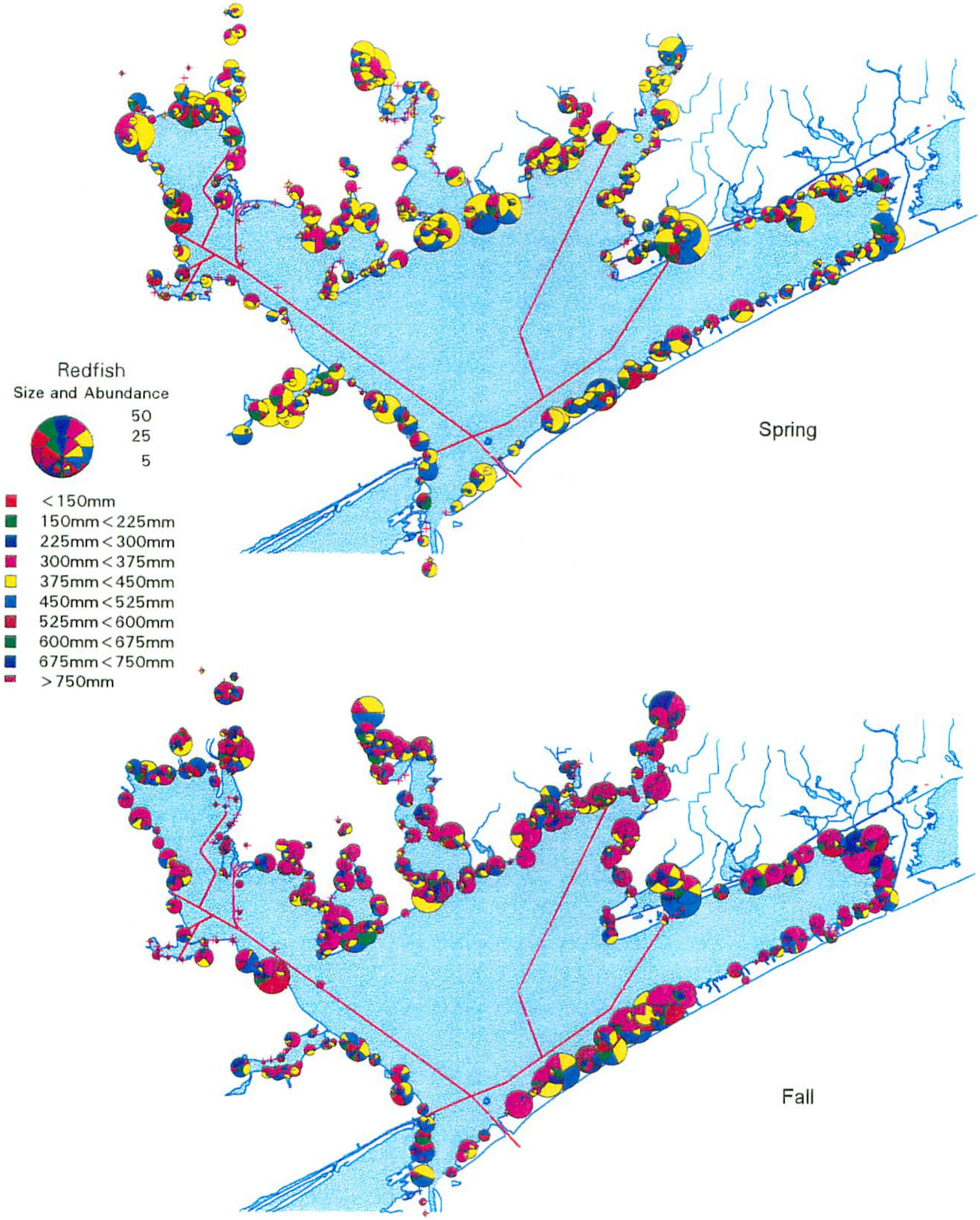


Figure 14. Distribution and abundance of redfish taken in gillnets in Matagorda Bay, Texas.

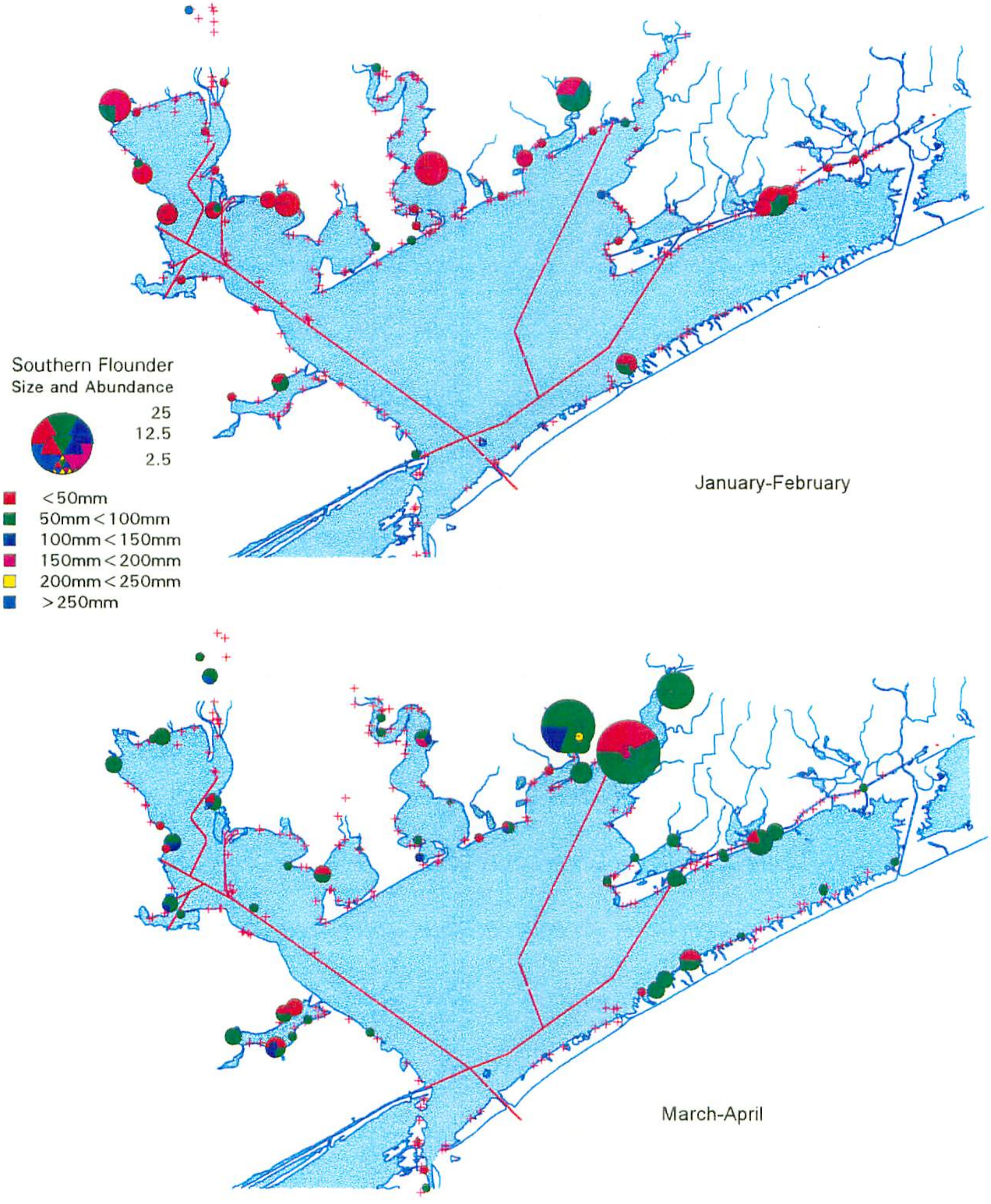


Figure 15a. Seasonal distribution and abundance of juvenile southern flounder in Matagorda Bay, Texas. January-April.

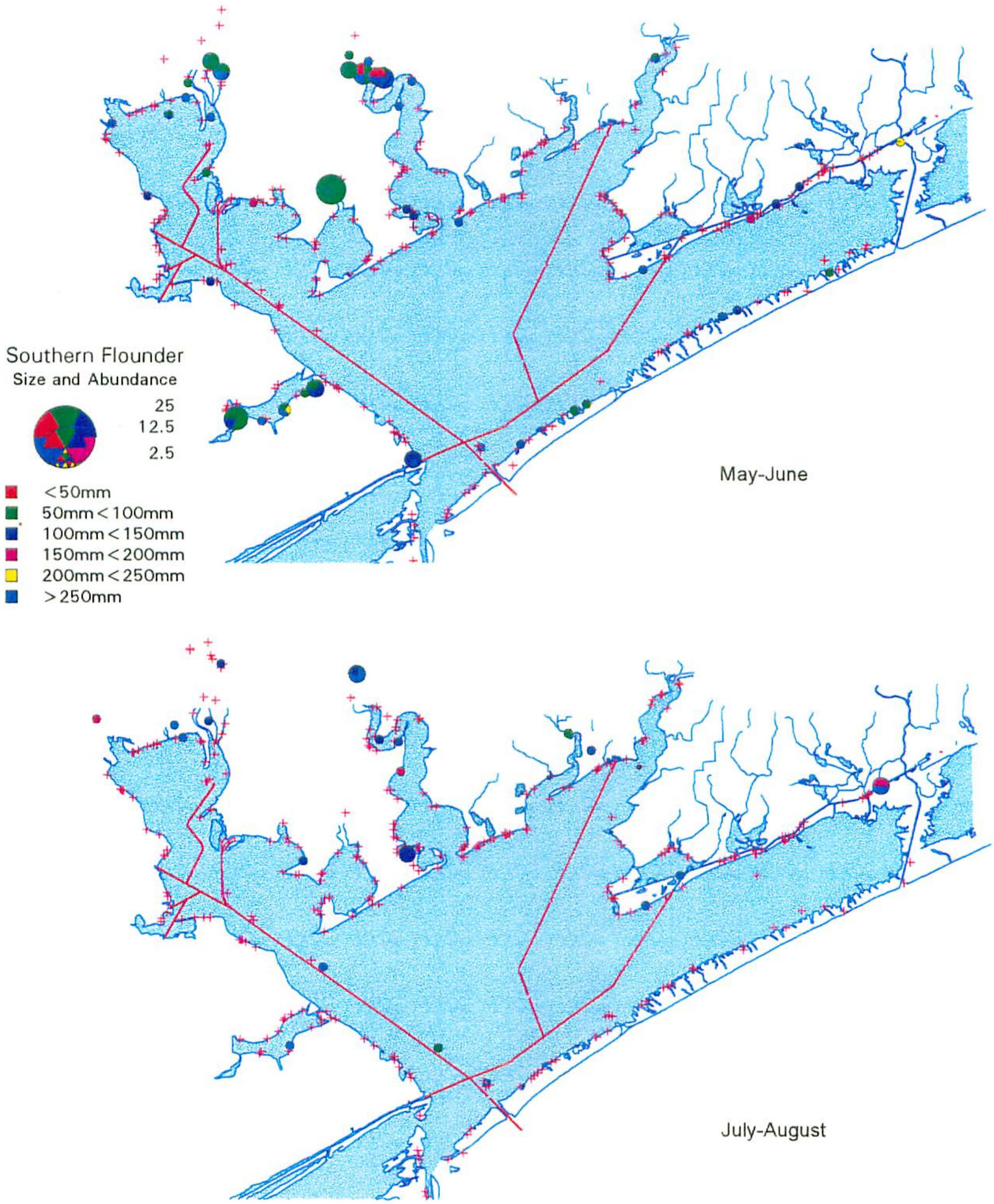


Figure 15b. Seasonal distribution and abundance of juvenile southern flounder in Matagorda bay, Texas. May-August.

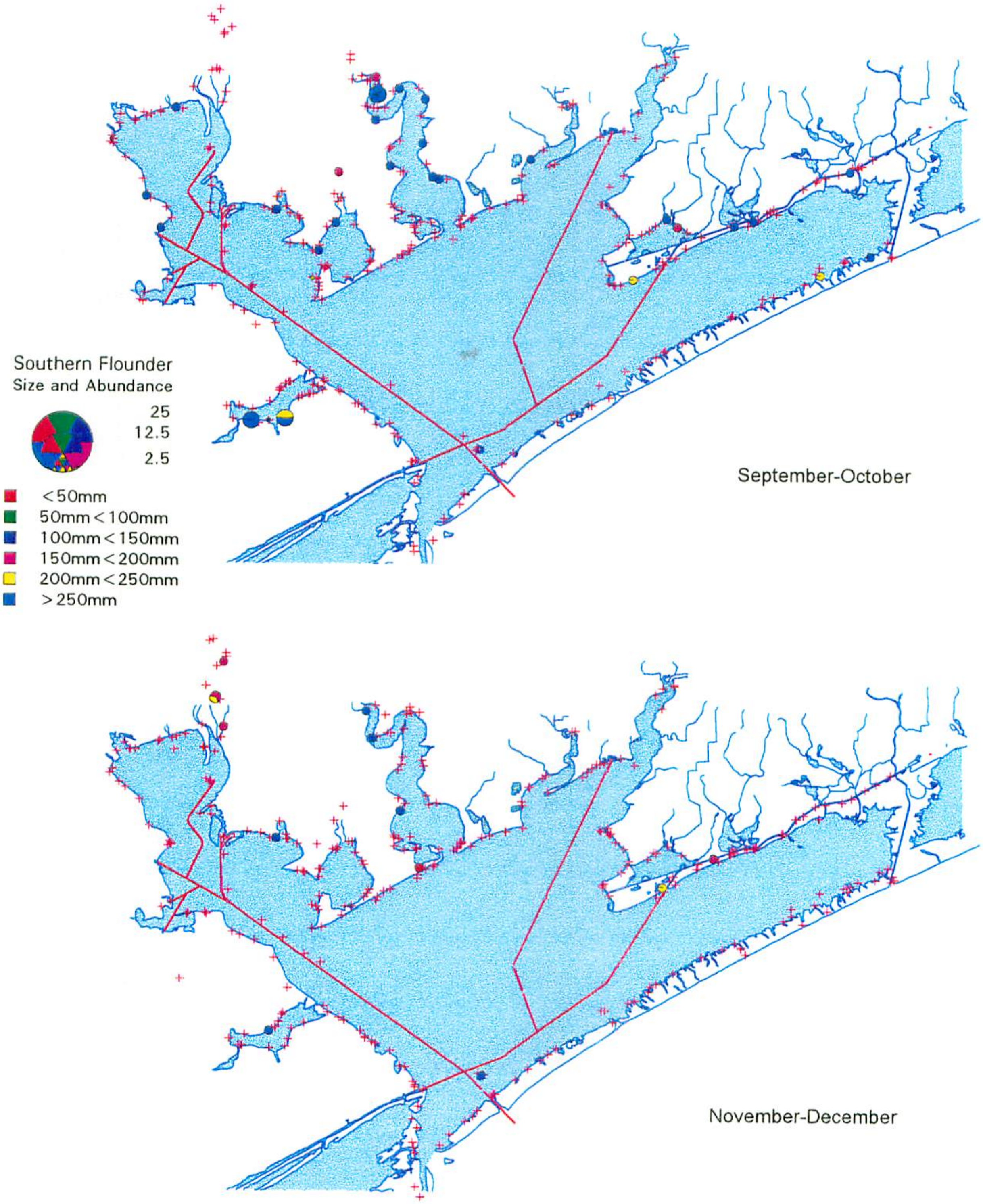


Figure 15c. Seasonal distribution and abundance of juvenile southern flounder in Matagorda Bay, Texas. September-Decemb

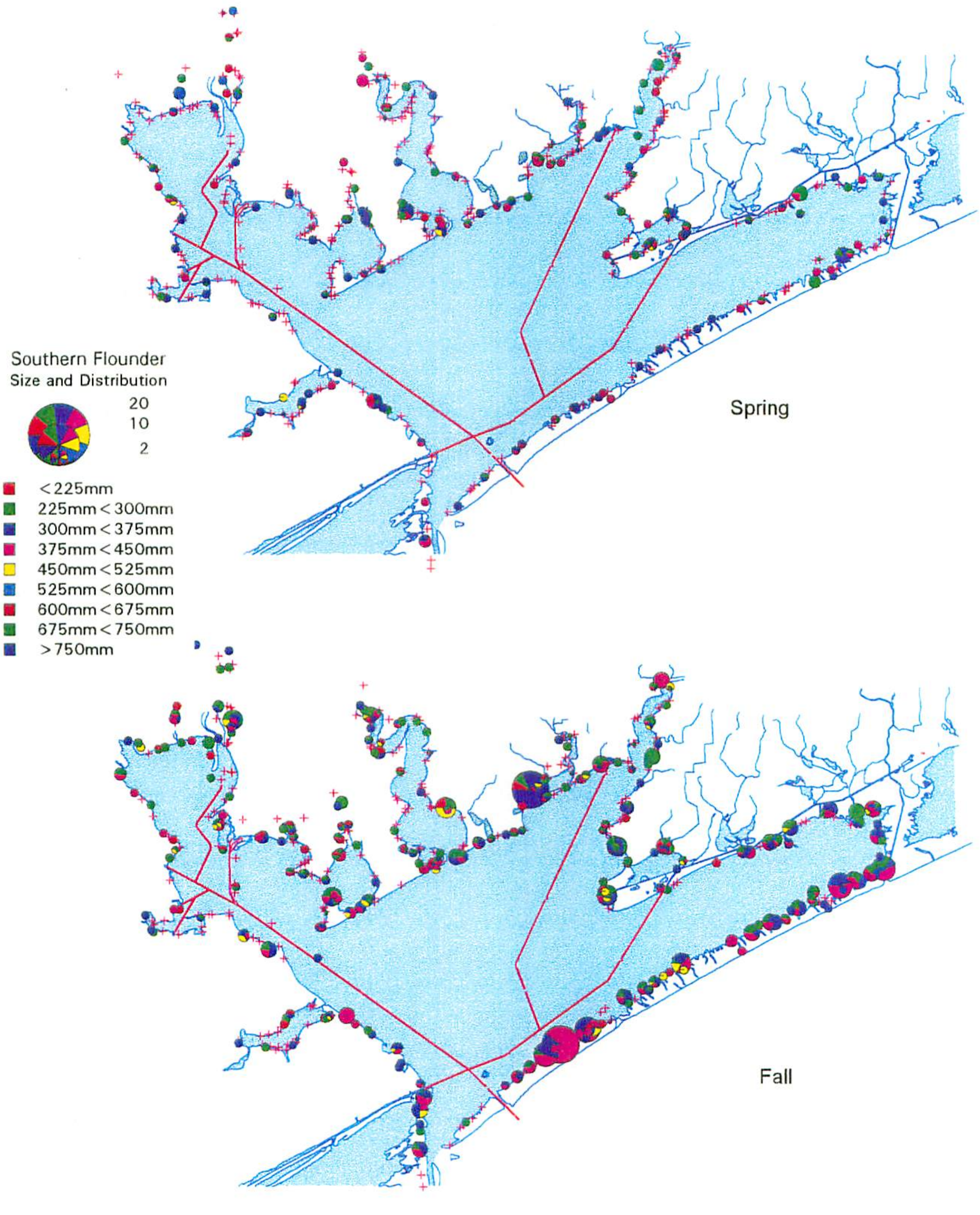


Figure 16. Distribution and abundance of adult southern flounder in Matagorda Bay, Texas.

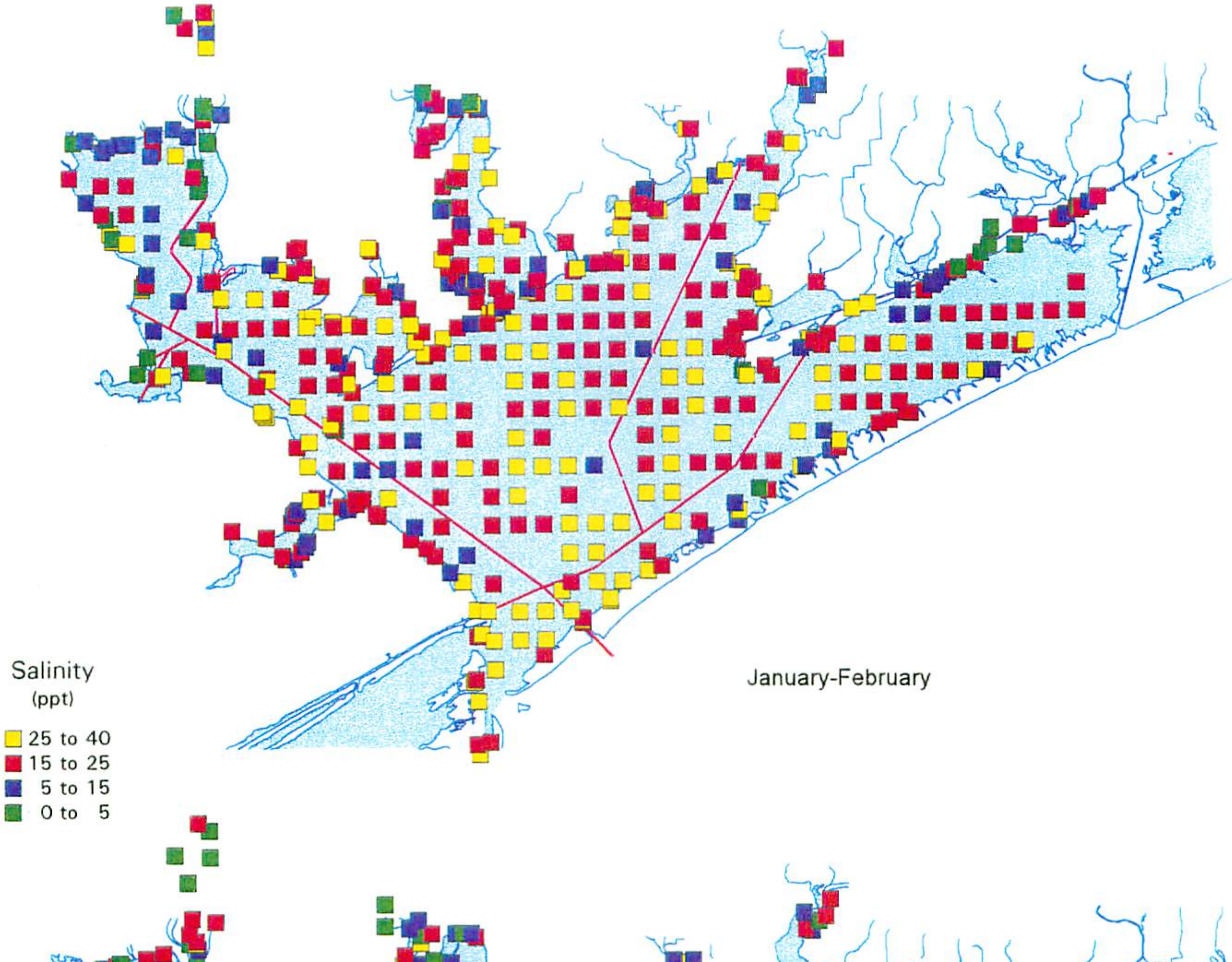
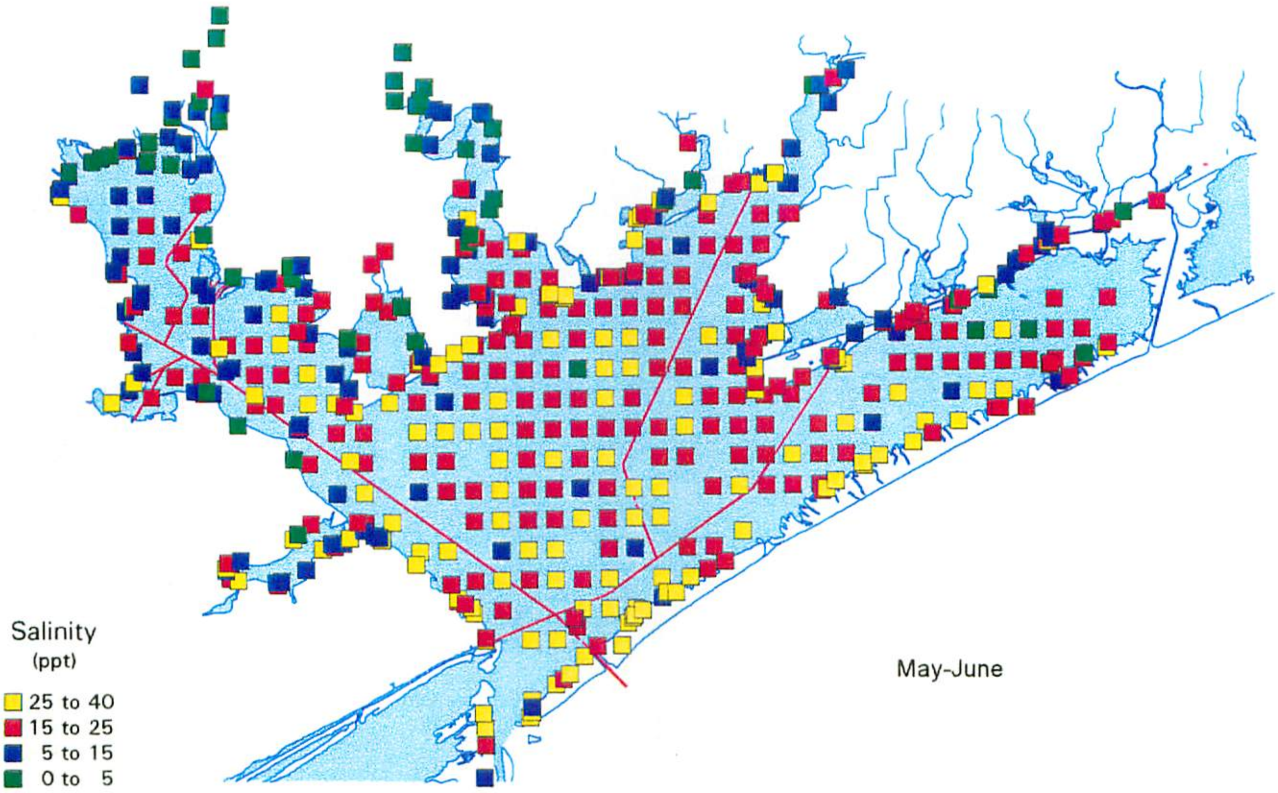
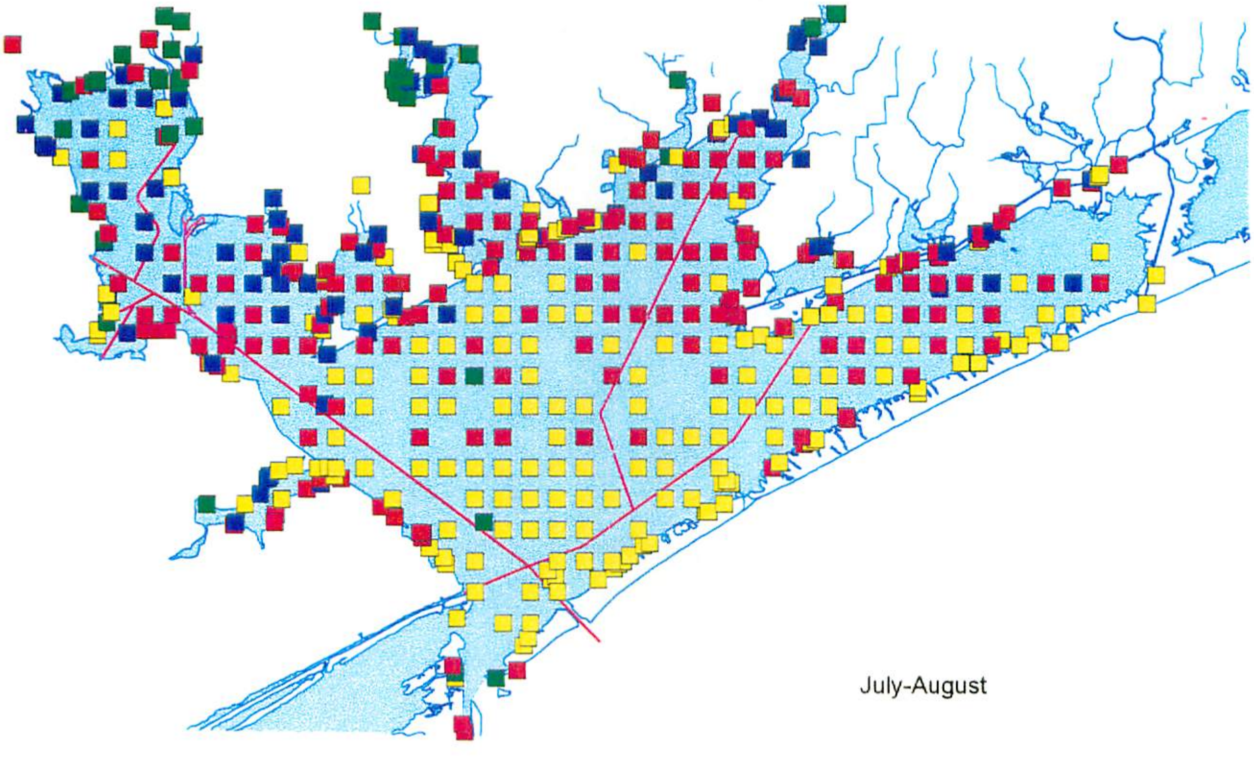


Figure 17a. Average salinity distribution in Matagorda Bay from January through April.

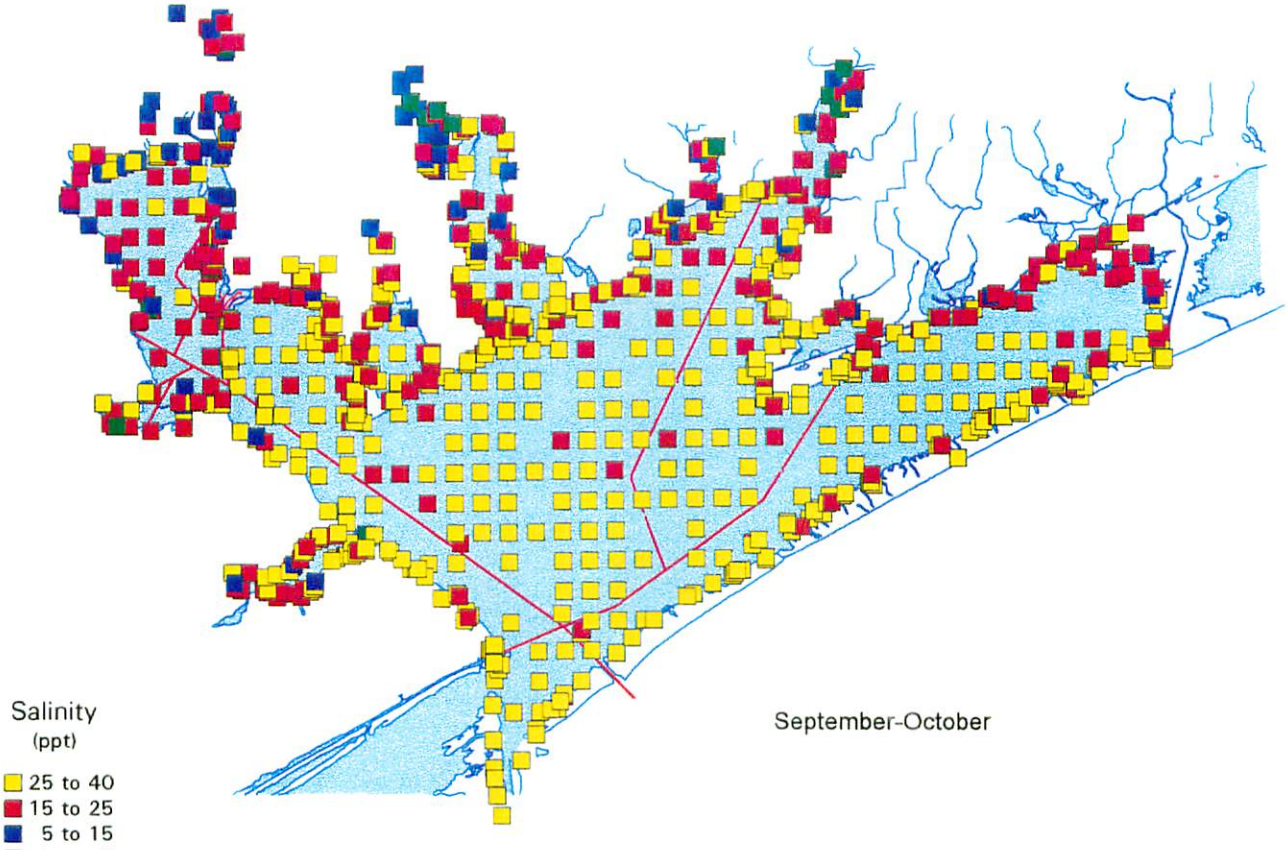


May-June

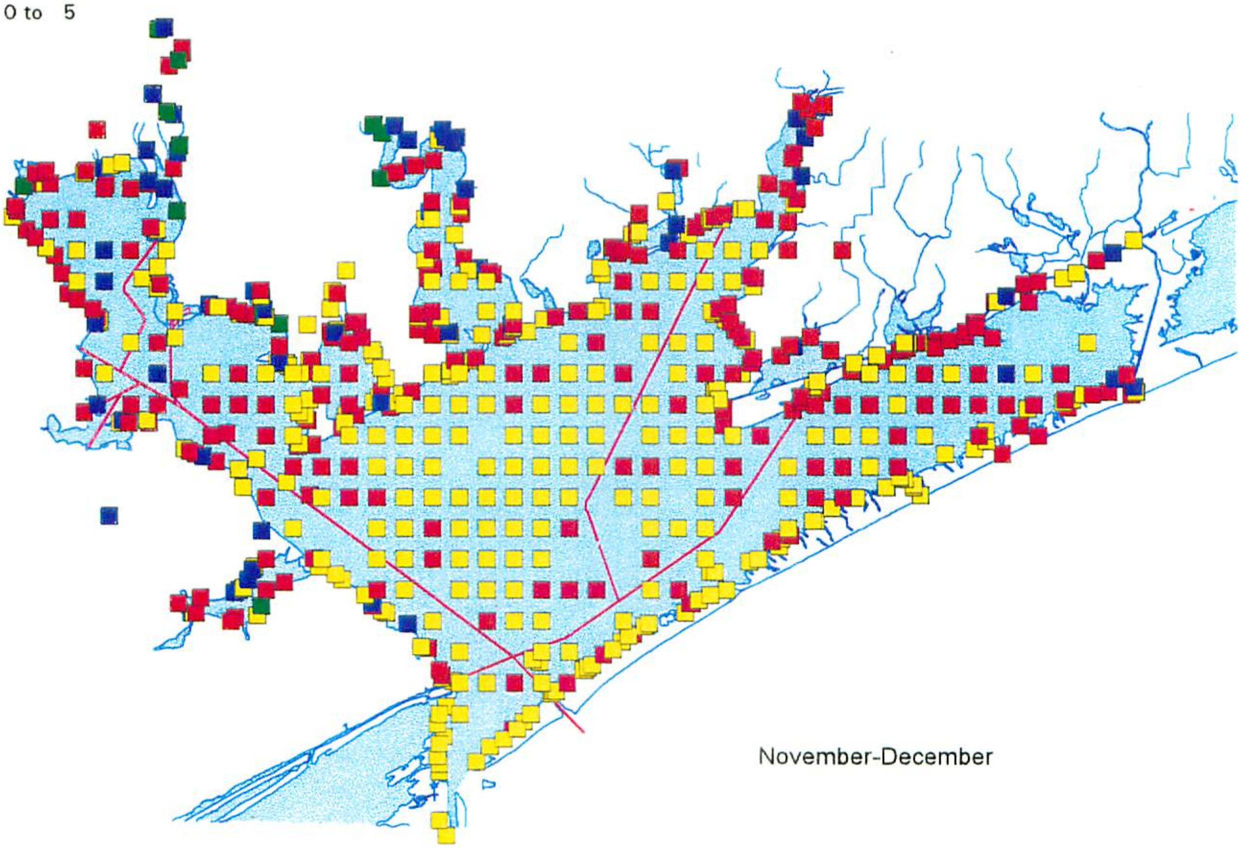


July-August

Figure 17b. Average salinity distribution in Matagorda Bay from May through August.



September-October



November-December

Figure 17c. Average seasonal salinity distribution in Matagorda Bay, September through December.

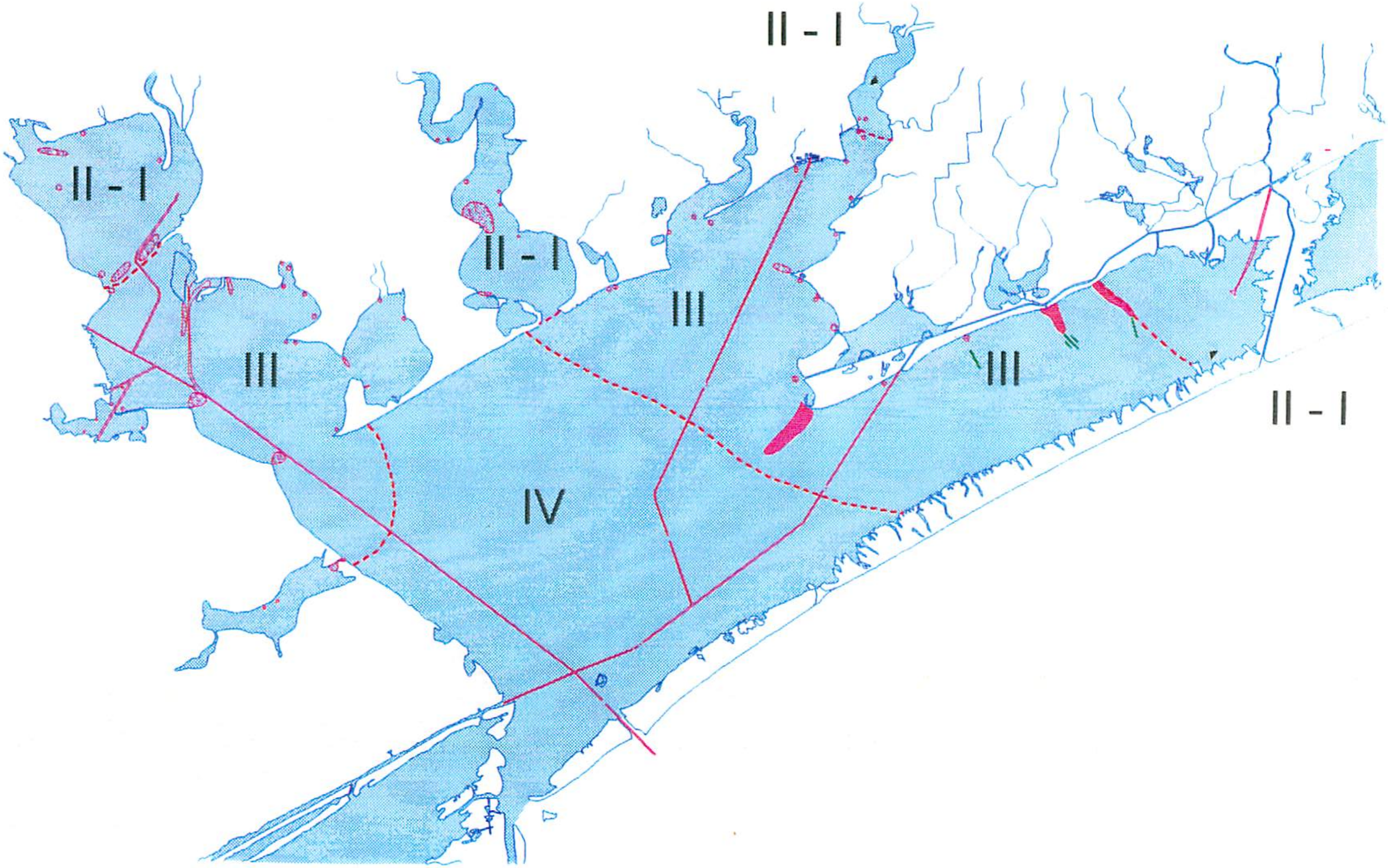


Figure 18. Recommended salinity zone distributions in Matagorda Bay, Texas.

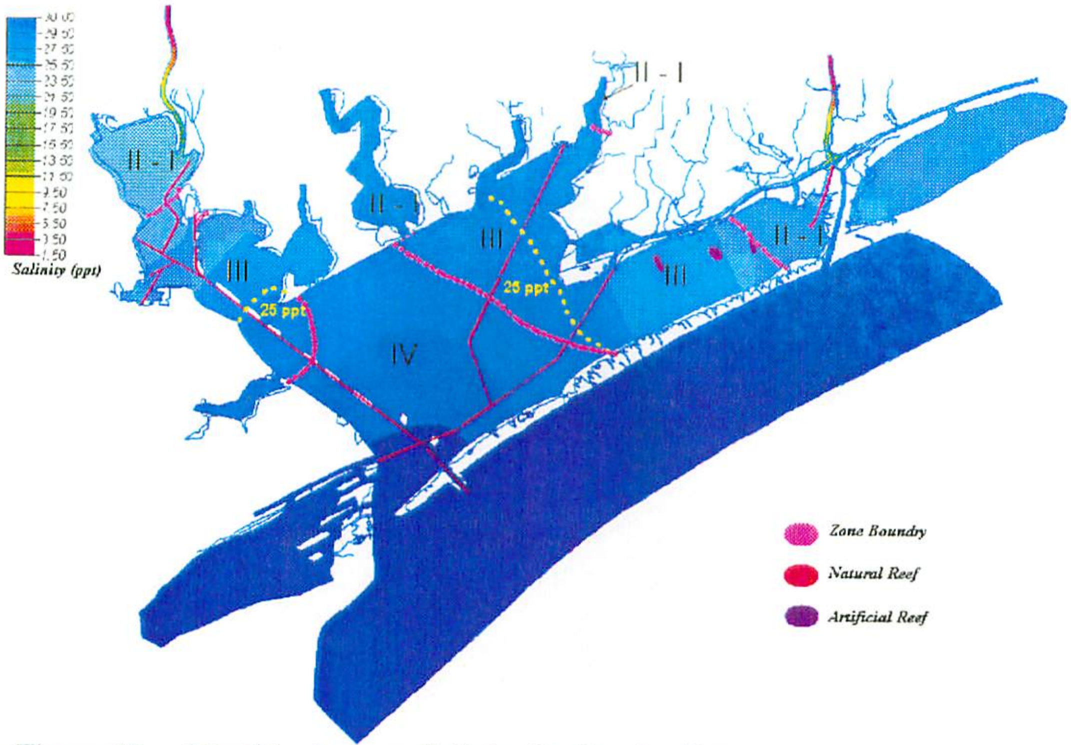


Figure 19 Monthly Average Salinity Profiles by Zone
Target Freshwater Inflow - January

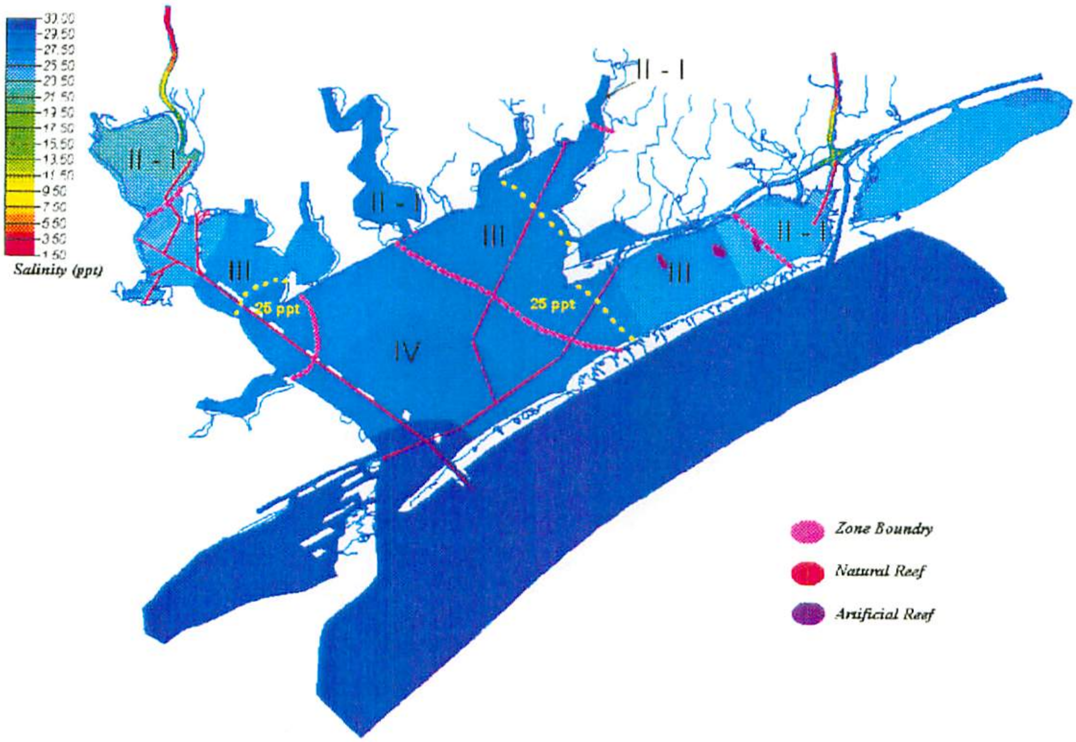


Figure 20 Monthly Average Salinity Profiles by Zone
Target Freshwater Inflow - February

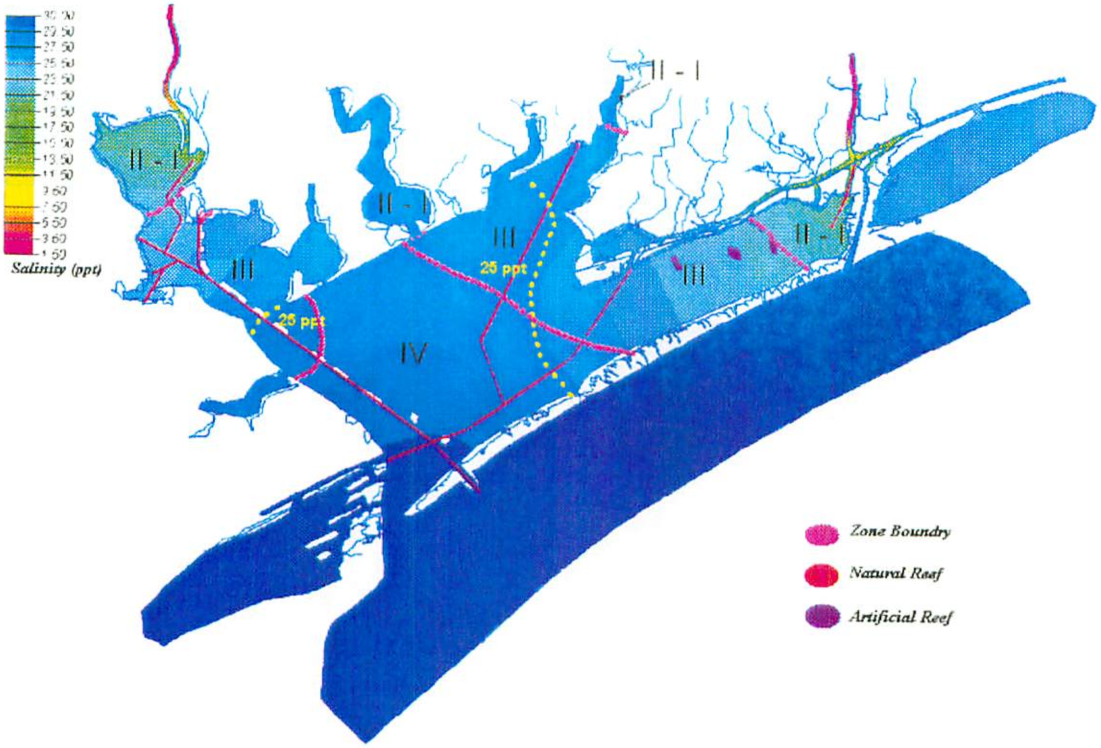


Figure 21 Monthly Average Salinity Profiles by Zone
Target Freshwater Inflow - March

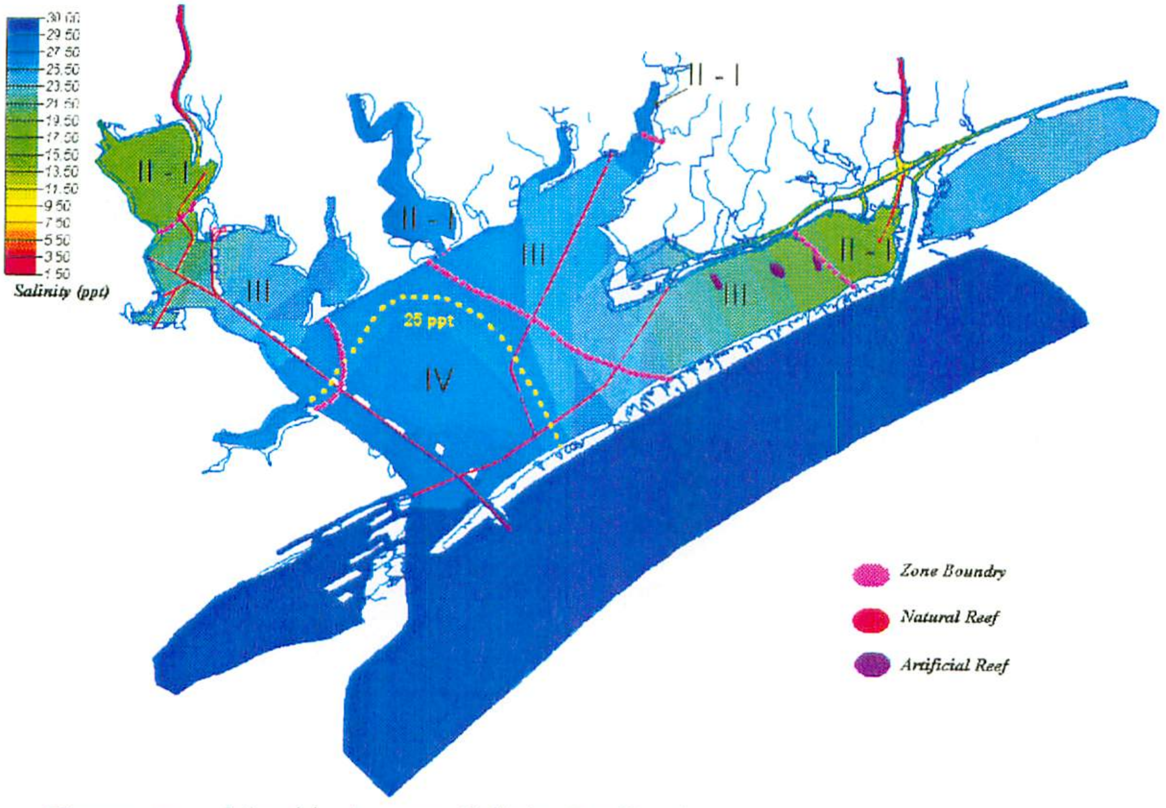


Figure 22 Monthly Average Salinity Profiles by Zone
Target Freshwater Inflow - April

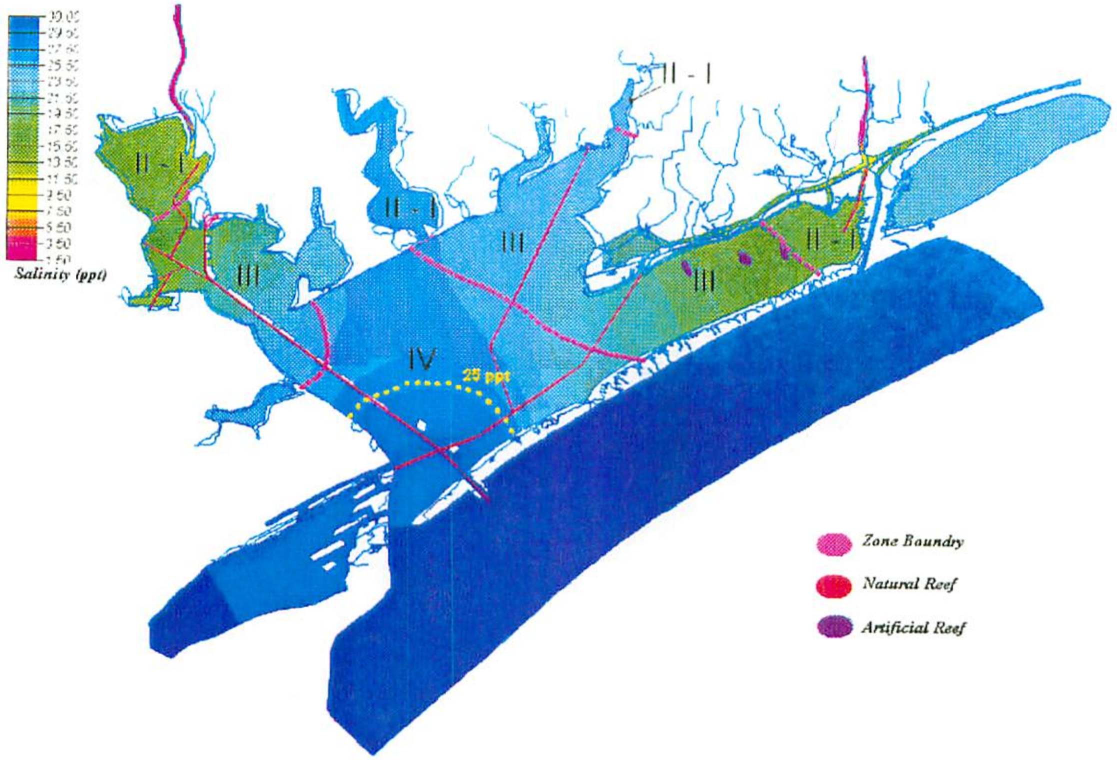


Figure 23 Monthly Average Salinity Profiles by Zone
Target Freshwater Inflow - May

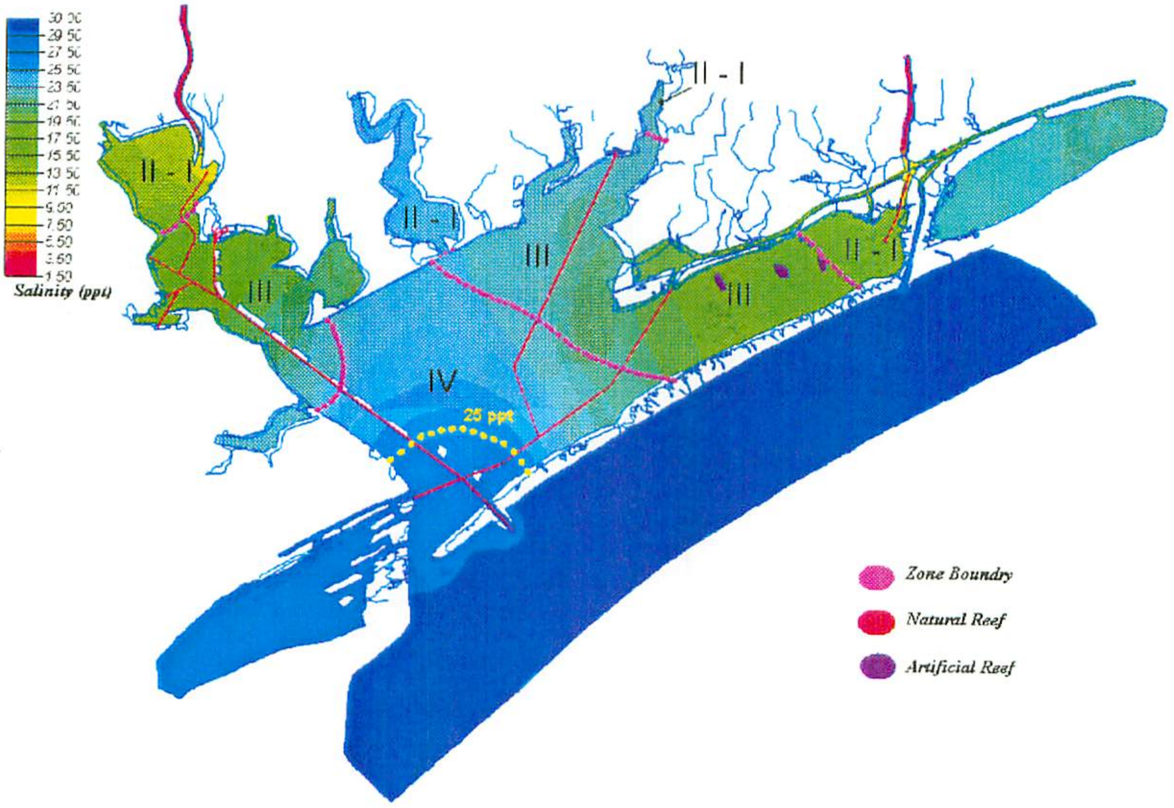


Figure 24 Monthly Average Salinity Profiles by Zone
Target Freshwater Inflow - June

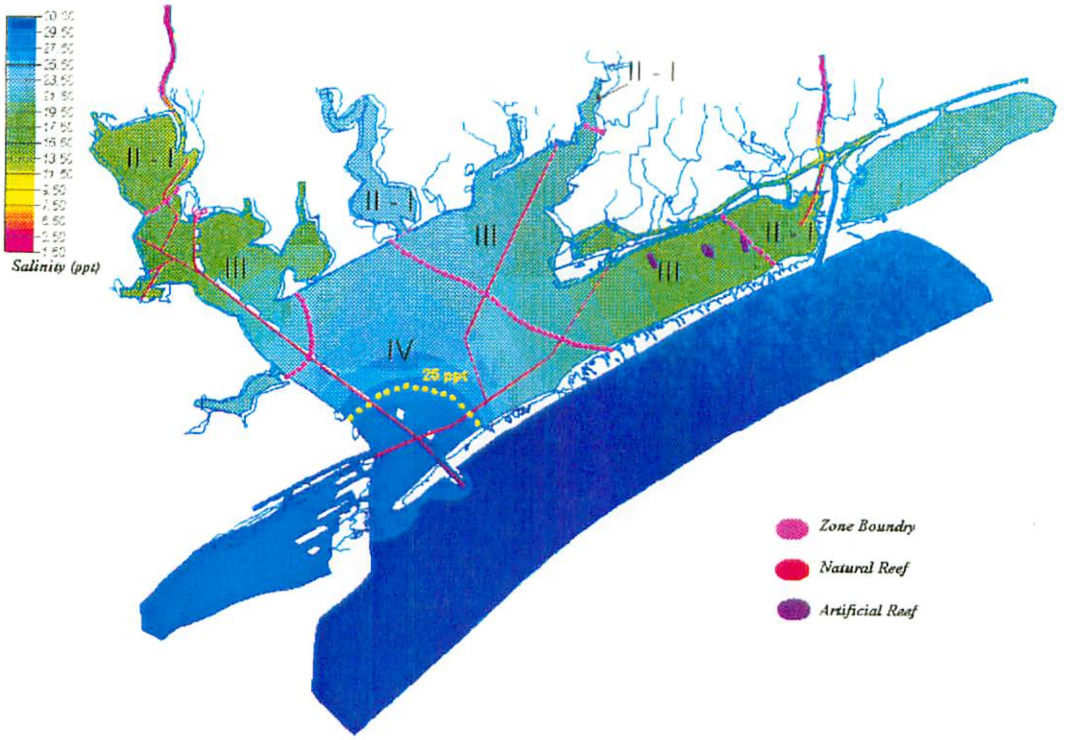


Figure 25 Monthly Average Salinity Profiles by Zone
Target Freshwater Inflow - July

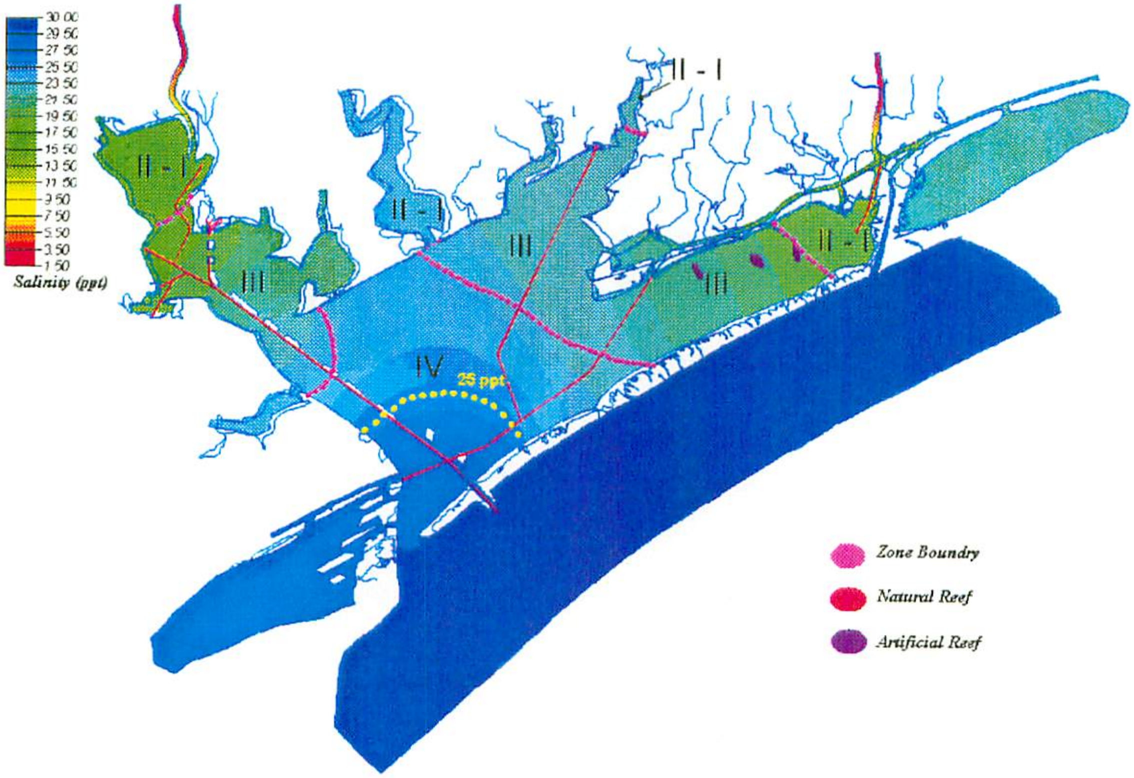


Figure 26 Monthly Average Salinity Profiles by Zone
Target Freshwater Inflow - August

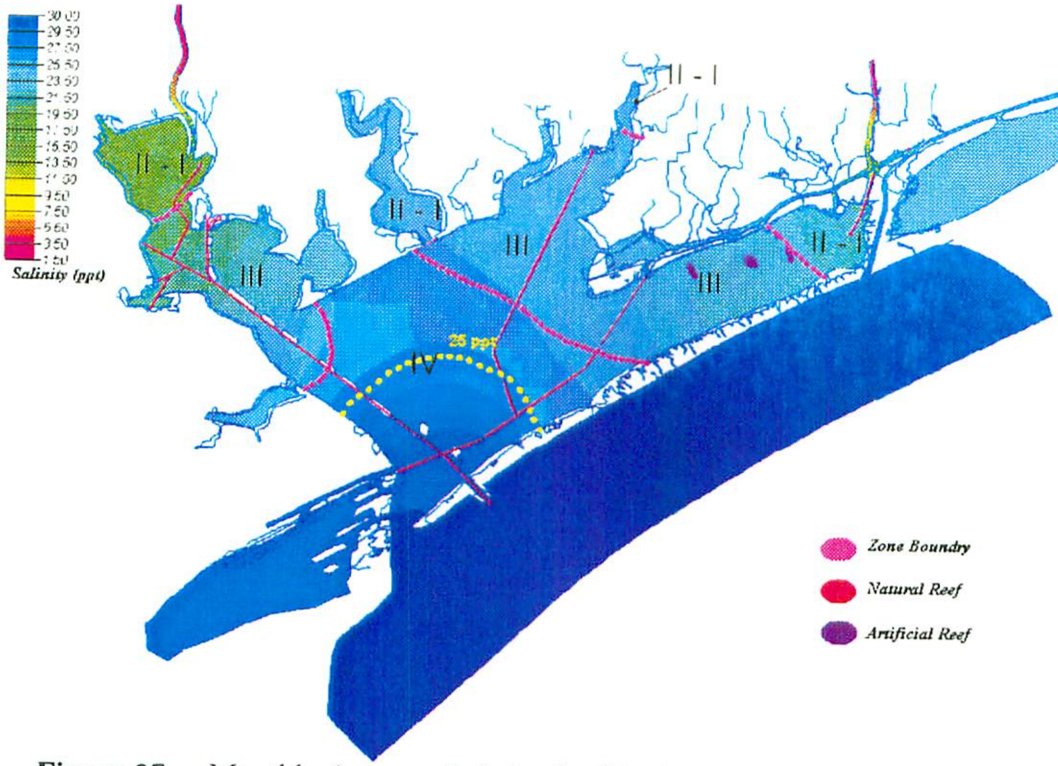


Figure 27 Monthly Average Salinity Profiles by Zone
Target Freshwater Inflow - September

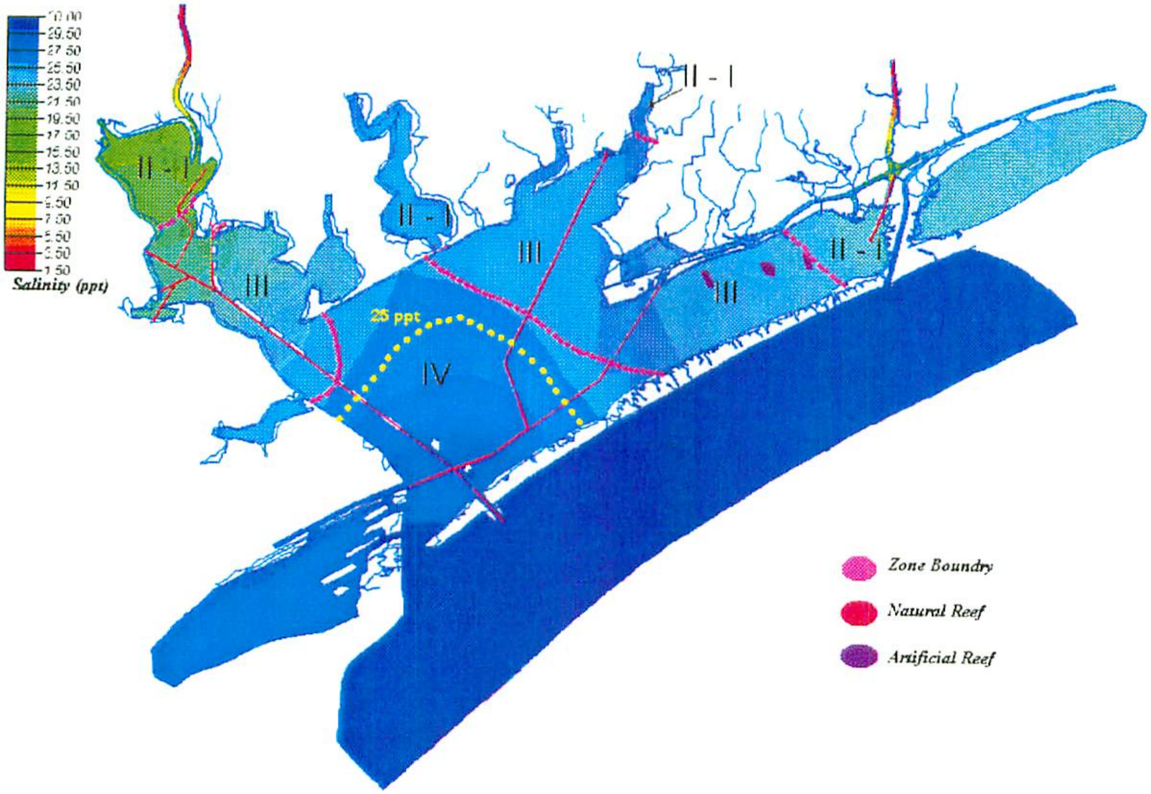


Figure 28 Monthly Average Salinity Profiles by Zone
Target Freshwater Inflow - October

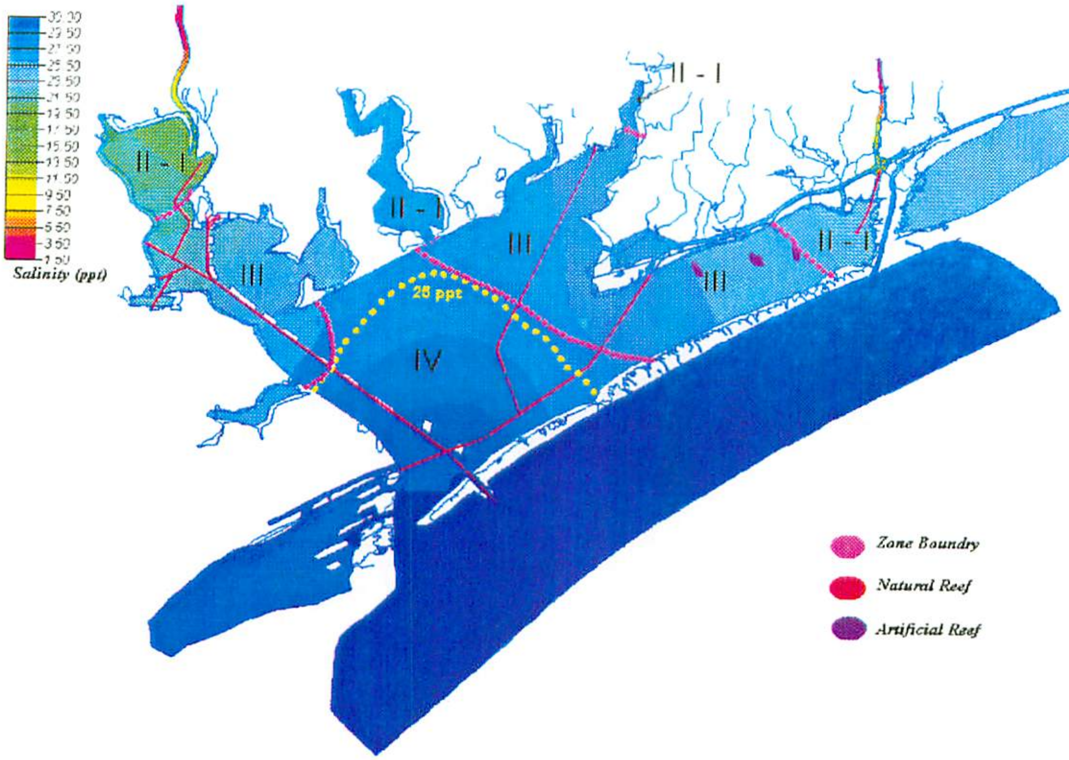


Figure 29 Monthly Average Salinity Profiles by Zone
Target Freshwater Inflow - November

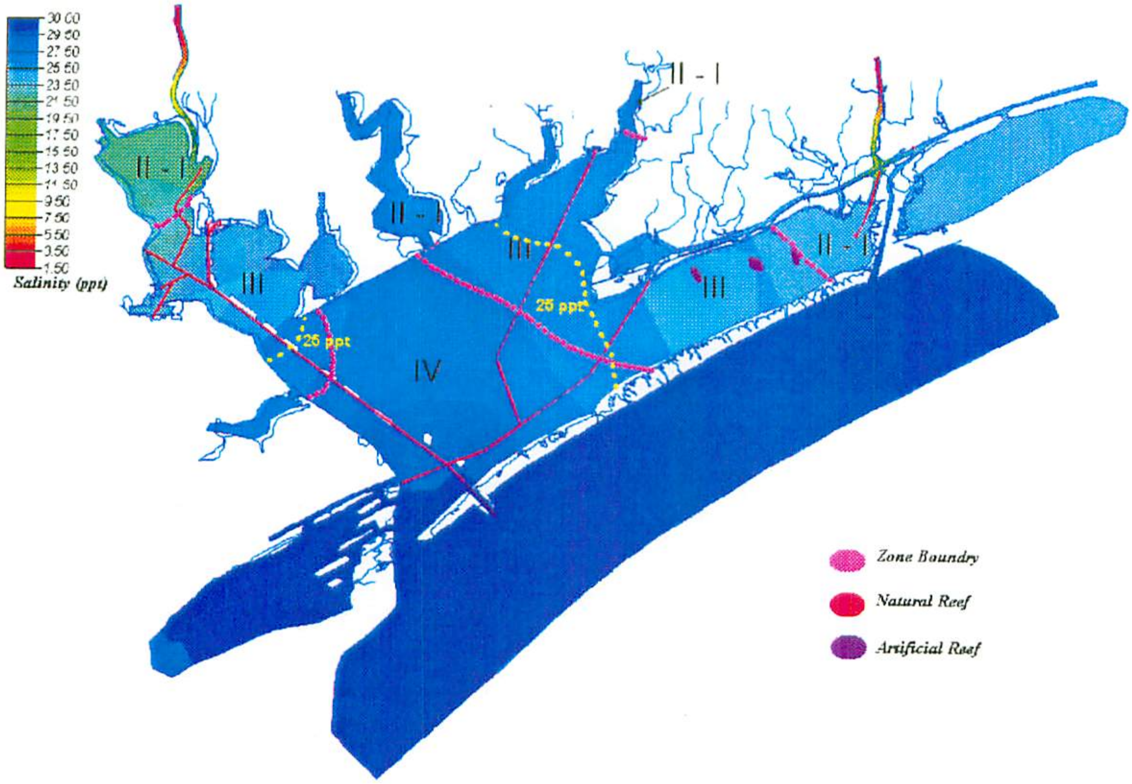


Figure 30 Monthly Average Salinity Profiles by Zone
Target Freshwater Inflow - December

Appendix A: Species collected in the Lavaca-Colorado Estuary
by the Texas Parks and Wildlife Department.

					Area			
Common Name		Family	Genus	Species	1	2	3	4
Sessile Tunicates	Ascidiacea				-	-	+	-
Starfish	Asteroidea		*Luidia*	*clathrata*	-	-	+	-
Starfish	Asteroidea				-	-	+	-
Eastern Oyster	Bivalva		*Crassostrea*	*virginica*	+	+	+	+
Atlantic Surf Clam	Bivalva		*Spissula*	*solidissima*	-	-	+	-
Finetooth Shark	Condrichthys	Carcharhinidae	*Carcharhinus*	*isodon*	-	+	-	+
Spinner Shark	Condrichthys	Carcharhinidae	*Carcharhinus*	*brevipinna*	+	-	-	-
Blacktip Shark	Condrichthys	Carcharhinidae	*Carcharhinus*	*limbatus*	+	+	+	+
Bull Shark	Condrichthys	Carcharhinidae	*Carcharhinus*	*leucas*	+	+	+	+
Lemon Shark	Condrichthys	Carcharhinidae	*Negaprion*	*brevirostris*	-	+	+	+
Atlantic Sharpnose Sh	Condrichthys	Carcharhinidae	*Rhizoprionodon*	*terraenovae*	+	+	+	+
Cownose Ray	Condrichthys	Myliobatidae	*Rhinoptera*	*bonasus*	+	+	+	+
Bonnethead	Condrichthys	Sphyrnidae	*Sphyrna*	*tiburo*	+	+	+	+
Pistol Shrimp	Crustacea		*Alpheus*	*heterochaelis*	-	-	+	-
Speckled Crab	Crustacea		*Arenaeus*	*cribrarius*	-	-	+	-
Shameface Crab	Crustacea		*Calappa*	*sulcata*	-	-	+	-
Gulf Crab	Crustacea		*Callinectes*	*danae*	+	+	+	-
Blue Crab	Crustacea		*Callinectes*	*sapidus*	+	+	+	+
Lesser Blue Crab	Crustacea		*Callinectes*	*similis*	+	+	+	+
Striped Hermit Crab	Crustacea		*Clibanarius*	*vittatus*	+	+	+	+
Flat Mud Crab	Crustacea		*Eurypanopeus*	*depressus*	-	+	-	-
Calico Crab	Crustacea		*Hepatus*	*epheliticus*	-	-	+	-
Long-armed Crab	Crustacea		*Leiolambrus*	*nitidus*	-	-	+	-
Spider Crab	Crustacea		*Libinia*	*emarginata*	-	+	+	+
Spider Crab	Crustacea		*Libinia*	*dubia*	+	+	+	+
River Shrimp	Crustacea		*Macrobrachium*	*ohione*	+	-	+	-
Stone Crab	Crustacea		*Menippe*	*mercenaria*	+	+	+	+
Xanthid Crab	Crustacea		*Neopanope*	*texana*	+	-	+	-
Lady Crab	Crustacea		*Ovalipes*	*guadulpensis*	-	+	+	-
Long Claw Crab	Crustacea		*Pagurus*	*longicarpus*	-	+	+	-
Big Claw Hermit Crab	Crustacea		*Pagurus*	*pollicaris*	+	+	+	+
Grass Shrimp	Crustacea		*Palaemonetes*	*kadiakensis*	+	+	+	+
Xanthid Crab	Crustacea		*Panopeus*	*herbstii*	-	+	-	-
Spider Crab	Crustacea		*Pelia*	*mutica*	+	-	+	+
Brown Shrimp	Crustacea		*Penaeus*	*azteca*	+	+	+	+
Pink Shrimp	Crustacea		*Penaeus*	*duorarum*	+	+	+	+
White Shrimp	Crustacea		*Penaeus*	*setiferus*	+	+	+	+
Purse Crab	Crustacea		*Persephona*	*aquilonaris*	-	+	+	-
Porcellanid Crab	Crustacea		*Petrolisthes*	*armatus*	+	+	+	+
Portunid Crab	Crustacea		*Portunus*	*spinimanus*	-	-	+	-
Purple Crab	Crustacea		*Portunus*	*gibbesii*	-	+	+	-
Rock Shrimp	Crustacea		*Sicyonia*	*brevirostris*	-	+	-	-
Lesser Rock Shrimp	Crustacea		*Sicyonia*	*dorsalis*	-	+	+	-
Mantis Shrimp	Crustacea		*Squilla*	*empusa*	+	+	+	+
Broken-necked shrimp	Crustacea		*Trachypenaeus*	*similis*	-	+	+	-
Ctenophores	Ctenophora				+	+	+	+
Sea Cucumbers	Holothuroidae				-	-	+	-

Area 1: Lavaca Bay, Chocolate Bay, Keller Bay; Area 2: Upper Matagorda Bay; Area 3: Lower Matagorda Bay; Area 4: Carancahua Bay, Turtle Bay, Tres Palacios Bay

Appendix A: Species collected in the Lavaca-Colorado Estuary
by the Texas Parks and Wildlife Department.

					Area			
Common Name		Family	Genus	Species	1	2	3	4
Atlantic Bottlenose Dol	Mammalia		*Tursiops*	*truncatus*	-	-	+	-
Brittle Stars	Ophiuroidae				-	-	+	-
Sargassumfish	Pisces	Antennariidae	*Histrio*	*histrio*	+	-	-	-
Hardhead Catfish	Pisces	Ariidae	*Arius*	*felis*	+	+	+	+
Gafftopsail Catfish	Pisces	Ariidae	*Bagre*	*marinus*	+	+	+	+
Rough Silverside	Pisces	Atherinidae	*Membras*	*martinica*	-	+	-	-
Tidewater Silverside	Pisces	Atherinidae	*Menidia*	*peninsulae*	-	-	+	-
Inland Silverside	Pisces	Atherinidae	*Menidia*	*beryllina*	+	+	+	+
Dotterel Filefish	Pisces	Balistidae	*Aluterus*	*heudeloti*	-	-	+	-
Orange Filefish	Pisces	Balistidae	*Aluterus*	*schoepfi*	-	-	+	-
Gray Triggerfish	Pisces	Balistidae	*Balistes*	*capriscus*	-	-	+	-
Orangespotted Filefish	Pisces	Balistidae	*Cantherhines*	*pullus*	-	-	+	-
Planehead Filefish	Pisces	Balistidae	*Monacanthus*	*hispidus*	-	-	+	-
Gulf Toadfish	Pisces	Bartachoididae	*Opsanus*	*tau*	+	+	+	+
Atlantic Midshipman	Pisces	Batrachoididae	*Porichthys*	*plectrodon*	+	+	+	+
Halfbeak	Pisces	Belonidae	*Hyporhamphus*	*unifasciatus*	-	+	-	-
Atlantic Needlefish	Pisces	Belonidae	*Strongylura*	*marina*	+	+	-	+
Freckled Blenny	Pisces	Blennidae	*Hypsoblennius*	*iothas*	-	-	-	+
Ocellated Flounder	Pisces	Bothidae	*Ancylopsetta*	*quadrocellata*	-	-	+	+
Bay Whiff	Pisces	Bothidae	*Citharichthys*	*spilopterus*	+	+	+	+
Gulf Flounder	Pisces	Bothidae	*Paralichthys*	*albigutta*	-	+	+	+
Southern Flounder	Pisces	Bothidae	*Paralichthys*	*lethostigma*	+	+	+	+
Shoal Flounder	Pisces	Bothidae	*Syacium*	*gunteri*	-	-	+	-
Hogchoker	Pisces	Bothidae	*Trinectes*	*maculatus*	+	+	+	+
Crevalle Jack	Pisces	Carangidae	*Caranx*	*hippos*	+	+	+	+
Horse-eye Jack	Pisces	Carangidae	*Caranx*	*latus*	+	+	+	+
Blue Runner	Pisces	Carangidae	*Caranx*	*crysos*	-	-	+	-
Bar Jack	Pisces	Carangidae	*Caranx*	*ruber*	-	+	+	+
Atlantic Bumper	Pisces	Carangidae	*Chloroscombrus*	*chrysurus*	+	+	+	+
Bluntnose Jack	Pisces	Carangidae	*Hemicaranx*	*amblyrhynchus*	+	+	+	+
Leatherjack	Pisces	Carangidae	*Oligoplites*	*saurus*	+	+	+	+
Atlantic Moonfish	Pisces	Carangidae	*Selene*	*setapinnis*	+	+	+	+
Lookdown	Pisces	Carangidae	*Selene*	*vomer*	+	+	+	+
Banded Rudderfish	Pisces	Carangidae	*Seriola*	*zonata*	-	+	-	-
Permit	Pisces	Carangidae	*Trachinotus*	*falcatus*	-	+	-	-
Florida Pompano	Pisces	Carangidae	*Trachinotus*	*carolinus*	+	+	+	+
Smallmouth Buffalo	Pisces	Catostomidae	*Ictiobus*	*bubalus*	+	-	-	+
Atlantic Spadefish	Pisces	Chaetodontidae	*Chaetodipterus*	*faber*	+	+	+	+
Skipjack Herring	Pisces	Clupeidae	*Alosa*	*chrysochloris*	+	+	+	+
Finescale Menhaden	Pisces	Clupeidae	*Brevoortia*	*gunteri*	+	+	+	+
Gulf Menhaden	Pisces	Clupeidae	*Brevoortia*	*mitchilli*	+	+	+	+
Scaled Sardine	Pisces	Clupeidae	*Harengula*	*jaguana*	+	+	+	+
Atlantic Threadfin	Pisces	Clupeidae	*Polydactylus*	*octonemus*	+	+	+	+
Spanish Sardine	Pisces	Clupeidae	*Sardinella*	*aurita*	+	+	-	-
Blackcheek Tonguefis	Pisces	Cynoglossidae	*Symphurus*	*plagusia*	+	+	+	+
Common Carp	Pisces	Cyprinidae	*Cyprinus*	*carpio*	+	+	-	+
Diamond Killifish	Pisces	Cyprinodontidae	*Adinia*	*xenica*	+	+	-	+

Area 1: Lavaca Bay, Chocolate Bay, Keller Bay; Area 2: Upper Matagorda Bay; Area 3: Lower Matagorda Bay; Area 4: Carancahua Bay, Turtle Bay, Tres Palacios Bay

Appendix A: Species collected in the Lavaca-Colorado Estuary
by the Texas Parks and Wildlife Department.

					Area			
Common Name		Family	Genus	Species	1	2	3	4
Sheepshead Minnow	Pisces	Cyprinodontidae	*Cyprinodon*	*variegatus*	+	+	+	+
Gulf Killifish	Pisces	Cyprinodontidae	*Fundulus*	*grandis*	+	+	+	+
Longnose Killifish	Pisces	Cyprinodontidae	*Fundulus*	*similis*	+	+	+	+
Rainwater Killifish	Pisces	Cyprinodontidae	*Lucania*	*parva*	+	+	+	-
Striped Burrfish	Pisces	Diodontidae	*Chilomycterus*	*schoepfi*	+	+	+	+
Tarpon	Pisces	Elopidae	*Megalops*	*atlanticus*	+	-	-	-
Bay Anchovy	Pisces	Engraulidae	*Anchoa*	*mitchilli*	+	+	+	+
Striped Anchovy	Pisces	Engraulidae	*Anchoa*	*hepsetus*	+	+	+	+
Southern Hake	Pisces	Gadidae	*Urophycis*	*floridana*	+	+	+	+
Mottled Mojarra	Pisces	Gerreidae	*Eucinostomus*	*lefroyi*	-	+	+	-
Spotfin Mojarra	Pisces	Gerreidae	*Eucinostomus*	*argenteus*	+	+	+	+
Silver Jenny	Pisces	Gerreidae	*Eucinostomus*	*gula*	+	+	+	+
Skilletfish	Pisces	Gobiesocidae	*Gobiesox*	*strumosus*	+	+	+	+
Sharptail Goby	Pisces	Gobiidae	*Gobionellus*	*hastatus*	-	+	-	+
Naked Goby	Pisces	Gobiidae	*Gobiosoma*	*bosci*	+	+	+	+
Ballyhoo	Pisces	Hemirhamphidae	*Hemirhampus*	*brasiliensis*	+	-	-	+
Channel Catfish	Pisces	Ictaluridae	*Ictalurus*	*punctatus*	+	-	-	-
Blue Catfish	Pisces	Ictaluridae	*Ictalurus*	*furcatus*	+	+	-	+
Longnose Gar	Pisces	Lepistosteiidae	*Lepisosteus*	*osseus*	+	+	-	+
Shortnose Gar	Pisces	Lepistosteiidae	*Lepisosteus*	*platostomus*	+	+	-	+
Spotted Gar	Pisces	Lepistosteiidae	*Lepisosteus*	*oculatus*	+	+	+	+
Alligator Gar	Pisces	Lepistosteiidae	*Lepisosteus*	*spatula*	+	+	+	+
Tripletail	Pisces	Lobotidae	*Lobotes*	*surinamensis*	+	+	+	+
Lane Snapper	Pisces	Lutjanidae	*Lutjanus*	*synagris*	-	-	+	-
Schoolmaster	Pisces	Lutjanidae	*Lutjanus*	*apodus*	+	+	-	-
Gray Snapper	Pisces	Lutjanidae	*Lutjanus*	*griseus*	+	+	-	+
Striped Mullet	Pisces	Mugilidae	*Mugil*	*cephalus*	+	+	+	+
White Mullet	Pisces	Mugilidae	*Mugil*	*curema*	+	+	+	+
Shrimp Eel	Pisces	Ophichthidae	*Ophichthus*	*gomesi*	+	+	+	+
Speckled Worm Eel	Pisces	Ophichthiidae	*Myrophis*	*punctatus*	-	-	-	+
Scrawled Cowfish	Pisces	Ostraciidae	*Lactophrys*	*quadricornis*	-	-	+	-
White Perch	Pisces	Percichthyidae	*Morone*	*americanus*	+	+	-	+
Striped Bass	Pisces	Percichthyidae	*Morone*	*saxatalis*	+	-	-	-
Mosquitofish	Pisces	Poeciliidae	*Gambusia*	*affinis*	-	-	-	+
Sailfin Molly	Pisces	Poecillidae	*Poecilia*	*latipinna*	+	-	-	+
Barred Grunt	Pisces	Pomadasyidae	*Conodon*	*nobilis*	-	-	+	-
Bluefish	Pisces	Pomatomidae	*Pomatomus*	*saltatrix*	+	+	+	+
Cobia	Pisces	Rachycentridae	*Rachycentron*	*canadum*	+	-	-	-
Silver Perch	Pisces	Sciaenidae	*Bairdiella*	*chrysoura*	+	+	+	+
Silver Seatrout	Pisces	Sciaenidae	*Cynoscion*	*nothus*	-	-	+	+
Spotted Seatrout	Pisces	Sciaenidae	*Cynoscion*	*nebulosus*	+	+	+	+
Sand Seatrout	Pisces	Sciaenidae	*Cynoscion*	*arenarius*	+	+	+	+
Banded Drum	Pisces	Sciaenidae	*Larimus*	*fasciatus*	-	+	+	-
Spot	Pisces	Sciaenidae	*Leiostomus*	*xanthurus*	+	+	+	+
Northern Kingfish	Pisces	Sciaenidae	*Menticirrhus*	*saxatilis*	-	-	+	-
Southern Kingfish	Pisces	Sciaenidae	*Menticirrhus*	*americanus*	+	+	+	+
Gulf Kingfish	Pisces	Sciaenidae	*Menticirrhus*	*littoralis*	+	+	+	+

Area 1: Lavaca Bay, Chocolate Bay, Keller Bay; Area 2: Upper Matagorda Bay; Area 3: Lower Matagorda Bay; Area 4: Carancahua Bay, Turtle Bay, Tres Palacios Bay

Common Name		Family	Genus	Species	Area 1	2	3	4
Atlantic Croaker	Pisces	Sciaenidae	*Micropogon*	*undulatus*	+	+	+	+
Black Drum	Pisces	Sciaenidae	*Pogonias*	*cromis*	+	+	+	+
Red Drum	Pisces	Sciaenidae	*Sciaenops*	*ocellatus*	+	+	+	+
Star Drum	Pisces	Sciaenidae	*Stellifer*	*lanceolatus*	+	+	+	+
Spanish Mackerel	Pisces	Scombridae	*Scomberomorus*	*maculatus*	-	-	+	+
King Mackerel	Pisces	Scombridae	*Scomberomorus*	*cavalla*	-	+	+	-
Lined Sole	Pisces	Soleidae	*Archirus*	*lineatus*	+	+	-	+
Sheepshead	Pisces	Sparidae	*Archosargus*	*probatocephalus*	+	+	+	+
Pinfish	Pisces	Sparidae	*Lagodon*	*rhomboides*	+	+	+	+
Pigfish	Pisces	Sparidae	*Orthopristis*	*chrysoptera*	+	+	+	+
Great Barracuda	Pisces	Sphyraenidae	*Sphyraena*	*barracuda*	-	-	+	-
Guaguanche	Pisces	Sphyraenidae	*Sphyraena*	*guachancho*	-	-	+	-
Harvestfish	Pisces	Stromateidae	*Peprilus*	*alepidotus*	+	+	+	+
Gulf Butterfish	Pisces	Stromateidae	*Peprilus*	*burti*	+	+	+	+
Dwarf Seahorse	Pisces	Syngnathidae	*Hippocampus*	*zosterae*	-	-	+	-
Lined Seahorse	Pisces	Syngnathidae	*Hippocampus*	*erectus*	-	+	-	-
Gulf Pipefish	Pisces	Syngnathidae	*Sygnathus*	*scovelli*	-	-	-	+
Chain Pipefish	Pisces	Syngnathidae	*Sygnathus*	*lousianae*	-	+	-	-
Inshore Lizardfish	Pisces	Synodontidae	*Synodus*	*foetens*	+	+	+	+
Smooth Puffer	Pisces	Tetraodontidae	*Lagocephalus*	*laevigatus*	+	-	-	-
Least Puffer	Pisces	Tetraodontidae	*Sphoeroides*	*parvus*	+	+	+	+
Atlantic Cutlassfish	Pisces	Trichiuridae	*Trichiurus*	*lepturus*	+	+	+	+
Blackfin Searobin	Pisces	Triglidae	*Prionotus*	*rubio*	+	+	+	+
Bighead Searobin	Pisces	Triglidae	*Prionotus*	*tribulus*	+	+	+	+
Southern Stargazer	Pisces	Uranoscopidae	*Astroscopus*	*y-graecum*	-	-	+	-
Sponges	Porifera				-	+	+	-
Reptantia	Reptantia				-	-	+	-
Diamondback terrapin	Reptilia		*Malaclemys*	*terrapin*	-	+	-	-
Smal Sea Star			*Astropecten*	*antillensis*	-	+	-	-
Moon Jellyfish			*Aurelia*	*aurita*	+	+	+	+
Large Comb Jelly			*Beroe*	*ovata*	+	+	+	+
Heart Urchin			*Brissopsis*	*alta*	-	-	+	-
Pear Whelk			*Busycon*	*spiratum*	-	-	+	-
Lightning Whelk			*Busycon*	*perversum*	-	+	+	-
Long-finned Squid			*Loligo*	*pealei*	-	+	+	-
Squid			*Loligo*	*brevis*	+	+	+	+
Brief Squid			*Lolliguncula*	*brevis*	+	+	+	+
Sand Dollar			*Mellita*	*quinquiesperforat*	-	-	+	-
Southern Quahog			*Mercenaria*	*campechiensis*	-	-	+	-
Lettered Olive			*Oliva*	*sayana*	-	-	+	-
Shark's Eye			*Polinices*	*duplicatus*	+	+	+	+
Common Rangia			*Rangia*	*cuneata*	+	+	-	+
Sea Pansy			*Renilla*	*mulleri*	-	-	+	-
Cabbagehead			*Stomolophus*	*meleagris*	+	+	+	+
Florida Rockshell			*Thais*	*haemostoma*	+	+	+	-
Yellow Cockle			*Trachycardium*	*muricatum*	-	-	+	-
Seabob			*Xiphopeneus*	*kroyeri*	-	+	+	+

Area 1: Lavaca Bay, Chocolate Bay, Keller Bay; Area 2: Upper Matagorda Bay; Area 3: Lower Matagorda Bay; Area 4: Carancahua Bay, Turtle Bay, Tres Palacios Bay

CHAPTER 7

ESTIMATION OF FRESHWATER INFLOW NEEDS

INTRODUCTION

The purpose of this chapter is to apply the computational process described in Chapter 1 to estimate the freshwater inflow needs of the Matagorda Bay estuarine system. This process involves the use of TWDB's TXEMP Model (Longley, ed., 1994; Matsumoto, et. al., 1994). The TXEMP model estimates the optimal monthly and seasonal freshwater inflow needs of an estuary by representing mathematically the varied and complex interactions between freshwater inflows and salinity, species productivity, and nutrient inflows. These relationships are developed and described in earlier chapters of this report. Sediment inflows are excluded due to a lack of data concerning the volume of sediment needed to balance erosion and subsidence in the Colorado and Lavaca River delta.

The results from TXEMP are then used in the TXBLEND model developed by TWDB and modified by the LCRA to simulate expected salinity conditions throughout the estuary. The simulated salinity is then compared to desired salinity ranges over broad areas of the estuary. If salinity is not within those ranges then constraints in TXEMP are modified to achieve the desired salinity.

The following sections in this report describe the application of the inflow-estimation process for this estuary.

FRESHWATER INFLOW ESTIMATION PROBLEM

The TXEMP model computes the monthly and seasonal inflows from the Colorado and Lavaca Rivers that achieve the optimal conditions desired in the Matagorda Bay system, within a permissible range of conditions. These conditions are expressed in terms of salinity, species productivity and nutrients.

The monthly river inflows are considered to be controllable variables in this analysis. Of course, this is only partially true since large portions of the watersheds are not controlled by large reservoirs and, even where large impoundments exist, they have a limited storage capability to control floods.

The unregulated inflows in the coastal basins contributing flow to the estuary are considered to be uncontrollable. However, these flows are affected by man's actions particularly in terms of return flows from irrigation. For this analysis, the inflows from the coastal basins will be assumed to be historical flows with a frequency equivalent to that from the two major river basins.

The inflow needs calculated depend upon the selected set of constraints and the objective function.

Performance Criteria

The optimal combination of river inflows is determined in the TXEMP model by a performance criterion or objective function. This criterion depends upon the conditions desired by the resource managers. For this study, the following criteria were considered independently:

- Minimize total river inflows
- Maximize total river inflows
- Maximize total species productivity

Constraints

There are certain conditions desired in the estuary which should be met regardless of the desired performance criterion selected. These specify the general environmental conditions that should be maintained to provide for the well being of the general estuarine ecosystem. These constraints relate to estuarine salinity, species productivity, and nutrient inflows. The following sections discuss each type of constraint in the TXEMP model for this estuary.

Salinity Constraints

The constraint on estuary salinity at location r during month t is expressed as:

$$S^{\min}_{rt} \leq S_{rt} \leq S^{\max}_{rt} \tag{1}$$

where S_{rt} is the average monthly salinity (ppt), and $S^{\min}_{rt}$ and $S^{\max}_{rt}$ are the minimum and maximum allowed average monthly salinity, respectively. For the Lavaca-Colorado estuary, there are two locations where this salinity constraint applies: upper Lavaca Bay and the eastern end of Matagorda Bay (sites A and B in Figure 1). The monthly salinity limits for each of these locations are given in Table 1.

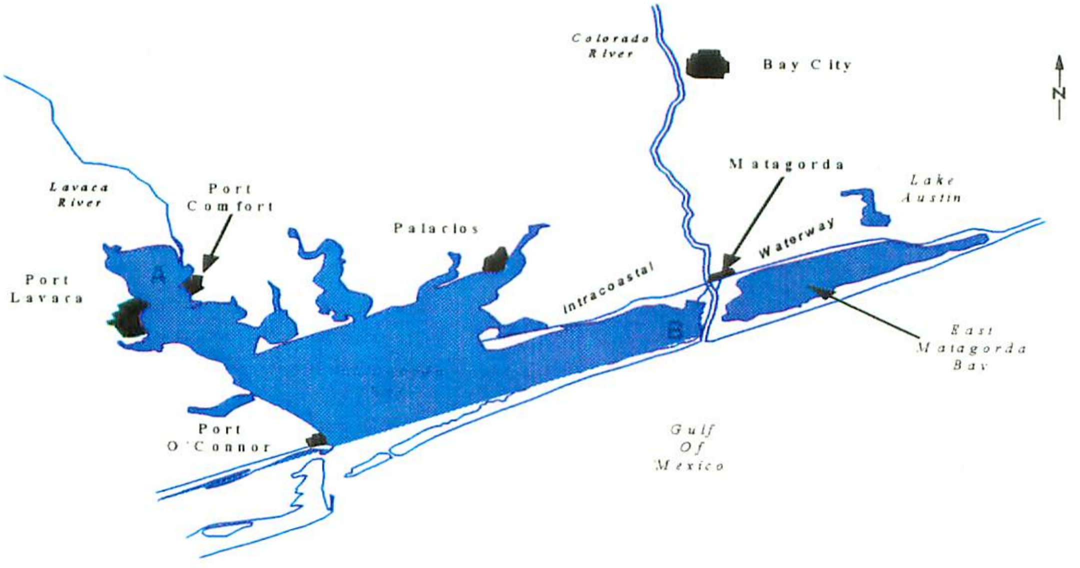


Figure 1. Location of Key Salinity Monitoring Sites

Table 1. Salinity Limits in TXEMP Model for Selected Sites in Lavaca-Colorado Estuary

Month	Lower Limits (ppt)	Upper Limits (ppt)	
		Normal Inflow Conditions	Drought Conditions
January	5	20	25
February	5	20	25
March	5	20	25
April	5	20	25
May	1	15	25
June	1	15	25
July	1	15	25
August	1	20	25
September	5	20	25
October	5	20	25
November	5	20	25
December	5	20	25

The values in Table 1 for the lower and upper normal limits were adopted from limits selected by the TWDB and TPWD in their study of estuarine inflow needs of the Guadalupe estuary, with the exception of the upper normal limit for August. TWDB and TPWD chose 15 ppt as the upper limit on salinity in August in the primary bay area near the mouth of Guadalupe. However, for the Matagorda Bay system, it was impossible to achieve that salinity with the monthly inflows of the Colorado River allowed to be no greater than the average monthly flows at Bay City. Since equity was desired between conditions desired in the eastern arm of Matagorda Bay and Lavaca Bay, the maximum monthly average salinity in normal inflow years was set to 20 ppt for both areas for this study. This change causes very little impact on the inflows needed from the Lavaca or Colorado Rivers, as will be discussed when the estimated inflow needs are presented later in this chapter.

The drought condition upper salinity limits in Table 1 where set at 25 ppt since that is an approximate salinity above which oysters suffer increased predation. Since oysters cannot migrate to new habitats, it is necessary to keep salinity in the oyster reefs off the mouths of the Lavaca and Colorado Rivers from become too saline even in drought conditions so that a resident population of oysters is maintained. When the drought ends, this oyster colony will be able to more rapidly repopulate oyster reefs throughout the bay system than would otherwise be possible if all the local population was devastated.

Average monthly salinity in upper Lavaca Bay in month t (SL_t) is a function of sum of the inflow from the Lake Texana and the Lavaca River at Edna (QL_t (in 1000 acre-feet)). The predictive equation is given below:

$$\begin{aligned} SL_t = 28.68 - 3.12\ln(QL_t) \\ -1.14\ln(QL_{t-1}) \end{aligned} \tag{2}$$

The salinity in the eastern end of Matagorda Bay in month t (SM_t) is a function of Colorado River inflow in month t (QC_t (in 1000 acre-feet)):

$$\begin{aligned} SM_t = 36.63 - 3.18\ln(QM_t) \\ -1.196\ln(QM_{t-1}) \end{aligned} \tag{3}$$

The monthly average salinity is a probabilistic variable. That is, for a given set of monthly freshwater inflows, the salinity is not a fixed value but may be any value within a probability distribution. Thus, the regression equations for salinity are not exact predictors. There is uncertainty in the salinity that will actually occur for any set of monthly inflows. Given this uncertainty, there is no assurance that the salinity constraint (Eq. 1) will be satisfied. However, it is possible to specify the level of uncertainty associated with the constraint being violated. Let $SalP_r$ be the probability level for which the salinity constraint is to be satisfied. The salinity constraint can be rewritten as the following chance constraint:

$$\mathbf{Prob}[S_{rt}^{\min} \le S_{rt} \le S_{rt}^{\max}] \ge SalP_r \tag{4}$$

where ***Prob*** represents probability. This constraint specifies that both the upper and lower salinity bounds must be satisfied in all months with at least the probability of $SalP_r$.

Figure 2 (Longley, ed., 1994) illustrates the salinity chance constraint when $SalP_r$ equals 50% and the salinity distribution follows the Student's *t*-distribution. This case corresponds to using the expected value predicted by the salinity regression equations since, with the expected value, there is an equal chance that the actual salinity is greater or less than the deterministic salinity value predicted by the equation.

To reduce the chance of violating the limits on salinity, the value of $SalP_r$ can be increased. As a further illustration, the probability of meeting the salinity constraint was increased to 70%. As shown in Figure 3 (Longley, ed., 1994), a larger range of possible salinity values (area shaded) now fall within the upper and lower limits when compared to the range in Figure 2.

Productivity Constraints

The constraint on species productivity is expressed as:

$$H_k \geq T_k \tag{5}$$

where H_k is the annual normalized productivity (biomass) of species k and T_k is the minimum allowed annual productivity of that species. For this estuary, species productivity is considered for: blue crab, eastern oyster, white shrimp, brown shrimp, black drum, and southern flounder, red drum, gulf menhaden and striped mullet.

Annual species productivities are expressed as functions of the total seasonal freshwater inflows (all river and coastal basins) using the statistical regression equations described in the Biology Chapter in this study. These functions are given in Table 2 in Chapter 6. As with salinity, the species

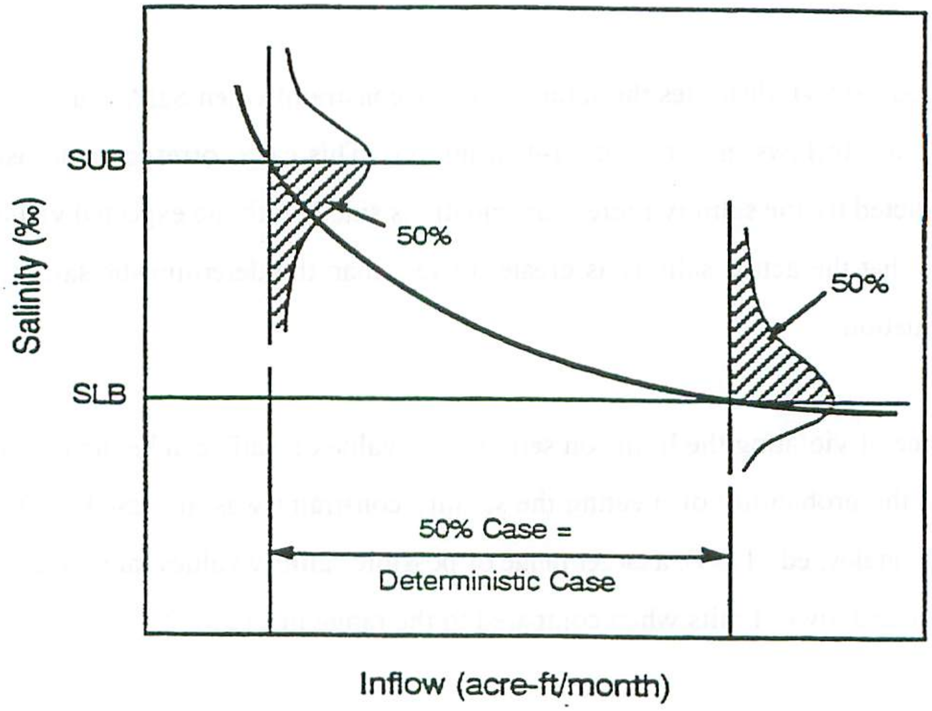


Figure 2. Feasible Range of Inflows for 50% Salinity Probability (Source: Longley, ed., 1994)

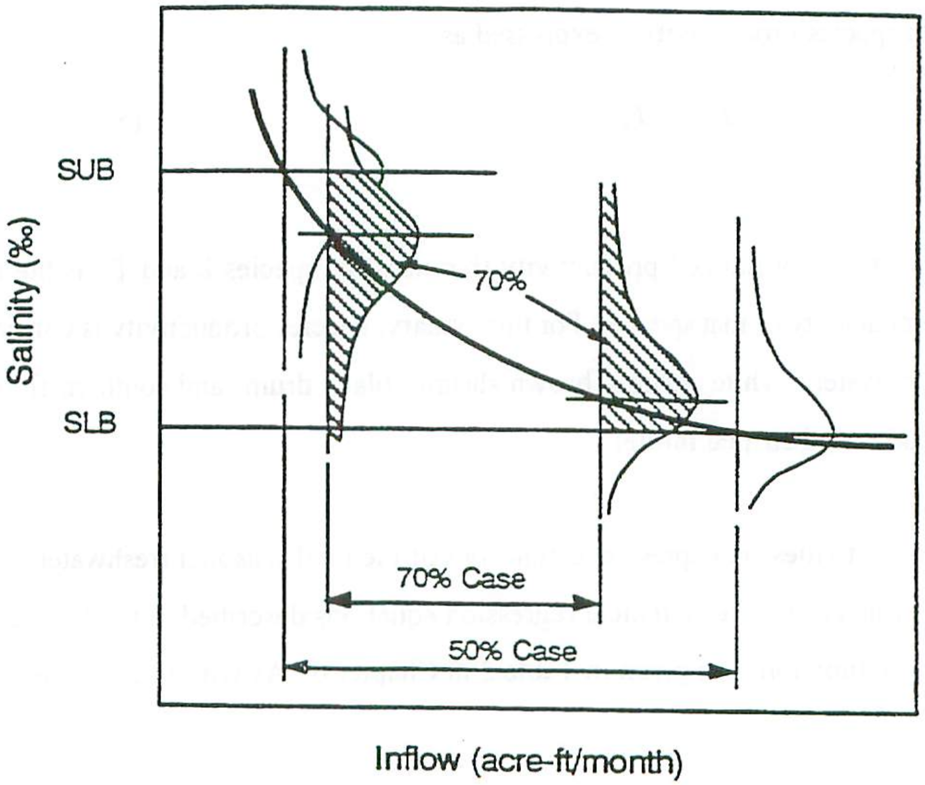


Figure 3. Feasible Range of Inflows for 70% Salinity Probability (Source: Longley, ed., 1994)

productivities are probabilistic variables. Similarly, the productivity constraint can be rewritten as the following chance constraint:

$$\mathbf{Prob}[H_k \geq T_k] \geq HarP_k \tag{6}$$

where HarP_k is the probability that the productivity constraint for species k will be satisfied.

Additional constraints are applied to the productivity in the form of upper and lower bounds on the ratio of the biomass density of each species (in biomass per hectare) to the total biomass density of the nine species combined. These constraints are intended to keep the species distribution of biomass densities within ranges that could be expected to occur naturally, thus avoiding freshwater inflow regimes that give radially different biomass density distributions than could be expected historically.

The constraints on population density ratios is expressed as:

$$RTMIN_k \leq \frac{H_k}{\sum_k H_k} \leq RTMAX_k \tag{7}$$

where

$$RTMIN_k = \frac{(\bar{H}_k - 2 * HSE_k)}{\sum_k \bar{H}_k} \tag{8}$$

and

$$RTMAX_k = \frac{(\bar{H}_k + 2 * HSE_k)}{\sum_k \bar{H}_k} \qquad (9)$$

where $\bar{H}_k$ and HSE_k are the mean and standard error, respectively, of the historical population density of species k.

Inflow Constraints

The freshwater inflows from the Lavaca and Colorado River basins are subject to additional monthly, seasonal and annual limits. The inflows in month t from the Lavaca River and Colorado River basins (QL_t and QC_t, respectively) have both upper and lower bounds:

$$QL_t^{\min} \le QL_t \le QL_t^{\max} \qquad (10)$$

and

$$QC_t^{\min} \le QC_t \le QC_t^{\max} \qquad (11)$$

where $QL^{min}{}_t$ and $QL^{max}{}_t$ are the minimum and maximum allowable inflows in month t from the Lavaca River basin, respectively; and $QC^{min}{}_t$ and $QC^{max}{}_t$ are the minimum and maximum allowable inflows in month t from the Colorado River basin, respectively. For the Lavaca River inflows, the upper limits are set at average historical inflow values, while the lower limits are the ten percent exceedence frequency. For the Colorado River inflow limits, the average measured flows at the Bay City streamgage were used as the upper bound, while the lower limits are the ten percent exceedence frequency of the historic estimated inflows. Average inflow were selected as the upper inflow bounds in past because limiting inflows to no more than their median historic values did not supply sufficient inflows to meet salinity limits. The inflow limits are indicated in Table 2. For reference purposes, the historic average monthly Colorado River inflows are given in Table 2.

The total of the monthly upper limits on Colorado River stream gage flows at Bay City in Table 2 is greater than the annual average historical Colorado River inflows. The limits on Colorado River inflows reflects future inflows to Matagorda Bay where virtually all the flow at Bay City will go into the Bay. Historical flows at Bay City only partially entered the Bay since there was a direct outlet to the Gulf of Mexico prior to completion of the Corps of Engineers' Mouth of the Colorado River Project in 1992. In the future, that will not be the case.

Table 2. Monthly Inflow Limits (1000 Acre-Feet) for Lavaca and Colorado River Basins

Month	Lavaca River Basin		Colorado River Basin		Estimated Historic Average Inflows from the Colorado River
	Lower Limit	Upper Limit	Lower Limit	Upper Limit	
January	1.5	52.0	29.8	146.6	105.0
February	2.8	51.0	26.6	150.8	104.0
March	2.8	39.0	21.2	142.9	100.0
April	3.5	66.0	21.9	166.8	116.0
May	5.6	95.0	27.8	244.5	153.0
June	4.5	93.0	19.4	240.1	151.0
July	2.2	28.0	17.3	107.0	81.3
August	1.6	16.0	16.9	59.4	52.9
September	5.4	67.0	25.3	111.7	80.2
October	1.4	49.0	27.9	136.4	91.6
November	0.6	43.0	25.2	143.3	98.0
December	1.2	41.0	22.3	145.9	109.0

In addition to monthly bounds, the inflows are subject to limits on a "seasonal" basis. These seasonal constraints are necessary to keep the flows within the ranges used to develop the salinity and productivity regression equations.

For the productivity equations, there are six seasons, each comprised of adjacent months beginning in January. The limits on flows in seasons related to the productivity equations are:

$$W_s^{\min} \le W_s \le W_s^{\max} \tag{12}$$

where

$$W_s = QCS_s + QLS_s + QUS_s \tag{13}$$

$$QCS_s = \sum_{n=a,a+1} QC_n \tag{14}$$

$$QLS_s = \sum_{n=a,a+1} QL_n \tag{15}$$

$$QUS_s = \sum_{n=a,a+1} QU_n \tag{16}$$

where QCS_s, QLS_s, and QUS_s are the inflow in season s from the Colorado, Lavaca and all other contribution drainage basins, respectively, and $a=2*(s-1)+1$. The seasonal limits on total inflow in Eq. 12 are given in Table 3.

The annual inflow from each of the major contributing river basins can also be bounded by:

$$TOL^{\min} \le TOL \le TOL^{\max} \tag{17}$$

and

$$TQC^{\min} \leq TQC \leq TQC^{\max} \qquad (18)$$

where TQL and TQC are the total annual inflow from the Lavaca and Colorado River basins, respectively; TQL^{min} and TQL^{max} are the minimum and maximum allowable annual inflows from the Lavaca River basin, respectively; and TQC^{min} and TQC^{max} are the minimum and maximum allowable annual inflows from the Colorado River basin, respectively.

Table 3. Seasonal and Monthly Total Inflow Limits for Productivity Regression Equations

Season	Lower Inflow Limit (1000 Acre-Feet)	Upper Inflow Limit (1000 Acre-Feet)
January-February	94	1,170
March-April	79	1,594
May-June	101	2,803
July-August	101	927
September-October	49	1,956
November-December	66	1,243
April	53	365
May	107	447

The seasonal estuarine inflows from the Colorado and Lavaca Rivers are treated as independent decision variables in the TXEMP model. However, there are definite seasonal and annual correlations between the inflows from the separate river basins, with similar weather patterns often occurring simultaneously in both. Such correlations, however, are not perfect, and inflow conditions do vary widely between the basins even within the same season.

To reflect the typical range of inflows between the seasonal and annual basin inflows, additional constraints are included to require that the ratios of the seasonal and annual inflows be within particular ranges around the historical ratios. These ranges are set initially at ten standard deviations about the mean so that the constraints would not influence the calculated inflows, but they were varied to determine the sensitivity of the model solution to these constraints.

The constraints are:

$$RQLCS_s*(1-\gamma_s) \leq QLS_s/QCS_s \leq RQLCS_s*(1+\gamma_s) \qquad (19)$$

$$RQLCT*(1-\xi) \leq TQL/TQC \leq RQLCT*(1+\xi) \qquad (20)$$

where $RQLCS_s$ and RQLCT are the historical ratios of Lavaca River basin inflows to those of the the Colorado River basin in season s and annually, respectively, and γ_s and ξ are constants.

The inflows from the Lavaca and Colorado River Basins are only a part of the total freshwater inflows to the estuary. The remaining inflows are from coastal river basins. These are assumed to be unregulated and uncontrollable and are thus not considered as decision variables in the TXEMP. However, these inflows must be specified to compute the seasonal inflows used in Eqs. 5 through 9. Thus, unregulated inflows can have a significant influence on the monthly and seasonal optimal inflows from the Lavaca and Colorado River basins computed by the TXEMP.

The inflows from the two major river basins and the unregulated inflows from the coastal basins are correlated in the historical record: years of high flows from the rivers are also years of high coastal inflows and similarly years of drought occur simultaneously over the coastal and major adjacent river basins. To appropriately represent this interconnected condition, a constraint is applied to the results of the TXEMP to force the annual inflows to be proportion to the historical inflow pattern adjusted for the new conditions in the Colorado River delta. The constraint requires that the ratio of the sum of the annual inflows from the two river basins to the annual inflow from the remaining drainage area (TQCR) is within a certain percentage (α) of the historical ratio of these two annual inflows (RHQ) as adjusted for changed inflow condition at the Colorado delta. This is represented by:

$$RHQ*(1-\alpha/2) \leq (TQC+TQL)/TQCR \leq RHQ*(1+\alpha/2) \qquad (21)$$

Nutrient Constraint

The nutrient constraint is included to insure that sufficient inflows, and their associated nutrients, occur to maintain the present nitrogen balance in the estuary. The prior analysis in this study of the nutrient budget for the estuary indicated that the total annual inflow should be 1.71 million acre-feet to provide the needed nitrogen. Thus the nutrient constraint can be expressed as the following total inflow limit:

$$TC \geq 1.71 \qquad (22)$$

where TQ is the total estuarine freshwater inflow (in million acre-feet) from all drainage basins, both major river and coastal.

ESTIMATION OF FRESHWATER INFLOWS NEEDS

The TXEMP model was solved for a variety of constraint and objective function combinations. The first solution of TXEMP was the set of inflows needed to maximize the sum of the normalized species biomass subject to all the constraints. The normalized species biomass was computed by dividing each species' estimated biomass by its historical average annual biomass. The computed freshwater inflow needs are termed the Target Freshwater Inflow Needs (FIN).

The second inflow need estimates were determined by finding the minimum total annual inflow needed to meet only the salinity constraints under drought conditions (Table 1). These freshwater inflows are designated as the Critical Freshwater Inflow Needs. Each of these analyses are described in the following sections.

Target Freshwater Inflow Needs

The TXEMP model was solved to find the inflows that will provide the maximum total normalized biomass of all species listed in Table 2 in Chapter 6 while meeting all the constraints (Eqs. 1 to 22). The constraints on the relative annual and seasonal inflows between the Colorado and Lavaca Rivers (Eqs. 19, 20 and 21) were set.

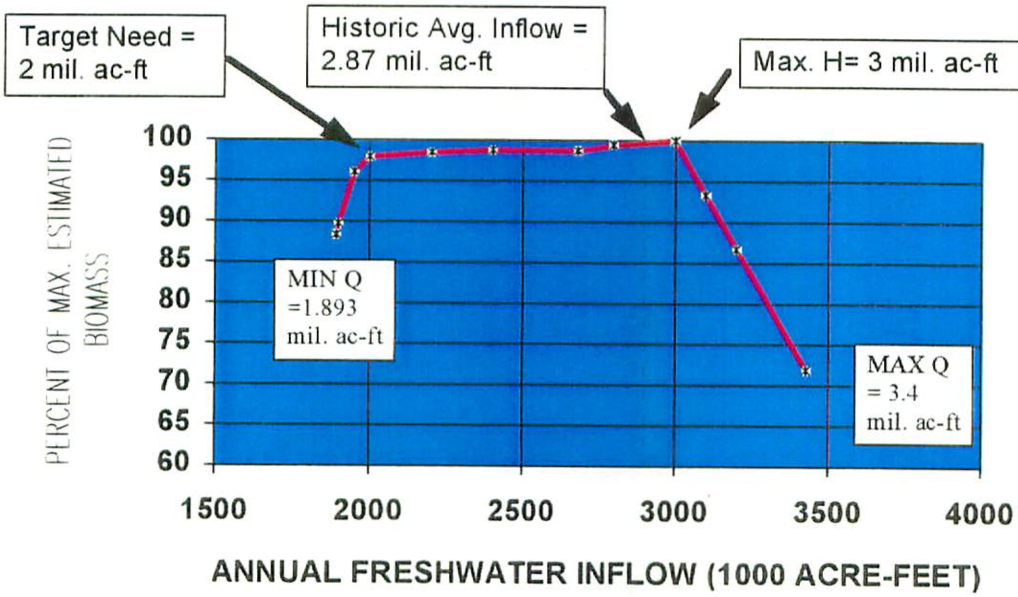


Figure 4. **Harvest Performance with Variation in Annual Freshwater Inflows as Predicted by TXEMP Model**

TXEMP was executed iteratively to determine the maximum biomass that could be provided for a variety of annual freshwater inflows. The resulting relative changes in biomass are indicated in Figure 4. The maximum estimated biomass (1.78 million pounds per 1,000 acres) is predicted at an annual inflow of 3.0 million acre-feet (MAX H), but the biomass changes little over a wide range of annual inflows. In fact, the predicted biomass is within about 98 percent of the estimated maximum from 2 to 3 million acre-feet of inflow. The biomass at the minimum inflow level (MIN Q) is estimated at 1.54 million pounds per 1,000 acres.

Given this insensitivity of population to inflows, it is prudent to select a Target FIN that considers the marginal benefits to biomass with additional freshwater inflows. A clear breakpoint in biomass increases per unit of annual inflow increase occurs at 2 million acre-feet (see Figure 4). There is a significant decrease in the rate of biomass increase at inflows greater than that level. Further, at that level of inflow, over 95 percent of the maximum estimated biomass is predicted to occur.

Therefore, the Target FIN was selected as 2 million acre-feet annually. The TXEMP model calculated the separate annual inflow needs from the Lavaca and Colorado Rivers at 346,200 and 1,033,100 acre-feet annually, respectively. The remaining contributing areas are estimated to provide an additional 620,700 acre-feet yearly, or 42% of the sum of the inflows from the two river basins. This percentage is the historical average percentage of the inflows from the non-river basin drainage basins to the sum from the two rivers, when adjusted for change in the Colorado River delta. Monthly inflow needs from each of these sources are given in Table 4. These estimates are subject to verification and possible modification using the TXBLEND salinity model to simulate bay-wide salinity patterns under this inflow regime.

The monthly Lavaca and Colorado River Target FIN are compared to the historical river flows in Figures 5 and 6. For the inflow regime specified by the Target FIN, the sum of the individual species biomasses is estimated at 1.75 million biomass per 1,000 acres. This is approximately twice the sum of the average historical density of 1.1 million pounds per 1,000 acres. All nine species have estimated biomass greater than their historical average, except for Black Drum which is at 82% of its average biomass..

The estimated biomass distribution among species for the historical freshwater inflows (Figure 7) does not vary greatly with the biomass distribution with target freshwater inflows (Figure 8). The species with the greatest biomass is Gulf Menhaden followed by Eastern Oyster and White

Shrimp. The estimated biomasses using the Target FIN should be viewed with caution since they exceed historical maximum biomasses for some species.

Table 4. Target Freshwater Inflow Needs (1000 Acre-Feet) for the Matagorda Bay System

Month	Colorado River Inflows	Lavaca River Inflows	Other Contributing Basin Inflows
January	44.1	14.8	35.4
February	45.3	14.5	40.3
March	129.1	33.9	32.9
April	150.7	57.3	44.1
May	162.2	60.1	76.3
June	159.3	58.8	71.4
July	107.0	28.0	59.6
August	59.4	16.0	24.8
September	38.8	21.9	90.6
October	47.4	16.0	78.2
November	44.4	12.8	35.4
December	45.2	12.2	31.7
Basin Total Inflow	1033.1	346.2	620.7
Total Inflow	2000.0		

These high biomass estimates occur because seasonal inflow constraints were broad and allowed flows highly advantageous to productivity but substantially deviating from historical patterns to develop in some months. The Target FIN are substantially less than the historical average inflows during the fall and winter and late spring (May and June) seasons and approximately equal to the average inflow in the remaining months. In deviating from the historical inflow distribution, the Target needs avoid inflows in seasons that reduce biomass while adding seasonal inflows that

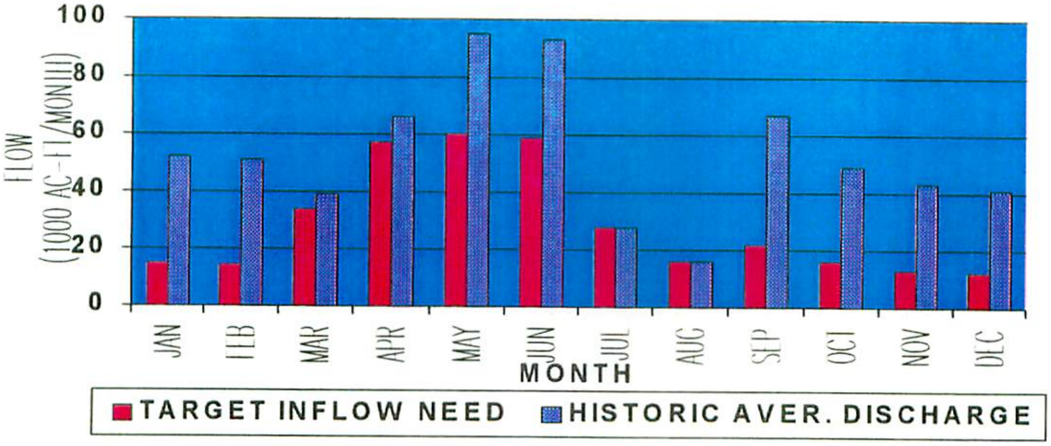


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Figure 5. Target Freshwater Inflow Needs and Average Historical Discharge for Lavaca River Basin

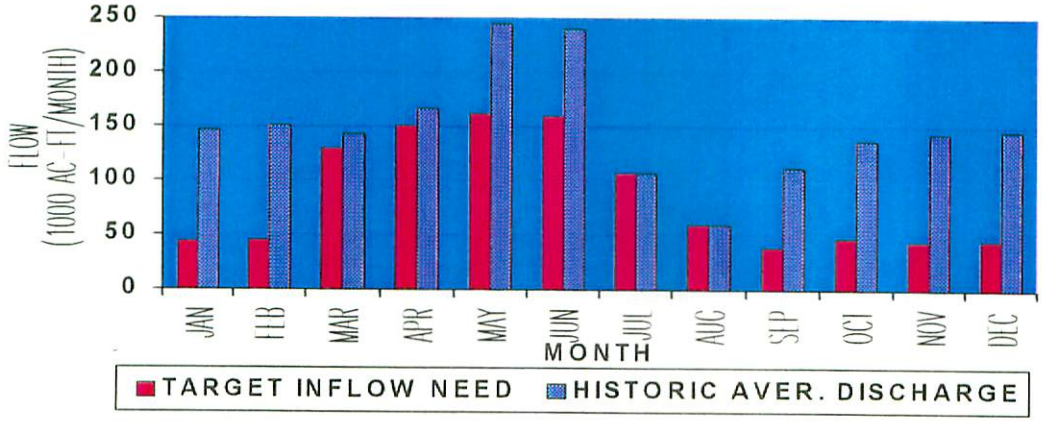

Figure 6. Target Freshwater Inflow Needs and Average Historical Discharge of Colorado River Basin

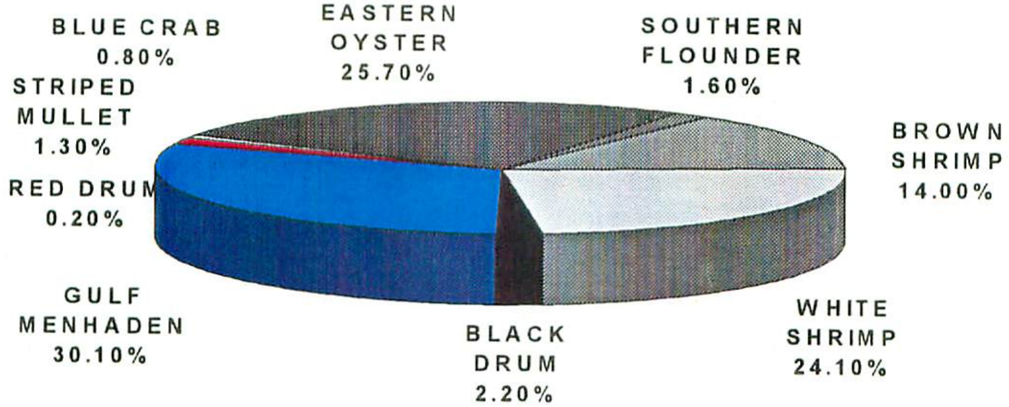

Figure 7. Average Biomass Distribution From Historical Sampling

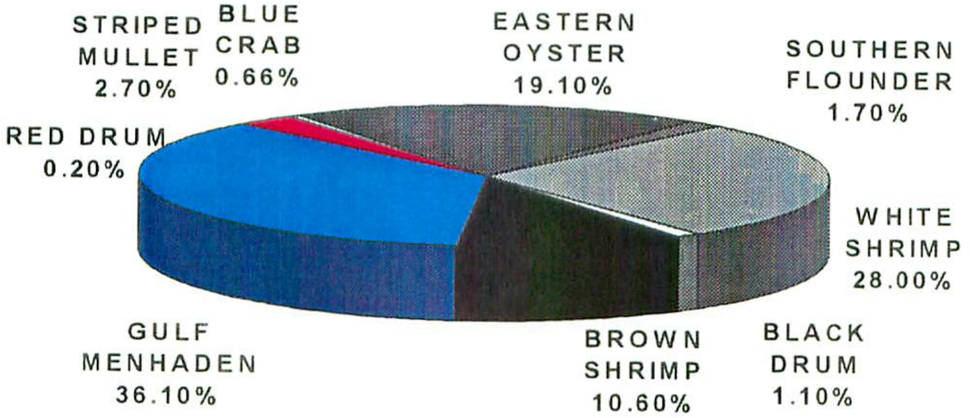

Figure 8. Estimated Fishery Biomass Distribution Under Target Inflow Needs

benefit the species. For example, in Table 2 of Chapter 6, the biomass equations show that inflows in January and February do not benefit any of the species, and in fact are detrimental to populations for five of the species. Thus it is not surprising that the target inflows are low in January and February. The inflow for these months is provided for salinity control to keep the salinity within the upper allowable limits.

The balancing constraints for the inflow between the Lavaca and Colorado River basins were removed to determine if the annual and seasonal inflows significantly changed. The results from TXEMP were substantially different fro total annual inflow less than 2 million acre-feet, but essentially equal at annual inflows of 2 million acre-feet or greater. Therefore, no adjustment was made in the inflow needs from those given in Table 4.

The estimated monthly average salinity is generally at or near the upper salinity limits set for both upper Lavaca and eastern Matagorda Bays (see Figures 9 and 10). The upper salinity limit is never equaled in upper Lavaca Bay. The upper salinity limit is reached in eastern Matagorda Bay in January, February, July and October. As noted earlier in this chapter, the upper limit for salinity in August (Table 1) was selected at 20 ppt rather than the proposed 15 ppt from TWDB and TPWD. The estimated salinity in August is about 17 ppt for Eastern Metagorda Bay (Figure 9) and about 14 ppt in upper Lavaca Bay (Figure 10). The former salinity are sufficiently close to the 15 ppt limit in August so that there is little impact on the inflow need estimates by not adopting the TWDB and TPWD proposed upper limit for August.

TXBLEND SIMULATIONS

The TxBLEND hydrodynamic and salinity transport model was used to simulate salinity conditions in the Matagorda Bay system with the Target FIN indicated in Table 4. The resulting simulated salinities are shown in Figures 19 through 30 of Chapter 6.

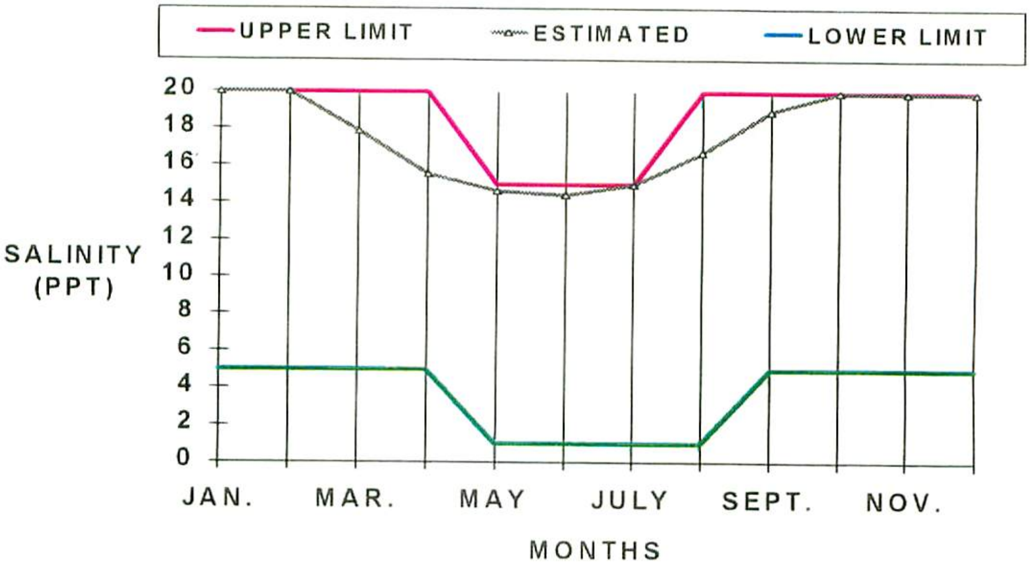

Figure 9. Eastern Matagorda Bay Salinity Limits and Estimated Salinity for Target Inflow Needs

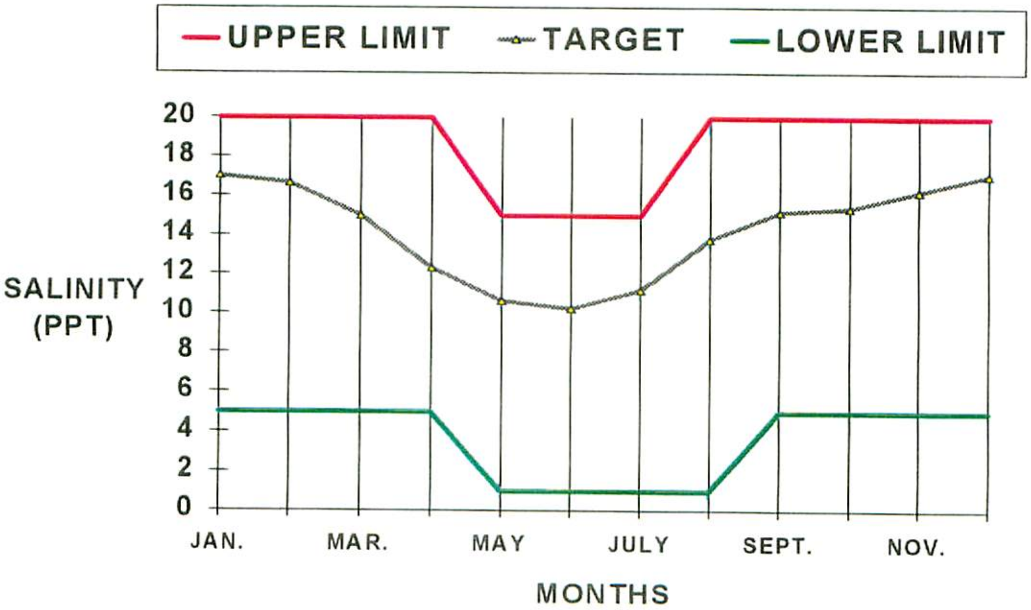

Figure 10. Upper Lavaca Bay Salinity Limits and Estimated Salinity for Target Inflow Needs

The estuary is divided into salinity zones as described in Chapter 6. Given the changes in salinity regimes anticipated in the eastern arm of Matagorda Bay as a result of the diversion of the Colorado River, there are no recent biological data to support a direct delineation of salinity zones in that arm. There are, however, good historical data on oyster populations in Matagorda Bay around the turn of the century, and the natural reefs that supported those fisheries are still present in the eastern arm of the bay. Consequently, the historical distribution of oysters were used as a baseline condition for the delineation of salinity zones in the eastern portion of the bay (Figure 18, Chapter 6).

In Figure 18 of Chapter 6, Zone IV represents relatively stable, outer bay salinities typically above 25 ppt. Zones III and II are intermediate regions with salinities varying from 25 to 15 ppt in Zone III (optimal salinity conditions for oyster reproduction and survival) and 20 to 15 ppt to near freshwater conditions near the river mouth in Zone II (Zone I of Green et al. (Chapter 7 *in* Longley 1994)).

Comparing the salinities in Figures 19 through 30 of Chapter 6 for the zones delineated in Figure 18, of Chapter 4 it is clear that the Target freshwater inflows result in values that meet the desired salinity conditions in all zones.

Critical Freshwater Inflow Needs

The TXEMP model was solved to find the minimum annual inflow needed to maintain the salinity near the river mouths within the limits indicated for drought conditions in Table 1. No other constraints were imposed on the inflows. These inflow needs are termed the critical needs since they are intended to provide a fishery sanctuary habitat during the most severe droughts. From this sanctuary, the finfish and shellfish species could be expected to recover and repopulate the bay when more normal weather conditions returned.

The optimal solution found by TXEMP for this case was to provide a total annual freshwater inflow of about 287,400 thousand acre-feet. Approximately 27,100 and 171,120 acre-feet would be provided from the Lavaca and Colorado River basins, respectively, with the remaining 89,200 acre-feet coming from the other contributing drainage basins. The monthly inflow needs are indicated in Table 5. The estimated salinity in upper Lavaca and eastern Matagorda Bays are at the drought condition upper limits of 25 ppt. given in Table 1.

The total annual inflow is less than the historical minimum inflow used to develop the statistical relationships species biomass densities. Thus, the species biomass predictive equations cannot be used with confidence to assess population changes for the critical inflow needs. Most certainly the biomasses will be dramatically less overall than the historical average.

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Matsumoto, Junji, Gary Powell, and David Brock. "Freshwater-Inflow Need of Estuary Computed by Texas Estuarine MP Model," Journal of Water Resources Planning and Management, ASCE, Vol. 120, No. 5, September/October, 1994.

Table 5. Critical Freshwater Inflow Needs (1000 Acre-Feet) for the Matagorda Bay System

Month	Colorado River Inflows	Lavaca River Inflows	Other Contributing Basin Inflows
January	14.26	2.26	5.08
February	14.26	2.26	5.08
March	14.26	2.26	4.45
April	14.26	2.26	6.14
May	14.26	2.26	10.70
June	14.26	2.26	10.70
July	14.26	2.26	8.92
August	14.26	2.26	3.57
September	14.26	2.26	13.38
October	14.26	2.26	11.59
November	14.26	2.26.	5.00
December	14.26	2.26	4.46
Basin Total Inflow	171.1	27.1	89.2
Total Inflow	287.4		

CHAPTER 8

FUTURE STUDY NEEDS FOR THE LAVACA-COLORADO ESTUARY

INTRODUCTION

The amount of inflow required to continue to maintain a healthy estuarine community is difficult to determine due to our limited understanding of the many interacting processes that occur in this system. Additional studies are needed to verify processes used in this study and to develop improved relationships between freshwater inflows and important indicators of estuarine conditions.

NUTRIENTS & PRIMARY PRODUCTIVITY

Additional information is needed of the nutrient concentrations and loadings per unit volume required to maintain a healthy algal population during critical periods for finfish and shellfish nourishment.

Nitrogen measurements should be taken at near-shore locations in the Gulf to determine near-shore concentrations, and locations and concentrations of the bay plume water. Nitrogen measurements (DIN and TKN) should continue to be taken at sites in the bay and at critical river and creek sites. The USGS water quality monitoring site at Midfield should be re-established. TNRCC monitors should begin to collect TKN data at present stations on rivers, creeks, and in the bay. Bottom water samples should be taken at critical sites in the bay, rivers and creeks.

Better estimates of ungaged flow nitrogen concentrations also need to be determined. Ungaged nitrogen concentrations could be determined by establishing monitoring sites on creeks that would be representative of the local watershed and that did not have a point source discharge located upstream of the sampling site.

Nitrogen loading associated with stream bed load should be studied. This could be a significant source of nutrients for the estuary.

Nitrogen dynamics in sediments of the Lavaca-Colorado Estuary should be studied to determine the storage capacity of nitrogen in the sediments, the flux if nitrogen in and out of the sediments, nitrogen fixation, denitrification, and permanent losses to the sediments. Uncertainty of the reliability of these values weakens the resolution of this analysis.

SALINITY

The inflow-salinity relationships developed for the eastern arm of Matagorda Bay rely on three years of data. Continued salinity data collection is essential to confirm or modify the relationships used in this study. Hourly monitoring at Sites 340 and 350 should continue so that the relationship between salinity concentrations and inflow can be used to determine what impact managed releases have upon the bay system. Hourly dissolved oxygen data at these sites can be used to determine primary productivity and community metabolism of the eastern arm of Matagorda Bay.

After an additional five years of data, the predictive equations for salinity should be reexamined and corrected if necessary. If those relationships change, then the target and critical freshwater inflow needs should be revised.

BIOLOGICAL PRODUCTIVITY

A relationship between nutrients, primary productivity, and secondary productivity should be developed to better understand the impact of nutrient loading upon the fisheries. Primary productivity measurements should continue to be taken at the two bay sites influenced by the Colorado River. Additional primary productivity measurement sites should be established to measure the influences of the Lavaca River.

The benthics study support by the TWDB and the LCRA to determine the effects of freshwater inflows should continue at least through a two year dry period.

Secondary productivity is measured effectively by the TPWD's ongoing fish and shellfish sampling program. The TPWD fish and shellfish monitoring program should continue.

SEDIMENTATION

The on-going study of sedimentation needs from the Lavaca River for the Lavaca River delta should be completed. The inflow needs from the Lavaca River should be review and revised, as necessary, based on the identified sedimentation needs.

The accumulation of sediment in the Colorado River delta at the terminus of the diversion channel should be monitored to document the extent of new marsh creation.

EAST MATAGORDA BAY

A separate freshwater inflow study of East Matagorda Bay should be conducted. Although this system does not have a managed river flowing into it, other management decisions need to be made about this system, such as the addition of new channels or the closure of existing ones.

APPENDIX-A

STUDY AGREEMENT

MEMORANDUM OF AGREEMENT

AMONG THE LOWER COLORADO RIVER AUTHORITY
TEXAS PARKS AND WILDLIFE DEPARTMENT
TEXAS WATER DEVELOPMENT BOARD AND
TEXAS WATER COMMISSION

WHEREAS, the Lower Colorado River Authority ("LCRA"), is a conservation and reclamation district created by the State of Texas with statutory responsibility for control and management of the waters of the Lower Colorado River watershed; and

WHEREAS, the Texas Parks and Wildlife Department ("TPWD") is the state agency with primary responsibility for protecting fish and wildlife resources in the State of Texas; and

WHEREAS, the Texas Water Development Board ("TWDB") is the state agency with primary responsibility to plan and finance the water resource needs of Texas; and

WHEREAS, the Texas Natural Resource Conservation Commission ("TNRCC") is the state agency given primary responsibility for implementing the constitution and laws of the state related to water; and

WHEREAS, the bays and estuaries of Texas are vital economic and natural resources for all citizens of Texas, and freshwater inflows are critical to providing nutrients, sediments and proper salinity balances to preserve and maintain the sound environment of the bays and estuaries; and

WHEREAS, the Lavaca-Colorado Estuary is a major estuary on the Texas Gulf Coast, ranking third in the state in surface area, and the Colorado River is the most important source of freshwater inflows to the Lavaca-Colorado Estuary; and

WHEREAS, LCRA is required by the TNRCC to submit amendments to the LCRA <u>Water Management Plan</u> to take into account freshwater inflow needs of the Lavaca-Colorado Estuary from the Colorado River; and

WHEREAS, establishing the freshwater inflow needs from the Colorado River is vital to the LCRA's management of its water rights in the Colorado River Basin for all beneficial purposes; and

WHEREAS, TWDB and TPWD are mandated by §16.058 of the Texas Water Code to study the ecology of the bays and estuaries and evaluate the needs for freshwater inflows; and

WHEREAS, TNRCC and TPWD are mandated by §11.1491 of the Texas Water Code to review studies prepared under §16.058, to determine inflow conditions necessary for the bays and estuaries; and

WHEREAS, State funding limitations will delay determination of freshwater inflow needs for the Lavaca-Colorado Estuary by TWDB and TPWD until at least February 1995; and

WHEREAS, consistent with Texas law and public policy, LCRA, TNRCC, TWDB, and TPWD mutually desire to protect and maintain a proper ecological environment and the health of related living marine resources in the Lavaca-Colorado Estuary.

NOW, THEREFORE, in consideration of the following promises, covenants, conditions, and the mutual benefits to accrue to the parties to this Agreement, the parties, desiring to cooperate in providing functions and services, agree as follows:

I
RESPONSIBILITIES OF EACH PARTY

A. Lower Colorado River Authority

(1) LCRA agrees to adapt or modify existing methods and apply those methods to compute alternative freshwater inflow needs for the Lavaca-Colorado Estuary by performing the tasks set forth in the Scope of Work in Attachment A, which is attached hereto and incorporated as if fully set forth herein (hereinafter referred to as the "study"). Completion of the study is contingent on the timely technical assistance to LCRA from the other participating parties. This assistance includes but is not limited to the transfer of technical information and procedures and advice on their usage to fulfill the purposes of this Agreement.

(2) Project management responsibility for the study shall rest solely with LCRA. LCRA shall appoint an individual to serve as the Project Manager and Chair of the Advisory Committee for this Agreement.

(3) LCRA agrees to make available to all parties to this Agreement all data, computer models, and information developed by LCRA in the study at any time upon reasonable written notice. At the completion of the study, LCRA will provide all data developed by LCRA to the Texas Natural Resources Information System in a computer-compatible format. Nothing herein shall be construed as limiting the LCRA's use, control, or ownership of any of the data developed in performing the study.

(4) LCRA may solicit funding from the parties to this Agreement and from other sources to complete the study.

(5) LCRA agrees to prepare a report on the methodology, data and results of the computation of alternative freshwater inflow needs of the Lavaca-Colorado Estuary. LCRA shall consider any modifications to the draft of the final report as recommended by any member of the Advisory Committee. If any party to this Agreement disagrees with any statements in the draft study report, LCRA is obligated to include a rebuttal statement in the final report. There will be no recommendations in the draft or final study report regarding adoption

of freshwater inflow needs presented unless all parties are in unanimous agreement. LCRA shall furnish all parties to this Agreement five (5) copies of the final report. The other parties in this Agreement reserve the right to take exception to any or all of the final report.
(6) LCRA reserves the right to recommend revisions to the Water Management Plan as it considers appropriate based on the findings of the study.

B. **Texas Water Development Board**
(1) TWDB shall assist in the transfer of technical information and procedures to LCRA pertinent to the evaluation of the needs for freshwater inflows to the Lavaca-Colorado Estuary. TWDB shall advise LCRA in using such information and procedures to fulfill the purposes of this Agreement.
(2) TWDB shall appoint an agency representative to serve on the Advisory Committee for this Agreement. This individual shall also act as the contact person for facilitating the transfer of technical information between TWDB and LCRA.
(3) TWDB shall make available to all parties in this Agreement the data and analyses completed by TWDB related to the 1993 intensive inflow study of Matagorda Bay and associated bays. These data and analyses shall be provided by November 1, 1993. TWDB will not be responsible for delivering gaged and ungaged inflow data related to the 1993 intensive inflow study, but TWDB will assist LCRA in developing gaged and ungaged inflows for the 1988 through 1992 period.

C. **Texas Parks and Wildlife Department**
(1) TPWD shall assist in the transfer of technical information and procedures to LCRA pertinent to the evaluation of the needs for freshwater inflows to the Lavaca-Colorado Estuary. TPWD shall advise LCRA in using such information and procedures to fulfill the purposes of this Agreement.
(2) TPWD shall appoint an agency representative to serve on the Advisory Committee for this Agreement. This individual shall also act as the contact person for facilitating the transfer of technical information between TPWD and LCRA.

D. **Texas Natural Resource Conservation Commission**
(1) TNRCC shall assist in the transfer of technical information and procedures to LCRA pertinent to the evaluation of the needs for freshwater inflows to the Lavaca-Colorado Estuary. TNRCC shall advise LCRA in using such information and procedures to fulfill the purposes of this Agreement.
(2) TNRCC shall appoint an agency representative to serve on the Advisory Committee for this Agreement. This individual shall also act as the contact person for facilitating the transfer of technical information between TNRCC and LCRA.

II
ADVISORY COMMITTEE

A. **Membership**
The Advisory Committee shall consist of one representative

from each participating party to this Agreement and the Lavaca-Navidad River Authority ("LNRA") should that agency choose to participate. LCRA shall appoint an individual to serve as Chair of the Advisory Committee for this Agreement.

B. **Duties**
The purpose of the Advisory Committee is to: (1) review study scope, schedule and technical methods; (2) facilitate inter-agency communication and cooperation; (3) formulate alternative management objectives required for the analyses; and (4) evaluate results of the analyses and make consensus recommendations on freshwater inflows and water management alternatives. The Committee shall be chaired by LCRA and shall meet quarterly at times and places chosen by LCRA. LCRA shall provide the Committee quarterly written status reports. LCRA shall provide draft reports to the Committee on each of the three major tasks identified in Appendix A according to the approximate dates shown in Figure 2. These reports will include the methodology, data and results of these tasks. The Committee members shall have a minimum sixty (60) day review period to review, comment, and make recommendations for changes. LCRA shall provide copies to the Committee of the draft final report on the methodology, data and results of the computation of alternative freshwater inflow needs of the Lavaca-Colorado Estuary. The Committee members shall have a minimum sixty (60) day review period to review, comment, and make recommendations for changes. LCRA will review the comments and recommendations with the Committee to attempt to resolve any differences.

III
GENERAL CONDITIONS

A. **Final Report**
The final report under the terms of this Agreement is not intended to replace the reporting requirements on the TWDB and TPWD under §11.1491 of the Texas Water Code. The results from the studies conducted under this Agreement may be used by TWDB and TPWD to fulfill the obligations under §11.1491.

B. **Term of Agreement**
The term of this Agreement shall be from October 1, 1993 until June 1, 1995.

C. **Ability To Perform**
Should any party's ability to perform its obligation under this Agreement depend upon the appropriation of funds or budget approval of funds from any governing body for the term of this Agreement and the funds are not appropriated or budget is not approved, upon written notice by the affected party to all other parties, this Agreement, or part thereof not funded, shall be terminated.

D. **Notice Of Termination**
Any party may terminate its participation in this Agreement upon thirty (30) days written notice to the other parties for any reason or for no reason.

E. **Contractors And Subcontractors**
Any use by any party of contractors or subcontractors in the performance of this Agreement shall be by unanimous consent of all parties.

F. **Cooperation of Parties**
(1) It is the intention of the parties that the details of providing the services in support of this Agreement shall be worked out, in good faith, by the parties.
(2) All parties shall continue their planned data collection programs in the Lavaca-Colorado Estuary during the duration of this Agreement. All data collected to complete this Agreement shall be shared among the participating parties.

G. **Notices**
Any notices required by this Agreement to be in writing shall be addressed to the respective party as follows:

Texas Natural Resource Conservation Commission
Attn. Mr. Bruce Moulton
1700 North Congress Ave.
P.O. Box 13087
Austin, Texas 78711-3087

Texas Water Development Board
Attn. Mr. Gary Powell
1700 North Congress Ave.
P.O. Box 13231
Austin, Texas 78711-3231

Texas Parks and Wildlife Department
Attn. Dr. Warren Pulich
4200 Smith School Road
Austin, Texas 78744

Lower Colorado River Authority
Attn. Dr. Quentin Martin
P. O. Box 220
Austin, Texas 78767-0220

H. **Effective Date Of Agreement**
This Agreement is effective upon execution below by all parties. By signing this Agreement, the signatories

acknowledge that they are acting under proper authority form their governing bodies.

Texas Natural Resource Conservation Commission

By: Anthony C. Grigsby

Title: EXECUTIVE DIRECTOR

Date: 10/20/1993

Texas Water Development Board

By: Craig D. Pede

Title: EXECUTIVE ADMINISTRATOR

Date: 10/20/1993

Parks and Wildlife Department

By: Andrew Sansom

Title: EXECUTIVE DIRECTOR

Date: 10/20/1993

Lower Colorado River Authority

By:

Title: GENERAL MANAGER

Date: 10/20/1993

ATTACHMENT A

SCOPE OF WORK

INTRODUCTION

This study will be a comprehensive assessment of the need for freshwater inflows to maintain and enhance the natural ecology of the Lavaca-Colorado Estuary (Figure 1). This assessment will use existing data and analyses from the Texas Water Development Board (TWDB) and Texas Parks and Wildlife Department (TPWD) in combination with additional data collection and evaluation by LCRA. The inflow needs will be computed separately for each of the Lavaca and Colorado Rivers and ungaged coastal areas except where the commingling of the impacts prohibits treating them in isolation. The freshwater inflow needs will be computed for a variety of alternative management options. This study will be closely coordinated with the activities of the LCRA Comprehensive Water Quality Assessment Program.

Emphasis will be on the estuary west of the Colorado River in determining freshwater inflows from the Colorado and Lavaca Rivers and coastal basins. To the extent possible, the impact of freshwater inflows on the environmental conditions in East Matagorda Bay will be evaluated. Full analysis of East Matagorda Bay will be contingent on adequate external funding to allow LCRA to contract for an evaluation of the hydrologic, salinity and biological data collected to date on the conditions in this bay.

PROJECT TASKS

Task 1: Technical Studies: There are three major technical tasks in this project. These involve assessing the biological, chemical and hydrologic interrelations in the estuary.

1. **Hydrology:** LCRA will evaluate historical freshwater inflows to the estuary. This task will revise inflow estimates already developed by TWDB to adjust for the new Colorado River Delta configuration. In addition, LCRA will participate in the TWDB intensive inflow study of the estuary to collect tidal, flow and water quality data reflecting the new channel modifications at the Colorado River Delta. LCRA will use this information to revise and recalibrate the TWDB TXBLEND.G hydrodynamic model of the estuary to account for the new geomorphology.

2. **Water Quality:** LCRA will continuously monitor salinity and other water quality field parameters in the river at Bay City and at two points in the eastern arm of Matagorda Bay. In the same part of the river and estuary, LCRA will conduct periodic sampling of nutrients, sediments and other water quality parameters. Data for the remainder of the estuary will be supplied by TWDB and TPWD. LCRA, in concert with TWDB, will develop a nutrient balance for the estuary. LCRA will develop

quantitative relationships between inflows from the Colorado and Lavaca Rivers, both separately and jointly, and salinity, nutrient deficit and sedimentation. LCRA will also determine sediment inflow needs from the Colorado River Basin. TWDB, in cooperation with LNRA, will determine the sediment inflow needs from the Lavaca River Basin. LCRA will revise and recalibrate the TWDB TXBLEND.G salinity transport model of the estuary to account for modifications to the Colorado River Delta.

3. **Biology:** LCRA will use existing data on freshwater inflows, salinity, harvest effort and other factors to estimate fish productivity and viability. Adult and juvenile fin and shell fish salinity preferences and tolerance ranges will be revised and updated.

4. **Management Decision Model:** LCRA will evaluate the interactions between inflows and estuarine conditions. LCRA will modify the TWDB Estuarine Mathematical Programming Model to fit conditions in the estuary.

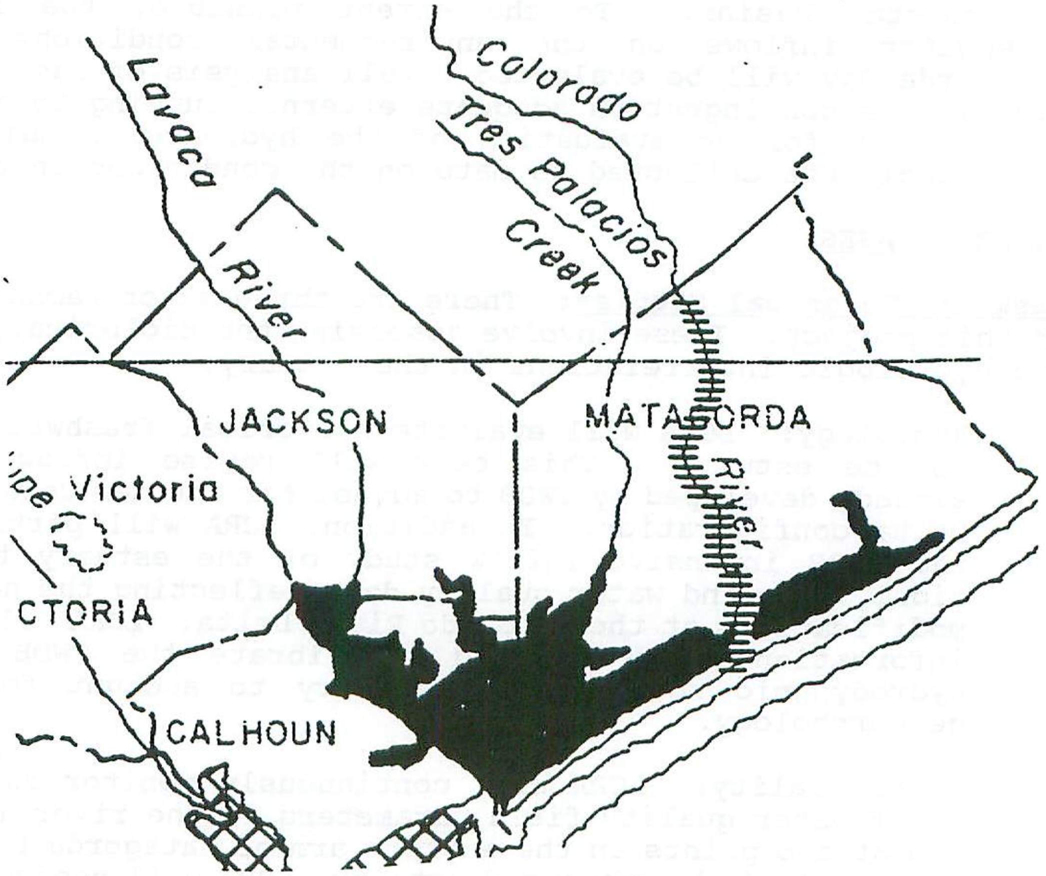
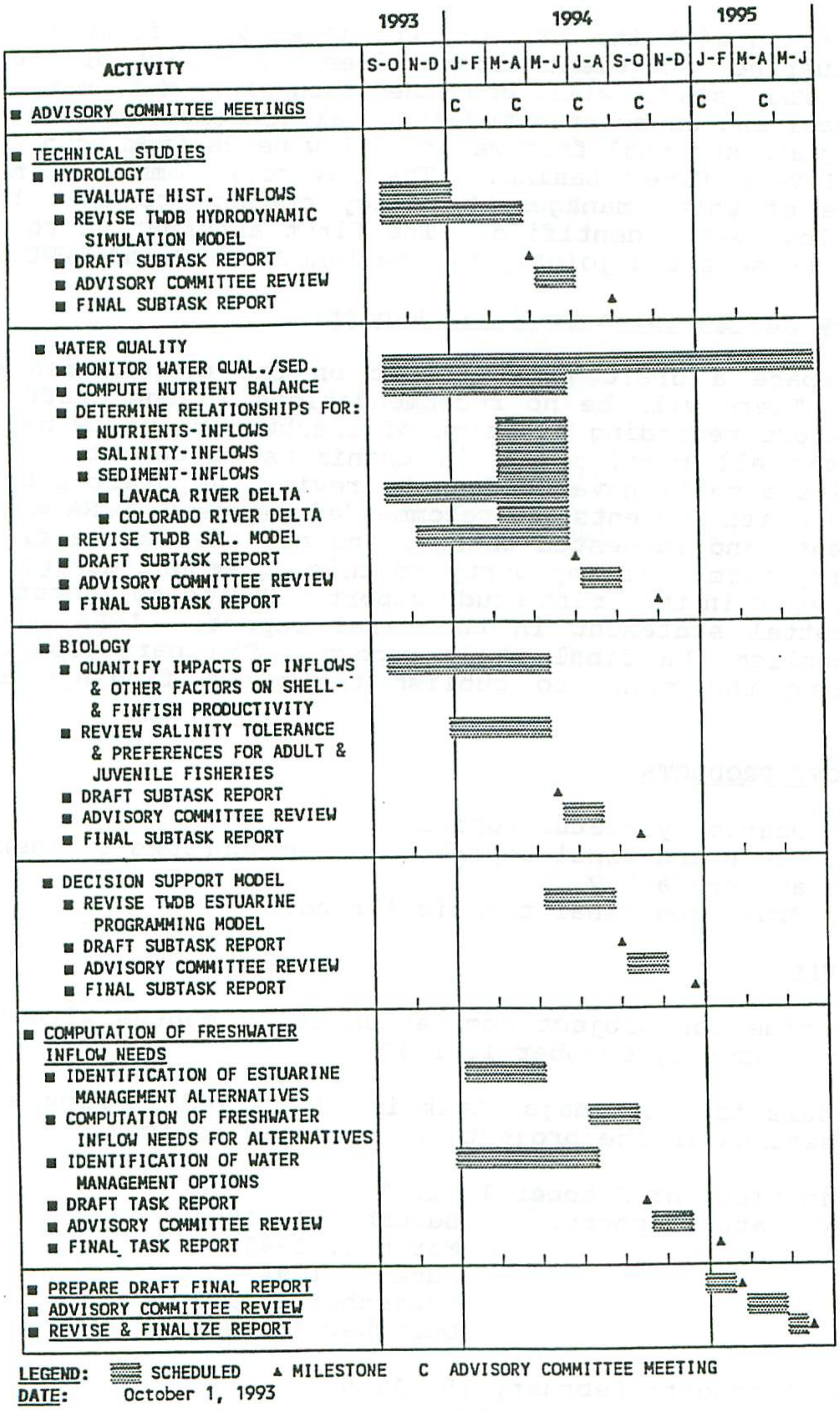


Figure 1. Lavaca-Colorado Estuary

FIGURE 2. PROJECT TIME SCHEDULE FOR MAJOR TASKS



Task 2. Computation Of Freshwater Inflow Needs:

LCRA in conjunction with the Advisory Committee will formulate a variety of estuarine management alternatives. For each of these alternatives, LCRA staff will use the Estuarine Mathematical Programming Model and associated models or alternative methods to compute monthly and seasonal freshwater inflow needs from both the Colorado and Lavaca River Basins. The Advisory Committee may select a range of water management policy options to meet the freshwater inflow needs identified. The first alternative to be evaluated will be selected jointly by the TNRCC, TWDB and TPWD.

Task 3. Review And Revision To Final Report:

LCRA shall prepare a draft final report on the computation of inflow needs. There will be no recommendations in the draft or final study report regarding adoption of freshwater inflow needs presented unless all parties are in unanimous agreement. The Advisory Committee shall have 60 days to review the draft report and provide LCRA with comments and recommended changes. LCRA shall consider comments and suggested changes and may revise the final report as appropriate. If any party to this Agreement disagrees with any statements in the draft study report, LCRA is obligated to include a rebuttal statement in the final report. LCRA shall prepare and publish the final study report. The participating agencies reserve the right to publish their own findings and conclusions.

DELIVERABLE WORK PRODUCTS

1. Quarterly status reports
2. Draft and final reports on four subtasks of Task 1 and on Task 2
3. Draft and final technical report

PROJECT SCHEDULE

The estimated time for project completion is 20 months with the study to be initiated by October 1, 1993.

The time schedule for each major task is identified in Figure 2. The major milestones in the project are noted as follows.

Program initiation: October 1, 1993
Quarterly status reports: December 1, 1993
March 1, 1993
June 1, 1994
September 1, 1994
December 1, 1994

Draft final report: February 15, 1995
Final report: June 1, 1995