LAVACA-TRES PALACIOS ESTUARY:
An Analysis of Bay Segment Boundaries, Physical Characteristics, and Nutrient Processes

TEXAS DEPARTMENT OF WATER RESOURCES
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AN ANALYSIS OF BAY SEGMENT BOUNDARIES, PHYSICAL CHARACTERISTICS, AND NUTRIENT PROCESSES

Prepared by the
Engineering and Environmental Systems Section
of the Planning and Development Division

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PREFACE

In 1976, the Section 208 Planning Program for nondesignated planning areas of Texas was initiated. Additional planning funds were subsequently made available by EPA to expand the scope of this planning effort and to consider other issues not previously addressed. These planning monies were available in early 1978 as a supplement to the EPA grant for Section 208 planning in nondesignated planning areas. A part of the funds were earmarked for development of analyses which could be used in future planning efforts for evaluation of the appropriateness of existing water quality standards in major Texas estuarine systems. Due to the short time frame of the supplemental grant funds, only three tasks were selected. Later these can be expanded upon throughout the continuing planning process. The three selected tasks are the subject of this report on the Lavaca-Tres Palacios estuary:

1. Analysis of the appropriateness of existing bay segment boundaries;
2. Analysis of the physical characteristics of the selected estuarine systems including mixing, transport, current patterns, and salinity patterns; and
3. Definition of nutrient processes in Texas estuarine systems, especially the effects of inflows on nutrient cycling and contributions from deltaic marsh areas.

The above tasks are basic to any consideration of the adequacy of water quality standards for Texas estuarine systems. Future tasks, which are necessary to complete a comprehensive assessment of coastal water quality standards, include definition of the water quality requirements to meet various water use criteria for estuarine/river systems, and an assessment of the costs and benefits of various uses.

LAVACA-TRES PALACIOS ESTUARY: AN ANALYSIS OF BAY SEGMENT BOUNDARIES, PHYSICAL CHARACTERISTICS, AND NUTRIENT PROCESSES

SUMMARY

This report is one in a series of reports on major Texas estuaries. The objective is to analyze existing data on the Lavaca-Tres Palacios estuary for the purpose of water quality planning under Section 208 of P.L. 92-500. The report has three sections. The first section presents an analysis of the appropriateness of existing bay segment boundaries for water quality planning purposes, and draws heavily upon the data analyses performed in the last two sections of the report. In the second section, the physical characteristics of the Lavaca-Tres Palacios estuary are presented along with a summary of circulation and salinity patterns under average conditions of tidal amplitude, wind and freshwater inflow normally experienced throughout the year. In section three of the report, the current state of knowledge of nutrient processes taking place in the Lavaca-Tres Palacios estuary, especially the effects of inflows on nutrient cycling and contributions of nutrients from deltaic marsh areas, is presented.

Circulation and salinity models of the Lavaca-Tres Palacios estuary were derived for use on a digital computer and were calibrated by sampling efforts in the estuary. This allowed simulation of circulation and salinity patterns under various conditions of freshwater inflow, tidal cycle and wind affects. A careful analysis of the model simulation runs had important implications for the placement or location of appropriate boundaries for the bay segments. It was generally found that the existing bay segment boundaries between Carancahua, Lavaca and Matagorda Bays adequately describe the real differences in salinity and circulation that normally exist in the estuary, and no changes in these segment boundaries are recommended. In Keller Bay it is recommended that the bay segment boundary be altered to include a portion of the river valley. The hydrodynamic simulations of Turtle and Tres Palacios Bays indicated that the addition of a Turtle Bay water quality segment was necessary and that the Tres Palacios water quality bay segment boundary of Matagorda Bay should be moved to a point slightly downstream of the City of Palacios.

The Lavaca-Tres Palacios estuary can be characterized by normal tides ranging from 0.5 foot (0.15 meters) in the bays to a maximum of about 2 feet (0.6 meters) along the Gulf shoreline. Wind is a major factor in influencing physical processes, including erosion, accretion and other changes in shoreline configurations. Because of the shallow depths throughout the estuary, wind can play a major role in the generation of waves and longshore currents. The peak influx of freshwater to the system normally corresponds with spring rains. Major impacts from these inflows include overbank flooding of marsh areas, extension and building of bay head and oceanic deltas, flushing of the bays, and salinity reduction.

An analysis of net circulation patterns simulated by the tidal hydrodynamic model indicated that internal circulation eddy currents were dominant in the Lavaca-Tres Palacios estuary. Depending upon the month simulated, the net circulation in Matagorda Bay revealed up to three individual currents, each moving in a circular pattern within the boundaries of the bay. Water in Matagorda Bay was readily mixed between these circulation currents; however, relatively little mixture of water, except during high inflow periods, took place between Matagorda Bay and Lavaca and Carancahua Bays. The circulation patterns in the latter two bays were also dominated by internal circulation currents. The simulated water movement in Tres Palacios Bay up to the City of Palacios was governed by the patterns of flow in Matagorda Bay.

Although simulated salinity concentrations throughout the Lavaca-Tres Palacios estuary varied, salinities were generally at their lowest during the month of June. Highest levels of salinities were generally found during the month of August.

Nutrient contributions to the Lavaca-Tres Palacios estuary have been derived primarily from river inflow, local runoff, and biogeochemical cycling in deltaic and peripheral salt or brackish water marshes. The adjacent Gulf of Mexico is nutrient poor, and resulting concentration gradients are such that a net transport of

nutrients out of the bay/estuary system toward the Gulf normally occurs. Numerous complicating factors such as the magnitude of freshwater inflows, winds, currents, and biological activity all contribute to the complexity of processes that may be occurring at any given time. The most important source of nutrients to the Lavaca-Tres Palacios estuary is the freshwater contributed by the Colorado, Lavaca and Navidad Rivers.

The Lavaca-Tres Palacios estuary is an extremely productive system, particularly in the deltaic marsh areas of the Lavaca and Colorado Rivers. Average annual net productivity was approximately 11,770 dry weight pounds per acre (1,319 g/m^2) for the Lavaca delta. In the Colorado delta, the average annual net productivity was estimated at approximately 8,150 dry weight pounds per acre (914 g/m^2).

Although the high productivity of these deltaic marshes results in significant quantities of detritus for potential transport to the estuary, actual detrital transport is dependent on the episodic nature of the marsh inundation and dewatering process. The vast majority of the primary production in the higher, sporadically flooded vegetative zones goes into peat production and is not exported; however, an estimated 45 percent of net production of the lower, frequently-flooded vegetative zone is exported to the estuarine waters.

Although a great deal has been gained thus far by detailed investigations and data collection activities focused on the Lavaca-Tres Palacios estuary, many questions can not yet be answered. Texas estuaries are very complex systems, having numerous variables, and many relationships among these variables. Measurement of system variables and the relationships among them are extremely difficult and time consuming to make. Additional studies of the Lavaca-Tres Palacios estuary will add to the knowledge gained to this point and allow more accurate descriptions of the processes taking place. Studies under the authorization of Senate Bill 137 are continuing, with results scheduled for publication by the end of 1979.

ANALYSIS OF BAY SEGMENT BOUNDARIES

A Texas estuary may be defined as the region from the tidally affected reaches of terrestial inflow sources to the Gulf of Mexico. Shallow bays, tidal marshes and bodies of water behind barrier islands are included under this definition. These estuarine systems are made up of subsystems, lesser but recognizable units with characteristic chemical, physical, and biological regimes. Estuaries are composed of interrelated parts: primary, secondary and tertiary bays, which require separate treatment for proper understanding and management.

An estuary's primary bay (e.g., Matagorda Bay) is directly connected to the Gulf of Mexico and is commonly characterized by brackish (50% seawater) to saline (100% seawater) salinities. Secondary bays (e.g., Lavaca Bay) empty into the primary bay of an estuary and are thus removed from direct flow exchange with the Gulf. Also, secondary bay salinities are generally more brackish than primary bay salinities. In most cases, tertiary bays (e.g., Swan Lake) may be found at the head of an estuary connected to one of the secondary bays. In terms of energy input to the estuarine systems, the most productive and dynamic of estuarine habitats are associated with tertiary bays, where sunlight can effectively penetrate the shallow, fresh to brackish water areas and support submerged vegetation. Substantial chemical energy is produced in these areas due to photosynthetic processes. These biostimulants are distributed through the estuarine system by tide and wave action.

Texas estuaries, due to their dynamic nature, are highly productive ecosystems. Severe droughts, floods, and hurricanes are the main factors that control and influence estuarine ecosystems. The number of species remain low, while numbers of organisms within a species fluctuates with the seasonal regime, and with drought and wet cycles. This type of regime provides for a continuing shift in dominant organisms, therefore preventing a specific species from maintaining a dominance; as compared to a lake, where through the process of euthrophication its biotic population becomes stagnant and dominated by a few species.

Texas has about 400 linear miles (644 kilometers) of coastline, 373 miles (600 kilometers) of open-ocean or Gulf shoreline and 1,419 miles (2,284 kilometers) of bay shoreline, along which are located seven major estuarine systems and three smaller estuaries (Figure 1). Eleven major river basins, ten with headwaters originating within the boundaries of the State, have estuaries of major or secondary importance. These estuarine systems, with a total surface area of more than 1.3 million acres (526,000 hectares), include many large shallow bays behind the barrier islands. Additional thousands of acres of adjacent marsh and bayous provide habitat for juvenile forms of important marine migratory species and also produce nutrients for the indigenous population in the estuaries. The ecosystems which have developed within these estuaries are in large part dependent upon the amount and seasonal and spatial distribution of

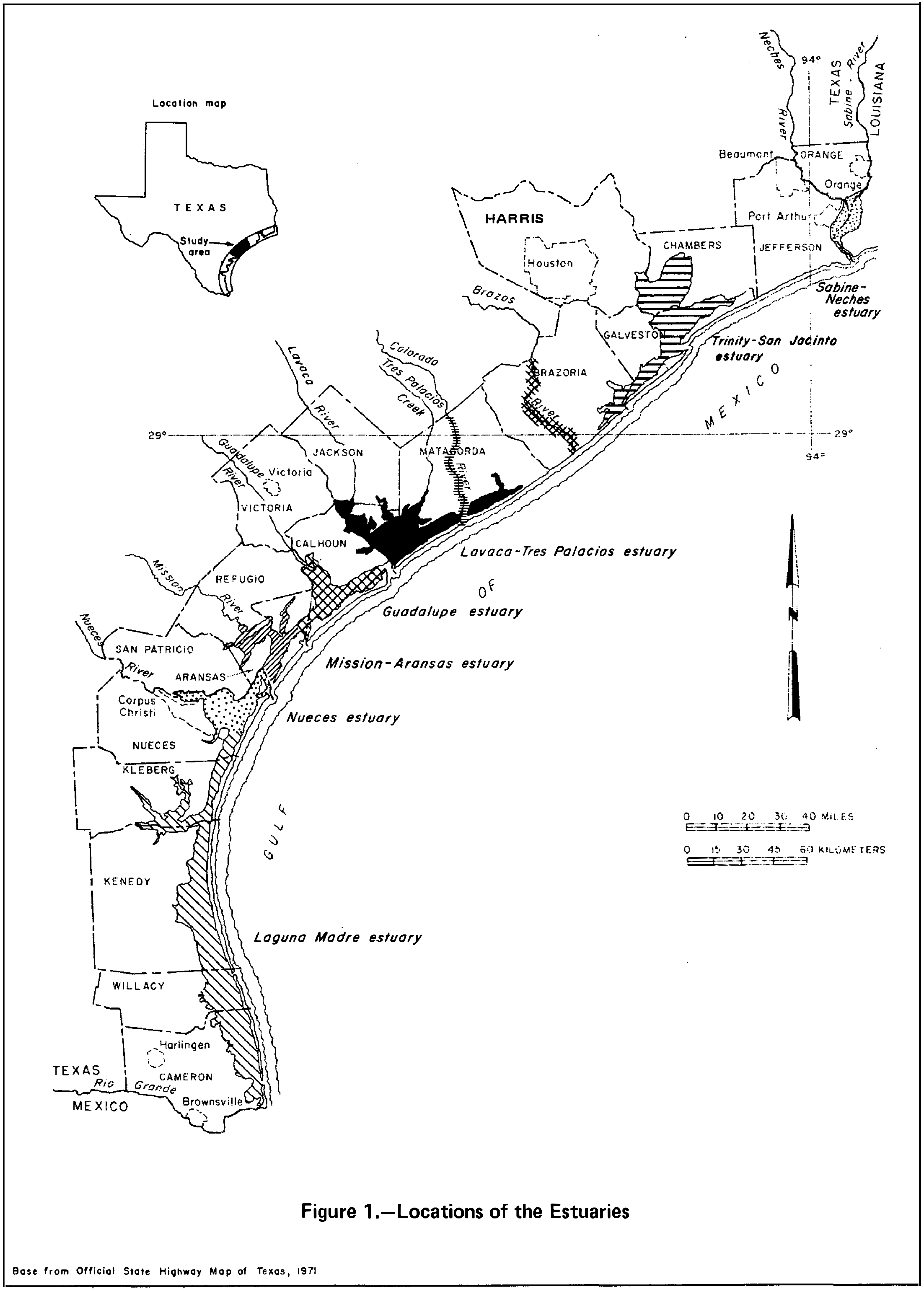

Figure 1.—Locations of the Estuaries

inflows of freshwater and associated nutrients from the rivers, coastal tributary streams, marsh areas and direct rainfall and runoff within the adjacent coastal basins.

The Lavaca-Tres Palacios estuary is currently divided into six segments for water quality planning purposes (Figure 2). The results of the tidal hydrodynamic and salinity mass transport simulations indicated that Lavaca Bay (Segment 2453) and Matagorda Bay (Segment 2451) are appropriate homogeneous segments for water quality planning purposes. In all of the monthly circulation pattern and salinity analyses, Lavaca Bay generally contained a closed circular eddy current and had limited net exchange with Matagorda Bay except during high freshwater inflows. The simulated salinity concentrations were also consistently lower in Lavaca Bay than in Matagorda Bay. Matagorda Bay similarly contained circulation patterns that thoroughly mixed the waters in both the central and eastern portions of the bay. Sharp salinity gradients were thus not evident in the simulated salinities over Matagorda Bay.

By observing the hydrodynamic simulations it is evident that Carancahua Bay (Segment 2456) and Keller Bay (Segment 2455) are dominated by internal circulation patterns not significantly influenced by current circulations in either Lavaca or Matagorda Bays. These two water quality segments also receive significant local freshwater inflows which resulted in lower simulated salinity concentrations than observed in adjacent areas of Lavaca or Matagorda Bay. In the case of Keller Bay it is recommended that the bay segment boundary be changed to include the flooded river valley for the stream entering the northern end of the bay since that section of the bay is tidally influenced by waters from the main body of Keller Bay.

Tres Palacios Bay is currently designated as a separate water quality planning segment (Segment 2452) with the boundary line separating the segment from Matagorda Bay lying approximately along a line connecting Palacios Point with the southern entrance to Turtle Bay. The hydrodynamic simulations indicated that the circulation patterns within Matagorda Bay dominated the water circulation in Tres Palacios Bay upstream to near the City of Palacios. The results of the salinity simulations indicated that the salinity concentrations in Matagorda Bay influence the salinity in Tres Palacios Bay much further into the bay than the present water quality segment boundary. It is therefore recommended that the Tres Palacios water quality bay segment boundary with Matagorda Bay be moved to a point slightly downstream from the City of Palacios and that Turtle Bay be included in existing Segment 2451 (Figure 3).

The Cox Bay water quality segment (Segment 2454) could not be accurately assessed with regard to internal circulation patterns arising from significant wastewater discharges which occur in that area. The tidal hydrodynamic simulation model has accuracy resolution down to only one square mile of water surface area. The simulated current patterns in Cox Bay were dominated by the current patterns in Lavaca Bay; however, it is impossible to determine from the present model any circulation patterns in the extreme eastern end of Cox Bay which may be dominated by wastewater discharges. Therefore, it is recommended that the Cox Bay water quality bay segment be retained, since accurate evaluation of the local circulation patterns can not be made using the large scale hydrodynamic model.

PHYSICAL CHARACTERISTICS

Introduction

The Lavaca-Tres Palacios estuary covers about 352 square miles (910 square kilometers) and consists of the tidal parts of the Colorado, Lavaca, and Navidad Rivers, Tres Palacios Creek and other tributaries, Powderhorn Lake, Turtle Bay, Lavaca Bay, Cox Bay, Keller Bay, Carancahua Bay, Tres Palacios Bay, Matagorda Bay, Matagorda Ship Channel Pass, Pass Cavallo, and parts of the Intracoastal Waterway. Water depth at mean low water varies from six feet (2 meters) in the Colorado River Channel to 13 feet (4 meters) or less in Matagorda Bay, except in parts of the Matagorda Ship Channel, where the depth is 36 feet (11 meters).

This study area lies in the Upper Coast climatological division of Texas in the warm temperate zone. Its climatic type is classified as subtropical (humid with warm summers). The climate is also predominantly marine because of the basin's proximity to the Gulf of Mexico. Prevailing winds are southeasterly to south-southeasterly throughout the year. Day-to-day weather during the summer offers little variation except for the occasional occurrence of thunderstorms. The sea breeze allows warmer daytime temperatures during winter and prevents the summer daytime temperatures from becoming as high as those observed further inland. Winters are mild and the moderate polar air masses which push rapidly southward out into the Gulf bring cool, cloudy, and rainy weather for brief periods.

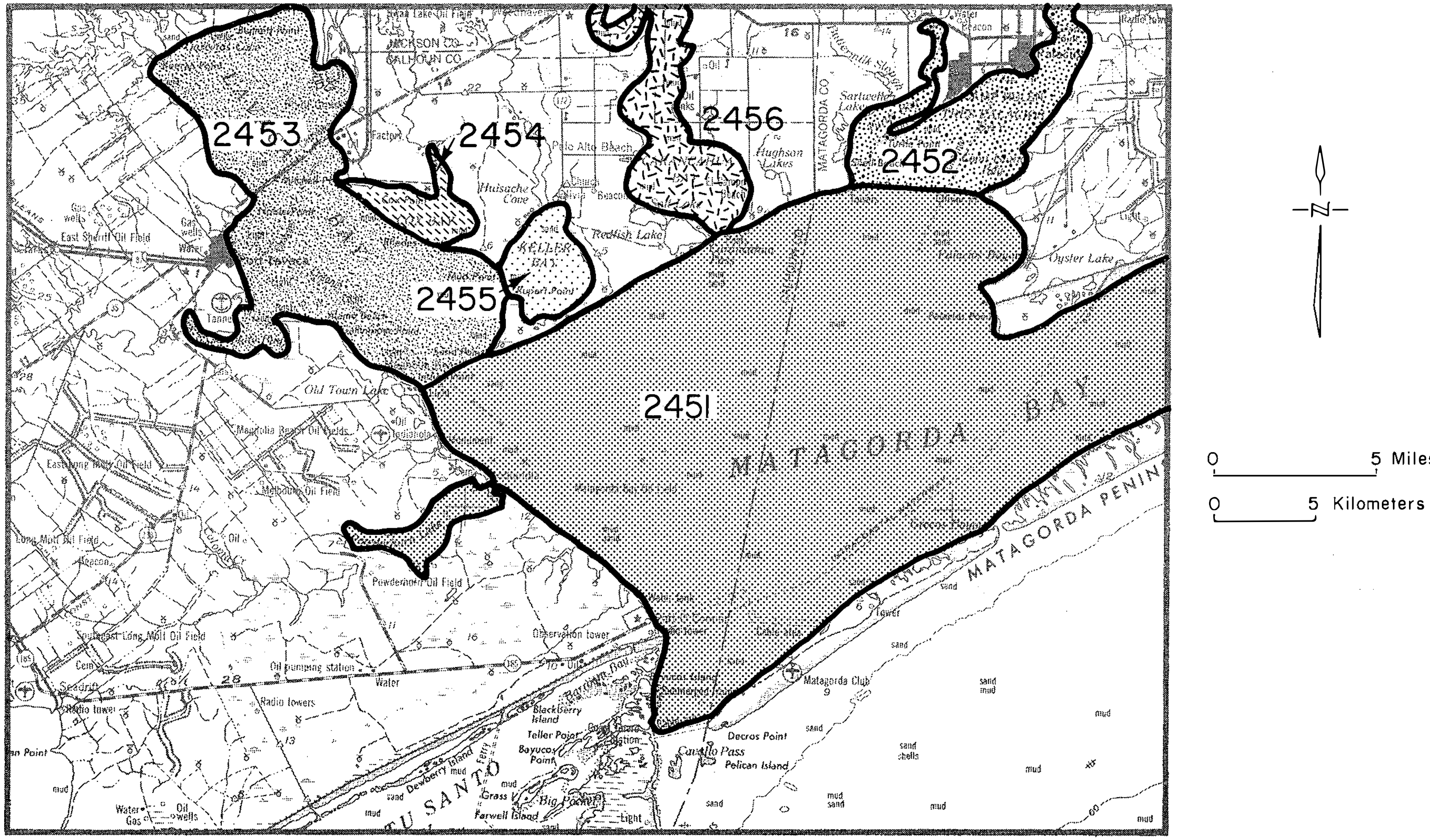

Figure 2.—Existing Bay Segment Boundaries (63)

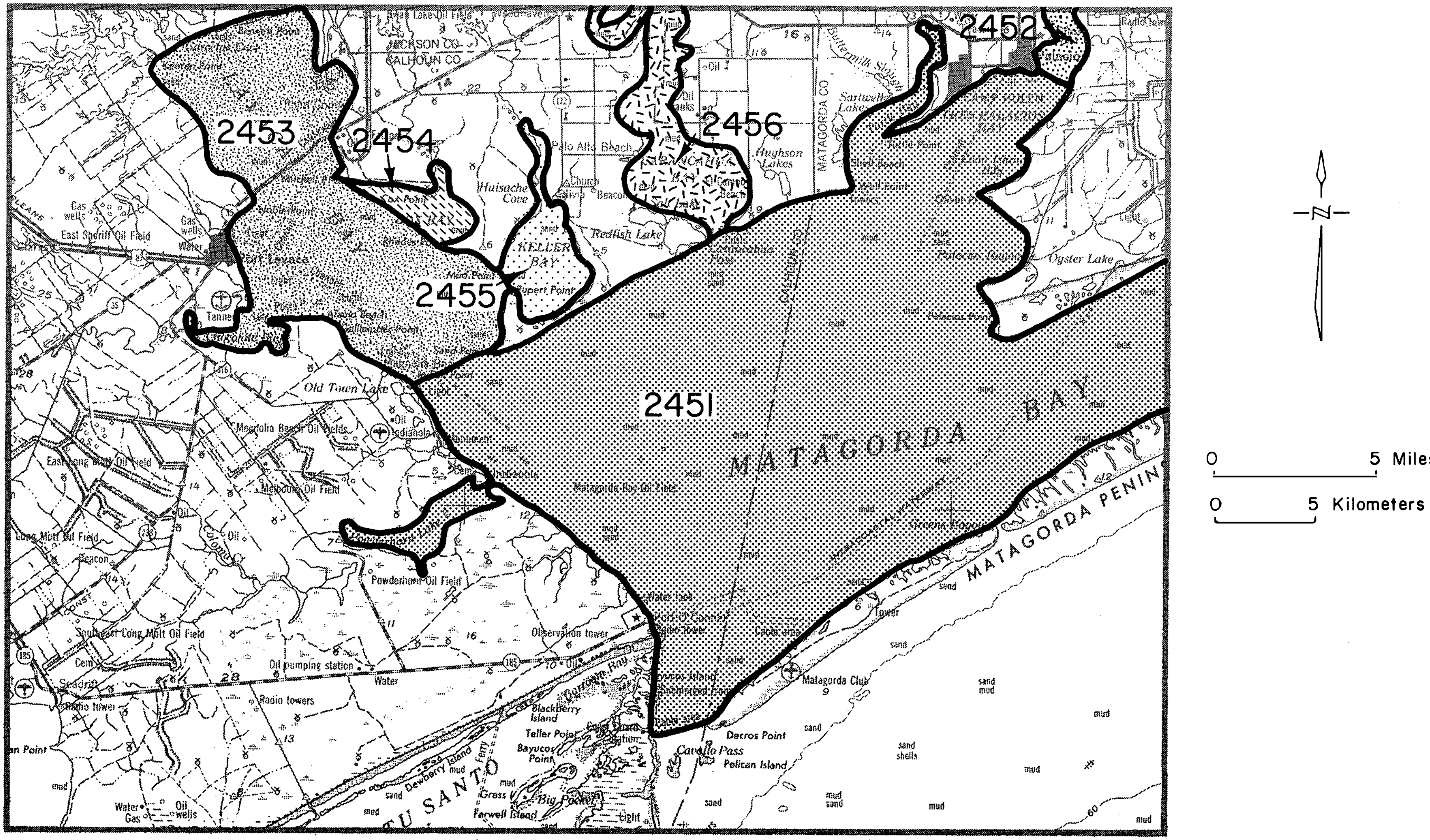

Figure 3.—Proposed Bay Segment Boundaries

Sedimentation and Erosion

The Navidad River carries an estimated average annual sediment load of 1.04 acre-feet per square mile (4.95 m^3/ha) of drainage area as it enters the Fayette Prairie physiographic province. Much of the sediment load is deposited in the floodplains of this area due to the decreased gradient of the stream. By the time the Navidad River reaches its confluence with the Lavaca River, the average annual sediment production rate has decreased to an estimated 0.24 acre-foot per square mile (1.1 m^3/ha) (29). This figure was developed by the U.S. Soil Conservation Service and includes both bedload and suspended-sediment load.

Sediment in a stream channel is generally divided into the two classifications: bedload material and suspended-sediment load. As flow conditions change, particles making up the bedload at one point may become suspended and subsequently be redeposited. Bedload measurements can be accurately determined only by very elaborate instrumentation which is suited only to certain types of streams. In the laboratory, bedload is defined as the difference between total load and suspended load. In the field, it must be estimated.

When the stream enters Lavaca Bay, flow velocities decrease and the transport capability is reduced; thus, sediment is deposited near the headwaters, forming a bay-head delta. The active delta forming at the mouth of the Lavaca River is of a type which develops under conditions of high sediment inflow into a relatively quiescent body of water (i.e., Lavaca Bay).

The mainland shore is characterized by near vertical bluffs cut into Pleiostocene sand, silt, and mud (Figure 4). Erosion of these bluffs furnishes sediment to the adjacent lakes, marshes, and bays. The type of sediment deposited depends on whether the adjacent bluff is composed of predominantly sand or mud. Energy levels (erosional capacity) in the Lavaca-Tres Palacios estuary are dominated by wind action since the range of astronomical tides is only about 0.5 foot (0.15 m). Winds blowing across the bay generate waves and cause a change in water level at the shoreline. These changes in water level produced by the wind are called wind tides.

The marsh areas in the Lavaca-Tres Palacios estuary system are associated with deltas. Delta plains of active deltas, such as the Lavaca-Navidad, are covered with salt, brackish, and freshwater marshes. In order for marshes to propagate there must be a balance between sediment deposition and compactional subsidence. If there is excessive vertical accretion, marsh vegetation is replaced by mainland grasses, shrubs, and trees. Where subsidence is more rapid than deposition, the plants drown and erosion by waves and currents deepen the marsh to form lakes or enlarged bay areas. At the present, marsh surface-water level relationships of Garcitas, Lavaca, and Colorado deltas are reported to be stable (38). Sedimentation rates and subsidence apparently have a constant relationship. Other important sources of estuarine sediments include:

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

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

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

Shoreline and vegetation changes within the Lavaca-Tres Palacios estuarine system and in other areas of the Texas Gulf Coast are the result of natural processes (40, 41). Shorelines are either in a state of erosion, accretion, or are stabilized either naturally or artificially. Erosion produces a net loss in land; accretion produces a net gain in land; and equilibrium conditions produce no net change in land area.

Most of the shoreline area associated with the Lavaca-Tres Palacios estuary are eroding (Figure 5), which indicates that the sediment volume supplied to Gulf and bay shorelines is insufficient to balance the amount of sediment removed by waves and longshore drift (38). Erosion can result in property damage to landowners nearby, as the beach recedes landward. The nature of beaches is an indicator of the extent of shoreline stability. Sediments of the mainland beaches are a mixture of sand, shell, and rock fragments, with shell and rock fragments the most common constituents. This is an indication that little sand is currently being supplied to these beaches by rivers.

Processes that are responsible for the present shoreline configuration and that are continually modifying shorelines in the Lavaca-Tres Palacios estuary include astronomical and wind tides, longshore currents, normal wind and waves, hurricanes, river flooding, and slumping along cliffed shorelines. Astronomical tides are low, ranging from about 0.5 foot (0.15 m) in the bays to a maximum of about 2 feet (0.6 m) along the Gulf shoreline. Wind is a major factor in influencing coastal processes. It can raise or lower water level along the Gulf and/or mainland shore according to the direction it is blowing. Wind also generates waves and longshore currents.

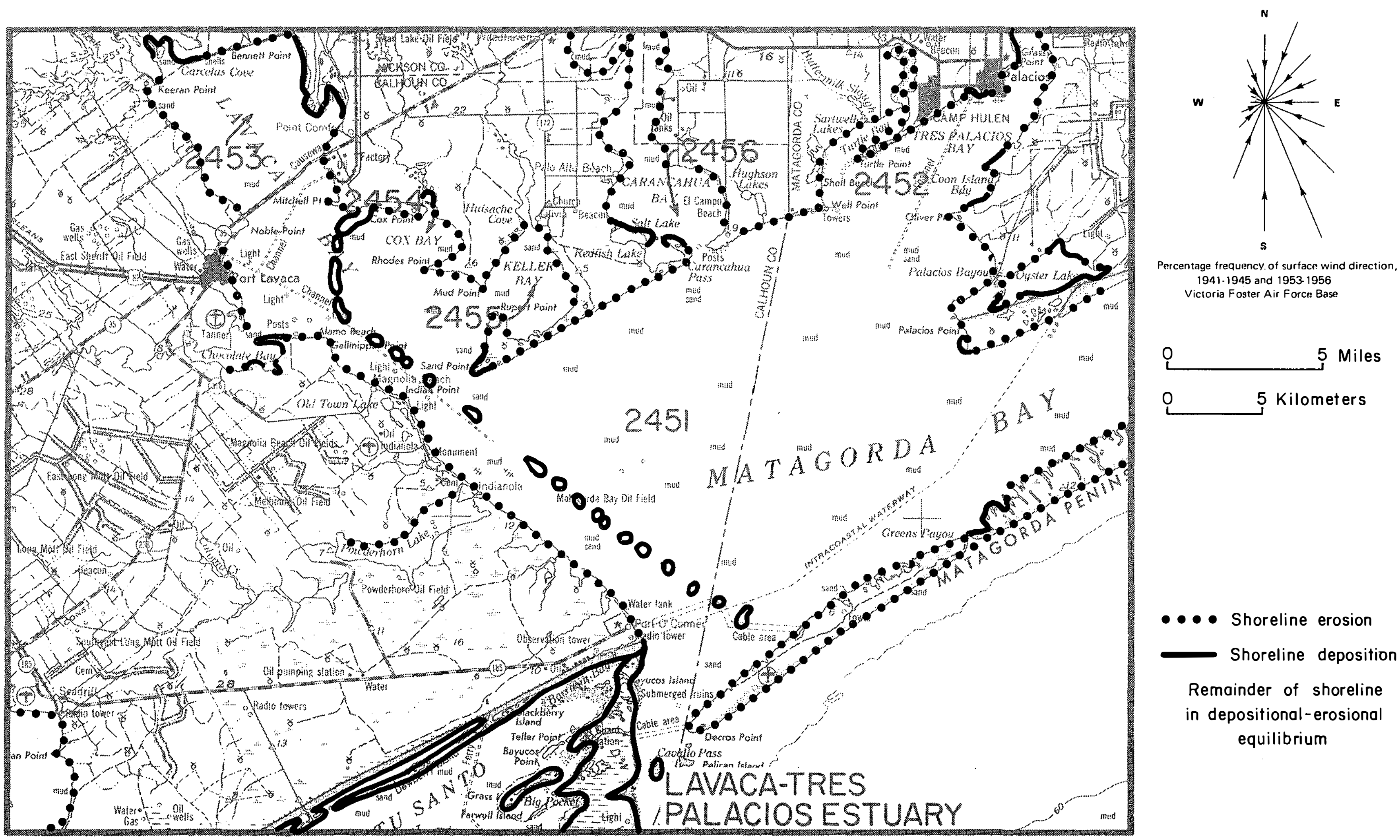

Figure 5.—Lavaca-Tres Palacios Estuary, Shoreline Physical Processes (40, 41)

The seasonal threat of wind and water damage associated with tropical cyclones occurring in the Gulf of Mexico exists each year from June through October. Wind damage from hurricanes and associated tornadoes can be costly, but the most severe losses occur from the flooding brought by heavy rains and high storm surges along the Coast. Gulf and mainland shorelines may be drastically altered during the approach, landfall, and inland passage of hurricanes (21). Storm surge flooding and attendant breaking waves may erode Gulf shorelines tens or hundreds of feet. Washovers along the barrier islands and peninsulas are common, and salt-water flooding may be extensive along the mainland shorelines.

Flooding of rivers and small streams normally corresponds with spring thunderstorms or the summer hurricane season. Rivers generally flood as a result of regional rainfall, but flooding along smaller streams may be activated by local thunderstorms (38). Some effects of flooding include: (1) overbank flooding into marsh areas of the floodplain and onto delta plains; (2) progradation of bayhead and oceanic deltas; (3) flushing of bays and estuaries; and (4) reduction of salinities.

Mineral and Energy Resources

The Texas coastal zone is richly endowed with mineral and energy resources. Dominant among these resources are oil and natural gas (Figure 6), which serve not only for fuel but also provide raw material for many petrochemical processes. In addition, the coastal zone contains important sources of chemical raw materials, such as sulfur, salt, and shell for lime. The great abundance of these chemical and petroelum raw materials and their occurrence in a zone with ocean access helps to make this area one of the major petrochemical and petroleum-refining centers of the world.

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

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

Dredged shell, with physical properties suitable for use as aggregate and road base, has chemical properties suitable for lime, cement, and other chemical uses. If shell were not used, these resources would have to be transported approximately 150 miles (240 km) from the nearest Central Texas source. Shell resources are finite, and at present rates of consumption they will be depleted in the near future. Substitute materials will then have to be imported, either from inland sources or by ocean barge from more distant locations.

Some high purity sand deposits have potential specialty uses in industry, such as for foundry sands, glass sands, and chemical silica. An inventory and analysis of coastal zone sands, including those of the barrier islands, as well as the older sands of the Pleistocene uplands, indicates that these sands require upgrading and benefication to qualify for special industrial use (39). The nearest market for such upgraded sands would be the Houston area, therefore it is unlikely that any sand deposits within the area of the Lavaca-Tres Palacios estuary would be used to supply the upper coastal zone markets.

Groundwater Resources

Groundwater resources in the area of the Lavaca-Tres Palacios estuary occur in a thick sedimentary sequence of interbedded gravel, sand, silt, and clay. The stratigraphic units included in this sequence are the Catahoula, Oakville, and Goliad Formations of Tertiary Age; and the Willis, Lissie, and Beaumont Formations of Quaternary Age. These ancient sedimentary units are not uniform in composition and thickness, but were deposited by the same natural processes that are now active in shaping the coastline. Thick layers of sand and gravel representing ancient river channel deposits grade laterally into silt and clay beds which were deposited by the overbank flooding of ancient rivers. Individual beds of predominantly sand and clay interfinger with each other and generally are hydrologically connected laterally and vertically. Because of this interconnection, groundwater can move from one bed to another and from one formation to another. The entire sequence of sediments function as a single aquifer, which is referred to as the Gulf Coast Aquifer.

Near the Lavaca-Tres Palacios estuary this fresh (up to 1,000 mg/l total dissolved solids) to slightly saline (1,000 to 3,000 mg/l total dissolved solids) portion of the aquifer extends to a maximum depth of about 1,600 feet (488 m). The most productive part of the aquifer is from 200 to 600 feet (61 to 183 m) thick (31).

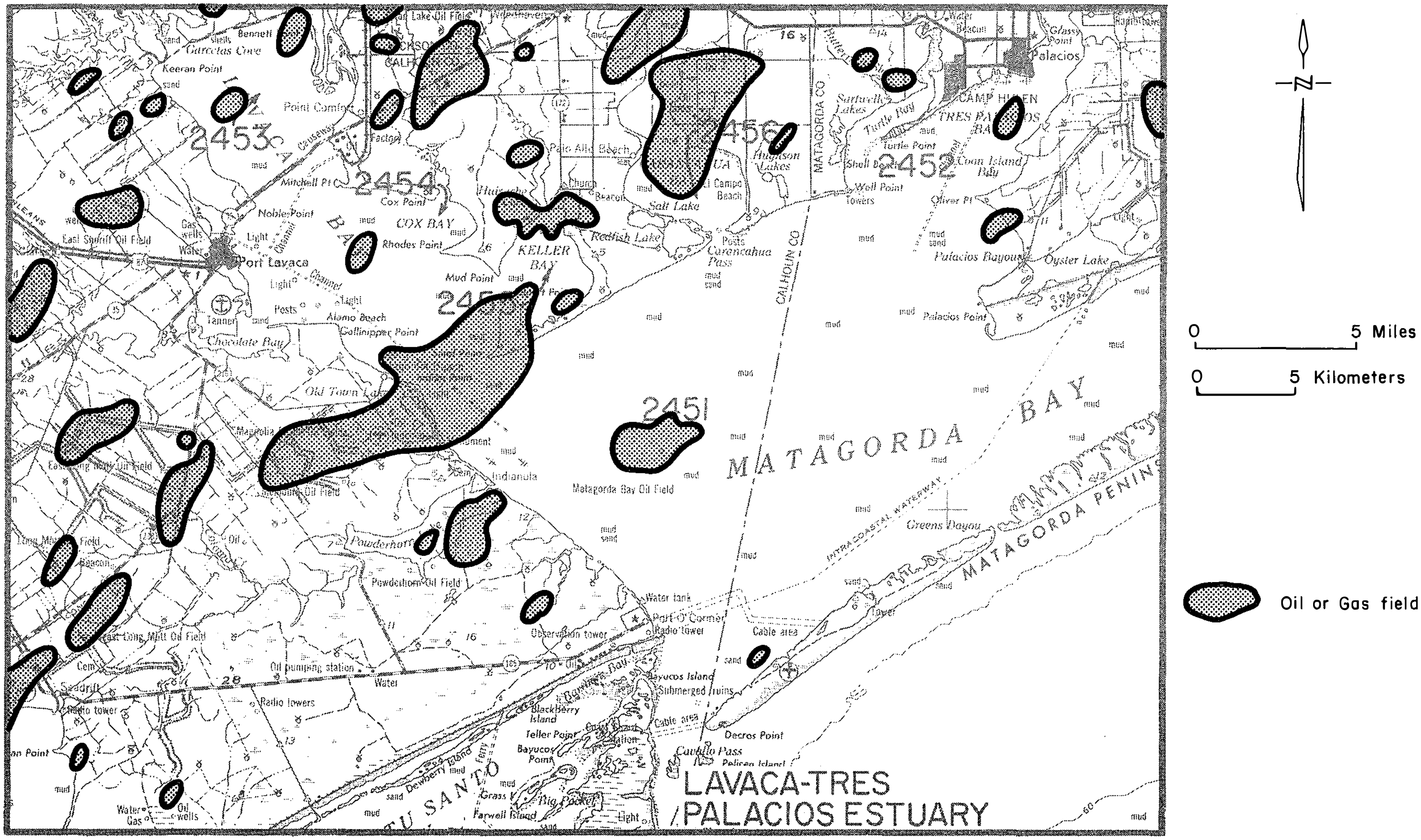

Figure 6.—Oil and Gas Fields

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

Data Collection Program

Studies by the Department of Water Resources of past and present freshwater inflows to Texas' estuaries have used all available sources of information on the physical, chemical, and biological characteristics of these estuarine systems in an effort to define the relationship between freshwater and nutrient inflows and estuarine environments. The Department realized during its planning activities that limited data were available on the estuaries of Texas. Several limited research programs were underway; however, these were largely independent of one another. The data collected under any one program were not comprehensive, and since sampling and measurement of environmental and ecological parameters under different programs were not accomplished simultaneously, the resulting data could not be reliably correlated. In some estuaries, virtually no data has been collected.

A program was therefore initiated by the Department, in cooperation with other agencies, to collect the data considered essential for analyses of the physical and water quality characteristics and ecosystems of Texas' bays and estuaries. To begin this program, the Department consulted with the U.S. Geological Survey and initiated a reconnaissance-level investigation program in September 1967. Specifically, the initial objectives of the program were to define: (1) the occurrence, source and distribution of nutrients; (2) current patterns, directions, and rates of water movement; (3) physical, organic, and inorganic water quality characteristics; and (4) the occurrence, quantity, and dispersion patterns of water (fresh and Gulf) entering the estuarine system. To avoid duplication of work and to promote coordination, discussions were held with other State, Federal and local agencies having interests in Texas estuarine systems and their management. Principally through this cooperative program with the U.S. Geological Survey, the Department is now collecting extensive data in all estuarine systems of the Texas Coast (Figures 7 and 8, Table 1).

Calibration of the estuarine models (discussed in a later section) required a considerable amount of data. Data requirements included information on the quantity of flow through the tidal passes during some specified period of reasonably constant hydrologic, meteorologic, and tidal conditions. In addition, a time history of tidal amplitudes and salinities at various locations throughout the bay was necessary. A comprehensive data collection program was undertaken on the Lavaca-Tres Palacios estuary on March 4-5, 1971 and October 16-19, 1972. Tidal amplitudes were measured simultaneously at numerous locations throughout the estuary (Figure 8). Tidal flow measurements were made at several different bay cross-sections (A, B, C, D, E, F, G, H and I of Figure 8). In addition, conductivity data were collected at many of the sampling stations shown in Figure 7.

Circulation and Salinity

Summary

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

To more fully evaluate the tidal hydrodynamic and salinity transport characteristics of estuarine systems, the Texas Department of Water Resources participated in the development of digital mathematical models representing the important mixing and physical exchange processes of the estuaries. These models were designed to simulate the tidal circulation patterns and salinity distributions in shallow, irregular and non-stratified estuaries. The basic concept utilized to represent each estuary was the segmentation of the physical system into a set or grid of discrete elements. The models utilize numerical analysis techniques to simulate the temporal and spatial behavior of circulation and salinity patterns in an estuary.

The numerical tidal hydrodynamic and salinity mass transport models were applied to the Lavaca-Tres Palacios estuary to determine the effects of the mean monthly freshwater inflows upon the flow circulation and salinity characteristics of the estuarine system. The monthly simulation utilized typical tidal and meteorological conditions observed historically for each month simulated.

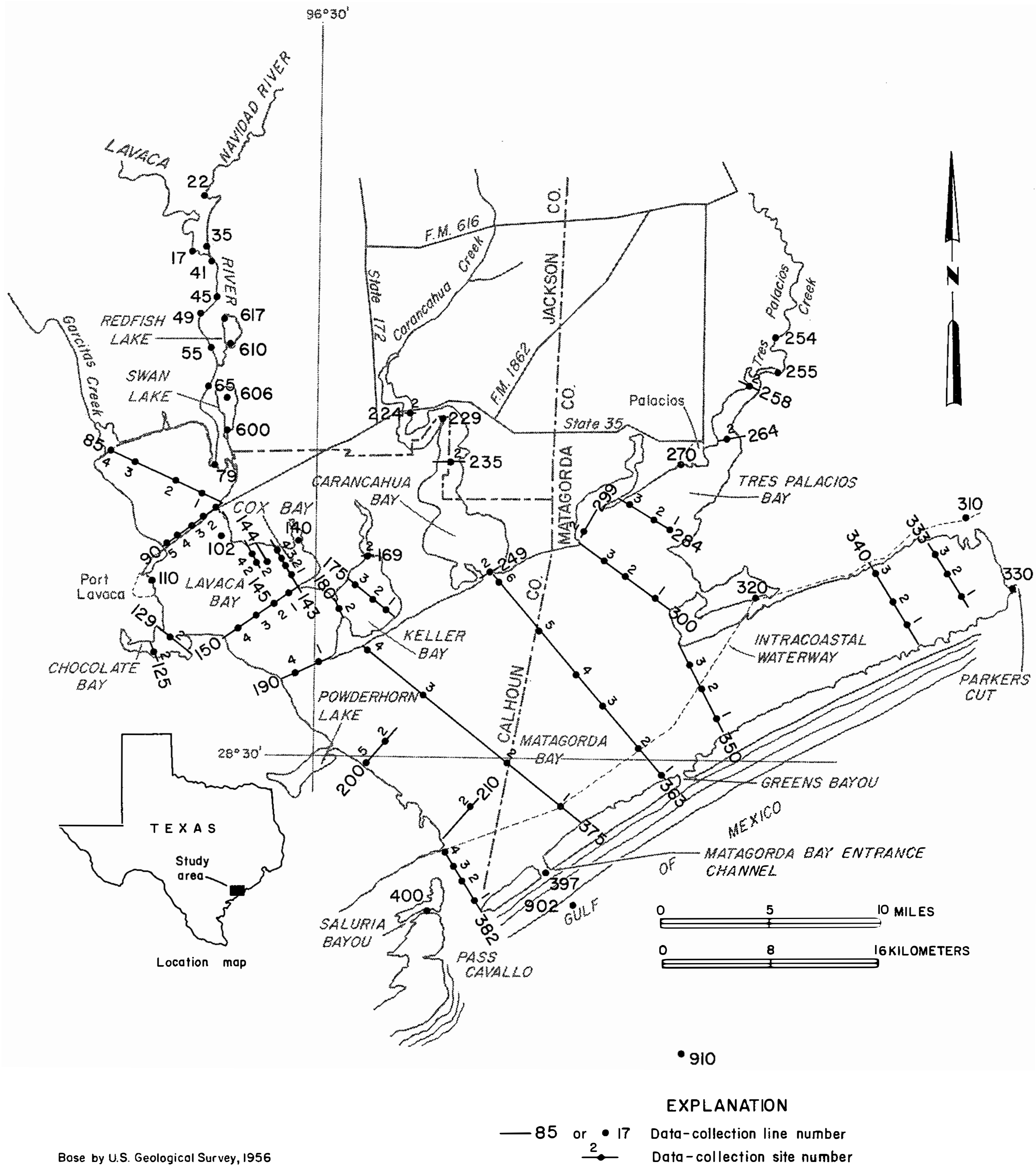

Figure 7. Data Collection Sites in the Lavaca-Tres Palacios Estuary

U. S. Geological Survey

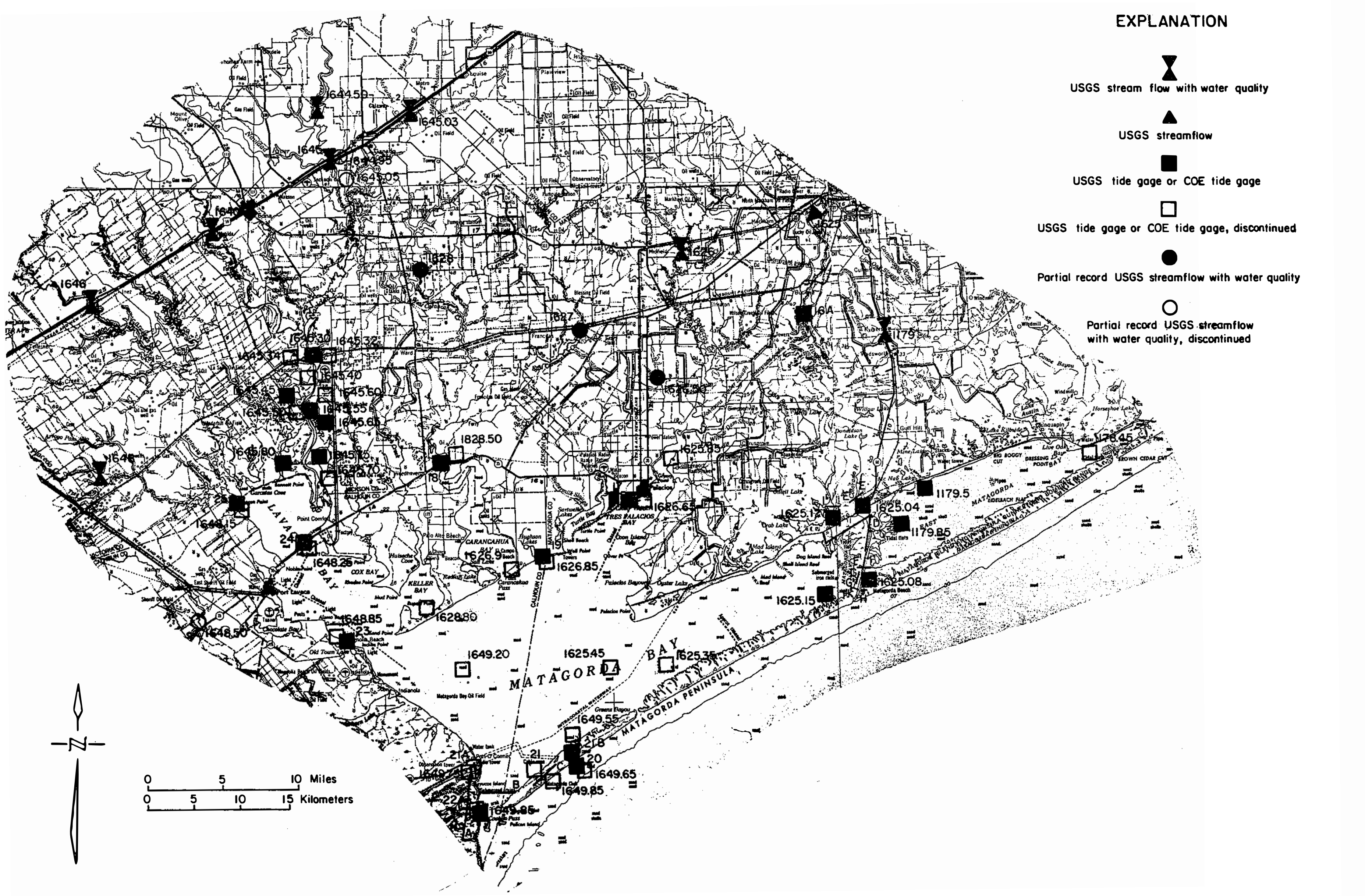

Figure 8. Locations of Gaging Stations, Lavaca-Tres Palacios Estuary

Table 1.—U.S. Geological Survey (USGS) or Corps of Engineers (COE) Gages, Lavaca-Tres Palacios Estuary

Station number	Station description	Period of record	Operating entity	Type of record
	Tide Gages			
16A	Colorado River nr. Wadsworth, Celenese Dock	1975-	COE	Continuous Recording
17	Tres Palacios Bay at Palacios, Sh. Bt. basin	1967-	COE	Continuous Recording
18	Carancahua Bay at Hwy. 35 bridge	1968-	COE	Continuous Recording
19	Piper Lakes, Fish & Wildlife	1968-	COE	Continuous Recording
20	Entrance, Matagorda Ship Channel	1963-	COE	Continuous Recording
21	Matagorda Bay, Range, Tr., Entrance Cut	1963-74	COE	Continuous Recording
21A	Matagorda Bay, GIWW, Air Force Dock	1970-71	COE	Continuous Recording
21B	Matagorda Bay, N. Dike, Entr. Channel	1975-	COE	Continuous Recording
22A	Saluria Bayou, Old Coast Guard Sta.	1964-69	COE	Continuous Recording
23	Lavaca Bay, Mag. Beach, Humble Oil	1968-	COE	Continuous Recording
24	Lavaca Bay, Hwy. 35 bridge	1964-	COE	Continuous Recording
25	Lavaca Bay, Six Mile Rd. Co. Park	1976-	COE	Continuous Recording
1178.45	East Matagorda Bay nr. Sargent	1973-75	USGS	Continuous Recording
1179.50	Intracoastal Waterway nr. Matagorda	1977-	USGS	Continuous Recording
1179.85	East Matagorda Bay nr. Matagorda	1973-	USGS	Continuous Recording

Table 1.—U.S. Geological Survey (USGS) or Corps of Engineers (COE) Gages, Lavaca-Tres Palacios Estuary—Continued

Station number	Station description	Period of record	Operating entity	Type of record
1625.04	Colorado River at Matagorda	1977-	USGS	Continuous Recording
1625.08	Colorado River nr. Tiger Island Cut	1977-	USGS	Continuous Recording
1625.12	Culver Cut nr. Matagorda	1977-	USGS	Continuous Recording
1625.15	Matagorda Bay nr. Matagorda	1972-	USGS	Continuous Recording
1625.35	Matagorda Bay nr. Palacios Point	1971-72	USGS	Continuous Recording
1625.45	Matagorda Bay nr. Half Moon Reef	1972-75	USGS	Continuous Recording
1625.85	Tres Palacios Bay nr. Collegeport	1973-75	USGS	Continuous Recording
1626.65	Tres Palacios Bay at Palacios	1967-76	USGS	Continuous Recording
1626.85	Matagorda Bay nr. Palacios	1968-76	USGS	Continuous Recording
1626.90	Carancahua Bay nr. Palacios	1968-76	USGS	Continuous Recording
1628.50	Carancahua Bay nr. Point Comfort	1968-76	USGS	Continuous Recording
1628.80	Keller Bay nr. Point Comfort	1973-75	USGS	Continuous Recording
1646.30	Lavaca River nr. Lolita	1973-	USGS	Continuous Recording
1645.32	Lavaca River nr. Lolita, east overflow	1974-76	USGS	Continuous Recording
1645.34	Lavaca River nr. Lolita, west overflow	1974-76	USGS	Continuous Recording
1645.40	Menefee Lake, No. 1, nr. Vanderbilt	1974-76	USGS	Continuous Recording

Table 1.—U.S. Geological Survey (USGS) or Corps of Engineers (COE) Gages, Lavaca-Tres Palacios Estuary—Continued

Station number	Station description	Period of record	Operating entity	Type of record
1645.45	Menefee Lake, No. 2, nr. Vanderbilt	1974-	USGS	Continuous Recording
1645.50	Menefee Bayou nr. Vanderbilt	1974-76	USGS	Continuous Recording
1645.55	Lavaca River nr. Vanderbilt	1974-	USGS	Continuous Recording
1645.60	Redfish Lake nr. Lolita (CSG)	1974-76	USGS	Continuous Recording
1645.65	Redfish Lake nr. Lolita	1976-	USGS	Continuous Recording
1645.70	Swan Lake No. 2 nr. Point Comfort	1974-76	USGS	Continuous Recording
1645.75	Swan Lake No. 1 nr. Point Comfort	1974-	USGS	Continuous Recording
1645.80	Venado Lake nr. Vanderbilt	1974-	USGS	Continuous Recording
1648.15	Lavaca Bay at Six Mile Rd. Co. Park	1968-76	USGS	Continuous Recording
1648.25	Lavaca Bay nr. Point Comfort	1963-76	USGS	Continuous Recording
1648.85	Lavaca Bay, Magnolia Beach nr. Pt. Lavaca	1968-76	USGS	Continuous Recording
1649.20	Matagorda Bay, Sandy Point, nr. Indianola	1971-77	USGS	Continuous Recording
1649.55	Matagorda Bay, Range Tower nr. Port O'Connor	1963-76	USGS	Continuous Recording
1649.65	Matagorda Bay, Entrance Channel, Port O'Connor	1963-76	USGS	Continuous Recording
1649.75	Intracoastal Waterway at Port O'Connor	1970-71	USGS	Continuous Recording
1649.85	Saluria Bayou nr. Port O'Connor	1971-	USGS	Continuous Recording

Table 1.—U.S. Geological Survey (USGS) or Corps of Engineers (COE) Gages, Lavaca-Tres Palacios Estuary—Continued

Station number	Station description	Period of record	Operating entity	Type of record
	Stream Gages			
1179.00	Big Boggy Cr. nr. Wadsworth	1970-77	USGS	Continuous Recording
1625.00	Colorado River at Bay City	1948-	USGS	Continuous Recording
1626.00	Tres Palacios Creek nr. Midfield	1970-	USGS	Continuous Recording
1640.00	Lavaca River nr. Edna	1938-	USGS	Continuous Recording
1644.50	Sandy Creek nr. Louise	1978-	USGS	Continuous Recording
1645.00	Navidad River nr. Ganado	1939-	USGS	Continuous Recording
1645.03	West Mustang Creek nr. Ganado	1978-	USGS	Continuous Recording
1646.00	Garcitas Creek nr. Inez	1969-	USGS	Continuous Recording
1648.00	Placedo Creek nr. Placedo	1970-	USGS	Continuous Recording
	Partial Record Stream Gages			
1626.50	Cashs Creek nr. Blessing	1969-	USGS	Limited Data
1627.00	East Carancahua Creek nr. Blessing	1967-68 1970-	USGS	Limited Data
1628.00	West Carancahua Creek nr. La Ward	1967-68 1970-	USGS	Limited Data
1644.95	Sandy Creek nr. Ganado	1975-77	USGS	Limited Data
1645.05	Mustang Creek below Ganado	1975-77	USGS	Limited Data
1648.50	Chocolate Bayou nr. Port Lavaca	1967-68 1970-	USGS	Limited Data

The net circulation patterns simulated by the tidal hydrodynamic model indicated that internal circulation eddy currents dominate the water movements in the Lavaca-Tres Palacios estuary. Depending upon the month simulated, the net circulation in Matagorda Bay revealed up to three individual currents, each moving in a circular pattern within the boundaries of the bay. Water in Matagorda Bay was readily mixed among these circulation currents; however, relatively little mixture of water, except during high freshwater inflow periods, took place among Matagorda Bay and Lavaca and Carancahua Bays. The circulation patterns in the latter two bays were also dominated by internal circulation currents. The simulated water movement in Tres Palacios Bay up to the City of Palacios was governed by the patterns of flow in Matagorda Bay.

The simulated salinity concentrations in the Lavaca-Tres Palacios estuary for the period 1941 through 1976 average freshwater inflows varied over a wide range annually. Salinities throughout the estuary were lowest in the month of June, with average simulated concentrations of less than 25 parts per thousand (ppt) over the entire estuary. The highest levels of simulated salinities occurred during the month of August, when salinities in Matagorda Bay near Pass Cavallo exceeded 30 ppt. The simulated salinities for Lavaca Bay were generally less than 15 ppt throughout the year. The major portion of Matagorda Bay generally had simulated salinities of between 20 and 25 ppt; however, during the high freshwater inflow months of May and June, the simulated concentrations of salinity in the bay were between 15 and 20 ppt.

Description of Estuarine Mathematical Models

Introduction

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

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

Description of the Modeling Process

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

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

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

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

Mathematical Model Development

The mathematical tidal hydrodynamics and conservative transport models for the Lavaca-Tres Palacios estuary were developed by Masch (18). These models were designed to simulate the tidal and circulation patterns and salinity distributions in a shallow, irregular, non-stratified estuary. The two models are sequential (Figure 9) in that the tidal hydrodynamic model computes temporal histories of tidal amplitudes and flows. These are then used as input to the conservative transport model to compute vertically averaged salinities (or any other conservative material) under the influence of various source salinities, evaporation, and rainfall. Both of these models have "stand alone" capabilities although it must be recognized that the transport model ordinarily cannot be operated unless the tidally generated convective inputs are available.

(1) Hydrodynamic Model

Under the assumption that the bays are vertically well-mixed, and the tidally generated convection in either of the two areawise coordinate directions can be represented with vertically integrated velocities, the mathematical characterization of the tidal hydrodynamics in a bay system requires the simultaneous solution of the two-dimensional dynamic equations of motion and the unsteady continuity equation. In summary, the equations of motion neglecting the Bernoulli terms but including wind stresses and the Coriolis acceleration can be written as

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

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

The equation of continuity for unsteady flow can be expressed as

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

In Equations [1], [2] and [3], q_x and q_y are vertically integrated flows per foot of width at time t in the x and y directions, respectively (x and y taken in the plane of the surface area); h is the water surface elevation (with respect to mean sea level (msl) as datum); d is the depth of water at (x, y, t) and is equal to (h − z) where z is the bottom elevation with respect to msl; $q = (q_x^2 + q_y^2)^{1/2}$; f is a nondimensional bed resistance coefficient determined from the Manning Equation; V_w is the wind speed at a specified elevation above the water surface; θ is the angle between the wind velocity vector and the x-axis; K is the nondimensional wind stress coefficient; and Ω is the Coriolis parameter equal to $2\omega\sin\Phi$, where ω is the angular velocity of the earth taken as 0.73×10^{-4} rad/sec and Φ is the latitude taken as 28°30' for the Lavaca-Tres Palacios estuary; r is the rainfall intensity; and e is the evaporation rate.

The numerical solution utilized in the hydrodynamic model of the Lavaca-Tres Palacios estuary involved an explicit computational scheme where Equations [1], [2] and [3] were solved over a rectangular grid of square cells used to represent in a discretized fashion the physiography and various boundary conditions found in this bay system as is shown conceptually in Figure 10. This explicit formulation of the hydrodynamic model requires for stability a computational time step, $\Delta t < \Delta s/(2gd_{max})^{1/2}$ where Δs is the cell size and d_{max} is the maximum water depth encountered in the computational matrix. The numerical solutions of the basic equations and the programming techniques have been described previously (18).

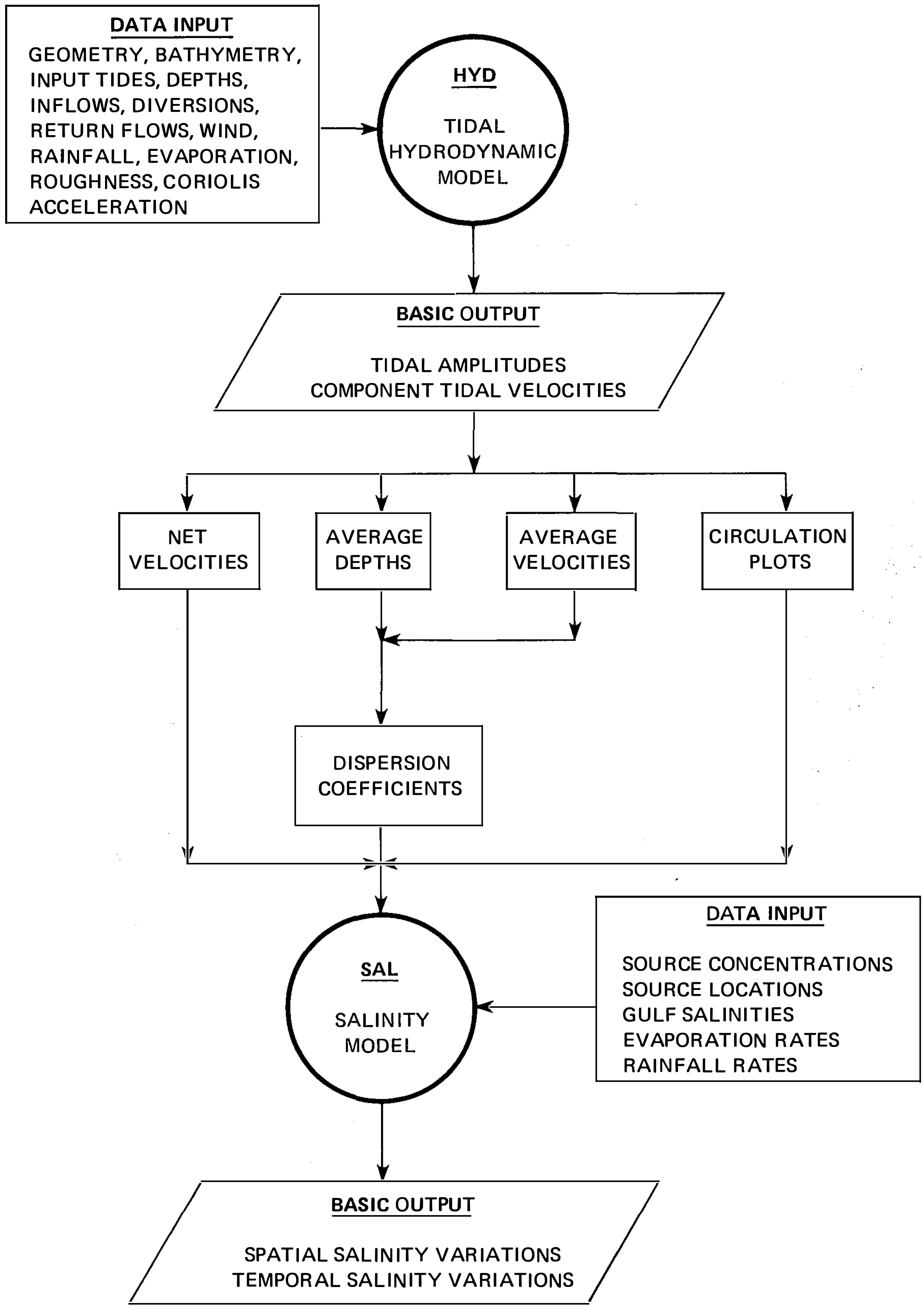

Figure 9.—Relationship Between Tidal Hydrodynamic and Salinity Models (18)

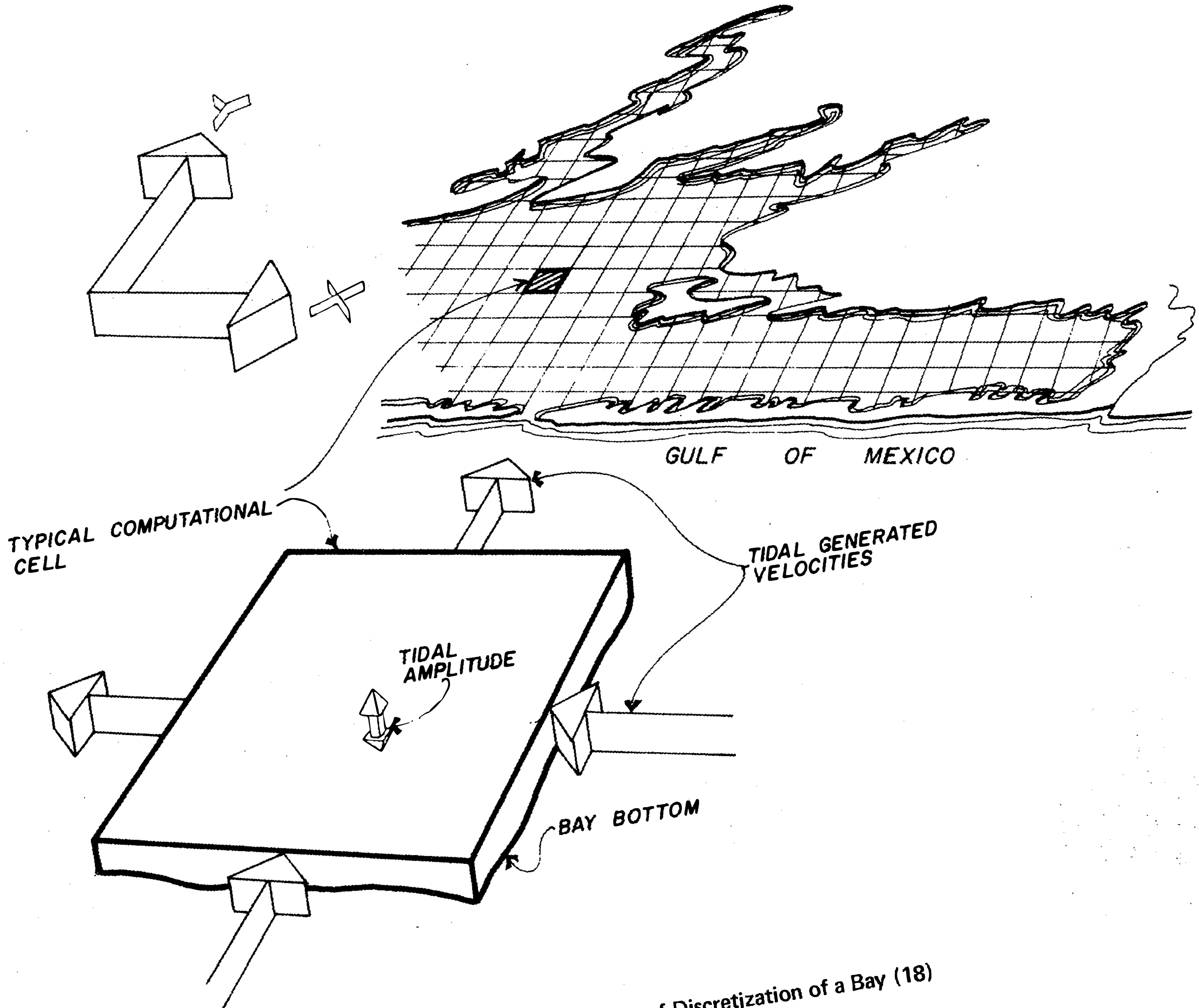

Figure 10.—Conceptual Illustration of Discretization of a Bay (18)

(2) Conservative Mass Transport Model

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

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

where C is the tidally averaged salinity or TDS concentration; $\bar{q}_x$ and $\bar{q}_y$ are the net flows over a tidal cycle in the x and y directions, respectively; D_x and D_y are the corresponding dispersion coefficients evaluated at a scale representative of total tidal mixing; and $\bar{d}$ is the average depth over a tidal cycle. The term $K_e C\bar{d}$, is a first-order reactive term included to represent the build-up of concentration due to evaporation from the bay surface and K_e is a coefficient determined volumetrically in accordance with methods described by Masch (18). The primary difference in the form of Equation [4] given above and that reported previously (18), is that Equation [4] is written in terms of net flows per foot of width rather than tidally averaged velocities.

The numerical technique employed in the salinity model involves an alternating direction implicit (ADI) solution of Equation [4] applied over the same grid configuration used in the tidal hydrodynamic model to determine the net flows and tidally averaged depths. Because of its implicit formulation the ADI solution scheme is unconditionally stable and there are no restrictions on the computational time step, Δt. However, to maintain accuracy and to minimize round-off and truncation errors, a condition corresponding to $\Delta t/\Delta \bar{s}^2 \leqslant 1/2$ was always maintained throughout this work. Details of the numerical solution of Equation [4] and programming techniques have also been previously described by Masch (18).

The computational grid network used to describe the Lavaca-Tres Palacios estuary is illustrated in Figure 11. The grid is superimposed on a map showing the general outline of the bay. Included in the grid network are the locations of islands (solid lines), submerged reefs (dash lines), inflow points, and tidal excitation cells. The x-axis of the grid system is aligned approximately parallel to the coastline, and the y-axis extends far enough landward to cover the lower reaches of all freshwater sources to the bay. The cell size (one square nautical mile) was based on the largest possible dimension that would provide sufficient accuracy, the density of available field data, computer storage requirements and computational time. Similar reasoning was used in selection of the computational time step except that the maximum possible time step in the hydrodynamic model was constrainted by the criterion for mathematical stability. In the indexing scheme shown in Figure 11, cells were numbered with the indices $1 < i < IMAX = 33$ and $1 < j < JMAX = 32$. With this arrangement, all model parameters such as water depths, flows in each coordinate direction, bottom function, and salinity could be identified with each cell in the grid.

(3) Data Sets Required

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

Physical Data

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

Hydrologic–Hydraulic Data

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

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

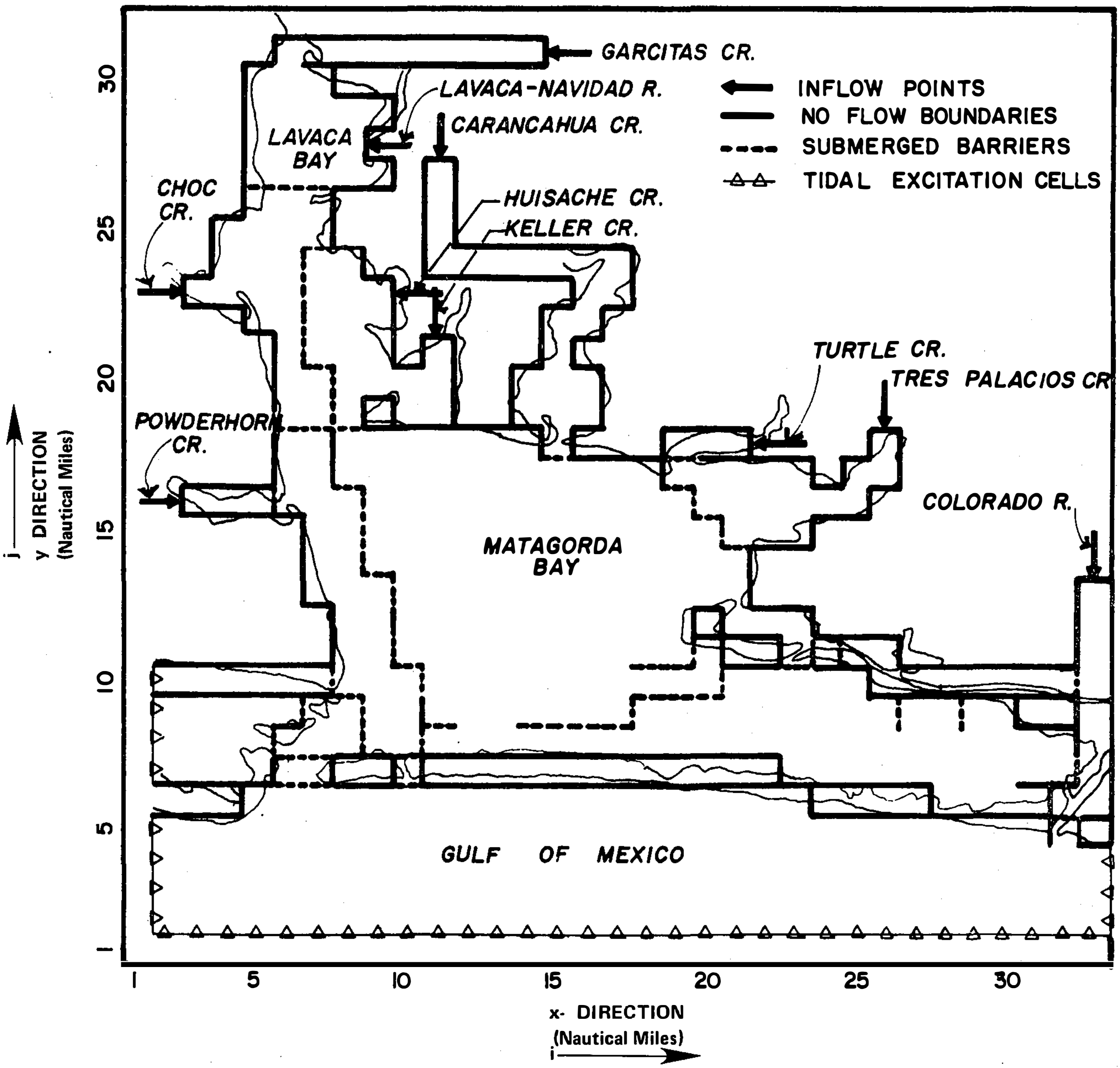

Figure 11.—Computational Grid, Lavaca-Tres Palacios Estuary

Application of Mathematical Models, Lavaca-Tres Palacios Estuary

The historic monthly total freshwater inflows to the Lavaca-Tres Palacios estuary for the years 1941 through 1976 were computed from gaged flow and precipitation records. Using these computed inflows, the mean inflows for each month were determined (Table 2). The tidal hydrodynamics model was operated using these mean monthly inflows along with typical tidal and meteorological conditions for each month as input to simulate average circulation patterns in the Lavaca-Tres Palacios estuary for each month of the year.

The output of the tidal hydrodynamics model consists of a set of tidal amplitudes and net flows computed for each cell in the 33 X 32 computational matrix representing the Lavaca-Tres Palacios estuary. The computed net flows are the average of the instantaneous flows calculated by the model over the tidal cycle. Thus, the circulation pattern represented by these net flows should not be interpreted as a set of currents that can be observed at any time during the tidal cycle, but rather a representation of the net movement of water created by the combined action of the Gulf tides, freshwater inflow and meteorological conditions during the tidal cycle.

The resultant circulation patterns can be best illustrated in the form of vector plots wherein each vector (or arrow) represents the net flow through each computational cell. The orientation of the vector represents the direction of flow and the length of the vector represents the magnitude of flow.

The tidal amplitudes and flows calculated by the tidal hydrodynamics model were used as input to operate the salinity transport model to simulate the salinity distributions in the Lavaca-Tres Palacios estuary for each of the mean monthly inflow periods. The resultant salinity distributions are illustrated in the form of salinity contour plots wherein lines of uniform salinity are shown in increments of five parts per thousand (ppt).

The numerical tidal hydrodynamic and salinity mass transport models described earlier were applied to the Lavaca-Tres Palacios estuary to determine the effects of the monthly average freshwater inflow upon the flow circulation and salinity characteristics of the estuarine system. The simulation models were general in nature and required adjustment or calibration to fit the conditions in the Lavaca-Tres Palacios system. Utilizing the recorded historical freshwater inflow, tidal elevations and velocities, and salinity measurements over the period 1971 through 1974, the appropriate coefficients in the simulation models were adjusted to provide reasonably close replications of observed historical conditions.

The models were then utilized to determine the steady-state monthly flow circulation and salinity patterns in the estuary for the average historical freshwater inflows and meteorological conditions over the period 1941 through 1976. Representative historical tides were selected for each month at the interchange points between the estuary, the Gulf of Mexico (through Cavallo Pass) and Espiritu Santo Bay.

The monthly simulated hydrodynamics are depicted graphically by vector plots which indicate the magnitude and direction of net flow over a tidal cycle for each computational "cell" in the system (Figures 12 through 23). The scale of magnitude for each flow vector is one inch for every 8,500 cubic feet per second (ft^3/sec) (or 238 m^3/sec). The simulated monthly salinities in the estuary are given by contour plots of salinity concentrations beginning at 10 parts per thousand (ppt) and increasing in increments of 5 ppt (Figures 24 through 35).

The results of the monthly hydrodynamic and salinity simulations were influenced primarily by the average volumes of freshwater inflows. As indicated in Figure 36, the average monthly freshwater inflows into the Lavaca-Tres Palacios estuary are greatest in May and reach a minimum during August. The average inflows for the months of January, March, November and December are almost identical, as are the months of February, April, September and October. It was found that the simulated monthly flow patterns and salinities in the estuary could be divided into five groupings based upon evident similarities: (1) November, December and January; (2) February, March and April; (3) May and June; (4) July, September and October; and (5) August. The flow and salinity characteristics exhibited by the numerical simulations in each of the five cases are discussed below.

Simulated November, December and January Circulation and Salinity Patterns Under Average Inflow Conditions

The flow circulations and salinity concentrations in the Lavaca-Tres Palacios estuary were simulated for historical average meteorological and freshwater inflows for the months of November, December and January. The predominant wind speed and direction of 10 miles per hour (mph) (or 4.5 m/sec) from the northeast varies only slightly between these late fall and winter months, as does the historical average freshwater inflows (Table 2).

Table 2.—Mean Monthly Freshwater Inflow, Lavaca-Tres Palacios Estuary, 1941-1976

Month	Powderhorn[a] Creek	Turtle[a] Creek	Tres-Palacios[b] Creek	Keller[a] Creek	Chocolate[a] Creek	Cox Creek	Carancahua[a] Creek	Lavaca[b] River	Colorado[b] River	Garcita[b] Creek
January	49	49	244	18	32	16	161	845	2,487	163
February	72	54	306	25	36	18	227	1,026	2,988	234
March	33	49	211	18	32	16	161	764	2,471	179
April	84	50	286	24	67	34	212	1,260	3,041	336
May	114	98	520	44	81	33	395	2,016	4,585	618
June	134	84	386	40	134	67	363	1,882	3,965	470
July	81	49	163	11	49	16	102	537	1,935	211
August	65	33	211	15	32	16	132	439	1,219	130
September	168	134	538	45	101	50	408	1,327	2,134	437
October	163	98	406	42	98	49	380	1,226	2,585	488
November	34	34	168	12	17	17	106	706	2,654	118
December	81	49	228	18	33	16	161	715	2,162	195

[a]Total ungaged flow in ft^3/sec.
[b]Total gaged and ungaged flow in ft^3/sec.

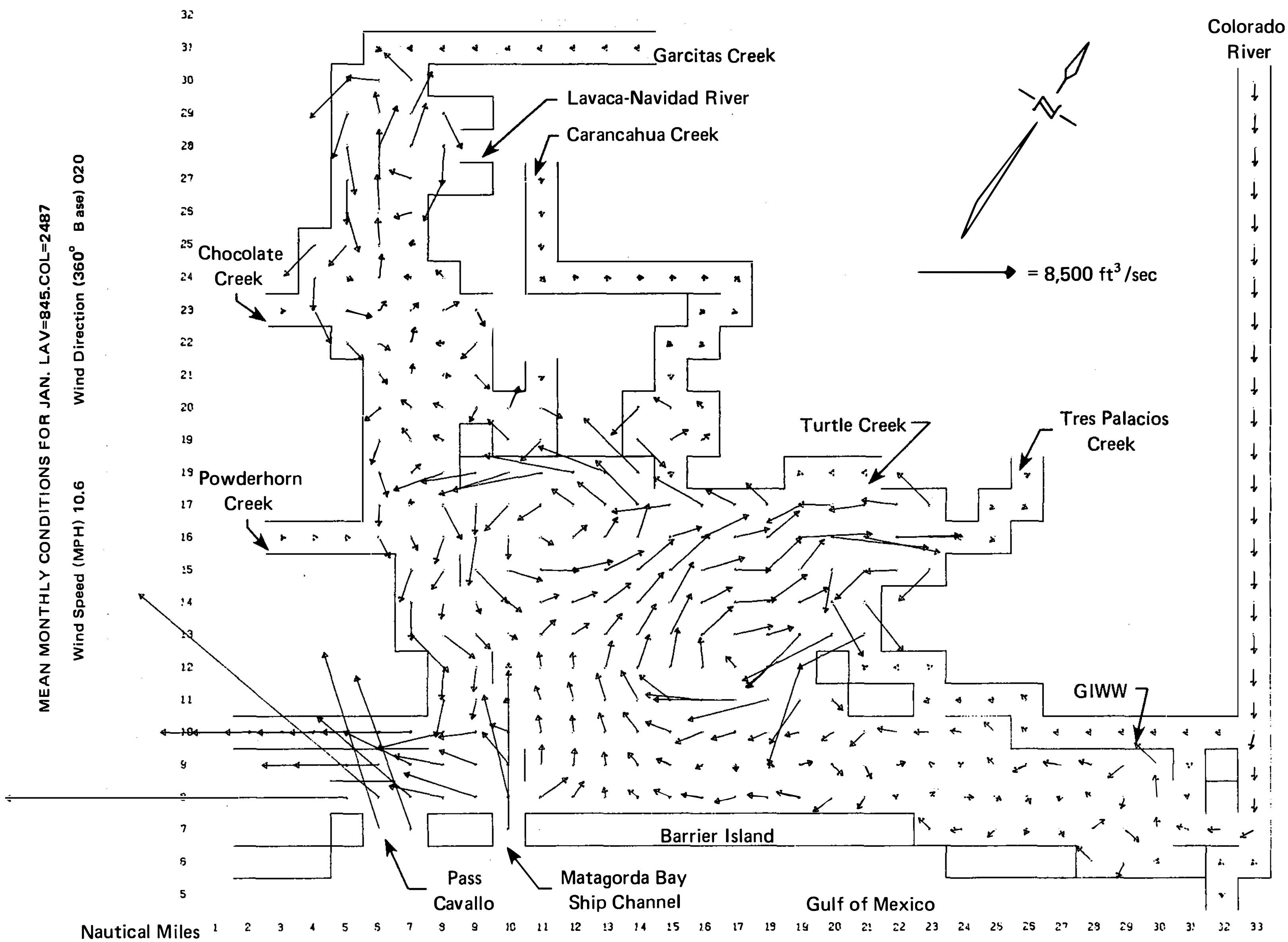

Figure 12.—Simulated Net Steady-State Flows in the Lavaca-Tres Palacios Estuary Under January Average Inflow

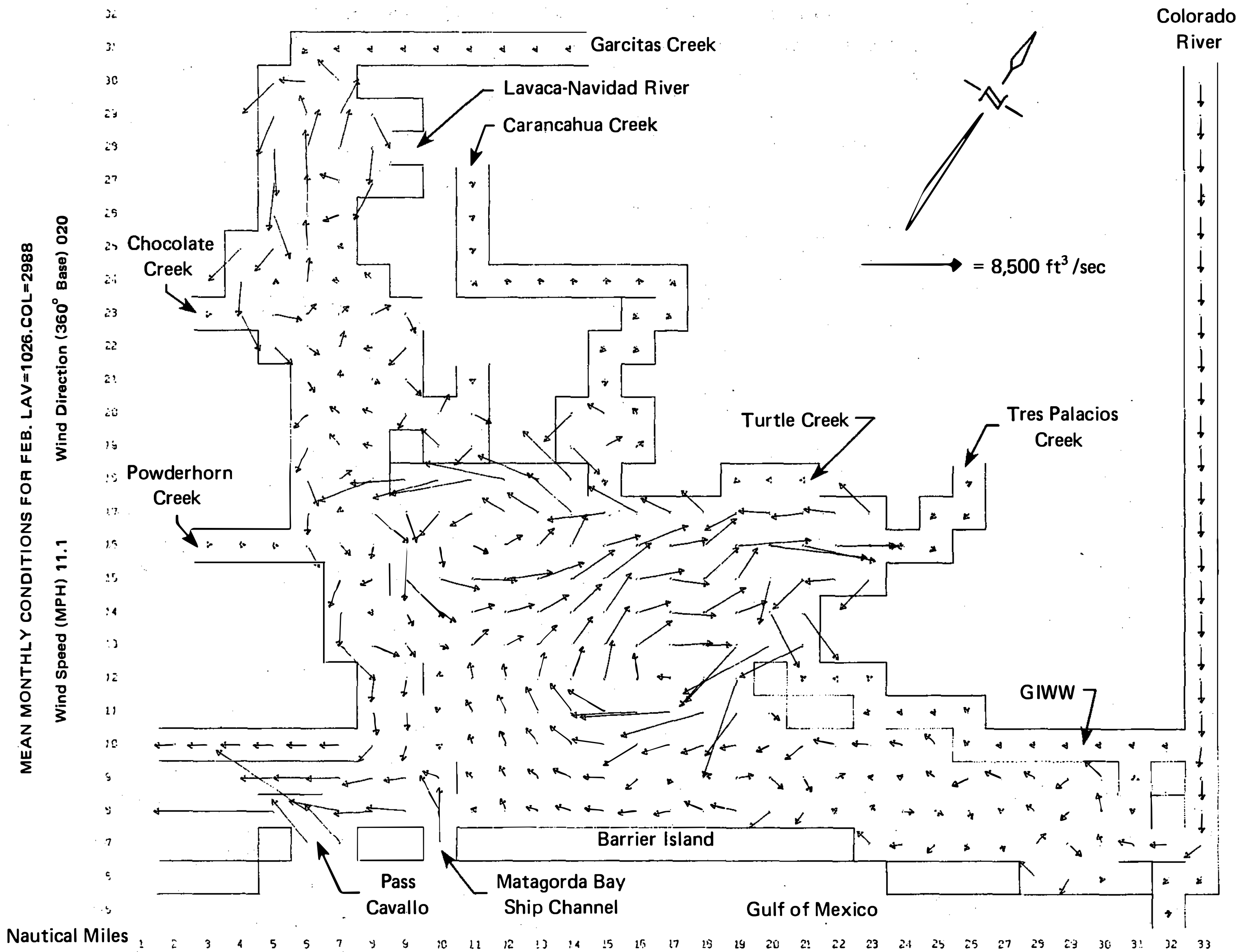

Figure 13.—Simulated Net Steady-State Flows in the Lavaca-Tres Palacios Estuary Under February Average Inflow

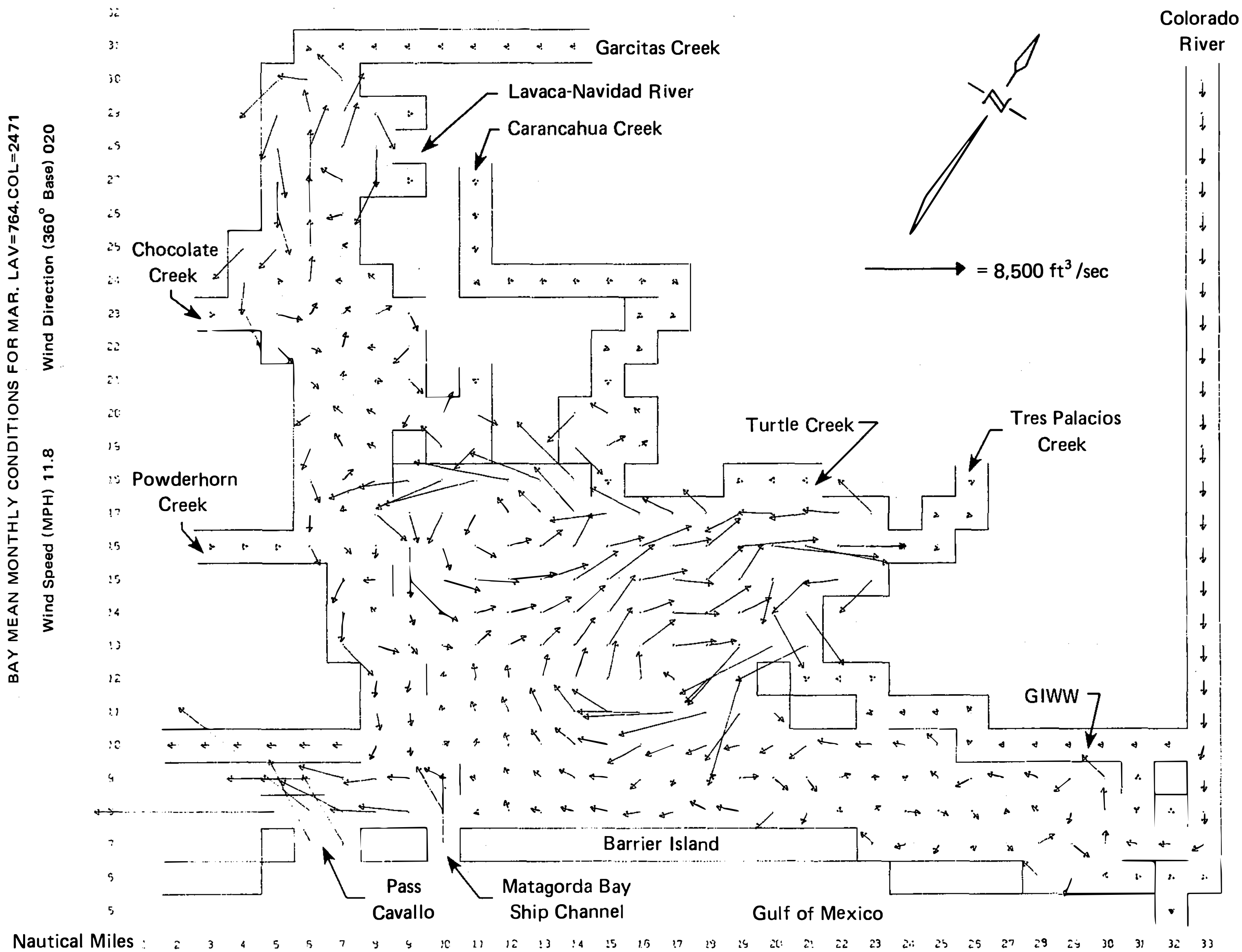

Figure 14.—Simulated Net Steady-State Flows in the Lavaca-Tres Palacios Estuary Under March Average Inflow

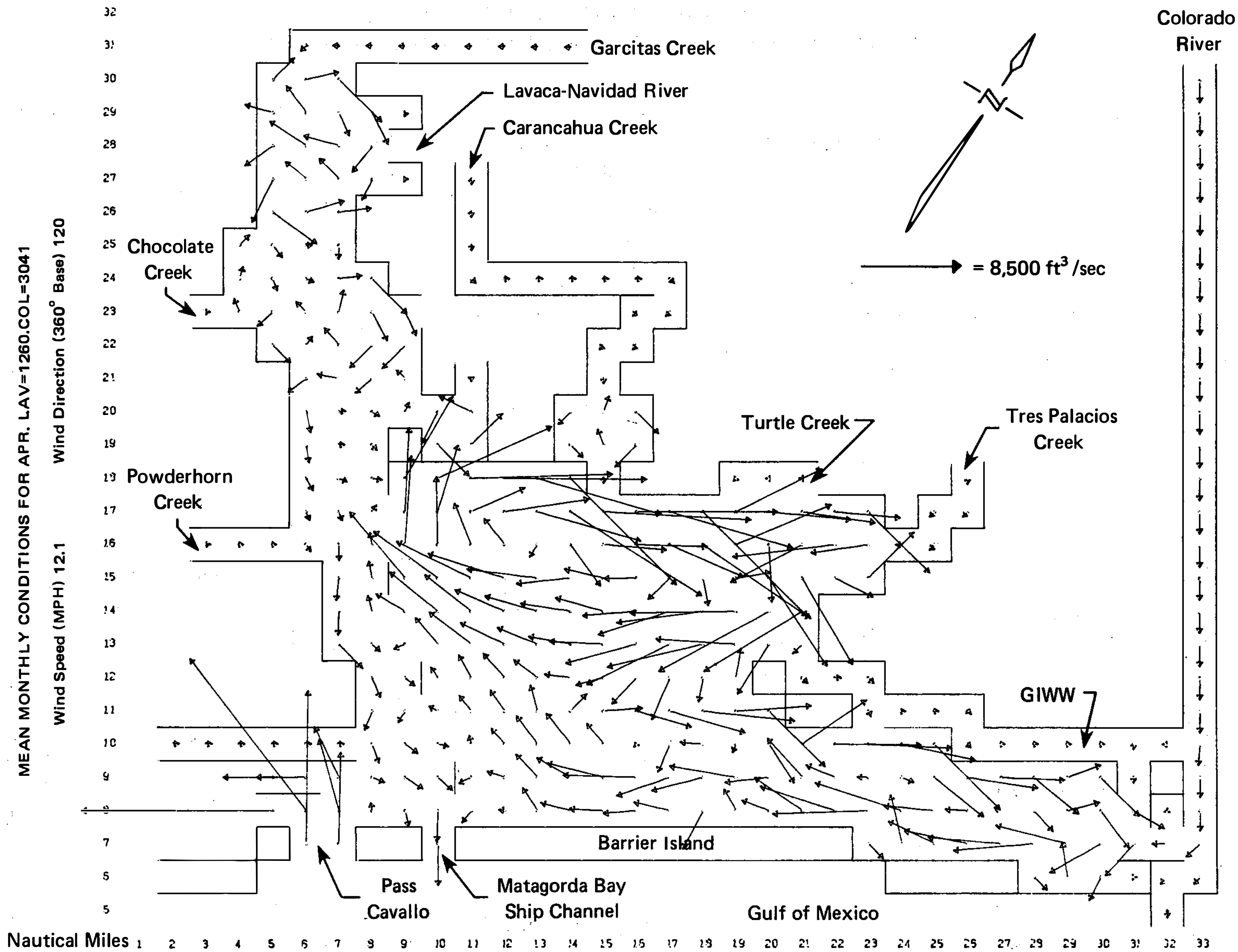

Figure 15.—Simulated Net Steady-State Flows in the Lavaca-Tres Palacios Estuary Under April Average Inflow

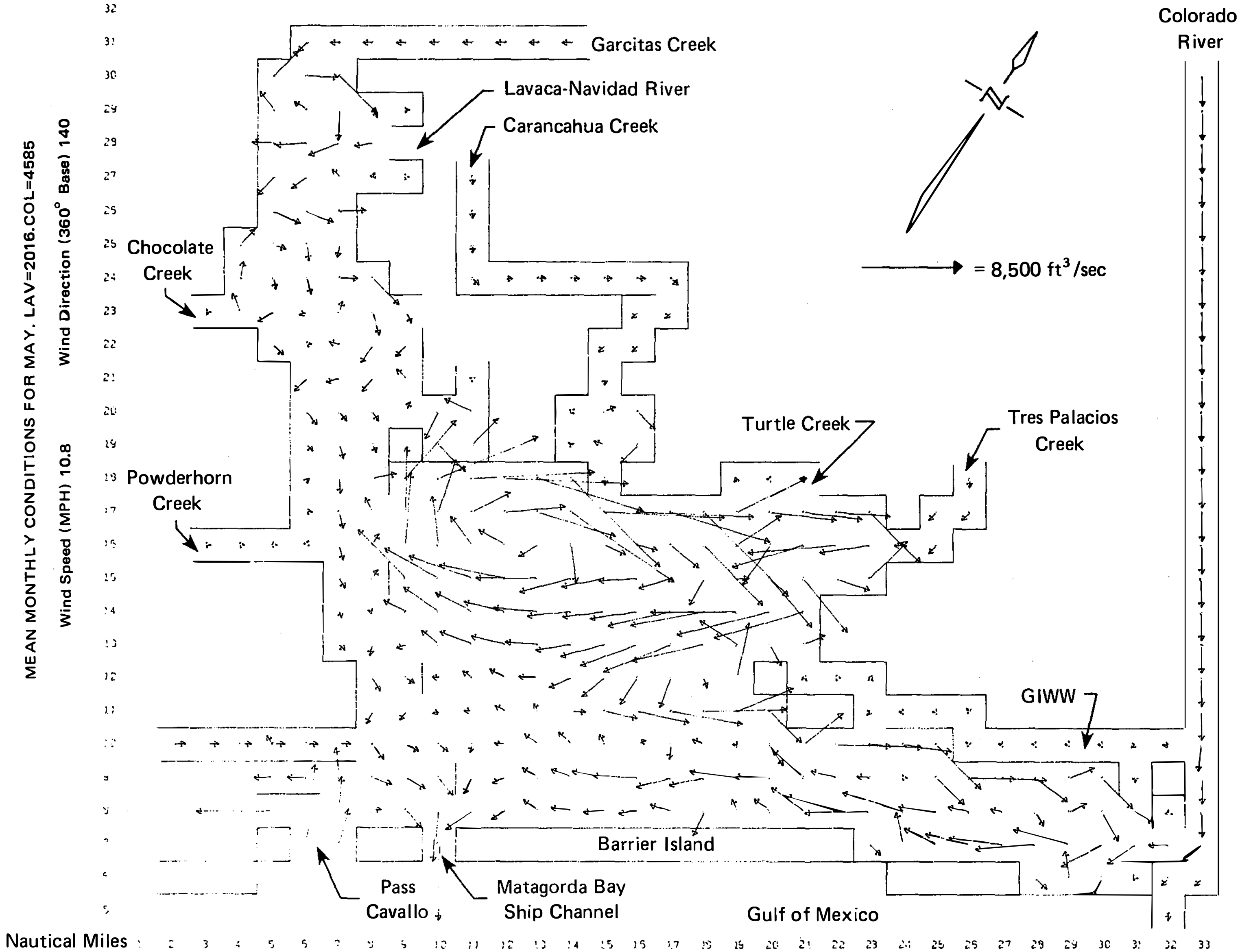

Figure 16.—Simulated Net Steady-State Flows in the Lavaca-Tres Palacios Estuary Under May Average Inflow

The most obvious circulation pattern evident for the estuary for these indicated months (Figures 22, 23 and 12) is a clockwise current eddy in the central and northeastern portions of Matagorda Bay. Smaller counter-clockwise flow circulation patterns are evident in upper Lavaca Bay and the northwestern portion of Matagorda Bay. Water is exchanged into the Guadalupe estuary to the southwest from the Gulf of Mexico via Pass Cavallo and the Matagorda Bay entrance channel and Matagorda Bay. No net flow is directed into the main body of Matagorda Bay from the Gulf of Mexico through Pass Cavallo. Flow from the Colorado River passes through the eastern portion of Matagorda Bay along the northern coast of the Matagorda Peninsula and joins in the major circulation pattern in the middle of Matagorda Bay. Small volumes of flow appear to be exchanged, but Lavaca Bay continues to have its own internal circulation pattern.

The simulation of estuarine salinities under average November, December and January inflow conditions and meteorology resulted in the greatest areal portion of Matagorda Bay having concentrations of salinity 20-25 ppt (Figures 34, 35 and 24). Lavaca Bay had simulated salinity concentrations of less than 15 ppt in its upper half and concentrations of 15-20 ppt in its lower portion. Salinity concentrations in excess of 25 ppt were simulated near Pass Cavallo, the Matagorda Bay Entrance Channel and Parker Cut (Tiger Island Cut).

Simulated February, March and April Circulation and Salinity Patterns Under Average Inflow Conditions

Average meteorological and freshwater inflow conditions were used to drive the simulation model computing the flow circulation patterns for the months of February, March and April (Figures 13, 14 and 15). The circulation patterns evident in the months of November through January are again predominant, with the main circulation being a clockwise vortex of flow in the middle of Matagorda Bay. The average wind speeds for the months of February, March and April are 11.1, 11.8 and 12.2 mph (or 5, 5.3 and 5.5 m/sec), respectively. The predominant wind direction shifts from northeast in February and March to southeast in April.

The flow through Pass Cavallo moves into the Guadalupe estuary and not into Matagorda Bay, whereas the flow through the Matagorda Bay Entrance Channel is directed into the Lavaca-Tres Palacios estuary from the Gulf of Mexico during the months of February and March, but out of the estuary during April.

Noticeable increases in flow rates can be observed in the vector plots for April over those of February and March. This reflects a more turbulent condition in the estuary system due to tidal action and wind effects (and possibly by a higher total freshwater inflow).

The simulation of salinity conditions over these late winter and early spring months (Figures 25, 26 and 27) indicates that the influence of the Colorado River and its distribution through the circulation patterns in Matagorda Bay resulted in the eastern portion of Matagorda Bay having 15-20 ppt salinities, with the remainder of the bay having concentrations of 20 to 25 ppt. The salinity in Lavaca Bay was simulated to be less than 15 ppt and 15-20 ppt in the upper and lower portions, respectively. Salinities in excess of 25 ppt were simulated near Pass Cavallo.

Simulated May and June Circulation and Salinity Patterns Under Average Inflow Conditions

The average flow circulation patterns in Lavaca-Tres Palacios estuary for May and June (Figures 16 and 17) reflected the influence of the two months of greatest historical freshwater inflow. The mean historical wind speed and direction for May and June are, respectively, 10.8 mph (4.9 m/sec) and 9.8 mph (3.4 m/sec) from the southeast.

The circulation pattern dominant in the estuary during these months is a clockwise rotating current eddy in the northern and central portions of Matagorda Bay. An additional circulation pattern is evident in the northeastern and eastern sections of the bay. This pattern causes flow from the central portion of Matagorda Bay to move toward Parker Cut near the mouth of the Colorado River along the northern banks of eastern Matagorda Bay. Near Parker Cut, water from Matagorda Bay is mixed with water from the Colorado River and the Gulf of Mexico and moved along the northern shore of Matagorda Peninsula which separates the estuary from the Gulf of Mexico. Flow through the Matagorda Bay Entrance Channel moves almost directly into Espiritu Santo Bay of the Guadalupe estuary and does not enter into the main body of Matagorda Bay. Flow from the Lavaca and Navidad Rivers in May and June resulted in a significant net flow from Lavaca Bay into Matagorda Bay. No discernable current eddy was evident in Lavaca Bay (due likely to high inflow predominating over the tidal action).

The salinity simulations for the months of May and June revealed the effects of significant freshwater inflows upon the salinity in the bay (Figures 28 and 29).

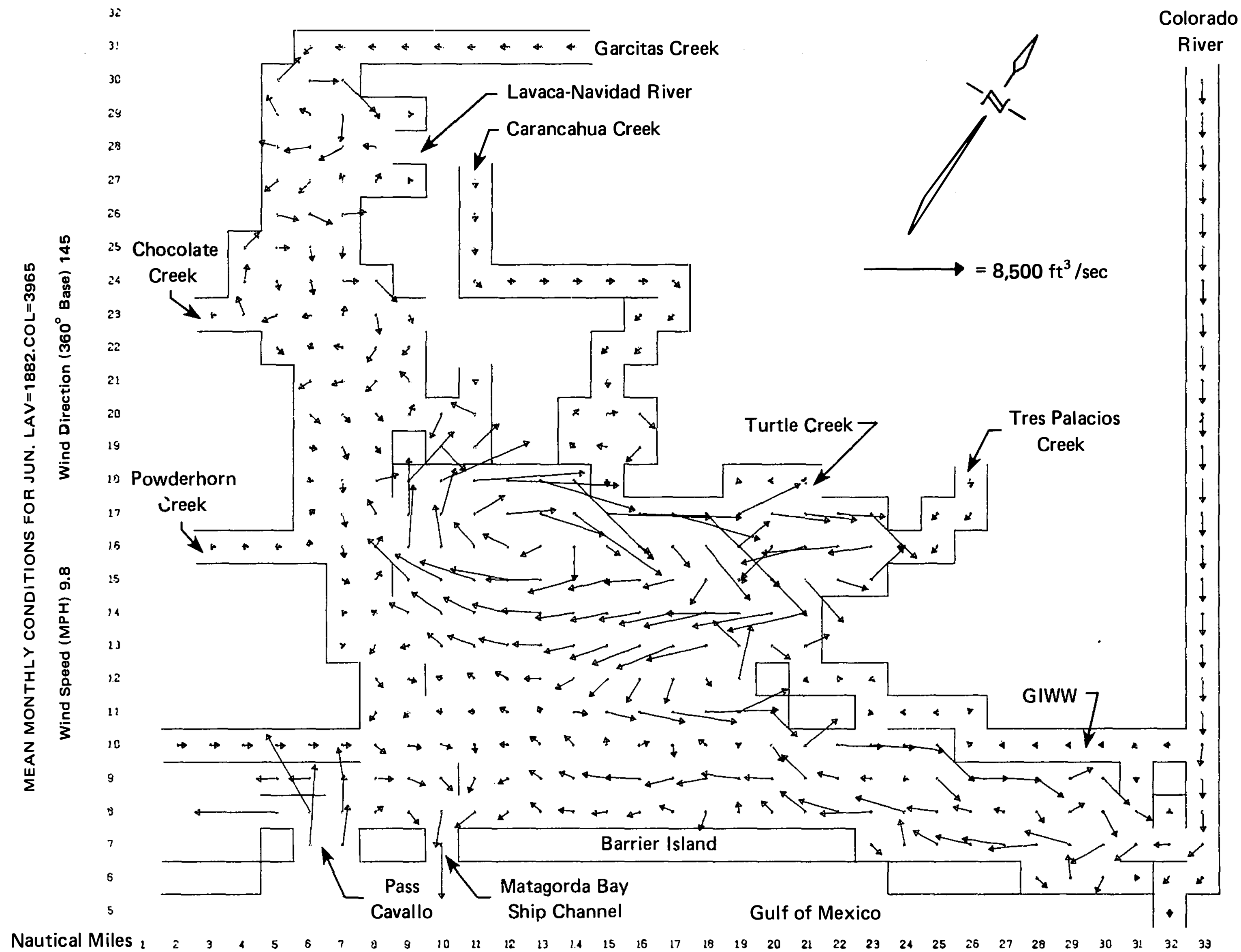

Figure 17.—Simulated Net Steady-State Flows in the Lavaca-Tres Palacios Estuary Under June Average Inflow

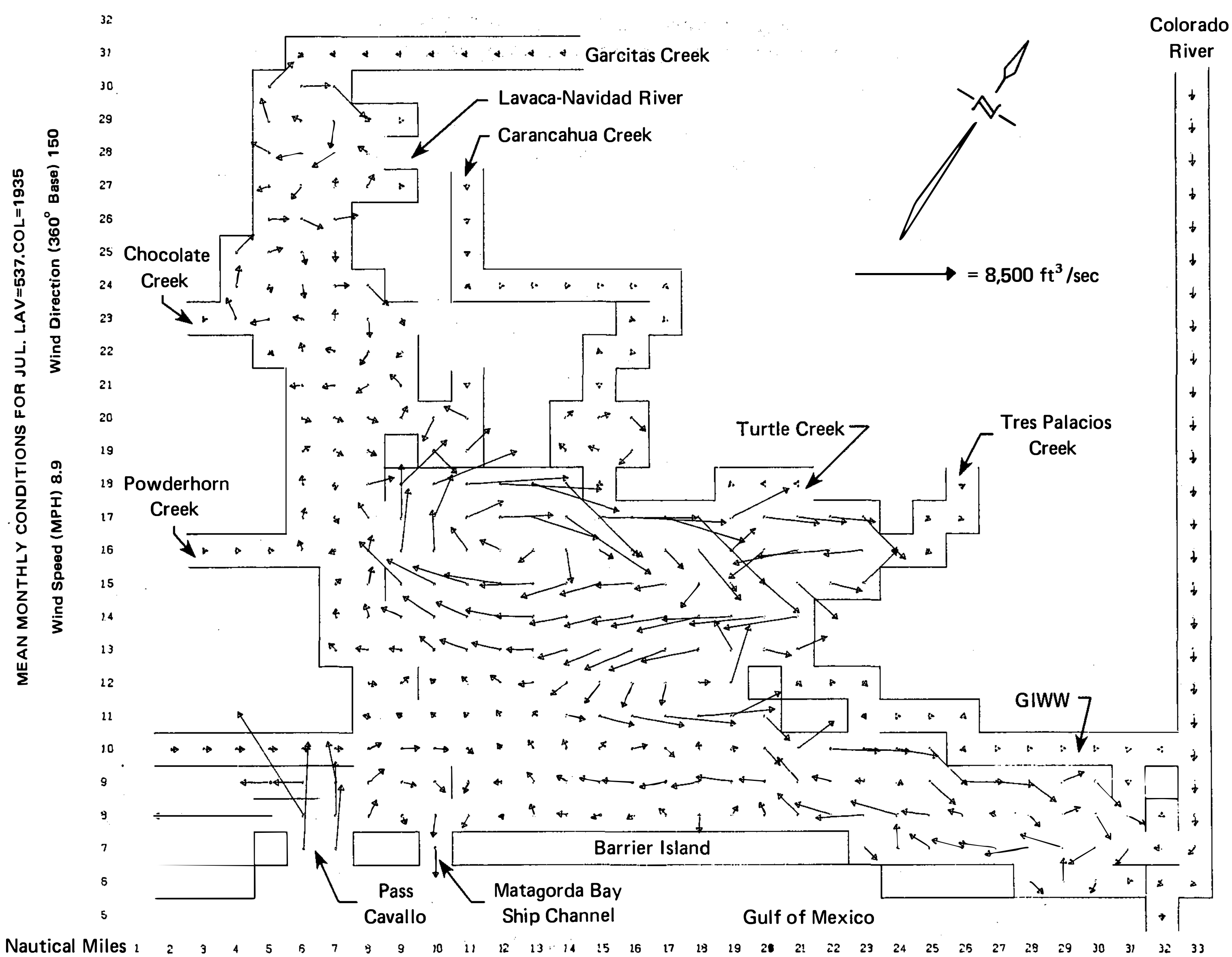

Figure 18.—Simulated Net Steady-State Flows in the Lavaca-Tres Palacios Estuary Under July Average Inflow

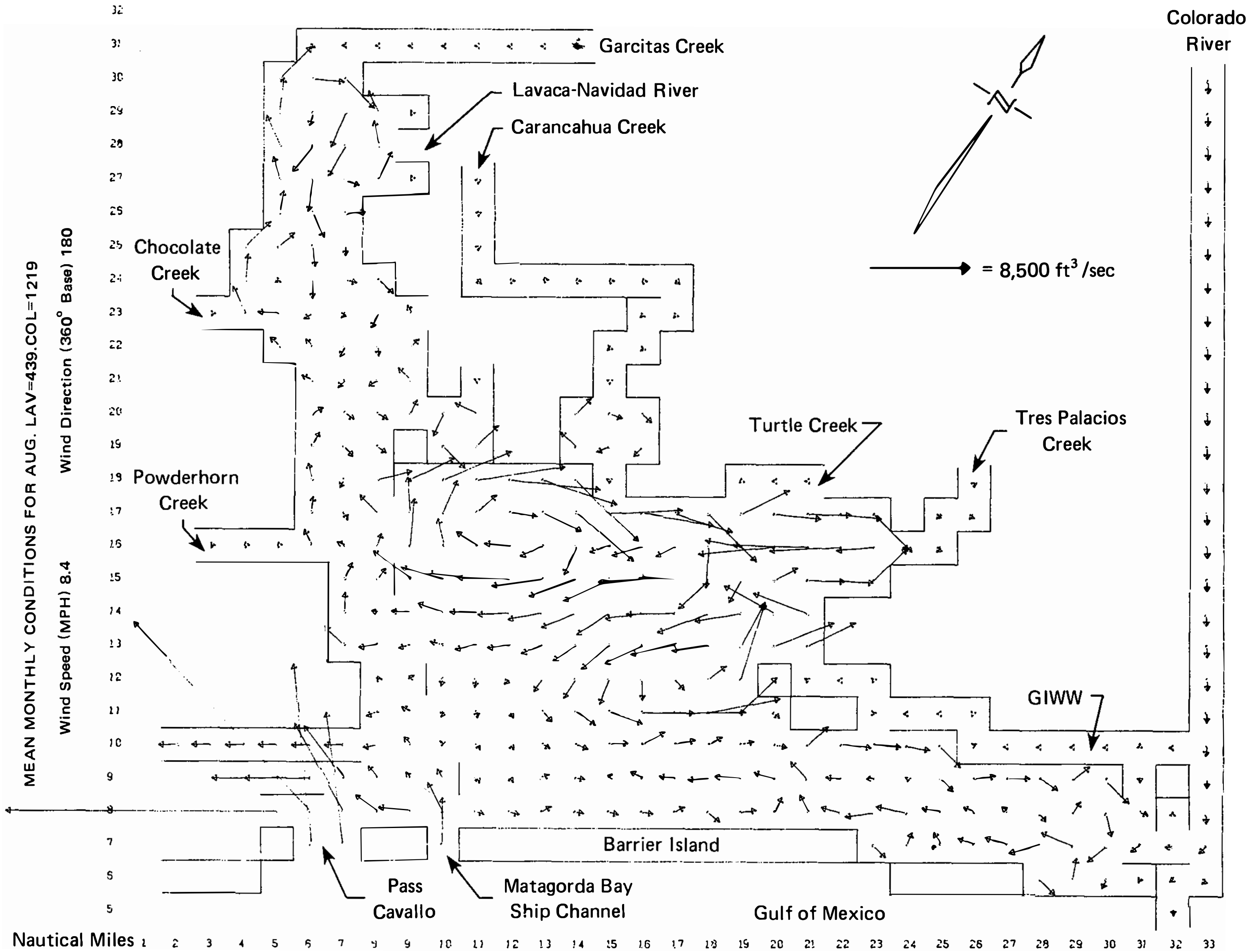

Figure 19.—Simulated Net Steady-State Flows in the Lavaca-Tres Palacios Estuary Under August Average Inflow

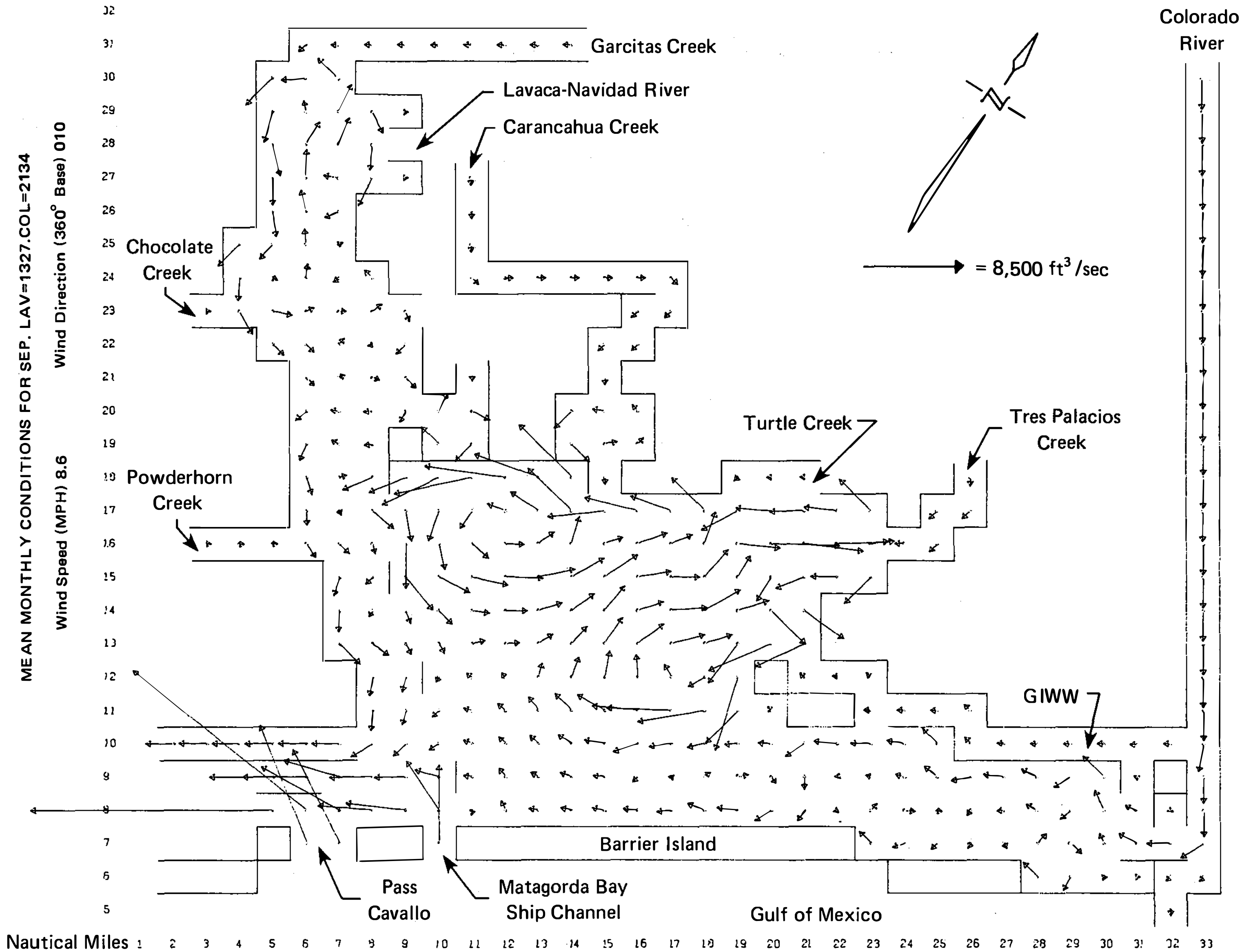

Figure 20.—Simulated Net Steady-State Flows in the Lavaca-Tres Palacios Estuary Under September Average Inflow

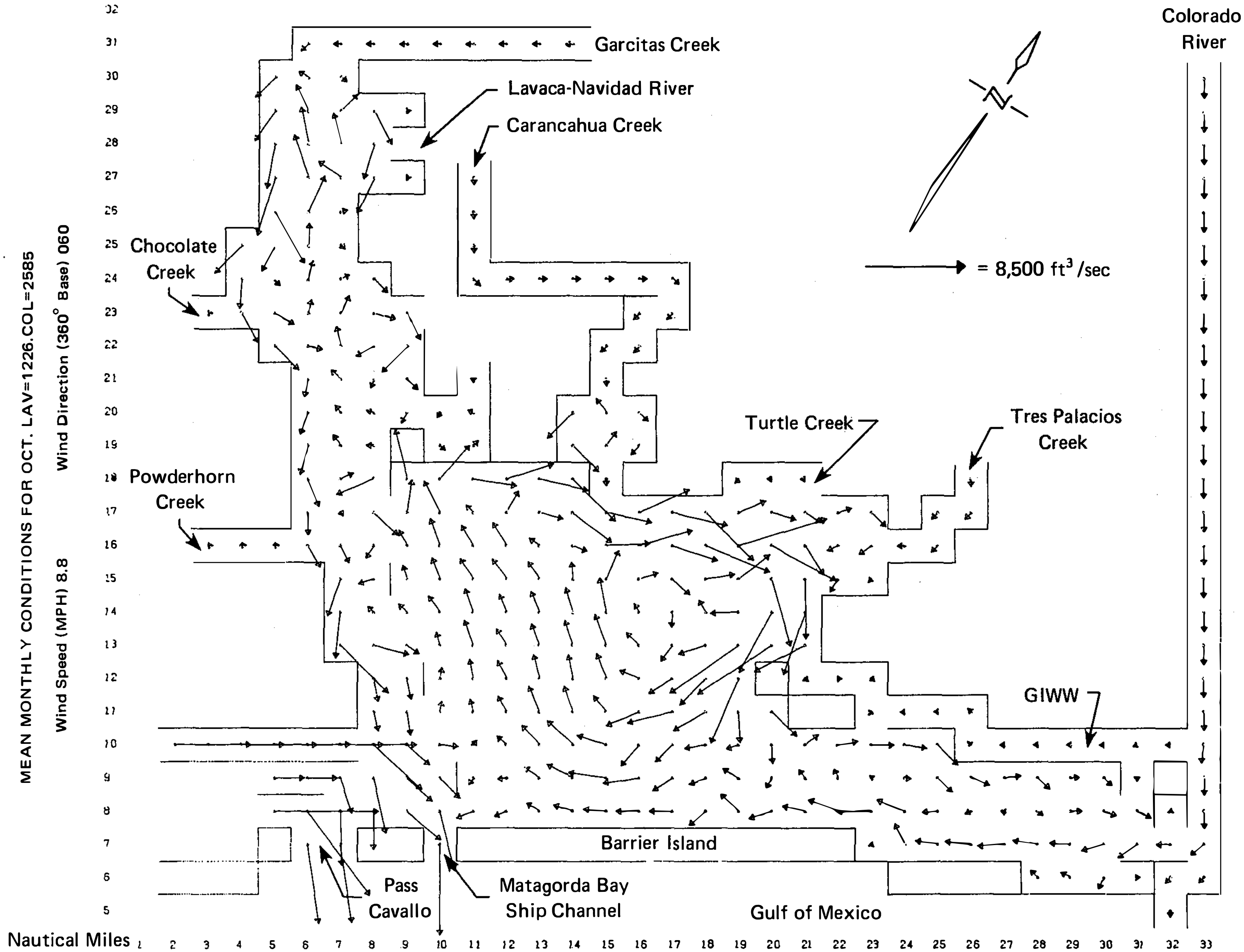

Figure 21.—Simulated Net Steady-State Flows in the Lavaca-Tres Palacios Estuary Under October Average Inflow

The only area of the bay exceeding 20 ppt salinity during both months was a small section in the vicinity of Pass Cavallo. All of Lavaca Bay had simulated salinities of less than 15 ppt, with eastern Matagorda Bay having similar salinity levels during May. The eastern portion of Matagorda Bay during June had salinities of 15-20 ppt except in the vicinity of Parker Cut where salinities exceeded 20 ppt.

Simulated July, September and October Circulation and Salinity Patterns Under Average Inflow Conditions

The hydrodynamic model for the Lavaca-Tres Palacios estuary for the months of July, September and October shows similar steady-state net flow circulation patterns throughout the period under average inflow and meteorological conditions (Figures 18, 20 and 21). The historical average wind speed for these months is approximately 8.8 mph (4 m/sec) (July, 8.9 mph; September, 8.6 mph; and October, 8.8 mph). However, the mean wind direction is southeasterly for July, northerly for September and northeasterly for October.

The most prominant circulation pattern in these simulated months was the clockwise rotating eddy in the central and northern portions of Matagorda Bay. During September an additional current eddy rotating in a counter-clockwise direction is also evident in upper Matagorda Bay. During the months of July and October, a clockwise circulation was simulated in the eastern portions of Matagorda Bay. Internal circulation patterns predominate in Lavaca Bay during these simulated months with only the month of October showing significant contributions of net flow from Lavaca Bay to Matagorda Bay.

Simulated net flows at the exchange points for the Lavaca-Tres Palacios estuary, the Gulf of Mexico and the Guadalupe estuary during these months showed no significant net contribution to Matagorda Bay except at Tiger Island Cut. At Pass Cavallo, the flows during July and September pass directly into the Guadalupe estuary. During October, water moves from Espiritu Santo Bay out into the Gulf without entering Matagorda Bay. At the Matagorda Bay Entrance Channel, water passes to the Gulf from Matagorda Bay in July and October, while flow moves into Espiritu Santo Bay from the Gulf in September.

The simulation of salinity conditions under average monthly inflows in the Lavaca-Tres Palacios estuary during July, September and October (Figures 30, 32 and 33) projected that average salinity concentrations of 20-25 ppt should occur over approximately half of Matagorda Bay with the remaining area experiencing concentrations of 15-20 ppt. Lavaca Bay had simulated salinity concentrations over the majority of its area of less than 15 ppt with only the lower third of the bay having salinities of 15-20 ppt. Salinities in the vicinity of the major exchange points with the Gulf of Mexico were approximated 25 ppt.

Simulated August Circulation and Salinity Patterns Under Average Inflow Conditions

The month of August has the lowest average historical monthly inflow of freshwater into the Lavaca-Tres Palacios estuary. The mean wind speed and direction during this month is 8.4 mph (3.8 m/sec) from the south.

The simulated net circulation patterns for July (Figure 19) indicated that the circulation in Matagorda Bay is governed by three patterns: a counter-clockwise rotating eddy in the central portion of the bay, a clockwise moving current in the upper part of the bay, and clockwise circulation vortex in the eastern part. Some net exchange of water from Matagorda Bay into Lavaca Bay appeared evident; however, a general clockwise rotating eddy current entirely within Lavaca Bay dominates net circulation in that Bay.

Little net flow exchange is evident between Matagorda Bay and the area in the vicinity of Pass Cavallo and the Matagorda Bay Entrance Channel during August. Water passes through these channels from the Gulf; however, this flow is directed into Espiritu Santo Bay of the Guadalupe estuary. Flow from the Gulf enters Matagorda Bay and water from the Colorado River enters through Tiger Island Cut.

In the August simulation of average inflow conditions the resulting salinity patterns in the estuary (Figure 31) indicated high levels of salinity within all of Matagorda Bay in excess of 20 ppt. Over 90 percent of Lavaca Bay had simulated salinities of 15-20 ppt. The salinity concentrations in excess of 25 ppt were also simulated over the extreme eastern and western ends of Matagorda Bay near the major flow exchange points.

NUTRIENT PROCESSES

Summary

Nutrient contributions to the Lavaca-Tres Palacios estuary are derived primarily from (1) river inflow; (2) local ungaged runoff; and (3) biogeochemical cycling

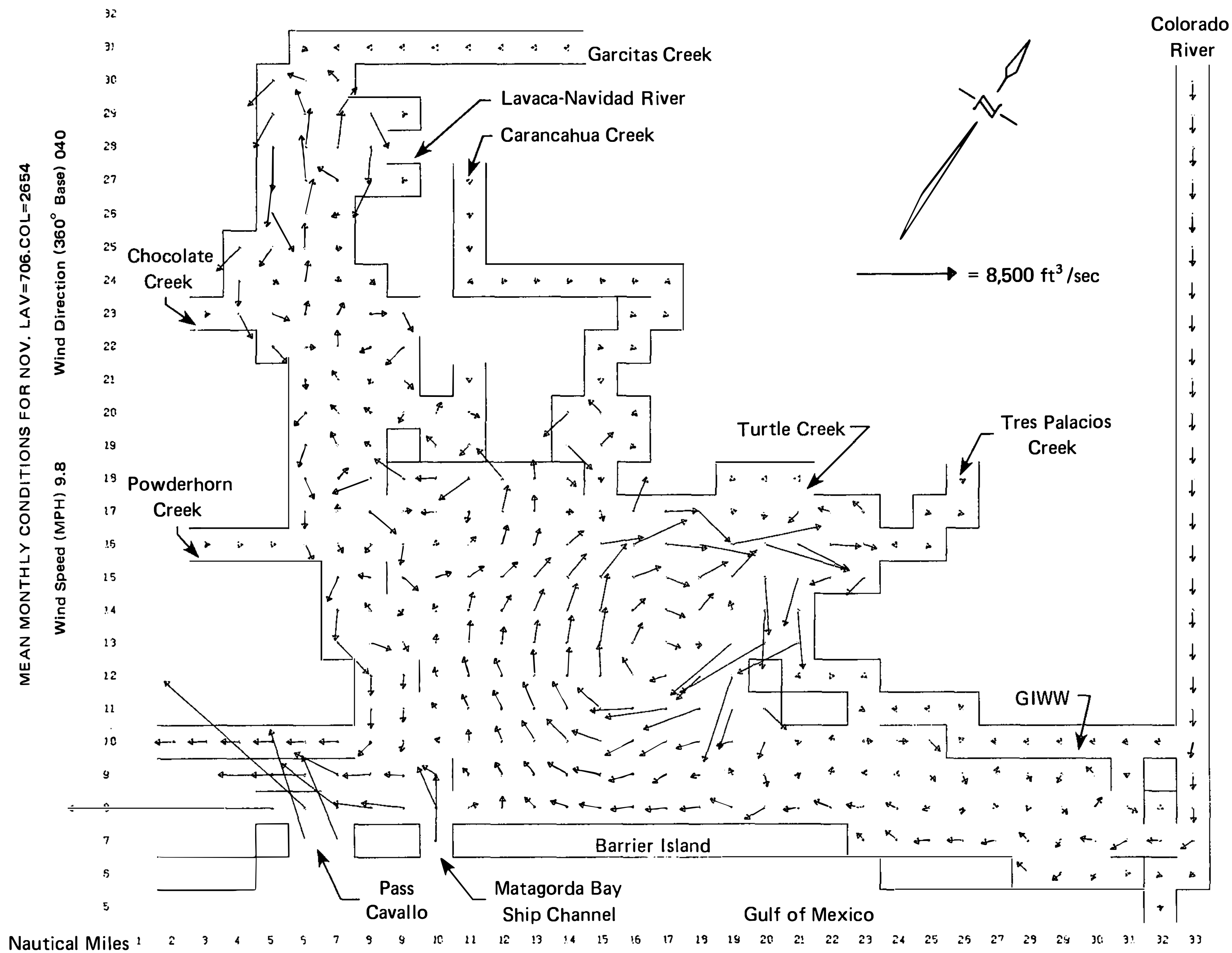

Figure 22.—Simulated Net Steady-State Flows in the Lavaca-Tres Palacios Estuary Under November Average Inflow

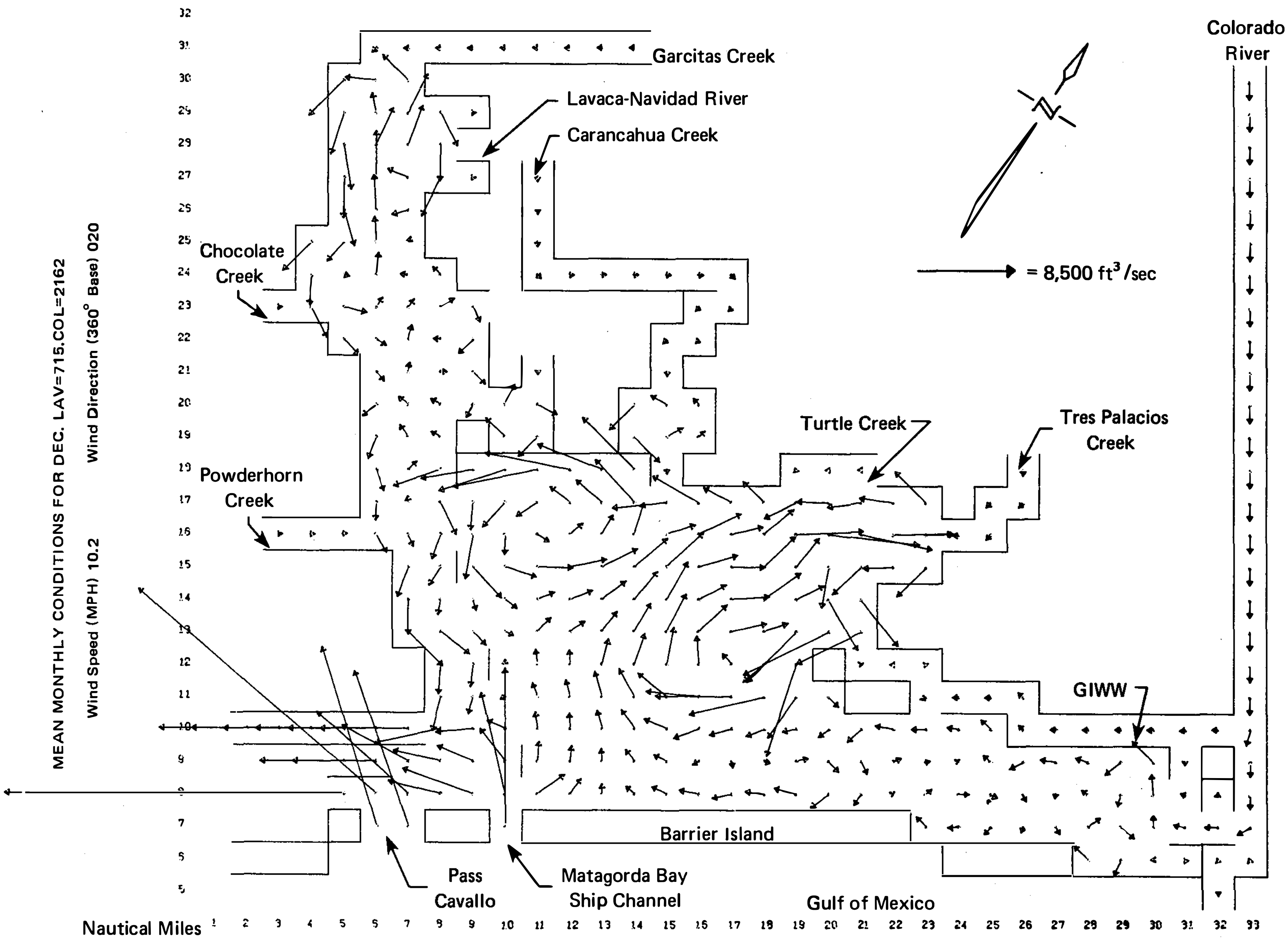

Figure 23.—Simulated Net Steady-State Flows in the Lavaca-Tres Palacios Estuary Under December Average Inflow

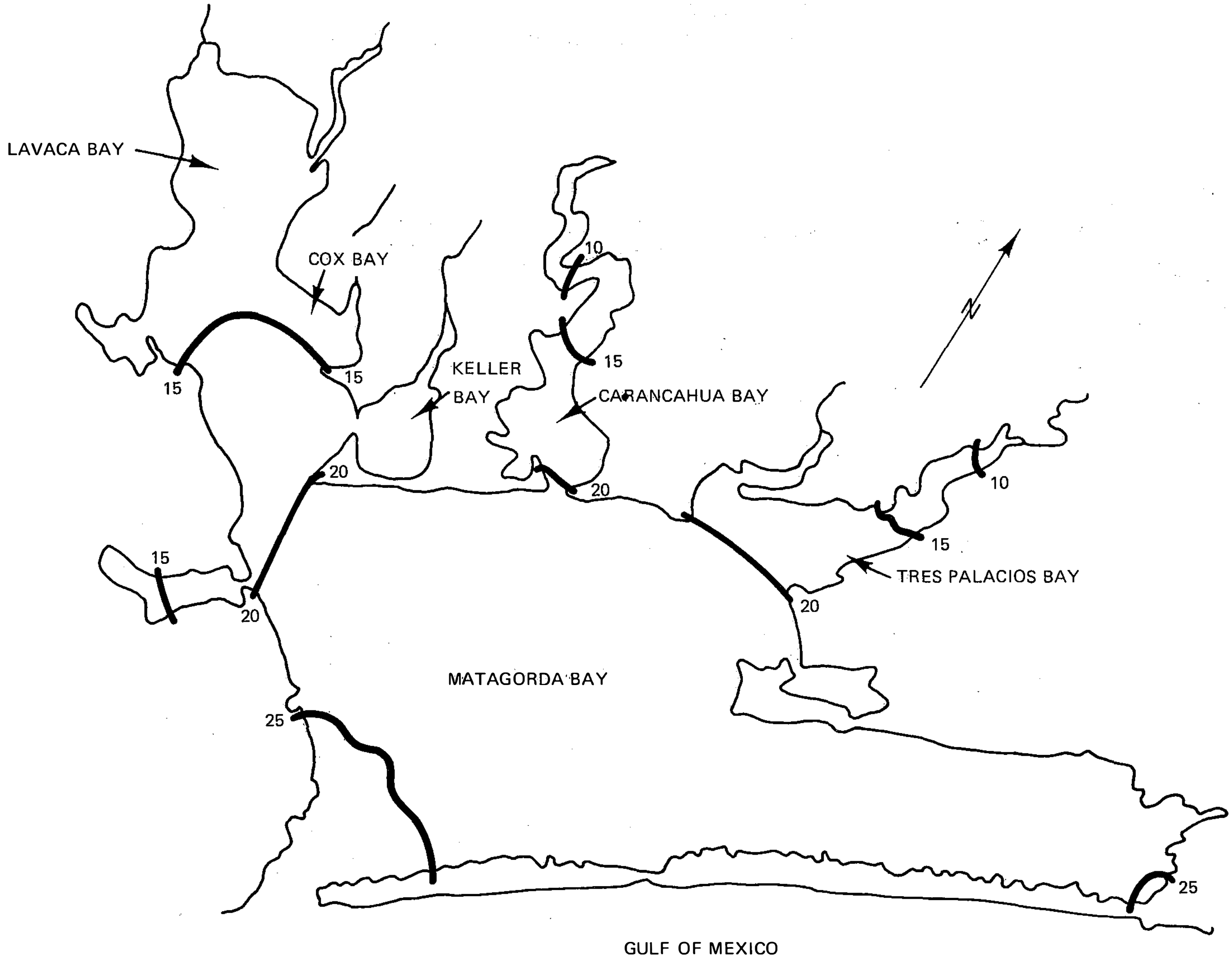

Figure 24.—Simulated Salinities in the Lavaca-Tres Palacios Estuary Under January Average Inflows (ppt)

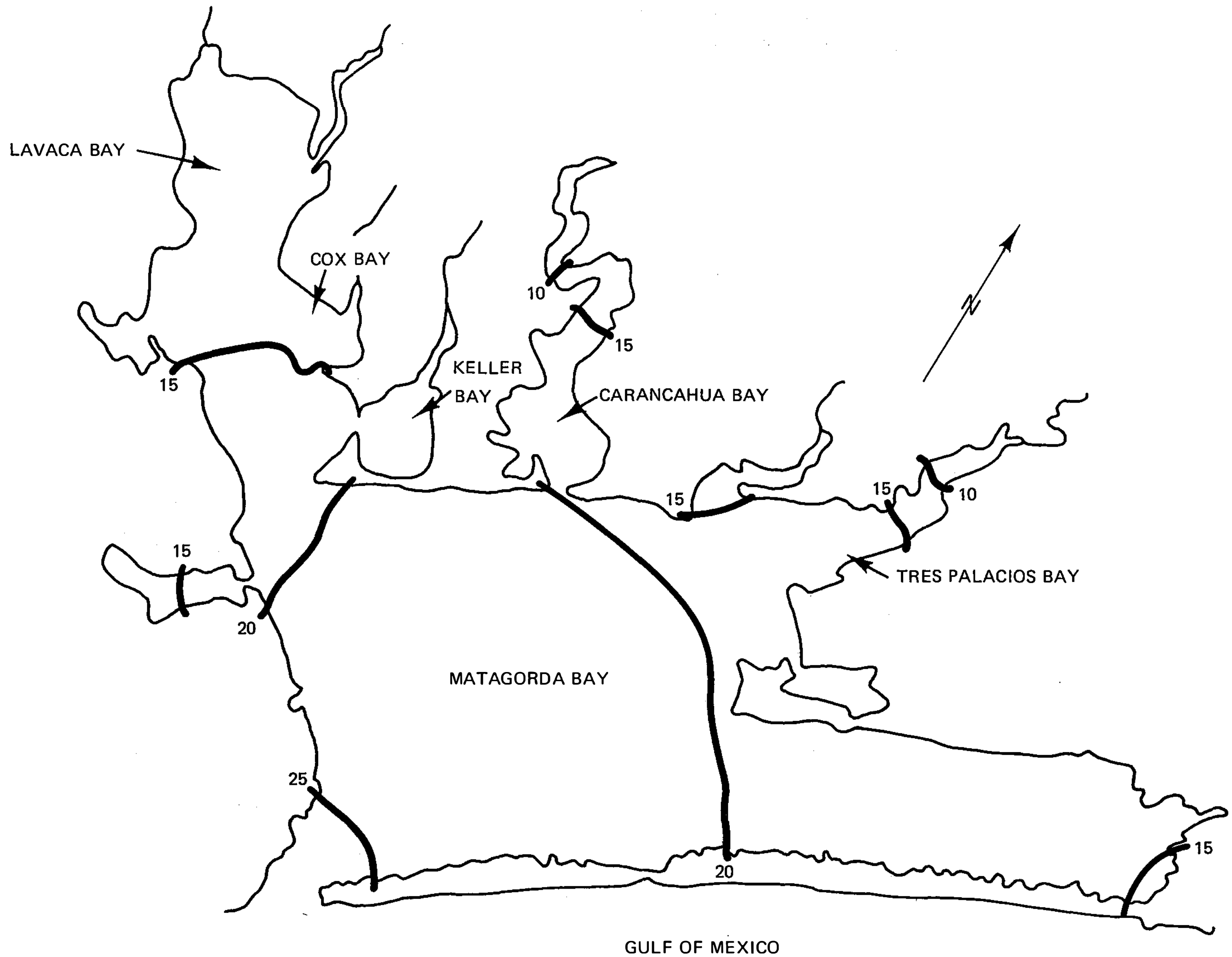

Figure 25.—Simulated Salinities in the Lavaca-Tres Palacios Estuary Under February Average Inflows (ppt)

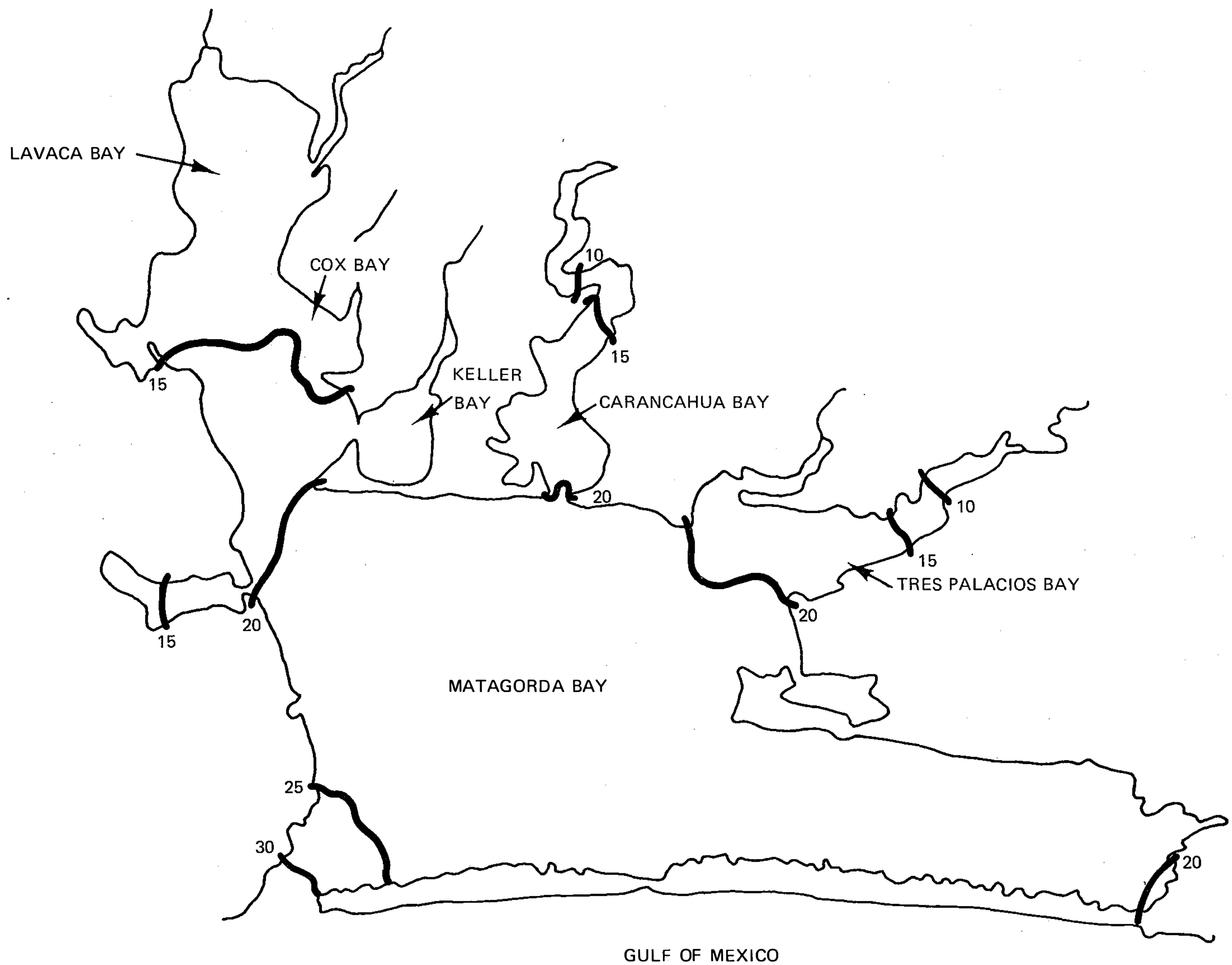

Figure 26.—Simulated Salinities in the Lavaca-Tres Palacios Estuary Under March Average Inflows (ppt)

in deltaic and peripheral salt or brackish water marshes. In addition, nutrients may be contributed by point source dischargers return flows. The adjacent Gulf of Mexico is nutrient poor. The resulting concentration gradients are such that the driving forces toward equilibrium result in the net transport of nutrients out of the estuarine system into the Gulf. Freshwater inflows, winds, currents, and biological activity all contribute to nutrient export from the estuarine system.

Freshwater inflow is the major source of nutrients into the Lavaca-Tres Palacios estuary. The Colorado River contributes freshwater and nutrients to the northern arm of the estuary near Matagorda, Texas through exchange passes at Tiger Island (Parker) and Culver Cuts. The contributions from the Lavaca-Navidad River system enter at the southwest extremity of the esturay at the Lavaca River delta near Port Lavaca, Texas.

U.S. Geological Survey discharge records for the Colorado River have been kept continuously since 1948 at Bay City, Texas. Water quality data, however, are absent until October 1974 when the USGS began chemical and biochemical analyses. Water quality data are available beginning in 1968 from the next upstream site at Wharton. Using these data or extrapolating these values to determine likely concentrations at Bay City is probably unsound at best since the likelihood exists for large periodic variations in nutrient concentrations downstream due to seasonal agricultural practices and local ungaged runoff.

USGS discharge data in the Lavaca and Navidad Rivers are available for the period of record since 1940. Like the Colorado basin, long-term water quality data are inadequate or altogether lacking.

Some field studies have been conducted in order to gain insight into nutrient contributions of the Lavaca and Colorado River delta Marshes (14, 48, 31). These studies involved seasonal intensive field sampling efforts over a one or two day period. While the deficiency of the volume of data in the data base leaves much to be desired, those data points available reveal trends and general magnitudes of nutrient contributions from these major sources.

The following sections describe the methodology used to estimate the nutrient contribution to the Lavaca-Tres Palacios estuary, the importance of deltaic marshes to biological primary productivity, and finally the role deltaic marshes play by trapping, storing, and converting inorganic nutrients to plant biomass and the subsequent transport of this biomass to the estuarine systems.

Nutrient Loading

Gaged freshwater discharges enter the Lavaca-Tres Palacios estuary from three major sources: the Colorado River, the Lavaca River and Tres Palacios Creek. The total mean annual discharge measured at the closest non-tidally affected gage for these sources is about 2.5 million acre-feet (3.1 billion m^3), of which Colorado River inflows account for almost 70 percent. Determining freshwater contributions to the estuary system from the Lavaca-Navidad and Tres Palacios drainage basins is relatively straightforward as these systems drain directly into the Lavaca-Tres Palacios estuary. Determining contributions by the Colorado River to the bay is a far more complex problem. The river discharges directly into the Gulf of Mexico and freshwater diversion through Tiger Island and Culver Cuts is complicated by several factors. Some of these factors are: tidal regimes in East and West Matagorda Bays as well as the Gulf of Mexico at the river mouth, the amount of freshwater inflow, the cross-sectional configuration of the mouth of the river and the adjacent river channel, and the manner of operation of the locks in the Intracoastal Waterway on either side of the intersection of that waterway with the Colorado River. Model simulation studies performed by TDWR personnel have indicated that under "normal" conditions (i.e., the river mouth at the Gulf of Mexico constricted or closed due to siltation and littoral transport of sediment as occurs during periods of low to moderate river flows) the freshwater diversions from the Colorado River through Tiger Island Cut into Matagorda Bay comprise 68 to 88 percent of the measured discharge at Bay City.

Water quality samples taken by the U.S. Geological Survey at the river gaging locations at Wharton and Bay City have been analyzed for concentrations of various chemical species (68). This data record is incomplete as the number of monthly samples and the number of parameters analyzed have varied. Total nitrogen concentrations ranged from 0.15 mg/l to 2.34 mg/l, total phosphorus ranged from 0.03 mg/l to 0.76 mg/l, and total organic carbon (TOC) concentrations ranged from 1.0 mg/l to 19.0 mg/l. The monthly concentration ranges were applied to the mean monthly gaged river discharges along with the percent of river flow diversion into Matagorda Bay via Tiger Island Cut as predicted by the delta hydrodynamic model for the given month and river discharges. The end result was a range of nutrient loading values that might be expected to occur during a "normal" year (Table 3). With few exceptions, highest nutrient loadings in Matagorda Bay occur in May and June during the period of greatest river flows. This is in spite of the fact that the predicted percentage of total river flows diverted into Matagorda Bay are at their lowest level during this same period.

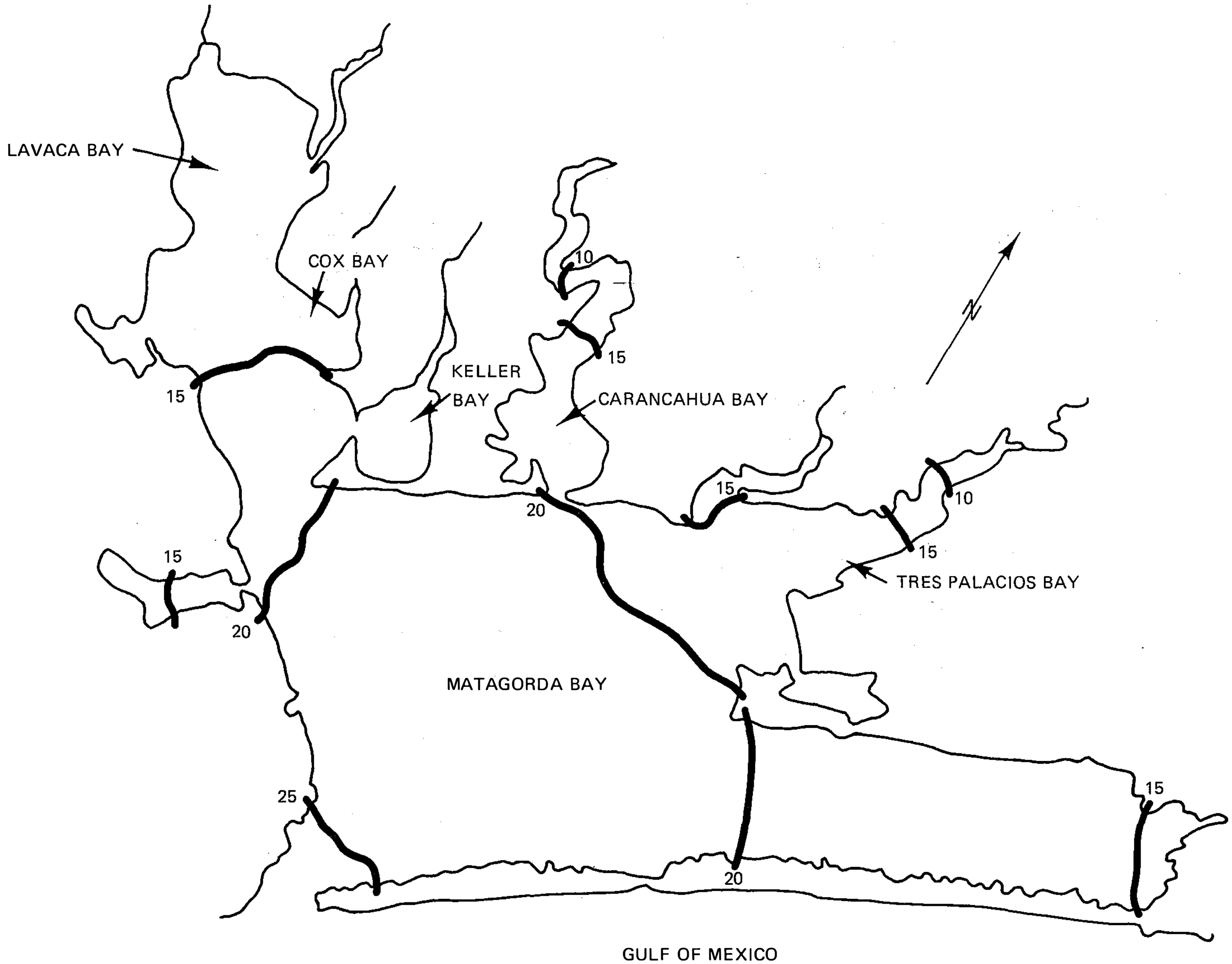

Figure 27.—Simulated Salinities in the Lavaca-Tres Palacios Estuary Under April Average Inflows (ppt)

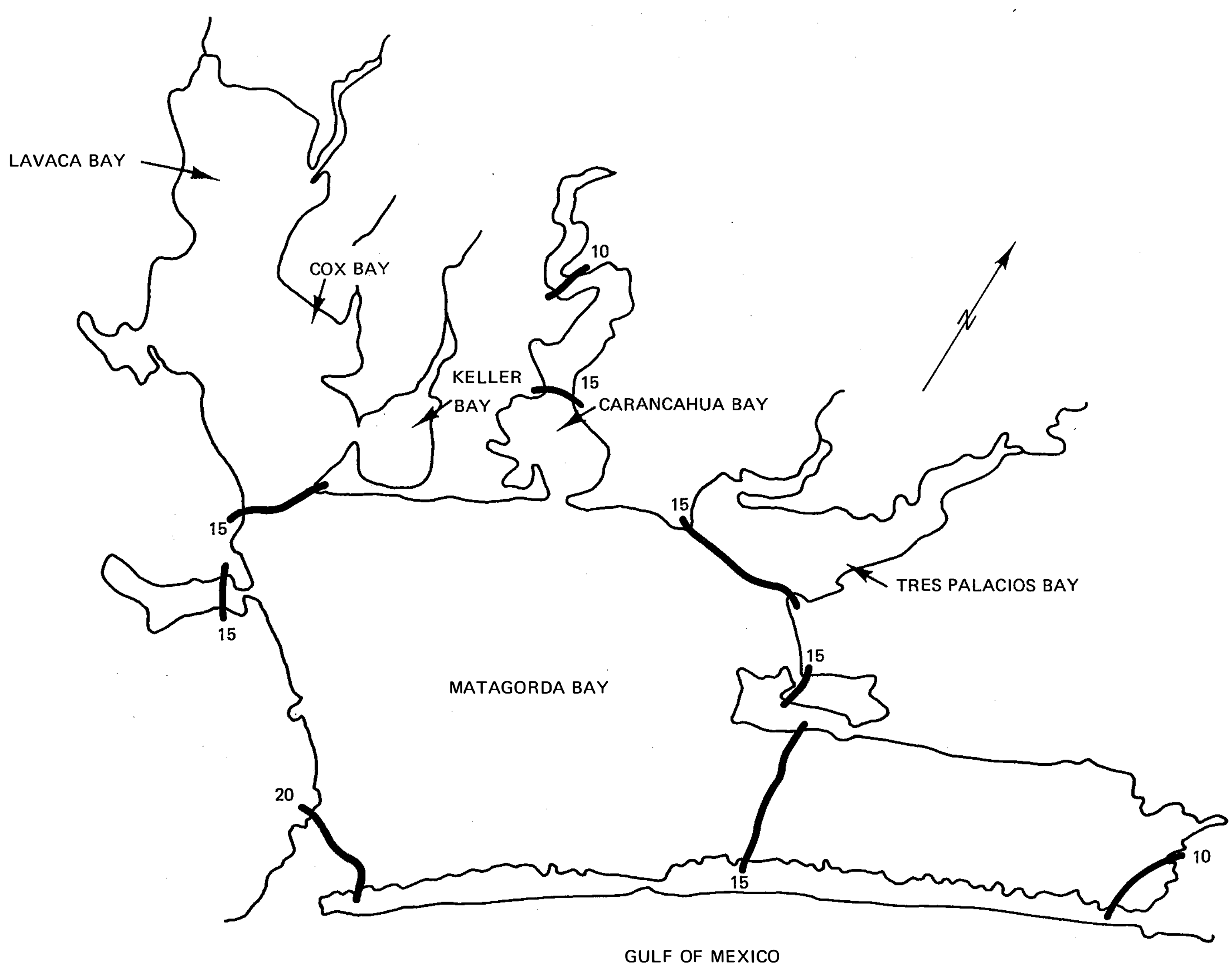

Figure 28.—Simulated Salinities in the Lavaca-Tres Palacios Estuary Under May Average Inflows (ppt)

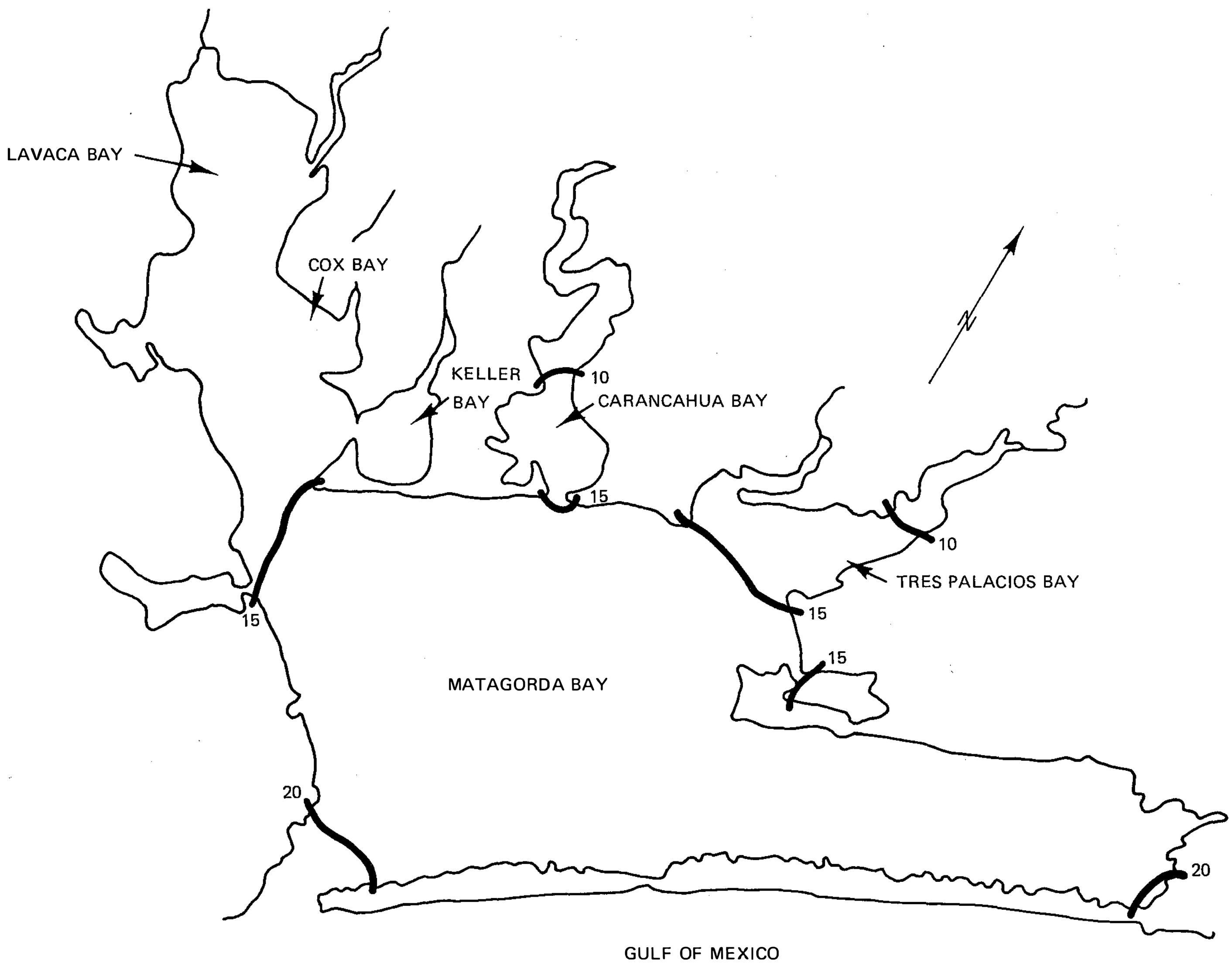

Figure 29.—Simulated Salinities in the Lavaca-Tres Palacios Estuary Under June Average Inflows (ppt)

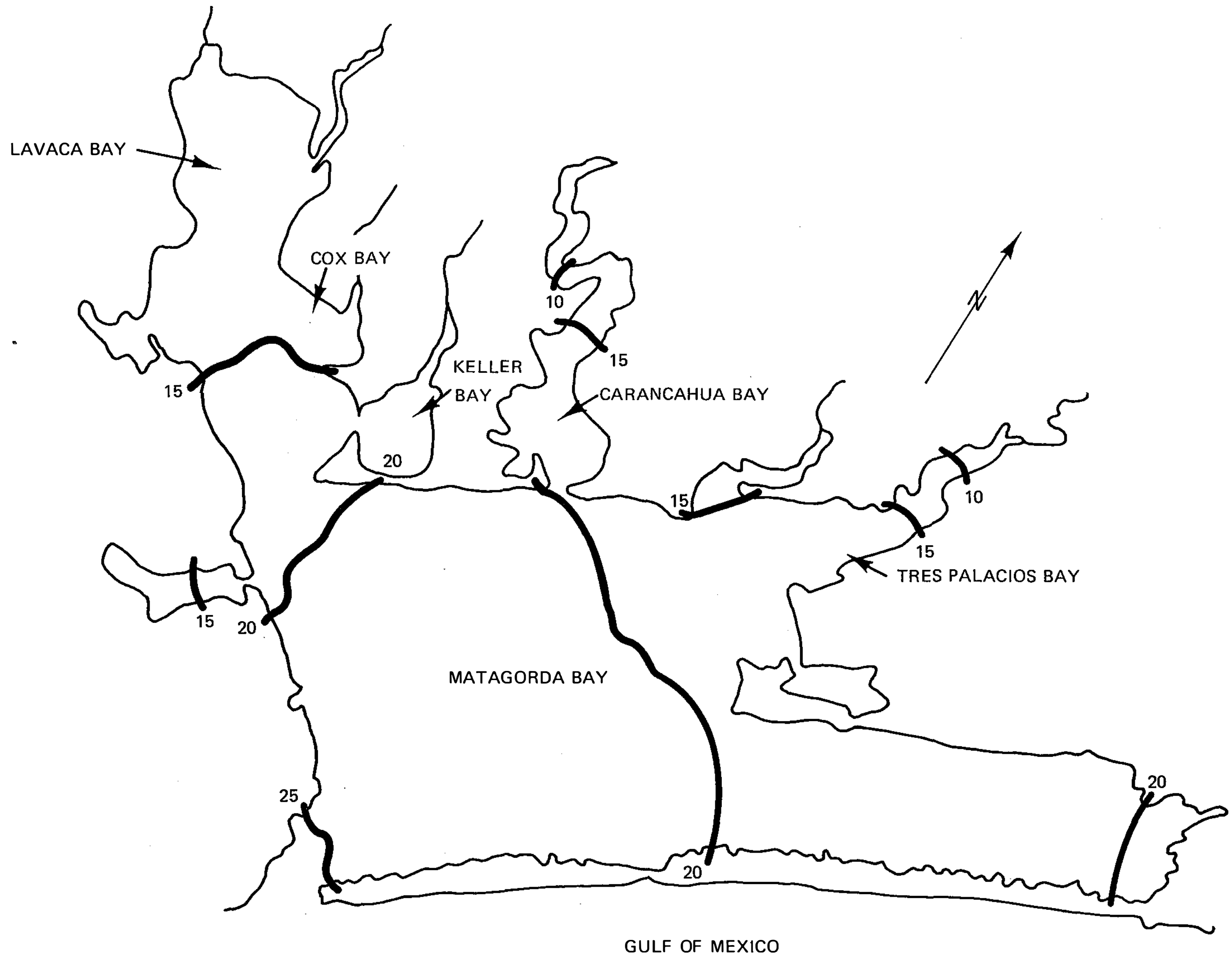

Figure 30.—Simulated Salinities in the Lavaca-Tres Palacios Estuary Under July Average Inflows (ppt)

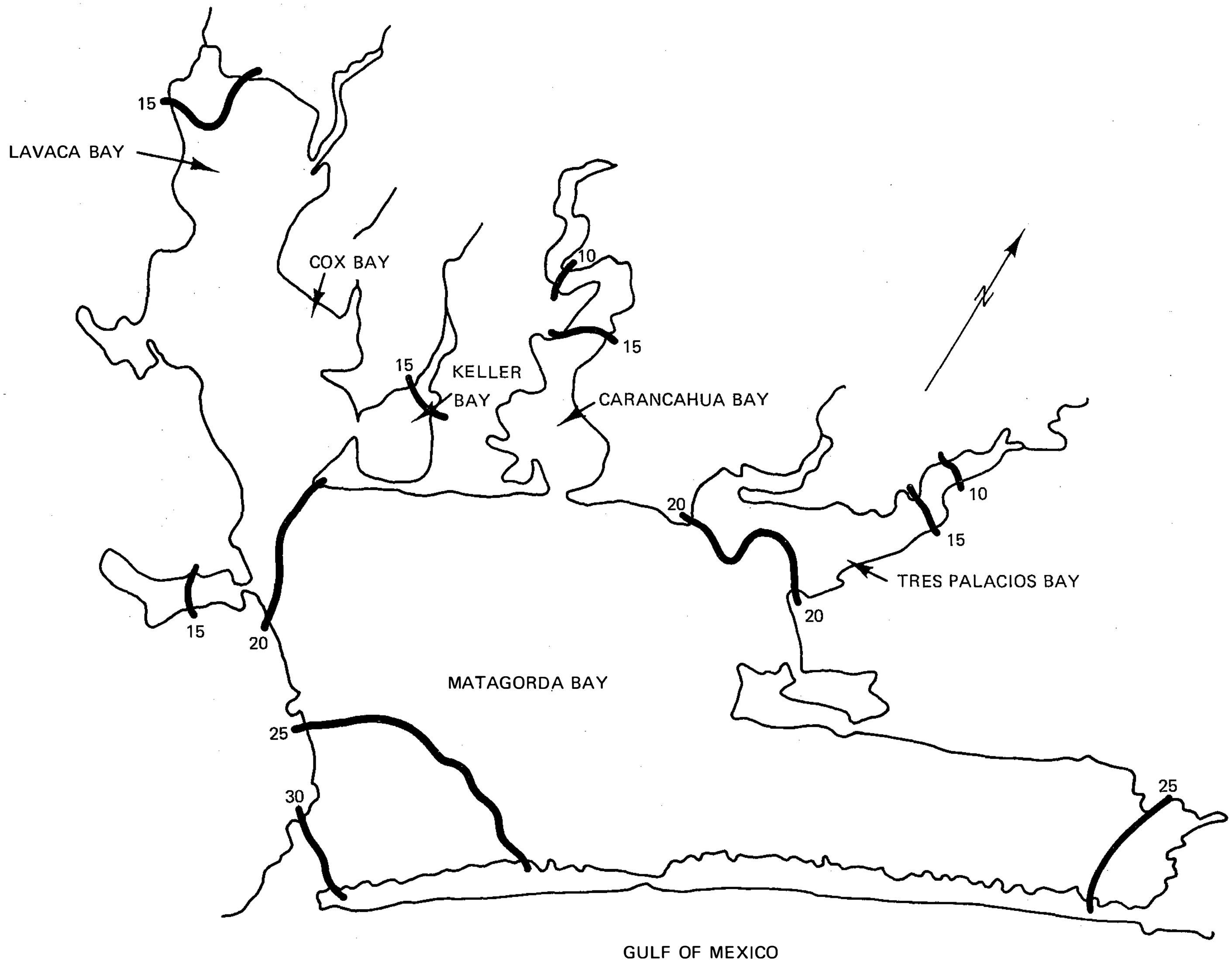

Figure 31.—Simulated Salinities in the Lavaca-Tres Palacios Estuary Under August Average Inflows (ppt)

This demonstrates the importance of freshwater discharge as the major factor in delivering nutrients to the bay. Table 3 presents the levels or orders of magnitude of nutrient loadings that are thought to have existed in the recent past. As previously mentioned, these results are subject to the inadequacies of changing conditions and a poor data base and are not to be considered as absolute.

Potential nutrient contributions have been calculated for the Navidad and Lavaca Rivers based on mean monthly discharges over the period of record and the highest and lowest concentrations observed for each nutrient from the few data points available. These loadings in kilograms/day are reported in Tables 4 and 5. The two rivers converge to become a single conveyance channel at a point about five miles (8 kilometers) upstream of the delta. The total nutrient contribution and discharge to Lavaca Bay (Table 6) is the summation of the respective parameters in Tables 4 and 5. Since the USGS takes biochemical data bimontly in the Lavaca River, a total expected contribution range has not been computed at this time for those months where data are lacking. Total carbon, phosphorus and nitrogen (CPN) loading rates for those months where Lavaca River concentrations are unavailable are undoubtedly greater than the loading rates for the Navidad River alone as reported in Table 4. A field study of the Lavaca delta (12) found CPN concentrations on the same order of magnitude and generally within the range of concentrations reported in the USGS water quality data used for those computations. River discharges during the study sample dates were substantially less than the mean discharges reported in the USGS data. The resulting nutrient loading rates were somewhat less than the minimum values reported in Tables 4 and 5. This is indicative of the importance of freshwater inflow as the primary driving force for delivering nutrients to the Lavaca delta and bay.

The third major source of riverine contribution of nutrients to the Lavaca-Tres Palacios system is Tres Palacios Creek which discharges into Tres Palacios Bay at the northeast corner of the estuary. The USGS has taken discharge measurements along with monthly water quality data since 1971 at a site near Midfield, Texas (Table 7).

A comparison of average monthly concentrations (Figures 37, 38, 39 and 40) reveal that, in general, Tres Palacios Creek consistently contains the highest concentrations of all nutrients measured. The Colorado River consisently maintains the second highest levels of nitrogen and phosphorus but less total organic carbon than the other river systems. Average nutrient concentrations in the Lavaca and Navidad Rivers are similar.

In general, organic nitrogen levels exhibit a major peak in concentration between March and June. A second, but slightly lower peak, is observed between September and November. Inorganic nitrogen concentration levels peak in the bay systems between December and May. All four rivers have the lowest inorganic nitrogen concentrations between July and September. Total phosphorus levels are generally low and consistently between 0.1 and 0.3 mg/l year round. The exception is the Tres Palacios Creek which exhibits a dramatic total phosphorus level increase during the fall-winter period which gradually diminishes to a low during early summer. Total organic carbon concentrations exhibit no clear-cut seasonal pattern of increase or decrease. Instead, concentrations seem to vary randomly between 5 and 15 mg/l. The Navidad River is an exception, however, as two major peaks in TOC levels occur during November and September. These may be misleading as the average values are based on only two to five field observations for those months. Total nutrient contribution to the Lavaca-Tres Palacios estuary from the Tres Palacios Creek was less than that from the other major river sources, this is in spite of the prevailing higher concentrations. In summary, freshwater inflow contribution from the Tres Palacios basin like that of both the Colorado and Lavaca-Navidad River basins appears to be the dominant factor in determining nutrient loading levels to their associated coastal estuarine systems.

Marsh Vegetative Production

In essence, an estuarine marsh is a complex physical, hydrological, and biogeochemical system which provides: (1) shoreline stabilization, (2) "nursey" habitats for economically important estuarine-dependent fisheries, (3) maintenance of water quality by filtering upland runoff and tidal waters, and (4) detrital materials (small decaying particles of plant tissue) that are a basic energy source of the aquatic food web. The most striking characteristic of a marsh is the large amount of photosynthesis (primary production) within the system by the total plant community which includes macrophytes, periphytes and benthic algae. As a result, the marshes are large-scale contributors to estuarine productivity, providing a source of substrate and nutrients for the microbial transformation processes at the base of the food web. Deltaic marshes are especially important since they form a vital link between the inflowing river and its resulting estuary.

The Lavaca-Tres Palacios estuary has two major contributing river deltas—the Lavaca River delta and the

Table 3.—Range of Expected Carbon, Nitrogen, and Phosphorus Loading into Matagorda Bay, Texas, Based on Mean Monthly Gaged Colorado River Discharges (kg/day)

		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Monthly Mean Gaged flows at Bay City P.O.R. 1947-76 (cfs)		2,100	2,835	2,035	2,556	4,206	3,741	1,525	912	1,963	2,549	2,506	1,979
Total Nitrogen Range (kg/d)	high	5,750	6,570	5,265	7,028	12,613	9,503	2,760	4,549	4,502	8,427	8,237	6,051
	low	1,268	3,883	4,738	2,179	11,702	3,300	2,388	292	2,193	2,046	4,789	1,280
Total Phosphorus Range (kg/d)	high	1,132	4,181	2,413	2,179	1,752	3,630	2,016	1,166	769	4,902	1,916	2,909
	low	680	597	439	545	0	660	465	0	385	980	958	194
Total Organic Carbon Range (kg/d)	high	27,166	113,490	57,037	43,585	70,072	98,987	24,809	19,439	34,627	107,165	28,734	31,031
	low	4,528	5,970	30,712	21,792	56,058	32,996	15,505	11,664	11,542	9,742	14,367	7,758

Table 4.—Range of Expected Carbon, Nitrogen and Phosphorus Loading into Lavaca Bay, Texas, Based on Mean Monthly Gaged Navidad River Discharges (kg/day)

		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Mean Gaged Flows Near Ganado (cfs)		480	581	403	672	951	1,003	298	232	728	509	375	300
Total Nitrogen Range (kg/d)	high	1,858	1,060	2,063	3,227	3,844	2,703	767	1,609	2,925	1,322	1,654	390
	low	388	305	266	1,613	606	1,843	387	352	571	710	275	80
Total Phosphorus Range (kg/d)	high	588	358	148	527	349	319	131	148	466	175	147	125
	low	35	13	49	165	186	172	58	57	285	112	37	29
Total Organic Carbon (kg/d)	high	23,520	7,290	21,721	23,050	39,609	17,692	6,498	3,865	53,508	9,727	26,644	15,435
	low	5,174	5,302	4,542	9,384	10,951	14,744	5,111	1,421	21,403	8,355	0	7,350

Table 5.—Range of Expected Carbon, Nitrogen, and Phosphorus Loading into Lavaca Bay, Texas, Based on Mean Monthly Gaged Lavaca River Discharges (kg/day)

		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Mean Gaged Flows Near Edna (cfs)		246	304	227	417	652	507	137	109	323	352	207	147
Total Nitrogen Range (kg/d)	high	1,036	*	884	*	3,163	*	427	*	1,218	*	543	*
	low	132	*	383	*	208	*	137	*	222	*	124	*
Total Phosphorus Range (kg/d)	high	127	*	117	*	447	*	50	*	182	*	107	*
	low	24	*	17	*	160	*	34	*	111	*	51	*
Total Organic Carbon Range (kg/d)	high	*	*	*	*	*	*	*	*	*	*	*	*
	low	*	*	*	*	*	*	*	*	*	*	*	*

*No available data.

Table 6.—Range of Expected Carbon, Nitrogen, and Phosphorus Loading from the Lavaca-Navidad Rivers to Lavaca Bay, Texas, Based on Mean Monthly River Discharges (kg/day)

		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Total Mean Gaged Flows (cfs)		726	*	630	*	1,803	*	435	*	1,051	*	582	*
Total Nitrogen Range (kg/d)	high	2,894	*	2,947	*	7,007	*	1,194	*	4,143	*	2,197	*
	low	520	*	649	*	814	*	524	*	793	*	399	*
Total Phosphorus Range (kg/d)	high	715	*	265	*	796	*	181	*	628	*	254	*
	low	59	*	66	*	346	*	92	*	396	*	88	*
Total Organic Carbon Range (kg/d)	high	*	*	*	*	*	*	*	*	*	*	*	*
	low	*	*	*	*	*	*	*	*	*	*	*	*

*Data unavailable or incomplete.

Table 7.—Range of Expected Carbon, Nitrogen, and Phosphorus Loading into Tres Palacios Bay, Texas, Based on Mean Monthly Gaged Tres Palacios Creek (kg/day)

		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Mean Gaged Flows at Midfield (cfs)		144	233	195	93	80	329	227	139	144	59	53	35
Total Nitrogen Range (kg/d)	high	1,104	2,169	1,916	513	468	1,491	590	388	752	228	445	152
	low	194	405	459	175	302	274	111	146	191	82	42	14
Total Phosphorus Range (kg/d)	high	353	360	358	80	90	202	167	109	159	54	100	76
	low	81	177	124	55	33	97	50	55	60	19	31	17
Total Organic Carbon Range (kg/d)	high	5,645	17,126	12,422	2,506	3,136	16,927	6,674	5,789	7,762	3,036	3,246	1,372
	low	1,482	2,854	2,007	1,481	1,372	7,013	3,837	4,427	4,586	752	701	515

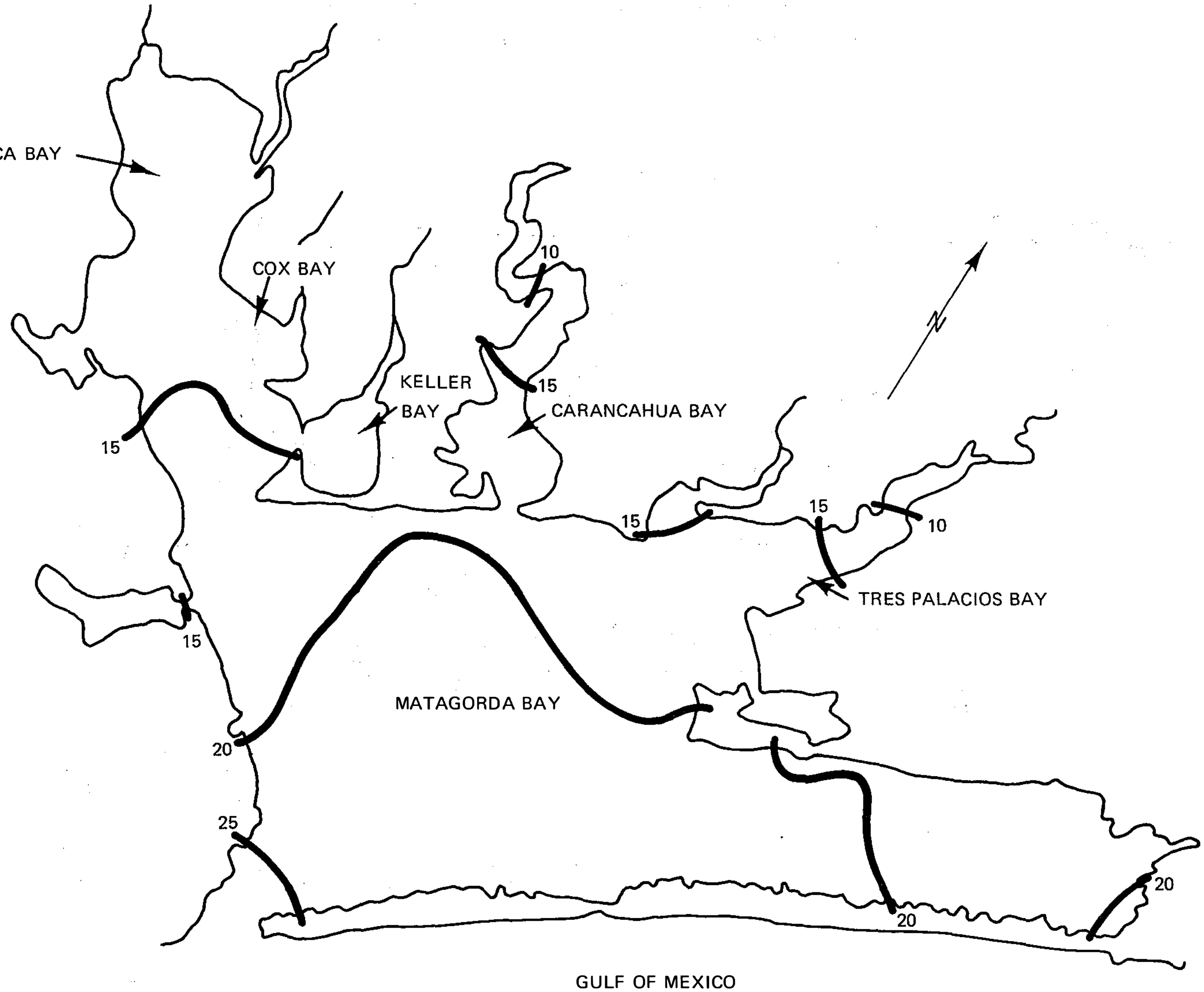

Figure 32.—Simulated Salinities in the Lavaca-Tres Palacios Estuary Under September Average Inflows (ppt)

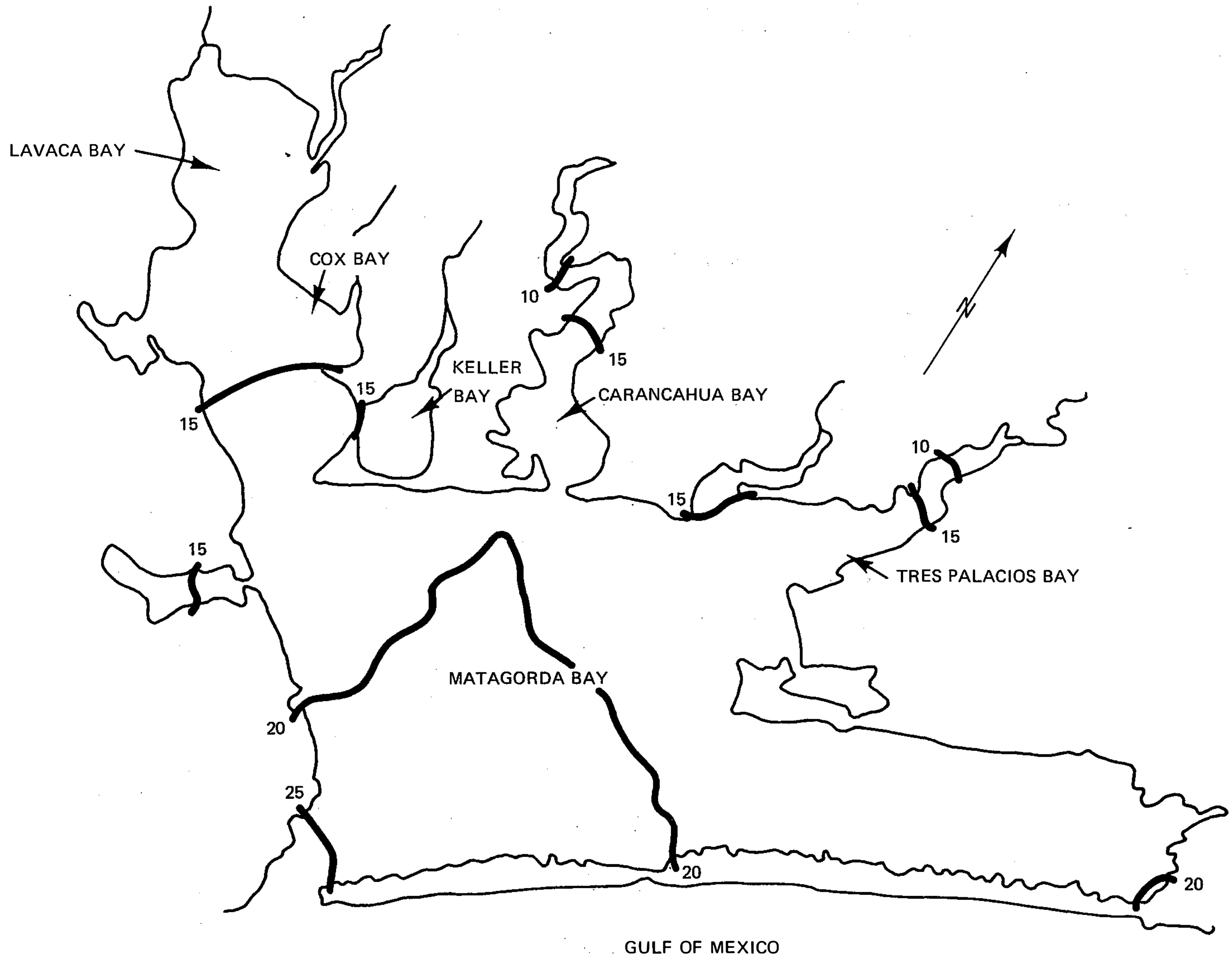

Figure 33.--Simulated Salinities in the Lavaca-Tres Palacios Estuary Under October Average Inflows (ppt)

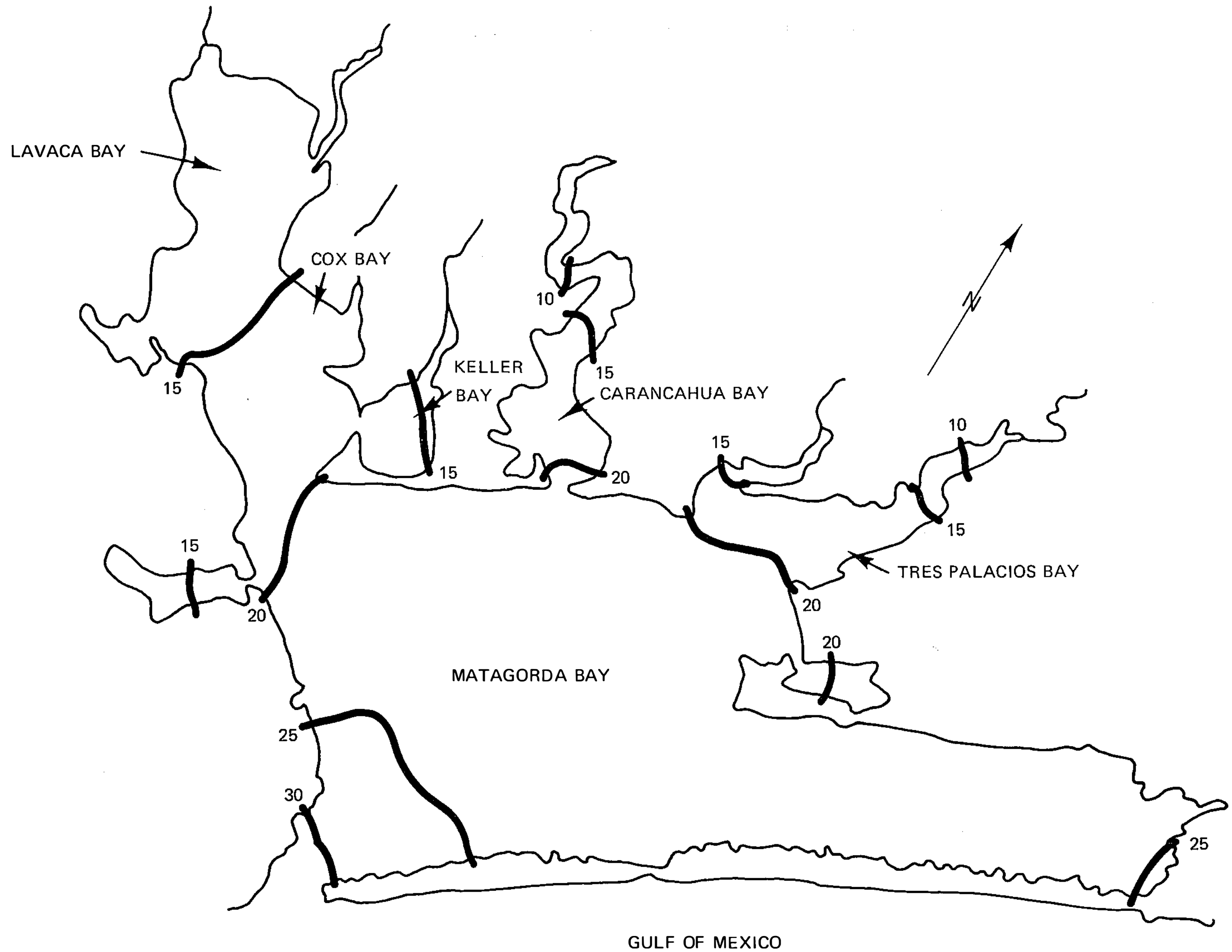

Figure 34.—Simulated Salinities in the Lavaca-Tres Palacios Estuary Under November Average Inflows (ppt)

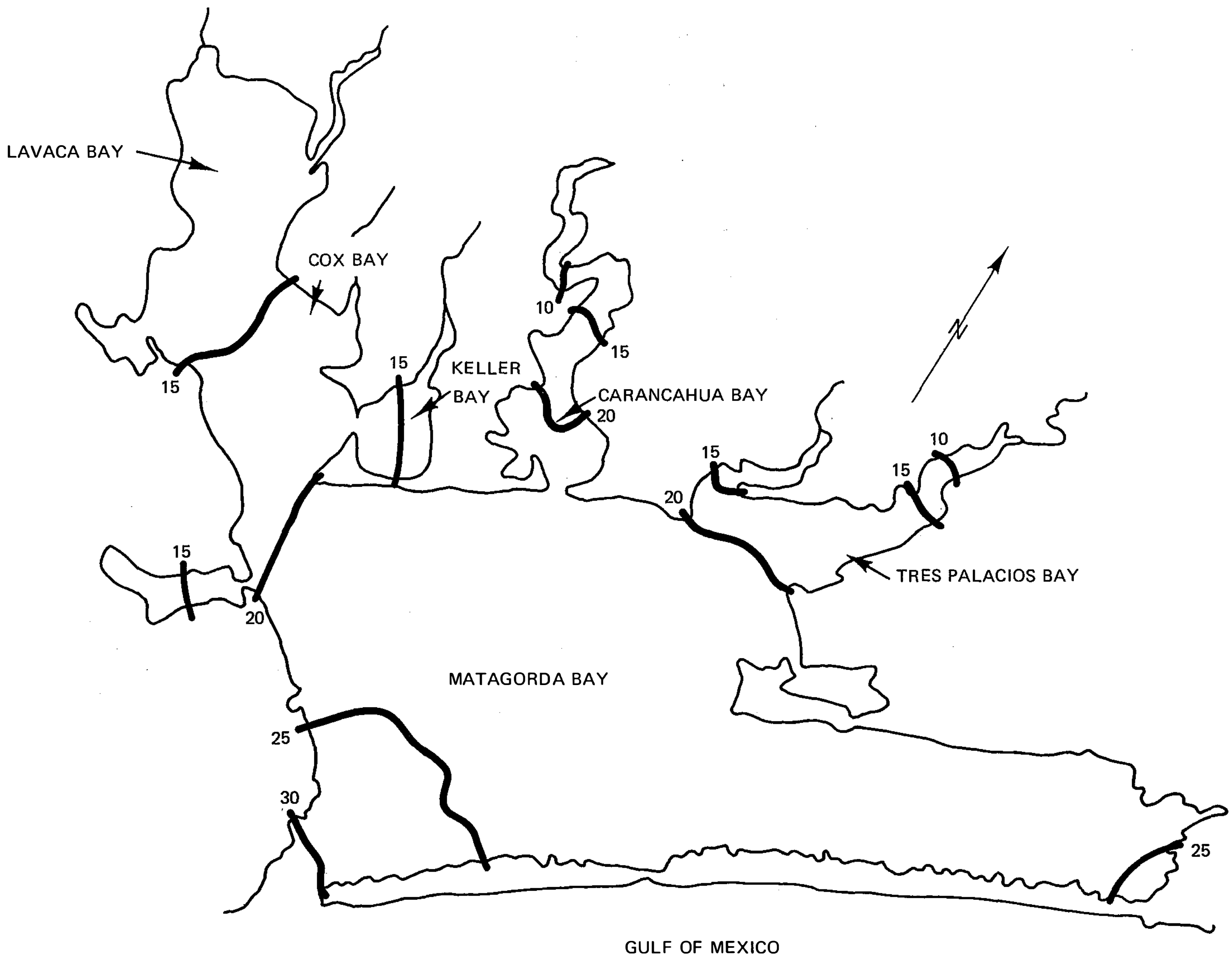

Figure 35.—Simulated Salinities in the Lavaca-Tres Palacios Estuary Under December Average Inflows (ppt)

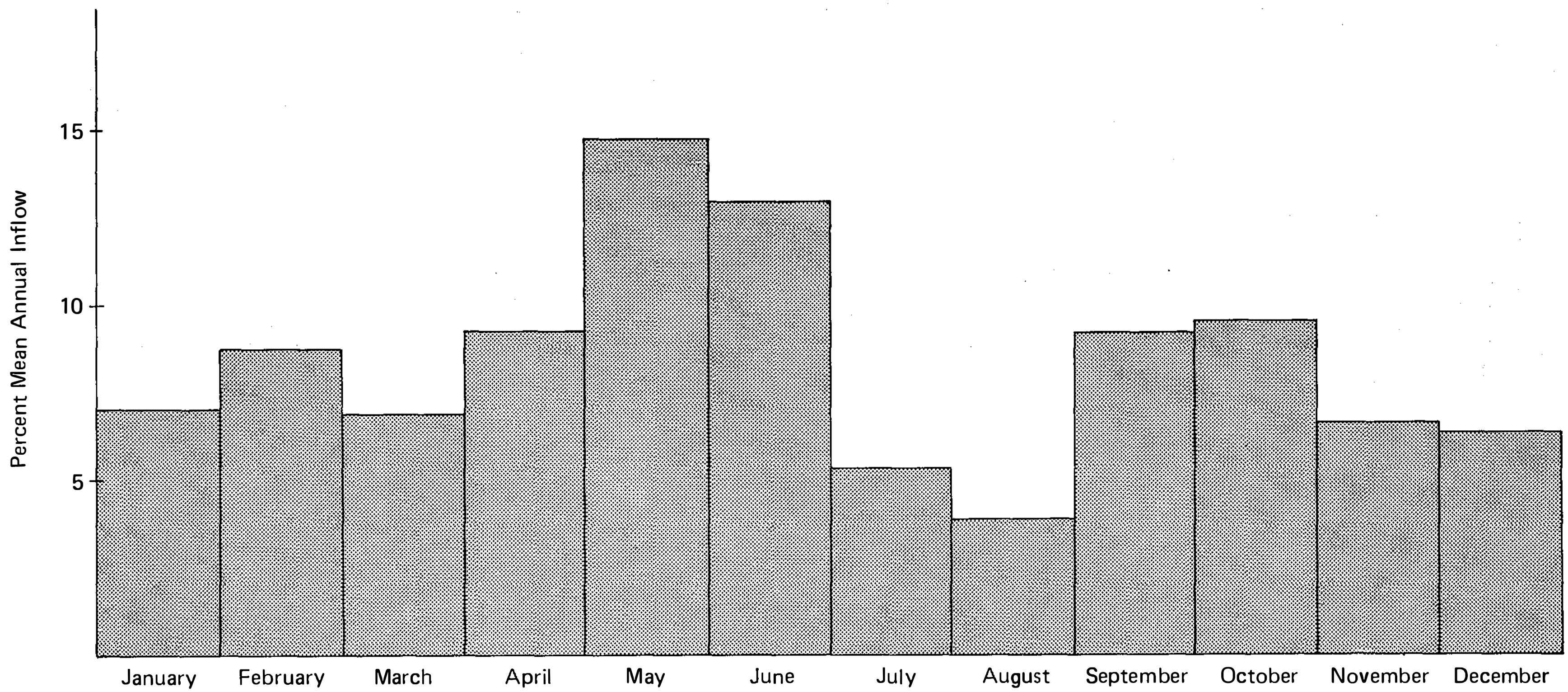

Figure 36.—Monthly Distribution of Mean Annual Total Gaged and Ungaged Inflow, Lavaca-Tres Palacios Estuary 1941-1976

Colorado River delta. Adams (13) delineated five hydrological units in the Lavaca delta and estimated above ground net primary production of the rooted vascular plants (macrophytes) at 99.2 million dry weight pounds per year (45,013 metric tons/year) over the 8,431 acre (3,412 hectare) study area. Average annual net productivity (ANP) was approximately 11,770 dry weight pounds per acre (1,319 g/m^2). In addition, periphyton production in 3,235 acres (1,309 hectare) of the Lavaca delta was estimated to range from a December minimum of 3,365 dry weight pounds per day (1,526 kg/day) to an overall average of 4,312 dry weight pounds per day (1,956 kg/day), assuming that an average 50 percent of the Lavaca delta study area was inundated (12). The inundated area thus had a estimated periphyton ANP of about 1.57 million dry weight pounds (714 metric tons).

Adams and Tingley (13) delineated 12 zones of marsh vegetation in the Colorado delta and estimated the macrophytic above ground ANP at 161.5 million dry weight pounds (73,243 metric tons). The average ANP across the 19,812 acre (8,018 hectare) study area can thus be estimated at approximately 8,150 dry weight pounds per acre (914 g/m^2).

Predominate vascular macrophytes of the Colorado delta include *Spartina spartinae, S. patens, S. alterniflora, Batis maritima,* and *Salicornia* spp. On the other hand, Lavaca delta vascular macrophytes are predominated by *Scirpus maritimus, Distichlis spicata, Spartina spartinae, S. patens,* and *Juncus roemerianus.* Although the high productivity of these deltaic marshes results in significant quantities of detritus for potential transport to the estuary, actual detrital transport is dependent on the episodic nature of the marsh inundation and dewatering process. Cooper (5) suggests that the vast majority of the primary production in the higher, irregularly-flooded vegetative zones goes into peat production and is not exported. However, Teal (23) has estimated that about 45 percent of net production of the lower, frequently-flushed vegetative zone characterized by *Spartina alterniflora* is exported to the estuarine waters.

Marsh Nutrient Cycling

Deltaic and other brackish and salt marshes are known to be sites of high biological productivity. Emergent macrophytes and blue-green algal mats serve to trap nutrients and sediment as flow velocities decrease. These nutrients are incorporated into the plant biomass during growth periods and are sloughed off and exported to the bay as detrital material during seasons of plant senescence and/or periods of inundation and increased flows into the open bay. Predominant marsh and wetland macrophytes species in the Lavaca River delta include *Salicornia virginica, Batis maritima, Phragmites australis, Scirpus maritimus, Spartina alterniflora,* and *Distichlis spicata* (24). Adams (13) reports *S. spartinae* as the dominant species in some parts of the delta while *S. maritimus* and *D. spicata* are co-dominant in other areas. Dominant species in the Colorado River delta reported by Adams and Tingley (14) are *S. spartinae, B. maritima, D. spicata,* and *S. maritimus.* Since the major macrophyte species are similar in the two river deltas that are situated at either end of the estuary it is assumed that the species reported by Benton, Adams, and Adams and Tingley are fairly ubiquitous in the brackish and salt marshes that occur elsewhere in the Lavaca-Tres Palacios estuary.

Studies by Armstrong et al (44), Dawson and Armstrong (48), Armstrong and Brown (47), and Armstrong and Gordon (45, 46) have been conducted to determine the role of the plants and deltaic sediments in nutrient exchange processes. In most cases these patterns seem to be similar from species to species (45). The rates of exchange were also found to be similar in magnitude to exchange rates in other Texas coastal marsh systems. For the most part inorganic nitrogen and phosphorus are taken up in the system while organic carbon is generally exported (44, 45, 46). Table 8 is a summary of nutrient exchange rates determined for typical Colorado River delta macrophytes. Total suspended solids and TOC are consistently exported while the inorganic nitrogen and phosphorus species appear to be absorbed.

Table 8.—Summary of Nutrient Exchange Rates for Macrophytes in the Colorado River Delta System (Units are kg ha^{-1} d^{-1}) (45)

Analysis	Spartina alterniflora	Sporobolis virginicus
TSS*	-6.77	-14.12
VSS	-0.57	0.94
BOD_5*	-0.02	0.00
TOC	-0.41	-0.52
TKN*	-0.01	0.00
TKN	-0.01	0.00
Org N	-0.01	0.00
NH_3-N	0.01	0.01
NO_2-N	0.00	0.00
NO_3-N	0.10	0.13
Tot. P*	-0.01	0.00
Tot. P	0.01	0.01
Ortho P	0.02	0.02

*Unfiltered samples; all others filtered.

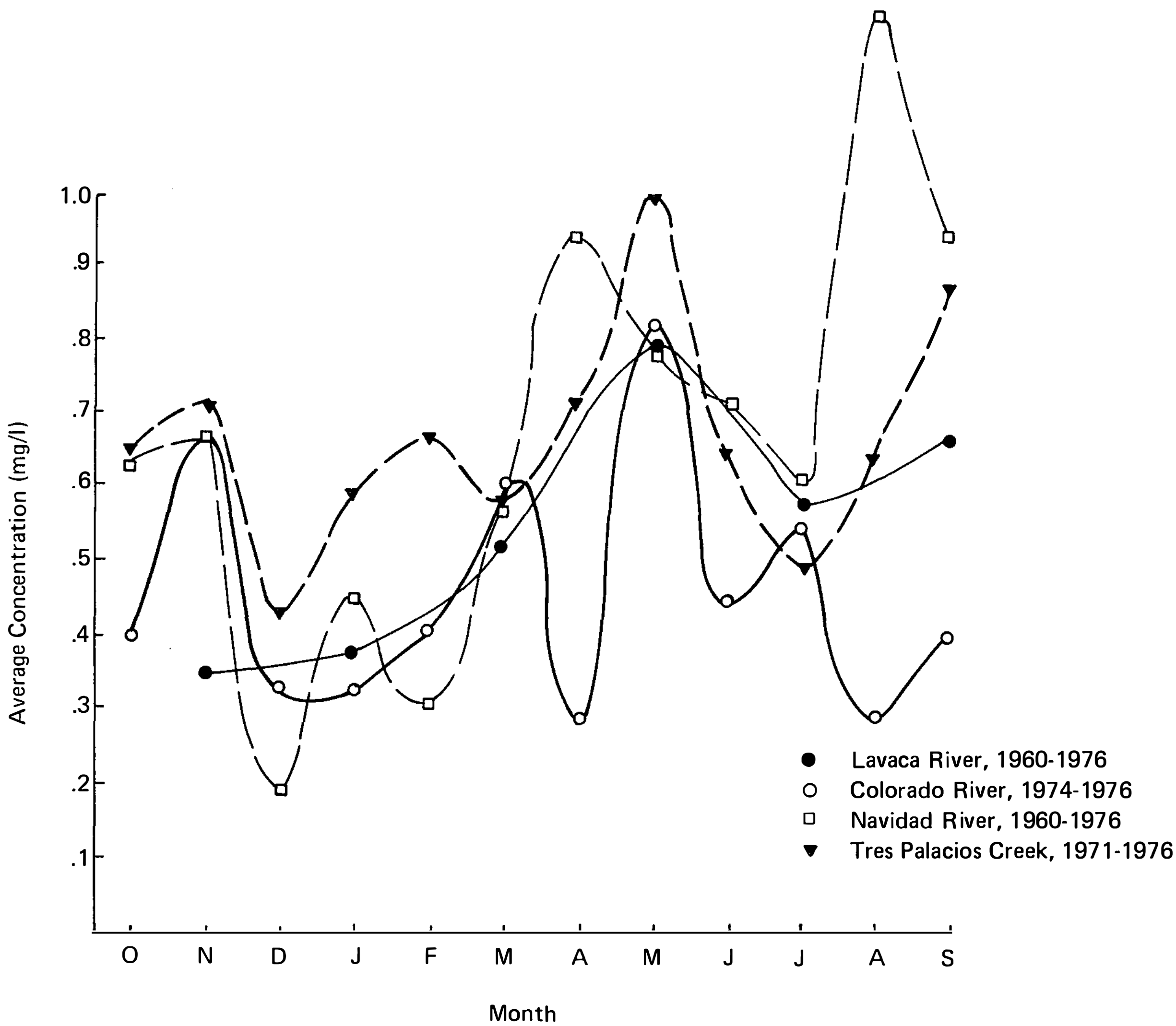

Figure 37.—Mean Monthly Organic Nitrogen Concentrations in Rivers Contributing to the Tres-Palacios Estuary

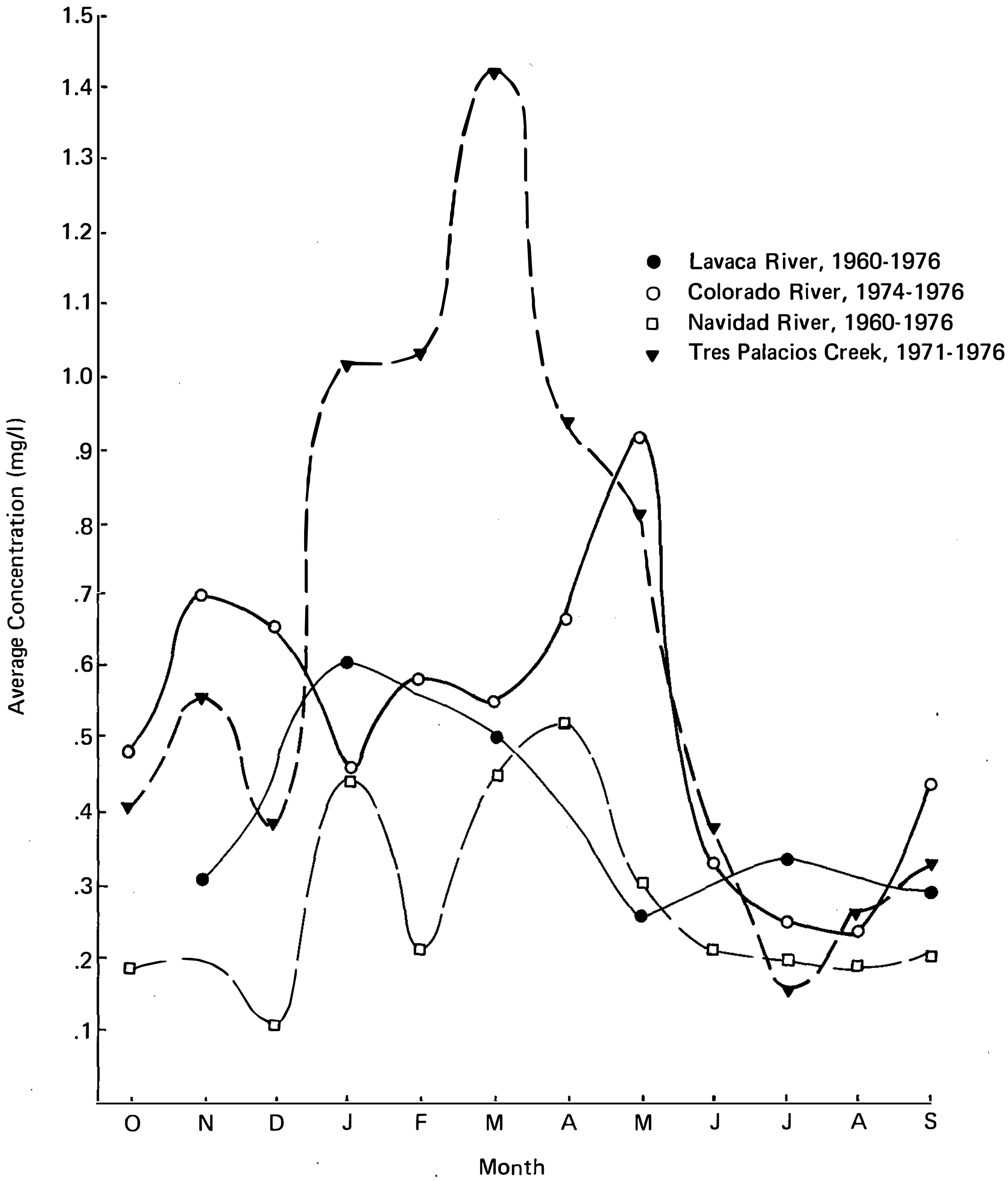

Figure 38.—Mean Monthly Inorganic Nitrogen Concentrations in Rivers Contributing to the Tres-Palacios Estuary

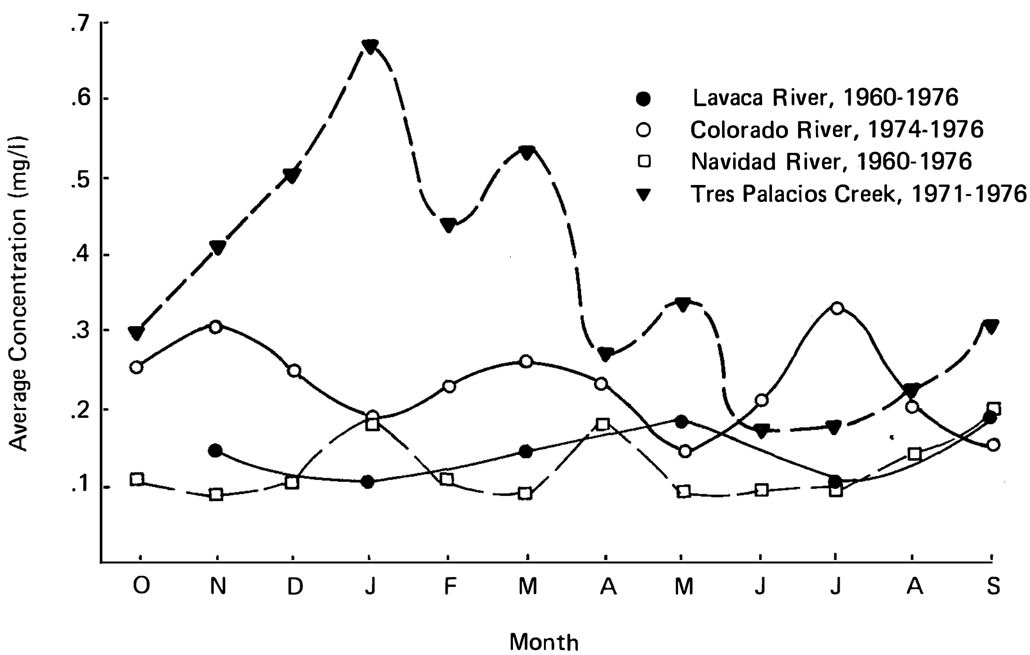

Figure 39.—Mean Monthly Total Phosphorus Concentrations in Rivers Contributing to the Tres-Palacios Estuary

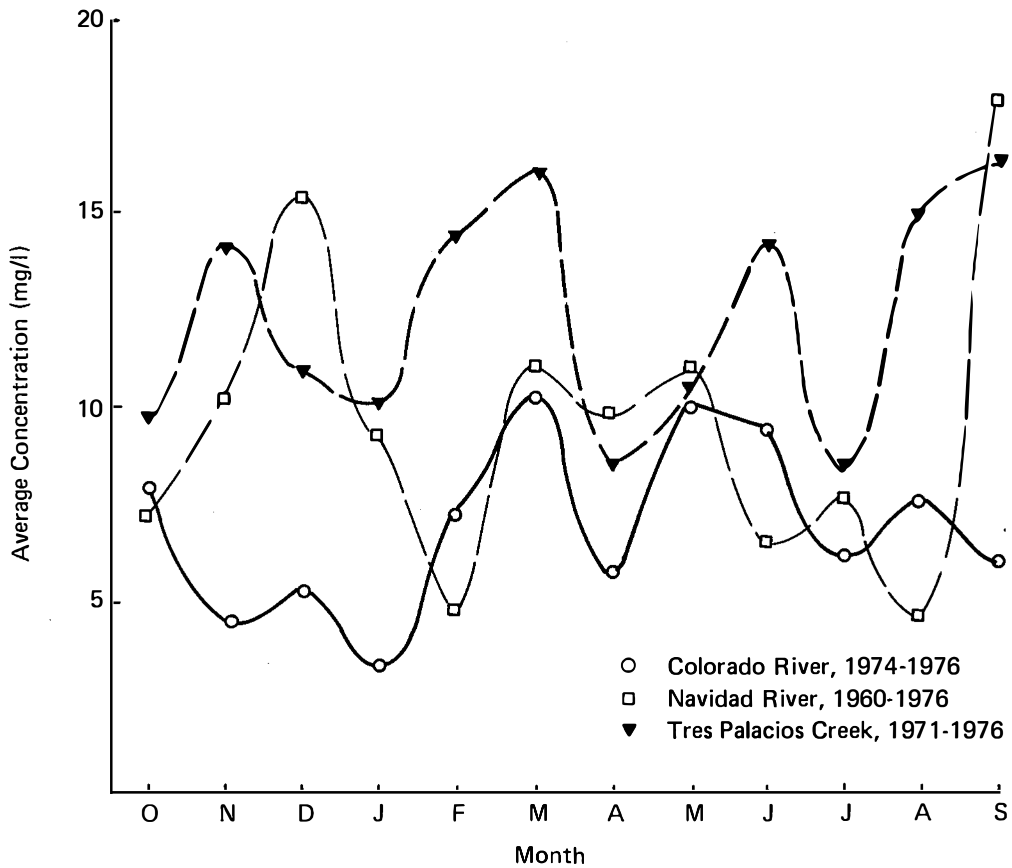

Figure 40.—Mean Monthly Total Organic Carbon Concentrations in Rivers Contributing to the Tres-Palacios Estuary

The total salt and brackish water marsh area in the Lavaca-Tres Palacios estuarine system is approximately 72,435 acres (29,315 hectares). Roughly 25,635 acres (10,375 hectares) of this marsh area is located in the Lavaca delta. The remaining 46,800 acres (18,940 hectares) are marsh lands lying between 0 to 5 feet elevation on the back side of the barrier island, in Tres Palacios Bay, Carancahua Bay, Turtle Bay, Keller Bay, Oyster Bay, and all marsh areas on the periphery of Matagorda Bay.

Tide stage, wind direction, wind velocity, and freshwater inflows are the forces that determine the extent and longevity of marsh inundation. Of the three factors, wind and tide stage are the dominant forces that control inundation of all of the marshes not directly associated with a major freshwater inflow source (i.e., the Colorado and Lavaca deltas). A recent TDWR study has indicated that these two factors are also the dominant forces that influence marsh inundation in the Colorado River delta (30). The banks of the Colorado River Channel are high enough to prevent overbanking under all but the most extreme hydrological events. The majority of freshwater induced marsh inundation in this system occurs then in the Lavaca delta.

If one assumes a range of TOC export from an inundated marsh in this estuarine system to be between 0.4 to 0.5 kg/ha/day as reported in Table 8 then during total inundation the Lavaca delta could be expected to contribute between 4,150 to 5,190 kg/day to the estuary. The Colorado River delta marshes might be expected to contribute between 2,450 and 3,070 kg/day TOC. Inorganic nitrogen and phosphorus are consistently taken up. Their contribution to the estuary would come during significant flood events when marsh detritus from senesced or decayed macrophytes would be flushed into the bays.

There is evidence (48) that following a prolonged period of emersion a sudden inundation event over the delta marshes will result in a short period of high nutrient release rates. This period, which may last for one or two days, is followed by a period where release rates decrease rapidly until they begin to approach a seasonal equilibrium. Therefore, during periods of high river discharges and/or extremely high tides that immediately follow prolonged dry periods, the contribution of C, P and N from the deltaic marshes to the estuary system can be expected to increase dramatically.

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