GUADALUPE ESTUARY:
An Analysis of Bay Segment Boundaries, Physical Characteristics, and Nutrient Processes

TEXAS DEPARTMENT OF WATER RESOURCES
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GUADALUPE ESTUARY:

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, which were available in early 1978 as a supplement to the EPA grant for Section 208 planning in nondesignated planning areas, 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 Guadalupe 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.

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SUMMARY

This report is one in a series of reports on major Texas estuaries. The objective is to analyze existing data on the Guadalupe 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 Guadalupe 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 Guadalupe 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 Guadalupe estuary were developed for use on a digital computer and were calibrated through two intensive 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 San Antonio Bay, Espiritu Santo Bay, and Mesquite Bay (61) adequately describe the real differences in salinity and circulation that normally exist in the estuary, and no changes in segment boundaries are recommended.

The Guadalupe 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, and flushing of the bays, which reduces salinities.

An analysis of net circulation patterns simulated by the tidal hydrodynamic model indicated that the dominant circulation pattern in the Guadalupe estuary was a net movement of water from Mesquite Bay northward through San Antonio Bay and Espiritu Santo Bay into Lavaca-Tres Palacios estuary. Simulated water movements in the upper and middle portions of San Antonio Bay were dominated by internal eddy currents induced and heightened by freshwater inflows from the Guadalupe River. Simulated flows in Espiritu Santo Bay were dominated by a major internal eddy circulation rotating in a clockwise manner. Circulation patterns described in this report should not be viewed as currents that could be observed at any particular time during a tidal cycle but rather a representation of the net movement of water created by the combined action of the Gulf tides, freshwater inflows and wind conditions averaged over a monthly time period.

Although simulated salinity concentrations throughout the Guadalupe estuary varied over a wide range annually, salinities were generally at their lowest in the month of June, corresponding with high freshwater inflows to the estuary. Highest levels of salinities were generally found during the months of March and August.

Nutrient contributions to the Guadalupe 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 Guadalupe estuary is probably the freshwater contributed by the San Antonio and Guadalupe Rivers. The contribution of nutrients from local runoff is thought to be significant, but lack of data hinders a definite determination. There are little quantitative data on the contribution of nutrients from inundation phenomenon in the Guadalupe delta marshes. The contribution of nitrogen, carbon and phosphorus from these sources is dependent upon available detritus and runoff necessary to introduce it into the system.

The Guadalupe estuary is an extremely productive system, particularly in the deltaic marsh areas surrounding the Guadalupe River. Annual net productivity in the Guadalupe delta was found to average approximately 10,100 dry weight pounds per acre (1,130 g/m^2), with maximum productivity estimated at 15,100 dry weight pounds per acre (1,700 g/m^2) in *Spartina spartinae* habitats. Studies on nutrient uptake rates in Guadalupe estuary tend to suggest that waters are nitrogen limited, particularly in San Antonio Bay. The introduction of nutrients to the estuary generally occurs in an episodic fashion, corresponding to periods of high river discharge and/or extremely high tides following prolonged dry periods. In these cases the contribution of carbon, phosphorus and nitrogen from deltaic marshes to the estuarine waters can be expected to increase dramatically.

Although a great deal has been gained thus far by detailed investigations and data collection activities focused on the Guadalupe 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 both the variables and the relationships are extremely difficult and time consuming to make. Additional studies of the Guadalupe estuary will add to the knowledge gained to this point and allow more accurate description of the processes taking place. Studies under the authorization of Senate Bill 137 are continuing, with results scheduled for publication in the later part 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., San Antonio 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., Guadalupe 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., Mission 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 limiting 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 annual 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 eutrophication its biological population becomes stagnant and dominated by a few organisms.

Texas has over 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

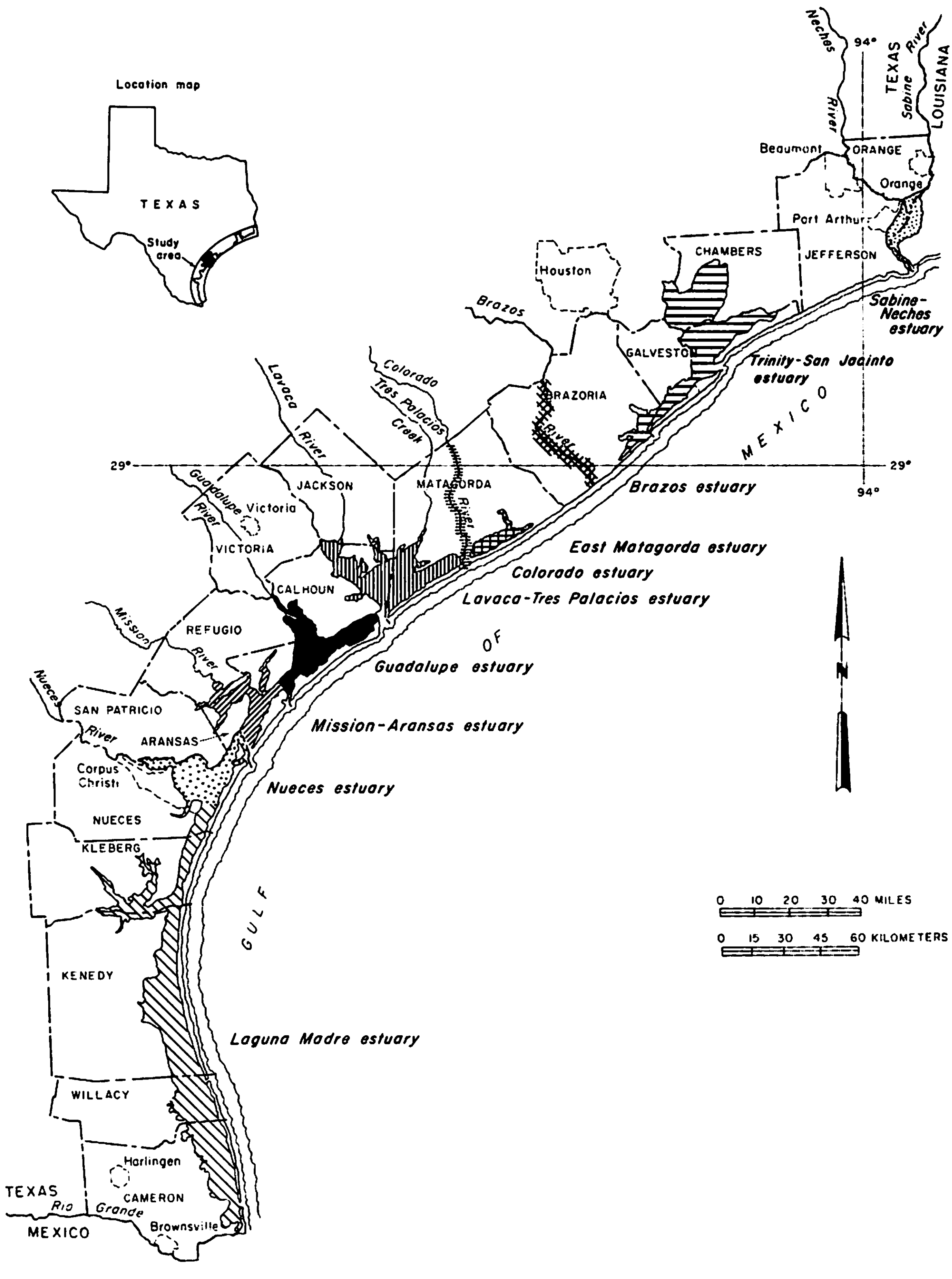

Figure 1.—Locations of the Estuaries

Base from Official State Highway Map of Texas, 1971 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 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 Guadalupe estuary is currently divided into three bay water segments (Figure 2): San Antonio Bay (segment 2462), Espiritu Santo Bay (segment 2461) and Mesquite Bay (segment 2463).

The simulation of net tidal hydrodynamic conditions in the Guadalupe estuary indicated that during the winter months the entire Espiritu Santo Bay was influenced by flow from San Antonio Bay, however, during the non-winter seasons the central and eastern portions of Espiritu Santo Bay had an internal circulation eddy which dominated the flow in that portion of the bay. In addition, the salinity concentrations were generally different in the two bays, Espiritu Santo Bay having higher average salinities. It is therefore recommended that the present bay segment boundary between Espiritu Santo Bay and San Antonio Bay (61), be retained (Figure 3).

The hydrodynamic model simulations indicated that net flow passed from Mesquite Bay into San Antonio Bay, thus water from the smaller bay influenced salinities in the larger bay. Based upon the model results, Mesquite Bay is not dominated by the circulation patterns of San Antonio Bay and Mesquite Bay has had consistently higher salinities. The existing segment boundary between these bays should be retained.

PHYSICAL CHARACTERISTICS

Introduction

The Guadalupe estuary, consisting of San Antonio, Espiritu Santo, and Mesquite Bays, is a shallow estuary with a mean depth of 2.5 feet (.76 m) and a total surface area of 143,000 acres (579 km^2). The Intracoastal Waterway traverses the bay from northeast to southwest and varies in depth from 12 to 15 feet (3.7 to 4.5 m) with a bottom width of about 125 feet (38.1 m).

The study area lies in the Upper Coast and South Central climatological divisions 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.

Sedimentation and Erosion

The Guadalupe estuary's main source of sediment is the Guadalupe/San Antonio River system. This system heads in the Edwards Plateau and flows southeasterly through the Blackland Prairie, East Texas Timberlands, Rio Grande Prairie and Coastal Prairie physiographic provinces.

Annual sediment production rates have been developed for stream channel sediment by the U.S. Soil Conservation Service. Sediment in a stream channel is generally divided into two classifications: bedload material and suspended 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 and 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 generally be estimated. Annual sediment production rates in the Edwards Plateau are low, ranging from 0.065 to 0.50 acre-foot per square mile (30 to 240 m^3/km^2) of drainage area. As the rivers flow over the Blackland Prairie the average annual sediment production rates reach a high of 1.50 acre-feet per square mile (710 m^3/km^2) of drainage area. Sediment production rates decrease as the Guadalupe and San Antonio Rivers flow through the East Texas Timbers, the Rio Grande, and on to the Coastal Prairie provinces (56).

Where a stream enters a bay, flow velocities decrease and the sediment transport capability is reduced; thus, bay-head deltas are formed where streams drop their bedload. The delta which formed at the mouth of the Guadalupe River is of a type which develops under conditions of high sediment inflow into a relatively quiescent body of water.

Approximately ten miles (16 kilometers) downstream from the confluence of the San Antonio

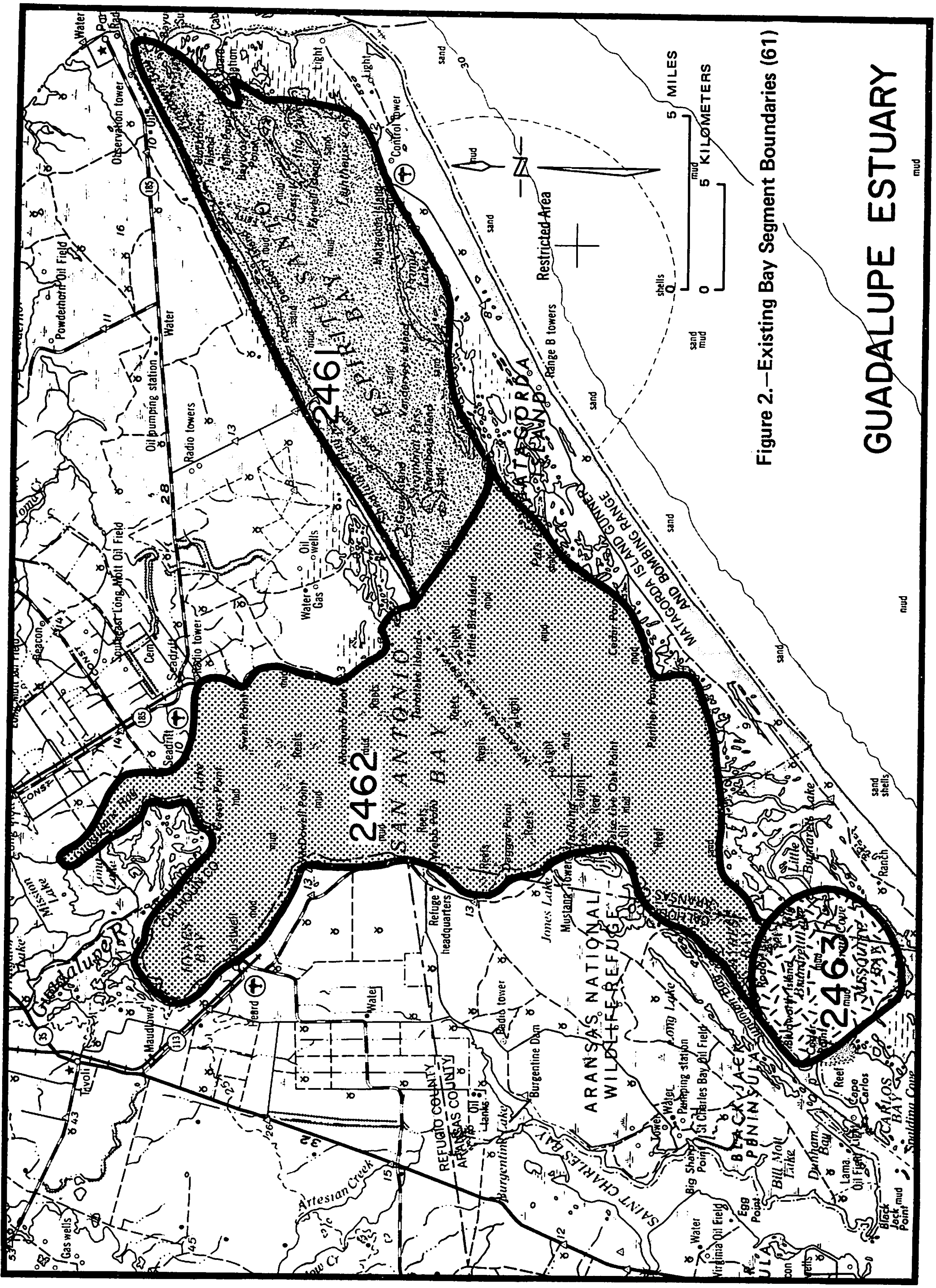

Figure 2.—Existing Bay Segment Boundaries (61)

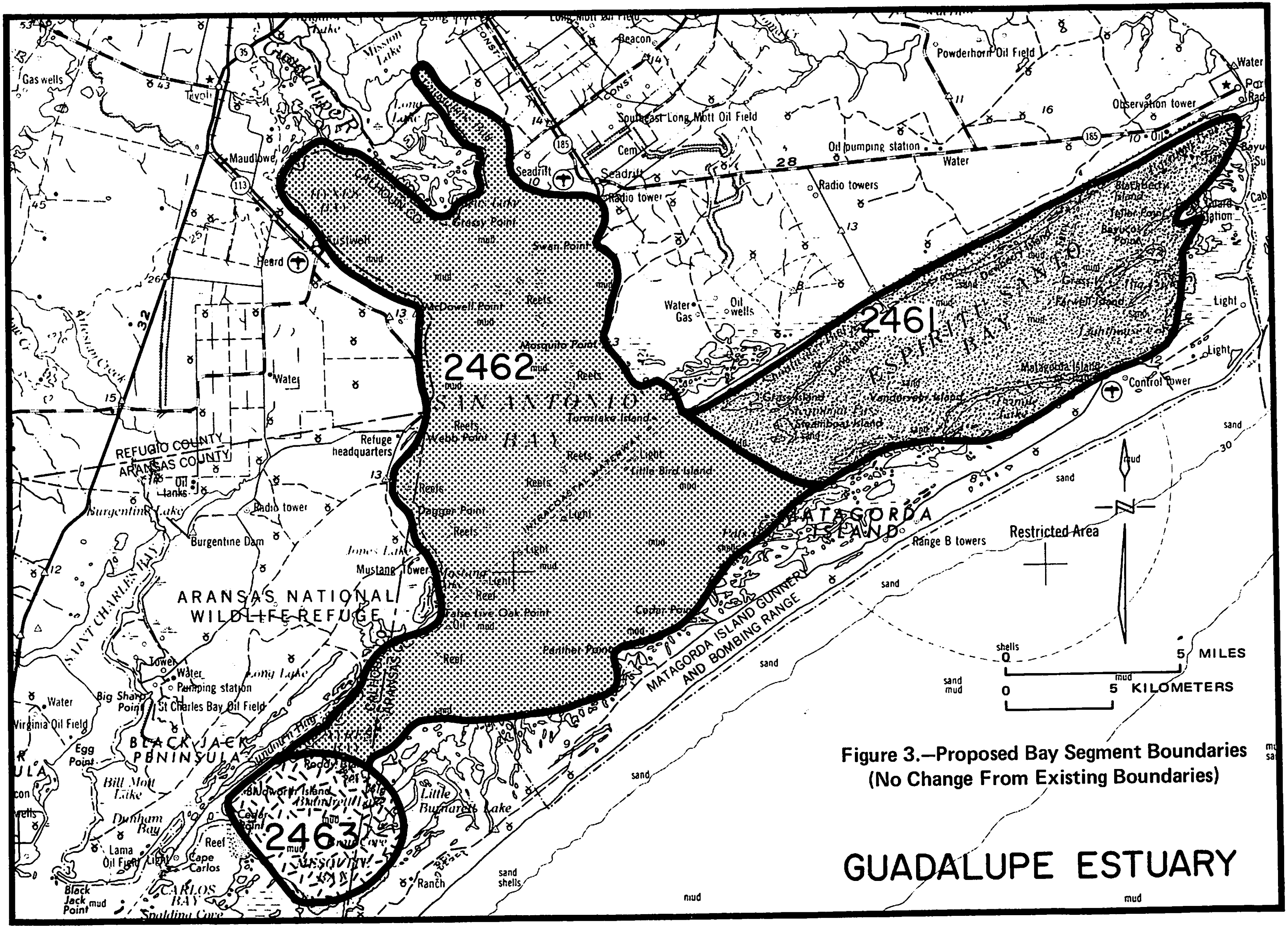

Figure 3.—Proposed Bay Segment Boundaries
(No Change From Existing Boundaries)

GUADALUPE ESTUARY

River and the Guadalupe River, a significant bay-head delta is forming. "The Traylor sub-delta began actively prograding into Mission Lake following the artificial trenching between Guadalupe River and Mission Lake in 1935" (7, p. 130). This fan delta has advanced into Mission Lake about 1,800 feet (550 meters) since it began forming. A significant portion of the Guadalupe River is diverted through this cut, thus furnishing abundant sediment for the formation of this relatively recent fan delta.

The marsh areas in the Guadalupe estuary are associated with these deltas. Delta plains 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 enlarge the bay area. Deposition has almost ceased on the lower two-thirds of the Guadalupe Delta as evidenced by the numerous lakes and extensive erosion. Lakes and ponds are an integral part to the coastal marsh-swamp complex. Water in these lakes and ponds varies from fresh to saline depending on climatological conditions and geographic location. Inland lakes such as Green Lake are fresh, while lakes and ponds associated with the Guadalupe Delta (Long Lake) are temporarily brackish to saline.

The mainland shore of the Guadalupe estuary is characterized by near vertical bluffs cut into Pleistocene 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 Guadalupe estuary are dominated by wind action since the range of astronomical tides is only about 0.5 foot (0.15 meters). Winds blowing across the bay generate waves which cause erosion along the shoreline.

The Texas coastal zone is experiencing geological, hydrological, biological and land use changes as a result of natural processes and man's activities. What was once a relatively undeveloped expanse of beach is presently undergoing considerable development. Competition for space exists for such activities as recreation, seasonal and permanent housing, industrial and commercial development, and mineral and other natural resource production (40).

Shorelines are either in a state of erosion, accretion, or are stabilized either naturally or artifically. 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 shorelines associated with the Guadalupe estuary are either in a state of equilibrium or deposition (Figure 5). This is an indication that the sediment volume being supplied to the Gulf shoreline and portions of the bay system shorelines is sufficient to balance the amount of sediment removed by wave action and longshore drift.

Processes that are responsible for the current shoreline configuration and that are continually modifying shorelines in the Guadalupe 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 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 coastal processes. It can raise or lower water level along the Gulf and/or mainland shore according to the direction it is blowing. Wind can also generate waves and longshore currents (25, 14, 44).

The seasonal threat of wind and water damage associated with tropical cyclones occurring in the Gulf of Mexico exists each year from June through October. Wind damage from hurricanes and associated tornadoes can be costly, but the most severe losses occur from the flooding brought by heavy rains and high storm tides along the coast. Gulf and mainland shorelines may be drastically altered during the approach, landfall, and inland passage of hurricanes (26). Storm surge flooding and attendant breaking waves erode Gulf shorelines from a few tens to a few hundreds of feet. Washovers along the barrier islands and peninsulas are common, and saltwater flooding may be extensive along the mainland shorelines.

Flooding of rivers and small streams normally corresponds with spring thunderstorms and the hurricane season. 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, and (3) flushing of bays and estuaries.

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

Figure 4.—Geologic Map

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

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

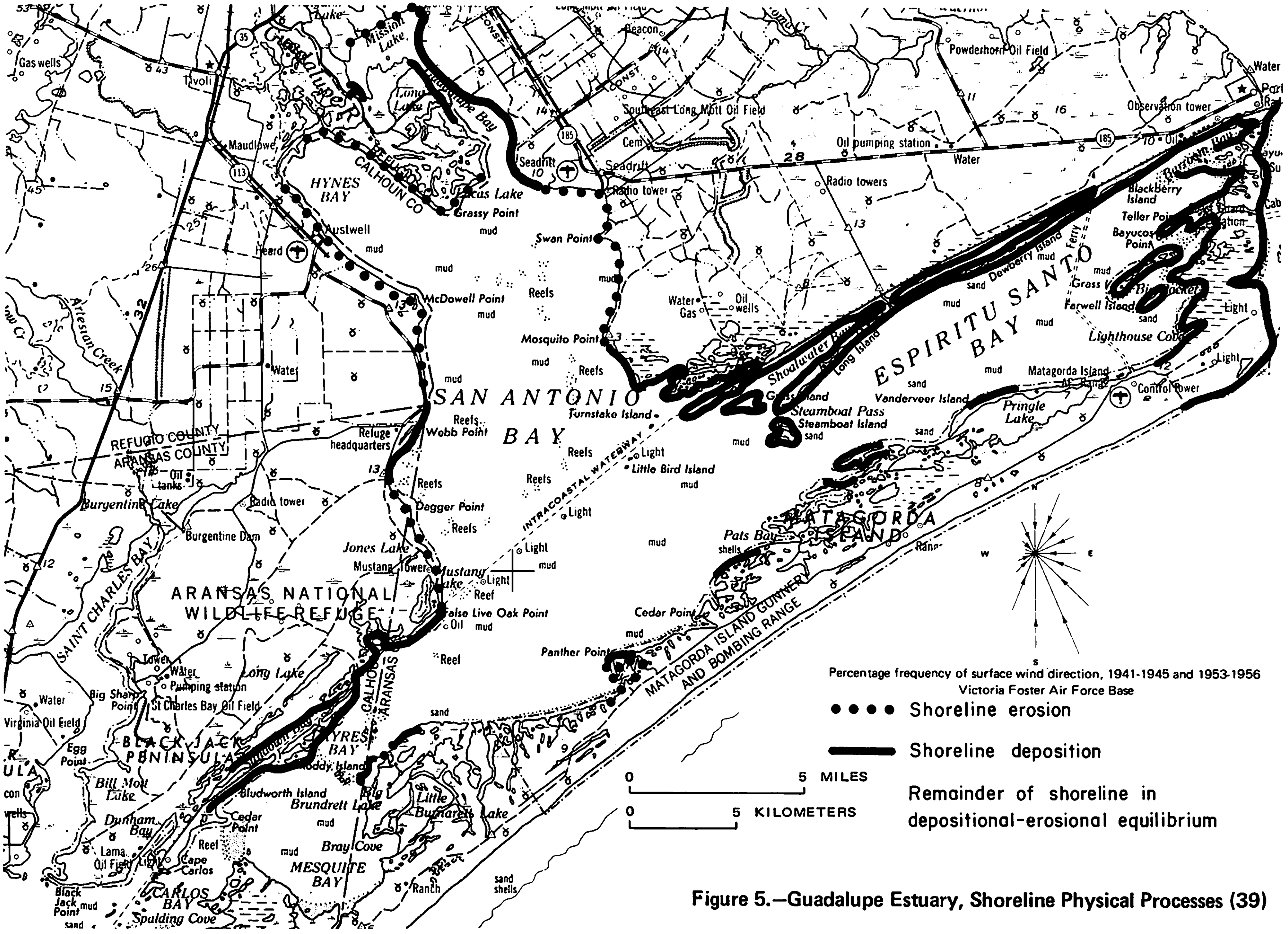

Figure 5.—Guadalupe Estuary, Shoreline Physical Processes (39)

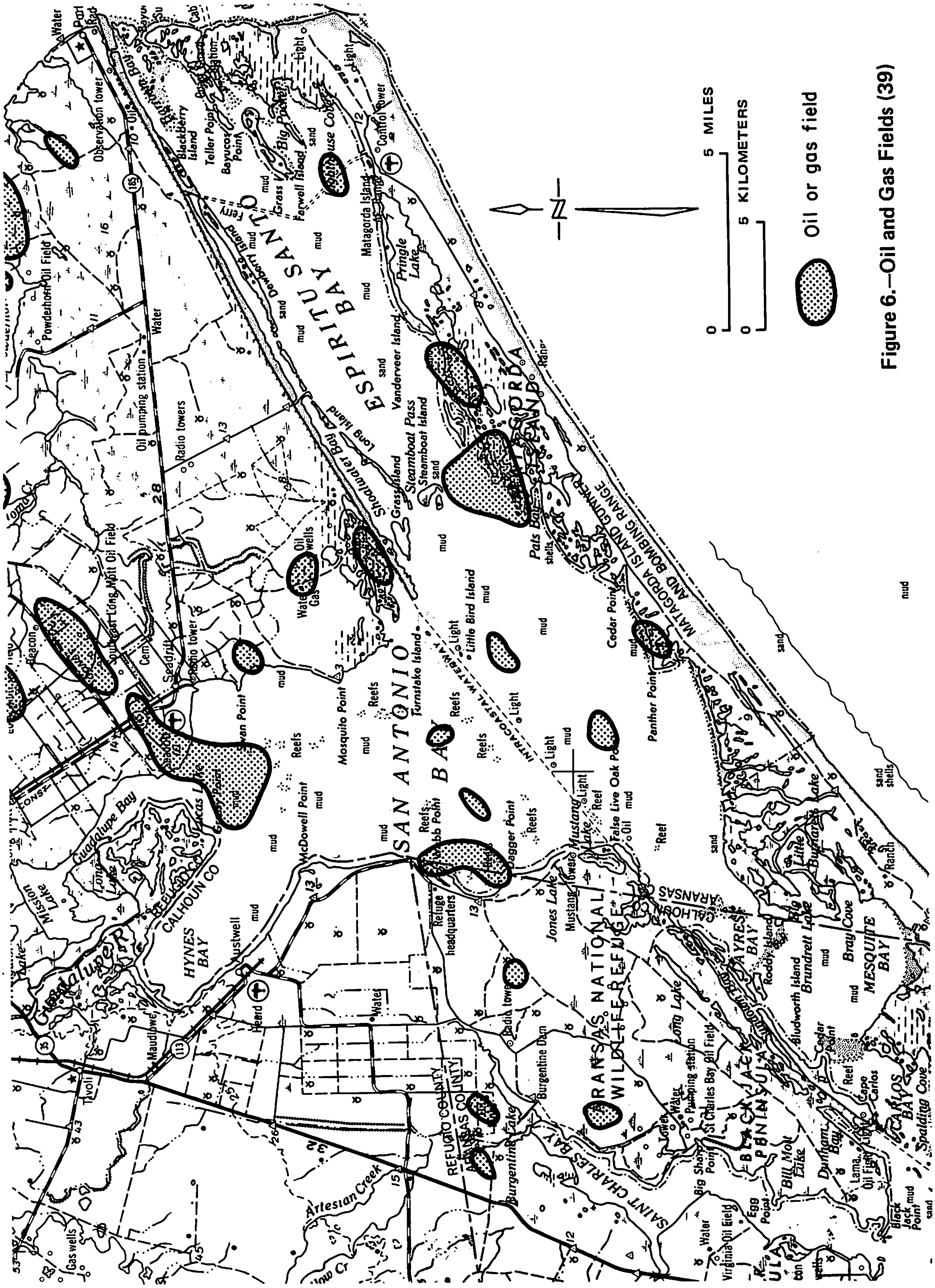

Figure 6.—Oil and Gas Fields (39)

contains important sources of chemical raw materials, such as sulfur, salt, and shell for lime. The great abundance of these chemical and petroleum raw materials and their occurrence in a zone with ocean access help to make this area one of the major petrochemical and petroleum-refining centers of the world.

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

Notably absent in the Texas coastal zone are 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 industralized 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 is suitable for aggregate, road base, lime, cement, and other chemical uses. If shell were not used, these resources would have to be transported approximately 150 miles (240 kilometers) from the nearest Central Texas source. The total resources of shell are finite, and at present rates of consumption 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 quality 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, indicate that these sands require upgrading and benefication to qualify for special industrial use (37). Since the nearest market for such upgraded sands would be the Houston area, it is unlikely that sand deposits within the Guadalupe estuary would be used to supply the upper coastal zone markets.

Groundwater Resources

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

Near the Guadalupe 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 1,800 feet (0.55 kilometers). The most productive part of the aquifer is from 200 to 800 (61 to 244 meters) thick (58).

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 ground-water 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. Additional problems may arise if subsidence causes damage to sewer lines, water lines, petroleum transmission lines, chemical storage tanks, and other facilities. There could also be a problem when subsidence areas which previously had not been subject to tidal inundation become flood prone during high tide.

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 had been collected.

A program was therefore initiated by the Department, in cooperation with other agencies, to collect the data considered essential for analyses of the physical and water quality characteristics and ecosystems of Texas' bays and estuaries. To begin this program, the Department consulted with the U.S. Geological Survey and initiated a reconnaissance-level investigation program in September 1967. Specifically, the initial objectives of the program were to define: (1) the occurrence, source and distribution of nutrients; (2) current patterns, directions, and rates of water movement; (3) physical, organic, and inorganic water quality characteristics; and (4) the occurrence, quantity, and dispersion patterns of water (fresh and Gulf) entering the estuarine system. To avoid duplication of work and to promote coordination, discussions were held with other State, Federal and local agencies having interests in Texas estuarine systems and their management. Principally through this cooperative program with the U.S. Geological Survey, the Department is now collecting extensive data in all estuarine systems of the Texas Coast (Figures 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 Guadalupe estuary on November 16-20, 1970 and August 6-9, 1973. 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, and H 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 tidal currents, freshwater inflows, and prevailing winds. 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.

The Department's tidal hydrodynamic and salinity mass transport models were applied to the Guadalupe estuary to determine the affects of the mean monthly freshwater inflows upon the flow circulation and salinity characteristics of the estuarine system. The monthly simulations utilized average tidal and meteorological conditions observed historically for each month simulated.

The net circulation patterns simulated by the tidal hydrodynamic model indicated that the dominate circulation pattern in the Guadalupe estuary was a net movement of water from Mesquite Bay through San Antonio Bay and Espiritu Santo Bay into the Lavaca-Tres Palacios estuary. Simulated water movements in the upper and middle portions of San Antonio Bay were dominated by internal eddy currents induced by freshwater inflows from the Guadalupe River. Simulated flows in Espiritu Santo Bay were governed by a major internal eddy circulation which moved with a clockwise rotation.

The simulated salinities in the Guadalupe estuary for the period 1941-1976 varied over a wide range annually. Salinities were at the lowest levels in the month of June, with average (1941-1976) simulated concentrations of less than 25 parts per thousand over the entire estuary. The highest levels of simulated salinities occurred during the months of March and August, when salinities in the lower portion of San Antonio Bay were between 20 and 25 parts per thousand. The simulated mean salinities for Mission Lake and Guadalupe Bay were never greater than 10 parts per thousand during any part of the year.

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

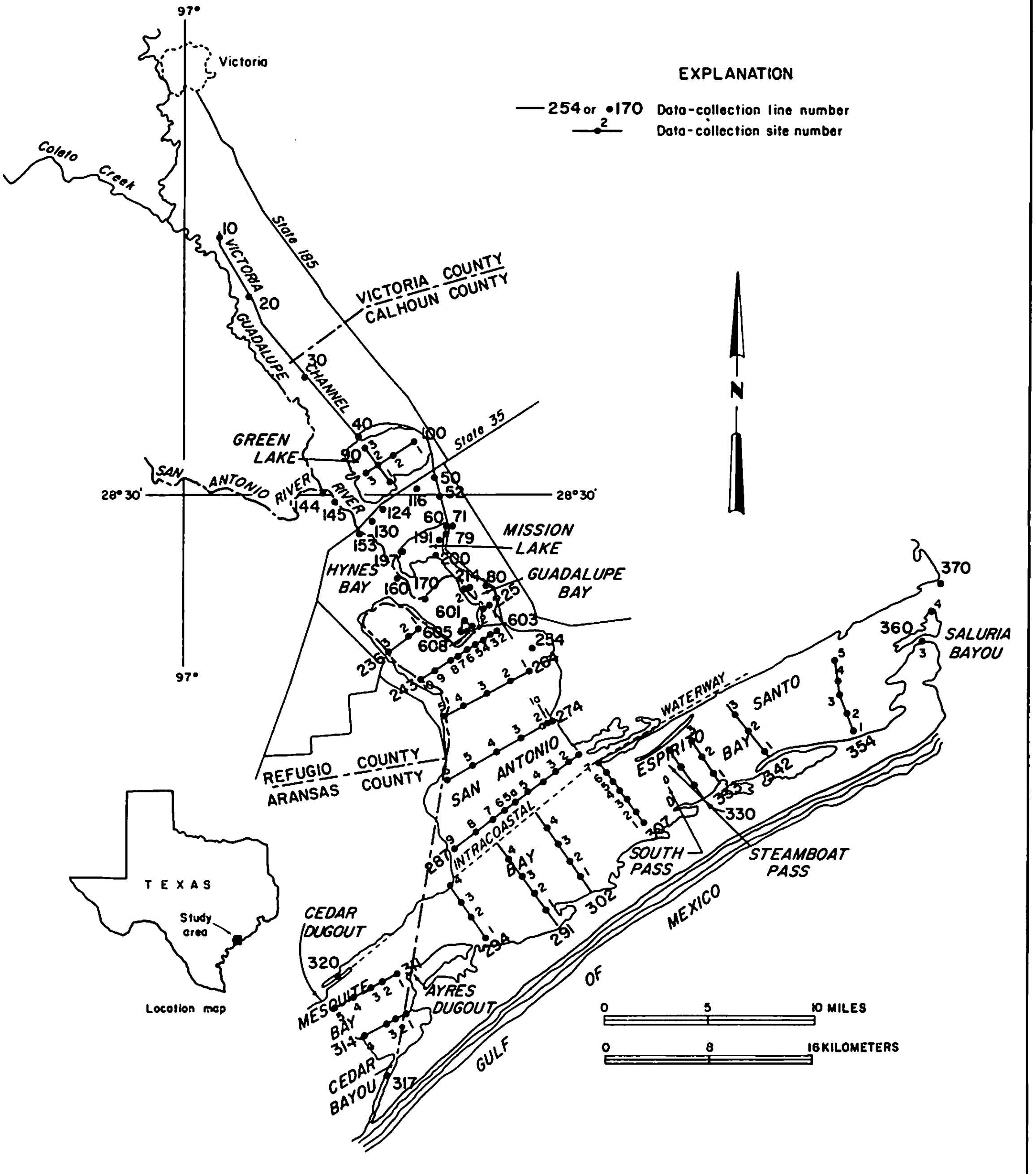

Figure 7.—Data-Collection Sites in the Guadalupe Estuary
U.S. Geological Survey

Base by U.S. Geological Survey, 1956

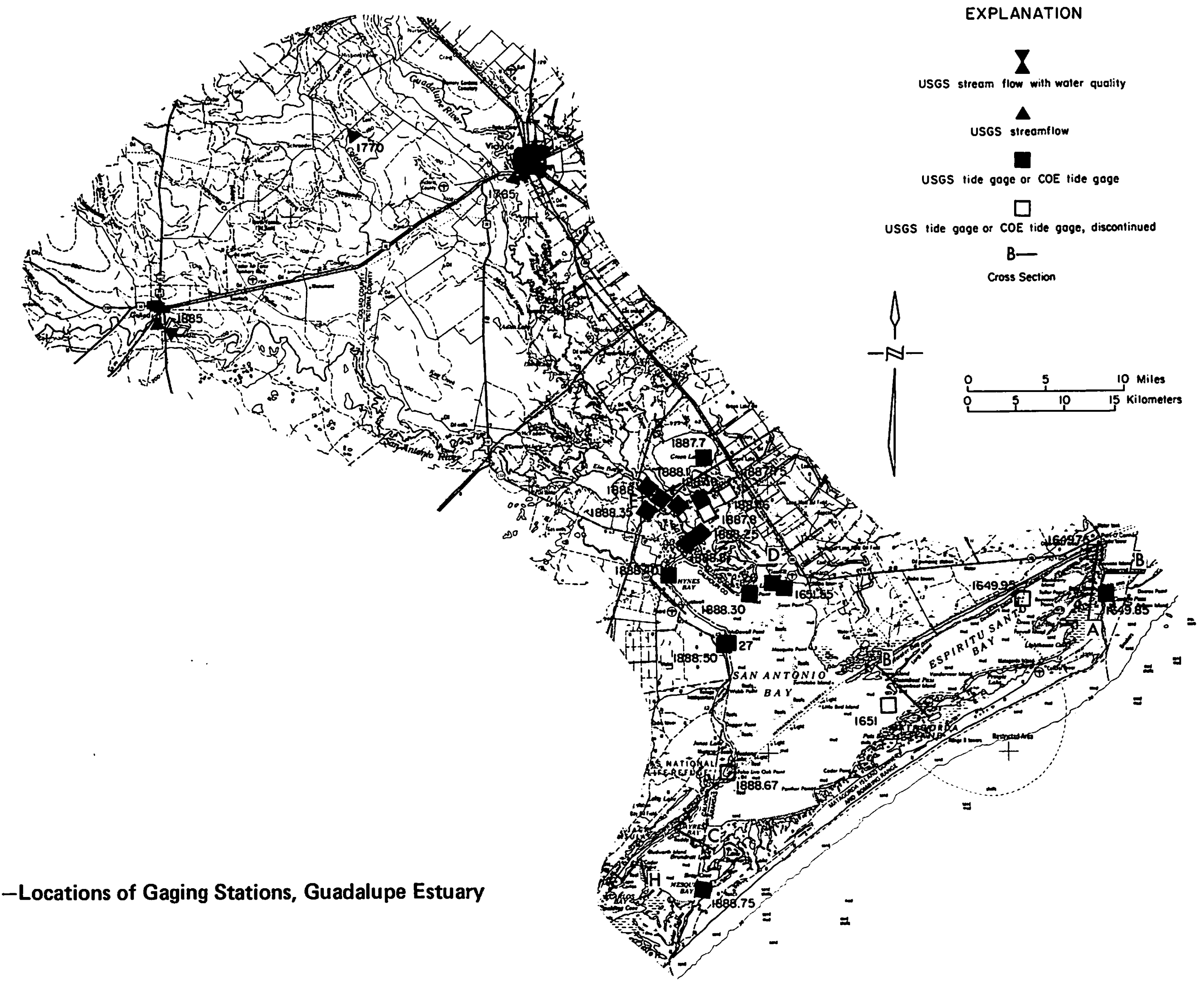

Figure 8.—Locations of Gaging Stations, Guadalupe Estuary

Table 1.–USGS or Corps of Engineers (COE) Gages, Guadalupe Estuary

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

Table 1.–USGS or Corps of Engineers (COE) Gages, Guadalupe Estuary–Continued

Station number	Station description	Period of record	Operating entity	Type of record
1888.20	Guadalupe River nr. Traylor Cut nr. Tivoli	1974-	USGS	Continuous Recording
1888.25	Traylor Cut nr. Tivoli	1974-	USGS	Continuous Recording
1888.30	Lucas Lake nr. Seadrift	1975-	USGS	Continuous Recording
1888.35	Townsend Bayou nr. Austwell	1975-	USGS	Continuous Recording
1888.40	Guadalupe Delta at Townsend Bayou nr. Austwell	1974-	USGS	Continuous Recording
1888.50	San Antonio Bay nr. Austwell	1969-	USGS	Continuous Recording
1888.67	San Antonio Bay nr. (Mus. Lake) nr. Austwell	1971-76	USGS	Continuous Recording
1888.75	Mesquite Bay (CED BA) nr. Fulton	1971-	USGS	Continuous Recording
	Stream Gages			
1765.00	Guadalupe River at Victoria	1934-	USGS	Continuous Recording
1770.00	Coleto Creek nr. Schroeder	1930-33 1952-	USGS	Continuous Recording
1885.00	San Antonio River at Goliad	1924-29 1939-	USGS	Continuous Recording

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 between 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 vice 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 adaptation 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 an acceptable method. The mathematical statement of a process consists of an input, a transfer function and an output. The output from a given system or component of a system is taken to be related to the input or some function of the input by the transfer function.

A numerical model of an estuarine system consists of a series of elements arranged in time and space so that the output from one element becomes the input to the next and so on. Each input is operated on by the transfer function for the element and through a succession of spatial and time steps, the entire functional behavior of the system is determined. One of the merits of the numerical representation is that it permits discretizing and more detailed characterization of the prototype.

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 adequate 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 constraints imposed on the solution method by budgets 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 mass transport models for the Guadalupe estuary (16) 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 can not 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 area-wise 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

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

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

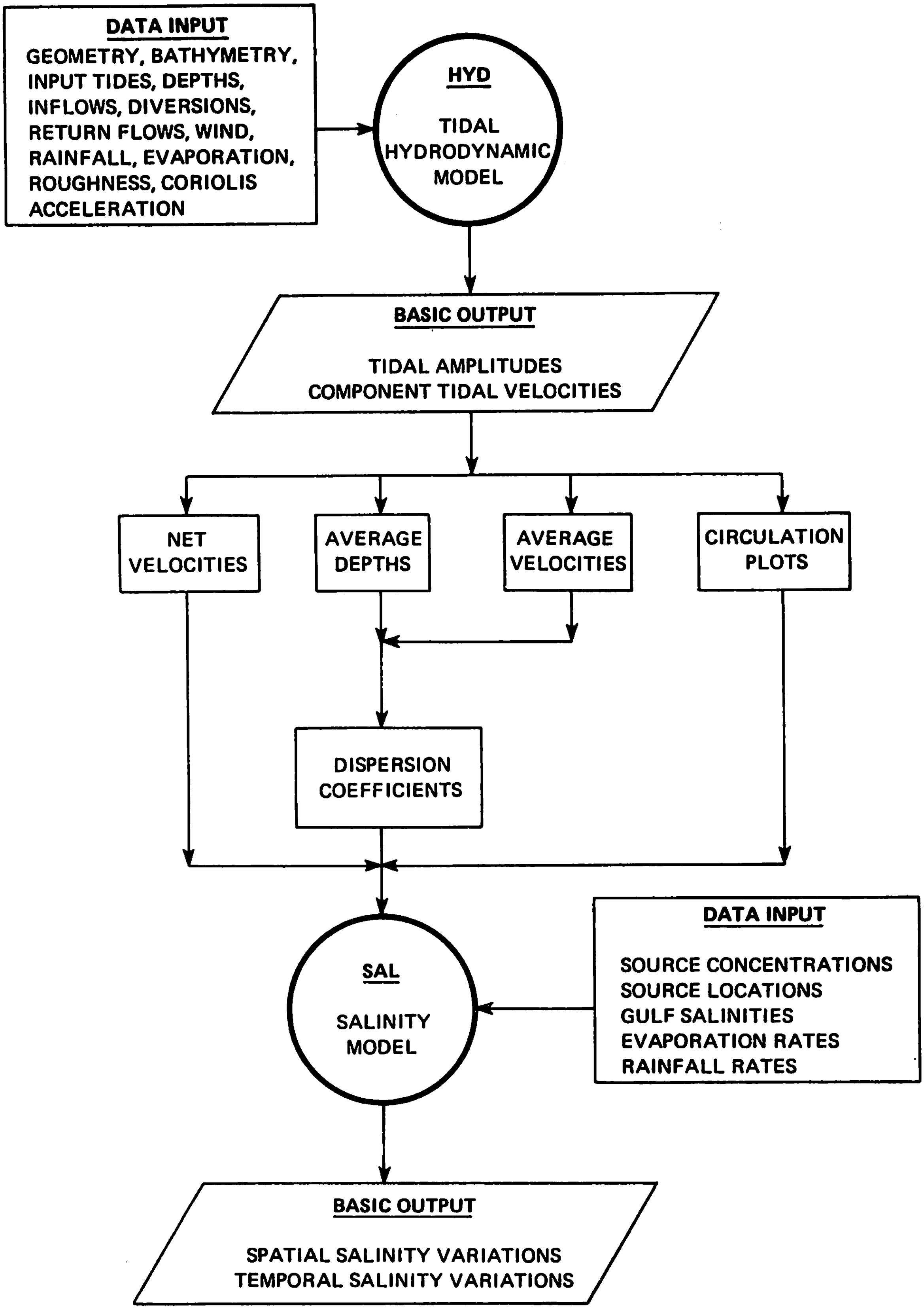

Figure 9.—Relationship Between Tidal Hydrodynamic and Salinity Models (16)

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; $q = (q_x^2 + q_y^2)^{\frac{1}{2}}$; f is a nondemensional 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 28.1° for the Guadalupe estuary; r is the rainfall intensity; and e is the evaporation rate.

The numerical solution utilized in the hydrodynamic model of the Guadalupe 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, $\Delta t < \Delta s/(2gd_{max})^{\frac{1}{2}}$ where Δs is the cell size and d_{max} is the maximum water depth encountered in the computational matrix. The numerical solutions of the basic equations and the programming techniques have been described previously (16).

(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

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

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 (16). The primary difference in the form of Equation [4] given above and that reported previously by Masch (16), 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 $\Delta t/\Delta \bar{s}^2 \leqslant \frac{1}{2}$ was always maintained throughout this work. Details of the numerical solution of Equation [4] and programming techniques have also been previously described by Masch (16).

The computational grid network used to describe the Guadalupe 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 constrained by the criterion for mathematical stability. In the indexing scheme shown in Figure 11, cells were numbered with the indices $1 < i < IMAX = 36$ and $1 < j < JMAX = 24$. With this arrangement, all model parameters such as water depths, flows in each coordinate direction, bottom function, and salinity could be identified with each cell in the grid.

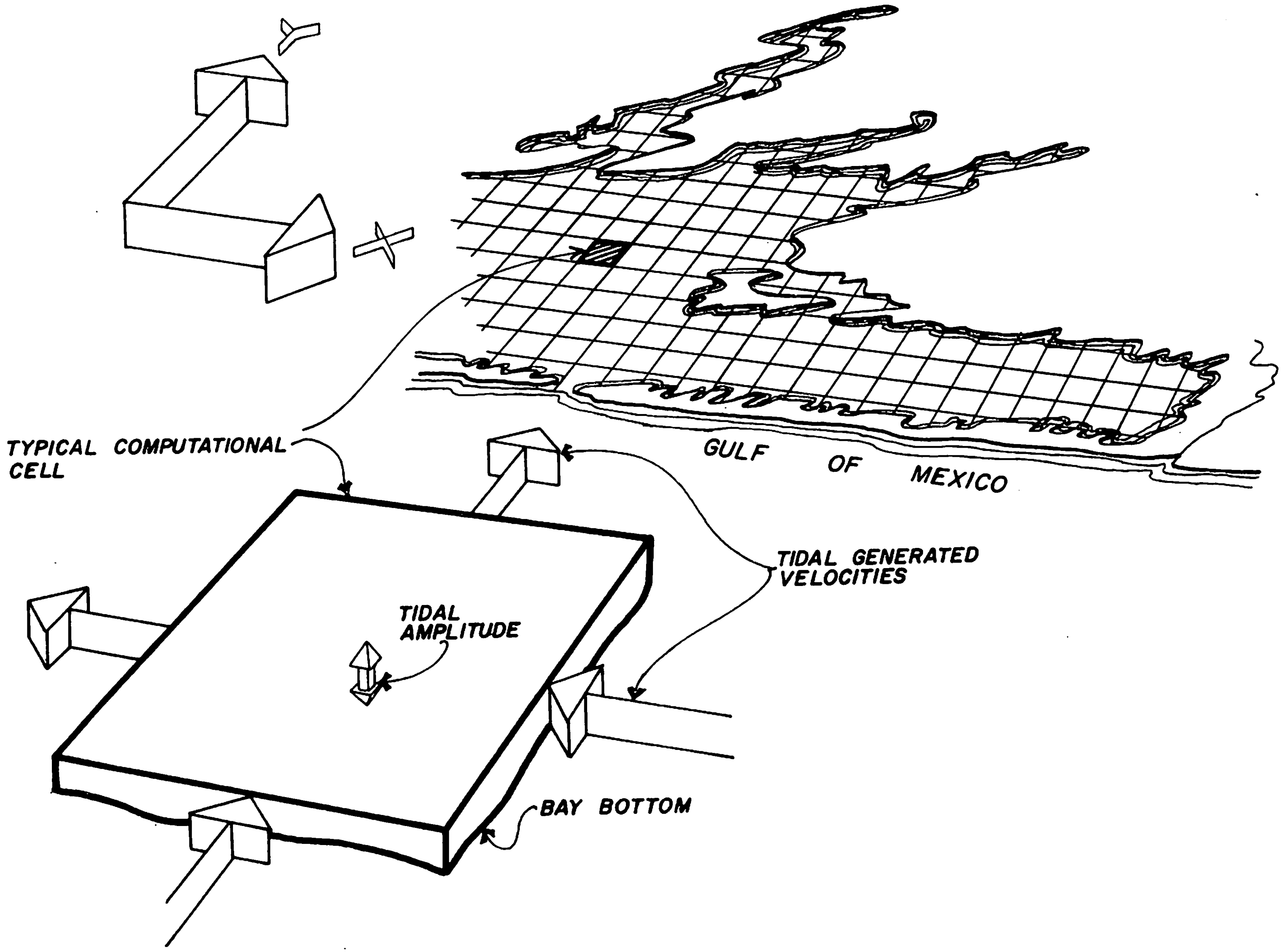

Figure 10.–Conceptual Illustration of Discretization of a Bay (16)

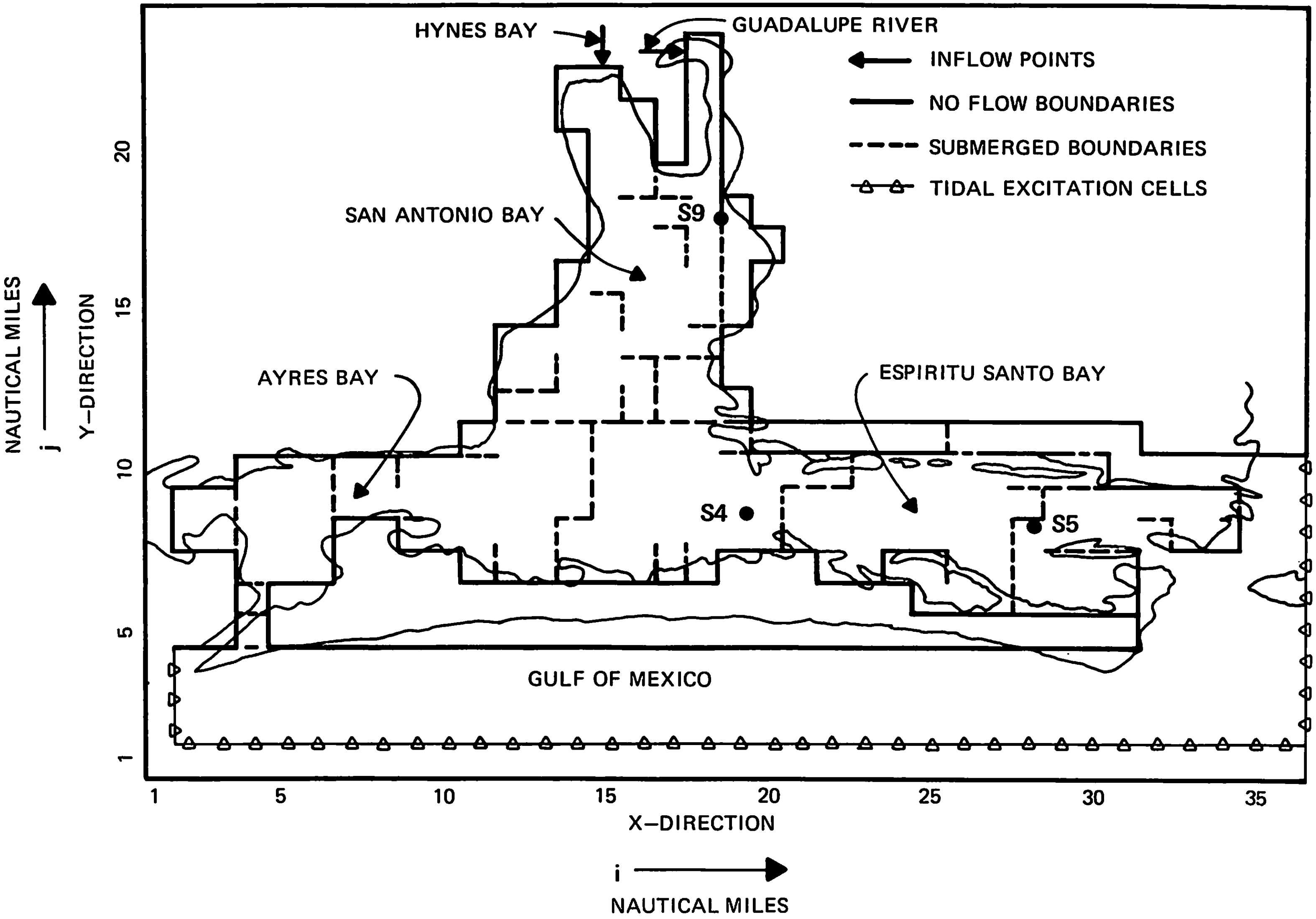

Figure 11.–Computational Grid, Guadalupe Estuary (16)

(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.

Application of Mathematical Models, Guadalupe Estuary

The historic monthly total freshwater inflows to the Guadalupe 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 average monthly freshwater inflows for the Guadalupe estuary over the period 1941 through 1976 are distributed according to the histogram given in Figure 12. The month with the greatest contribution of freshwater inflows is May, with slightly over 13 percent of the total annual inflow, while August has the lowest average historical inflow accounting for slightly over four percent of the total inflows into the estuary. 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 Guadalupe estuary for each month of the year.

Table 2.—Mean Monthly Freshwater
Inflow Guadalupe Estuary, 1941-1976

Month	Inflow[a]
January	2640
February	3075
March	2390
April	3195
May	4825
June	3730
July	2385
August	1630
September	3865
October	3950
November	2640
December	2455

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

The output of the tidal hydrodynamics model consists of a set of tidal amplitudes and net flows computed for each cell in the 36 x 24 computational matrix representing the Guadalupe estuary. The computed net flows are the average of the instantaneous flows calculated by the model over the tidal cycle. Thus, the circulation pattern represented by these net flows should not be interpreted as a set of currents that can be observed at any time during the tidal cycle, but rather 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 Guadalupe 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).

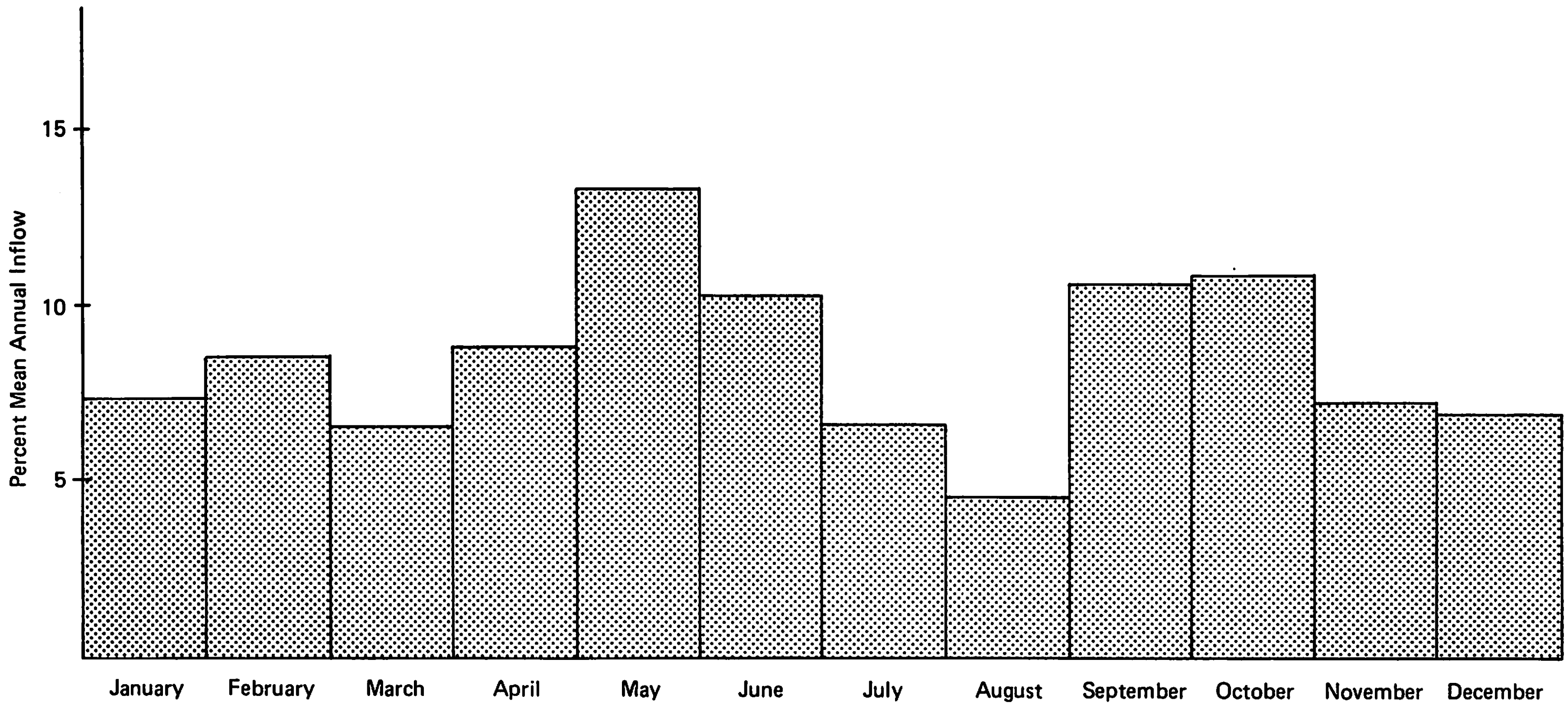

Figure 12.—Monthly Distribution of Mean Annual Total Gaged and Ungaged Inflow, Guadalupe Estuary 1941-1976

Simulated Flow Patterns.

The simulated steady-state net flows in the estuary are given in Figures 13 through 24 for each of the twelve months. The magnitude and direction of net flow in each computational "cell" is indicated by an arrow or vector. The magnitude of flow is indicated by the length of each vector with one inch corresponding to approximately 20,000 cubic feet per second (ft^3/sec) (or 570 m^3/sec).

Examination of the current plots for each of the numerical simulations using average monthly inflows revealed that the circulation patterns in the Guadalupe estuary during the months of December, January and February were very similar while the current patterns for the other months of the year also closely resembled each other. This breakdown of the circulation patterns into essentially non-winter and winter periods will facilitate the following discussion of the simulated monthly hydrodynamic conditions.

(1) Simulated Winter Circulation Patterns Under Average Inflow Conditions.

The winter months of December, January and February have very similar values for historical average freshwater inflows into the estuary (see Figure 12). The average wind speed and direction for these months are also quite similar with the wind velocity being approximately 10 miles per hour (mph) (or 4.5 m/sec) for each of the months and the wind directions being from the north-northeast.

Examination of the simulated circulation patterns in the bays for these three months (Figure 24, 13 and 14) indicates that the predominant net water circulation under these simulated conditions is from Carlos Bay in the Mission-Aransas estuary into Mesquite Bay of the Guadalupe estuary and continuing northeastward through San Antonio and Espiritu Santo Bays into the Lavaca-Tres Palacios estuary.

The circulation patterns in the middle and upper portions of San Antonio Bay have several circular eddy currents which dominate the circulation pattern. The flow from the Guadalupe River appears to be the dominant factor inducing these eddy currents in the upper portion of San Antonio Bay.

Several simulated secondary currents in the lower San Antonio and Espiritu Santo Bays resulted in flow along the northern shore of Mustang Island being directed in a southwesterly direction. These flows are the result of counterclockwise rotating eddy currents.

The major exchange points between the Guadalupe estuary and the Mission-Aransas estuary, the Guadalupe estuary and the Gulf of Mexico were evaluated for net flow volume and direction during these winter months. The primary exchange points were from the Mission-Aransas estuary into Mesquite Bay and from Espiritu Santo Bay into the Lavaca-Tres Palacios estuary. Net exchange directly between the Guadalupe estuary and the Gulf of Mexico was relatively small.

(2) Simulated Non-Winter Circulation Patterns Under Average Inflow Conditions.

The simulation of the tidal hydrodynamic conditions in the Guadalupe estuary indicated that the current patterns under average monthly flow conditions for each of the non-winter months had similar characteristics (Figures 15 through 23). This occurred even though the historical mean wind speed and direction for the non-wiinter months varied considerably from month-to-month. The month with the highest wind velocity is April with a mean wind speed of 12.8 mph (5.7 m/sec) from the south-southeast. August has the lowest recorded wind speed of 8.1 mph (3.6 m/sec) from the southeast. Wind direction over the period March through November is predominantly from the east and southeast.

The predominant net flow circulation simulated for the non-winter months was from Mesquite Bay in the southeast, through the lower portion of San Antonio Bay adjacent to the northern coast of Mustang Island, into Espiritu Santo Bay, then in and adjacent to the intracoastal waterway along the northern shore of Espiritu Santo Bay, and finally out of the estuary through the passes leading to the Lavaca-Tres Palacios estuary. The second most significant current pattern simulated moved from the mouth of the Guadalupe River into the main portion of San Antonio Bay and then down to the intracoastal waterway where it joined the current moving from Mesquite Bay.

Several circular eddy currents were observed in the simulation of the non-winter months. The most significant of these was in the eastern portion of Espiritu Santo Bay. This eddy current moved in a clockwise rotation and appeared to exchange flow with the primary current moving from Mesquite

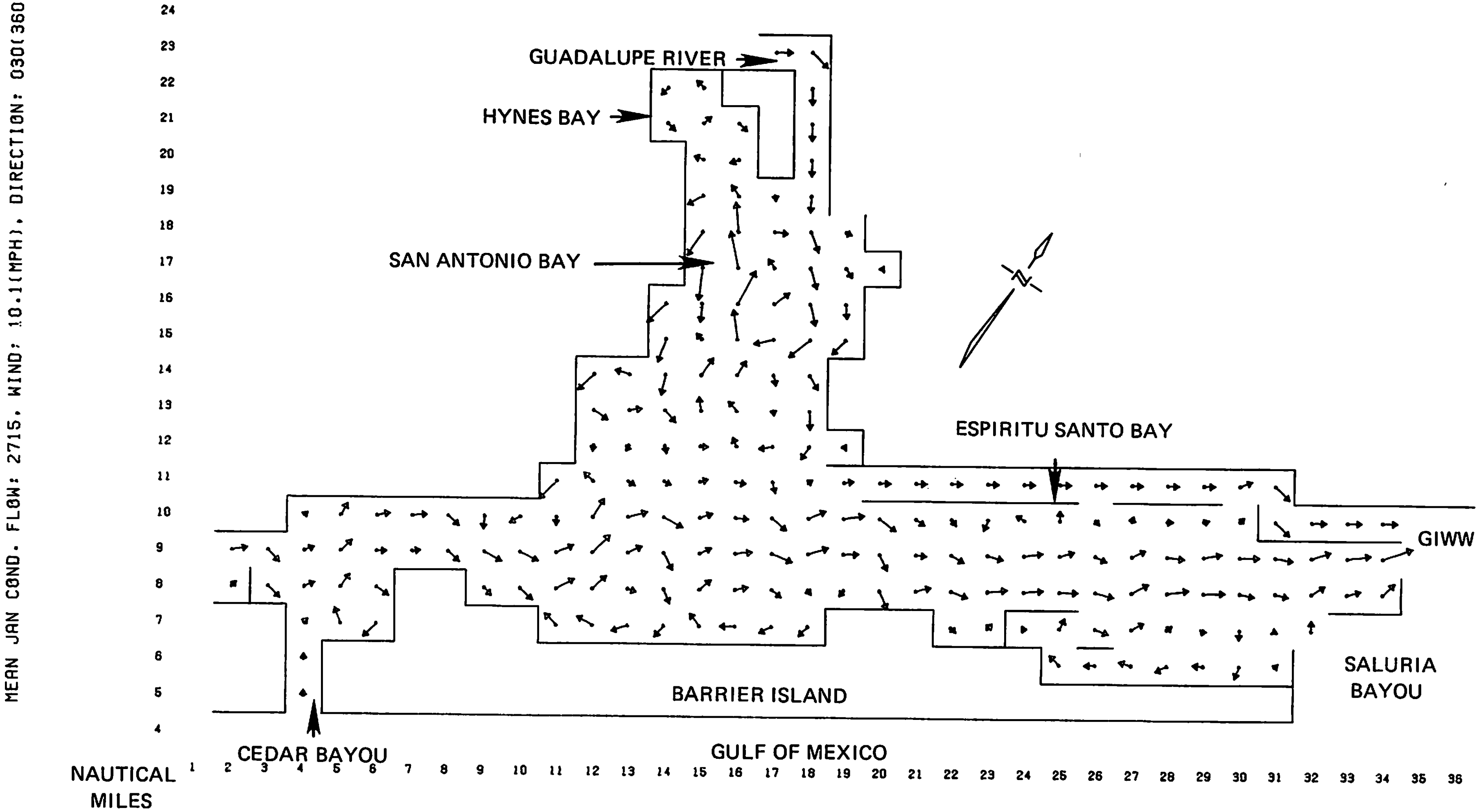

Figure 13.—Simulated Net Steady-State Flows in the Guadalupe Estuary Under January Average Inflow

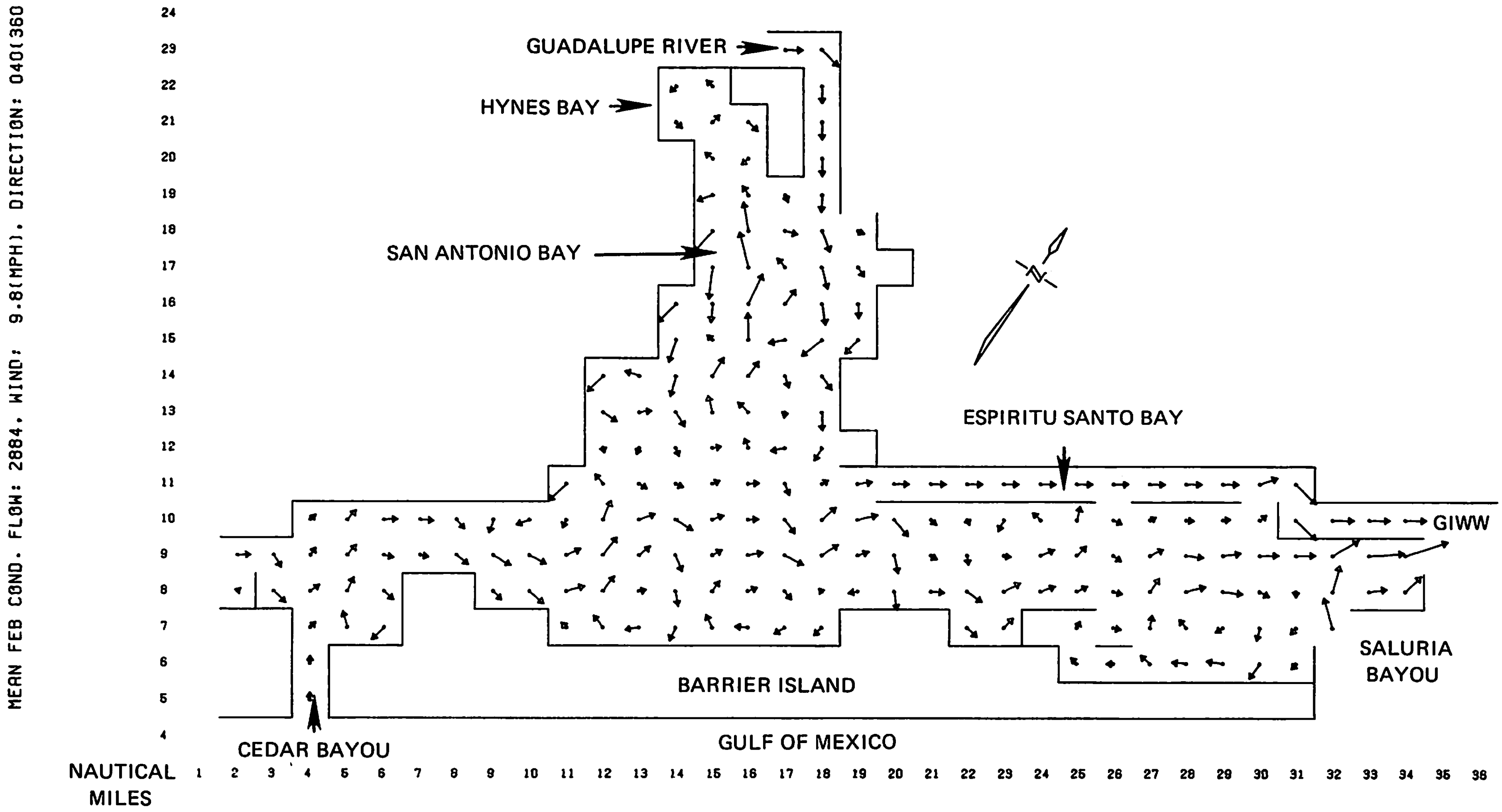

Figure 14.—Simulated Net Steady-State Flows in the Guadalupe Estuary Under February Average Inflow

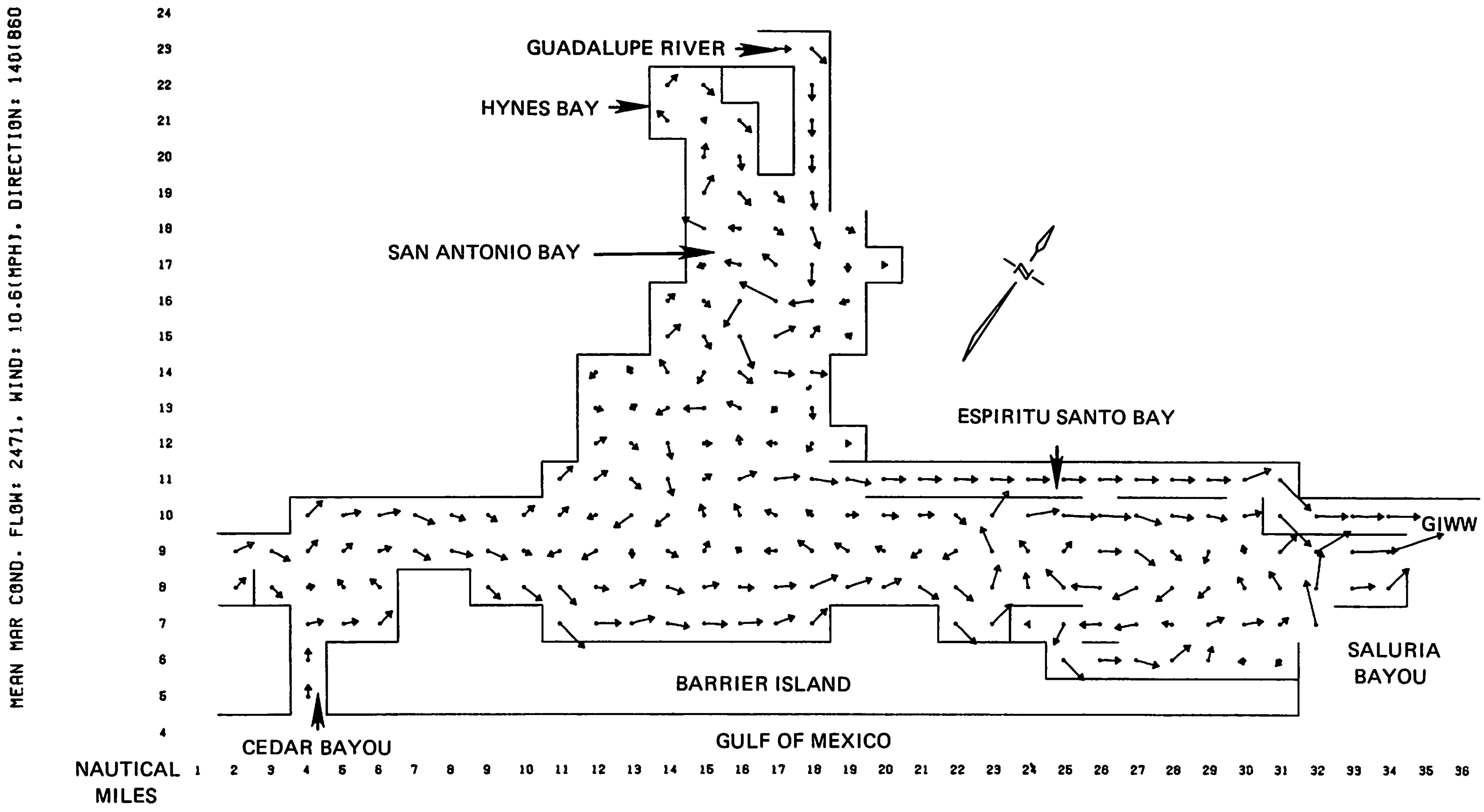

Figure 15.—Simulated Net Steady-State Flows in the Guadalupe Estuary Under March Average Inflow

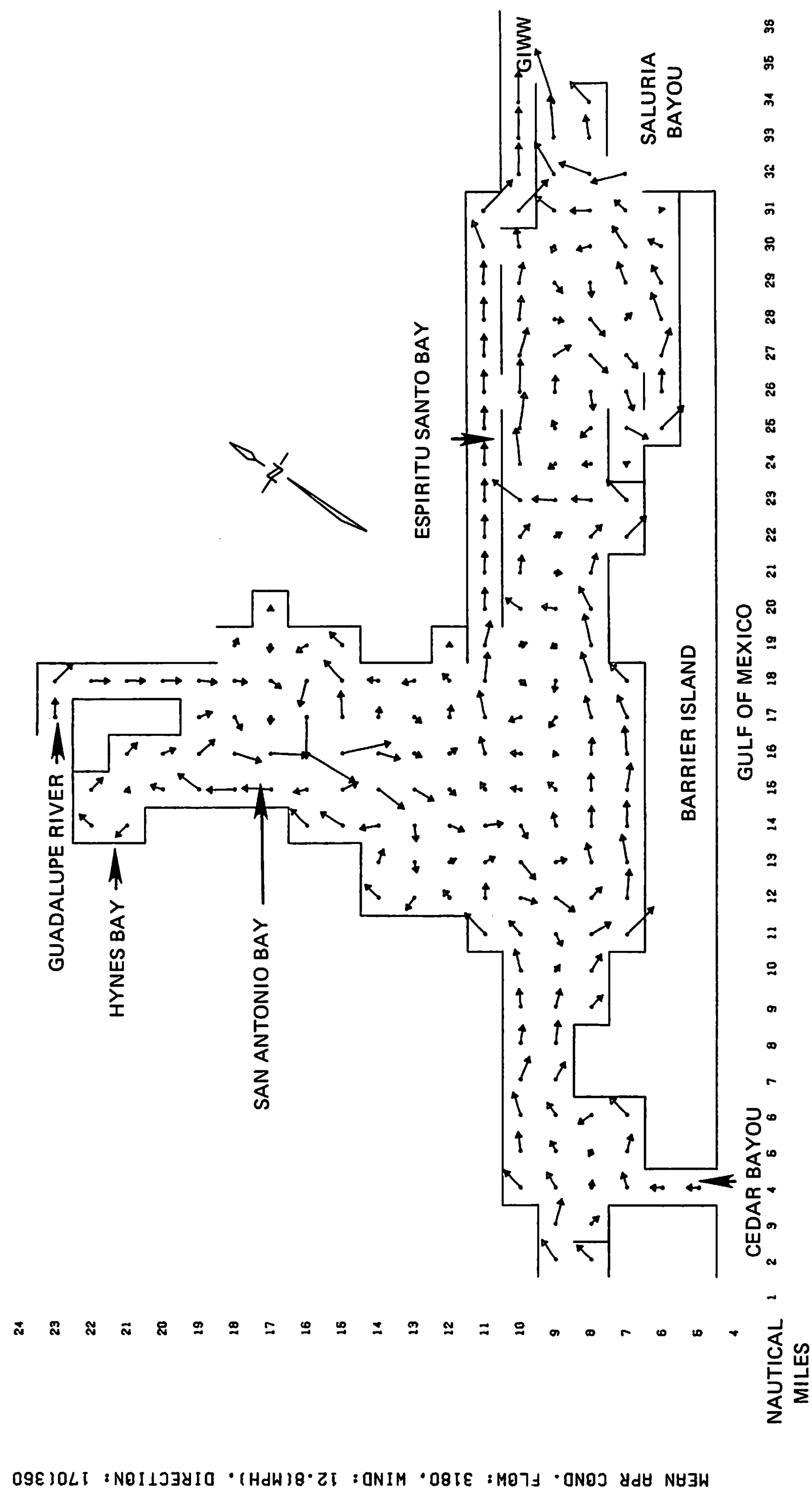

Figure 16.—Simulated Net Steady-State Flows in the Guadalupe Estuary Under April Average Inflow

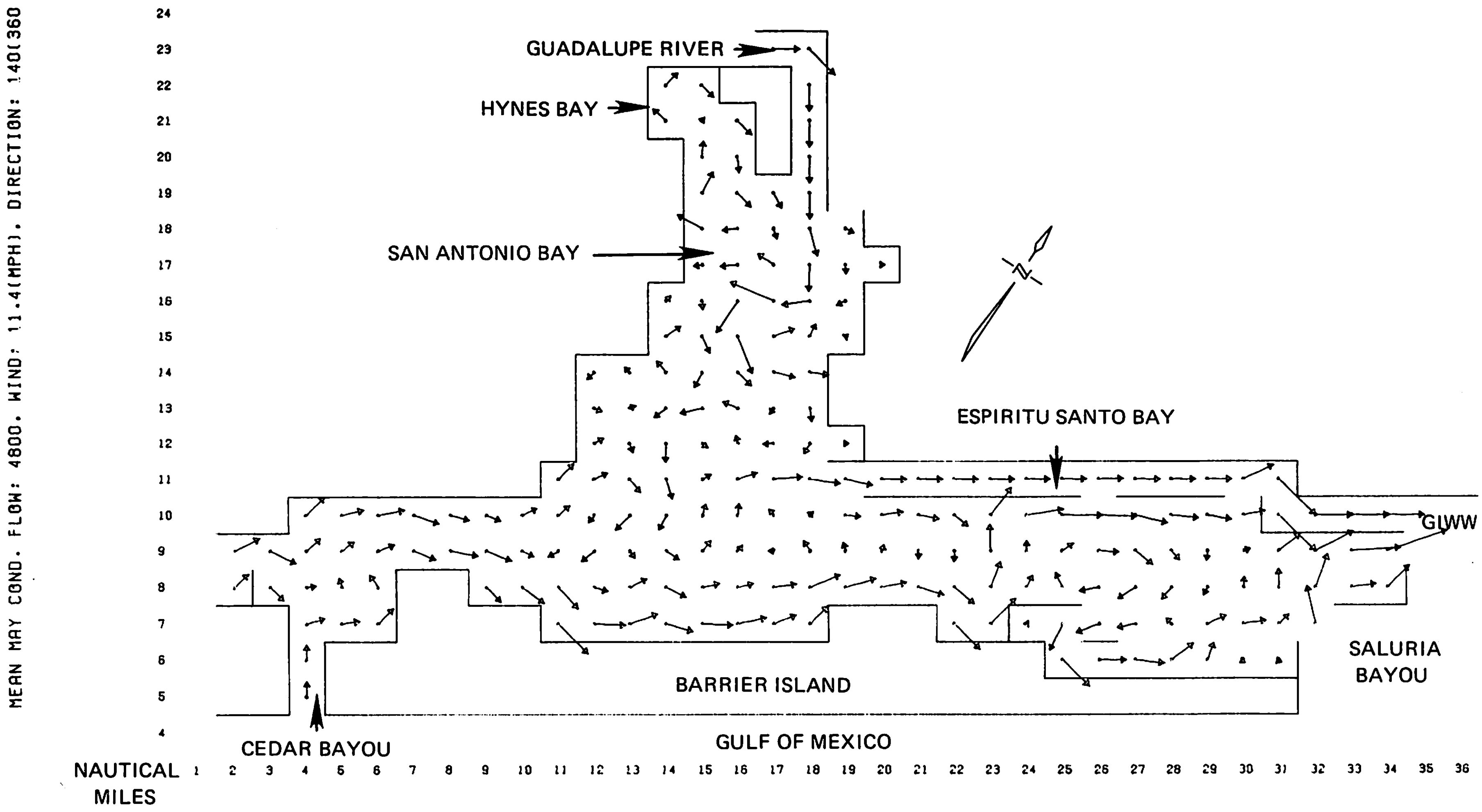

Figure 17.–Simulated Net Steady-State Flows in the Guadalupe Estuary Under May Average Inflow

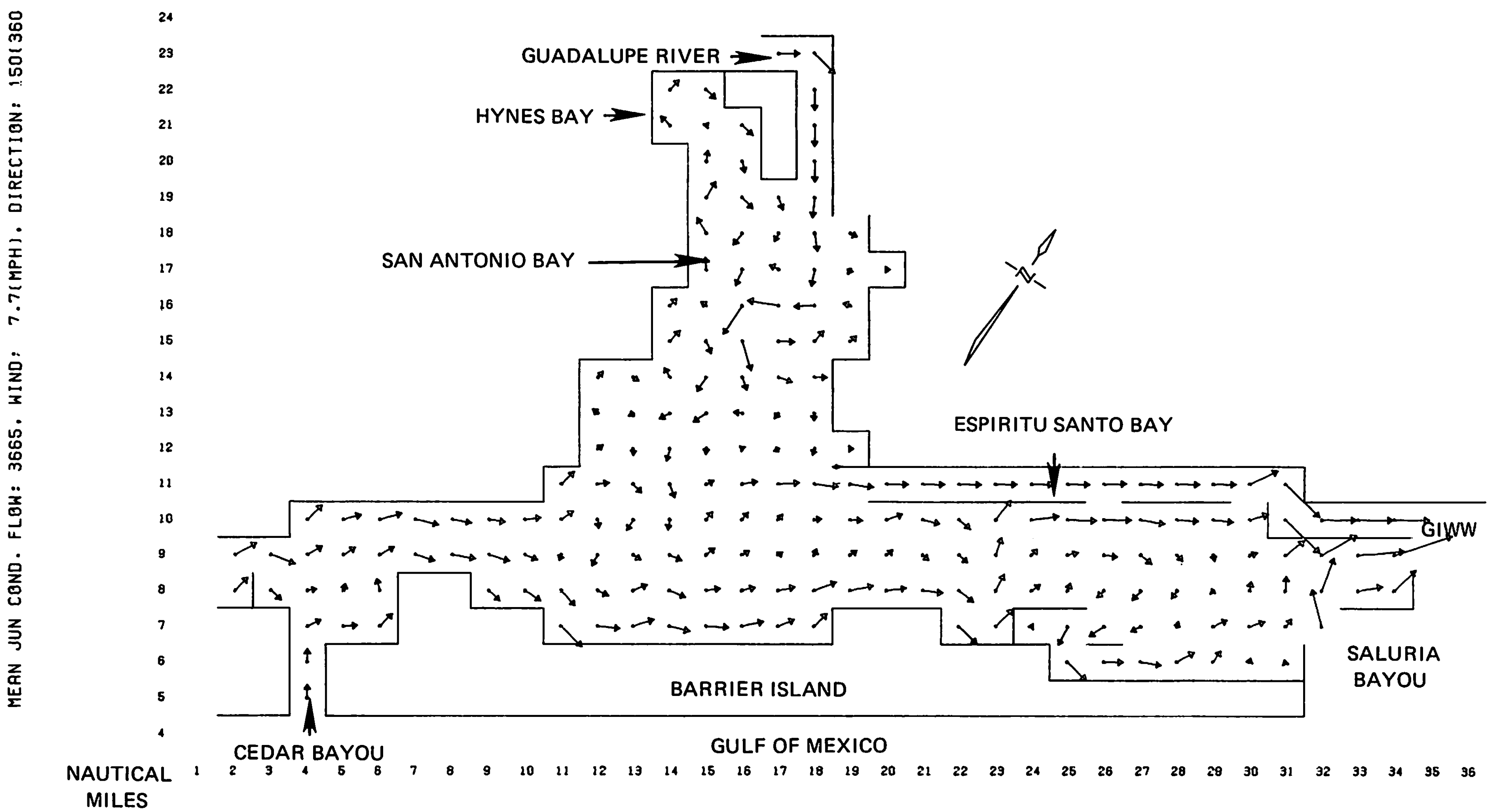

Figure 18.—Simulated Net Steady-State Flows in the Guadalupe Estuary Under June Average Inflow

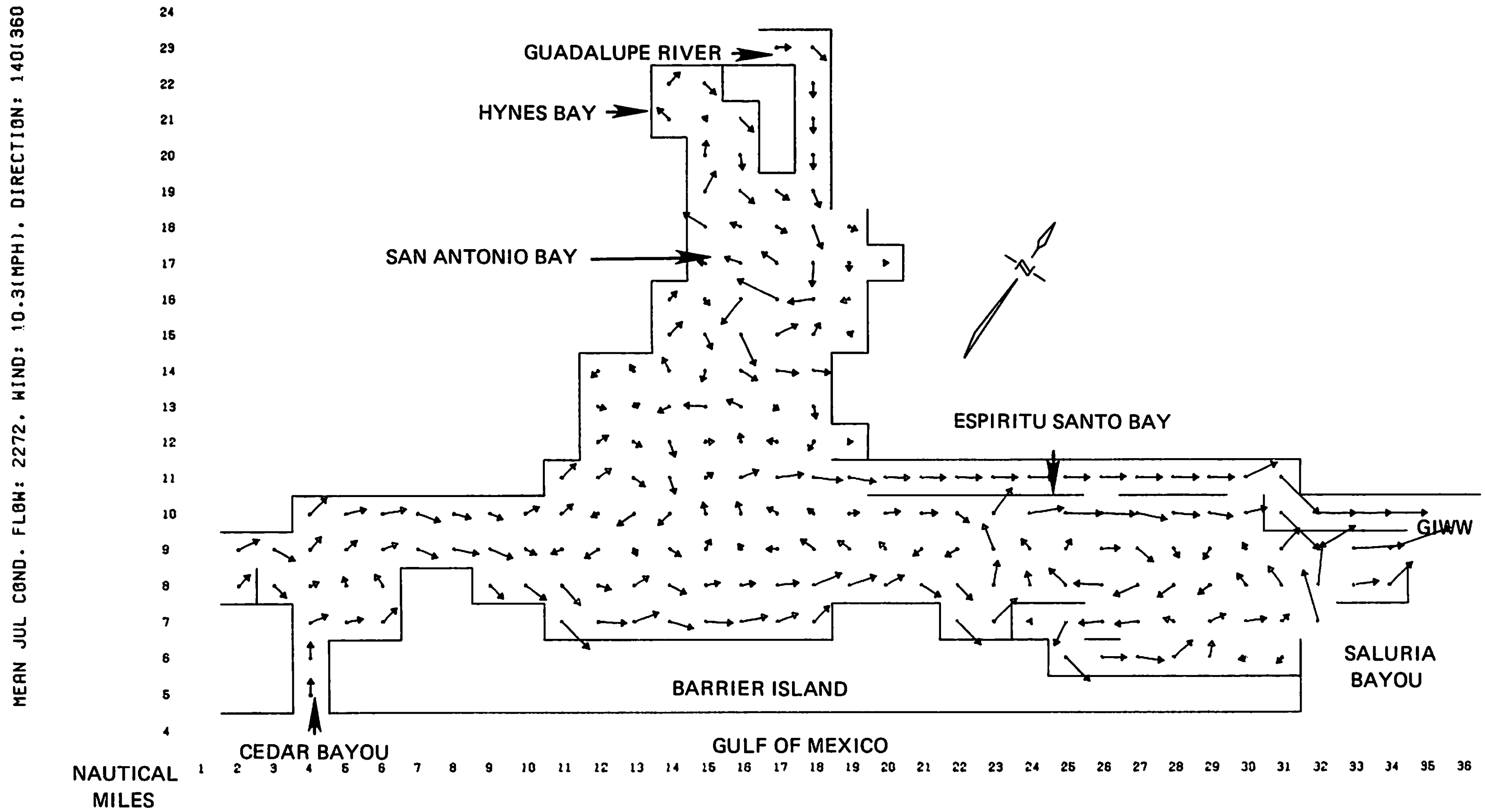

Figure 19.–Simulated Net Steady-State Flows in the Guadalupe Estuary Under July Average Inflow

Bay. Other evident eddy current circulations occurred in Hynes Bay and in the central portion of upper San Antonio Bay.

Examination of the simulated flows at the major flow exchange points indicated that net flow into the estuary occurred at each of the passes with the Gulf of Mexico (Cedar Bayou and Pass Cavallo via Saluria Bayou) and at Cedar Dugout. The passes connecting the Guadalupe and Lavaca-Tres Palacios estuaries, the Intracoastal Waterway channel and Big Bayou, had a simulated net flow out of the Guadalupe estuary.

Simulated Salinity Patterns.

The hydrodynamic simulation results were used to provide the basic flow circulation information to execute the salinity transport model for the Guadalupe estuary. The application of the salinity model was undertaken for each of the average historical monthly conditions.

An evaluation of the simulated monthly salinities in the Guadalupe estuary (Figures 25 through 36) revealed that there were a wider range of salinity patterns evident over the twelve monthly periods than there were circulation patterns. Examination of the simulated salinities in the estuary revealed that the monthly salinity distributions could be divided into four monthly groups having similar characteristics: November, December, January and February; March and August; April, May, July, September and October; and June. The pattern of salinities evident in each of these groupings are discussed in the following paragraphs.

(1) Simulated November, December, January and February Salinity Patterns Under Average Inflow Conditions.

The salinities simulated by the numerical salinity transport model for the months of November, December, January and February ranged from below 10 parts per thousand (ppt) to over 30 ppt in the Guadalupe estuary (Figures 35, 36, 25 and 26). Mesquite Bay had simulated salinities of over 30 ppt in its area adjacent to Cedar Bayou. The salinity decreased from Mesquite Bay into San Antonio Bay, where concentrations in the lower portion of the latter bay were between 15 and 20 ppt. Simulated salinities in Hynes and upper San Antonio Bay were less than 15 ppt with Guadalupe Bay and Mission Lake having concentrations of less than 10 parts per thousand. Salinities increased from San Antonio Bay into Espiritu Santo Bay where the salinities ranged from 20 ppt at its western limits to 30 ppt at its extreme eastern end near Saluria Bayou.

(2) Simulated March and August Salinity Patterns Under Average Inflow Conditions.

The simulated salinities for the months of March and August resulted in similar salinity distributions over the Guadalupe estuary (Figures 27 and 32). Some differences, however, occurred between the two monthly simulations for Mesquite Bay. The simulated concentrations in March for that bay resulted in salinities of over 30 ppt whereas the simulated salinities in August gave concentrations of between 25 and 30 ppt. For both months, salinities in the San Antonio Bay were simulated to be between 20 and 25 ppt in the lower half of the bay with salinities less than 20 ppt in the remainder. Guadalupe Bay and Mission Lake had simulated salinities of less than 10 ppt. The salinities in Espiritu Santo Bay ranged between 20 and 25 ppt in its western third to over 30 ppt in its eastern third.

(3) Simulated April, May, July, September and October Salinity Patterns Under Average Inflow Conditions.

The distribution of salinities over the Guadalupe estuary showed definite similarities for the months of April, May, July, September and October (Figures 28, 29, 31, 33 and 34). The only significant variation in the simulated salinity patterns in the estuary between these months occurred in Espiritu Santo Bay. During the months of April and July the salinity in the western half of Espiritu Santo Bay was simulated to be greater than 20 ppt whereas in the other three months the salinities were less than 20 parts per thousand. The extreme eastern end of Espiritu Santo Bay had simulated salinities of over 25 ppt for each of the five months.

In all of these months Mesquite Bay had simulated salinities ranging from 20 to 25 ppt. Salinities of lower concentrations occurred in San Antonio Bay with the lower half of the bay having concentrations of between 15 and 20 ppt whereas the upper portion of the bay had concentrations less than 15 ppt. The salinity in Hynes Bay was simulated to be between 10 and 15 ppt. The area in San Antonio Bay immediately adjacent to Guadalupe Bay had simulated salinities of less than 10 ppt as did Guadalupe Bay and Mission Lake.

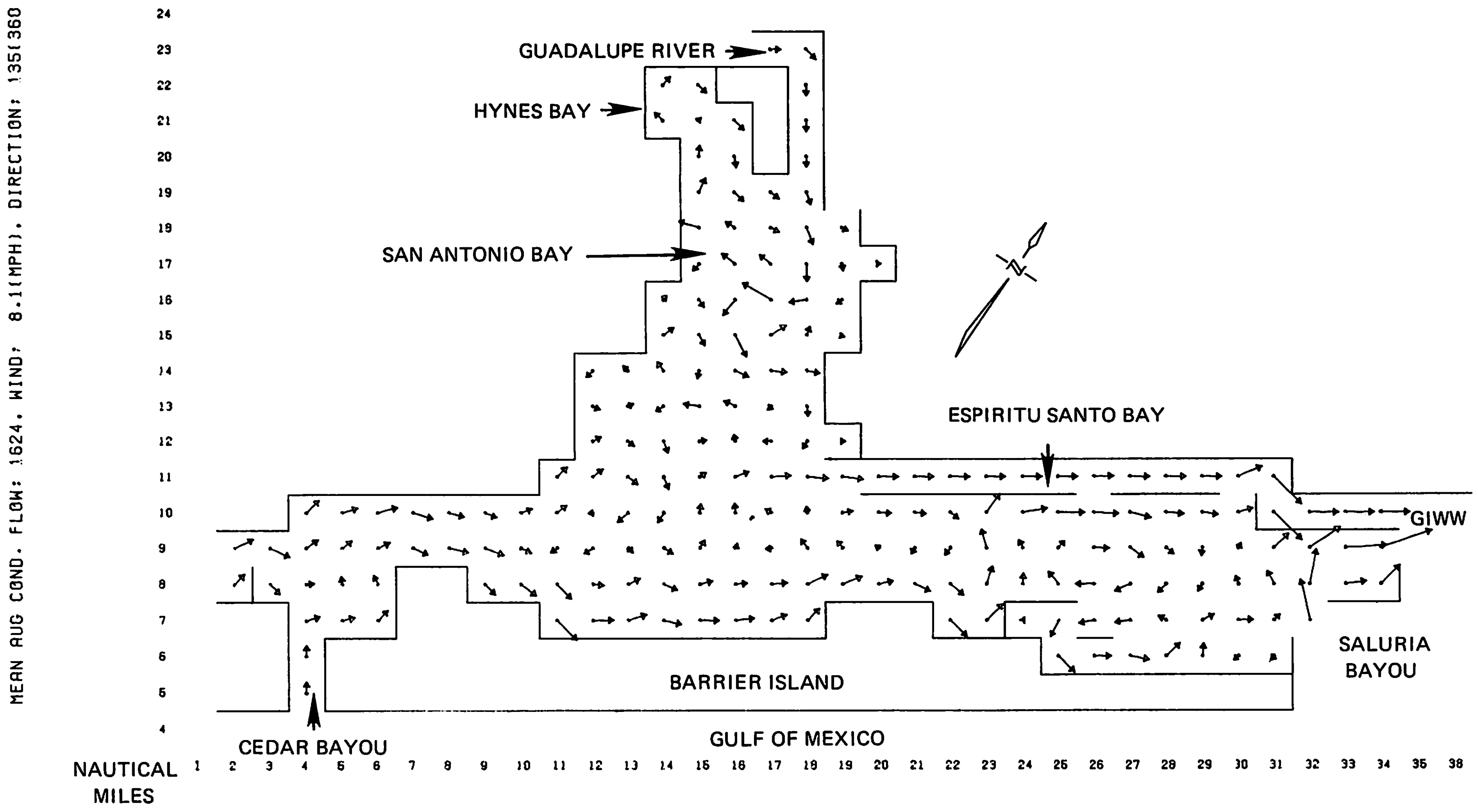

Figure 20.—Simulated Net Steady-State Flows in the Guadalupe Estuary Under August Average Inflow

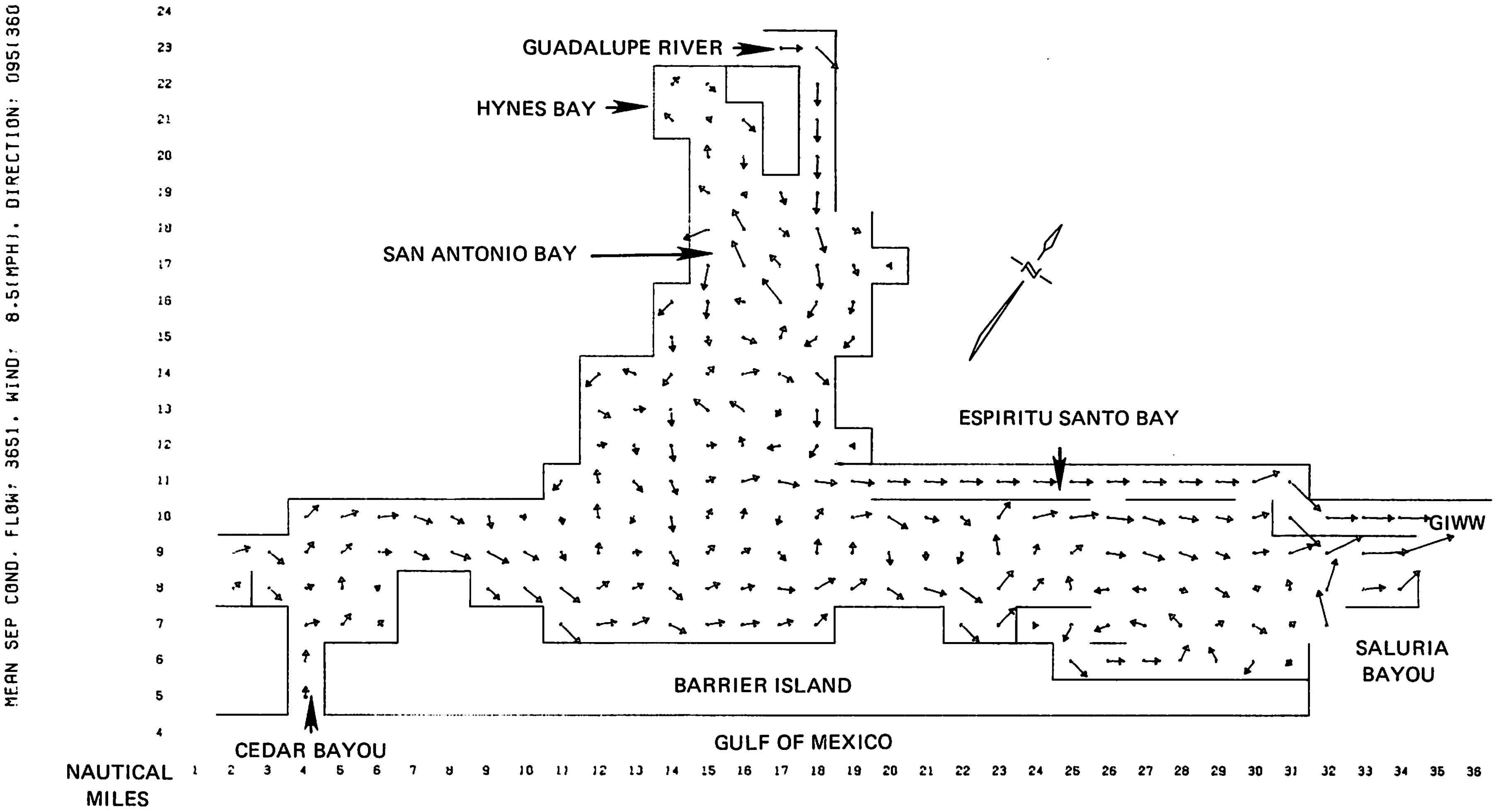

Figure 21.—Simulated Net Steady-State Flows in the Guadalupe Estuary Under September Average Inflow

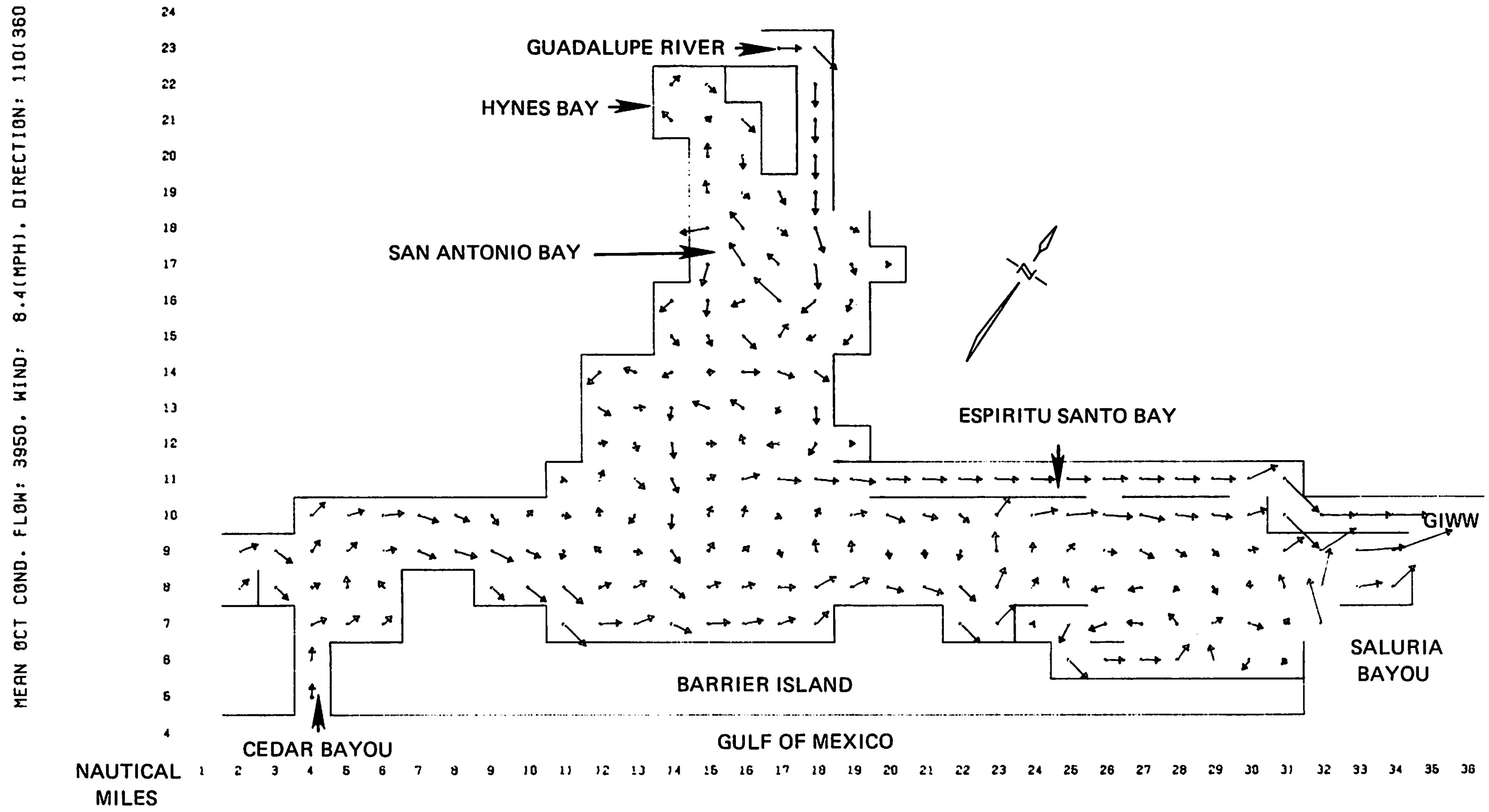

Figure 22.—Simulated Net Steady-State Flows in the Guadalupe Estuary Under October Average Inflow

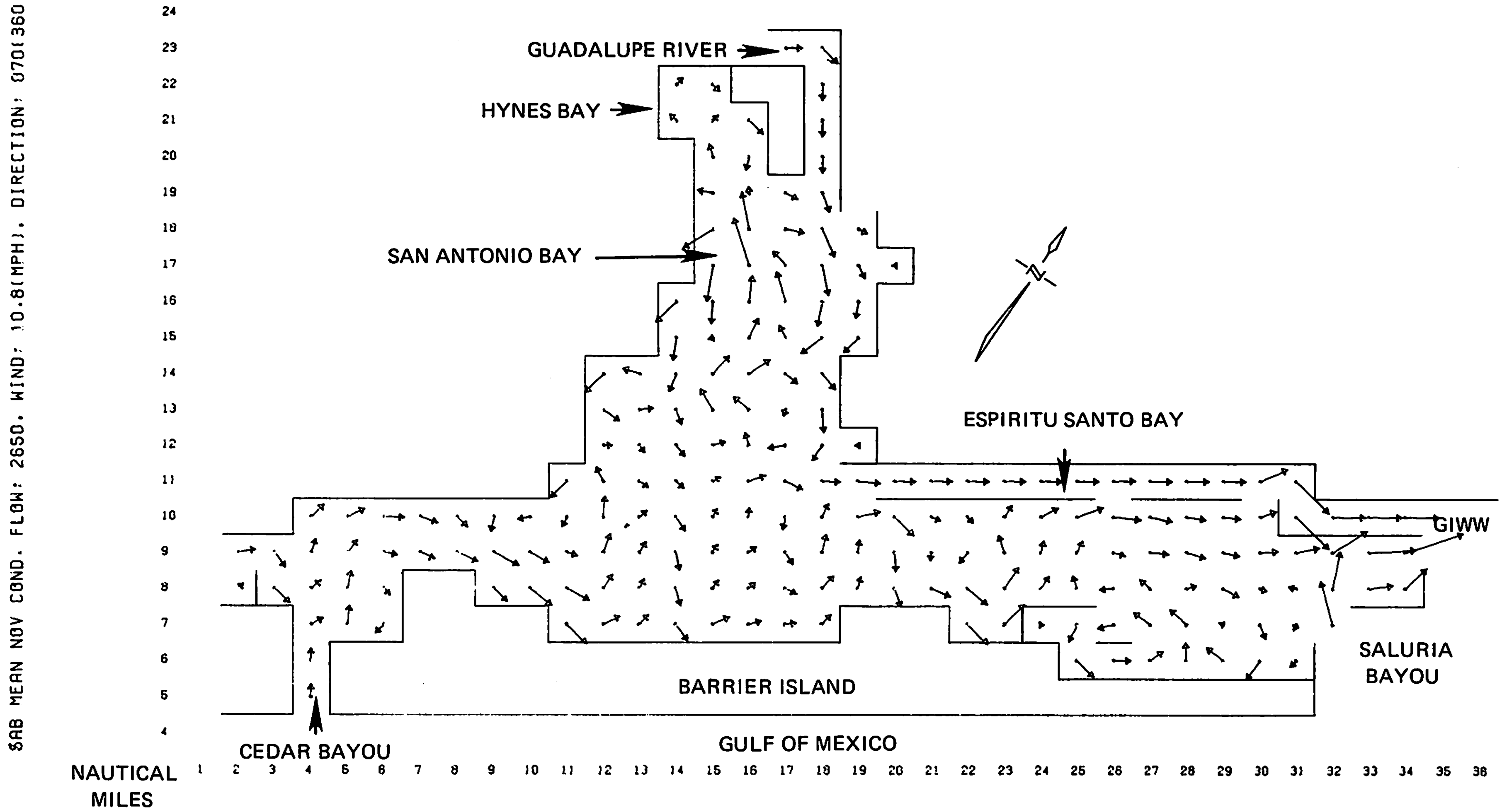

Figure 23.—Simulated Net Steady-State Flows in the Guadalupe Estuary Under November Average Inflow

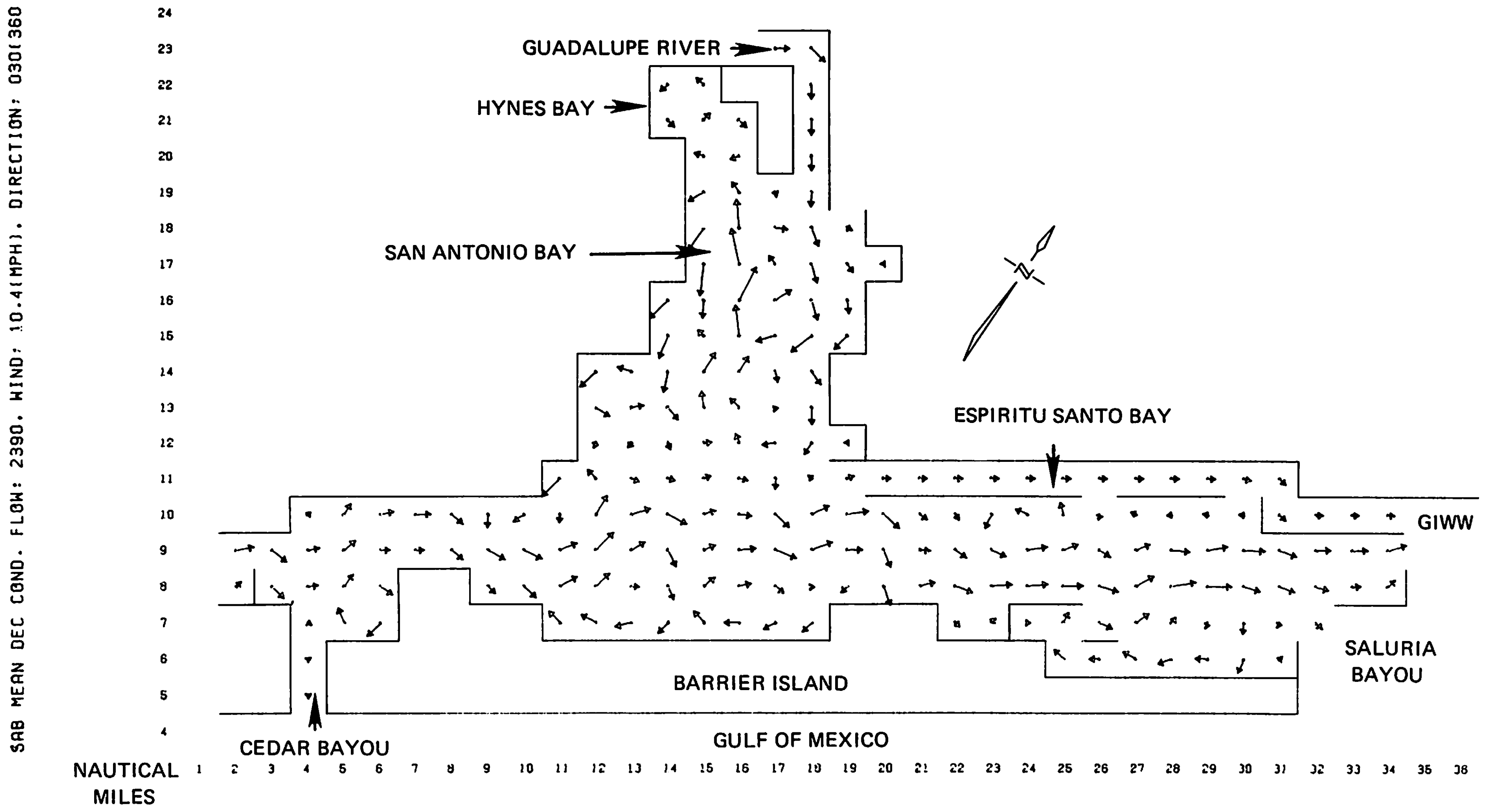

Figure 24.—Simulated Net Steady-State Flows in the Guadalupe Estuary Under December Average Inflow

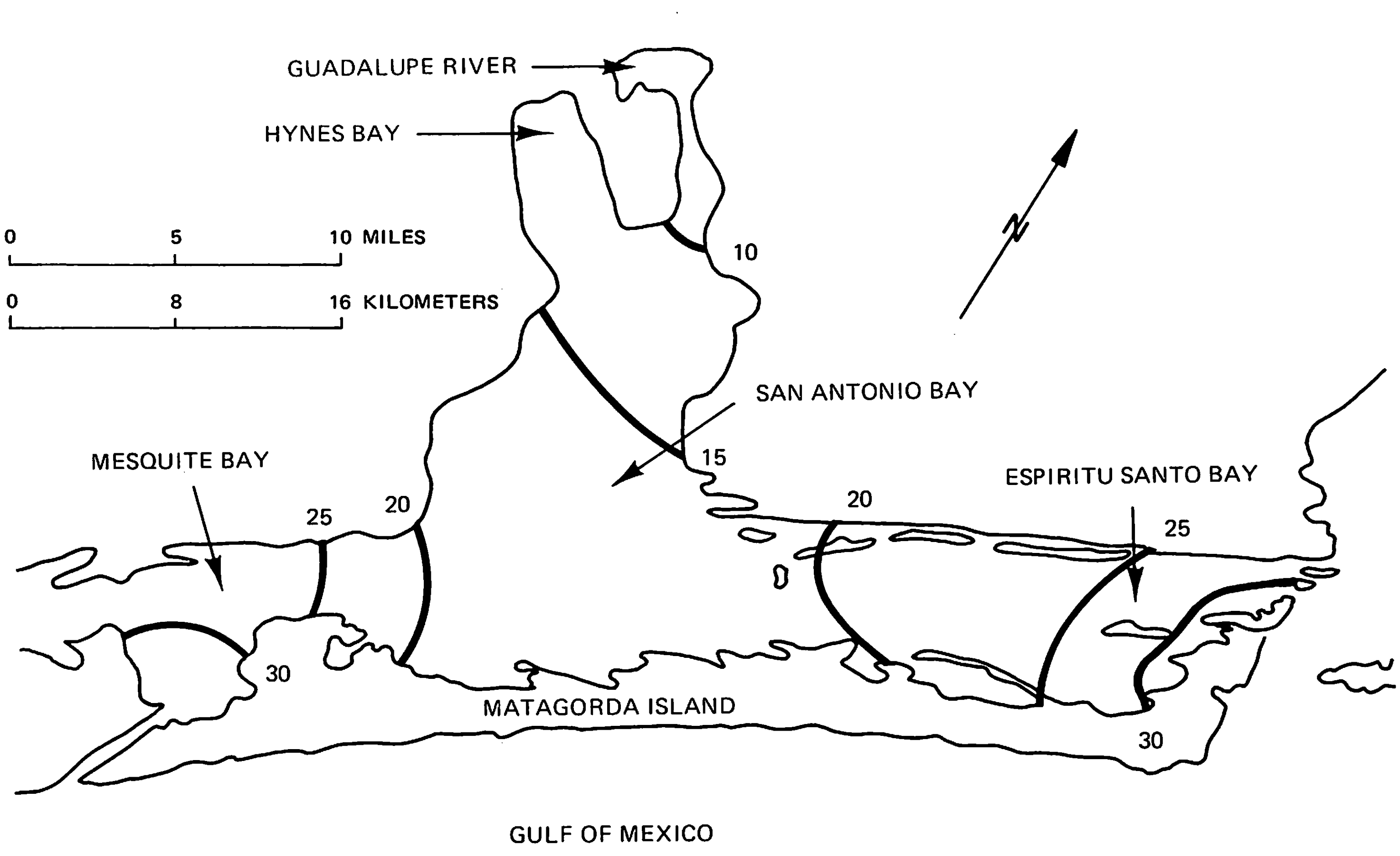

Figure 25.—Simulated Salinities in the Guadalupe Estuary Under January Average Inflow (ppt)

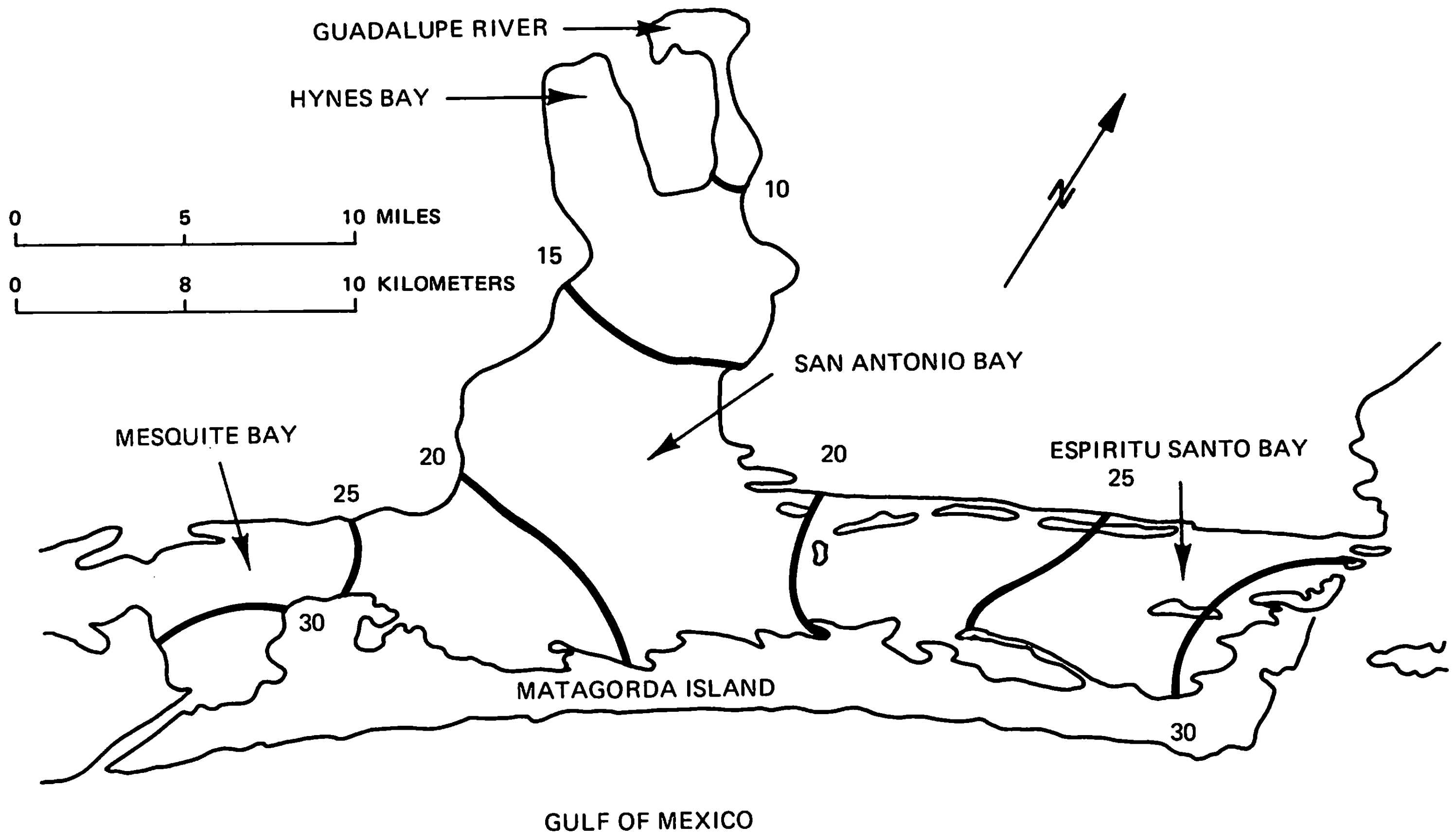

Figure 26.—Simulated Salinities in the Guadalupe Estuary Under February Average Inflow (ppt)

(4) Simulated June Salinity Patterns Under Average Inflow Conditions.

The simulated salinities for the month of June had the lowest concentrations for the Guadalupe estuary of any of the monthly periods (Figure 30). The simulated salinities in the estuary did not exceed a concentration of 25 ppt. The concentration in Mesquite Bay was between 20 and 25 ppt. The estuarine waters became less saline in San Antonio Bay with concentrations of between 15 and 20 ppt in both the extreme western and eastern ends. The great majority of San Antonio Bay had simulated concentrations of less than 15 ppt with approximately the upper 20 percent of the bay having concentrations of under 10 ppt.

Salinities in Espiritu Santo Bay ranged from 15 ppt at its western boundary with San Antonio Bay to slightly over 20 ppt at its extreme eastern end.

NUTRIENT PROCESSES

Summary

Nutrient contributions to the Guadalupe estuary are derived primarily from: (1) river inflow; (2) local ungaged runoff; and (3) biogeochemical cycling in deltaic and peripheral salt or brackish water marshes. In addition, nutrients may be contributed by point source discharges of 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 bay/estuary system into the Gulf. This is an over-simplification since a combination of forces such as freshwater inflows, winds, currents, and biological activity all contribute in one way or another to nutrient export from the estuarine system.

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

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

Nutrient Loadings

Nutrient concentrations in the Guadalupe and San Antonio Rivers at Victoria and Goliad respectively were calculated for the period of data available from streamflow and water quality data provided by the USGS Water Resources Data for Texas, 1968 through 1973, and presented in an unpublished draft report prepared previously by the Texas Department of Water Resources staff (31). A subsequent update of this information using 1974 through 1976 data from the USGS source was recently completed (31). The data were reduced and tabulated to a form comparable with the earlier report. Nutrient concentrations (carbon, nitrogen, and phosphorous) from the 1968 through 1973 data were compared with concentrations observed during 1974 through 1976. This comparison is presented in Tables 3, 4, 5, and 6. The 1968 through 1973 results show no apparent significant seasonal variation in carbon levels but a definite relationship exists between inorganic carbon concentrations and streamflow. Inorganic carbon occurs in an equilibrium between carbonate or bicarbonate ions and carbon dioxide in accordance with the equation:

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

This equilibrium is dependent on pH. The H_2CO_3 (carbonic acid) form predominates at pH levels less than 4.5. The CO_3^{-2} (carbonate) is not found unless pH levels are greater than 8.3. Since pH values in both the Guadalupe and San Antonio Rivers are usually between 7.0 and 8.0, HCO^-_3 (bicarbonate) is the dominant species. As streamflow increases, inorganic carbon concentrations decrease. Most inorganic carbon can be attributed to the groundwater contribution that either originates or flows through the limestone aquifers in and around the Edwards Plateau. This is a principal source of the dissolved bicarbonate ion. At low river flows, a

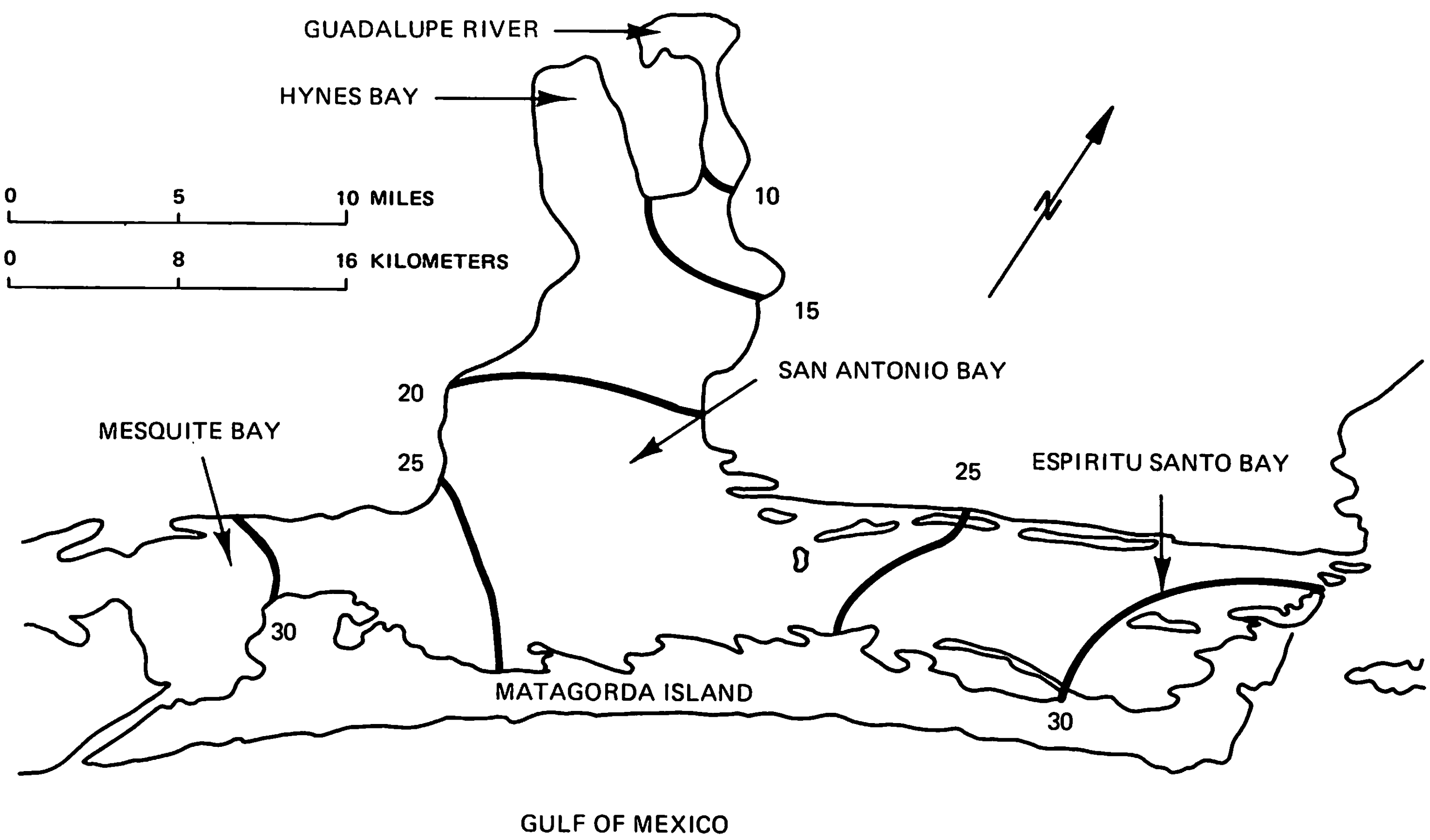

Figure 27.–Simulated Salinities in the Guadalupe Estuary Under March Average Inflow (ppt)

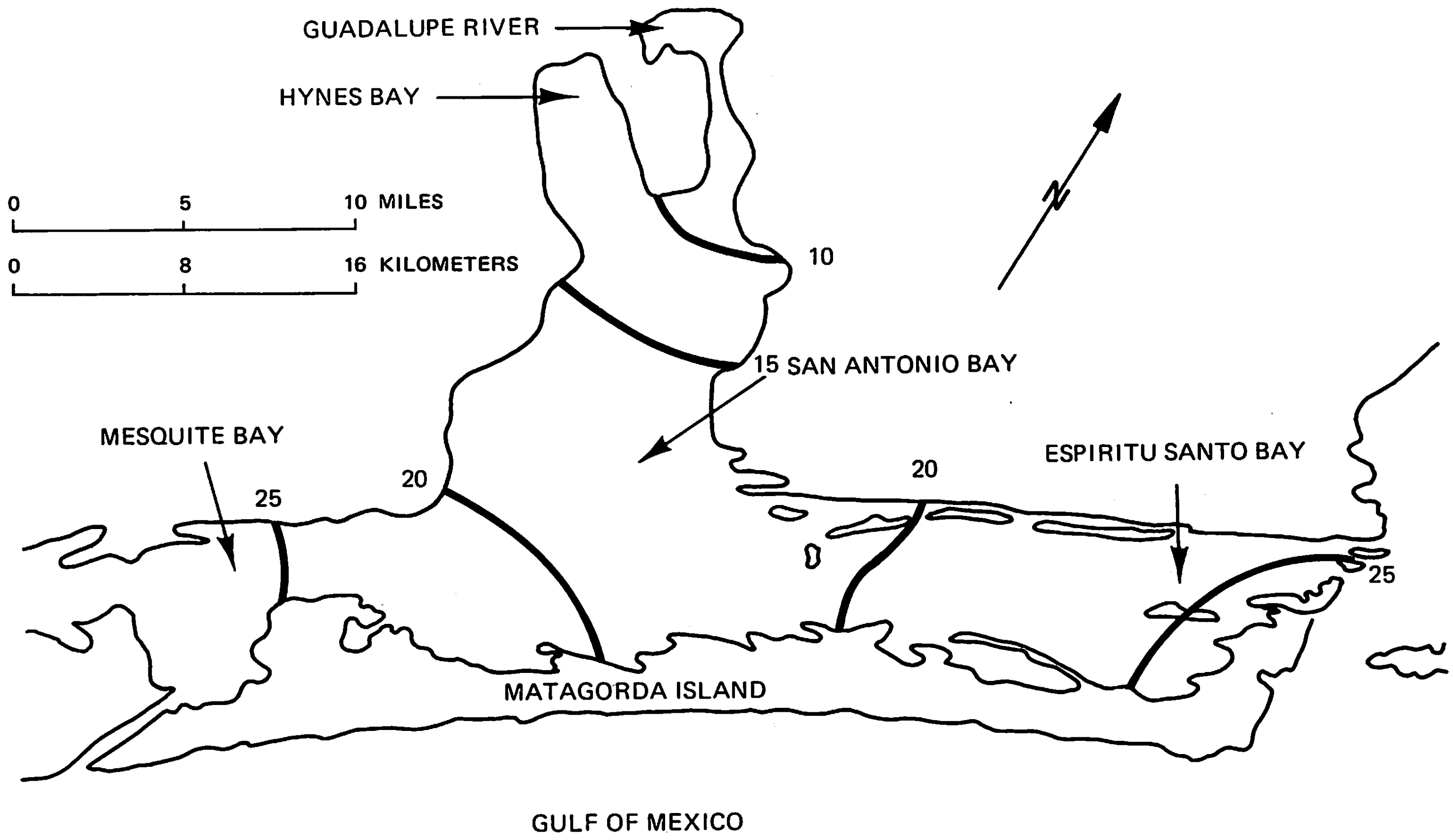

Figure 28.—Simulated Salinities in the Guadalupe Estuary Under April Average Inflow (ppt)

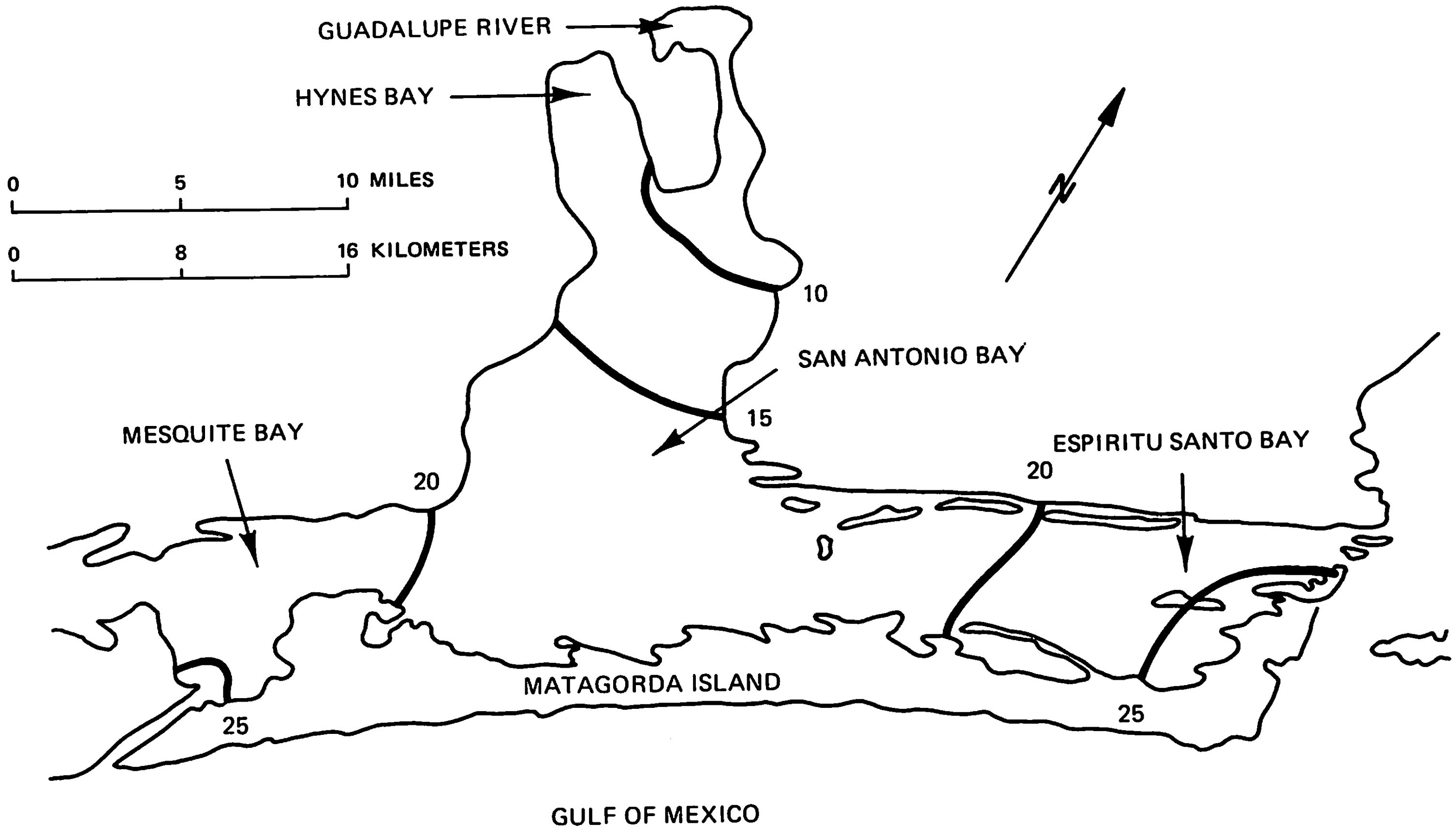

Figure 29.—Simulated Salinities in the Guadalupe Estuary Under May Average Inflow (ppt)

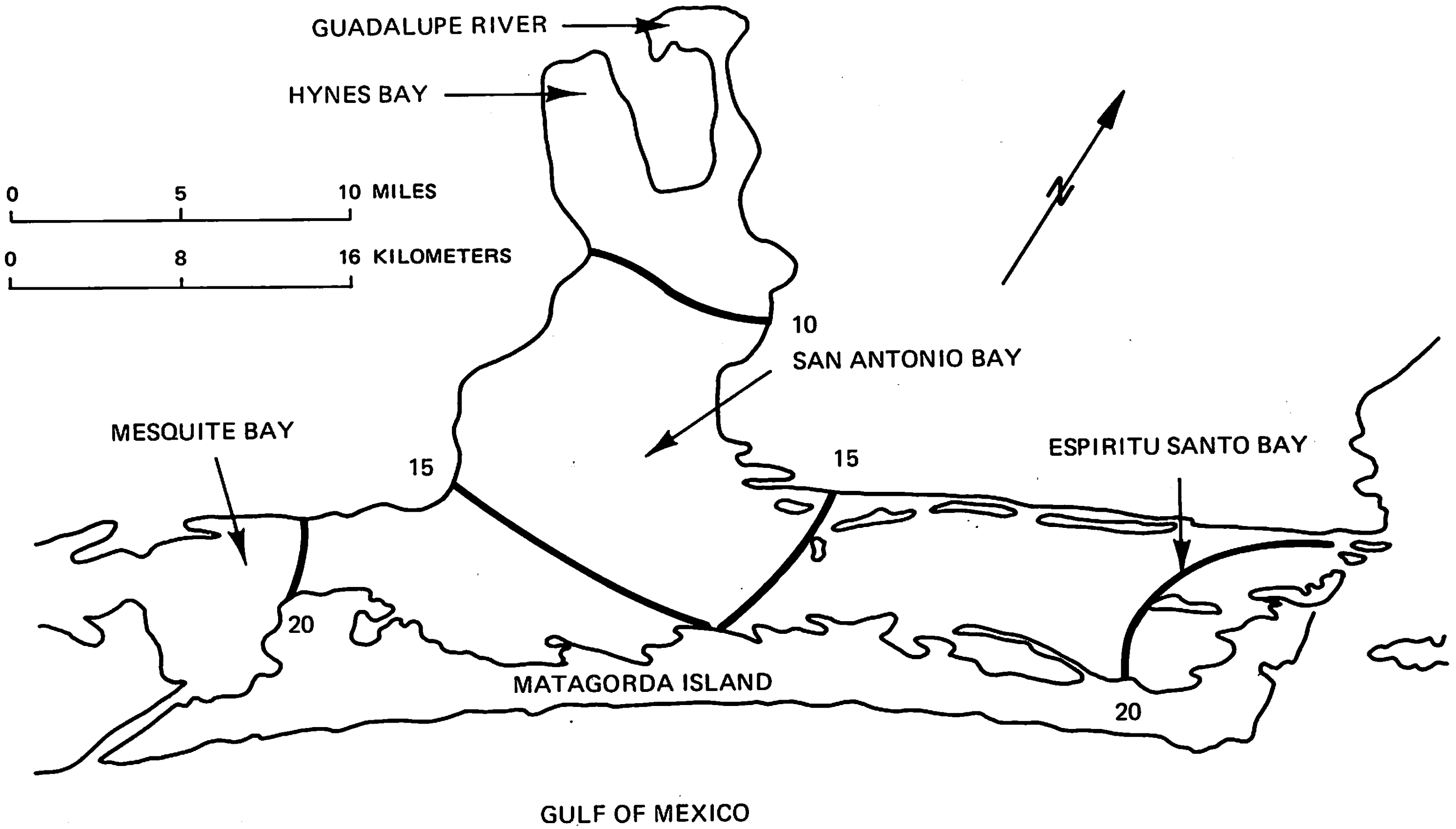

Figure 30.—Simulated Salinities in the Guadalupe Estuary Under June Average Inflow (ppt)

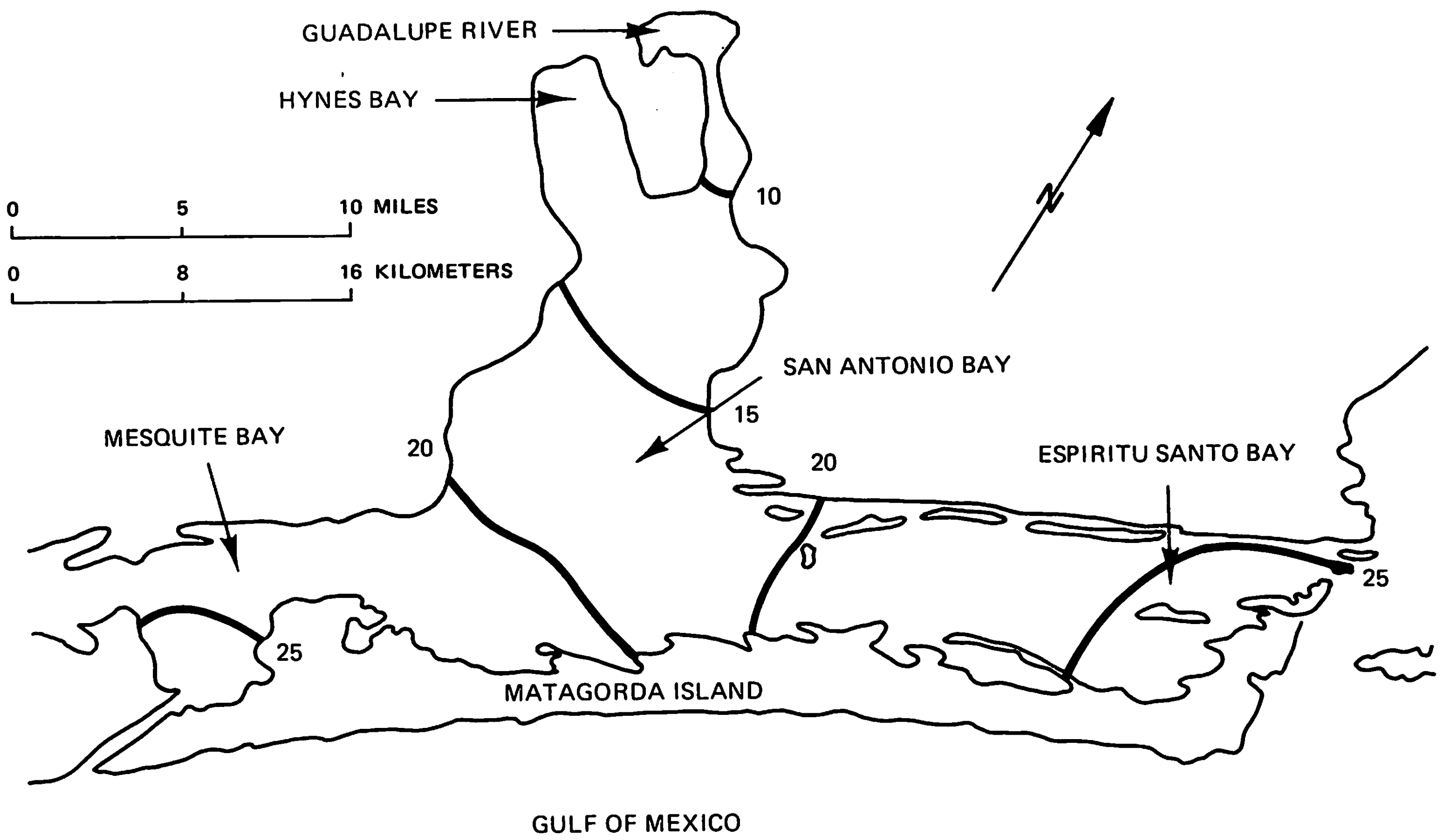

Figure 31.—Simulated Salinities in the Guadalupe Estuary Under July Average Inflow (ppt)

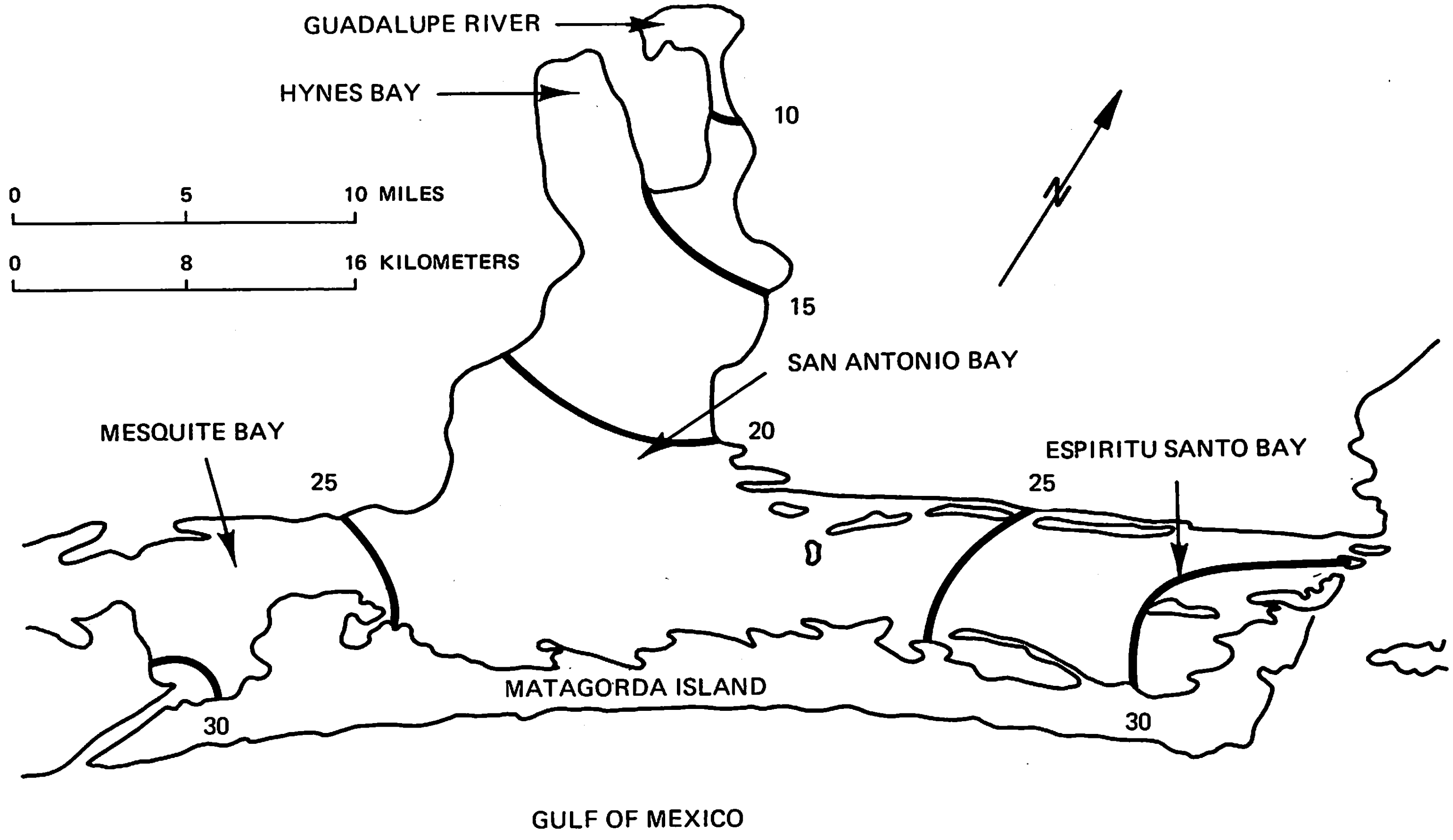

Figure 32.—Simulated Salinities in the Guadalupe Estuary Under August Average Inflow (ppt)

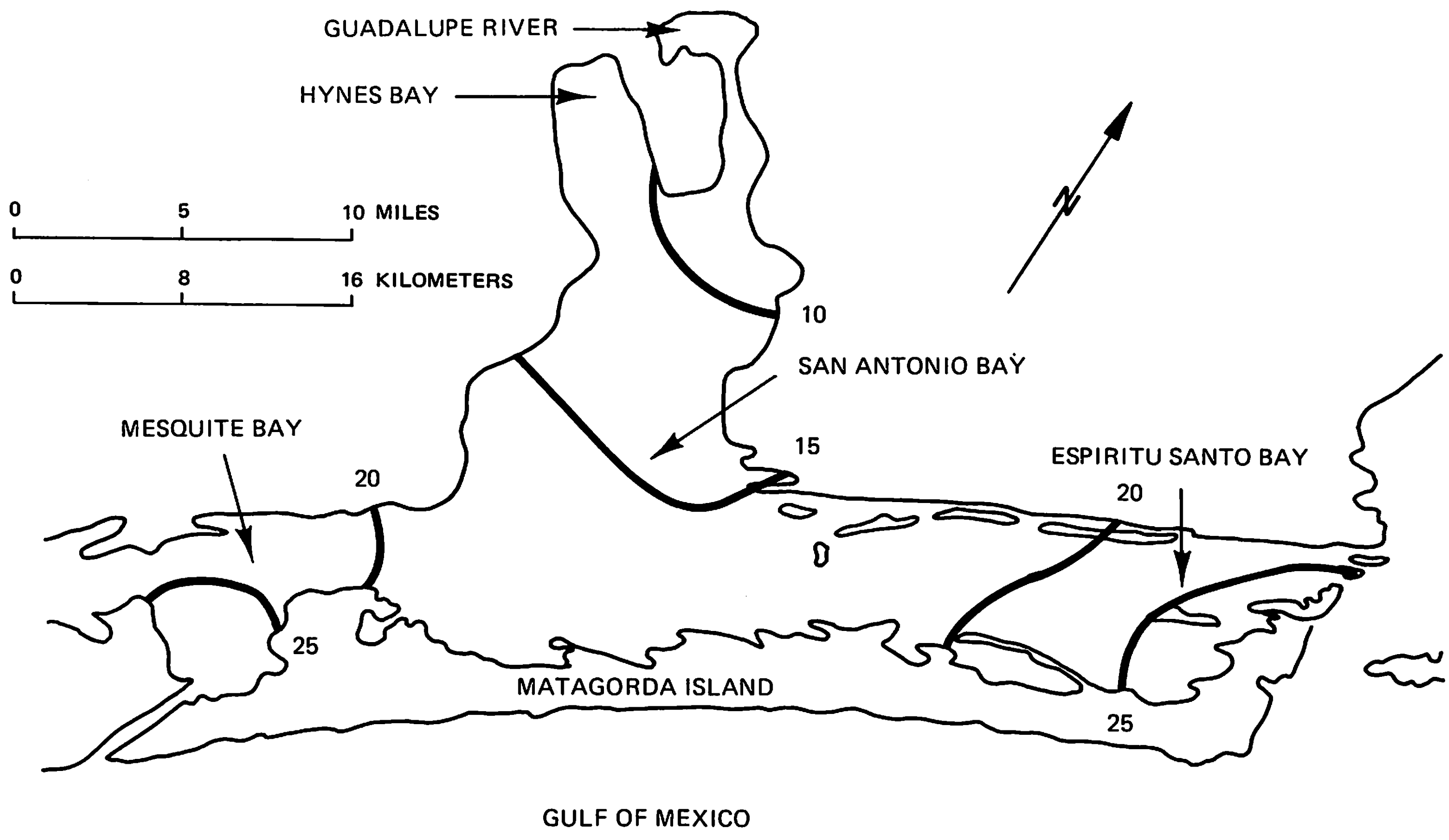

Figure 33.—Simulated Salinities in the Guadalupe Estuary Under September Average Inflow (ppt)

greater percentage of the water is contributed by the aquifers. At higher flows, resulting from increased rainfall and surface runoff, the percentage of total flow contributed by the aquifers decreases. As the bicarbonate ion contributed by groundwater is diluted, the inorganic carbon concentrations decrease. Inorganic carbon concentrations ranged from 8.4 to 15.4 mg/l higher during 1974 through 1976 than in 1968 through 1973 (Table 3). No detailed explanation of this phenomenon will be attempted at this time.

Table 3.—Carbon Levels* in the San Antonio and Guadalupe Rivers at the Goliad and Victoria Gages (mg/l)

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

*As total C based on CO_3-C and HCO_3-C concentrations

There is a scarcity of total organic carbon data collected by the USGS. Available data show total organic carbon (TOC) concentrations generally less than 10-12 ppm. Steed (27) attempted to identify the sources of particulate and dissolved organic carbon in the Guadalupe and San Antonio Rivers as well as San Antonio Bay. He noted that particulate organic carbon (POC) concentrations in the Guadalupe River roughly followed patterns of river discharge; that is, POC concentrations were generally higher at peak river discharges. The same pattern was observed for POC concentrations in the San Antonio River. Dissolved organic carbon (DOC) concentrations were similar to POC concentrations in the Guadalupe River but roughly half the observed POC concentrations in the San Antonio River. The San Antonio River had higher POC and DOC concentrations than did the Guadalupe but the total organic carbon (TOC) contributed was less since the Guadalupe River contributed 96.8 percent of the total river discharge to San Antonio Bay during the study. Below the confluence of the two rivers and Elm Bayou the POC concentrations ranged from 1.33 to 8.0 mg/l and averaged 3.77 mg/l. DOC concentrations ranged from 1.28 to 6.9 mg/l, averaging 2.95 mg/l during the study period. Based on the combined river discharge rates of gaged freshwater inflows from the Guadalupe and San Antonio River basins, DOC and POC loading to San Antonio Bay was 20.67 x 10^6 kg/yr (56,630 kg/day) and 26.84 x 10^6 kg/yr (73,534 kg/day), respectively. When one combines the DOC and POC concentrations reported by Steed (27), the total TOC values are comparable to those few data points available from the USGS.

Organic carbon does not, as a rule, stimulate primary productivity. Under certain conditions it can be used in conjunction with other data such as chlorophyll *a* concentrations as an indicator of the amount of primary productivity occuring in an ecosystem. Atmospheric or dissolved carbon dioxide (co_2) is the main source of carbon fixed and converted to vegetative biomass by photosynthetic processes responsible for primary production.

Analysis of USGS water quality data show that inorganic nitrogen levels were lowest in summer and fall and highest in the winter months during the 1968 through 1973 period (Table 4). A similar trend, not as distinct, was noted for the 1974 through 1976 data. The data also show a decrease in concentration during higher flows, probably due to increased dilution of nitrogen sources, although absolute quantities contributed are larger during high inflow events.

Organic nitrogen contributions are similar for the two periods, 1968 through 1973 and 1974 through 1976 (Table 5). If a trend exists, it is for increased concentrations with increased streamflow. This can be attributed to organic nitrogen of detrital origin being introduced into the system during periods of high runoff.

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

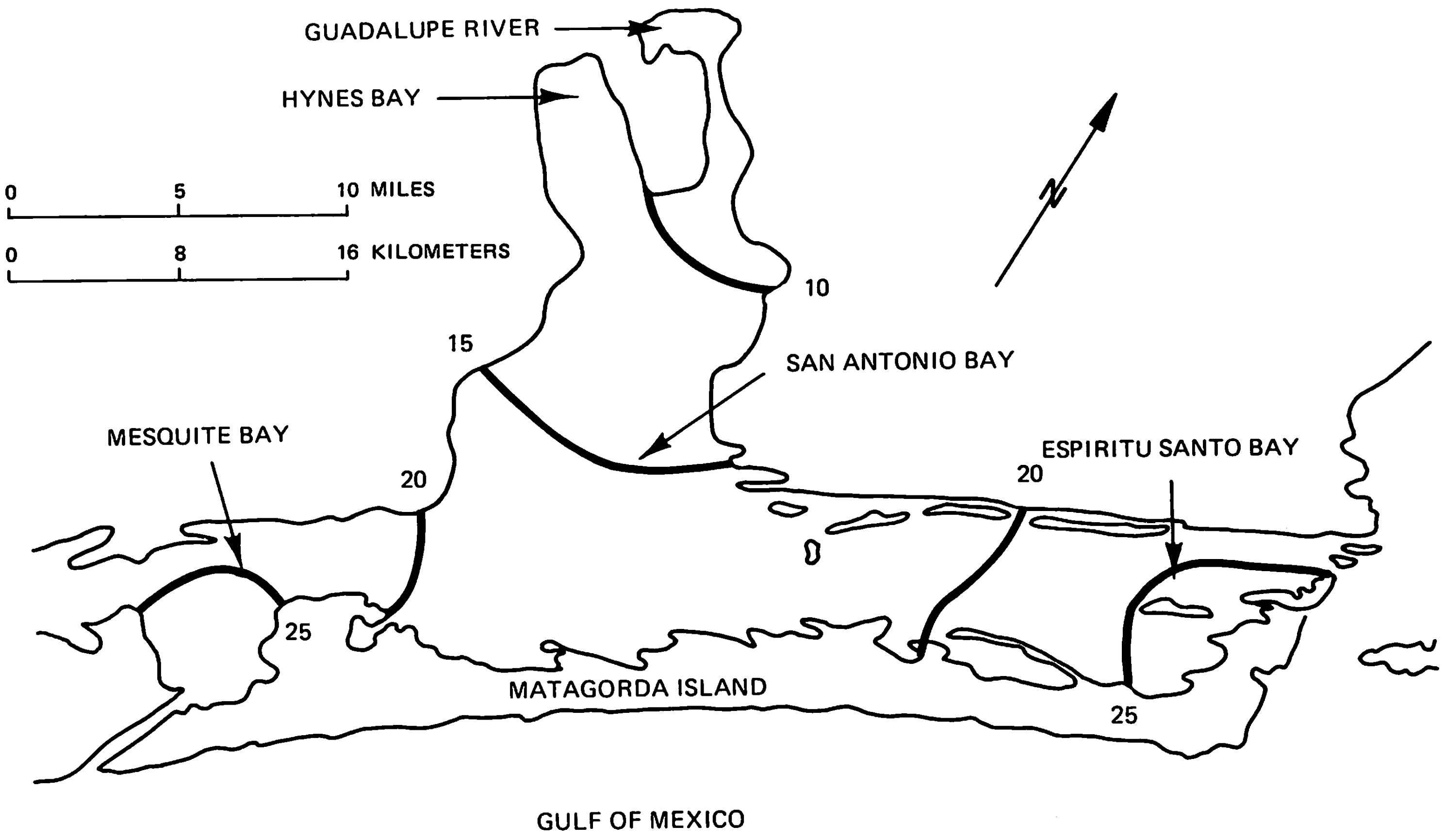

Figure 34.—Simulated Salinities in the Guadalupe Estuary Under October Average Inflow (ppt)

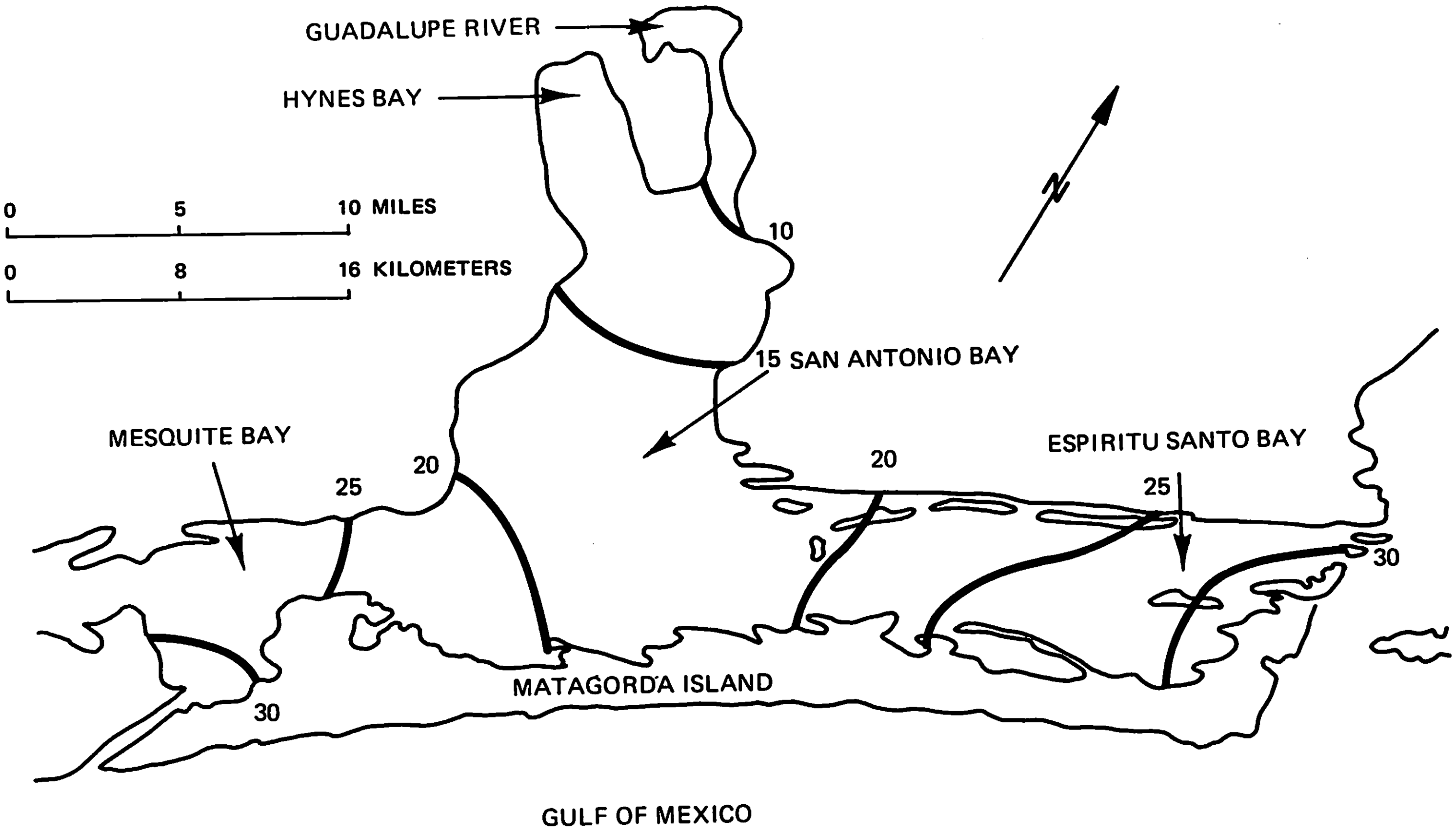

Figure 35.—Simulated Salinities in the Guadalupe Estuary Under November Average Inflow (ppt)

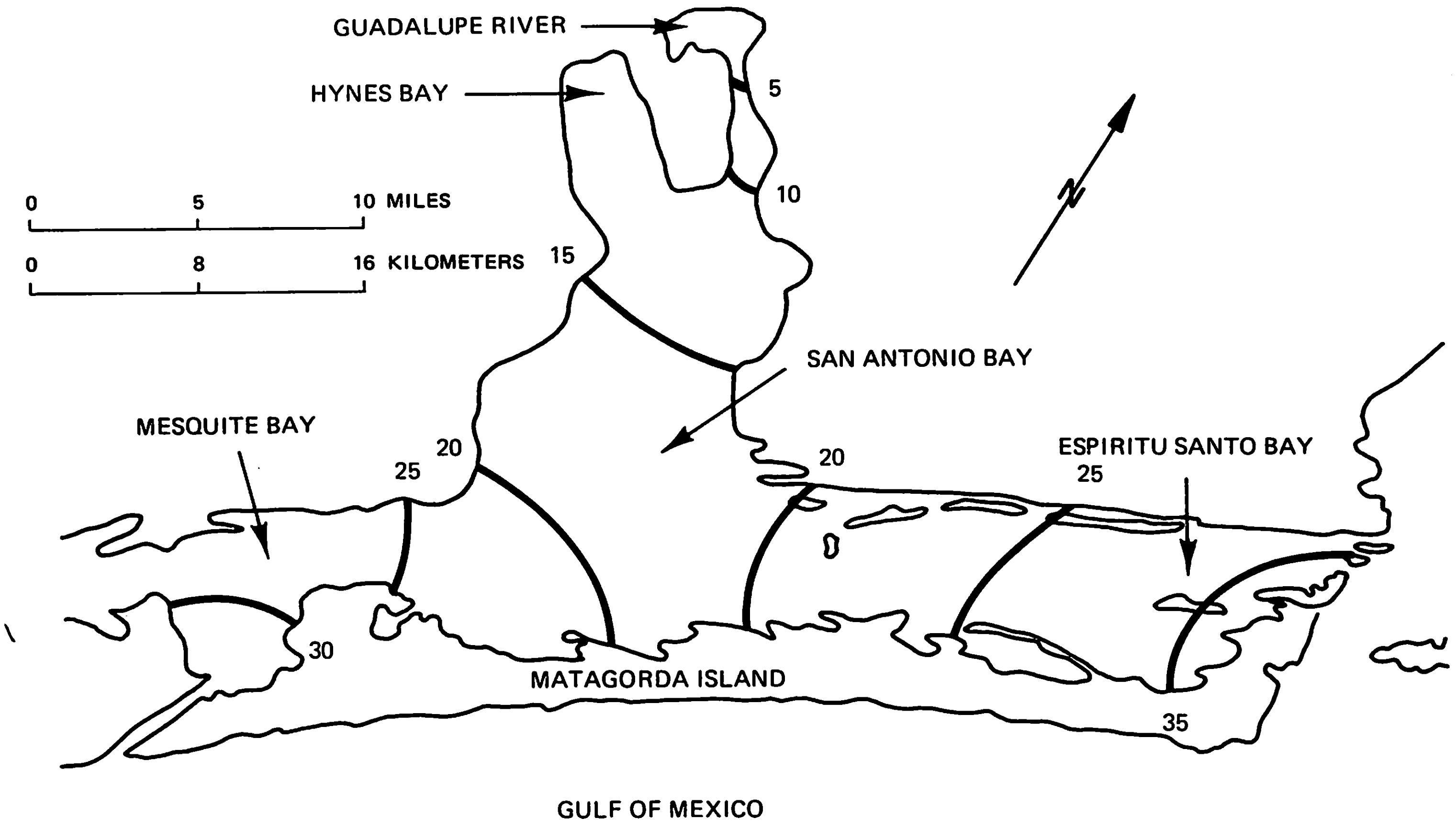

Figure 36.—Simulated Salinities in the Guadalupe Estuary Under December Average Inflow (ppt)

Table 4.—Inorganic Nitrogen Levels* in the San Antonio and Guadalupe Rivers at the Goliad and Victoria Gages (mg/l)

San Antonio River

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

Guadalupe River

Season or Months	Jan-April		May-Sept		Oct-Dec	
Flow Range (cfs)	**68-73**	**74-76**	**68-73**	**74-76**	**68-73**	**74-76**
0-500	2.0		0.6		0.6	
500-1,000	1.5	1.1	0.7	1.3	0.6	
1,000-5,000	0.9	1.1	0.9	1.1	0.6	0.9
5,000-10,000	0.5	0.6	0.8	0.8	0.6	
10,000-up	0.3		0.5		0.6	

***As total N based on NO_3-N, NO_2-N, and NH_4-N concentrations**

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

Data reduction and computation revealed that the mean monthly discharge of the Guadalupe River measured at Victoria averaged 73 percent of the total measured discharge from the Guadalupe and San Antonio Rivers (Tables 7, 8, 9). Even though the Guadalupe River contributes the majority of the flow, the San Antonio River contributes the larger percentage of the total amounts of inorganic nitrogen and total phosphorus (Table 10). These are nutrients of great concern as they directly stimulate biological productivity. The contributions of organic nitrogen, as discussed earlier, are dependent on available detritus and runoff necessary to introduce it into the system.

Table 5.—Organic Nitrogen Levels in the San Antonio and Guadalupe Rivers at the Goliad and Victoria Gages (mg/l)

San Antonio River

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

Guadalupe River

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

Inorganic carbon loading, since it is based on bicarbonate ion concentrations, more nearly reflects the relative percentages of water contributed from each watershed. Total nutrient loading based on 1974 through 1976 data in kilograms/day are presented in Table 11 to give the reader an illustration of the potential amount of nutrients that can be contributed by the watershed of each contributing river basin. However, the reader is cautioned that the data of Table 11 are taken from an apparent small sample of the time series data.

Childress et al. (35) found NO_2-N (nitrite) and NO_3-N (nitrate) concentrations in the Guadalupe River at the State Highway 35 bridge to be similar to concentrations reported in the USGS data. They report a much larger range of nutrient contributions in kg/day than the 1968 through 1976 analysis of nitrogen contributions presented in Table 11. This increase in total nitrogen loading can be attributed to greater river discharges reported over the September 1971 to May 1974 study period. Total phosphorus concentrations reported by Childress et al. (35) are also similar to USGS values in Table 6. Like nitrogen, total phosphorus loading is greater than that given in Table 11 due to larger river flow volumes discharged to the estuary. The study also noted the phenomenon of highest N and P concentrations during periods of

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

San Antonio River

Season or Months	Jan-Mar Winter		April-June Spring		July-Sept Summer		Oct-Dec Fall	
Flow Range (cfs)	68-73	74-76	68-73	74-76	68-73	74-76	68-73	74-76
0-500	2.0	2.7	1.7	2.0	1.2	2.7	1.4	1.6
500-1,000	2.0	1.5	1.2	1.3	1.2	1.3	0.7	1.7
1,000-5,000	1.0	6.1	0.6	0.6	1.0	1.1	0.7	1.1
5,000-10,000	0.9		0.6		0.5		0.7	
10,000-up	0.9		0.6		0.5		0.7	

Guadalupe River

Season or Months	Jan-Mar Winter		April-June Spring		July-Sept Summer		Oct-Dec Fall	
Flow Range (cfs)	68-73*	74-76	68-73*	74-76	68-73*	74-76	68-73*	74-76
0-500								
500-1,000		0.1		0.1				
1,000-5,000		0.1		0.1		0.1		0.1
5,000-10,000		0.2		0.1		0.0		0.1
10,000-up								

*1968-1973 data for the Guadalupe at Victoria was not presented in this form in the San Antonio Bay Report

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

Marsh Vegetative Production

In essence, an estuarine marsh is a complex physical, hydrological and biogeochemical system which provides (1) shoreline stabilization, (2) "nursery" 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 processess at the base of the food web. Deltaic marshes are

Table 7.–Discharge Data–Guadalupe River at Victoria (ft^3/sec)

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

especially important since they form a vital link between the inflowing river and its resulting estuary.

The Guadalupe estuary receives its major hydrologic input from the Guadalupe River and the marshes of the Guadalupe delta. Adams (12) delineated 14 hydrological units in the Guadalupe delta and estimated above ground net primary production of the rooted vascular plants (macrophytes) at 120.4 million dry weight pounds per year (54,623.7 metric tons/year) over the 11,943 acre (4,833 hectare) study area. Annual net productivity (ANP) averaged approximately 10,100 dry weight pounds per acre (1,130 g/m^2) over the entire area, with maximum ANP in *Spartina spartinae* habitats estimated at 15,100 dry weight pounds per acre (1,700 g/m^2). Predominant macrophytes include *Spartina spartinae, S. patens, Scirpus maritimus, Distichlis spicata, Monanthochloe littoralis, Borrichia frutescens, and Phragmites communis.*

In addition, Wiersema, et. al. (13) estimated net periphyton production to range from a minimum of 1.64 dry weight pounds per acre-day (0.184 g/m^2.day) in December to a maximum 2.91 dry weight pounds per acre-day (0.326 g/m^2.day) in April. Assuming that an average 40 percent of the study area was inundated, the periphyton ANP can be estimated at approximately 3.95 million dry weight pounds (1,790 metric tons).

Although the high productivity of these deltaic marsh habitats 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 (4) 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 (28) has estimated that about 45 percent of the 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 biological productivity.

Table 8.–Discharge Data–San Antonio River at Goliad (ft^3/sec)

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

Emergent macrophytes and blue-green algae mats serve to trap nutrients and sediment as flow velocities decrease. These nutrients are incorporated into the plant biomass during growth periods and are sloughed off and exported to the bay as detrital material during seasons of plant senescence and/or periods of inundation and increased flows into the open bay.

Studies by Armstrong, et. al. (51), Dawson and Armstrong (52), Armstrong and Brown (53), and Armstrong and Gordon (47, 49) have been conducted to determine the role of the plants and deltaic sediments in nutrient exchange processes. Carbon, nitrogen, and phosphorus exchange rates tend to follow seasonal patterns. In most cases these patterns seem to be similar from species to species (Figures 37-43). The rates also appear to be similar to those rates observed from similar plant types in other Texas marshes. The order of magnitude of exchange rates appears to be very similar among the species for uptake or release of total organic carbon and nitrogen and phosphorus nutrients. Figures 37-43 indicate that the deltaic marshes are releasing total organic carbon year-round, with highest export rates occurring during winter and summer. Total phosphorus is generally exported with the greatest rates also occurring in late winter and summer. Nitrate nitrogen and ammonia nitrogen are continually absorbed while nitrite nitrogen and total kjeldahl nitrogen are neither taken up nor released in sizable amounts. This general uptake of nitrogen tends to support the contention of Langdon and Davis (55) and Davis (54) that San Antonio Bay waters are nitrogen limited.

Using C, P, and N exchange rates observed from a linear marsh model containing a representative corss-section of marsh vegetation (49), an export of 11,000 to 17,000 kg/day TOC and up to 50 kg/day total phosphorus from the Guadalupe deltaic marshes can be expected during periods of continous inundation. There is evidence (52) that following a prolonged period of drying a sudden inundation event over the delta marshes will result in a short period of high nutrient release. This period, which may last for one or two days, is subsequently followed by a period where release rates decrease rapidly until they begin to approach a seasonal equilibrium. Therefore, during periods of high river discharges and/or extremely high tides that immediately follow prolonged dry periods, the contribution of C, P and N from the deltaic marshes to the estuarine waters can be expected to increase dramatically.

Table 9.—Percent Total Flow Contribution of the Guadalupe and San Antonio Rivers

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

Table 10.—Average Percent Total Contribution of Nutrients From the Guadalupe and San Antonio Rivers 1974-76

	Guadalupe River at Victoria	San Antonio River at Goliad
Inorganic Nitrogen	44%	56%
Organic Nitrogen	53%	47%
Total Phosphorus	18%	82%
Inorganic Carbon	71%	29%

Range of Percent Contributions of Nutrients 1974-76

	Guadalupe River at Victoria	San Antonio River at Goliad
Inorganic Nitrogen	39-49%	51-61%
Organic Nitrogen	46-51%	39-54%
Total Phosphorus	17-19%	81-83%
Inorganic Carbon	66-75%	25-34%

Table 11.--1974-76 Nutrient Contributions by the Guadalupe and San Antonio Rivers (kg/day)

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

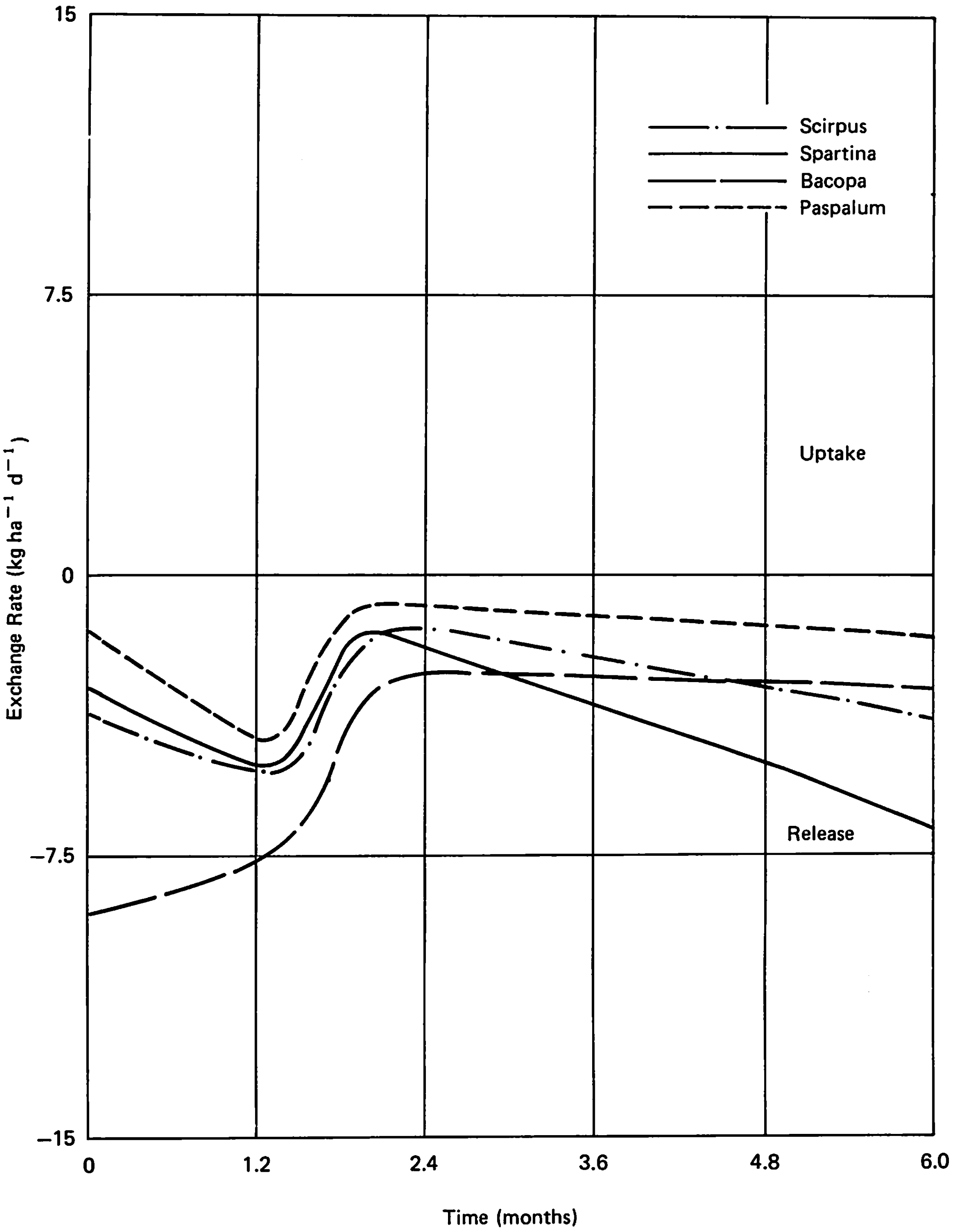

Figure 37.—Exchange Rates For Total Organic Carbon in Guadalupe Estuary (49)

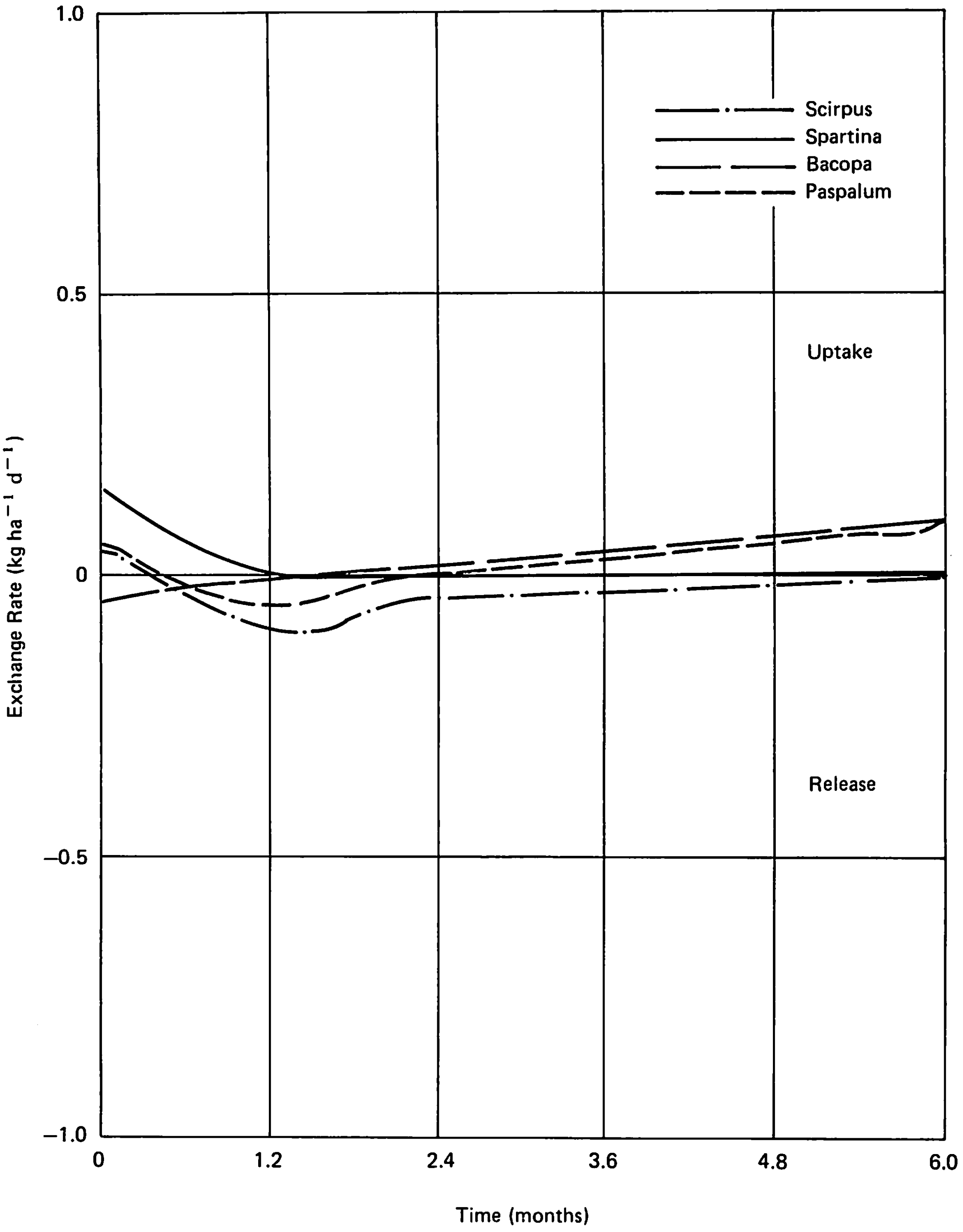

Figure 38.—Exchange Rates For Unfiltered Total Kjeldahl Nitrogen in Guadalupe Estuary (49)

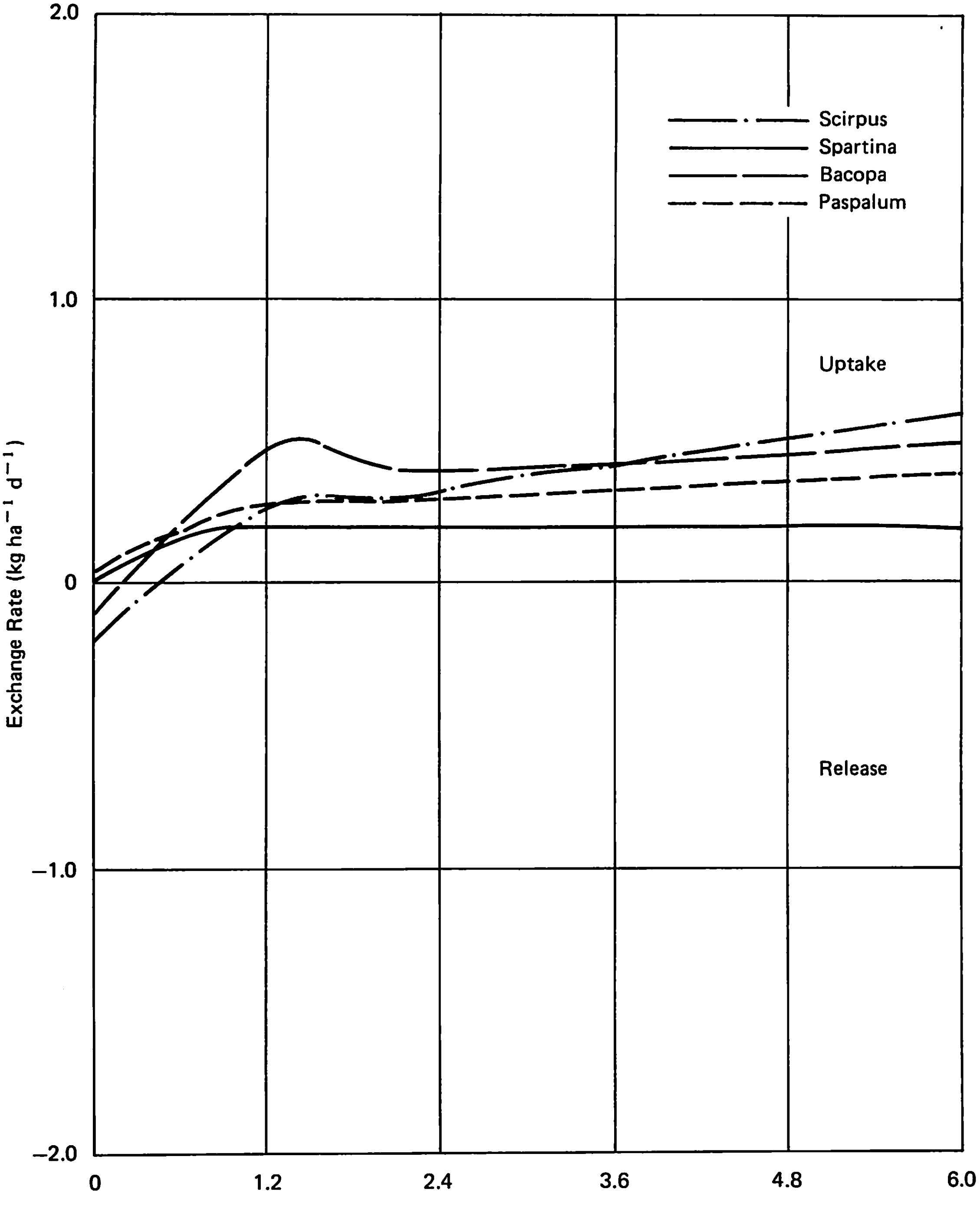

Figure 39.—Exchange Rates For Ammonia Nitrogen in Guadalupe Estuary (49)

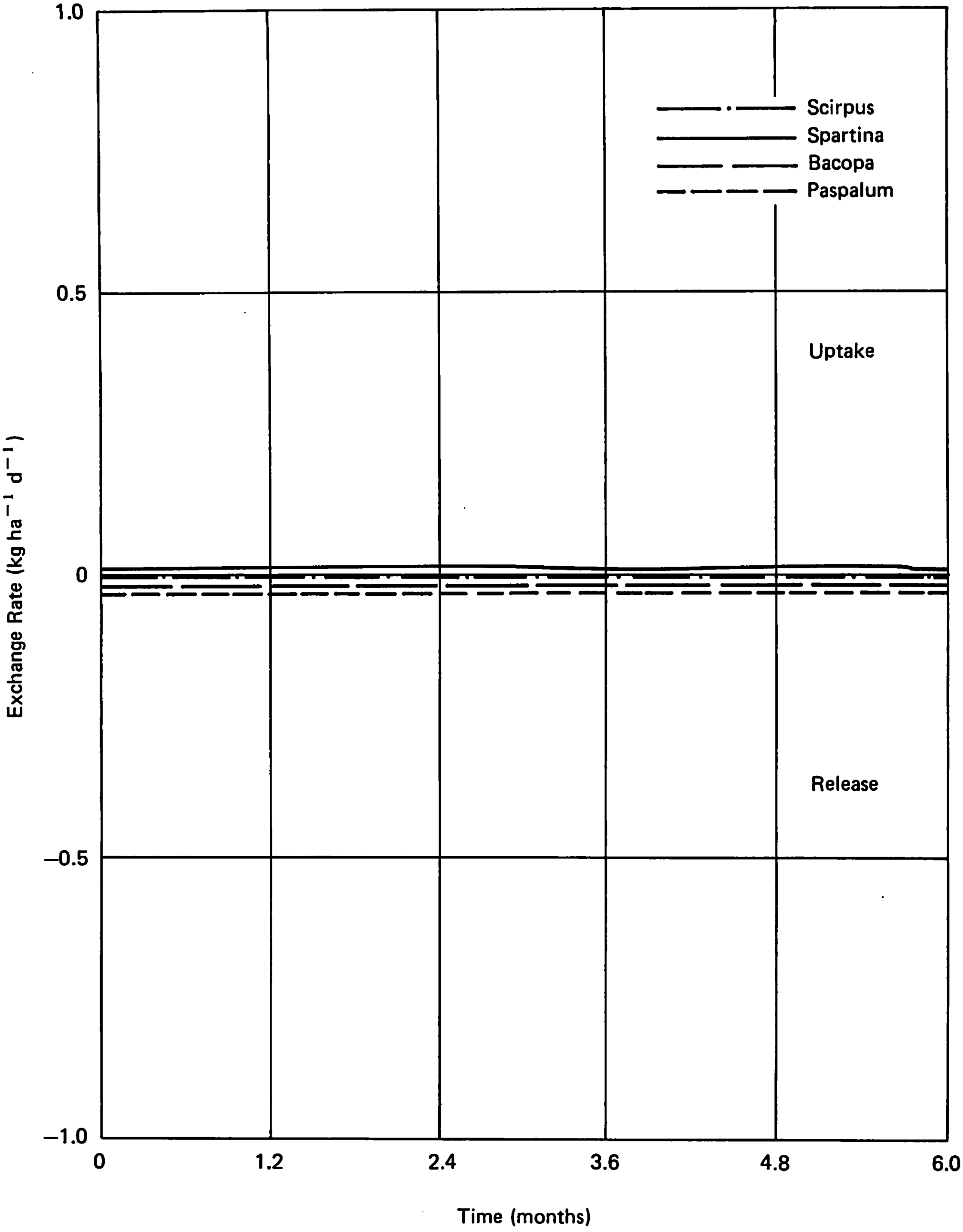

Figure 40.—Exchange Rates For Nitrite Nitrogen in Guadalupe Estuary (49)

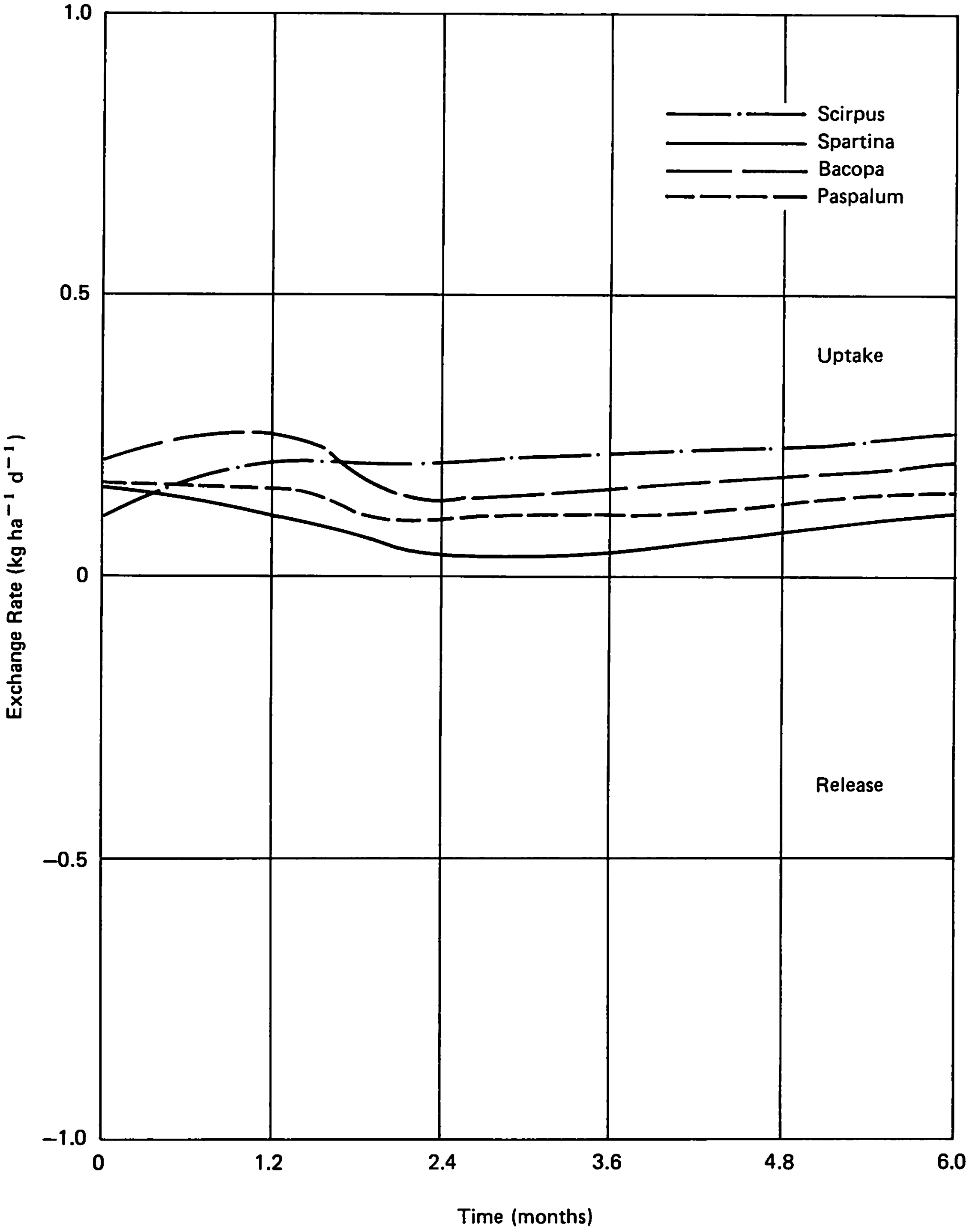

Figure 41.—Exchange Rates For Nitrate Nitrogen in Guadalupe Estuary (49)

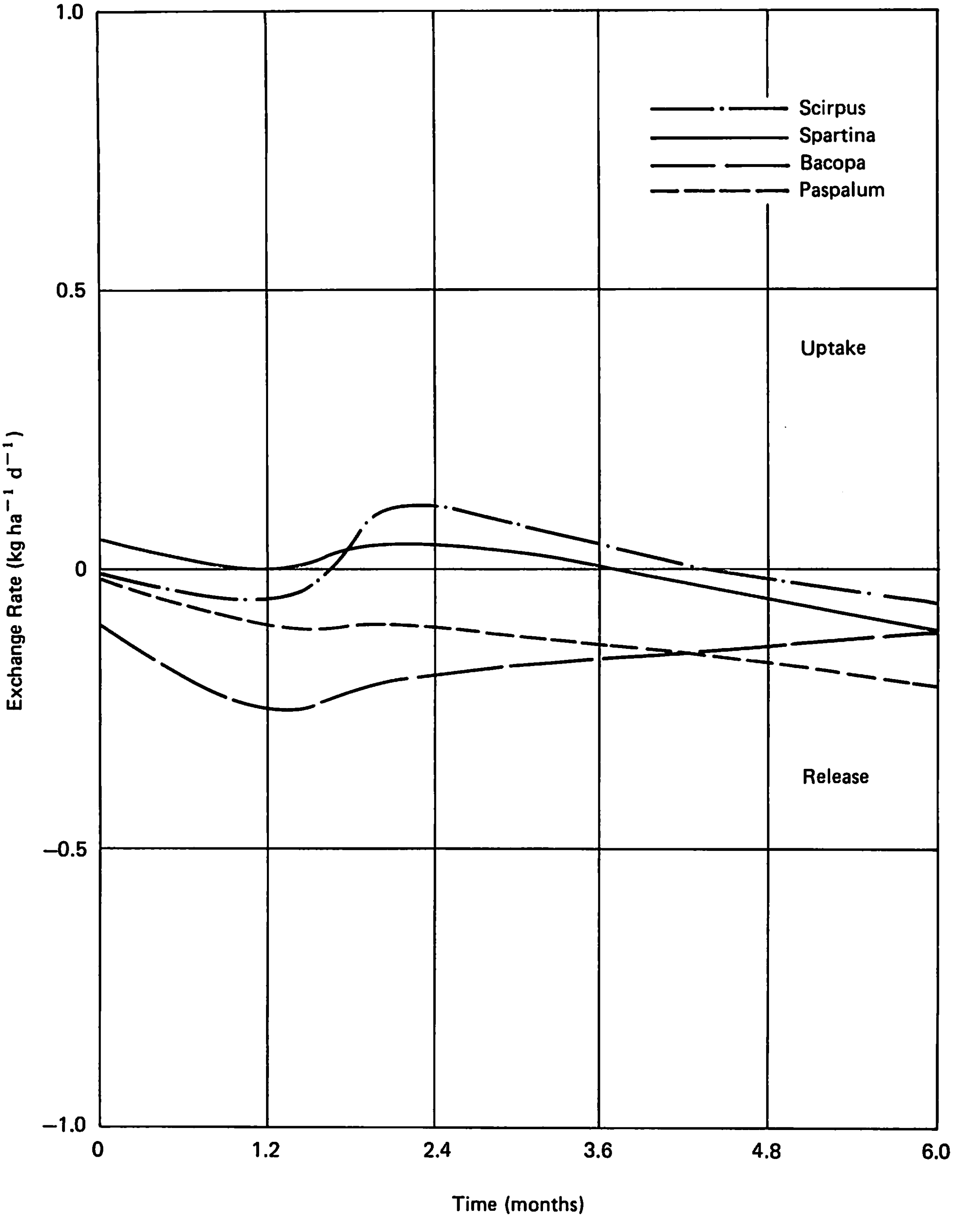

Figure 42.—Exchange Rates For Unfiltered Total Phosphorus in Guadalupe Estuary (49)

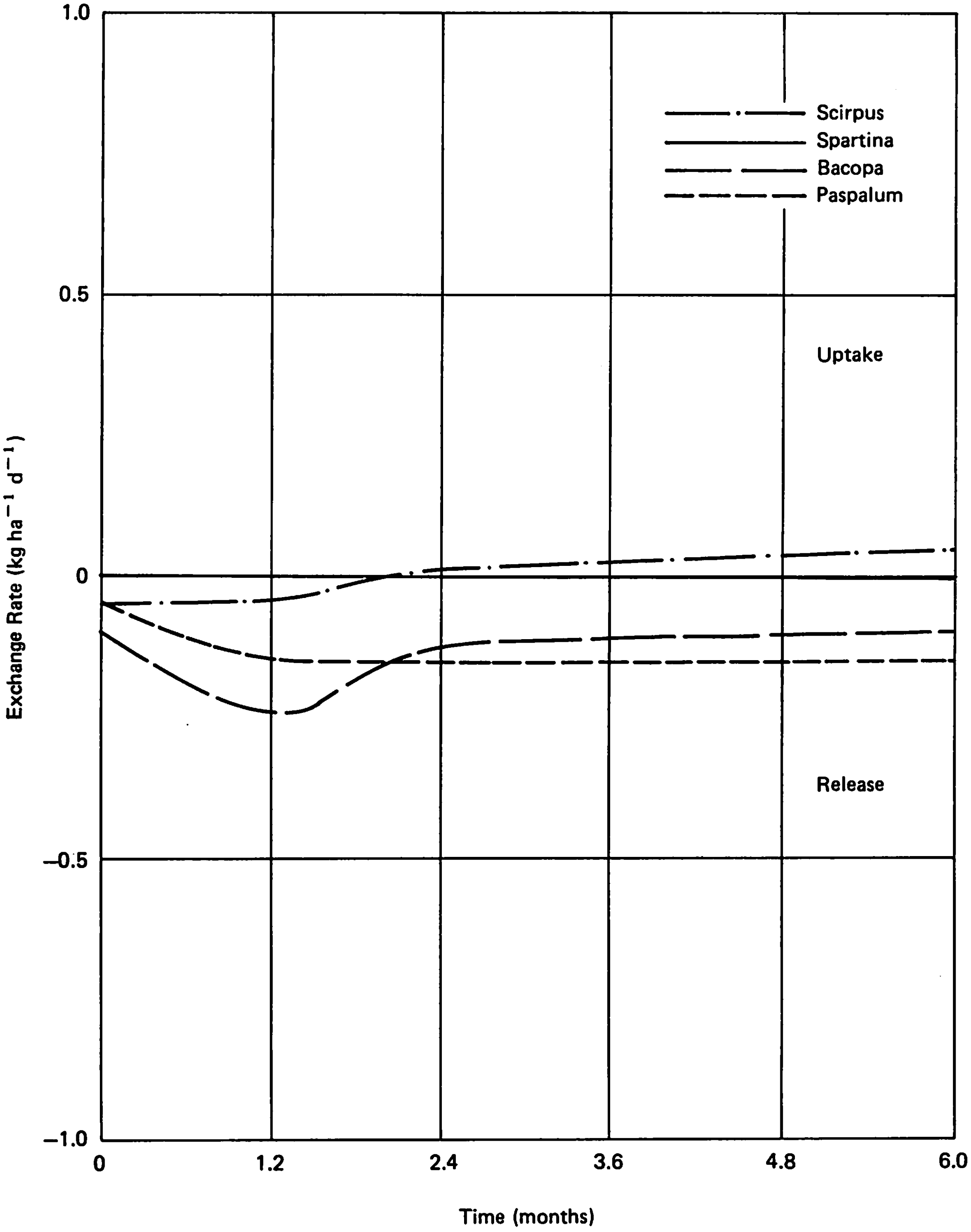

Figure 43.—Exchange Rates For Ortho-Phosphorus in Guadalupe Estuary (49)

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