THE STATE OF TEXAS

TRINITY-SAN JACINTO ESTUARY: An Analysis of Bay Segment Boundaries, Physical Characteristics, and Nutrient Processes

TEXAS DEPARTMENT OF WATER RESOURCES
LP-86
March 1982

TRINITY - SAN JACINTO 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 were available in early 1978 as a supplement to the EPA grant for Section 208 planning in nondesignated planning areas. A part of the funds were earmarked for development of analyses which could be used in future planning efforts for evaluation of the appropriateness of existing water quality standards in major Texas estuarine systems. Due to the short time frame of the supplemental grant funds, only three tasks were selected. Later these can be expanded upon throughout the continuing planning process. The three selected tasks are the subject of this report on the Trinity-San Jacinto 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.

TRINITY-SAN JACINTO ESTUARY: AN ANALYSIS OF BAY SEGMENT BOUNDARIES, PHYSICAL CHARACTERISTICS, AND NUTRIENT PROCESSES

SUMMARY

This report is one in a series of reports on major Texas estuaries. The objective is to analyze existing data on the Trinity-San Jacinto 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 Trinity-San Jacinto 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. Section three of the report presents the current state of knowledge of nurient processes taking place in the Trinity-San Jacinto estuary, especially the effects of inflows on nutrient cycling and contributions of nutrients from deltaic marsh areas.

Circulation and salinity models of the Trinity-San Jacinto estuary were derived for use on a digital computer and were calibrated by sampling efforts in the estuary. This allowed simulation of circulation and salinity patterns under various conditions of freshwater inflow, tidal cycle and wind effects. A careful analysis of the model simulation runs had important implications for the placement or location of appropriate boundaries for the bay segments. The degree of resolution of the tidal hydrodynamic and salinity mass transport models was not sufficient to evaluate circulation and salinity patterns in many of the small inlets that are part of the Trinity-San Jacinto estuary. As a result of the above limitations, it is recommended that all the existing small bay segments be retained as listed on page 6. In addition, the results of the model simulations suggest retention of the Trinity Bay and West Bay segments without modification. Due to the influence of Hanna Reef on circulation, it is recommended that the present bay segment boundary between Galveston and East Bay be relocated to the east of its present location. As a result of the salinity simulations it was recommended that the existing Galveston Bay segment be divided into two new bay segments, Upper and Lower Galveston Bay (segments 2421 and 2439, respectively).

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

An analysis of net circulation patterns simulated by the tidal hydrodynamic model indicated that the dominant circulation in Galveston Bay was a net movement of water along the Houston Ship Channel. The simulated circulation patterns in Trinity, East and West Bays were generally dominated by internal circulation currents.

Although simulated salinity concentrations throughout the Trinity-San Jacinto estuary varied, salinities were generally at their lowest during the month of June. Highest levels of salinities were generally found during the months of February and August.

Nutrient contributions to the Trinity-San Jacinto 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 Trinity-San Jacinto estuary is the freshwater inflow from the Trinity and San Jacinto Rivers.

The Trinity-San Jacinto estuary is an extremely productive system, particularly in the deltaic marsh

area of the Trinity River. Average annual net productivity was approximately 7,220 dry weight pounds per acre (820 g/m^2) for the Trinity River delta.

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

Although a great deal has been gained thus far by detailed investigations and data collection activities focused on the Trinity-San Jacinto estuary, many questions cannot yet be answered. Texas estuaries are very complex systems, having numerous variables, and many relationships among these variables. Measurement of both variables and the relationship between them are extremely difficult and time consuming to make. Additional studies of the Trinity-San Jacinto estuary will add to the knowledge gained to this point and allow more accurate descriptions of the processes taking place. Studies under the authorization of Senate Bill 137 are continuing, with results scheduled for publication in the latter 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., Galveston 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., Trinity 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., Anahuac Lake) may be found at the head of an estuary connected to one of the secondary bays. In terms of energy input to the estuarine systems, the most productive and dynamic of estuarine habitats are associated with tertiary bays, where sunlight can effectively penetrate the shallow, fresh to brackish water areas and support submerged vegetation. Substantial chemical energy is produced in these areas due to photosynthetic processes. These biostimulants are distributed through the estuarine system by tide and wave action.

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

Texas has about 400 linear miles (644 kilometers) of coastline, 373 miles, (600 kilometers) of open-ocean or Gulf shoreline and 1,419 miles, (2,284 kilometers) of bay shoreline, along which are located seven major estuarine systems and three smaller estuaries (Figure 1). Eleven major river basins, ten with headwaters originating within the boundaries of the State, have estuaries of major or secondary importance. These estuarine systems, with a total surface area of more than 1.3 million acres (526,000 hectares), include many large shallow bays behind the barrier islands. Additional thousands of acres of adjacent marsh and bayous provide habitat for juvenile forms of important marine migratory species between the Gulf of Mexico and also produce nutrients for the indigneous 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 Trinity-San Jacinto estuary is currently divided into 18 segments for water quality planning purposes (Figures 2 and 3). The major open-water segments are Trinity Bay (segment 2422), East Bay (segment 2423), Galveston Bay (segment 2421) and West Bay (segment 2424). Additional water quality segments in the Trinity-San Jacinto estuary are designated for ship channels and minor inlets. The degree of resolution of the tidal hydrodynamic and salinity mass transport models was not sufficient to evaluate the circulation and salinity patterns in the small inlets or ship channels of the Trinity-San Jacinto estuary designated as individual bay segments. This does not imply that these small segments are not appropriate for planning purposes, but that more detailed evaluation of local conditions may be needed. In light of this consideration, it is recommended that the existing boundaries be retained in the following bay segments since the large scale mathematical models gave little insight: Tabbs Bay

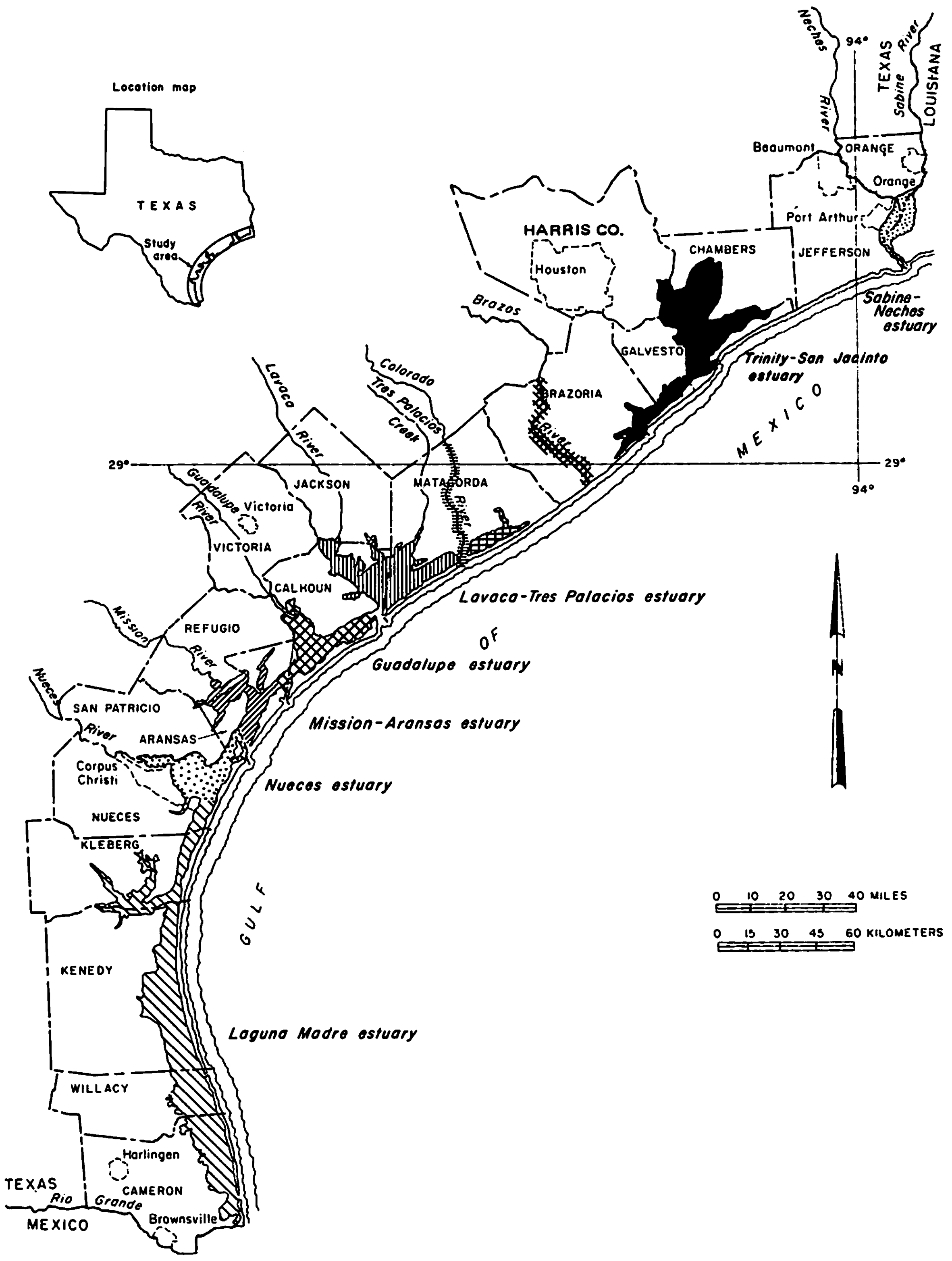
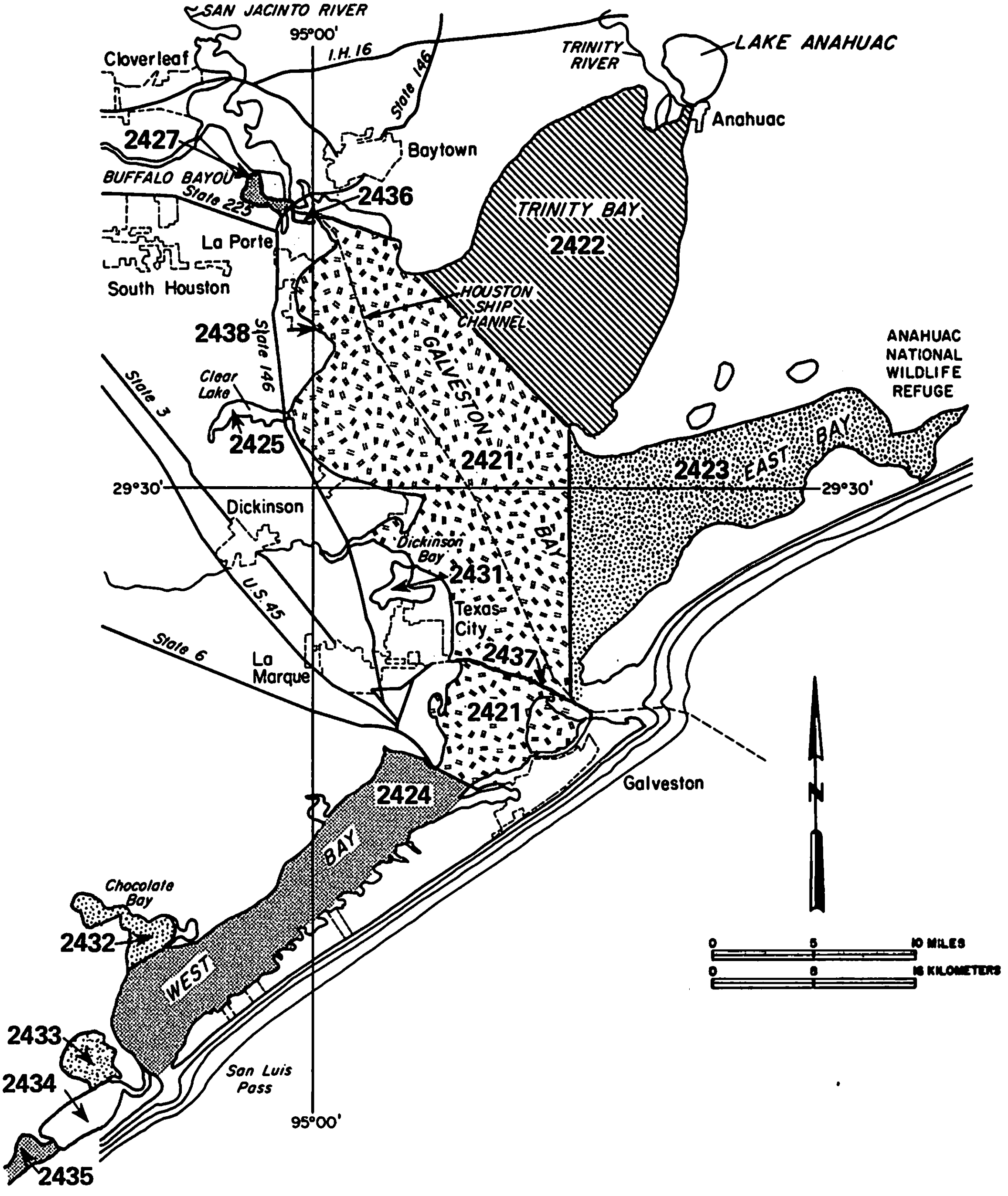


Figure 1.—Location of Estuaries

Base from Official State Highway Map of Texas, 1971



Figures 2.— 3.—Existing Bay Segment Boundaries, Trinity-San Jacinto Estuary (Figures 2 and 3 Have Been Combined for Final Report)

(segment 2426), Black Duck Bay (segment 2428), Scott Bay (segment 2429), Burnett Bay (segment 2430), Clear Lake (segment 2425), San Jacinto Bay (segment 2427), Moses Lake (segment 2431), Chocolate Bay (segment 2432), Bastrop Bay (segment 2433), Christmas Bay (segment 2434), Drum Bay (segment 2435), Barbours Cut (segment 2436), Texas City Ship Channel (segment 2437) and Bayport Channel (segment 2438).

The results of the tidal hydrodynamic and salinity mass transport simulations indicated that Trinity Bay (segment 2422) and West Bay (segment 2424) were appropriate homogenous segments for water quality planning purposes without modification of their boundary lines. In all the monthly circulation and salinity analyses, Trinity Bay generally contained a major closed circular current which dominated internal water movements. Further, the simulated salinity concentrations were consistently lower in Trinity Bay than in the adjacent Galveston Bay. West Bay had simulated circulation patterns which were not dominated by the adjacent Galveston Bay water movements. Similarly, salinity concentrations differed between West Bay and Galveston Bay in the simulated analyses (Figure 4).

In analyzing the hydrodynamic simulations it was evident that the western portion of East Bay was influenced by circulation patterns in Galveston Bay. The central and eastern portions of East Bay, however, had simulated internal circulation patterns and simulated salinity concentrations lower than adjacent portions of Galveston Bay. The currents entering East Bay from Galveston Bay were the result of the location of Hanna Reef which directs flow from Galveston Bay into and out of East Bay. Due to the occurrence of this physical barrier it is recommended that the boundary line between the Galveston Bay and East Bay water quality planning segments (segments 2421 and 2423, respectively) be relocated to the east of the present segment boundary line. This proposed new segment boundary is indicated in Figure 5.

Simulated salinities were found to vary over Galveston Bay, with the lower portion of the bay adjacent to the Gulf of Mexico having higher salinity concentrations by 10 to 15 parts per thousand than the upper portion of the bay. It is therefore recommended that the present Galveston Bay segment be divided into two new segments, with the boundary line crossing Galveston Bay from Smith Point to Eagle Point as indicated in Figure 5.

PHYSICAL CHARACTERISTICS

Introduction

The Trinity-San Jacinto estuary covers about 600 square miles (1,600 square kilometers) and consists of the tidal parts of the San Jacinto and Trinity Rivers, East Bay, Galveston Bay, Trinity Bay, West Bay, and several smaller bays. Water depth at mean low water varies from less than six feet (1.8 meters) in West Bay to over 10 feet (3.1 meters) in Galveston Bay. Depths in the dredged channels range up to 40 feet (12 meters).

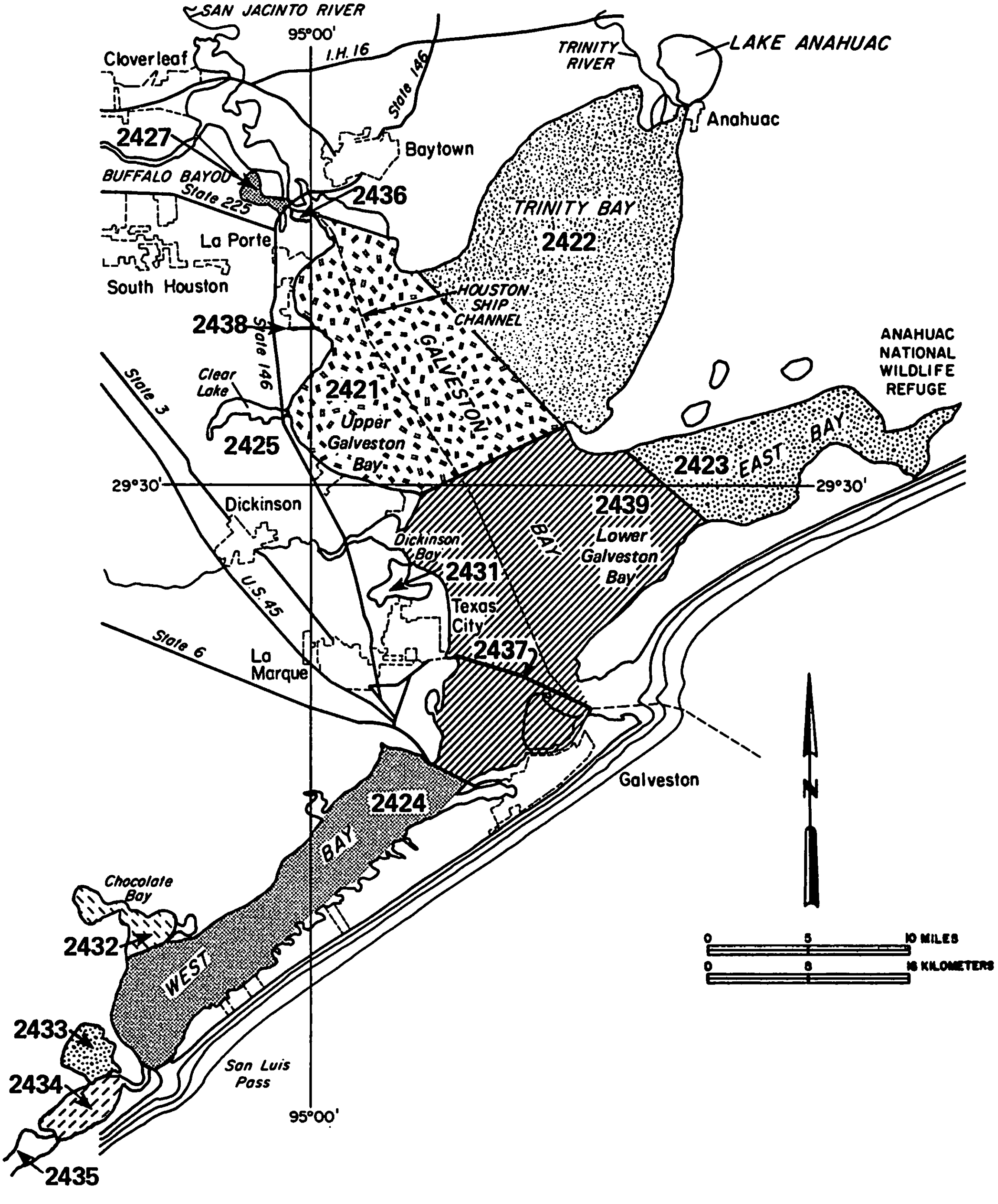
The study area lies in the Upper Coast climatological division of Texas in the warm temperate zone. Its climatic type is classified as subtropical-humid with warm summers. The proximity of the Gulf of Mexico provides an abundant moisture source, high relative humidity, and sea breezes, which prevent extreme high temperatures in summer and moderate in the cool of winter. Polar Canadian air masses frequent the basin in winter causing brief periods of cool, foggy, and rainy weather (77).

Sedimentation and Erosion

The main source of sediment that is deposited into the Trinity-San Jacinto estuary is carried by the Trinity River. Headwaters of the Trinity River carry sediment ranging from 0.70 acre-foot/square mile (3.33 m^3/ha) to 1.06 acre-feet/square mile (5.05 m^3/ha) annually as it flows through the North Central Prairie, Western Cross Timbers, Grand Prairie, and Eastern Cross Timbers physiographic provinces. Within the Blackland Prairie the annual sediment production rate is 0.77 to 0.85 acre-foot/square mile (3.7 to 4.1 m^3/ha). As the Trinity River flows southward into the East Texas Timberlands the annual sediment production rate decreases to 0.16 acre-foot/square mile (1.76 m^3/ha). Because its drainage area is significantly smaller and Lake Houston acts as a sediment trap, the San Jacinto River contributes little sediment to the estuary even though the sediment production rates are about the same as those of the lower reaches of the Trinity River (51).

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

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



Figures 4.– 5.–Proposed Bay Segment Boundaries, Trinity-San Jacinto Estuary
(Figures 4 and 5 Have Been Combined for Final Report)

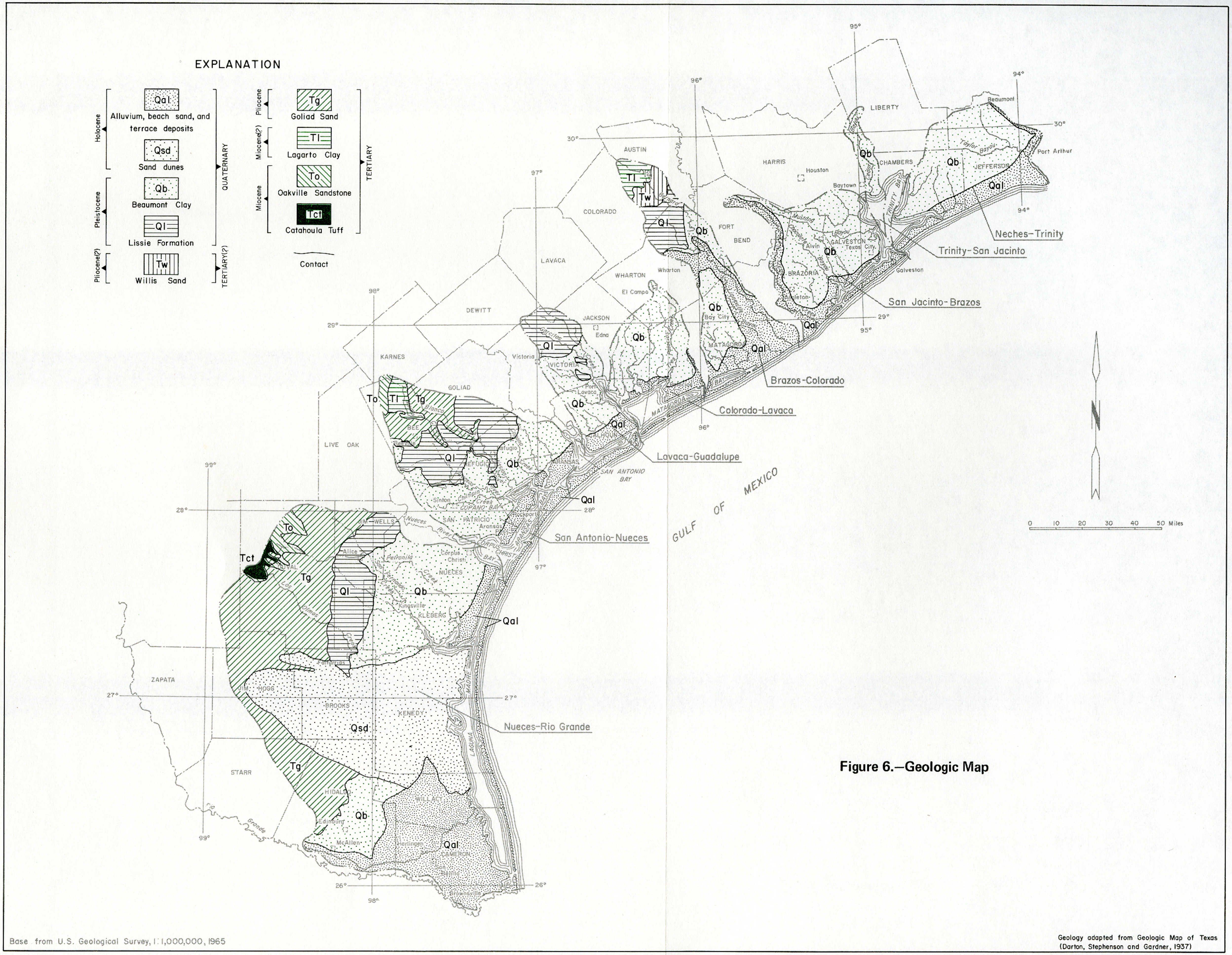
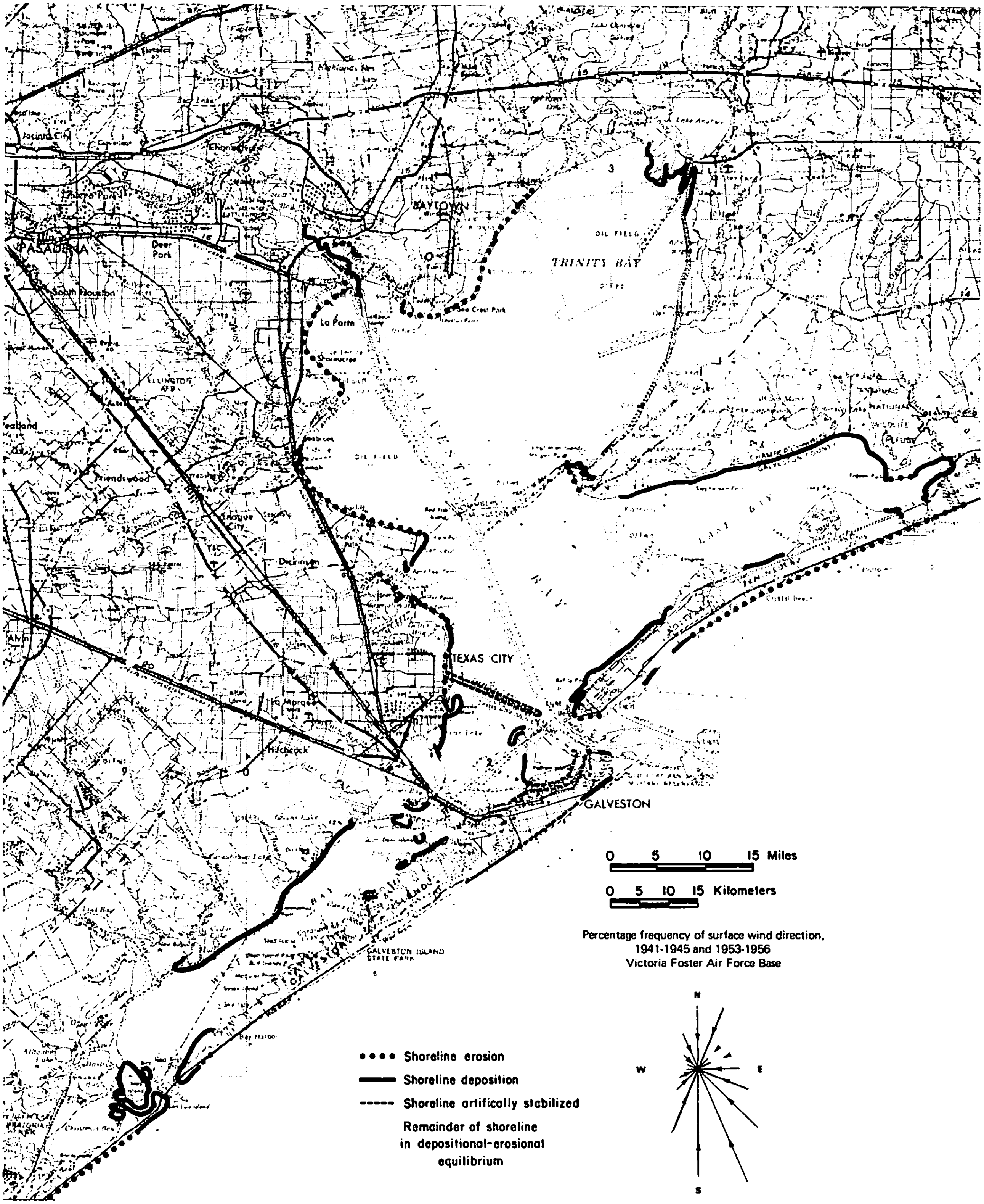


Figure 6.—Geologic Map

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

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



Figures 7.–8.–Shoreline Physical Processes, Trinity-San Jacinto Estuary (59)
(Figures 7 and 8 Have Been Combined for Final Report)

The marsh areas in the Trinity-San Jacinto estuary are associated with 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 enlarged bay areas. At present, marsh surface-water level relationships of the Trinity delta are stable. Sedimentation rates and subsidence apparently are in equilibrium. Other important sources of estuarine sediments include:

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

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

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

The mainland shore is characterized by near vertical bluffs cut into Pleistocene sand, silt, and mud (Figure 6). 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 predominately sand or mud. Energy levels (erosional capacity) in the Trinity-San Jacinto estuary are dominated by wind action since the range of astronomical tides is only about 0.5 foot (0.15 m). Winds blowing across the bay generate tides of 2 or 3 feet (0.6 or 1 m) and cause a change in water level at the shoreline (59). These changes in water levels produced by the wind are called wind tides.

Shoreline and vegetation changes within the Trinity-San Jacinto estuarine system and in other areas of the Texas Gulf Coast are the result of natural processes (61). Shorelines are in a state of erosion, accretion, or are stabilized either naturally or artificially. Erosion produces a net loss in land; accretion produces a net gain in land; and equilibrium conditions produce no net change in land area.

Most of the shoreline areas associated with the Trinity-San Jacinto estuary are balanced between erosion and deposition (Figures 7 and 8). The nature of beaches is an indicator of the extent of shoreline stability. Sediments of the mainland beaches are a mixture of sand, shell, and rock fragments, with shell and rock fragments the most common constituents. This is an indication that little sand is currently being supplied to these beaches by rivers.

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

The seasonal threat of wind and water damage associated with tropical cyclones occurring in the Gulf of Mexico exists each year from June through October. Wind damage from hurricanes and associated tornadoes can be costly, but the most severe losses occur from the flooding brought by heavy rains and high storm surges along the Coast. Gulf and mainland shorelines may be drastically altered during the approach, landfall, and inland passage of hurricanes (40). Storm surge flooding and attendant breaking waves may erode Gulf shorelines tens or hundreds of feet. Washovers along the barrier islands and peninsulas are common, and salt-water flooding may be extensive along the mainland shorelines.

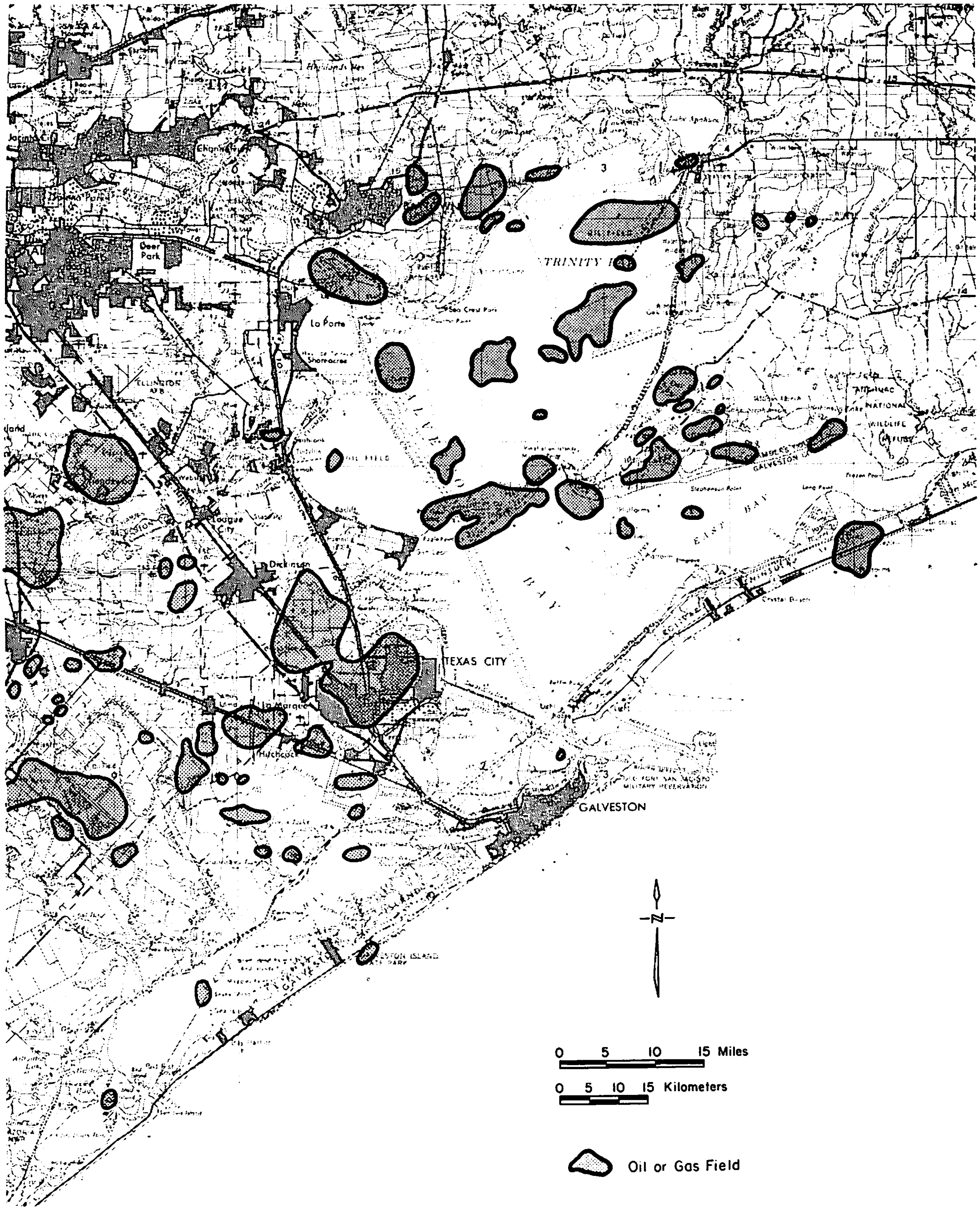
Flooding of rivers and small streams normally corresponds with spring thunderstorms and the hurricane season. Some effects of flooding include: (1) overbank flooding into marsh areas of the floodplain and onto delta plains; (2) progradation of bayhead and oceanic deltas; (3) flushing of bays and estuaries; and (4) reduction of salinities.

Mineral and Energy Resources

The Texas coastal zone is richly endowed with mineral and energy resources. Dominant among these resources are oil and natural gas (Figures 9 and 10) which serve not only for fuel but also provide raw material for many petrochemical processes.

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

Dredged shell, with physical properties suitable for use as aggregate and road base, has chemical properties suitable for lime, cement, and other chemical uses. If shell were not used, these resources would have to be transported approximately 170 miles (270 km) from the nearest Central Texas source. Shell resources are finite, and at present rates of consumption they will be depleted in the near future. Substitute materials will then have to be imported, either from inland sources or by ocean barge from more distant locations.



Figures 9.–10.–Oil and Gas Fields, Trinity-San Jacinto Estuary (59)
(Figures 9 and 10 Have Been Combined for Final Report)

An inventory and analysis of coastal sand included those of the barrier islands, as well as the older sands of the Pleistocene uplands (60). Some high quality sand deposits have potential specialty uses in industry, such as for foundry sands, glass sands, and chemical silica with upgrading and benefication.

Groundwater Resources

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

Near the Trinity-San Jacinto 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 3,000 feet (914 m). The most productive part of the aquifer is from 400 to 1,200 feet (122 to 366 m) thick (53).

Excessive pumping of groundwater can cause land surface subsidence and saltwater encroachment, which are both irreversible. Locally the shallow aquifer may contain saltwater, whereas the deeper aquifer sands may have freshwater. Excessive pumping of freshwater will allow saline waters to encroach into the freshwater zone, contaminating wells and degrading the general groundwater quality. The principal effects of subsidence are activation of surface faults, loss of ground elevation in critical low-lying areas already prone to flooding, and alteration of natural slopes and drainage patterns (Figures 11 and 12). 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 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 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 involved in the collection of data in all major estuarine systems of the Texas Coast (Figures 13 and 14, 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 a specified period of nearly constant hydrologic, meteorologic, and tidal conditions. In addition, the time history of tidal amplitudes and salinities at various locations throughout the bay were necessary. A comprehensive data collection program was undertaken on the Trinity-San Jacinto estuary on July 20-23, 1976. Tidal flow measurements were made at several different bay cross-sections (A - A' through L - L' of Figure 14). In addition, conductivity data were collected at many of the sampling stations shown in Figure 13.

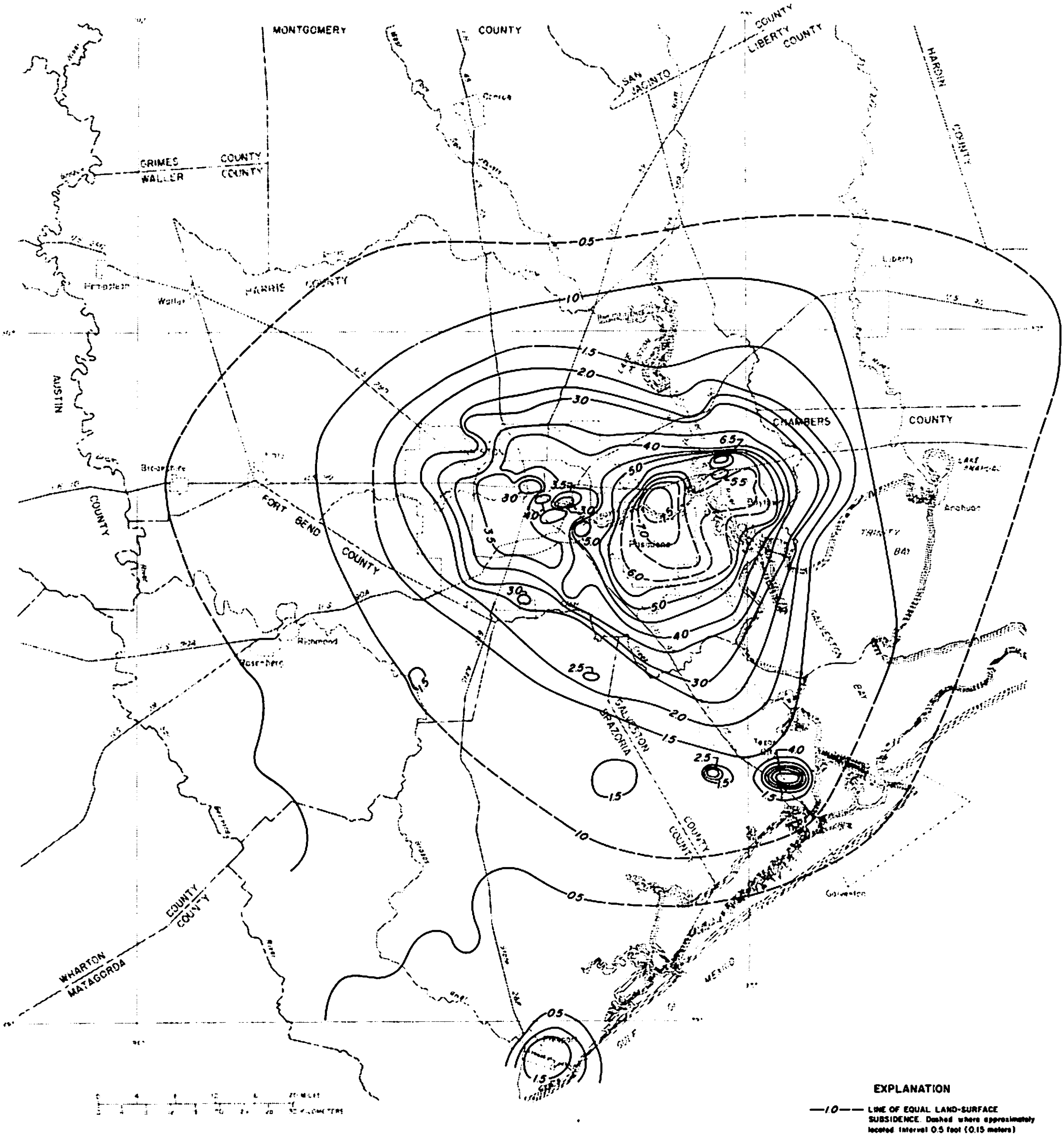


Figure 11.–12.–Land-Surface Subsidence in the Houston Area (1964-1973) (164)

Base from Texas Highway Department county highway maps

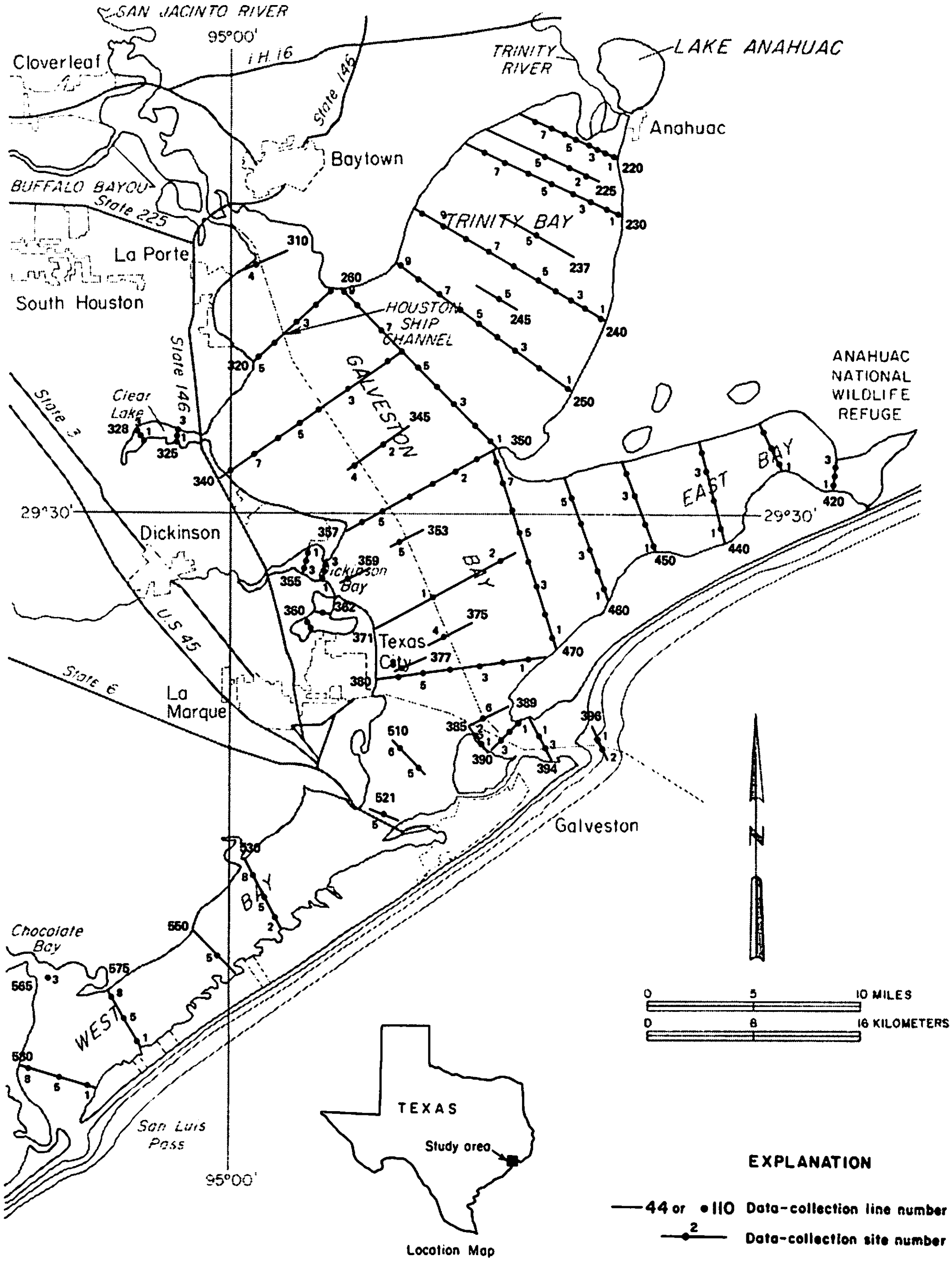


Figure 13.—Data Collection Sites in Trinity-San Jacinto Estuary

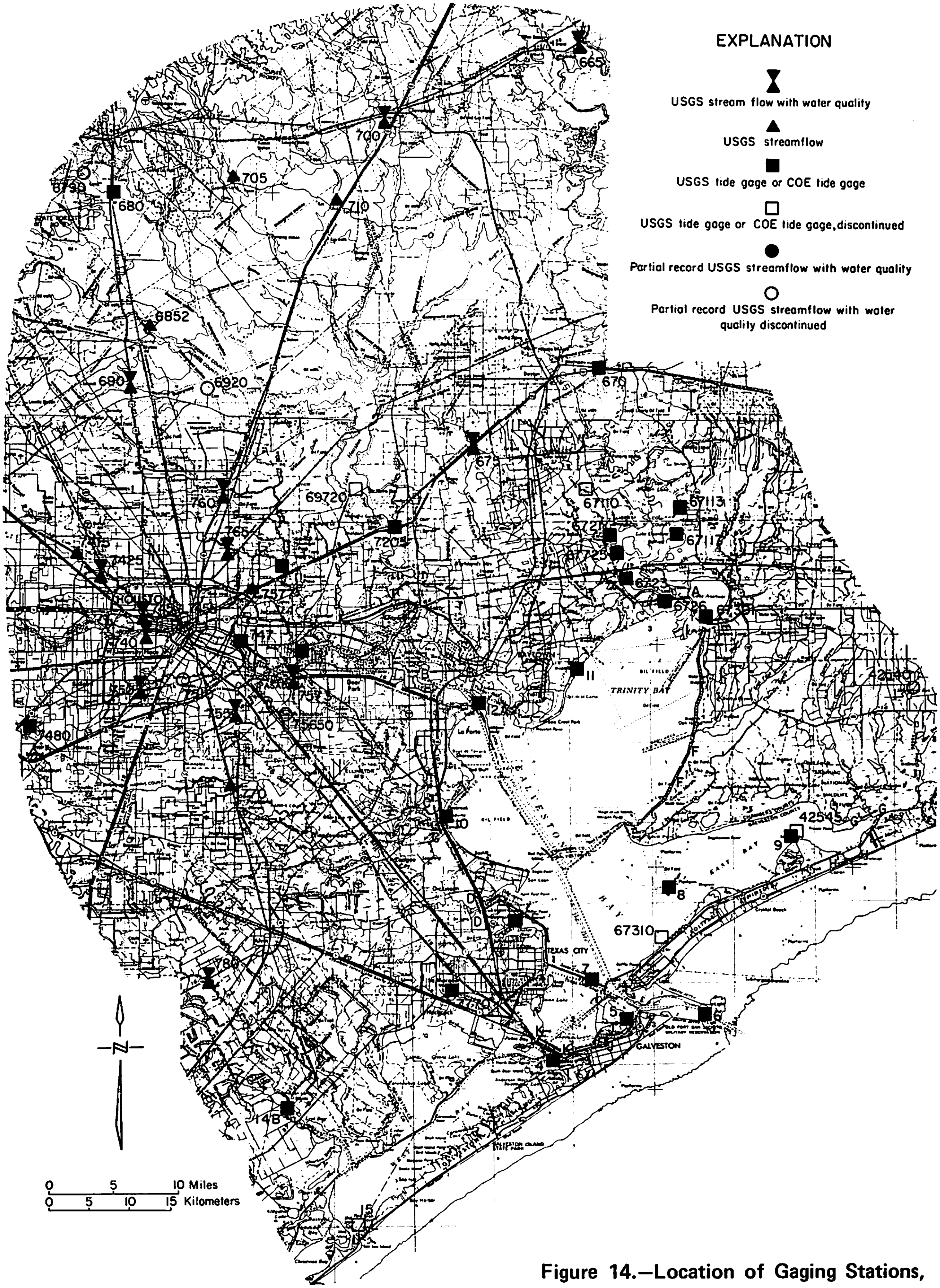


Figure 14.—Location of Gaging Stations, Trinity-San Jacinto Estuary

Table 1.—USGS or Corps of Engineers Gages (COE)
Trinity-San Jacinto Estuary

Station Number	Station Description	Period of Record	Operating Entity[1]	Type of Record
	Stream Gages			
42540	East Bay Bayou nr. Stowell, Tx.	1967-72	USGS	Continuous Recording
66500	Trinity River at Romayor	1924-	USGS	Continuous Recording
67500	Cedar Bayou nr. Crosby, Tx.	1971-	USGS	Continuous Recording
68000	West Fork San Jacinto River nr. Conroe	1961-	USGS	Continuous Recording
68520	Spring Creek at Spring	1939-	USGS	Continuous Recording
69000	Cypress Creek nr. Westfield	1944-	USGS	Continuous Recording
69720	Lake Houston nr. Sheldon	1954-	USGS	Continuous Recording
70000	East Fork San Jacinto River nr. Cleveland	1939-	USGS	Continuous Recording
70500	Caney Creek nr. Splendora	1943-	USGS	Continuous Recording
71000	Peak Creek at Splendora	1943-	USGS	Continuous Recording
73700	Piney Cr. nr. Piney Point	1963-	USGS	Continuous Recording
74150	Cole Creek at Deihl Rd., Houston	1964-	USGS	Continuous Recording
74250	Brickhouse Gulley at Costa Rica St., Houston	1964-	USGS	Continuous Recording
74500	Whiteoak Bayou at Houston	1936-	USGS	Continuous Recording
75000	Brays Bayou at Houston	1936-	USGS	Continuous Recording
75500	Sims Bayou at Houston	1952-	USGS	Continuous Recording
75730	Vince Bayou at Pasadena	1971-	USGS	Continuous Recording
75770	Hunting Bayou at Hwy. 610	1964-	USGS	Continuous Recording
76000	Greens Bayou nr. Houston	1952-	USGS	Continuous Recording
76500	Halls Bayou at Houston	1952-	USGS	Continuous Recording
76700	Greens Bayou at Ley Road	1962, 1964, 1971-	USGS	Continuous Recording

Table 1.—USGS or Corps of Engineers Gages (COE)
Trinity-San Jacinto Estuary
(continued)

Station Number	Station Description	Period of Record	Operating Entity[1]	Type of Record
77000	Clear Creek nr. Pearland	1963-	USGS	Continuous Recording
78000	Chocolate Bayou nr. Alvin	1959-	USGS	Continuous Recording
	Partial Record			
67900	Lake Creek nr. Conroe	1968-	USGS	Partial Record
69200	Cypress Creek nr. Humble	1970-	USGS	Partial Record
74550	Little White Oak Bayou at Houston	1971-	USGS	Partial Record
75100	Brays Bayou at Scott Street	1971-	USGS	Partial Record
75650	Berry Bayou at Forest Oaks Street	1964-	USGS	Partial Record
	Tide Gages			
4	Railroad Causeway to Mainland	1962-	COE	Continuous Recording
5	Galveston Harbor, Ft. Point	1968-	COE	Continuous Recording
6	Galveston Bay Entr. Channel, So.	1962-	COE	Continuous Recording
7	North Texas City Dyke	1962-	COE	Continuous Recording
8	Hanna Reef, Moody Pass	1962-	COE	Continuous Recording
9	Marsh Point, Sun Oil Channel	1962-	COE	Continuous Recording
10	Seabrook, Texas Parks & Wildlife	1970-	COE	Continuous Recording
11	Trinity Bay, Point Barrow	1962-	COE	Continuous Recording
12A	Morgan Point, Barbours Cut	1962-65	COE	Continuous Recording
13	Texaco Oil Dock, Galenda Park	1962-	COE	Continuous Recording
14B	Chocolate Bayou, Lost Lake, AMOCO Dock	1975-	COE	Continuous Recording
15	Highway Bridge, San Louis Pass	1968-	COE	Continuous Recording
42545	Galveston Bay nr. Marsh Point	1975-76	USGS	Continuous Recording

Table 1.—USGS or Corps of Engineers Gages (COE)
Trinity-San Jacinto Estuary
(continued)

Station Number	Station Description	Period of Record	Operating Entity[1]	Type of Record
67000	Trinity River nr. Liberty	1922-	USGS	Continuous Recording
67110	Big Caney Creek nr. Mont Belvieu	1976-77	USGS	Continuous Recording
67113	Sulfur Barge Canal nr. Wallisville	1976-77	USGS	Continuous Recording
67117	Lake Charlott nr. Wallisville	1976-	USGS	Continuous Recording
67210	Old River nr. Mont Belvieu	1977-	USGS	Continuous Recording
67230	Old River Lake nr. Wallisville	1976-	USGS	Continuous Recording
67725	Lost River nr. Wallisville	1976-	USGS	Continuous Recording
67260	Old River Cutoff Channel nr. Wallisville	1976-	USGS	Continuous Recording
67301	Anahuac Channel at Anahuac	1976-	USGS	Continuous Recording
67310	Galveston Bay nr. Crystal Beach	1975-76	USGS	Continuous Recording
697205	San Jacinto nr. Sheldon	1970-	USGS	Continuous Recording
74700	Buffalo Bayou at 69th St. Houston	1961-	USGS	Continuous Recording
74800	Keegans Bayou at Roark Rd. Houston	1964-	USGS	Continuous Recording
77650	Moses Lake — Galveston Bay nr. Tex. City	1967-	USGS	Continuous Recording
77700	Highland Bayou at Hitchcock	1963-	USGS	Continuous Recording

[1] USGS — U.S. Geological Survey
COE — Corps of Engineers

Circulation and Salinity

Summary

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

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

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

The net circulation patterns simulated by the tidal hydrodynamic model indicated that the dominant circulation in Galveston Bay was a net movement of water along the Houston Ship Channel. This dominant pattern influenced circulation in other areas of Galveston Bay. The simulated net water movements in Trinity, East and West Bays were generally dominated by internal eddy currents.

The simulated salinities in the Trinity-San Jacinto estuary varied over a wide range throughout the twelve monthly periods. Salinities were lowest in the month of June, with simulated concentrations of less than 20 parts per thousand (ppt) over the entire estuary except near San Luis Pass at the western end of West Bay. The highest levels of simulated salinities occurred during the months of February and August, when salinities in the lower portion of Galveston Bay were greater than 25 ppt. The simulated salinities in Trinity Bay were generally less than 10 ppt.

Description of Estuarine Mathematical Models

Introduction

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

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

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

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

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

Mathematical Model Development

A mathematical model to simulate the tidal and circulation patterns in the Trinity-San Jacinto estuary was developed by Tracor Inc. for the Texas Water Quality Board's Galveston Bay Project (94). This model was modified by personnel of the Engineering and Environmental Systems Section for use as a long-range water resources planning tool. A conservative transport model designed to simulate salinity distributions in the Trinity-San Jacinto estuary was adapted from a similar model developed by Masch (31) for the Lavaca-Tres Palacios estuary. The two models are sequential (Figure 15) in that the tidal hydrodynamic model computes temporal histories of tidal amplitudes and flows. These are then used as input to the conservative mass transport model to compute vertically averaged salinities (or concentration of 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 mass transport model ordinarily cannot be operated unless the tidally generated convective inputs are available.

(1) *Hydrodynamic Model.* Under the assumption that the bays are vertically well-mixed, and the tidally generated convection in either of the two 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

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

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

The equation of continuity for unsteady flow can be expressed as

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

In equations [1], [2] and [3], q_x and q_y are vertically integrated flows per foot of width at time t in the x and y directions, respectively (x and y taken in the plane of the surface area); h is the water surface elevation [with respect to mean sea level (msl) as datum]; d is the depth of water at (x, y, t) and is equal to (h - z) where z is the bottom elevation with respect to msl; $q = (q_x^2 + q_y^2)^{1/2}$; f is a nondimensional bed resistance coefficient determined from the Manning Equation; V_w is the wind speed at a specified elevation above the water surface; Θ is the angle between the wind velocity vector and the x-axis; K is the nondimensional wind stress coefficient; and Ω is the Coriolis parameter equal to $2\,\omega \sin\Phi$, where ω is the angular velocity of the earth taken as 0.73×10^{-4} rad/sec and Φ is the latitude taken as 29°30′ for the Trinity-San Jacinto estuary; r is the rainfall intensity; and e is the evaporation rate.

The numerical solution utilized in the hydrodynamic model of the Trinity-San Jacinto estuary involved an explicit computational scheme. Equations [1], [2] and [3] were solved over a rectangular grid of square cells used to represent conceptually in a discretized fashion, the physiography and various boundary conditions found in this bay system (Figure 16). This explicit formulation of the hydrodynamic model requires for stability a computational time step $\Delta t < \Delta s/(2gd_{max})^{1/2}$, where Δs is the cell size and d_{max} is the maximum water depth encountered in the computational matrix. The numerical solutions of

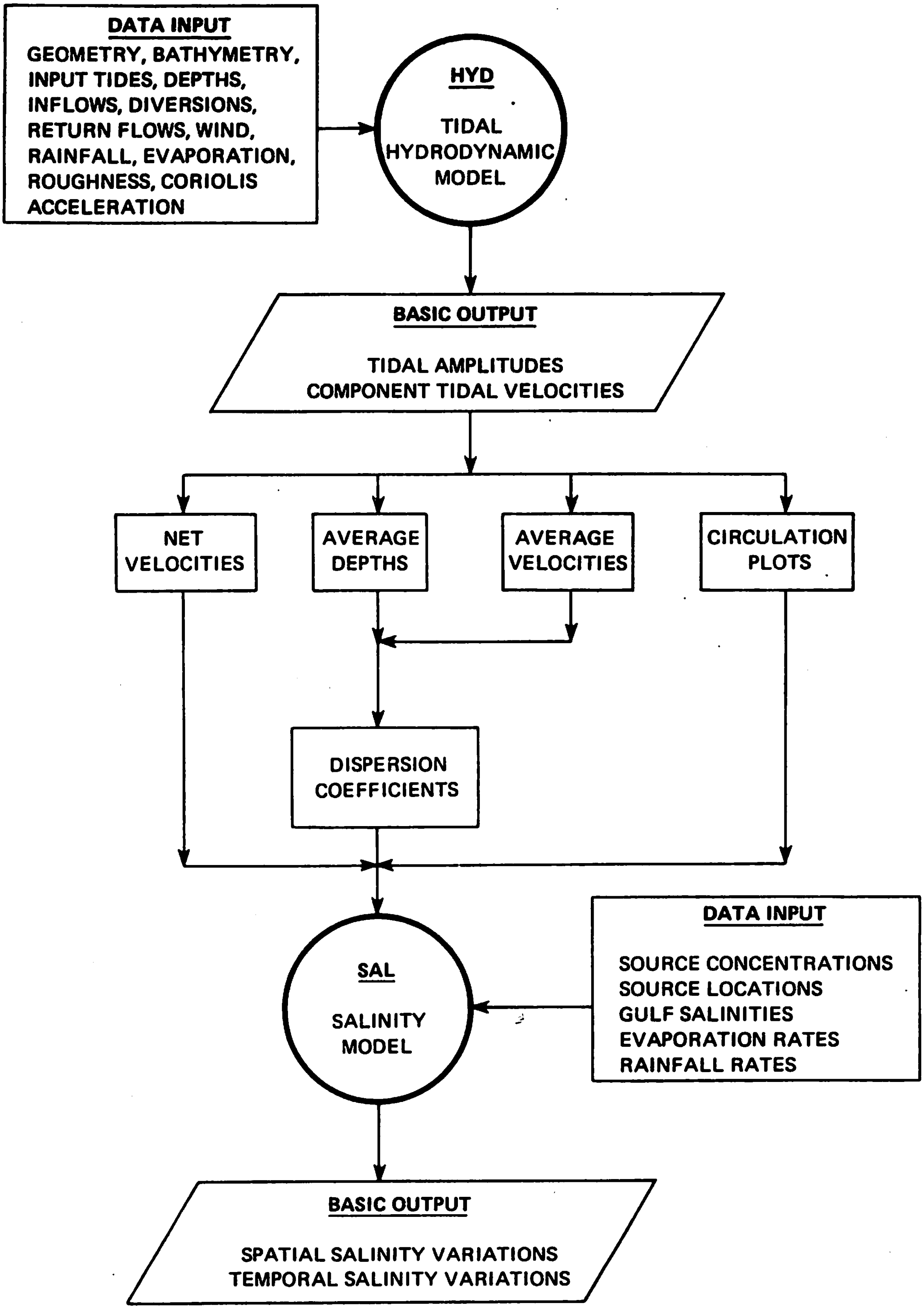


Figure 15.—Relationships Between Tidal Hydrodynamic and Salinity Models

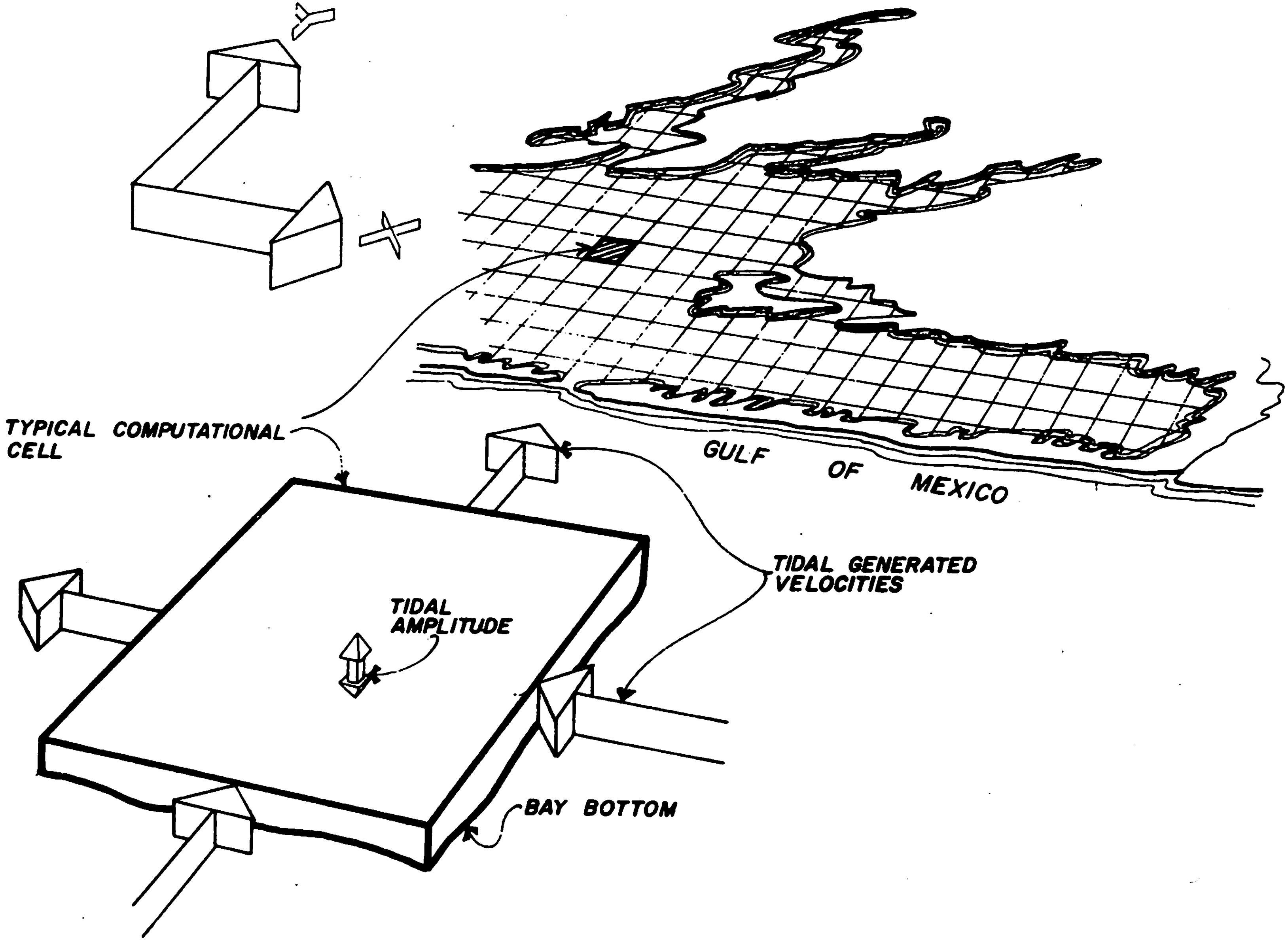


Figure 16.--Conceptual Illustration of Discretization of a Bay

the basic equations and the programming techniques have been described previously (94).

(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

$$\frac{\partial(Cd)}{\partial t} + \frac{\partial(q_x C)}{\partial_x} + \frac{\partial(q_y C)}{\partial_y} = \frac{\partial}{\partial x}\left[D_x \frac{\partial(Cd)}{\partial_x}\right] + \frac{\partial}{\partial y}\left[D_y \frac{\partial(Cd)}{\partial_y}\right] + K_e Cd \qquad [4]$$

where C is the tidally averaged salinity or TDS concentration; $q_{\bar{x}}$ and $q_{\bar{y}}$ 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 d is the average depth over a tidal cycle. The term K_eCd, 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 (31). The primary difference in the form of Equation [4] given above and that reported previously (31), is that Equation [4] is written in terms of net flows per foot of width rather than tidally averaged velocities.

The numerical technique employed in the salinity model involves an alternating direction implicit (ADI) solution of Equation [4] applied over the same grid configuration used in the tidal hydrodynamic model to determine the net flows and tidally averaged depths. Because of its implicit formulation the ADI solution scheme is unconditionally stable and there are no restrictions on the computational time step, Δt. However, to maintain accuracy and to minimize round-off and truncation errors, a condition corresponding to $\Delta t/\Delta s^{-2} \leqslant 1/2$ was always maintained throughout this work. Details of the numerical solution of Equation [4] and programming techniques have also been previously described by Masch (31).

The computational grid network used to describe the Trinity-San Jacinto estuary is illustrated in Figure 17. 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 the 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 17, cells were numbered with the indices $1 < i < IMAX = 46$ and $1 < j < JMAX = 32$. With this arrangement, all model parameters such as water depths, flows in each coordinate direction, bottom friction, and salinity could be identified with each cell in the grid.

The grid network used in this work differs from the network originally developed for the Galveston Bay Project. Rollover Pass has been included as an exchange point between the Gulf and East Bay. The Houston Ship Channel above Morgans Point has been removed from the network. This has the effect of removing the inflows from all the basins above Morgan's Point, including the San Jacinto River, as an input to the models and replacing them with the tide measured at the Morgans Point tide gage.

(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 with 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, including the output from the tidal hydrodynamics model, the salinity concentrations of all inflows to the estuary, and an initial distribution with the estuary.

Application of Mathematical Models, Trinity-San Jacinto Estuary

The historic monthly total freshwater inflows to the Trinity-San Jacinto estuary for the years 1941

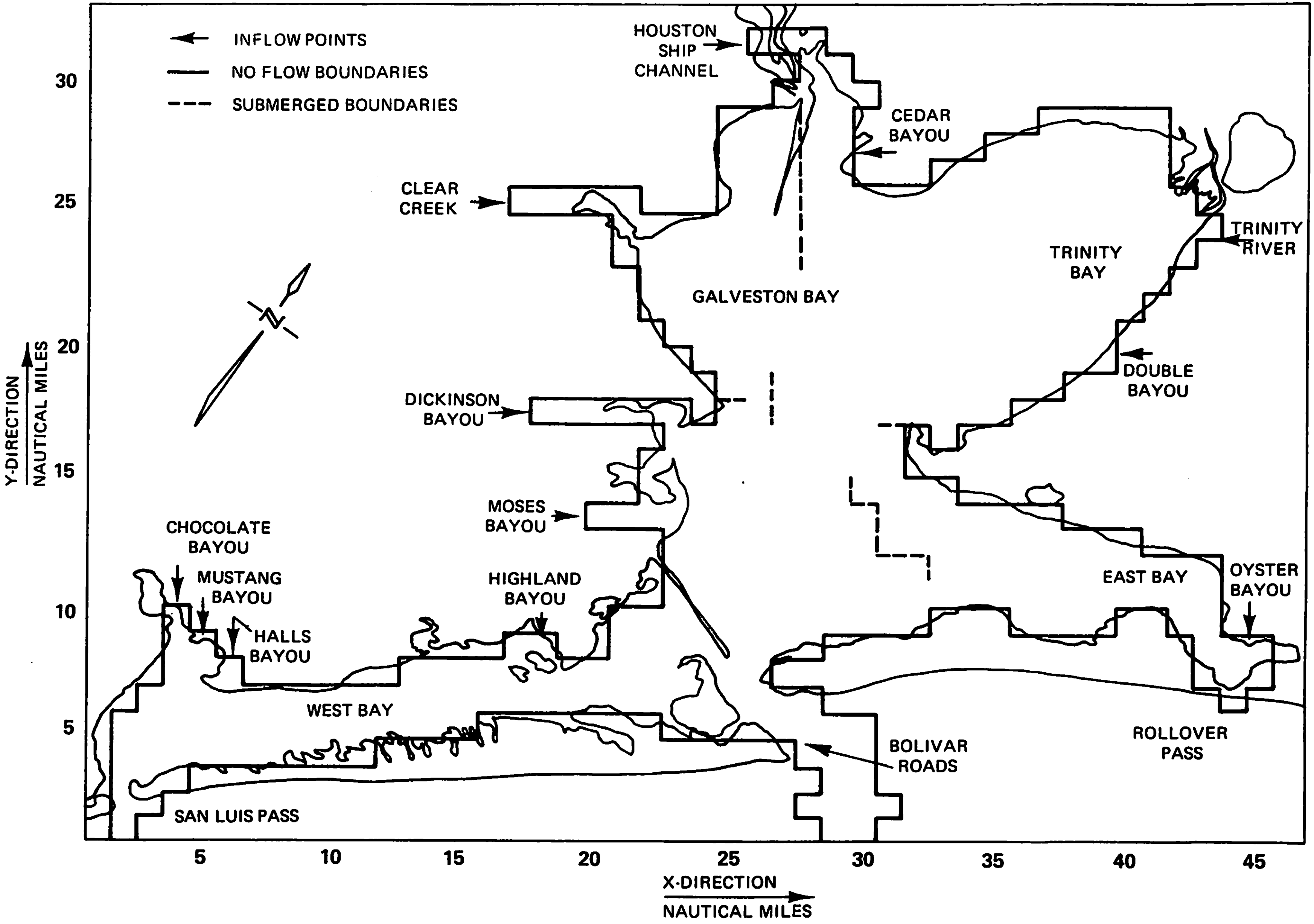


Figure 17.—Computational Grid, Trinity-San Jacinto Estuary

through 1976 were computed from gaged flow and precipitation records.[1] Using these computed inflows, the mean inflows for each month were determined (Table 2). The average monthly freshwater inflows for the Trinity-San Jacinto estuary over the period 1941 through 1976 (excluding the San Jacinto River) were distributed according to the histogram given in Figure 18. The month with the greatest contribution of freshwater inflow is May, with 15.4 percent of the total annual inflow; August has the lowest average historical inflow, accounting for 4.0 percent of the total freshwater inflow to 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 Trinity-San Jacinto estuary for each month of the year.

The output of the tidal hydrodynamics model consists of a set of tidal amplitudes and net flows computed for each cell in the 46 × 32 computational matrix representing the Trinity-San Jacinto estuary. The computed net flows are the average of the instantaneous flows calculated by the model over the tidal cycle. 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 Trinity-San Jacinto estuary for each of the mean monthly inflow periods. The resultant salinity distributions are illustrated in the form of salinity contour plots wherein lines of uniform salinity are shown in increments of five parts per thousand (ppt).

The numerical tidal hydrodynamic and salinity mass transport models described earlier were applied to the Trinity-San Jacinto estuary to determine the effects of the monthly average freshwater inflow upon the flow circulation and salinity characteristics of the estuarine system. The simulation models were general in nature and required adjustment or calibration to fit the conditions in the Trinity-San Jacinto system. The models were calibrated using tidal amplitudes, tidal flows, and salinities measured during the comprehensive data collection program of July 20-23, 1976. In addition, in order to test the reliability of the salinity transport model to properly replicate historically observed salinities, the recorded historical freshwater inflow rates and tidal elevations for 1974 through 1976 were used to simulate the salinity distributions in the Trinity-San Jacinto estuary. The appropriate coefficients in the simulation models were adjusted to provide reasonably close replications of observed historical conditions.

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

Simulated Flow Patterns

The simulated steady-state net flows in the Trinity-San Jacinto estuary are given in Figures 19 through 30 for each of the twelve months. The magnitude of flow is given by the length of each vector, with one inch corresponding to approximately 24,000 cubic feet per second (ft^3/sec).

Examination of the circulation plots for each of the numerical situations (using the average monthly inflows and representative tides) revealed that the general circulation patterns in the Trinity-San Jacinto estuary could be divided into three groupings based upon similar patterns: (1) March, August and October; (2) January, February, July, September, November and December; and (3) April, May and June. The circulation patterns exhibited by the numerical simulations in each of the three cases are discussed below.

(1) Simulated March, August and October Circulation Patterns Under Average Monthly Inflow Conditions.

The flow circulation in the Trinity-San Jacinto estuary is simulated under historical average meteorological and freshwater inflows indicated similar circulation patterns for the months of March, August and October (Figures 21, 26 and 28). The most evident circulation pattern in the estuary during the indicated months was a northwesterly directed current in the Houston Ship Channel toward Morgans Point. The magnitude of the net flow in the Ship Channel was exceeded only by the flow rate in the vicinity of Bolivar Pass. The dominant pattern in Trinity Bay was a clockwise circulation induced by inflow from the Trinity River as it moved along the eastern shore of Trinity Bay. The current in West Bay was predominantly directed in a northeasterly direction from San Luis Pass through the Galveston Ship Channel. The movement of water in East Bay was generally in an

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[1] The San Jacinto River was excluded from these computations since the tidal stage at Morgans Point was used to drive the model rather than the San Jacinto River inflows.

Table 2.—Mean Monthly Freshwater Inflow Trinity-San Jacinto Estuary 1941-1976

Month	Trinity[1] Bayou	Halls[2] Bayou	Highland[2] Bayou	Mustang[3] Bayou	Oyster[2] Bayou	Chocolate[1] Bayou	Moses[3] Bayou	Dickinson[2] Bayou	Double[2] Bayou	Clear[1] Creek	Cedar[1] Bayou
January	9,316	33	33	244	443	163	81	130	228	959	341
February	10,224	36	36	306	504	198	108	162	252	954	360
March	10,064	33	33	244	325	146	65	130	163	683	211
April	12,415	34	34	218	538	168	101	118	286	470	403
May	18,290	49	49	293	537	244	163	146	276	1,203	390
June	11,911	50	50	336	454	302	114	185	235	1,138	370
July	5,333	98	98	195	943	553	97	114	634	1,642	780
August	2,585	16	16	163	471	163	65	81	244	1,626	211
September	3,511	84	84	319	706	437	84	168	487	1,646	588
October	4,634	49	49	211	553	370	81	114	423	894	537
November	6,266	34	34	185	302	151	67	101	168	873	269
December	8,682	33	33	211	423	179	81	114	228	813	325

[1] Total gaged and ungaged flow and municipal, industrial, and irrigation return flow and diversions in ft^3/sec

[2] Total ungaged flow and irrigation return flow in ft^3/sec

[3] Total ungaged flow in ft^3/sec

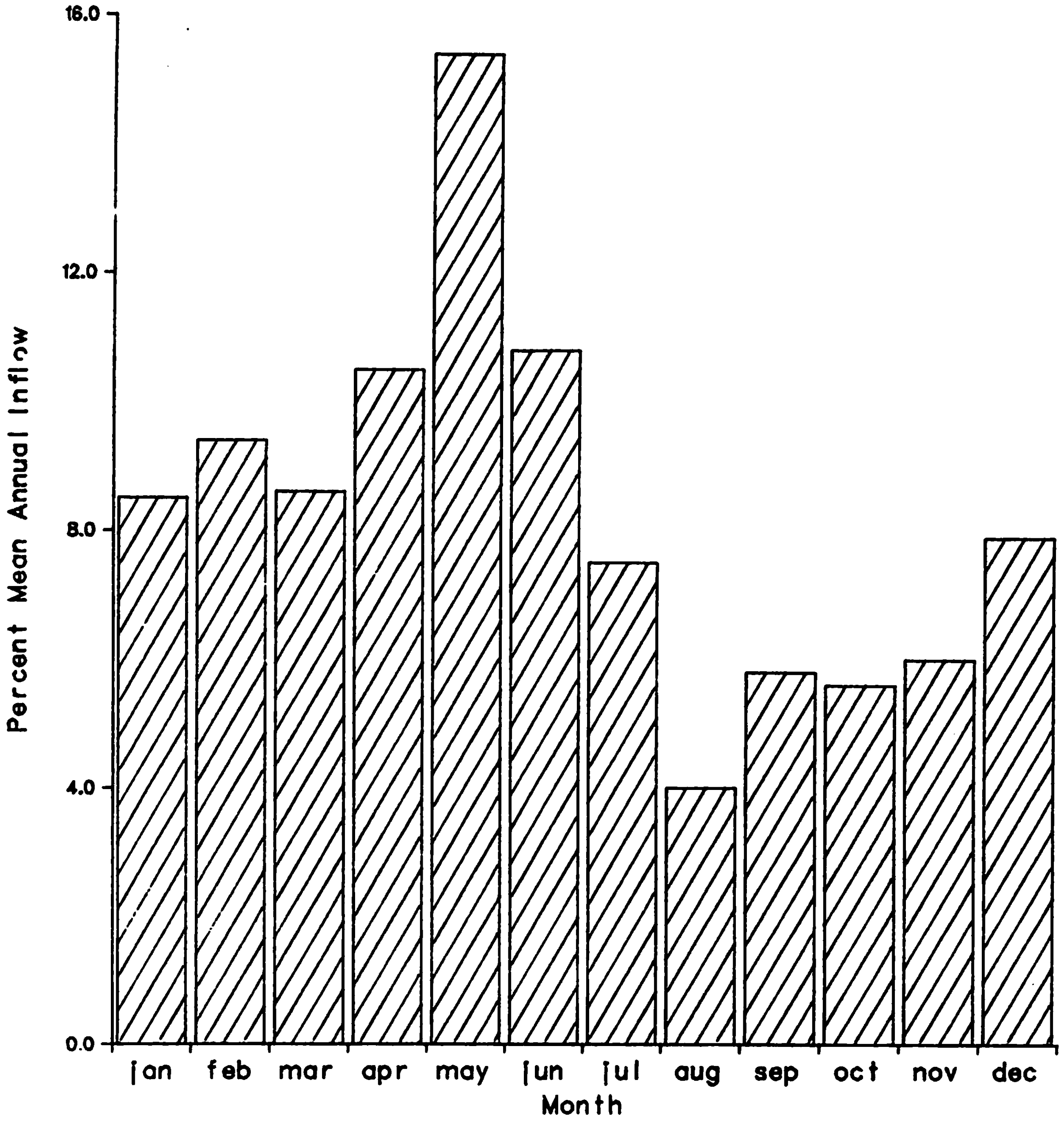

Figure 18.—Total Mean Monthly Inflow Distribution Trinity-San Jacinto Estuary, Gaged, Ungaged, and Return Flows Excluding San Jacinto River

easterly direction from Galveston Bay through Rollover Pass at the eastern end of Bolivar peninsula.

The dominant flow pattern in Galveston Bay was a movement of water up the Houston Ship Channel toward Morgans Point. This northwesterly movement of water along the Ship Channel induced return currents on either side of the Channel moving in the opposite direction; thus, there was a net southeasterly current along the western shore of Galveston Bay.

The simulated net circulation of water among the various bays was predominanatly from the Trinity River into Galveston Bay and from Galveston Bay into East Bay. Limited exchange occurred between Galveston Bay and West Bay. The net flow through Bolivar Pass during these months was out of the estuary into the Gulf, except during the month of August when flow was from the Gulf into Galveston Bay.

(2) Simulated January, February, July, September, November and December Circulation Patterns Under Average Monthly Inflow Conditions.

The flow circulations in the Trinity-San Jacinto estuary simulated under historical average meteorological and freshwater inflows indicated similar flow patterns for the months of January, February, July, September, November and December (Figures 19, 20, 25, 27, 29 and 30). The most evident circulation pattern in the estuary during these indicated months was a southeasterly directed current in the Houston Ship Channel. The magnitude of the simulated current in the Ship Channel was generally exceeded only by the flow rates in the vicinity of Bolivar Pass. The dominant flow in Trinity Bay was a counterclockwise rotating circulation induced by the inflow from the Trinity River moving along the northwesterly shore of Trinity Bay. The circulation patterns in West Bay indicated that an internal current rotating counter-clockwise predominated, with the net water movement from Bolivar Pass through the Galveston Ship Channel into West Bay, and from West Bay through San Luis Pass into the Gulf of Mexico. The simulated net flow of water in the western portion of East Bay is dominated by a northerly current from Galveston Bay into Trinity Bay. A secondary net flow was found in West Bay which moved from Galveston Bay through Rollover Pass at the eastern end of Bolivar peninsula.

The circulation pattern for Galveston Bay showed a net movement of water down the Houston Ship Channel toward the Gulf. The movement of water along the Ship Channel generally induced return currents on either side moving in the opposite direction.

The circulation patterns simulated for the various bay systems indicated a predominant net flow from Trinity Bay into Galveston Bay and then into East Bay. Only limited exchange occurred between Galveston Bay and West Bay. The net flow through Bolivar Pass during these months was directed toward the estuary from the Gulf. The month of September was an exception, when flow moved from Galveston Bay toward the Gulf of Mexico.

(3) Simulated April, May and June Circulation Patterns Under Average Monthly Inflow Conditions

The flow circulations in the Trinity-San Jacinto estuary simulated under historical average meteorological and freshwater inflows revealed similar flow patterns for the months of April, May and June (Figures 22, 23 and 24). The most evident circulation pattern for the estuary for the indicated months was a southeasterly current in the Houston Ship Channel. The magnitude of the current in the ship channel was exceeded only by flow rates in the vicinity of Bolivar Pass. The dominant flow circulations in Trinity Bay included a counter-clockwise moving current during both April and May and a clockwise rotating current in June, both induced by the inflow from the Trinity River. The simulated current patterns in West Bay showed water movement predominantly in a northeasterly direction from San Luis Pass through the Galveston Ship Channel. The movement of water in East Bay was generally in an easterly direction from Galveston Bay through Rollover Pass at the eastern end of Bolivar Peninsula.

The simulated circulation pattern predominating in Galveston Bay indicated a circulation based upon the movement of water southeastward along the Houston Ship Channel toward the Gulf of Mexico. This movement of water in the Ship Channel induced return currents on either side moving in the opposite direction in the months of April and May. The net simulated water movement was uniformly southerly over Galveston Bay in the June simulation.

The circulation patterns simulated for the various bay systems indicated a predominant net flow from Trinity Bay into Galveston Bay and then into East Bay. Net flow exchange also occurred from West Bay into Galveston Bay. The net flow through Bolivar Pass during these months was toward the Gulf, while the net simulated flow through San Luis Pass was into West Bay from the Gulf.

Simulated Salinity Patterns

The results of the hydrodynamic simulations using the mean monthly inflows were utilized to execute the salinity transport model. An application of the salinity model was undertaken for each of the average historical monthly conditions. The evaluation of the simulated monthly salinities in the Trinity-San Jacinto estuary resulting from these model operations (Figures 31 through 42) revealed two distinct salinity distribution patterns: one during

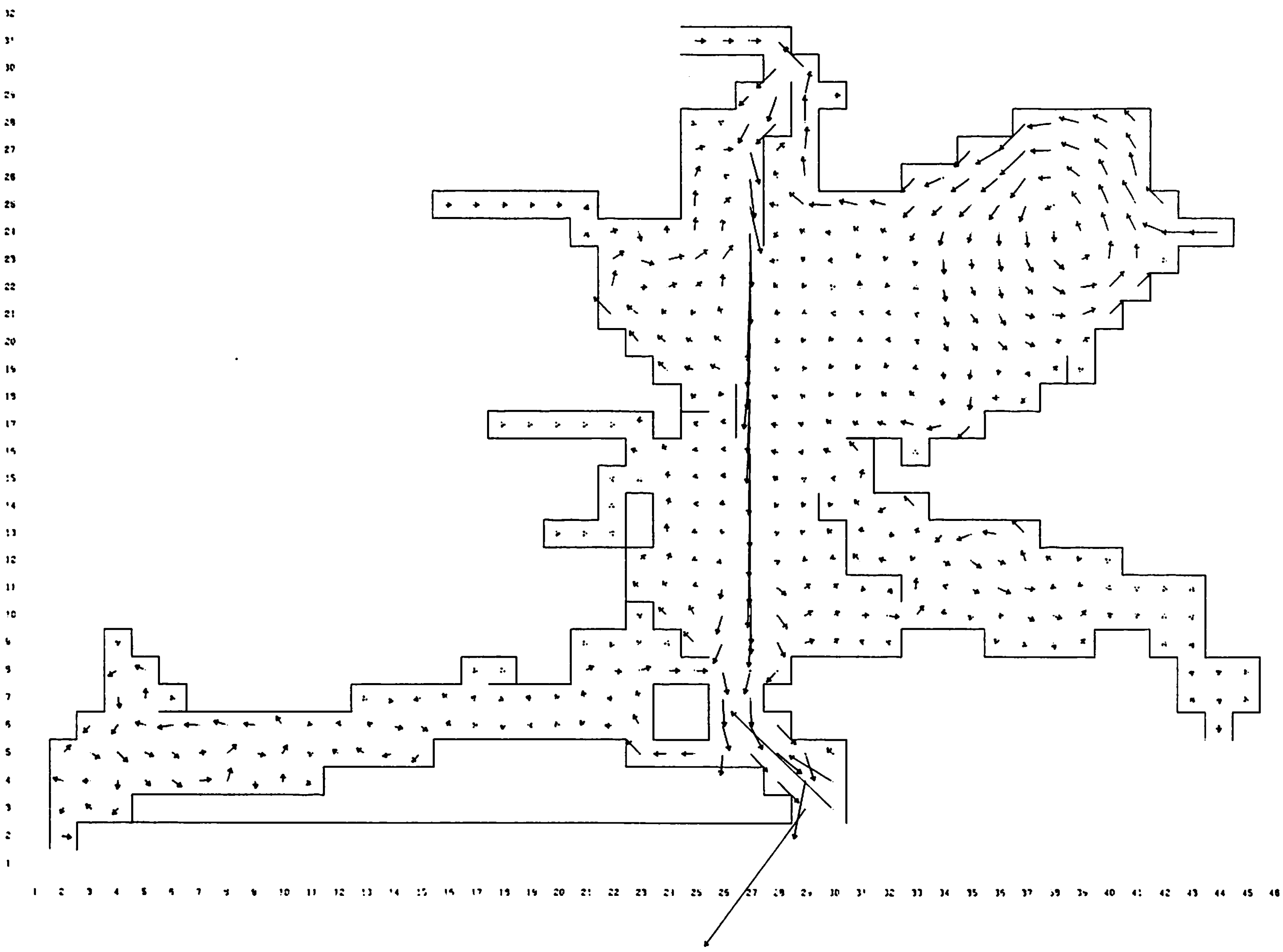

Figure 19.—Simulated Net Steady-State Flows in the Trinity-San Jacinto Estuary Under January Average Inflow (1941-1976)

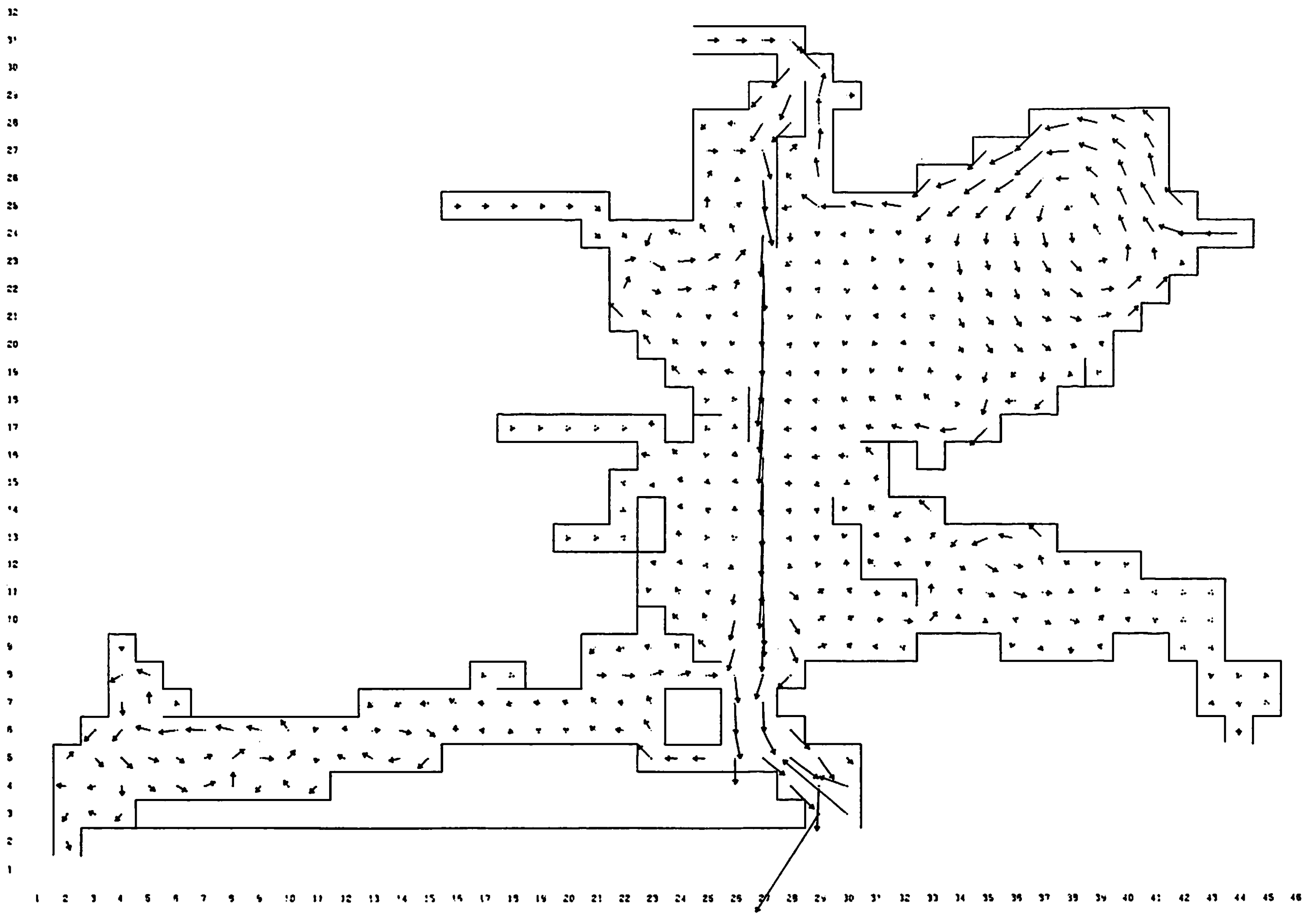

Figure 20.—Simulated Net Steady-State Flows in the Trinity-San Jacinto Estuary Under February Average Inflow (1941-1976)

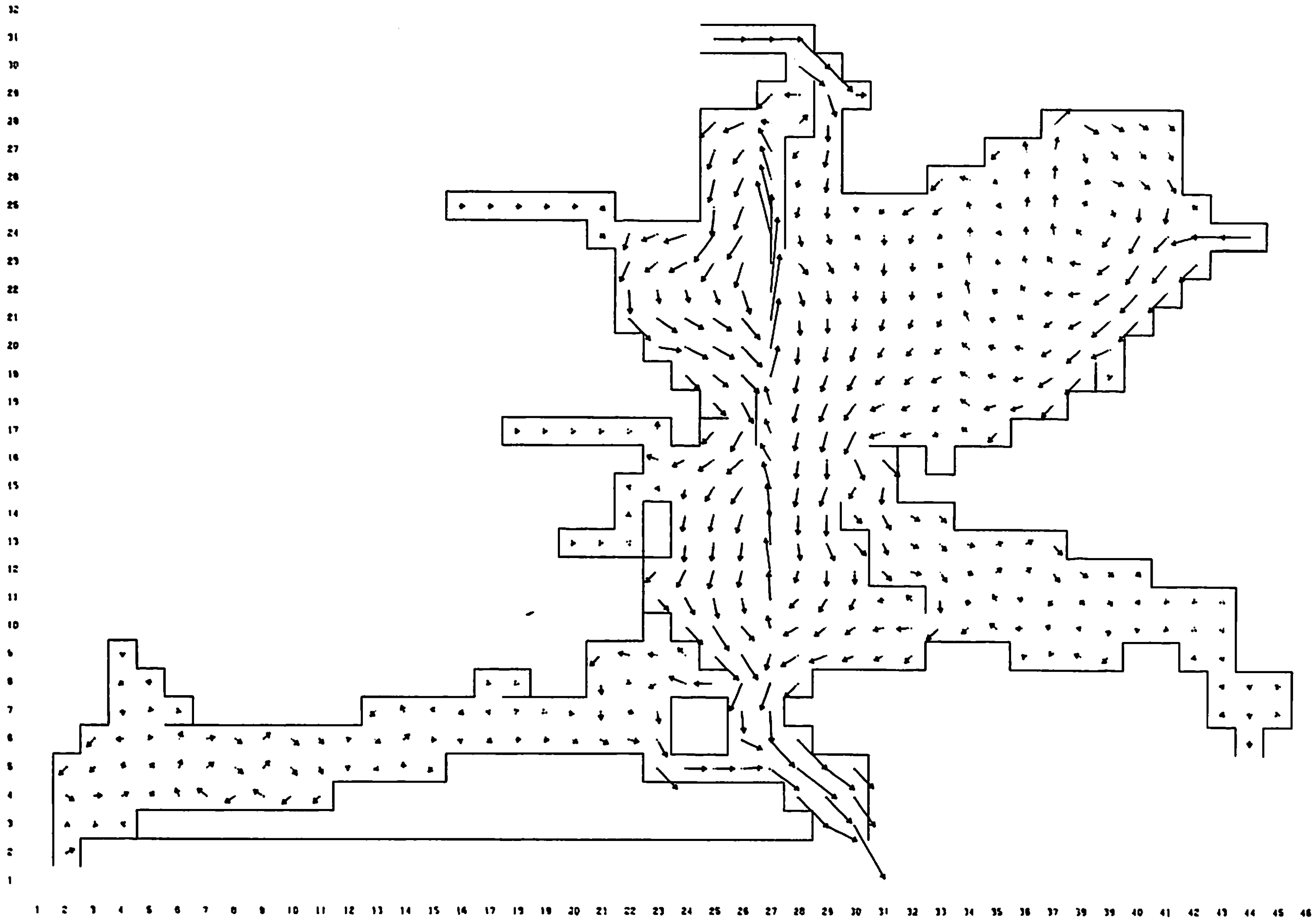

Figure 21.—Simulated Net Steady-State Flows in the Trinity-San Jacinto Estuary Under March Average Inflow (1941-1976)

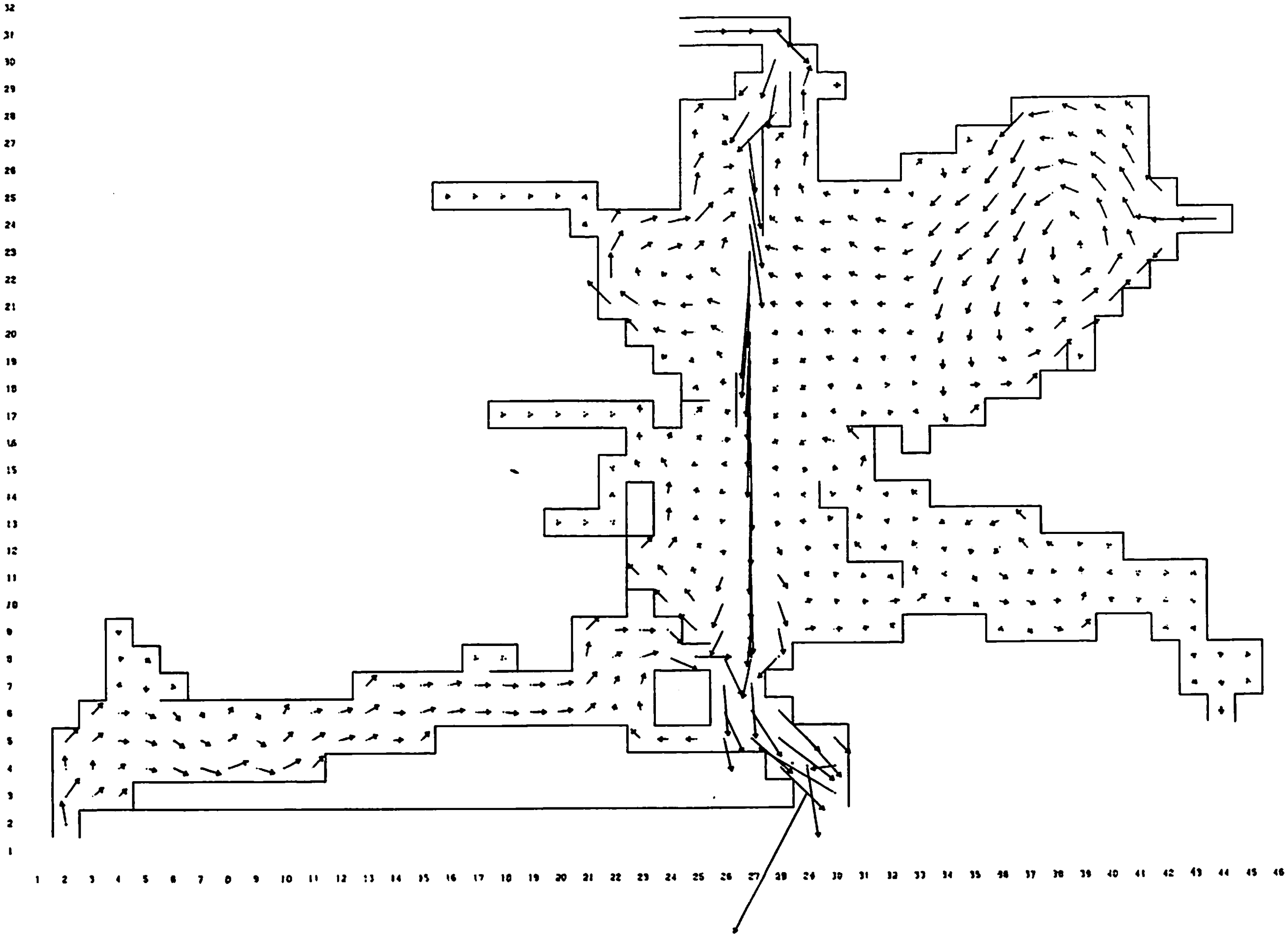

Figure 22.--Simulated Net Steady-State Flows in the Trinity-San Jacinto Estuary Under April Average Inflow (1941-1976)

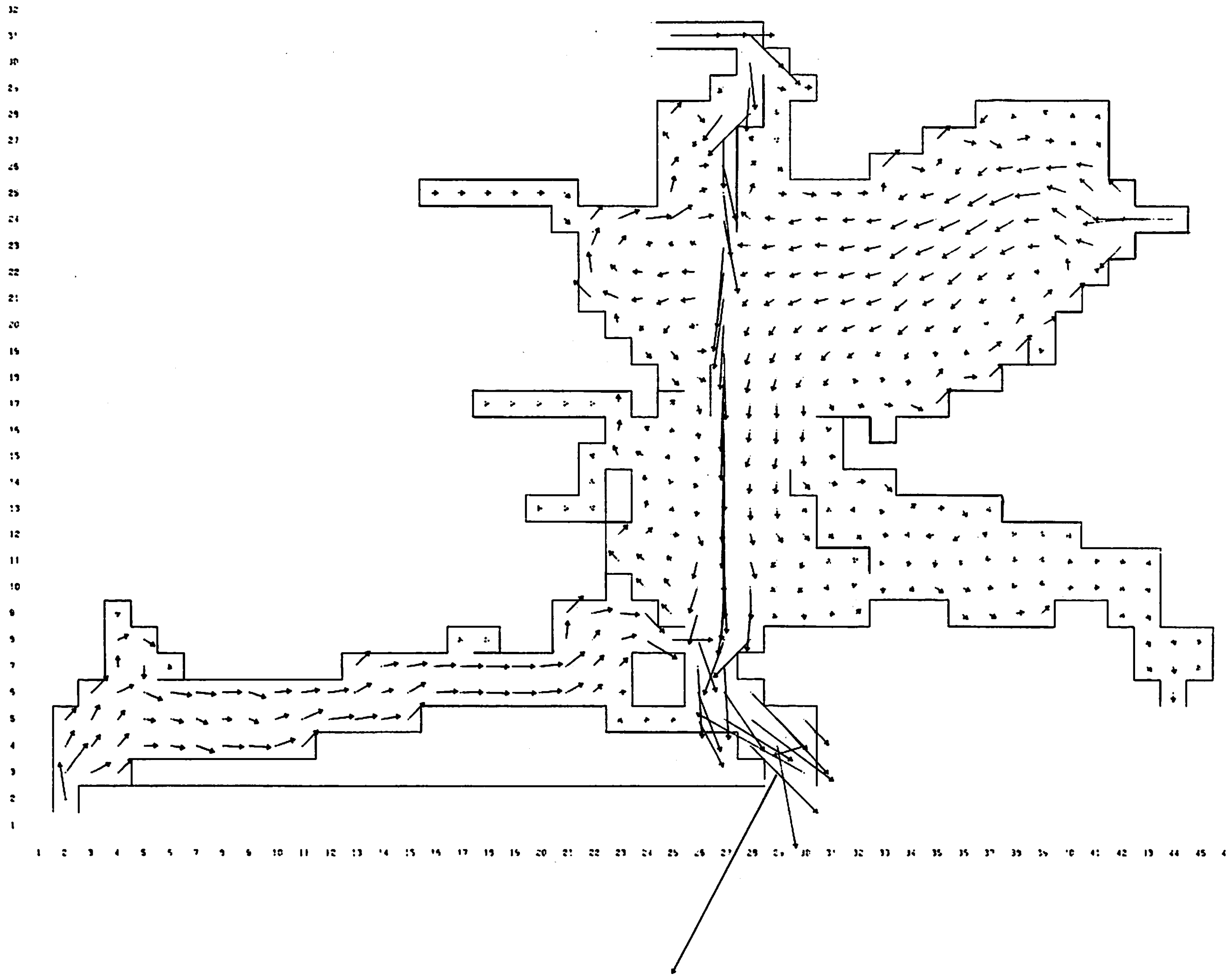

Figure 23.—Simulated Net Steady-State Flows in the Trinity-San Jacinto Estuary Under May Average Inflow (1941-1976)

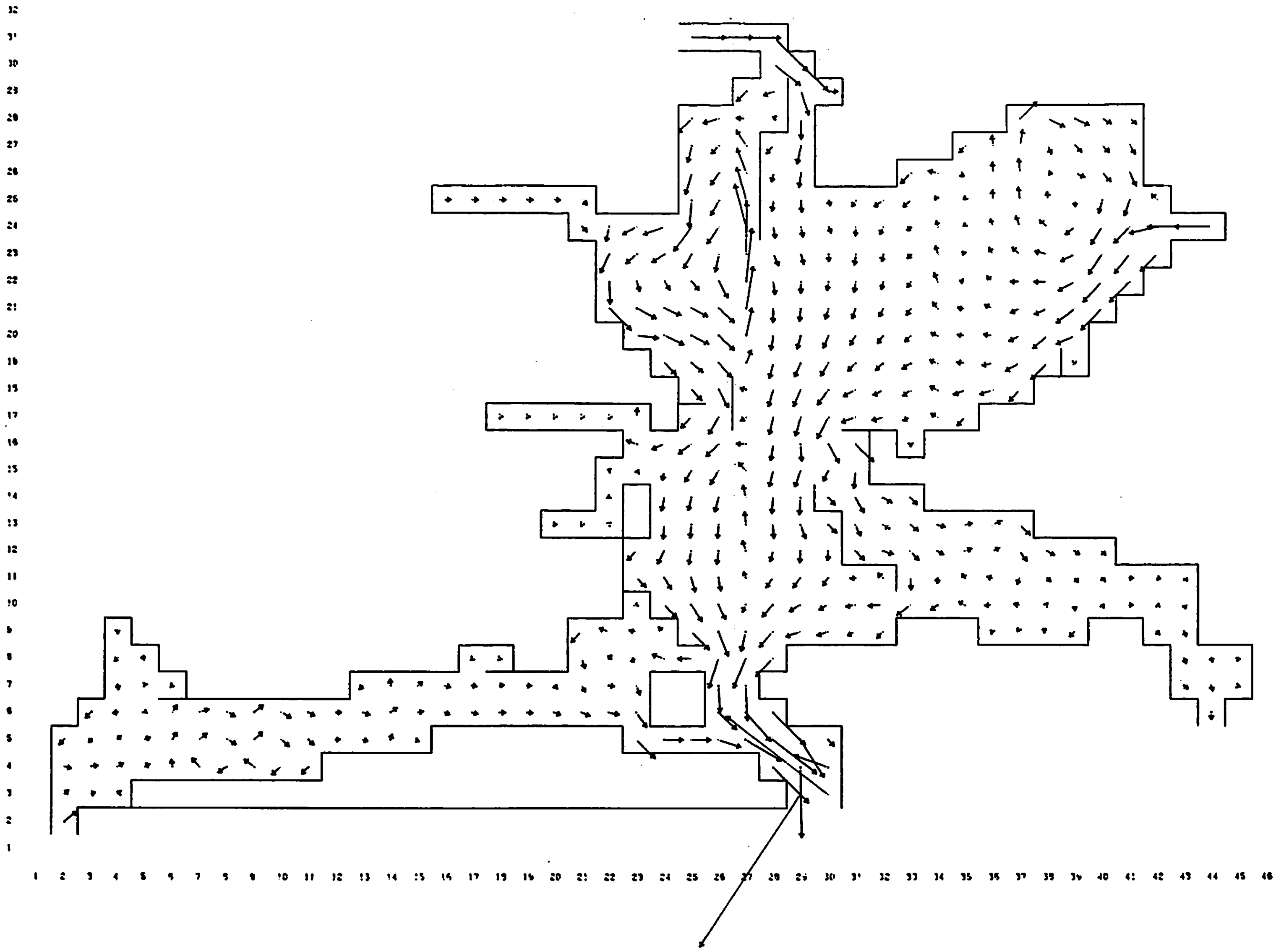

Figure 24.—Simulated Net Steady-State Flows in the Trinity-San Jacinto Estuary Under June Average Inflow (1941-1976)

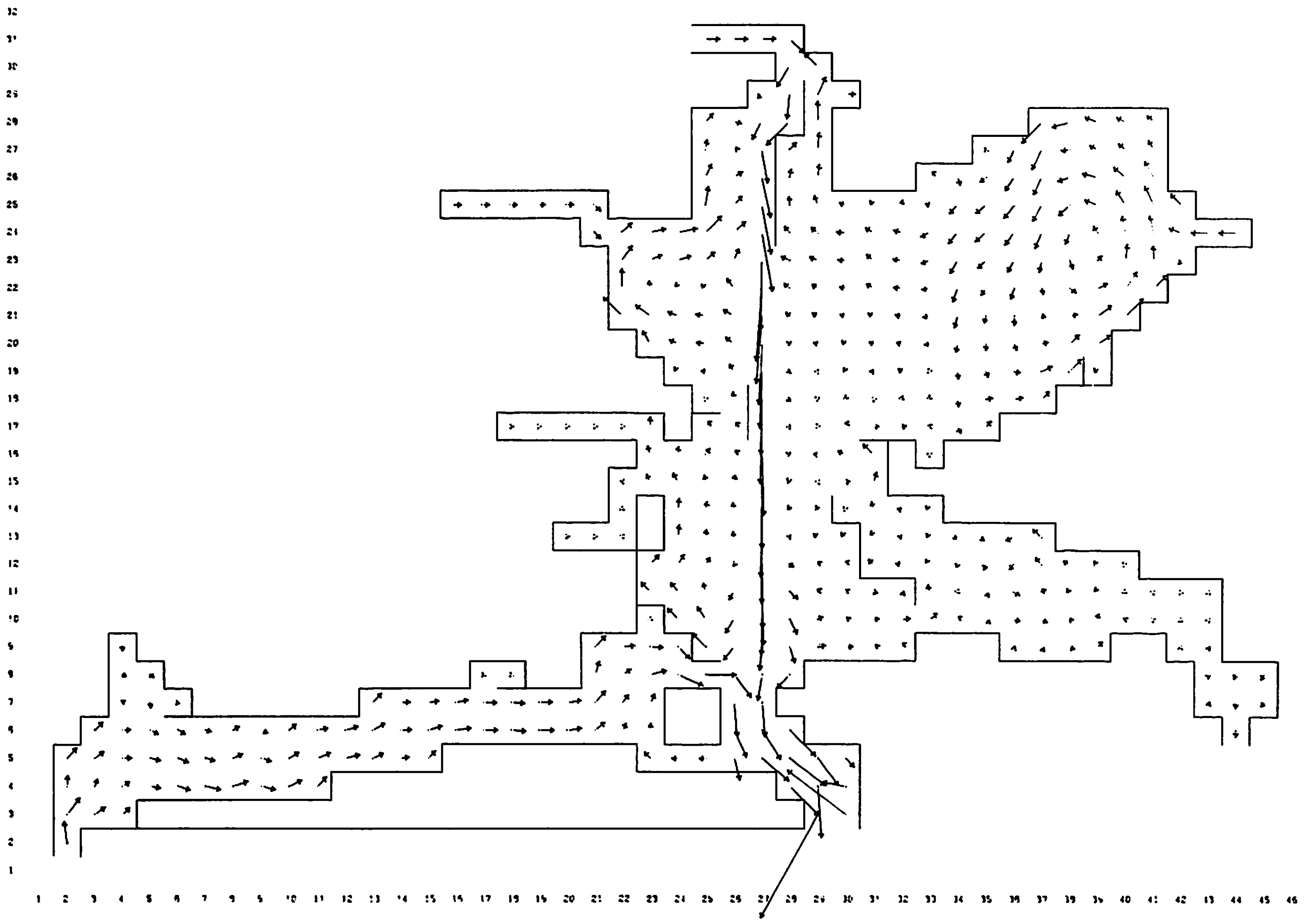

Figure 25.—Simulated Net Steady-State Flows in the Trinity-San Jacinto Estuary Under July Average Inflow (1941-1976)

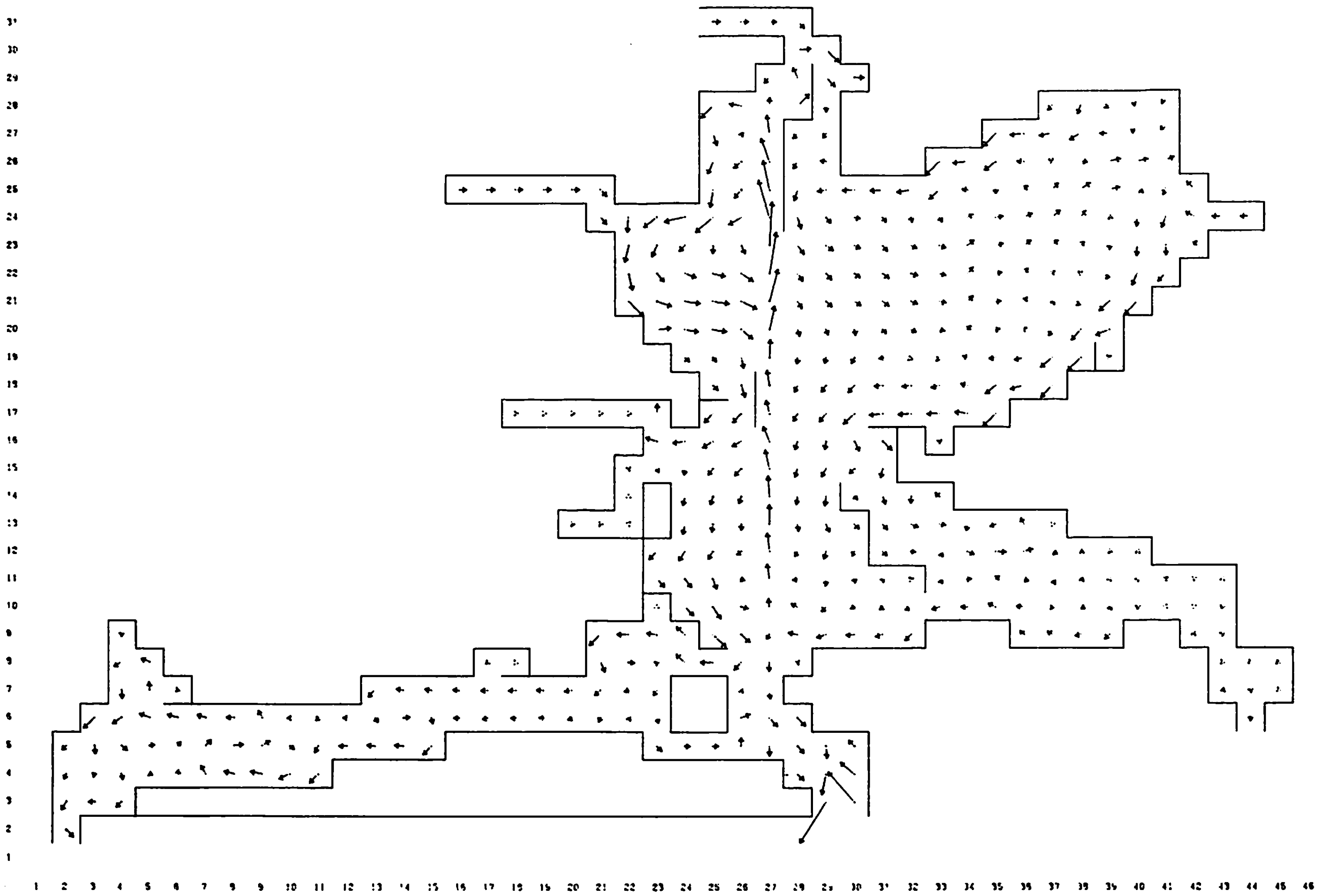

Figure 26.—Simulated Net Steady-State Flows in the Trinity-San Jacinto Estuary Under August Average Inflow (1941-1976)

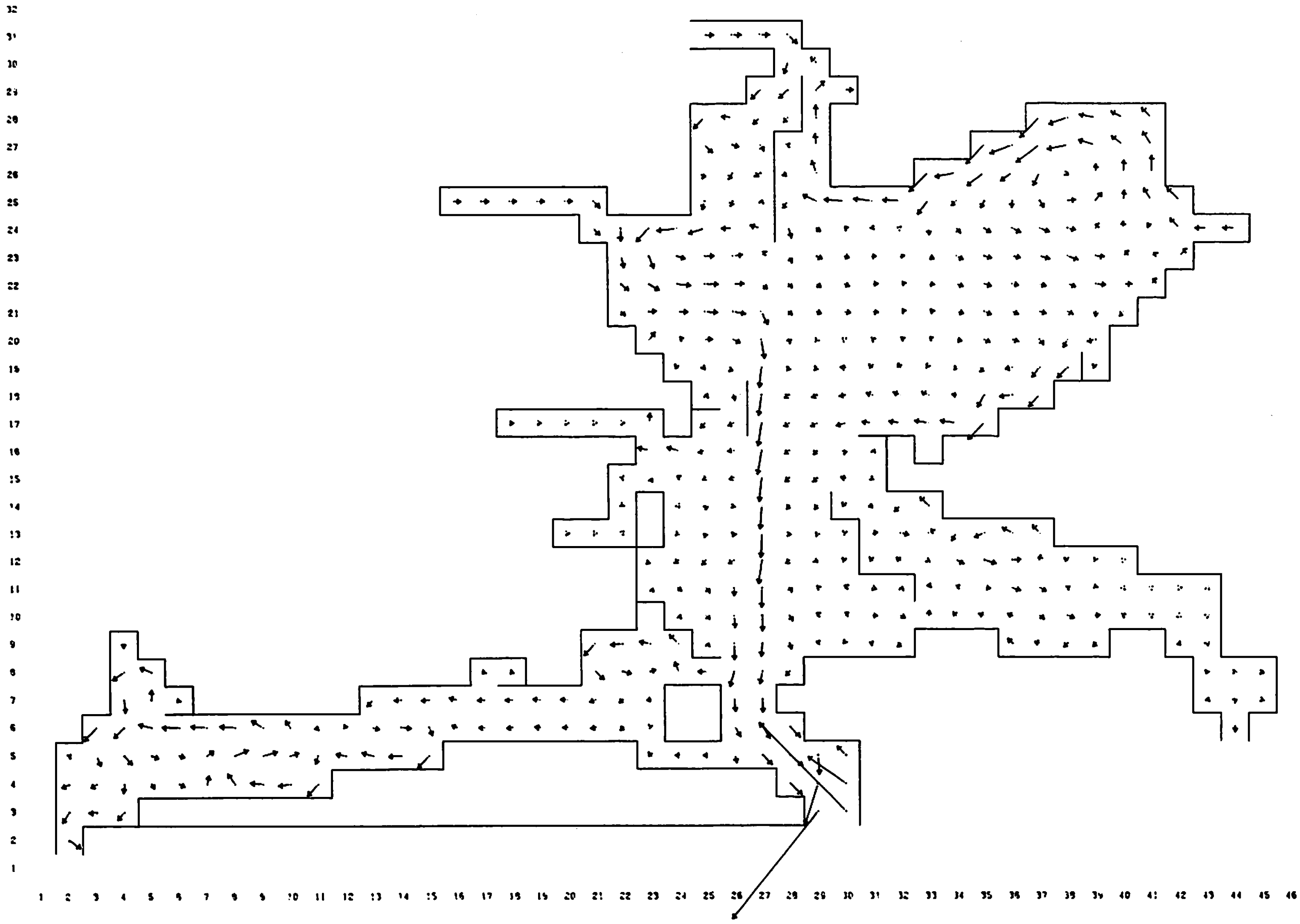

Figure 27.—Simulated Net Steady-State Flows in the Trinity-San Jacinto Estuary Under September Average Inflow (1941-1976)

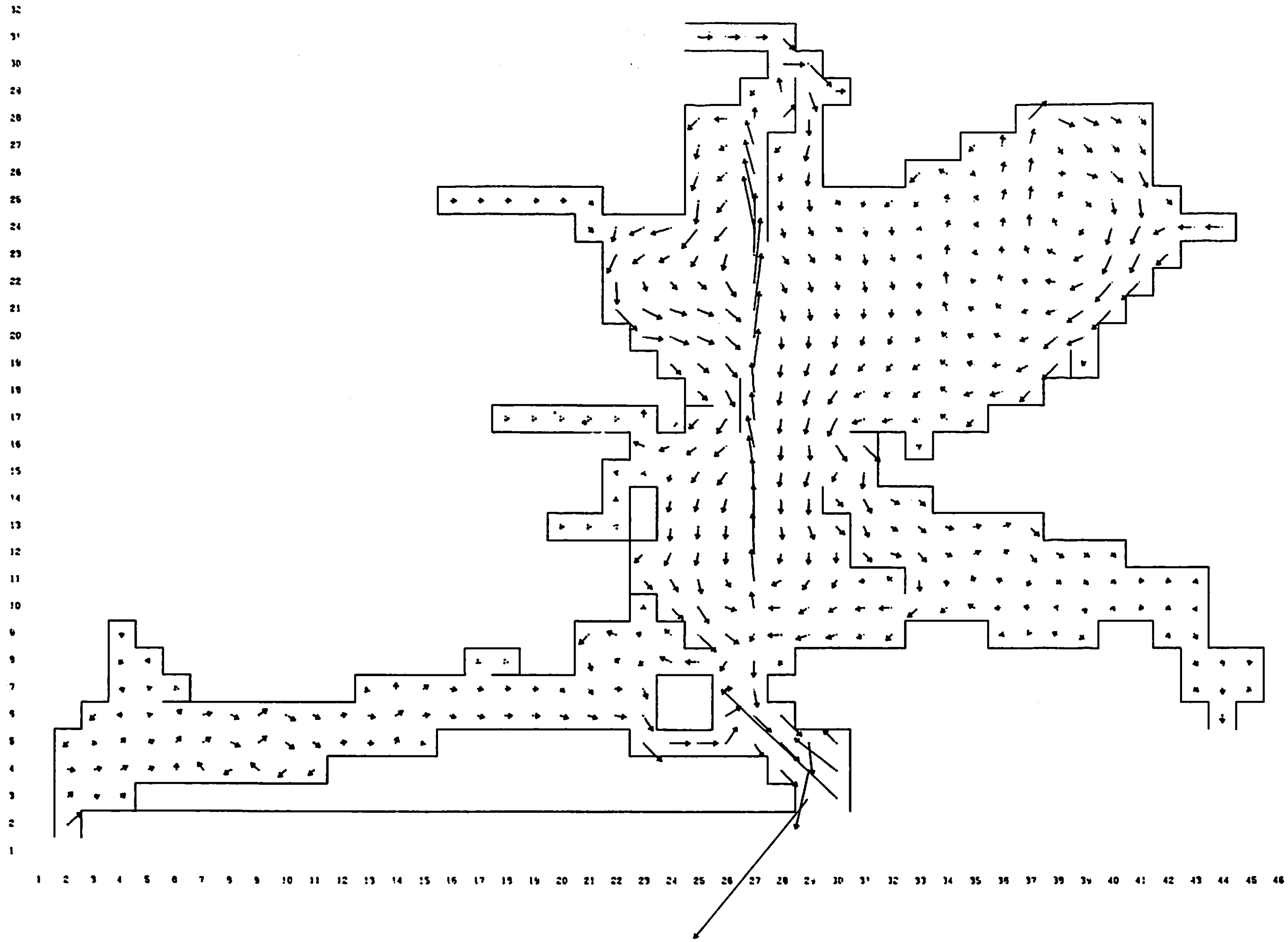

Figure 28.—Simulated Net Steady-State Flows in the Trinity-San Jacinto Estuary Under October Average Inflow (1941-1976)

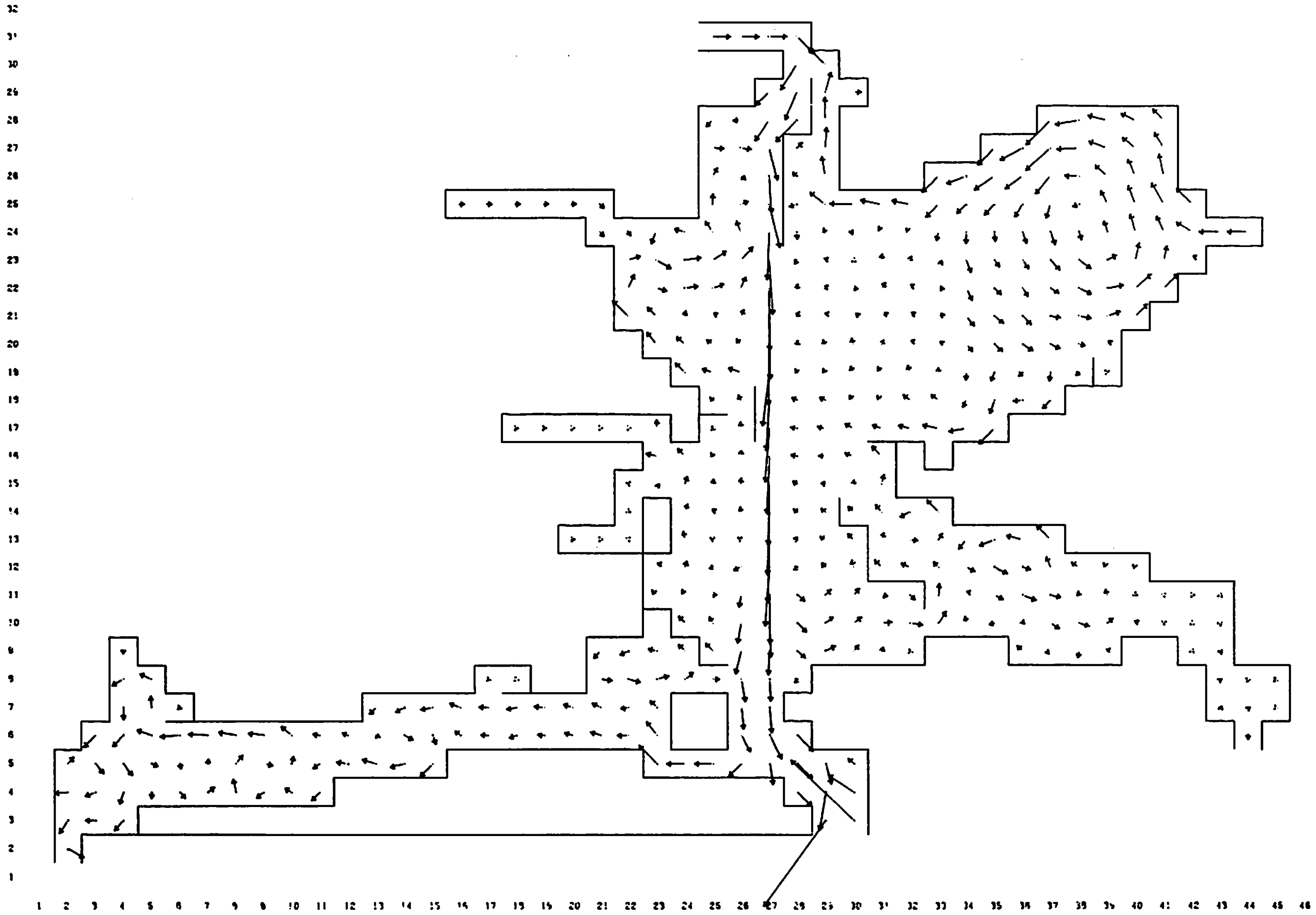

Figure 29.—Simulated Net Steady-State Flows in the Trinity-San Jacinto Estuary Under November Average Inflow (1941-1976)

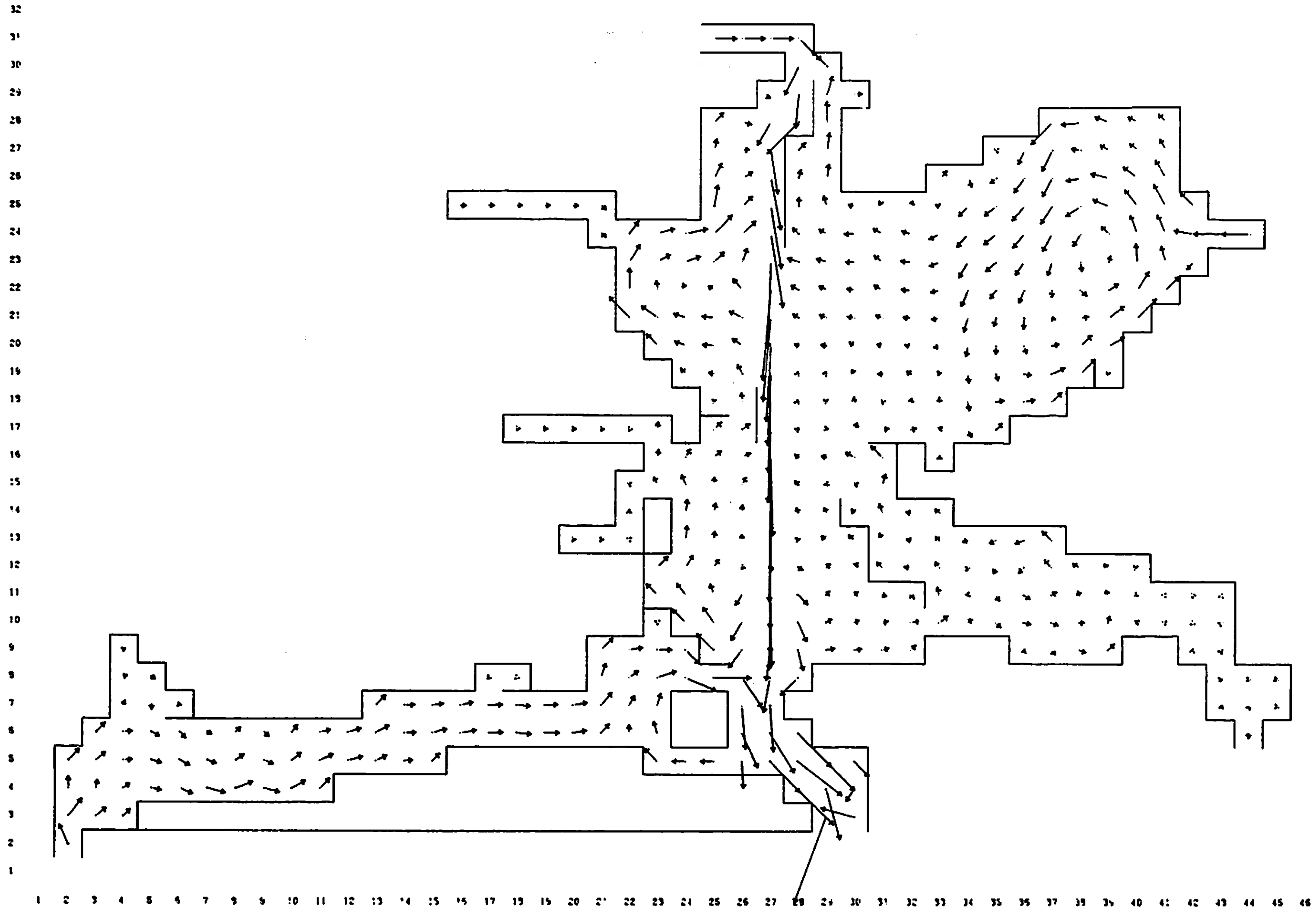

Figure 30.—Simulated Net Steady-State Flows in the Trinity-San Jacinto Estuary Under December Average Inflow (1941-1976)

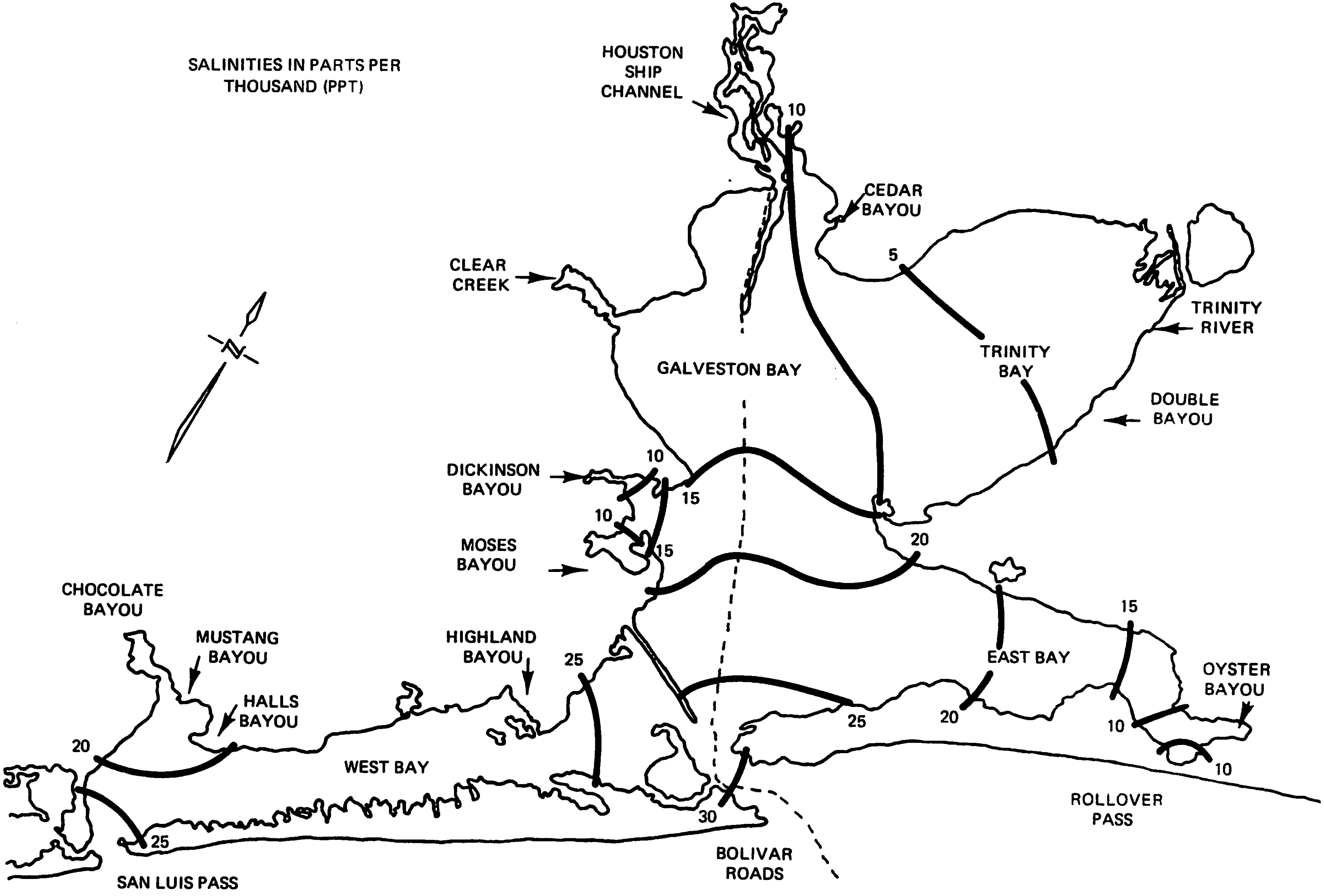

Figure 31.–Simulated Salinities in the Trinity-San Jacinto Estuary Under January Average Inflows

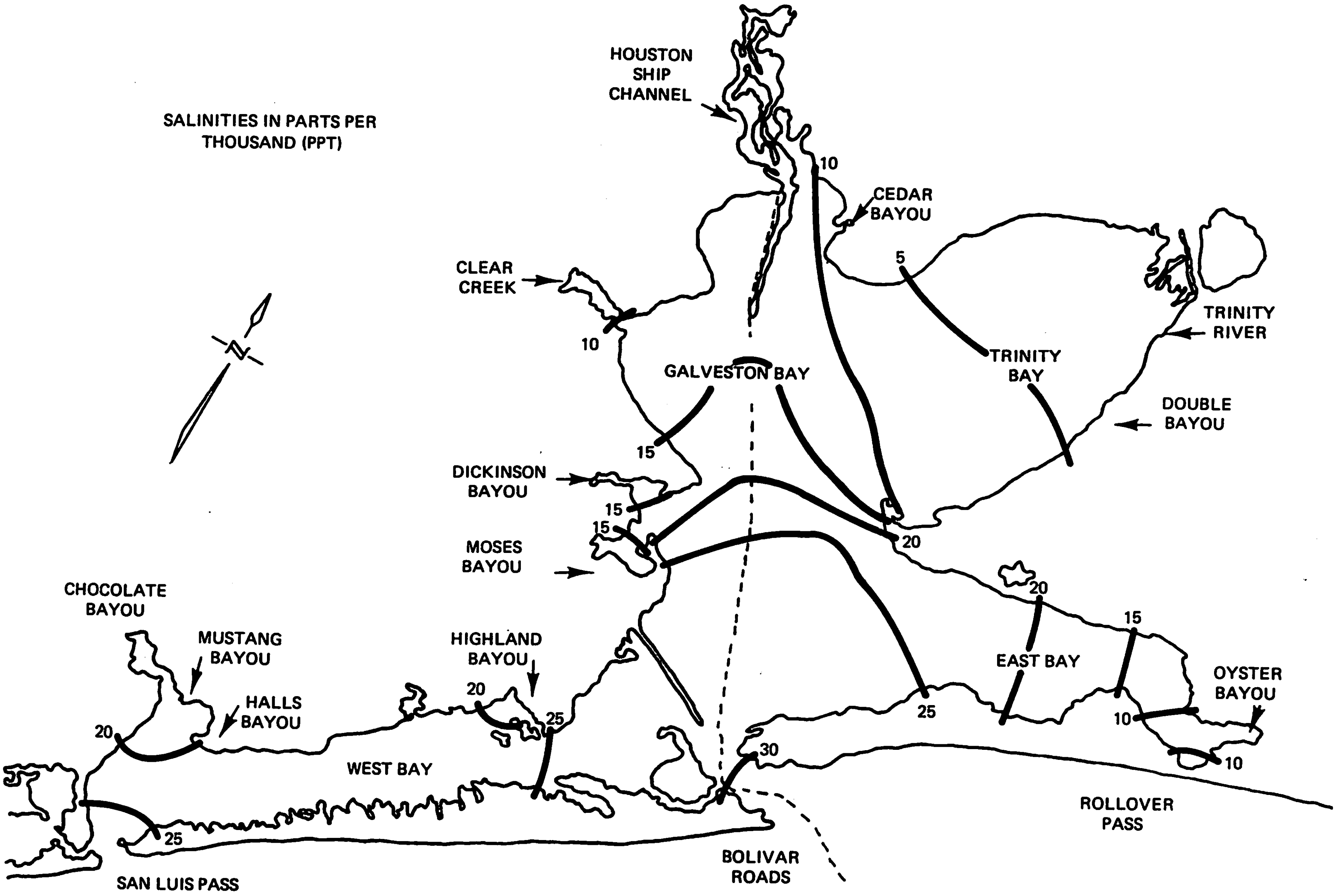

Figure 32.—Simulated Salinities in the Trinity-San Jacinto Estuary Under February Average Inflows

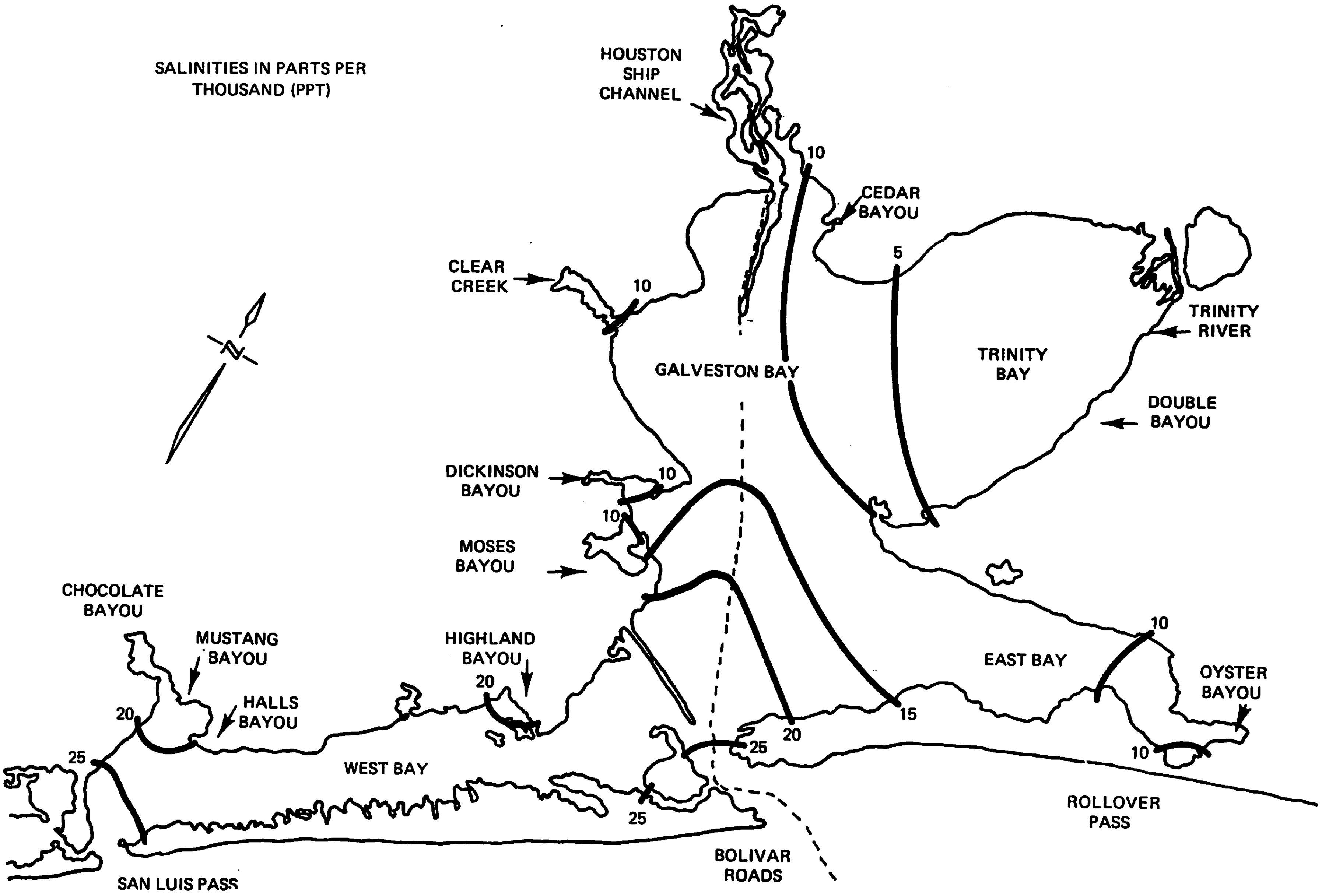

Figure 33.—Simulated Salinities in the Trinity-San Jacinto Estuary Under March Average Inflows

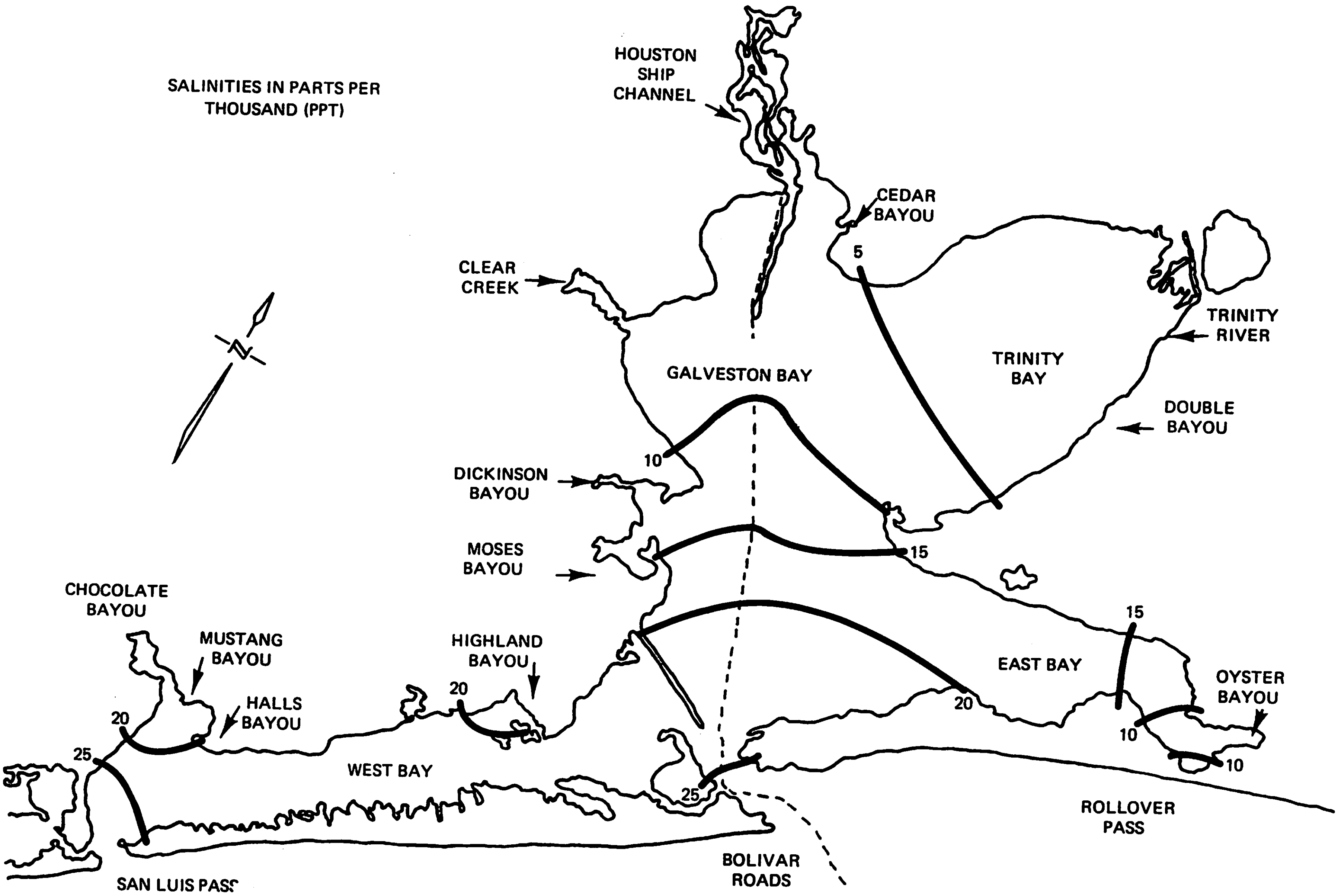

Figure 34.—Simulated Salinities in the Trinity-San Jacinto Estuary Under April Average Inflows

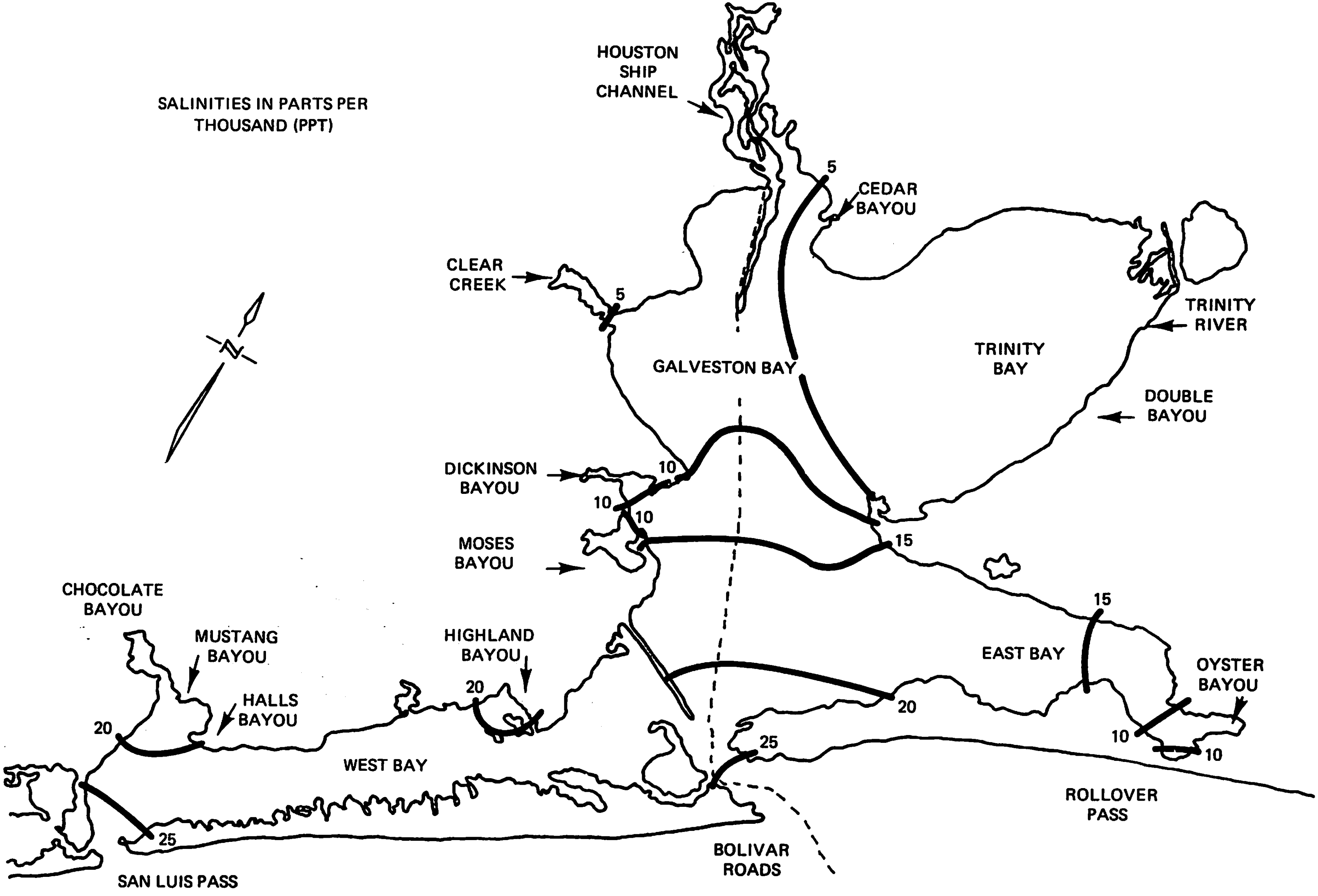

Figure 35.—Simulated Salinities in the Trinity-San Jacinto Estuary Under May Average Inflows

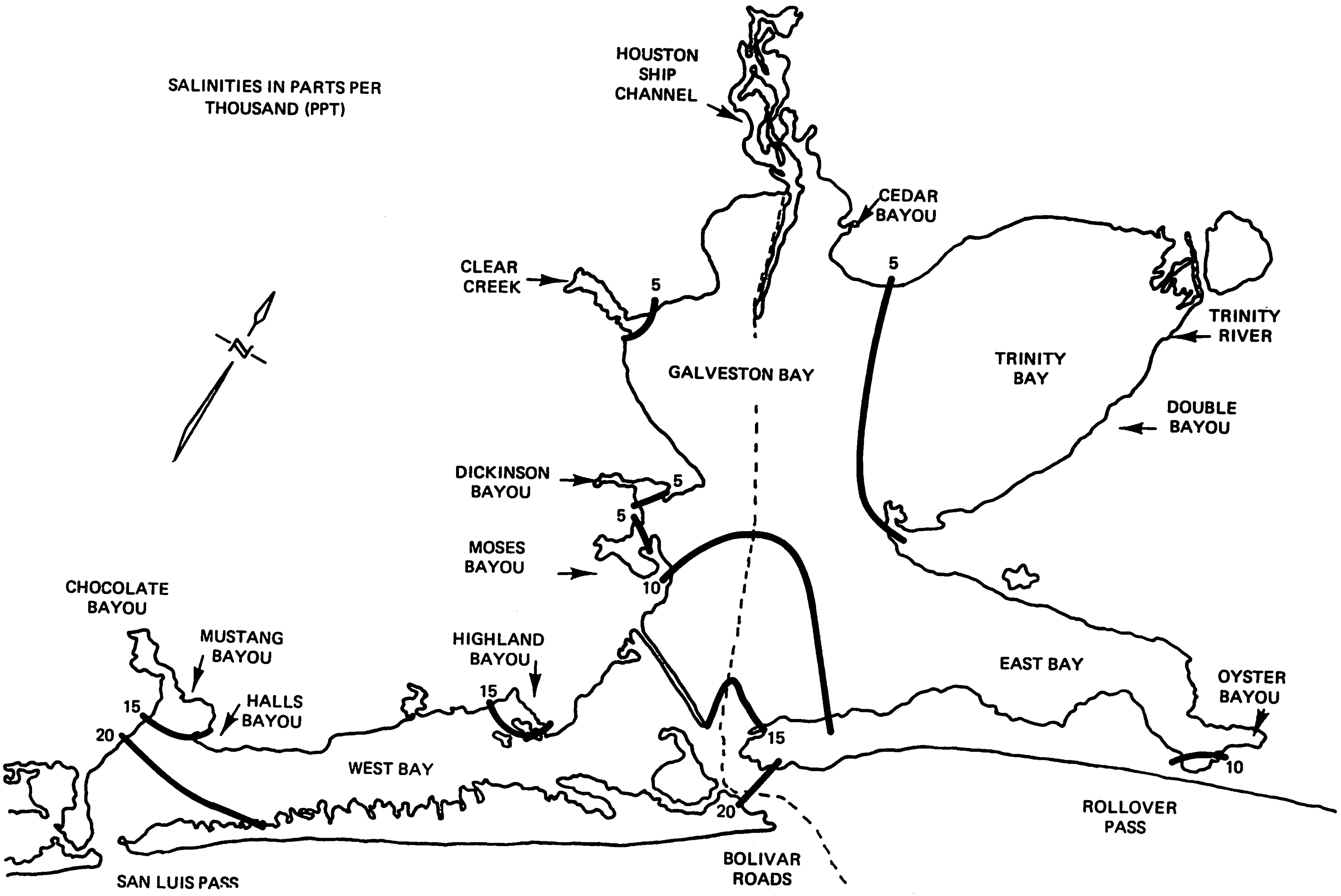

Figure 36.—Simulated Salinities in the Trinity-San Jacinto Estuary Under June Average Inflows

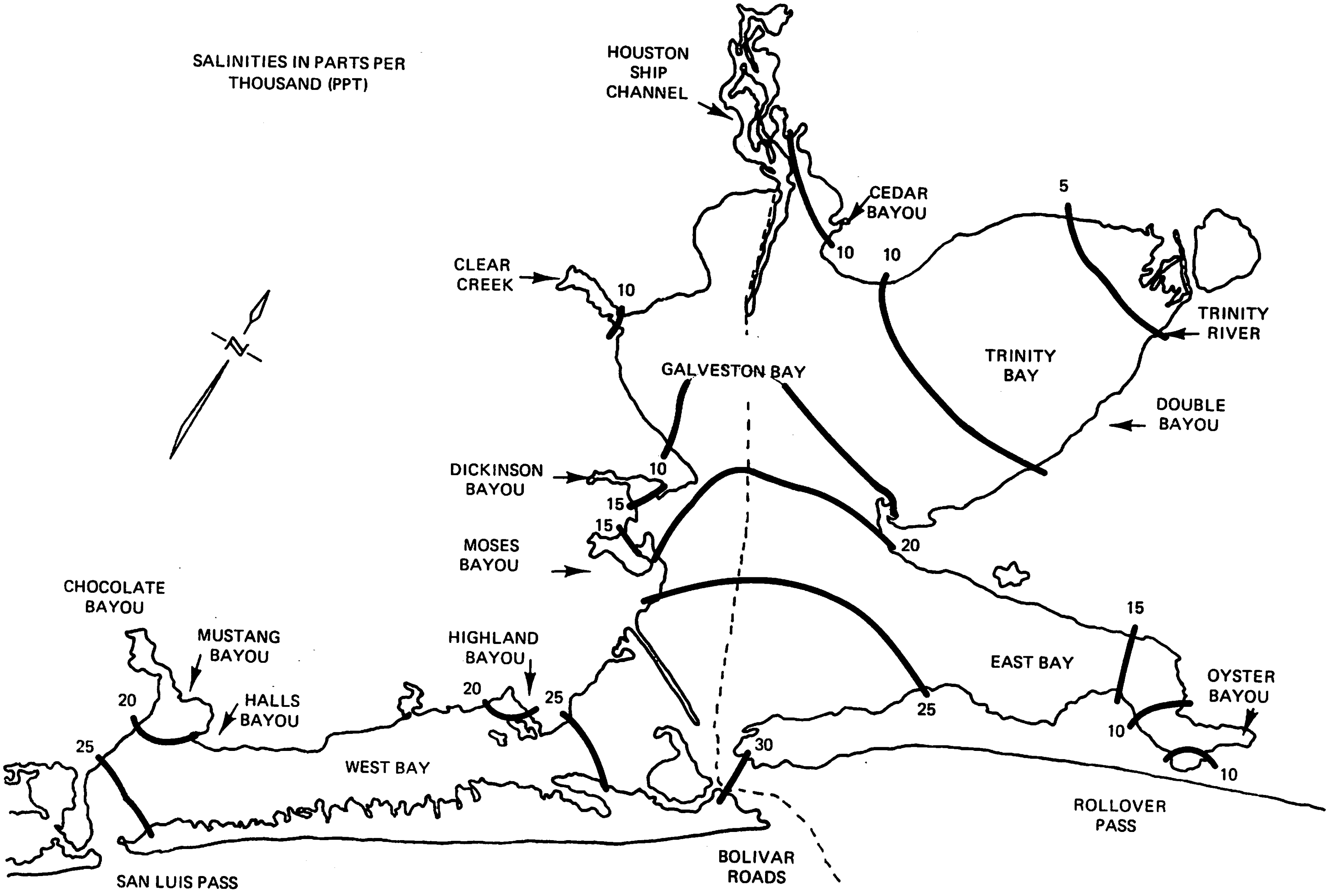

Figure 37.—Simulated Salinities in the Trinity-San Jacinto Estuary Under July Average Inflows

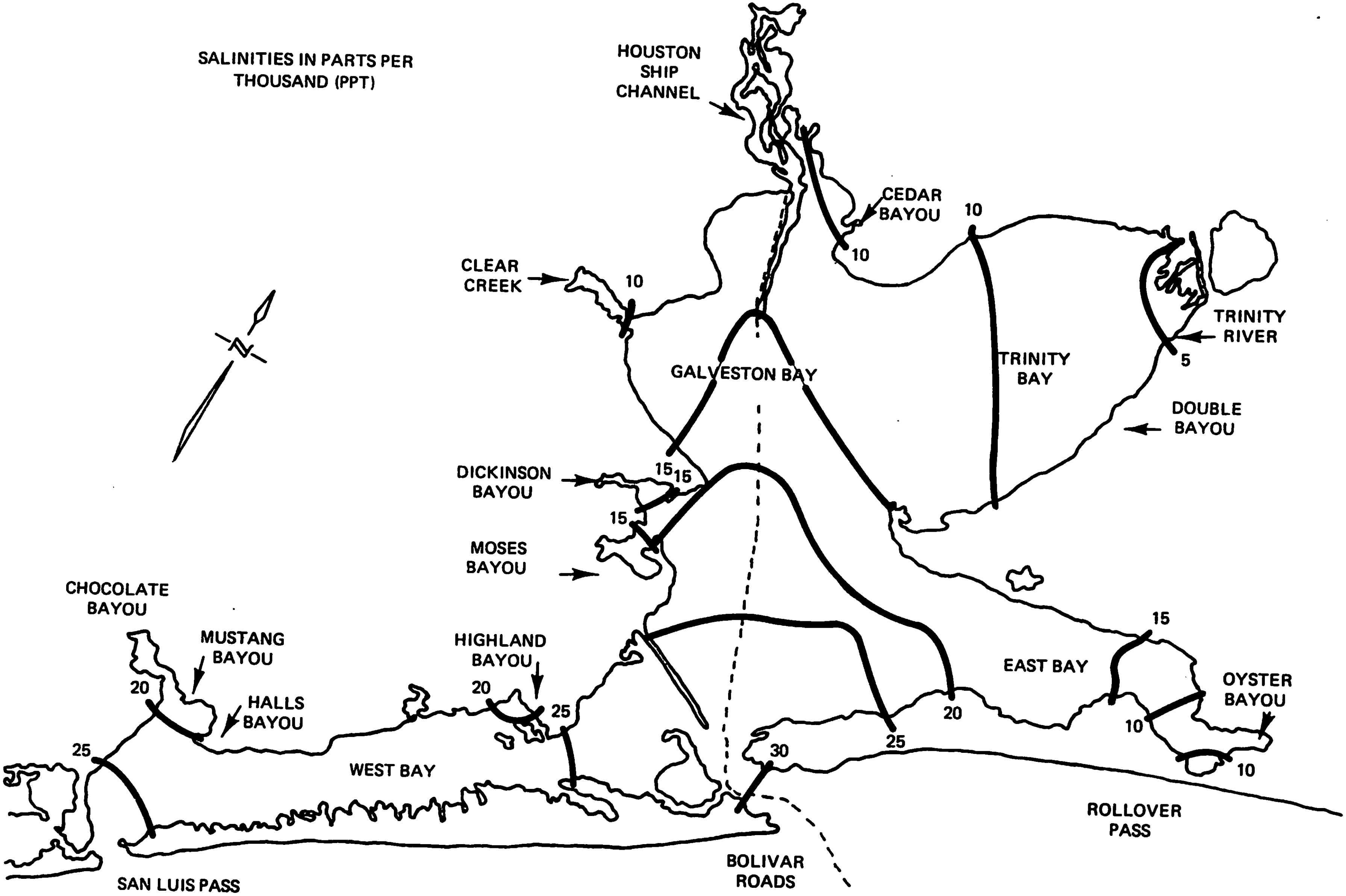

Figure 38.--Simulated Salinities in the Trinity-San Jacinto Estuary Under August Average Inflows

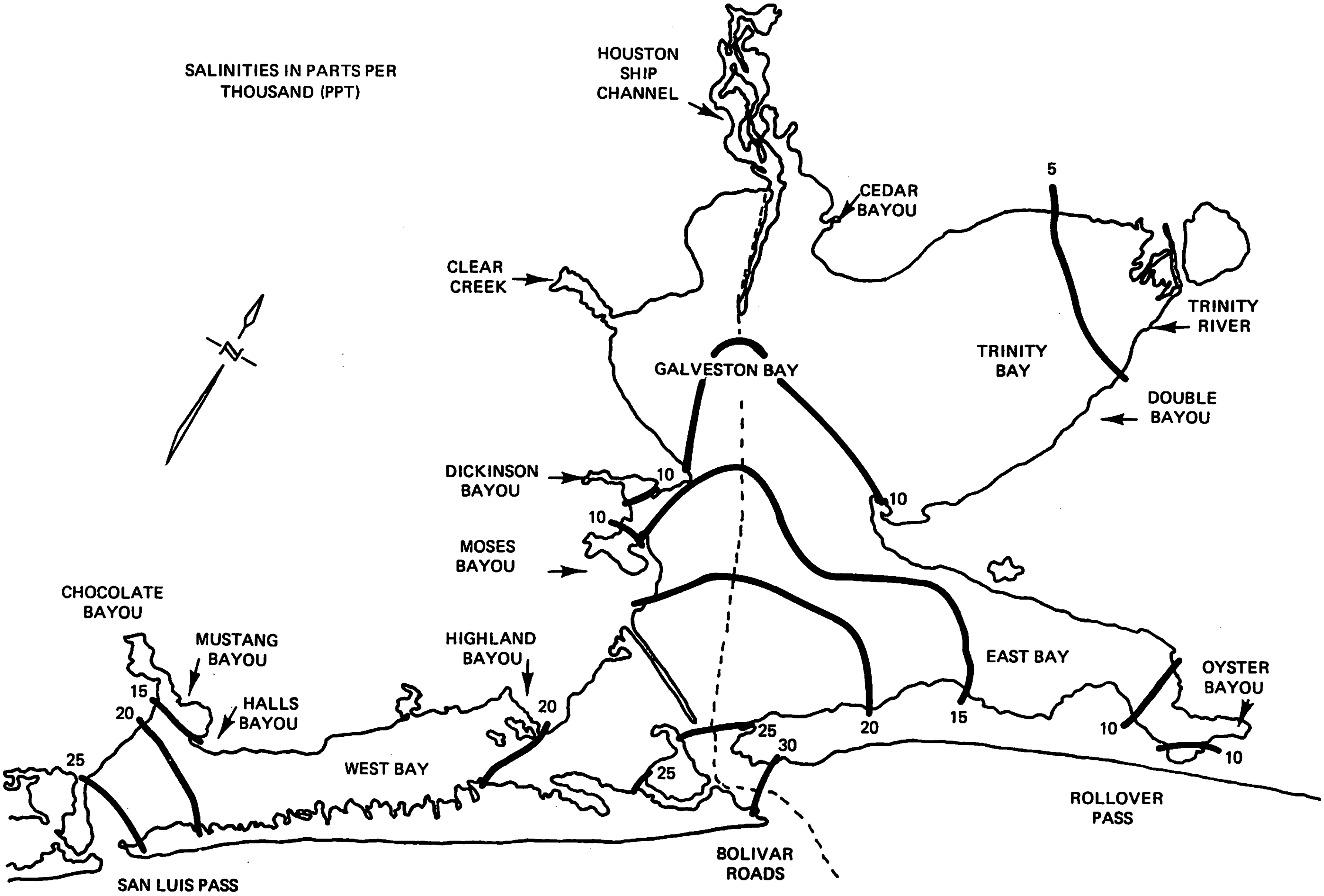

Figure 39.—Simulated Salinities in the Trinity-San Jacinto Estuary Under September Average Inflows

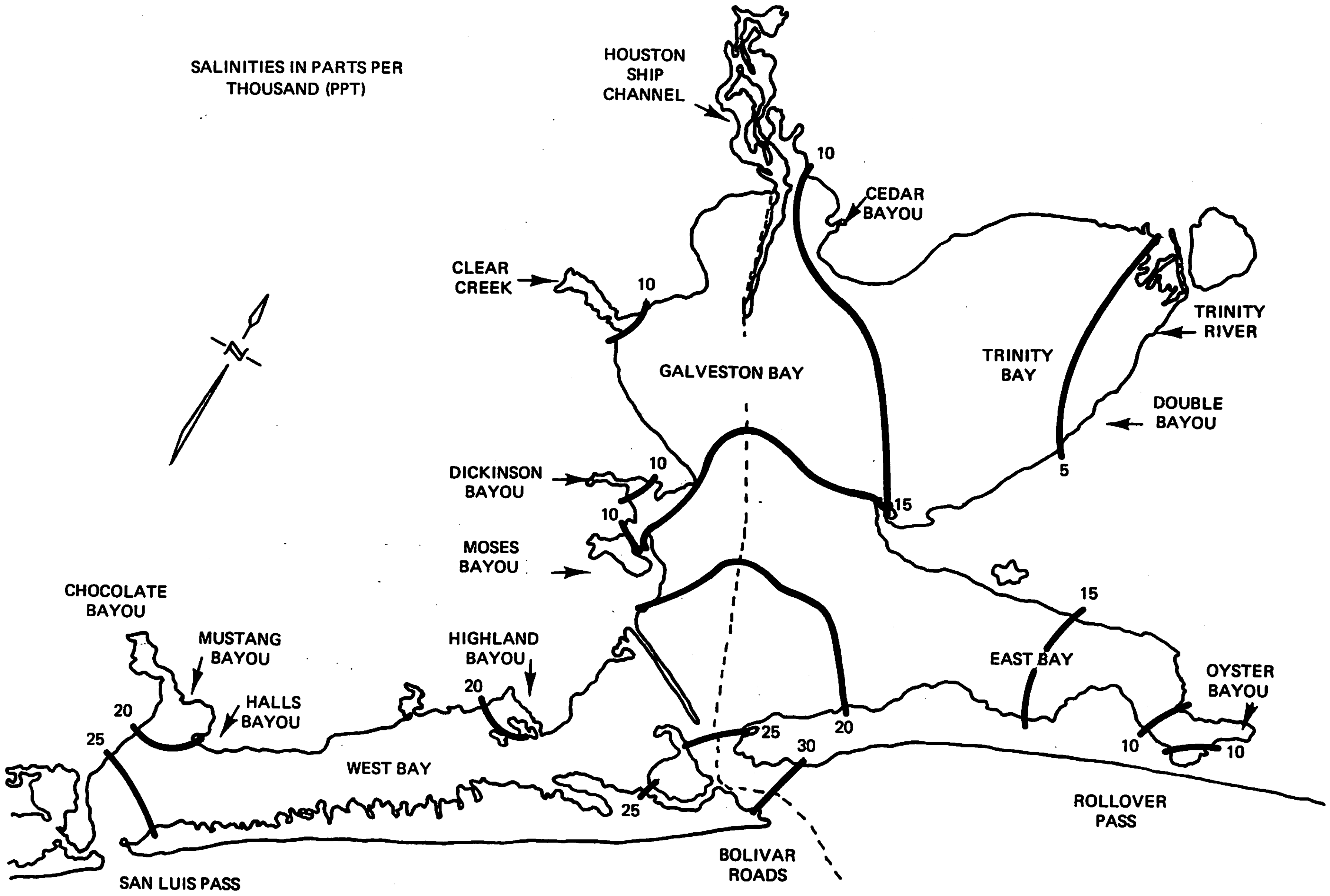

Figure 40.—Simulated Salinities in the Trinity-San Jacinto Estuary Under October Average Inflows

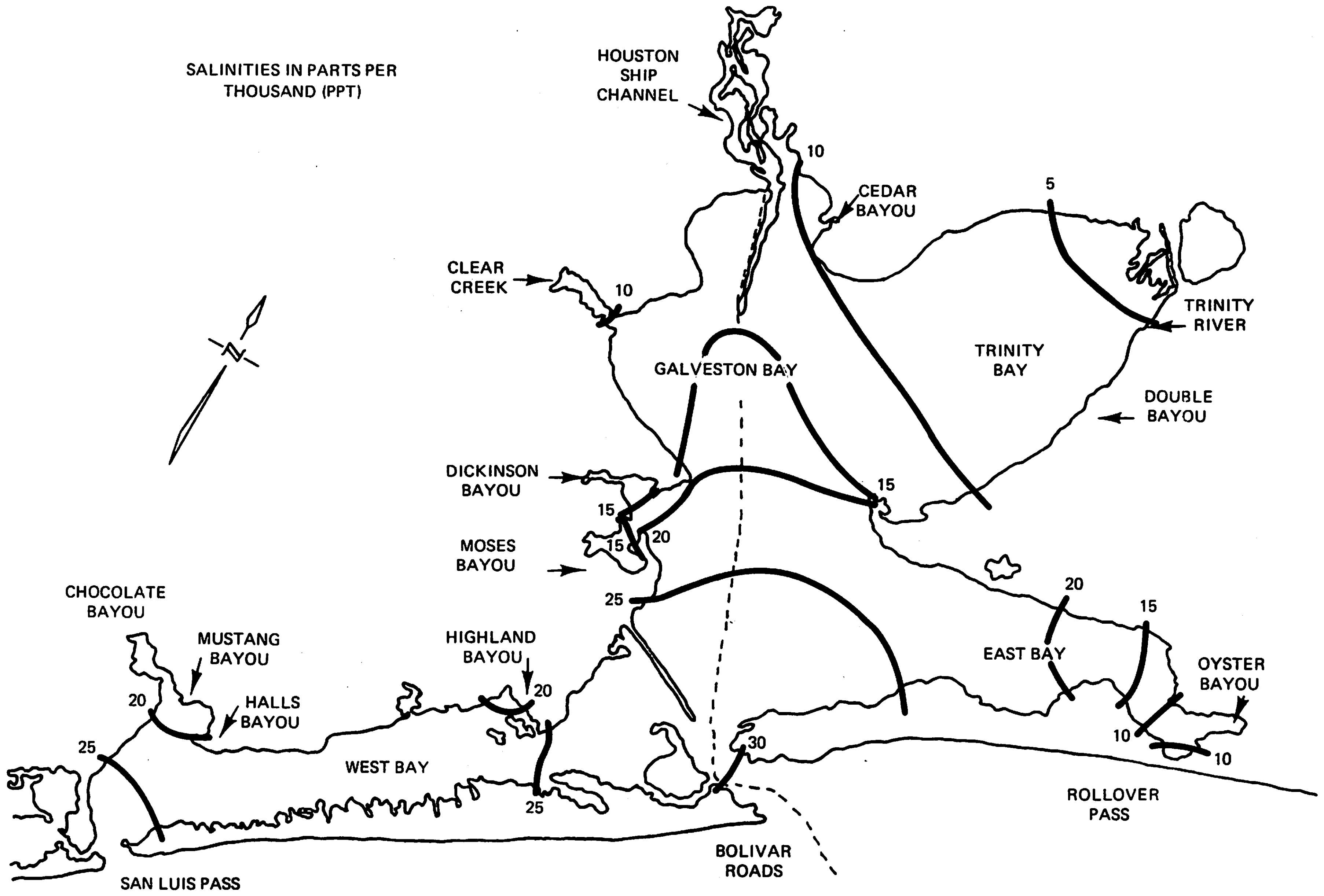

Figure 41.–Simulated Salinities in the Trinity-San Jacinto Estuary Under November Average Inflows

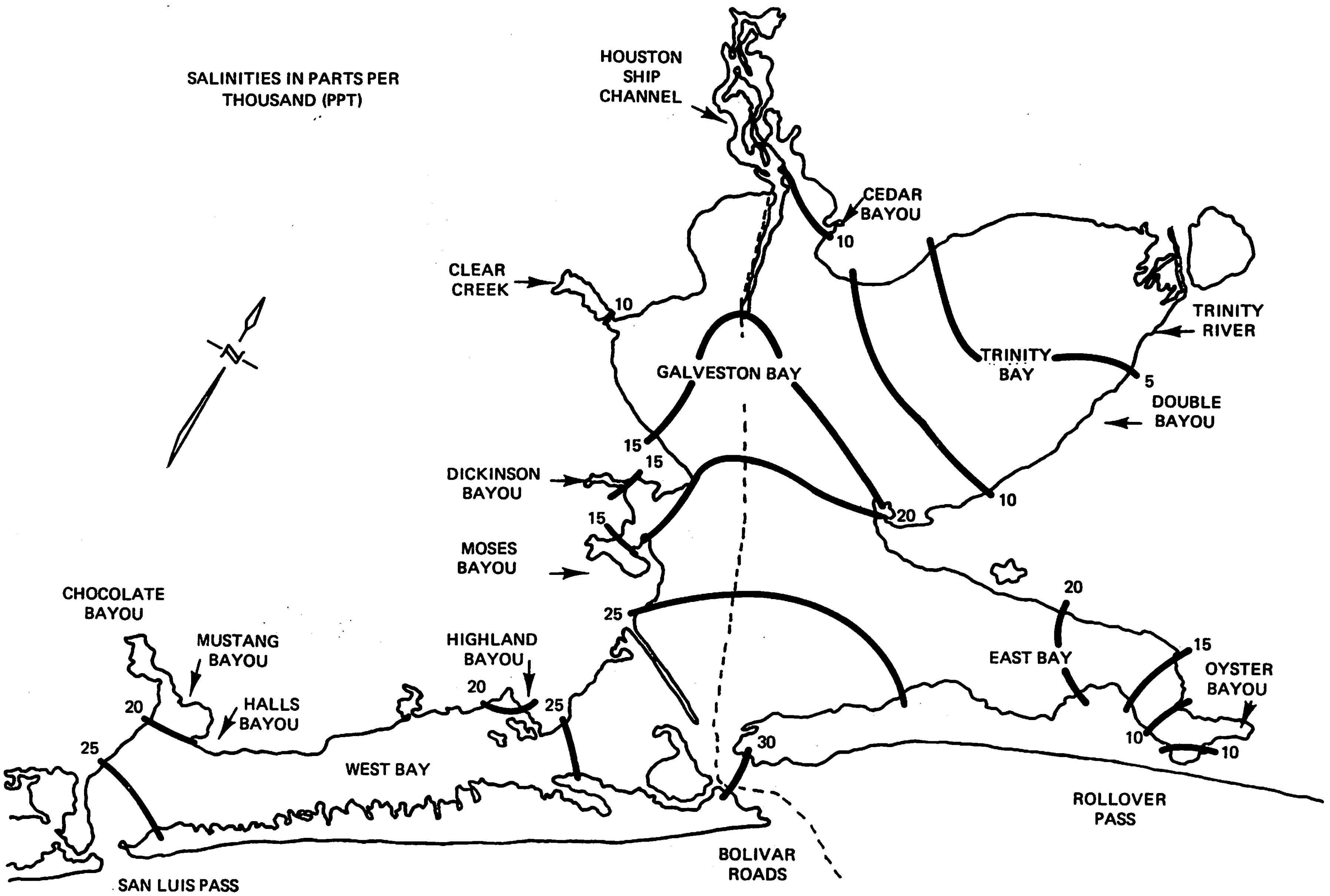

Figure 42.–Simulated Salinities in the Trinity-San Jacinto Estuary Under December Average Inflows

the high inflow months of March, April, May and June; and the other during the remainder of the year.

(1) Simulated Spring and Early Summer Salinity Patterns under Average Historical Freshwater Inflow Conditions

The salinity simulations under March, April, May and June average historical inflows projected that salinities over the Trinity-San Jacinto estuary would vary from less then 5 parts per thousand (ppt) in Trinity Bay to slightly over 25 ppt near San Luis and Bolivar Passes between the estuary and the Gulf of Mexico (Figures 33 through 36). The salinity simulations for these months revealed that salinities in Trinity Bay were less than 5 ppt over almost all of the bay. Salinities in Galveston Bay ranged from between 5 and 10 ppt in its upper portion to 25 ppt at the mouth of the bay near Bolivar Pass. The simulated salinities in West Bay ranged between 20 and 25 ppt. The simulated salinity distributions for East Bay during these months ranged between 10 and 15 ppt.

For all months during this period an intrusion of more highly saline water was evident along and either side of the Houston Ship Channel; this simulated condition corresponded to observed variations in salinity. Intrusion of high saline water along the Houston Ship Channel is due to its 40 foot depth compared to the adjacent shallow areas in Galveston Bay. The simulated salinities for the month of June indicated the lowest simulated salinities for any of the twelve monthly periods evaluated. Trinity Bay had simulated salinities of less than 5 ppt, while Galveston Bay had salinities ranging from between 5 ppt to 15 ppt near Galveston Island. Simulated salinities in West Bay were similarly less than in the spring months, with concentrations between 15 ppt to over 20 ppt near San Luis Pass. Salinity distributions simulated for East Bay were between 5 and 10 ppt.

(2) Simulated Late Summer, Fall and Winter Salinity Patterns under Average Historical Freshwater Inflow Conditions

Simulated salinity distributions in the Trinity-San Jacinto estuary showed relatively similar patterns for the remainder of the year (Figures 31-32 and 37-42). For Trinity Bay the simulated salinities were at a minimum near the Trinity River delta with concentrations lower than 5 ppt during the eight remaining months. Maximum simulated salinities in Trinity Bay were between 10 and 15 ppt, except in the months of October and November when the salinities were less than 10 ppt.

The simulated salinities for Galveston Bay ranged from less than 10 ppt in the upper portion of the bay near Morgans Point to over 25 ppt near Bolivar Pass. Simulated salinities for West Bay ranged from a maximum of over 25 ppt near Bolivar Pass to less than 20 ppt. East Bay salinities fell to a minimum value of less than 10 ppt near the eastern end of the bay and to a maximum of 25 ppt at the boundary line between East Bay and Galveston Bay. Simulated salinities were above 10 ppt at Rollover Pass, between East Bay and the Gulf of Mexico.

NUTRIENT PROCESSES

Summary

Nutrient contributions to the Trinity-San Jacinto 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 maybe contributed by point source discharges of return flows. The adjacent Gulf of Mexico is by comparison nutrient poor; 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, current, and biological activity all contribute to the complexity of processes that may be occurring at any time.

Freshwater inflow is the major source of nutrients to the Trinity-San Jacinto estuary. The Trinity River contributes freshwater and nutrients to the northeast arm of the estuary, Trinity Bay, near Wallisville, Texas. Several watercourses—White Oak Creek, Caney Creek, Peach Creek, Spring Creek, and Cypress Creek along with the east and west forks of the San Jacinto River—empty into Lake Houston northeast of the City of Houston. Downstream the San Jacinto River channel is the common watercourse that carries freshwater and nutrient contributions from the basin to the estuary.

Greens Bayou, Hunting Bayou, Halls Bayou, White Oak Bayou, Brays Bayou and Sims Bayou drain areas in and around Houston and contribute discharge and nutrients to Buffalo Bayou, known as the Houston Ship Channel in its downstream reach.

Water quality records are available for portions of many watercourses of the area. U.S. Geological Survey discharge and water quality data over the period of record 1970 through 1977 were used to calculate the potential nutrient loading contribution from the Trinity River, the San Jacinto River tributaries, and the Buffalo Bayou tributaries. The results of analyses of nutrient loadings from each freshwater inflow source should be interpreted as estimates based on limited data. The estimated loadings reflect the order of magnitude and range that might be expected during periods of similar climatic and streamflow conditions.

Studies were conducted in the Trinity River delta (11, 66) to gain insight into nutrient contributions from this brackish intertidal marsh of the Trinity estuary. The studies involved seasonal intensive field sampling efforts over a one or two day period and laboratory tests using vegetation/sediment cores taken from the delta. As is the case with riverine water quality, an analysis of the deltaic marsh contribution is not possible based upon data collected over one or two years on a seasonal basis. In order to determine the actual value of nutrient loading from the deltaic marsh to the estuarine system more data are needed, particularly for extreme events such as floods, hurricanes, and droughts.

The following sections describe the results of computations to estimate the nutrient contribution to the Trinity-San Jacinto estuary. In addition, the discussion focuses on the role that deltaic marshes play in biological productivity by trapping, storing, and ultimately converting inorganic nutrients to plant biomass, and the subsequent transport of this biomass to the estuarine system.

Nutrient Loading

The mean annual total discharge[1] to the Trinity-San Jacinto estuary from the major freshwater inflow sources is about 6.93 million acre-feet (8,550 million m^3). The Trinity River contributes an average annual inflow of 5.42 million acre-feet (78.2 percent of the total) to the estuary. Contributions from the San Jacinto River and its tributaries to Lake Houston are about 0.88 million acre-feet (12.6 percent). Since significant diversions are made from Lake Houston to supply the needs of the City of Houston, the amount of freshwater contributed to the estuary from this source is much less, usually negligible. Mean annual contributions from Buffalo Bayou upstream from the Houston Ship Channel and those streams contributing to it are 0.47 million acre-feet (6.8 percent), including return flows from the City of Houston. There are three additional sources of gaged freshwater inflow to the Trinity-San Jacinto estuary: (1) Cedar Bayou, 56 thousand acre-feet/year (0.8 percent); (2) Clear Creek, 26 thousand acre-feet/year (0.4 percent); and (3) Chocolate Bayou, 78 thousand acre-feet/year (1.1 percent).

Water quality data collected by the U.S. Geological Survey indicated mean monthly organic nitrogen concentrations in the Trinity River at Romayor, Texas ranged from 0.39 mg/l to 0.79 mg/l. Mean monthly organic nitrogen concentrations in Cedar Bayou, Trinity River, and the West Fork San Jacinto River were consistently within a similar concentration range (Figure 43). Mean monthly organic nitrogen concentrations in Buffalo Bayou and its tributaries throughout the City of Houston generally ranged from 1.0 mg/l to slightly more than 2.0 mg/l. In light of the other data, unusually high mean organic nitrogen values observed in Halls Bayou during October and August (Figure 43) may not have been representative of the true mean. The October mean is based on only two data points while the August mean includes an unusually high organic nitrogen value of 16.0 mg/l recorded in 1977. Excluding these data the mean monthly concentration for August is calculated to be 1.02 mg/l, in line with those values observed for other nearby watercourses in the City of Houston drainage. No obvious seasonal patterns of organic nitrogen concentration variation are apparent from the data.

The majority of the mean monthly inorganic nitrogen concentrations in the Trinity River, the West Fork San Jacinto River, Cedar Bayou, and Chocolate Bayou were less than 1.0 mg/l. The one exception was a value of 1.47 mg/l for May in Chocolate Bayou (Figure 44). This appears to be the peak of a springtime rise in inorganic nitrogen concentration for this watercourse.

With the exception of Greens Bayou, mean monthly inorganic nitrogen concentrations in watercourses that empty into the Houston Ship Channel ranged between 2 mg/l to slightly higher than 8 mg/l. Concentrations in Greens Bayou were generally 1.0 mg/l or less. With the exception of Chocolate Bayou, there are no apparent seasonal trends for inorganic nitrogen concentrations in these watercourses.

The lowest mean monthly total phosphorous concentrations occurred in the Trinity River, Cedar Bayou, the West Fork San Jacinto River and Chocolate Bayou (Figure 45). These concentrations were all generally less than 1.0 mg/l. Mean monthly total phosphorous concentrations in the other watercourses ranged from 1.0 mg/l to 5.0 mg/l. Halls Bayou, however, is an exception as several concentration values exceeded 5.0 mg/l. Halls Bayou is also the only watercourse where a seasonal trend may be evident, with the highest concentrations occurring in the fall and the lowest occurring in winter.

Mean monthly total organic carbon (TOC) concentrations ranged between about 6.0 mg/l and 27 mg/l (Figure 46). Concentrations in the Trinity River and West Fork San Jacinto River were as a rule lower than those in the other watercourses. The distinction is less obvious for TOC than it is for the nitrogen and phosphorous parameters. There are no apparent seasonal trends for TOC in any of these watercourses.

The potential ranges for nutrient contributions from each stream to the Trinity-San Jacinto estuary are presented in Tables 3-6. Nutrient contributions (in kilograms per day) were calculated using the maximum and minimum concentration observed for each of the twelve months over the period of record (1970 through 1977) and the mean monthly discharges for each stream. Nutrient concentration data were not readily available for several of the tributary streams

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[1] measured at the closest non-tidally influenced gages

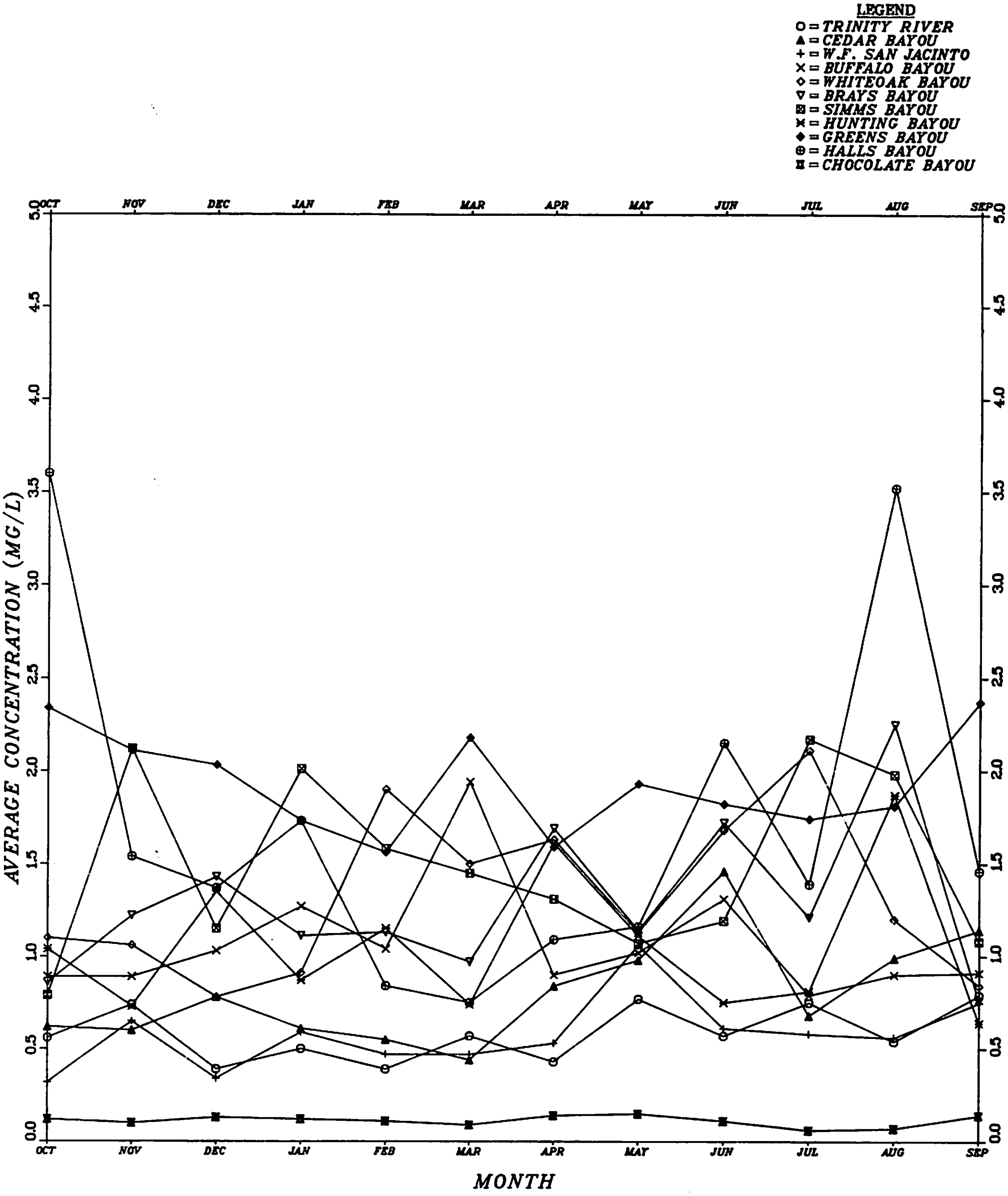

Figure 43.—Mean Monthly Organic Nitrogen Concentrations of Streams Contributing to the Trinity-San Jacinto Estuary

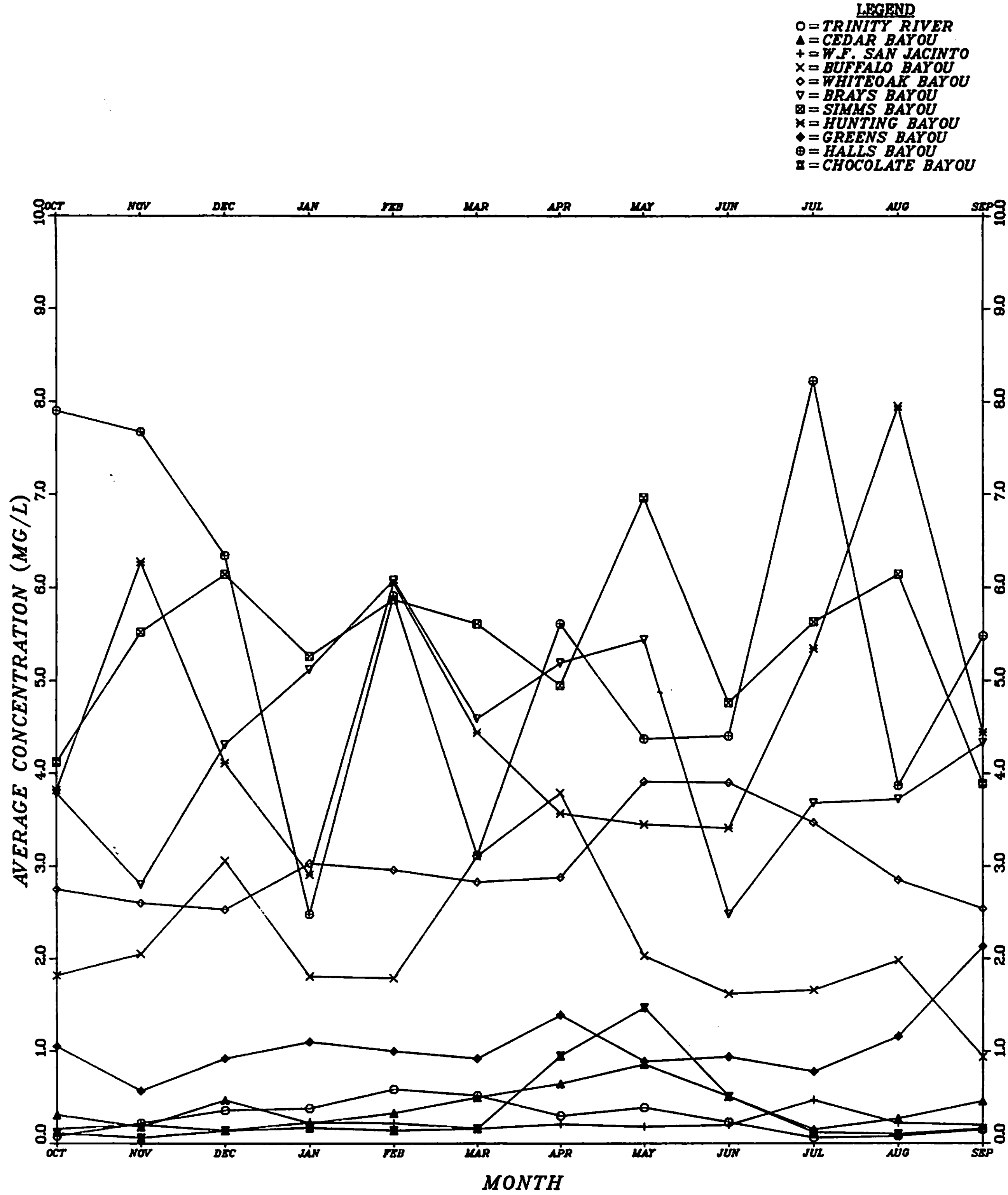

Figure 44.—Mean Monthly Inorganic Nitrogen Concentrations of Streams Contributing to the Trinity-San Jacinto Estuary

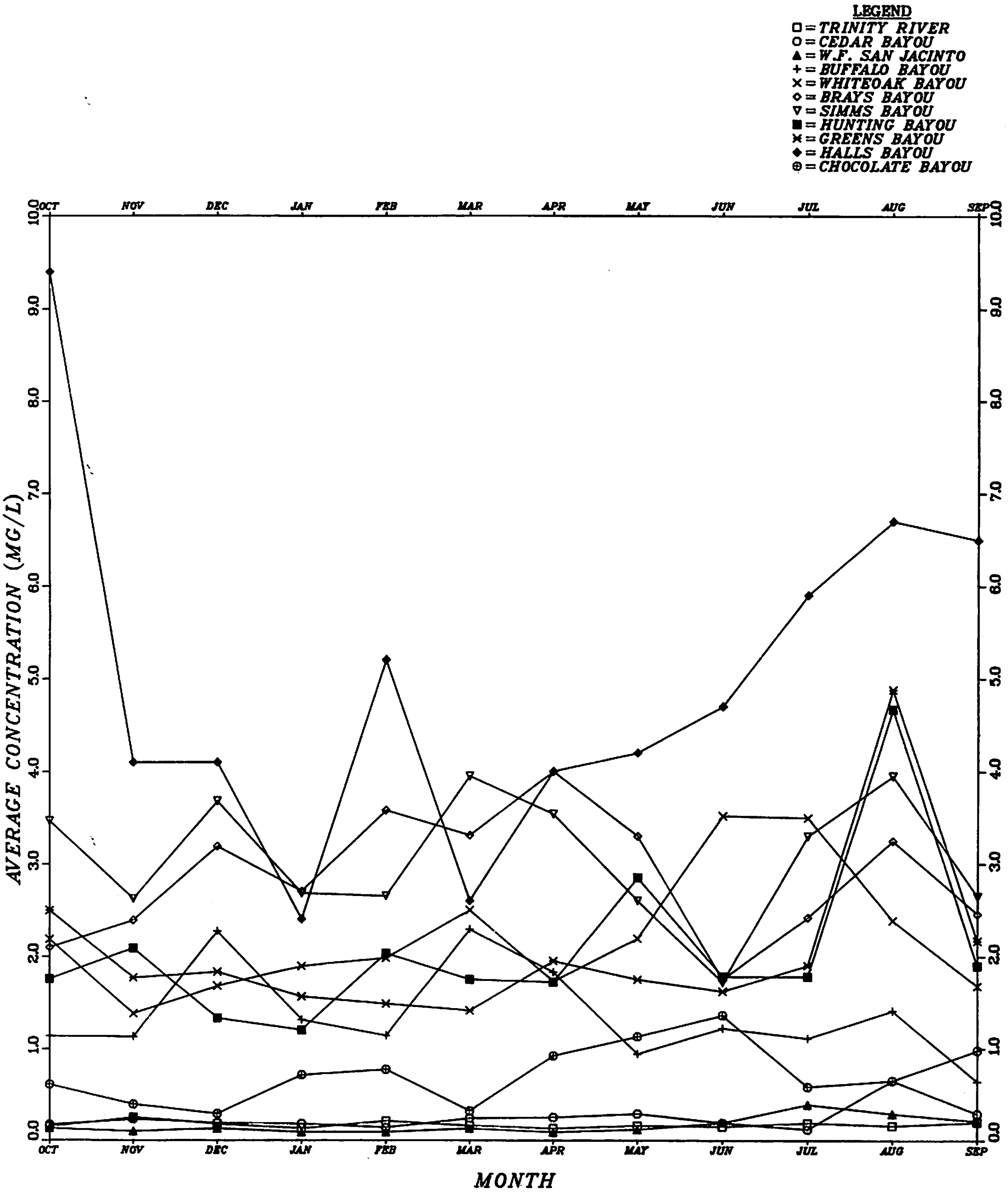

Figure 45.—Mean Monthly Total Phosphorus Concentrations of Streams Contributing to the Trinity-San Jacinto Estuary

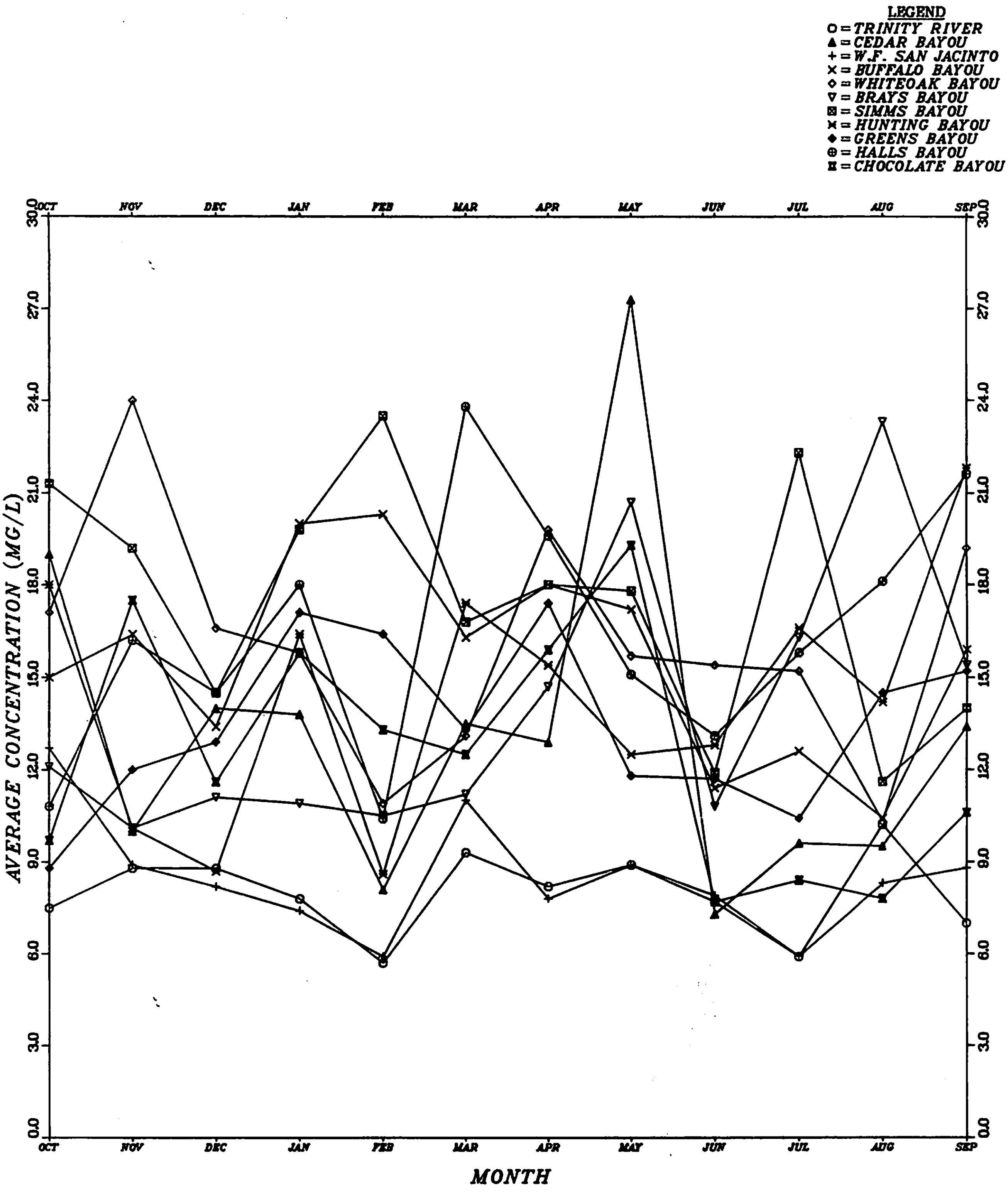

Figure 46.—Mean Monthly Total Organic Carbon Concentrations of Streams Contributing to the Trinity-San Jacinto Estuary

Table 3.—Range of Expected Inorganic Nitrogen Loading to Trinity-San Jacinto Estuary Based on Mean Monthly Gaged Discharges Kilograms/Day

		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Trinity	high	11,454	21,939	1,687	16,113	27,210	10,819	1,501	972	1,389	2,510	5,418	17,230
River	low	2,813	3,011	337	537	4,535	1,056	0	40	58	179	1,761	562
Cedar	high	87	72	80	443	385	323	20	22	207	57	81	355
Bayou	low	37	7	12	30	74	65	6	5	28	40	23	23
San Jacinto	high	1,277	1,970	650	2,454	1,061	2,180	1,079	502	419	557	1,238	762
River/	low	681	229	217	94	367	67	131	0	183	144	232	166
Lake Houston													
Buffalo	high	2,058	2,362	3,425	5,336	2,766	2,741	1,580	1,789	1,004	2,697	5,573	5,479
Bayou	low	799	528	565	192	1,241	365	479	309	330	470	605	448
White Oak	high	1,243	1,159	607	975	1,902	2,322	886	420	1,061	804	1,789	877
Bayou	low	200	500	341	325	293	179	148	291	128	106	153	68
Brays	high	2,382	2,943	1,315	1,856	3,385	2,203	1,914	957	2,164	1,558	3,438	2,313
Bayou	low	568	1,242	370	715	450	186	294	451	483	133	381	138
Simms	high	1,531	2,987	1,029	1,136	3,244	4,447	1,079	988	1,727	1,578	2,073	2,048
Bayou	low	222	519	289	320	312	72	105	209	85	74	147	184
Hunting	high	307	613	297	264	504	522	327	497	711	291	431	297
Bayou	low	18	110	52	81	81	74	76	62	103	85	81	82
Greens	high	687	504	228	389	590	578	326	191	617	403	353	662
Bayou	low	181	106	33	84	120	23	39	65	97	147	187	73
Halls	high	254	796	263	679	677	680	1,070	433	794	572	447	701
Bayou	low	102	247	14	147	105	20	277	4	114	241	180	190
Chocolate	high	75	62	77	495	637	383	55	79	100	79	15	78
Bayou	low	17	5	1	27	92	90	14	5	20	7	8	13

Table 4.—Range of Expected Organic Nitrogen Loading to Trinity-San Jacinto Estuary Based on Mean Monthly Gaged Discharges Kilograms/Day

		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Trinity	high	13,263	15,701	2,474	21,484	41,226	26,389	10,504	3,604	4,687	7,710	13,546	16,106
River	low	5,426	2,366	450	5,908	24,323	5,278	6,860	2,592	4,456	717	8,367	0
Cedar	high	240	159	64	396	412	945	112	171	349	127	253	283
Bayou	low	58	29	26	84	70	176	29	14	87	70	44	82
San Jacinto	high	3,234	3,528	1,570	4,058	6,531	3,052	992	800	1,256	1,078	2,747	3,116
River/	low	1,745	870	541	849	2,041	671	316	58	850	233	2,399	0
Lake Houston													
Buffalo	high	2,216	1,736	4,110	1,103	2,151	1,827	764	762	1,465	878	1,242	1,389
Bayou	low	119	8	34	197	323	208	127	99	161	201	240	108
White Oak	high	499	884	549	834	654	949	1,165	336	335	435	831	305
Bayou	low	48	189	38	58	70	58	36	44	56	38	44	20
Brays	high	1,076	582	547	912	866	1,291	684	554	385	354	880	845
Bayou	low	30	162	72	82	123	118	89	306	89	73	91	51
Simms	high	1,229	623	701	609	504	533	831	659	296	279	844	447
Bayou	low	34	60	38	61	98	220	47	0	47	49	38	32
Hunting	high	113	150	62	126	228	121	69	191	65	119	55	147
Bayou	low	9	5	7	17	23	24	8	14	16	17	6	9
Greens	high	306	313	192	593	348	173	147	153	796	129	140	185
Bayou	low	22	38	18	52	77	42	32	15	25	118	20	70

Table 4.—Range of Expected Organic Nitrogen Loading to Trinity-San Jacinto Estuary Based on Mean Monthly Gaged Discharges Kilograms/Day—Continued

		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Halls	high	384	141	57	205	266	331	229	110	212	268	227	115
Bayou	low	11	17	8	27	18	18	0	10	21	103	15	30
Chocolate	high	302	322	102	337	1,051	1,040	269	306	533	182	135	129
Bayou	low	43	53	8	91	115	175	81	79	137	70	38	23

Table 5.—Range of Expected Total Phosphorus Loading to Trinity-San Jacinto Estuary Based on Mean Monthly Gaged Discharges Kilograms/Day

		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Trinity	high	3,215	12,905	495	6,445	8,245	4,486	3,430	972	1,331	1,793	5,689	4,120
River	low	1,407	860	225	2,417	4,535	2,639	1,286	324	810	717	1,626	936
Cedar	high	60	25	34	171	158	68	23	182	111	40	71	72
Bayou	low	34	17	16	15	12	55	6	6	39	13	37	33
San Jacinto	high	553	550	839	849	857	2,046	600	451	432	629	658	829
River/ Lake Houston	low	298	137	81	0	286	101	153	44	65	108	232	99
Buffalo	high	1,583	1,962	2,512	2,148	1,564	2,076	1,019	1,211	571	1,631	3,064	4,013
Bayou	low	483	400	320	366	518	349	331	202	410	445	497	478
White Oak	high	760	791	679	399	857	2,048	821	456	838	644	701	785
Bayou	low	183	205	246	272	50	129	25	144	106	118	135	68
Brays	high	1,285	1,488	887	1,417	2,466	1,519	1,139	1,166	1,393	843	1,499	2,395
Bayou	low	173	679	321	528	333	106	180	268	199	218	212	169
Simms	high	819	1,480	739	905	1,225	941	1,052	628	1,044	726	764	1,285
Bayou	low	149	312	280	244	130	110	47	48	83	80	76	242
Hunting	high	124	132	100	116	441	283	82	134	176	135	125	103
Bayou	low	27	57	25	37	125	40	29	51	44	51	31	42
Greens	high	573	522	225	390	600	535	383	280	343	412	280	516
Bayou	low	57	137	27	139	70	26	44	64	85	176	66	93
Halls	high	261	882	159	542	840	735	500	588	794	617	392	548
Bayou	low	58	176	19	35	69	28	235	59	79	350	147	76
Chocolate	high	41	32	20	44	76	71	35	38	70	65	34	43
Bayou	low	17	7	4	17	19	33	9	10	30	12	8	18

Table 6.—Range of Expected Total Organic Carbon Loading to the Trinity-San Jacinto Estuary Based on Mean Monthly Gaged Discharges Kilograms/Day

		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Trinity	high	221,044	172,068	22,491	375,962	453,488	263,890	87,894	64,798	63,656	80,681	176,099	224,734
River	low	118,560	86,034	17,093	53,709	272,093	163,611	50,378	31,994	28,935	46,616	59,603	86,148
Cedar	high	6,029	1,301	2,842	5,444	8,232	3,259	1,024	1,529	4,361	3,026	2,994	4,373
Bayou	low	1,232	1,055	510	1,089	1,873	1,857	829	282	1,396	3,026	230	2,315
San Jacinto	high	36,599	41,234	32,487	61,343	53,062	36,895	10,030	13,098	15,700	32,325	46,423	36,463
River/ Lake Houston	low	26,811	10,079	27,073	15,100	22,858	17,776	4,143	2,620	6,803	16,552	20,116	13,259

Table 6.—Range of Expected Total Organic Carbon Loading to the Trinity-San Jacinto Estuary Based on Mean Monthly Gaged Discharges Kilograms/Day—Continued

		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Buffalo	high	26,906	26,411	13,700	15,097	25,416	14,950	7,644	6,277	153,836	13,171	18,218	13,120
Bayou	low	9,496	9,810	6,279	4,065	8,602	5,897	3,720	3,676	9,303	5,519	7,287	5,865
White Oak	high	7,367	5,121	2,313	5,439	4,057	5,821	3,119	1,321	6,517	4,175	10,907	7,414
Bayou	low	2,852	466	1,214	1,632	2,705	2,587	1,642	1,080	1,676	1,461	3,116	1,701
Brays	high	5,380	6,468	2,641	5,522	11,329	5,317	6,608	1,643	6,225	5,983	5,865	4,508
Bayou	low	1,734	1,455	1,339	1,921	4,665	2,620	2,506	726	3,172	1,686	1,043	2,141
Simms	high	5,772	9,609	2,930	3,827	5,762	4,390	4,025	1,955	3,479	4,469	6,052	3,724
Bayou	low	1,303	3,376	1,249	2,105	2,641	2,383	1,428	484	1,600	1,815	1,242	2,048
Hunting	high	1,563	573	1,874	1,117	1,176	1,617	995	860	1,529	970	666	402
Bayou	low	205	265	187	349	698	590	216	207	1,000	970	274	402
Greens	high	3,695	4,140	1,666	3,758	3,097	2,602	2,029	1,975	2,470	1,764	3,312	2,249
Bayou	low	981	1,409	625	289	1,819	882	518	440	1,386	306	612	741
Halls	high	2,195	1,411	1,985	1,852	2,230	1,176	1,529	1,176	2,381	1,029	2,266	1,274
Bayou	low	604	176	441	662	695	492	412	278	390	82	355	701
Chocolate	high	6,039	5,527	2,830	5,478	7,963	4,398	2,602	2,166	4,665	2,793	3,161	4,290
Bayou	low	1,466	691	512	1,117	3,822	2,837	2,255	790	2,266	1,653	969	1,565

to the San Jacinto River above Lake Houston, nor were suitable data available for the reach of the San Jacinto River below Lake Houston. USGS water quality data have been recorded only from the West Fork San Jacinto River. Texas Department of Water Resources statewide water quality monitoring network data (for the East Fork San Jacinto River) were available. Carbon, phosphorus, and nitrogen (CPN) concentrations in the East Fork were within the concentration range of reported observations from the West Fork in the USGS records. The range of CPN values reported in the USGS data for the West Fork San Jacinto River were assumed to be representative of the concentrations expected in the East Fork San Jacinto River, Spring Creek, Cypress Creek, Caney Creek, and Peach Creek where discharge measurements but not water quality data were available. The mean monthly discharges of these six tributaries to Lake Houston were summed for each of the twelve months to arrive at a total monthly inflow. The CPN ranges reported by the USGS for the West Fork San Jacinto River were applied to these monthly totals to determine the potential nutrient loading into Lake Houston. These values are presented in Tables 3-6 under the heading: San Jacinto River/Lake Houston. At present the percentage of these values passed through Lake Houston to the estuary is unknown. The data are presented for comparison of the potential nutrient contribution of the San Jacinto River system with the other streams that contribute to the estuarine system.

The Trinity River, which contributes 78 percent of the gaged freshwater inflow to the estuary, is also responsible for contribution of the bulk of the nutrient loading; thus demonstrating that the amount of freshwater discharge is the most significant factor in the transport of nutrients to the estuarine system. This is in spite of the fact that CPN concentrations there are relatively low when compared with some of the other streams, particularly those in the City of Houston drainage. Watercourses draining the area in and around the City of Houston are an exception. While they contribute only 6.9 percent of the gaged flows to the estuary compared to 12.6 percent from the San Jacinto River and other tributaries into Lake Houston. A greater load of each nutrient species is contributed by those watercourses that traverse the City of Houston drainage and empty into the Houston Ship Channel. CPN concentrations in runoff and return flow from the City are sufficiently high to override nutrient loading based on relative discharge volumes.

Marsh Vegetative Production

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) that takes place within the system as a result of the plant community including macrophytes, periphytes, and benthic algae. As a result, the marshes are large-scale contributors to estuarine productivity, providing a substrate and sources of nutrients for the microbial transformation processes at the base of the food web. Deltaic marshes are especially important since they form a vital link between the inflowing river and its associated estuary.

The Trinity-San Jacinto estuary receives its major hydrologic input from the Trinity River and the marshes of the Trinity delta. Adams and Tingley (11) delineated nine vegetation zones which represent the major distinguishable vegetative communities in the delta. The above ground net primary production of the rooted vascular plants (macrophytes) was estimated at 96.6 million dry weight pounds per year (43,900 metric tons/year) over the 13, 380 acre (5,420 hectare) study area. Annual net production (ANP) varied from a low of 1, 920 dry weight pounds per acre (215 g/m^2) in sampled stands of arrowhead (*Sagittaria graminea*) to a high of 26,600 dry weight pounds per acre (2,980 g/m^2) in sampled stands of the common reed *Phragmites communis*. The average ANP over the entire study area was estimated to be 7,220 dry weight pounds per acre (820 g/m^2) with approximately 51 percent of the total ANP occurring in the lower delta marshes south of Old River Lake and west of the Trinity River, 20 percent in the middle delta marshes south of IH-10 between Old River Lake and the Trinity River, and 29 percent in the upper delta marshes north of IH-10. Important plant species of the Trinity delta are listed in Table 7, where the most predominant macrophytes include *Spartina patens*, *Aster subulatus*, *Echinochloa muricata*, *Alternanthera philoxeroides*, *Paspalum lividum*, *Phragmites communis*, *Persicaria punctata*, and *Sagittaria graminea* (Table 7).

While the nine vegetation zones delineated by Adams and Tingley (11) comprise a total of 13,380 acres (5,420 hectares), they represent only 27 percent of the total 49,880 acres (20,200 hectares) of Trinity deltaic wetlands. The remaining 73 percent (36,500 acres or 14,780 hectares) includes many unvegetated areas and consists of cypress swamps (16,870 acres or 6,830 hectares), fresh to brackish lakes (8,550 acres or 3,460 hectares), diked areas (6,340 acres or 2,570 hectares), and small components of mud flats, dredged material, upland vegetation and surface waters such as marsh ponds, bayous, and river areas (4,740 acres or 1,920 hectares).

In addition, Adams and Tingley (11) measured net periphyton production to range from a low of 1.38 dry weight pounds per acre per day (0.155 g/m^2/day) to a high of 11.5 dry weight pounds per acre per day

Table 7.—Scientific and Common Names of Important Plant Species Occurring in the Trinity River Delta (11)

Scientific Name	Common Name
Acnida tamariscina	Water hemp
Alternanthera philoxeroides	Alligator weed
Ambrosia trifida	Giant ragweed
Ammania coccinea	Tooth-cup
Aster subulatus	Saltmarsh aster
Baccharis halimifolia	Sumpweed
Bacopa monnieri	Water hyssop
Celtis laevigata	Hackberry
Cyperus articulatus	Sedge
Cyperus odoratus	Sedge
Echinochloa muricata v. *muricata*	
Eichornia crassipes	Water hyacinth
Gaura filiformis	Gaura
Gleditsia triacanthos	Honey locust
Heterotheca pillosa	Gold aster
Hymenocallis sp.	Spider lily
Iva annua	Marsh-elder
Leptochloa fascicularis	Sprangletop
Leptochloa uninerva	Sprangletop
Paspalum lividum	Longtom
Paspalum vaginatum	Paspalum
Persicaria punctata	Water smartweed
Pluchea purpurascens	Marsh fleabane
Phragmites communis	Common reed
Rhynchospora corniculata	Horned rush
Sagittaria graminea	Arrowhead
Salix nigra	Willow
Saprium sebiferum	Tallow tree
Scirpus americanus v. *longispicatum*	Bulrush
Scirpus maritimus	Salt-marsh bulrush
Sesbania drummondii	Rattlebush
Spartina alterniflora	Smooth cordgrass
Spartina patens	Saltmeadow cordgrass
Spartina spartinae	Gulf cordgrass
Sphenoclea zeylanica	Chicken spike
Typha sp.	Cat-tail
Vigna luteola	Pea-vine

(1.29 g/m²/day), averaging 4.78 dry weight pounds per acre per day (0.536 g/m²/day) overall. Assuming that about 13,600 acres (5,500 hectares) of the delta were inundated, the periphyton ANP can be estimated at 23.7 million dry weight pounds (10,760 metric tons) or 65,000 dry weight pounds per day (29.5 metric tons/day).

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 upon the episodic nature of the marsh inundation and dewatering process. Cooper (6) suggests that the vast majority of the primary production in the higher, irregularly-flooded vegetative zones goes into peat production and is not exported. The lower, frequently-flushed vegetative zone characterized by *Spartina alterniflora* may contribute about 45 percent of its net production to the estuarine waters (42).

Marsh Nutrient Cycling

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

The Trinity River delta contains a large and dynamic marsh system. In addition, the system is characterized by diversity of habitats and species. These range from the predominantly intertidal brackish marshes south of the Wallisville levee to the freshwater cypress bottoms and oxbows that occur northward to Liberty, Texas.

Studies by Armstrong et al. (62), Dawson and Armstrong (64), Armstrong and Brown (63), Armstrong and Gordon (65), and Armstrong, Harris, and Gordon (66) have been conducted for the purpose of determining the role of plants and deltaic sediments in nutrient exchange processes. In most cases these patterns seem to be similar from species to species (65). The rates of nutrient exchange for marsh macrophytic species and associated sediments in the Trinity delta were found by Armstrong, Harris, and Gordon (66) to be similar in magnitude but somewhat lower than exchange rates reported for other Texas coastal marsh systems (Table 8). This study was also unique in that portions of the marsh habitat were sufficiently diverse to allow comparison of CPN exchange rates among the vegetation and sediment cores from the intertidal zone and the nearby freshwater dominated zone containing very different types of vegetation. The results are presented in Table 9. Both areas of the marsh exported particulate organic material, however, the rates from the predominantly freshwater/cypress dominated area around Mac Lake were substantially lower than those from laboratory reactor samples collected from the intertidal zone below the Wallisville levee. The results from the study also indicate an active uptake of nitrogen and phosphorous species in the intertidal marsh zone while there appears to be no net uptake or release of these nutrients from the samples collected in the Mac Lake area. There is evidence that attached algae dominate the exchange process. Such algae were found in those laboratory samples collected in the lower delta while absent in samples from Mac Lake.

The results from a linear marsh model containing a cross-section of the lower delta vegetation and sediment are believed to more accurately represent actual CPN exchange rates than those calculated from the laboratory core reactor studies (Table 10). These results are more in line with those reported in the literature for other Texas coastal marshes (Table 8).

Hauck and Ward (14) determined that the marsh lying to the south of the Wallisville levee is primarily intertidal and largely uninfluenced by Trinity River water elevations. This portion of the marsh is approximately 10 square miles (2,590 hectares) in area. Applying CPN exchange rates given in Table 10, this portion of the marsh might potentially export as much as 11,000 kg/day of TOC under the proper combination of seasonal conditions and tidal elevation (inundation). Likewise, proper conditions might result in the release of 250 kg/day total phosphorus, 114 kg/day inorganic nitrogen, and 205 kg/day organic nitrogen. Results from the linear marsh model suggest that under certain conditions the lower delta may act as a TOC and nitrogen sink.

The deltaic marshes are important sources of nutrients for the estuary. Periodic inundation events are necessary in order for the Trinity delta marshes to deliver their potential nutrient stores to the open waters of the bay. This occurs as the water moving across the delta sweeps decayed macrophytic and dried algal mat material out of the system. Following a period of emersion, a sudden inundation event over the delta marshes will result in a short period of high nutrient release from the established vegetation and sediments (64). This period may last for one or two days and is followed by a rapid decrease in release rates toward the seasonal equilibrium. During periods of high river discharge and/or extremely high tides that immediately follow prolonged dry periods, the contribution of carbon, phosphorus, and nitrogen from the deltaic marshes to the estuarine system can be expected to increase dramatically.

Table 8.—Summary of Nutrient Exchange Rates (66) (Units are kg ha^{-1} d^{-1})

	DOC[1]	POC[2]	VSS	Nitrogen		P	Tide Range	Inundation Regularity
				Total	Organic			
Saltwater Marsh								
Pomeroy *et al* (35)						-0.1	large	high
Reinold (37)						-6.3	large	high
Settlemyer and Gardner (39)			-18.4			-0.18	medium	high
Woodwell *et al* (16)	- 0.23	+1.6					medium	high
Odum and de la Cruz (34)			-2 to 28				large	high
Brackish Marsh								
Stevenson *et al* (71)				-0.029		-0.025	medium	medium
Armstrong and Hinson (1)								
Lavaca Bay								
Flood Drainage	-12.6			-1.3	-1.2	-0.1	small	low
Small Net Exchange	- 0.94		- 1.5	-0.21	-0.21	-0.01	small	low
Normal w/Drying	-27.3		-83.6	-1.2	-1.1	-0.16	small	low
Dawson and Armstrong (64)								
Normal Tidal Exchange	- 2.3			-0.39		-0.08	small	low
Following Drying	- 5.9			-2.1		-0.19	small	low
Armstrong and Brown (63)								
Sediment Only				-0.74		-0.1	none	none
Armstrong and Gordon (65)								
Nueces Bay (Reactors)	-1.62		- 3.08	-0.08		-0.03	small	high
San Antonio Bay (Reactors)	- 2.42		- 3.54	-0.02		-0.08	small	high
Copano Bay (Linear Marsh)	- 3.75		- 0.86	-0.06		0.00		
Armstrong and Gordon (65)								
Colorado River Delta (Reactors)	- 0.46		- 0.18	0.0	0.0	0.0	none	none
This Study								
Trinity River Delta (Reactors)	0.0		- 0.86	0.01	0.0	0.02	none	none
Trinity River Delta (Linear Marsh)	- 1.36		0.40	-0.05		-0.02		

[1] DOC: Dissolved Organic Carbon

[2] POC: Particulate Organic Carbon

Table 9.—Summary of Nutrient Exchange Rates for Plant Types from the Lower Trinity River Delta Marshes Corrected for Wall Effects (66)
(Units are kg ha^{-1} d^{-1})

	Mac Lake		Lower Delta			
Analysis	*Lythrum lanceolatum*	*Rhynchospora macrostachya*	*Rhynchospora macrostachya*	*Spartina patens*	*Scirpus americanus*	*Sagittaria lancifolia*
Salinity	1.0	2.	19.	-68.	15.	38.
TSS*	-0.136	-0.096	-3.854	-7.587	-4.483	-2.274
VSS	-0.013	-0.003	-0.641	-1.465	-0.587	-0.754
BOD$_5$*	0.000	0.000	-0.008	-0.096	-0.017	- .019
TOC	-0.004	-0.002	0.283	-0.449	0.260	-0.100
TKN*	0.000	0.000	0.007	0.024	0.006	0.012
TKN	0.000	0.000	0.001	0.002	0.005	0.008
Part. TKN	0.000	0.000	0.007	0.007	0.002	0.004
Drg-N	0.000	0.000	0.000	0.001	0.005	0.008
NH_3-N	0.000	0.000	0.016	0.026	0.017	0.018
NO_2-N	0.000	0.000	0.000	0.001	0.000	0.000
NO_3-N	0.000	0.000	0.075	0.126	0.078	0.080
Tot. P*	0.000	0.000	0.018	0.024	0.026	0.018
Tot. P	0.000	0.000	0.018	0.036	0.025	0.020
Part. TP	0.000	0.000	0.033	0.061	0.033	0.048
Ortho P	0.000	0.000	0.014	0.039	0.026	0.022

*Results for unfiltered samples.

Table 10.—Exchange Rates of Carbon, Nitrogen, and Phosporus in the Linear Marsh from the Trinity River Delta (66)
(kg ha^{-1} d^{-1})

	Stage			
Nutrient	**Normal**	**Flood**	**Following Flood**	**Low**
Total Susp. Solids	-65.49	-52.19	15.228	-37.79
Volatile Susp. Solids	- 3.941	- 9.11	3.384	11.28
BOD$_5$	0.742	- 1.18	1.523	0.82
Total Organic Carbon	- 0.464	2.07	-2.82	- 4.23
Total Kjeldahl - N (Un F)	- 0.046	- 0.041	-0.028	- 0.085
Total Kjeldahl - N	- 0.046	0.083	-0.028	- 0.028
Ammonia - N	- 0.0023	- 0.059	-0.0085*	- 0.006
Nitrite - N	--*	--*	--*	- 0.014*
Nitrate - N	--*	0.094	-0.0113	- 0.024*
Total P (Un F)	- 0.0417	0.0041	0.071	- 0.096
Total P	- 0.035	- 0.046		- 0.003
Ortho P	- 0.0058*	- 0.021	0.032	0*

*Some or all data below detectable limits.

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