FRESHWATER RUNOFF AND SALINITY DISTRIBUTION IN THE LOXAHATCHEE RIVER ESTUARY, SOUTHEASTERN FLORIDA, 1980-82

By Gary M. Russell and Benjamin F. McPherson

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CONVERSION FACTORS

For use of readers who prefer to use metric units, conversion factors for terms used in this report are listed below:

Multiply	By	To obtain
inch (in)	25.4	millimeter (mm)
	2.54	centimeter (cm)
mile (mi)	1.609	kilometer (km)
foot (ft)	0.3048	meter (m)
square mile (mi^2)	2.590	square kilometer (km^2)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
acre-foot (acre-ft)	1,233	cubic meter (m^3)
micromho per centimeter at 25° Celsius (umhos/cm at 25°C)	1.000	microsiemens per centimeter at 25° Celsius (uS/cm at 25°C)

Temperature in degrees Celsius (°C) can be converted to degrees Fahrenheit (°F) as follows:

$$°F = 1.8°C + 32$$

National Geodetic Vertical Datum of 1929 (NGVD of 1929): A geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called mean sea level, is referred to as sea level in this report.

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ABSTRACT

During a recent study, freshwater mixed with seawater over a distance of 5 to 10 river miles in the Loxahatchee River estuary. Large freshwater inflows vertically stratified the estuary and shifted the mixing zone seaward. In the northwest fork of the estuary, the saltwater-freshwater inferface moved daily about 0.5 to 1.5 river miles as a result of tides and annually about 3 to 5 miles as a result of seasonal changes in freshwater inflow. In the southwest fork, saltwater movement upstream was blocked by a gate and dam structure in Canal-18, 4.7 miles upstream from the Atlantic Ocean. Although Canal-18 discharged about one-third of the total freshwater tributary inflow to the estuary, the effects of canal discharge on salinity were limited to relatively brief periods. Much of the time, no freshwater was discharged.

INTRODUCTION

Freshwater inflow and tidal flushing affect various estuarine properties and largely determine the salinity distribution in an estuary. Man's increased emphasis on river impoundment and diversion has caused concern about how these activities might affect salinity, which in turn is a major controlling factor on estuarine biota (Emery and others, 1957; Copeland, 1966). Effects of runoff on estuarine salinity have been of interest to a number of investigators (Schroeder, 1978; Conomos, 1979; Biggs and Cronin, 1981).

In southeastern Florida, freshwater runoff is largely controlled by an extensive system of canals, control structures, pumping stations, and water-storage areas. Canal discharges are made to the estuaries at control structures near the coast. To meet the future freshwater needs of the growing population, water-management plans call for a reduction of discharge to the estuaries (U.S. Army Corps of Engineers, 1961; South Florida Water Management District, 1978). Freshwater in coastal canals would be backpumped west into the Everglades and held in water-conservation areas in the interior. A similar plan is also being considered for part of the Loxahatchee River basin (Breedlove Associates, Inc., 1982). If these plans are implemented, the reduction of freshwater flow to the estuaries would, among other possible changes, increase salinity and decrease nutrient input, which would in turn affect estuarine biota and productivity.

Unlike most estuaries in southeastern Florida, parts of the Loxahatchee River estuary and its surrounding lands are undeveloped. The distinct distribution of biota that developed over many years persists today. Seagrass beds and oyster bars grow in the lower estuary but diminish and disappear several miles upstream from the inlet. Cypress forest in the upper reach of the river, within JDSP (Jonathan Dickinson State Park), merges with mangrove forest along several miles near its downstream limit.

This report presents baseline information on the areal and seasonal variations of salinity in the Loxahatchee River estuary and evaluates effects of freshwater inflow on that salinity regime. The report contains information on salinity distribution, freshwater inflow, tidal fluctuations, and rainfall. The relation between freshwater inflow, tides, and salinity is evaluated by regression analysis. The report presents the results of one phase of a U.S. Geological Survey investigation of the Loxahatchee River estuary (McPherson and Sabanskas, 1980).

DESCRIPTION OF STUDY AREA

The Loxahatchee River estuary empties into the Atlantic Ocean at Jupiter Inlet (fig. 1). The estuary includes three forks - southwest fork, north fork, and the northwest fork (Loxahatchee River) which has the longest reach. The three forks converge approximately 2 miles upstream from the ocean to form the central embayment of the estuary. Between the confluence of the three forks and Jupiter Inlet, the estuary is intersected by the Intracoastal Waterway (fig. 2). Estuarine conditions extend from Jupiter Inlet to about 5 river miles up the southwest fork, 6 river miles up the north fork, and 10 river miles up the northwest fork. Four major river tributaries discharge to the northwest fork. Canal-18 (C-18), built in 1957-58, is the major tributary to the southwest fork. The north fork has several small, unnamed tributaries (fig. 2).

The Loxahatchee River estuary is shallow with an average depth of about 4 feet. Sand bars and oyster bars in the central embayment are occasionally exposed at low tide as is much of the forested flood plain in the northwest fork. Some deeper parts of the estuary are a result of dredging. In the northwest fork, a natural river channel with maximum depths ranging from about 10 to 20 feet extends upstream approximately 9 river miles. Farther upstream, maximum depths are generally less than 10 feet.

Historical evidence indicates the estuary periodically closed and opened to the sea as a result of natural causes. Originally, flow not only from the Loxahatchee River but also from Lake Worth Creek and Jupiter Sound helped keep the inlet open (fig. 2). Near the turn of the century, some of this flow was diverted by creation of the Intracoastal Waterway and the Lake Worth Inlet and by modification of the St. Lucie Inlet (Vines, 1970). Subsequently, Jupiter Inlet remained closed much of the time until 1947, except when periodically dredged. After 1947, it was kept open by dredging (U.S. Army Corps of Engineers, 1966). A detailed description of dredging in the inlet and in the estuary is outlined by McPherson and others (1982).

After 1900, man began to influence the estuary not only by dredging activities but also by altering drainage in the basin. Generally, ground-water levels have been lowered and freshwater inflow reduced or altered in direction or period of flow (McPherson and Sabanskas, 1980). The major surface flow to the estuary historically was into the northwest fork from the Loxahatchee Marsh and the Hungryland Slough (fig. 1). Both of these drained north from the low divides near SR-710 (State Road 710) (Parker and others, 1955). A small agricultural canal was dug before 1928 to divert water from Loxahatchee Marsh to the southwest fork. In 1957-58, C-18 was constructed in the natural drainage path to divert flow from the northwest fork of the estuary to the southwest fork. A culvert was installed in 1974 to allow water to be rediverted from C-18 to the northwest fork (fig. 1).

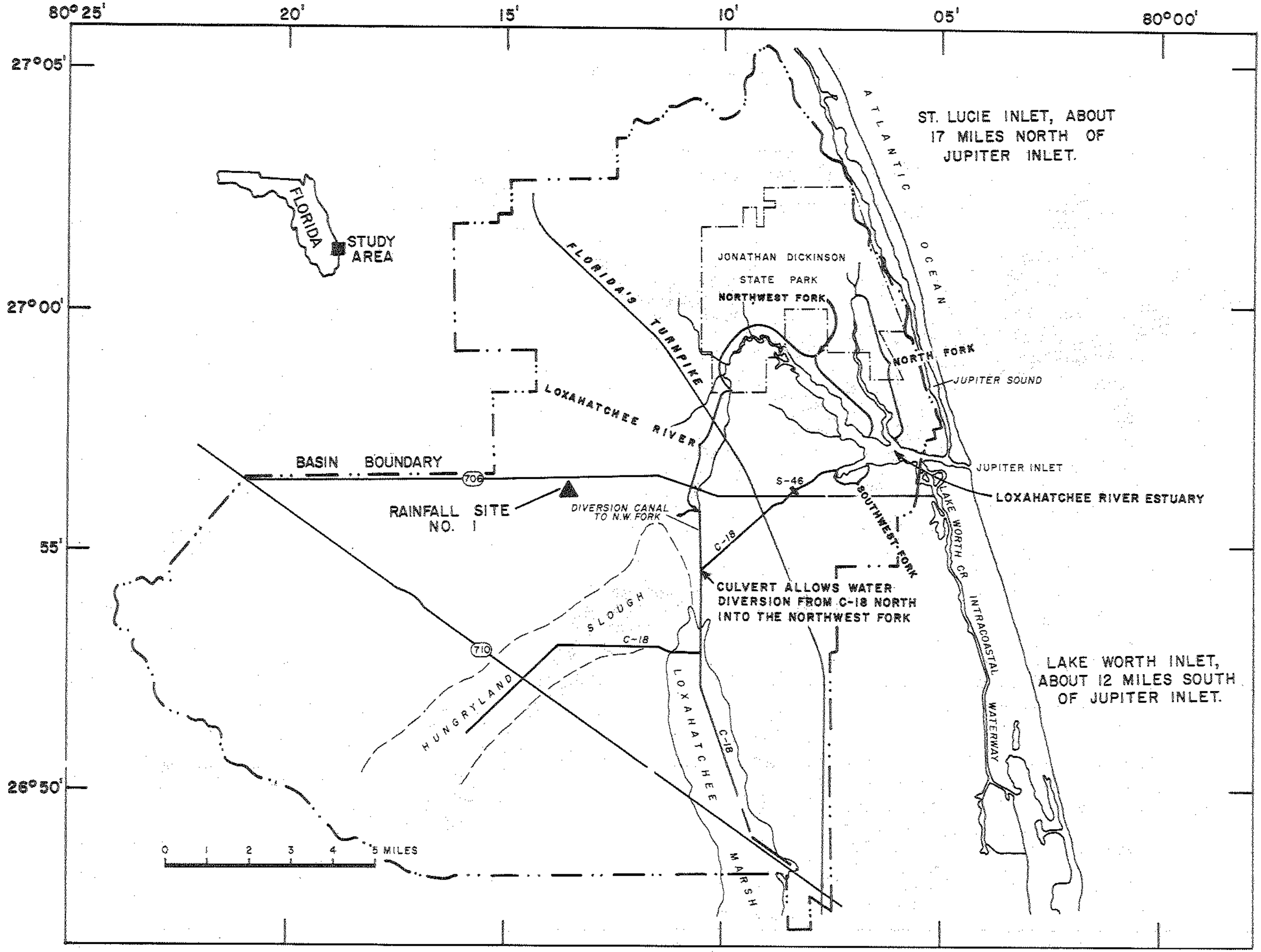

Figure 1.--Loxahatchee River drainage basin, southeastern Florida.

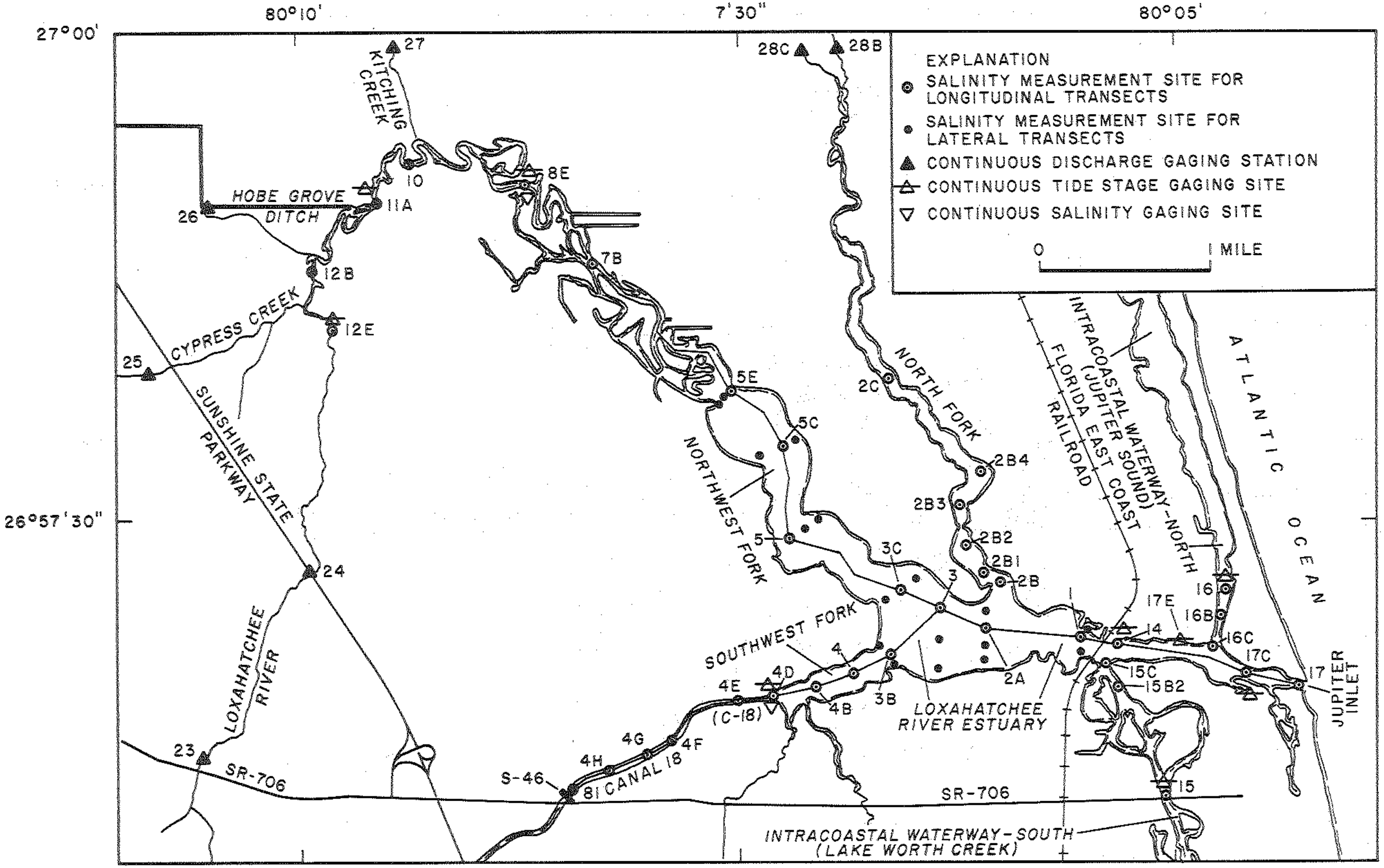

Figure 2.--Location of discharge, stage, and salinity measurement sites on the Loxahatchee River estuary and tributary streams.

DATA COLLECTION

Primary and secondary salinity-measurement sites were established in the estuary (fig. 2). The primary sites were along longitudinal transects that extended from Jupiter Inlet and the Intracoastal Waterway into the three forks of the estuary. Secondary sites were in wider parts of the estuary and formed lateral transects perpendicular to the longitudinal transects (fig. 2).

Salinity determinations were based on in place measurements of specific conductance. The instrument calibration was verified each day before and after field measurements. Specific conductance, in micromhos per square centimeter at 25°C, was converted to salinity, in ppt (parts per thousand), based upon a U.S. Geological Survey computer program (R. L. Cory, written commun., 1980). Water with a salinity of less than 0.5 ppt was called "fresh," and water with a salinity greater than 0.5 ppt but less than 15 ppt was called "brackish."

Salinity is defined as "the total amount of solid material in grams contained in 1 kg of seawater when all the carbonate has been converted to oxide, the bromine and iodine replaced by chlorine, and all organic matter completely oxidized" (Forch and others, 1902). Even though this formal definition refers to salinity as an amount, in practice salinity is generally expressed as a concentration, in ppt.

Salinity was determined along the transects on both high and low tides every other month between November 1980 and August 1981. At each site, measurements were made 1 foot below the water surface and 1 foot above the bottom of the estuary and, in some cases, at intermediate depths. Measurements were scheduled to coincide with extreme monthly tides predicted in the National Oceanic and Atmospheric Administration tide tables. Measurements at each site were made as close as possible to slack high or slack low tides. A 1- to 2-hour time lag for slack tide between Jupiter Inlet and the farthest upstream site (12E) allowed most measurements to be made approximately on these slack tides.

In addition to the salinity-transect measurements, 2 recording instruments capable of measuring specific conductance either continuously or at 10-minute intervals were installed in the estuary. One instrument, measuring at 10-minute intervals was installed in the northwest fork at site 8E (fig. 2) in June 1980 and was operational through April 1982. The sensor probe was near the center of the river channel near the bottom at a depth of about 10 to 12 feet. The other instrument measuring continuously was installed in the southwest fork at site 4D (fig. 2). The sensor probe was in the center of the channel about 2 feet above the bottom from June to October 1980. Because changes in bottom salinity were small and did not appear to be affected by freshwater discharges, this probe was raised to about 0 to 2 feet below the water surface (depending on the tide stage) and operated at that position between October 1980 and March 1982.

Continuous tide-stage records were available from nine stations during the course of this study (fig. 2). Records from these stations were evaluated to determine time lag and changes in amplitude of tidal waves. The tide gage at site 14 was selected as representative, and values from this gage were used in this report.

Freshwater inflow to the estuary was measured at discharge-gaging stations on the major tributaries (fig. 2). A stage-discharge relation was established for each station and rating tables prepared. The mean daily discharge was computed from continuous water-level recorders and the rating tables. The South Florida Water Management District provided stage and discharge data for C-18 at control structure S-46 and the rainfall data for site 1.

RESULTS AND DISCUSSION

Tides

Tides in the Loxahatchee River estuary are mixed-semidiurnal (twice daily with varying amplitudes) and range from about 2 to 3 feet (fig. 3). The tidal wave advances up the estuary at about 5 to 10 mi/h and shows little change in amplitude or range over a distance of 10 river miles. Winds have a significant effect on the height of the tide in the estuary. Strong northeast winds, which prevail during autumn and winter for example, push additional water into the estuary and result in higher than average tides. The mean tidal prism of the Loxahatchee River estuary at site 14 (fig. 2) was estimated at 3,226 acre-ft (McPherson and others, 1982). A summary of tide-stage data, February 1980 through September 1981, at site 14 is given in table 1.

River and Canal Discharges

Freshwater enters the Loxahatchee River estuary by river and canal discharge, storm drains, direct land runoff, and subsurface flow. River and canal discharges drain most of the basin and predominate as indicated by salinity gradients associated with these sources. Storm-drain runoff and subsurface flow directly to the estuary come from a small basin area compared with that area drained by the major tributaries.

Freshwater inflow is seasonal, and most occurs during the wet season (May to November) caused by heavy rainfall sometimes associated with tropical storms and hurricanes. During this study, the largest runoff occurred in August 1981 following Tropical Storm Dennis, which passed over the study area on August 18, 1981. Rainfall in the vicinity of the Loxahatchee River estuary was about 3 to 5 inches on this date. Runoff was exceptionally large for several days after the storm. Average daily discharge from the major tributaries of the estuary increased from 81 ft^3/s during 5 days preceding the storm to 1,141 ft^3/s during the first 5 days of stormwater runoff. Much of the estuary was fresh or brackish immediately after the storm.

The four major streams, which are tributaries to the northwest fork (Loxahatchee River, Cypress Creek, Hobe Grove Ditch, and Kitchen Creek), discharge more than 8 river miles upstream of the ocean. Of these, the main stem of the Loxahatchee River is usually the major contributor (table 2) and at site 23 accounted for, on the average, 49 percent of the total discharge to the northwest fork (table 3). On a monthly basis, however, discharge at

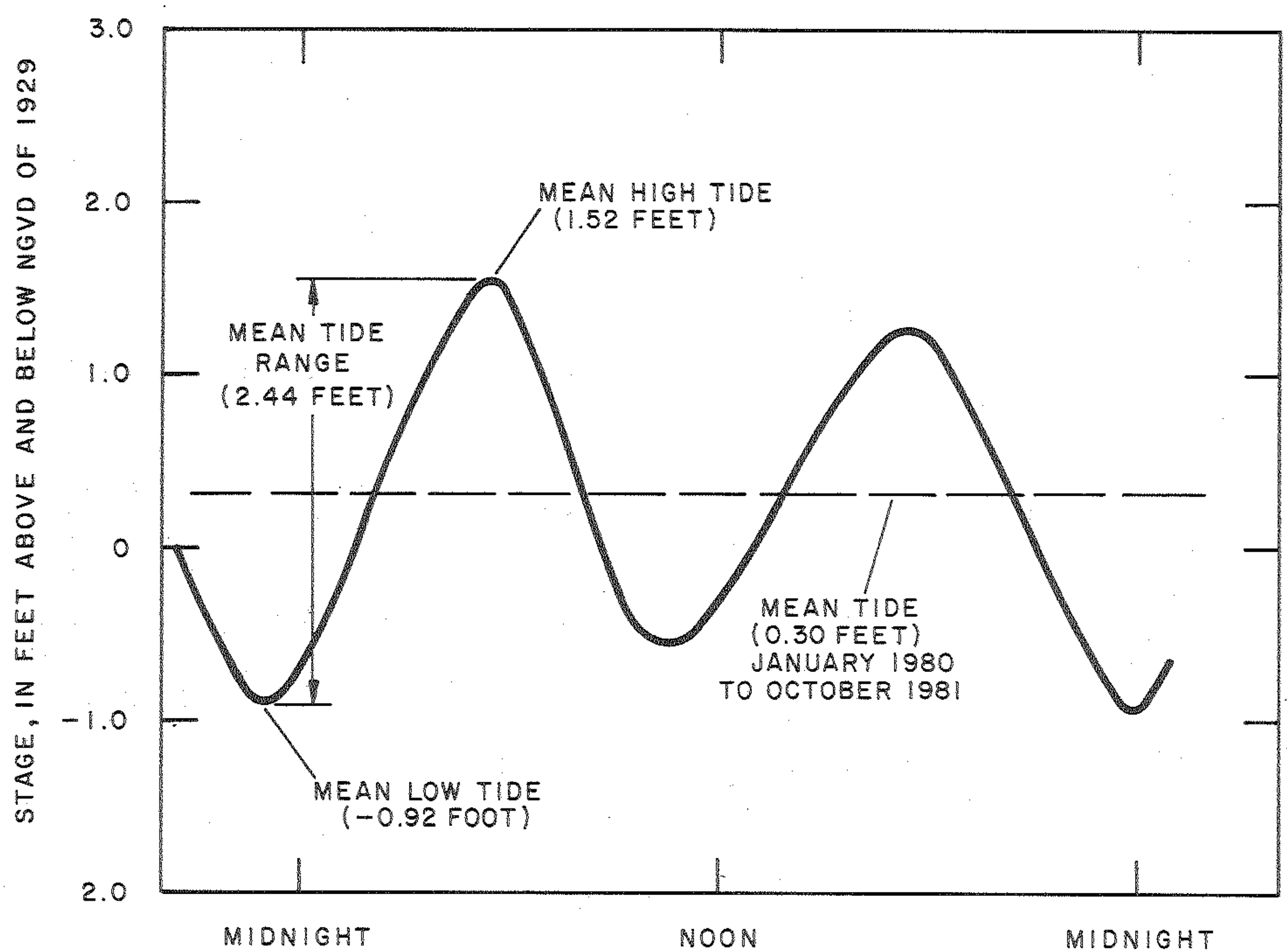

Figure 3.--Typical mixed-semidiurnal tidal cycle for the Loxahatchee River estuary at site 14.

Table 1.--Summary of tide-stage data at site 14, Loxahatchee River estuary, 1980-81

[Values are in feet above sea level]

Month	1980 mean monthly			1981 mean monthly		
	High	Low	Range	High	Low	Range
January	--	--	--	1.56	-0.82	2.38
February	1.78	-0.58	2.36	1.49	- .85	2.34
March	1.27	-1.08	2.35	1.42	- .86	2.28
April	1.42	-1.02	2.44	1.16	-1.14	2.30
May	1.58	- .94	2.52	1.53	- .89	2.42
June	1.59	-1.03	2.62	1.09	-1.35	2.44
July	1.28	-1.30	2.58	1.39	-1.05	2.44
August	1.30	-1.24	2.54	1.52	- .85	2.37
September	1.81	- .71	2.52	1.84	- .47	2.31
October	1.81	- .63	2.44	--	--	--
November	1.88	- .54	2.82	--	--	--
December	1.71	- .69	2.40	--	--	--

Mean tide range	2.44
Mean tide	0.30
Mean high tide	1.52
Mean low tide	-0.92
Maximum high tide	+2.68
Minimum low tide	-1.80

Table 2.--Average freshwater inflow into the three forks of the Loxahatchee River estuary from the major tributaries for selected periods during 1980-82

[Values in cubic feet per second]

Site	1980 wet season, May-Oct 184 days	1980-81 extended dry season, Nov 1980 - July 1981 273 days	1981 wet season, Aug-Sept 61 days	1981 Tropical storm, August 18-22 5 days	1982 early spring storm, Mar 29-Apr 6 9 days
Northwest fork					
Loxahatchee River at site 23	65	28	106	242	236
Freshwater inflow between sites 23 and 24.	17	3	32	198	44
Cypress Creek, site 25	45	20	132	265	190
Hobe Grove, site 26	12	4.5	18	108	51
Kitchen Creek, site 27	8	1.7	17	21	ND
Subtotal	147	57.2	305	834	521
North fork					
Unnamed, sites 28B, 28C	4	.7	13	6	ND
Southwest fork					
Canal-18 at S-46	32	0	187	301	488
Total	183	58	305	1,141	1,009
Number of days for total freshwater inflow to equal volume[1]/ of estuary west of A1A.	14	44	8	2.3	2.5

1/ 5,100 acre-feet, McPherson and others (1982).

ND, No data.

Table 3.--Relative magnitude of monthly freshwater inflow to the northwest fork of the Loxahatchee River estuary from four major tributaries, March 1980-82

[Values in percentage of total]

Date	Loxahatchee River at		Cypress Creek	Hobe Grove	Kitchen Creek
	Site 23	Site 24			
3/80	55	73	21	5	1
4/80	49	53	36	8	3
5/80	28	39	38	17	6
6/80	50	63	27	6	4
7/80	46	60	30	6	4
8/80	58	65	28	4	3
9/80	34	43	39	7	11
10/80	52	63	24	5	8
11/80	50	56	34	6	4
12/80	53	61	29	5	5
1/81	47	53	38	6	3
2/81	34	46	44	7	3
3/81	37	52	34	13	1
4/81	45	52	36	11	1
5/81	56	63	28	8	1
6/81	38	45	38	17	.5
7/81	61	60	30	9	1
8/81	34	47	40	9	4
9/81	37	43	47	2	8
10/81	55	63	32	2	3
11/81	65	75	20	4	1
12/81	72	74	22	3	1
1/82	58	67	27	5	1
2/82	66	68	21	7	4
3/82	51	56	26	8	10
Average	49	57	32	7	4

site 23 ranged from as little as 28 percent (May 1980) to as much as 72 percent (December 1981) of the total discharge (table 3). The monthly discharge at site 23 and the total of the monthly discharges for the four major streams (Loxahatchee River, Cypress Creek, Hobe Grove Ditch, and Kitchen Creek) are shown in figure 4.

The average daily discharge of the Loxahatchee River at site 23 for the 9-year period (1973-82) was 51 ft^3/s. During this study, the average discharge at site 23 was 68 ft^3/s. This higher than average discharge is attributed to the prolonged rains from Tropical Storm Dennis, an abnormally wet dry season (February to April 1982), and an increase inflow of water to the river from C-18 through the diversion culvert (see fig. 1).

During the study period, site 24 was measured to determine additional runoff into the Loxahatchee River above the tidal reaches of the river. Data for this site are shown in table 2 as a difference in freshwater inflow between sites 23 and 24.

Discharge from Cypress Creek is usually less than but occasionally more than those in the Loxahatchee River at site 23 and 24 (tables 2 and 3). During the period of this study, Cypress Creek discharged an average of 32 percent of the total tributary discharge to the northwest fork. Discharge from Hobe Grove Ditch and Kitchen Creek averaged 7.4 percent and 3.6 percent of the discharge to the northwest fork, respectively. Freshwater flow upstream of the U.S. Geological Survey gaging sites in Cypress Creek, Hobe Grove Ditch, and Kitchen Creek is managed by agricultural interests.

Canal-18 discharges to the estuary at control structure S-46 (site 22), 4.7 miles upstream of the ocean, considerably farther downstream than the major tributaries in the northwest fork. Structure S-46 is an automated structure with gates that open when water levels rise above a predetermined level. As a result, discharge usually begins and ends abruptly whereas that of the other major tributaries are more continuous over time and recede slowly to baseline conditions. Normal operation dictates that the gates open when canal water levels exceed 15 feet above sea level during the dry season and 14 feet above sea level during the wet season. The gates remain open until water levels recede by 1 foot. During the 1980 water year, S-46 operated as described above. However, during the 1981 water year, the operating procedure was changed, and the structure remained on a dry-season schedule throughout the year. Discharge from C-18 to the estuary constitutes a significant amount of freshwater, particularly during high rainfall periods. For example, discharge from C-18 during an early spring storm (March 29 to April 6, 1982) exceeded input from any other tributary (table 2). However, during most of the study period, the canal did not discharge freshwater to the estuary.

Water is discharged from C-18 to the northwest fork of the river at the diversion culvert, depending on relation between water levels in the canal and in the river at SR-706 (near site 23). Water is diverted to the river when levels in the canal exceed 12.5 feet above sea level and when levels at SR-706 are below 11.7 feet above sea level. More water has been diverted from C-18 in recent years (including the study period) because water levels

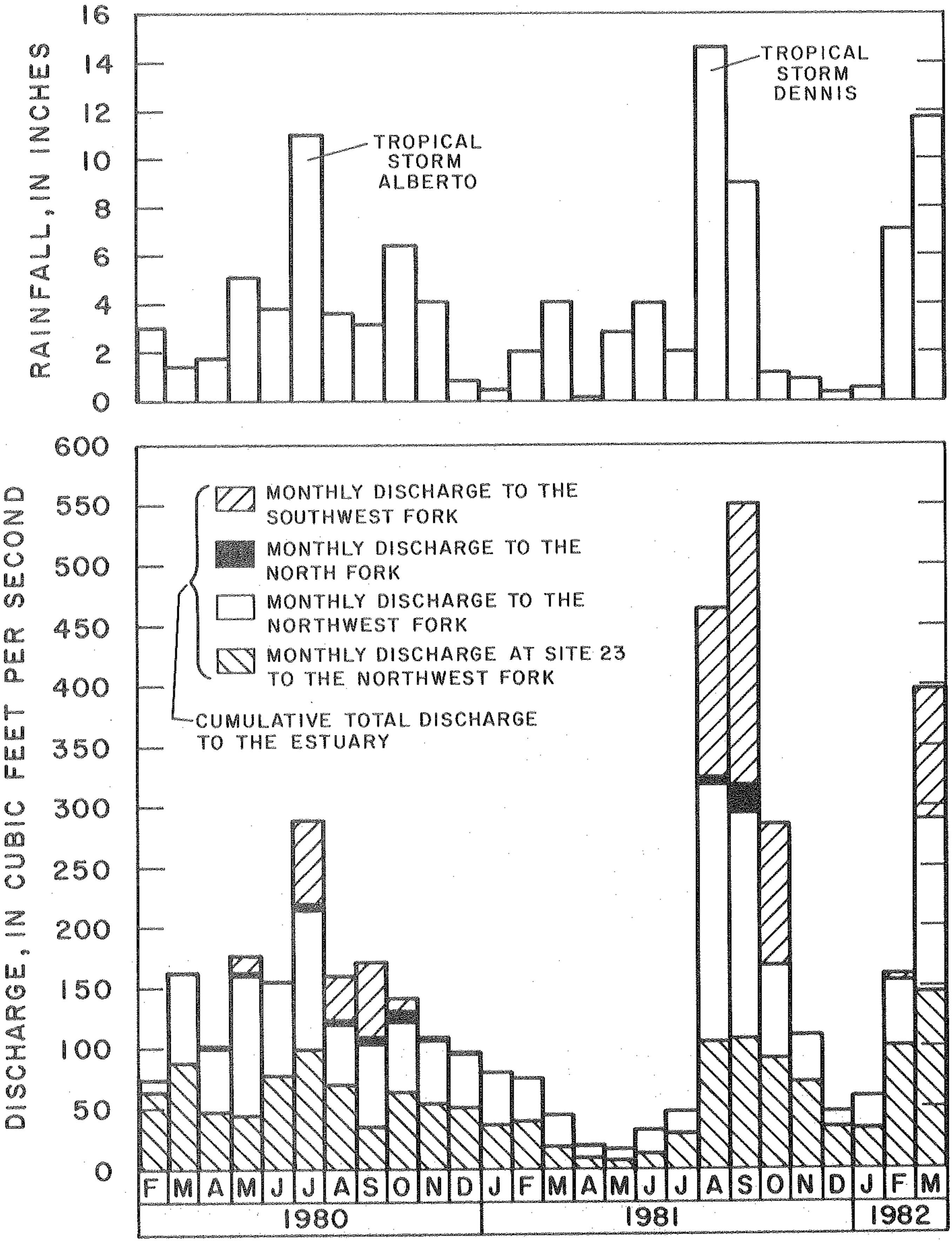

Figure 4.—Average monthly discharge to the Loxahatchee River estuary from various tributaries and total monthly rainfall at site 1.

in the canal are maintained higher, and water levels at SR-706 are lower owing to erosion of a small weir (Lainhart Dam) about 0.1 mile downstream of SR-706. Erosion of the weir along with canal construction in the basin have probably increased drainage in the area and also contributed to the increased discharge in the river.

Freshwater inflow to the north fork of the Loxahatchee River estuary is uncontrolled and is quite small compared with inflow from the other forks (table 2). In the 1981 water year, the tributaries of the north fork were dry at the gaging stations (fig. 2) from March through mid-August. During the rest of the 1981 water year, discharge to the north fork averaged 4.15 ft^3/s.

Discharge to the north fork following Tropical Storm Dennis was small for the amount of rainfall associated with the storm. Daily discharge for the last 10 days of August 1981 averaged 10 ft^3/s but increased in September 1981 to 23 ft^3/s. Discharges to the southwest fork and the northwest fork were at or near peak after the storm in August 1981 (see table 2 and fig. 4).

The average daily rate of freshwater inflow to the estuary from the major tributaries ranged from 58 to 1,173 ft^3/s for selected periods in 1980-82 (table 2). At these rates, freshwater inflow would equal the volume of the estuary west of site 14 (5,100 acre-ft; McPherson and others, 1982) in as few as 2.3 days (5-day runoff from Tropical Storm Dennis) and in as many as 44 days (runoff during an extended dry season). At the average daily rate of freshwater inflow for the 1981 water year, inflows from the tributaries would equal the volume of the estuary in 19 days.

Salinity Distribution

Salinity distribution in the Loxahatchee River estuary is characterized by longitudinal and vertical salinity gradients that change daily with tides and seasonally with the quantity of freshwater inflow (figs. 5-17). Freshwater inflow is greatest in the wet season (June to October) and is associated with heavy rainfall, sometimes derived from tropical storms and hurricanes (fig. 4).

During this study, the greatest concentration of freshwater inflow occurred following Tropical Storm Dennis, which passed over the study area on August 18, 1981. On this date, rainfall at site 1 was 4.68 inches with above-average runoff continuing several days after the storm. Salinity decreased immediately after the storm, as shown at sites 4D and 8E (fig. 6), and fresh to slightly brackish (0.5 to 5 ppt) water at the surface extended eastward to about 2.5 miles of Jupiter Inlet. The estuary was highly stratified in areas (figs. 7-10) with fresh to brackish water at the surface and water with salinities greater than 30 ppt near the bottom.

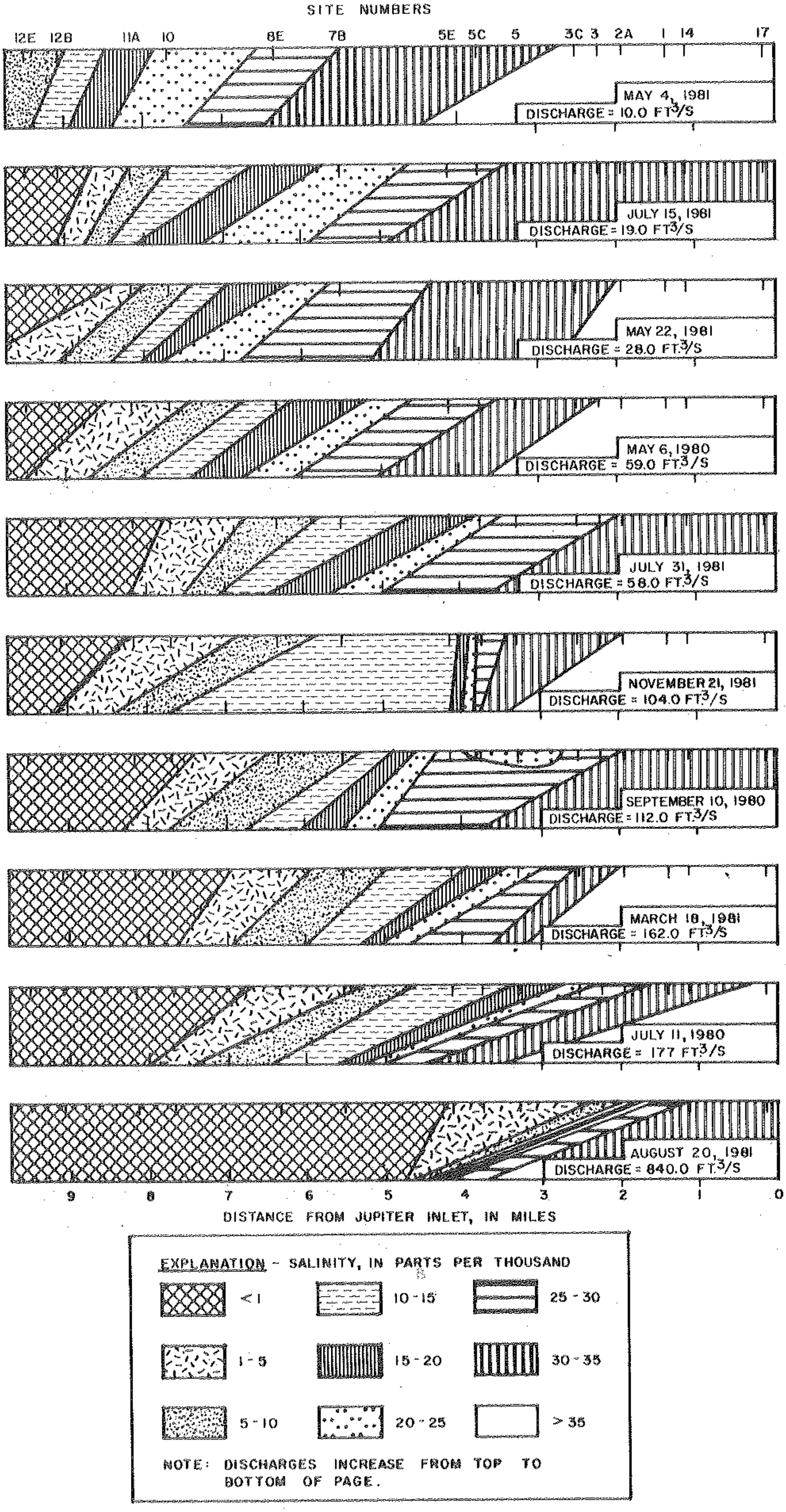

Figure 5.—Salinity profiles in the northwest fork of the Loxahatchee River estuary during high tide at different discharges.

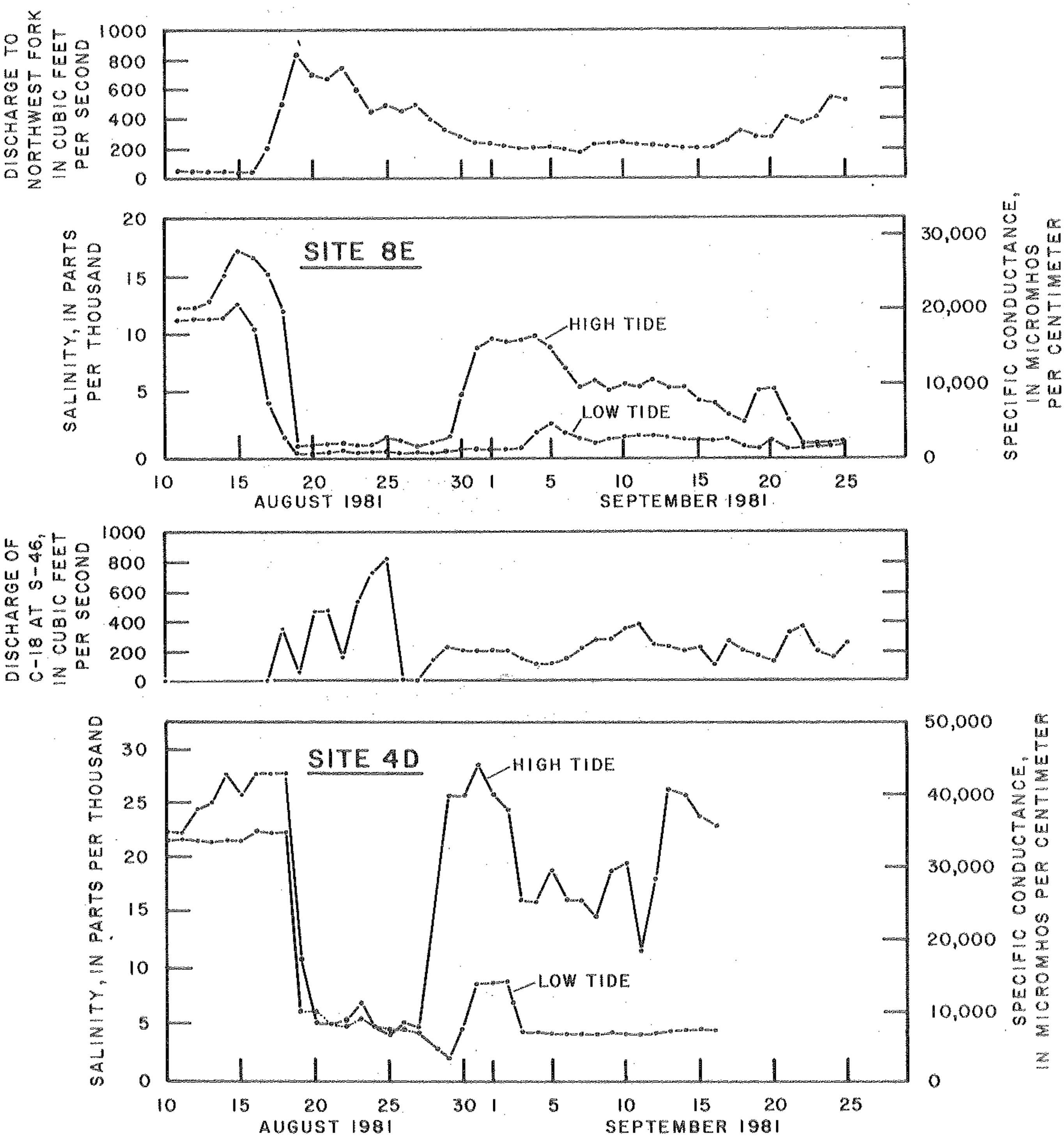

Figure 6.—Effects of Tropical Storm Dennis on discharge and top salinity at site 4D and bottom salinity at site 8E in the Loxahatchee River estuary, August to September 1981.

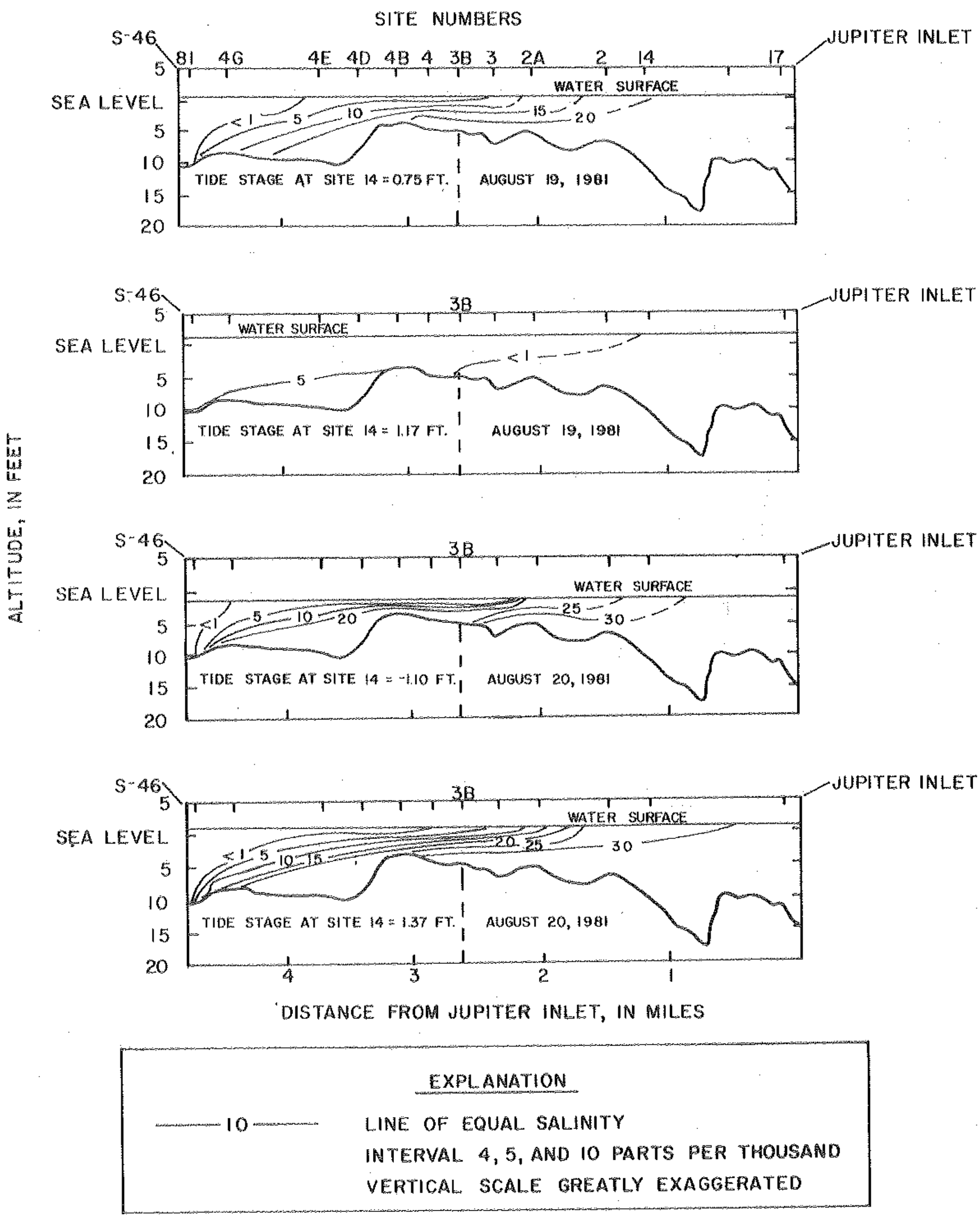

Figure 7.--Salinity profiles in the southwest fork of the Loxahatchee River estuary following Tropical Storm Dennis (August 19-20, 1981).

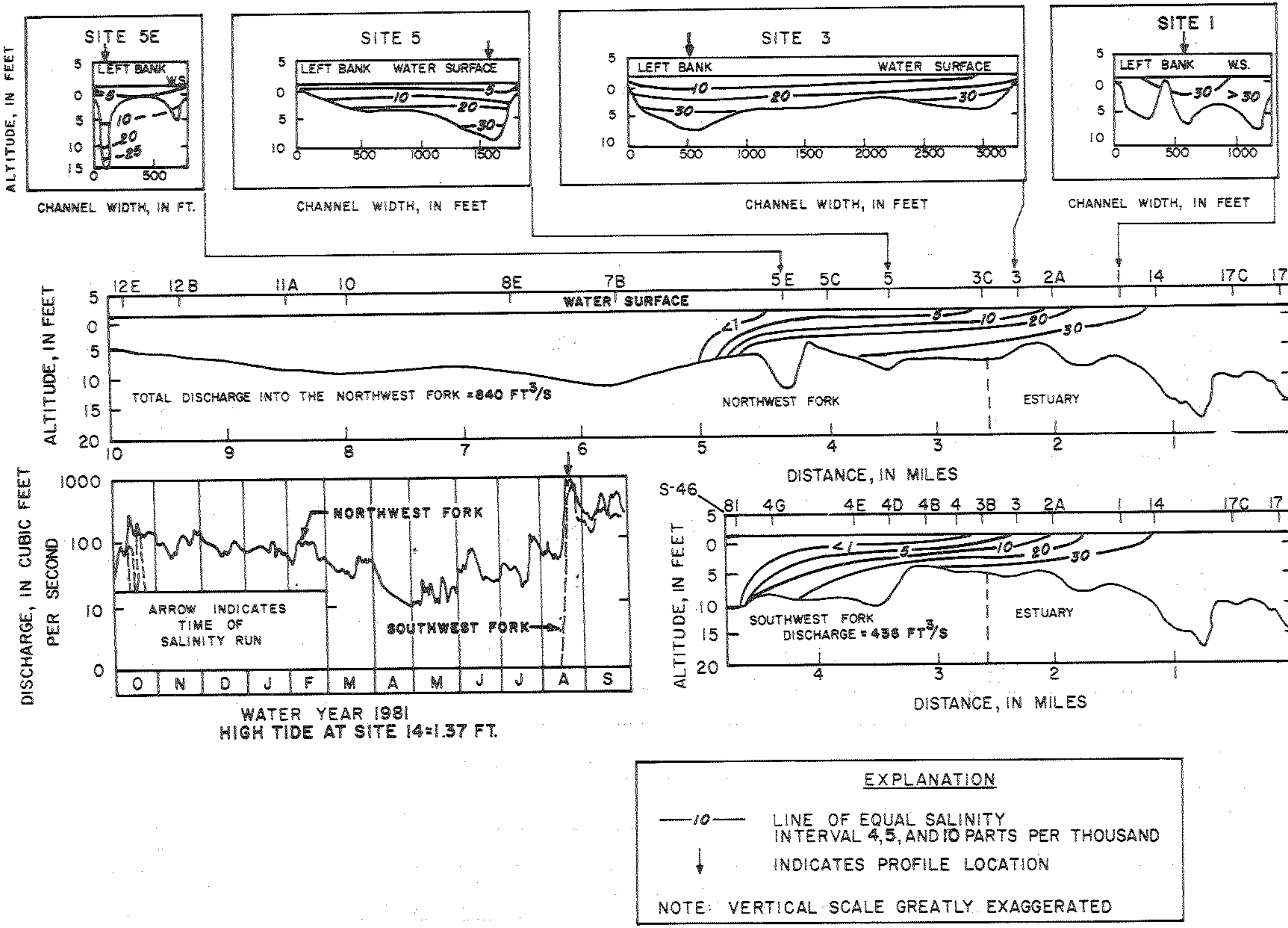

Figure 8.--High-tide salinity profiles in the Loxahatchee River estuary following Tropical Storm Dennis (August 20, 1981).

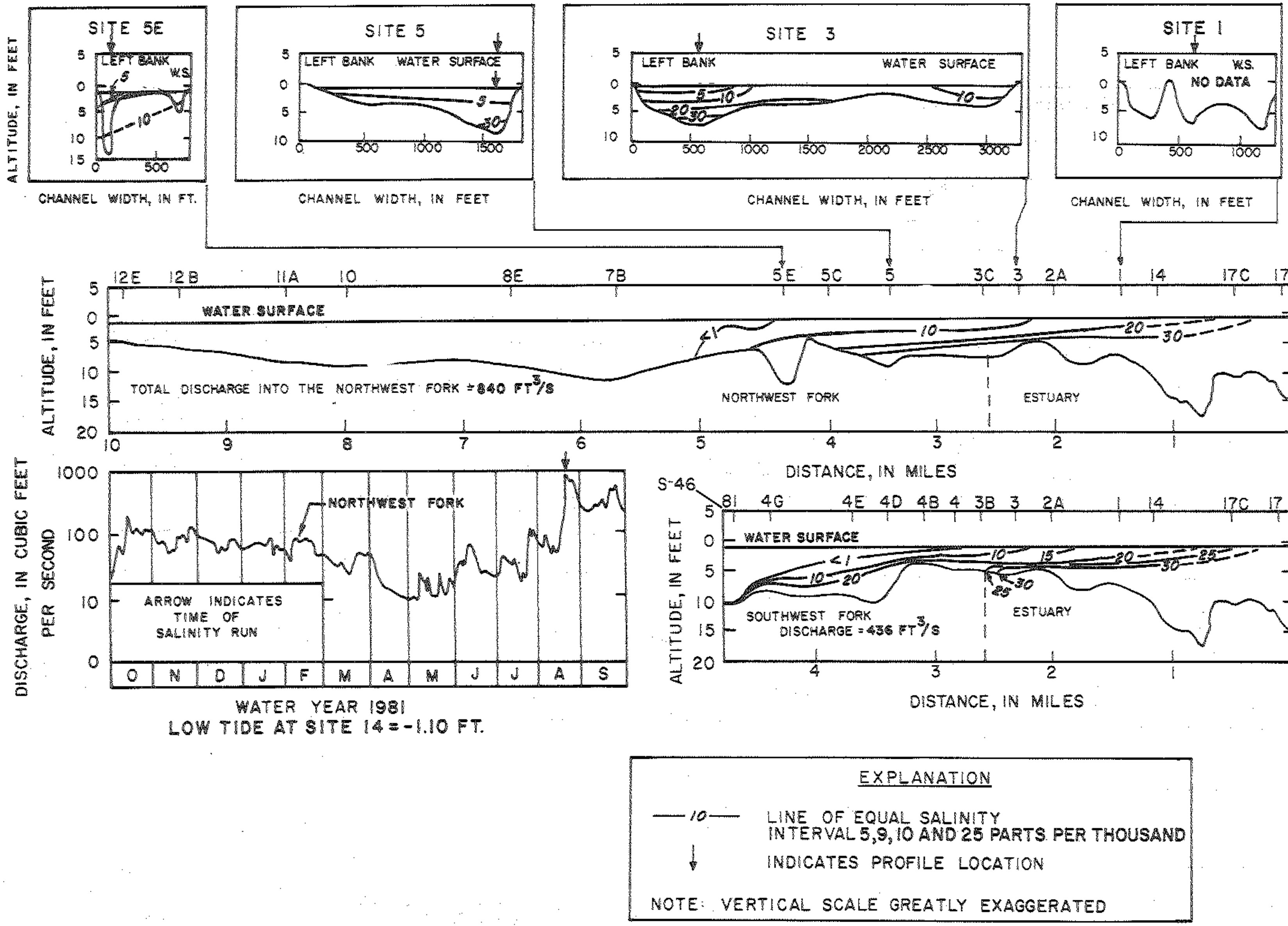

Figure 9.--Low-tide salinity profiles in the Loxahatchee River estuary following Tropical Storm Dennis (August 20, 1981).

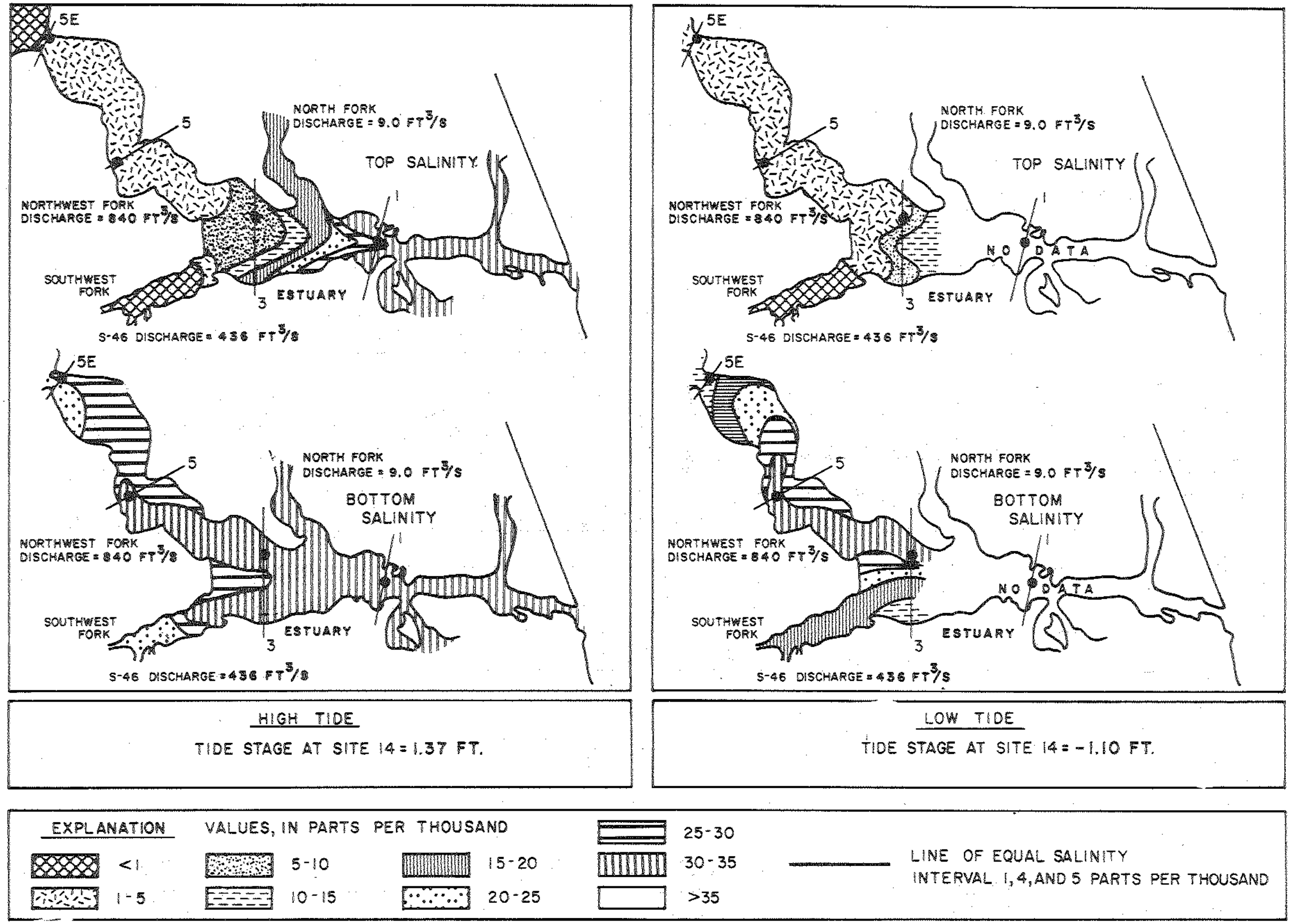

Figure 10.--Areal-salinity distribution in the Loxahatchee River estuary for high and low tides following Tropical Storm Dennis (August 20, 1981).

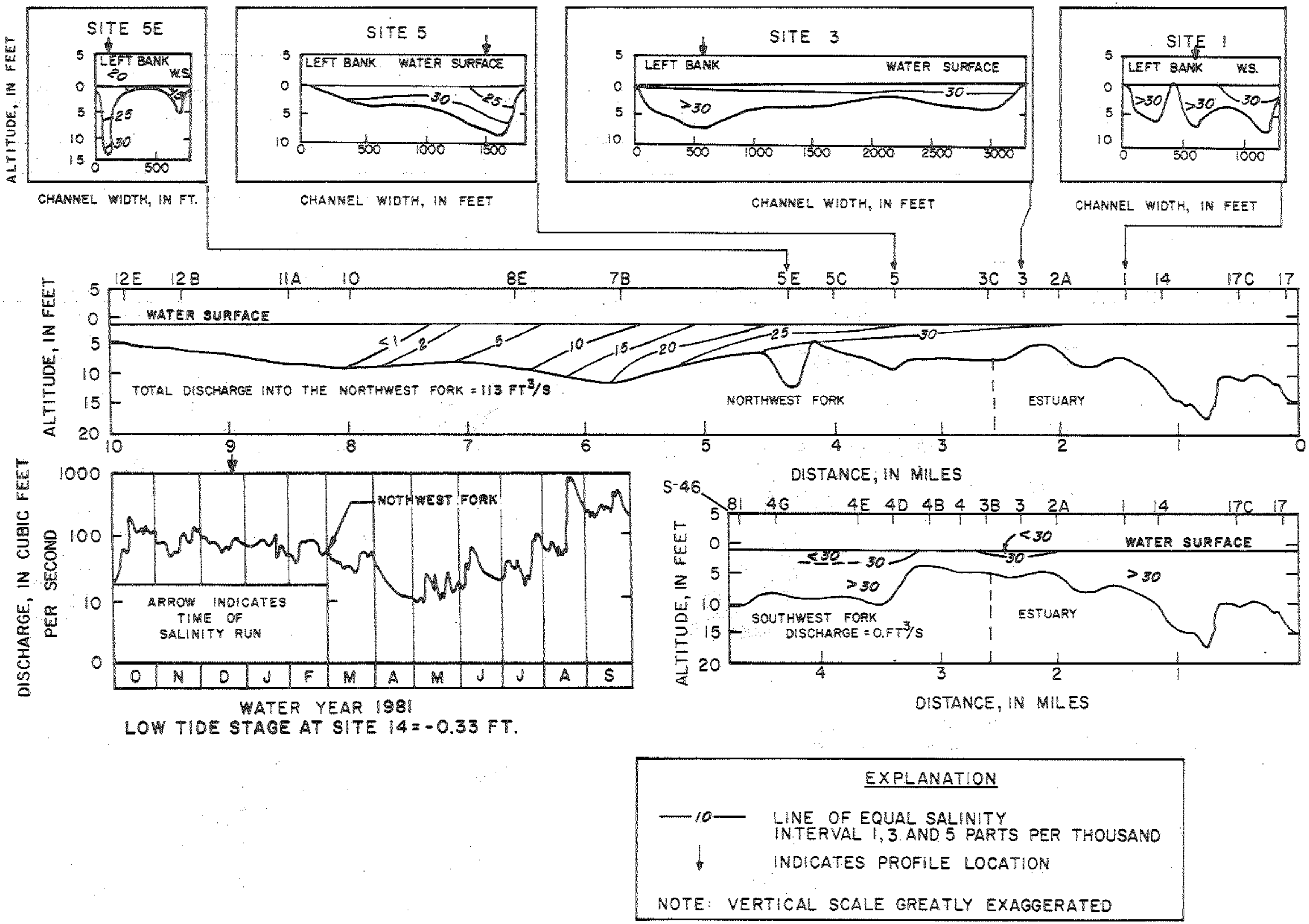

Figure 11.--Low-tide salinity profiles in the Loxahatchee River estuary during typical wet season (November 20, 1980).

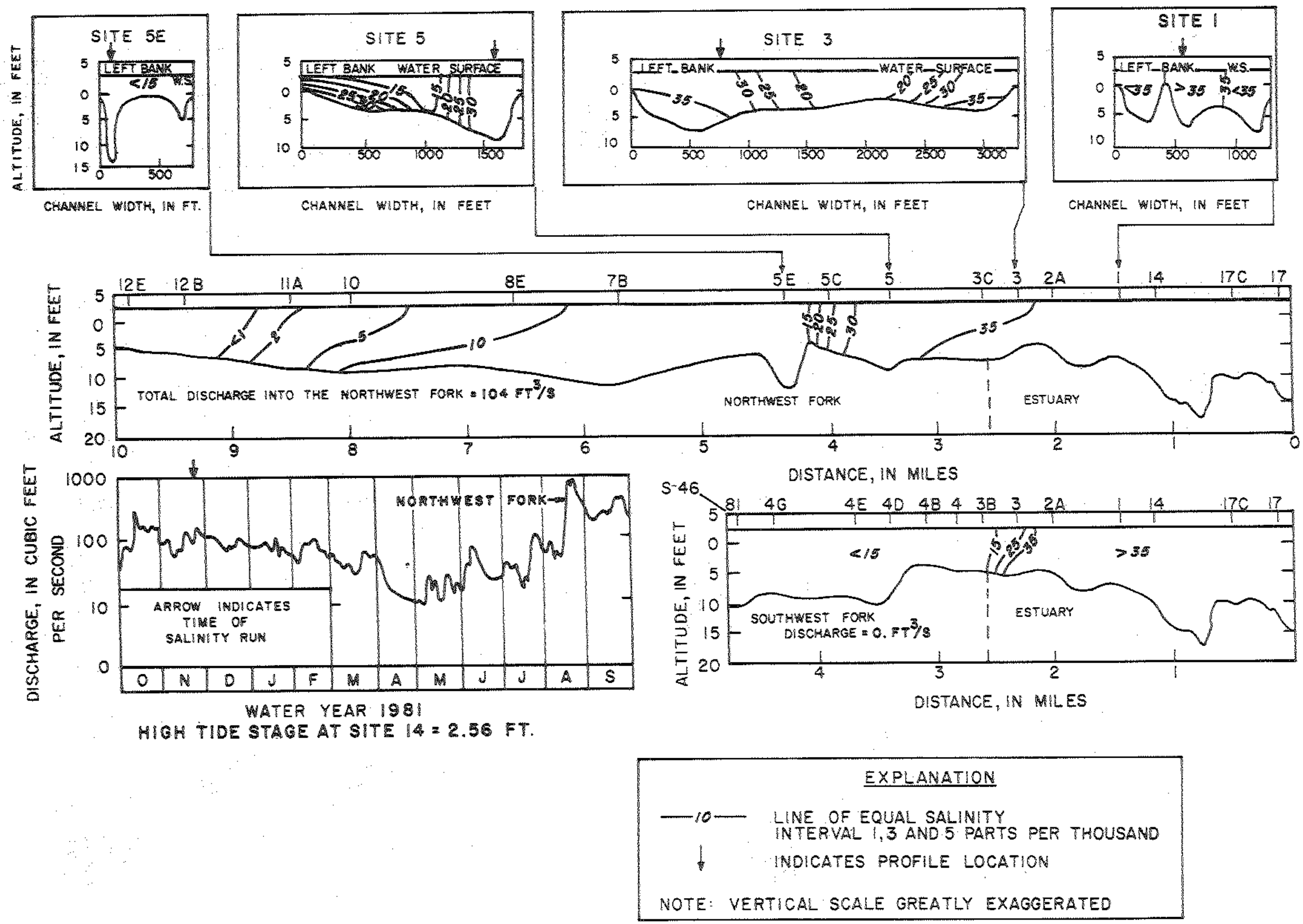

Figure 12.--High-tide salinity profiles in the Loxahatchee River estuary during typical wet season (November 21, 1980).

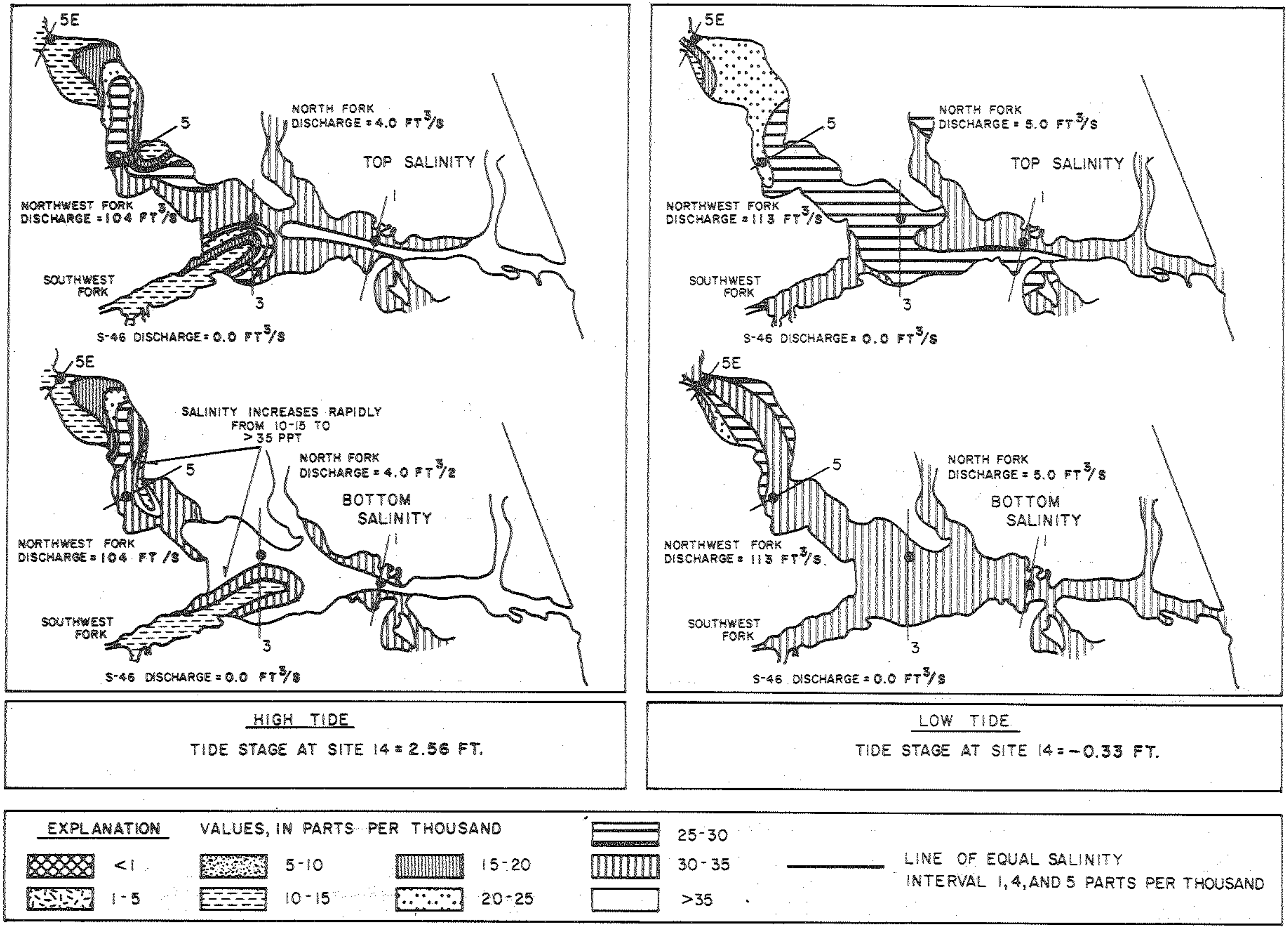

Figure 13.--Areal-salinity distribution in the Loxahatchee River estuary for high and low tides during typical wet season (November 20-21, 1980).

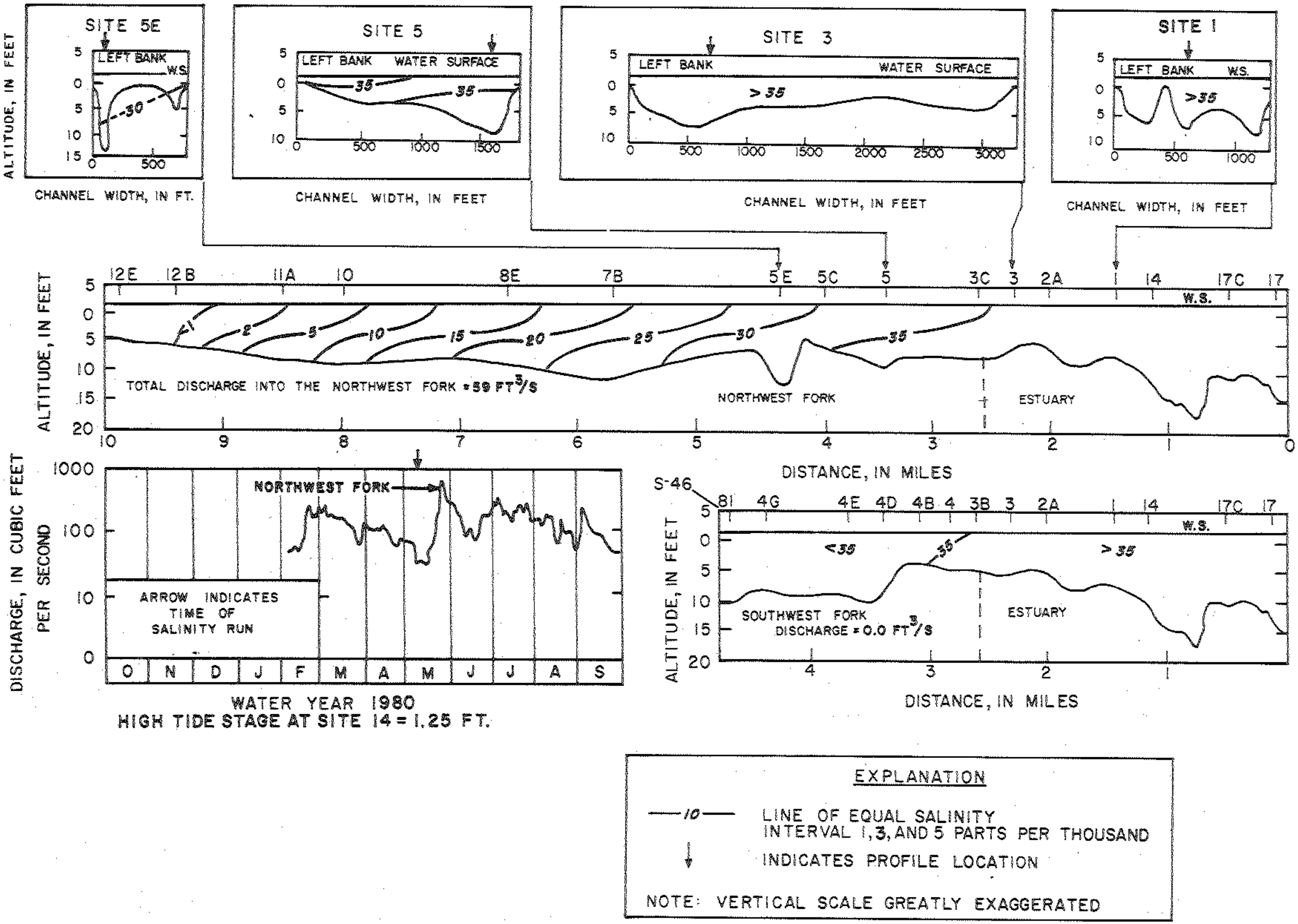

Figure 14.--High-tide salinity profiles in the Loxahatchee River estuary during typical dry season (May 6, 1980)

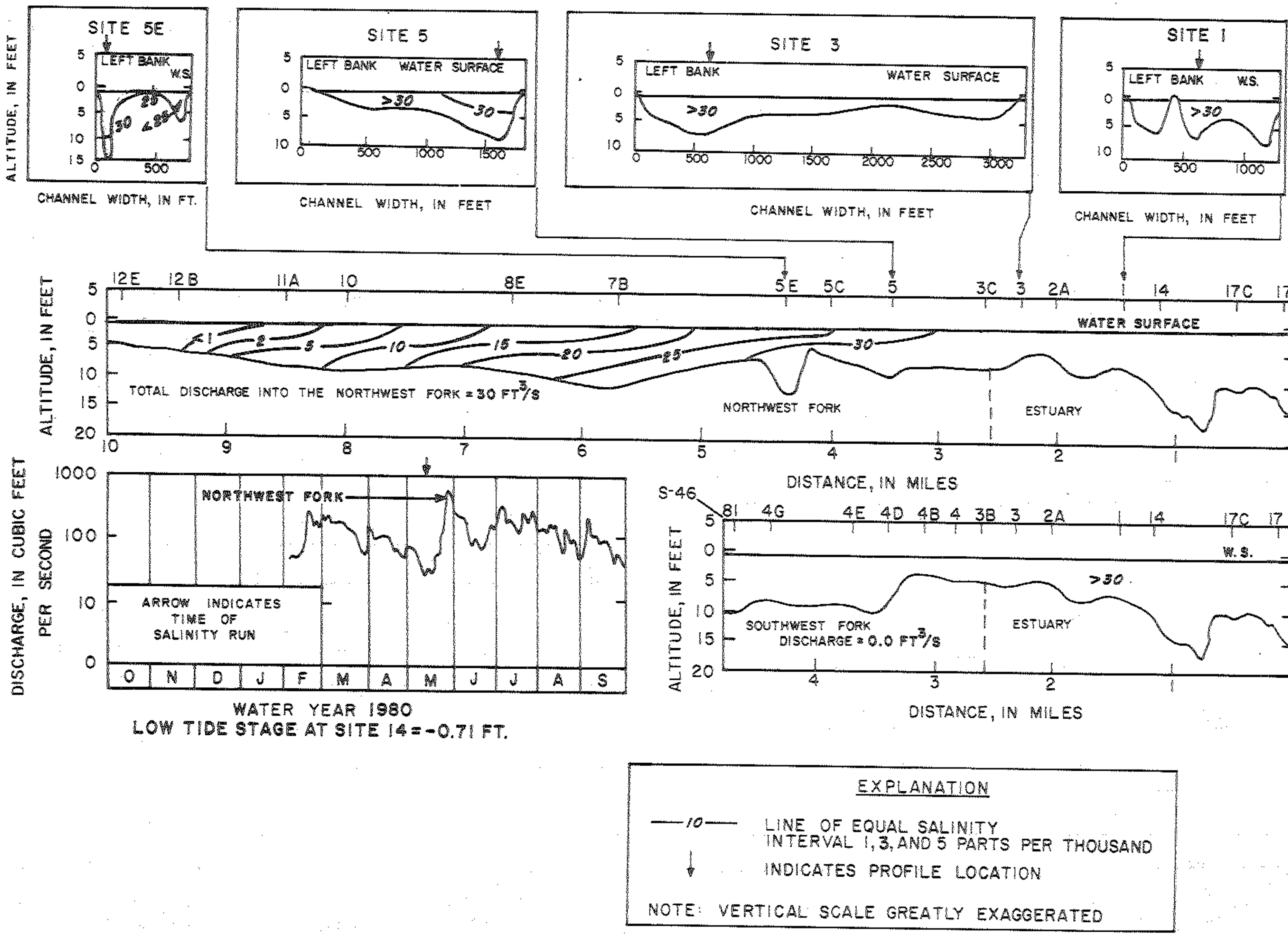

Figure 15.--Low-tide salinity profiles in the Loxahatchee River estuary during typical dry season (May 7, 1980).

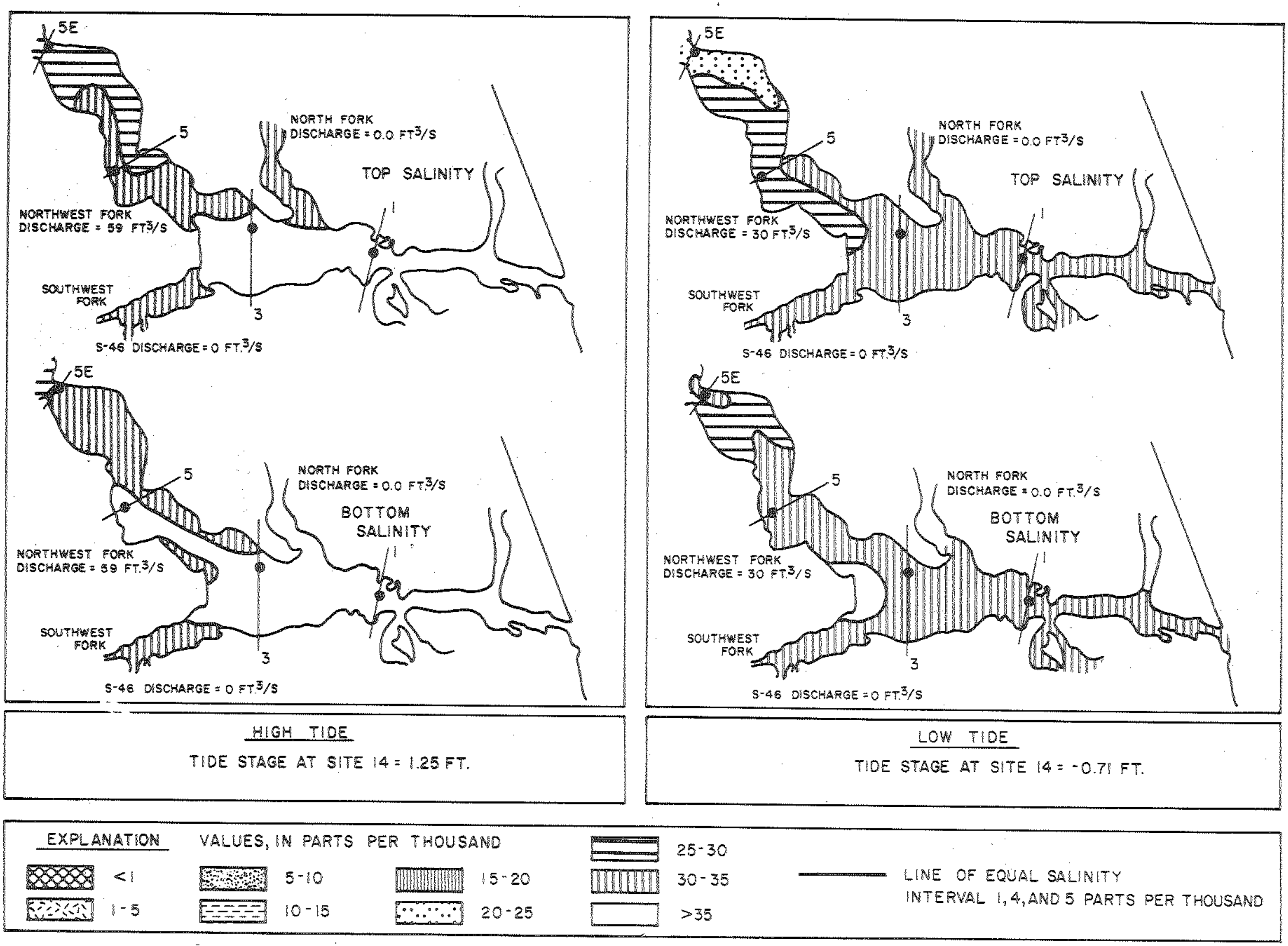

Figure 16.--Areal-salinity distribution in the Loxahatchee River estuary for high and low tides during typical dry season (May 6-7, 1980).

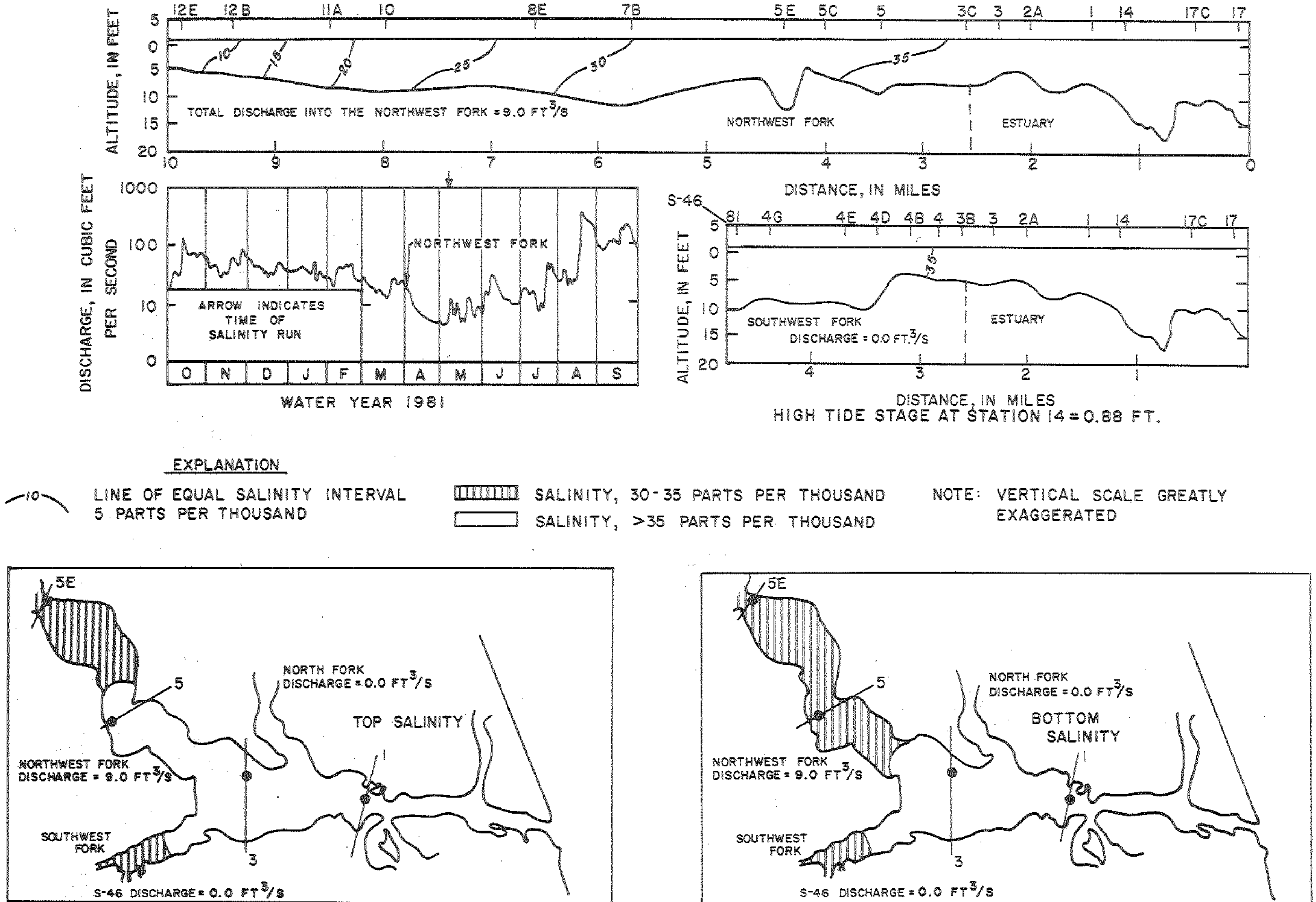

Figure 17.--High-tide salinity distribution in the Loxahatchee River estuary during extreme dry season (May 4, 1981).

Salinity distribution under typical wet-season conditions for high and low tides are shown in figures 11 to 13. Under low-tide conditions on November 20, 1980 (fig. 11), salinity in the lower estuary (site 17 at Jupiter Inlet to about site 3) ranged from about 30 to 35 ppt, indicating a vertically well-mixed system with vertical stratification occurring in the northwest fork. On an above-average high tide on November 21, 1981 (fig. 12), the salinity distribution was characterized by a plume of low-salinity (10-15 ppt) water extending from C-18 into the southwest fork and the central embayment and by a high salinity (25-35 ppt) plume extending up the northwest fork (fig. 13). Although discharge from C-18 was reported by SFWMD (South Florida Water Management District) as zero on November 21, 1980, freshwater discharge probably occurred as indicated by the plume in the southwest fork. This discrepancy may be due to repair work on S-46 that resulted in un reported discharge. Both plumes constitute narrow transition zones (isosalinity lines close together on the longitudinal salinity profiles in fig. 12) between seawater (greater than 30 ppt) and brackish water (less than 15 ppt). Isosalinity contours in the northwest fork between sites 7B and 12E moved upstream about 1 mile on the November 21, 1980 high tide from their locations on the November 20 low tide (figs. 11-12). Freshwater discharges from C-18, however, were intermittent, and tidal flow of high-salinity (greater than 25 ppt) waters dominated the southwest fork much of the time even during the wet season.

The salinity distributions under typical dry-season conditions for high and low tides are shown in figures 14 to 16. Under both high and low tides, much of the northwest fork of the estuary (but not the southwest fork) was stratified, and changes in salinity distribution between the two tides were small. Salinity, however, was slightly higher (greater than 35 ppt in the lower estuary, inlet to site 5) on the May 6, 1980 high tide than on the May 7, 1980 low tide. Also, higher salinity water extended a little farther upstream in the northwest fork on the high tide. During the dry season, C-18 seldom discharged freshwater to the estuary, and salinities in the southwest fork remained near that of seawater.

Drought conditions were most severe during this study in May 1981. Total mean daily discharge to the northwest fork decreased to only 9 ft^3/s during the drought while average daily discharge for the previous 2 months was 18 ft^3/s. High salinity (greater than 30 ppt) prevailed throughout much of the estuary (fig. 17). Salinity of 7 ppt was measured at Trapper Nelson (site 12E), 10 miles upstream of Jupiter Inlet on May 4, 1981. Vertical stratification of salinity was slight (fig. 17).

Freshwater Discharge, Tides, and Salinity Relation in the Northwest Fork

The salinity distribution in the Loxahatchee River estuary is determined primarily by freshwater discharge and by tidal flow. The influence of freshwater discharge is largely seasonal and storm related (fig. 18). In contrast, tidal flows fluctuate in hours and influence salinity in a more short-term, cyclic manner. Salinities at a given location may increase by 5 to 10 ppt in the few hours between low and high tides.

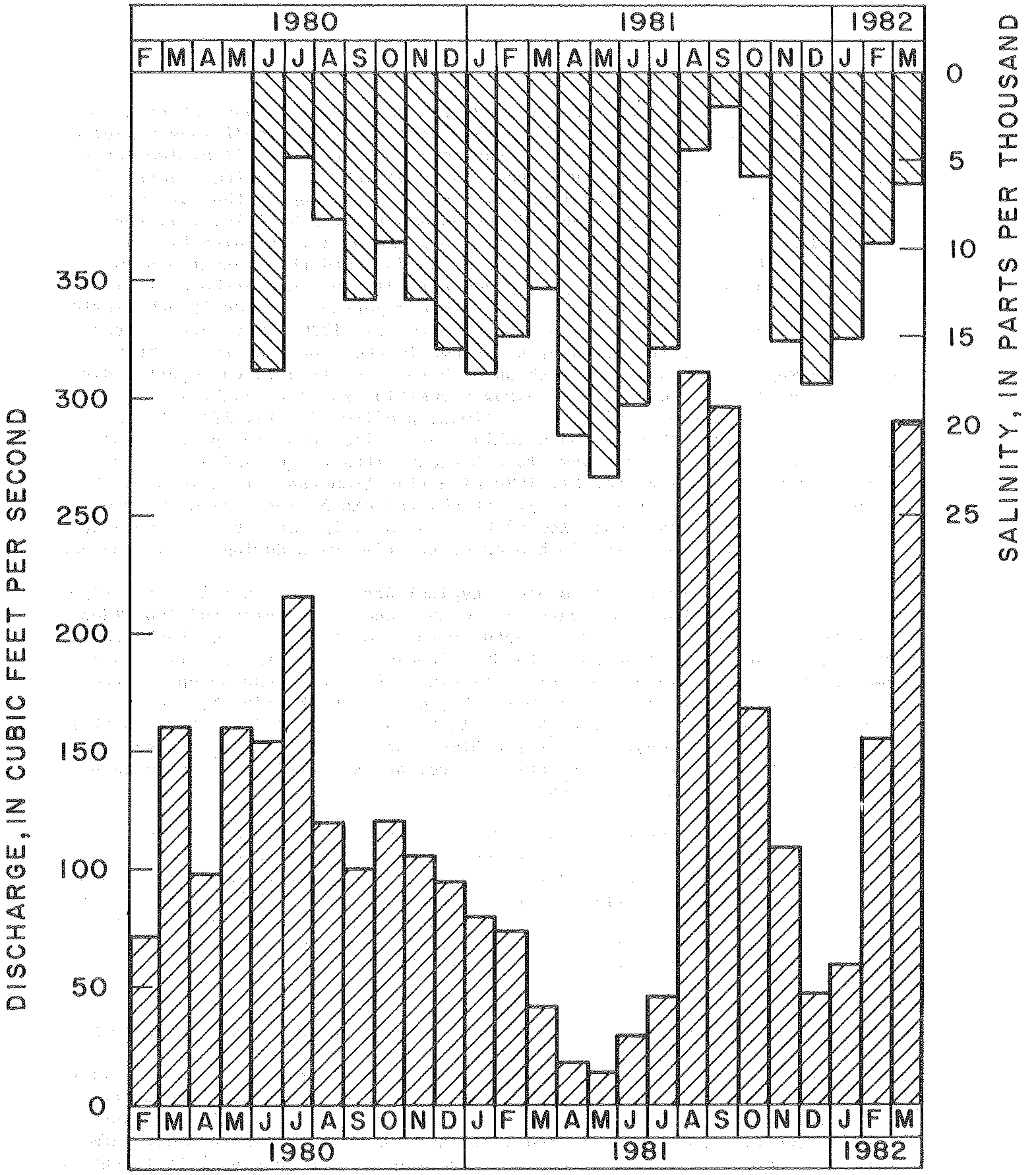

Figure 18.--Total mean monthly discharge to the northwest fork and mean monthly salinity of bottom water at site 8E in the northwest fork of the Loxahatchee River estuary.

Freshwater inflow to the estuary from the major tributaries constitutes a relatively small percentage when compared with the tidal prism of the estuary (table 4). During the different periods evaluated, freshwater inflow ranged from about 1 to 17 percent of tidal discharge. The higher percentages (15 and 17 percent) were for several days during and following heavy rainfall. Most of the time, freshwater inflow was less than 5 percent of the tidal discharge during the wet season and less than 1 percent during the dry season.

To evaluate the relationship between freshwater inflow and salinity, it was necessary to adjust for the effect of tides. To do this, salinity was normalized salinity to mean high tide. The procedure for normalization was as follows:

1. Bottom-water salinity was measured along the transect (fig. 2) from Jupiter Inlet (site 17) to a location in the upstream northwest fork (sites 8E to 12E).

2. The relation between bottom-water salinity and the distance from Jupiter Inlet was established for high and low tides.

3. The relation between bottom-water salinity and distance at high tide was compared graphically with that at low tide for 2 days when discharge was approximately the same discharge (fig. 19).

4. The bottom-water salinity versus distance relation was adjusted to mean high tide by linear interpolation based on the assumption that changes in distance were proportional to changes in tide stage. Interpolations were made to span a wide range in the quantity of freshwater inflow to the northwest fork (fig. 19 shows two interpolations). Mean high tide was selected because it represents the tide that would on the average result in greatest upstream movement of saltwater.

The relation between bottom-water salinity and distance from Jupiter Inlet adjusted to mean high tide is shown for different freshwater discharges in figure 20. The relation was characterized by sharp changes in salinity over relatively short distances of 1 to 2 river miles. The zone of marked changes in salinity moved downstream 4 to 5 river miles as the total discharge increased from 30 to 840 ft^3/s.

A relatively, well-defined saltwater wedge occurs in the northwest fork. The upstream tip of the wedge was defined by a salinity of 2 ppt occurring near the bottom. Using this value, the upstream location of the saltwater wedge was estimated at different tides and discharges and adjusted to mean high tide as follows: (1) The difference between the location of the saltwater wedge at a high and low tide with approximately the same discharge was divided by the tidal range for these two tides to give a conversion factor (river miles per foot of tidal difference); (2) four conversion factors were determined for four different discharges between 30 and 840 ft^3/s; (3) a relation between discharge and the conversion factors was developed; (4) using this relation, an appropriate conversion factor for a particular discharge was determined and used to adjust the location of the saltwater wedge to a location at mean high tide; and (5) these adjusted values were plotted against total freshwater inflow (fig. 21).

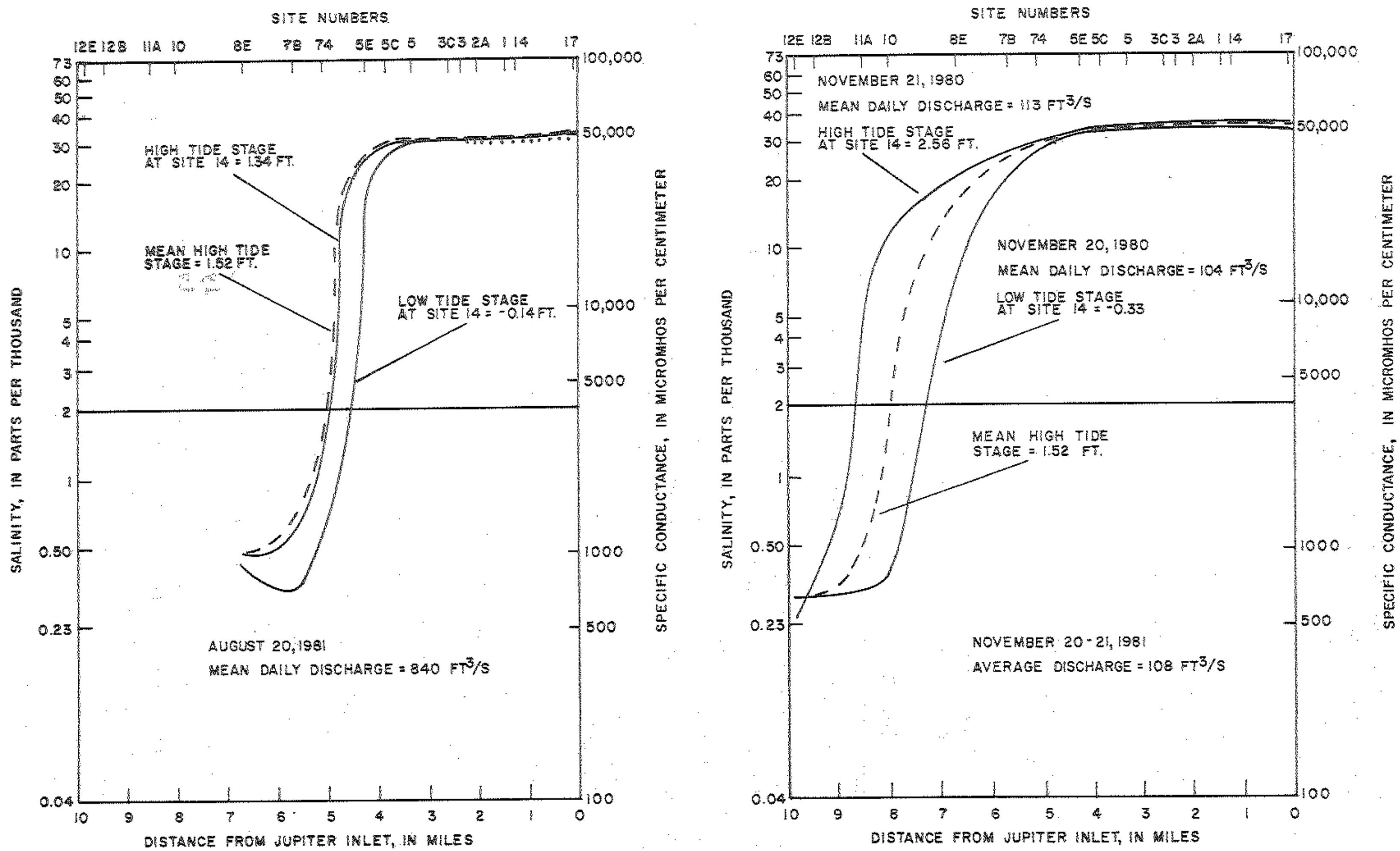

Figure 19.--Relation between bottom-water salinity and distance from Jupiter Inlet for selected rates of freshwater inflow to the northwest fork of the Loxahatchee River estuary.

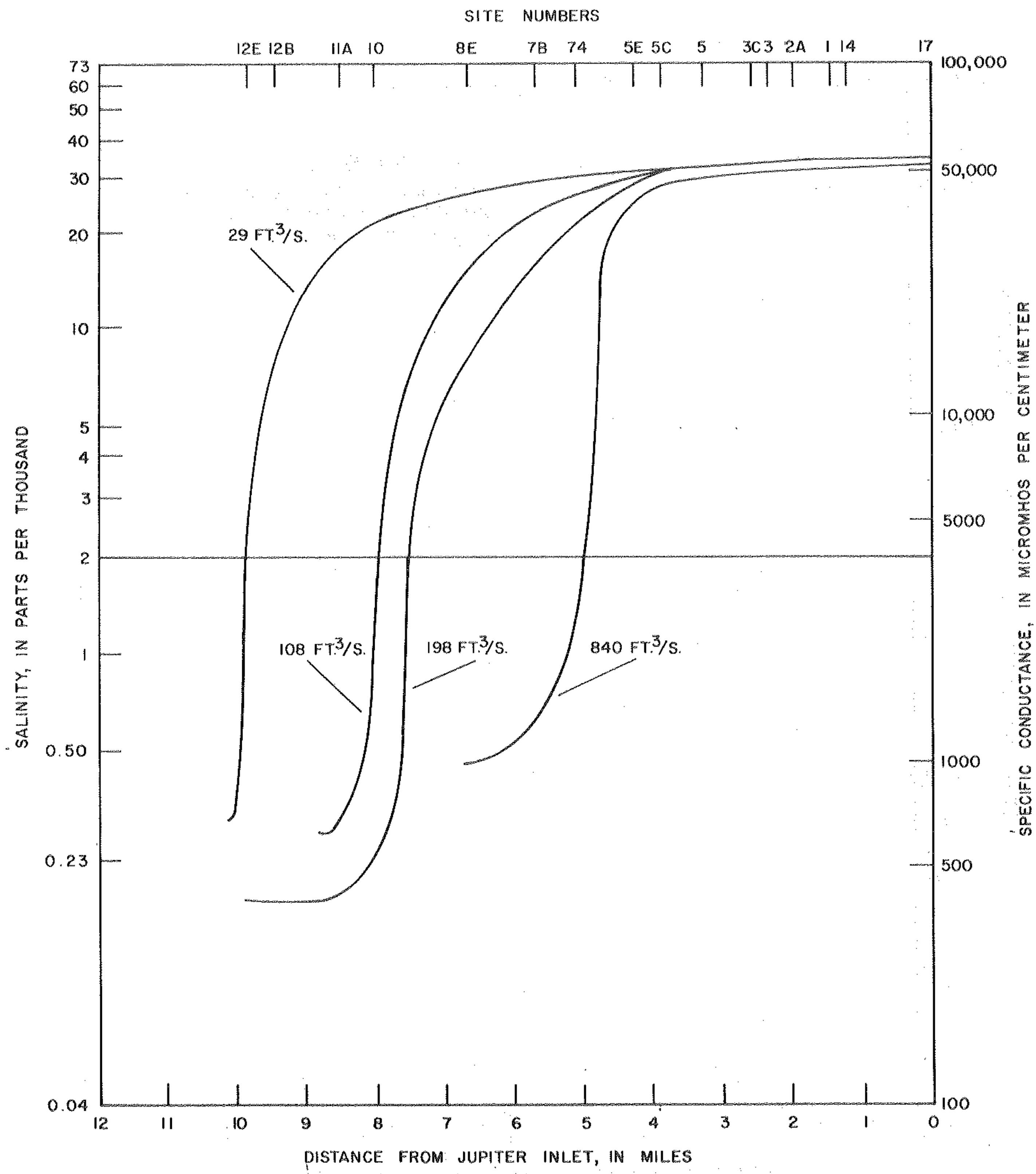

Figure 20.—Relation between bottom-water salinity and distance from Jupiter Inlet adjusted to mean high tide for selected rates of freshwater inflow to the northwest fork of the Loxahatchee River estuary.

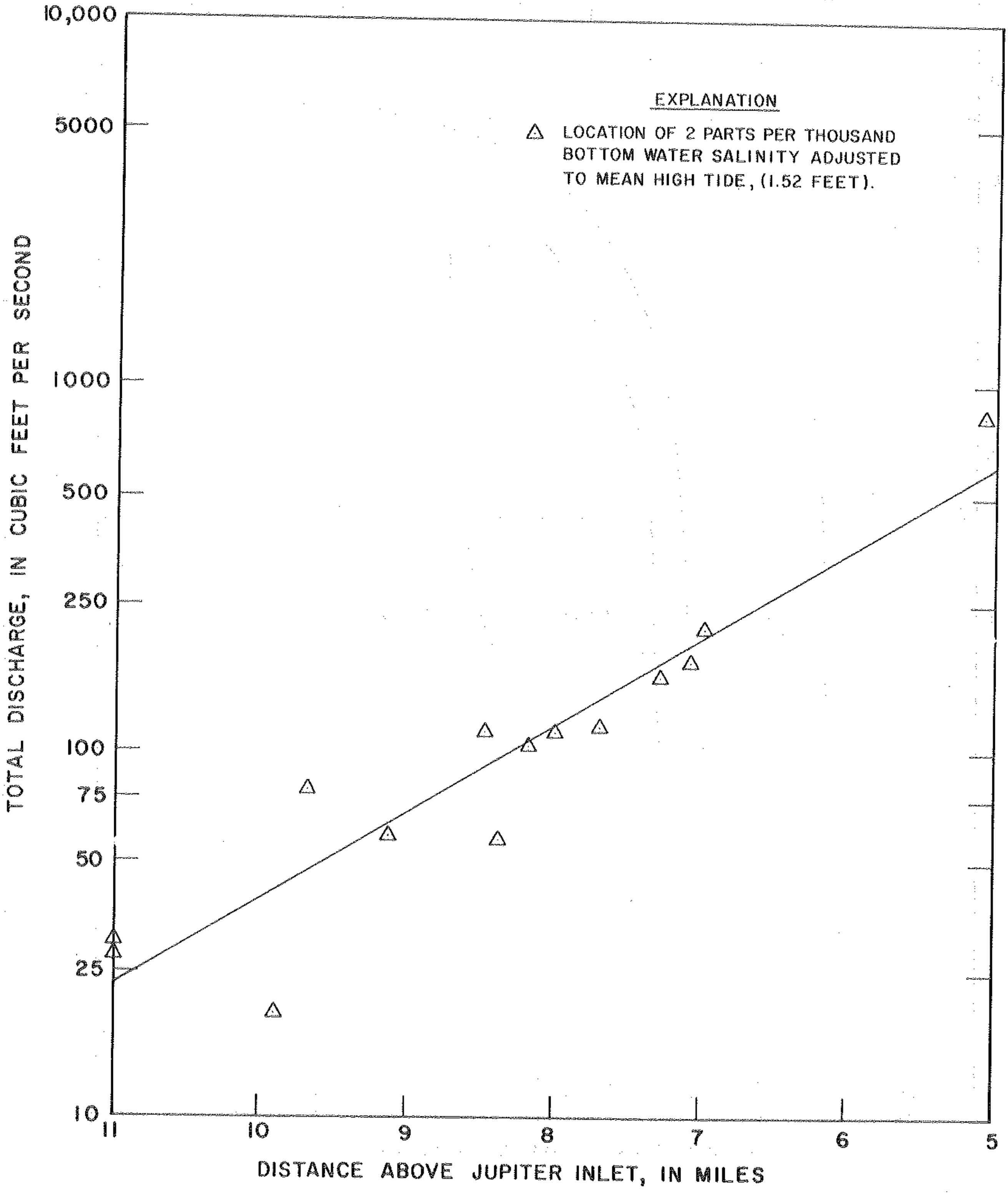

Figure 21.--Location of the toe of the saltwater wedge at different freshwater discharges in the northwest fork of the Loxahatchee River estuary.

Table 4.--Average freshwater inflow to the Loxahatchee River estuary from the major tributaries compared with tidal discharge[1]/ of the estuary at site 14

[Values in cubic feet per second, except as noted]

Freshwater inflow	1980 wet season, 184 days	1980-81 dry season, 273 days	1981 wet season, 61 days	1981 Tropical storm, 5 days	1982 early spring storm, 9 days
Average freshwater inflow per day	183	58	305	1,141	1,009
Average freshwater inflow per 1/2 tidal cycle	44	14	74	276	244
Freshwater inflow compared with tidal prism[2]/	.03	.009	.05	.17	.15

1/ Based on 1,626 ft^3/s mean tidal prism (McPherson and others, 1982).

2/ $\frac{\text{Freshwater inflow per 1/2 tidal cycle}}{\text{mean tidal prism}}$ = Mixing Index (Schubel, 1971)

Total discharge to the northwest fork was used to estimate the location of the toe of the saltwater wedge in figure 21 because total discharge gave a better correlation then discharge at a single long-term tributary station (Loxahatchee River at site 23). The poor correlation between salinity and discharge at site 23 is caused by the varying percentage of the total discharge contributed by the Loxahatchee River at this site (see table 3). Although the river at this site discharges on the average roughly half of the total, its discharge may vary monthly from about 30 to 70 percent of the total.

The upstream extent (in river miles) of saltwater (2 ppt) in the northwest fork at mean high tide and at different discharges was estimated using figure 21 as follows:

Total mean daily freshwater discharge, in cubic feet per second	Upstream extent of saltwater wedge, in river miles
220	7.0
130	8.0
120	8.2
75	9.0
43	10.0
26	11.0

Restricting saltwater intrusion from the section of the river at about river mile 6.15 in JDSP (fig. 1) would require a total mean daily discharge exceeding 220 ft^3/s. Restricting saltwater intrusion in the upstream reach of the river (about river mile 8) would require a total mean daily discharge of 130 ft^3/s. At this total discharge, saltwater would move farther upstream on higher tides; however, its duration there would be brief. For comparison, during the study period (February 1980 to March 1982), the total mean daily discharge was 120 ft^3/s.

In the southwest fork, C-18 is the major tributary; however, during much of the year, the canal does not discharge freshwater. As a result, tidal flows predominate in this fork, and salinity remains near that of seawater during much of the year. However, when large freshwater discharge does occur (for example, during August 19-20, 1981, when discharge exceeded 800 ft^3/s), the southwest fork may become nearly fresh or highly stratified depending upon tide (fig. 7). At discharge less than 500 ft^3/s, the fork remained stratified with bottom salinities near that of seawater (fig. 8).

SUMMARY

In the northwest fork of the Loxahatchee River estuary, the mixing of freshwater with seawater occurs over a distance of 5 to 10 river miles. Large freshwater inflows vertically stratified a large part of the estuary and shifted the mixing zone seaward. The saltwater-freshwater interface or salt wedge (2 ppt bottom-water salinity) moved daily over about 0.5 to 1.5 river miles as a result of tides and seasonally over about 3 to 5 river miles as a result of changes in the freshwater inflow.

If tidal discharges are not altered, the amount of freshwater needed to restrict brackish water (2 ppt and higher salinity) from the upstream reach of the northwest fork at mean high tide can be estimated as follows:

Total mean daily freshwater discharge, in cubic feet per second	Upstream extent of saltwater wedge, in river miles
220	7.0
130	8.0
120	8.2
75	9.0
43	10.0
26	11.0

For comparison, average inflow of freshwater to the northwest fork during the 1980-81 extended dry season was 57 cubic feet per second. Freshwater discharge from Canal-18 to the southwest fork can cause extreme vertical stratification with a freshwater layer on the surface overlying denser seawater. However, much of the time, no freshwater is discharged from Canal-18, and tidal flows of high-salinity (greater than 25 ppt) waters predominate in the southwest fork.

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