SURFACE-WATER HYDROLOGY AND SALINITY OF THE ANCLOTE RIVER ESTUARY, FLORIDA

By Mario Fernandez, Jr.

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DEPARTMENT OF THE INTERIOR
MANUEL LUJAN, JR., Secretary

U.S. GEOLOGICAL SURVEY
Dallas L. Peck, Director

For additional information write to:

District Chief
U.S. Geological Survey
Suite 3015
227 North Bronough Street
Tallahassee, Florida 32301

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ABSTRACT

The Anclote River is on the central west coast of peninsular Florida and has a drainage area of 112 square miles and a tidally affected reach of about 13 miles. The variability and distribution of salinity in the Anclote River Estuary are important factors that influence the habitat available for estuarine flora and fauna. This report presents the results of a study made from January 1984 through May 1986 to determine salinity distribution in the river as a function of streamflow, tides, and related hydrologic conditions.

Monthly mean streamflows from January 1984 through May 1986 generally were lower than the corresponding long-term monthly averages, yet representative of flows that typically enter the estuary. Results of regression analysis inferred that pumpage from individual well fields in or near the basin and streamflow was not significantly related; however, the relation of total well-field pumpage and streamflow was significant at the 5-percent level.

Tides at the mouth of the Anclote River Estuary are mixed, typically have a range of about 3 feet, and generally include low-low, high-low, low-high, and high-high tides daily. Findings indicate that stage at a point 13 miles upstream from the mouth is affected as much as 1 foot by the tide. A wide 3-mile reach of the lower river that is braided through saltmarshes apparently dampens the upstream tide and seems to modify the effects of streamflow on the salinity gradient within the reach.

The upstream daily location of water having 0.44-, 5.0-, 10-, and 18-parts-per-thousand salinity was estimated by using multiple-regression techniques. Streamflow used in the analysis ranged from 2.3 to 204 cubic feet per second, and high tides ranged from 0.25 foot below to 2.76 feet above sea level. Vertical salinity profiles indicated partially to well-mixed conditions throughout the estuary during the observed range of streamflow.

Results of the regression analyses indicate that streamflow has a significant effect on the location of the saltwater-freshwater interface (defined as 0.44-part-per-thousand salinity) as well as the location of water having a salinity of 5.0-parts-per-thousand. The location of water having salinities greater than 5.0-parts-per-thousand is affected increasingly by tide, with a corresponding decrease in effect by streamflow. The coefficients of determination and root mean square errors of the regressions ranged from 70.0 to 91.8 percent and from ±0.24 to ±0.74 mile, respectively. The computed long-term average location of the 0.44-part-per-thousand salinity line, based on average annual streamflow and an average high-high tide, is within 0.1 mile of the vegetative demarcation between estuarine and riverine conditions.

INTRODUCTION

The coastal areas of Pinellas and Pasco Counties are among the most rapidly growing coastal areas in Florida and in the Nation (fig. 1). The competition for water in these coastal areas will increase as the rapid growth in population continues. As demands for freshwater in coastal areas of west-central Florida increase, streams that discharge into the Gulf of Mexico, such as the Anclote River, may be affected by increased pumpage at well fields near their headwaters.

Effects that result from diversion of freshwater from coastal streams include upstream intrusion of saltwater and increased salinity concentrations in the estuarine reaches. An estuarine reach is that part of a stream where seawater and freshwater mix, and salinity commonly ranges from near seawater concentrations at the mouth to freshwater some distance upstream. Estuaries are important habitats for many species that support sport and commercial fisheries. Changes in salinity may produce adverse changes in the flora and fauna of the Anclote River Estuary and adjacent coastal areas of the Gulf of Mexico. The effects on the environment of diversion of freshwater from the Anclote River are not fully known. It will be useful to evaluate salinity distributions in these areas, under existing and possible future developmental conditions, prior to the possible diversion of surface-water supplies.

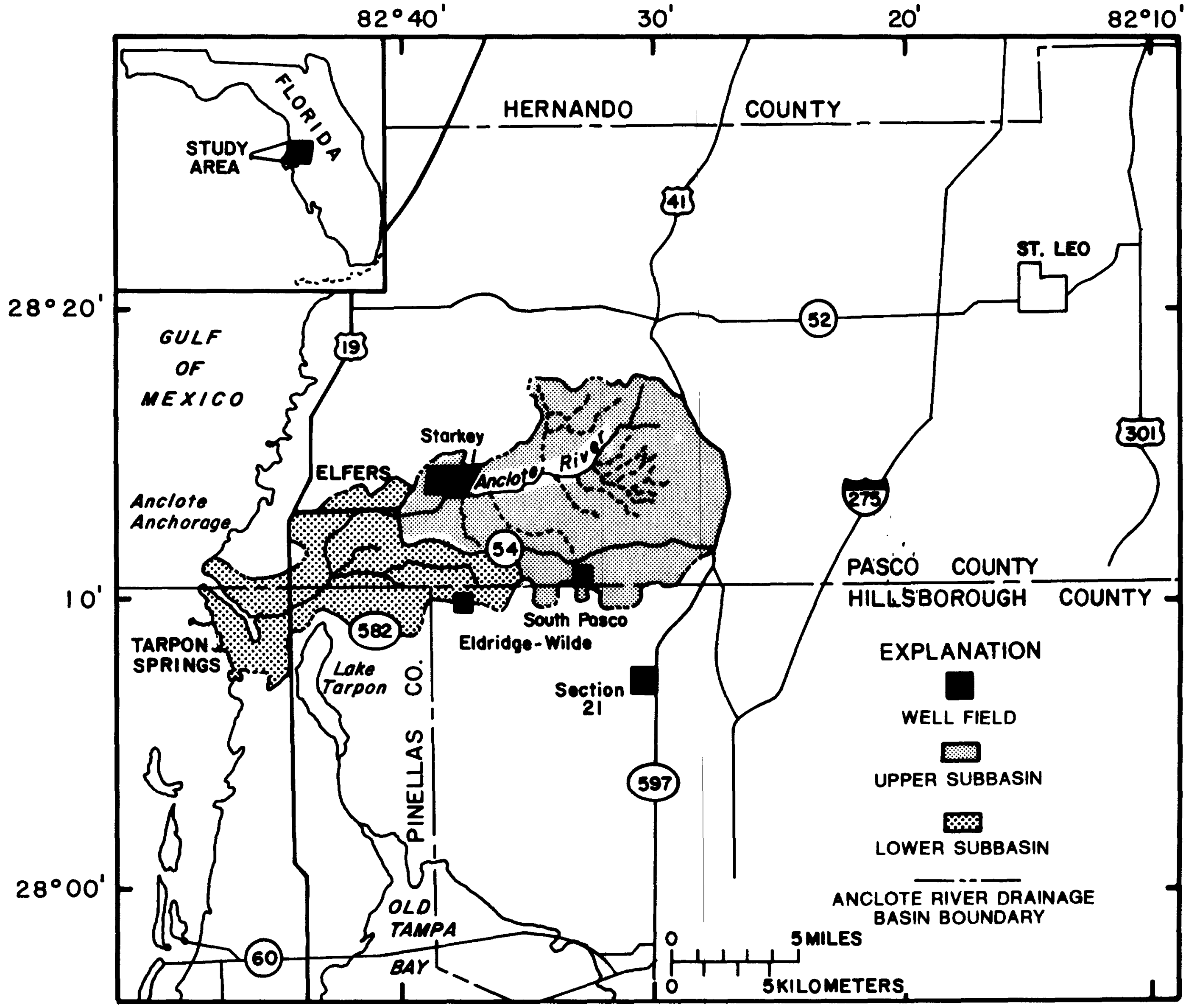

Figure 1.—Location of the Anclote River basin.

Purpose and Scope

This report provides the supporting data and an analysis of salinity distributions along the tidal reach of the Anclote River. The specific objectives of the study were to:

1. Describe the salinity distribution in the estuary as a function of freshwater inflow and tides;
2. Determine the location of the freshwater-saltwater interface (0.44-part-per-thousand salinity) and other lines of equal salinity for a range of freshwater inflow and tidal conditions;
3. Determine the relation of Anclote River streamflow to precipitation, evaporation, and well-field pumpage.

Direct measurements of streamflow, tides, and salinity in the Anclote River Estuary were made during the period from January 1984 through May 1986; historical streamflow data were compared to that measured during the study; the influence of well-field pumpage on streamflow was evaluated; and regression relations between salinity, tide, and average daily streamflow were developed. Streamflow was computed from stage records at a point 14.8 miles upstream from

Hickory Point, a shoreline feature near the mouth of the estuary. Tidal stage and salinity were recorded at Hickory Point and at two sites located 2.2 and 8.7 miles upstream. Salinity records were supplemented with 32 field runs to define vertical and longitudinal salinity distribution in the estuary. The upstream daily location of water having 0.44-, 5.0-, 10-, and 18-ppt (parts-per-thousand) salinity was quantified using multiple-regression techniques.

Previous Studies

Several studies have focused on the Anclote River area. Cherry and others (1970, p. 86) inferred from streamflow, rainfall, and pumpage records that ground-water withdrawals reduced the flow of the Anclote River. They also estimated that seepage from the Upper Floridan aquifer to the river averaged about 10 ft^3/s, or about 10 percent of the flow, for the period of study (1964–66) for the reach upstream of the discharge station at Elfers, Fla. The water needs of the Anclote River watershed were analyzed by Reynolds, Smith and Hills, Inc. (1972), with emphasis directed to conservation of water and land resources. Coble (1973) reported that the Anclote River was a suitable source for supplemental water supply that could be used in conjunction with ground-water supplies. The river water in the freshwater zone (riverine zone) usually met water-quality standards; however, further studies were recommended due to occasional objectionable levels of phenolic compounds, arsenic, and bacteria (Coble, 1973).

Coble (1973), in delineating the extent of the saltwater and transition zones, reported that the saltwater zone extended less than 1 mile upstream from U.S. Highway 19 and that the transition zone extended more than 1 mile upstream from Perrine Ranch Road. The effects of saltwater uptake (for powerplant cooling purposes) at the mouth of the Anclote River Estuary and the effects of heated discharge water on the Anclote-Anchorage area along the mouth of the river were discussed by Mayer and Maynard (1975).

Physical Description of Study Area

The study area includes the Anclote River Estuary and drainage basin. The entire Anclote River drainage basin encompasses about 112 mi^2 (fig. 1). For purposes of this study, the upper subbasin encompasses the reach upstream from State Road 54. The easternmost boundary of the upper subbasin is near U.S. Highway 41 in Pasco County. The lower subbasin extends from the river's mouth at Tarpon Springs in northwestern Pinellas County to State Road 54 (fig. 1).

Florida Power Corporation's Anclote generating facility is in the lower subbasin at the mouth of the river (fig. 2) and has two 550–MW oil-fired units. The facility uses saltwater taken at the mouth of the river to cool the system. Cooling water drawn into the system varies from about 1,382 ft^3/s in the winter to a maximum of about 4,436 ft^3/s in the summer (Florida Power Corporation, written commun., 1985). The cooling water outfall is into the Anclote Anchorage.

The tidally affected reach of the river is from the mouth to the subreach between State Road 54 and Cedar Street or about 13 miles upstream from Hickory Point (fig. 2). Data indicate that the stage at Cedar Street is affected as much as 1 foot by the tide. Salinity concentrations of 0.44 ppt, which indicate the presence of the saltwater interface, were not detected at Cedar Street.

Stream width is highly variable. It is about 1,800 feet wide at Hickory Point and narrows to about 250 feet at U.S. Alternate 19, 2.2 miles upstream from Hickory Point (fig. 2). Between U.S. Alternate 19 and U.S. Highway 19 (4.2 miles upstream from Hickory Point), the river again widens to about 1,700 feet, including large areas of saltmarsh, and then narrows again to about 400 feet at U.S. Highway 19. Upstream from U.S. Highway 19, it again widens to about 3,000 feet to include more saltmarsh, including Salt Lake (fig. 2). Between river miles 2.3 and 5.5, the river is braided and has no single channel. This expansive reach of the river may act to attenuate and delay upstream tidal propagation and also to modify the effects of streamflow on the salinity gradient within this reach. Upstream from river mile 5.5, the river narrows to 50 feet.

Precipitation

There are two National Oceanic and Atmospheric Administration (NOAA) climatic recording stations in the Anclote River basin, one at Tarpon Springs and one at St. Leo (fig. 1). In this report, rainfall reported at Tarpon Springs is considered representative of the lower subbasin, and rainfall recorded at St. Leo is considered representative of the upper subbasin of the Anclote River (fig. 1). Rainfall records date from 1891 at Tarpon Springs and from 1895 at St. Leo. The total monthly rainfall, in inches, at Tarpon Springs and St. Leo for January 1947 through December 1985 (corresponding to the period of record for streamflow) is shown in figure 3. The departure of annual rainfall from the mean for the period of record is presented in figure 4. The range of departures for Tarpon Springs and St. Leo are similar. The mean annual rainfall, in inches, and years of minimum and maximum rainfall recorded at Tarpon Springs and St. Leo are as follows (National Oceanic and Atmospheric Administration, 1932–86):

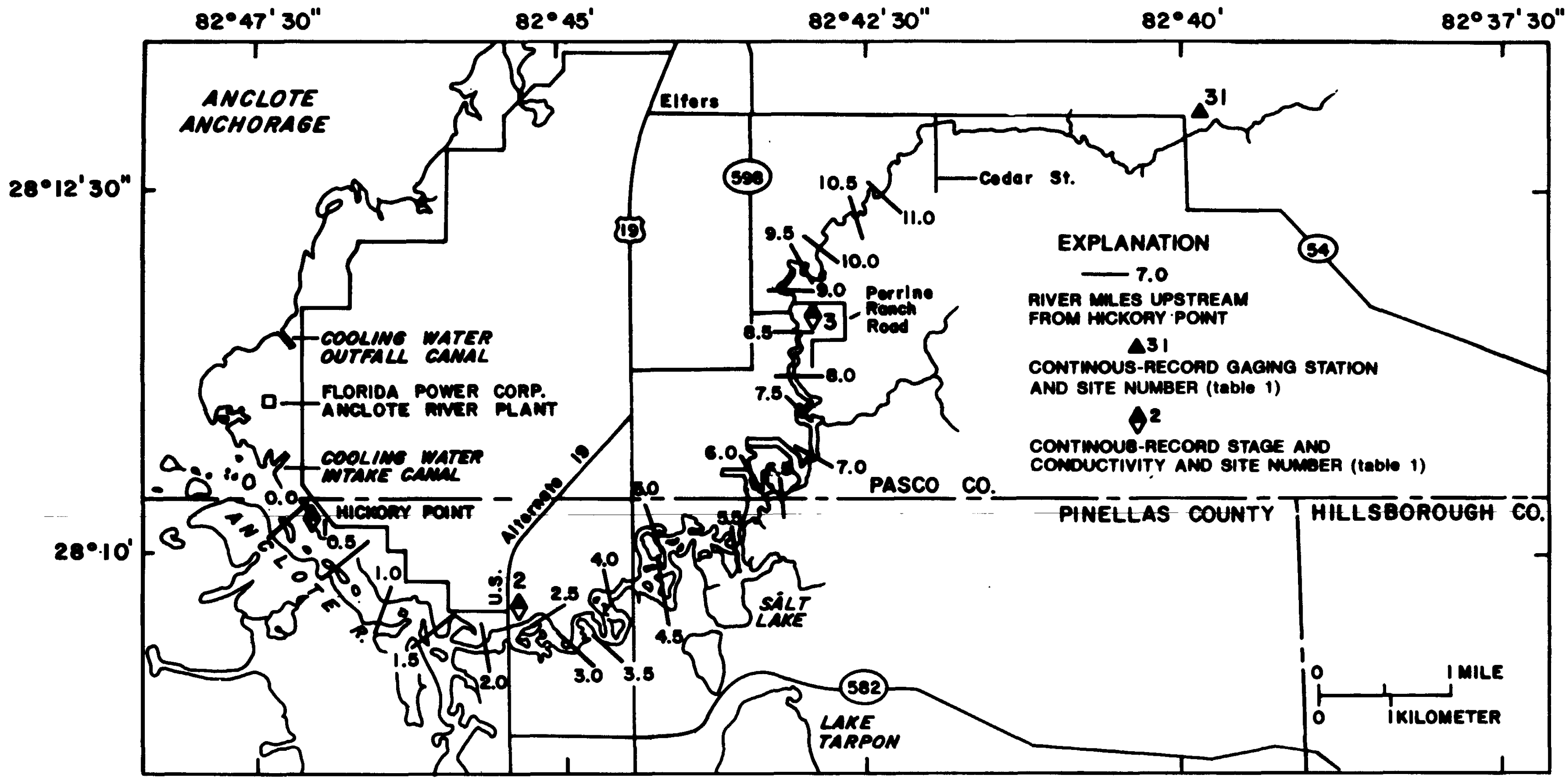

Figure 2.—Locations of continuous monitoring sites along the Anclote River study reach.

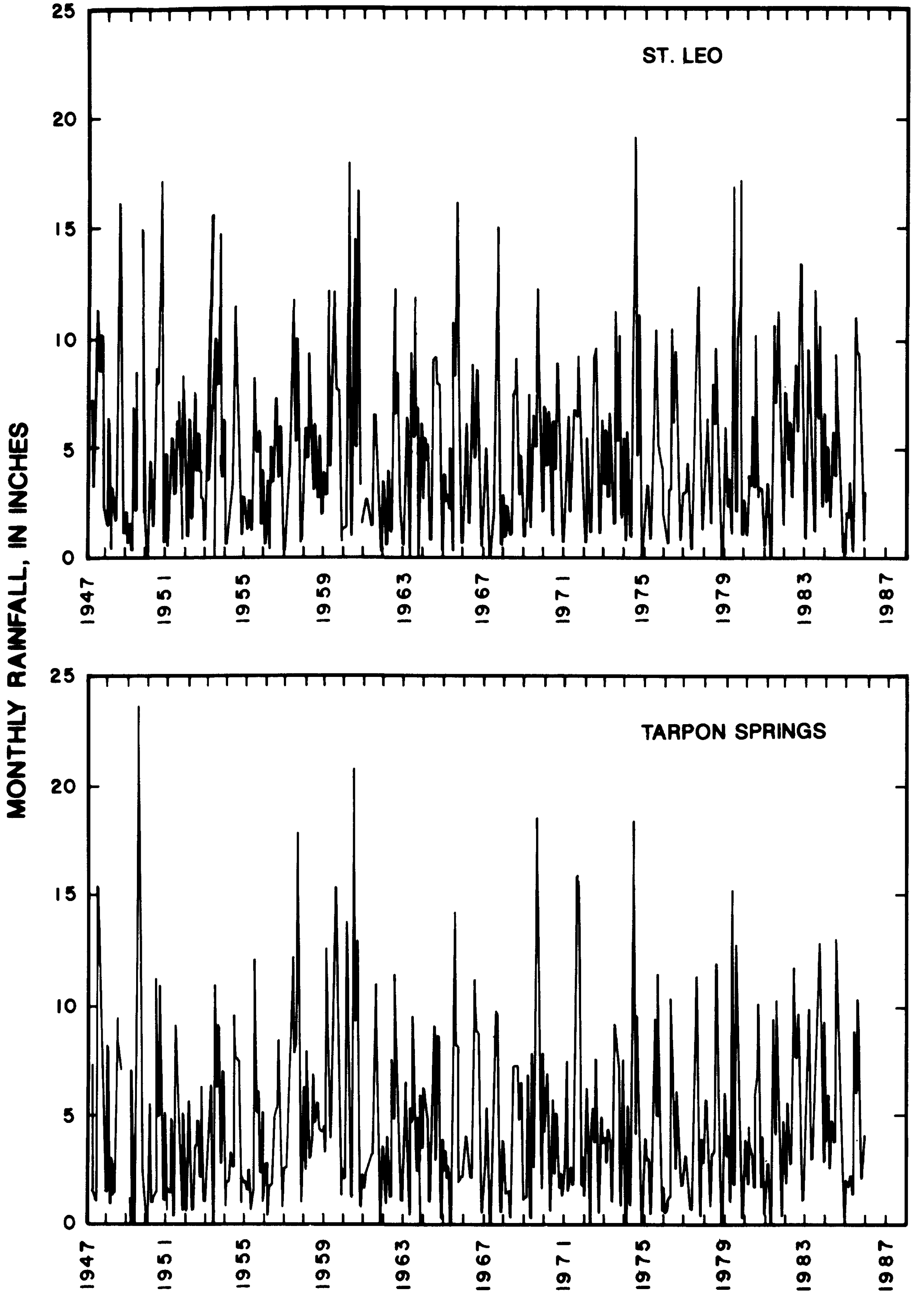

Figure 3.—Monthly rainfall at Tarpon Springs and St. Leo, 1947 through 1985.

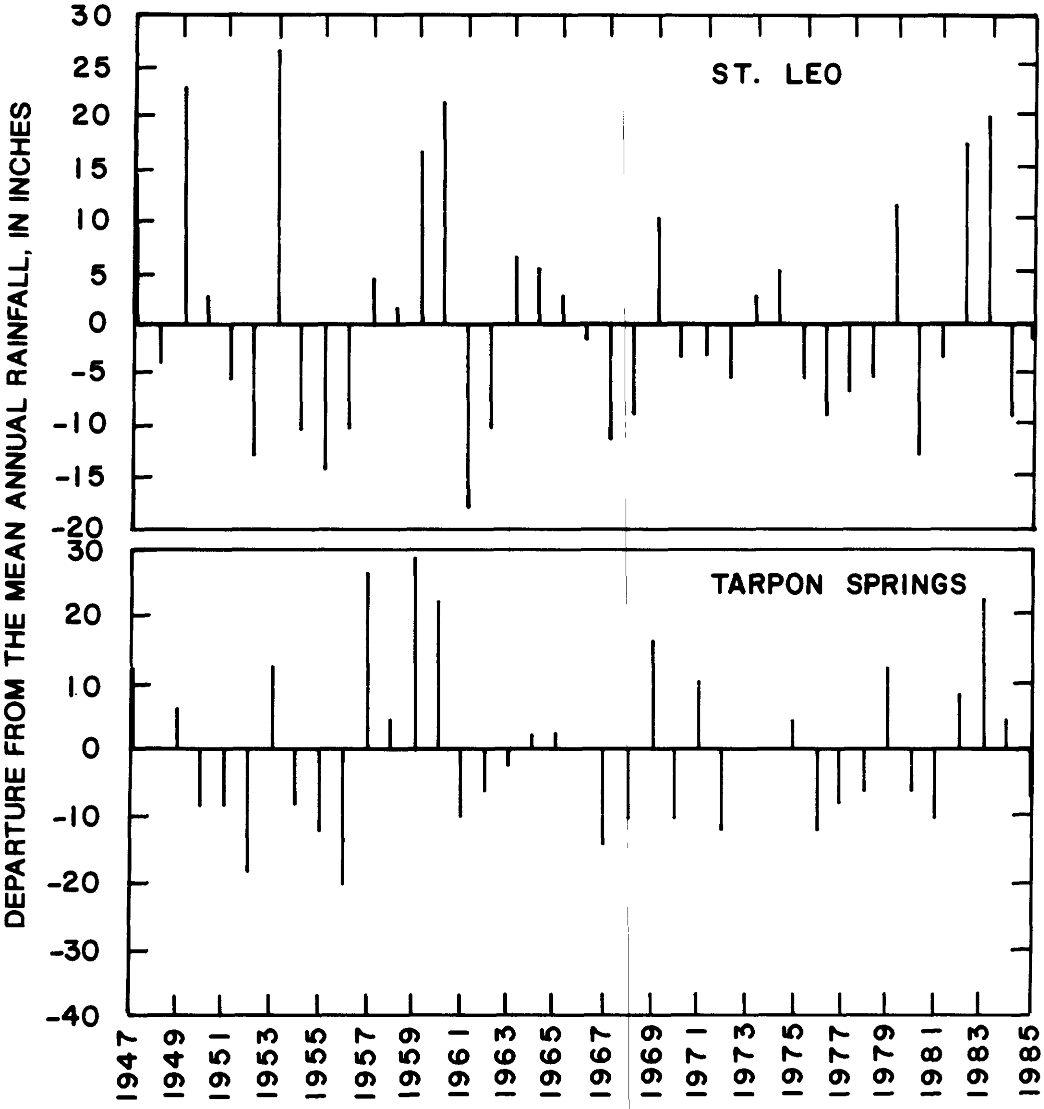

Figure 4.—Departure from the mean annual rainfall at Tarpon Springs and St. Leo, 1947 through 1985.

	Mean	Minimum	Maximum
Tarpon Springs	52.65	32.89 (1956)	83.20 (1959)
St. Leo	55.37	37.31 (1961)	81.13 (1953)

The Cox-Stuart test for trend (Daniel, 1978, p. 58) was performed to determine whether there was a trend in annual rainfall at Tarpon Springs and St. Leo during the period before well-field pumping began (1947–62) and after pumping was started (1963–85). Results indicated that there were no trends at a significance level of 0.05.

Rainfall records for the period from January 1984 through December 1985 show that the autumn of 1984 and the winter and spring of 1985 were relatively dry (fig. 5). The mean annual rainfall for the period of study was 51.31 inches at Tarpon Springs and 50.28 inches at St. Leo. Monthly departure from the mean (39 years for the period of record for Tarpon Springs and St. Leo) averaged –0.17 and –0.19 inches, respectively (fig. 6).

METHOD OF INVESTIGATION

Data-Collection Network

Data collection consisted of field reconnaissance surveys and measurement of streamflow, tidal stage, and specific conductance. The continuous-record gaging station, Anclote River near Elfers at State Road 54 (fig. 2), was used to compute daily streamflow into the estuary. Three sites were selected for continuous tidal stage and salinity monitoring: Hickory Point, 1 mile upstream from the mouth of the river; U.S. Alternate 19, 2.2 miles upstream from Hickory Point; and Perrine Ranch Road, 8.7 miles upstream from Hickory Point

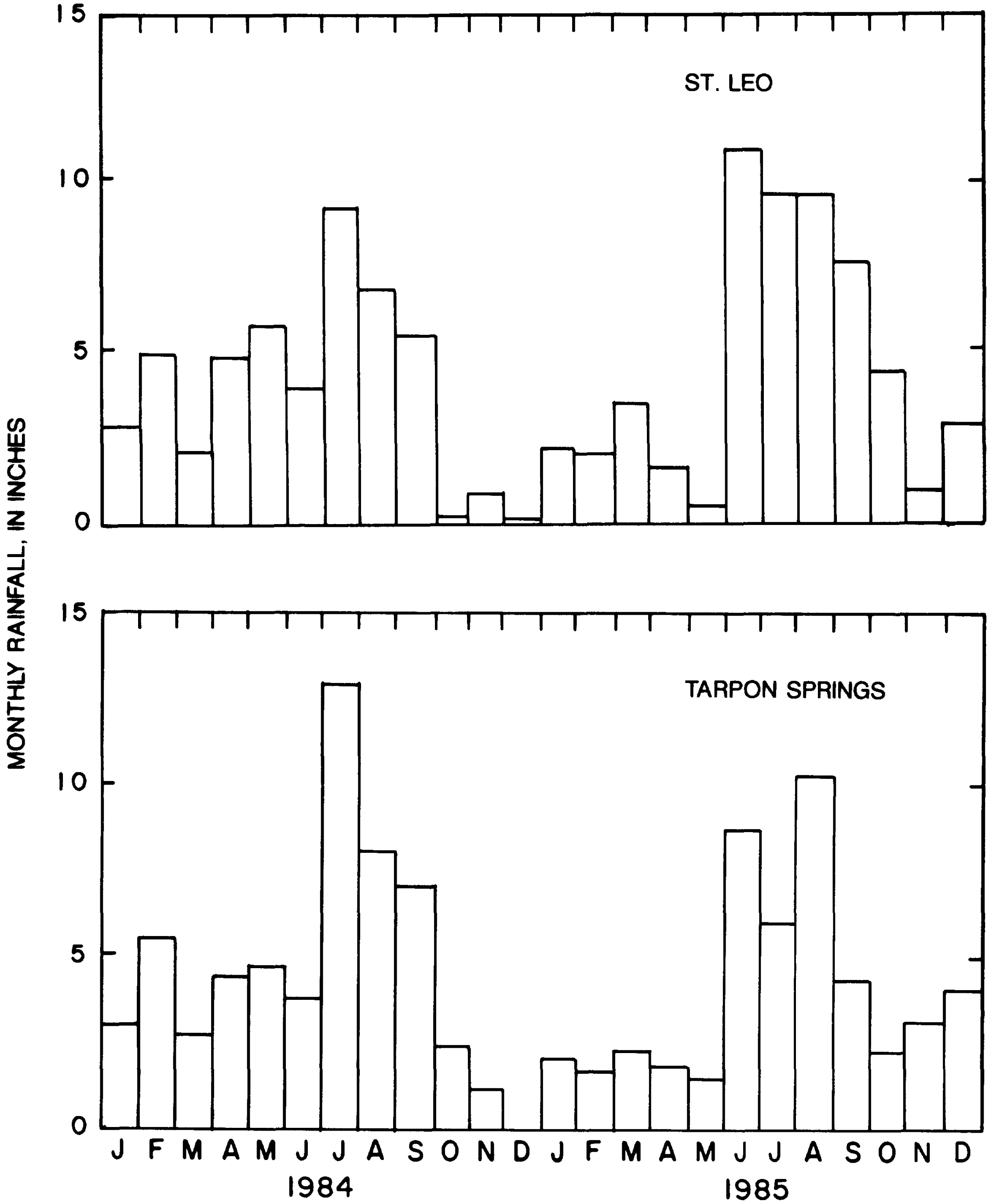

Figure 5.—Monthly rainfall at Tarpon Springs and St. Leo, January 1984 through December 1985.

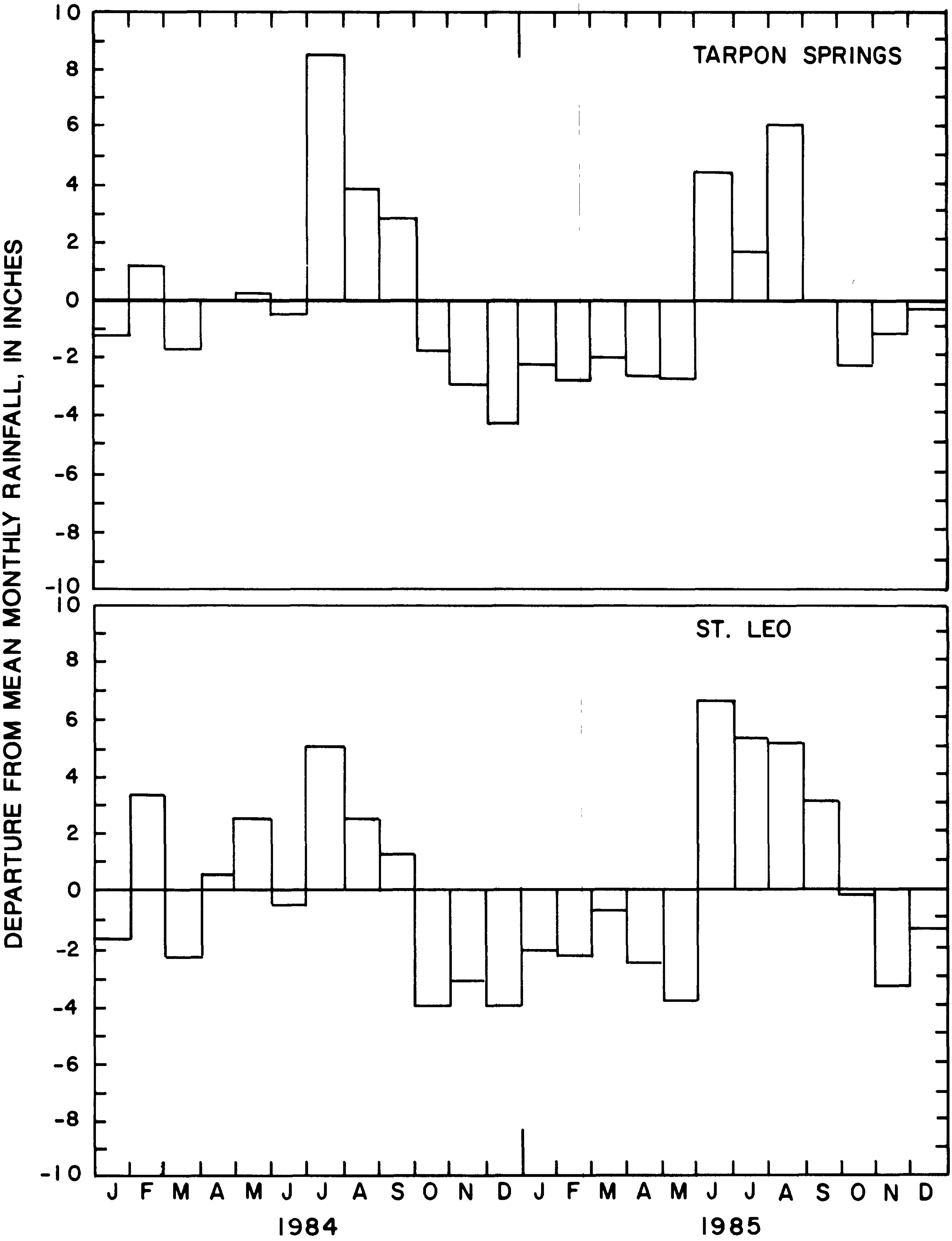

Figure 6.—Departure from mean monthly rainfall at Tarpon Springs and St. Leo, January 1984 through December 1985.

Table 1.—*Description of monitoring sites on the Anclote River*

Site name	Site number	Distance upstream from Hickory Point (miles)	Variables measured
Hickory Point	1	0.0	Salinity, stage
U.S. Alternate 19	2	2.2	Salinity, stage
	3	2.65	Salinity
	4	3.10	Salinity
	5	3.85	Salinity
U.S. Highway 19	6	4.20	Salinity
	7	4.60	Salinity
	8	4.90	Salinity
	9	5.15	Salinity
	10	5.45	Salinity
	11	5.65	Salinity
	12	6.20	Salinity
	13	6.80	Salinity
	14	7.20	Salinity
	15	7.40	Salinity
	16	7.70	Salinity
	17	8.00	Salinity
	18	8.25	Salinity
Perrine Ranch Road[1]	19	8.70	Salinity, stage
	20	9.00	Salinity
	21	9.40	Salinity
	22	9.70	Salinity
	23	9.95	Salinity
	24	10.25	Salinity
	25	10.35	Salinity
	26	10.45	Salinity
	27	10.55	Salinity
	28	10.70	Salinity
	29	10.85	Salinity
Cedar Street	30	12.20	Salinity, stage
State Road 54[2]	31	14.80	Stage, streamflow

[1]Anclote River at Perrine Ranch Road near Elfers.
[2]Anclote River near Elfers.

(fig. 2). Perrine Ranch Road is an established U.S. Geological Survey monitoring site with 4 years of tidal-stage and specific-conductance data.

In addition to fixed monitoring at the three sites, measurements of specific conductance were made at various streamflow and tide conditions at 28 selected sites by personnel of the Southwest Florida Water Management District. The sites were selected by the Water Management District based on channel geometry and length of subreach (fig. 2). Descriptions of the sites are given in table 1, and the locations are shown in figure 7. Thirty-two salinity surveys were made. Each survey consisted of measuring the river depth and specific conductance at depth intervals of about 3 feet from about 1.5 feet below water surface to the bottom of the channel. Measurements were made sequentially from the most downstream site to the upstream limit of saltwater in an attempt to follow the upstream propagation of tidal peaks. Multiple measurements were typically made to define the location of the saltwater-freshwater interface at high slack tide. A summary of tides and streamflows for the 32 surveys is presented in table 2. The tide (table 2) is the altitude of the low-high or high-high tide in the river at the time of the salinity measurements, as measured at Hickory Point. Streamflow is that measured at State Road 54.

Determination of Salinity

Direct measurement of salinity in the field is tactically very difficult and labor intensive; therefore, alternate methods of estimating salinity have been developed. The greater the concentration of chloride ions in water, the greater the ability of water to conduct electricity. Therefore, the electrical conductance of seawater can be used as an indicator of salinity. The method used to estimate salinity from specific-conductance measurements is based on equations presented by Cox and others (1967) and is summarized in table 3. Specific conductance in table 3 was rounded to the nearest 5 μS/cm. For this study, all specific-conductance values were converted to and reported as salinity, in parts per thousand.

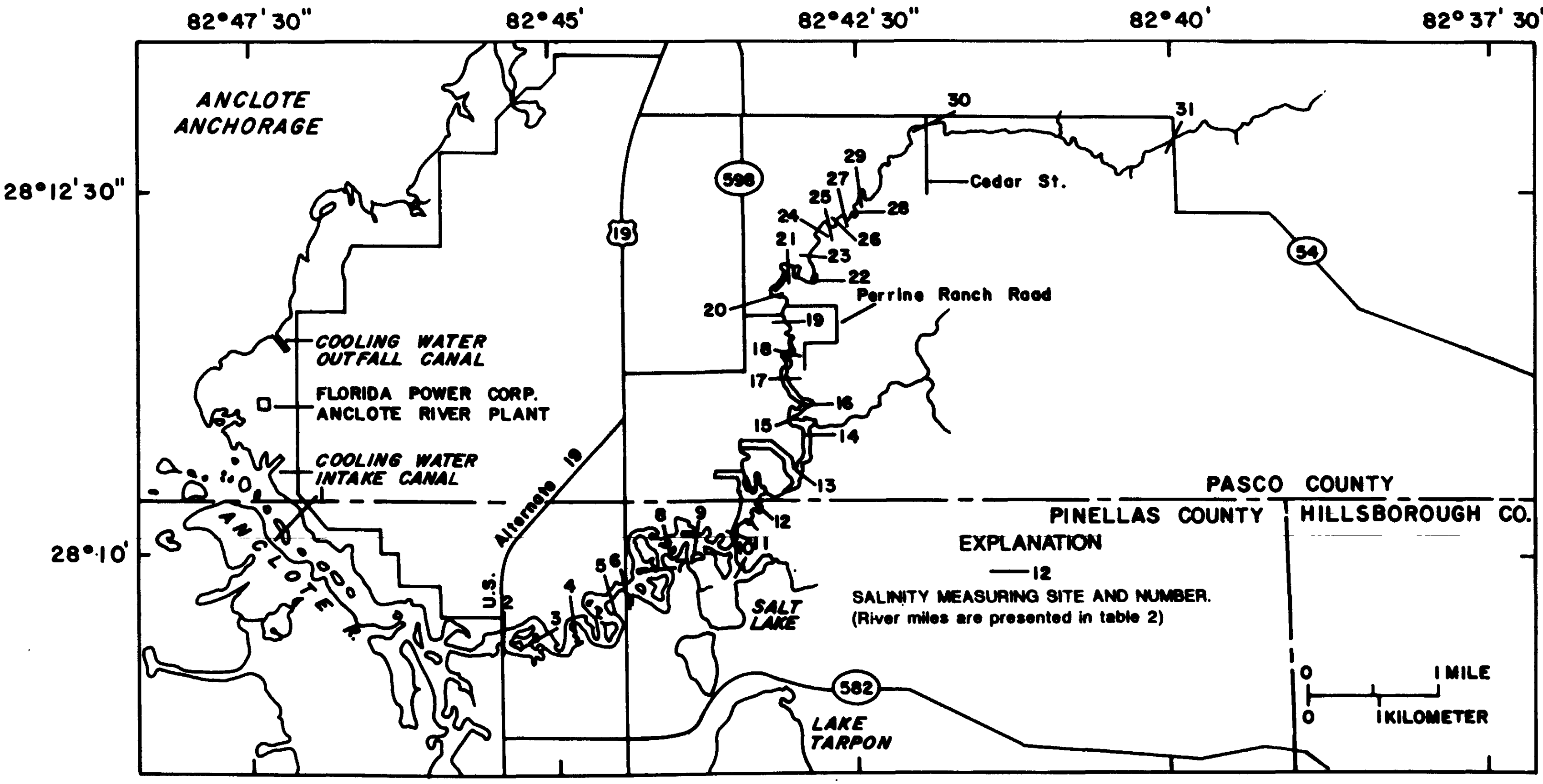

Figure 7.—Location of salinity measuring sites, Anclote River Estuary.

Table 2.—*Tide and streamflow at time of survey*

[Tide, in feet above sea level; streamflow, in cubic feet per second]

Date	Tide at Hickory Point	Streamflow at State Road 54
1984		
January 30	0.83	67.0
February 15	1.00	69.0
March 13	1.09	55.0
April 13	1.97	92.0
May 11	1.37	4.2
June 11	2.58	4.7
July 9	2.04	122.0
August 24	2.43	263.0
September 21	1.96	11.0
October 22	2.70	5.0
November 20	1.47	2.8
December 4	1.32	2.9
1985		
January 16	.64	2.8
March 5	1.23	2.6
March 18	-.03	2.8
April 29	1.46	3.1
July 16	2.47	3.8
August 15	2.76	195.0
August 27	2.17	158.0
September 10	2.24	204.0
September 27	2.57	41.0
October 10	2.12	16.0
October 23	2.61	5.5
November 25	1.53	6.4
December 10	1.45	3.1
December 26	-.25	7.0
1986		
January 21	.28	181.0
February 4	1.05	45.0
March 5	.76	23.0
April 2	.76	14.0
April 7	1.82	6.8
May 16	1.55	2.3

SURFACE-WATER HYDROLOGY

Streamflow Characteristics

Streamflow on the Anclote River has been gaged by the U.S. Geological Survey since May 1946. The gaging station, Anclote River near Elfers, is at State Road 54 (table 1) and receives runoff from about 71.4 mi^2 of the upper drainage subbasin (fig. 2).

On an annual basis, streamflow near Elfers, for the period of record, averages about 70.1 ft^3/s, with maximum and minimum mean annual flows of 226 ft^3/s (1959) and 9.2 ft^3/s (1981), respectively. Annual departures from the mean for the period of record are presented in figure 8.

Figures 9, 10, and 11 are three graphical means to illustrate how streamflow characteristics during the study period compare to streamflow characteristics for the entire period of record at the station near Elfers. Figure 9 shows the maximum, average, and minimum mean monthly streamflows for the period of record superimposed on the mean monthly streamflow measured during the period of study (note that the hydrographs showing maximum, average, and minimum measurements repeat themselves each year). Interestingly, the monthly mean streamflows measured from January through March 1985 are the lowest of record at this site. In fact, there are few months during the study period in which flow was greater than the long-term monthly mean.

The actual departures from mean monthly streamflow during the study period are presented in figure 10, which shows lower monthly streamflows during the study for 22 of 29 months. The mean departure during the study is about −15.5 ft^3/s.

Table 3.—*Relation between specific conductance and salinity*

[Modified from Cox and others, 1967. Specific conductance is rounded off to the nearest 5 microsiemens per centimeter at 25 degrees Celsius]

Specific conductance, in microsiemens per centimeter at 25 degrees Celsius	Salinity, in parts per thousand
53,045	35.0
49,660	32.5
46,235	30.0
42,770	27.5
39,260	25.0
35,705	22.5
32,100	20.0
29,180	18.0
29,445	17.5
24,730	15.0
20,945	12.5
17,080	10.0
13,110	7.5
9,005	5.0
5,600	3.0
3,830	2.0
2,095	1.0
1,105	.5
1,000	.44
735	.30
360	.10

Another useful comparison is the duration analysis shown in figure 11. This analysis portrays the percentage of time, days in this instance, that daily mean streamflows were exceeded for both the period of record and the period of study. This analysis indicates that the usual range of measurements for streamflow during the study period was achieved less frequently than would be expected based on the streamflow history at the section. The median flow for the period of study, for example, is 7.6 ft^3/s, whereas the median flow for the period of record is nearly double at 14 ft^3/s.

The daily mean streamflow in the Anclote River near Elfers during the period of study ranged from 2.3 to 263 ft^3/s and is representative of long-term streamflow conditions that occur between 8 and 98 percent of the time. Daily mean streamflow for the Anclote River near Elfers for the period from January 1984 through May 1986 averaged 50.8 ft^3/s and ranged from 2.0 ft^3/s on May 29, 1986, to 1,240 ft^3/s on September 3, 1985 (fig. 12). The period of extended low flow is easily recognized from late 1984 through mid-1985. A reduced frequency of higher flow during the study was considered fortuitous as it allowed more data to be collected during lower flows when saltwater intrusion in the river was more extensive.

The Cox-Stuart test for trend was performed on annual mean streamflows at Elfers for the period of record to determine whether a trend existed in streamflow during the period before (1947–62) and after (1963–85) well-field pumping began. Results of the trend test indicate that, between 1947 and 1985, there was no increasing or decreasing streamflow trend at the 0.05-significance level.

Tidal Flow Characteristics

Tides in the Anclote River are mixed, having approximately equal diurnal and semidiurnal influences, generally consisting of low-low, high-low, low-high, and high-high events each tidal day. Predicted tides at the Anclote River, published by the National Oceanic and Atmospheric Administration (1984), can vary from actual tides because predictions do not account for climatic conditions. To monitor the tides, three continuous-stage monitoring stations were constructed at Hickory Point, U.S. Alternate 19, and Perrine Ranch Road (fig. 2). The station at Hickory Point was installed about 1 mile upstream from the mouth of the river and 0.45 mile upstream from the cooling-water intake of the Florida Power Corporation powerplant (fig. 2) to avoid any possible effects that pumping could cause on tide measurements.

Tide cycles for May 6, 1985, for the Anclote River at Hickory Point, U.S. Alternate 19, and Perrine Ranch Road are shown in figure 13. The high-high tidal peak shifted in time and decreased in height as the tide moved upstream. The mean and standard deviation of time-of-travel for the peak high-high tide from Hickory Point to U.S. Alternate 19 (2.2 miles upstream from Hickory Point) and Perrine Ranch Road (8.7 miles upstream), computed for 30 nonconsecutive days during the period

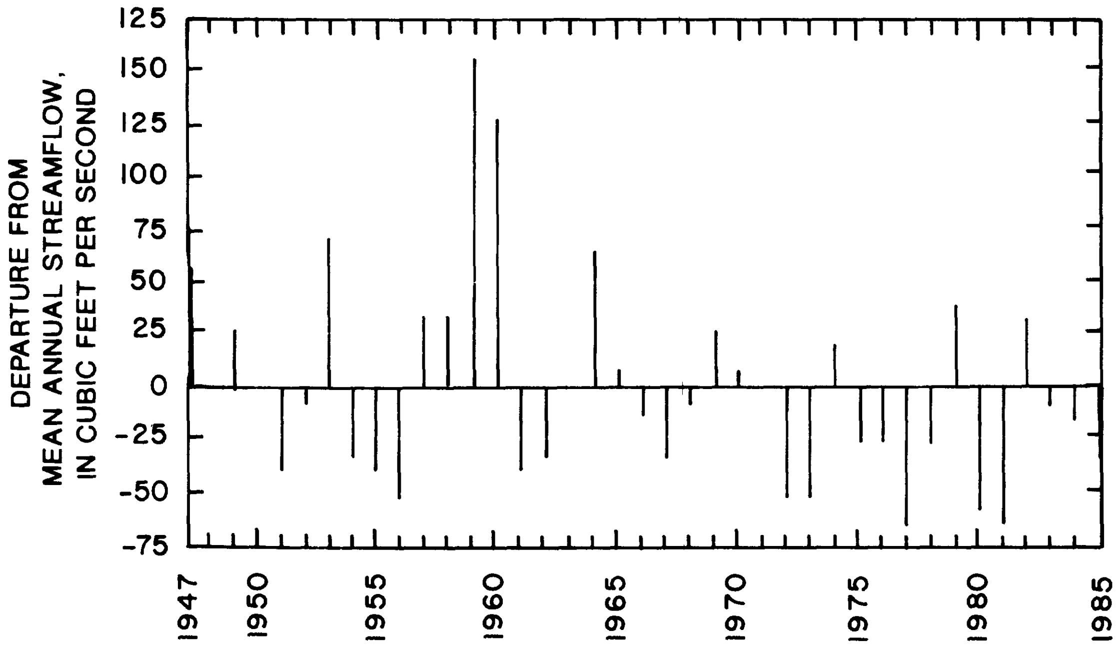

Figure 8.—Departure from mean annual streamflow, Anclote River near Elfers, 1947 through 1985.

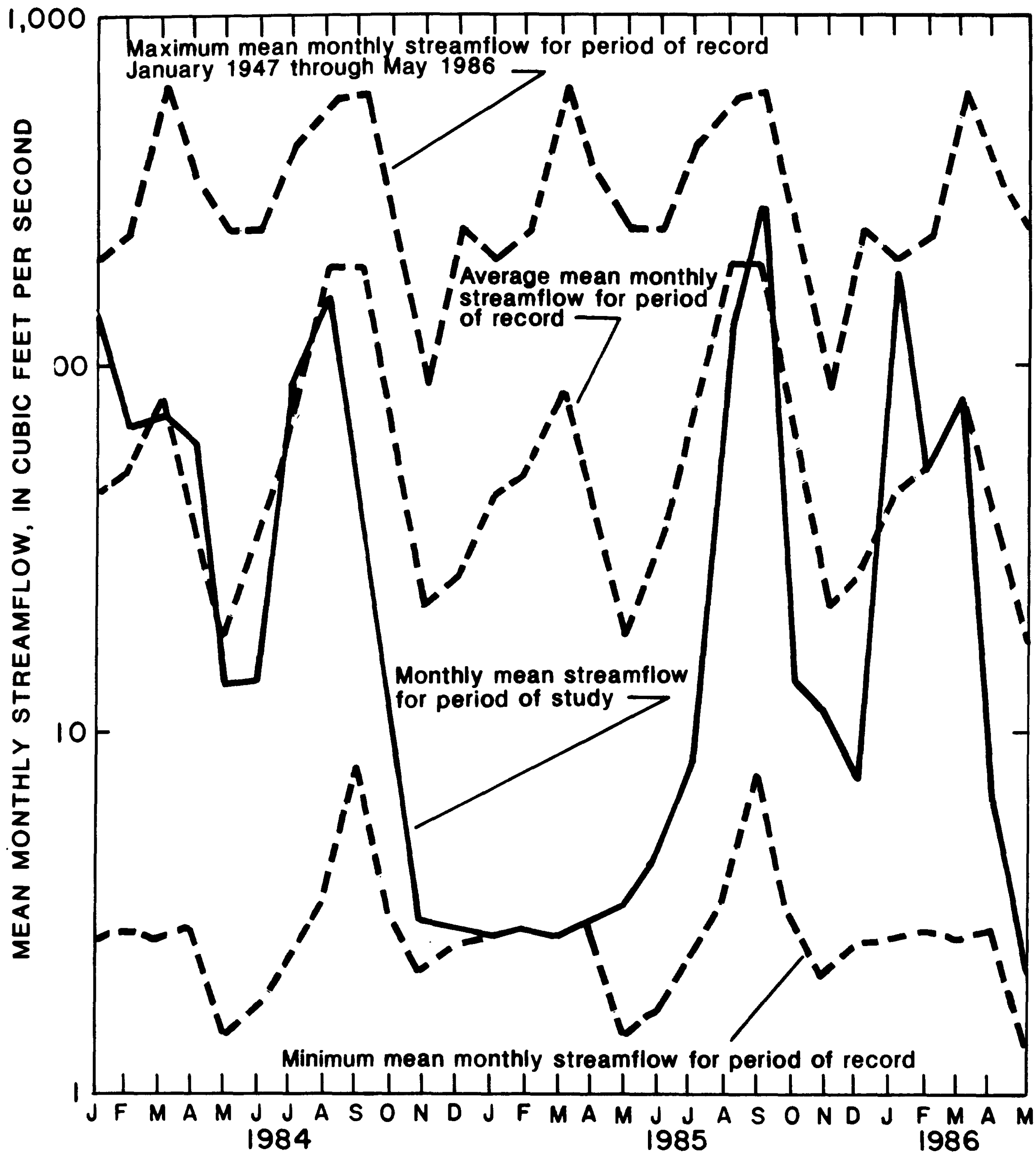

Figure 9.—Maximum, average, and minimum mean monthly streamflow for period of record and monthly mean streamflow for period of study.

of study, were 0.5±0.3 and 2.5±0.5 hours, respectively. A summary of tide data by month and for the period of study is presented in table 4. The maximum recorded high-high tide of 5.21 feet for the period of study was during Hurricane Elena, August 31 and September 1, 1985. The storm surge was not considered in preparing table 4 because it did not represent a normal tide.

Hydrologic Factors Affecting Streamflow

An attempt was made to establish a relation between streamflow and precipitation, potential evaporation, and well-field pumpage. There are four well fields within, or in close proximity to, the Anclote River drainage basin (fig. 1). Pumping began at the well fields as follows:

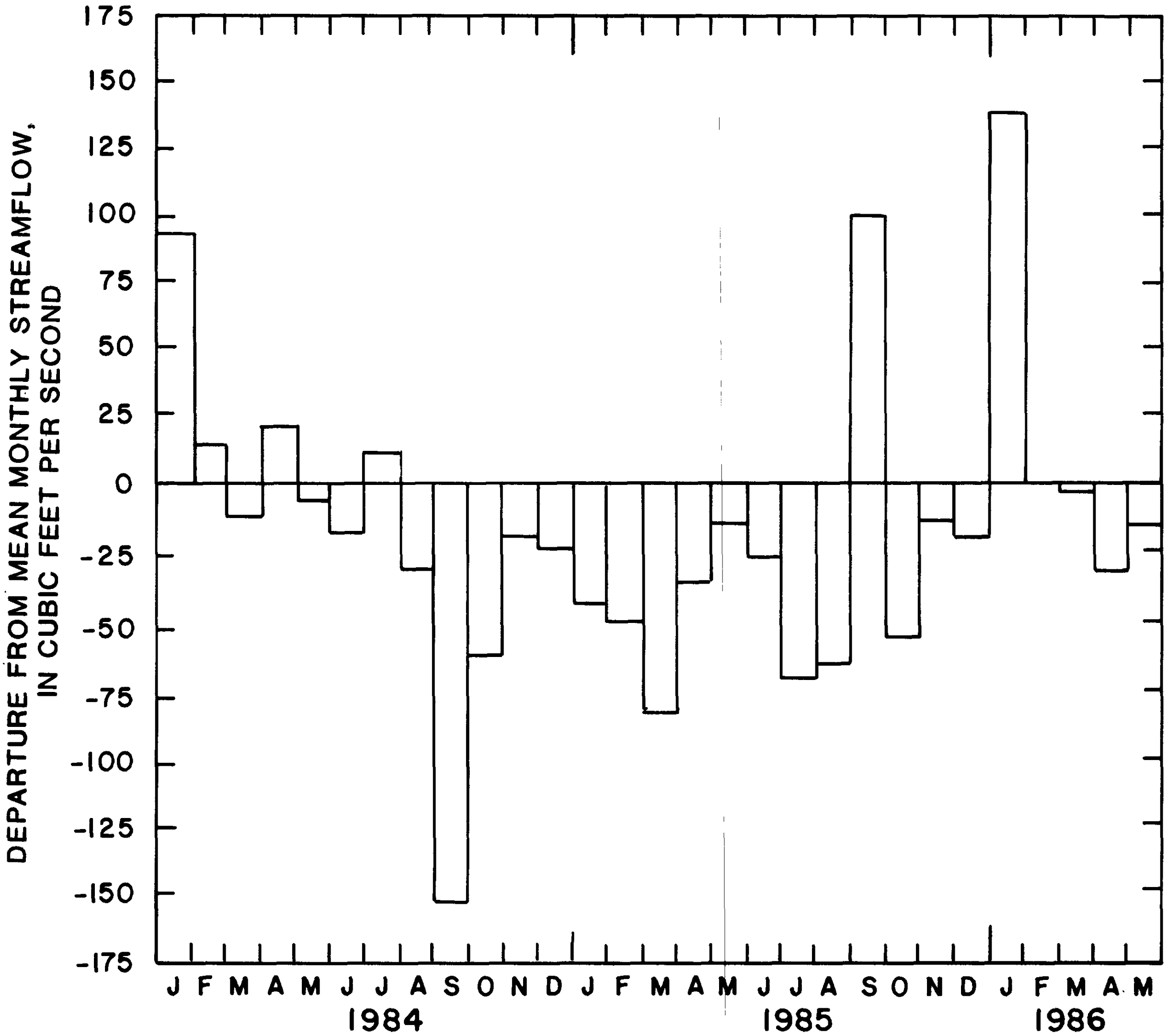

Figure 10.—Departure from mean monthly streamflow, Anclote River near Elfers, January 1984 through May 1986.

Section-21	February 1963
Eldridge-Wilde	January 1965
South Pasco	March 1973
Starkey	March 1976

The method used to define the relation is based on regression analysis using streamflow as the dependent variable and precipitation at Tarpon Springs and St. Leo (fig. 3), potential evaporation (Chow, 1964, p. 11–29), monthly mean average well-field pumpage at each well field (J.D. Fretwell, U.S. Geological Survey, written commun., 1985), and total monthly pumpage at all well fields as the independent variables. The above independent variables also were lagged 1 and 2 months. A stepwise multiple regression analysis method was used (Statistical Analysis Systems Institute, Inc., 1985).

The statistic used to evaluate the multiple-regression analysis is the coefficient of determination (R^2), or the percentage of variation of the dependent variable explained by the independent variables. Although the R^2 computes as a decimal with a range of 0 to 1, it is reported as a percentage. For this study, the level of significance used to determine if the regression coefficients are statistically different from zero has been set to equal 0.05.

Two approaches are used in relating streamflow to the independent variables. The difference in the approaches is the time increment of data. The two approaches consisted of analyzing (1) monthly data from January 1976 through December 1985, which represents the period when all well fields were on-line; and (2) annual data from 1946 through 1985, which includes the entire period of records for streamflow and well-field pumpage. The results are discussed in the following sections.

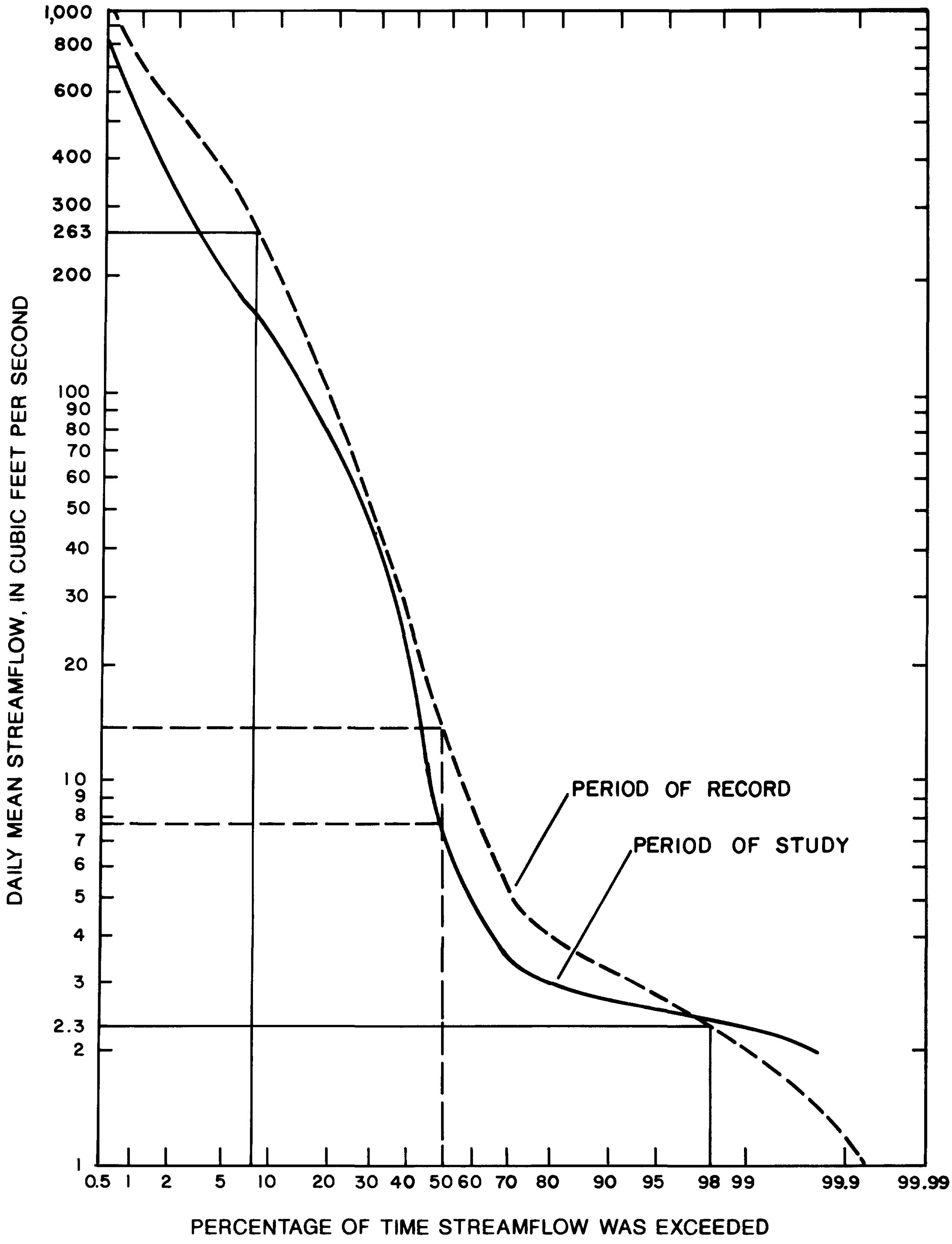

Figure 11.—Flow-duration curves for the Anclote River near Elfers for period of record, 1947 through 1985, and for period of study, January 1984 through May 1986.

Streamflow Analysis Using Monthly Data

During January 1976 through December 1985, the average streamflow at Elfers was 70.0 ft^3/s, and the monthly rainfall at Tarpon Springs and St. Leo averaged 4.36 and 4.66 inches, respectively. The mean pumpage at each well field was:

Section-21	8.8	Mgal/d
Eldridge-Wilde	29.2	Mgal/d
South Pasco	12.5	Mgal/d
Starkey	4.4	Mgal/d

The equation for estimating the monthly mean streamflow is:

$$QM = 16.7 + 12.1\,(TRPN) + 9.46\,(LAG1TRPN) - 3.98\,(LAG2POTVAP) \qquad (1)$$

where

QM = monthly mean streamflow, in cubic feet per second;

TRPN = monthly rainfall measured at Tarpon Springs, in inches;

LAG1TRPN = monthly rainfall at Tarpon Springs, lagged 1 month, in inches; and

LAG2POTVAP = monthly potential evaporation, lagged 2 months, in inches.

Only the above three independent variables were significant at the 0.05 level. The R^2 for the equation is 0.44, and the root mean square error is ±60.7 ft^3/s, or ±85.7 percent about the mean. Individual well-field pumpages were not statistically significant at the 0.05 level. Because no pumpages were retained as independent variables, it is concluded that a statistical relation between monthly streamflow and individual well-field pumpage could not be established.

Streamflow Analysis Using Annual Data

During 1947 through 1985, the average streamflow was about 70.1 ft^3/s, and the annual rainfall at Tarpon Springs and St. Leo averaged 52.65 and 55.28 inches, respectively. The mean annual pumpage at each well field was:

Section-21	11.6	Mgal/d
Eldridge-Wilde	27.7	Mgal/d
South Pasco	13.0	Mgal/d
Starkey	4.4	Mgal/d

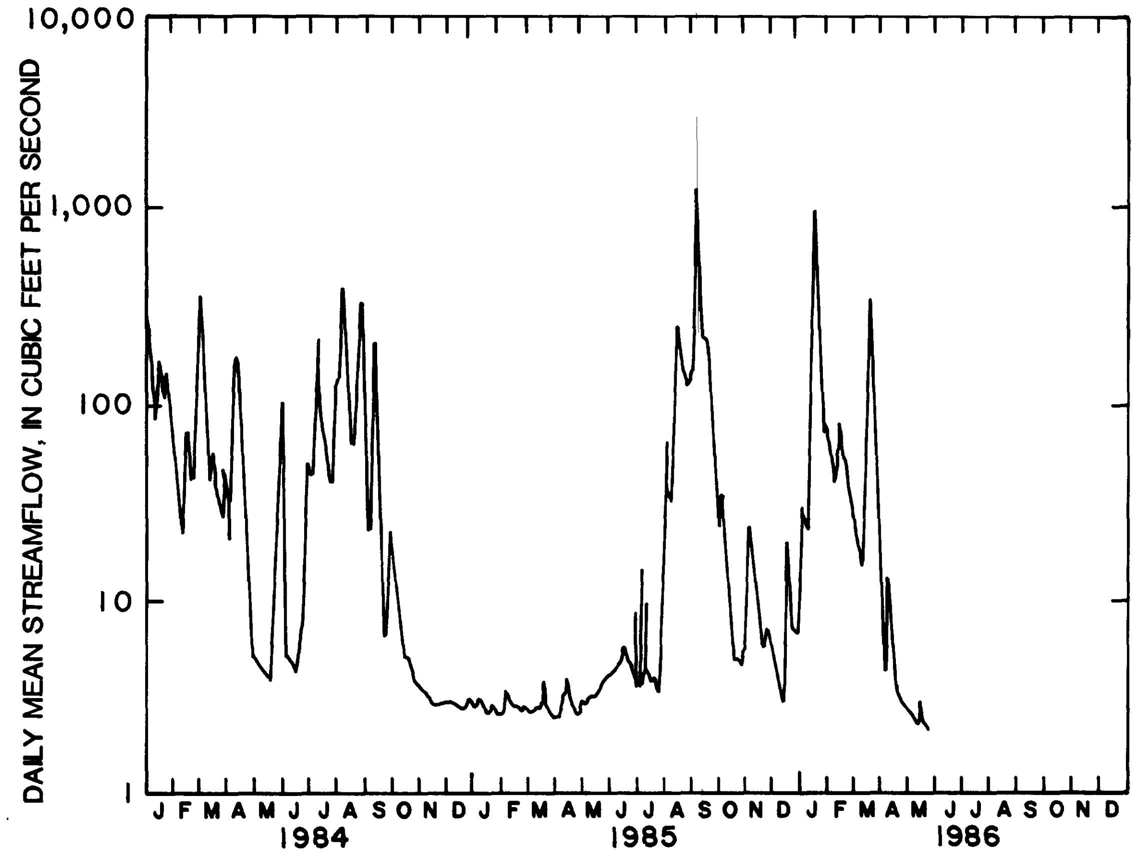

Figure 12.—Daily mean streamflow for Anclote River near Elfers, January 1984 through May 1986.

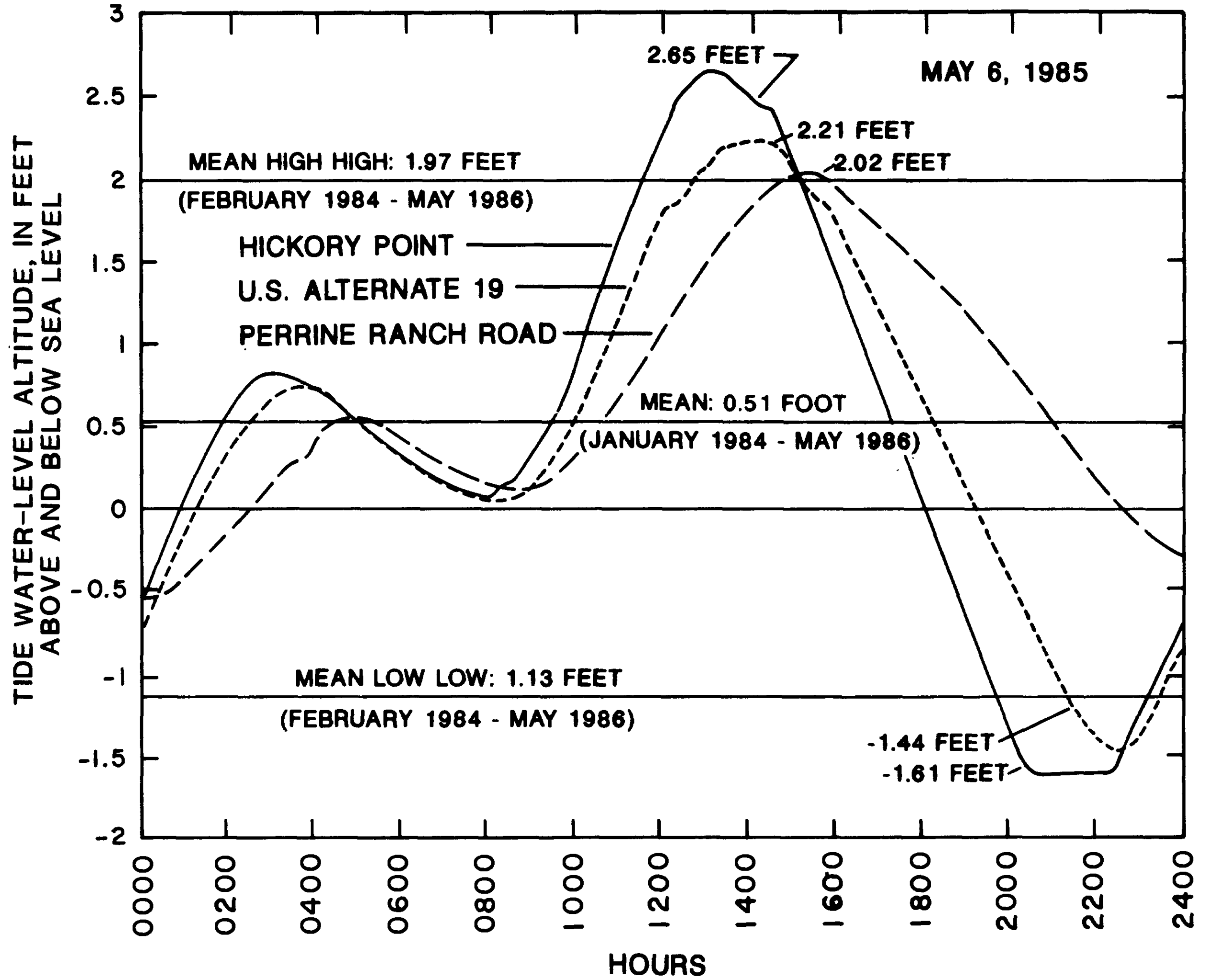

Figure 13.—Typical semidiurnal tide cycle for the Anclote River at Hickory Point, U.S. Alternate 19, and Perrine Ranch Road.

The equation for estimating the annual streamflow is:

$$Q_Y = -43{,}724 - 19.5\,(SSUMQ) + 612\,(SLGTRPN) + 794\,(SLG2SLEO) \quad (2)$$

where

Q_Y = annual mean streamflow, in cubic feet per second;
SSUMQ = total annual pumpage for all four well fields, in cubic feet per second;
SLGTRPN = annual rainfall at Tarpon Springs, lagged 1 month, in inches; and
SLG2SLEO = annual rainfall at St. Leo, lagged 2 months, in inches.

Only the above three independent variables were significant at the 0.05 level. The R^2 for the equation is 0.81, and the root mean square error is ±22 ft^3/s, or ±31.4 percent about the mean. Individual well fields were not included at the significance level of 0.05; however, the sum of pumpages from the well fields was significant. Because there were no individual well-field pumpages as independent variables, it is concluded that a statistical relation between annual streamflow and annual individual well-field pumpage could not be established; however, a relation was established between annual streamflow and the annual sum of well-field pumpage.

SALINITY

Factors Affecting Salinity

The Anclote River Estuary, within the 8.65-mile study reach between U.S. Alternate 19 and at a point about 2.15 miles upstream from Perrine Ranch Road, is vertically well mixed to partially mixed for flows ranging from 2.3 to 204 ft^3/s, respectively. Figures 14 through 19 present salinity values along the thalweg of the river for streamflows of 2.3, 6.8, 23, 45, 158, and 204 ft^3/s and high tides of 1.55, 1.82, 0.76, 1.05, 2.17, and 2.24 feet above sea level, respectively. Streamflows were measured at State Road 54 (fig. 2), or about 12.6 miles upstream from U.S. Alternate 19.

Table 4.—*Summary of average monthly tide data for the Anclote River Estuary at Hickory Point*

[HHT, mean high-high tide; LLT, mean low-low tide. All tides are referenced to sea level; —, no data]

Month	1984 HHT	1984 LLT	1984 Range	1985 HHT	1985 LLT	1985 Range	1986 HHT	1986 LLT	1986 Range
January	(1)	(1)	(1)	1.93	-1.13	3.04	1.71	-1.46	3.16
February	1.60	-1.58	3.20	1.67	-1.40	3.01	(1)	(1)	(1)
March	1.65	-1.45	3.10	1.60	-1.34	2.95	1.77	-1.30	3.08
April	1.70	-1.31	3.00	1.74	-1.35	3.11	2.12	-1.18	3.29
May	1.74	-1.45	3.18	1.96	-1.15	3.12	2.37	- .77	3.16
June	2.07	-1.29	3.41	2.11	-1.29	3.43	(2)	—	—
July	2.08	-1.46	3.56	2.10	-1.16	3.24	(2)	—	—
August	2.11	- .91	3.02	2.31	- .76	3.08	(2)	—	—
September	2.44	- .43	2.86	2.15	- .61	2.72	(2)	—	—
October	(1)	(1)	(1)	2.46	- .34	2.82	(2)	—	—
November	(1)	(1)	(1)	2.22	- .92	3.15	(2)	—	—
December	(1)	(1)	(1)	1.85	-1.39	3.31	(2)	—	—

Summary for period of study

Mean high-high tide	1.97 feet	
Mean low-low tide	-1.14 feet	
Range	3.10 feet	
Maximum high-high tide	4.02 feet	(November 1, 1985)
Minimum low-low tide	-2.63 feet	(December 26, 1985)
Maximum high-high tide due to Hurricane Elena	5.21 feet	(August 31 and September 1, 1985)

[1]Insufficient or lost data.
[2]Data not collected.

The salinity profiles presented in figures 14 through 19 depict the range of salinity conditions measured in the Anclote River Estuary during this study. In general, lower streamflows allow saltwater to intrude farther upstream and result in mostly well-mixed conditions from top to bottom. High streamflows allow less saltwater intrusion and cause more partially mixed conditions, as shown by greater deviations of equal-salinity lines from the vertical. The freshwater-saltwater interface (0.44 ppt) was measured to move downstream about 3.5 miles with increase in streamflow from 2.3 to 45 ft^3/s (figs. 14 and 17), yet further streamflow increases from 45 to 204 ft^3/s (fig. 19) produced additional interfacial movement of only about 1.0 mile. The upstream extent of the interface is very sensitive to changes in low streamflow.

Significantly nonvertical lines of equal salinity during low streamflow (figs. 15 and 16) are thought to be caused by localized bathymetry that may sometimes trap pockets of saltwater farther upstream than would otherwise happen. In the vicinity of mile 7.0 for instance, a deep hole appears to exist just upstream of a 2-mile reach of consistently shallower water. Dense saltwater could remain in the deep area long after a high tide and locally could influence salinity measurements.

The effect of tides is not as visually apparent as the effect of streamflow in figures 14 through 19. The positions of the 18-ppt and 10-ppt lines of equal salinity in figures 16 and 17 are, however, one indication that tides are a factor in salinity distribution. Expected downstream displacement of these two salinity lines does not occur as streamflow is increased from 23 to 45 ft^3/s. The likely reason is that the higher tide has induced greater upstream movement of saline water.

On the basis of continuous salinity measurements during the period of study, a salinity duration table (table 5) for the daily mean, maximum, and minimum salinities was computed for the continuous salinity-monitoring stations at Hickory Point, U.S. Alternate 19, and Perrine Ranch Road. Table 5 presents the percentage of time for the period of study that the indicated salinity was exceeded.

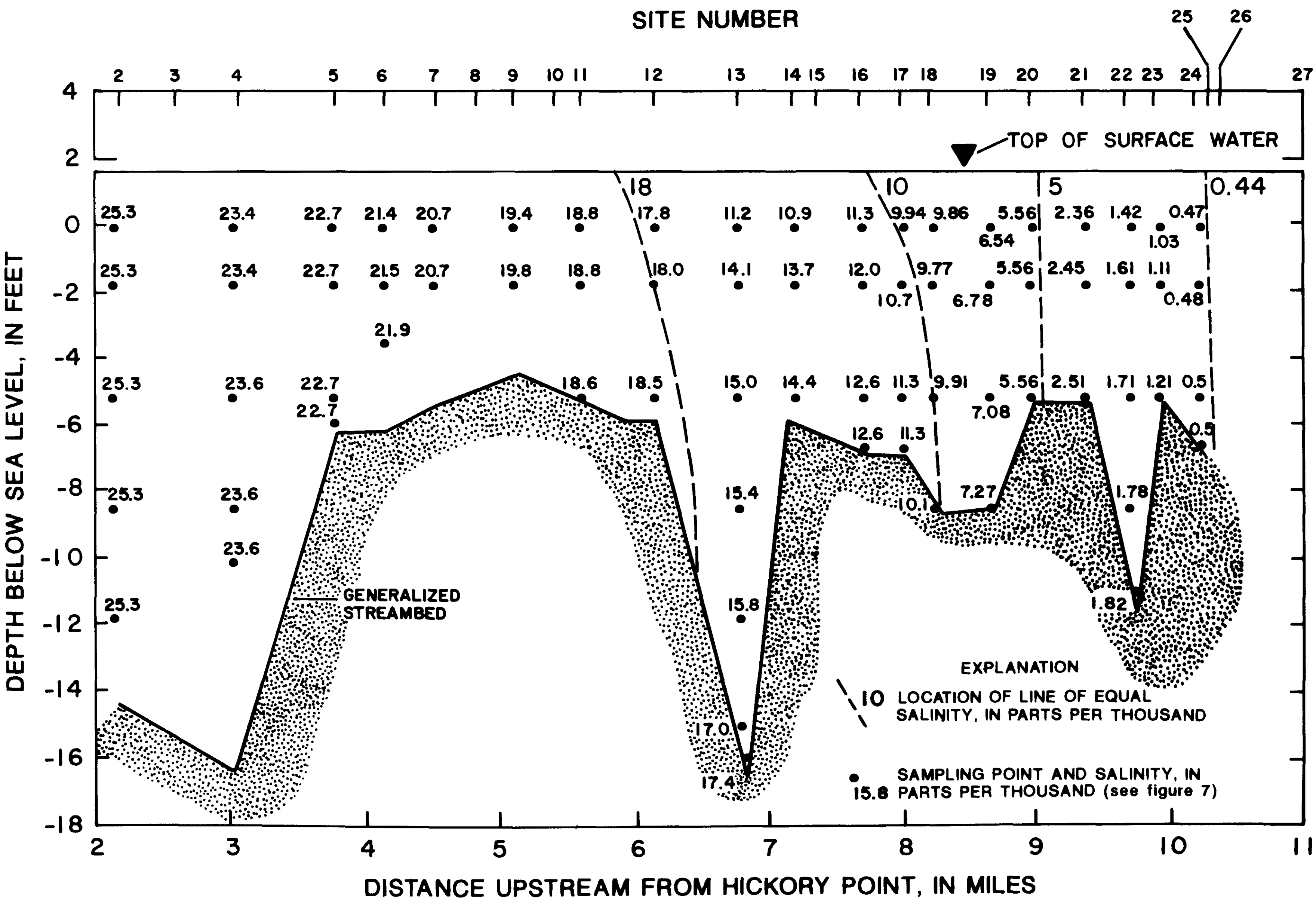

Figure 14.—Salinity of the Anclote River Estuary at a streamflow of 2.3 cubic feet per second and a tide of 1.55 feet above sea level, May 16, 1986.

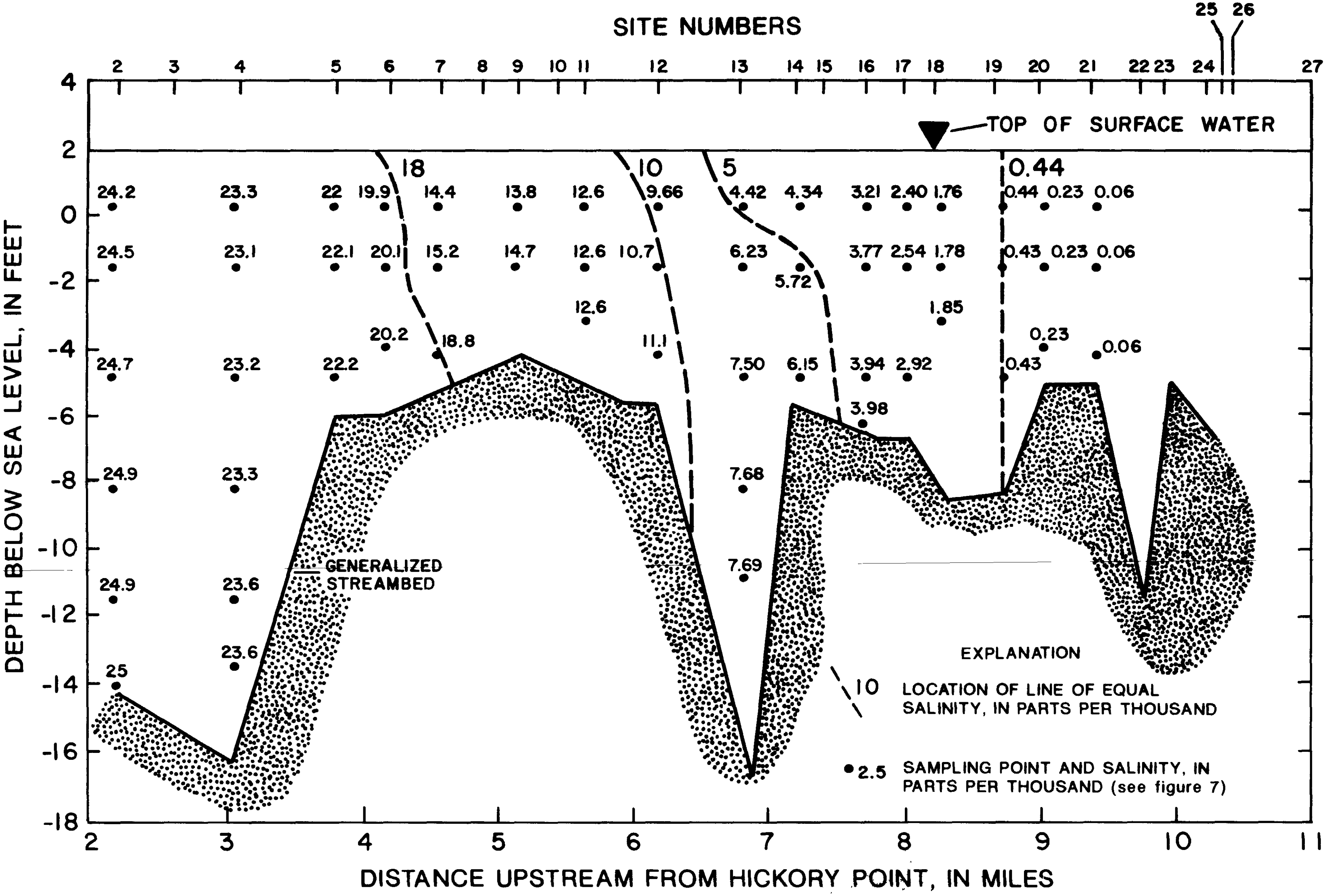

Figure 15.—Salinity of the Anclote River Estuary at a streamflow of 6.8 cubic feet per second and a tide of 1.82 feet above sea level, April 7, 1986.

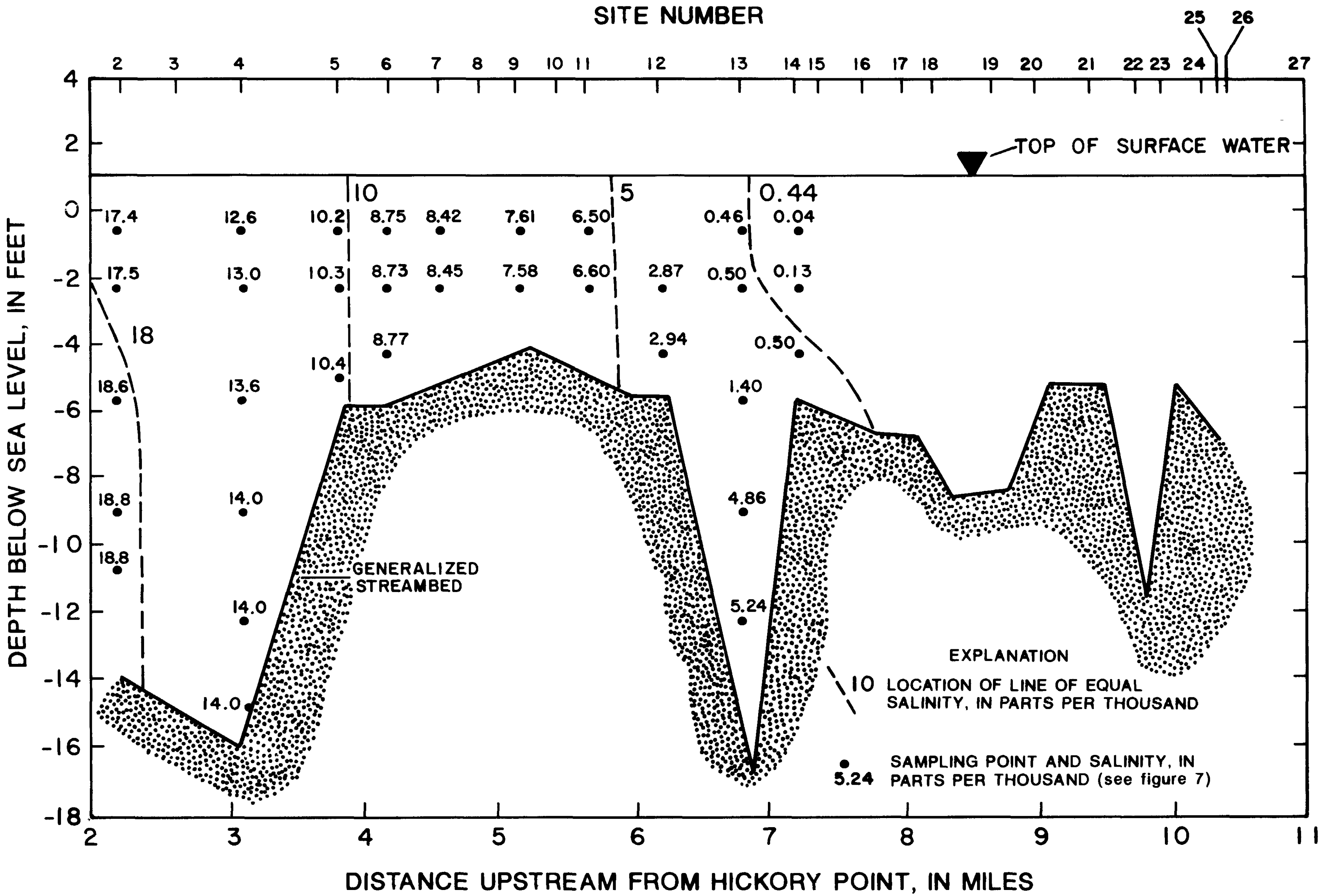

Figure 16.—Salinity of the Anclote River Estuary at a streamflow of 23 cubic feet per second and a tide of 0.76 foot above sea level, March 5, 1986.

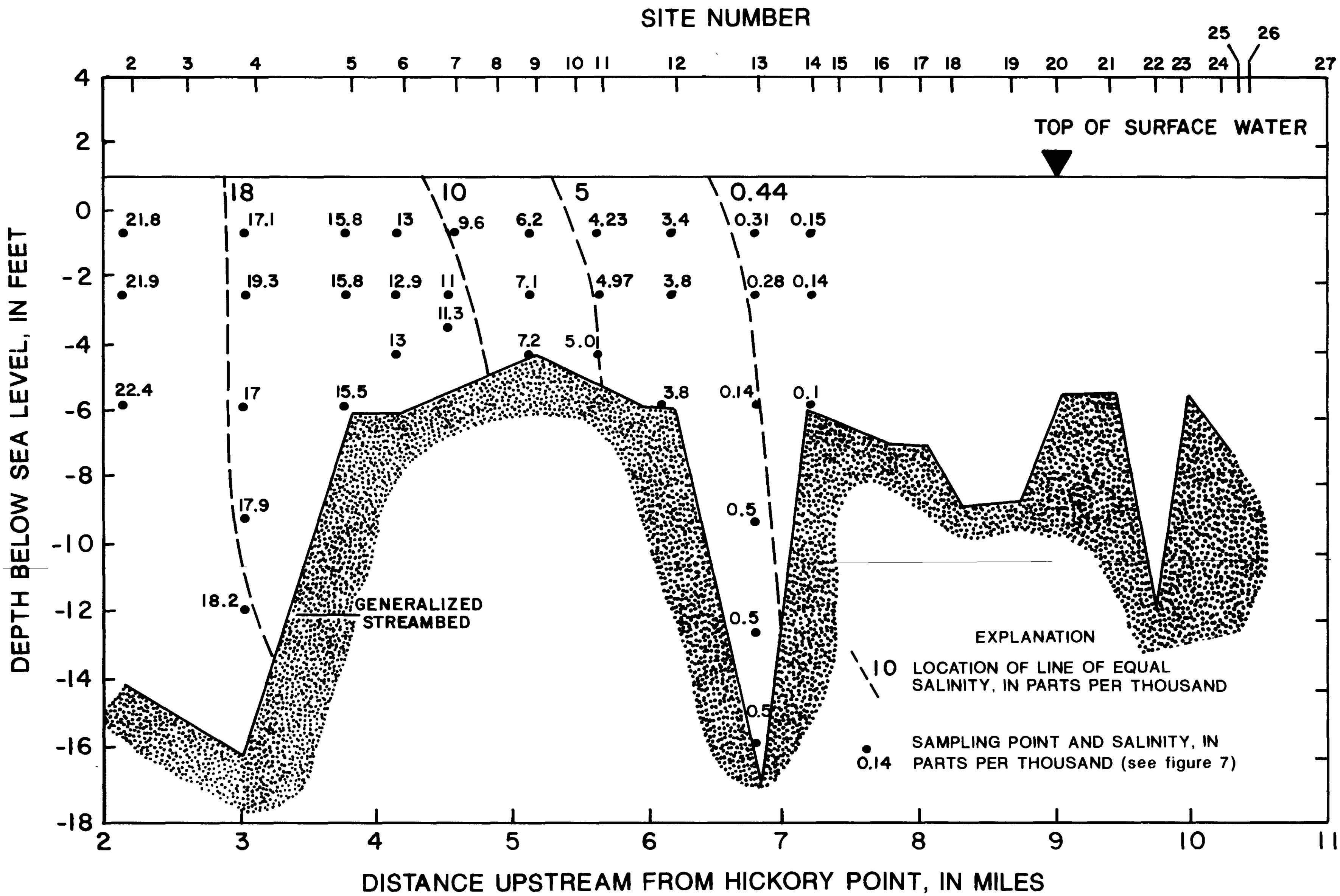

Figure 17.—Salinity of the Anclote River Estuary at a streamflow of 45 cubic feet per second and a tide of 1.05 feet above sea level, February 4, 1986.

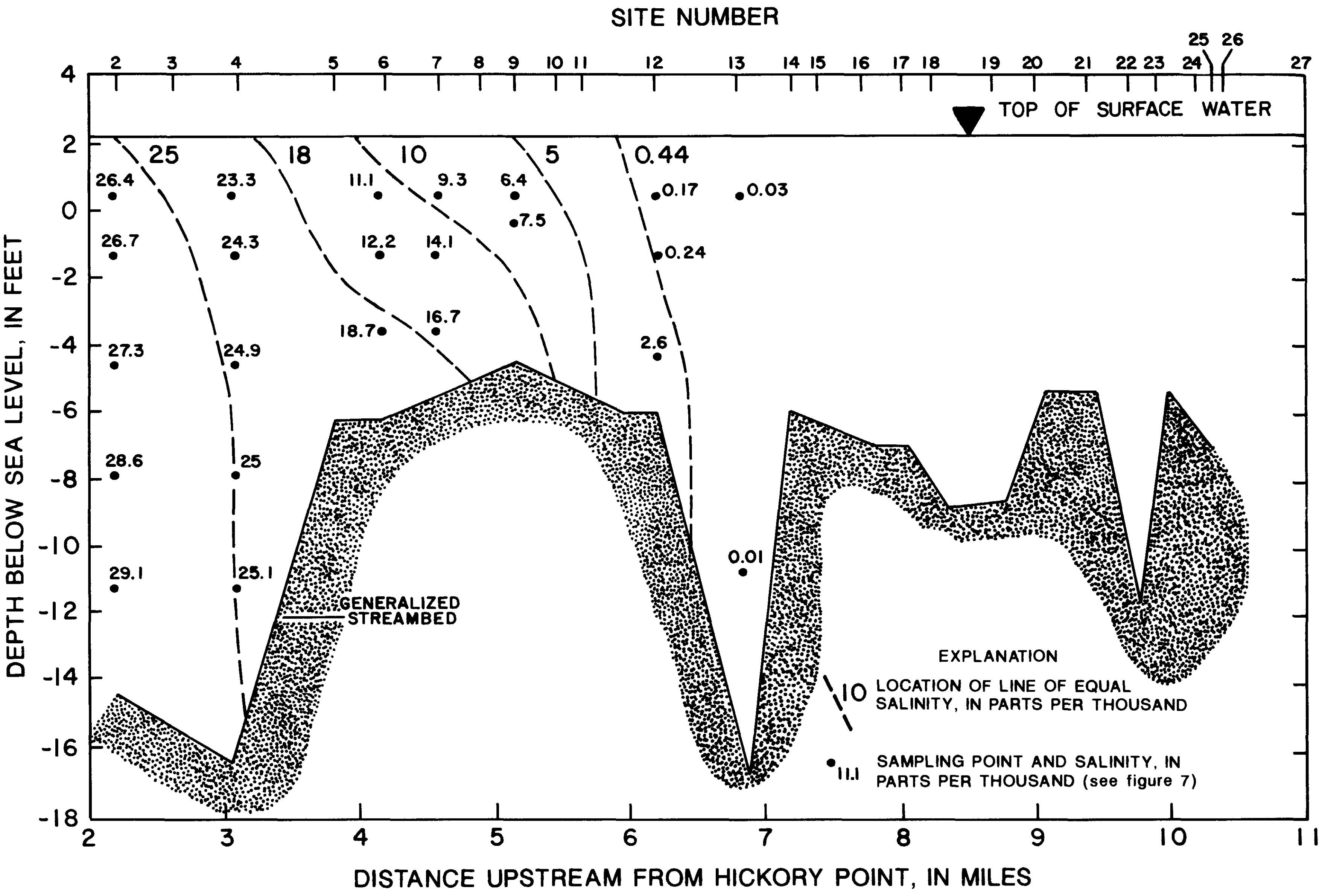

Figure 18.—Salinity of the Anclote River Estuary at a streamflow of 158 cubic feet per second and a tide of 2.17 feet above sea level, August 27, 1985.

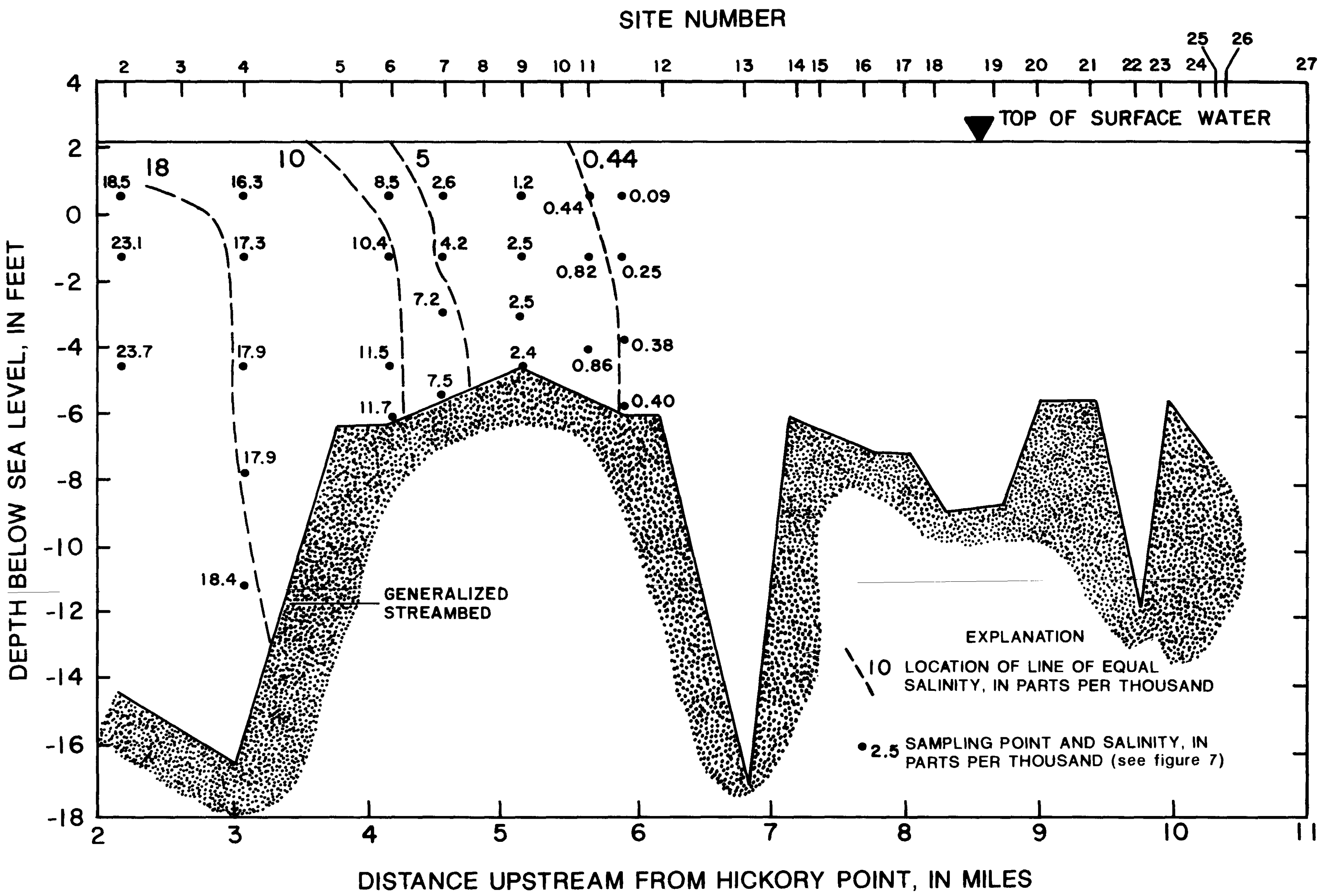

Figure 19.—Salinity of the Anclote River Estuary at a streamflow of 204 cubic feet per second and a tide of 2.24 feet above sea level, September 10, 1985.

Table 5.—*Salinity duration table for the Anclote River at Hickory Point, U.S. Alternate 19, and Perrine Ranch Road monitoring sites for period of study*

[Mean, maximum, and minimum daily salinities are reported in parts per thousand]

Percentage of time salinity is exceeded	Hickory Point			U.S. Alternate 19			Perrine Ranch Road		
	Mean	Maximum	Minimum	Mean	Maximum	Minimum	Mean	Maximum	Minimum
5	32.15	33.77	30.22	29.44	33.27	25.81	11.77	17.72	5.60
10	31.66	33.22	29.52	28.68	32.39	24.89	8.30	14.18	3.78
15	31.27	32.89	29.07	28.14	31.89	23.62	6.88	12.67	2.89
20	30.85	32.45	28.50	27.48	31.36	22.92	6.08	11.45	2.38
25	30.31	31.99	27.99	26.45	30.77	22.23	5.35	10.20	1.98
30	29.91	31.55	27.34	26.39	30.19	21.31	4.46	9.31	1.26
35	29.42	31.21	26.77	25.69	29.68	20.55	3.75	8.30	.88
40	29.09	30.85	25.99	25.00	29.10	20.00	2.33	6.26	.60
45	28.70	30.45	25.56	24.41	28.53	19.29	2.07	5.01	.39
50	28.23	29.99	25.14	23.65	28.05	18.42	1.16	3.23	.23
55	27.66	29.46	24.71	23.11	27.74	17.54	.45	1.15	.12
60	27.19	29.08	24.07	22.62	27.51	15.61	.20	.28	.11
65	26.62	28.53	23.31	21.79	27.00	13.02	.10	.12	.02
70	26.30	28.14	22.56	20.09	26.43	10.03	.06	.12	.02
75	25.21	27.63	21.65	18.55	25.88	8.28	.03	.07	.02
80	24.94	27.30	20.71	17.74	25.17	7.31	.02	.07	.00
85	24.35	26.81	19.29	16.68	24.18	5.85	.00	.02	.00
90	23.68	26.09	17.67	15.14	22.85	4.52	.00	.02	.00
95	22.04	24.76	13.69	11.65	21.30	2.21	.00	.02	.00

Relation of Salinity to Tide and Streamflow

Equations defining the locations of the saltwater-freshwater interface (0.44 ppt) and water having 5.0-, 10-, and 18-ppt salinity were determined by multiple-regression analysis. Bottom salinity locations (in miles upstream from Hickory Point) were used as the dependent variable, and the preceding low-high or high-high tide at Hickory Point and mean daily discharge at State Road 54 were used as the independent variables.

Locations of the interface were based on direct field measurements. Locations of bottom water having 5.0-, 10-, and 18-ppt salinity were determined by interpolation of data collected at the salinity observation sites (fig. 7). Streamflows used to derive the multiple regression equations ranged from 2.3 to 263 ft^3/s, which are exceeded about 98 and 8 percent of the time, respectively, for the period of record (fig. 11). The range of streamflow for the study period represents about 90 percent of the total range of streamflow recorded during the period of record (fig. 11). The tidal altitudes used in the regression were the antecedent high tides that affected the salinity distribution during each salinity measurement run. Altitudes of the antecedent high tide for the salinity distribution measurements ranged from 0.25 foot below to 2.76 feet above sea level. The resulting equations for estimating the distance from the reference site at Hickory Point of the selected salinities are discussed in the following sections.

Due to the observed nonlinear relation between the location of the interface and the corresponding streamflows during the period of study (2.3–263 ft^3/s), two equations were developed to describe the relation between the location of the interface (0.44-ppt salinity) and daily mean streamflow and antecedent high tide at the time when the location of the interface was measured. The equations were determined by establishing two subsets of the total streamflow range that, when regressed separately, produced maximum values of R^2, minimum values of standard error, and no trend of residuals when plotted versus the independent variables (Neter and Wasserman, 1974, p. 99). The two streamflow ranges so determined and used in equations 1 and 2 (table 6) were 10 to 263 ft^3/s and 2.3 to 20 ft^3/s, respectively. The corresponding ranges of the antecedent high tide were -0.28 to 2.76 feet and -0.25 to 2.70 feet, respectively. The R^2 and root mean square error for equation 1 are 91.8 percent and ±0.24 mile (±3.5 percent about the mean) and for equation 2 are 90.7 percent and ±0.30 mile (3.1 percent about the mean). For application of the equations at streamflows between 10 and 20 ft^3/s, it is desirable that the mean value for the

Table 6.—*Summary of predicting equations and statistics for mean location of the 0.44-, 5.0-, 10-, and 18-parts-per-thousand salinities*

[ppt, parts per thousand; ft³/s, cubic feet per second]

Equation No.	Salinity (ppt)	High-tide range[1] (feet)	Streamflow range[2] (ft^3/s)	Predictive equation[3]	Number of observations	R^2 (percent)	$\sqrt{MSE}$[4] (mile)
1	0.44	-0.28 — 2.76	10<Q<263	Y = 9.56 + (0.31 HT) – (1.77 LQ)	16	91.8	±0.24
2	0.44	-0.25 — 2.70	2.3<Q<20	Y = 11.69 + (0.21 HT) – (3.50 LQ)	19	90.7	±0.30
3	5.0	-0.25 — 2.76	2.3<Q<204	Y = 9.41 + (0.49 HT) – (2.44 LQ)	21	89.9	±0.59
4	10	-0.28 — 2.76	10<Q<204	Y = 5.60 + (0.94 HT) – (1.33 LQ)	10	86.7	±0.39
5	10	-0.25 — 2.76	2.3<Q<20	Y = 10.4 – (3.38 LQ)	11	70.0	±0.74
6	18	-0.25 — 2.76	2.3<Q<204	Y = 1.38 + (0.93 HT) + (952/Q)	14	83.9	±0.61

[1]High-tide range used in developing predictive equation, referenced to sea level.
[2]Streamflow range used in developing predictive equation, in cubic feet per second.
[3]Used to calculate mean location of salinity, in miles upstream from Hickory Point
where
Y = mean location of salinity;
HT = high tide referenced to sea level;
LQ = log of daily mean streamflow, in cubic feet per second; and
1/Q = reciprocal of daily mean streamflow, in cubic feet per second.
[4] $\sqrt{MSE}$ is the square root of the mean square error, or an estimator of the standard deviation for the regression model.

two equations be used to locate the interface; however, it should be noted that the reliability of R^2, root mean square error, and the residual analyses do not apply for the range of streamflow values that is common to both equations 1 and 2.

Equation 3 (table 6) locates the 5.0-ppt salinity line and is based on streamflows that range from 2.3 to 204 ft^3/s and a tide range of 0.25 foot below to 2.76 feet above sea level (table 6). The R^2 value is 89.9 percent, and the root mean square error is ±0.59 mile, or ±8.3 percent about the mean.

Equations 4 and 5 (table 6) were used to predict the location of the line of 10-ppt salinity. The equations were developed using a range of streamflow measurements from 2.3 to 204 ft^3/s. Equation 4 is for streamflows of more than 10 ft^3/s and a high-tide range of 0.28 foot below to 2.76 feet above sea level. Equation 5 is for streamflows of less than 20 ft^3/s and a tide range of 0.25 foot below to 2.76 feet above sea level. In the application of the equations at streamflows between 10 and 20 ft^3/s, both equations are used, and the mean location of the salinity is computed. The R^2 values for equations 4 and 5 are 86.7 and 70.0 percent, respectively, and the root mean square errors are ±0.39 and ±0.74 mile, or ±8.1 and ±9.8 percent about the mean, respectively.

Equation 6 (table 6) locates the 18-ppt salinity line and is based on streamflows that range from 2.3 to 204 ft^3/s and a tide range of 0.25 foot below to 2.76 feet above sea level. The R^2 value for equation 6 is 83.9 percent, and the root mean square error is ±0.61 mile, or ±13 percent about the mean.

Salinity Duration Analysis

Results of applying the predictive equations (table 6), using daily discharge and the average high-high tide for the period of study, are presented in figure 20 as a family of duration curves for the maximum daily upstream location of water having various salinities. The example presented in figure 20 indicates that the maximum upstream location of the 0.44-, 5.0-, 10-, and 18-ppt salinities will be at least 8.0, 7.5, 6.3, and 4.6 miles upstream from Hickory Point, respectively, for 60 percent of the days. The information in figure 20 is also given in map form in figures 21 through 24.

The regression equations that were developed for streamflow and tides measured during the period of study also were applied using daily streamflow for the period of record and an average high tide for the study period (table 4) to estimate the historic duration for the 0.44- and 5.0-ppt salinities. Only these two salinities were used because tide data for the period of record were not available and tide is not a highly significant variable in these two equations.

Results of computations for the period of record are shown in figure 25 and indicate less intrusion than the estimate of intrusion for the period of study (fig. 20). The example presented in figure 25 indicates that the computed maximum upstream locations of the 0.44- and 5.0-ppt salinities for the period of record were at least 7.7 and 6.9 miles upstream from Hickory Point, respectively, for 60 percent of the days. Also, the location of water having 0.44-ppt salinity is seaward of river mile 6.1 about 10 percent of the time and landward of river mile 10.4 about 10 percent of the time.

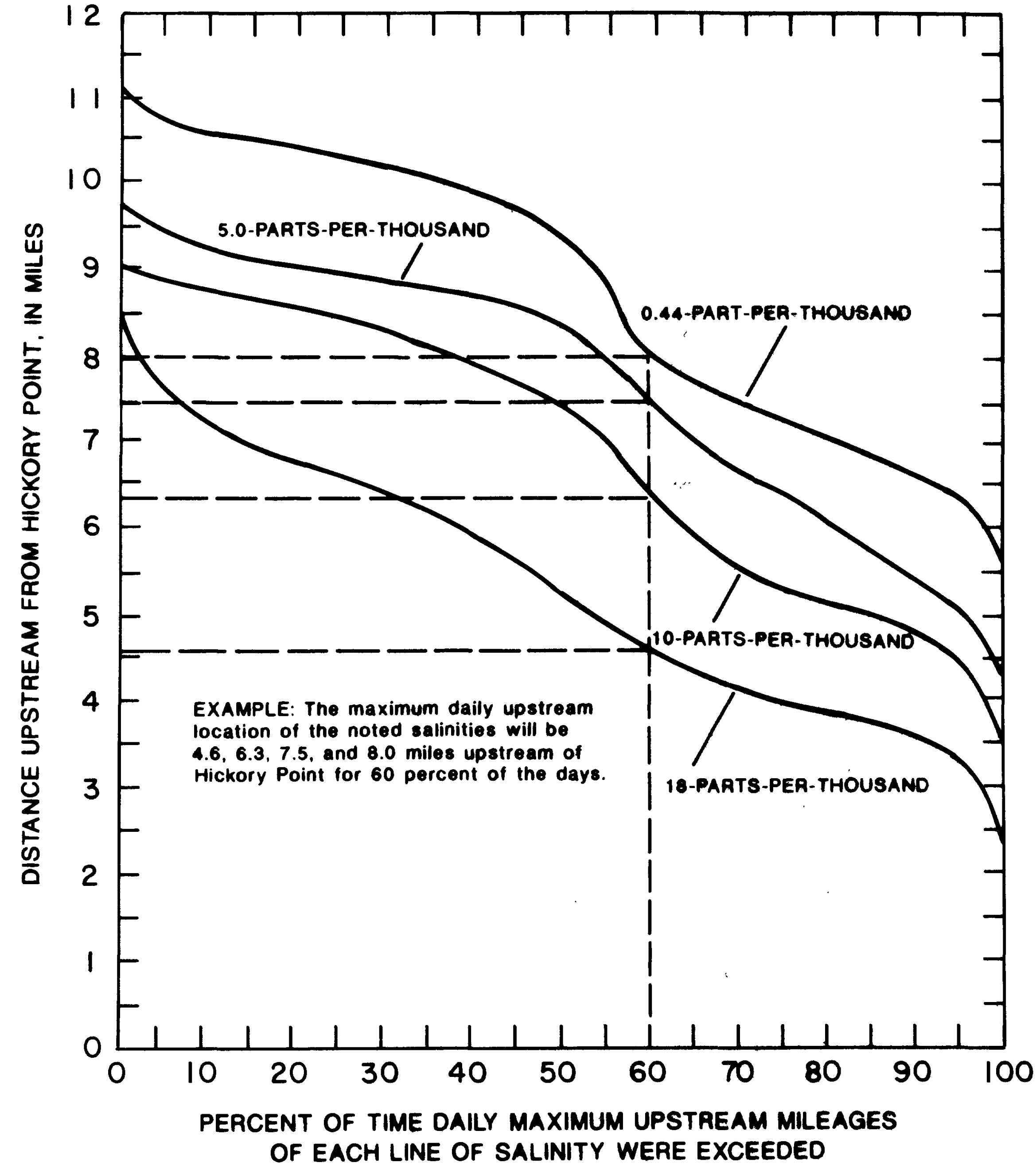

Figure 20.—Duration curves for 0.44-, 5.0-, 10-, and 18-parts-per-thousand salinities for maximum daily upstream mileages, January 1984 through May 1986.

An independent confirmation of one point on the historic duration analysis presented in figure 25 is possible on the basis of information published by the U.S. Fish and Wildlife Service's National Wetlands Inventory (1988). The inventory, among other things, locates an estuarine-riverine demarcation line where the saline tolerant estuarine vegetative habitat ends and the nonsaline, or freshwater, vegetative system begins. This line is based on interpretation of infrared aerial photographs with ground truthing of submergent and emergent vegetation. In the Anclote River, this line is about 7.0 miles upstream of Hickory Point. Application of equation 1, table 6 (for 0.44-ppt salinity), using a long-term average streamflow of 70.1 ft^3/s and an average high-high tide of 1.97 feet above sea level, gives an estimated location of 6.9 miles upstream from

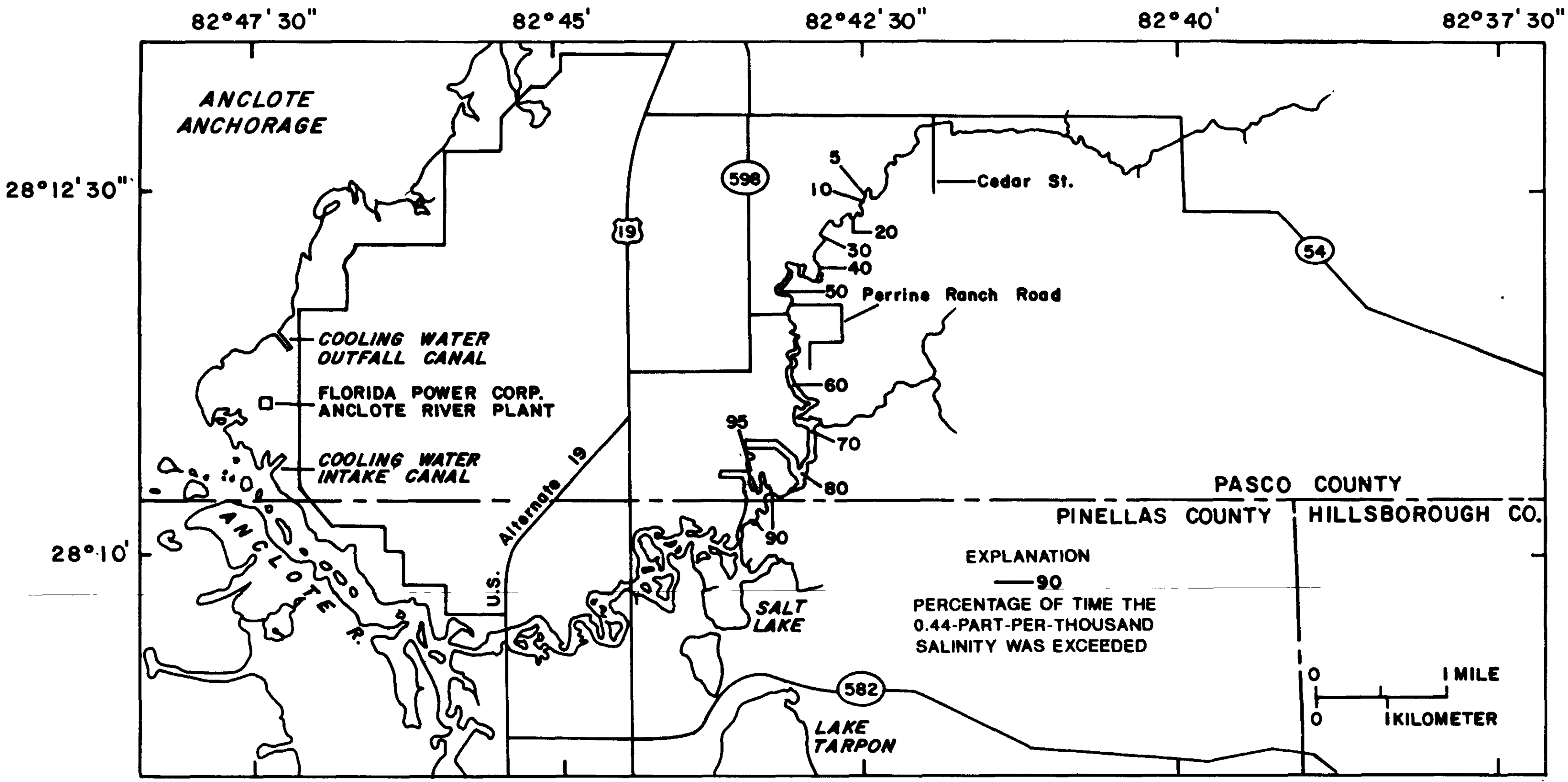

Figure 21.—Maximum daily upstream mileage where the 0.44-part-per-thousand salinity was exceeded for the indicated percentage of time, January 1984 through May 1986.

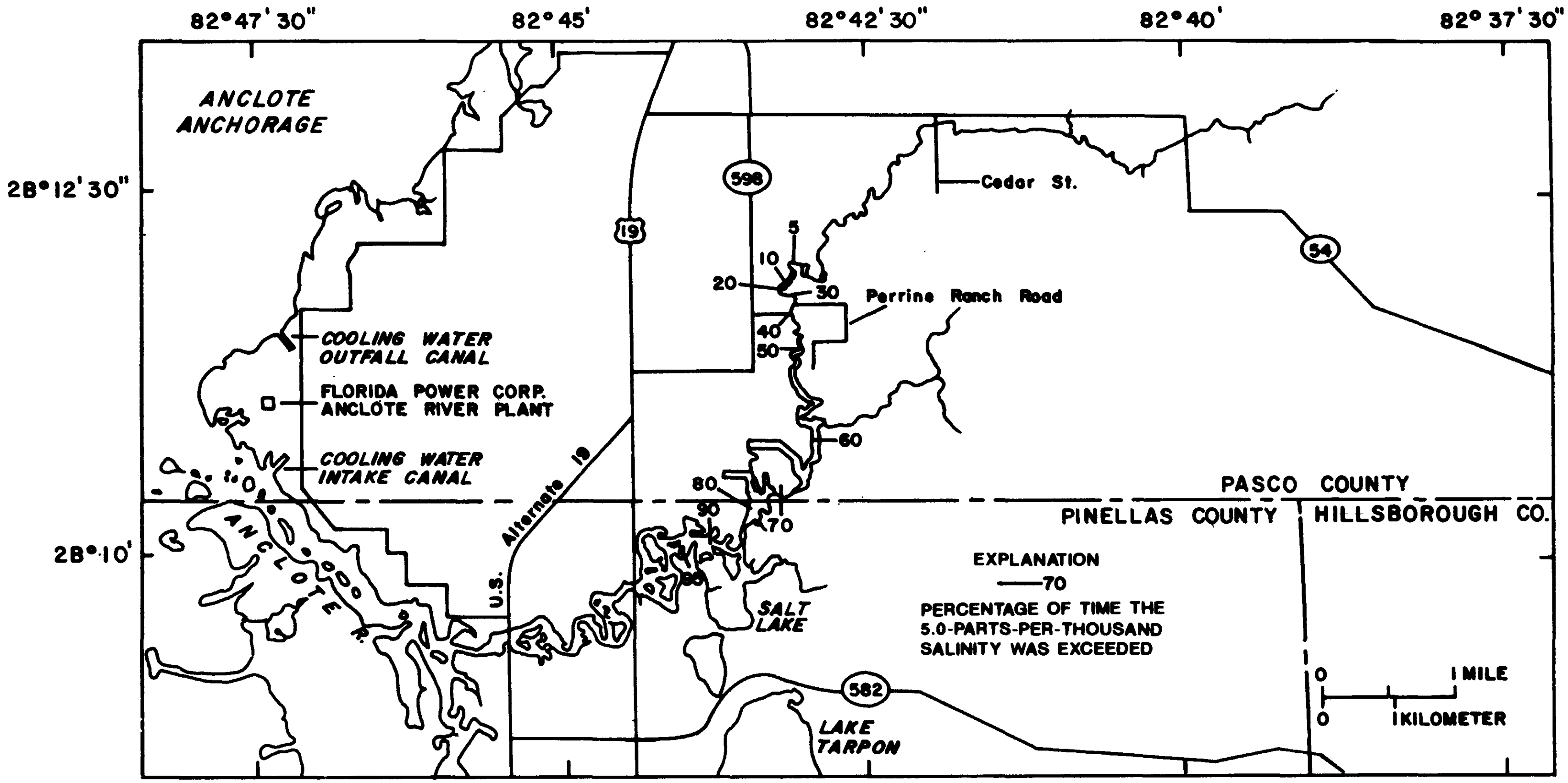

Figure 22.—Maximum daily upstream mileage where the 5.0-parts-per-thousand salinity was exceeded for the indicated percentage of time, January 1984 through May 1986.

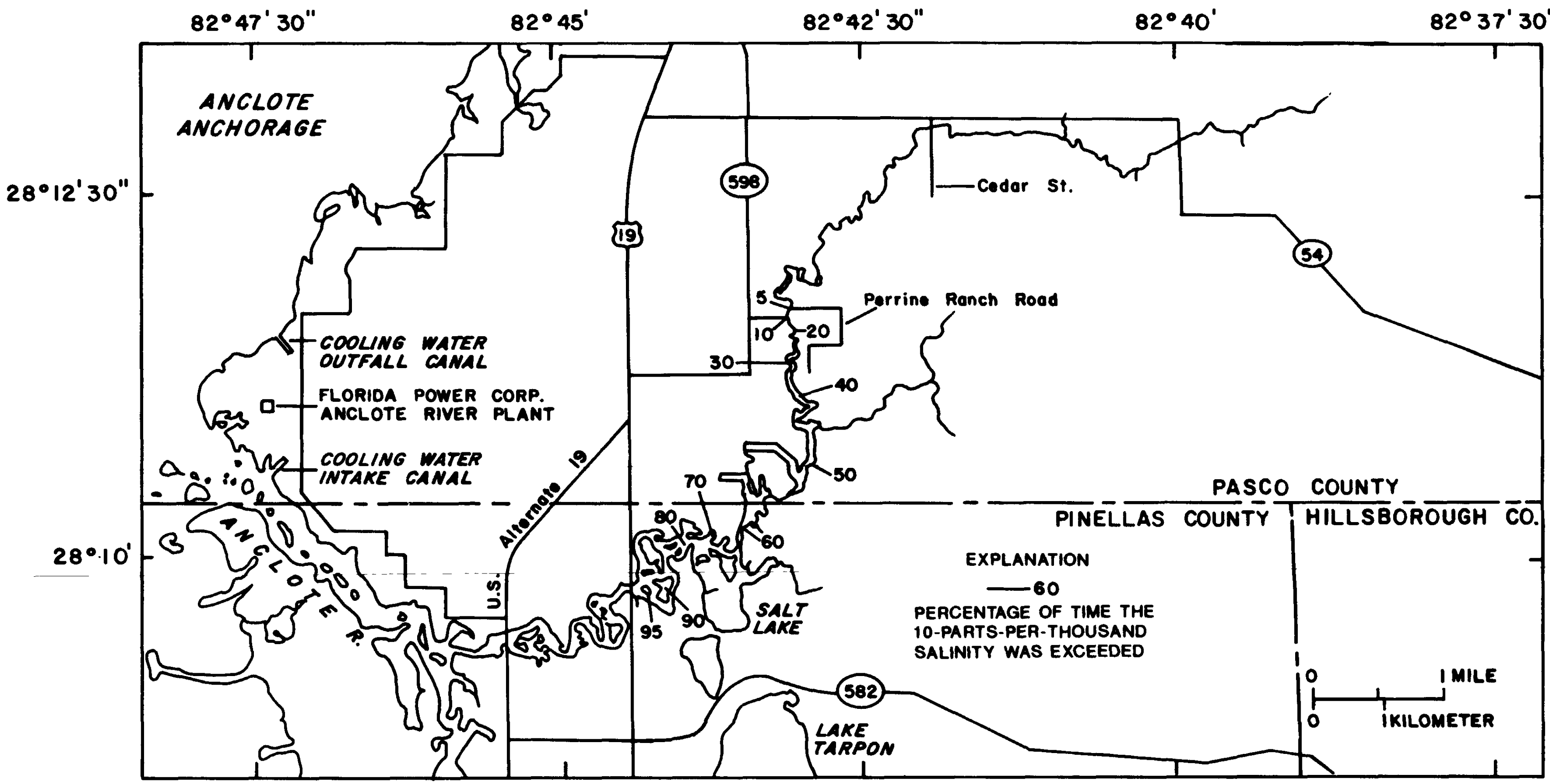

Figure 23.—Maximum daily upstream mileage where the 10-parts-per-thousand salinity was exceeded for the indicated percentage of time, January 1984 through May 1986.

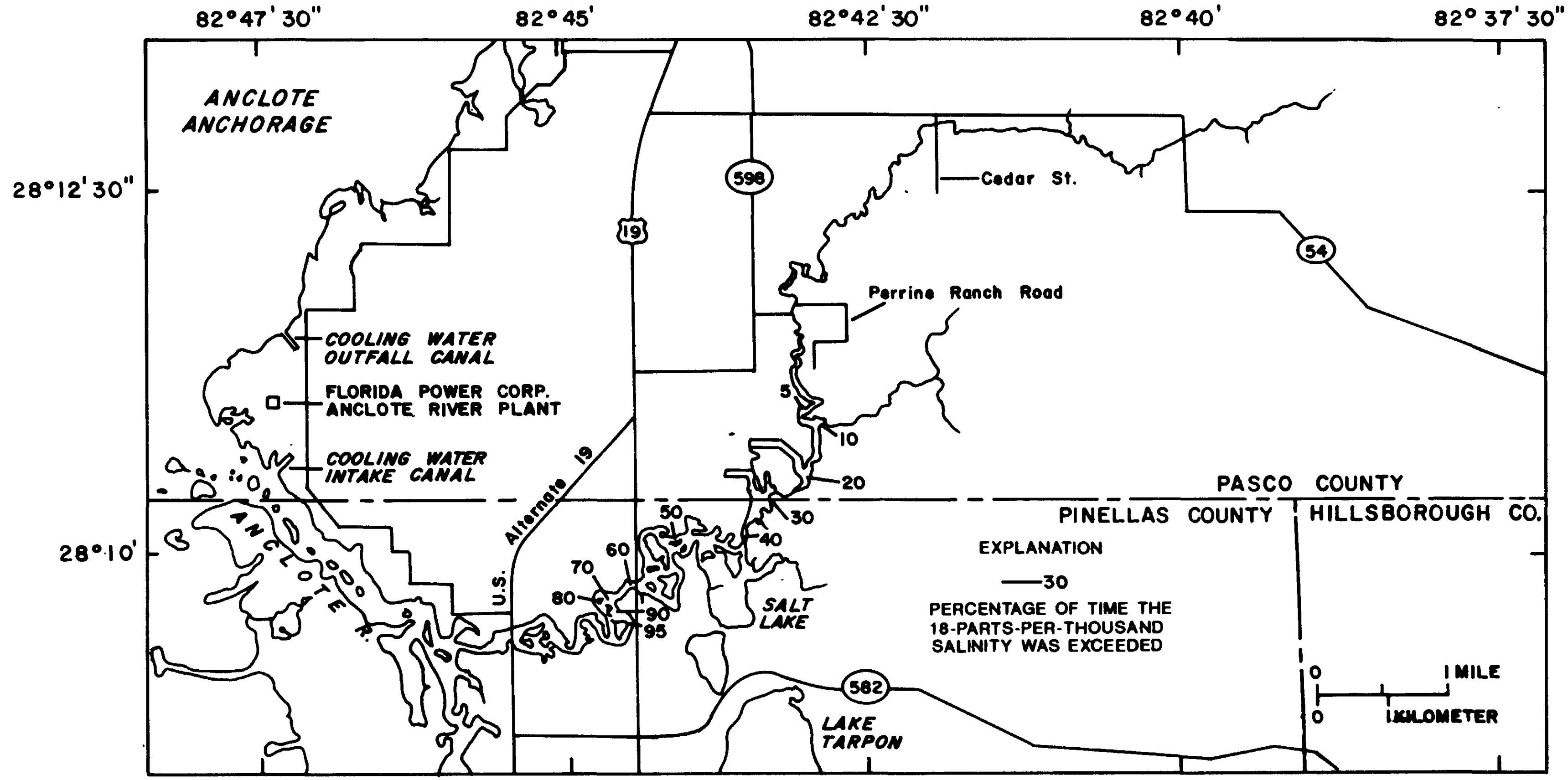

Figure 24.—Maximum daily upstream mileage where the 18-parts-per-thousand salinity was exceeded for the indicated percentage of time, January 1984 through May 1986.

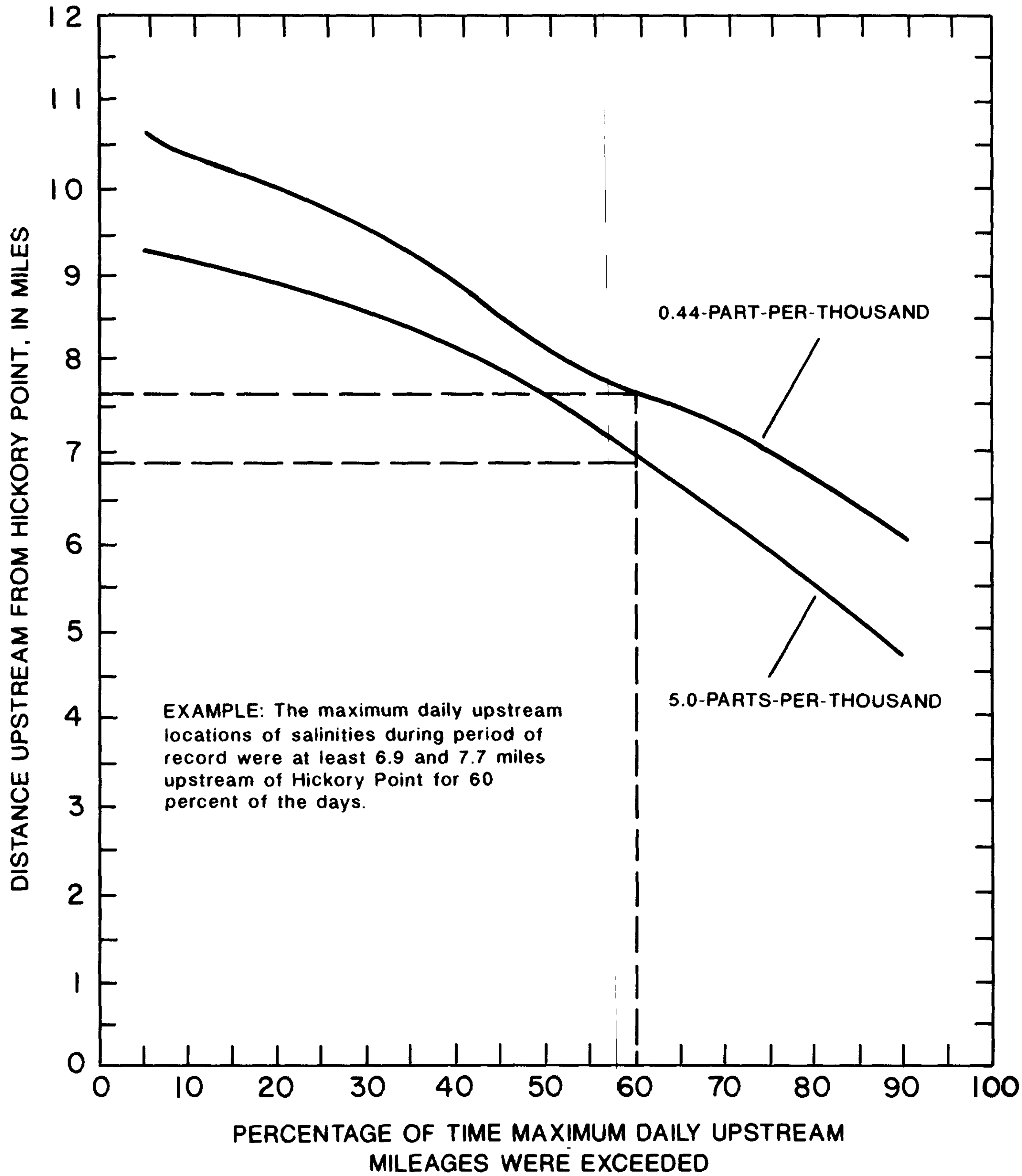

Figure 25.—Duration curves for 0.44-and 5.0-parts-per-thousand salinities for maximum daily upstream mileages, 1947 through 1985.

Hickory Point, which is very close to the observed location and well within the error of the equation. Any permanent reduction of streamflow that may cause a shift of the long-term average location of the 0.44-ppt salinity line farther upstream probably will alter the vegetative profile of the river.

SUMMARY AND CONCLUSIONS

This report presents analysis and interpretation of data relating the causes and variability of salinity distribution along the tidal reach of the Anclote River, specifically, (1) it describes the salinity distribution in the estuary as a function of freshwater inflow and tides, (2) determines the location of the freshwater-saltwater interface (0.44-part-per-thousand salinity) and other lines of equal salinity for a range of freshwater inflow and tidal conditions, and (3) determines the relation of Anclote River streamflow to precipitation, evaporation, and well-field pumpage.

The Anclote River has a drainage basin of about 112 mi^2 and a tidally affected reach that extends upstream about 13 miles from its mouth near Hickory Point. The stream width is highly variable in its lower reaches, ranging between 250 and 3,000 feet. Between river mile 2.3 and 5.5, the river is braided and winds through vast areas of saltmarshes. This braided section apparently functions to dampen the tide as it progresses upstream and also modifies the relation between streamflow and the longitudinal salinity gradient from that observed in reaches with a more well-defined channel.

The data-collection network consisted of 3 recording tidal stage and salinity monitoring sites at Hickory Point, U.S. Alternate Highway 19, and Perrine Ranch Road and 28 temporary sites at which vertical salinity profiles were measured during 32 field surveys from January 1984 to May 1986. Streamflow was measured at a continuous-record gaging station near Elfers at State Road 54. Precipitation data for the lower and upper river subbasins were obtained by the National Oceanic and Atmospheric Administration at the Tarpon Springs and St. Leo stations, respectively.

Trend analysis was performed to determine if there was a trend in annual rainfall and streamflow during the period before well-field pumpage began (1947–62) and after pumpage was started (1963–85). Multiple regression analysis was used to establish relations among the locations of select lines of equal salinity in the river and high tide and streamflow.

Results of the Cox-Stuart test inferred there was no trend in annual rainfall at either Tarpon Springs or St. Leo during the period 1947 to 1985, at a significance level of 0.05, that might obscure a possible relation between streamflow and well-field pumping, which began in 1963. Results of trend analysis on mean annual streamflows for the period of record indicate that, before pumping began, there was no increasing or decreasing streamflow trend at the 0.05-significance level. For the period after pumpage began, findings also indicate no decreasing or increasing trend in streamflow with time at a significance level of 0.05.

On an annual basis, streamflow near Elfers for the period of record averages about 70.1 ft^3/s, with maximum and minimum mean annual flows of 226 ft^3/s (1959) and 9.2 ft^3/s (1981), respectively. Daily mean streamflow for the period from January 1984 through May 1986 averaged 50.8 ft^3/s and ranged from 2.0 ft^3/s in May 1986 to 1,240 ft^3/s on September 3, 1985. A graphical comparison of the monthly mean streamflow measured during the period of study with the maximum, average, and minimum mean monthly streamflow for the period of record indicates that the monthly mean streamflows measured from January through March 1985 are the lowest of record at this site. In fact, there are few months during the study period when flow was greater than the long-term monthly mean. A duration analysis of streamflow indicates that the range of streamflows measured during the period of study occurred less frequently than would be expected on the basis of streamflow history of the station. In spite of the difference in streamflow characteristics, the measured streamflows during salinity observations in the estuary, ranging from 2.3 to 263 ft^3/s, are representative of long-term streamflow conditions that occur between 8 and 98 percent of the time.

Tides in the Anclote River Estuary are mixed and generally include daily low-low, high-low, low-high, and high-high events. The tides were observed at Hickory Point, 0.45 mile upstream from the cooling-water intake of the Florida Power Corporation powerplant. The mean tidal range for the period of study was 1.14 feet below to 1.97 feet above sea level. Low-high and high-high tides that were used in developing the regression equation ranged from 0.25 foot below to 2.76 feet above sea level.

Analysis of the relation between streamflow and precipitation, potential evaporation, and well-field pumpage was based on regression analysis using streamflow as the dependent variable. Results of the stepwise multiple-regression analysis using monthly data indicate that three independent variables were significant at the 0.05 level: rainfall at Tarpon Springs, rainfall lagged 1 month, and potential evaporation lagged 2 months. Individual well-field effects were not significant at the 0.05 significance level; therefore, it is concluded that a statistical relation between monthly streamflow and individual well-field pumpage could not be established.

Results of the stepwise multiple-regression analysis using annual data indicated that three independent variables were significant at the 0.05 significance level: total pumpage for all four well fields, annual rainfall in Tarpon Springs lagged 1 month, and annual rainfall at St. Leo lagged 2 months. Individual well-field effects were not included at the 0.05 significance level; therefore, it is concluded that a statistical relation between annual streamflow and individual well-field pumpage could not be established. A relation was established, however, between annual streamflow and the sum of well-field pumpages.

Vertical and longitudinal salinity distributions were measured at near high-tide conditions for streamflows of 2.3, 6.8, 23, 45, 158, and 204 ft^3/s in the Anclote River Estuary. Conditions were found to be well mixed to partially mixed, except for localized anomalies related to unusual bathymetry.

Six linear-regression equations were developed that relate the locations of the 0.44-, 5.0-, 10-, and 18-ppt salinities to streamflow and high tide. Two equations each were used to define the maximum upstream locations of the 0.44- and 10-ppt salinities; one equation each was used to define the locations of the 5.0- and 18-ppt salinities. For the six equations, the coefficient of determination ranged from 70.0 to 91.8 percent, and root mean square error ranged from ±0.24 to ±0.74 mile. A duration analysis of maximum upstream locations, based on the regression equations, indicates that the location of water having 0.44-ppt salinity is seaward of river mile 6.1 about 10 percent of the time and landward of river mile 10.4 about 10 percent of the time. The duration analysis also indicates that, about 60 percent of the time, the estimated maximum upstream locations of the 0.44- and 5.0-ppt salinities were at or upstream of river miles 7.7 and 6.9, respectively.

The long-term average location of water having 0.44-ppt salinity, as determined from this analysis, agrees well with the estuarine-riverine vegetative demarcation determined by the U.S. Fish and Wildlife Service's National Wetlands Inventory. By use of average streamflow and an average high tide, the regression equation gives a location of 6.9 miles upstream from Hickory Point, very close to the vegetative line at 7.0 miles. Any permanent reduction of streamflow that may cause a shift of the long-term average location of the 0.44-ppt salinity line farther upstream may alter the vegetative profile of the river.

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