SEDIMENT CONCENTRATIONS AND LOADS IN THE LOXAHATCHEE RIVER ESTUARY, FLORIDA, 1980-82

By Wayne H. Sonntag and Benjamin F. McPherson

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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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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)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
square mile (mi^2)	2.590	square kilometer (km^2)
cubic foot per second (ft^3/s)	0.0283	cubic meter per second (m^3/s)
ton (short) (ton)	0.907	metric ton (t)
ton (short) per day (ton/d)	0.907	metric ton per day (t/d)
acre-foot (acre-ft)	1,233	cubic meter (m^3)

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, called mean sea level, is referred to as sea level in this report.

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ABSTRACT

A study was conducted to estimate the magnitude and composition of sediment loads and the general spatial and temporal patterns of sediment transport in the Loxahatchee River estuary.

Mean concentrations of suspended sediment generally were higher in the Jupiter Inlet area than in the remainder of the embayment area, ranging from 14 to 60 milligrams per liter at maximum tidal flows. Organic material accounted for 13 to 45 percent of the suspended sediment on incoming and outgoing tides at sites in the inlet area. During slack tides, much of the sediment stayed in suspension, and concentrations at sites near Jupiter Inlet remained about 9 to 12 milligrams per liter. Mean concentrations in the estuary embayment area usually ranged from 8 to 20 milligrams per liter during outgoing tides and from 10 to 18 milligrams per liter during incoming tides. Organic material generally comprised 24 to 50 percent of the suspended sediment in the embayment area.

Concentrations of suspended sediment in the tributaries varied with season and weather conditions. Mean suspended-sediment concentrations during the study period ranged from 8 to 23 milligrams per liter, but concentrations in selected tributaries immediately following Tropical Storm Dennis in August 1981 increased as much as 16 times over concentrations before the storm. Organic material accounted for an average of 28 to 46 percent of the suspended sediment during the study period.

Suspended-sediment loads from the tributaries were highly seasonal and storm related. For example, during a 61-day period of above-average rainfall that included Tropical Storm Dennis, the 5 major tributaries (Loxahatchee River at State Road 706, Cypress Creek, Kitching Creek, Hobe Grove Ditch, and Canal 18 at control structure 46) discharged 926 tons (short; 2,000 pounds) of suspended sediment to the estuary, accounting for 74 percent of the input for the 1981 water year (October 1, 1980, through September 30, 1981) and 49 percent of the input for the 20-month study period. Loads of suspended sediment increased from 9 tons (short) during a 5-day prestorm period to 302 tons (short) during a 5-day, stormwater-runoff period. Runoff from the storm accounted for 24 percent of the suspended sediment transported by the tributaries during the 1981 water year.

Suspended-sediment loads at Jupiter Inlet and at the mouth of the estuary embayment on both incoming and outgoing tides far exceeded tributary loads, but the direction of long-term, net-tidal transport was not determined. Tidal loads on outgoing tides ranged from 124 to 1,060 tons (short) at the inlet and from 97.5 to 175 tons (short) at the mouth of the embayment. Tidal loads on incoming tides ranged from 113 to 724 tons (short) at the inlet and from 86.5 to 183 tons (short) at the mouth of the embayment. Total loads from the tributaries during an average 6-hour tidal cycle during the 1981 water year was about 0.83 ton (short).

INTRODUCTION

In recent years, the environmental condition of the Loxahatchee River and estuary has become a major concern to many citizens and agencies. Controversy has arisen about the environmental well-being of the river and estuary, as well as certain related management proposals and decisions (Cary Publications, Inc., 1978).

One major concern is the type and amount of suspended sediment transported to and from the estuary. Large amounts of sediment that settle in an estuary might smother bottom life or alter circulation patterns (Cronin, 1967). If the sediment is largely organic, oxygen supplies near the bottom might be depleted. Also, concentrations of harmful constituents, such as heavy metals and pesticides, can adsorb on the sediment particles (Mattraw, 1973) and concentration buildup might occur.

Purpose and Scope

The purpose of this study was to estimate the magnitude and composition of sediment loads and the general spatial and temporal patterns of sediment transport in the Loxahatchee River estuary (fig. 1). Information gathered during the study (October 1979 through March 1982) and presented in this report includes:

1. Suspended-sediment concentrations and loads from the major tributaries to the estuary during different seasonal and runoff conditions;

2. Magnitude and composition of instantaneous suspended-sediment loads and bedloads and total suspended-sediment loads associated with movement of water in and out of the estuary in the inlet area;

3. Areal and vertical distribution of suspended sediment in the inlet and embayment area.

The direction of long-term, net-tidal transport of sediment was not determined.

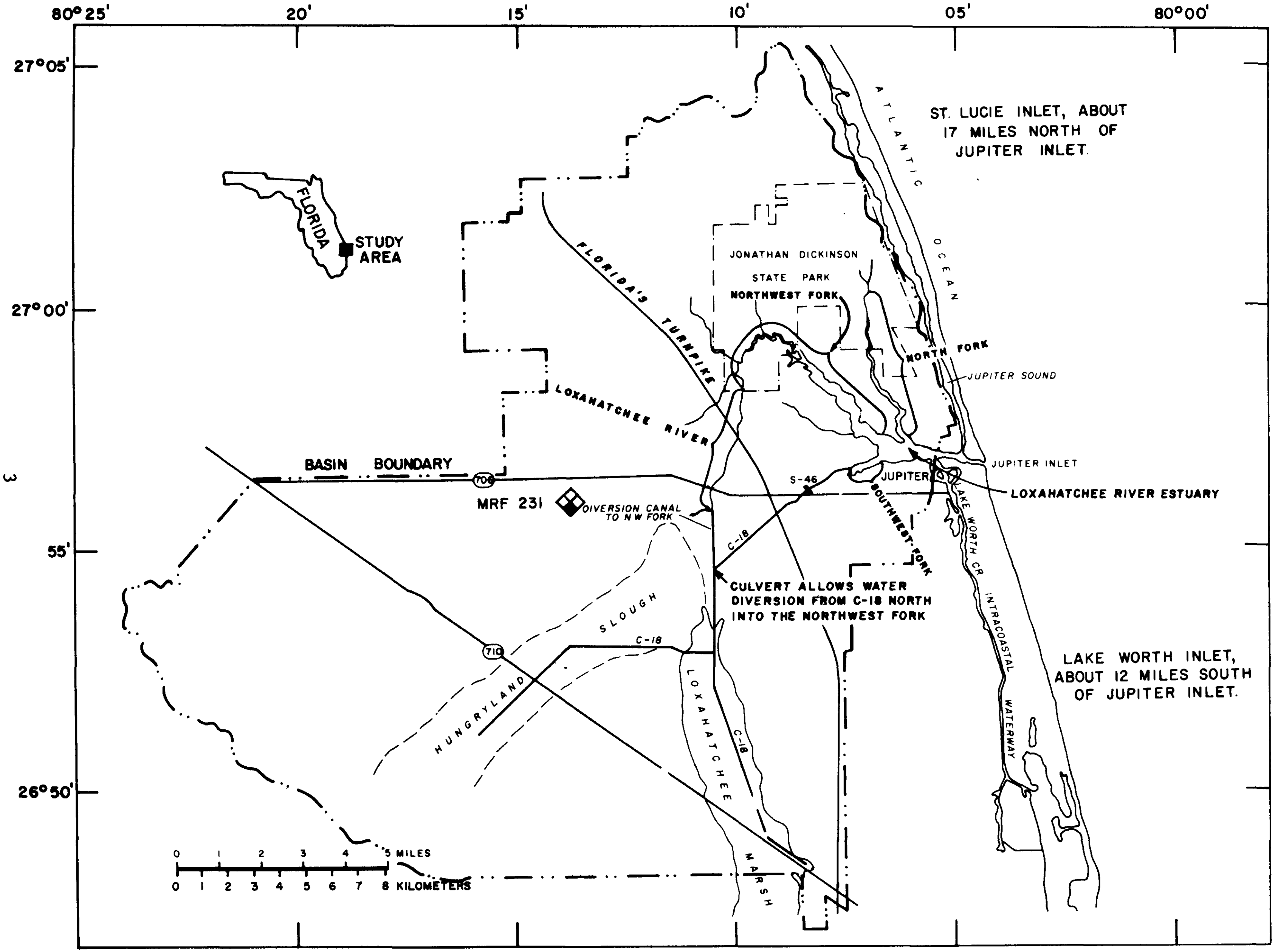


Figure 1.--Location of the Loxahatchee River drainage basin, southeastern Florida.

Description of Study Area

The Loxahatchee River estuary, consisting of approximately 210 mi^2 in southeast Florida, empties into the Atlantic Ocean near the town of Jupiter. The estuarine system is composed of three forks: the North Fork, the Southwest Fork, and the northwest fork (fig. 1) which is the longest and the main prong of the system. The forks converge into a wide embayment area approximately 2 miles upstream from the ocean. Between the confluence of the three forks and the Atlantic Ocean, the estuary is intersected by the Intracoastal Waterway. 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 (McPherson and Sabanskas, 1980). Four major tributaries (the Loxahatchee River, Cypress Creek, Kitching Creek, and Hobe Grove Ditch) discharge to the northwest fork of the estuary. One major tributary, Canal-18 (C-18), discharges to the Southwest Fork of the estuary (fig. 2).

The Loxahatchee River estuary is shallow with an average depth of about 4 feet. Sand 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. In the northwest fork, a natural river channel with a maximum depth of 20 feet extends upstream 9 miles. Beyond that, maximum depths are generally less than 10 feet.

Since the turn of the century, the Loxahatchee River basin has been altered by man to an extent that almost all the natural drainage patterns of the basin have been affected by some development. What was once marshland (Davis, 1943) has become a network of drainage canals and ditches, roads, highways, well-drained truck farms and citrus groves, and residential and recreational developments (Vines, 1970). The drainage network has permanently lowered ground-water levels and altered patterns of surface-water inflow to the estuary.

Prior to the 1900's, the Loxahatchee River received flow into its northwest fork from the Loxahatchee Marsh and the Hungryland Slough, both of which drained north from the low divides near State Road 710 (SR-710) (Parker and others, 1955). C-18 of the South Florida Water Management District was constructed in these natural drainage features and diverted their flow to the Southwest Fork of the estuary. Because this diversion to the Southwest Fork might be detrimental to the freshwater vegetation in the northwest fork, a culvert was placed in C-18 in the early 1970's so that as much as 50 ft^3/s could be redirected to the northwest fork (fig. 1).

Alterations along the coast have also affected the Loxahatchee River estuary. Jupiter Inlet, the natural mouth of the estuary, has opened and closed many times. Originally, the inlet was maintained open not only by flow from the Loxahatchee River but from Lake Worth Creek and Jupiter Sound (fig. 2). Near the turn of the century, some of this flow was diverted from Jupiter Inlet to other inlets 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 between 1900 and 1947, except when it was periodically dredged. After 1947, the inlet was maintained open by regular dredging (U.S. Army Corps of Engineers, 1966).

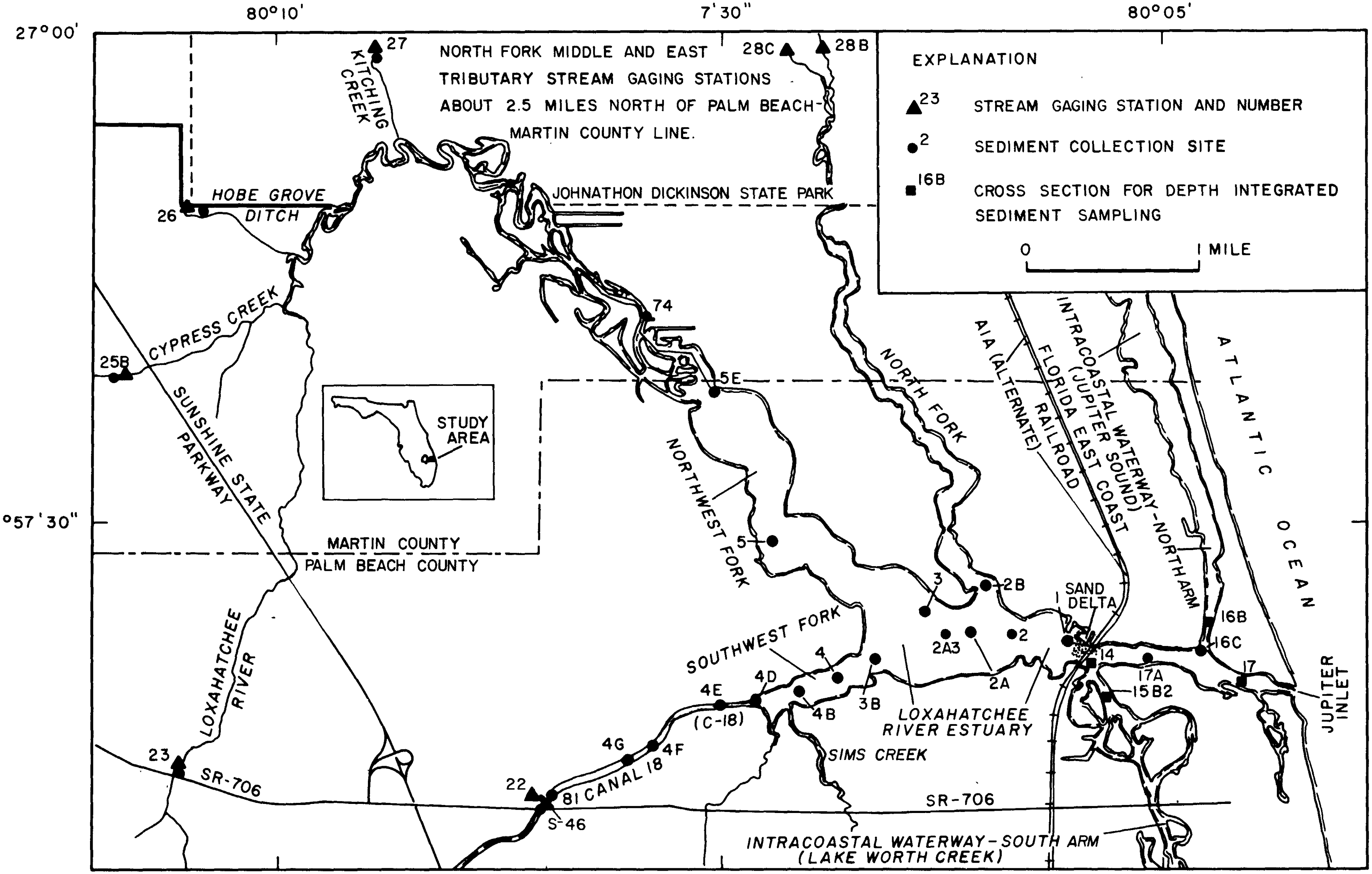


Figure 2.--Location of stream-gaging stations and sampling sites for suspended sediment, Loxahatchee River, Jupiter, Florida.

SAMPLING SITES AND METHODS

Tributary Sites

Freshwater inflow to the estuary was measured at seven stream-gaging stations (sites 22, 23, 25B, 26, 27, 28B, 28C) 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 records and the rating tables. The South Florida Water Management District provided discharge data for C-18 at control structure 46 (S-46).

Suspended-sediment sampling sites were selected in the major tributaries; 5 sites near the gaging stations and 19 sites downstream in the estuary (fig. 2). The sampling frequency of suspended sediment was based primarily on hydrologic conditions with more frequent sampling done during extreme conditions, such as floods or droughts. Frequency of sampling was also based on the size and importance of the tributary. For example, C-18 and several of the northwest fork tributaries were sampled more often than the smaller tributaries.

Generally, all suspended-sediment samples from the tributaries were depth integrated whereas those in the estuary were point samples (collected at a specific depth), or depth integrated, depending upon the purpose of the sampling. Only depth-integrated samples were used to compute sediment loads associated with freshwater inflow from the tributaries. Point samples were used to evaluate sediment distribution in the water column.

Depth-integrated, suspended-sediment samples were collected using a "DH-48" depth-integrating sampler with a 1/4-inch nozzle. Early in the investigation, depth-integrated, suspended-sediment samples were collected at several points across the width of the stream or canal to determine cross-sectional variability. An analysis of these samples showed that the sediment concentrations were not significantly different across the channel. Therefore, during the remainder of the investigation, depth-integrated samples were collected only at a single vertical in the center of the channel.

Calculation of suspended-sediment loads was performed by using a flow-duration, sediment rating curve method of computing suspended-sediment discharge (Miller, 1951). A curve commonly referred to as an instantaneous sediment-transport rating curve was developed for each site by plotting instantaneous suspended-sediment discharge versus instantaneous water discharge. One composite sediment-transport rating curve was developed for each site and used with various periods of streamflow record. Water discharges within the various periods were taken from flow-duration tables. The corresponding instantaneous sediment-discharge rate was obtained from the sediment-transport curve. Average sediment discharge for each time interval was computed and multiplied by the length of each respective time interval (expressed as a percentage of total time), giving products which were summed to give average sediment discharge rate in tons (short) per day for each of the various periods of months analyzed. Based on the average sediment discharge rate in tons per day, amounts of total suspended sediment were determined for the various periods of months analyzed.

To estimate what percentage of the suspended sediment was composed of organic material, ash-free weight was determined on selected samples of suspended sediment. Samples were fired at 550°C to determine what percentage of the total suspended-sediment concentration was lost on ignition, thereby estimating the percentage of volatile or organic material in the samples. Ash-free weight may include nonorganic material if clay minerals occur in the sample (Mook and Hoskin, 1982). However, because these minerals constitute a small percentage of the sediment in the Loxahatchee River estuary (Wanless and others, 1984), the ash-free weight represents primarily organic material.

Inlet and Longitudinal Sites

Figure 2 shows the location of the inlet sites near Jupiter Inlet (sites 14, 15B2, 16B, and 17). Discharge and sediment concentrations were measured at these four inlet sites over selected tidal cycles during typical spring and neap tides and during extreme tidal conditions. Water velocity and direction of flow were measured at 10 to 15 sampling verticals across the channel at 0.2, 0.6, and 0.8 of the total depth using a Marsh-McBurney1/ velocity meter. These measurements were made 15 to 20 times during each tidal cycle. At the same time, depth-integrated samples of suspended sediment were taken at each sampling vertical across the channel using a "DH-48" suspended-sediment sampler. Stage data and channel bathymetry were used to determine the area of each sampling cross section for each particular tidal stage. Using the velocity data and area of the sampling cross section, 15 to 20 values of instantaneous discharge during the selected tidal cycles were computed for each site. From these values of instantaneous discharge, curves showing discharge for the selected tidal cycles were developed for each site. A suspended-sediment concentration curve was also developed for the selected tidal cycles for each site. Using the mean interval method of computing sediment discharge (Porterfield, 1972), suspended-sediment discharge during the selected tidal cycles was computed for each site.

Instantaneous bedload sediment-transport rates were also determined at selected sites using a Helly-Smith bedload sampler. Samples were obtained during selected tidal cycles at each sampling vertical across the channel about the same time as suspended-sediment sampling was conducted. Particle-size distribution was also determined on the bedload samples. Using measurements of the wetted perimeter of the channel cross section in conjunction with bedload data (in terms of mass per unit time per unit width), instantaneous bedload-transport rates (a width weighted average for the cross section) were determined.

Suspended-sediment concentrations and water velocity were also measured along longitudinal transects which extended from the inlet area through the embayment area and up the Southwest Fork and the northwest fork of the estuary. The northwest fork transect consisted of inlet sites 14, 17, and 17A, and longitudinal sites 1, 2, 2A3, 3, 5, and 5E (fig. 2). The Southwest Fork transect consisted of longitudinal sites 2A, 3B, 4, 4B, 4D, 4E, 4F, 4G, and 81 (fig. 2).

1/ Use of brand names in this report is for identification purposes only and does not constitute endorsement by the U.S. Geological Survey.

Measurements of suspended-sediment concentrations and water velocity were made at specific depths to determine the aerial distribution of suspended sediment in the estuary and the vertical distribution of suspended sediment in the water column. Suspended sediment was sampled using a pump with a 1/4-inch diameter nozzle. A comparison was made of the data collected using the pump and data collected at the same time and depth using a modification of the "DH-48" suspended-sediment sampler procedure to collect a point sample. Differences in the concentration of suspended sediment using the two sampling methods were insignificant, and all subsequent samplings were conducted using the pump.

RUNOFF AND TIDAL MOVEMENT OF WATER

Freshwater Flow

Freshwater runoff enters the Loxahatchee River estuary by river and canal discharge, by storm drains, and by overland and subsurface inflow. Four major tributaries (Loxahatchee River at SR-706, site 23; Cypress Creek, site 25B; Kitching Creek, site 27; and Hobe Grove Ditch, site 26) discharge to the northwest fork (see fig. 2). Freshwater flow upstream of U.S. Geological Survey gaging stations in Cypress Creek, Hobe Grove Ditch, and Kitching Creek is controlled by agricultural interests in the area. Another major tributary, C-18, drains into the Southwest Fork at S-46 about 4.7 miles upstream from Jupiter Inlet. Discharges from C-18 usually begin or end abruptly whereas discharges from the other tributaries increase or decrease gradually.

Most of the freshwater from the tributaries is discharged to the northwest fork of the estuary. From February 1, 1980, to September 30, 1981, for example, 77.3 percent of the freshwater was discharged into the northwest fork, 20.5 percent into the Southwest Fork, and 2.2 percent into the North Fork. The Loxahatchee River at SR-706, site 23 (fig. 2), contributed the greatest percentage of flow to the estuary (37.9 percent) of all the tributaries (table 1).

Freshwater runoff from the tributaries generally varies seasonally (fig. 3), occurring chiefly during the wet season (May to October). During this study, the greatest runoff occurred following Tropical Storm Dennis, which passed over the study area on August 18, 1981. Rainfall in the vicinity of the Loxahatchee River estuary at the South Florida Water Management District monthly rainfall station MRF-231 was 4.68 inches (Russell and McPherson, 1983, p. 14) on that date, and above-average runoff continued several days after the storm. Average discharge from all tributaries of the estuary (discharge for Loxahatchee River measured at Florida's Turnpike) increased from 81 ft^3/s during the 5 days preceding the storm to 1,141 ft^3/s during the 5 succeeding days of storm runoff (McPherson and Sonntag, 1983, p. 27).

During the 61-day period August 1 through September 30, 1981, which included Tropical Storm Dennis, the greatest percentage of discharge to the estuary was from C-18 at S-46 (39.6 percent) and Cypress Creek which contributed 27.8 percent (table 1). Occasionally, smaller tributaries discharge relatively large volumes of freshwater to the estuary. For example, Sims Creek on the Southwest Fork (see fig. 2) had a substantial instantaneous discharge (estimated at 106 ft^3/s) on August 18, 1981, during Tropical Storm Dennis. Although freshwater inflows from small tributaries and storm drains could be substantial, they were generally of short duration.

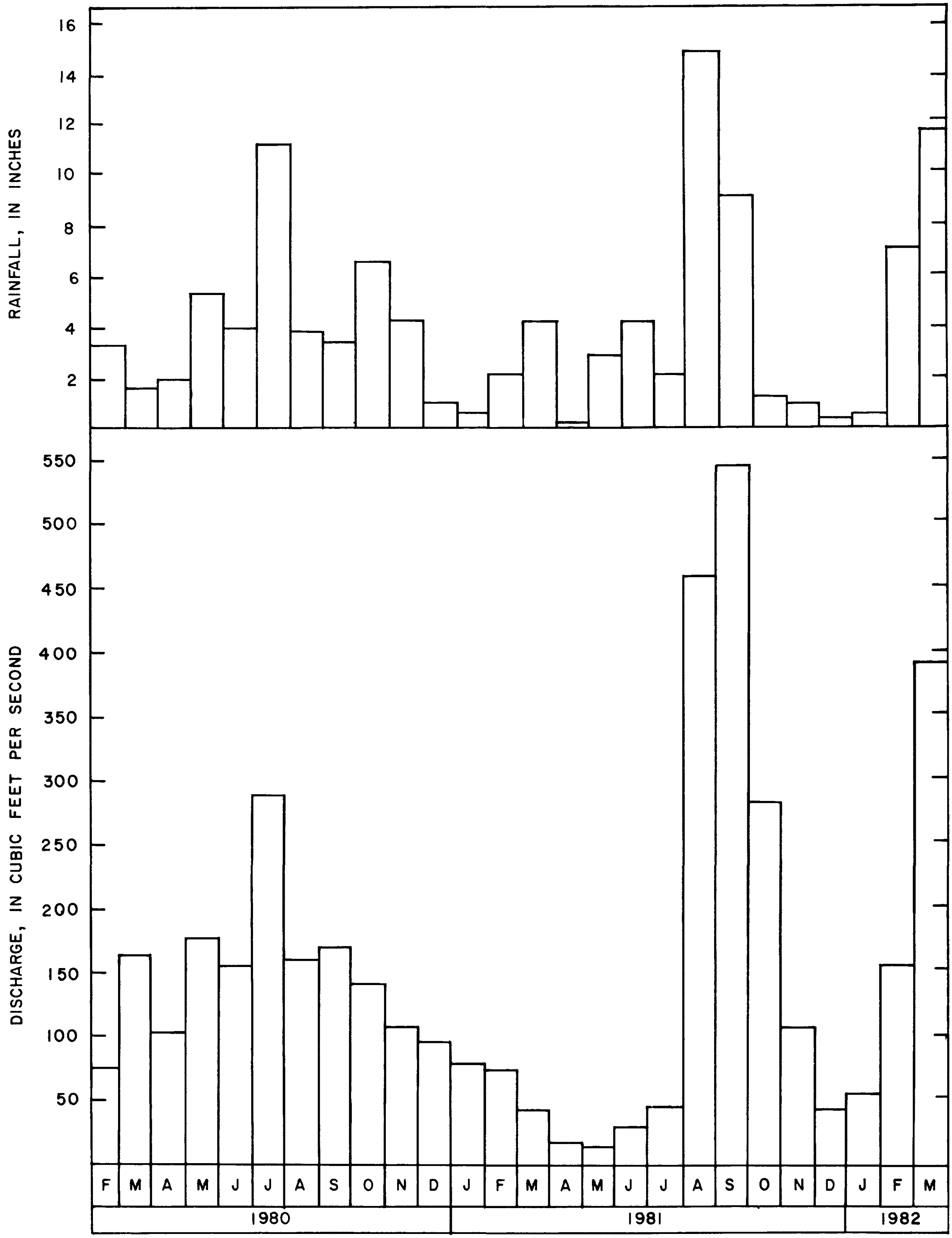


Figure 3.--Monthly average discharge from all tributaries to the Loxahatchee River estuary and monthly total rainfall at rainfall station MRF-231.

Table 1.--Percentage of discharge from selected tributaries to the Loxahatchee River estuary

[Values are in percent]

Site No.	Tributary	20-month period, 2/80-9/81	Water year 1981, 10/80-9/81	1980 wet season, 5/80-10/80	61-day wet period, 8/81-9/81	Extended[1] dry period, 11/80-7/81
22	C-18 at S-46[2]	20.5	24.6	19.4	39.6	0.0
23	Loxahatchee River at SR-706	37.9	33.6	39.2	22.5	51.0
25B	Cypress Creek	29.4	30.1	27.2	27.8	36.4
26	Hobe Grove Ditch	6.2	5.2	6.9	3.8	8.1
27	Kitching Creek	3.8	3.8	4.8	3.5	3.1
28B	East tributary north fork	1.0	1.1	1.1	1.2	.6
28C	Middle tributary north fork	1.2	1.6	1.4	1.6	.7

1/ Total percentage of discharge from selected tributaries during the extended dry period rounded to nearest tenth of a percent.

2/ C-18 discharged for 103 days from February 1, 1980, to September 30, 1981; 61 days during the 1980 wet season; and 42 days during the 61-day wet period.

During an extended dry period, November 1980 through July 1981, low rainfall and runoff conditions prevailed throughout the Loxahatchee River basin. Several tributaries had no flow at the gaging stations from March through July. During the dry period, the Loxahatchee River at SR-706 contributed the greatest percentage of discharge to the estuary (51.0 percent), with Cypress Creek contributing 36.4 percent and Hobe Grove Ditch and Kitching Creek together contributing 11.2 percent (table 1). C-18 was kept closed at S-46 and did not discharge at any time during the dry period.

Tidal Flow

Tidal flow into and out of the estuary is much larger than freshwater inflow from the major tributaries. On August 27, 1980, during the 1980 wet season, the tidal discharge at Jupiter Inlet (site 17) for the incoming and outgoing tides was about 6,700 and 6,200 acre-ft, respectively (McPherson and others, 1982). During the same tidal cycle, the combined freshwater discharge from the major tributaries was 94 acre-ft, or about 1.5 percent of the outgoing tidal flow. During most of the study period, freshwater inflow per tide cycle accounted for 2 percent or less of the average tidal inflow as measured at Jupiter Inlet (site 17). During Tropical Storm Dennis, freshwater inflow per tidal cycle increased to 18 percent of average tidal inflow (McPherson and Sonntag, 1983, p. 30).

Tides in the Loxahatchee River estuary are mixed semidiurnal (twice daily with varying amplitude) and have a range of about 2 to 3 feet at Alternate A1A bridge (site 14). The tidal wave advances up the estuary at a rate of about 5 to 10 mi/h and shows little change in amplitude over 10 river miles (McPherson and Sonntag, 1983, p. 29). Winds may have a significant effect on the range of tides in the estuary. Strong northeast winds which prevail during autumn and winter, for example, push additional water into the estuary causing higher than average tides.

DISTRIBUTION, CONCENTRATION, AND COMPOSITION OF SUSPENDED SEDIMENT

The distribution and transport of suspended sediment in an estuary are affected by particle size, availability of sediment, salinity, and water velocity. The types of sediment that are found in the Loxahatchee River estuary include: (1) fine-grained suspended material brought into the estuary from the ocean through Jupiter Inlet; (2) biological material produced in the estuary; (3) fine-grained suspended material, including sand and detritus, carried down the river or other tributaries; (4) fine, medium, and coarse sand suspended during turbulent storms; and (5) medium to coarse sand transported as bedload (Wanless and others, 1984). In the main body of the estuary, most of the bed sediment (to a depth of about 30 cm below the sediment surface) is dominated by bioturbated mud or mottled, muddy sand. The biological reworking of the near-surface sediment is interpreted as a result of increased marine influences, possibly associated with "permanently" opening and maintaining Jupiter Inlet since the late 1940's and with altered freshwater flow (Wanless and others, 1984).

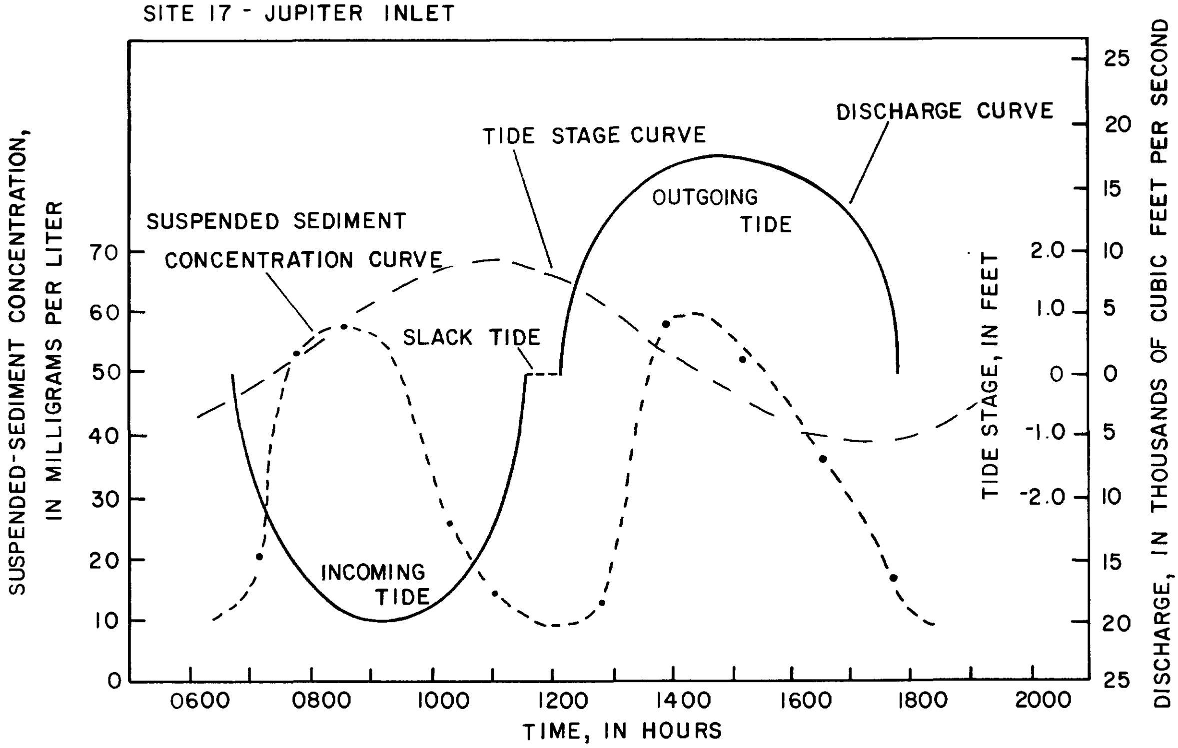
In the Loxahatchee River estuary, as in most estuaries, concentrations of suspended sediment (at the inlet and longitudinal sites) were highly variable with time and distance. Generally, mean concentrations were highest in the inlet area sites (14, 15B2, 16B, 16C, and 17), ranging from 14 to 60 mg/L (milligrams per liter) with maximum concentrations frequently exceeding 60 mg/L (table 2). During an outgoing tide on April 6, 1981, when north winds caused turbulence and resuspension of sediment at site 16B, suspended-sediment concentrations as high as 351 mg/L were measured (table 2). During slack tides, much of the sediment stayed in suspension with concentrations at sites 14 and 17 ranging from 9 to 12 mg/L (fig. 4).

Concentrations were generally highest at the inlet (site 17) during peak tidal velocity (2.2 to 4.0 ft/s) on outgoing tides. This may partly reflect input of suspended sediment from the north arm of the Intracoastal Waterway on outgoing tides. At site 14, concentrations of suspended sediment on both incoming and outgoing tides (fig. 4) generally were lower than at the inlet (site 17) corresponding with lower and less-variable tidal velocities. Organic material accounted for 13 to 22 percent of the suspended sediment on incoming and outgoing tides at site 17 and accounted for 18 to 28 percent at site 14 (table 3).

At site 15B2, the south arm of the Intracoastal Waterway, mean suspended-sediment concentrations were generally lower than at sites 14 or 17 (table 2). Organic materials at site 15B2 accounted for as much as 45 percent of suspended sediment. The high percentage of organic material in the south arm may be due to poor flushing of water in this arm. Most of the incoming tidal water from Jupiter Inlet enters the embayment or the north arm of the Intracoastal Waterway. With poor flushing in the south arm, particulate organic material may remain rather than be flushed from the estuary.

Mean concentrations of suspended sediment were lower in the embayment area (sites 1-5E) than at the inlet area (sites 14, 15B2, 16B, 16C, and 17) and usually ranged from 8 to 20 mg/L during outgoing tides and from 10 to 18 mg/L during incoming tides (table 2). Organic material in the embayment generally comprised 24 to 50 percent of the suspended sediment (table 3). Slightly higher concentrations of suspended sediment occasionally occur at constrictions in the estuary, such as at site 14 (fig. 5).

The longitudinal and vertical distribution of suspended sediment on selected incoming and outgoing tides during wet and dry seasons is shown in figure 5. These graphs show suspended-sediment concentrations during peak tidal flows and generally represent maximum concentrations for each tidal cycle. The greatest vertical variations of suspended-sediment concentration occurred at sites 17 and 17A and generally were larger on measured outgoing tides than on incoming tides. Maximum concentrations at site 17 (54 mg/L on 4/18/80 and 76 mg/L on 9/24/80) occurred near the bottom of the channel during outoing tides (fig. 5). At site 17A, the maximum concentration of suspended sediment occurred at middepth during an outgoing tide on April 18, 1980 (fig. 5). On two incoming tides at site 17, maximum suspended sediment concentrations (33 mg/L on 4/18/80 and 34 mg/L on 9/24/80) occurred at the surface and near the bottom of the channel, respectively (fig. 5).



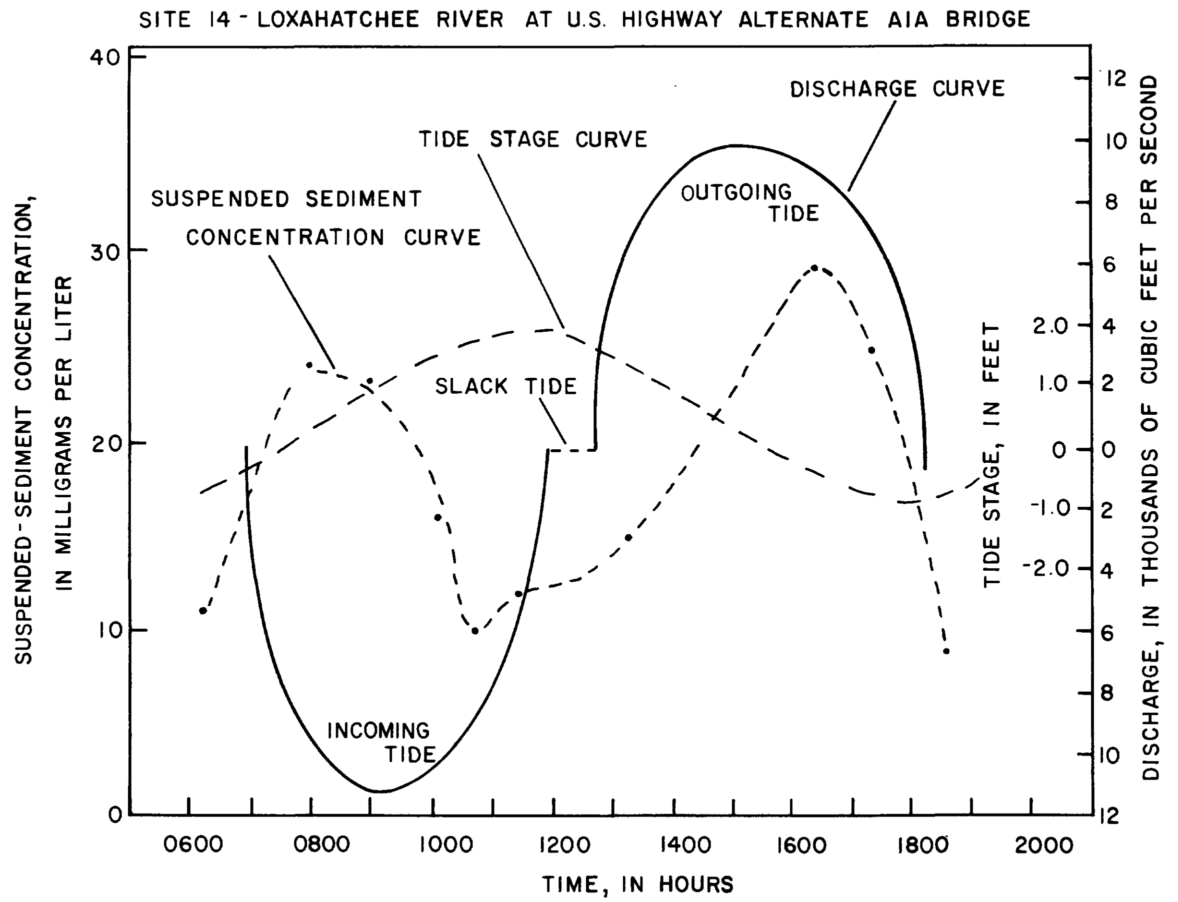


Figure 4.--Discharge, suspended-sediment concentrations, and tide stage curves, Loxahatchee River at Jupiter Inlet (site 17) and at the U.S. Highway AlA bridge (site 14), Jupiter, Florida, August 28, 1980.

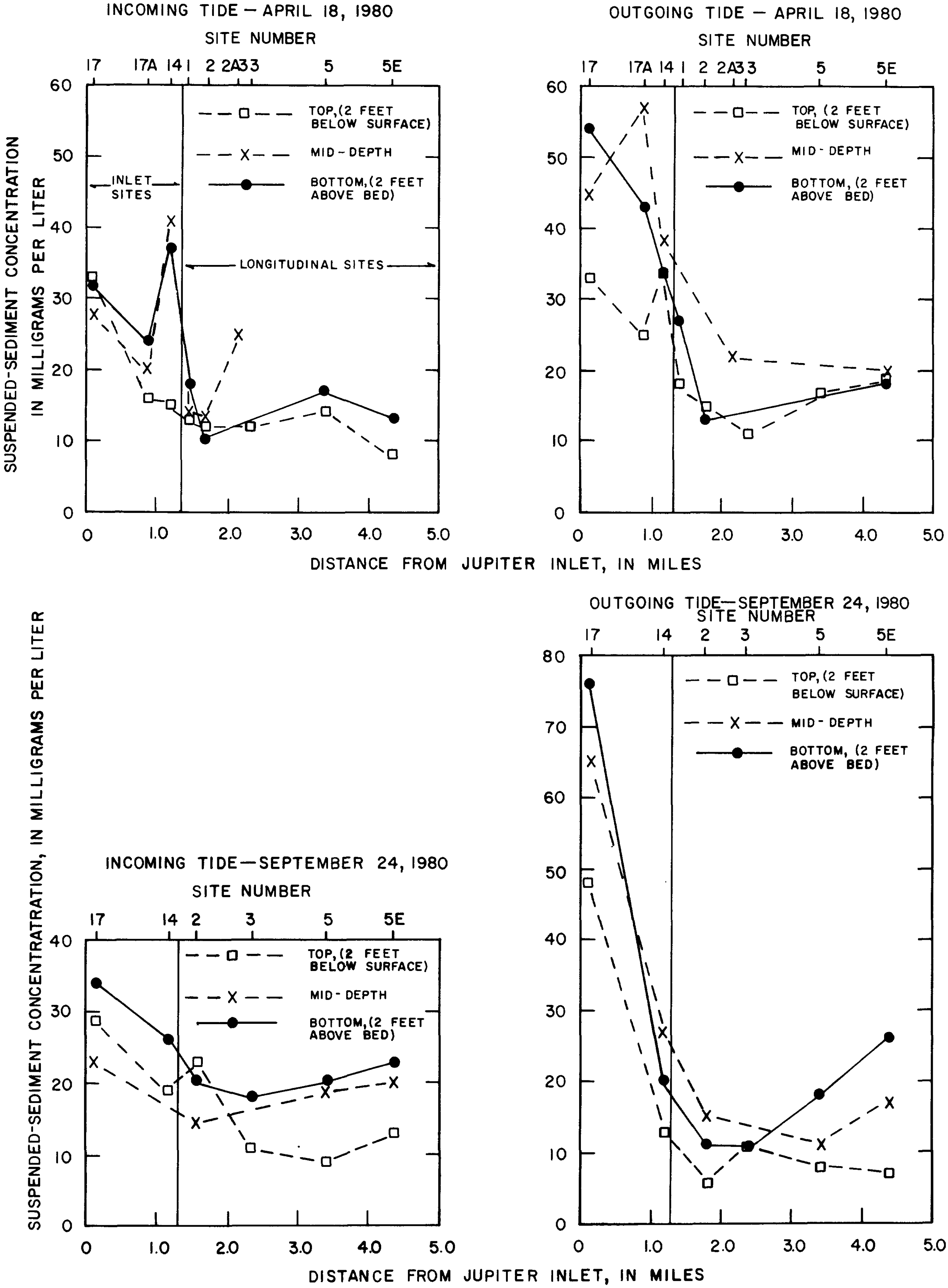


Figure 5.--Concentrations of suspended sediment at selected sites in the northwest fork, Southwest Fork, and inlet, Loxahatchee River estuary.

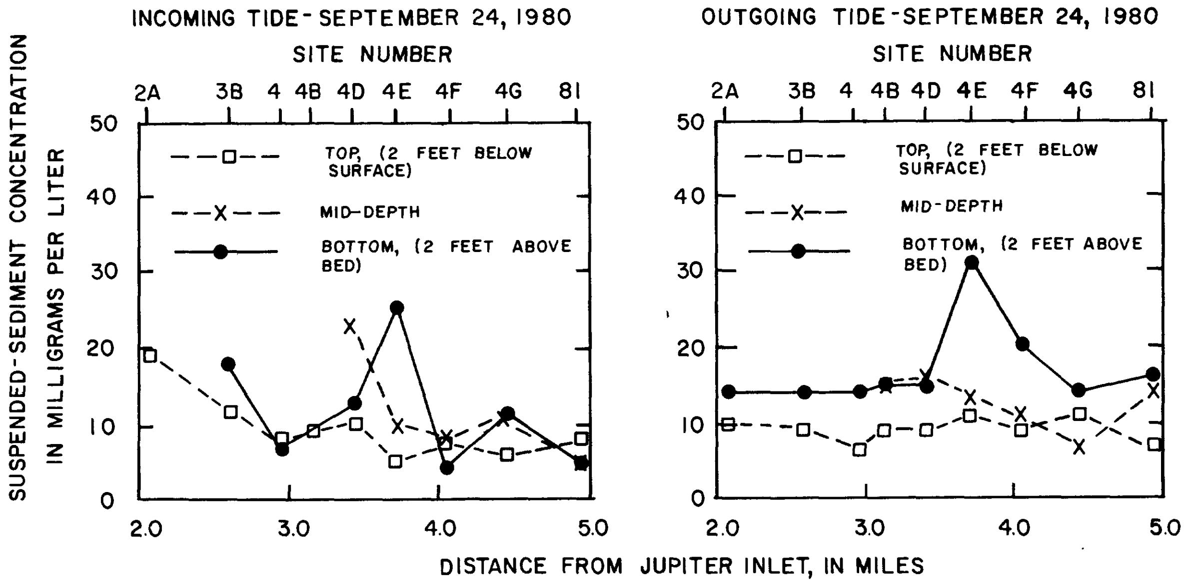


Figure 5.--Concentrations of suspended sediment at selected sites in the northwest fork, Southwest Fork, and inlet, Loxahatchee River estuary--Continued.

Table 2.--Mean and maximum suspended-sediment concentrations for the inlet, longitudinal, and tributary sites during selected incoming and outgoing tides measured during the study period

[Concentrations are in milligrams per liter]

Site No.	Location	Incoming tides Mean	Incoming tides Maximum	Outgoing tides Mean	Outgoing tides Maximum
	Inlet Sites				
14	Loxahatchee River estuary at A1A bridge.	33	144	43	180
15B2	South arm Intracoastal Waterway	20	40	17	45
16B	North arm Intracoastal Waterway	38	119	60	351
16C	North arm Intracoastal Waterway	14	20	15	26
17	Jupiter Inlet	20	50	21	52
	Longitudinal Sites (Embayment Area)				
1		12	19	12	23
2		12	22	10	20
2A		18	48	15	29
2A3		17	25	16	37
2B		10	18	8	11
3		10	15	9	14
3B		11	18	12	23
4		11	14	12	29
4B		11	12	9	12
4D		10	11	10	13
5		13	16	11	17
5E		14	20	16	23
74		--	--	20	20

Site No.	Location			Freshwater inflow Mean	Freshwater inflow Maximum
	Tributary Sites				
22	C-18 at S-46	--	--	14	66
23	Loxahatchee River at SR-706	--	--	9	111
25B	Cypress Creek	--	--	23	127
26	Hobe Grove Ditch	--	--	10	252
27	Kitching Creek	--	--	8	38

Table 3.--Average percentage of organic content of suspended sediment for selected tributary, inlet, and longitudinal sites, Loxahatchee River estuary

[Values are in percent]

Site No.	Location	20-month period, 2/80-9/81	1980 wet season, 5/80-10/80	61-day wet period, 8/81-9/81	Extended dry period, 11/80-7/81
		Tributary Sites			
22	C-18 at S-46	35.0	44.7	33.0	--
23	Loxahatchee River at SR-706.	38.1	40.4	28.0	45.7
25B	Cypress Creek	39.5	34.0	29.9	--
26	Hobe Grove Ditch	28.1	23.3	18.4	41.8
27	Kitching Creek	46.2	58.5	--	53.2

Site No.	Location	April 1980		August 1980	
		In-coming tide	Out-going tide	In-coming tide	Out-going tide
	Inlet Sites				
14	Loxahatchee River estuary at A1A bridge.	18	20	25	28
15B2	South arm Intracoastal Waterway	22	27	44	45
16B	North arm Intracoastal Waterway	21	23	13	19
17	Jupiter Inlet	19	22	13	19
	Longitudinal Sites (Embayment Area)				
2		--	--	24	31
3		--	--	40	38
4		--	--	50	40
5E		--	--	32	39

The vertical variation of suspended-sediment concentration at site 14 was generally less than that at sites 17 and 17A (fig. 5). An exception to this occurred on April 18, 1980, during an incoming tide, when the greatest vertical variation of suspended-sediment concentration occurred at site 14.

No distinctive patterns in the vertical variation of suspended-sediment concentrations were observed in the embayment area (longitudinal sites 1, 2, 2A3, and 3). This is probably due to the nearly complete mixing of the water column caused by the large tidal flows in the embayment (G. M. Russell, written commun., 1983).

In the northwest fork of the estuary, greater vertical variations of suspended-sediment concentration were observed at sites 5 and 5E during both incoming and outgoing tides on September 24, 1980, than on the April 18, 1980, tides or at the sites located in the embayment area (fig. 5). Presumably, greater water velocities, particularly at 2 feet above the bottom and at middepth, associated with higher tide stages on September 24, 1980, than on April 18, 1980, contributed to the greater vertical variation of suspended sediment at sites 5 and 5E.

In the Southwest Fork of the estuary, the highest concentrations of suspended sediment generally occurred at middepth or at 2 feet above the bottom (fig. 5). A peak in the suspended-sediment concentration was observed at 2 feet above the bottom at site 4E during both incoming and outgoing tides on September 24, 1980. Because the Southwest Fork narrows in this area and flow is constricted at site 4E, erosion and resuspension of bed sediment may occur at this site. Bathymetric data collected by McPherson and others (1982) show a 10-foot deep pool (adjusted to give depth relative to sea level) between sites 4D and 4E, possibly indicating erosion of bed sediments in this area.

In the tributaries, concentrations of suspended sediment and the percentage of sediment composed of organic material were variable with season and weather conditions (tables 2 and 3). From February 1, 1980, to September 30, 1981, mean suspended-sediment concentrations in the tributaries (sites 22, 23, 25B, 26, and 27) ranged from 8 to 23 mg/L (table 2); organic material accounted for an average of 28 to 46 percent of the suspended sediment during the study period (table 3). However, during and immediately following Tropical Storm Dennis (August 18-22, 1981), suspended-sediment concentrations in the major tributaries increased substantially (fig. 6). The greatest increases were observed in Cypress Creek, the Loxahatchee River at SR-706, and C-18 at S-46 where concentrations of suspended sediment increased as much as 16 times over concentrations before the storm. For example, the suspended-sediment concentration in Cypress Creek was 3 mg/L on August 14, 1981, increasing to 28 mg/L on August 18, 1981, and to 50 mg/L on August 22, 1981 (fig. 6).

Concentrations of suspended sediment in the tributaries also changed as a result of man's upstream activities. During September 1981, suspended-sediment concentrations in Cypress Creek and Hobe Grove Ditch increased as much as 21 times over concentrations in early September (fig. 6). Cleaning and dredging operations on irrigation canals connected to Cypress Creek and

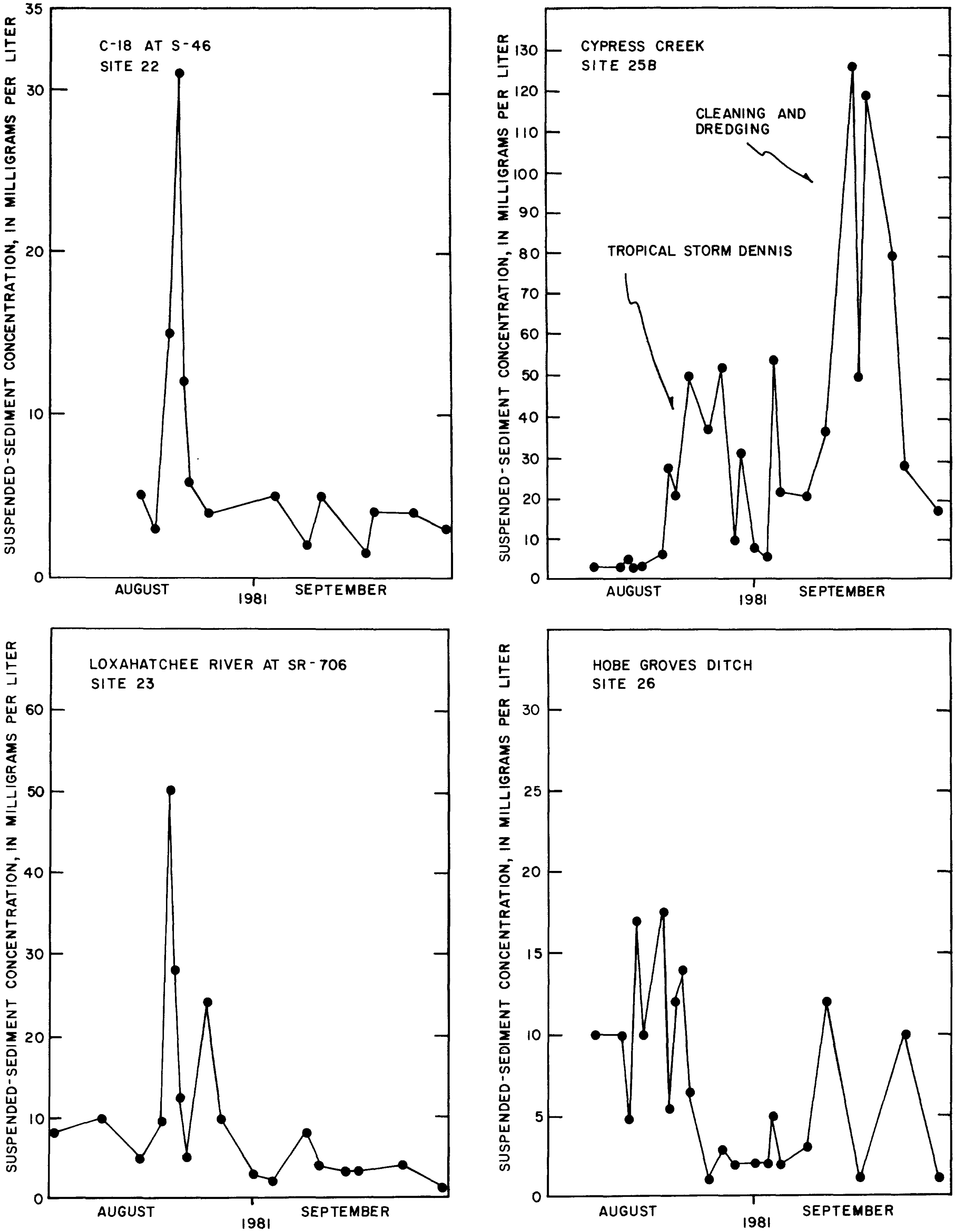


Figure 6.--Suspended-sediment concentrations for selected tributaries to the Loxahatchee River estuary, August and September 1981.

Hobe Grove Ditch were presumably responsible for the high concentrations in mid- and late September. Rainfall in late September (fig. 3) could have increased suspended-sediment concentrations in the tributaries by stream bank erosion from runoff. However, increased concentrations were not observed in the Loxahatchee River at SR-706 and C-18 at S-46 during late September.

Discharges and suspended-sediment concentrations of selected tributaries during a storm in late March 1982 are shown in table 4. Discharges during this storm exceeded those measured in August and September 1981. Rainfall during this storm on March 28 and 29 was 2.2 and 3.2 inches, respectively, at rainfall station MRF-231 (fig. 1). Suspended-sediment concentrations in all tributaries, except C-18, were comparable to those observed during the 61-day wet period of August and September 1981. The suspended-sediment concentration in C-18 at S-46 was much higher on March 29, 1982 (58.5 mg/L), than at any time during August or September 1981 (fig. 6).

SUSPENDED-SEDIMENT LOADS FROM THE TRIBUTARIES

Suspended-sediment loads from the tributaries are highly seasonal and storm related. The 5 major tributaries to the Loxahatchee River estuary (Loxahatchee River at SR-706, Cypress Creek, Kitching Creek, Hobe Grove Ditch, and C-18 at S-46) discharged 1,904 tons of suspended sediment to the estuary during the 20-month period (February 1, 1980, to September 30, 1981) (table 5). During a 61-day period of above-average rainfall (August 1 to September 30, 1981) that included Tropical Storm Dennis, the major tributaries discharged 926 tons of suspended sediment to the estuary (table 5). This accounted for about 49 percent of the suspended sediment discharged to the estuary during the 20-month period and about 74 percent of the suspended sediment discharged during the 1981 water year. Sediment loads from C-18, Loxahatchee River at SR-706, and Cypress Creek accounted for more than 94 percent of the total tributary input of sediment from the 5 major tributaries in the 1981 water year. Input of sediment directly associated with Tropical Storm Dennis was estimated for several days of stormwater runoff. Loads of suspended sediment from the major tributaries increased from 9 tons during a 5-day prestorm period to 302 tons during a 5-day poststorm period of stormwater runoff (McPherson and Sonntag, 1983). The 5-day poststorm runoff accounted for 24 percent of the suspended sediment transported by the tributaries during the 1981 water year.

Cypress Creek discharged the largest sediment loads (table 5) and had the highest rates of sediment transport (table 6) of all tributaries during the 20-month period, the 1981 water year, and the 61-day wet period. The large total contribution of suspended sediment by Cypress Creek was due to the high concentrations of suspended sediment in September 1981 attributed to cleaning and dredging operations on nearby irrigation canals.

During the 1980 wet season (May through October 1980), the Loxahatchee River at SR-706 discharged 258 tons of suspended sediment to the estuary and had a transport rate of 1.4 tons/d (tables 5 and 6). This is slightly more than the suspended-sediment load (239 tons) and the transport rate (1.3 tons/d) measured in Cypress Creek during the same period.

Table 4.--Storm discharges and suspended-sediment concentrations for selected tributaries to the Loxahatchee River estuary, March 29-31, 1982

Site No.	Tributary	Date	Instantaneous discharge (ft^3/s)	Instantaneous suspended-sediment concentrations (mg/L)
22	C-18 at S-46 1/	3/29/82	1,109	58.5
		3/30/82	975	17
23	Loxahatchee River at SR-706.	3/31/82	282	16
25B	Cypress Creek	3/29/82	382	61
		3/30/82	321	96
27	Kitching Creek	3/31/82	109	6.0

1/ Discharge data supplied by the South Florida Water Management District.

Table 5.--Suspended-sediment loads for selected major tributaries to the Loxahatchee River estuary1/

[Loads are in tons (short)]

Site No.	Tributary	20-month period, 2/80-9/81	Water year 1981, 10/80-9/81	1980 wet season, 5/80-10/80	61-day wet period, 8/81-9/81	Extended dry period, 11/80-7/81
22	C-18 at S-46 2/	324	292	32	202	0.0
23	Loxahatchee River at SR-706	669	328	258	214	82
25B	Cypress Creek	790	584	239	476	79
26	Hobe Grove Ditch	91	36	40	26	11
27	Kitching Creek	30	15	13	8.5	5.5
Total		1,904	1,255	582	926	178

1/ Loads calculated by flow-duration, sediment-transport rating curve method (Miller, 1951).

2/ C-18 discharged for 103 days from February 1, 1980, to September 30, 1981; 61 days during the 1980 wet season; and 42 days during the 61-day wet period.

Table 6.--Suspended-sediment transport rates for selected major tributaries to the Loxahatchee River estuary1/

[Rates are in tons (short) per day]

Site No.	Tributary	20-month period, 2/80-9/81	Water year 1981, 10/80-9/81	1980 wet season, 5/80-10/80	61-day wet period, 8/81-9/81	Extended dry period, 11/80-7/81	Maximum daily suspended-sediment transport rate during study period and date when observed
22	C-18 at S-46 2/	--	0.8	0.5	4.8	--	27.74 (8/18/81)
23	Loxahatchee River at SR-706.	1.1	.9	1.4	3.5	0.3	29.06 (8/18/81)
25B	Cypress Creek	1.3	1.6	1.3	7.8	.29	41.58 (8/21/81)
26	Hobe Grove Ditch	.15	.10	.22	.42	.04	5.35 (8/18/81)
27	Kitching Creek	.05	.04	.07	.14	.02	--

1/ Transport rates calculated by flow-duration, sediment-transport rating curve method (Miller, 1951).

2/ C-18 discharged for 103 days from February 1, 1980, to September 30, 1981; 61 days during the 1980 wet season; and 42 days during the 61-day wet period.

Discharge of suspended sediment to the estuary from the major tributaries was at a minimum during the extended dry period of November 1980 through July 1981. During this period, the Loxahatchee River at SR-706 and Cypress Creek discharged most of the suspended sediment (90.7 percent) of the 5 major tributaries to the estuary (table 5). Loads of suspended sediment discharged from the 5 major tributaries during the 9-month dry period accounted for only 9.3 percent of the total suspended-sediment load discharged during the 20-month period. Table 6 shows the suspended-sediment transport rates associated with the dry period.

SEDIMENT LOADS IN THE INLET AREA

The net suspended-sediment loads moving towards the ocean at Jupiter Inlet (site 17) and at the mouth of the embayment (site 14) far exceeded the total of all tributary loads. Tidal loads on outgoing tides ranged from 124 to 1,060 tons at site 17 and from 97.5 to 175 tons at site 14 (table 7). Tidal loads on incoming tides ranged from 113 to 724 tons at site 17 and from 86.5 to 183 tons at site 14 (table 7). Total load from the tributaries during the 1981 water year was 1,255 tons (table 5), which averages about 0.83 ton during a 6-hour tidal cycle. Total load from the tributaries during the extended dry period (November 1980 to July 1981) averaged 0.16 ton per 6-hour tidal cycle and for the 61-day wet period (August to September 1981) averaged 3.68 tons per 6-hour tidal cycle.

Suspended sediment that enters Jupiter Inlet is transported into the embayment and into the north arm of the Intracoastal Waterway, but only a small percentage enters the south arm of the Intracoastal Waterway; flow there represents only a small part of the total inflow at the inlet (McPherson and others, 1982). Most of the incoming tidal water moves up the north arm (Chiu, 1975, reported 45 percent; McPherson and others, 1982, reported 39 percent) or into the embayment (Chiu, 1975, 44 percent; McPherson and others, 1982, 57 percent). On an incoming tide on August 28, 1980, 340 tons of suspended sediment entered the inlet at site 17, and 86.5 tons entered the embayment at site 14 (table 7). No suspended sediment loads in the north arm of the Intracoastal Waterway were measured on this date. However, on August 27, 1980, on an incoming tide when 278 tons of suspended sediment entered the inlet at site 17, 167 tons moved up the north arm of the Intracoastal Waterway (site 16B).

The embayment and the north arm are also sources for suspended-sediment loading to the inlet during outgoing tides. On August 28, 1980, on an outgoing tide, 375 tons of suspended sediment were discharged to the ocean through the inlet (site 17). On the same tide, 120 tons passed through site 14. Under similar tidal and weather conditions on August 27, 1980, 314 tons were discharged to the ocean through the inlet (site 17), while 224 tons of suspended sediment were discharged from the north arm of the Intracoastal Waterway (site 16B).

Table 7.--Sediment rates and loads for selected sites, Loxahatchee River estuary

[Rate and loads are in tons (short) per day and tons (short), respectively]

Site No.	Location	Date	Tide	Maximum instantaneous suspended-sediment transport rate	Tidal suspended-sediment load	Amount and direction of net tidal suspended-sediment load
14	Loxahatchee River estuary at A1A bridge (embayment).	4/16/80	In	1,110	158	17 Out
			Out	1,350	175	
		8/26/80	In	1,550	183	85.5 In
			Out	523	97.5	
		8/28/80	In	702	86.5	33.5 Out
			Out	900	120	
		4/6/81	In	--	--	--
			Out	900	120	
16B	Intracoastal Waterway north arm near SR-707.	4/15/80	Out	--	--	--
		8/27/80	In	1,750	167	57 Out
			Out	1,770	224	
		4/6/81	In	--	--	--
			Out	7,100	709	
		4/7/81	In	2,100	233	57 Out
			Out	2,100	290	
17	Jupiter Inlet	4/14/80	In	8,790	724	336 Out
		4/15/80	Out	8,230	1,060	
		4/24/80	In	889	113	9 Out
		4/25/80	Out	878	124	
		8/27/80	In	2,050	278	36 Out
			Out	2,310	314	
		8/28/80	In	3,080	340	35 Out
			Out	2,770	375	
		4/7/81	In	5,300	486	320 Out
			Out	5,880	806	

Generally, suspended-sediment loads in the north arm of the Intracoastal Waterway were in the same range as that at the mouth of the embayment (table 7). An exception was a tidal discharge of 709 tons from the north arm (site 16B) on April 6, 1981. This relatively large load was primarily due to the suspending of bed sediments caused by strong north winds. Because this arm is alined north to south, winds from either direction are unimpeded and can easily cause turbulence, wave action, and resuspension of sediment. "Plumes" of suspended sediment were observed in the north arm, and concentrations of suspended-sediment averaged 142 mg/L on this tide.

Transport of sediment as bedload can constitute a significant part of the total sediment transport in the inlet, but bedload transport becomes less significant in the embayment. In the inlet, at site 17, instantaneous bedload-transport rates ranged from 32.5 to 1,330 tons/d, comprising 2 to 28 percent of the total instantaneous sediment-transport rates (table 8). At the mouth of the embayment at site 14, instantaneous bedload-transport rates ranged from 0.44 to 2.37 tons/d, comprising 0.08 to 0.35 percent of the total instantaneous sediment-transport rates. On an incoming tide on August 28, 1980, the bedload-transport rate decreased from 60.4 tons/d at site 17 to 2.37 tons/d at site 14. Most of the sand transported as bedload ranged in size from 0.25 mm to less than 0.5 mm (table 8).

Wanless and others (1984) reported that some sediment moving as bedload entered the embayment (at site 14) and was deposited on the seaward side of the sand delta (about 0.3 mile west of site 14). However, the predominant source of sediment deposited on the delta was sediment transported in suspension. This conclusion is based on the particle size of the surface sands on the delta which were mainly less than 0.2 mm. Sands less than this amount are generally transported in suspension once there is sufficient bottom shear to entrain them (Shields, 1936). Bedload and suspended-sediment data collected on April 16 and August 28 at site 14 during incoming tides tend to support this. On these 2 incoming tides, bedload transport rates accounted for less than 1 percent of the total sediment-transport rate as measured at site 14 (table 8).

SEDIMENTATION RATES AND NET-SEDIMENT TRANSPORT

Sedimentation rates infer net accumulation over a period of time. This rate represents the sum of the episodes of accumulation, erosion, and nondeposition. Wanless and others (1984) found that sediment is being provided to the Loxahatchee River estuary at much higher rates than it is actually accumulating. Cores taken in the main body of the estuary indicate that sedimentation rates have decreased from 0.69 mm/y about 7,000 years ago to about 0.25 mm/y 1,000 years ago. Cores taken in artificially dredged canals adjacent to the estuary, which penetrated more than a meter of very soft, organic-rich mud with essentially no sand component, show sedimentation rates of at least 1.5 cm/y and may be as high as 3.0 cm/y, nearly 100 times the rate of sediment accumulation documented in the main body of the estuary (Wanless and others, 1984). This suggests that large amounts of fine sediment are available to the estuary, and that high sedimentation rates are occurring in the true sediment sinks (such as the dredged canals adjacent to the estuary). This also suggests that dynamic physical processess of circulation and flushing are inhibiting rapid sediment accumulation in the main body of the estuary.

Table 8.--Instantaneous bedload and suspended-sediment transport rates and particle-size analysis for selected sites, Loxahatchee River estuary

[Rates are in tons (short) per day]

Site No.	Site	Date	Tide	Mean instantaneous velocity (ft/s)	Instantaneous bedload transport rate	Instantaneous sediment transport rate	Percent of total instantaneous sediment transport rate composed of bedload	Bedload material particle size, in millimeters, percent finer than									
								32	16	8	4	2	1	0.5	0.25	0.125	0.062
17	Jupiter Inlet	1/ 4/15/80	Out	2.60	32.5	1,030	3										
			Out	2.85	44	1,420	3										
			Out	3.30	1,330	4,400	23										
		8/27/80	In	2.05	96.1	559	15										
			Out	3.45	632	1,630	28		100	99	99	98	95	80	5	1.0	0.3
		8/28/80	In	3.45	60.4	2,650	2	100	97	94	92	90	88	75	3	1.3	.4
			Out	3.70	636	2,180	23		100	98	98	97	91	74	4	.3	.1
		4/7/81	In	2.74	934	5,230	15										
			In	2.80	592	4,690	11										
			In	2.11	711	2,410	23										
			Out	2.06	259	1,610	14										
			Out	2.58	204	5,150	3.8										
			Out	2.96	947	5,750	14										
14	Loxahatchee River estuary at A1A bridge.	4/16/80	In	1.95	.44	522	.08										
			Out	2.00	1.49	1,260	.1			100	86	71	57	43	14	7	0
		8/28/80	In	2.40	2.37	677	.35										
			Out	--	--	--	--		100	96	92	84	74	61	12	6.8	.1
16B	Intracoastal Waterway, north arm 1,000 feet south of SR-707.	8/27/80	Out	1.75	24.3	1,500	1.6										
			Out	1.88	58.5	1,690	3.4										

1/ Sediment-transport rates measured on the same outgoing tide; 4/15/80.

Two types of sedimentation events apparently occur in the main body of the estuary: (1) accumulation of fine-grained, organic-rich muds which are deposited during low-energy periods; and (2) fine to coarse sand that is carried into the estuary through Jupiter Inlet or from riverine discharge during turbulent storms (Wanless and others, 1984).

Suspended-sediment data collected during selected tides at Jupiter Inlet (site 17) and at site 14 indicate an erosional trend to the net transport of suspended sediment in the inlet area. Only one sampled tidal cycle on August 26, 1980, showed a net transport of suspended sediment inward towards the estuary at site 14 (table 7). During all other sampled tidal cycles at site 14, data show a net loss of sediment through site 14 towards the inlet. At site 17 (Jupiter Inlet), the net transport of suspended sediment was towards the ocean during all sampled tidal cycles (table 7).

Although the limited amount of sediment-transport data collected during this study indicates a net loss of sediment from the estuary, it is apparent from aerial photography and visual observation that localized deposition has been occurring since the 1940's in certain areas of the estuary. For example, McPherson and others (1982) documented by aerial photography that the sand delta, 0.3 mile west of site 14, has enlarged and migrated landward over the past 40 years.

SUMMARY

In recent years, the environmental condition of the Loxahatchee River and estuary has become a major concern to many citizens and agencies. One major concern is the type and amount of suspended sediment transported to and from the estuary. The concentration and transport of suspended sediment in an estuary are affected by several factors including particle size, availability of sediment, and water velocity.

Generally, mean concentrations of suspended sediment in the Loxahatchee River estuary were higher in the Jupiter Inlet area than in the embayment, ranging from 14 to 60 mg/L at maximum tidal flows. During slack tides, much of the sediment stayed in suspension with concentrations at sites near Jupiter Inlet ranging from 9 to 12 mg/L. On two sampled outgoing tidal cycles (April 18, 1980, and September 24, 1980), maximum concentrations at Jupiter Inlet (site 17) (54 and 76 mg/L, respectively) generally occurred near the channel bottom on outgoing tides. On two incoming tides, maximum suspended-sediment concentrations (33 mg/L on 4/18/80 and 34 mg/L on 9/24/80) occurred near the surface and near the bottom of the channel, respectively. Organic material accounted for 13 to 22 percent of the suspended sediment on incoming and outgoing tides at the inlet (site 17) and for 18 to 28 percent at the mouth of the embayment area (site 14).

Mean concentrations of suspended sediment were lower in the embayment area than at the Jupiter Inlet area and usually ranged from 8 to 20 mg/L during outgoing tides and from 10 to 18 mg/L during incoming tides. Organic material in the embayment generally comprised 24 to 50 percent of the suspended sediment.

In the tributaries, concentrations of suspended sediment and the percentage of sediment composed of organic material were quite variable with season and weather conditions. Mean suspended-sediment concentrations during the study period in selected tributaries generally ranged from 8 to 23 mg/L; about 25 to 50 percent of the sediment was composed of organic material. However, during and immediately following Tropical Storm Dennis, suspended-sediment concentrations in selected tributaries increased substantially. The greatest increases were observed in Cypress Creek, Loxahatchee River at SR-706, and C-18 at S-46 where concentrations of suspended sediment increased as much as 16 times over concentrations before the storm.

Suspended-sediment loads from the tributaries were highly seasonal and storm related. The 5 major tributaries to the Loxahatchee River estuary discharged 1,904 tons of suspended sediment to the estuary during the study period. During a 61-day period of above-average rainfall that included Tropical Storm Dennis, the 5 major tributaries discharged 926 tons of suspended sediment to the estuary, accounting for 49 percent of the suspended sediment discharged to the estuary by the tributaries during the 20-month study period and for about 74 percent of the suspended sediment discharged during the 1981 water year.

Cypress Creek discharged the largest sediment loads and had the highest rates of sediment transport of all of the tributaries during the 20-month study period, the 1981 water year, and the 61-day wet period attributed to high suspended-sediment concentrations resulting from cleaning and dredging of irrigation canals nearby.

Tidal suspended-sediment loads at Jupiter Inlet (site 17) and at the mouth of the embayment (site 14) far exceeded tributary loads. Tital loading from the tributaries to the estuary during the 1981 water year was 1,255 tons, averaging about 0.8 ton during a 6-hour tidal cycle. Tidal loading during 6-hour tidal cycles at site 17 ranged from 113 to 1,060 tons and at site 14 from 86.5 to 183 tons. Large sediment loads also occurred in the north arm of the Intracoastal Waterway from strong north winds causing turbulence in the channel and resuspension of large amounts of sediment.

Transport of sediment as bedload can constitute a significant part of the total sediment transport in the inlet, but bedload transport becomes less significant in the embayment area. At Jupiter Inlet (site 17), instantaneous bedload-transport rates were between 2 to 28 percent of the total instantaneous sediment-transport rates. At the mouth of the embayment (site 14), instantaneous bedload-transport rates were between 0.08 to 0.35 percent of the total instantaneous suspended-sediment transport rates.

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