Resuspension of Bottom Sediments, Sedimentation, and Tributary Storm Discharge at Bayboro Harbor and the Port of St. Petersburg, Florida

By David H. Schoellhamer

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Multiply	By	To obtain
inch (in.)	0.0254	meter
foot (ft)	0.3048	meter
foot per second (ft/s)	0.3048	meter per second
foot per minute (ft/min)	0.3048	meter per minute
foot per year (ft/yr)	0.3048	meter per year
mile (mi)	1,609	meter
knots	0.5143	meter per second
foot squared (ft^2)	0.09294	meter squared
foot per second squared (ft/s^2)	30.48	centimeter per second squared
cubic foot per second (ft^3/s)	0.02832	cubic meter per second

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

$$°C = (°F - 32)/1.8$$

Acronyms used in this report:

GIS	Geographic Information System
OBS	Optical backscatterance

Abbreviated water-quality units used in this report:

cm	centimeter
cm/s^2	centimeter per second squared
g/cm^3	gram per cubic centimeter
(g/cm)/s	gram per centimeter per second
µm	micron
µS/cm	microsiemens per centimeter at 25 degrees Celsius
mg/L	milligrams per liter
NTU	nephelometric turbidity units

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Abstract

Bayboro Harbor and the Port of St. Petersburg, Florida, form a manmade basin adjacent to Tampa Bay that may supply turbid water to the bay and subsequently affect light penetration in water in the bay. To address concerns about the nature and extent of this potential problem, resuspension of bottom sediments, sedimentation, and tributary storm discharge in the basin were studied. Sediment resuspension was monitored at a pier by using automatic monitoring instrumentation. Study results indicated that small tidal currents did not resuspend bottom sediments. The nearly enclosed basin limited the generation of wind waves and the entry of waves from Tampa Bay, so wave motion in the basin did not cause resuspension of bottom sediments. Infrequent seiche motion and small vessel wakes did not resuspend bottom sediments either.

Water samples were collected and water-quality measurements were made throughout the port during a cruise ship departure in 1988 and again during a cruise ship arrival in 1990. The maneuvering of the cruise ship resuspended bottom sediments, but these sediments settled within 2 hours. Tidal currents and wave action were not large enough to prevent the resuspended sediments from settling in the basin. Analysis of bathymetric surveys of the port made in 1981, 1986, 1987, and 1989 indicates that the cruise ship has deepened the port along its route and that the displaced sediment has deposited elsewhere within the port.

The storm discharge from two tributaries and the effect of tributary storm runoff on the water quality of the harbor were studied during a storm on November 9, 1989. Booker Creek, which drains an urban watershed, was stratified with a thin layer of turbid freshwater flowing into the harbor over a layer of less turbid saltwater. Salt Creek, which primarily drains Lake Maggiore, was only partially stratified and was less turbid. The turbid water from the creeks only slightly increased the turbidity in the harbor, probably because of mixing with less turbid water and particle settling. Thus, the basin provides mixing and settling, which diminish or eliminate the potentially adverse effect on Tampa Bay from tributary storm runoff and large vessel traffic in the basin.

INTRODUCTION

Light attenuation in the waters of Tampa Bay may adversely affect benthic organisms, seagrasses, and fish and other marine communities that are dependent upon the seagrasses. Resuspension of sediment on the bottom of the bay, which contributes to light attenuation, and the mechanisms that cause sediment resuspension in Tampa Bay have not been studied extensively. The U.S. Geological Survey, in cooperation with the Southwest Florida Water Management

District, Hillsborough County, Pinellas County, the City of St. Petersburg, the City of Tampa, and the Tampa Port Authority, began a study in 1987 to determine the effect of fine sediment resuspension on light attenuation in Tampa Bay and to determine the mechanisms that cause resuspension of fine sediments.

Resuspension of bottom sediments, sedimentation rates, and tributary storm discharge at Bayboro Harbor and the Port of St. Petersburg are of interest because of sedimentation in the port and the potential effects that these processes in this and other similar basins may have on adjacent Tampa Bay. This basin was selected for study because a U.S. Coast Guard pier at the Port of St. Petersburg provided an accessible site for the deployment of sediment resuspension monitoring equipment, and a cruise ship that operates out of the port provided the opportunity to study vessel-generated resuspension of bottom sediments and the fate of the resuspended sediment. Tributary storm discharge is another process that may affect light penetration in the water in Tampa Bay, independent of the resuspension of bottom sediments. The nearly enclosed basin provided the opportunity to study the effects of tributary storm discharge on water quality in a confined basin.

Purpose and Scope

This report presents the results of sediment resuspension monitoring, sampling of vessel-generated sediment resuspension, sedimentation rate calculations, and sampling of tributary storm discharge at Bayboro Harbor and the Port of St. Petersburg. Sediment resuspension monitoring equipment was deployed at the port from May 28, 1988, to June 29, 1988. Sediment resuspension associated with the departure and arrival of the cruise ship was sampled on June 21, 1988, and May 18, 1990, respectively. Bathymetric surveys from 1981, 1986, 1987, and 1989 were used to calculate sedimentation rates at the port. Finally, storm discharge from Salt Creek and Booker Creek, which enter Bayboro Harbor, and water quality of the creeks and the harbor were measured during a storm on November 9, 1989.

Description of Study Area

Tampa Bay is located approximately at the midpoint of the west coast of Florida (fig. 1). Tampa Bay is a well-mixed estuary because of relatively small inflows and shallow depths (Goodwin, 1987). The tides in Tampa Bay are a mixture of both diurnal and semidiurnal components with a range of about 2 to 3 ft. The Port of St. Petersburg and Bayboro Harbor are each part of a manmade, dredged, nearly enclosed basin in Pinellas County west of the central part of Tampa Bay (fig. 2). A dredged channel connects the basin and Tampa Bay, and most of the basin shoreline is protected by seawalls. Bayboro Harbor is west of the peninsula near the center of the basin and contains a commercial small-craft marina. The Port of St. Petersburg is east of the peninsula. A U.S. Coast Guard station is on the eastern shore of the port and a cruise ship terminal is along the western half of the northern seawall of the port. According to navigation charts, the average depth at mean lower low water in January 1986 was 11 ft in Bayboro Harbor and 20 ft in the Port of St. Petersburg. Salt Creek, which drains Lake Maggiore in St. Petersburg, enters the south side of Bayboro Harbor. Booker Creek, which drains part of downtown St. Petersburg, enters the southwestern corner of the harbor.

Acknowledgments

The author gratefully acknowledges the U.S. Coast Guard Group at St. Petersburg, which permitted use of one of its piers for the deployment of resuspension monitoring equipment in May and June 1988. Special thanks are extended to Chief Kleinschmidt of the U.S. Coast Guard Group's Facilities Engineering Office, who cooperated with construction, diving, and sampling activities, and to Tim Travis, Director, Port of St. Petersburg, who provided bathymetric surveys of the port.

DATA-COLLECTION METHODOLOGY

Four data-collection activities were undertaken during this study. This section describes the data-collection methodology for monitoring sediment resuspension from a pier in the port, for sampling sediment resuspension caused by a cruise ship, for determining sedimentation rates in the port, and for sampling tributary storm discharge at Bayboro Harbor.

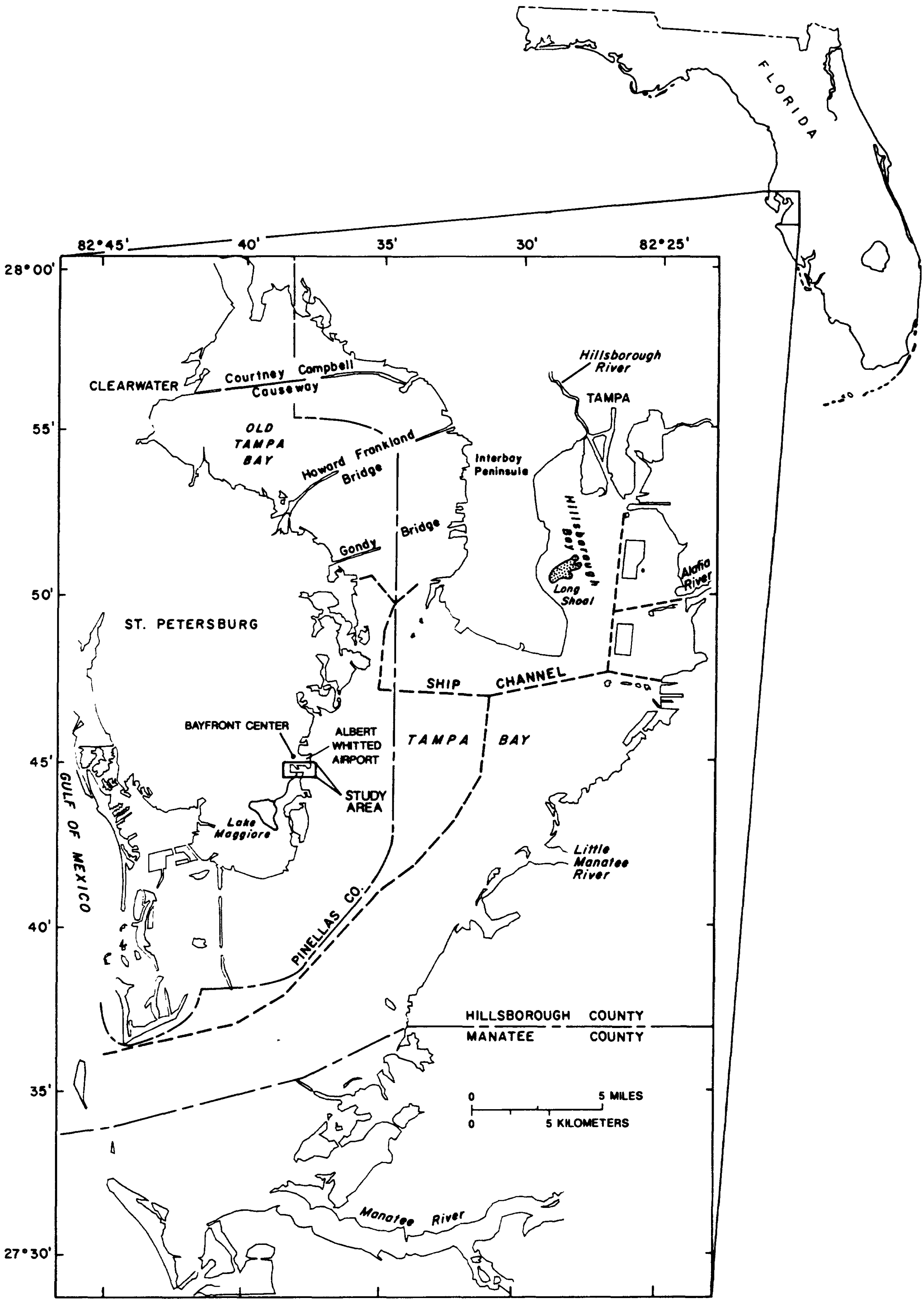


Figure 1. Location of study area.

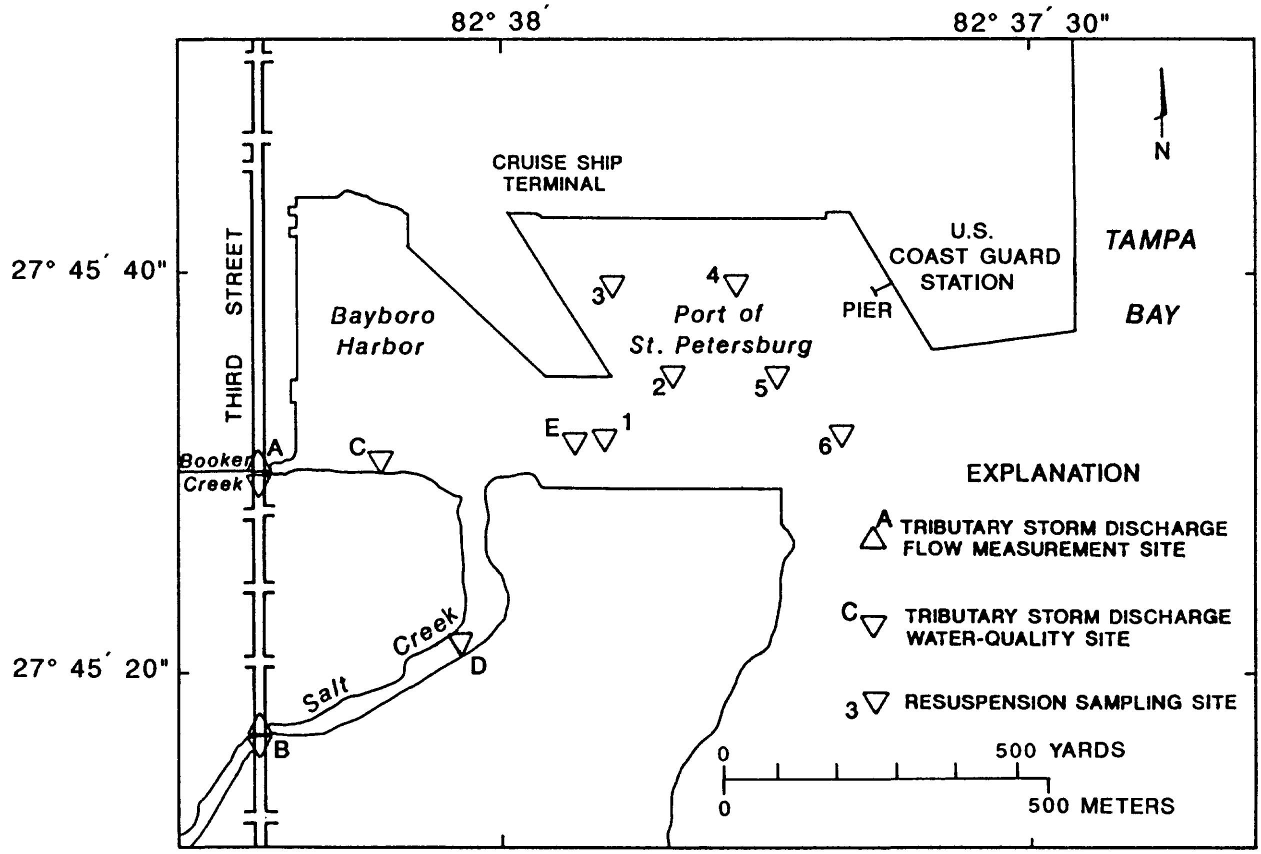


Figure 2. Detail of study area.

Resuspension Monitoring and Sampling

Instrumentation to monitor sediment resuspension was deployed at the end of a U.S. Coast Guard pier (fig. 2) from May 28, 1988, to June 29, 1988, to provide information on the resuspension of bottom sediments in the Port of St. Petersburg. The instrumentation was installed at the pier because the site was accessible from land, the instrumentation was protected from vessel traffic, and the bottom sediment size distribution at the site was similar to that in other areas of the port, though slightly coarser (table 1). The average depth at the end of the pier was about 16 ft.

The instrument sensors were mounted to two supports attached to the outermost pile on the pier. Each support was made of a 1-in. diameter, 2-ft long aluminum pipe welded perpendicular to and at the center of an aluminum base plate. Each base plate was slightly curved and was bolted to the pile so that the instruments were 0.8 and 8.2 ft above the bed and the pipes were parallel with the pier.

Table 1. Percentage of fine material and mean particle size of bottom sediments in the Port of St. Petersburg

[<, less than]

Site	Latitude	Longitude	Percent fines	Mean particle size (microns)
Pier	27°45′39"N	82°37′38"W	14.5	139
1	27°45′34"N	82°37′50"W	79.3	< 63
2	27°45′36"N	82°37′46"W	66.5	< 63
3	27°45′42"N	82°37′49"W	38.8	100
4	27°45′42"N	82°37′43"W	42.2	97
5	27°45′36"N	82°37′42"W	31.7	130
6	27°45′34"N	82°37′39"W	14.4	114

Water velocities were measured using Marsh-McBirney, Inc., model 512 bidirectional electromagnetic current meters. One current meter was mounted to the end of each pipe. Below the mounting area of the electromagnetic current meters, there is a 3/8-in. diameter rod that is about 6 in. long with a golf-ball size sphere near the end of the rod. The sphere establishes a magnetic field, and water moving through the magnetic field produces an electrical current that is converted to two output voltages that are proportional to the water velocities in two perpendicular directions. The long axes of the current meters were mounted vertically and the meters were rotated so that the northward and eastward velocity vector components were measured. Data collected from the electromagnetic current meters were corrected for the effect of an electronic output filter as described by Guza (1988). The current meters must be calibrated in a hydraulic laboratory to accurately convert output voltage to water velocity, but once calibrated, they have proven to be accurate velocity measurement devices (Guza and others, 1988).

Two optical backscatterance (OBS) sensors for measuring suspended-solids concentration were mounted at the midpoint of each pipe. The OBS sensors are thumb-size and they have an optical window at the relative position of the thumbnail (Downing and others, 1981; Downing, 1983). The optical window is used to transmit an infrared pulse of light that scatters off particles in the water up to a distance of about 10 to 20 cm in front of the window. Some of this scattered light returns to the optical window where a receiver converts the backscattered light to an output voltage. The output voltage is proportional to the suspended-solids concentration and turbidity. The calibration of the OBS output to suspended-solids concentration will vary depending on the size and optical properties of the suspended solids, so the OBS sensors must be calibrated either in the field or in a laboratory with the same suspended material as that at the deployment site. One of the OBS sensors on each pipe was coated with an antifoulant for optical surfaces (Spinard, 1987), and the other OBS sensor was left untreated because the coating reduces light transmission.

A shelter was temporarily installed on the boardwalk of the pier to house instrument electronics, batteries, and a data recorder. The data recorder, a Campbell Scientific, Inc., model CR-10, was programmed to turn the instruments on 10 seconds before the hour, sample all of the instruments at a 1-second interval for 5 minutes, store all of the collected data on an external storage module, and turn the instruments off 5 minutes after the hour. During the study period, 762 of these hourly burst measurements were made.

A Kemmerer tube was used to collect water samples from the pier at the two instrument depths every 4 to 5 days during servicing trips. The samples were analyzed for turbidity and total suspended-solids concentration using methods described by Fishman and Friedman (1989). Fouling on some of the instruments was removed by divers on June 16, 1988. Weather information for the period was available from the control tower at Albert Whitted Airport, 0.5 mi north of the pier, and from a National Weather Service weather station at the St. Petersburg Bayfront, 0.5 mi northwest of the pier.

Cruise Ship Departure and Arrival

The Port of St. Petersburg was the home port of a passenger ship that made daily cruises to the Gulf of Mexico. The draft of the ship was 17 ft, and the average low tide depth in the port was about 22 ft, so bottom sediments were likely to be resuspended by the cruise ship.

Water samples were collected, OBS measurements of total suspended solids were made with a portable OBS sensor, and aerial photographs were taken in the port during a cruise ship departure at 1000 hours on June 21, 1988, and during the cruise ship arrival at 1700 hours on May 18, 1990. The sites at which samples were collected and measurements were made from a sampling boat in the port are shown in figure 2. The percentage of fine material (particle size less than 63 mm) and the mean particle size at each of the six sites and at the end of the U.S. Coast Guard pier are listed in table 1. Samples were collected from selected depths and were analyzed for turbidity, total suspended solids, volatile suspended solids, chloride, and specific conductance using methods described by Fishman and Friedman (1989). Measurements with an OBS sensor were made to help identify areas of resuspension, to help identify the vertical extent of resuspended sediments in the water column, and to quantify the concentration of total suspended solids. The OBS sensor output was calibrated with the concentration of total suspended solids after the samples were analyzed. Measurements were made and samples were collected before the cruise ship maneuvered in the port and as soon after the cruise ship passed each site as time and safety would permit. Sampling and measurement at the most affected sites continued for about 2 hours until the resuspension plume was barely detectable. Aerial photographs were taken and aerial observations were used to help identify the sites with substantial resuspension.

Sedimentation Rates in the Port

The sedimentation rate and areas of deepening and shoaling were determined from four bathymetric surveys. The four surveys were conducted in April 1981, January 1986, September 1987, and March and May 1989 (Tim Travis, Director, Port of St. Petersburg, written commun., 1989). The April 1981 survey was conducted by the U.S. Army Corps of Engineers after the port had been dredged and deepened. The vertical datum for all the surveys was mean low water. The survey data were digitized and entered into a computer, and a Geographic Information System (GIS) was used to analyze the data collected during the four surveys.

Tributary Storm Discharge Sampling

National Weather Service radio and radar were monitored on selected days in the fall of 1989 to determine whether significant rainfall was likely. During the early morning of November 9, 1989, rainfall developed in the northeastern Gulf of Mexico in association with a cold front moving rapidly to the southeast toward the Tampa Bay area.

Two bridge-sampling crews departed from Tampa for St. Petersburg as the rain began in Tampa at about 0800 hours. One crew traveled to the Third Street bridge over Booker Creek (site A, fig. 2), and a second crew proceeded to the Third Street bridge over Salt Creek (site B, fig. 2). Both crews made discharge measurements from the bridges and collected depth-integrated water samples from the deepest part of the channel in the respective creeks approximately every 15 minutes and also collected some point samples. Most of the collected water samples were analyzed for turbidity, total suspended solids, volatile suspended solids, chloride, and specific conductance.

At Booker Creek, five discharge measurements were made and many water samples were collected between 0920 and 1513 hours. Selected depth-integrated water samples (samples collected at about 30-minute intervals) and all point samples were sent to the laboratory for analysis of water-quality characteristics; other depth-integrated samples were stored in a refrigerator. Results of the analyses indicated that laboratory analysis of all of the samples would be beneficial. The refrigerated depth-integrated samples that had been in storage were then sent to the laboratory (about 3 months after collection). These samples were analyzed, but probably chemical precipitation in the samples had lowered the specific conductance and increased the turbidity, so the results of the analyses of the later batch of samples were disregarded. Point samples collected near the surface and near the bottom would have been more appropriate for the highly stratified conditions in Booker Creek. A high degree of stratification was not anticipated before the event and, because of a lack of communication in the field, a decision to change the sampling scheme was not made until after several depth-integrated samples had been collected. Depth-integrated sampling was continued to maintain consistent data-collection methodology. Point samples were collected 1 and 3 ft below the water surface at 1530 hours.

At Salt Creek, seven discharge measurements were made and many water samples were collected between 1115 and 1540 hours. Selected depth-integrated water samples (samples collected at about 30-minute intervals) and point samples, collected at the water surface and 1 ft above the bottom at 1550 hours, were sent to the laboratory for analysis; other depth-integrated samples collected at the site were stored in a refrigerator. Interpretation of the laboratory analyses of the Salt Creek samples indicated that analysis of the additional samples stored in the refrigerator was not warranted.

A third crew made water-quality measurements and collected water samples from a boat in the harbor and in Salt Creek downstream from the Third Street bridge during this storm. The water-quality measurements made were vertical profiles of temperature, specific conductance, and OBS. These field measurements allowed the boat crew to make immediate interpretations concerning the location and magnitude of storm runoff and to adjust the sampling sites and procedures accordingly. Several sites were sampled during the morning of November 9, 1989, to determine the condition of the harbor. During the early afternoon, sampling was limited to three sites: south side of the harbor (site C, fig. 2), Salt Creek bend (site D, fig. 2), and south of the peninsula (site E, fig. 2). Most of the water samples were analyzed for turbidity, total suspended solids, volatile suspended solids, chloride, and specific conductance.

RESUSPENSION MONITORING AND SAMPLING RESULTS

This section presents sediment resuspension monitoring results from instrumentation deployed at the U.S. Coast Guard pier in the port and an analysis of turbidity at the pier during the instrument deployment period. Instrumentation was deployed from May 28, 1988, to June 29, 1988.

Data from Instrumentation Deployed at the Pier

Water velocities at the sampling site were usually small. The maximum tidal velocities were 0.12 ft/s at the upper current meter (8.2 ft above the bottom) and 0.09 ft/s at the lower current meter (0.8 ft above the bottom). The predominant velocity azimuth angle at the upper meter was 120 to 140 degrees (current to the southeast) during ebbtide and 300 to 330 degrees (current to the northwest) during floodtide. At the lower meter, the ebbtide azimuth was 145 to 160 degrees (current to the south-southeast), and there was no predominant floodtide direction. High-frequency wave motion (chop and swell) inside the basin was small because the nearly enclosed shape of the basin prevented waves generated in Tampa Bay from entering the basin and protected the basin from wind and associated wind waves. Small U.S. Coast Guard vessels use the pier at which the instrumentation was deployed. Several wakes from these vessels were observed with velocities as much as 0.8 ft/s at the lower meter and 2.5 ft/s at the upper meter.

All water bodies have natural frequencies at which they will oscillate if properly excited by wind, earthquakes, or a change in atmospheric pressure (Dean and Dalrymple, 1984). Small low-frequency (periods from 20-128 seconds) oscillations, called seiches, were sometimes observed at the pier. Velocity components 8.2 ft above the bed during a seiche at 1300 hours on May 29, 1988, are shown in figure 3. The high-frequency variations in velocity in this figure are caused by wind waves (or chop). High-frequency variations can be removed from time series data by using a numerical low-pass filter to better analyze low-frequency seiche motions (Chuang and Boicourt, 1989). The two velocity component time series data were low-pass filtered to remove frequencies greater than 0.1 Hz (wind waves). The resulting time series, also shown in figure 3, clearly shows the seiche oscillations in the basin. The seiche amplitude of the east velocity component is greater than that for the north velocity component and the minimum and maximum of the filtered velocity components generally coincide. Thus, the seiche seems to be oscillating perpendicular to the western and eastern shores of the port. Normally, low-frequency motion is not present, only small winds waves are present.

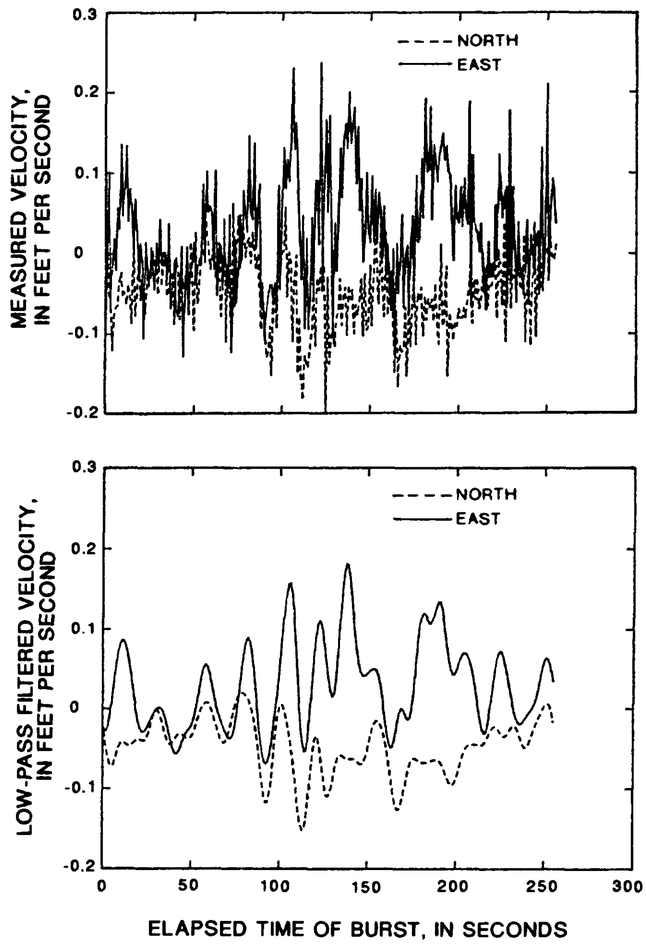


Figure 3. Measured and low-pass filtered north and east velocity components, 8.2 feet above the bed at the U.S. Coast Guard pier, beginning at 1300 hours, May 29, 1988.

A strong, sustained wind blowing perpendicular to the eastern basin seawall apparently caused the seiche that was observed at 1300 hours on May 29, 1988 (fig. 3). The wind had been from the east-northeast at 10 to 15 knots during the late morning and early afternoon according to measurements at Albert Whitted Airport, 0.5 mi north of the pier. Several other seiches were observed under similar wind conditions, but not all strong and sustained east-northeast winds caused seiches. One seiche occurred during a light northeasterly wind and a rapid decrease in atmospheric pressure, which may have caused the seiche.

The seiche periods of a rectangular basin of uniform depth can be calculated from the equation

$$T = \frac{2L}{n\sqrt{gh}} \qquad (1)$$

in which L is the length of the basin; n is the mode, which is the number of nodes in the oscillation; g is the acceleration of gravity; and h is the water depth (Dean and Dalrymple, 1984). For the Port of St. Petersburg, equation 1 can be applied if the quadrilateral basin is assumed to be rectangular. Assuming that the basin length is about 1,500 ft and the average depth is about 22 ft, the seiche periods for the four lowest modes are 112.7, 56.4, 37.6, and 28.2 seconds. Spectral analysis of the current meter data indicates that the seiche energy is present at wave periods from about 20 to 128 seconds, which is in agreement with the lower modes that are usually prevalent (Dean and Dalrymple, 1984). Thus, the field data are consistent with seiche theory.

The OBS sensors at the pier could not be calibrated with the suspended-solids concentration and turbidity data for the water samples collected at the site. The concentration of total suspended solids ranged from 3 to 50 mg/L, and the turbidity ranged from 0.2 to 4.3 NTU in these samples. The maximum values in these ranges are near the threshold above which the OBS sensors are reliable. Thus, there was not enough suspended material in the water to obtain reliable measurements from the OBS sensors.

Two other factors affecting the operation of the OBS sensors were fouling and interference (high backscatterance readings) caused by fish. The lower OBS sensor that was uncoated with antifoulant for optical surfaces did not foul until 1 week after cleaning (June 16); the uncoated upper OBS sensor fouled 1 week after deployment and cleaning (May 28). The output from the upper coated sensor became more erratic and generally higher 1 week after cleaning; the output from the lower coated sensor became somewhat erratic 3 days after cleaning, apparently due to fouling. From the pier and during dives, fish were observed congregating around the pier and occasionally would either swim past the OBS sensors or eat algae growing on the sensor support hardware. The infrared light pulse would reflect off the fish and produce a high spike during the burst sample collection. Usually no more than a few spikes would occur during a burst, but they were large enough to significantly affect the resulting mean value for the burst, so the median value proved to be a simple and more appropriate measure of the burst average OBS measurement.

Despite the calibration difficulties, fouling, and interference from fish, the output from the OBS sensors indicated that no substantial increases in suspended solids occurred at the pier. Observed tidal currents, seiches, wind waves, and vessel wakes did not cause substantial resuspension at the pier. Plumes of resuspended sediment generated by the cruise ship were not observed at the end of the pier during this deployment. U.S. Coast Guard personnel, however, said that they had observed plumes of resuspended sediment at the pier that had been generated by a different cruise ship that had ceased to call on the Port of St. Petersburg.

Turbidity During the Deployment Period

Analysis of water samples collected during instrument deployment indicates that turbidity increased, possibly as a result of runoff into the basin. The turbidity data collected at two depths at the pier during the instrument deployment period and the accumulated precipitation at the nearby Bayfront are shown in figure 4. Turbidity tended to increase slightly following periods of precipitation during the deployment period.

The turbidity at the instrument deployment site also varied during the tidal cycle and these variations indicate that the bay may have been slightly more turbid than the basin at the start of the deployment period. During a floodtide, water generally moves

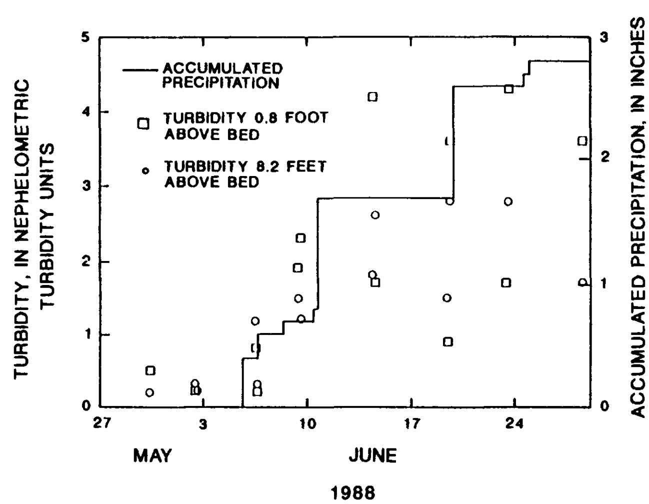


Figure 4. Turbidity and accumulated precipitation at the Port of St. Petersburg during the deployment of resuspension monitoring instrumentation.

landward, and during an ebbtide, water generally moves seaward. Thus, changes in turbidity at the pier during the tidal cycle may be caused by the arrival of water from either the bay during floodtide or the basin during ebbtide. If a turbidity gradient exists between the bay and basin, the tide will move this gradient back and forth and the turbidity variation at the pier during a tidal cycle can be used to estimate whether the bay or basin is more turbid. During instrument servicing and water-sampling trips, water samples were collected at the pier soon after project personnel arrived at the pier and shortly before they departed, so the samples were collected several hours apart and can be used to estimate whether the bay or basin was more turbid. Figure 4 shows that the turbidity data became more scattered during the deployment period, indicating that the tidal-cycle variation in turbidity increased during the deployment period. These data will be presented in detail and indicate that the bay may have been slightly more turbid than the basin at the start of the deployment period, but that the basin was more turbid by the end of the deployment period.

At the beginning of the deployment period, the turbidity at the pier was the lowest measured during the deployment period, and the change in turbidity during the tidal cycle was negligible. The relatively low turbidity may be due to relatively little runoff prior to the deployment period. During May 1988, the only measured precipitation at the Bayfront was 1.80 in. that fell on May 25. The first samples were collected on May 31. The bay and basin appeared to have virtually the same turbidity at the start of the deployment period. Two sets of samples were collected on June 3 for which the turbidities did not change from 0905 to 1315 hours despite a predicted floodtide (National Oceanic and Atmospheric Administration, 1987).

The turbidity and the range of values increased slightly on June 7 after 0.4 in. of rain on June 6. Middepth and bottom turbidities were measured twice on June 7, at 1105 and 1330 hours. The turbidity values ranged from 0.2 to 1.2 NTU and were lower during ebbtide than at high tide (fig. 5), which indicates that the turbidity increased in the seaward direction. The turbidity in the bay was apparently greater than that in the basin, probably because the rainfall did not cause enough runoff to immediately affect the turbidity in the basin. The same axes scales are used in figure 5 and similar subsequent figures to assist visual comparison. The water levels shown in figure 5 are predicted values from the National Oceanic and Atmospheric Administration (1987).

On June 10, 1988, the turbidity values again increased slightly after another 0.3 in. of rain on June 7 and June 9. The small increase in turbidity may have been caused by increased plankton productivity due to increased nutrients supplied by runoff or by turbid runoff in the basin, or both. Turbidities were measured at 0905 and 1305 hours and did not change significantly (fig. 6). Because of the intervening high tide at 1124 hours, the net tidal excursion during the period may have been small so that a turbidity gradient could not be observed. Another possibility is that the turbidity value in the basin had increased to the turbidity value in the bay so that no turbidity gradient was present.

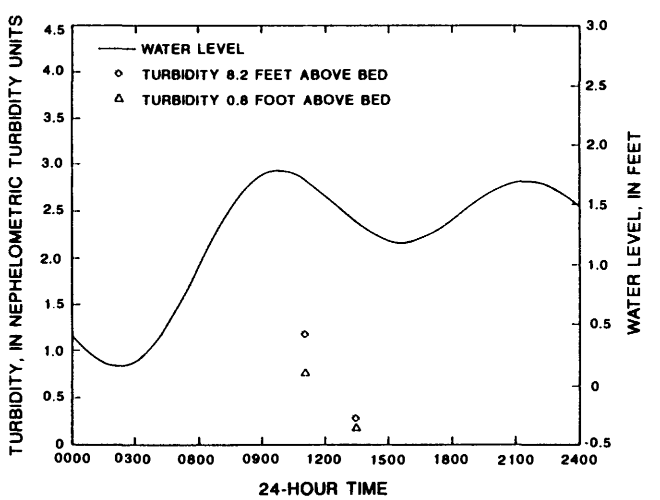


Figure 5. Measured turbidity and predicted water level, Port of St. Petersburg, June 7, 1988.

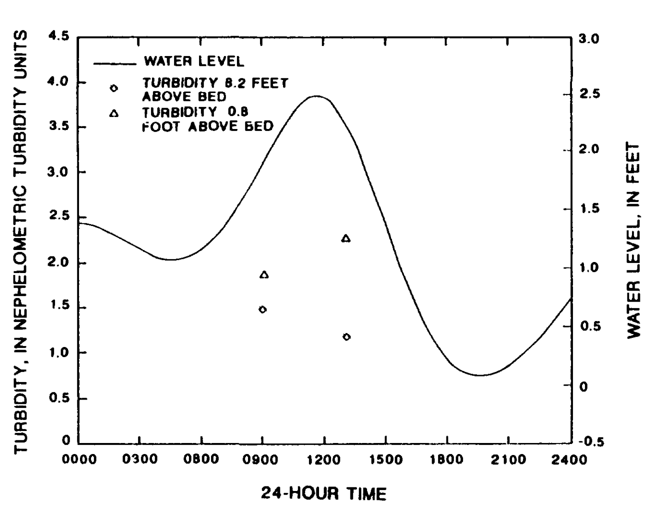


Figure 6. Measured turbidity and predicted water level, Port of St. Petersburg, June 10, 1988.

On June 15, 1988, four days after 1.00 in. of rain occurred in the basin, the turbidity values ranged from 1.7 to 4.2 NTU. From 0905 to 1305 hours on June 15 during a floodtide, the bottom turbidity decreased more than the middepth turbidity increased (fig. 7), which indicates that the mean turbidity probably decreased during the floodtide. Thus, turbidity apparently increased from the bay to the basin, whereas 8 days earlier, the turbidity apparently increased in the opposite direction.

There was no rain between June 15 and June 20, 1988, when the next samples were collected, and the turbidity decreased slightly. The decrease in turbidity may have been caused by differences in the tidal phase, the lack of additional rainfall, or mixing with less turbid bay water. Water samples were collected shortly after a high tide at 0905 hours and shortly after a low tide at 1305 hours (fig. 8). Turbidity increased during the intervening ebbtide, indicating that turbidity decreased in the seaward direction.

On June 24, 1988, four days after 0.9 in. of rain occurred, the turbidity values were slightly higher (1.7 to 4.3 NTU). Samples were collected shortly before a high tide at 0905 hours and during an ebbtide at 1305 hours (fig. 9). Turbidity increased during this period of predominantly ebbtide, indicating that basin turbidity was greater than bay turbidity.

Turbidity in the basin seems to correlate with rainfall and tidal phase. Turbidity increases after each storm and decreases during periods with no rainfall. Increased turbidity may be caused by turbid runoff entering the basin, or increased plankton productivity from an increased supply of nutrients, or both. A probable increase in water temperature, which was not measured but normally increases in Tampa Bay during June, may have contributed to the increased turbidity by increasing plankton productivity. The tidal-cycle variation of turbidity indicates that the bay may have been slightly more turbid than the basin at the start of the deployment period but that the basin was more turbid by the end of the deployment period. The differences in turbidity between specific samples are small, but the general trends of observed turbidity are consistent.

The concentration of total suspended solids did not show similar trends as those found for turbidity during the deployment period and during the tidal cycle. Poor correlation between suspended-solids concentration and turbidity in Tampa Bay at turbidities below 10 NTU has been observed by Goodwin and Michaelis (1984). This may be a result of the difficulty of measuring small differences in turbidity below 10 NTU and the sensitivity of low turbidity measurements to small differences in clay content.

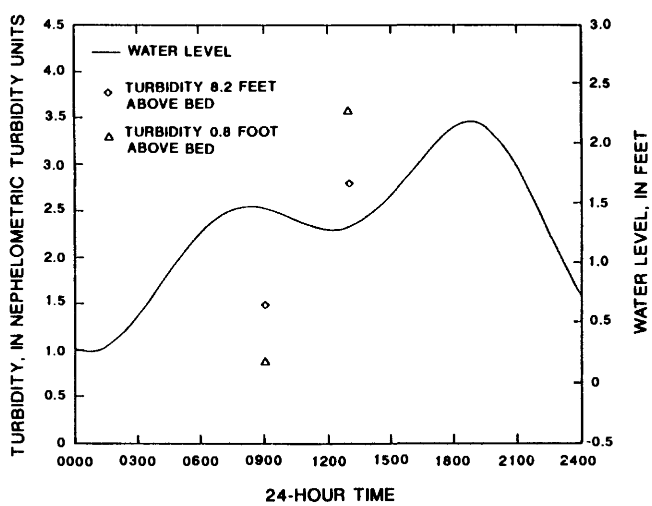


Figure 8. Measured turbidity and predicted water level, Port of St. Petersburg, June 20, 1988.

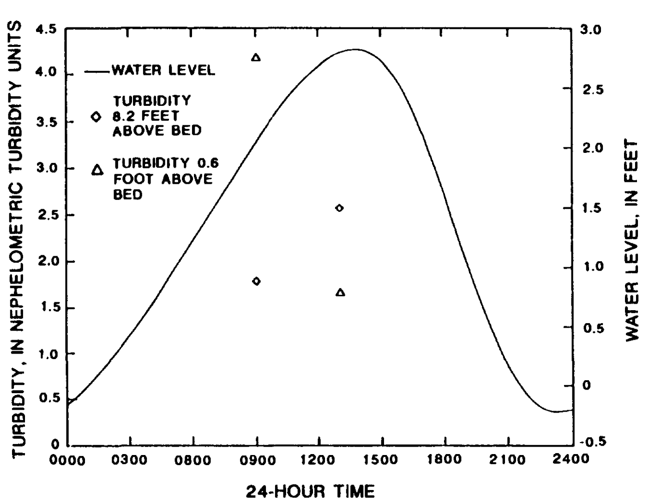


Figure 7. Measured turbidity and predicted water level, Port of St. Petersburg, June 15, 1988.

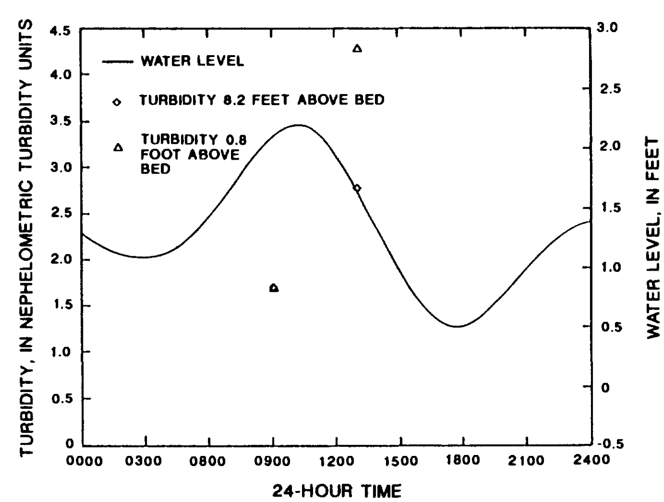


Figure 9. Measured turbidity and predicted water level, Port of St. Petersburg, June 24, 1988.

CRUISE SHIP DEPARTURE AND ARRIVAL SAMPLING RESULTS

Departure June 21, 1988

On June 21, 1988, water samples were collected and OBS measurements were made throughout the Port of St. Petersburg to monitor sediments resuspended during the departure of a cruise ship that set sail from the terminal at 1000 hours with the help of two tugboats (fig. 10). The background concentration of total suspended solids averaged about 21 mg/L throughout the basin before departure. The tugboats swung the bow into position for the cruise ship to leave the port under its own power shortly after 1020 hours. Normally, the tugboats are not used, but at the time, the side thrusters of the cruise ship were not operating (Tim Travis, Director, Port of St. Petersburg, oral commun., 1988). Water sampling and OBS measurements commenced in the port as soon as possible after the cruise ship departed. The sampling was conducted during an ebbtide, which decreased the water level in the basin about 0.5 ft from 0850 to 1203 hours.

Some resuspension of bottom sediments was caused by the displacement of water by the moving hull of the cruise ship. Resuspended sediments can be seen along the starboard side (right side of ship looking forward) of the ship at 1010 hours (fig. 10). This was probably caused by excess water on the port (left) side (the direction in which the ship was being pulled) rapidly flowing underneath the ship to the starboard side where water was needed to fill in the volume formerly occupied by the hull.

Propwash also apparently caused resuspension of bottom sediments. Shortly before 1010 hours, the cruise ship used its starboard propeller to provide a push to help the tugboats with the hard left turn needed to leave the port (Tim Travis, Director, Port of St. Petersburg, oral commun., 1988). A distinct plume of suspended sediments with clockwise rotation was formed shortly before 1010 hours. The plume can be seen drifting to the east near the northern seawall of the port in photographs taken at 1015 and 1020 hours (fig. 10). When the ship was leaving the basin at 1020 hours, a line of resuspended sediments could be seen astern. These sediments were probably resuspended by the propwash as the cruise ship accelerated. Another possibility is that the sediments were resuspended by high velocities under the cruise ship caused by hull displacement of water, but resuspension generated in this manner often is seen amidship, which was not apparent in the photograph taken at 1020 hours.

The output from the portable OBS sensor was calibrated with total suspended-solids concentrations in three background samples and eight postdeparture samples collected at various sites and depths within the basin. The relation between OBS output in millivolts and total suspended-solids concentration during the calibration process is shown in figure 11 (correlation coefficient $r = 0.948$). A least squares fit of the data gives a linear regression described by the equation

$$\text{total suspended solids (mg/L)} = 1{,}826 \bullet \text{OBS (volts)} + 28.55. \qquad (2)$$

The data used to develop the relation shown in figure 11 are distributed near and below a concentration of 50 mg/L, mainly because the backscatterance from suspended solids in the background samples did not exceed the response threshold of the OBS sensor. The OBS sensor seemed to produce reasonable results, however, when used to measure low concentrations of suspended solids after the bottom sediments had been resuspended and mostly settled, which indicates there were still enough suspended-sediment particles to backscatter a significant fraction of the OBS light pulse. Thus, the OBS sensor appears to have more success sampling low concentrations near the conclusion of settling than low ambient concentrations.

Some of the scatter shown in figure 11 also can be accounted for by the delay between the OBS measurement and the collection of the sample. The sampling procedure was to make a vertical OBS profile at a site and then collect a point sample at a certain depth, if desired. The OBS output sometimes varied rapidly because the sediment plume expanded horizontally and settled vertically. Thus, even a short delay between OBS measurement and sample collection could produce inconsistent results. Despite threshold and sampling difficulties, however, the resulting calibration was judged to be suitable for estimating total suspended-solids concentrations from OBS measurements.

Total suspended-solids concentrations at 5-ft vertical increments, as interpreted from the calibrated OBS output using equation 2, at sites 2, 3, 4, and 5 in the port (see fig. 2) are shown in figures 12 through 15, respectively. These figures have the same vertical and horizontal scales and the duration of the cruise ship departure is shown.

Figure 10. Cruise ship departure and associated sediment resuspension, June 21, 1988.

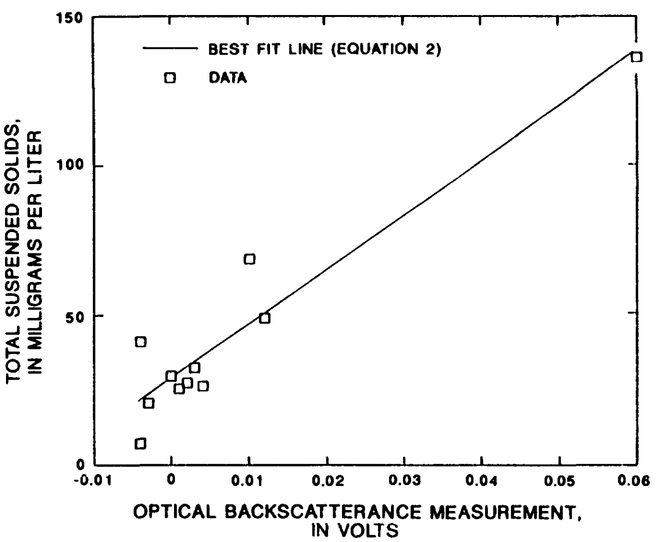


Figure 11. Calibration of optical backscatterance sensor, Port of St. Petersburg, June 21, 1988.

Site 2 had the greatest concentration of total suspended solids because it was nearest the path of the ship and it was sampled only 3 minutes after the ship had passed. At 1020 hours, the water column at this site had a fairly uniform total suspended-solids concentration of about 125 mg/L (fig. 12). At 1035 hours, the material was settling and the suspended-solids concentration estimated from the OBS measurement 20 ft below the surface had increased slightly. A water sample from this depth had a suspended-solids concentration of 136 mg/L. The concentration decreased with distance above the bed and the concentration 5 ft below the surface had almost returned to the background level. At 1048 hours, suspended-solids concentrations at site 2 had decreased to a range of 25 to 50 mg/L. For the measurement at 1059 hours and for subsequent measurements, the concentrations of suspended solids, as estimated from OBS measurements, were slightly above the background level, and the vertical distribution of suspended solids in the water column was fairly uniform.

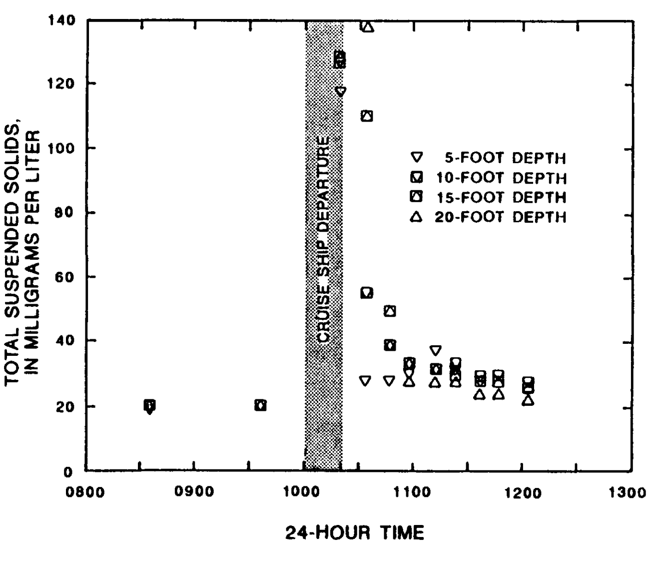


Figure 12. Total suspended solids at site 2, Port of St. Petersburg, June 21, 1988.

Site 3 also was near the path of the cruise ship, but the elapsed time (10 minutes) from the passage of the ship to the initial sample (at 1022 hours) was greater than that for site 2. The maximum concentration of suspended solids at site 3 (70 mg/L) was about half that measured at site 2. At 1022 hours, the total suspended-solids concentration increased from about 40 mg/L 5 ft below the water surface to about 60 mg/L 20 ft below the water surface. At 1037 hours, concentrations 15 and 20 ft below the surface increased slightly, possibly due to settling and to dispersion of the sediment plume into the corner of the basin. After 1101 hours, vertical distribution of suspended solids was fairly uniform and the concentration decreased asymptotically toward the background level. The asymptotic decrease in concentration at site 3, as compared to the more rapid decrease at site 2, may have been related to the fact that site 3 was located near the corner of the basin and farther from the channel than site 2. Thus, after initial mixing, advection and dispersion at site 3 are expected to be limited, compared to site 2, so settling is the primary mechanism for plume dissipation at site 3.

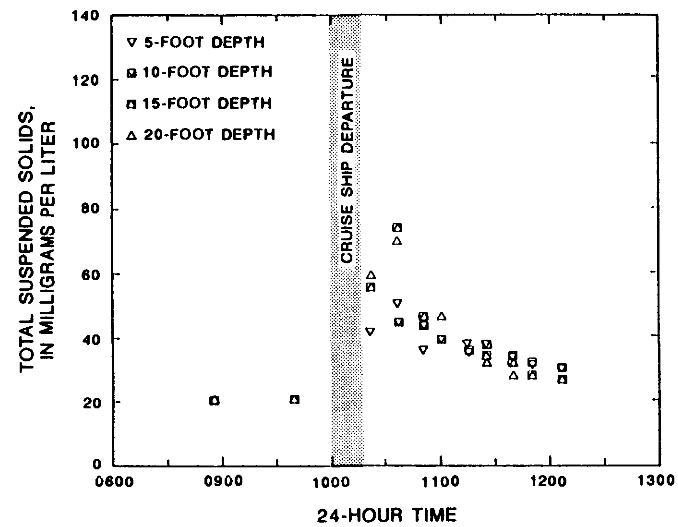


Figure 13. Total suspended solids at site 3, Port of St. Petersburg, June 21, 1988.

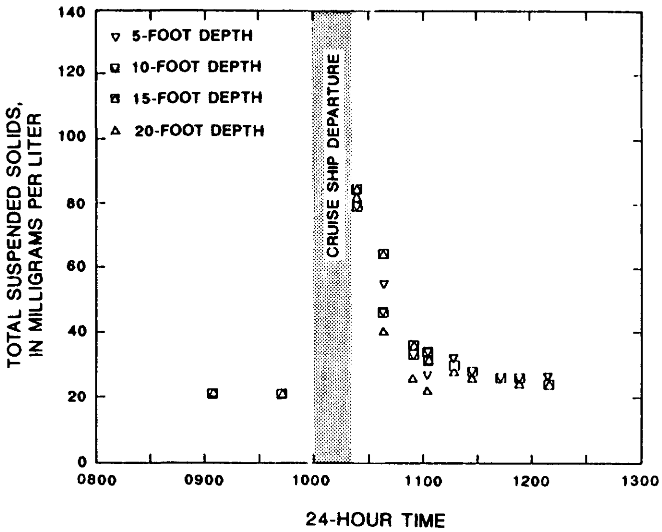


Figure 14. Total suspended solids at site 4, Port of St. Petersburg, June 21, 1988.

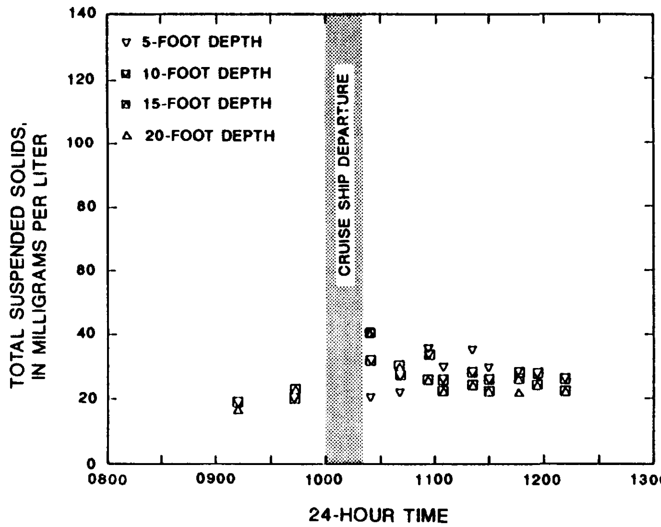


Figure 15. Total suspended solids at site 5, Port of St. Petersburg, June 21, 1988.

The theory that settling is the only significant plume dissipation mechanism after 1101 hours at site 3 can be checked by applying the settling equation for a vertically averaged water column

$$\frac{\partial C}{\partial t} = -\frac{w}{d}C \qquad (3)$$

in which C is the suspended-solids concentration, t is time, w is settling velocity, and d is the depth (Mehta and others, 1984). The solution of this first-order ordinary differential equation is

$$C = C_o \exp\left(-\frac{w}{d}\Delta t\right) \qquad (4)$$

in which C_0 is the initial concentration and Δt is the elapsed time. The suspended-solids concentrations at 1101 hours are the first set of nearly vertically well-mixed data, so it will be used as the initial condition. The depth was approximately 24.2 ft.

Equation 4 can be solved for the settling velocity, w, and mean suspended particle size, D. Assuming that the particles are spherical, the settling velocity can be related to the particle size by Stokes law,

$$D = \left(\frac{18\,\mu\, w}{g(\rho_s - \rho_w)}\right)^{1/2} \qquad (5)$$

in which μ is the dynamic viscosity of water (0.00894 (g/cm)/s at 25 °C), g is gravitational acceleration (980 cm/s^2), ρ_s is the density of the solid assumed to be 2.65 g/cm^3, and ρ_w is the density of water assumed to be 1.02 g/cm^3 (Simons and Senturk, 1977). Table 2 lists the time of day, elapsed time since 1101 hours, average concentration from four OBS readings at 5-ft vertical increments, the computed settling velocity during the elapsed time, and the computed mean particle size that settled during the elapsed time. The settling velocity and mean particle size decrease with time, as is expected. As listed in table 1, the mean particle size is 100 µm, and 39 percent of the bottom sediment at site 3 is finer than 63 µm. The computed particle sizes are smaller than 100 µm because particles larger than 31 µm probably settled before 1101 hours when the preceding calculations were not applicable because dispersion was probably not negligible and the water column was not vertically well mixed. The theoretical particle size calculated from observed vertical concentration profiles at site 3 compare reasonably well with the observed particle size of the bottom material, and, thus, settling seems to be the dominant process at site 3 after 1101 hours. This analysis procedure was not as

Table 2. Computed settling velocities and mean settled particle size at site 3, Port of St. Petersburg, June 21, 1988
[mg/L, milligrams per liter; ft/min, feet per minute]

Time	Elapsed time (minutes)	Concentration (mg/L)	Settling velocity (ft/min)	Mean settled particle size (microns)
1101	0	41.3	-	-
1116	15	36.8	0.186	30.9
1126	25	34.9	.163	28.9
1140	39	32.2	.154	28.1
1151	50	30.4	.148	27.5
1207	66	28.5	.136	26.4

successful at the other sites because the water column was not well mixed or advection or dispersion were significant processes.

The distinct plume generated by the propwash of the cruise ship passed site 4, which is south of the bow of the largest vessel docked on the northern seawall of the port (fig. 10). Samples were obtained at 1024 hours when the edge of the plume generated by the starboard propeller of the cruise ship reached site 4. Thus, the concentration of total suspended solids at 1024 hours of about 80 mg/L is the highest concentration observed at site 4. The plume probably contained a much higher initial concentration because it had been generated about 15 minutes beforehand. Because of inertia and an ebbtide, the plume continued to drift to the east, and the concentration of total suspended solids at site 4 decreased rapidly.

Little or no noticeable resuspension of bottom sediments occurred at several sites. At site 5, which was not adjacent to any of the primary resuspension locations, the increase in total suspended-solids concentration after departure of the cruise ship was less than 20 mg/L (fig. 15). The small increases were probably caused by dispersion of resuspension plumes. There was no substantial increase in the concentration of total suspended solids at either site 1, at the western boundary of the port, or site 6, at the eastern boundary of the port and at the outlet to Tampa Bay.

The results of the suspended-solids analyses and OBS measurements indicate that the sediments that were resuspended by the cruise ship departure remained in the port. Figures 12 through 15 show that, by 1200 hours, most of the resuspended sediment had settled to the bottom of the port and suspended-solids concentrations at all sites had virtually returned to the background levels observed before departure. The lack of a substantial increase in suspended-solids concentration at site 6 indicated that the observed ebbtide did not generate sufficient velocities to transport resuspended sediments out of the basin and into Tampa Bay.

Arrival May 18, 1990

On May 18, 1990, water samples were collected for suspended-solids analysis, and OBS measurements were made to monitor sediments resuspended by the arrival of a cruise ship at the Port of St. Petersburg. Before the arrival of the ship, background total suspended-solids concentrations in the basin ranged from 8 to 28 mg/L. At 1700 hours, the cruise ship entered the basin from the east at a speed of approximately 6 knots. At 1703 hours, the cruise ship was turning to starboard (right) as it exited the channel and entered the port (fig. 16). Propwash or large return velocities under the ship had generated a narrow line of resuspended sediments (fig. 16) as the ship moved through the channel. At about this time, the cruise ship reversed its starboard propeller to slow down and to help execute the sharp turn.

At 1706 hours, the cruise ship had completed a 180-degree turn and was reversing its engines to back into the cruise terminal near the northwestern corner of the port. A plume of resuspended sediment off the stern (rear) and forward of the stern on the starboard side was observed. The plume was probably caused by the propwash of the reversing engines. The lack of a plume on the port side may have been due to greater or exclusive reversal of the starboard propeller to assist with the turn and hull displacement of water as the stern swung toward the northwest as the ship backed into the terminal.

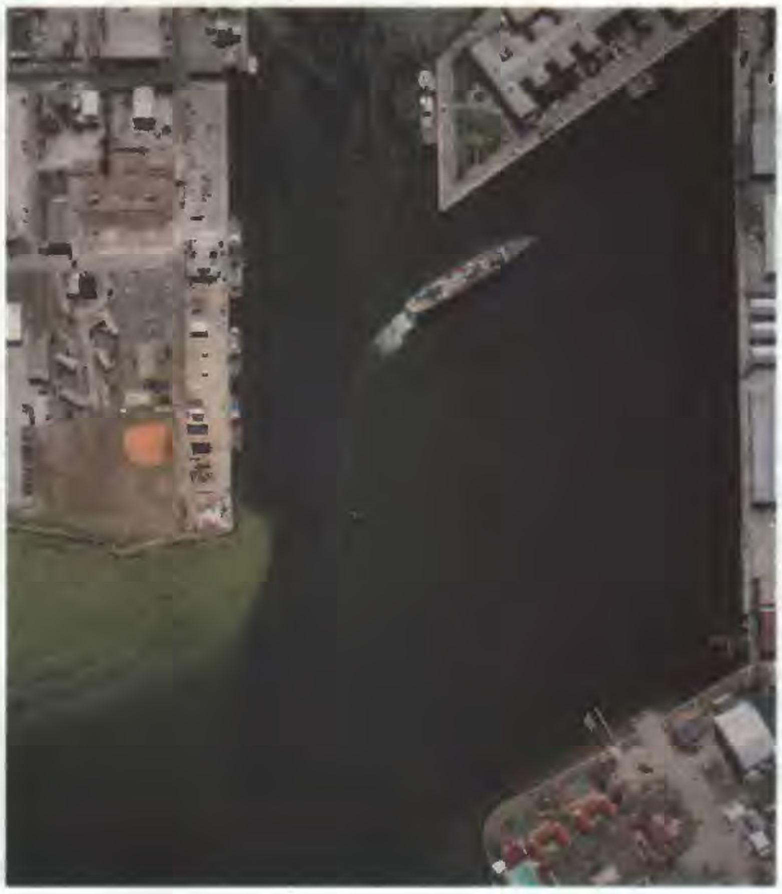
Personnel in the sampling boat observed that the water in the vicinity of the stern of the cruise ship was brown with sediment and that there was an odor that had been detected previously during collection of bottom-sediment samples in the basin. Neither discoloration of the water nor odor was noticed during the departure of the cruise ship in 1988. At 1711 hours, the cruise ship had virtually completed its docking maneuvers, but a plume of resuspended sediments remained in the area (fig. 16). The sampling boat was at site 3 where the edge of the plume could be clearly identified.

Sampling and measurements commenced at sites 1 through 6 (fig. 2) as soon as possible after the cruise ship had passed and continued until 1849 hours. A weak floodtide occurred during the sampling period.

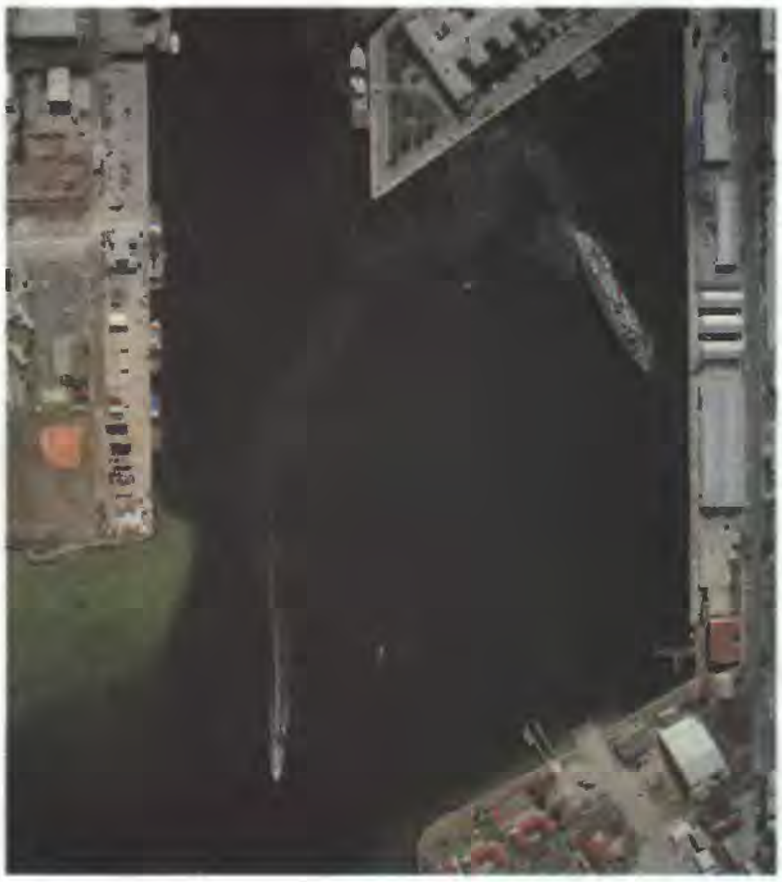
The output from the portable OBS sensor was calibrated with total suspended-solids concentrations in 15 samples collected at various times, sites, and depths in the port. The relation between total suspended-solids concentration and OBS output voltage is shown in figure 17 (correlation coefficient $r = 0.985$). A least squares fit of the data gives a linear regression described by the equation

$$\text{total suspended solids (mg/L)} = 1{,}600 \cdot \text{OBS (volts)} + 9.33. \qquad (6)$$

The relation between OBS values and total suspended-solids concentrations for the cruise ship departure (eq. 2) differs from that for the cruise ship arrival (eq. 6) because the portable OBS electronics were adjusted



1703
hours



1706
hours

1711
hours

Figure 16. Cruise ship arrival and associated sediment resuspension, May 18, 1990.

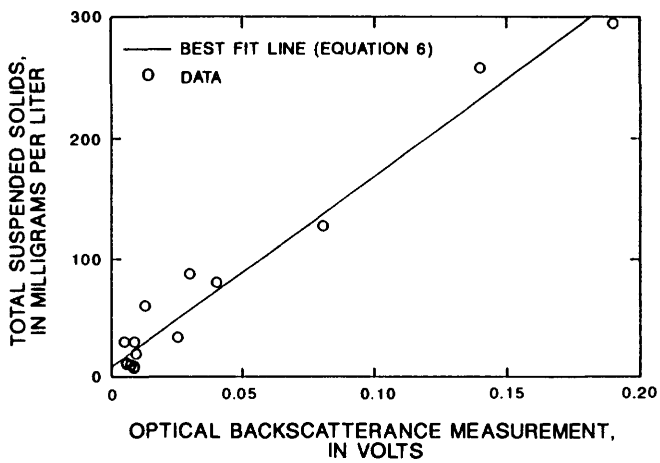


Figure 17. Calibration of optical backscatterance sensor, Port of St. Petersburg, May 18, 1990.

between the two sampling efforts. As mentioned previously, low ambient concentrations and difficulty in collecting the same water as the OBS sensor measures can produce inconsistent results. Despite threshold and sampling difficulties, however, the resulting relation was fairly linear and was considered suitable for estimating total suspended solids from the measured OBS profiles.

The total suspended solids at 5-, 10-, and 15-ft depths, as interpreted from the calibrated OBS output with equation 6, at sites 3 and 4 in the port (see fig. 2) are shown in figures 18 and 19, respectively. These figures have the same vertical and horizontal scales and the duration of the cruise ship maneuvering upon arrival is shown.

Site 3 was closest to the area where the cruise ship reversed its engines and had the highest concentrations of suspended solids. At 1711 hours, a brown sediment was clearly visible at the water surface. A water sample collected 5 ft below the water surface at this site had a concentration of suspended solids of 127 mg/L, and the OBS sensor indicated that the suspended-solids concentrations were 140, 130, and 220 mg/L at depths of 5, 10, and 15 ft, respectively. After the cruise ship docked, the suspended-solids concentration at site 3 increased between 1711 and 1717 hours indicating that the highest concentrations in the sediment plume were not exactly at site 3 and that the sediment plume was expanding. At 1717 hours, a water sample collected 5 ft below the water surface had a concentration of 296 mg/L, and the OBS measurement at that depth indicated a concentration of 310 mg/L (fig. 18). This was the highest concentration sampled in the basin during the cruise ship arrival and was more than twice the highest concentration sampled during the departure of the cruise ship in 1988 (136 mg/L). The concentrations at site 3 decreased between 1717 and 1722 hours and at 1722 hours ranged from 170 to 230 mg/L. The suspended-solids concentrations at site 3 were varying rapidly as the plume expanded by dispersion, mixed with ambient water, and settled. From 1722 to 1734 hours, the concentrations decreased to a range of 40 to 75 mg/L, probably because of a combination of settling and dispersion. At 1748 hours, the rate of decrease in concentrations had slowed as the concentrations approached background levels. An unusual feature of

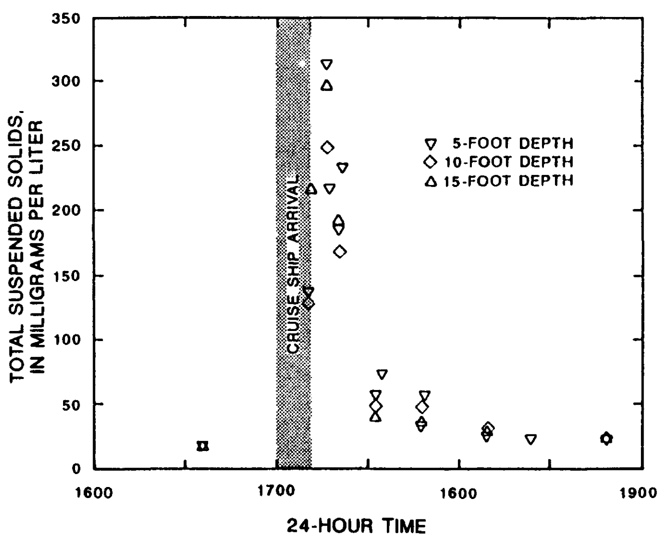


Figure 18. Total suspended solids at site 3, Port of St. Petersburg, May 18, 1990.

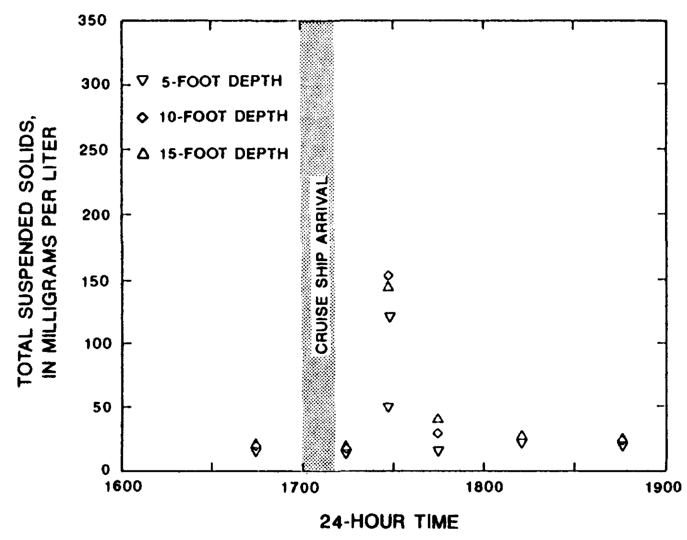


Figure 19. Total suspended solids at site 4, Port of St. Petersburg, May 18, 1990.

the total suspended-solids concentrations at site 3 from 1717 to 1748 hours is that the concentration generally was higher near the water surface and lower near the bottom. Stronger advection and dispersion near the surface may account for these concentration profiles. After 1800 hours, the concentrations virtually returned to background levels.

The theoretical Stokes law settling calculation (eqs. 4 and 5) performed for the departure of the cruise ship was difficult to repeat for the arrival data because the water column was not homogeneous until 1810 hours. Using the average suspended-solids concentration at 1810 hours of 30 mg/L as the initial condition for settling, the 1849 hour average concentration of 24 mg/L gave a settling velocity of 0.137 ft/min during the period. The mean settled particle size during the period was 26.5 μm, which is in agreement with the finer part of the observed bottom sediment size distribution (table 1) and with the settled particle sizes calculated for the departure of the cruise ship (table 2). Thus, as with the cruise ship departure, the assumption that settling was the dominant plume dissipation process at site 3 is valid about 1 hour after the cruise ship had resuspended the bottom sediments.

Site 4 was east of the origin of the main plume of resuspended sediment, so the resuspended sediment did not arrive at site 4 for several minutes. The resuspended sediment had not reached site 4 at 1715 hours, and the suspended-solids concentration, as estimated from the calibrated OBS sensor, was about 20 mg/L (fig. 19). At 1729 hours, however, the plume had spread by dispersion, and the concentrations ranged from 50 to 150 mg/L in the water column and were varying rapidly at this site. By 1745 hours, the suspended-solids concentrations had decreased and were between 15 and 40 mg/L. After 1800 hours, concentrations had virtually returned to background levels.

Resuspension caused by the cruise ship was much less evident at the other sampling sites. OBS measurements at site 1 at the western boundary of the port at 1759 and 1840 hours indicated a slight increase in the suspended-solids concentration 15 ft below the water surface (19-30 mg/L). A water sample collected 15 ft below the water surface at 1802 hours had a suspended-solids concentration of 58 mg/L. At site 2, the suspended-solids concentrations were not more than 10 mg/L above the background concentrations. At site 5, OBS measurements at 1811 and 1844 hours were at background levels. At site 6, the eastern boundary of the basin in the channel, OBS measurements 15 ft below the water surface at 1705 hours indicated that the suspended-solids concentration was varying from 20 to 140 mg/L because of the passage of the cruise ship and resuspension in the entrance channel. No resuspended sediment was detected 5 or 10 ft below the water surface at site 6. After 1800 hours, OBS measurements indicated that the suspended-solids concentrations at site 6 were virtually at background levels. The results indicate that the large plume of resuspended sediments observed at sites 3 and 4 did not enter the harbor to the west or Tampa Bay to the east.

CALCULATED SEDIMENTATION RATES IN THE PORT

The areas of shoaling and deepening and sedimentation rates were calculated within a quadrilateral subarea of the deeper part of the port from bathymetric surveys conducted in 1981, 1986, 1987, and 1989. The quadrilateral subarea was selected for study because some of the surveys did not include all of the basin and most of the surveys had limited data in shallow water. A three-dimensional view of the 1981 bathymetry of the port and the quadrilateral subarea is shown in figure 20. The flat, elevated parts of figure 20 represent land (see fig. 2). All of the bathymetric surveys have complete coverage within the quadrilateral. The coordinates of the four corner points of the quadrilateral, using the Cartesian (x,y) coordinate system of the 1981, 1986, and 1987 surveys, which are in units of feet, are northwest (6676, 906), northeast (5663, 906), southeast (4824, 167), and southwest

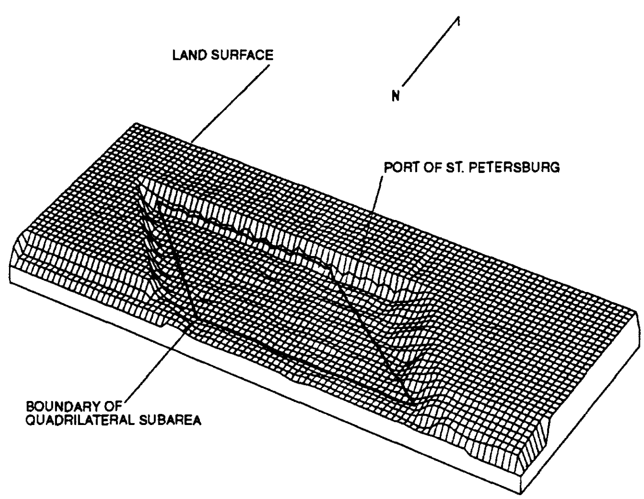


Figure 20. April 1981 bathymetric data and the quadrilateral subarea for bed elevation change calculations, Port of St. Petersburg.

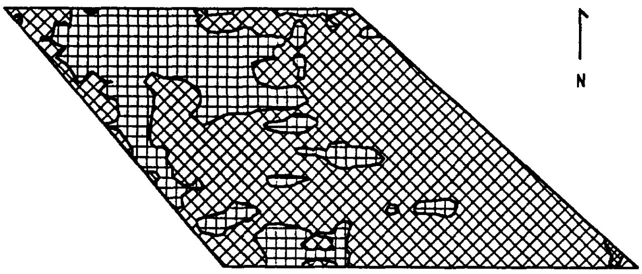


Figure 21. Bed elevation changes in quadrilateral subarea, April 1981 to September 1987.

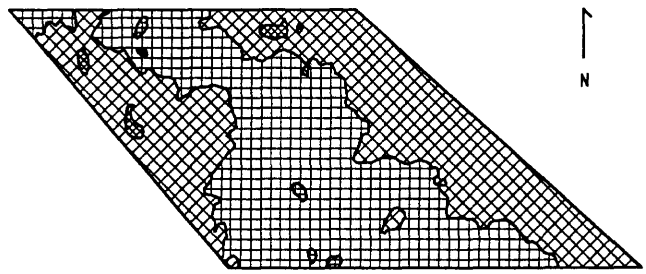


Figure 22. Bed elevation changes in quadrilateral subarea, September 1987 to spring 1989.

(6037, 167). The x coordinate is positive to the west, and the y coordinate is positive to the north. The area of the quadrilateral is 822,507 ft^2.

The change in bottom elevation within the quadrilateral from April 1981 to September 1987 is shown in figure 21. Less than 4 ft of shoaling occurred in most of the quadrilateral, the exceptions being the area adjacent to the cruise-ship terminal (upper left on fig. 21), which deepened, and some small, isolated areas that shoaled more than 4 ft. Cruise ships probably called on the port no more frequently than once a week during this period. Daily cruises from the port did not begin until December 1987.

The change in bottom elevation within the quadrilateral from September 1987 to spring 1989 is shown in figure 22. During the 1987-89 period, the bed elevation decreased along the path of the cruise ship, forming a shallow channel from the cruise ship terminal to the southern boundary of the quadrilateral. The bed elevation decreased more than 4 ft in parts of this channel during the period, and the greatest deepening occurred adjacent to the cruise-ship terminal, possibly because of engine reversal by the cruise ship during docking operations. Shoaling seemed to increase with distance from the channel and accounted for increases in bed elevations of more than 4 ft in a few small areas during this period. This redistribution of sediment in the quadrilateral was probably caused by the almost daily cruises from the port during this period.

The average change in bed elevation within the quadrilateral during the periods between surveys was calculated. The average bed elevation inside the quadrilateral increased 1.4 ft with a rate of change of 0.3 ft/yr from April 1981 to January 1986. The average bed elevation inside the quadrilateral decreased 0.5 ft with a rate of change of -0.3 ft/yr from January 1986 to September 1987. The average bed elevation inside the quadrilateral increased 0.1 ft with a rate of change of less than 0.1 ft/yr from September 1987 to spring (April) 1989. All calculations are reported to the nearest 0.1 ft because this was the precision of the bathymetric survey data. An error in transferring the field data to the correct datum would significantly affect these results, although there is no evidence an error was made.

The analysis of this change in bed elevation data was complicated by the probability of net transport of sediment between the quadrilateral and the shallower part of the port outside the quadrilateral. The increase in bed elevation after the 1981 postdredging survey could have been caused by sliding of shallower sediments outside the quadrilateral into the newly dredged part of the port. A possible explanation for the decrease in bed elevation inside the quadrilateral during 1986 and 1987 is that the sides of the port had stopped sliding and the deep bottom sediments were consolidating. Little change in the average bed elevation occurred inside the quadrilateral despite the bathymetric changes from 1987 to 1989 (fig. 22); perhaps the bed sediment had reached a state of dynamic equilibrium in the late 1980's. Because there is no major source of sediment to the port and there has been little change in bed elevation since daily cruises from the port began in December 1987, the sediments resuspended by the cruise ship seem to remain in the port.

TRIBUTARY STORM DISCHARGE SAMPLING RESULTS

On November 9, 1989, tributary storm discharge and water-quality data were collected at sites on Booker and Salt Creeks. Water-quality data also were collected at several sites in Bayboro Harbor. This sampling and data-collection effort was conducted to study the effects of runoff from a storm on water quality in Bayboro Harbor. The storm produced 0.50 in. of rain at the St. Petersburg Bayfront Center approximately 0.5 mi north of the sampling sites between 0700 and 1000 hours.

Booker Creek Discharge

The initial observations and measurements of velocity in Booker Creek at approximately 0920 hours showed virtually no net discharge under the Third Street bridge (site A, fig. 2). The floodtide that preceded a high tide at about 1100 hours apparently offset the freshwater inflow from Booker Creek. Thus, no significant storm discharge flowed past the bridge until the intensity of the floodtide diminished shortly before high tide. At approximately 1030 hours, a significant discharge from Booker Creek began to flow into the harbor.

Calculation of discharge from Booker Creek was complicated by both density stratification and unsteady flow. The channel cross section and velocity measurements made between 1055 and 1200 hours are shown in figure 23. A bridge pier is at the center of the channel. Booker Creek was stratified with a thin layer (about 1.5 ft) of freshwater flowing over relatively stagnant saltwater. The density stratification was confirmed by point samples collected from the deepest part of the creek at 1530 hours. The specific conductance was 2,730 and 38,400 µS/cm at 1 and 3 ft below the water surface, respectively. Because of tidal action and storm runoff, the velocities in Booker Creek were unsteady. Figure 24 shows that the velocities at 0.2 of the total depth below the water surface at the deepest part of the channel decreased almost linearly during runoff; therefore, the velocities shown in figure 23 are not an instantaneous "snapshot" of the flow in the creek. Under these conditions, accurate calculation of instantaneous discharge from data collected over a period of about 1 hour is not possible.

Because of the stratification, it was necessary to estimate the discharge from an effective depth of flow, below which the velocity was assumed to be negligible, and near-surface velocity measurements (usually taken at 0.2 of the total depth) according to the equation

$$Q_{fw} = \sum_{i=1}^{N} (d_e\, b\, v_s)_i \qquad (7)$$

in which d_e is the effective flow depth in subarea i, b is the width of subarea i, v_s is the near-surface velocity in subarea i, and N is the number of subareas in the total cross section. An effective depth of 1.5 ft was selected for the velocity measurements shown in figure 23. The estimated freshwater discharges are shown in figure 25 as a function of the time of day

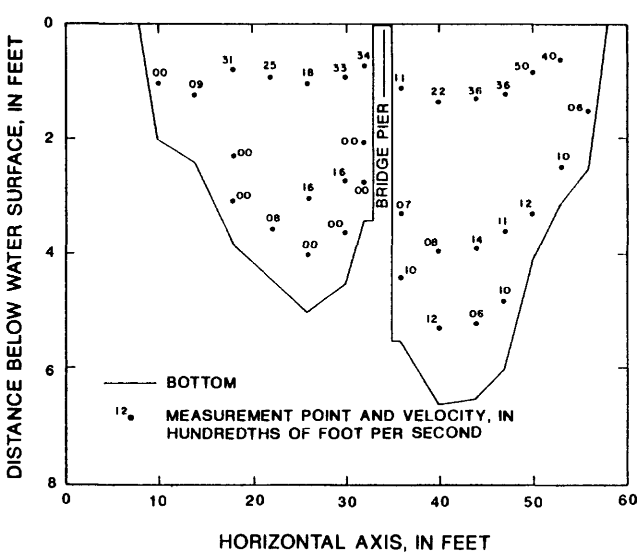


Figure 23. Velocities in Booker Creek at the Third Street bridge, 1055 to 1200 hours, November 9, 1989.

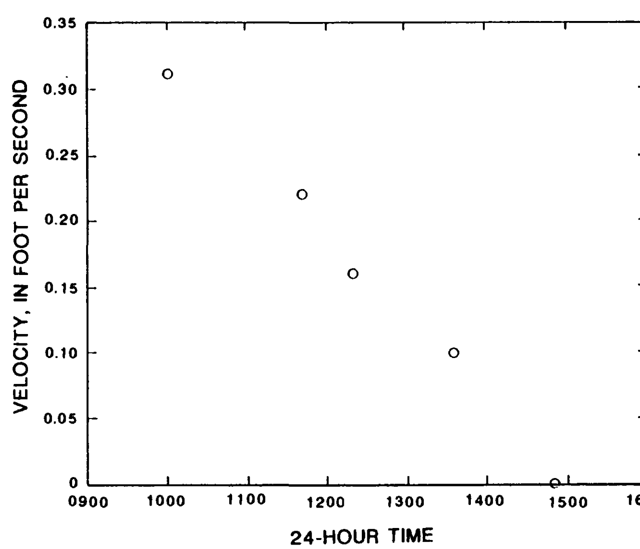


Figure 24. Velocities at 0.2 depth at the deepest part of Booker Creek at the Third Street bridge, November 9, 1989.

$$f = \frac{C - C_{fw}}{C_{sw} - C_{fw}} \qquad (8)$$

in which C is the depth-integrated specific conductance, C_{fw} is the specific conductance of freshwater, and C_{sw} is the specific conductance of saltwater (41,300 μS/cm). The specific conductance of freshwater is assumed to be 2,730 μS/cm, the value of the sample collected 1 ft below the water surface at 1530 hours. Again applying mixing theory, the freshwater turbidity (T_{fw}) can then be determined from the fraction of saltwater at the Booker Creek site (f) and the turbidity of the saltwater (T_{sw}) using the equation

$$T_{fw} = \frac{T - fT_{sw}}{1 - f} \qquad (9)$$

in which T is the depth-integrated turbidity and T_{sw} is assumed to be 1.0 NTU, the lowest value measured in the harbor. The estimated freshwater turbidities during the sampling period, which were calculated in this manner, are shown in figure 28. The estimated freshwater turbidity was approximately 20 NTU prior to 1500 hours when it decreased to about 12 NTU. This estimated value is in good agreement with the turbidity of a sample collected 1 ft below the surface at 1530 hours (10 NTU). The estimated freshwater turbidity at 0945 hours (5.0 NTU) is relatively low because the turbidity of the depth-integrated sample is relatively low (1.2 NTU, fig. 27) and is nearly equal to the assumed seawater turbidity (1.0 NTU).

Depth-integrated suspended-solids concentrations in Booker Creek at the Third Street bridge did not coherently vary in time and did not correlate with

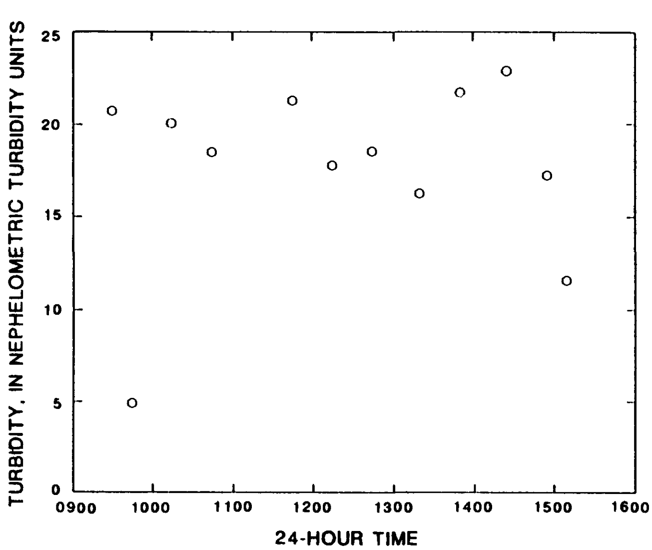


Figure 28. Estimated freshwater turbidity in Booker Creek at the Third Street bridge, November 9, 1989.

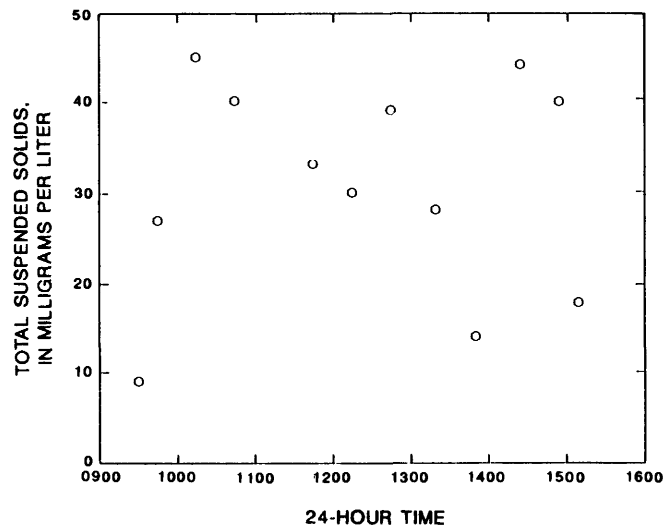


Figure 29. Depth-integrated total suspended solids in Booker Creek at the Third Street ' -idge, November 9, 1989.

either freshwater runoff or turbi / (fig. 29). As mentioned previously, poor cor ition between suspended-solids concentratior id turbidity in Tampa Bay at turbidities belov J NTU has been observed previously (Goodwi nd Michaelis, 1984).

Salt Creek Discharge

The discharge from Salt Creek (site B, fig. 2) during the sampled November 9, 1989, runoff was greatest around 1200 hours. Because of the variability in discharge, the starting and concluding times of the seven discharge measurements are shown in figure 30, similar to figure 25 for the discharge from Booker Creek. A high tide occurred at about 1100 hours, slightly before the Salt Creek discharge measurements began. The high tide delayed the freshwater runoff at Booker Creek, but the extent to which this occurred at Salt Creek is unknown because of the later initial measurements. The discharge from Salt Creek was larger than the Booker Creek discharge and decreased during the afternoon ebbtide.

Salt Creek was partially stratified and did not have a well-defined layer of stagnant saltwater near the bed as did Booker Creek. The near-bed velocities at 0.8 of the depth at Salt Creek were usually nonzero, although the near-bed velocities generally decreased more during the afternoon than did the near-surface velocities at 0.2 of the depth. The 0.2 and 0.8 of depth velocities 35 ft from the north bank of Salt Creek are

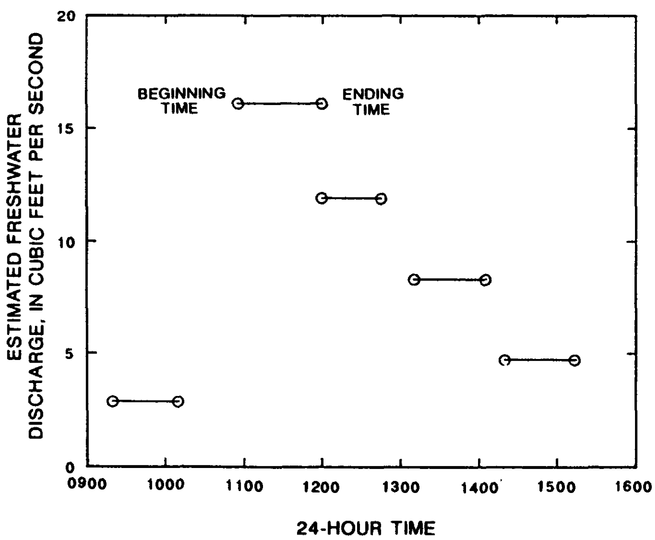


Figure 25. Estimated freshwater discharge of Booker Creek at the Third Street bridge, November 9, 1989.

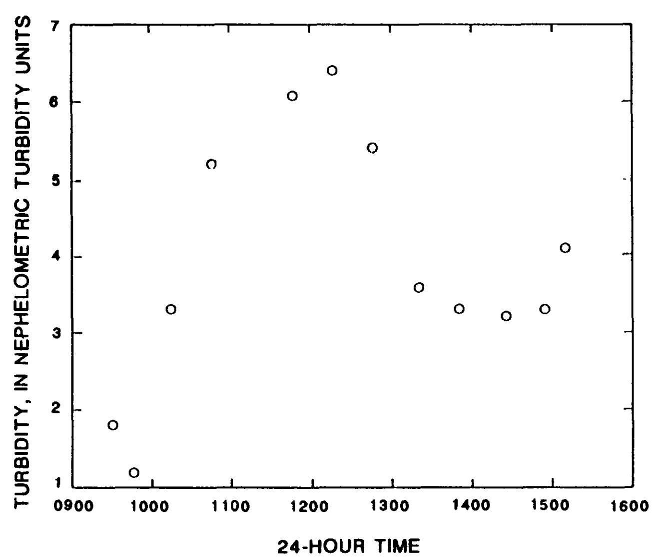


Figure 27. Depth-integrated turbidity of Booker Creek at the Third Street bridge, November 9, 1989.

during which the velocity measurements were taken. For example, the data from 1200 to 1245 hours produced an estimated freshwater discharge of about 12 ft^3/s, but the instantaneous discharge at 1200 hours was probably greater than 12 ft^3/s, and the instantaneous discharge at 1245 hours was probably less than 12 ft^3/s. The estimated freshwater discharge peaked rapidly as the floodtide slackened before 1100 hours and then steadily declined.

Freshwater discharge from Booker Creek increased dramatically as the floodtide slackened and reversed. Before 1000 hours, the depth-integrated

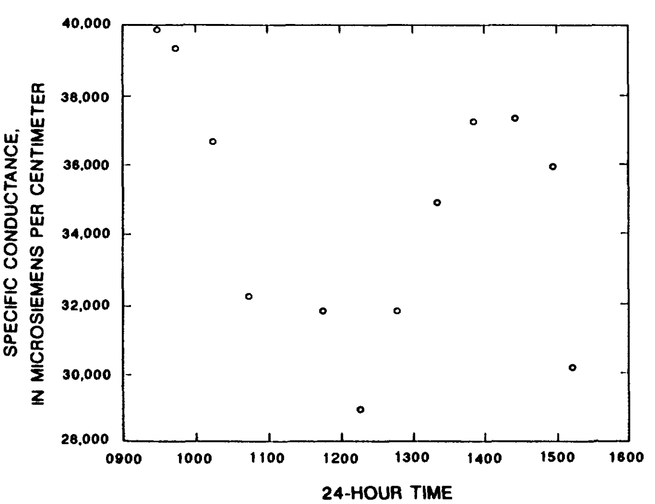


Figure 26. Depth-integrated specific conductance of Booker Creek at the Third Street bridge, November 9, 1989.

specific conductance indicated that the water under the Third Street bridge at Booker Creek was predominantly saltwater. The depth-integrated specific conductance at the site was 39,900 µS/cm at 0920 hours. This value was only slightly less than the specific conductance of 41,300 µS/cm measured at site E, the most seaward sampling site, which is assumed to be equal to the specific conductance of seawater for this study. Although the rain had been falling for about 2 hours, the specific conductance at 0920 hours indicates that the floodtide delayed the introduction of freshwater runoff from Booker Creek into the harbor. The depth-integrated specific conductance at the Third Street bridge decreased to a minimum of 29,000 µS/cm at 1215 hours because of dilution from freshwater runoff and then increased as the freshwater runoff decreased in the afternoon (fig. 26).

The depth-integrated turbidity was inversely related to the specific conductance. The depth-integrated turbidity increased during the morning hours, as the ratio of freshwater to saltwater increased (fig. 27). The turbidity decreased and the specific conductance increased in the afternoon. At 1530 hours, point samples indicated that turbidity 1 and 3 ft below the water surface was 10 and 2.1 NTU, respectively. Thus, the freshwater runoff was more turbid than the saltwater.

The turbidity of the freshwater runoff in Booker Creek at the Third Street bridge can be estimated from the depth-integrated specific conductance and turbidity data. From mixing theory, the fraction of saltwater at the Booker Creek site is defined by the equation shown in figure 31. The near-bed velocities in Booker Creek were almost exclusively zero. Water samples collected at 1550 hours from the deepest part of Salt Creek indicated that specific conductance was 32,800 μS/cm at the water surface and 38,700 μS/cm 1 ft above the bed. These samples confirm that Salt Creek was partially stratified and the magnitude of the stratification was much less than in Booker Creek.

The depth-integrated specific conductance in Salt Creek at the Third Street bridge decreased during the early afternoon ebbtide (fig. 32) as the fraction of freshwater at the site increased. In order to analyze why the fraction of freshwater at the site increased, it is assumed that there were three types of water at the site: saltwater from the bay, freshwater from Lake Maggiore, and freshwater runoff from the storm. If the maximum storm runoff occurred at about the same time in Salt Creek as in Booker Creek, between 1100 and 1200 hours, then the amount of freshwater from storm runoff in Salt Creek decreased during the afternoon. As the tide begins to ebb in the late morning and early afternoon, the amount of saltwater from the bay in Salt Creek decreased and the amount of freshwater from Lake Maggiore increased. The net result of having less freshwater from runoff, more freshwater from Lake Maggiore, and less saltwater from the bay at the site is an increase in the fraction of freshwater. Therefore, salinity and specific conductance decrease during the early afternoon.

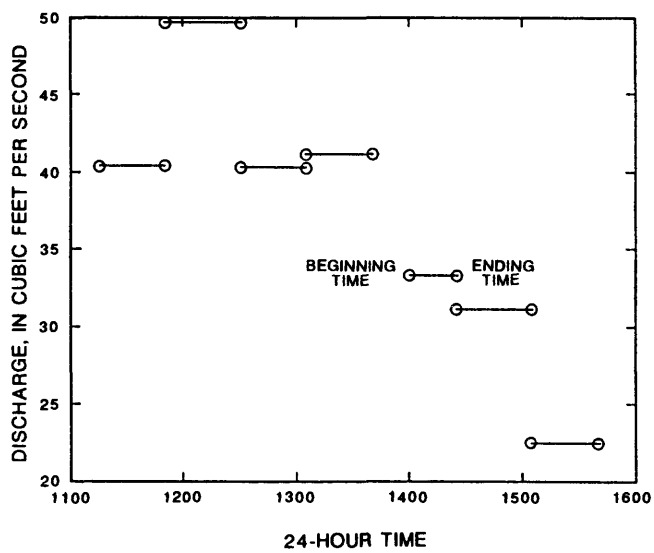


Figure 30. Salt Creek discharge, November 9, 1989.

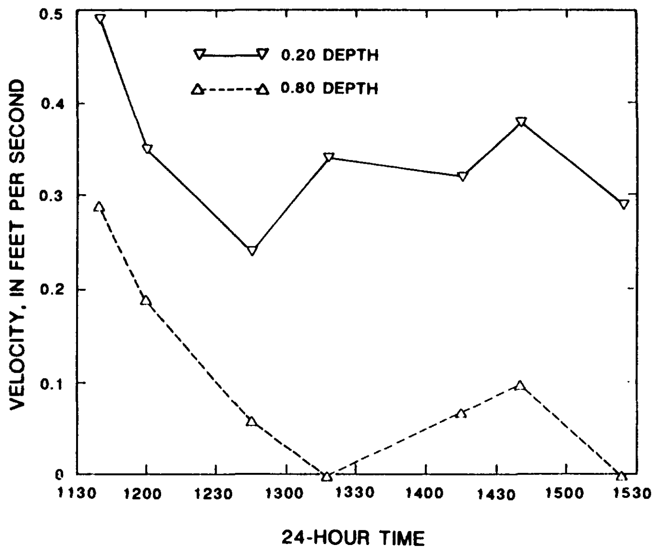


Figure 31. Velocities at 0.2 and 0.8 depth, 35 feet from the north bank of Salt Creek at the Third Street bridge, November 9, 1989.

The depth-integrated specific conductance began to increase after 1430 hours despite the continued ebbtide because the fraction of freshwater at the site decreased. The ebbtide was predicted to end at 1637 hours, so the amount of freshwater from Lake Maggiore was probably increasing slightly and the amount of saltwater from the bay was decreasing slightly during this period. The amount of freshwater runoff continued to decrease. The net result of having less freshwater from runoff, slightly more freshwater from Lake Maggiore, and slightly less saltwater from the bay is a decrease in the fraction of freshwater at the site. Therefore, salinity and specific conductance increased after 1430 hours.

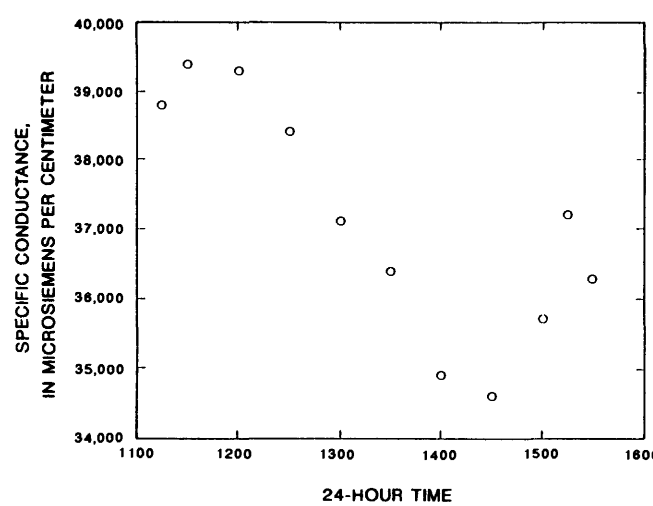


Figure 32. Depth-integrated specific conductance in Salt Creek at the Third Street bridge, November 9, 1989.

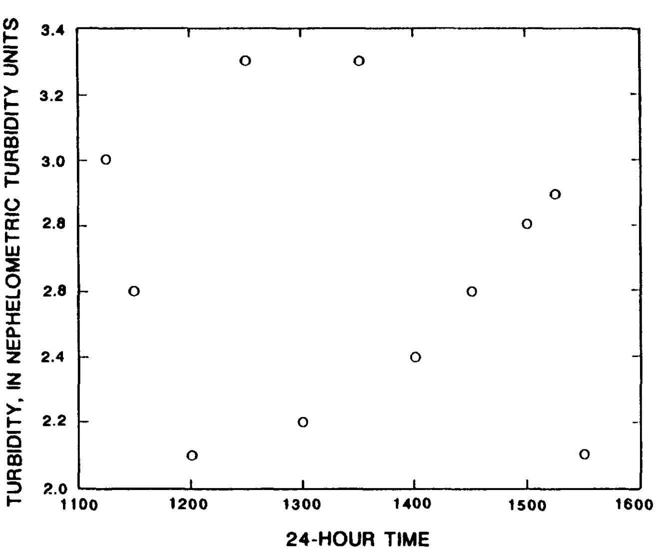


Figure 33. Depth-integrated turbidity in Salt Creek at the Third Street bridge, November 9, 1989.

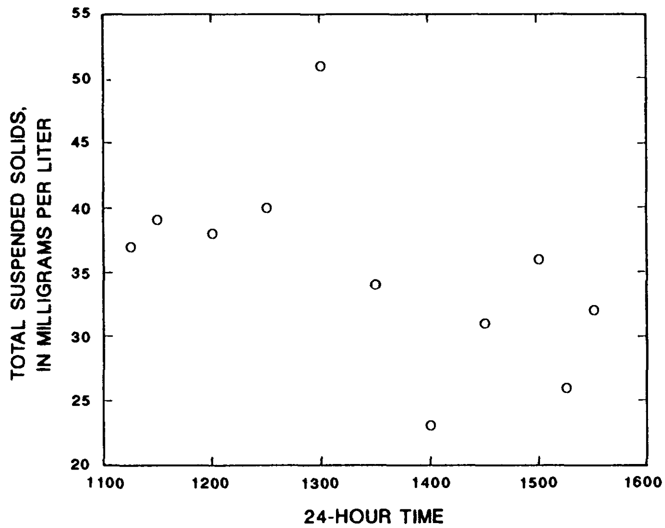


Figure 34. Depth-integrated total suspended solids in Salt Creek at the Third Street bridge, November 9, 1989.

The magnitude and fluctuation of depth-integrated turbidity in Salt Creek was less than that of Booker Creek, but the observed fluctuations of turbidity in Salt Creek were small and sometimes difficult to explain. The turbidity decreased from 3.0 to 2.1 NTU from 1115 to 1200 hours (fig. 33) as the turbid freshwater runoff reached a maximum and decreased after the high tide at 1100 hours. Turbidity in Salt Creek increased during the early afternoon as specific conductance decreased because of the higher turbidity of the freshwater runoff and the probable higher turbidity of freshwater from Lake Maggiore compared to saltwater. The two relatively high values for turbidity at 1230 and 1330 hours may be outliers and indicate the difficulty in interpreting the relatively small changes in turbidity observed in Salt Creek. The maximum measured depth-integrated turbidities in Salt Creek were about one-half the maximum turbidities measured in Booker Creek. The increase in specific conductance at 1500 and 1515 hours in Salt Creek has been attributed to a decrease in freshwater runoff, but the turbidity continued to increase, which is contradictory. The observed increase in specific conductance was greater than the expected error, but the observed increase in turbidity was within the expected error, so the conclusion that the freshwater runoff decreased after 1430 hours seems to be valid. Another possible explanation for the apparent contradiction is that the turbidity of the freshwater increased after 1430 hours.

The depth-integrated concentrations of total suspended solids in Salt Creek were steadier than the Booker Creek concentrations. The Salt Creek concentrations ranged from 23 to 51 mg/L and were fairly consistent in the 30- to 40-mg/L range (fig. 34), whereas the Booker Creek concentrations ranged from 9 to 45 mg/L (fig. 28). The smaller variation in the Salt Creek total suspended-solids concentrations was probably caused by the hydraulic and sediment stability provided by both the lake discharge and the less urban watershed.

South Side of Harbor

Water-quality measurements were made and water samples were collected at site C on the south side of Bayboro Harbor (fig. 2) during the sampling period on November 9, 1989. Only slight stratification occurred at this site, and the freshwater discharge from Booker Creek had a minimal effect, probably because the freshwater was quickly mixed with the more abundant saltwater in the harbor. Vertical profiles of specific conductance at this site (fig. 35) show that, within 8 ft of the water surface, specific conductance was as much as 8,000 µS/cm less than the specific conductance at depths greater than 8 ft. Specific conductance 3 ft below the water surface slowly increased from 1146 to 1534 hours, indicating saltwater mixing with the freshwater inflow. Variability caused by the gradient of specific conductance near the water surface may account for the inconsistent specific conductances 1 ft below the water surface. A water sample collected from 1 ft below the water surface at 1344 hours, however, had a specific conductance of 34,900 µS/cm, which is consistent with the profiles presented in figure 35. Below a depth of 8 ft, specific conductances did not vary with time.

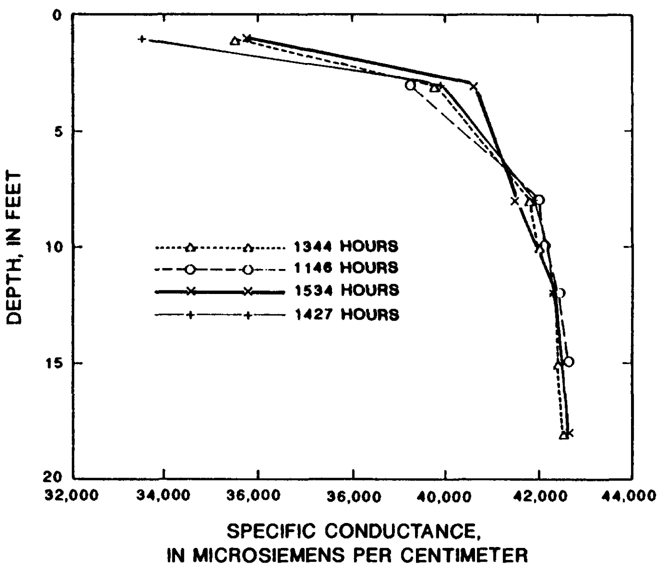


Figure 35. Vertical profiles of specific conductance at site C on the south side of the harbor, November 9, 1989.

Turbidity near the water surface at site C was affected by turbid storm runoff during the sampling period. Vertical profiles were taken with a portable OBS sensor to qualitatively evaluate the turbidity of the water at this site (fig. 36). A higher OBS reading indicates greater turbidity. At 1146 hours, there was no indication that the turbid freshwater runoff had reached the site. The greatest near-surface OBS readings were measured at 1345 hours, and a water sample collected 1 ft below the water surface at 1345 hours had a turbidity of 3.2 NTU. The most probable source of the turbid water at site C is Booker Creek due to the afternoon ebbtide. The near-surface OBS readings at 1427 hours had partially decreased, probably due to dilution of the turbid runoff and particle settling.

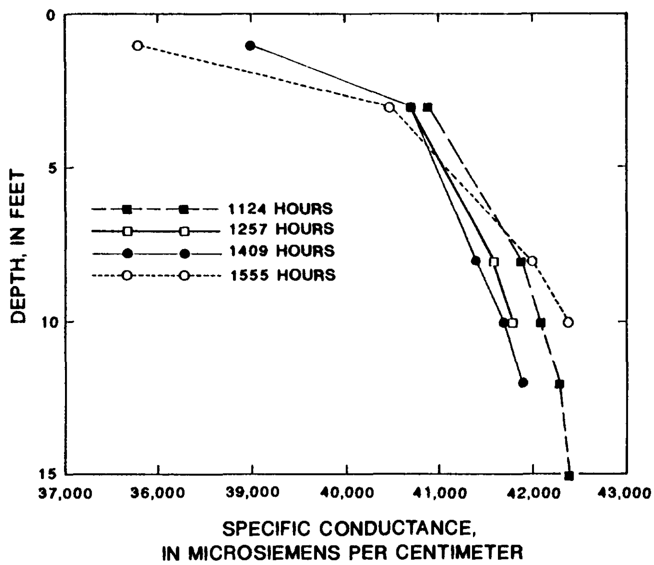


Figure 37. Vertical profiles of specific conductance at site D at the Salt Creek bend, November 9, 1989.

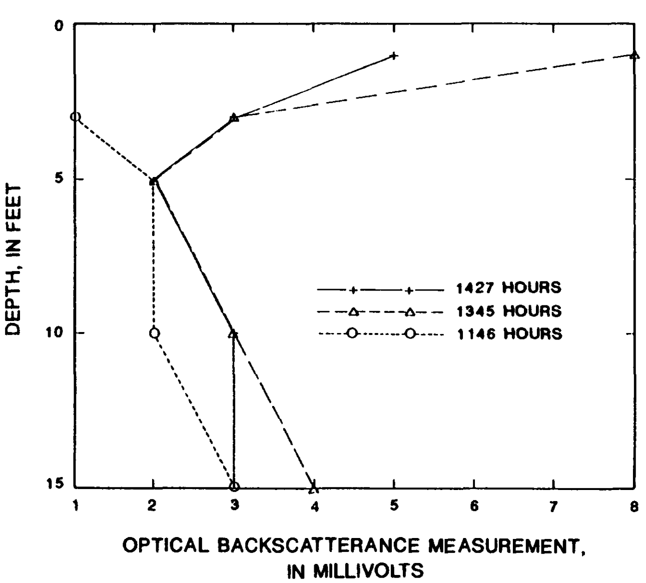


Figure 36. Vertical profiles of optical backscatterance readings at site C on the south side of the harbor, November 9, 1989.

Salt Creek Bend

Water-quality measurements were made and water samples were collected at site D upstream of the first bend in Salt Creek (fig. 2) during the sampling period on November 9, 1989. Vertical profiles of specific conductance at this site are shown in figure 37. The specific-conductance profiles indicate that the water column at site D was less stratified than that at site C. This observation is consistent with the partially stratified conditions observed upstream at the bridge. Depth-integrated specific-conductance and turbidity values and concentrations of chloride and total suspended solids at this site are listed in table 3. The 1417-hour sample was collected soon after a large yacht passed the sampling site and resuspended bottom sediments, temporarily increasing turbidity and suspended-solids concentrations. The other values presented in table 3 are consistent with the upstream values at the bridge.

Table 3. Depth-integrated water-quality data at site D upstream from Salt Creek bend, November 9, 1989

[µS/cm, microsiemens per centimeter; mg/L, milligrams per liter; NTU, nephelometric turbidity units]

Time	Specific conductance (µS/cm)	Dissolved chloride (mg/L)	Turbidity (NTU)	Total suspended solids (mg/L)
1128	40,800	15,000	1.8	27
1304	40,500	15,000	3.1	33
1417[a]	39,000	14,000	5.1	50
1555	39,200	15,000	2.2	36

[a]Yacht passed the sampling site shortly before sample collection.

South of the Peninsula

Water-quality measurements and water samples collected at site E south of the peninsula (fig. 2) during the sampling period on November 9, 1989, indicate that this site was not noticeably affected by the tributary storm runoff. Vertical profiles of specific conductance (fig. 38) indicate that approximately the upper 2 ft of the water column at this site was partially stratified during the sampling period. Water-quality data from samples collected south of the peninsula are presented in table 4. At 1110 hours, the depth-integrated turbidity was 3.7 NTU, which was more than the 1128-hour turbidity of 1.8 NTU at the Salt Creek bend and more than the 1146-hour turbidity of 1.0 NTU at

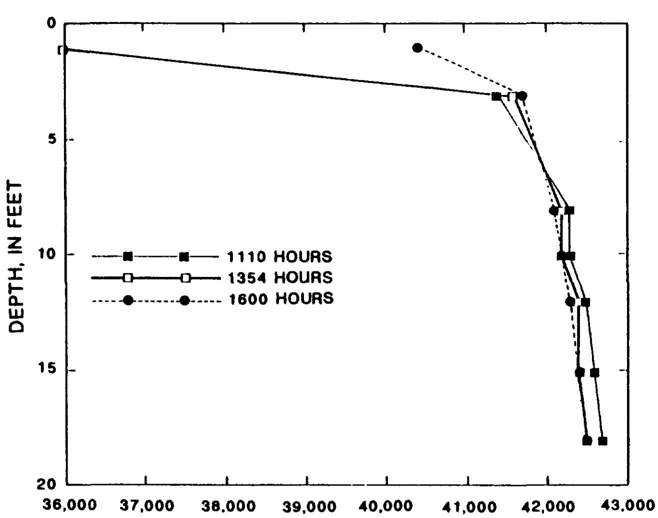


Figure 38. Vertical profiles of specific conductance at site E south of the peninsula, November 9, 1989.

the south side of the marina. At 1404 hours, the portable OBS sensor indicated that the upper 2 ft of the water column was more turbid than the water below and a grab sample taken from 1 ft below the water surface had a turbidity of 8.6 NTU, whereas the depth-integrated turbidity was 3.1 NTU. The depth-integrated turbidity at 1600 hours had decreased to 1.9 NTU, and the near-surface stratification was less pronounced (fig. 38). The turbidity south of the peninsula decreased throughout the afternoon, whereas the turbidity at the Salt Creek and harbor sites increased in the early and midafternoon and then decreased in the late afternoon. Thus, the magnitude and variation of turbidity south of the peninsula do not seem to correlate well with the turbidity in Salt and Booker Creeks. A possible explanation is that the turbidity at site E may be affected more by local runoff from pavement and boatyards. Because this site was not noticeably affected by the tributary storm runoff and it is the closest site to Tampa Bay, the effects on Tampa Bay from the two tributaries probably were minimal.

Table 4. Depth-integrated water-quality data at site E south of the peninsula, November 9, 1989

[µS/cm, microsiemens per centimeter; mg/L, milligrams per liter; NTU, nephelometric turbidity units; ft, foot]

Time	Specific conductance (µS/cm)	Dissolved chloride (mg/L)	Turbidity (NTU)	Total suspended solids (mg/L)
1110	40,900	15,000	3.7	13
1403	40,600	15,000	3.1	47
1404[a]	32,200	12,000	8.6	43
1600	40,700	16,000	1.9	34

[a]Point sample 1 ft below water surface.

SUMMARY AND CONCLUSIONS

Significant increases in light attenuation in Tampa Bay can adversely affect the ecology of the bay. Several nearly enclosed basins, such as the basin containing Bayboro Harbor and the Port of St. Petersburg, adjacent to the bay are potential sources of suspended solids and turbidity to the bay, which can affect light attenuation in the bay. Therefore, several processes that may affect water quality in the basin were studied.

Instruments deployed from May 28 to June 29, 1988, from a U.S. Coast Guard pier at the Port of St. Petersburg did not detect sediment resuspension. Tidal currents at the pier did not exceed 0.12 ft/s and were not large enough to resuspend bottom sediments. The port is part of a nearly enclosed basin that is protected from waves in Tampa Bay and reduces the fetch and the size of wind waves in the basin. Thus, wind waves did not resuspend bottom sediments. Several seiches, usually caused by strong and sustained east-northeasterly winds, also did not resuspend bottom sediments. Several wakes from small U.S. Coast Guard vessels that use the pier were observed, but they did not cause resuspension. Plumes of sediment resuspended by a cruise ship that used the port were not observed at the pier.

The results of analysis of water samples collected at the pier during the instrument deployment period indicate that turbidity in the basin increased slightly in conjunction with local precipitation and runoff and varied during the tidal cycle. Samples collected at different times during the tidal cycle indicated that the turbidity was slightly greater in the bay than in the basin at the beginning of the deployment period, but, as runoff from precipitation increased the turbidity in the basin during the deployment period, the basin became more turbid than the bay. Concentrations of total suspended solids during the deployment period were not observed to follow these trends, probably because of poor correlation between turbidity and suspended-solids concentrations at turbidities less than 10 NTU.

A cruise ship that sailed daily from the Port of St. Petersburg was observed to resuspend bottom sediments in the port. Water samples were collected and OBS measurements were made at six sites during a departure of the cruise ship on June 21, 1988, and upon an arrival on May 18, 1990. The maximum suspended-solids concentrations from collected water samples was 136 mg/L during the departure and 296 mg/L during the arrival. Background suspended-solids concentrations were 20 to 30 mg/L. The cruise ship resuspended more sediment during its arrival because the vessel reversed its propellers to slow down, turn around, and dock at the terminal. During the departure and arrival, most of the resuspended sediments settled within 2 hours after the cruise ship had departed or docked. The lack of strong tidal currents, the lack of large waves, and sufficiently large settling velocities of the fine sand and silt-sized bottom sediments cause rapid settling of resuspended sediments. Small tidal currents also transport constituents in the water column slowly, so there is sufficient time for resuspended particles to settle before they can enter Tampa Bay.

The patterns and rates of sedimentation in the port have been determined by analyzing bathymetric surveys. During the late 1980's, the port became deeper along a line proceeding southeast from the cruise ship terminal and shoaling occurred on either side of this line. This pattern probably was caused by increased use of the terminal during this period. The average bottom elevation during this period did not change much (increased less than 0.1 ft/yr), which indicates that sediments resuspended by cruise ships remained in the port. This conclusion is consistent with the observed fate of sediments resuspended in the port by the cruise ship.

Tributary storm discharge from Booker and Salt Creeks and its effect on Bayboro Harbor were studied on November 9, 1989, when 0.50 in. of rain fell in a 3-hour period. The freshwater storm discharge from Booker Creek, which drains part of the city of St. Petersburg, was delayed by a high tide. When the freshwater storm discharge began, Booker Creek became stratified with an approximately 1.5-ft layer of turbid freshwater flowing downstream into the harbor over a relatively stagnant layer of less turbid saltwater. Salt Creek, which primarily drains Lake Maggiore, was less turbid and only partially stratified. The harbor became slightly stratified, with a thin layer of relatively fresh and turbid water above the less turbid seawater. The turbidity from the creeks only slightly increased the turbidity in the harbor, probably because of mixing with less turbid water and particle settling.

Constituents that may adversely affect light availability in Tampa Bay can be introduced to the waters of the Port of St. Petersburg and Bayboro Harbor basin by tributary storm runoff and large-vessel traffic. The large volume and enclosed shape of the basin provide mixing and settling. These characteristics of the basin diminish or eliminate the potentially adverse effect on Tampa Bay of turbidity from tributary storm runoff and sediments resuspended by large-vessel traffic in the basin.

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