Appearance and Water Quality of Turbidity Plumes Produced by Dredging in Tampa Bay, Florida

United States Geological Survey Water-Supply Paper 2192

Prepared in cooperation with the U.S. Army Corps of Engineers, Jacksonville District

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By CARL R. GOODWIN and D. M. MICHAELIS

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Appearance and Water Quality of Turbidity Plumes Produced by Dredging in Tampa Bay, Florida

By Carl R. Goodwin *and* D. M. Michaelis

Abstract

Turbidity plumes in Tampa Bay, Florida, produced during ship-channel dredging operations from February 1977 to August 1978, were monitored in order to document plume appearance and water quality, evaluate plume influence on the characteristics of Tampa Bay water, and provide a data base for comparison with other areas that have similar sediment, dredge, placement, containment, and tide conditions. The plumes investigated originated from the operation of one hopper dredge and three cutterhead-pipeline dredges.

Composition of bottom sediment was found to vary from 85 percent sand and shell fragments to 60 percent silt and clay. Placement methods for dredged sediment included beach nourishment, stationary submerged discharge, oscillating surface discharge, and construction of emergent dikes. Tidal currents ranged from slack water to flow velocities of 0.60 meter per second.

Plumes were monitored simultaneously by (1) oblique and vertical 35-millimeter aerial photography and (2) water-quality sampling to determine water clarity and concentrations of nutrients, metals, pesticides, and industrial compounds. Forty-nine photographs depict plumes ranging in length from a few tens of meters to several kilometers and ranging in turbidity level from <10 to 200,000 nephelometric turbidity units.

The most visible turbidity plumes were produced by surface discharge of material with high sand content into unconfined placement areas during times of strong tidal currents. The least visible turbidity plumes were produced by discharge of material with high silt and clay content into areas enclosed by floating turbidity barriers during times of weak tidal currents. Beach nourishment from hopper-dredge unloading operations also produced plumes of low visibility.

Primary turbidity plumes were produced directly by dredging and placement operations; secondary plumes were produced indirectly by resuspension of previously deposited material. Secondary plumes were formed both by erosion, in areas of high-velocity tidal currents, and by turbulence from vessels passing over fine material deposited in shallow areas.

Where turbidity barriers were not used, turbidity plumes visible at the surface were good indicators of the location of turbid water at depth. Where turbidity barriers were used, turbid bottom water was found at locations having no visible surface plumes.

A region of rapidly accelerating then decelerating flow near the mouth of Tampa Bay produced a two-part or separated plume. Flow acceleration contracted the width of the visible plume, and subsequent flow deceleration caused plume expansion. The two wide segments of the plume appeared to be separated from each other because of the intervening narrow part.

Waters ambient to the plumes were tested for clarity in two sections of Tampa Bay. Ambient-water transparency in Tampa Bay was about three times greater near its mouth, in South Tampa Bay, than near its head, in Hillsborough Bay. Two other measures of water clarity, turbidity and suspended solids, showed no statistically significant difference between the two areas, however, indicating that transparency is a more sensitive measure of ambient water clarity than either turbidity or suspended solids.

The nutrient and metal concentrations for samples of plume water and water ambient to the plumes in Tampa Bay were statistically equivalent, indicating no detectable changes due to dredging. The concentrations of dissolved copper, lead, mercury, and total mercury, however, were greater in plumes in Hillsborough Bay than in South Tampa Bay. In Hillsborough Bay, six occurrences of the herbicide 2,4-D at concentrations near the detection limit, 0.01 to 0.05 micrograms per liter, were unrelated to dredging activity.

Data recorded for longer than the study period indicate that from 1976 through 1979 few average turbidity characteristics in South Tampa and Hillsborough Bays can be directly attributed to dredging operations. Average maximum turbidity levels appear to be independent of dredging activity. Seasonal minimum turbidity levels in Hillsborough Bay, however, were about 2 nephelometric turbidity units higher during dredging than nondredging periods, a difference that may be attributable to dredging activity.

INTRODUCTION

Movement of commerce through the Gulf of Mexico to port facilities in Hillsborough Bay, upper Tampa Bay, Florida, has required modifications of the bay since 1907 (U.S. Army Corps of Engineers, 1969). As vessels of increasingly deeper draft came to be used, dredging projects were undertaken to improve the navigability of the channel. In 1950, Congress authorized deepening of the ship channel to 10.4 m and widening to 122 m (U.S. Army Corps of Engineers, 1969). That project was completed in 1960.

In 1970, further enlargement of the ship channel was authorized by Congress to accommodate large bulk carriers of phosphate, petroleum, and other products. Channel dimensions after the proposed Tampa Harbor Deepening Project were to be a depth of 13.1 m and a width of 152 m. The quantity of material to be dredged was estimated at 53.8×10^6 m^3 (U.S. Army Corps of Engineers, 1974), making this one of the largest projects of its type ever authorized in the United States.

To detect environmental effects of the activities involved in the planned construction, the U.S. Geological Survey conducted a monitoring program from February 1977 to August 1978. The program provided, on a monthly basis, photographic and water-quality data in areas affected by dredging operations.

Background

Plumes of suspended material caused by dredging (turbidity plumes) can have detrimental effects on bodies of water. Fine material settling from a plume may cause significant changes in particle-size distributions of surficial bottom sediments that, in turn, may affect the abundance and diversity of benthic flora and fauna. Noxious or toxic substances adhering to fine dredged material may enter the food chain through either grazing by filter-feeding organisms and zooplankton on sediment particles within turbidity plumes or ingestion by benthic organisms at the bay bottom.

Turbidity plumes reflect sunlight that would otherwise penetrate deeper into the water column, and thus they reduce the depth to which photosynthesis may occur. Moreover, suspended oxygen-demanding material from the bottom can also reduce the amount of dissolved oxygen available for aquatic biological processes within a turbidity plume.

Apart from their physical and chemical properties, turbidity plumes also have an aesthetic importance to those interested in or responsible for balancing environmental and developmental interests in an aquatic environment. The way that the public and agencies acting for the public perceive visible aspects of dredging significantly affects the acceptance or rejection of proposed dredging projects or dredging methods.

Prior to the dredging or filling in of tidally affected aquatic environments, government agencies and concerned individuals commonly ask two questions regarding turbidity plumes associated with such projects:

1. What will be the extent and appearance of the turbidity plumes?
2. What will be the chemical and physical effects of the dredged material on the receiving water bodies?

These questions are not easily answered in spite of progress made in understanding turbidity plumes (Barnard, 1978).

Turbidity plumes are regions of water containing higher concentrations of suspended particles than adjacent regions. Plume appearance can vary widely depending upon sediment, dredge, placement, and receiving-water characteristics. Typically, they appear as elongated shapes having a lighter color than the surrounding water. They are a visible result of hydraulic dredging, wherein dredged bottom sediment is initially agitated and dispersed as a water-sediment slurry, then pumped to a placement site, and finally discharged to the water. Particles the size of sand or larger settle quickly; silt and clay particles settle slowly and are distributed by hydraulic forces until they reach the bottom—hours, days, or weeks later. Because particulate settling is a gradual process and because much of a plume is submerged, the boundaries of turbidity plumes are virtually indeterminable; the visible part of plumes is commonly taken to be a practical indicator of plume extent.

A distinction between primary and secondary turbidity plumes is made in this report. Primary plumes are those produced directly by dredging equipment as dredged material is moved from its initial location on the bay bottom to its point of deposition. Secondary plumes are those associated with the overall dredging activity but not produced directly by dredge operations. Examples of secondary plumes include those produced by propeller wash from construction vessels or by the erosion of previously deposited material by tidal currents.

This report provides information concerning the appearance and water quality of many turbidity plumes produced by dredging activities. Turbidity plumes discussed in this report were generated by dredges operating in South Tampa Bay between February 1977 and October 1977 and by dredges operating in Hillsborough Bay from November 1977 to August 1978. Both are areas of Tampa Bay, on the central Gulf Coast of Florida (fig. 1). Photographs and water-clarity data for each plume document plume appearance. The sediment, dredge, placement, and tide conditions contributing to the appearance of the plumes are discussed, and conclusions regarding their influence on plume characteristics are drawn. Water-quality samples were collected from each plume and compared to samples of ambient water to determine how much toxic and noxious material was resuspended or dissolved due to dredging. Analyses included those for constituents affecting water clarity and for selected nutrients, metals, pesticides, and industrial compounds. An analysis of turbidity from 1976 to 1980 in samples of water from areas ambient to the plumes in Hillsborough Bay and South Tampa Bay is also presented. The results can be applied to other areas having similar sediment, dredge, placement, and tide conditions.

Location and Description

Tampa Bay is a Y-shaped coastal-plain estuary whose surface is about 1,000 km^2 and whose average depth is 3.5 m. Major subareas are Hillsborough Bay, the eastern arm; Old Tampa Bay, the western arm; and North and South Tampa Bays (fig. 1).

Major manmade features include three bridges, a causeway, several islands and filled shoreline areas, and a 60-km ship channel that connects the Gulf of Mexico with port facilities at the city of Tampa. In tonnage, the port of Tampa is third largest in exports and seventh largest overall in the United States (Tampa Port Authority, 1979). Phosphate, sulfur, and petroleum are the primary products handled by the port.

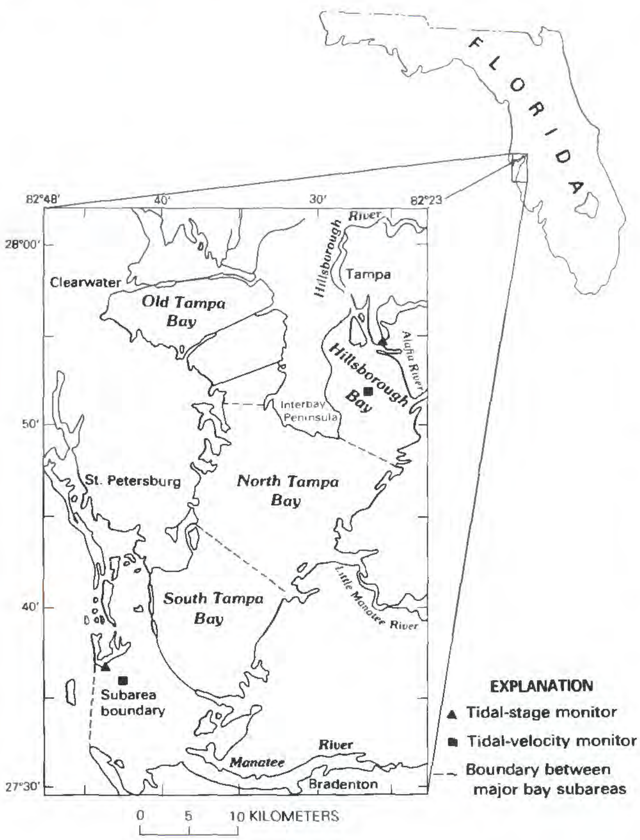

Figure 1. Tampa Bay subareas and tidal-stage and tidal-velocity monitor sites.

Major cities bordering on Tampa Bay are Tampa, St. Petersburg, Clearwater, and Bradenton. The Standard Metropolitan Statistical Areas of Tampa-St. Petersburg and Bradenton have a population of about 1.66 million (estimate for April 1, 1979) and a growth rate of 74,000 residents per year. In 1978, at least 6.2 million people visited the area (Thompson, 1980).

Tampa Bay occupies an ancient river valley that was eroded from limestone (Brooks, 1973). Bay-bottom sediments that overlie the limestone range in thickness from near 0 to 30 m and are composed of varying amounts of sand, shell fragments, silt, clay, and organic material. Fine mineral and organic material occur most commonly near the head of the embayment; coarse materials are predominant near its mouth (Goodell and Gorsline, 1961).

Tides in Tampa Bay have nearly equal diurnal and semidiurnal components that produce an irregular pattern of water-surface fluctuations. The average tide range is about 0.6 m. Tidal currents are also irregular, with periods of alternating strong flood and ebb currents interspersed with periods of weak and variable currents (U.S. Department of Commerce, 1977). Current speeds near the mouth of Tampa Bay are normally 1 to 1.5 m/s but can be more. Current speeds near the central portions of Hillsborough and Old Tampa Bays can reach 0.3 and 0.5 m/s, respectively (U.S. Department of Commerce, 1977).

Tributary inflow averages about 54 m^3/s. Application of the tidal-prism concept shows that an average semidiurnal tidal flow of about 25,000 m^3/s at the mouth of Tampa Bay is required to satisfy the volume of the bay between average low and high tides. Because of the shallow depths, tidally dominated flows, and supplementary vertical mixing due to wind, the bay is mostly well mixed vertically, with little density stratification.

Factors That Affect Appearance and Water Quality

The appearance and water quality of turbidity plumes are influenced by many interacting factors. These factors include the characteristics of the dredged material, the method of dredging, the manner of placement of dredged material, and characteristics of the receiving waters.

Physical and Chemical Properties of Dredged Material

The unconsolidated sedimentary material dredged from many estuaries, bays, and tidal streams is composed of particles ranging in size from large boulders 1 m or more in diameter to colloids 1 µm or less in diameter. Small or trace amounts of inorganic and organic substances are often associated with the sediment particles or the interstitial water between the particles.

The size and shape of a sediment particle directly affect its rate of settling in quiescent water. Large particles reach the bottom rapidly, whereas small particles may remain in suspension indefinitely. At 20°C, representative settling rates for various sizes of spherical particles, based on Stokes Law (Tschebotarioff, 1951), are shown below.

Particle size, in millimeters	*Settling rate, in millimeters per second*
1.0	900
.1	9
.01	.09
.001	.0009

The less spherical and more plate-shaped a particle is, the longer it will take to settle. Correction factors to Stokes Law have been developed to account for this shape effect (Tschebotarioff, 1951).

Turbidity plumes are composed of slowly settling silt and clay particles less than 0.03 mm in diameter or of small masses of agglomerated particles or both (Barnard, 1978). In general, the finer or smaller the diameter of the particles, the more visible the turbidity plume will be. Sediments in Tampa Bay have been reported to contain a significant amount of silt and clay (Goodell and Gorsline, 1961; Taylor and Saloman, 1969). Laboratory analyses of unconsolidated sediments in Tampa Bay were found to contain from less than 1 percent to more than 80 percent fine material (Taylor, 1973). Surficial sediments in an area adjacent to Tampa Bay contain from about 1 percent to more than 60 percent fine material (Sinclair, 1974).

Cohesive properties of fine sediments induce faster settling than would be predicted from the size and shape of their particles. Compaction of fine sediments by overburden pressure rearranges the particles to fit more tightly together, increases grain-to-grain contact, and promotes physical and chemical bonding (cohesion) between particles (Tschebotarioff, 1951). If cohesive sediments are agitated during dredging, they are likely to be incompletely dispersed and, therefore, to settle as particle clusters and not as individual particles. Some clays, for instance, remain intact during hydraulic dredging operations, are formed into balls in the discharge pipe, and are ejected at the placement site as rapidly settling particles.

Plume visibility and appearance are largely determined by the amount, distribution, and color of the light reflected from the surfaces of the uppermost sediment particles in the water column. Surfaces reflecting light over a large water area cause an apparently large plume. The amount of reflected light is a function of the characteristics of the material reflecting it. A dense arrangement of particles reflects light more intensely than does a diffuse arrangement. A bright sediment surface reflects more light than a dark surface; a colored surface reflects colored light.

Many chemical constituents, either anions or cations, are adsorbed to the surfaces of fine particles (Buckman and Brady, 1964). In some instances, these constituents are released from particle surfaces into the water, increasing the dissolved concentration of those constituents. Sediment particles may also "scavenge" constituents from the water as they settle to the bottom, thereby decreasing the dissolved concentrations. In either case, the region of chemical activity (i.e., of ion exchange) is at the particle surface. The greater the sediment surface area exposed to receiving waters during dredging, the greater is the potential for chemical interaction.

The specific surface (surface area per unit mass) of clay materials ranges from 5 to 800 m^2/g (Meade, 1964). Assuming that clays in Tampa Bay bottom sediments have a density of 2.65 g/cm^3 and a specific surface of 5 m^2/g, less than 100 m^3 of this clay contains a potentially active ion-exchange surface area that is equal to the 1,000 km^2 surface area of Tampa Bay. The external surface area of colloidal clays has been estimated to be at least 1,000 times that of an equivalent weight of coarse sand (Buckman and Brady, 1964).

Type, Size, and Operation of Dredge

The size of dredge equipment and the procedure used to move sediment from one location to another can cause significant differences in turbidity plumes. Large dredges discharge more sediment, create larger and more dense plumes, and have greater short-term potential for significant water-sediment chemical activity than do small dredges; smaller dredges, however, take longer to complete a job, and so they create smaller, less dense plumes over longer time periods. Of the two types of dredges, mechanical and hydraulic, the hydraulic dredge is more frequently used in the United States. Information on turbidity plumes from two types of hydraulic dredges, hopper and cutterhead-pipeline, is presented in this report. Dredge types are discussed by Gren (1976).

Hopper dredges are vessels similar in appearance to many cargo ships or barges. The term "hopper" is descriptive of the storage bins these dredges use to transport dredged material to placement sites. The material is released there through large doors on the bottom of each bin. Many hopper dredges can also unload by pumping dredged material out of the bins. Pumping facilities enable the transfer of material to shallow water or to upland placement sites. Both types of unloading create turbidity plumes.

Hopper dredges have one to three large-diameter pipes, called drag arms, extending from the dredge to the bay bottom. A centrifugal pump creates a suction in the pipes that lifts unconsolidated material into the hopper bins. As the ship moves forward, drag heads connected to the end of the suction pipes loosen material, direct it into the pipes and then into the bins. The normal loading operation of hopper dredges results in an overflow of turbid water from the bins; that overflow is discharged into the bay and produces a turbidity plume.

Hopper dredge bin capacities range from a few hundred cubic meters to over 10,000 m^3. The hopper dredge *Ezra Sensibar*, which operated in Tampa Bay during this study, has two pumps with 760-mm-diameter intake pipes powered by 11,500 metric-horsepower motors. The total bin capacity is 11,500 m^3.

The terms "cutterhead-pipeline," or simply "pipeline," are descriptive of the other type of dredge used in Tampa Bay during the study. A cutterhead is attached to the end of a rotating shaft supported by a large boom or "ladder" on one end of a barge. The cutterhead position can be moved vertically and horizontally. A suction pipe located near the cutterhead draws in water and loosened sediment, and the resultant slurry passes through the pump and discharge pipe to the placement site.

Cutterhead-pipeline dredge sizes are commonly measured in terms of the diameter of the discharge pipe; they range from 150 to 1,070 mm. Several dredges of this type were operated in Tampa Bay during the study. The largest was the *Western Condor*, which has a 1,070-mm-diameter discharge pipe, a 10,000 metric-horsepower pump, and a 2,500 metric-horsepower engine turning the cutterhead.

Methods for Placement and Containment of Dredged Material

After dredging, sediment is transported to placement sites chosen to receive the material. Placement methods can result in significant differences in turbidity plumes. Common methods include (1) beach nourishment or replacement of eroded beach material for shoreline protection, (2) submergent open-water deposition, (3) emergent open-water deposition, and (4) upland deposition (not used during the study).

Materials used for beach nourishment generally have a high percentage of sand that enables them to withstand normal wave action and makes them suitable for recreational use. Large plumes are generally not created by beach nourishment. However, placement of dredged material that contains large quantities of fine particles can produce large plumes.

Figure 2 shows three submergent open-water discharge methods used in Tampa Bay; stationary surface discharge, oscillating surface discharge, and submerged discharge. In the stationary and oscillating surface discharge methods, the dredged material settles through the entire water column. As a result, the material remains in contact with the receiving water for long periods, so that both plume visibility and the potential for exchange of chemical constituents between sediment and water are maximized. The oscillating surface-discharge method creates larger and more visible plumes than the stationary discharge method because it broadcasts dredged material over a much larger area. A submerged discharge pipe eliminates the need for all particles to settle through the entire water column. The plume appears smaller than those resulting from either of the other two methods, and the time available for water-sediment chemical interaction is also reduced. Additional information on disposal methods is given in a review by Barnard (1978). Turbidity plumes from oyster shell dredging and disposal operations in Tampa Bay were investigated by Simon and others (1976).

After dredging operations have ceased, secondary turbidity plumes are generated from open-water

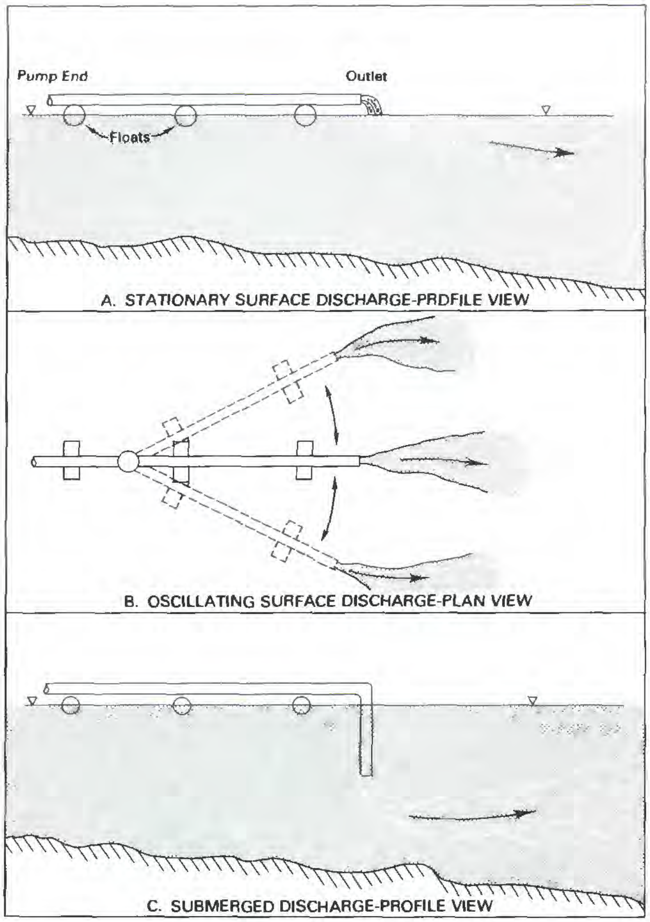

Figure 2. Three pipeline-dredge discharge methods.

placement sites if water velocities are sufficient to erode the deposited material. The characteristics of secondary erosional plumes are determined by the particle size of the material and the magnitude and duration of erosive-current velocities.

Emergent placement areas are constructed from dredged material by building submerged mounds until they break the water surface. The material can then be shaped and elevated into a dike enclosing an impoundment. The impoundment then receives additional dredged material and acts like a solid-liquid separation system (Krizek and others, 1976). Overflow water from the impoundment is discharged to surrounding water through weirs and pipes placed in the dike. Fine, slow-settling particles sometimes remain in the overflow water; in such cases, they form turbidity plumes when discharged from the impoundment.

Turbidity barriers or screens are often used to limit the extent and visibility of the plume as well as potential water-sediment chemical interaction during open-water placement of dredged material. Turbidity barriers (fig. 3) consist of linear flotation units with an attached weighted fabric forming a skirt that extends 1 or 2 m below the water surface. The units are joined to form long barriers enclosing a turbidity source. Turbidity barriers do not completely contain the particles. Settling particles escape beneath the skirt, either as turbid water or as fluid mud (fig. 3). The distinction between turbidity and fluid mud, as reported by Barnard (1978), occurs at an approximate suspended-solids concentration of 10,000 mg/L. As with the submerged discharge method (fig. 2), the plume from a turbidity barrier forms at depth, thereby limiting plume visibility.

The movement of fluid mud is a significant factor related to placement and containment of dredged material, especially in Hillsborough Bay. Mounds of deposited and consolidating silt and clay often become unstable and then flow outward from discharge sites,

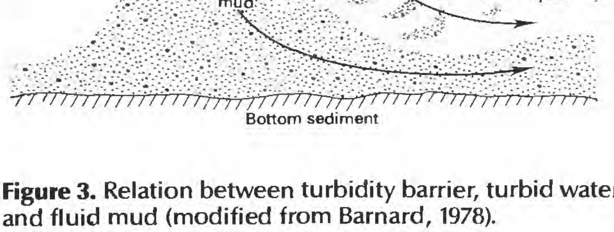

Figure 3. Relation between turbidity barrier, turbid water, and fluid mud (modified from Barnard, 1978).

under turbidity barriers, and beyond placement area boundaries. Secondary turbidity plumes are often produced if this fluid mud is deposited in areas affected by wind waves, erosion by tidal currents, or ship turbulence. Fluid mud is generally not visible from the surface, so it has little influence on the appearance of primary turbidity plumes.

Physical, Chemical, and Hydraulic Properties of Receiving Water

Properties of the water receiving dredged material produce differences in turbidity plumes. The mechanisms that affect solubility and exchangeability of toxic heavy metals in turbidity plumes are cation-exchange reactions, formation of insoluble precipitates, colloidal adsorption, organic complexation, and chelation. We acknowledge the occurrence and importance of these processes, but it is beyond the scope of this paper to discuss them. Additional information can be found in a paper by Gambrell and others (1976).

In brackish or saline water, one important process affecting turbidity-plume appearance is the aggregation or flocculation of minute particles into larger particles called aggregates or flocculants (flocs). Flocs settle to the bottom more rapidly than individual particles. Increased settling rates of fine dredged material due to flocculation reduce the extent and visibility of turbidity plumes and reduce the amount of water-sediment chemical interaction.

Factors promoting increased settling rates of fine particles by flocculation include the occurrence of (1) certain types of clay minerals, chiefly montmorillonite, (2) at least a 1,000–2,000-mg/L concentration of sodium chloride, and (3) sufficient water turbulence to ensure particle collisions (Cogley and others, 1976). All three of these conditions occur in Tampa Bay. The presence of sufficient sodium chloride has been verified (Goodwin and others, 1974, 1975; Saloman and Taylor, 1972; Goetz and Goodwin, 1978; Wilkins, 1978). Tidal currents create sufficient turbulence. Previously unpublished U.S. Geological Survey data in table 1 show the presence of montmorillonite in Tampa Bay sediments, primarily in mixed-layer form with illite; montmorillonite has also been identified as a component of mixed-layer clays in surficial sediments adjacent to Tampa Bay (Sinclair, 1974).

In addition to its importance in the flocculation process, turbulence prolongs overall particle settling times, tends to resuspend deposited material, and contributes to vertical and horizontal dispersion of fine particles. Because fine particles from dredging operations often remain visible for many hours after discharge, the appearance of turbidity plumes in unsteady tidal flows can be significantly different from the appearance of those in streams having steady flow condi-

Table 1. Clay mineralogy of Tampa Bay sediments

Sample location		Weight percent				
Latitude	Longitude	Chlorite	Kaolinite	Illite	Montmorillonite	Illite and montmorillonite
27°47'10"	82°32'29"	0	0	0	0	25
27°53'5"	82°26'25"	0	0	0	9	5
27°48'12"	82°27'58"	0	0	0	0	65
27°38'7"	82°37'30"	0	0	5	1	4

tions. Discharge into streams generally produces plumes that expand in width with increasing downstream distance on account of turbulent dispersion. Discharge into unsteady tidal flows causes buildups of turbidity and suspended-sediment concentration during periods of slack water (Grenney and Bella, 1972). A color-enhanced Landsat satellite image (fig. 4) shows a turbidity plume in Tampa Bay generated by 1972 shell-dredging operations (described by Simon and others, 1976) that serves as an illustration of how tidal flow can affect plume shape. The plume has a barbell appearance due to turbidity buildup during two successive slack-water periods and an intervening period of ebb flow. Selected shallow areas along the margin of Tampa Bay are incorrectly interpreted, by the color-enhancement process, to be the same as turbid water within the plume.

Figure 4. Color-enhanced satellite image of turbidity plume in Tampa Bay, 1972.

The spatial variability of tidal flow also affects plume appearance. Identical dredges discharging similar material at separate locations in an estuary may produce dissimilar plumes because of different magnitudes of tidal flows; durations of flood, ebb, or slack conditions; and local variations in flow directions.

Acknowledgments

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STUDY METHODS

Aerial photography and satellite imagery were both considered as possible methods for documenting the appearance of turbidity plumes in Tampa Bay. Aerial photography provides greater scheduling flexibility during seasons of limited cloud-free conditions and therefore was chosen as the primary method. Satellite imagery was used in a few instances to present information unavailable on aerial photographs. Between February 1977 and August 1978, about 1,900 vertical and oblique 35-mm photographs were taken during 20 flights over South Tampa Bay and Hillsborough Bay. Water-quality data were collected from a boat during 15 of the flights.

The schedule of data collection was restricted by weather and light conditions. The Tampa Bay area averages less than 6 days per month when there is at least a 30° solar altitude, which is the minimum recommended sun angle above the horizon for aerial photography, and an average of 10 percent or less cloudiness from sunrise to sunset (Smith and Anson, 1968). In addition, reflection and glare from the water caused by large sun angles limited photography to specific times during optimum days. The areas studied are also subject to high-density air traffic, which often restricted our choice of flight times and altitudes.

For purposes of comparison, water samples were regularly collected at one or more sites within each turbidity plume, and also a sample of ambient water at one site not visibly affected by dredging was collected. Values were measured for (1) water-clarity and related parameters (turbidity, suspended solids, volatile solids, and transparency) and (2) concentrations of filtered and unfiltered nutrients, metals, pesticides, and industrial compounds. Water-clarity parameters were determined at several sites within visible plumes.

Positioning of the sampling boat required two-way radio communication with an observer in the aircraft because turbidity plumes were often not visible from the boat. Radio communication also enabled the nearly simultaneous collection of photography and water samples. The estimated maximum time difference between sampling and corresponding photography was 5 minutes, the average time required to complete sampling.

Supplementary data on meteorologic, photographic, sediment-composition, dredge, dredged-material placement and containment, tidal-stage, and tidal-velocity conditions during times of plume monitoring were also collected. These data were used to evaluate plume appearance, and they may aid in the application of information collected during this study to other areas where dredging is contemplated.

Aerial Photography

Vertical aerial photography was effected by use of a flexible, low-cost system (Meyer, 1973) that was assembled using a portable camera mount (fig. 5), a fiber-optic sight, a camera, and a rental aircraft. The mount, fastened to the door of the aircraft, allowed retraction of the camera for film loading. The fiber-optic sight provided a view of the target area. The photography system included a single-lens reflex 35-mm camera having motorized film advance, automatic shutter cocking, and both remote and internal shutter release mechanisms. Oblique photographs were taken with another 35-mm camera.

Figure 5. Camera and mount used for vertical aerial photography (modified from Meyer, 1973).

GROUP SYMBOLS	TYPICAL NAMES
GW	Well-graded gravels, gravel-sand mixtures, few or no fines
GP	Poorly graded gravels, gravel-sand mixtures, few or no fines
GM	Silty gravels, poorly graded gravel-sand-silt mixtures
GC	Clayey gravels, poorly graded gravel-sand-clay mixtures
SW	Well-graded sands, gravelly sands, few or no fines
SP	Poorly graded sands, gravelly sands, few or no fines
SM	Silty sands, poorly graded sand-silt mixtures
SC	Clayey sands, poorly graded sand-clay mixtures
ML	Inorganic silts and very fine sands, rock flour, silty or clayey fine sands with slight plasticity
CL	Inorganic clays of low to medium plasticity, gravelly clays, sandy clays, silty clays, and lean clays
OL	Organic silts and organic silt-clays of low plasticity
MH	Inorganic silts, micaceous or diatomaceous fine sandy or silty soils, and elastic silts
CH	Inorganic clays of high plasticity, flat clays
OH	Organic clays of medium to high plasticity
PT	Peat and other highly organic soils

Figure 6. Category symbols used in Unified Soil Classification System (U.S. Department of the Interior, 1960).

Kodachrome[1] 64 color-reversal film was used to produce a positive transparency, commonly called a "slide," usable for light-table scanning, projection, and production of glossy photographs. An ultraviolet filter

[1]Any use of brand names in this report is for purposes of description only and does not imply endorsement by the U.S. Geological Survey.

was used to penetrate atmospheric haze. Additional information on the use of aerial photography for water-resources surveillance is given by Fraga and Holland (1974) and the California Water Resources Control Board (1978).

Water Sampling and Analysis

Water samples were collected and field measurements were made by the Hillsborough County Environmental Protection Commission. Water clarity was observed in the field by measuring water transparency with a Secchi disc (Wetzel, 1975). Filtered and unfiltered samples were analyzed for nutrients: phosphorus, orthophosphorus, nitrate, nitrite, ammonia, and organic nitrogen. Filtered and unfiltered samples from Hillsborough Bay were analyzed to detect arsenic, cadmium, chromium, copper, iron, lead, manganese, nickel, zinc, and mercury. Filtered and unfiltered sam-

ALTITUDE (FEET) a	DEPTH (FEET) b	LEGEND c	CLASSIFICATION OF MATERIALS (Description) d
−26.0	0.0		
−39.2	13.2		SAND, fine to medium quartz, clayey, gray, (SC); slightly silty from −26.0 to −27.5; shelly, light gray from −29.0 to −39.2
−43.7	17.7		ORGANIC CLAY, black, slightly sandy, (OH)
−45.0	19.0		Bed of brown shelly silt, organic stain, from −43.7 to −45.0
−47.0	21.0		SAND, fine to medium, quartz, light brown, (SP)
−51.0	25.0		SAND, fine to medium, quartz, clayey, many thin beds medium-hard limestone, shelly light gray, (SC)

A

ALTITUDE (FEET) a	DEPTH (FEET) b	LEGEND c	CLASSIFICATION OF MATERIALS (Description) d
−37.6	0.0		
−41.6	4.0		ORGANIC SILT, sandy, dark brown (OL)
−42.6	5.0		Bed of silty sand from −41.6 to −42.6 (SM)
−43.1	5.5		
−45.1	7.5		LIMESTONE, soft, weathered, seams of calcareous silt, white; bed of green clay (CL) from −42.6 to −43.1
−47.6	10.0		SILT, calcareous, soft, limestone lenses and fragments white (ML)
−50.1	12.5		LIMESTONE, soft, weathered, seams calcareous silt, white

B

ALTITUDE (FEET) a	DEPTH (FEET) b	LEGEND c	CLASSIFICATION OF MATERIALS (Description) d
−24.0	0.0		
−24.7	0.7		SAND, fine, quartz, silty, dark gray, slightly shelly
−26.0	2.0		SAND, fine, quartz, slightly silty, clayey, very shelly (70% shell) (SC)
−34.5	10.5		SAND, fine, quartz, silty, slightly clayey, very shelly (70% shell), light gray (SM) Shelly (40% shell) from −28.5 to −34.5
−37.5	13.5		SAND, fine to medium, quartz, slightly silty, gray, slightly shelly, (SP)
−41.0	17.0		SAND, fine to medium, quartz, clayey, light gray, slightly calcareous (SC)
−43.5	19.5		LIMESTONE, soft, weathered, seams of calcareous silt, seams of green clay, slightly fossiliferous, buff, massive bedded
−45.0	21.0		Calcareous silt (ML) from −43.5 to −45.0
−46.5	22.5		Medium-hard limestone, porous permeable, tan from −45.0 to −46.5
−47.5	23.5		Bed of green clay (CL) from −46.5 to −47.5
−49.0	25.0		Calcareous silt, compacted, lenses of limestone from −47.5 to −49.0
−50.0	26.0		LIMESTONE, hard, porous, seams calcareous silt

C

Figure 7. Three sample drillers' logs, showing sediment classification and description.

Table 2. Particle-size gradation and cohesiveness designation for 10 of the soil categories of the Unified Soil Classification System (U.S. Department of the Interior, 1960)

Unified Soil Classification System category[1]	Percentage of material at centroid of size category			Cohesive?
	Sand	Silt	Clay	
SW	86	7	7	No
SP	86	7	7	No
SM	62	28	10	No
SC	57	19	24	No
ML	22	68	10	No
CL	31	31	38	Yes
OL	10	65	25	No
MH	18	57	25	No
CH	17	17	66	Yes
OH	8	21	71	Yes

[1] See figure 6 for explanation of symbols.

Table 3. Sample calculation of approximate particle-size gradation

[Data taken from drillers' log C in fig. 7]

Horizon number (i)	Altitude at top of horizon (ft)	Horizon thickness (ft) (t_i)	Textural classification	Percent larger than sand size (a_i)	Percent sand (b_i)	Percent silt (c_i)	Percent clay (d_i)
1	-24.0	0.7	SM	0	62	28	10
2	-24.7	1.3	SC	70*	17	6	7
3	-26.0	2.5	SM	70*	19	8	3
4	-28.5	6.0	SM	40*	37	17	6
5	-34.5	3.0	SP	0	86	7	7
6	-37.5	3.5	SC	0	57	19	24
7	-41.0	2.5	(**)	50	10	20	20
8	-43.5	1.5	ML	0	22	68	10

Number of horizons (n) = 8

Total thickness (T) = 21.0 ft

Calculation of bulk particle-size distribution by thickness-weighed average:

$$\text{Percent larger than sand size} = \frac{1}{T}\sum_{i=1}^{n} t_i \cdot a_i \cong 30^{***}$$

$$\text{Percent sand} = \frac{1}{T}\sum_{i=1}^{n} t_i \cdot b_i \cong 40^{***}$$

$$\text{Percent silt} = \frac{1}{T}\sum_{i=1}^{n} t_i \cdot c_i \cong 20^{***}$$

$$\text{Percent clay} = \frac{1}{T}\sum_{i=1}^{n} t_i \cdot d_i \cong 10^{***}$$

* Percent shell values taken to be of shell fragments predominantly larger than sand size (Joseph S. Gentile, U.S. Army Corps of Engineers, oral commun., July 9, 1980).

** Size distribution estimated from material description rather than from textural classification.

*** Rounded to nearest 5 percent because of the nature of the data.

ples from South Tampa Bay were analyzed to detect copper, iron, lead, manganese, zinc, and mercury. Analyses were made to detect the following pesticides and industrial compounds in unfiltered water samples: polychlorinated napthalenes, polychlorinated biphenyls, aldrin, lindane, chlordane, DDD, DDE, DDT, dieldrin, endosulfan, endrin, toxaphene, heptachlor, heptachlor epoxide, 2,4-D, 2,4,5-T, mirex, and silvex. Other water-clarity determinations were made in the laboratory by analyzing for turbidity, suspended solids, and volatile solids. All laboratory analyses were performed by the U.S. Geological Survey according to methods described by Skougstad and others (1979) and Goerlitz and Brown (1972). Concentrations determined using filtered and unfiltered water samples closely approximate dissolved and total (dissolved plus suspended) concentrations of a constituent, respectively.

The data were used to determine (1) relations between the water-clarity parameters, (2) whether concentrations of constituents in samples from plumes were higher than from samples of ambient water, and (3) whether turbidity plumes in South Tampa Bay had water-quality characteristics different from those of plumes in Hillsborough Bay.

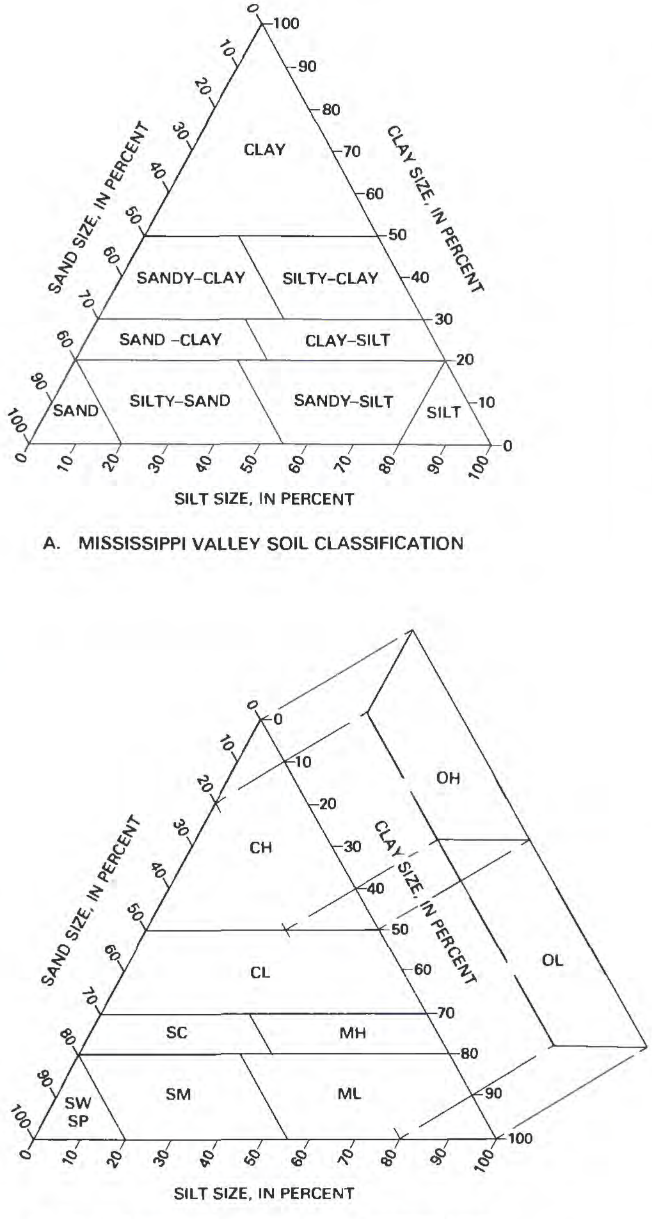


Figure 8. *A*, Mississippi Valley triangular soil classification chart (Casagrande, 1948); *B*, relation to Unified Soil Classification System (fig. 6).

Dredged-Material Classification

Information on particle-size gradation and the percentages of cohesive material in Tampa Bay sediments was obtained from an extensive test-drilling program conducted by the U.S. Army Corps of Engineers. Cores were obtained approximately every 150 m along the ship channel (U.S. Army Corps of Engineers, 1975, 1976, 1977) to determine kinds of material that would be encountered during dredging. The textures of the cores were described in the field, using the Unified Soil Classification System shown in figure 6, and were recorded on drillers' logs, such as those in figure 7. Data from test holes drilled close to each dredge location are included as an indication of soil types being dredged at the time of plume photography.

The approximate particle-size composition of dredged material was determined using a combination of the Unified Soil Classification System (fig. 6, categories SW through OH) and the Mississippi Valley triangular soil classification chart (fig. 8*A*) (Casagrande, 1948). Figure 8*B* shows the category definitions used in this study. Of several soil classification triangles available, the Mississippi Valley triangle is considered best suited to be the basis for comparison with field textural analyses (Tschebotarioff, 1951; Johnson and others, 1968).

Particle-size percentages at the centroid of each category element shown in figure 8*B* and summarized in table 2 were used to derive an approximation for the percentage of sand, silt, and clay of each similarly classified material on the drillers' logs. The percentage of larger-than-sand-size particles (pebbles, gravel, large shell fragments, and limestone) was assigned to a separate size category. The values for the particle-size categories (sand, silt, clay, and larger than sand) for each layer in the drillers' logs were averaged using the thickness of each horizon as a weighting factor. The result is an estimate of the particle-size distribution of material in the vicinity of the dredge. Table 3 gives a sample calculation using data from drillers' log C in figure 7.

To approximate the quantity of cohesive material being dredged, the thickness of cohesive material, based on drillers' logs, was computed as a percentage, given here to the nearest 5 percent, of the total thickness of material drilled. Table 2 shows which soil classifications (SW to OH) are considered cohesive for the purposes of this study.

Determination of Tidal Conditions, Dredge Equipment, and Dredged-Material Placement

Tidal stage and velocity data were determined by a combination of field measurements and simulation modeling. Measurements of tidal stage were made at gages near the mouth of Tampa Bay and near the head of

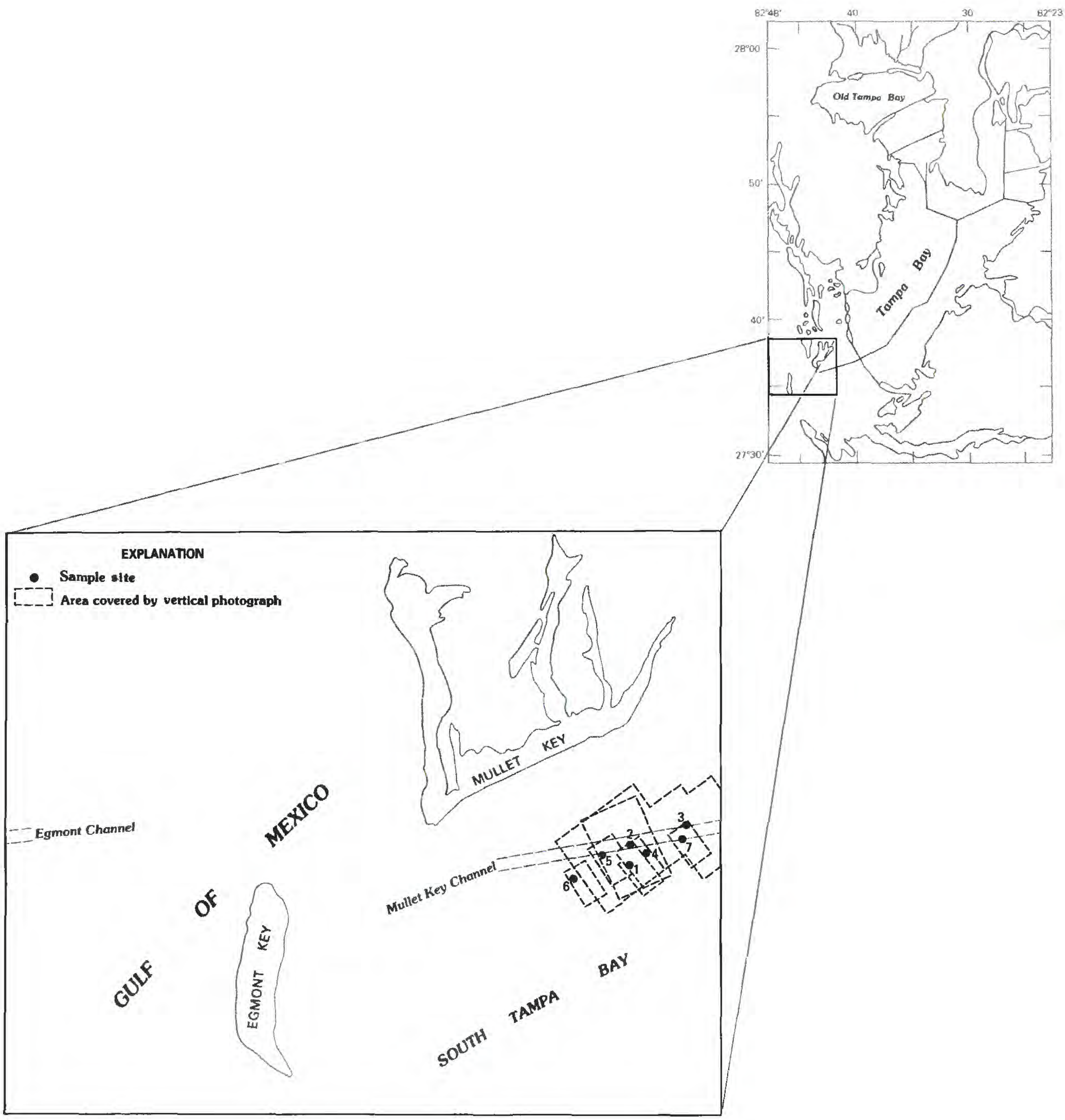


Figure 9. Hopper-dredge loading during floodtide: sample sites 1–7 and respective photograph areas.

Hillsborough Bay (fig. 1). The velocity of water flow at times of plume photography was approximated using information from two-dimensional, hydrodynamic computer-simulated models of Tampa and Hillsborough Bays (Goodwin, 1977). The approximations were cross-checked with published predictions (U.S. Department of Commerce, 1976, 1977).

Information on the type and size of dredge equipment operating during the study was furnished by the U.S. Army Corps of Engineers. Disposal methods were observed from the aircraft or the sampling boat.

APPEARANCE AND WATER-CLARITY DATA

The water-clarity data and accompanying photographs presented in this section describe turbidity plumes produced by the following types of dredging operations: (1) hopper dredges loading, maneuvering, and unloading; (2) pipeline dredges with submerged and oscillating surface discharges; (3) pipeline dredges discharging to open water and to emergent dikes with turbidity barriers. For each dredging operation discussed, the following are presented: location map, sampling conditions, tidal conditions, water-clarity data, and photographs. As listed in the table of contents, the first six operations pertain to plumes in South Tampa Bay, near the entrance to Tampa Bay; the last three pertain to plumes in Hillsborough Bay, near the head of the easterly arm of Tampa Bay.

The location maps show dredge location(s), discharge site(s), sampling sites, orientation of and approximate area covered by each vertical photograph, and orientation of each oblique photograph. Data concerning flight, meteorologic, photographic, sediment, and construction conditions are given in tabular form. Tidal stage and tidal velocity are presented graphically.

On each photograph, a north-pointing arrow provides for coordination with the location map; locations of the sampling boat are circled. With each photograph is provided a caption statement, sampling time, water depth, approximate photograph scale (if applicable), and data on turbidity, suspended solids, and transparency.

Dredging Operations

Hopper-Dredge Loading During Floodtide

On February 17, 1977, the hopper dredge *Ezra Sensibar* was operating in Mullet Key Channel in South Tampa Bay. Because the dredge was in motion, its location and discharge sites were variable and are not plotted on the location map (fig. 9). The dredge had been operating in the area almost continuously for at least two days prior to sampling. Because of a strong floodtide during and for several hours prior to data collection (fig. 10), the turbidity plume was elongated. Plume length exceeded 2 km, and its average width was about 100 m. Seventy-five percent of the material dredged was sand or larger size particles (table 4) and was described as slightly silty and very shelly fine to medium sand.

The dredge in operation and an ambient-water sample site about 200 m from the dredge are shown in figure 11*A*. Interestingly, the sample site shown in figure 12*A* was only a few meters outside the edge of the visible plume yet had clearer water than the site 200 m away. Sample sites at various locations within the plume are shown in figures 11*B*, 11*C*, 12*B*, 12*C*, and 12*D*; the sampling of these sites represents about 1 hour and 40 minutes during active dredge operation. Figure 12*B* was taken as the dredge reversed direction and discharged additional sediment onto its previously generated plume. Back-and-forth operation caused a plume of variable width, best seen in the mosaic photograph, figure 11*C*.

Turbidity levels and suspended-solids concentrations were measured during hopper-dredge loading operations under conditions of strong tidal flow with a relatively low percentage of fine material in the dredged sediment. Turbidity values within the plume were mostly within one or two units of that measured at the ambient-water site and four or five units greater than the sample site having the least turbidity.

Under sediment, dredge, and tide conditions similar to those just described, turbidity plumes from hopper-dredge loading operations can be expected to be visible for long distances and have turbidity levels slightly above ambient conditions.

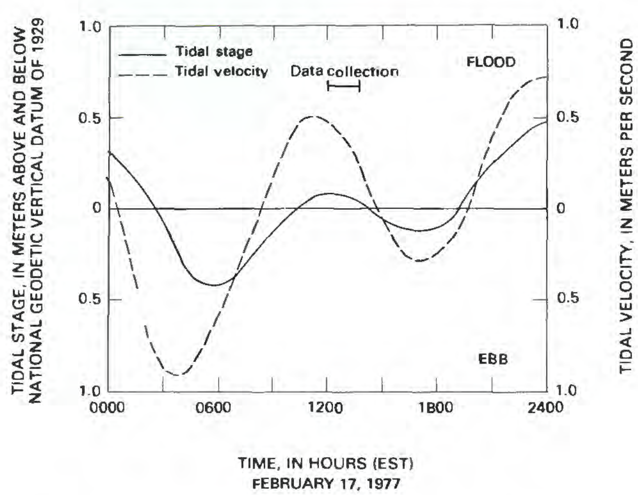


Figure 10. Hopper-dredge loading during floodtide: tidal stage and tidal velocity at South Tampa Bay monitoring sites.

A, Site 1: Vertical view of sample site 200 m southwest of dredge. Time: 1213. Depth: 8.2 m. Scale (approx): 1:9,100.

	Turbidity (NTU)	*Suspended solids (mg/L)*	*Transparency (cm)*
Top	7	29	46
Middle	7	29	—
Bottom	9	32	—

B, Site 2: Vertical view of sample site 400 m east of dredge. Time: 1322. Depth: 11.3 m. Scale (approx): 1:18,200.

	Turbidity (NTU)	*Suspended solids (mg/L)*	*Transparency (cm)*
Top	6	29	61
Middle	6	29	—
Bottom	8	46	—

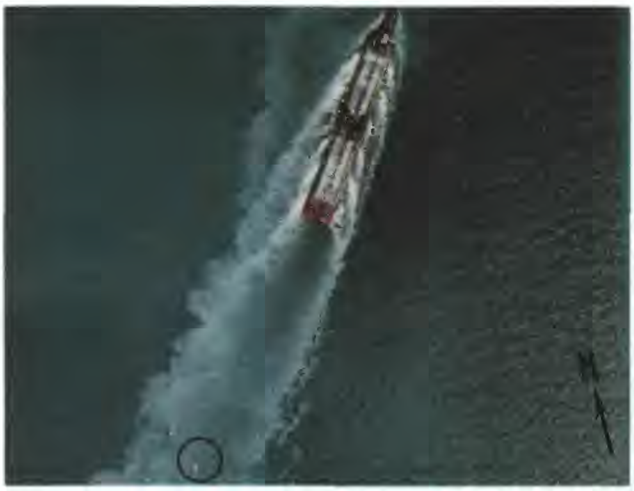
C, Site 3: Mosaic of hopper-dredge plume, sample site 900 m east of dredge. Time: 1340. Depth: 8.2 m. Scale (approx): 1:36,400.

	Turbidity (NTU)	*Suspended solids (mg/L)*	*Transparency (cm)*
Top	7	29	46
Middle	7	29	—
Bottom	9	32	—

Figure 11. Hopper-dredge loading during floodtide: photographs of and water-clarity data for sites 1–3. Circle indicates location of sampling boat.

A, Site 4: Vertical view of sample site outside of plume, 1,300 m east of dredge. Time: 1219. Depth: 9.1 m. Scale (approx): 1:9,100.

	Turbidity (NTU)	*Suspended solids (mg/L)*	*Transparency (cm)*
Top	3	15	91
Middle	2	14	—
Bottom	3	14	—



B, Site 5: Vertical view of dredge backing up. Sample site 300 m west of dredge. Time: 1245. Depth: 10.7 m. Scale (approx): 1:9,100.

	Turbidity (NTU)	*Suspended solids (mg/L)*	*Transparency (cm)*
Top	8	35	46
Middle	8	45	—
Bottom	8	45	—

C, Site 6: Vertical view of sample site 1,000 m east of dredge. Time: 1203. Depth: 9.1 m. Scale (approx): 1:9,100.

	Turbidity (NTU)	*Suspended solids (mg/L)*	*Transparency (cm)*
Top	9	26	91
Middle	15	23	—
Bottom	15	28	—

D, Site 7: Vertical view of sample site 1,000 m east of dredge. Time: 1302. Depth: 11.0 m. Scale (approx): 1:9,100.

	Turbidity (NTU)	*Suspended solids (mg/L)*	*Transparency (cm)*
Top	4	15	91
Middle	6	24	—
Bottom	6	22	—

Figure 12. Hopper-dredge loading during floodtide: photographs of and water-clarity data for sites 4–7. Circle indicates location of sampling boat.

Table 4. Sampling conditions for hopper-dredge loading during floodtide

Flight data:

Time: 1203 to 1340 EST, February 17, 1977
Location: Mullet Key, South Tampa Bay

Meteorologic data:

Visibility: Light haze
Solar altitude: 40^{o} above horizon
Wind speed: 13 km/h
Wind direction: from north

Photographic data:

Film: Kodachrome, ASA 64
Filter: ultraviolet, haze

Sediment data:

Approximate size gradation and percentage of cohesive material

Percent larger than sand size	Percent sand	Percent silt	Percent clay	Percent cohesive material
30	45	20	5	0

Construction data:

Dredge(s): <u>Ezra Sensibar</u>
Containment of dredged materials: none
Placement method: hopper overflow

Hopper-Dredge Maneuvering and Pipeline Dredge with Submerged Discharge at Slack Water

On March 15, 1977, two dredges were working in South Tampa Bay south of Mullet Key (fig. 13). During data collection (fig. 14), the cutterhead-pipeline dredge *Dave Blackburn* was operating in Mullet Key Channel, discharging dredged material into open water about 800 m south of the channel; the hopper dredge *Ezra Sensibar* had finished loading and was maneuvering to unload at a pier on Mullet Key. There were weak and variable tidal currents associated with this period of slack water. Seventy percent of the material discharged by the pipeline dredge was composed of sand and larger-than-sand size particles (table 5). Water-clarity and photographic data are given in figure 15 for sites 8, 9, and 10.

A turbidity plume from the cutterhead-pipeline dredge with a submerged discharge pipe (fig. 2*C*) is shown in figure 15*B* (site 9). The light-blue spots in the upper-central part of that photograph mark the shallowest areas. These had been formed during prior placement operations. Water depths at two of these spots were measured to be 0.9 m and 2.1 m below the surface. The sampling site was in the most visibly turbid region, about 30 m from the discharge point. Although the discharge pipe was submerged, a significant portion of the plume appears to have been reflected to the surface from the bottom before drifting to the north. Turbidity levels ranged from 25 to 70 NTU at site 9.

On the basis of this study, open-water disposal at slack tide can be expected to produce plumes having a limited extent, a generally circular shape, and high visibility. The shape will be modified over time by tidal currents as shown in figure 4 and discussed in the section on "Physical, Chemical, and Hydraulic Properties of Receiving Water."

Turbid patches of water formed as the hopper dredge maneuvered to reach the unloading facility at a pier on Mullet Key (site 10, fig. 15*C*). The turbidity was not a direct result of dredging, but rather an indirect or secondary effect caused by alternate forward and reverse propeller thrusts (prop wash) stirring the local bottom material. Maneuvering of the hopper dredge during slack tide produced turbid water patches with turbidity levels of 30 to 50 NTU.

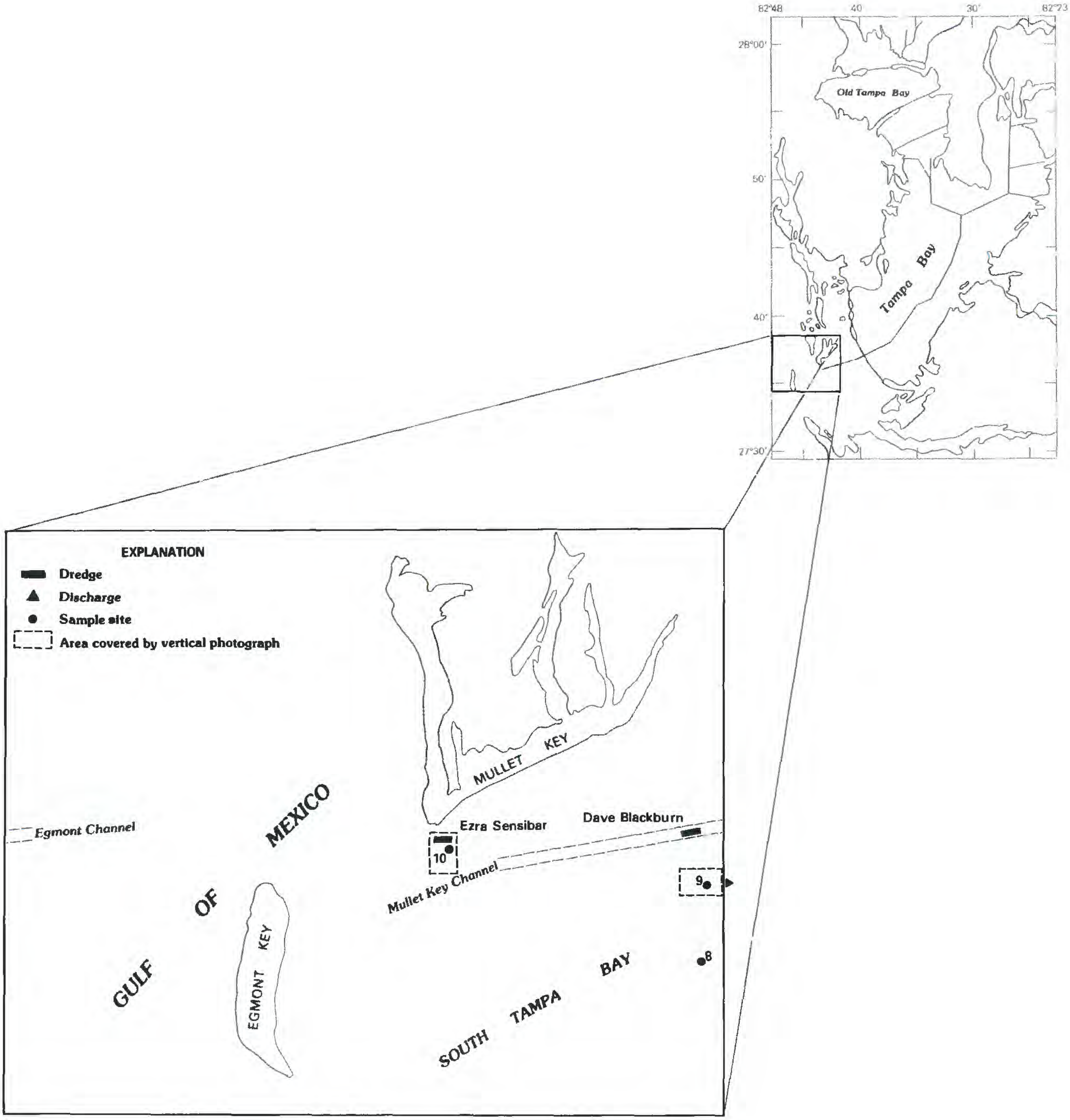


Figure 13. Hopper-dredge maneuvering and pipeline dredge with submerged discharge at slack water: sample sites 8–10 and respective photograph areas.

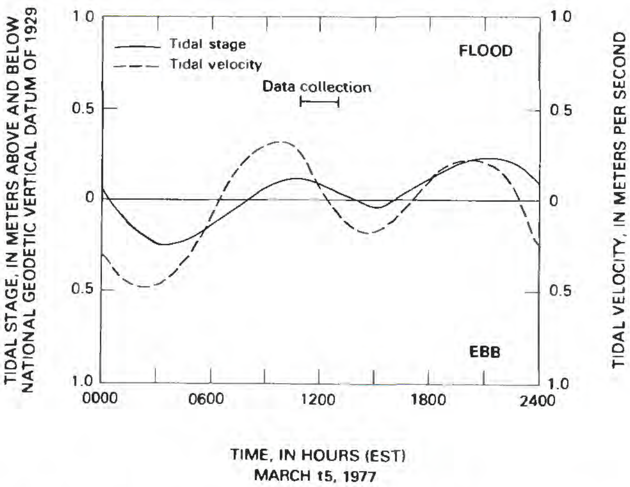


Figure 14. Hopper-dredge maneuvering and pipeline dredge with submerged discharge at slack water: tidal stage and tidal velocity at South Tampa Bay monitoring sites.

A, Site 8: Ambient-water sample site—no photograph taken. Time: 1215. Depth: 13.7 m.

	Turbidity (NTU)	*Suspended solids (mg/L)*	*Transparency (cm)*
Top	2	11	229
Middle	4	11	—
Bottom	6	18	—

B, Site 9: Vertical view of discharge into open water at slack water. Time: 1240. Depth 7.0 m. Scale (approx): 1:9,100.

	Turbidity (NTU)	*Suspended solids (mg/L)*	*Transparency (cm)*
Top	25	60	15
Middle	70	234	—
Bottom	65	197	—

C, Site 10: Vertical view of hopper dredge maneuvering for docking. Time: 1300. Depth: 9.1 m. Scale (approx): 1:9,100.

	Turbidity (NTU)	*Suspended solids (mg/L)*	*Transparency (cm)*
Top	50	88	30
Middle	30	48	—
Bottom	45	80	—

Figure 15. Hopper-dredge maneuvering and pipeline dredge with submerged discharge at slack water: photographs of and water-clarity data for sites 8–10. Circle indicates location of sampling boat.

Table 5. Sampling conditions for hopper-dredge maneuvering and pipeline dredge with submerged discharge at slack water.

Flight data:

Time: 1215 to 1300 EST, March 15, 1977
Location: Mullet Key Channel, South Tampa Bay

Meteorologic data:

Visibility: clear
Solar altitude: 45^{o} above horizon
Wind speed: light
Wind direction: variable

Photographic data:

Film: Kodachrome, ASA 64
Filter: ultraviolet, haze

Sediment data:

Approximate size gradation and percentage of cohesive material

Percent larger than sand size	Percent sand	Percent silt	Percent clay	Percent cohesive material
15	55	20	10	0

Construction data:

Dredges(s): Ezra Sensibar and Dave Blackburn
Containment of dredged materials: none
Placement method: submerged pipe

Hopper-Dredge Unloading During Floodtide

On April 7, 1977, dredged material from the hopper dredge *Ezra Sensibar* was being pumped to a beach nourishment area on the western shore of Mullet Key (fig. 16). The material discharged was primarily sand or larger material. Fifteen percent of the material was estimated to be silt and clay (table 6). A strong floodtide during data collection (fig. 17) caused a southward flow along the beach toward the entrance to Tampa Bay. Visible turbidity plumes were restricted to the vicinity of the discharge pipe and a narrow region along the beach. Turbidity levels ranging from 15 to 85 NTU were measured within 150 m of the discharge pipe (sites 12 and 13, figs. 18*B* and 18*C*). Ambient-water data (fig. 18*A*) were collected at site 11.

Beach nourishment produced a turbidity plume with low to moderate turbidity levels along a narrow band near the beach. This band rapidly merged with and became visibly indistinguishable from natural turbidity

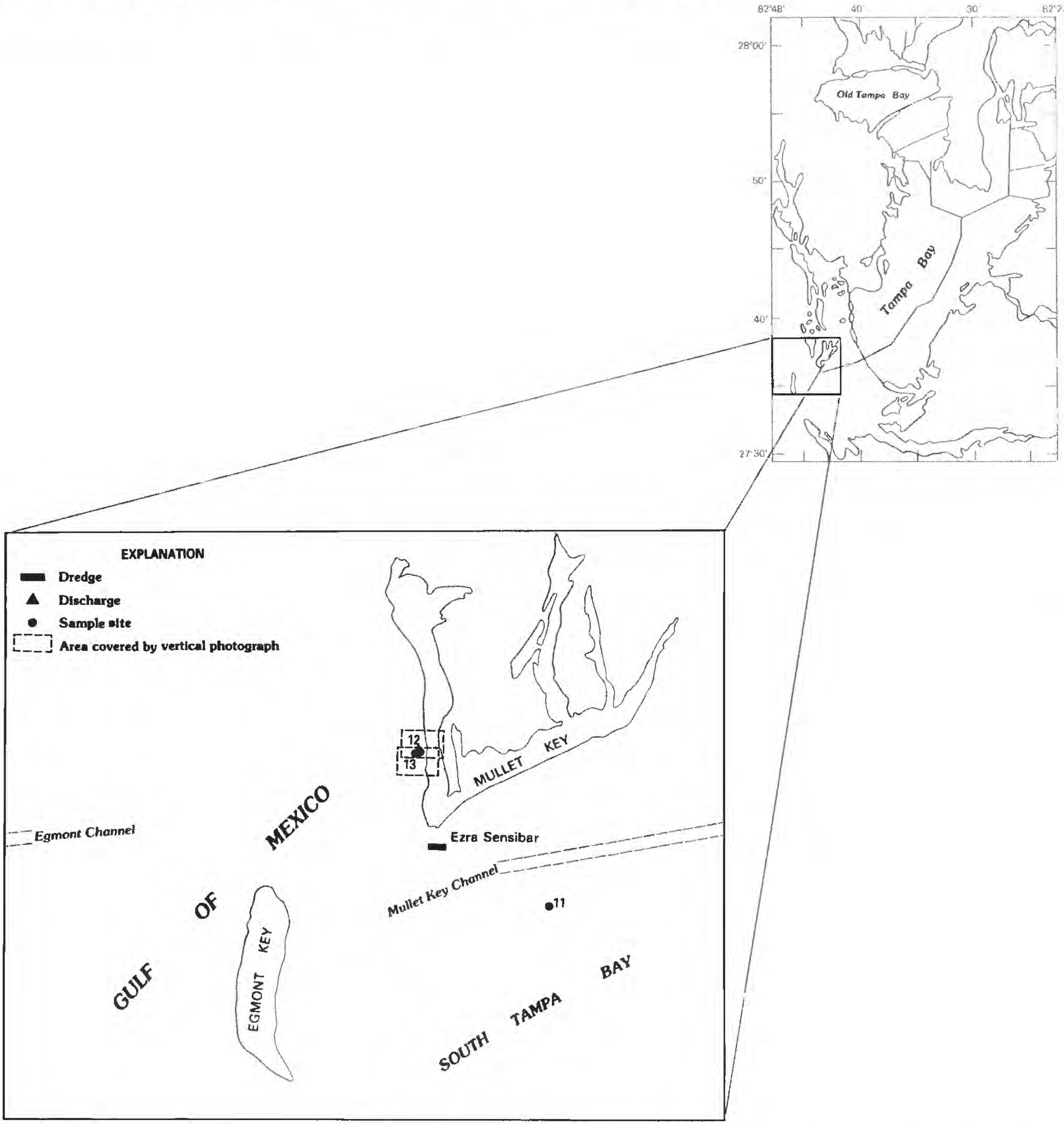


Figure 16. Hopper-dredge unloading during floodtide: sample sites 11–13 and respective photograph areas.

in the surf zone (site 13, fig. 18*C*). Beach nourishment operations of this type can be expected to produce turbidity plumes of low visibility and limited extent.

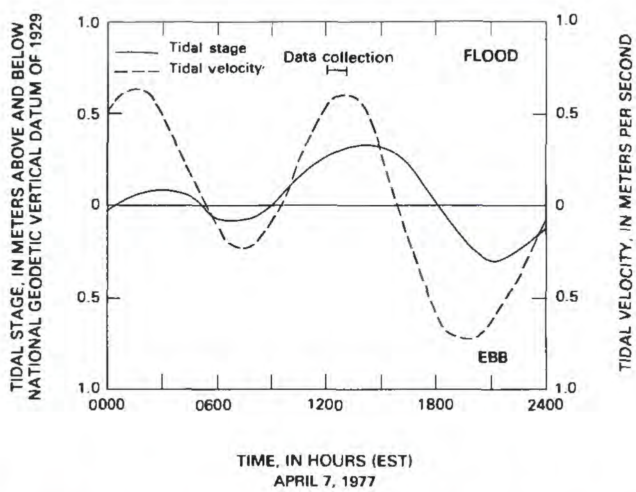


Figure 17. Hopper-dredge unloading during floodtide: tidal stage and tidal velocity at South Tampa Bay monitoring sites.

Table 6. Sampling conditions for hopper-dredge unloading during floodtide

Flight data:

Time: 1200 to 1250 EST, April 7, 1977
Location: west shore of Mullet Key, South Tampa Bay

Meteorologic data:

Visibility: clear
Solar altitude: 58° above horizon
Wind speed: 19 km/h
Wind direction: from northeast

Photographic data:

Film: Kodak Plus-x, ASA 125
Filter: ultraviolet, haze

Sediment data:

Approximate size gradation and percentage of cohesive material

Percent larger than sand size	Percent sand	Percent silt	Percent clay	Percent cohesive material
60	25	10	5	0

Construction data:

Dredge(s): Ezra Sensibar
Containment of dredged materials: none
Placement method: beach nourishment

A, Site 11: Ambient-water sample site—no photograph taken. Time: 1250. Depth: 7.3 m.

	Turbidity (NTU)	Suspended solids (mg/L)	Transparency (cm)
Top	5	10	152
Middle	6	9	—
Bottom	10	18	—

B, Site 12: Vertical view of beach nourishment on west shore of Mullet Key. Time: 1200. Depth: 2.7 m. Scale (approx): 1:9,100.

	Turbidity (NTU)	Suspended solids (mg/L)	Transparency (cm)
Top	85	108	15
Middle	65	86	—
Bottom	15	21	—

C, Site 13: Vertical view of beach nourishment on west shore of Mullet Key. Time: 1212. Depth: 2.4 m. Scale (approx): 1:9,100.

	Turbidity (NTU)	Suspended solids (mg/L)	Transparency (cm)
Top	60	79	15
Middle	50	57	—
Bottom	40	48	—

Figure 18. Hopper-dredge unloading during floodtide: photographs of and water-clarity data for sites 11–13. Circle indicates location of sampling boat.

Hopper-Dredge Unloading and Pipeline-Dredge Smoothing Dredged-Material Placement Area at Slack Water

On May 24, 1977, the hopper dredge *Ezra Sensibar* was discharging dredged material to a beach nourishment area on the south shore of Mullet Key (fig. 19). The cutterhead-pipeline dredge *Dave Blackburn* was smoothing off high spots in a dredged-material placement area about 800 m south of Mullet Key Channel (fig. 19). Conditions during time of photography are given in figure 20 and table 7. Ambient-water data (fig. 21*A*) were collected at site 14. Visible turbidity caused by beach nourishment using predominantly coarse material was confined to a strip about 100 m wide along the beach (sites 15 and 16, figs. 21*B* and 21*C*). The high turbidity level measured at site 16 is attributed to prolonged suspension of fine particles due to the shallow depth (0.5 m), and turbulence from waves along the beach surf zone. In general, hopper-dredge beach nourishment operations that deposit material having a small percentage of silt and clay create turbidity plumes of limited visibility and localized areas of high turbidity levels.

In figure 21*D*, the tops of previously deposited sediment mounds are shown being dredged at site 17 to provide sufficient water depth for safe boating. Fine sediment was removed from the material when initially dredged and deposited. Particle-size data from cores drilled in the ship channel are, therefore, not appropriate for association with the cutterhead-generated plume shown in figure 21*D*. Reduced quantities of fine material and near-slack-water conditions resulted in a plume that was limited in visible extent (about 100 m in diameter) and of moderate turbidity (12 to 28 NTU).

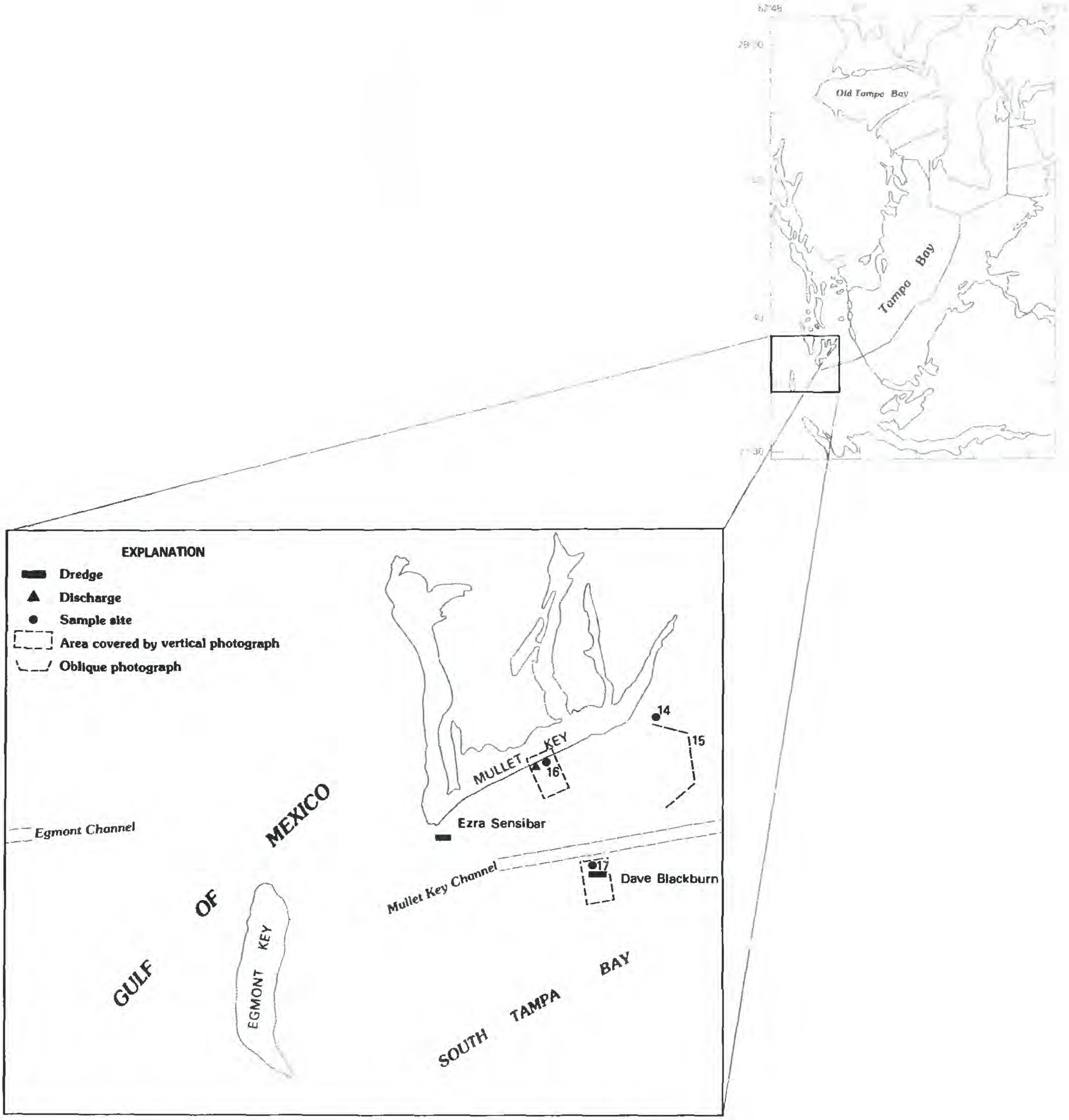


Figure 19. Hopper-dredge unloading and pipeline-dredge smoothing dredged-material placement area at slack water: sample sites 14–17 and respective photograph areas.

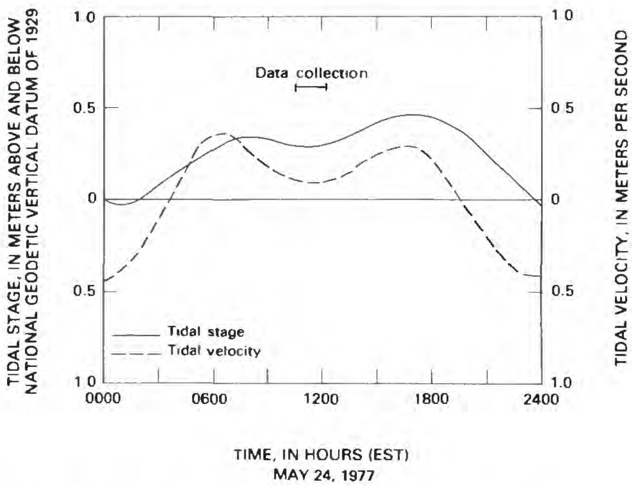


Figure 20. Hopper-dredge unloading and pipeline-dredge smoothing dredged-material placement area at slack water: tidal stage and tidal velocity at South Tampa Bay monitoring sites.

A, Site 14: Ambient-water sample site—no photograph taken. Time: 1200. Depth: 1.0 m.

	Turbidity (NTU)	*Suspended solids (mg/L)*	*Transparency (cm)*
Top	4	31	Visible to bottom

B, Site 15: Oblique view of south shore of Mullet Key during beach nourishment. Time: 1210.

C, Site 16: Vertical view of south shore of Mullet Key during beach nourishment. Time: 1140. Depth: 0.5 m. Scale (approx): 1:9,100.

	Turbidity (NTU)	*Suspended solids (mg/L)*	*Transparency (cm)*
Middle	400	325	3

D, Site 17: Vertical view of pipeline dredge lowering the elevation of shoal areas. Time: 1105. Depth: 3.0 m. Scale (approx): 1:9,100.

	Turbidity (NTU)	*Suspended solids (mg/L)*	*Transparency (cm)*
Top	28	89	107
Middle	13	42	—
Bottom	12	40	—

Figure 21. Hopper-dredge unloading and pipeline-dredge smoothing dredged-material placement area at slack water: photographs of and water-clarity data for sites 14–17. Circle indicates location of sampling boat.

Table 7. Sampling conditions for hopper-dredge unloading and pipeline-dredge smoothing dredged-material placement area at slack water

Flight data:

Time: 1105 to 1210 EST, May 24, 1977
Location: south shore of Mullet Key and Mullet Key Channel, South Tampa Bay

Meteorologic data:

Visibility: 8 km with haze
Solar altitude: 64° above horizon
Wind speed: 8 km/h
Wind direction: from south

Photographic data:

Film: Kodachrome, ASA 64
Filter: ultraviolet, haze

Sediment data for hopper-dredge unloading:

Approximate size gradation and percentage of cohesive material

Percent larger than sand size	Percent sand	Percent silt	Percent clay	Percent cohesive material
60	25	10	5	0

Construction data:

Dredge(s): _Ezra Sensibar_ and _Dave Blackburn_
Containment of dredged material: none
Placement method: beach nourishment

Pipeline Dredge with Oscillating Surface Discharge and Secondary Erosional Plume During Floodtide

On June 29, 1977, the cutterhead dredge *Western Condor* was operating at the entrance to Tampa Bay in Egmont Channel (fig. 22). The *Condor* had been discharging to an unconfined placement area about 1,200 m south of Egmont Channel for about two days.

Bottom material of Egmont Channel in the area being dredged consisted of pebble-size shell fragments and medium to fine gray sand, together with about 15 percent silt (table 8). The water velocity at a point well inside the bay mouth (fig. 1) averaged about 0.5 m/s on floodtide during data collection (fig. 23). The velocity was probably higher at the disposal site (fig. 22). A light-colored turbidity plume was highly visible against the blue-green background of the surrounding water

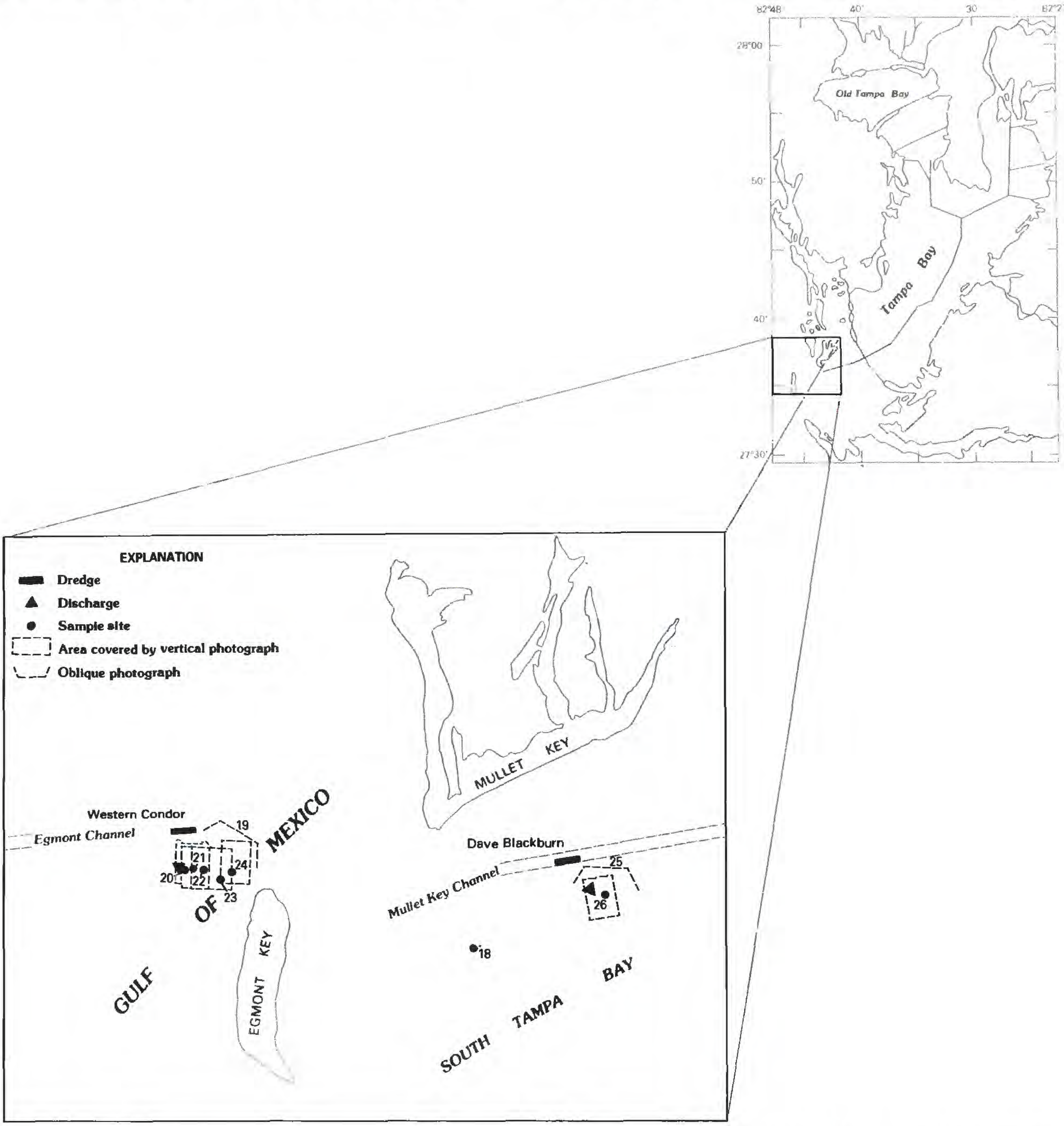


Figure 22. Pipeline dredge with oscillating discharge and secondary erosional plume during floodtide: sample sites 18–26 and respective photograph areas.

Table 8. Sampling conditions for pipeline dredge with oscillating discharge and secondary erosional plume during floodtide

Flight data:

Time: 0915 to 1035 EST, June 29, 1977
Location: Egmont Channel, Mullet Key Channel, South Tampa Bay

Meteorologic data:

Visibility: 14 km, haze
Solar altitude: 62° above horizon
Wind speed: 8 km/h
Wind direction: from west

Photographic data:

Film: Kodacolor II, ASA 80; Kodachrome, ASA 64
Filter: ultraviolet, haze

Sediment data:

Approximate size gradation and percentage of cohesive material

Percent larger than sand size	Percent sand	Percent silt	Percent clay	Percent cohesive material
		Egmont Channel		
70	15	15	0	0
		Mullet Key Channel		
30	35	30	5	0

Construction data:

Dredge(s): Western Condor and Dave Blackburn
Containment of dredged materials: none
Placement method: oscillating surface discharge

(sites 19–24, figs. 24*B–E* and 25*A–B*). The most visible part of the plume was about 2 km long and 300 m wide at its widest point. The plume narrowed to less than 100 m in width toward Egmont Key, as shown at the eastern extremity of figure 25*B*. An S-shaped pattern, caused by oscillating movement of the discharge pipe, was visible in the plume for about 500 m east of the discharge point (sites 19–21). A satellite image made on June 28, 1977 (fig. 26), during a similar tide shows a tapering plume to the west of Egmont Key.

The light area to the east of Egmont Key in figure 26 is postulated to be an extension or separated part of the turbidity plume. Both of the separated parts are indicated by arrows on the photograph. Plume contraction and expansion is a surface expression of the rapidly accelerating and decelerating flow on either side of the relatively narrow (800 m) and locally deep (20–30 m) entrance channel to Tampa Bay between

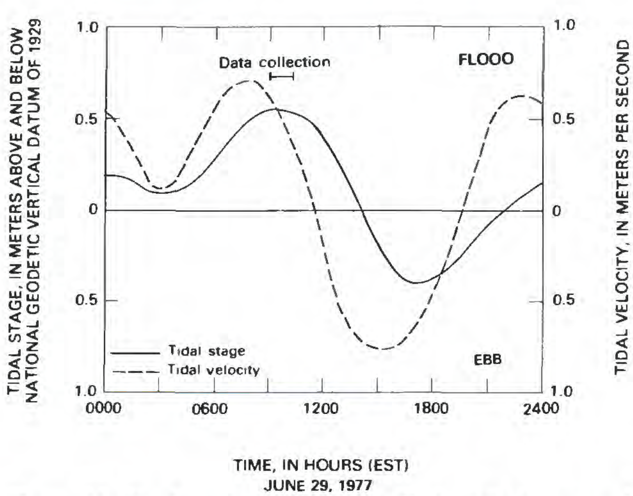


Figure 23. Pipeline dredge with oscillating discharge and secondary erosional plume during floodtide: tidal stage and tidal velocity at South Tampa Bay monitoring sites.

A, Site 18: Ambient-water sample site—no photograph taken. Time: 0930. Depth: 7.6 m.

	Turbidity (NTU)	*Suspended solids (mg/L)*	*Transparency (cm)*
Top	50	132	274
Middle	3	110	—
Bottom	9	122	—

B, Site 19: Oblique view of uncontained open-water turbidity plume. Discharge outlet at top of picture is swinging from side to side causing the "S" patterns in the plume.

C, Site 20: Vertical view of *Western Condor* discharge pipe. Sample site about 50 m from discharge point. Time: 0950. Depth: 3.4 m. Scale (approx): 1:9,100.

	Turbidity (NTU)	*Suspended solids (mg/L)*	*Transparency (cm)*
Top	65	113	30
Middle	120	220	—
Bottom	100	182	—

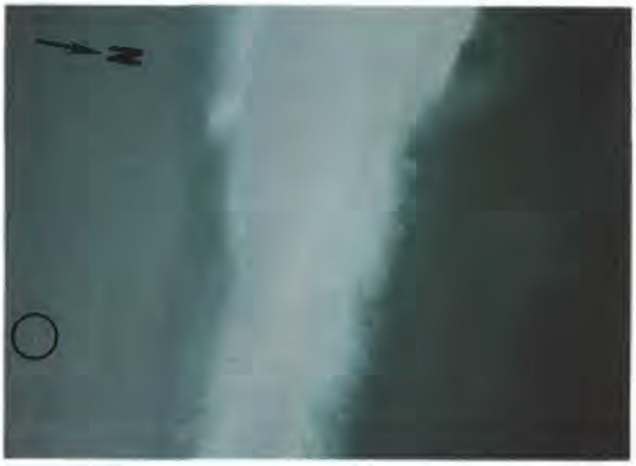
D, Site 21: Vertical view of sample site about 350 m from discharge point. Erosion of previously deposited material visible to right of plume. Time: 1000. Depth: 4.0 m. Scale (approx): 1:9,100.

	Turbidity (NTU)	*Suspended solids (mg/L)*	*Transparency (cm)*
Top	350	556	15
Middle	100	180	—
Bottom	130	182	—

E, Site 22: Vertical view of sample site about 200 m from discharge point. Plume convergence noticeable. Time: 1012. Depth: 3.4 m. Scale (approx): 1:9,100.

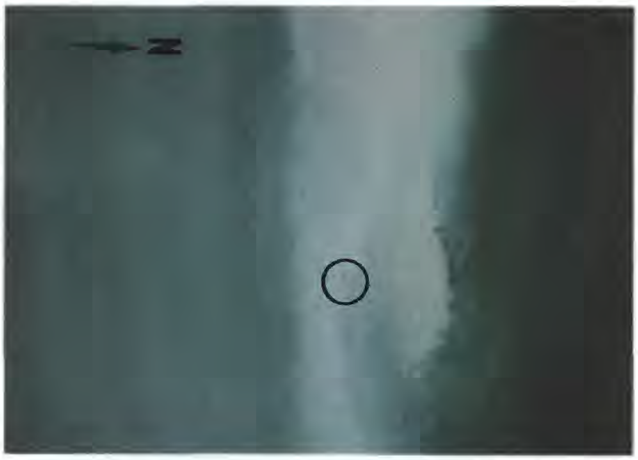
	Turbidity (NTU)	*Suspended solids (mg/L)*	*Transparency (cm)*
Top	50	118	30
Middle	55	111	—
Bottom	65	138	—

Figure 24. Pipeline dredge with oscillating discharge and secondary erosional plume during floodtide: photographs of and water-clarity data for sites 18–22. Circle indicates location of sampling boat.



A, Site 23: Vertical view of sample site outside of main plume about 1,200 m from discharge point—convergence continuing. Time: 1020. Depth: 4.3 m. Scale (approx): 1:9,100.

	Turbidity (NTU)	*Suspended solids (mg/L)*	*Transparency (cm)*
Top	80	182	107
Middle	10	83	—
Bottom	15	75	—



B, Site 24: Vertical view of sample site about 1,400 m from discharge point—convergence nearly complete. Time: 1015. Depth: 5.5 m. Scale (approx): 1:9,100.

	Turbidity (NTU)	*Suspended solids (mg/L)*	*Transparency (cm)*
Top	35	94	46
Middle	30	93	—
Bottom	35	105	—

C, Site 25: Oblique view of secondary erosional plume from previously deposited material in open-water site. Dredge not operating.

D, Site 26: Vertical view of secondary erosional plumes from previously deposited material. Time: 0915. Depth: 5.2 m. Scale (approx): 1:9,100.

	Turbidity (NTU)	*Suspended solids (mg/L)*	*Transparency (cm)*
Top	85	207	107
Middle	15	66	—
Bottom	140	103	—

Figure 25. Pipeline dredge with oscillating discharge and secondary erosional plume during floodtide: photographs of and water-clarity data for sites 23–26. Circle indicates location of sampling boat.

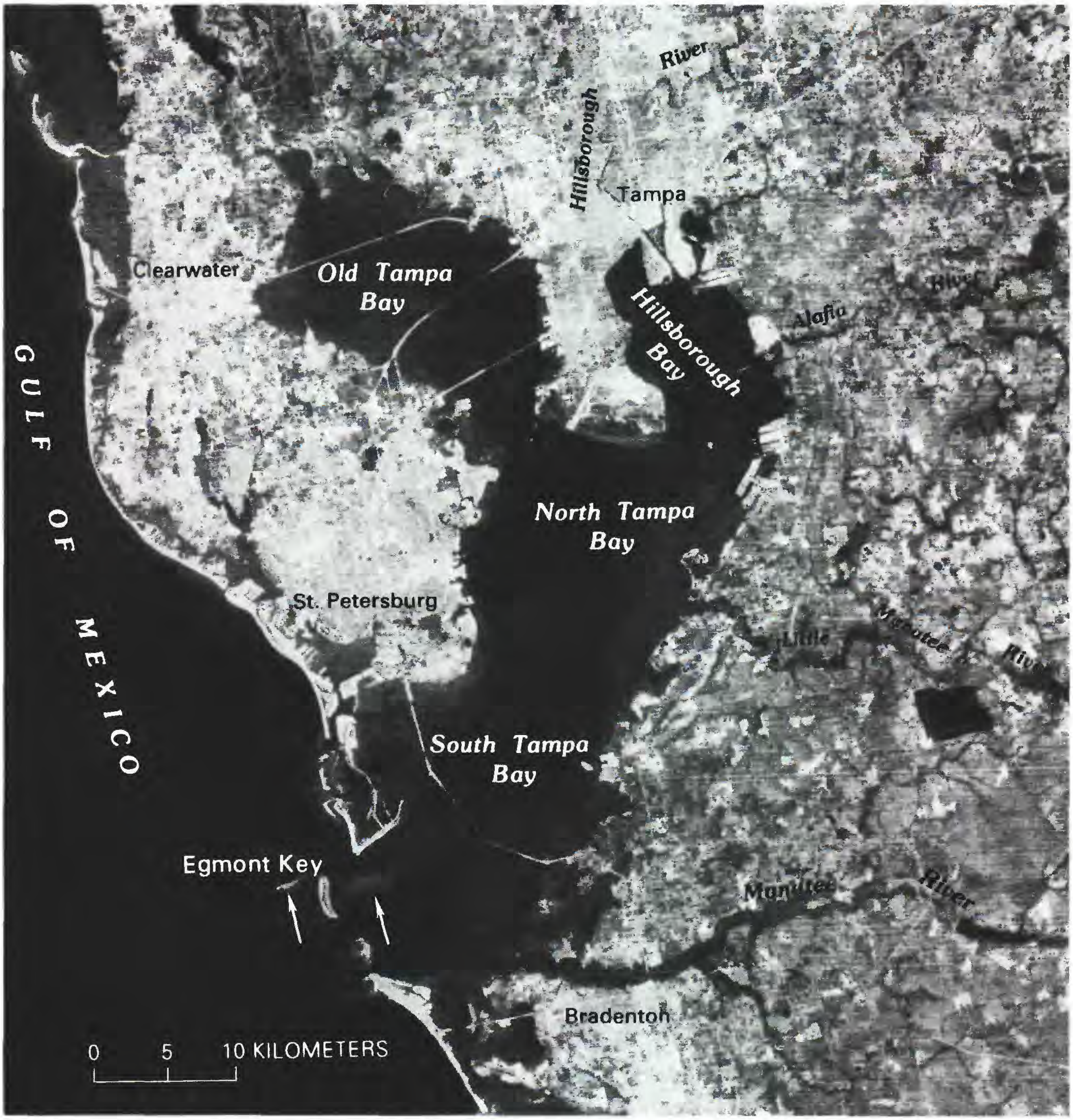


Figure 26. Satellite image of west-central Florida, showing both parts of a separated turbidity plume at entrance to Tampa Bay.

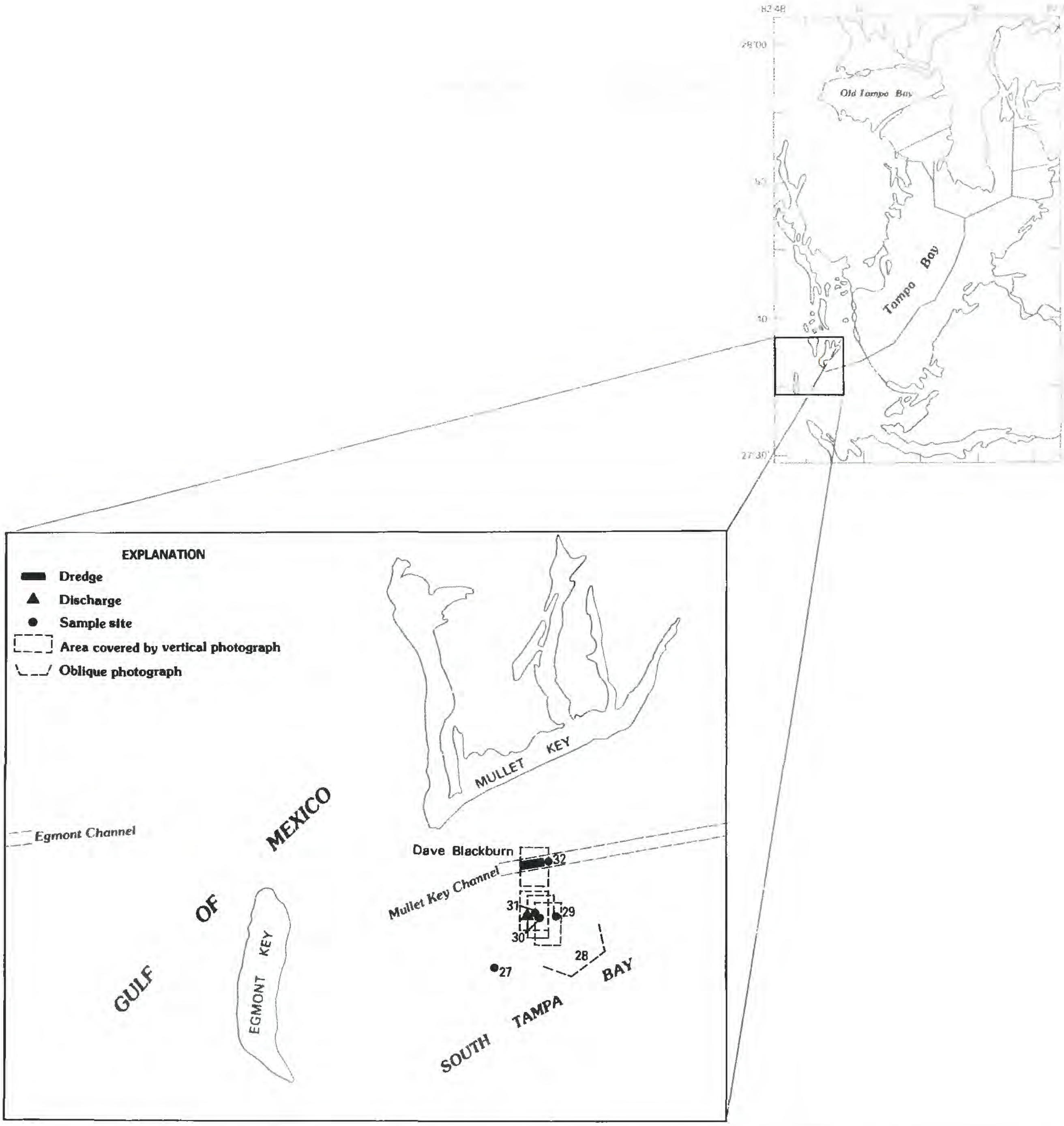


Figure 27. Pipeline dredge with intermittent discharge and secondary erosional plume during floodtide: sample sites 27–32 and respective photograph areas.

Egmont and Mullet Keys. In the region of highest velocities, at the northern tip of Egmont Key, the plume becomes narrow enough to lose its identity. One plume, therefore, comes to appear as two distinct units; we call this a "separated plume."

Secondary turbidity caused by erosion of previously deposited dredged material is visible in figures 24*B*–*D*, especially along the edges and openings of the primary S-shaped plume. Visible indications of turbidity from eroding material are characterized by a linear series of dispersing puffs emanating from numerous points on the bottom. At a distance of about 500 m from the discharge pipe, the primary and secondary plumes lose their separate identities and merge.

Turbidity levels within the plume varied from 30 to 350 NTU as indicated by measurements at sites 20, 21, 22, and 24 (figs. 24*C*–*E* and 25*B*). Higher levels generally occurred near the discharge pipe at the head of the plume; lower levels, primarily near the tail or at the edges of the plume. Significant deviations from the general pattern occur, however, indicating that distance from the primary discharge point is not always a good predictor of turbidity levels. For instance, a turbidity level of 80 NTU was measured at the top of the water column, 1,200 m from the discharge point, whereas a level of 65 NTU was measured only 50 m from the discharge point. We conclude that the heterogeneous nature of the composition of plumes such as this makes it difficult to characterize plume turbidity levels satisfactorily on the basis of a few point samples. A similar conclusion was reached by Simon and others (1976).

Water-clarity data for ambient-water site 18 are given in figure 24*A*. Unfortunately, the presence of a separated plume at Egmont Key, recognized only after the time of data collection, may have influenced the data.

Large, highly visible plumes can be expected from the use of oscillating surface-discharge placement methods, even when dredged material has low silt and clay content. High tidal velocities elongate the plume and regions of accelerating and decelerating flow can separate the visible plume.

Also on June 29, 1977, the cutterhead-pipeline dredge *Dave Blackburn* was in Mullet Key Channel and had been discharging in an unconfined area about 1,200 m south of the channel (fig. 22) at a series of stationary pipeline positions. The dredge was not operating during the data-collection period, so a primary turbidity plume was not created then. A large secondary erosional plume extending about 1,000 m from the end of the discharge pipe and having an average width of about 500 m is visible in figures 25*C* and 25*D*. Tidal velocity during data collection averaged about 0.5 m/s (fig. 23). Bottom materials in the area of the dredge consisted of hard, porous, tan limestone and medium to fine gray sand, with some silt and shell. Because some fine material had been winnowed from the dredged sediment as it was initially deposited, the fine materials remaining for erosion and resuspension probably totaled less than 35 percent (table 8). Data from site 26 indicate significant levels of turbidity (15–140 NTU) and suspended solids (66–207 mg/L) within the secondary plume. It is not known how long secondary erosional plumes persist after active dredging operations cease.

Secondary turbidity plumes can be generated by erosion of previously deposited, submerged dredged material during periods of high tidal-flow velocities. Turbidity levels in erosional plumes can be of the same order as in primary plumes. Erosional plumes appear as a series of linear, enlarging puffs extending downstream from one or more points, which probably are high spots protruding above the bottom into areas with higher flow velocities.

Pipeline Dredge with Intermittent Discharge and Secondary Erosional Plume During Floodtide

On October 27, 1977, the cutterhead dredge *Dave Blackburn* was operating in South Tampa Bay. It had been operating in the Mullet Key Channel for at least 24 of the previous 48 hours and was discharging to an open-water site about 1,800 m south of the channel (fig. 27). Materials being dredged were silt, sand, and larger material (table 9). Sampling was done during floodtide with channel velocities of about 0.5 m/s (fig. 28). The data for site 27 (fig. 29*A*) define ambient water-clarity conditions. Figure 29*B* provides an overall view of the dredge and dredged-material placement site; Mullet Key appears in the background. Turbidity from the placement site included a secondary erosional plume, produced by the strong floodtide conditions, and an intermittently active primary plume. As shown in figure 29*B*, the secondary plume forms a straight swath of turbidity that runs at an angle from left to right; the intermittent primary plume shows as two larger turbid patches in the lower right corner of the photograph. Turbidity from the placement area was visible for about 800 m from the discharge point.

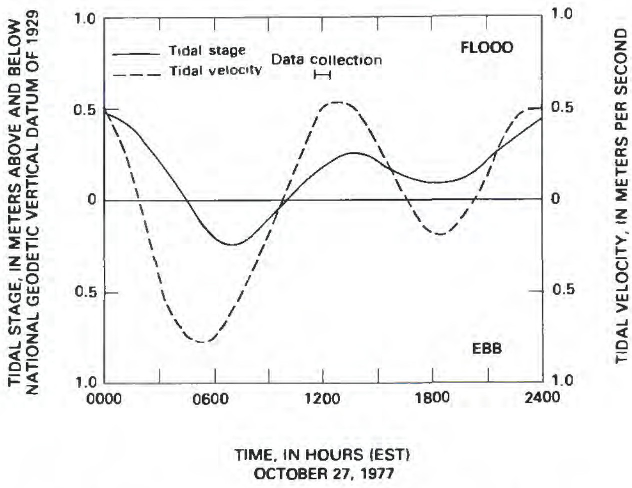


Figure 28. Pipeline dredge with intermittent discharge and secondary erosional plume during floodtide: tidal stage and tidal velocity at South Tampa Bay monitoring sites.

Table 9. Sampling conditions for pipeline dredge with intermittent discharge and secondary erosional plume during floodtide

Flight data:

Time: 1135 to 1225 EST, October 27, 1977
Location: Mullet Key Channel, South Tampa Bay

Meteorologic data:

Visibility: 11 km
Solar altitude: 45° above horizon
Wind speed: light
Wind direction: variable

Photographic data:

Film: Kodachrome, ASA 64
Filter: ultraviolet, haze

Sediment data:

Approximate size gradation and percentage of cohesive material

Percent larger than sand size	Percent sand	Percent silt	Percent clay	Percent cohesive material
30	40	25	5	0

Construction data:

Dredge(s): Dave Blackburn
Containment of dredged material: none
Placement method: submerged discharge

Sample sites 29–31 (figs. 29*C*, and 30*A*, *B*), which are successively closer to the pipeline discharge outlet, had progressively higher levels of turbidity and suspended solids. The intermittent presence of the primary plume is due either to noncontinuous dredge operation or to hard limestone and consequent difficult dredging conditions. Figure 30*C* shows a sample site in a small turbid patch apparently produced by the dredge.

All bottom samples show consistently greater turbidity than samples higher in the water column, reflecting rapid sediment settling and the development of plumes at depth by the cutterhead or by secondary erosional processes.

A, Site 27: Ambient-water sample site about 750 m from discharge—no photograph taken. Time: 1150. Depth: 7.6 m.

	Turbidity (NTU)	*Suspended solids (mg/L)*	*Transparency (cm)*
Top	4	10	236
Middle	9	23	—
Bottom	12	43	—

B, Site 28: Oblique view of open-water dredged-material placement area showing secondary erosional plume and intermittent primary plume with cutterhead dredge *Dave Blackburn* in background.

C, Site 29: Vertical view of sample site in intermittent primary plume about 500 m from discharge point. Time: 1135. Depth: 7.9 m. Scale (approx): 1:6,100.

	Turbidity (NTU)	*Suspended solids (mg/L)*	*Transparency (cm)*
Top	6	28	61
Middle	8	34	—
Bottom	55	195	—

Figure 29. Pipeline dredge with intermittent discharge and secondary erosional plume during floodtide: photographs of and water-clarity data for sites 27–29. Circle indicates location of sampling boat.

A, Site 30: Vertical view of sample site about 210 m from discharge point. Time: 1215. Depth: 7.9 m. Scale (approx): 1:6,100.

	Turbidity (NTU)	*Suspended solids (mg/L)*	*Transparency (cm)*
Top	15	61	61
Middle	18	42	—
Bottom	45	151	—

B, Site 31: Vertical view of sample site about 90 m from discharge point. Time: 1225. Depth: 7.9 m. Scale (approx): 1:6,100.

	Turbidity (NTU)	*Suspended solids (mg/L)*	*Transparency (cm)*
Top	25	138	30
Middle	40	196	—
Bottom	120	480	—

C, Site 32: Vertical view of cutterhead dredge *Dave Blackburn* in operation. Sample site is about 110 m from dredge. Time: 1200. Depth: 15.5 m. Scale (approx): 1:6,100.

	Turbidity (NTU)	*Suspended solids (mg/L)*	*Transparency (cm)*
Top	17	58	61
Middle	16	35	—
Bottom	45	335	—

Figure 30. Pipeline dredge with intermittent discharge and secondary erosional plume during floodtide: photographs of and water-clarity data for sites 30–32. Circle indicates location of sampling boat.

Pipeline Dredge Discharging Within Turbidity Barrier During Ebbtide

On March 13, 1978, the cutterhead-pipeline dredge *Hendry No. 5* was operating in Cut C Channel in Hillsborough Bay (fig. 31). The dredge was discharging material to form a dike about 500 m east of the channel. A turbidity barrier was in place around the placement site. Bottom materials near the dredge consisted of gray silt, green clay, and weathered limestone and contained about 60 percent fine material and 60 percent cohesive material (table 10). As slack water approached, tidal velocity became weak and variable (fig. 32).

An ambient-water sample (site 33, fig. 33*A*) was collected about 750 m west of the discharge point. The relatively high bottom turbidity at the ambient-water site suggests the presence of a more widespread plume near the bay bottom than is indicated by the visible plume near the water surface. Figure 33 shows overviews of the plume from three different vantage points shown in figure 31. The visible turbidity plume extends to the west-southwest for about 2 km from the discharge point. Sample sites 34–36 lie within the plume and outside the turbidity barrier. Figure 34 shows sample sites within the turbidity barrier or at points of incomplete barrier closure.

Samples collected outside the barrier showed moderate turbidity levels at top and middle depths and high turbidity levels at the bottom, indicating that the visible plume was not an adequate indicator of turbidity levels near the bottom. Suspended material had probably been removed from the upper part of the water column because of (1) the high percentage of cohesive material (table 10), (2) the flocculation of silts and clays, and (3) the relatively effective use of turbidity barriers. The visible surface plume was chiefly the result of turbid water escaping around the southern end of the barrier (fig. 33*B*) and through a 10-m gap in the barrier (fig. 34*D*). In spite of these two locations of incomplete barrier closure, the data indicate that most of the suspended material was at a depth greater than the limited water-penetrating capability of the photography.

Sites 37–40 (figs. 34*A–D*) are numbered in the order in which they were taken, over a period of 40 minutes. A substantial quantity of turbid water is shown

Table 10. Sampling conditions for pipeline-dredge discharging within turbidity barrier during ebbtide

Flight data:

Time: 1035 to 1135 EST, March 13, 1978
Location: Cut C Channel, Hillsborough Bay

Meteorologic data:

Visibility: 16 km, haze
Solar altitude: 45° above horizon
Wind speed: 10 km/h
Wind direction: from southeast

Photographic data:

Film: Kodachrome, ASA 64
Filter: ultraviolet, haze

Sediment data:

Approximate size gradation and percentage of cohesive material

Percent larger than sand size	Percent sand	Percent silt	Percent clay	Percent cohesive material
15	25	35	25	60

Construction data:

Dredge(s): Hendry No. 5
Containment of dredged materials: turbidity barrier
Placement method: emergent dike

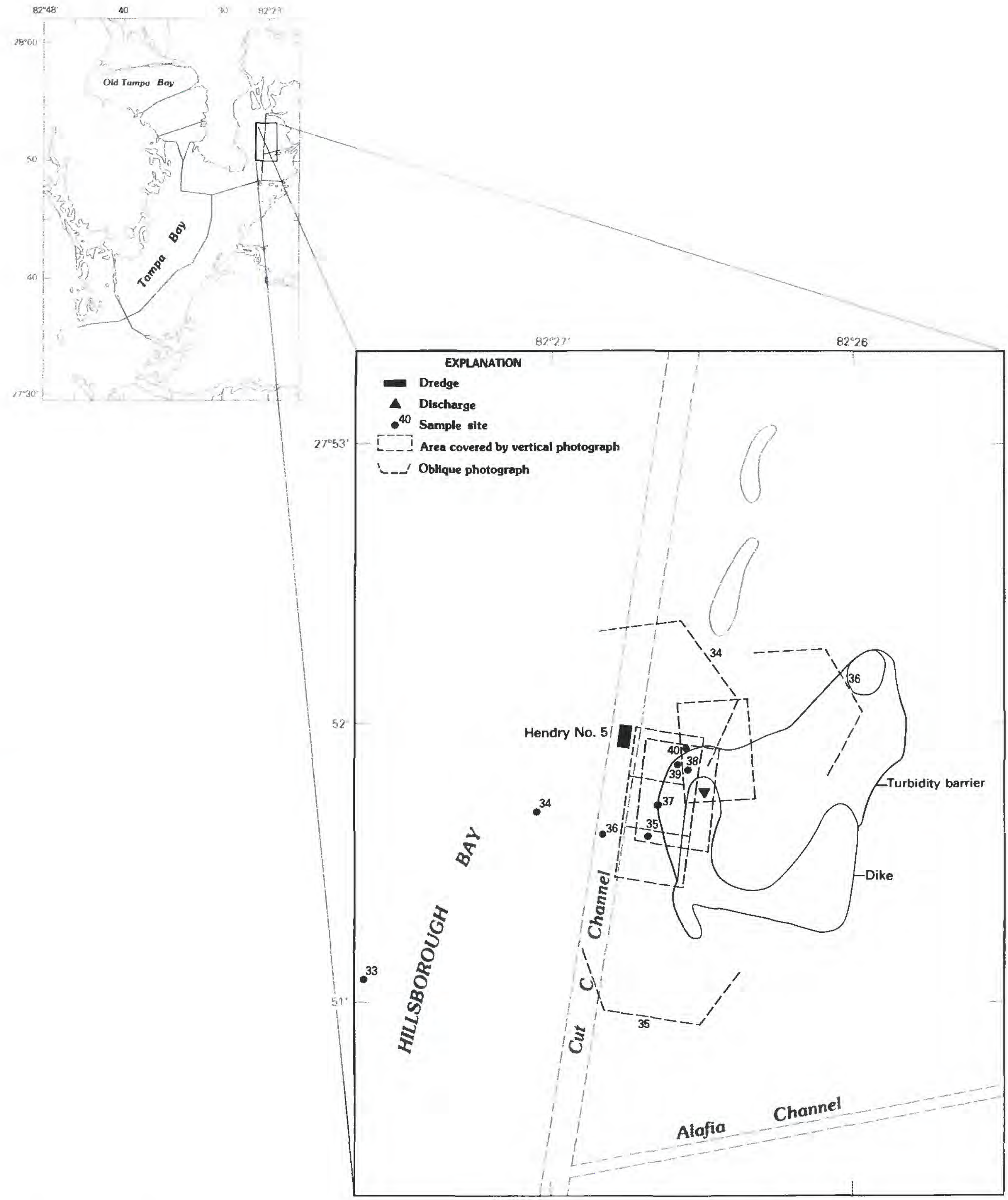


Figure 31. Pipeline-dredge discharging within turbidity barrier during ebbtide: sample sites 33–40 and respective photograph areas.

flowing around the southern end of the turbidity barrier in figure 34*A*. Later photographs show that this source of turbid water has been closed off due to changing tidal-flow direction. If the turbidity barrier were completely enclosed, surface discharge of turbid water would be reduced, but the total amount of material escaping the barrier may not be significantly affected. All material could be discharged under the barrier, effectively reducing the visible surface plume but increasing the size or intensity of the bottom plume or mud flow.

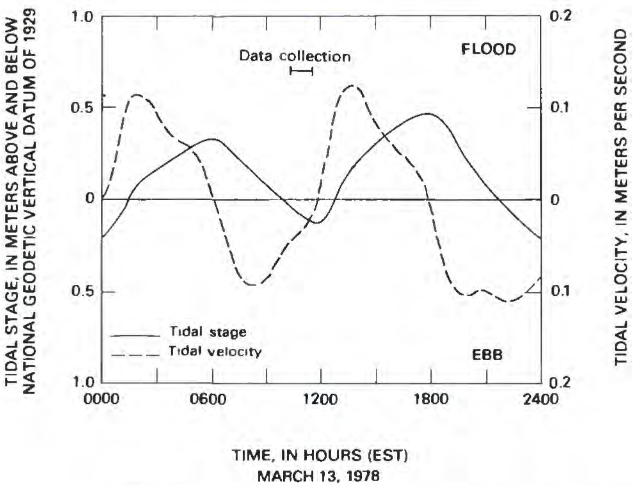


Figure 32. Pipeline-dredge discharging within turbidity barrier during ebbtide: tidal stage and tidal velocity at Hillsborough Bay monitoring sites.

A, Site 33: Ambient-water sample site—750 m west of discharge point. No photograph taken. Time: 1035. Depth: 3.0 m.

	Turbidity (NTU)	*Suspended solids (mg/L)*	*Transparency (cm)*
Top	2	30	61
Middle	4	32	—
Bottom	70	133	—

B, Site 34: Oblique view of sample site near edge of visible plume, 600 m from discharge point. Time: 1100. Depth: 4.9 m.

	Turbidity (NTU)	*Suspended solids (mg/L)*	*Transparency (cm)*
Top	8	31	76
Middle	12	39	—
Bottom	160	166	—

C, Site 35: Oblique view of sample site, 340 m from discharge point. Time 1105. Depth: 3.4 m.

	Turbidity (NTU)	*Suspended solids (mg/L)*	*Transparency (cm)*
Top	90	114	76
Middle	25	52	—
Bottom	40	100	—

D, Site 36: Oblique view of construction area and environs. Sampling boat is in channel, about 500 m from discharge point. Time: 1055. Depth: 13.7 m.

	Turbidity (NTU)	*Suspended solids (mg/L)*	*Transparency (cm)*
Top	16	29	46
Middle	7	38	—
Bottom	1,200	2,990	—

Figure 33. Pipeline-dredge discharging within turbidity barrier during ebbtide: photographs of and water-clarity data for sites 33–36. Circle indicates location of sampling boat.

A, Site 37: Vertical view of sample site at opening between barrier and dike, 170 m from discharge point. Time: 1115. Depth: 2.1 m. Scale (approx): 1:9,100.

	Turbidity (NTU)	*Suspended solids (mg/L)*	*Transparency (cm)*
Top	25	52	30
Middle	18	60	—
Bottom	120	240	—

B, Site 38: Vertical view of sample site, 130 m from discharge point. Vessels are creating a secondary plume. Time: 1125. Depth: 1.2 m. Scale (approx): 1:9,100.

	Turbidity (NTU)	*Suspended solids (mg/L)*	*Transparency (cm)*
Top	85	128	15
Middle	1,500	2,020	—
Bottom	800	1,580	—

C, Site 39: Vertical view of sample site next to turbidity barrier, 270 m from discharge point. Time: 1130. Depth: 1.2 m. Scale (approx): 1:9,100.

	Turbidity (NTU)	*Suspended solids (mg/L)*	*Transparency (cm)*
Top	30	81	30
Middle	35	92	—
Bottom	40	108	—

D, Site 40: Vertical view of sample site near gap, 320 m from discharge point. Time: 1135. Depth: 2.1 m. Scale (approx): 1:9,100.

	Turbidity (NTU)	*Suspended solids (mg/L)*	*Transparency (cm)*
Top	70	129	15
Middle	60	156	—
Bottom	100	246	—

Figure 34. Pipeline-dredge discharging within turbidity barrier during ebbtide: photographs of and water-clarity data for sites 37–40. Circle indicates location of sampling boat.

Pipeline Dredge Discharging to Emergent Dike with Turbidity Barrier During Floodtide

On April 4, 1978, the *Western Condor* cutterhead-pipeline dredge was operating in Cut C Channel in Hillsborough Bay. Material was being discharged to a dike construction site about 1 km east of the channel (fig. 35). The dredge had been operating about 75 percent of the time during the previous 72 hours. Bottom materials in the area included sandy organic silts, clayey sands, sandy organic clay, and weathered limestone with seams of calcareous silt and green clay. Silt and clay composed about 60 percent of the material, and 35 percent of the material was considered to be cohesive (table 11).

A turbidity barrier was deployed across the northern end of a horseshoe-shaped, partly completed, diked impoundment (fig. 35). Sample collection was during floodtide (fig. 36) and the flow was northward. Ambient water-clarity data were collected at site 41 (fig. 37*A*). An overall view of the construction site is shown in figure 37*B* (site 42). A visible plume about 500 m long was sampled at two sites outside the barrier (sites 43 and 44, figs. 37*C*, *D*). Turbidity data at site 43 indicate that the barrier was effective; high levels of turbidity and solids were measured near the bottom where apparently fluid mud (fig. 3) was escaping. The mud flow had not reached site 44, since moderate turbidity levels were measured there at all depths.

A plume near the discharge point and within the turbidity barrier is shown in figures 37*E* and 38*A–C* (sites 45–48). Turbidity inside the barrier was dramatically higher than outside. At sites 45–48, relatively low turbidity levels and suspended-solids concentrations at the surface indicated rapid settling of fine material before it escaped confinement by the turbidity barrier. In freshwater or in the absence of montmorillonite clay minerals, the fine material in the dredged sediment would not settle as rapidly as documented here. Rapid buildup of fine materials on the bay bottom, however, is conducive to the formation of mud flows that carry material along the bottom for long distances from the original point of deposition.

Figure 38*D*, a computer-aided, color-enhanced photograph showing the same place as 38*C*, served as a basis to evaluate a method for more complete definition of plume characteristics than is possible with a few point measurements. In addition to point water-clarity

Table 11. Sampling conditions for pipeline-dredge discharging to emergent dike with turbidity barrier during floodtide

Flight data:

Time: 0940 to 1055 EST, April 4, 1978
Location: Cut C Channel, Hillsborough Bay

Meteorologic data:

Visibility: 16 km
Solar altitude: 50° above horizon
Wind speed: 16 km/h
Wind direction: from southeast

Photographic data:

Film: Kodachrome, ASA 64
Filter: ultraviolet, haze

Sediment data:

Approximate size gradation and percentage of cohesive material

Percent larger than sand size	Percent sand	Percent silt	Percent clay	Percent cohesive material
5	35	35	25	35

Construction data:

Dredge(s): Western Condor
Containment of dredged materials: turbidity barrier
Placement method: emergent dike

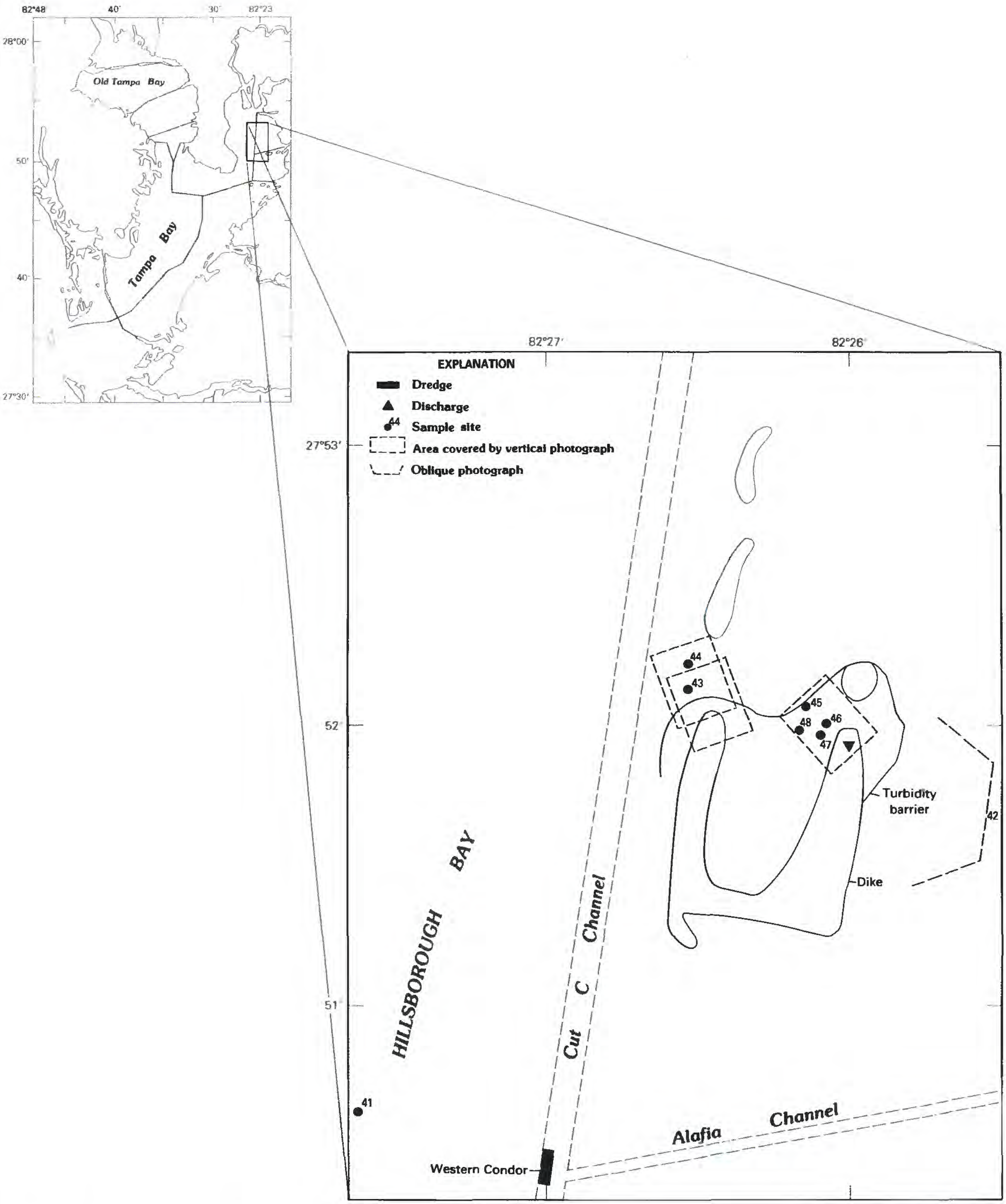


Figure 35. Pipeline-dredge discharging to emergent dike with turbidity barrier during floodtide: sample sites 41–49 and respective photograph areas.

data, semiquantitative indicators of total suspended load within a plume and total plume area may be possible using this technique. Since each color represents a narrow range of photographic film density, we can discriminate between many areas of differing light intensities. We found that general correlation of colors with plume shapes and visible plume patterns were discernible. Detailed correlation of colors with turbidity levels or with suspended-solids concentrations was not attempted because of water-surface glare and unequal light exposure over the entire photograph. The method was judged to have potential for more fully characterizing turbidity plumes.

Under conditions similar to those described here, fine dredged material can be expected to settle rapidly because of effective flocculation in seawater of sediment containing montmorillonite. Turbidity barriers effectively limit the extent, intensity, and visibility of surface plumes outside the barrier. Rapid settling appears to induce formation of mudflows on the bottom.

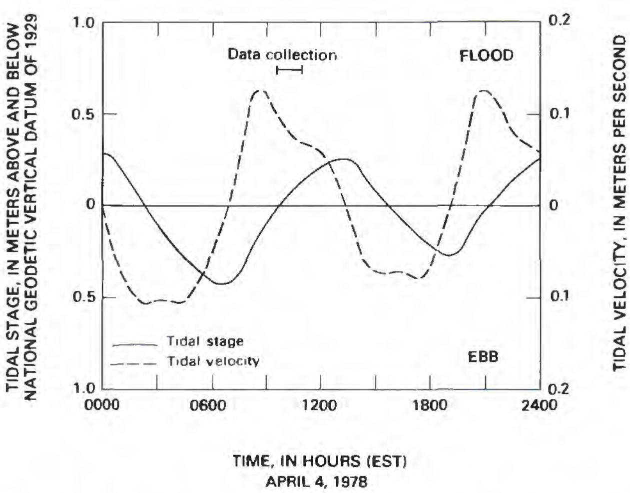


Figure 36. Pipeline-dredge discharging to emergent dike with turbidity barrier during floodtide: tidal stage and tidal velocity at Hillsborough Bay monitoring sites.

A, Site 41: Ambient-water sample site, about 1,500 m southwest of discharge point—no photograph taken. Time: 0940. Depth: 4.0 m.

	Turbidity (NTU)	*Suspended solids (mg/L)*	*Transparency (cm)*
Top	3	20	61
Middle	4	13	—
Bottom	7	26	—

B, Site 42: Oblique view of partially completed diked impoundment with turbidity barrier. Dredge discharge point on northern end of foreground dike.

C, Site 43: Vertical view of sample site outside turbidity barrier. Time: 1000. Depth: 3.0 m. Scale (approx): 1:9,100.

	Turbidity (NTU)	*Suspended solids (mg/L)*	*Transparency (cm)*
Top	7	45	30
Middle	7	54	—
Bottom	2,000	3,000	—

D, Site 44: Vertical view of sample site near edge of visible plume. Time: 1013. Depth: 2.4 m. Scale (approx): 1:9,100.

	Turbidity (NTU)	*Suspended solids (mg/L)*	*Transparency (cm)*
Top	20	39	51
Middle	15	68	—
Bottom	14	25	—

E, Site 45: Vertical view of sample site just inside turbidity barrier. Time: 1023. Depth: 2.1 m. Scale (approx): 1:9,100.

	Turbidity (NTU)	*Suspended solids (mg/L)*	*Transparency (cm)*
Top	55	93	20
Middle	320	296	—
Bottom	18,000	19,400	—

Figure 37. Pipeline-dredge discharging to emergent dike with turbidity barrier during floodtide: photographs of and water-clarity data for sites 41–45. Circle indicates location of sampling boat.

A, Site 46: Vertical view of sample site inside barrier near discharge point. Time: 1033. Depth: 1.2 m. Scale (approx): 1:9,100.

	Turbidity (NTU)	*Suspended solids (mg/L)*	*Transparency (cm)*
Top	12,000	6,260	15
Middle	3,700	7,200	—
Bottom	200,000	130,000	—

B, Site 47: Vertical view of sample site in light-gray area inside barrier. Time: 1045. Depth: 0.9 m. Scale (approx): 1:9,100.

	Turbidity (NTU)	*Suspended solids (mg/L)*	*Transparency (cm)*
Top	230	200	15
Middle	3,600	3,290	—
Bottom	22,000	17,500	—

C, Site 48: Vertical view of sample site in dark area inside barrier. Time: 1055. Depth: 2.8 m. Scale (approx): 1:9,100.

	Turbidity (NTU)	*Suspended solids (mg/L)*	*Transparency (cm)*
Top	25	36	41
Middle	60,000	27,000	—
Bottom	120,000	116,000	—

D, Site 49: Computer-generated color enhancement of *C.*

Green = emergent dredged material

Gray, Orange, Purple, Pink, Blue, Yellow, White } range of surface turbidity levels, from greatest (gray) to least (white)

Figure 38. Pipeline-dredge discharging to emergent dike with turbidity barrier during floodtide: photographs of and water-clarity data for sites 46–49. Circle indicates location of sampling boat.

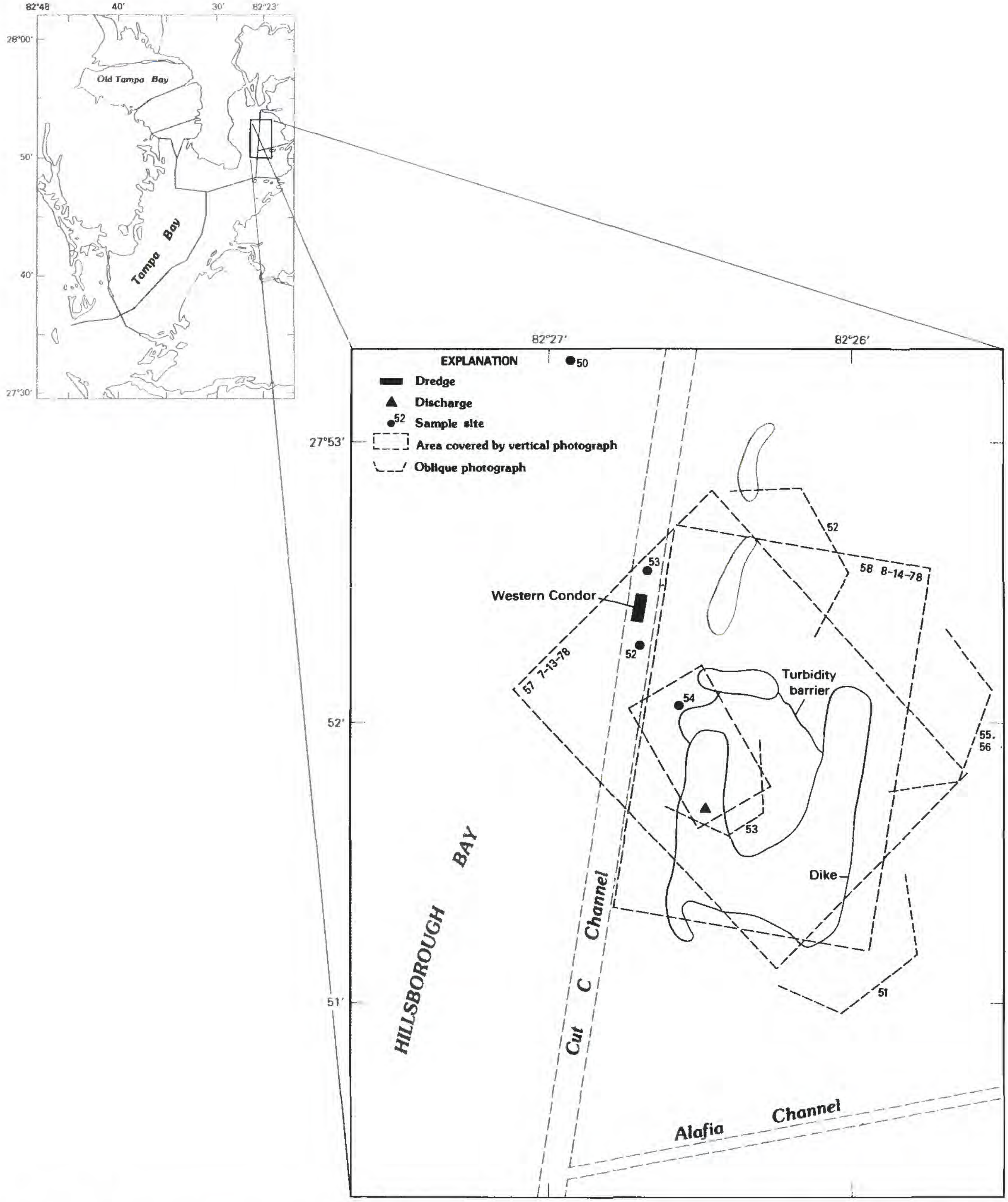


Figure 39. Pipeline-dredge discharging to partly enclosed dike with turbidity barrier during floodtide: sample sites 50–58 and respective photograph areas.

Pipeline Dredge Discharging to Partly Enclosed Dike with Turbidity Barrier during Floodtide

The *Western Condor* cutterhead-pipeline dredge was operating in Cut C Channel in Hillsborough Bay on May 11, 1978, discharging to a diked impoundment construction area about 1 km to the southeast (fig. 39). The dredge had been operating about 60 percent of the time during the previous 72 hours. The data were collected during floodtide conditions with velocities of about 0.05 m/s (fig. 40). Bottom materials in the area included calcareous silt, shell and limestone fragments, weathered limestone with seams of calcareous silt, and hard limestone. Average particle-size gradation and estimated percentage of cohesive material are given in table 12.

Ambient-water data were collected at site 50 (fig. 41*A*), northwest of the dredging area (fig. 39). Neither a well-defined plume nor a turbid area was visible near the dredge or dredged-material placement area outside the turbidity barrier (site 51, fig. 41*B*). Two samples were taken near the dredge (sites 52, 53), and one was

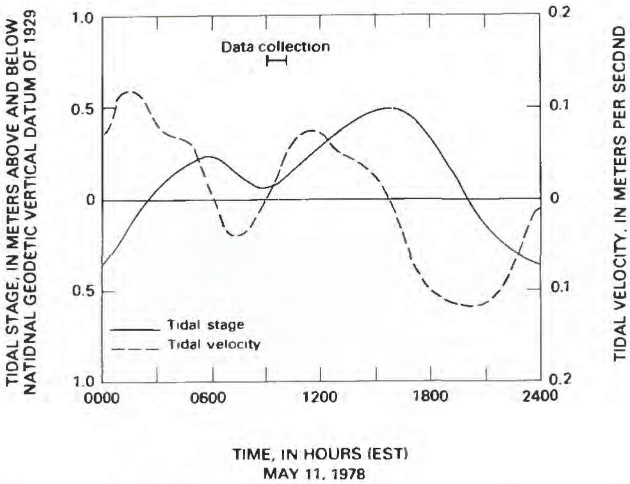


Figure 40. Pipeline-dredge discharging to partly enclosed dike with turbidity barrier during floodtide: tidal stage and tidal velocity at Hillsborough Bay monitoring sites.

Table 12. Sampling conditions for pipeline-dredge discharging to partly enclosed dike with turbidity barrier during floodtide

Flight data:

Time: 0900 to 1000 EST, May 11, 1978
Location: Cut C Channel, Hillsborough Bay

Meteorologic data:

Visibility: 16 km
Solar altitude: 65° above horizon
Wind speed: 16 km/h
Wind direction: from east

Photographic data:

Film: Kodachrome, ASA 64
Filter: ultraviolet, haze

Sediment data:

Approximate size gradation and percentage of cohesive material

Percent larger than sand size	Percent sand	Percent silt	Percent clay	Percent cohesive material
35	35	15	15	55

Construction data:

Dredge(s): Western Condor
Containment of dredged materials: turbidity barrier
Placement method: emergent dike

A, Site 50: Ambient-water sample site about 300 m northwest of discharge point—no photograph taken. Time: 0900. Depth: 2.7 m.

	Turbidity (NTU)	*Suspended solids (mg/L)*	*Transparency (cm)*
Top	11	2	61
Middle	12	41	—
Bottom	40	130	

B, Site 51: Oblique view of study area. *Western Condor* dredge is in upper right with partly completed diked impoundment in center.

C, Site 52: Oblique view of sample site near *Western Condor* dredge. Time: 0915. Depth: 13.7 m.

	Turbidity (NTU)	*Suspended solids (mg/L)*	*Transparency (cm)*
Top	25	63	30
Middle	9	24	—
Bottom	3,200	3,080	—

D, Site 53: Oblique view of sample site, showing dredge discharge in foreground, sampling boat in background near dredge. Time: 0945. Depth: 11.6 m.

	Turbidity (NTU)	*Suspended solids (mg/L)*	*Transparency (cm)*
Top	19	45	46
Middle	17	43	—
Bottom	3,200	8,750	—

Figure 41. Pipeline-dredge discharging to partly enclosed dike with turbidity barrier during floodtide: photographs of and water-clarity data for sites 50–53. Circle indicates location of sampling boat.

Figure 42. Pipeline-dredge discharging to partly enclosed dike with turbidity barrier during floodtide: photographs of and water-clarity data for sites 54–58. Circle indicates location of sampling boat.

A, Site 54: Vertical view of sample site near turbidity barrier. Time: 1000. Depth: 1.5 m. Scale (approx): 1:9,100.

	Turbidity (NTU)	*Suspended solids (mg/L)*	*Transparency (cm)*
Top	50	66	15
Middle	45	77	—
Bottom	2,000	5,430	—

B, Site 55: Oblique view showing secondary turbidity plume in wake of vessel towing pipeline. Time 0920.

C, Site 56: Oblique view taken 45 minutes after site 55 photograph showing dispersion of secondary plume. One stop greater exposure than that used for site 55.

D, Site 57: Vertical view of nearly completed impoundment taken on July 13, 1978, showing fine material escaping to the north. Scale (approx): 1:36,400.

E, Site 58: Vertical view of completed impoundment taken on August 14, 1978, showing containment of fine material by turbidity barrier. Scale (approx): 1:36,400.

taken outside the barrier nearest the pipeline discharge point (site 54, fig. 42*A*). High bottom turbidity in the construction area (sites 52–54) indicated probable movement of fluid mud from the partly completed impoundment. Lower turbidity values at top and middle depths indicated rapid settling of fine material and effective operation of turbidity barriers. Sites 55 and 56 (figs. 42*B*, *C*) show an example of the generation of a secondary turbidity plume by turbulence from a pipe-towing vessel resuspending settled dredge material. Site 56 was photographed 45 minutes after site 55 at the same shutter speed but with a wider aperture. Some of the feathery texture in these two photographs may be bay-bottom features and edges of the secondary plume.

Under conditions similar to those defined here, complete turbidity-barrier enclosure of a source of dredged-material discharge can be expected to produce turbidity plumes of low visibility and small surface extent. Fine material is carried away from the discharge site by mudflows along the bottom and by turbidity plumes near the bottom. The normal operation of construction vessels over recently deposited fine material can generate highly visible plumes by a process of turbulent resuspension.

About half of the north dike remained to be closed on July 13, 1978 (fig. 42*D*). Figure 42*E*, a photograph taken on August 14, 1978, shows the enclosure completed. A large area of fine material north of the island is shown enclosed by a turbidity barrier.

Summary of Appearance and Water-Clarity Data

The appearance of and water-clarity data for turbidity plumes in South Tampa Bay and Hillsborough Bay (fig. 1) from February 1977 to August 1978 varied greatly due to various types and sizes of dredges, a wide range of sediment types, different methods of dredged-material placement and containment, and tide conditions. Visible plumes in both South Tampa Bay and Hillsborough Bay varied in length from about 100 m to more than 2 km. Plume turbidity ranged from 4 to 350 NTU in South Tampa Bay and from 8 to 3,200 NTU outside turbidity barriers in Hillsborough Bay. Levels as high as 200,000 NTU were measured inside turbidity barriers in Hillsborough Bay.

A smaller quantity of fine material (silt and clay) was present in the dredged sediment of South Tampa Bay than in Hillsborough Bay, yet some of the most highly visible plumes were found in South Tampa Bay. Strong tidal currents and the use of surface-discharge methods distributed the fine material over a large area. Conversely, weak tidal currents in Hillsborough Bay and the use of turbidity barriers often resulted in a small size for the visible plumes in spite of the large amount of fine sediment in the material dredged there. Hopper-dredge unloading for beach nourishment in South Tampa Bay produced plumes of 100–150 m in width along the beach that rapidly became indistinguishable from normal shoreline turbidity.

Not all turbidity plumes observed during the study were directly caused by dredging. Secondary erosional plumes were often formed in South Tampa Bay by strong tidal currents eroding recently deposited dredged material. In Hillsborough Bay, unstable mounds of fine material built up on the bottom at the placement site and flowed outward from there. Also, secondary turbidity plumes were produced by turbulence from construction vessels passing over and resuspending previously deposited fine material. Turbidity in secondary erosional plumes in South Tampa Bay ranged from 15 to 140 NTU. Turbidity samples were not collected from turbulence-induced plumes produced by construction vessels in Hillsborough Bay.

Water-clarity data suggest that the extent of visible plumes in South Tampa Bay was a good indicator of their extent deeper in the water column. In Hillsborough Bay, however, visible plumes were not good indicators of plume extent at depth. There, turbidity barriers were used and either wholly or partly eliminated surface discharge of turbid water; thus turbid water was usually introduced at depths beyond effective photographic penetration.

Flocculation of fine sediment was rapid. Seawater and the presence of montmorillonite aided the flocculation process; if either had been absent, turbidity values might have averaged many times those measured.

WATER-QUALITY DATA

Water-quality data for turbidity plumes in South Tampa Bay and Hillsborough Bay were compared with ambient-water data to determine whether turbidity plumes tended to degrade water quality and to test whether varying sediment, tide, dredged-material placement, and containment conditions would produce plumes having significantly different water quality. Ambient-water data from each bay were also compared to detect differences that might affect the comparisons with plume data.

Results are presented in tables showing (1) the number of samples and arithmetic mean of each item being compared, (2) whether the means are significantly different, and (3) the P value, or level of significance at the borderline between acceptance and rejection of a difference between the means (Brownlee, 1967). The more the value of P falls below the chosen level of significance, 0.02, the greater is the confidence that the means are significantly different. The higher the *P* value rises above 0.02, the greater is the confidence that the means are not significantly different.

Because the purpose of the analysis was to investigate water quality and not sediment quality, any data associated with samples having suspended-solids concentrations greater than 10,000 mg/L were excluded from these statistical computations. For concentrations above about 10,000 mg/L, particles in suspension do not settle independently and the material they compose exhibits the characteristics of low-density fluid mud (Barnard, 1978).

Water-Clarity Parameters

Results of tests to determine whether plume samples and samples of water ambient to the plumes of South Tampa Bay and Hillsborough Bay have significantly different mean values of turbidity, suspended solids, volatile solids, and transparency are summarized in table 13. The means differ significantly for each of the parameters except transparency in Hillsborough Bay and volatile solids in South Tampa Bay.

The reasons that average plume- and ambient-water transparency values in Hillsborough Bay show no significant difference are that (1) plume surface water had high clarity due to use of turbidity barriers, and (2) too few observations were made at ambient sites. The *P* value, 0.0219 (only slightly higher than the chosen significance level of 0.02), indicates that with additional data the transparencies of ambient and plume samples might have shown a significant difference. The average levels of volatile solids in ambient and plume samples from South Tampa Bay are the same, indicating that the sediments of South Tampa Bay contain less organic material than do those of Hillsborough Bay.

Table 13. Comparison of mean turbidity, suspended-solids, volatile-solids, and transparency values for samples of plume and ambient water

[N = number of samples analyzed; P = level of significance at borderline between acceptance and rejection of difference]

Property	Ambient water		Plume water		Means significantly different? (at 0.02 level)	P value
	N	Mean	N	Mean		
HILLSBOROUGH BAY						
Turbidity (NTU)	20	20	85	440	Yes	0.0052
Suspended solids (mg/L)	21	50	85	640	Yes	.0006
Volatile solids (mg/L)	21	15	85	87	Yes	.0019
Transparency (cm)	7	74	32	36	No	.0219
SOUTH TAMPA BAY						
Turbidity (NTU)	18	10	109	50	Yes	.0001
Suspended solids (mg/L)	21	50	122	100	Yes	.0005
Volatile solids (mg/L)	12	20	62	24	No	.2071
Transparency (cm)	7	208	42	64	Yes	.0001

Results of clarity-parameter comparisons between South Tampa Bay and Hillsborough Bay are summarized in table 14. In general, ambient waters in Hillsborough and South Tampa Bays are similar for all parameters except transparency. Transparency is about three times greater in South Tampa Bay; we infer from that difference that transparency is highly sensitive to small changes in turbidity at low turbidity levels. The plumes generated in the two bays, are dissimilar, however. The high turbidity, high concentrations of suspended solids, and low transparency in Hillsborough Bay plumes are attributed to the high percentage of fine particles within the dredged material and to weak tidal velocities with proportionally less capability for dilution. High volatile-solids concentrations in Hillsborough Bay plumes are attributed to the presence of organic matter in the dredged sediment.

Water transparency may help us understand why photographs of Hillsborough Bay do not, in general, show as great a contrast between plumes and adjacent ambient waters as do photographs of South Tampa Bay. The greater average transparency value for samples of ambient water from South Tampa Bay means that significantly more light penetrates the water there than in Hillsborough Bay. The greater light penetration produces a darker looking background against which even low concentrations of fine, white, shell fragments create a striking contrast. Conversely, a higher concentration of darker, silty, bottom material would have to be discharged into the less transparent ambient waters of Hillsborough Bay to produce the same degree of contrast as in South Tampa Bay.

In spite of the significant differences of plume-water clarity averages between Hillsborough and South

Table 14. Comparison of mean turbidity, suspended-solids, volatile-solids, and transparency values for samples from Hillsborough and South Tampa Bays.

[N = number of samples analyzed; P = level of significance at borderline between acceptance and rejection of difference]

Property	South Tampa Bay		Hillsborough Bay		Means significantly different? (at 0.02 level)	P value
	N	Mean	N	Mean		
Ambient water						
Turbidity (NTU)	18	10	20	20	No	0.1447
Suspended solids (mg/L)	21	50	21	50	No	.4705
Volatile solids (mg/L)	12	20	21	15	No	.1817
Transparency (cm)	7	208	7	74	Yes	.0015
Plume water						
Turbidity (NTU)	109	50	85	440	Yes	.0086
Suspended solids (mg/L)	122	100	85	640	Yes	.0013
Volatile solids (mg/L)	62	24	85	87	Yes	.0050
Transparency (cm)	42	64	32	36	Yes	.0032

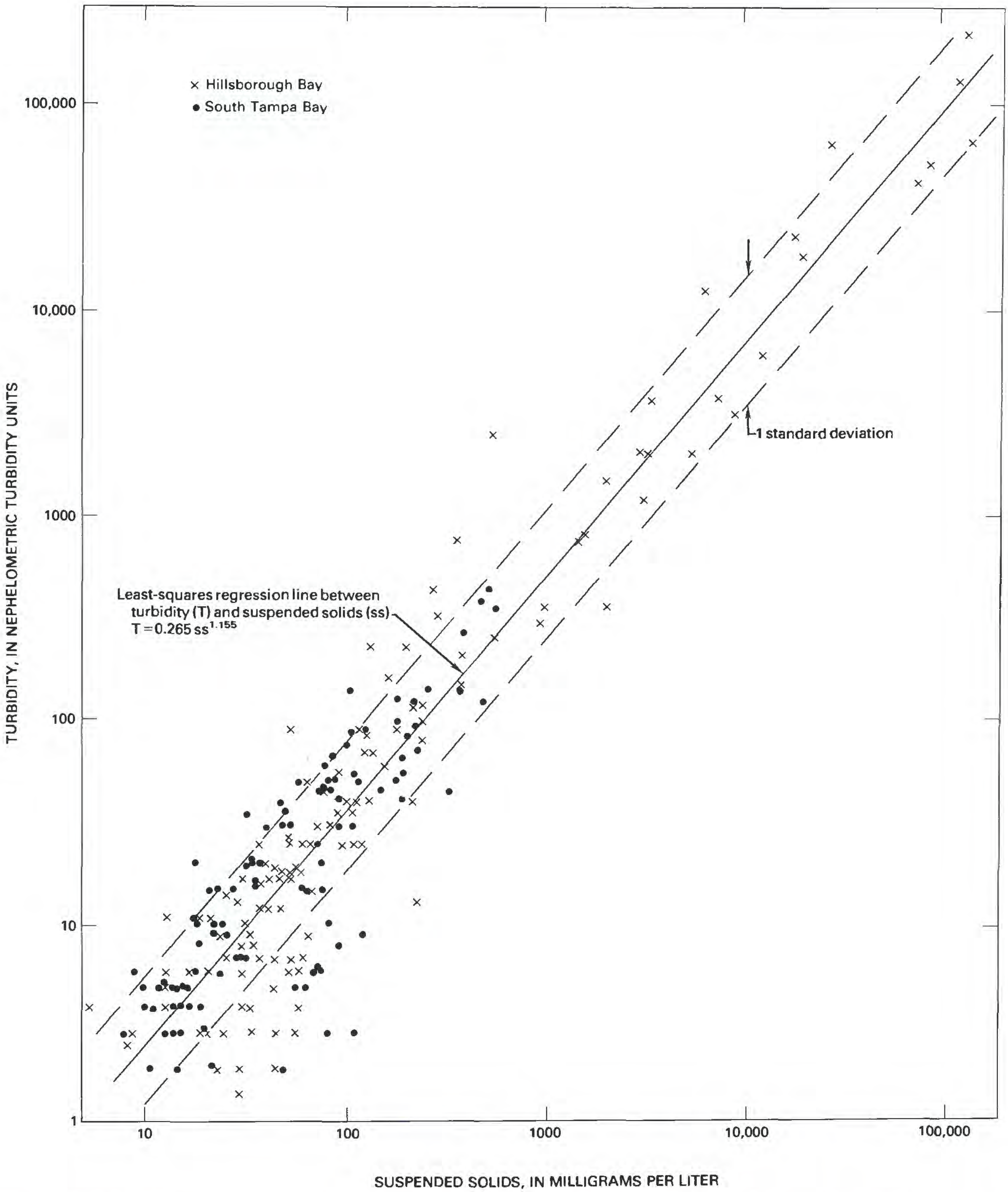


Figure 43. Relation between suspended solids and turbidity for samples from Hillsborough Bay and South Tampa Bay.

Tampa Bays (table 14), relations between parameters measured in both subareas are similar. Relations among turbidity, suspended-solids, volatile-solids, and transparency values for plume and ambient-water samples in South Tampa and Hillsborough Bays are given in figures 43–45. Despite wide variability in the types of dredged material, application of regression analysis indicates a strong correlation ($r=0.93$) between turbidity and suspended-solids values. The increase in scatter below 10 NTU is probably related to the difficulty of measuring small differences in turbidity below 10 NTU and the sensitivity of low turbidity measurements to small differences in clay content (see Ritter and Brown, 1971). The level of volatile solids, which is an index of the concentration of suspended organic material, is also shown in figure 44 to be strongly correlated with the concentration of suspended solids ($r=0.95$).

The inverse relation between transparency and surface-turbidity values is shown in figure 45; that is, high turbidity is associated with low light penetration, and vice versa. In figure 45, the turbidity scale has been truncated and is presented in arithmetic form to emphasize the hyperbolic relation between these two variables. Scatter of the data is caused by (1) subjectivity[2] of the transparency measurement, (2) comparison of turbidity data determined from water sampled at points near the surface with transparency data that represents conditions over a measured water depth, and (3) a possible lapse of several minutes between times of

[2]Water transparency is determined by measurement of the water depth at which alternating black and white quadrants on a standard disk (Secchi disc) become indistinguishable. The measurement requires a subjective determination by the observer.

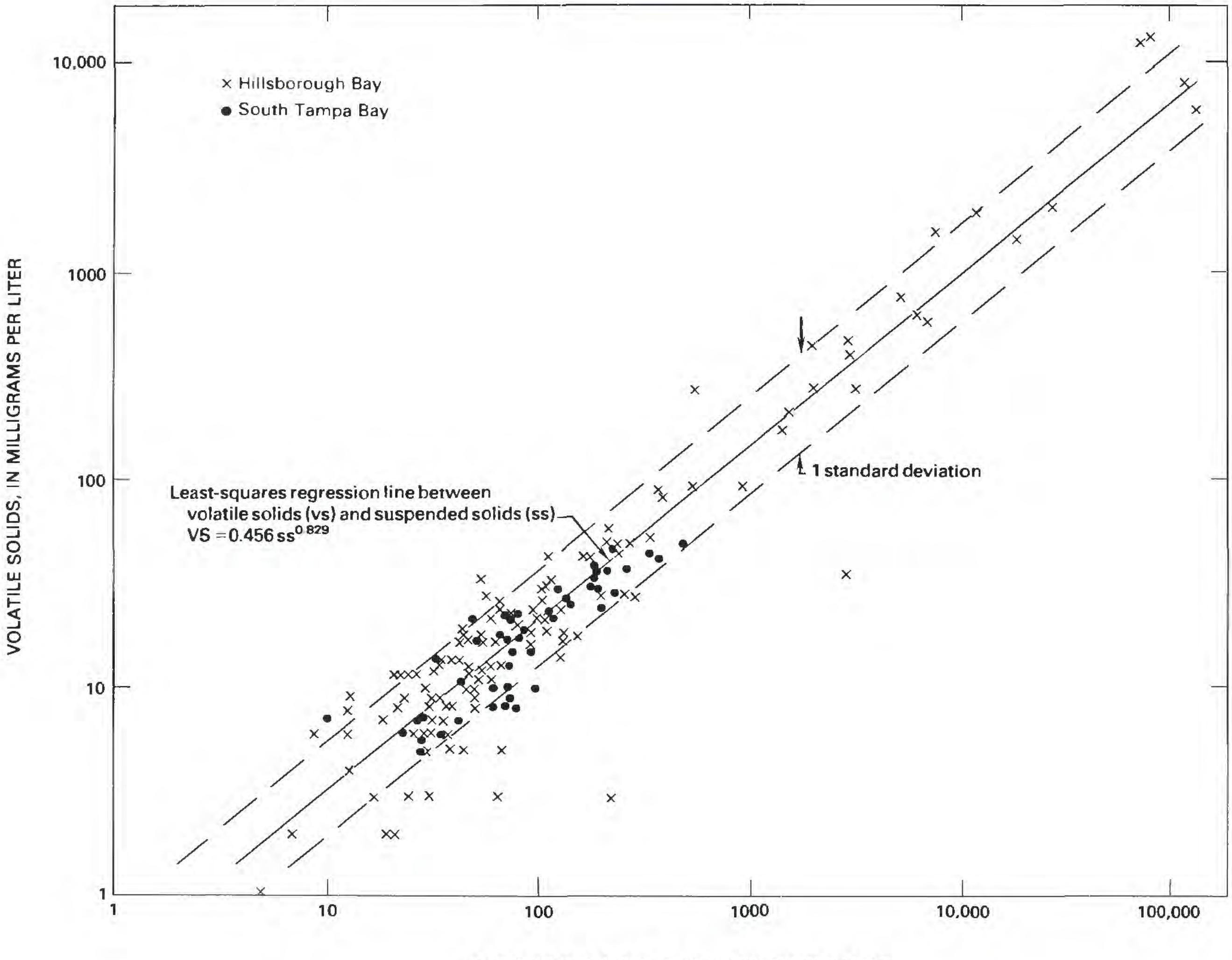


Figure 44. Relation between suspended solids and volatile solids for samples from Hillsborough Bay and South Tampa Bay.

collection of a given turbidity sample and the associated transparency observation. Five apparent outlying points were not plotted in figure 45.

Chemical Constituents

Nutrients

To determine whether plume water is enriched with dissolved or particulate nutrients, the levels of various forms of nitrogen and phosphorus were determined for filtered and unfiltered samples of plume water and water ambient to plumes. Results of comparisons between mean nutrient concentrations in samples of plume and ambient waters are summarized in table 15. In no case is the average concentration of any dissolved or total constituent in samples from plumes significantly different from the average concentration in the corresponding samples from ambient water. The data indicate that dredge plumes in both Hillsborough and South Tampa Bays do not significantly increase dissolved or total nutrient concentration. The average concentration of all forms of phosphorus in samples of plume water from Hillsborough Bay was actually lower than the average in samples of ambient water. Although

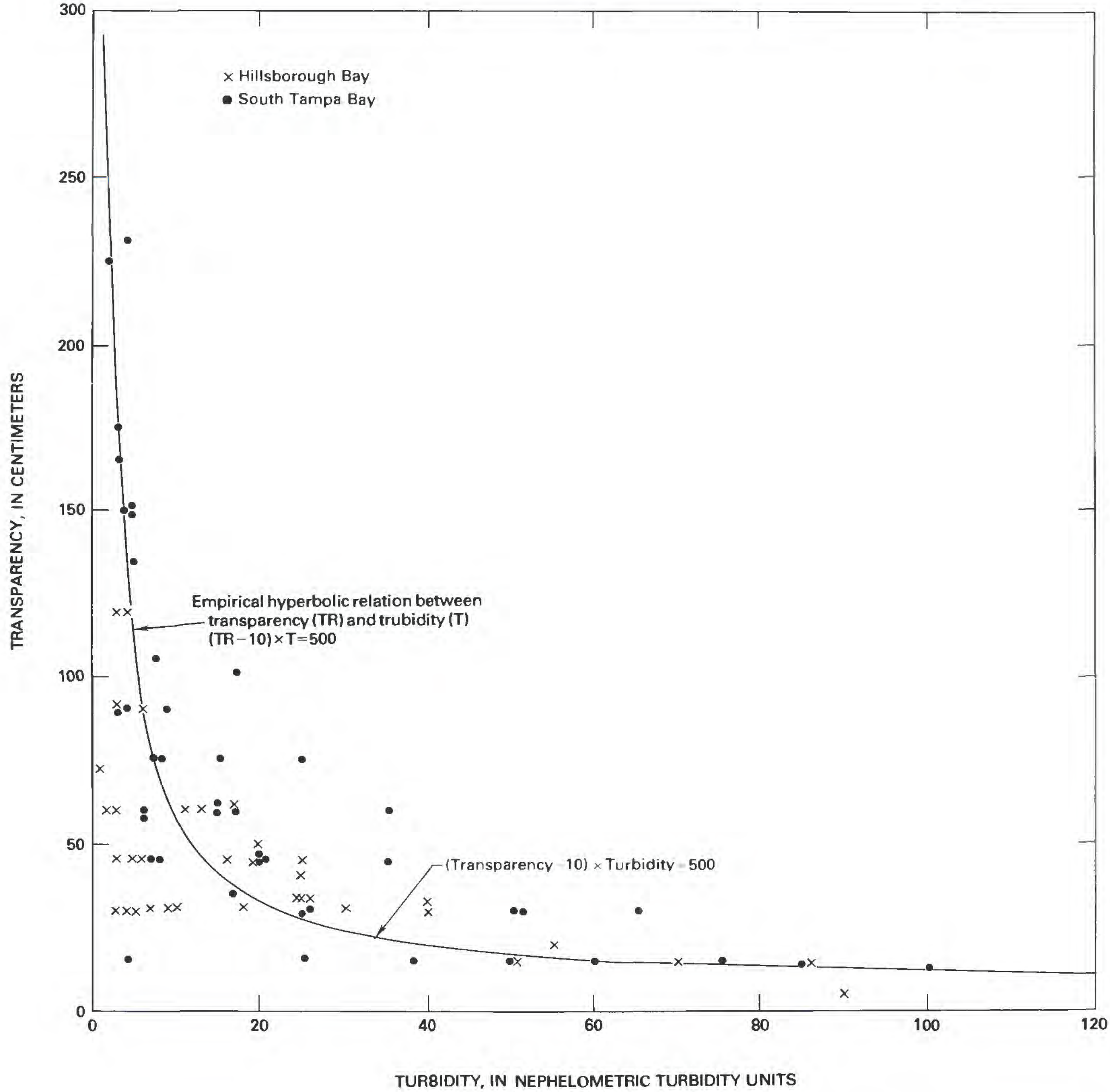


Figure 45. Relation between turbidity and transparency for samples from Hillsborough Bay and South Tampa Bay.

the difference is not statistically significant, it indicates that dredged sediment may scavenge phosphorus from the water.

Average nutrient concentration differences between turbidity plumes in Hillsborough Bay and South Tampa Bay and average ambient-water nutrient concentration differences between the bays are shown in table 16. Total and dissolved organic-nitrogen concentrations in plumes are significantly higher in Hillsborough Bay than in South Tampa Bay. This difference supports the observation in the section "Water-Clarity Parameters" that sediments in Hillsborough Bay contain more organic material than do sediments in South Tampa Bay. Levels of organic nitrogen in ambient water were also higher in Hillsborough Bay than South Tampa Bay, but similar differences between the two subareas were not detected in ambient levels of volatile solids. This indicates either that organic nitrogen is a more sensitive parameter than volatile solids for detecting organic material or that there is more nitrogen associated with organic material in Hillsborough Bay than in South Tampa Bay. Higher dissolved-nitrate levels were

Table 15. Comparison of mean nutrient-concentration values for samples of plume and ambient water

[N = number of samples analyzed; P = level of significance at borderline between acceptance and rejection of difference]

Constituent	Ambient water		Plume water		Means significantly different? (at 0.02 level)	P value
	N	Mean (mg/L)	N	Mean (mg/L)		
HILLSBOROUGH BAY						
Organic N-total	7	0.88	7	1.21	No	0.1223
Organic N-dissolved	7	.64	7	.64	No	.4914
Ammonia N-total	7	.05	7	.07	No	.1741
Ammonia N-dissolved	7	.03	7	.07	No	.1303
Nitrite N-total	7	.01	9	.01	No	.3463
Nitrite N-dissolved	7	0	9	.01	No	.1114
Nitrate N-total	7	.01	8	.02	No	.3819
Nitrate N-dissolved	7	.03	8	.02	No	.0901
Phosphorus-total	7	1.6	9	1.5	No	.3578
Phosphorus-dissolved	7	1.7	9	1.4	No	.1418
Ortho P-total	7	1.6	9	1.2	No	.1155
Ortho P-dissolved	7	1.5	9	1.4	No	.2439
SOUTH TAMPA BAY						
Organic N-total	7	.24	14	.33	No	.0291
Organic N-dissolved	7	.24	14	.30	No	.2111
Ammonia N-total	7	.13	14	.10	No	.3738
Ammonia N-dissolved	7	.06	13	.08	No	.3426
Nitrite N-total	7	0	14	0	No	.5000
Nitrite N-dissolved	7	0	14	0	No	.5000
Nitrate N-total	7	0	14	0	No	.3853
Nitrate N-dissolved	7	0	14	0	No	.1809
Phosphorus-total	7	.1	14	.3	No	.0789
Phosphorus-dissolved	7	.1	14	.2	No	.2038
Ortho P-total	7	.1	14	.2	No	.1464
Ortho P-dissolved	7	.1	14	.2	No	.1910

found for both plume and ambient samples in Hillsborough Bay than in South Tampa Bay (table 16).

All phosphorus concentrations in samples of plume and ambient water are significantly higher for Hillsborough Bay than for South Tampa Bay; this finding confirms previously published data (Goodwin and others, 1974, 1975; Goetz and Goodwin, 1978; Wilkins, 1978).

In summary, nutrient concentrations in turbidity plumes in Hillsborough and South Tampa Bays are about equal to nutrient concentrations in the ambient water surrounding the plumes; nutrient data alone cannot be used to determine whether water samples had been collected from sites within turbidity plumes or from adjacent sites. Therefore, dredging operations were not detected to have any significant impact on nutrient concentrations.

Trace Metals and Arsenic

Water samples were analyzed for trace metals and arsenic to determine whether significant amounts of these potentially harmful elements had been introduced

Table 16. Comparison of mean nutrient-concentration values for samples from Hillsborough and South Tampa Bays

[N = number of samples analyzed; P = level of significance at borderline between acceptance and rejection of difference]

Constituent	South Tampa Bay N	South Tampa Bay Mean (mg/L)	Hillsborough Bay N	Hillsborough Bay Mean (mg/L)	Means significantly different? (at 0.02 level)	P value
AMBIENT WATER						
Organic N-total	7	0.24	7	0.88	Yes	0.0001
Organic N-dissolved	7	.24	7	.64	Yes	.0001
Ammonia N-total	7	.13	7	.05	No	.1956
Ammonia N-dissolved	7	.06	7	.03	No	.2058
Nitrite N-total	7	0	7	.01	No	.0495
Nitrite N-dissolved	7	0	7	0	No	.3314
Nitrate N-total	7	0	7	.01	No	.1132
Nitrate N-dissolved	7	0	7	.03	Yes	.0084
Phosphorus-total	7	.1	7	1.6	Yes	.0002
Phosphorus-dissolved	7	.1	7	1.7	Yes	.0008
Ortho P-total	7	.1	7	1.6	Yes	.0002
Ortho p-dissolved	7	.1	7	1.5	Yes	.0001
PLUME WATER						
Organic N-total	14	.33	9	1.21	Yes	.0042
Organic N-dissolved	14	.30	9	.64	Yes	.0003
Ammonia N-total	14	.10	9	.09	No	.3818
Ammonia N-dissolved	13	.08	9	.07	No	.4784
Nitrite N-total	14	0	9	.01	No	.0227
Nitrite N-dissolved	14	0	9	.01	No	.0352
Nitrate N-total	14	0	8	.02	No	.0845
Nitrate N-dissolved	14	0	8	.02	Yes	.0029
Phosphorus-total	14	.3	9	1.5	Yes	.0001
Phosphorus-dissolved	14	.2	9	1.4	Yes	.0001
Ortho P-total	14	.2	9	1.2	Yes	.0002
Ortho P-dissolved	14	.2	9	1.4	Yes	.0001

into the water column as a result of dredging operations. Tables 17 and 18 summarize the results of statistical analyses of the data. Arsenic, cadmium, chromium, and nickel were not analyzed in samples from South Tampa Bay.

Results of comparisons between mean values of dissolved and total metal concentrations at ambient-water and plume sites are given in table 17. The differences between the means were not found to be significant for any parameter. Additional observations will be necessary to determine whether some apparently large differences, particularly for total iron, are significant.

Results of comparisons of mean values for dissolved and total metal concentrations between Hillsborough and South Tampa Bays are given in table 18 for plume and ambient water. No differences in concentrations among samples of ambient waters were

Table 17. Comparison of mean arsenic and trace-metal concentration values for samples of plume and ambient water

[N = number of samples analyzed; P = level of significance at borderline between acceptance and rejection of difference]

Location and constituent	Ambient water		Plume water		Means significantly different? (at 0.02 level)	P value
	N	Mean (μg/L)	N	Mean (μg/L)		
HILLSBOROUGH BAY						
Arsenic-total	6	1	9	3	No	0.1831
Arsenic-dissolved	6	1	9	2	No	.1568
Cadmium-total	6	4	9	2	No	.1229
Cadmium-dissolved	6	3	9	4	No	.3705
Chromium-total	6	30	8	30	No	.4800
Chromium-dissolved	6	8	9	12	No	.3706
Copper-total	6	3	9	5	No	.1384
Copper-dissolved	6	1	9	2	No	.0436
Iron-total	6	190	9	580	No	.0361
Iron-dissolved	6	30	9	40	No	.0258
Lead-total	5	46	9	27	No	.1597
Lead-dissolved	6	23	8	33	No	.2629
Manganese-total	6	50	9	50	No	.3512
Manganese-dissolved	6	40	9	40	No	.4587
Nickel-total	6	7	9	10	No	.0773
Nickel-dissolved	6	1	9	1	No	.4406
Zinc-total	6	40	9	50	No	.1141
Zinc-dissolved	6	30	9	40	No	.3088
Mercury-total	6	.5	9	.5	No	.1816
Mercury-dissolved	6	.5	9	.5	No	.1816
SOUTH TAMPA BAY						
Copper-total	6	1	12	3	No	.1644
Copper-dissolved	6	0	12	0	No	.4189
Iron-total	6	220	10	370	No	.2190
Iron-dissolved	6	40	12	40	No	.3937
Lead-total	6	15	12	19	No	.1755
Lead-dissolved	6	6	12	7	No	.3456
Manganese-total	6	50	12	60	No	.1741
Manganese-dissolved	6	40	12	50	No	.3106
Zinc-total	6	70	12	120	No	.2126
Zinc-dissolved	6	40	12	40	No	.4398
Mercury-total	5	0	10	0	No	.4071
Mercury-dissolved	6	.5	12	0	No	.2530

detected. The apparent higher concentration of total and dissolved lead in Hillsborough Bay requires additional samples for verification. Dissolved copper, dissolved lead, and total and dissolved mercury were found to have significantly greater mean concentrations in samples from plumes in Hillsborough Bay than from plumes in South Tampa Bay. No such result is given by any of the other metal comparison tests; perhaps the significant differences found reflect greater test sensitivity of the "plume" data in table 18 due to the larger number of observations. On the basis of this test, we conclude that dredging of Hillsborough Bay sediments can introduce additional quantities of dissolved copper, dissolved lead, and both total and dissolved mercury into the water column.

Pesticides and Industrial Compounds

Samples collected at 16 sites in Hillsborough and South Tampa Bays were analyzed for pesticides and industrial compounds. Twelve samples were collected in turbidity plumes, and four were collected at ambient-water sites. All the samples were analyzed for aldrin,

Table 18. Comparison of mean trace-metal concentration values for samples from Hillsborough and South Tampa Bays

[N = number of samples analyzed; P = level of significance at borderline between acceptance and rejection of difference]

Constituent	South Tampa		Hillsborough		Means significantly different? (at 0.02 level)	P value
	N	Mean (μg/L)	N	Mean (μg/L)		
AMBIENT WATER						
Copper-total	6	1	6	3	No	0.0793
Copper-dissolved	6	0	6	1	No	.1298
Iron-total	6	220	6	190	No	.3330
Iron-dissolved	6	40	6	30	No	.2230
Lead-total	6	15	5	46	No	.0771
Lead-dissolved	6	6	6	23	No	.1003
Manganese-total	6	50	6	50	No	.2869
Manganese-dissolved	6	40	6	40	No	.1893
Zinc-total	6	70	6	40	No	.1286
Zinc-dissolved	6	40	6	30	No	.3411
Mercury-total	5	0	6	.5	No	.0365
Mercury-dissolved	6	.5	6	.5	No	.1995
PLUME WATER						
Copper-total	12	3	9	5	No	.1530
Copper-dissolved	12	0	9	2	Yes	.0009
Iron-total	10	370	9	580	No	.1955
Iron-dissolved	12	40	9	40	No	.2769
Lead-total	12	19	9	27	No	.3091
Lead-dissolved	12	7	8	33	Yes	.0199
Manganese-total	12	60	9	50	No	.1377
Manganese-dissolved	12	50	9	40	No	.0464
Zinc-total	12	120	9	50	No	.1580
Zinc-dissolved	12	40	9	40	No	.3633
Mercury-total	10	0	9	.5	Yes	.0007
Mercury-dissolved	12	0	9	.5	Yes	.0041

chlordane, DDD, DDE, DDT, dieldrin, endosulfan, endrin, heptachlor, heptachlor expoxide, lindane, toxaphene, 2,4-D, 2,4,5-T, silvex, polychlorinated biphenyls, and polychlorinated naphthalenes. Of the 272 total determinations, only 6 showed measurable amounts. In each case, the samples were from Hillsborough Bay and contained low concentrations (0.01–0.05 μg/L) of the herbicide 2,4-D (table 19). The concentrations measured are close to the detection limits for the analytical methods used.

The concentration of 2,4-D appears to bear little relation to turbidity and dredging operations. The sample collected on November 21, 1977, had a turbidity of 6,000 NTU, and 2,4-D was not detected in it, whereas the highest concentration of 2,4-D (0.05 μg/L) was associated with a turbidity of 7 NTU.

Samples collected in Hillsborough Bay on November 21, 1977, and January 5, 1978, did not con-

Table 19. Concentrations of 2,4-D in water samples

Date	Time	Sampling depth (ft)	Sampling site	Turbidity (NTU)	Concentration of 2,4-D (μg/L)	Bay
2-17-77	1204	15	Plume water	15	0	South Tampa Bay
2-17-77	1214	13	Ambient water	4	0	
3-15-77	1101	12	Plume water	3	0	South Tampa Bay
3-15-77	1116	16	Plume water	4	0	
3-15-77	1141	19	Plume water	20	0	
11-21-77	1111	8.5	Plume water	35	0	Hillsborough Bay
11-21-77	1151	4.0	Plume water	6,000	0	
1-05-78	1056	6.5	Plume water	120	0	Hillsborough Bay
1-05-78	1106	4.0	Ambient water	2	0	
1-05-78	1131	4.0	Plume water	25	0	
1-30-78	1126	6.5	Plume water	6	.02	Hillsborough Bay
1-30-78	1136	4.5	Ambient water	[1]4/6	.02	
1-30-78	1151	2.5	Plume water	17	.01	
3-13-78	1056	22	Plume water	7	.04	Hillsborough Bay
4-04-78	1001	5.0	Plume water	7	.05	Hillsborough Bay
7-13-78	0906	5.5	Plume water	[1]10/210	.04	Hillsborough Bay

[1] No turbidity measurement at the sample depth, so values above and below sample depth are given as above/below.

tain any 2,4-D; samples collected on or after January 30, 1978, contained 0.01–0.05 μg/L of 2,4-D. Of these latter samples, the later ones, collected in March, April, and July of 1978, appear to contain slightly higher concentrations than those collected earlier. This trend may be related to seasonal changes in application to land areas or water courses that drain into Hillsborough Bay.

Summary of Water-Quality Data

Water-clarity data from both plume and ambient-water sites in Hillsborough and South Tampa Bays support the following generalizations:

1. Generally, water is clearer at ambient-water sites than within turbidity plumes. The use of turbidity barriers in Hillsborough Bay, however, produced clarity of plume samples taken near the surface similar to clarity of ambient surface samples (as measured by Secchi disc transparency readings).
2. Samples of ambient water in both bays have similar clarity. One exception, however, is that transparency of ambient water in South Tampa Bay is about three times greater than it is in Hillsborough Bay; that difference indicates that transparency is very sensitive to small changes in turbidity at low turbidity levels.
3. Plumes in Hillsborough Bay have higher turbidity levels than plumes in South Tampa Bay. Hillsborough Bay has a greater quantity of fine particles in the dredged material, and dilution there is limited because of low tidal velocities.
4. Relations between turbidity, suspended-solids, volatile-solids, and transparency are virtually the same in both Hillsborough and South Tampa Bays; this correspondence suggests the presence of similar types of fine sediment in both bays.

Analysis of nutrient concentrations from filtered and unfiltered samples at plume- and ambient-water sites in both Hillsborough and South Tampa Bays indicates the following:

1. No significant difference in concentration of any nutrient could be detected between plume and ambient-water samples in either bay.
2. The average concentration of phosphorus within plumes in Hillsborough Bay is lower than the concentration in ambient waters, although not at a statistically significant level; it is possible that sediment particles within the plumes scavenge phosphorus from the water.
3. Average concentrations of total and dissolved organic nitrogen, dissolved nitrate nitrogen, and all forms of phosphorus were higher in Hillsborough Bay samples of ambient water than in South Tampa Bay ambient-water samples. These constituents were also more concentrated in Hillsborough Bay plume samples than in South Tampa Bay plume samples.
4. Average concentrations of nutrients within turbidity plumes in both South Tampa and Hillsborough Bays were about the same as concentrations in the ambient waters. No effects of dredging on nutrient concentrations were detected.

Analysis of concentrations of total and dissolved arsenic and trace metals in both Hillsborough and South Tampa Bays indicates the following:

1. Average concentrations of arsenic and trace metals were statistically the same in samples of plume and ambient water from Hillsborough Bay and in samples from South Tampa Bay.
2. Average concentrations of arsenic and trace metals in ambient waters were statistically the same for both bays.
3. Hillsborough Bay plumes had higher average concentrations of dissolved copper, lead, mercury, and total mercury than did South Tampa Bay plumes, indicating that dredging in Hillsborough Bay can introduce additional quantities of these constituents to the water column.

Analysis for 17 pesticides and industrial compounds revealed 6 samples in Hillsborough Bay whose concentrations of the herbicide 2,4-D were between 0.01 and 0.05 μg/L. The occurrences apparently were unrelated to dredging operations. No other pesticides or industrial compounds were detected.

LONG-TERM TURBIDITY TRENDS

Turbidity data collected at many sites in Hillsborough and South Tampa Bays from 1976 through mid-1980 by the Hillsborough County Environmental Protection Commission and approximate dredged-material production rates from 1977 through mid-1980 taken from unpublished records of the U.S. Army Corps of Engineers were used to evaluate long-term trends in turbidity levels. Monthly mean turbidity, the standard error of that mean, and the trend of minimum turbidity values are shown in figures 46 and 47 for South

Tampa Bay and Hillsborough Bay, respectively. Dredged-material production rates are also given. Turbidity in South Tampa Bay (fig. 46) shows a repeating pattern with two periods of relatively low turbidity per year; a winter low occurs in December, January, or February, and a summer low occurs between May and October. The minimum turbidities range from 1.6 to 3.4 NTU and show a gently increasing trend of about 0.3 NTU per year throughout the dredging period. In May 1980, after dredging ceased, the turbidity dropped to its lowest level.

Two turbidity maxima occurred each year, one during April or May and another during November or December. Maximum turbidities varied more widely

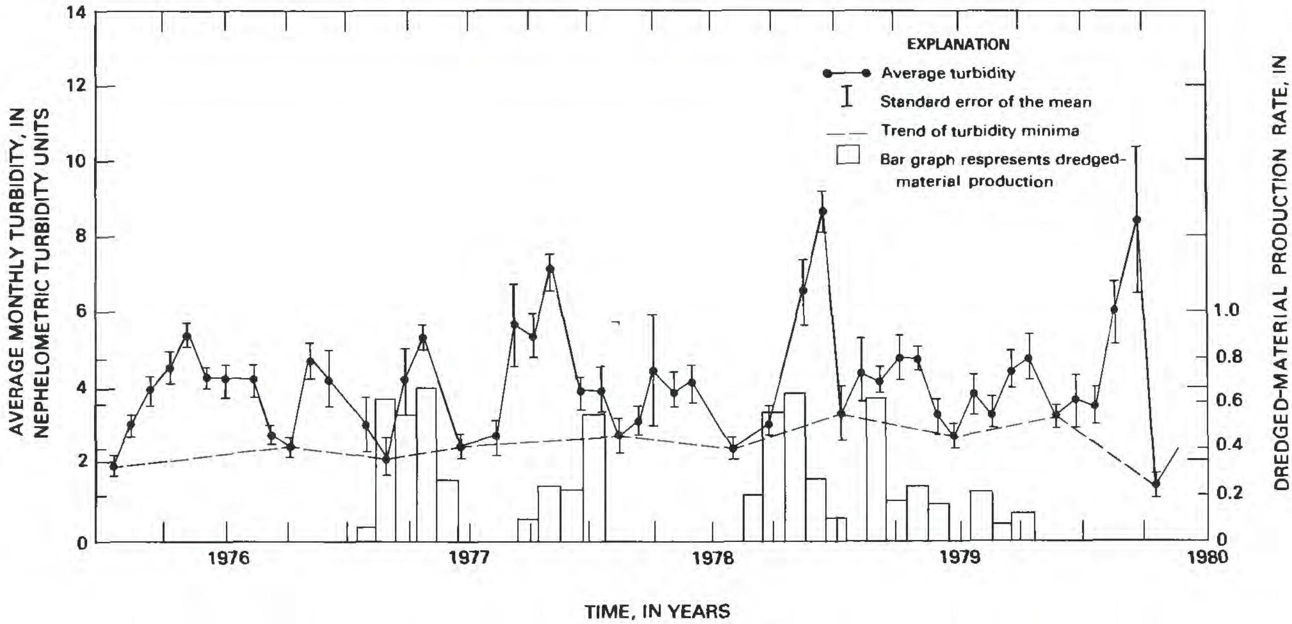


Figure 46. Average monthly turbidity and monthly dredged-material production rates in South Tampa Bay.

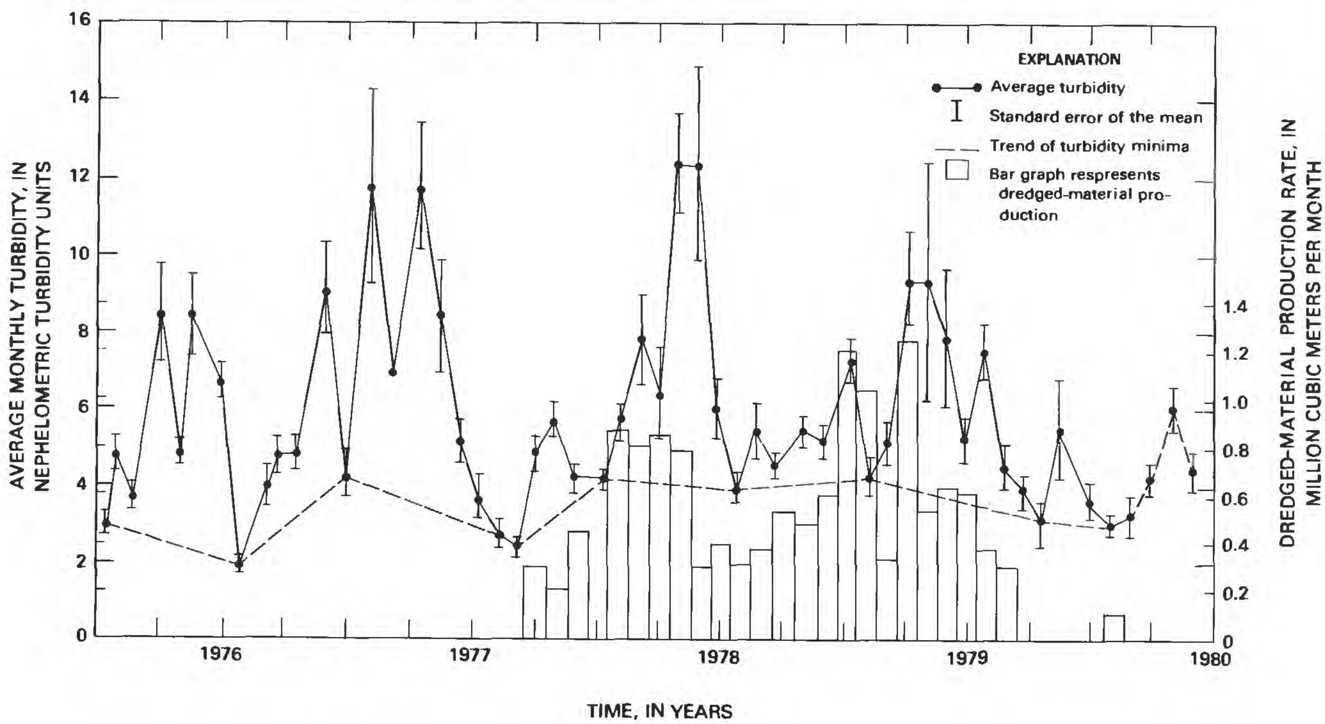


Figure 47. Average monthly turbidity and monthly dredged-material production rates in Hillsborough Bay.

than minimum turbidities (4.5–8.6 NTU). The highest mean turbidity levels occurred in December 1978, at a time of relatively high production of dredged materials, and in April 1980 during a period of no dredging activity. In short, the turbidity maxima presented in figure 46 seem to be unaffected by dredging.

For the most part, turbidities in South Tampa Bay during periods of no dredging were about the same as those during periods of high dredging activity. Data in figure 46 show that dredging may cause a seasonal trend toward increasing turbidity minima followed by a rapid return to predredging levels once dredging ceases.

Average turbidity levels in Hillsborough Bay (fig. 47) show less consistency than those in South Tampa Bay. However, similar seasonal characteristics can be observed. Winter lows occurred in January and February; summer lows from August to October. Low average turbidity levels ranged from 1.8 to 4.3 NTU. Maximum turbidities ranged from 5.8 to 12.2 NTU and occurred seasonally in November and December as well as in March to May. Data in figure 47 indicate that maximum average turbidities measured during dredging periods were no higher than those measured during nondredging periods. The variability of monthly averages, as measured by the standard error of the mean, was generally greater for Hillsborough Bay than for South Tampa Bay, indicating less areal uniformity in Hillsborough Bay turbidity levels.

The trends of turbidity and dredged-material production rates from early 1977 to early 1979, as shown in figure 47, are somewhat similar; that similarity indicates that dredging may have affected average turbidity levels in Hillsborough Bay. The fact that the usual seasonal variations in turbidity were maintained during the period of dredging, however, could indicate either that the impact of dredging was insufficient to disrupt the seasonal pattern or only that by coincidence the dredged-material production rate duplicated and reinforced the natural seasonal pattern.

Once each year, prior to dredging, the average turbidity in Hillsborough Bay dropped to about 2 NTU. During dredging, the lowest average seasonal turbidities were consistently about 4 NTU (fig. 47). After dredging ended in 1979, seasonal low turbidity levels started to decline.

The fact that in both Hillsborough and South Tampa Bays' seasonal low turbidity levels dropped in response to a reduction in dredged-material production rates indicates that long-term residual turbidity from dredging is unlikely to occur. During long periods of continuous dredging, however, minimum seasonal turbidities may be increased by about 2 NTU in Hillsborough Bay.

In general, seasonal turbidity trends and maximum average turbidity levels in both South Tampa Bay and Hillsborough Bay seem to be unaffected by dredging. Minimum average turbidity levels in both bays are apparently elevated during dredging periods, more so in Hillsborough Bay than South Tampa Bay.

SUMMARY AND CONCLUSIONS

Turbidity-plume appearance in Tampa Bay was highly variable, depending on sediment, dredge, dredged-material placement and containment, and tide conditions. Plumes in South Tampa Bay generally were highly visible and elongated and had low to moderate turbidity levels; the exceptions to those generalizations were that plumes could be very compact during slack-water periods and that beach nourishment plumes were not highly visible. Plumes in Hillsborough Bay were generally faintly visible and diffuse and had moderate to high turbidity levels; the exceptions to those generalizations were that low turbidity levels were often found near the top of the water column and that plume visibility increased where turbidity barriers incompletely enclosed dredged-material discharge sites.

Surface discharge to unconfined dredged-material placement areas in South Tampa Bay produced highly visible plumes. This was true in spite of high dilution rates due to fast-flowing tidal currents and low silt and clay content in the dredged material. The use of turbidity barriers in Hillsborough Bay was effective in limiting the visibility of turbidity plumes. Outside of turbidity barriers in Hillsborough Bay, plumes of low visibility were produced from material with high silt and clay content discharged into slow-moving tidal currents whose low velocities induced low dilution rates. The submerged, nonvisible parts of plumes in Hillsborough Bay were significantly more turbid, however, than were those parts of plumes in South Tampa Bay.

Moderate to high turbidity levels occurred in secondary plumes that were produced in both Hillsborough and South Tampa Bays by resuspension of previously deposited dredged material. In South Tampa Bay, secondary plumes were generated as high-velocity tidal currents eroded material from the sediment mounds that had developed within submerged dredged-material placement areas. Turbulence, both from hopper-dredge maneuvering in South Tampa Bay and from work boats operating in Hillsborough Bay, also produced secondary turbidity plumes of high visibility as bottom material was suspended in the water column.

Rapid flocculation of fine dredged material in Hillsborough Bay and South Tampa Bay caused turbidity plumes to be less extensive than they would otherwise have been. This flocculation was promoted by the presence of salt in the receiving water and the presence of montmorillonite clay minerals in dredged material.

During floodtide conditions, a two-part or separated plume was formed from dredged material being discharged west of the northern tip of Egmont Key. The plume narrowed as incoming water accelerated past Egmont Key and widened again as the water decelerated after it passed the constriction. The result was a plume that appeared to have two separate parts.

In both Hillsborough and South Tampa Bays, average concentrations of nutrients within turbidity plumes were not distinguishable at the 98-percent level of significance ($\alpha = 0.02$) from concentrations of nutrients in the ambient water in each bay. The data indicate that dredging did not increase nutrient levels in Tampa Bay waters.

Analysis of limited numbers of observations of 10 trace metals does not indicate a significant difference ($\alpha = 0.02$) between average plume and ambient-water levels. Nevertheless, data suggest that average concentrations of dissolved copper, lead, and mercury and total mercury were higher in Hillsborough Bay plumes than in South Tampa Bay plumes. Dredging apparently could introduce these constituents into Hillsborough Bay water.

In 262 samples analyzed for 17 pesticide and industrial compounds, all these components were below the detection limits, except for 6 samples in Hillsborough Bay found to contain 2,4-D. No relation was found between the 2,4-D samples and the dredging operation.

Seasonal trends in average turbidity levels (two highs and two lows per year) were found to be similar during dredging and nondredging periods in both Hillsborough Bay and South Tampa Bay. During dredging and nondredging periods, high average turbidity levels also differed very little in each bay. Low average turbidity levels, however, did show an increasing trend of about 0.3 NTU per year in South Tampa Bay and a uniform increase of about 2 NTU in Hillsborough Bay during dredging periods. The only significant effect of dredging on average turbidity levels appears to be a modest and temporary rise in seasonal minima in both Hillsborough and South Tampa Bays.

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METRIC CONVERSION FACTORS AND ABBREVIATIONS

Factors for converting International System (SI) units to inch-pound units, with abbreviations of units

Multiply SI (metric) unit	*By*	*To obtain inch-pound unit*
micrometer (μm)	3.937×10^{-5}	inch (in.)
millimeter (mm)	3.937×10^{-2}	inch (in.)
centimeter (cm)	3.281×10^{-2}	foot (ft)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
square kilometer (km^2)	0.3861	square mile (mi^2)
cubic meter (m^3)	35.31	cubic foot (ft^3)
millimeter per second (mm/s)	3.281×10^{-3}	foot per second (ft/s)
meter per second (m/s)	3.281	foot per second (ft/s)
kilometer per hour (km/h)	0.6214	mile per hour (mi/h)
cubic meter per second (m^3/s)	35.31	cubic foot per second (ft^3/s)
square meter per gram (m^2/g)	4,480	square foot per pound (ft^2/lb)
gram per cubic centimeter (g/cm^3)	62.43	pound per cubic foot (lb/ft^3)
milligram per liter (mg/L)	1.000	parts per million (ppm)
microgram per liter (μg/L)	1.000	parts per billion (ppb)

ASA, American Standards Association film exposure index number
EST, eastern standard time
NTU, nephelometric turbidity units

National Geodetic Vertical Datum of 1929 (NGVD of 1929).— Formerly called "mean sea level"; a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada. The datum was derived from the average sea level during many years at 26 tide stations along the Atlantic, Gulf of Mexico, and Pacific coasts.