APPEARANCE AND WATER QUALITY OF TURBIDITY PLUMES CREATED BY DREDGING IN TAMPA BAY, FLORIDA

U.S. GEOLOGICAL SURVEY

WATER-RESOURCES INVESTIGATIONS

OPEN-FILE REPORT 81-541

Prepared in cooperation with the

U.S. ARMY CORPS OF ENGINEERS,

Jacksonville District

UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

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UNITED STATES DEPARTMENT OF THE INTERIOR

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GEOLOGICAL SURVEY

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ABBREVIATIONS AND CONVERSION FACTORS

Factors for converting International System (SI) units to inch-pound units and abbreviation of units

Multiply SI (metric) unit	By	To obtain inch-pound unit
micrometer (um)	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)	4,880	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	part per million (ppm)
microgram per liter (ug/L)	1.000	part per billion (ppb)

The following abbreviations have been used in the text:

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).--A geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called "mean sea level." 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.

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ABSTRACT

Turbidity plumes in Tampa Bay, Florida, were monitored during ship-channel dredging operations from February 1977 to August 1978 to document plume appearance and water quality, evaluate plume influence on the characteristics of Tampa Bay water, and provide a basis for transferring the information to other areas having generally similar sediment, dredge, disposal, containment, and tide conditions.

Sediment composition varied from 85 percent sand and shell fragments to 60 percent silt and clay. Plumes originating from the operation of one hopper dredge and three cutterhead-pipeline dredges, including one of the largest in the world, were investigated. Disposal methods included beach nourishment, stationary submerged discharge, oscillating surface discharge, and creation of emergent dikes using turbidity barrier containment. 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 for determination of 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 having turbidity levels ranging from less than 10 to 200,000 nephelometric turbidity units.

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

Primary turbidity plumes were created directly by dredging and disposal operations and secondary plumes were created indirectly by resuspension of previously deposited material. Secondary plumes with significant turbidity levels were formed by erosion in areas of high-velocity tidal currents and by turbulence from vessels passing over fine material deposited in shallow areas.

Turbidity plumes visible at the surface were good indicators of the location of turbid water at depth when turbidity barriers were not used. When 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 parts of the plume appeared to be separated from each other because of the intervening narrow part.

Background water transparency was about three times greater near the mouth of Tampa Bay in South Tampa Bay than near the head in Hillsborough Bay. Other measures of water clarity, turbidity and suspended solids, showed no statistically significant difference between the two areas, indicating that transparency is a sensitive measure of background water clarity. The relation between water-clarity parameters was the same regardless of sample location--whether it was South Tampa Bay, Hillsborough Bay, plume, or background.

Nutrient and metal concentrations were statistically the same in samples from turbidity plumes and ambient background waters, indicating no detectable change in nutrient and metal concentrations in Tampa Bay 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. Six occurrences of the herbicide 2,4-D in Hillsborough Bay at concentrations near the detection limit, 0.01 to 0.05 microgram per liter, were unrelated to dredging activity.

Few long-term turbidity characteristics in Tampa Bay from 1976 through 1979 can be directly attributed to dredging operations. Average maximum turbidity levels are apparently independent of dredging activity. Seasonal minimum turbidity levels in Hillsborough Bay, however, were about 2 nephelometric turbidity units higher during dredging than nondredging periods.

INTRODUCTION

Prior to dredging or filling in tidally affected aquatic environments, two questions regarding plumes of suspended material (turbidity plumes) associated with such projects are frequently asked by agencies or individuals.

1. What will be the extent and appearance of the turbidity plumes?
2. How will receiving water bodies be affected by dredged material and associated chemical constituents?

These questions are not easily answered in spite of progress made in understanding the physical and chemical processes associated with turbidity plumes.

Turbidity plumes can be defined as regions of the receiving water containing suspended particles and are a visible result of hydraulic dredging. Dredged bottom sediment is initially dispersed as a water-sediment slurry, transported to a disposal site, and discharged. Sand and larger particles settle quickly; silt and clay particles settle slowly and are distributed within the receiving water by hydraulic forces until the particles reach the bottom--hours, days, or weeks later. Because particulate settling is a gradual process and because much of the plumes are submerged, boundaries of turbidity plumes are virtually indeterminate. The visible part of plumes is often taken as an indication 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 and erosion of previously deposited material by tidal currents.

Problems Associated with Turbidity Plumes

Turbidity plumes can have detrimental effects on water bodies. 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 associated with fine dredged material may enter the food chain through (1) grazing by filter-feeding organisims and zooplankton on sediment particles within turbidity plumes, and (2) ingestion by benthic organisms at the bay bottom.

Turbidity plumes reflect sunlight that would otherwise penetrate deeper into the water column, thus reducing the depth to which photosynthesis may occur for phytoplankton, algae, and sea grasses attached to the bottom. Oxygen-demanding bottom material can also reduce the amount of dissolved oxygen available for aquatic biological processes within turbidity plumes. Turbidity plumes impact on man's recreational enjoyment because they are considered esthetically displeasing to many people.

Apart from their physical and chemical properties, turbidity plumes also have symbolic importance to those interested in or responsible for balancing environmental and developmental interests in an aquatic environment. How the public and agencies acting for the public perceive visible aspects of dredging (turbidity plumes) plays a significant role in the acceptance of proposed dredging projects or dredging methods.

Purpose and Scope

Movement of waterborne commerce from the Gulf of Mexico to port facilities in upper Hillsborough Bay, a part of Tampa Bay, Fla., has required navigation improvements to the bay since 1907 (U.S. Army Corps of Engineers, 1969). As progressively deeper draft vessels were used, dredging projects were undertaken to improve the channel. Congress authorized deepening to 10.4 meters and widening to 122 meters of the ship channel in 1950 (U.S. Army Corps of Engineers, 1969). The 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 for the proposed Tampa Harbor Deepening Project were set at a depth of 13.1 meters and a width of 152 meters. The quantity of material to be dredged was estimated at 53.8×10^6 m^3 (U.S. Army Corps of Engineers, 1974), one of the largest projects of its type ever authorized in the country.

To detect environmental effects during construction of the Tampa Harbor Deepening Project, the U.S. Geological Survey conducted a water-quality monitoring program from February 1977 to August 1978. The program provided monthly photographic, water-clarity, and water-quality information in areas affected by dredging operations.

The purpose of this report is to provide information and interpretations about the appearance and water quality of a variety of turbidity plumes measured in Tampa Bay. The information is presented so that results can be transferred and applied to other areas having similar sediment, dredge, disposal, and tide conditions.

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 subareas of Tampa Bay on the central Gulf Coast of Florida (fig. 1). Photographs and water-clarity data for each plume are presented to document plume appearance. The wide range of sediment, dredge, disposal, and tide conditions contributing to the appearance of the plumes is discussed and conclusions regarding their influence on plume characteristics are drawn. Water-quality samples were collected from each plume and compared to background reference samples to determine how much toxic and noxious material was resuspended or dissolved due to dredging. Constituents analyzed include water-clarity parameters and selected nutrients, metals, pesticides, and industrial compounds. An analysis of background turbidity from 1976 to 1980 in Hillsborough Bay and South Tampa Bay is also presented.

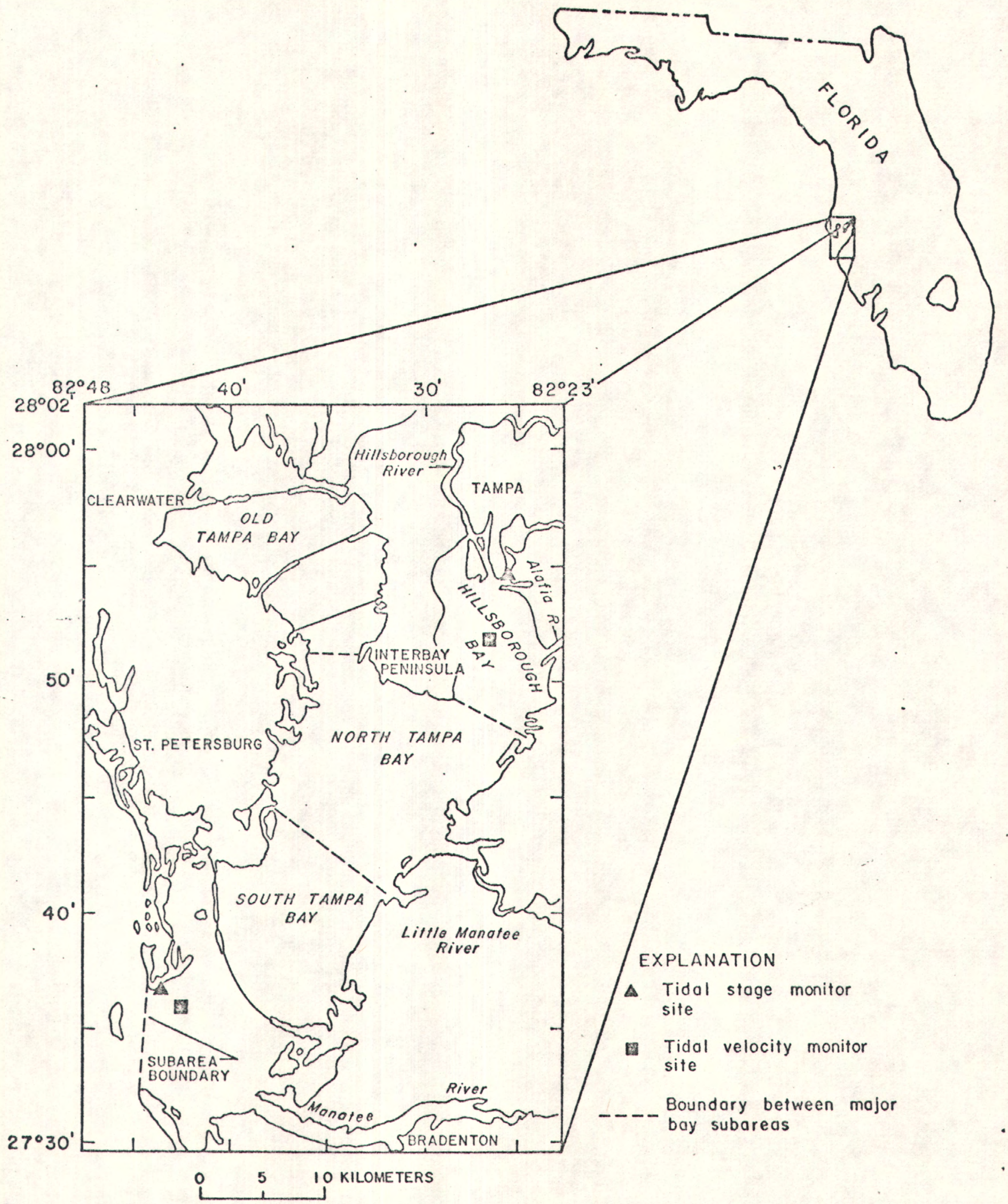


Figure 1.--Location of Tampa Bay subarea boundaries and tidal stage and tidal velocity monitor sites.

Location and Description of Study Area

Tampa Bay is a Y-shaped, coastal plain estuary that has a surface area of about 910 km^2 and an average depth of 3.5 meters. Major subareas include Hillsborough Bay and Old Tampa Bay that comprise the eastern and western arms of Tampa Bay, respectively, and North and South Tampa Bay (fig. 1).

Major manmade features include three bridges, a causeway, several islands and filled shoreline areas, and a 60-kilometer ship channel connecting 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.

Major cities bordering on Tampa Bay are Tampa, Saint Petersburg, Clearwater, and Bradenton. The Standard Metropolitan Statistical Areas of Tampa-Saint Petersburg and Bradenton have a population of about 1.66 million (estimate for April 1, 1979) and a growth rate of about 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 zero to 30 meters 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 relatively equal diurnal and semidiurnal components that produce an irregular pattern of water-surface fluctuations. The average tide range is about 0.6 meter. Tidal velocity is 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 may exceed 1 to 1.5 m/s. Current speeds near the central portions of Hillsborough and Old Tampa Bays reach 0.3 and 0.5 m/s, respectively (U.S. Department of Commerce, 1977).

Tributary inflow averages about 64 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 tide levels. Because of the relatively shallow depths, tidally dominated flows, and supplementary vertical mixing due to wind, the bay is predominantly a vertically well-mixed system with little density stratification.

Acknowledgments

This investigation was conducted in cooperation with the U.S. Army Corps of Engineers. Assistance of the Hillsborough County Environmental Protection Commission (HCEPC) in collection of water-quality samples is gratefully acknowledged. Special thanks are given to controllers at the Tampa Air Traffic Control Center for their help and patience during our photographic flights. Frequent weather briefings by National Weather Service personnel were also appreciated.

FACTORS THAT INFLUENCE THE APPEARANCE AND WATER QUALITY OF TURBIDITY PLUMES

Appearance and water quality of turbidity plumes are influenced by many complex and interacting factors. These factors include character of dredged material, method of dredging, disposal of dredged material, and character of receiving waters.

Physical and Chemical Properties of Dredged Material

Unconsolidated, sedimentary material dredged from many estuaries, bays, and tidal streams is composed of particles ranging in size from large boulders 1 meter or more in diameter to colloids 1 micrometer or less in diameter. Trace or small amounts of inorganic and organic substances are often associated with the sediment particles or interstitial water between the particles.

The size and shape of a sediment particle have a direct effect on its rate of settling in quiescent water. Large particles reach the bottom rapidly, whereas small particles may remain in suspension indefinitely. Representative settling rates of various size spherical particles, based on Stokes Law (Tschebotarioff, 1951), at 20°C, 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 platey a particle is, the longer it will take to settle. Correction factors to Stokes Law have been developed to account for this effect (Tschebotarioff, 1951).

Turbidity plumes are composed of slowly settling silt and clay particles having diameters of less than 0.03 millimeter or small masses of agglomerated particles (Barnard, 1978). In general, the finer or smaller diameter the material, 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 about 1 percent to more than 60 percent fine material (Sinclair, 1974).

Cohesive properties of fine sediments induce faster settling than predicted by particle size and shape characteristics. Compaction of fine sediments by overburden pressure rearranges soil particles to fit more tightly together, increases grain-to-grain contact, and promotes physical and chemical bonding (cohesion) between particles (Tschebotarioff, 1951). Cohesive sediments are not likely to be completely dispersed when agitated during dredging and, therefore, settle as particle clusters and not as individual particles.

Cohesive forces tend to keep fine sediment from dispersing during dredging operations. Many cohesive sediment particles remain bound to each other throughout the dredging process and settle more rapidly than if each acted independently. Some clays, for instance, remain intact during hydraulic dredging operations, are formed into balls in the discharge pipe, and are ejected at the disposal site as rapidly settling particles.

The amount of sediment surface area exposed to receiving water has an effect on properties of turbidity plumes that are important to their appearance and water quality. Plume visibility and appearance are largely determined by the amount, distribution, and color of light reflected from the surfaces of the uppermost sediment particles in the water column. Particulate surfaces reflecting light over a large water area appear as a large plume. A dense arrangement of particles reflects light more intensely than 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-grained particles (Buckman and Brady, 1964). In some instances chemical constituents are released from particle surfaces to the water, which increases the dissolved concentration of the constituent. Sediment particles may also scavenge constituents from the water while settling to the bottom, thereby decreasing the dissolved concentration of the constituent. In either case, the region of chemical activity, or ion exchange, is at the particle surface. The more sediment surface area exposed to receiving waters during dredging, the greater the potential for sediment-water chemical interaction.

The specific surface (surface area per unit mass) of clay materials range from 5 to 800 m^2/g (Meade, 1964). Assuming 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 equal to the 910 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

Design and operation of dredge equipment used to move sediment from one location to another influence the appearance and water quality of turbidity plumes. Of the two basic types of dredges, mechanical and hydraulic, the hydraulic dredge is presently (1980) most 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. Information on dredge types is given in a review article 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 used to transport dredged material to disposal sites. The material is released through large doors on the bottom of each bin. Many hopper dredges can unload by pumping dredged material out of the bins. Pumping facilities allow transfer of material to shallow water or upland disposal sites. 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 and direct material into the pipes.

Normal loading operation of hopper dredges results in an overflow of turbid water from the bins; the overflow is discharged into the bay creating a turbidity plume. Removal of sediment from the bay bottom, turbulence in the pump and pipelines, overflow during loading, and additional turbulence during unloading operations all disperse sediment and increase the sediment surface area exposed to the receiving waters.

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

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

Dredge size is an important factor in turbidity plume appearance and water quality. Large dredges discharge more sediment, create larger and more dense plumes, and have greater short-term potential for significant water-sediment chemical activity than small dredges. Smaller dredges, however, must work longer to complete a job, thereby creating smaller, less dense plumes over longer time periods.

Another factor affecting the appearance of turbidity plumes in tidal waters is the schedule of dredge operation. Stopping and starting of a dredge produces an intermittent plume that appears different than a plume generated from continuous operation.

Methods for Disposal and Containment of Dredged Material

After dredging, sediment must be transported for disposal. Disposal methods can have a significant influence on appearance and water quality of turbidity plumes. Common disposal practices include (1) beach nourishment or replacement of eroded beach material for shoreline protection, (2) submergent open-water disposal, (3) emergent open-water disposal, and (4) upland disposal (not used during the study).

Materials used for beach nourishment generally have a high percentage of sand to withstand normal wave action and to be suitable for recreational use. Large plumes are generally not created by beach nourishment disposal.

Disposal of dredged material containing large quantities of fine particles significantly influence plume appearance. Figure 2 shows three open-water pipeline dredge discharge methods used in Tampa Bay: (a) stationary surface discharge, (b) oscillating surface discharge, and (c) 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, maximizing plume visibility and the potential for exchange of chemical constituents between sediment and water. The oscillating surface discharge method creates larger and more visible plumes then 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 that for 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).

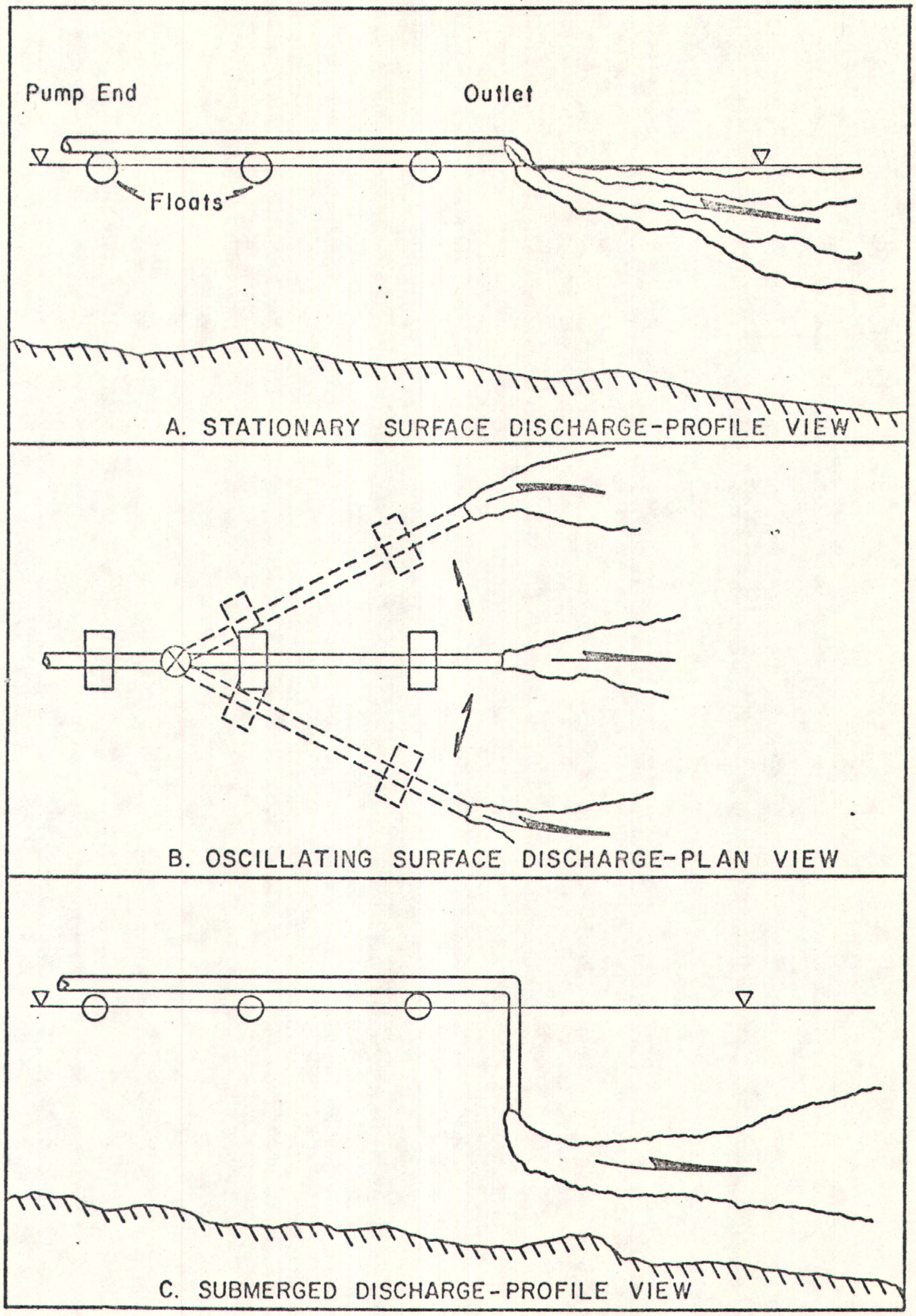


Figure 2.--Three pipeline dredge discharge methods.

Secondary turbidity plumes are generated from open-water disposal sites after dredging operations have ceased if water velocities are sufficient to erode deposited material. Secondary erosional plume characteristics are determined by the size of the material and the magnitude and duration of erosive current velocities.

Emergent disposal areas are created 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 and form turbidity plumes when discharged from the impoundment.

Turbidity barriers or screens are often used to limit plume extent and visibility and potential water-sediment chemical interaction during open-water disposal. Turbidity barriers (fig. 3) consist of linear flotation units with an attached weighted fabric forming a skirt that extends 1 or 2 meters below the water surface. The units are joined to form long barriers enclosing a turbidity source.

Fig. 3 near here

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), is at an approximate suspended solids concentration of 10,000 mg/L. As with the submerged discharge disposal method (fig. 2), the plume from a turbidity barrier forms at depth, thereby limiting plume visibility.

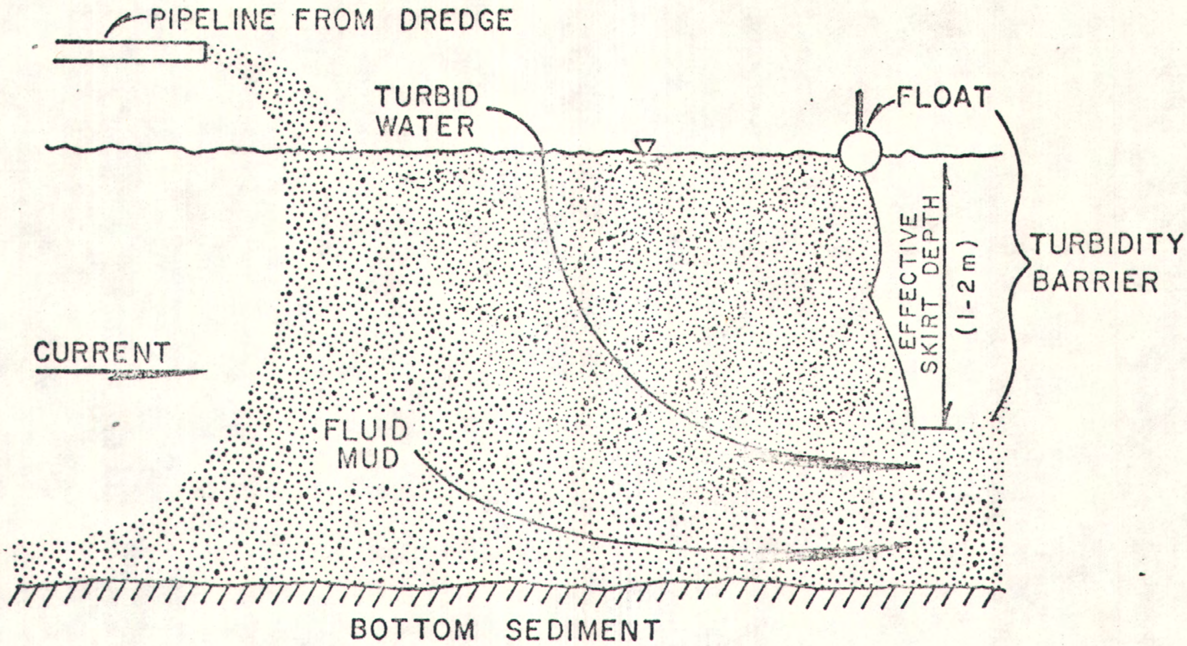


Figure 3.--Relation between turbidity barrier, turbid water, and fluid mud (modified from Barnard, 1978).

Movement of fluid mud is another phenomenon related to disposal and containment of dredged material having particular significance in Hillsborough Bay. Mounds of settled and consolidating silts and clays often become unstable and flow outward from discharge sites, along the bottom, under turbidity barriers, and beyond disposal area boundaries. Fluid mud is generally not visible from the surface so has little influence on the appearance of primary turbidity plumes. Secondary turbidity plumes are often produced, however, if fluid mud is distributed to areas affected by wind waves, erosion by tidal currents, or ship turbulence.

Physical, Chemical, and Hydraulic Properties of Receiving Water

Properties of water receiving dredged material influence the appearance and water quality of turbidity plumes. 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. It is beyond the scope of this paper to discuss these processes except to acknowledge their existence and importance. 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 one particle called an aggregate or flocculant (floc). The floc settles to the bottom more rapidly than individual particles. Increased settling rates of fine dredged material due to flocculation reduces the extent and visibility of turbidity plumes and reduces the amount of water-sediment chemical interaction.

Factors promoting increased settling rates of fine particles by flocculation include (1) presence of certain types of clay minerals, chiefly montmorillonite, (2) at least 1,000 or 2,000 mg/L concentration of sodium chloride, and (3) sufficient water turbulence to ensure particle collisions (Cogley and others, 1976). All three conditions are met in Tampa Bay. Presence of sufficient sodium chloride has been verified (Goodwin and others, 1974 and 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).

Table 1.--Clay mineralogy of Tampa Bay sediments

Sample location		Weight percent				
Latitude	Longitude	Chlorite	Kao-linite	Illite	Mont-moril-lonite	Illite-mont-moril-lonite
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

In addition to its importance in the flocculation process, turbulence (1) prolongs overall particle settling times, (2) tends to resuspend deposited material, and (3) contributes to vertical and horizontal dispersion of fine particles. Because fine particles from dredging operations often remain visible for many hours after discharge, turbidity plume appearance in unsteady tidal flows can be significantly different than in streams having steady flow conditions. Discharge into streams generally produces plumes that expand in width with increasing downstream distance due to turbulent dispersion. Discharge into unsteady tidal flows cause 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 illustrates how tidal flow can affect plume shape. The plume has a bar bell 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 interpreted by the enhancement method used as being the same as turbid water within the plume.

The spatial variability of tidal flow also affects plume appearance and shape. Identical dredges discharging similar material at separate locations in an estuary may not produce similar plumes because of different magnitudes of tidal flows; durations of flood, ebb, or slack conditions; and local variations in flow directions.

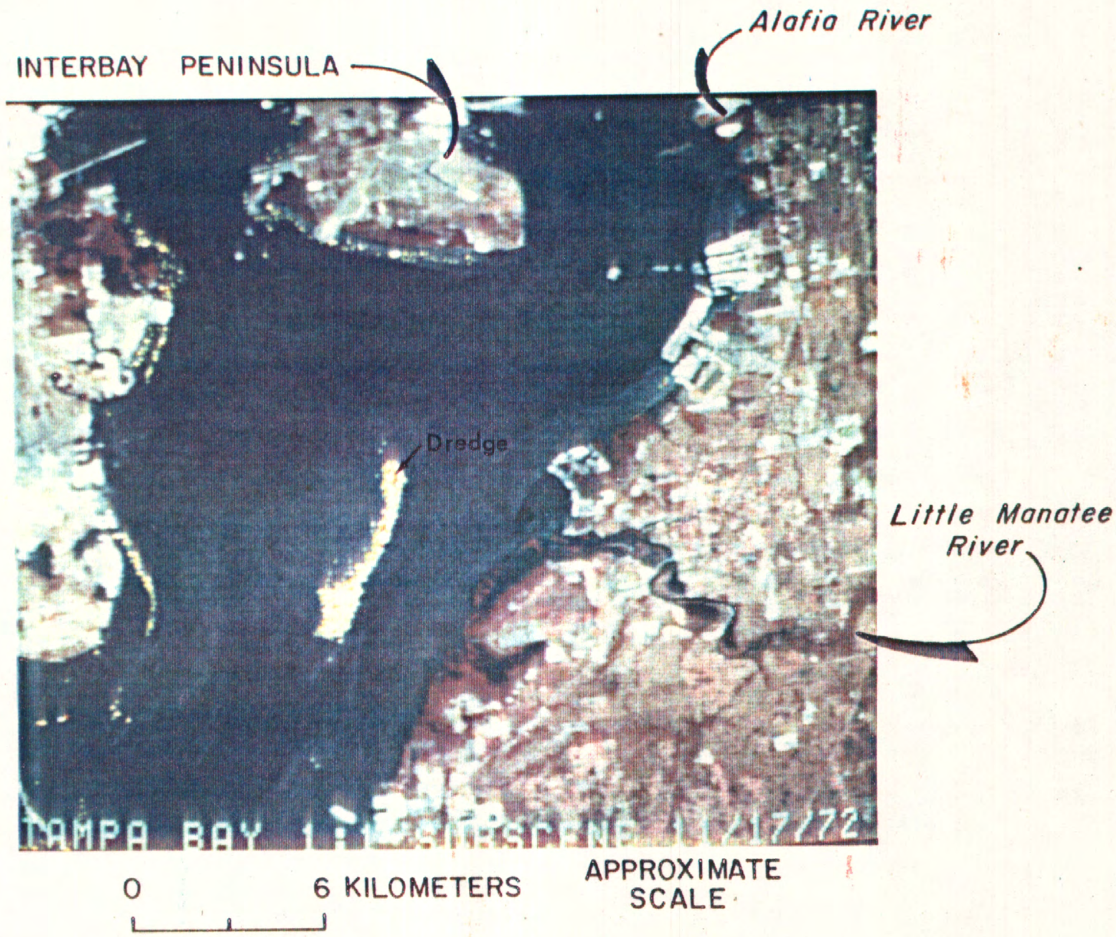


Figure 4.--Color-enhanced satellite image of turbidity plume in Tampa Bay.

STUDY METHODS

Aerial photography and satellite imagery were both considered as methods for documenting the appearance of turbidity plumes in Tampa Bay. Aerial photography provided greater scheduling flexibility during seasons of limited cloud-free conditions and 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-millimeter 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.

Scheduling of data collection was restricted by meteorological conditions. The Tampa Bay area averages less than 6 days per month when there is at least a 30 degree solar altitude, the minimum recommended sun angle above the horizon for aerial photography, and 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 that often restricted choice of flight times and altitudes.

Mid-depth water-quality samples were collected at one or more sites in each turbidity plume and at one site not visibly affected by dredging for analysis of (1) levels of turbidity and related water-clarity parameters (total suspended solids, volatile suspended solids, and transparency), and (2) possible resuspension and solution of nutrients, metals, pesticides, and industrial compounds due to dredging. Turbidity and related parameters were also sampled at top, middle, and bottom depths at several additional sites within visible plumes.

Positioning of the sample 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 allowed nearly simultaneous collection of photography and water-quality samples. The estimated timing precision between sampling and corresponding photography was 5 minutes, the average time required to complete sampling.

Supplementary data on meteorologic, photographic, sediment, dredge, containment, tidal stage, and tidal velocity conditions during times of plume monitoring were also collected. These data were used in evaluating plume appearance and may aid in transfer of plume appearance and water-clarity information to other areas where dredging is contemplated.

Aerial Photography

Aerial photography was obtained by use of a flexible, low-cost system (Meyer, 1973) that was assembled using a portable camera mount (fig. 5), a fiber-optic sight, 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-millimeter camera having motorized film advance, automatic shutter cocking, and both remote and internal shutter release mechanisms.

Kodachrome[1/] 64 color reversal film was used in the study. The first generation product is a positive transparency, commonly called a "slide," usable for light-table scanning, projection, and production of glossy photographs. An ultraviolet filter was used for penetration of atmospheric haze. Additional information on use of aerial photography for water-resources surveillance is given by Fraga and Holland (1974) and the California Water Resources Control Board (1978).

Fig. 5 near here

1/ The use of brand names in this report does not imply endorsement by the U.S. Geological Survey.

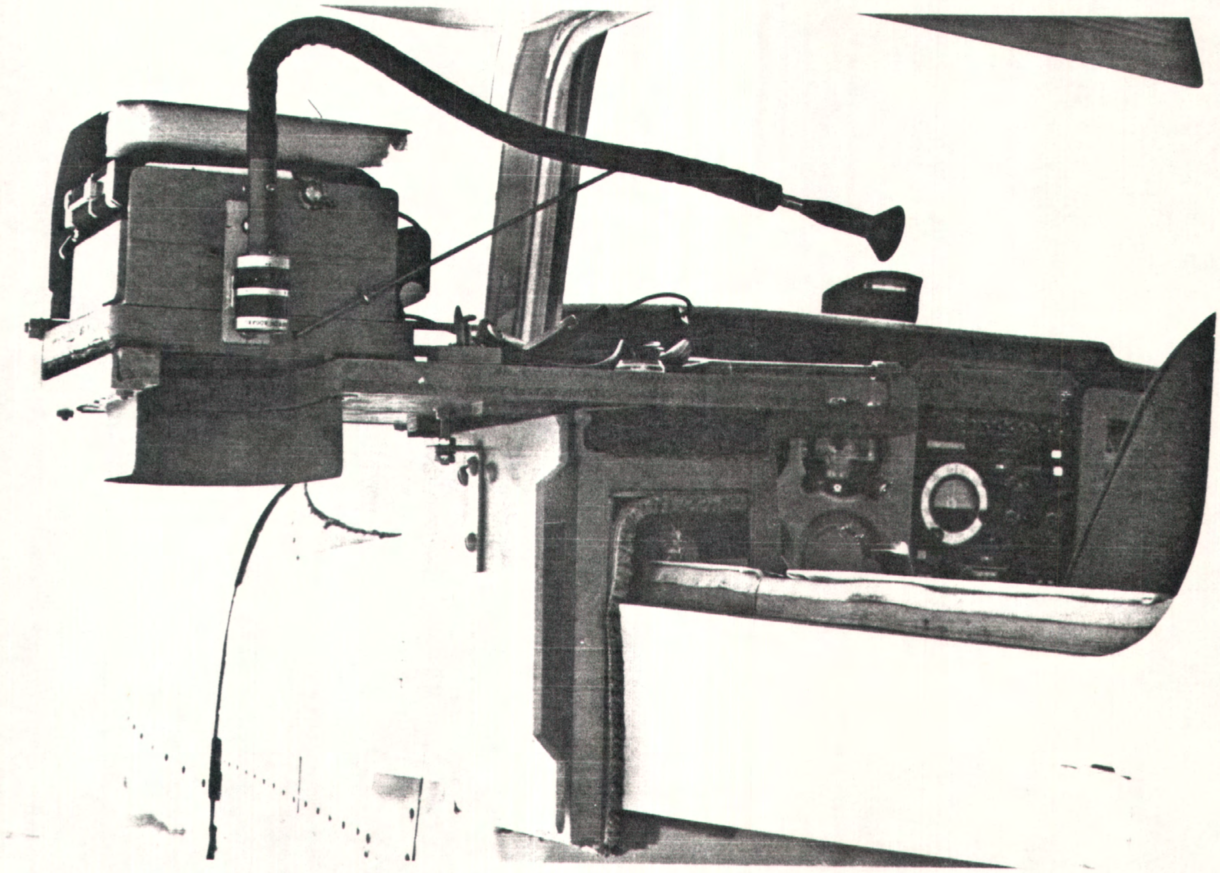


Figure 5.--Camera and mount used for vertical aerial photography (modified from Meyer, 1973).

Water-Quality Sampling

Water samples were collected by the Hillsborough County Environmental Protection Commission. Conductance, pH, temperature, and dissolved oxygen were measured in the field with a portable, multiparameter, water-quality monitoring system. Water transparency was measured in the field using a Secchi disc (Wetzel, 1975). Filtered and unfiltered samples were analyzed for nutrient parameters including: phosphorus, orthophosphorus, nitrate, nitrite, ammonia, and organic nitrogen. Filtered and unfiltered samples were also analyzed for: arsenic, cadmium, chromium, copper, iron, lead, manganese, nickel, zinc, and mercury. Arsenic, cadmium, chromium, and nickel were not analyzed in samples from South Tampa Bay. Analyses for the following pesticides and industrial compounds were made using 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 parameters analyzed include turbidity, total suspended solids, and volatile suspended 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).

The data were used to determine (1) relations between turbidity and other water-clarity parameters, (2) whether constituents were more concentrated in samples from plume sites than from background sites, and (3) whether turbidity plumes in South Tampa Bay had different water-quality characteristics than plumes in Hillsborough Bay.

Character of Dredged Material

Information on particle size gradation and percentage 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 meters 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 cores were texturally described in the field, using the Unified Soil Classification System shown in figure 6, and recorded on drillers' logs, such as those in figure 7. Information 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, figure 8a (Casagrande, 1948). Figure 8b shows the category definitions used in this study. Of several soil classification triangles available, the Mississippi Valley triangle is considered to be most suited 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 8b and summarized in table 2 were used as an approximation of the percentage of sand, silt, and clay of each similarly classified material on the drillers' logs. The percentage of larger-than-sand-sized particles (pebbles, gravel, large shell fragments, and limestone) was assigned to a separate size category.

GROUP SYMBOLS	TYPICAL NAMES
GW	Well graded gravels, gravel-sand mixtures, little or no fines.
GP	Poorly graded gravels, gravel-sand mixtures, little 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, little or no fines.
SP	Poorly graded sands, gravelly sands, little 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, lean clays.
OL	Organic silts and organic silt-clays of low plasticity.
MH	Inorganic silts, micaceous or diatomaceous fine sandy or silty soils, elastic silts.
CH	Inorganic clays of high plasticity, fat clays.
OH	Organic clays of medium to high plasticity.
Pt	Peat and other highly organic soils.

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

A

ELEVATION 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)

B

ELEVATION 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		LIMESTONE, soft, weathered, seams of calcareous silt, white, bed of green clay (CL) from -42.6 to -43.1
-45.1	7.5		
-47.6	10.0		SILT, calcareous, soft, limestone lenses and fragments, white (ML)
-50.1	12.5		LIMESTONE, soft, weathered, seams calcareous silt, white

C

ELEVATION 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 grey, 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, slighty 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, many 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

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

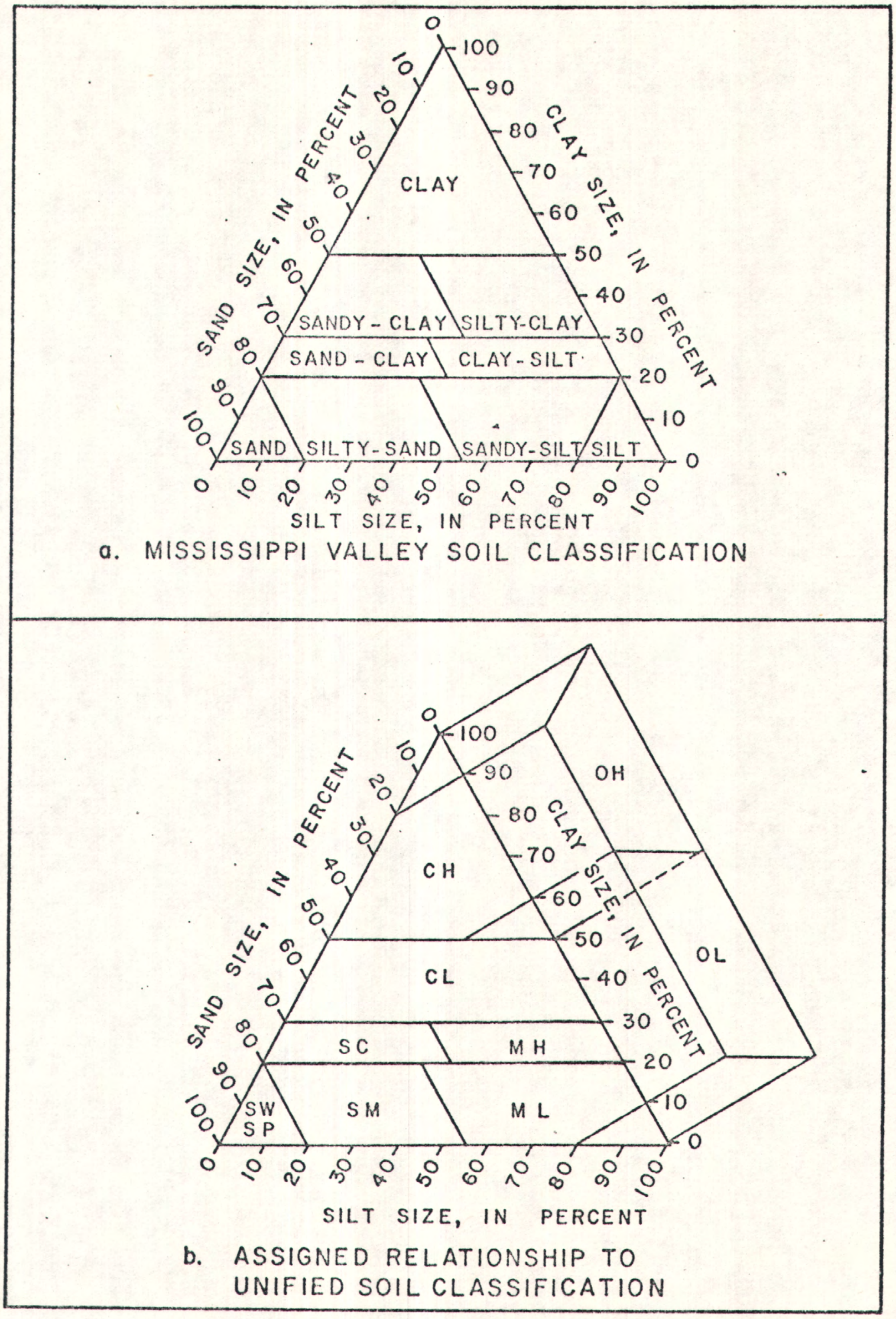


Figure 8.--(a) Mississippi Valley triangular soil classification chart (Cassagrande, 1948) and (b) assigned relation to Unified Classification System.

Table 2.--Particle size gradation and cohesive 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.

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 determine an approximate quantity of cohesive material being dredged, the thickness of cohesive material, based on drillers' logs, was computed as a percentage, 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.

Table 3.--Sample calculation of approximate particle size gradation

Horizon number (i)	Altitude at top of horizon in feet	Horizon thickness in feet (t_i)	Textural classification	Percent greater than sand (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	30
8	-43.5	1.5	ML	0	22	68	10

Number of horizons (n) = 8

Total thickness (T) = 21.0 feet

Estimate of bulk particle size distribution by thickness weighed average:

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

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

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

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

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

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

***Rounded to nearest 5 percent due to approximate nature of procedure.

Tidal Conditions, Dredge Equipment, and Disposal Methods

Tidal stage and velocity data were determined by a combination of measurement and simulation modeling. Measurements of tidal stage were made at gages near the mouth of Tampa Bay and near the head of Hillsborough Bay (fig. 1). The velocity of water flow at times of plume photography was approximated using information from two-dimensional, computer-simulation models of Tampa and Hillsborough Bays (Goodwin, 1977). Approximations were cross-checked with harmonic 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 sampling boat.

TURBIDITY PLUME APPEARANCE AND WATER-CLARITY DATA

Photographic, water-quality, and supplementary data presented in this section illustrate turbidity plumes for various types of dredging operations, such as:

hopper-dredge loading

hopper-dredge maneuvering

hopper-dredge unloading

pipeline dredge with submerged discharge

pipeline dredge with oscillating surface discharge

pipeline dredge discharging within turbidity barrier

pipeline dredge discharging to emergent dike with turbidity barrier

pipeline dredge discharging to partly enclosed dike with turbidity barrier

For each type of dredging operation, the following data are presented: location map, sampling conditions, tidal conditions, water-clarity data, and photographic data. The first six presentations in this section of the report show plumes in South Tampa Bay near the entrance to Tampa Bay; the last three presentations show plumes in Hillsborough Bay near the head of the easterly arm of Tampa Bay.

For each dredging operation, a detailed location map shows dredge location(s), discharge site(s), water-quality sites, orientation 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.

Photographs of dredging operations are displayed with north arrows for orientation with the location map, and locations of the sample boat are circled. An abbreviated description of each photograph includes: a caption statement, sample time, water depth, approximate photograph scale (if applicable) and turbidity, suspended solids, and transparency data.

Hopper-Dredge Loading, Flood Tide

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

The dredge in operation and a background sampling site about 200 meters from the dredge are shown in photograph 1 (fig. 11). The sample site in photograph 4 (fig. 12), a few meters outside the edge of the visible plume, measured clearer water than at the background site. Sample sites at various locations within the plume are shown in photographs 2, 3, 5, 6, and 7 (figs. 11 and 12) over a time period of about 1 hour and 40 minutes during active dredge operation. Photograph 5 was taken as the dredge reversed direction and discharged additional turbid water onto its previously generated plume. Back-and-forth operation caused a plume of variable width, best seen in the mosaic, photograph 3.

Turbidity levels and suspended solids concentration 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 background site and four or five units greater than the sample site having the least turbidity.

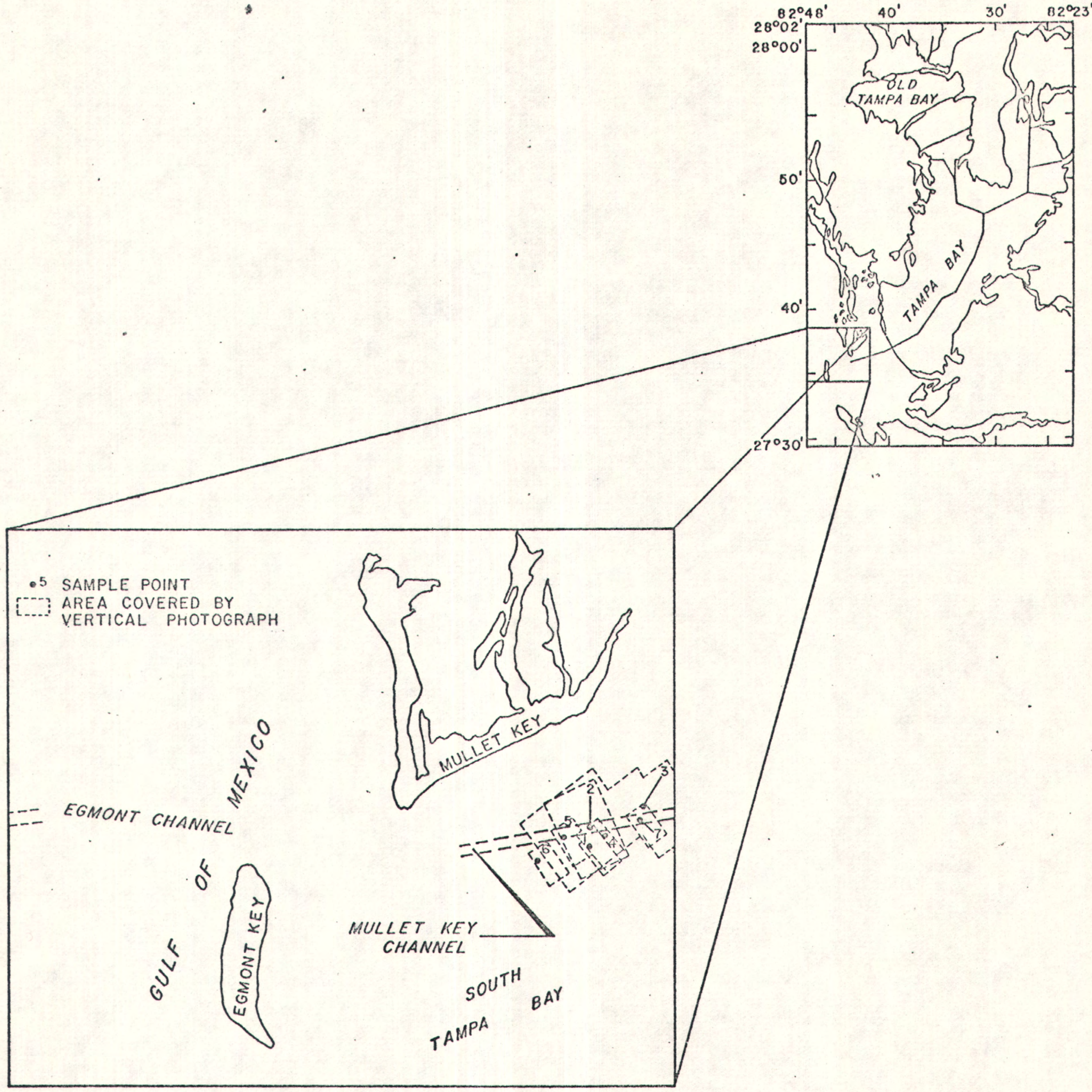


Figure 9.--Hopper-dredge loading, flood tide: data-collection sites.

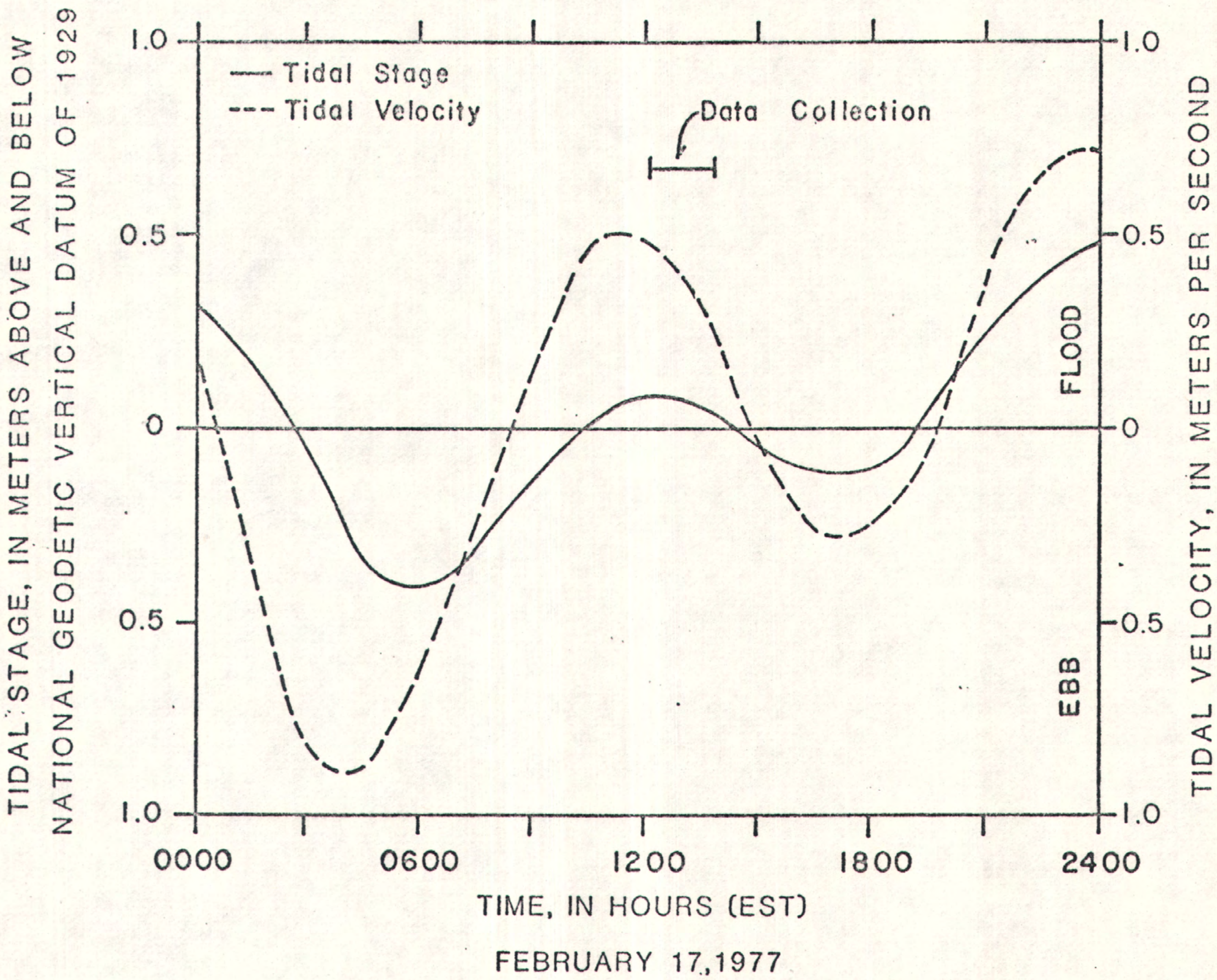
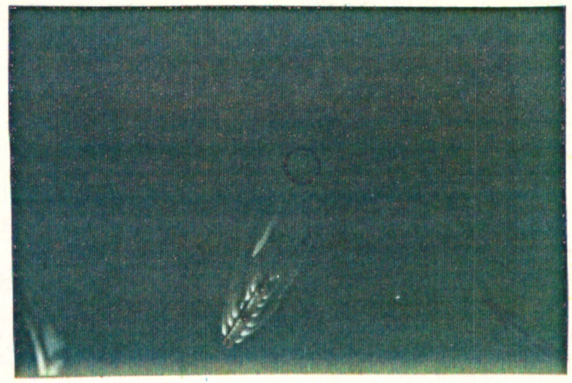


Figure 10.--Hopper-dredge loading, flood tide: tidal stage and tidal velocity at South Tampa Bay monitoring sites.

Site 1. Vertical view of background sample site 200 m southwest of dredge.

Time: 1213 Depth: 8.2 m
Scale (approx.): 1:9,100

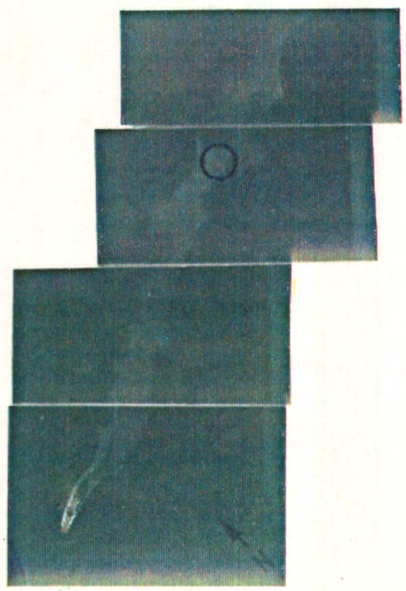
	Turbidity (NTU)	Suspended solids (mg/L)	Transparency (cm)
Top	7	29	46
Middle	7	29	--
Bottom	9	32	--



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	--



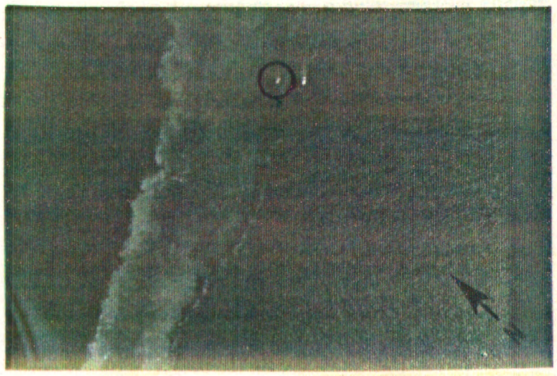
Note:
Circle indicates location of sampling boat.

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	--

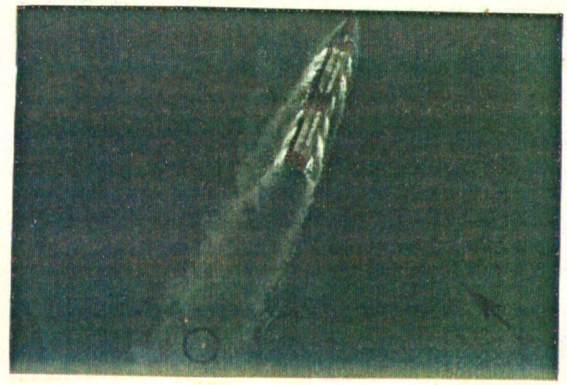
Figure 11.--Hopper-dredge loading, flood tide: photographs and water-clarity data for sites 1 through 3.



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

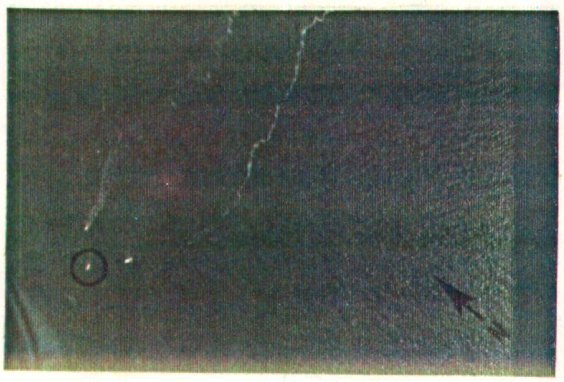
	Turbidity (NTU)	Suspended solids (mg/L)	Transparency (cm)
Top	3	15	91
Middle	2	14	--
Bottom	3	14	--



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

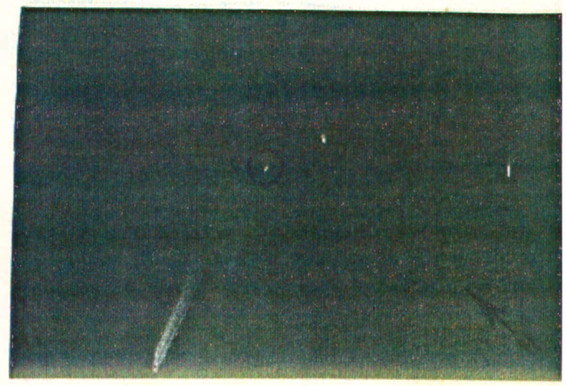
	Turbidity (NTU)	Suspended solids (mg/L)	Transparency (cm)
Top	8	35	46
Middle	8	45	--
Bottom	8	45	--



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	--



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	--

Note: Circle indicates location of sampling boat.

Figure 12.--Hopper-dredge loading, flood tide: photographs and water-clarity data for sites 4 through 7.

Table 4.--Sampling conditions for hopper-dredge loading, flood tide

Flight

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

Meteorologic

Visibility: Light haze
Solar altitude: 40° above horizon
Wind speed: 13 km/h
Wind direction: from north

Photographic

Film: Kodachrome, ASA 64
Filter: ultraviolet, haze

Sediment

Approximate size gradation and percentage of cohesive material

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

Construction

Dredge(s): Ezra Sensibar
Disposal: hopper overflow

Containment: none

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

Hopper-Dredge Maneuvering and Pipeline Dredge with Submerged Discharge, Slack Tide

On March 15, 1977, two dredges were working in South Tampa Bay south of Mullet Key (fig. 13). The cutterhead-pipeline dredge Dave Blackburn was operating in Mullet Key Channel, discharging dredged material into open water about 800 meters south of the channel. The hopper dredge Ezra Sensibar had finished loading and was maneuvering to unload at a pier on Mullet Key. Weak and variable tidal currents associated with slack tide existed during the time of data collection (fig. 14). The material being discharged by the pipeline dredge was composed of 70 percent sand and larger sized 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. 2c) is shown in photograph 9 (fig. 15). The light-blue spots in the upper-central part of photograph 9 mark the shallowest areas. These were formed during prior disposal operations. Water depths at two of these spots were measured to be 0.9 meter and 2.1 meters below the surface. The sampling site was in the most visibly turbid region, about 30 meters from the discharge point. Although the discharge pipe was submerged, a significant portion of the plume was apparently reflected to the surface from the bottom before drifting to the north. Turbidity levels ranged from 25 to 70 NTU at site 9.

Open-water disposal at slack tide can be expected to produce plumes having a limited extent, a generally circular shape, and high visibility (see fig. 4 and associated discussion).

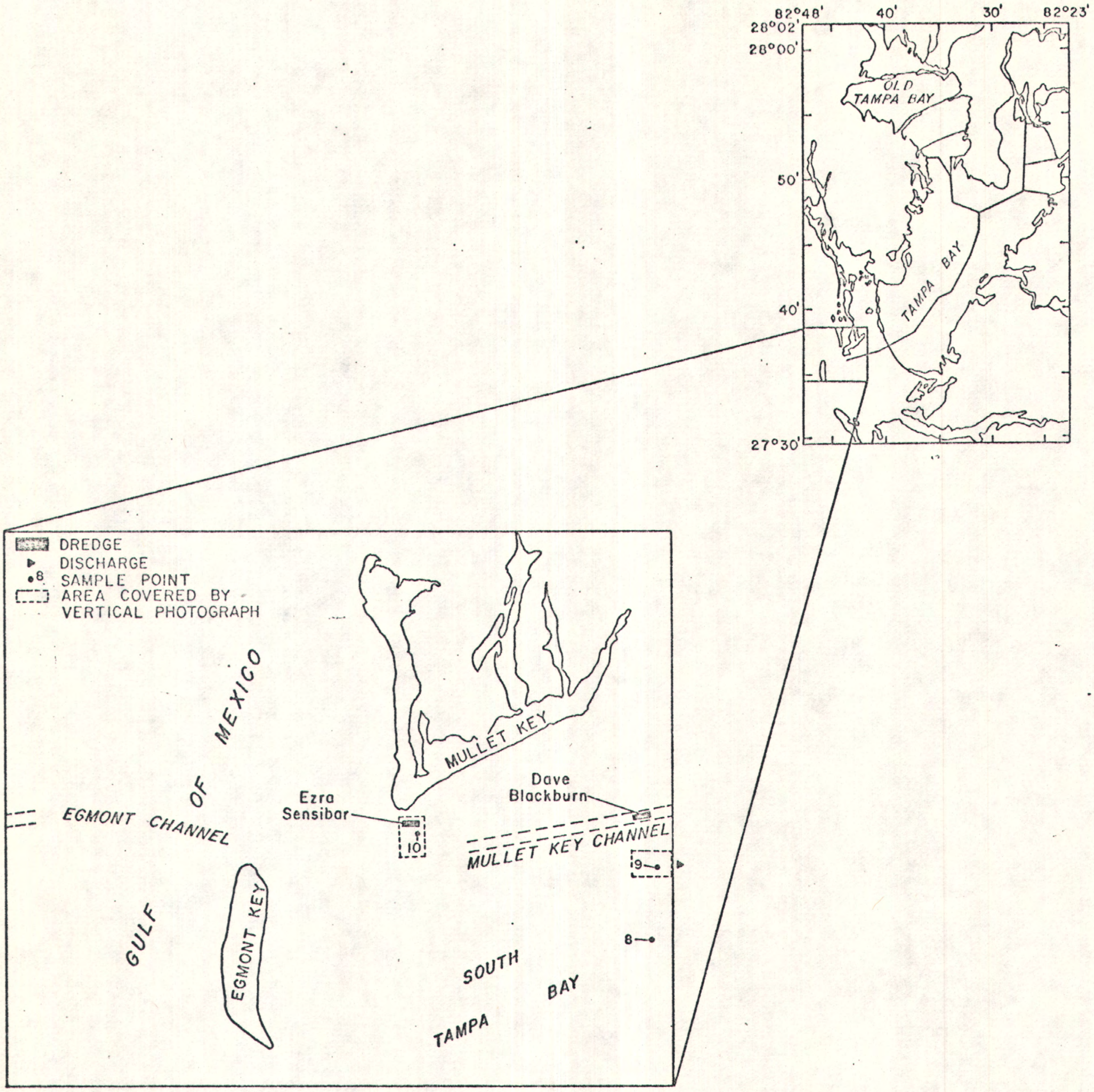


Figure 13.--Hopper-dredge maneuvering and pipeline dredge with submerged discharge, slack tide: data-collection sites.

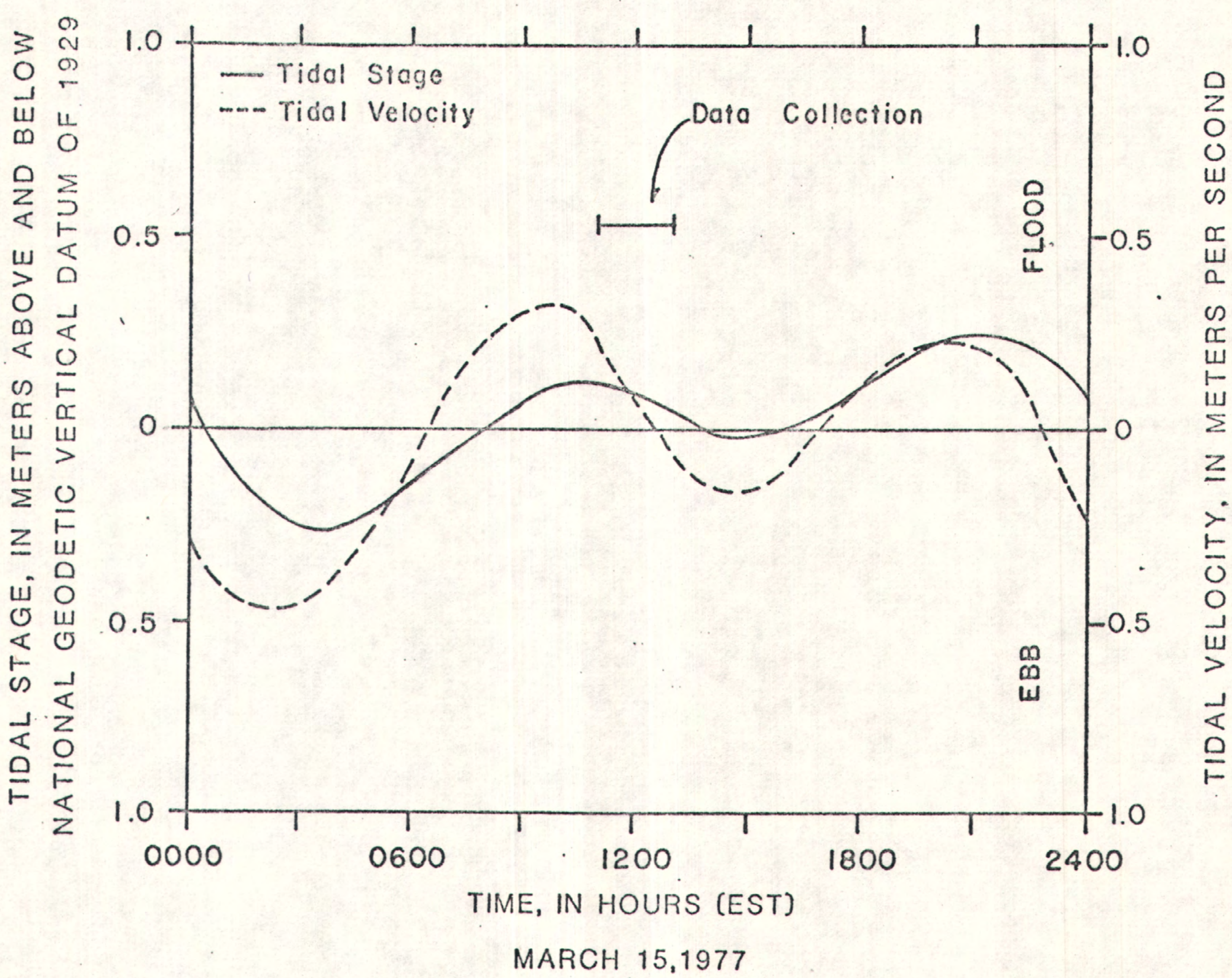


Figure 14.--Hopper-dredge maneuvering and pipeline dredge with submerged discharge, slack tide: tidal stage and tidal velocity at South Tampa Bay monitoring sites.

Site 8. Background sample--no photograph

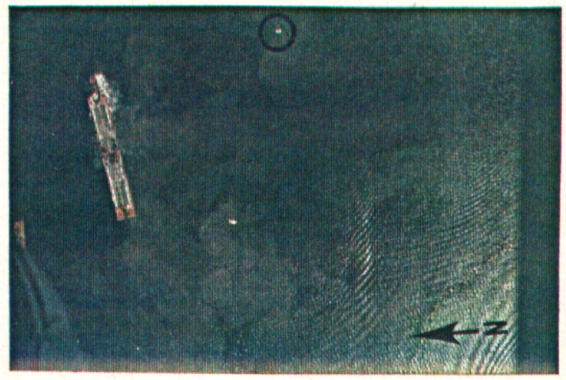
Time: 1215 Depth: 13.7 m

	Turbidity (NTU)	Suspended solids (mg/L)	Trans-parency (cm)
Top	2	11	229
Middle	4	11	--
Bottom	6	18	--

Site 9. Vertical view of open water disposal at slack tide.

Time: 1240 Depth: 7.0 m
Scale (approx.): 1:9,100

	Turbidity (NTU)	Suspended solids (mg/L)	Trans-parency (cm)
Top	25	60	15
Middle	70	234	--
Bottom	65	197	--



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)	Trans-parency (cm)
Top	50	88	30
Middle	30	48	--
Bottom	45	80	--

Note: Circle indicates location of sampling boat.

Figure 15.--Hopper-dredge maneuvering and pipeline dredge with submerged discharge, slack tide: photographs and water-clarity data for sites 8 through 10.

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

Flight

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

Meteorologic

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

Photographic

Film: Kodachrome, ASA 64
Filter: ultraviolet, haze

Sediment

Approximate size gradation and percentage of cohesive material

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

Construction

Dredge(s): Ezra Sensibar and Dave Blackburn
Disposal: submerged pipe

Containment: none

Turbid patches of water formed as the hopper dredge maneuvered to reach the unloading facility at a pier on Mullet Key, photograph 10 (fig. 15). The turbidity is 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 having turbidity levels of 30 to 50 NTU.

Hopper-Dredge Unloading, Flood Tide

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). Material being discharged was primarily sand or larger material. Fifteen percent of the material was estimated to be silt and clay (table 6). A strong flood tide 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 meters of the discharge pipe (photographs 12 and 13, fig. 18). Background data (fig. 18, no photograph) were collected at site 11.

Beach nourishment, using material with little silt and clay, 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 in the surf zone (photograph 13). Beach nourishment operations can be expected to produce turbidity plumes of low visibility and limited extent.

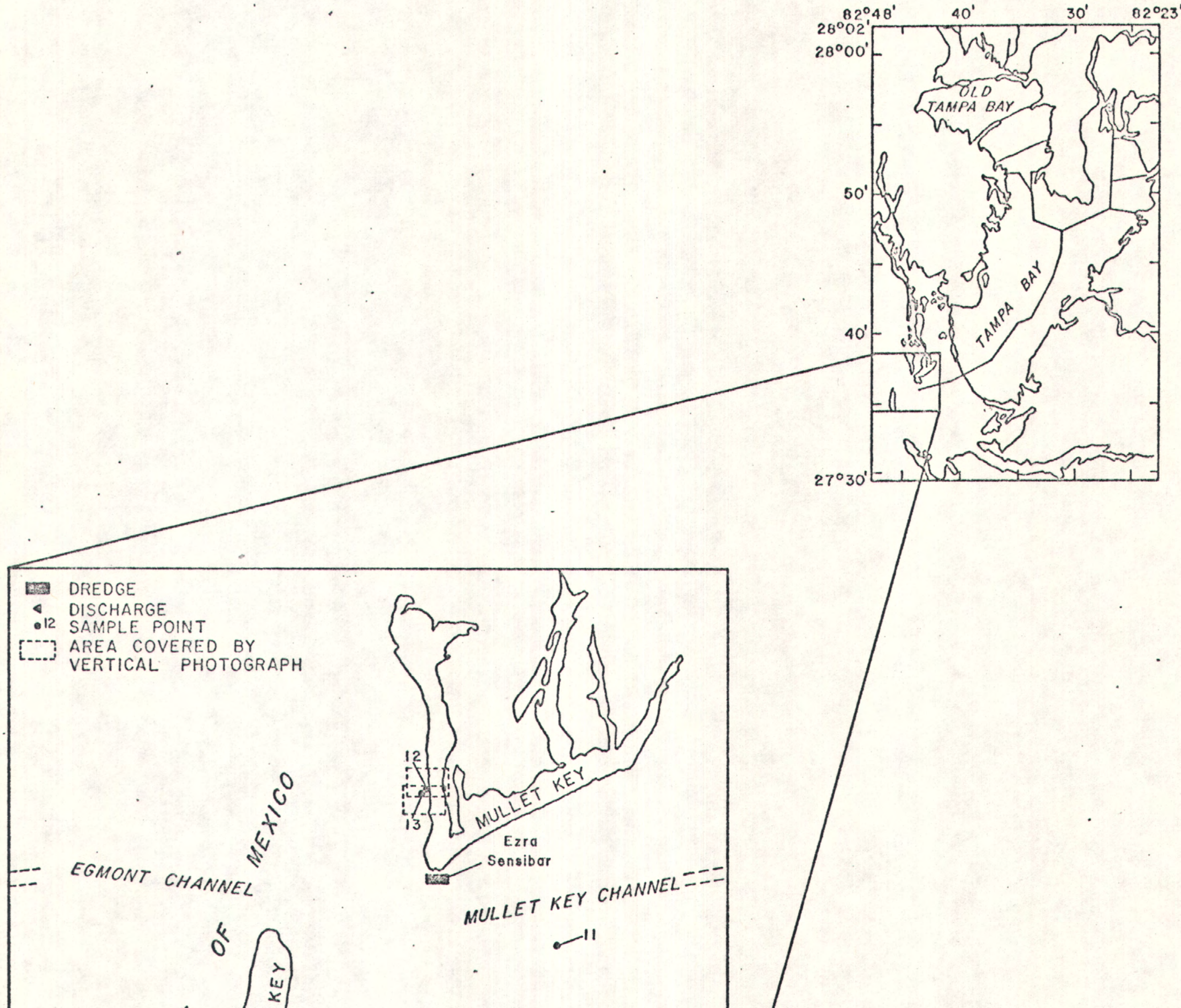


Figure 16.--Hopper-dredge unloading, flood tide: date-collection sites.

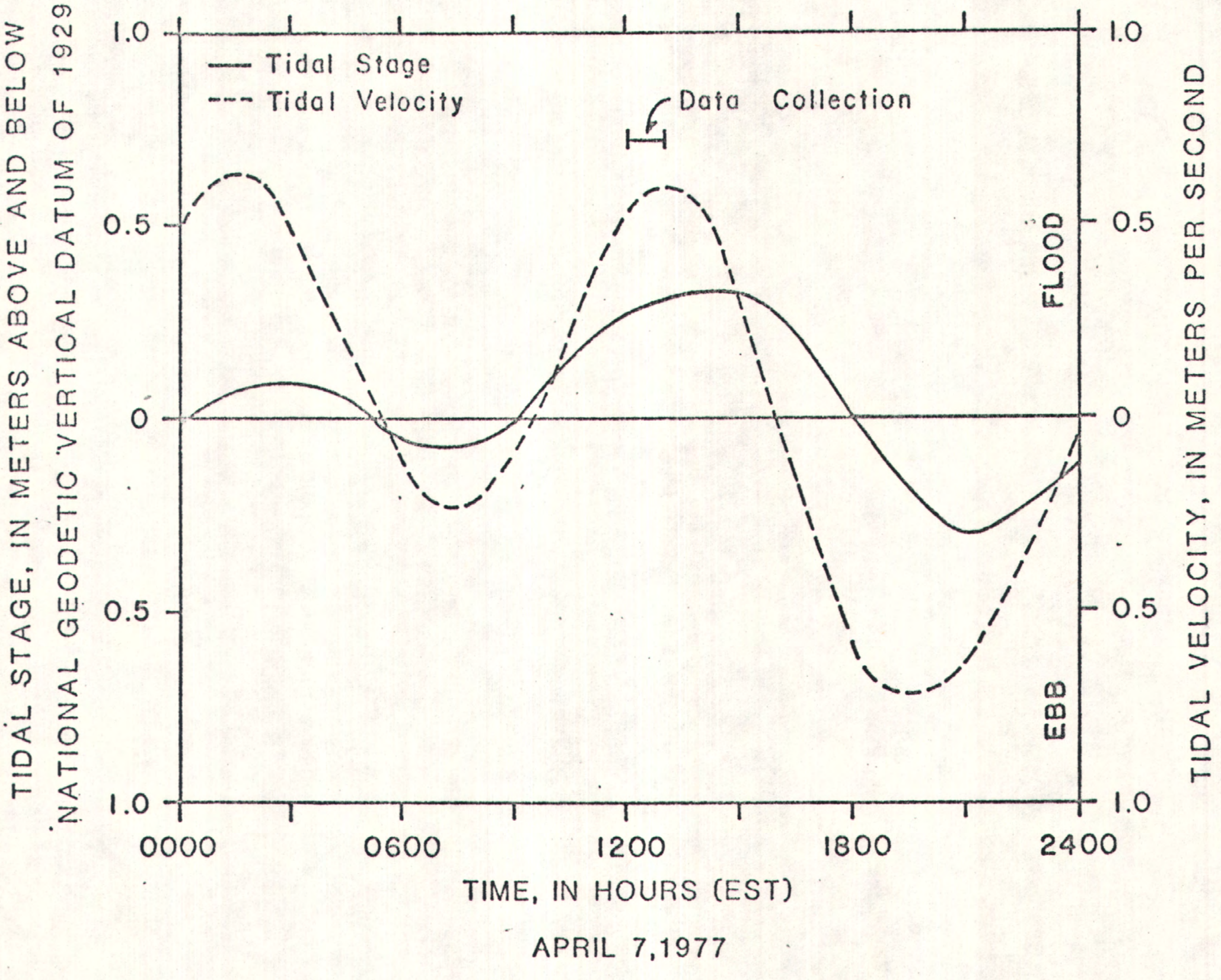
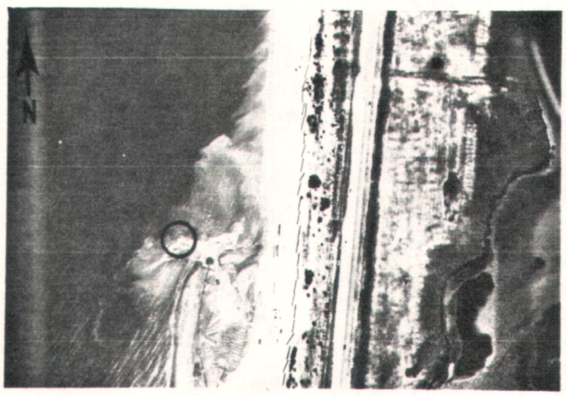


Figure 17.--Hopper-dredge unloading, flood tide: tidal stage and tidal velocity at South Tampa Bay monitoring sites.

Site 11. Background sample--no photograph.

Time: 1250 Depth: 7.3 m

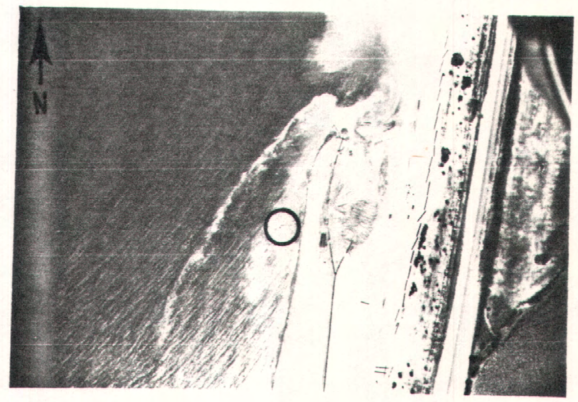
	Turbidity (NTU)	Suspended solids (mg/L)	Trans-parency (cm)
Top	5	10	152
Middle	6	9	--
Bottom	10	18	--



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)	Trans-parency (cm)
Top	85	108	15
Middle	65	86	--
Bottom	15	21	--



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)	Trans-parency (cm)
Top	60	79	15
Middle	50	57	--
Bottom	40	48	--

Note: Circle indicates location of sampling boat.

Figure 18.--Hopper-dredge unloading, flood tide: photographs and water-clarity data for sites 11 through 13.

Table 6.--Sampling conditions for hopper-dredge unloading, flood tide

Flight

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

Meteorologic

Visibility: clear
Solar altitude: 58° above horizon

Wind speed: 19 km/h
Wind direction: from northeast

Photographic

Film: Kodak Plus-x, ASA 125

Filter: ultraviolet, haze

Sediment

Approximate size gradation and percentage of cohesive material

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

Construction

Dredge(s): Ezra Sensibar

Disposal: beach nourishment

Containment: none

Hopper-Dredge Unloading and Pipeline-Dredge Smoothing

Disposal Area, Slack Tide

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 disposal area about 800 meters south of Mullet Key Channel (fig. 19). Conditions during time of photography are given in figure 20 and table 7. Background data (fig. 21, no photograph) were collected at site 14. Visible turbidity from beach nourishment using predominantly coarse material was confined to a strip about 100 meters wide along the beach (photographs 15 and 16, fig. 21). The high turbidity level measured at site 16 is attributed to prolonged suspension of fine particles due to the shallow depth, 0.5 meter, 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.

The tops of previously deposited disposal mounds are shown being dredged in photograph 17, figure 21, 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 applicable for association with the cutterhead generated plume shown in photograph 17. Reduced quantities of fine material and near slack-tide conditions resulted in a plume that was limited in visible extent, about 100 meters in diameter, and of moderate turbidity, 12 to 28 NTU.

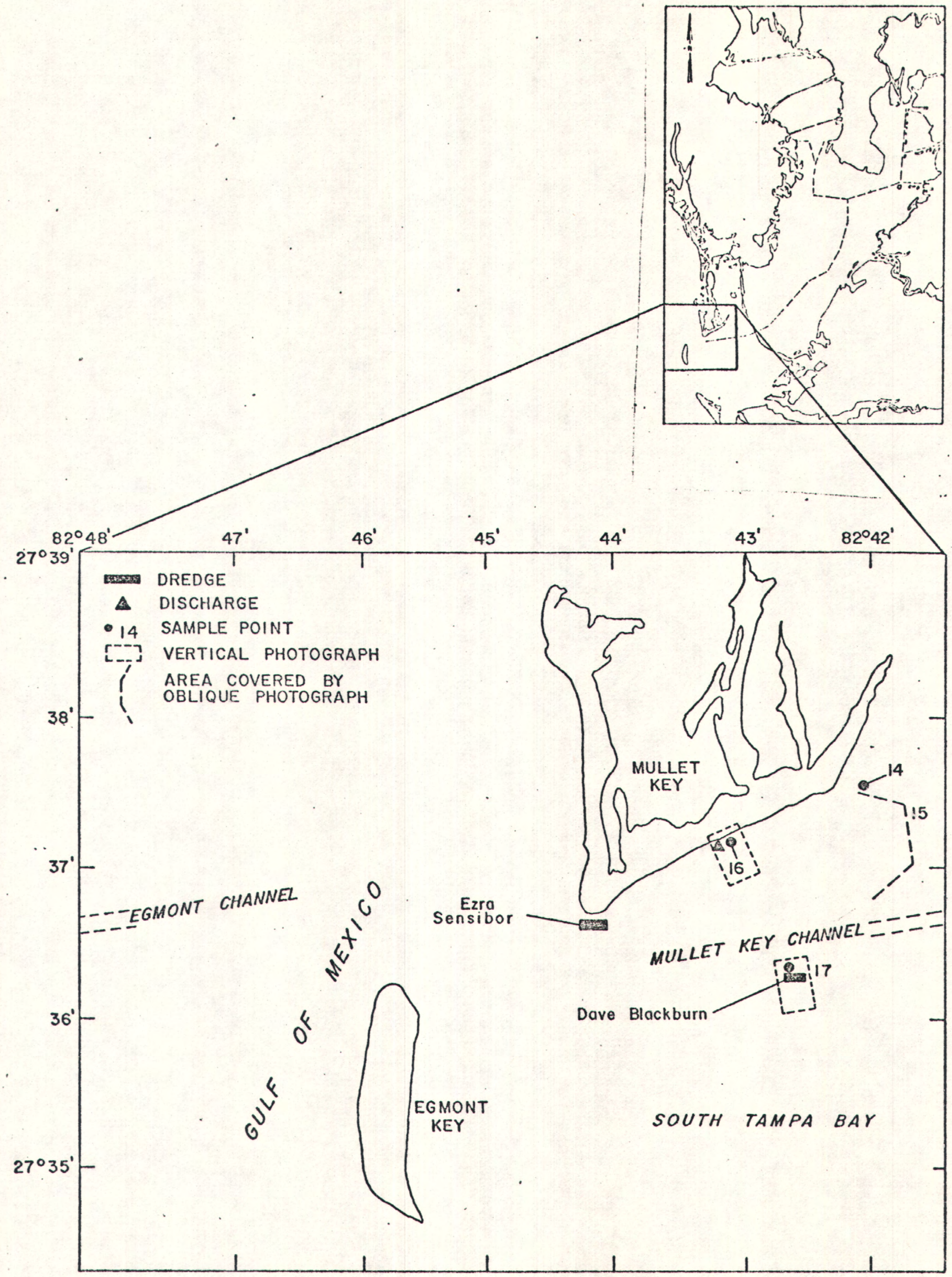


Figure 19.--Hopper-dredge unloading and pipeline-dredge smoothing disposal area, slack tide: data-collection sites.

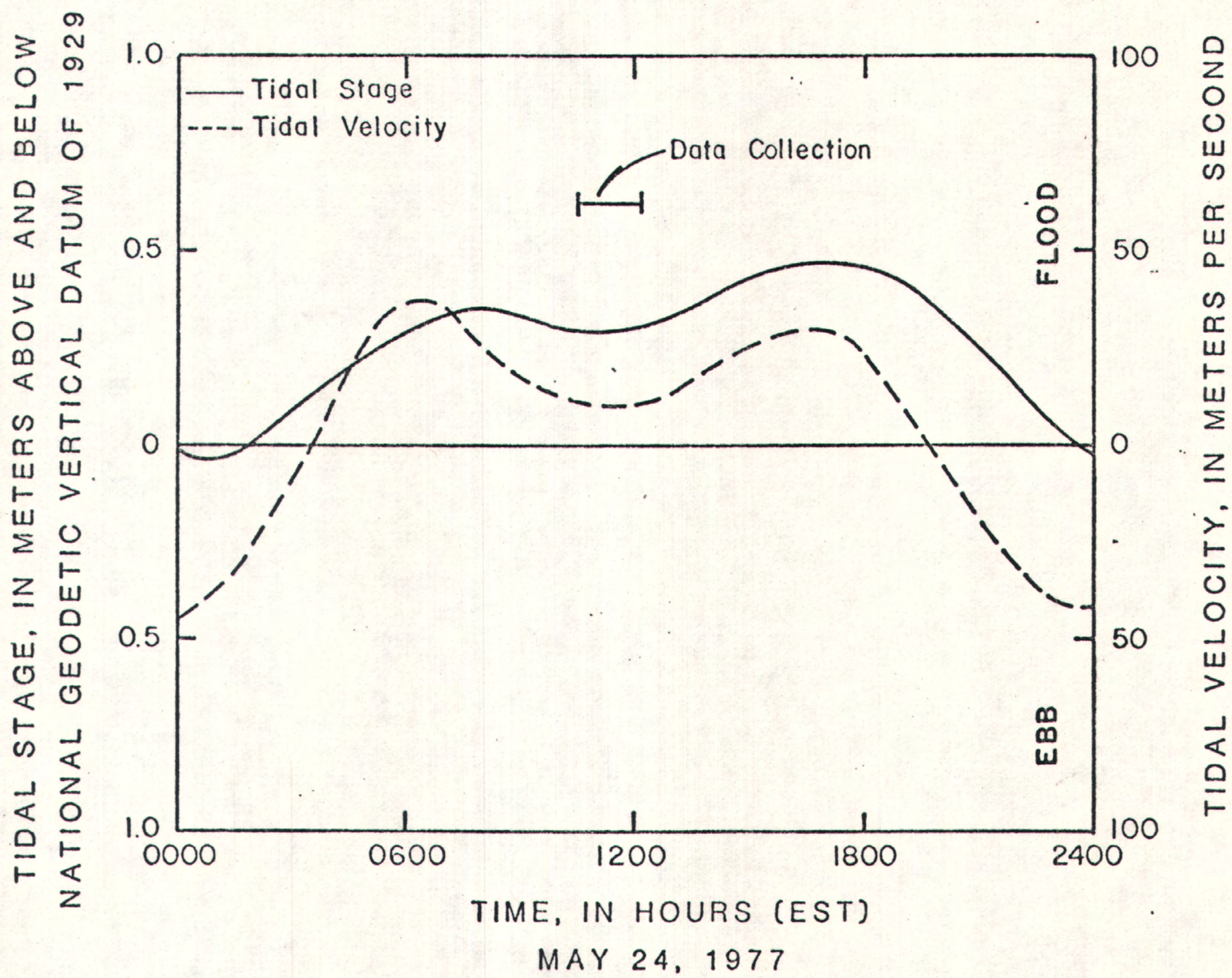
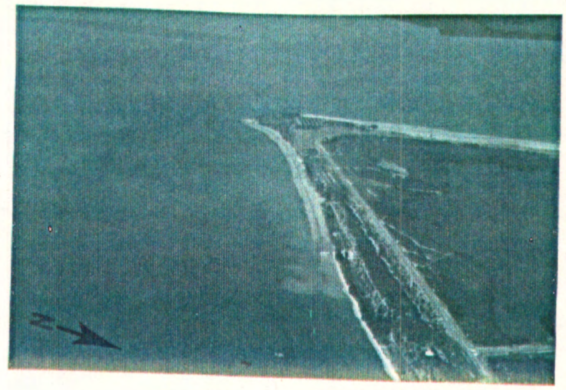


Figure 20.--Hopper-dredge unloading and pipeline-dredge smoothing disposal area, slack tide: tidal stage and tidal velocity at South Tampa Bay monitoring sites.

Site 14. Background sample--no photograph.

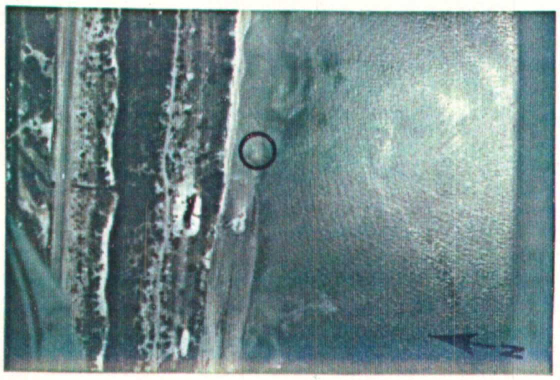
Time: 1200 Depth: 1.0 m

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



Site 15. Oblique view of beach nourishment on south shore of Mullet Key.

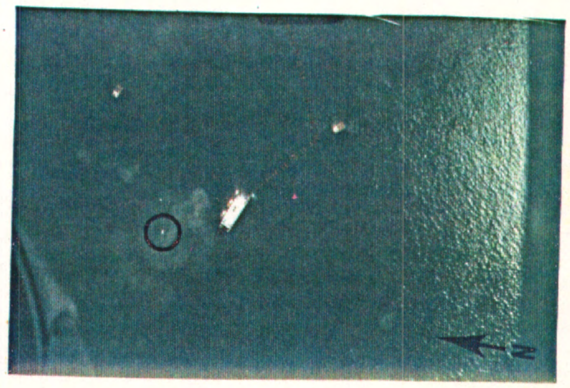
Time: 1210



Site 16. Vertical view of beach nourishment on south shore of Mullet Key.

Time: 1140 Depth: 0.5 m
Scale (approx.): 1:9,100

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



Site 17. Vertical view of pipeline dredge lowering 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	--

Note: Circle indicates location of sampling boat.

Figure 21.--Hopper-dredge unloading and pipeline-dredge smoothing disposal area, slack tide: photographs and water-clarity data for sites 14 through 17.

Table 7.--Sampling conditions for hopper-dredge unloading and pipeline-dredge smoothing disposal area, slack tide

Flight

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

Meteorologic

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

Photographic

Film: Kodachrome, ASA 64
Filter: ultraviolet, haze

Sediment

Approximate size gradation and percentage of cohesive material

Percent greater than sand	Percent sand	Percent silt	Percent clay	Percent cohesive material
Beach nourishment				
60	25	10	5	0

Construction

Dredge(s): Ezra Sensibar and Dave Blackburn
Disposal: beach nourishment

Containment: none

Pipeline Dredge with Oscillating Surface Discharge and Secondary Erosional Plume, Flood Tide

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 area about 1,200 meters south of Egmont Channel for about 2 days.

Bottom material of Egmont Channel in the area being dredged consisted of pebble-size shell fragments and medium to fine gray sands and 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 flood tide 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 (photographs 19-24, figs. 24 and 25). The most visible part of the plume was about 2 kilometers long and 300 meters wide at its widest point. The plume narrowed to less than 100 meters in width toward Egmont Key, as shown at the eastern extremity of photograph 24. An S-shaped pattern, caused by oscillating movement of the discharge pipe, was visible in the plume for about 500 meters east of the discharge point (photographs 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. The separated parts are indicated by arrows. Plume contraction and expansion is a surface expression of the rapidly accelerating and decelerating flow on either side of the relatively narrow, 800 meter, and locally deep, 20 to 30 meter, entrance channel to Tampa Bay between 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, appears as two distinct units, a separated plume.

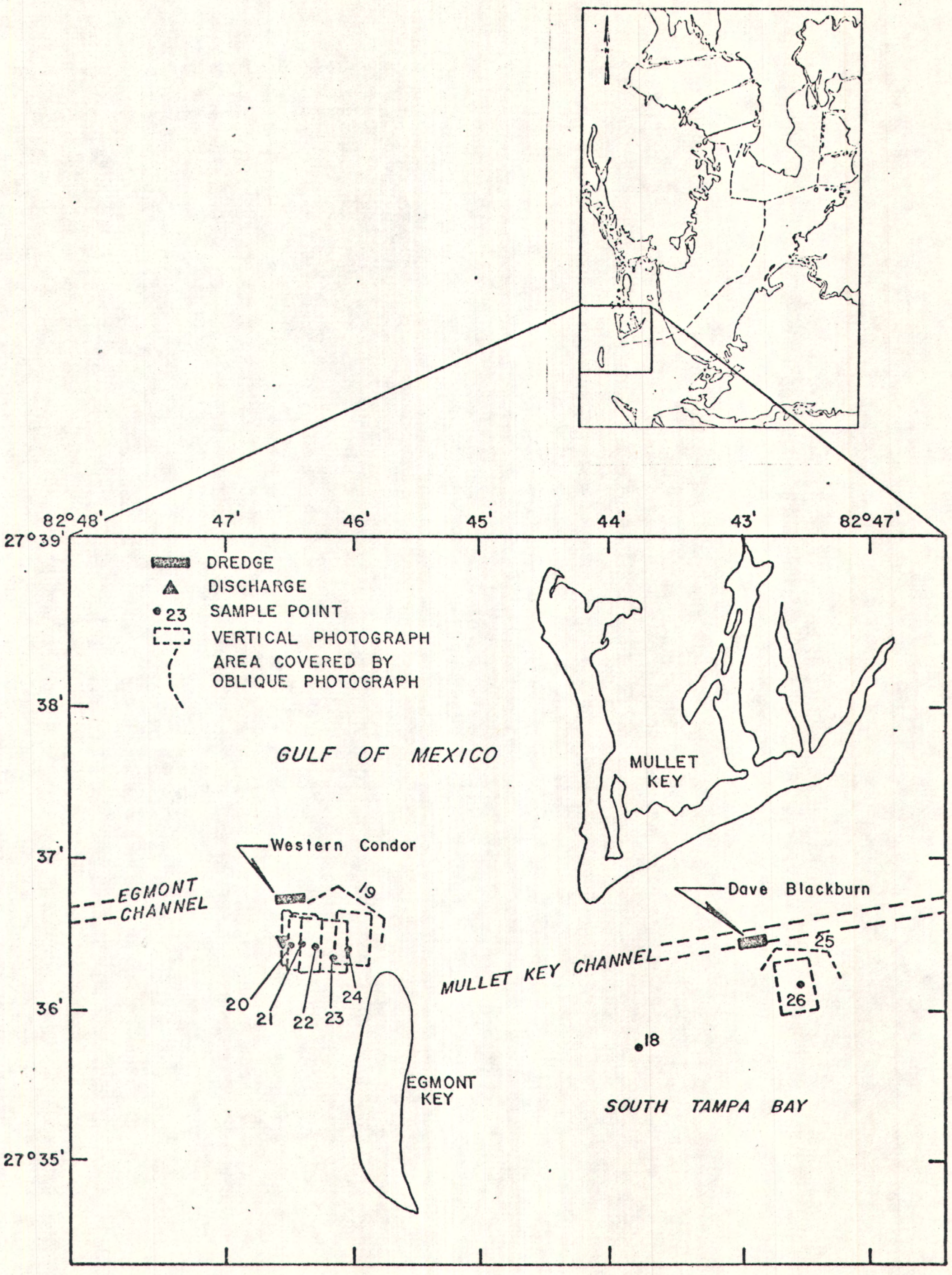


Figure 22.--Pipeline dredge with oscillating discharge and secondary erosional plume, flood tide: data-collection sites.

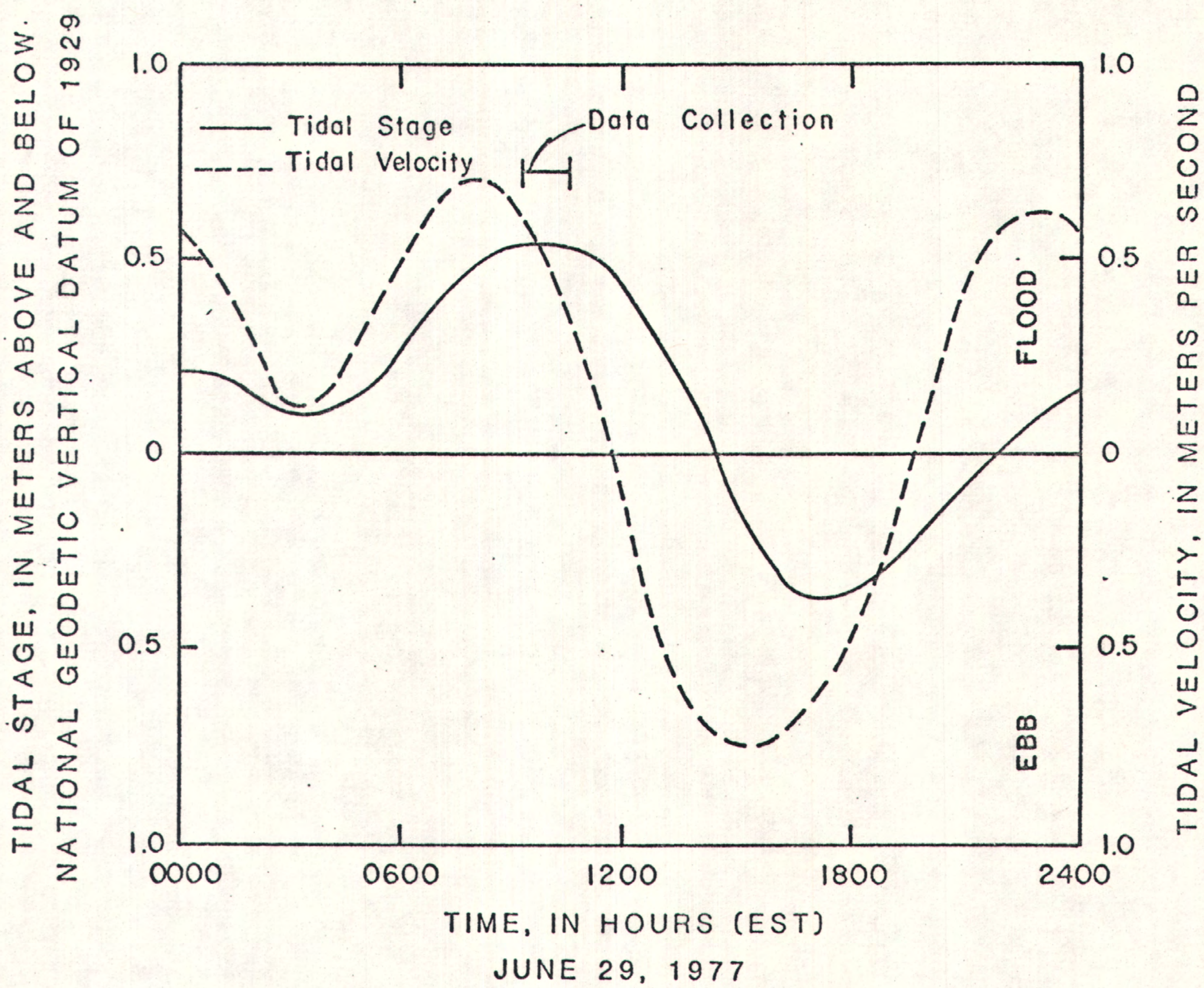


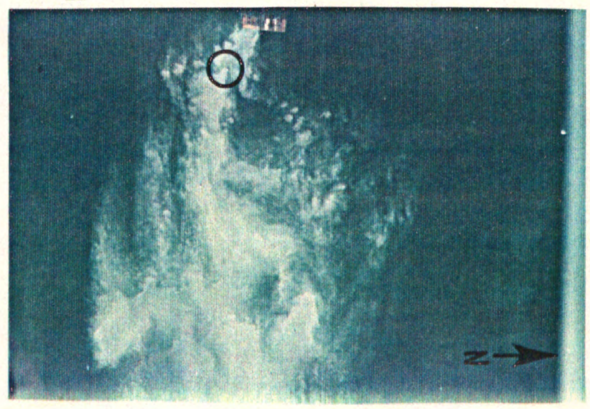
Figure 23.--Pipeline dredge with oscillating discharge and secondary erosional plume, flood tide: tidal stage and tidal velocity at South Tampa Bay monitoring sites.

Site 18. Background sample--not shown.

Time: 0930 Depth: 7.6 m

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

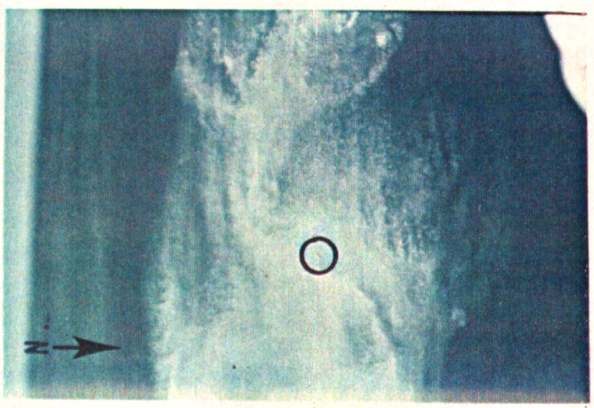
Site 19. Oblique view of uncontained open water spoil disposal turbidity plume. Discharge outlet at top of picture is swinging from side to side causing the "S" patterns in the plume.



Site 20. Vertical view of <u>Western Condor</u> disposal pipe. Sample site about 50 m from source.

Time: 0950 Depth: 3.4 m
Scale (approx.): 1:9,100

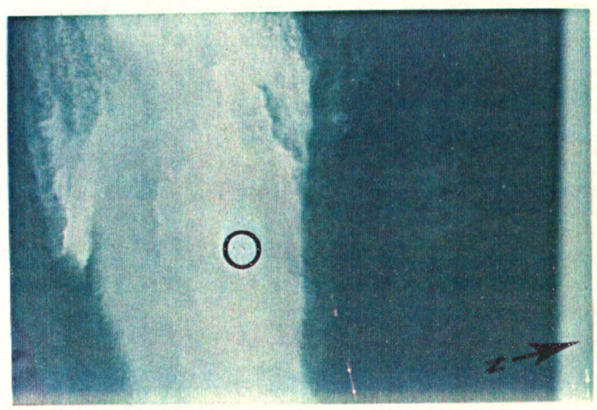
	Turbidity (NTU)	Suspended solids (mg/L)	Transparency (cm)
Top	65	113	30
Middle	120	220	--
Bottom	100	182	--



Site 21. Vertical view of sample site about 350 m from source. Erosion of previously deposited spoil 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	--



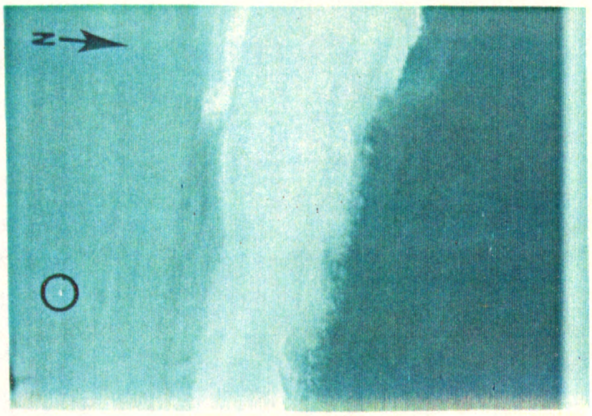
Site 22. Vertical view of sample site about 200 m from source. Plume convergence noticeable.

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	--

Note: Circle indicates location of sampling boat.

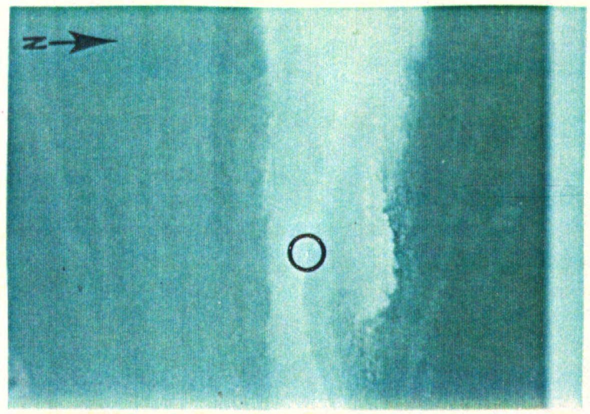
Figure 24.--Pipeline dredge with oscillating discharge and secondary erosional plume, flood tide: photographs and water-clarity data for sites 18 through 22.



Site 23. Vertical view of sample site outside of main plume about 1,200 m from source. 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	--

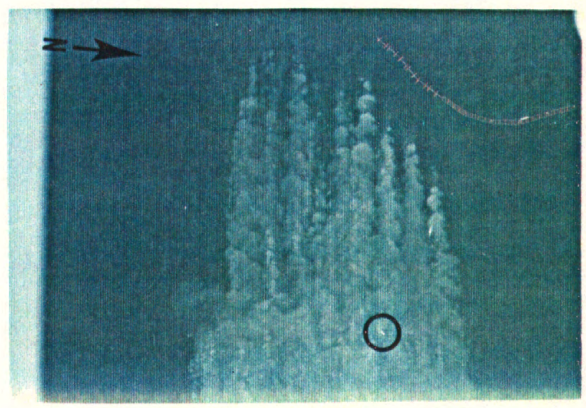


Site 24. Vertical view of sample site about 1,400 m from source. Convergence nearly complete.

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	--

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



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	--

Note: Circle indicates location of sampling boat.

Figure 25.--Pipeline dredge with oscillating discharge and secondary erosional plume, flood tide: photographs and water-clarity data for sites 23 through 26.

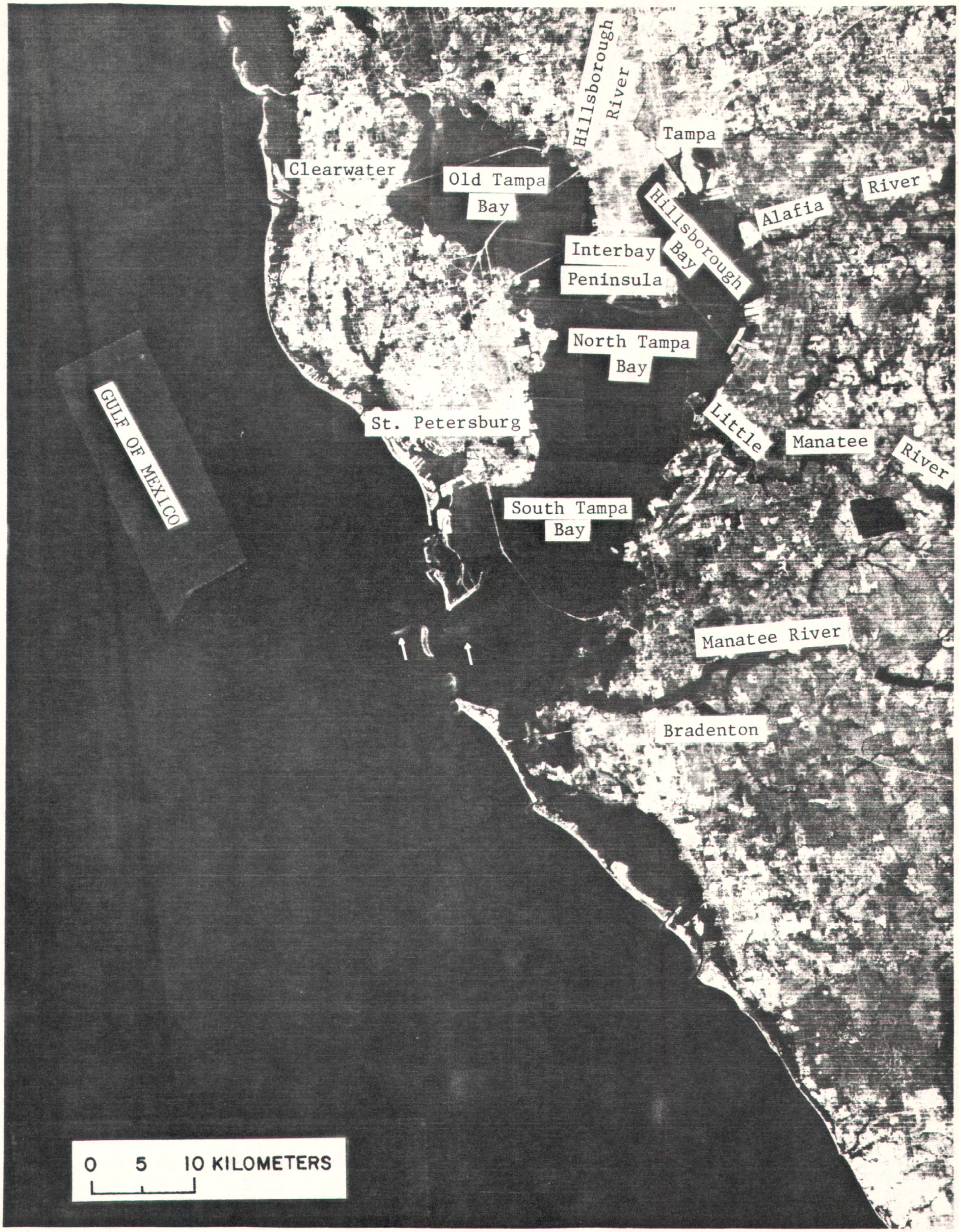


Figure 26.--Satellite image of west-central Florida showing both parts of a separated turbidity plume (arrows) at entrance to Tampa Bay.

Table 8.--Sampling conditions for pipeline dredge with oscillating discharge and secondary erosional plumes, flood tide

Flight

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

Meteorologic

Visibility: 14 km, haze
Solar altitude: 62° above horizon

Wind speed: 8 km/h
Wind direction: from west

Photographic

Film: Kodacolor II, ASA 80
Kodachrome, ASA 64

Filter: ultraviolet, haze

Sediment

Approximate size gradation and percentage of cohesive material

Percent greater than sand	Percent sand	Percent silt	Percent clay	Percent cohesive material
Egmont				
70	15	15	0	0
Mullet				
30	35	30	5	0

Construction

Dredge(s): Western Condor and Dave Blackburn

Disposal: oscillating discharge

Containment: none

Secondary turbidity caused by erosion of previously deposited dredged material is visible in photographs 19, 20, and 21, particularly along the edges and openings in the primary S-shaped plume. Turbidity from eroding material is visually characterized by a linear series of dispersing puffs emanating from numerous points on the bottom. At a distance of about 500 meters from the discharge pipe, the primary and secondary plumes lose their identity and merge.

Turbidity levels within the plume varied from 30 to 350 NTU as indicated by measurements at sites shown in photographs 20, 21, 22, and 24. Higher levels generally occurred near the discharge pipe at the head of the plume and 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 turbidity source 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 meters from the discharge point, whereas a level of 65 NTU was measured only 50 meters from the source. The nonhomogeneous nature of plumes such as this make it difficult to completely characterize plume turbidity levels with a few point samples. A similar conclusion was reached by Simon and others (1976).

Background water-clarity data for site 18 (no photograph) are given in figure 24. Unfortunately, the existence of a separated plume at Egmont Key was not recognized at the time of data collection, and background data at sample site 18 may have been influenced by the separated part of the discharge plume.

Large, highly visible plumes can be expected from dredges using an oscillating surface discharge disposal method 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 meters south of the channel (fig. 22) using a series of stationary pipeline positions. The dredge was not operating during the data-collection period so a primary turbidity plume was not created. A large secondary erosional plume extending about 1,000 meters from the end of the discharge pipe and having an average width of about 500 meters was visible in photographs 25 and 26 (fig. 25). 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 were probably less than 35 percent (table 8). Data from site 26 indicate significant levels of turbidity (15 to 140 NTU) and suspended solids (66 to 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, probably high spots protruding above the bottom into higher flow velocities.

Pipeline Dredge with Intermittent Discharge and Secondary Erosional Plume, Flood Tide

On October 27, 1977, the cutterhead dredge Dave Blackburn was operating in South Tampa Bay. It had been operating in the Mullet Key Channel at least 24 of the previous 48 hours and was discharging to an open-water site about 1,800 meters south of the channel (fig. 27). Materials being dredged were silt, sand, and larger material (table 9). Sampling was done during flood tide with channel velocities of about 0.5 m/s (fig. 28). Site 27 (fig. 29, no photograph) defines background water-clarity conditions. Photograph 28 (fig. 29) shows an overall view of dredge and disposal sites with Mullet Key in the background. Turbidity from the disposal site included a secondary erosional plume created by the strong flood-tide conditions and an intermittently active primary plume. The secondary plume forms a straight swath of turbidity at an angle from left to right, and the intermittent primary plume is shown by two larger turbid patches in the lower right corner of photograph 28. Turbidity from the disposal area was visible for about 800 meters from the discharge point.

Sampling locations successively closer to the pipeline discharge outlet, each having higher levels of turbidity and suspended solids, are shown in photographs 29, 30, and 31 (figs. 29 and 30). The intermittent nature of the primary plume is due to noncontinuous dredge operation or presence of hard limestone and difficult dredging conditions. Photograph 32 (fig. 30) shows a sample site in a small turbid patch apparently created by the dredge.

All bottom samples show consistently higher turbidity levels, reflecting rapid settling and creation of plumes at depth by the cutterhead or by secondary erosional processes.

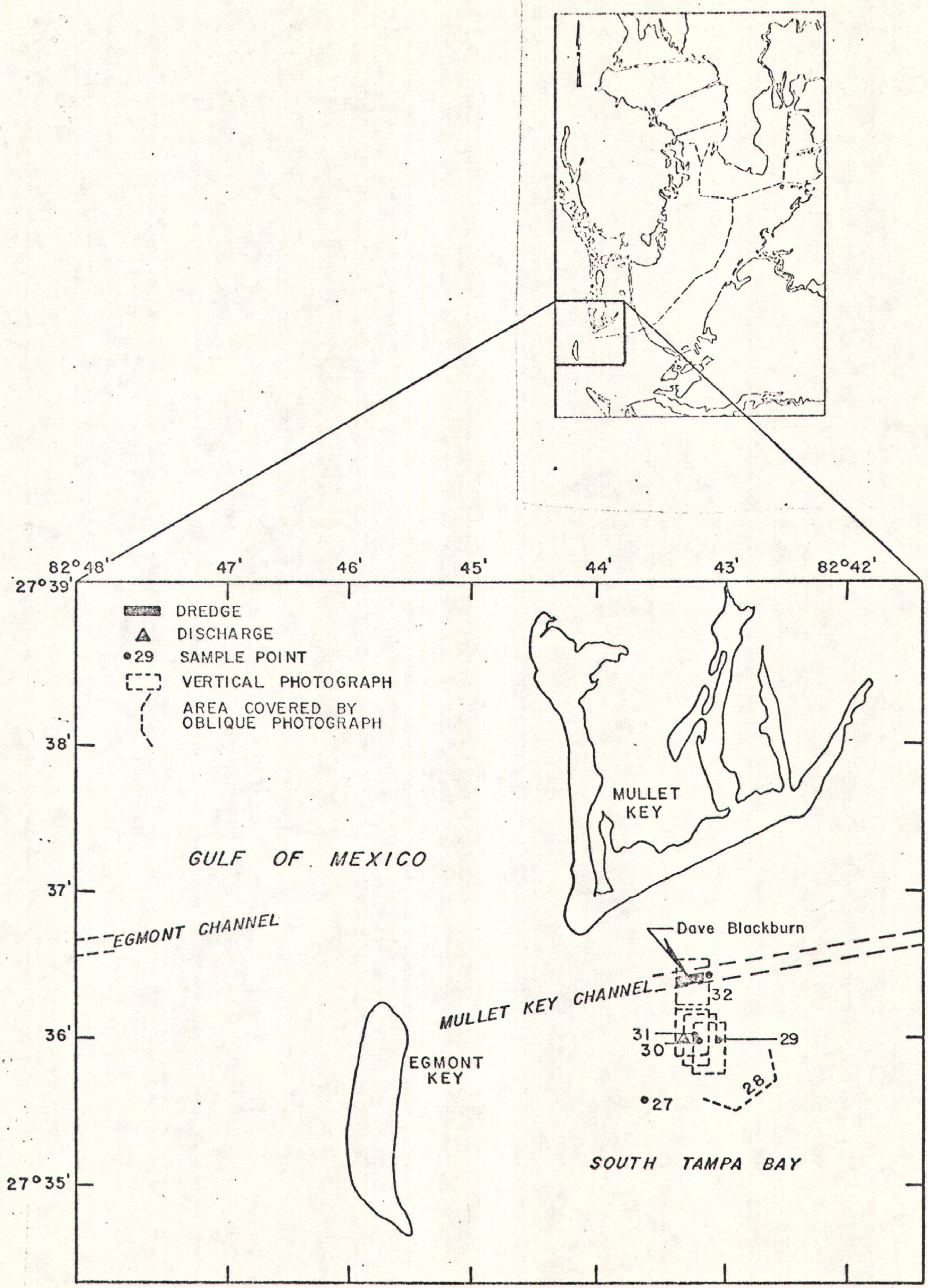


Figure 27.--Pipeline dredge with intermittent discharge and secondary erosional plume, flood tide: data-collection sites.

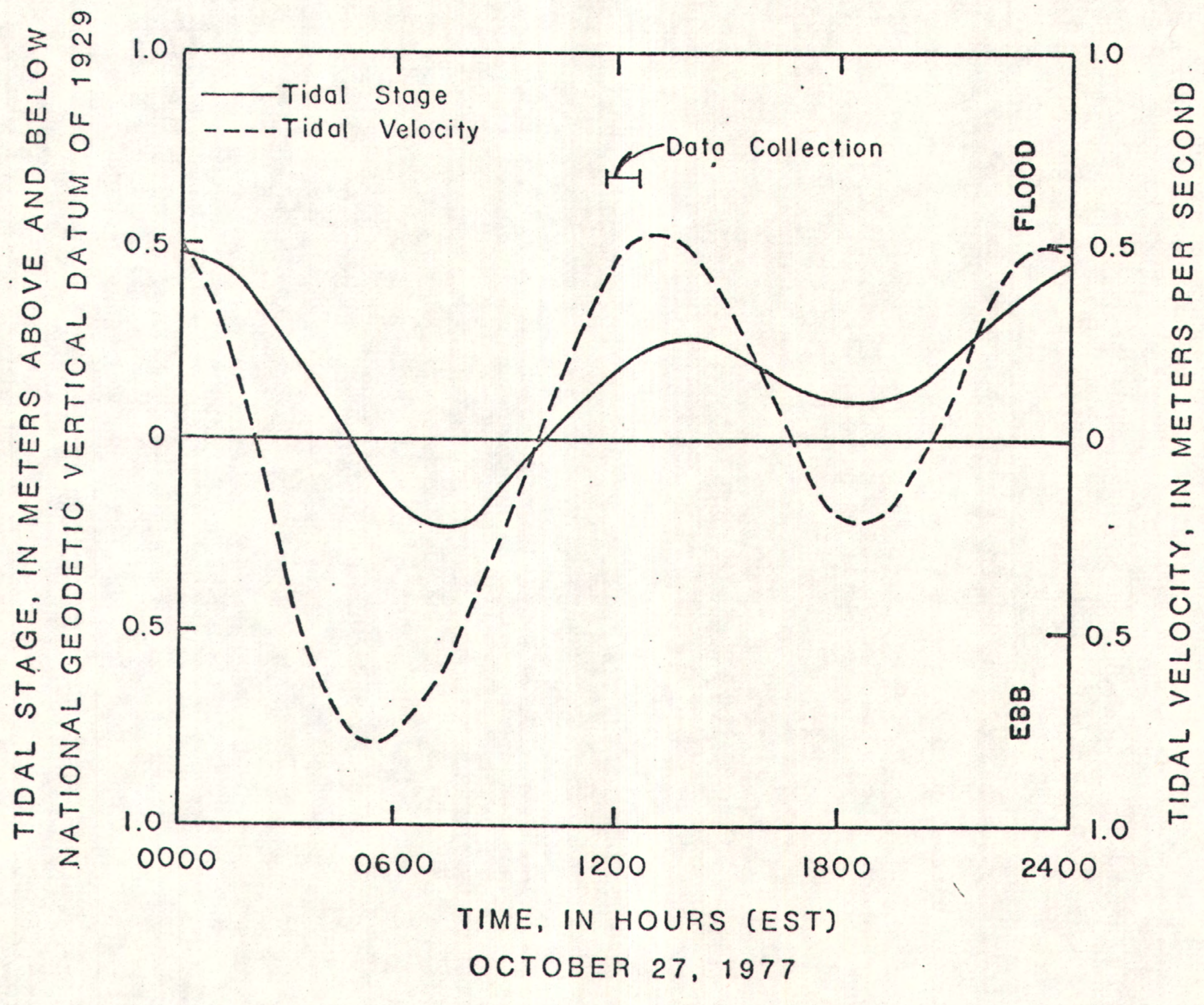
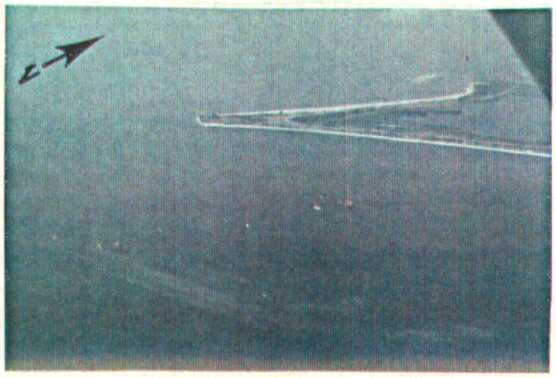


Figure 28.--Pipeline dredge with intermittent discharge and secondary erosional plume, flood tide: tidal stage and tidal velocity at South Tampa Bay monitoring sites.

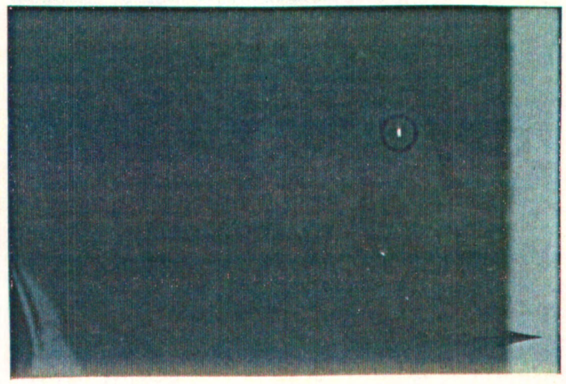
Site 27. Background site about 750 m from discharge, not shown.

Time: 1150 Depth: 7.6 m

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



Site 28. Oblique view of open water disposal area showing secondary erosional plume and intermittent primary plume with cutterhead dredge Blackburn in background.



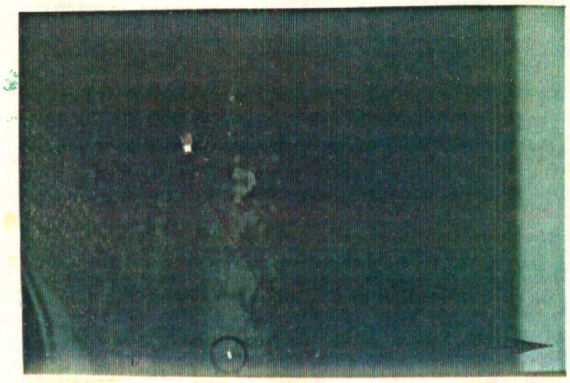
Site 29. Vertical view of sample site about 500 m from discharge in intermittent primary plume.

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	--

Note: Circle indicates location of sampling boat.

Figure 29.--Pipeline dredge with intermittent discharge and secondary erosional plume, flood tide: photographs and water-clarity data for sites 27 through 29.



Site 30. Vertical view of sample site about 210 m from discharge.

Time: 1215 Depth: 7.9 m
Scale (approx.): 1:6,100

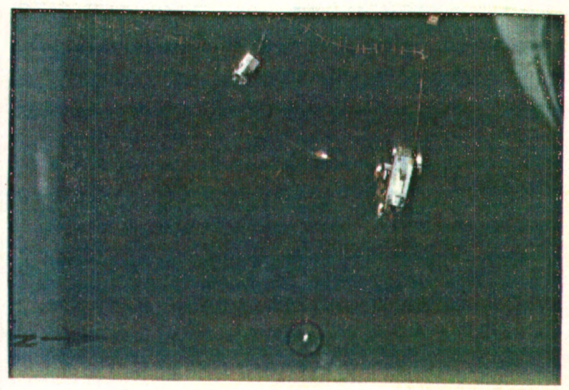
	Turbidity (NTU)	Suspended solids (mg/L)	Transparency (cm)
Top	15	61	61
Middle	18	42	--
Bottom	45	151	--

Site 31. Vertical view of sample site about 90 m from discharge.

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	--

Note: Circle indicates location of sampling boat.



Site 32. Vertical view of cutterhead dredge 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, flood tide: photographs and water-clarity data for sites 30 through 32.

Table 9.--Sampling conditions for pipeline dredge with intermittent discharge and secondary erosional plume, flood tide

Flight

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

Meteorologic

Visibility: 11 km
Solar altitude: 45°

Wind speed: light
Wind direction: variable

Photographic

Film: Kodachrome, ASA 64

Filter: ultraviolet, haze

Sediment

Approximate size gradation and percentage of cohesive material

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

Construction

Dredge(s): Dave Blackburn

Disposal: submerged discharge

Containment: none

Pipeline Dredge Discharging within Turbidity Barrier, Ebb Tide

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 meters east of the channel. A turbidity barrier was in place around the disposal site. Bottom materials near the dredge consisted of gray silt, green clay, and weathered limestone with about 60 percent fine material and 60 percent cohesive material content (table 10). Tidal velocity was weak and variable, approaching slack tide (fig. 32).

Fig. 31 near here

Table 10 near here

Fig. 32 near here

A background sample (site 33, no photograph, fig. 33) was collected about 750 meters west of the discharge site. The relatively high bottom turbidity at the background site suggests a more widespread plume near the bay bottom than indicated by the visible plume near the water surface. Oblique photographs 34, 35, and 36 (fig. 33) show overviews of the area from three different vantage points (fig. 31). The visible turbidity plume extends to the west-southwest from the discharge site for about 2 kilometers. Sample sites shown in oblique photographs 34, 35, and 36 are within the plumes and outside the turbidity barrier. Vertical photographs 37, 38, 39, and 40 (fig. 34) show sample sites within the turbidity barrier or at points of incomplete barrier closure.

Fig. 33 near here

Fig. 34 near here

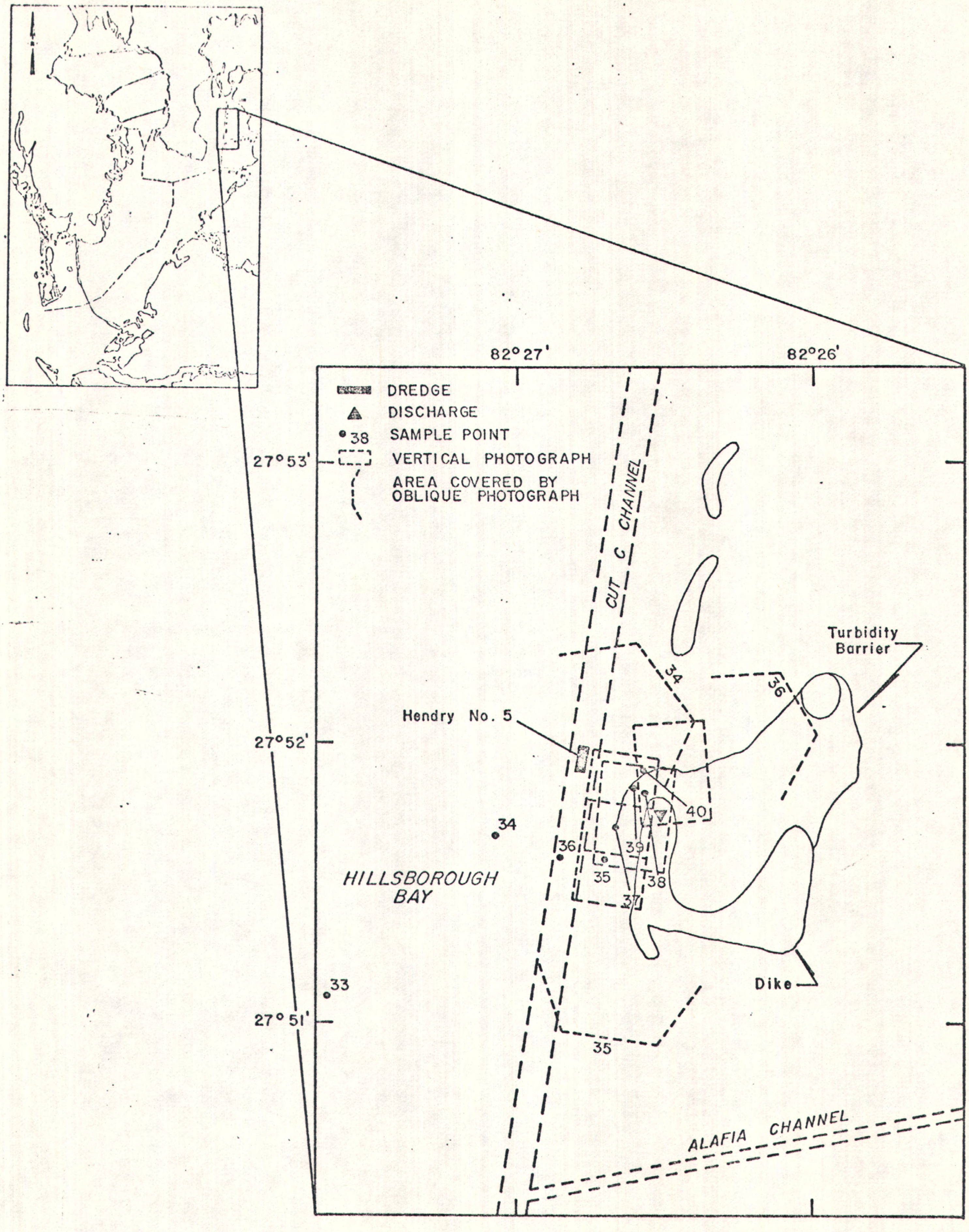


Figure 31.--Pipeline dredge discharging within turbidity barrier, ebb tide: data-collection sites.

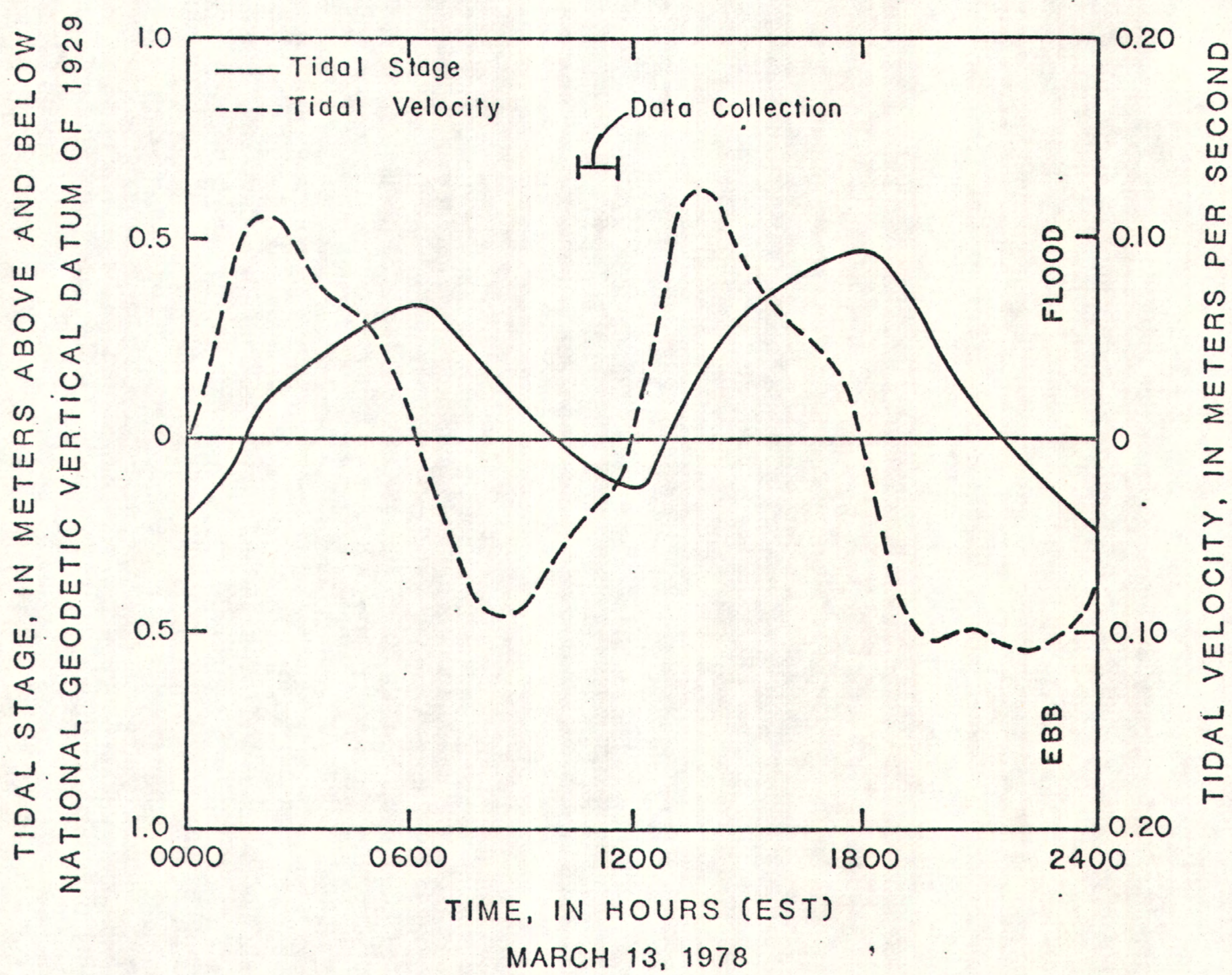
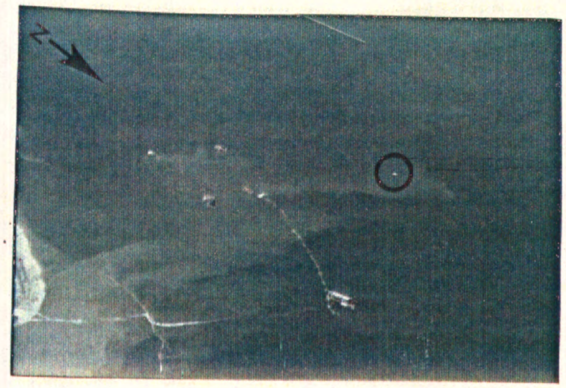


Figure 32.--Pipeline dredge discharging within turbidity barrier, ebb tide: tidal stage and tidal velocity at Hillsborough Bay monitoring sites.

Site 33. Background sample, not shown, 750 m west of source.

Time: 1035 Depth: 3.0 m

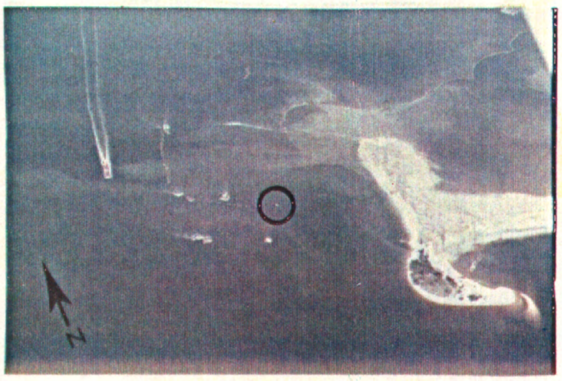
	Turbidity (NTU)	Suspended solids (mg/L)	Transparency (cm)
Top	2	30	61
Middle	4	32	--
Bottom	70	133	--



Site 34. Oblique view of sample site near edge of visible plume, 600 m from source.

Time: 1100 Depth: 4.9 m

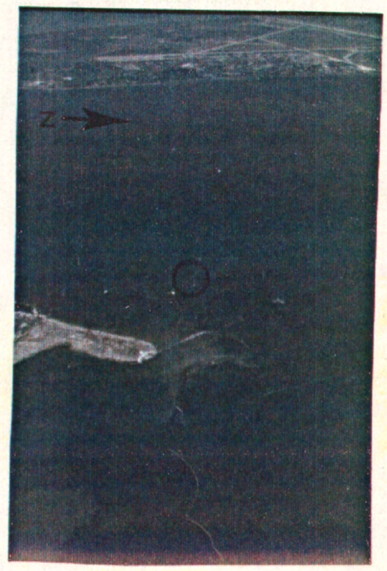
	Turbidity (NTU)	Suspended solids (mg/L)	Transparency (cm)
Top	8	31	76
Middle	12	39	--
Bottom	160	166	--



Site 35. Oblique view of sample site, 340 m from source.

Time: 1105 Depth: 3.4 m

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



Site 36. Oblique view showing construction scene. Sample boat is in channel, about 500 m from source.

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	--

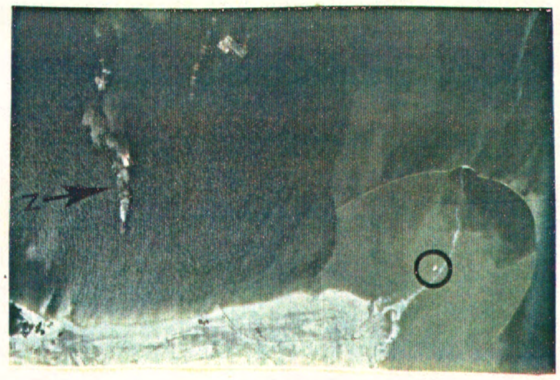
Note: Circle indicates location of sampling boat.

Figure 33.--Pipeline dredge discharging within turbidity barrier, ebb tide: photographs and water-clarity data for sites 33 through 36.

Site 37. Vertical view of sample site at opening between barrier and dike, 170 m from source.

Time: 1115 Depth: 2.1 m
Scale (approx.): 1:9,100

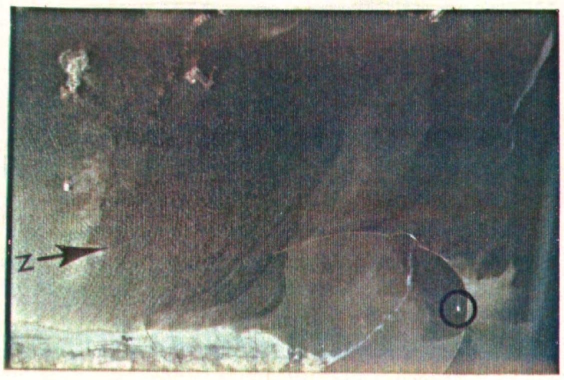
	Turbidity (NTU)	Suspended solids (mg/L)	Transparency (cm)
Top	25	52	30
Middle	18	60	--
Bottom	120	240	--



Site 38. Vertical view of sample site, 130 m from construction source, vessels creating 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	--



Site 39. Vertical view of sample site next to silt curtain, 270 m from source.

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	--

Site 40. Vertical view of sample site near gap, 320 m from source.

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	--

Note: Circle indicates location of sampling boat.

Figure 34.--Pipeline dredge discharging within turbidity barrier, ebb tide: photographs and water-clarity data for sites 37 through 40.

Table 10.--Sampling conditions for pipeline dredge discharging within turbidity barrier, ebb tide

Flight

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

Meteorologic

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

Photographic

Film: Kodachrome, ASA 64
Filter: ultraviolet, haze

Sediment

Approximate size gradation and percentage of cohesive material

Percent greater than sand	Percent sand	Percent silt	Percent clay	Percent cohesive material
15	25	35	25	60

Construction

Dredge(s): Hendry No. 5
Disposal: emergent

Containment: turbidity barrier

Samples collected outside the barrier showed moderate turbidity levels at top- and mid-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 was probably removed from the upper part of the water column because of: (1) the large percentage of cohesive material (table 11), (2) flocculation of silts and clays, and (3) relatively effective use of turbidity barriers. The visible surface plume was chiefly created by turbid water escaping around the southern end of the barrier (photograph 34) and through a 10-meter gap in the barrier (photograph 40). In spite of these two locations of incomplete barrier closure, the data indicate most of the suspended material to be at a depth greater than the water penetrating capability of the photography.

In chronological sequence, photographs 37, 38, 39, and 40 cover a period of 40 minutes. A substantial quantity of turbid water is shown flowing around the southern end of the turbidity barrier in photograph 37. Later photographs show this source of turbid water being 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.

Pipeline Dredge Discharging to Emergent Dike with Turbidity Barrier, Flood Tide

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 kilometer 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 flood tide and the flow was northward (fig. 36). Background water-clarity data were collected at site 41 (fig. 37, no photograph). An overall view of the construction site is shown in photograph 42 (fig. 37). A visible plume about 500 meters long was sampled at two sites outside the barrier (photographs 43 and 44, fig. 37). Turbidity data at site 43 indicate that the barrier was effective; high values of turbidity and solids were measured near the bottom where fluid mud (fig. 3) apparently was escaping. The mud flow had apparently not reached site 44 where moderate turbidity was measured at all depths.

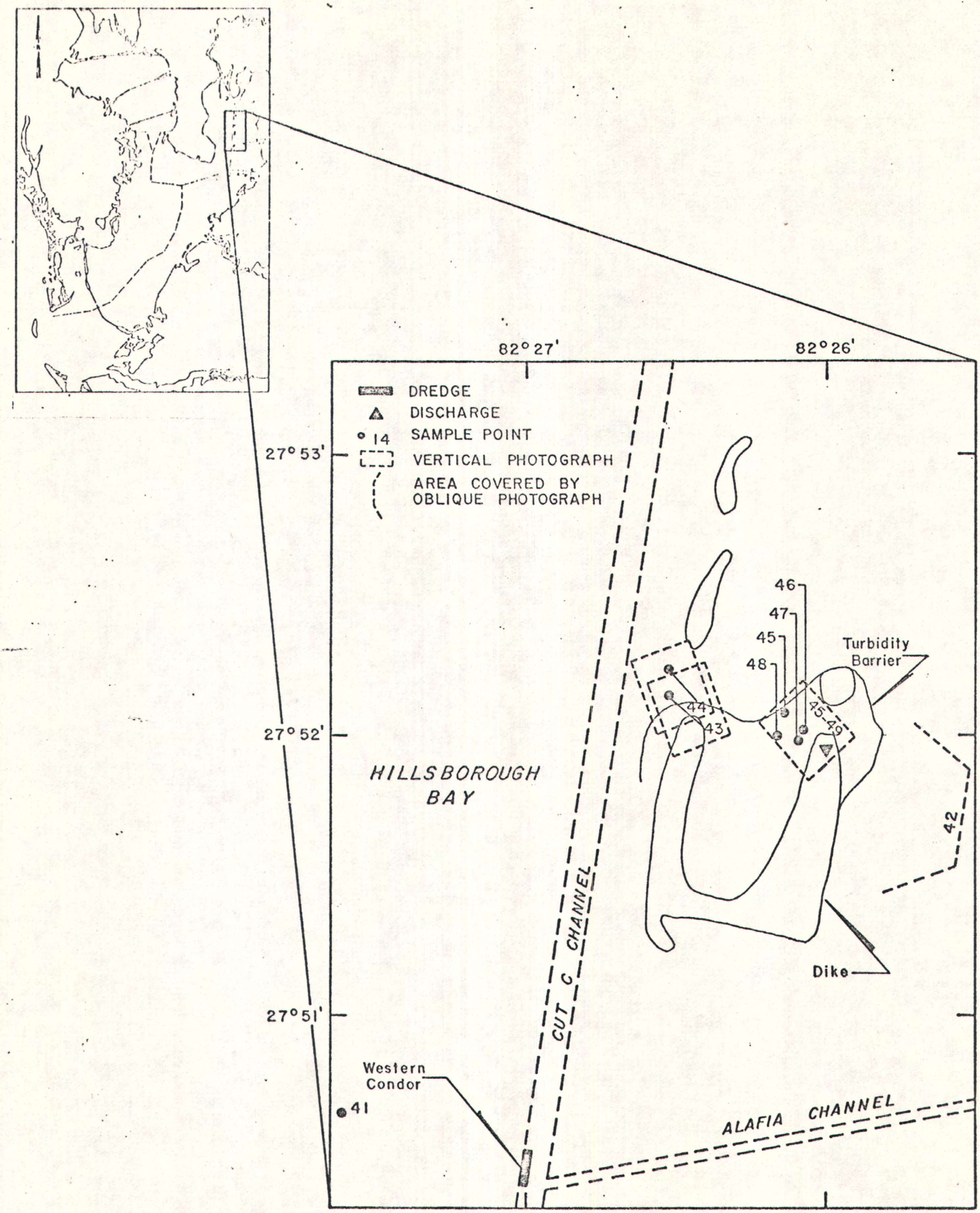


Figure 35.--Pipeline dredge discharging to emergent dike with turbidity barrier, flood tide: data-collection sites.

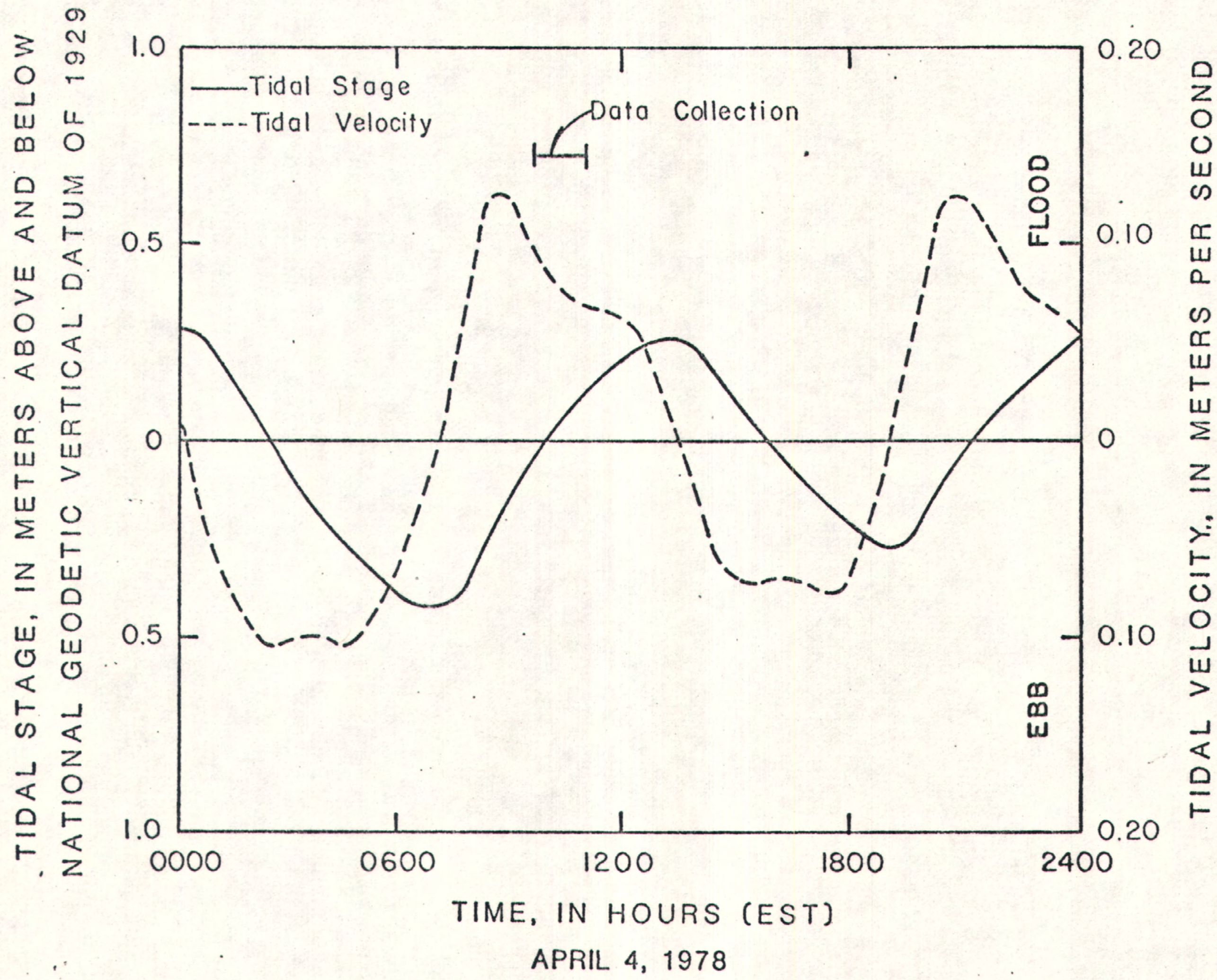
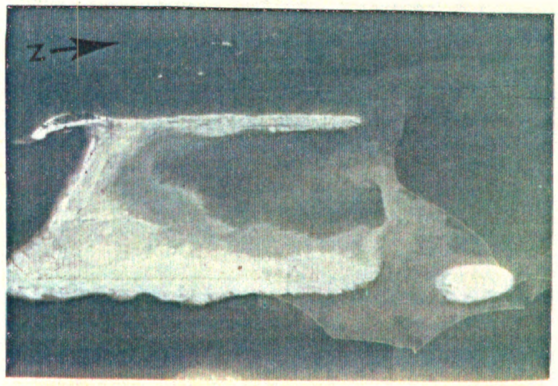


Figure 36.--Pipeline dredge discharging to emergent dike with turbidity barrier, flood tide: tidal stage and tidal velocity at Hillsborough Bay monitoring sites.

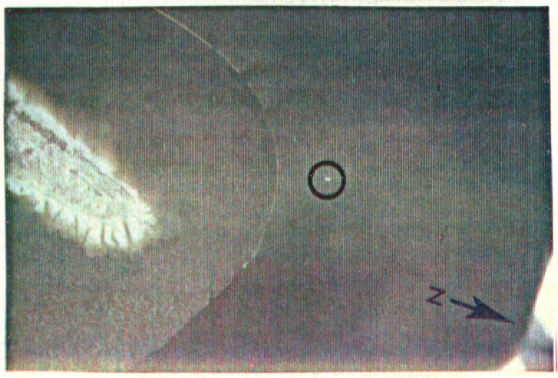
Site 41. Background sample, not shown, about 1,500 m southwest of discharge site.

Time: 0940 Depth: 4.0 m

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



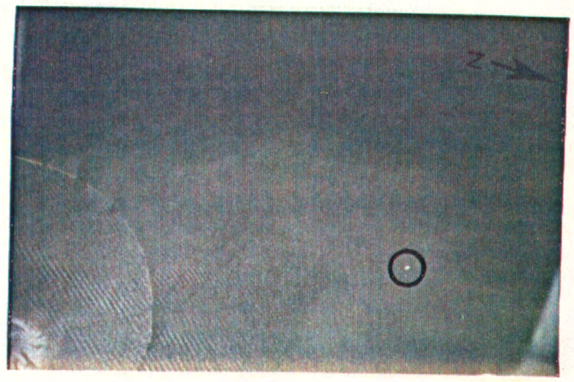
Site 42. Oblique view of partially completed diked impoundment with turbidity barrier in at dredge discharge on northern end of foreground dike.



Site 43. Vertical view of sample site outside turbidity barrier.

Time: 1000 Depth: 3.0 m
Scale (approx.): 1:9,100

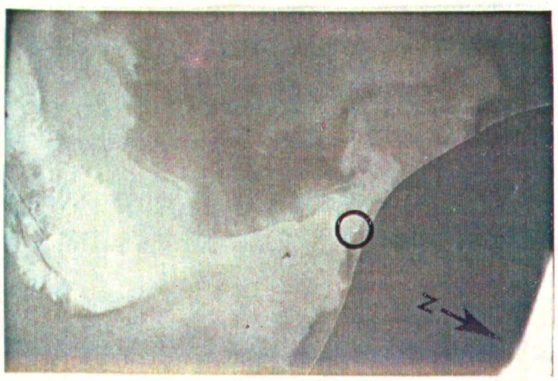
	Turbidity (NTU)	Suspended solids (mg/L)	Transparency (cm)
Top	7	45	30
Middle	7	54	--
Bottom	2,000	3,000	--



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	--



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	--

Note: Circle indicates location of sampling boat.

Figure 37.--Pipeline dredge discharging to emergent dike with turbidity barrier, flood tide: photographs and water-clarity data for sites 41 through 45.

Table 11.--Sampling conditions for pipeline dredge discharging to emergent dike with turbidity barrier, flood tide

Flight

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

Meteorologic

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

Photographic

Film: Kodachrome, ASA 64
Filter: ultraviolet, haze

Sediment

Approximate size gradation and percentage of cohesive material

Percent greater than sand	Percent sand	Percent silt	Percent clay	Percent cohesive material
5	35	35	25	35

Construction

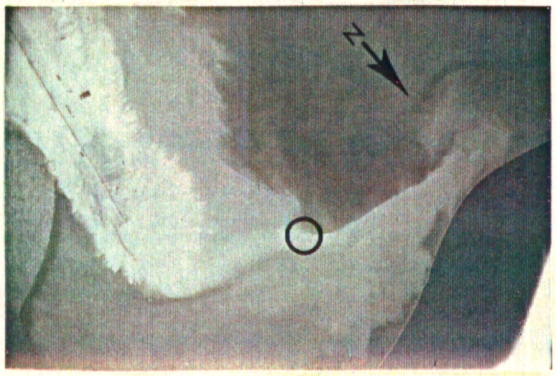
Dredge(s): Western Condor
Disposal: emergent

Containment: turbidity barrier

A plume near the discharge site and within the turbidity barrier is shown in photographs 45 to 48 (figs. 37 and 38). Turbidity inside the barrier was dramatically higher than outside. At sites 45, 47, and 48, relatively low turbidity levels and suspended solids concentrations at the surface indicated rapid settling of fine material before escaping confinement by the turbidity barrier. In freshwater or without presence of montmorillonite clay minerals, the fine material in the dredged sediment would not settle as rapidly as documented here. Rapid build-up of fines 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.

A computer-aided color enhancement of photograph 48 (fig. 38) served as a test for evaluating visible turbidity plumes based on overall plume characteristics rather than a few point measurements (photograph 49). Semiquantitative indicators of total suspended load and total plume area may be possible using this technique. Each color represents a narrow range of film density, thereby amplifying the ability to discern areas of equal light intensity on the original photograph. General correlation of colors to plume shape and visible plume patterns was achieved. Detailed correlation of colors with turbidity levels or suspended solids concentrations was not attempted because of unequal light exposure over the entire photograph and water-surface glare.

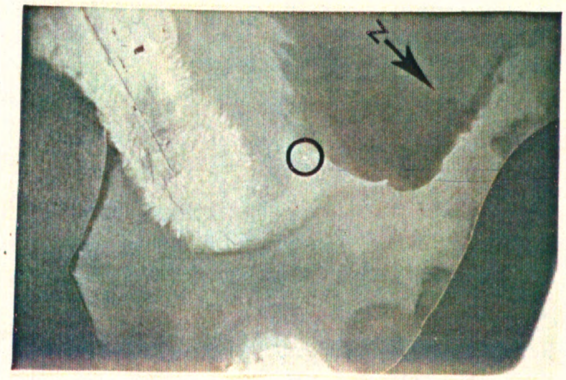
For conditions similar to those given here, fine dredged material can be expected to settle rapidly due to effective flocculation of sediment containing montmorillonite in seawater. Turbidity barriers are effective in limiting the extent, intensity, and visibility of surface plumes outside the barrier. Rapid settling appears to induce formation of mud flows on the bottom.



Site 46. Vertical view of sample site inside barrier near discharge outlet.

Time: 1033 Depth: 1.2 m
Scale (approx.): 1:9,100

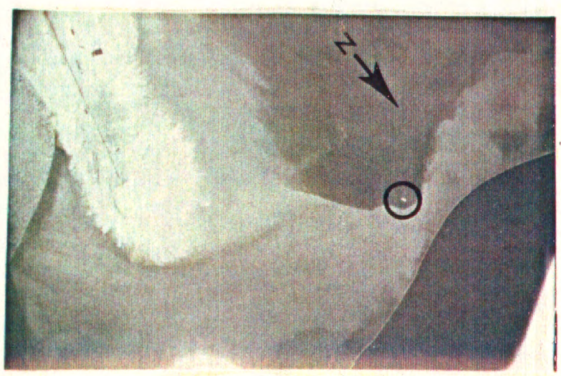
	Turbidity (NTU)	Suspended solids (mg/L)	Transparency (cm)
Top	12,000	6,260	15
Middle	3,700	7,200	--
Bottom	200,000	130,000	--



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	--



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	27,830	--
Bottom	120,000	116,000	--

Site 49. Computer generated color enhancement of photograph 48.

Creen = emergent dredged material
Gray = maximum surface turbidity
Orange =
Purple =
Pink = range of intermediate
Blue = turbidity levels
Yellow =
White = minimum surface turbidity

Note: Circle indicates location of sampling boat.

Figure 38.--Pipeline dredge discharging to emergent dike with turbidity barrier, flood tide: photographs and water-clarity data for sites 46 through 49.

Pipeline Dredge Discharging to Partly Enclosed Dike with Turbidity Barrier, Flood Tide

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 1,000 meters to the southeast (fig. 39). The dredge had been operating about 60 percent of the time during the previous 72 hours. Flood-tide conditions existed during data collection 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 size gradation and estimated percentage of cohesive material are given in table 12.

A background sample, site 50 (fig. 41, no photograph), was collected northwest of the dredging area (fig. 39). A well-defined plume or turbid area was not visible near the dredge or disposal site outside the turbidity barrier (photograph 51, fig. 41). Two samples were taken near the dredge (photographs 52 and 53), and one was taken outside the barrier nearest the pipeline discharge site (photograph 54). High bottom turbidity in the construction area (sites 52, 53, and 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. Photographs 55 and 56 (fig. 42) show an example of the generation of a secondary turbidity plume induced by turbulence from a pipe-towing vessel resuspending settled dredge material. Photograph 56 was taken 45 minutes after photograph 55 at the same shutter speed with a more open aperture. Some of the feathery texture visible in these two photographs may be bay-bottom features and edges of the secondary plume.

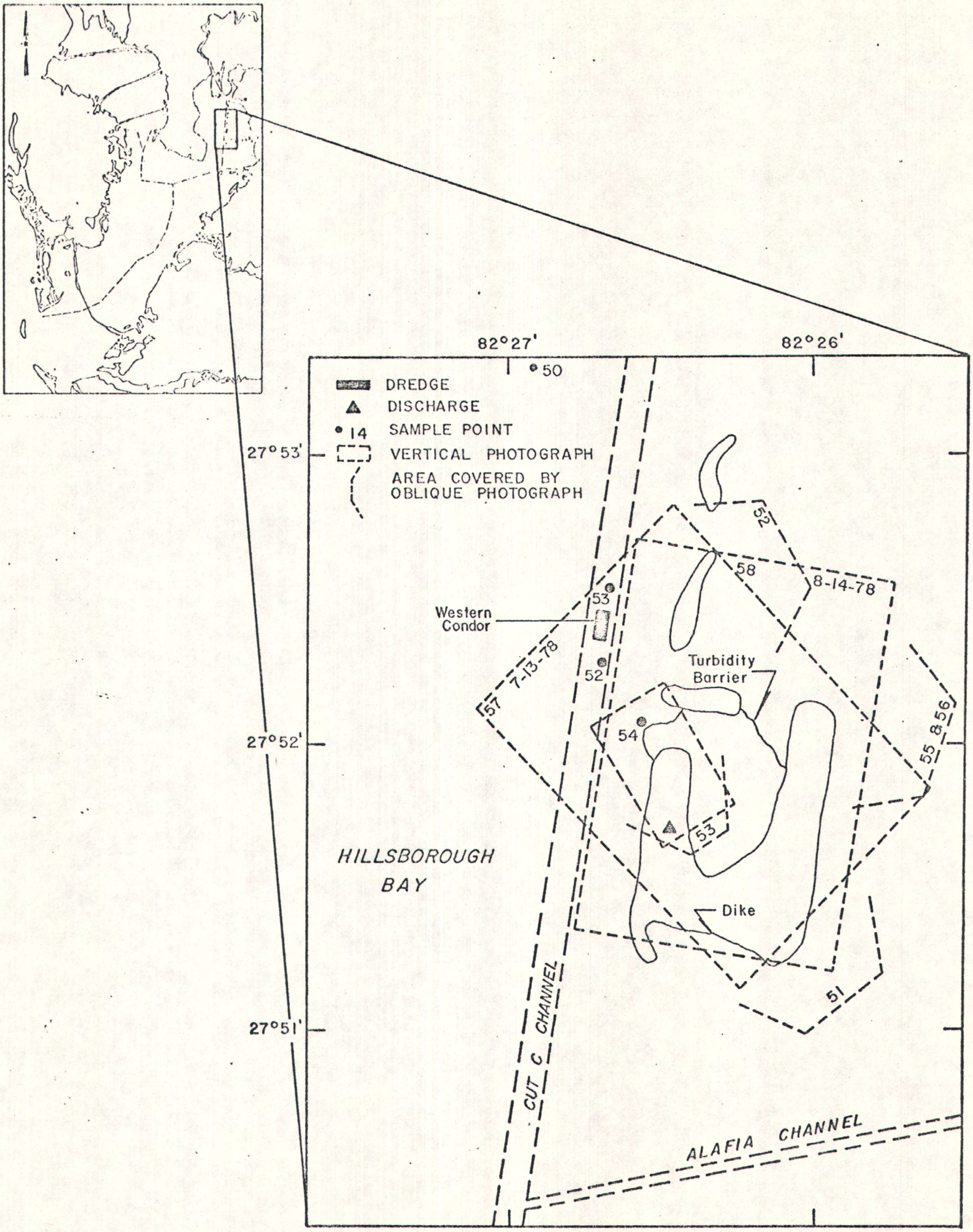


Figure 39--Pipeline dredge discharging to partly enclosed dike with turbidity barrier, flood tide: data-collection sites.

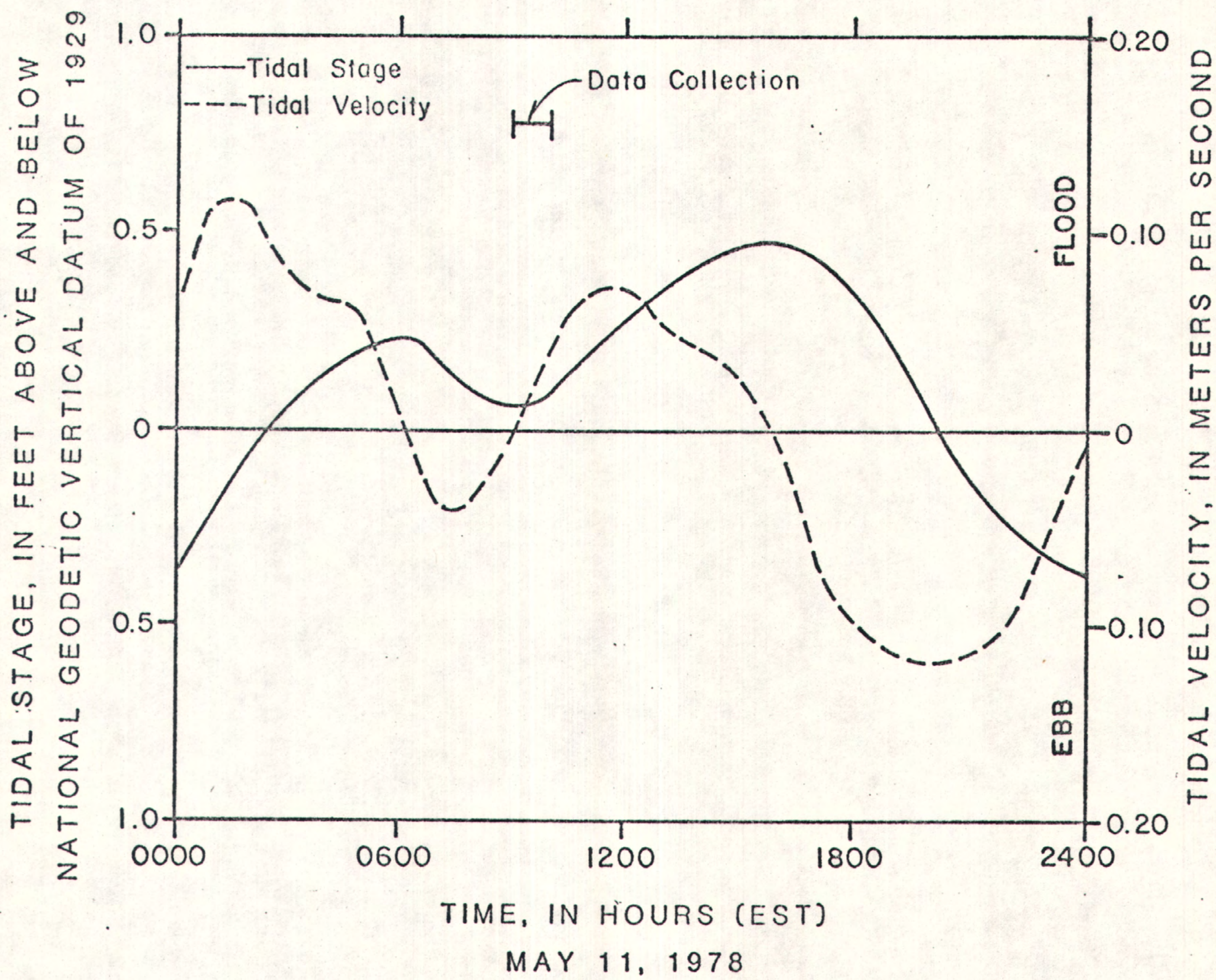
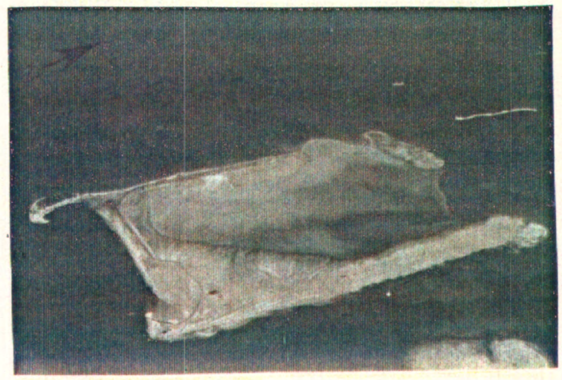


Figure 40.--Pipeline dredge discharging to partly enclosed dike with turbidity barrier, flood tide: tidal stage and tidal velocity at Hillsborough Bay monitoring sites.

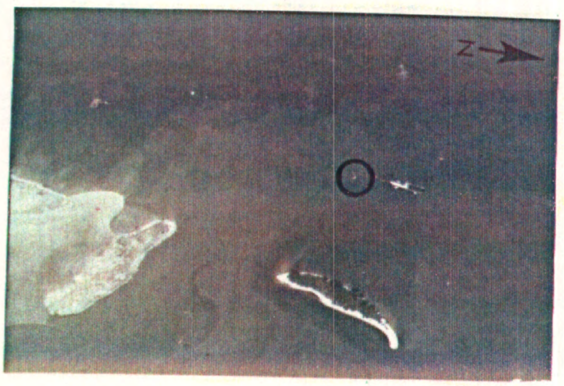
Site 50. Background sample about 300 m northwest of source, not shown.

Time: 0900 Depth: 2.7 m

	Turbidity (NTU)	Suspended solids (mg/L)	Trans- parency (cm)
Top	11	2	61
Middle	12	41	--
Bottom	40	130	--



Site 51. Oblique view of study area. Western Condor dredge is in upper right with partially complete diked spoil impoundment in center.

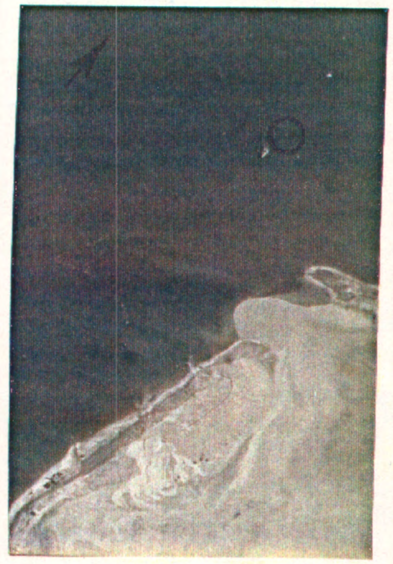


Site 52. Oblique view of sample site near Condor dredge.

Time: 0915 Depth: 13.7 m

	Turbidity (NTU)	Suspended solids (mg/L)	Trans- parency (cm)
Top	25	63	30
Middle	9	24	--
Bottom	3,200	3,080	--

Note: Circle indicates location of sampling boat.

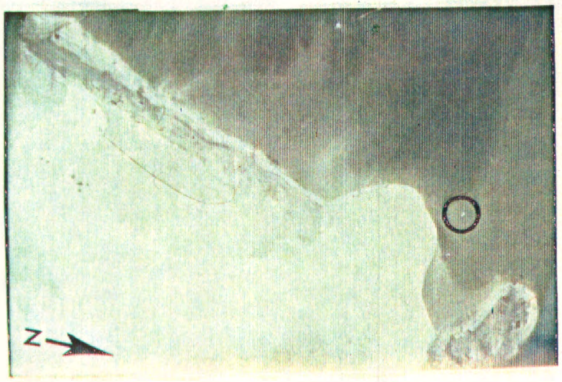


Site 53. Oblique view showing dredge discharge in foreground, sample boat in background near dredge.

Time: 0945 Depth: 11.6 m

	Turbidity (NTU)	Suspended solids (mg/L)	Trans- parency (cm)
Top	19	45	46
Middle	17	43	--
Bottom	3,200	8,750	--

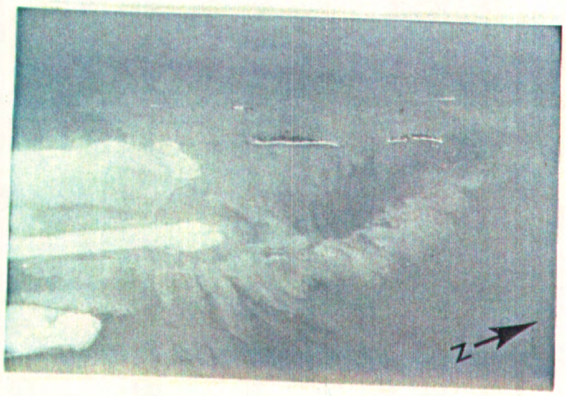
Figure 41.--Pipeline dredge discharging to partly enclosed dike with turbidity barrier, flood tide: photographs and water-clarity data for sites 50 through 53.



Site 54. Vertical view of sample site near turbidity barrier.

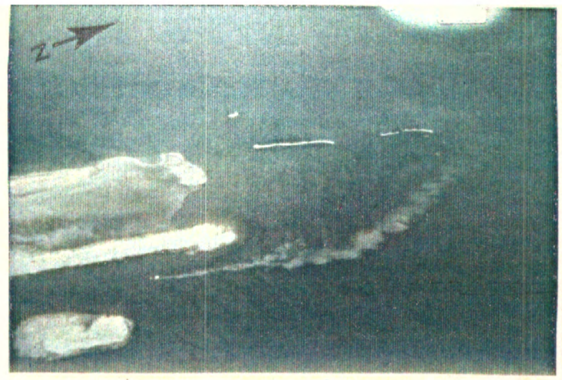
Time: 1000 Depth: 1.5 m
Scale (approx.): 1:9,100

	Turbidity (NTU)	Suspended solids (mg/L)	Trans-parency (cm)
Top	50	66	15
Middle	45	77	--
Bottom	2,000	5,430	--



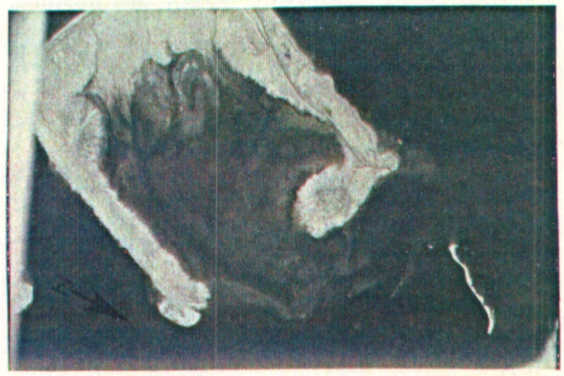
Site 56. Oblique view taken 45 minutes after photograph 55 showing dispersion of secondary plume. One stop greater exposure than photograph 55.

Note: Circle indicates location of sampling boat.



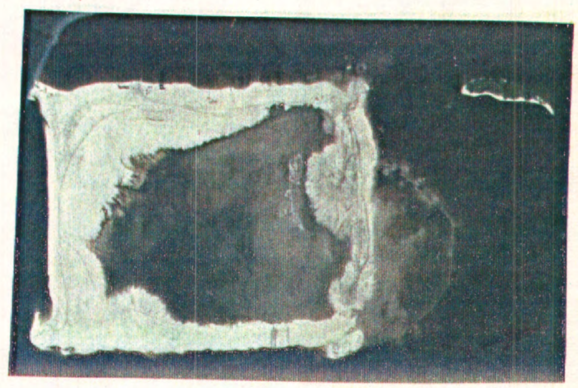
Site 55. Oblique view showing secondary turbidity plume in wake of vessel towing pipeline.

Time: 0920



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



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

Figure 42.--Pipeline dredge discharging to partly enclosed dike with turbidity barrier, flood tide: photographs and water-clarity data for sites 54 through 58.

Table 12.--Sampling conditions for pipeline dredge discharging to partly enclosed dike with turbidity barrier, flood tide

Flight

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

Meteorologic

Visibility: 16 km
Solar altitude: 65° above horizon

Wind speed: 16 km/h
Wind direction: from east

Photographic

Film: Kodachrome, ASA 64

Filter: ultraviolet, haze

Sediment

Approximate size gradation and percentage of cohesive material

Percent greater than sand	Percent sand	Percent silt	Percent clay	Percent cohesive material
35	35	15	15	55

Construction

Dredge(s): Western Condor

Disposal: emergent

Containment: turbidity barrier

Complete turbidity barrier enclosure of a source of dredged material discharge under conditions similar to those defined here can be expected to produce turbidity plumes of limited visibility and surface extent. Distribution of fine material away from the discharge site is by creation of mud flows along the bottom and turbidity plumes near the bottom. Normal operation of construction vessels over recently deposited fine material can generate highly visible plumes by turbulent resuspension.

About half of the north dike remained to be closed on July 13, 1978 (photograph 57). Photograph 58, 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 Turbidity Plume Appearance and Water-Clarity Results

The visibility and water-clarity characteristics of turbidity plumes measured in South Tampa Bay and Hillsborough Bay (fig. 1) from February 1977 to August 1978 varied widely due to a wide range of sediment, dredge, disposal, containment, and tide conditions. Visible plumes in both South Tampa Bay and Hillsborough Bay varied in extent from a few tens of meters to several kilometers. Plume intensity ranged from less than ten to several hundred NTU in South Tampa Bay and from less than ten to several thousand NTU outside turbidity barriers in Hillsborough Bay. Levels as high as 200,000 NTU were measured inside turbidity barriers in Hillsborough Bay.

Less 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 use of surface discharge methods distributed the fine material over a large area. Conversely, weak tidal currents and use of turbidity barriers often resulted in small visible plumes in Hillsborough Bay in spite of the large amount of fine sediment in the dredged material. Hopper-dredge unloading for beach nourishment in South Tampa Bay produced plumes of limited extent.

Not all turbidity plumes observed during the study were directly caused by dredging. As an indirect consequence of 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 and flowed outward from the disposal site. Secondary turbidity plumes were created by turbulence from construction vessels passing over and resuspending fine material deposited near the disposal sites. Turbidity measurements in secondary erosional plumes in South Tampa Bay ranged from 15 to 140 NTU. Turbidity samples were not collected in turbulence-induced plumes created by construction vessels.

Water-clarity data indicated that visible plumes in South Tampa Bay were a good indicator of plume extent deeper in the water column. Visible plumes in Hillsborough Bay, however, were not good indicators of plume extent at depth. Turbidity barriers used in Hillsborough Bay either wholly or partly eliminated surface discharge of turbid water. Turbid water was primarily introduced into Hillsborough Bay at depths often greater than effective photographic penetration.

Flocculation of fine sediment was found to be rapid. Seawater and the presence of montmorillonite aided the flocculation process. Without these two substances, turbidity values may have averaged many times higher than those measured.

WATER QUALITY OF TURBIDITY PLUMES

Water-quality data for turbidity plumes in South Tampa Bay and Hillsborough Bay were compared with background data to determine if turbidity plumes tended to degrade water quality and to test whether different sediment, tide, disposal, and containment conditions would produce plumes having significantly different water quality. Background data from each bay were also compared to detect differences that might influence comparisons.

Results of the comparisons are presented in tables showing (1) the number of samples and arithmetic means, (2) whether the means are significantly different, and (3) the $\underline{P}$ value, or level of confidence at the borderline between significance and insignificance (Brownlee, 1967). The lower the value of $\underline{P}$ is below the chosen level of significance, 0.02, the greater the confidence that the means are significantly different. The higher the $\underline{P}$ value above 0.02, the greater the confidence that the means are not significantly different.

Any data associated with samples having suspended solids concentrations greater than 10,000 mg/L were excluded from statistical computations because the purpose of the analysis was to determine water quality and not sediment quality. For concentrations above about 10,000 mg/L, particles in suspension do not settle independently and exhibit characteristics of low density fluid mud (Barnard, 1978).

Turbidity, Total Suspended Solids, Volatile Suspended Solids, and Transparency

Results of tests to determine whether mean values of turbidity, suspended solids, volatile solids, and transparency in plume samples are significantly different than the mean values measured in background samples for South Tampa Bay and Hillsborough Bay are summarized in table 13. The means shown are significantly different for each parameter except transparency in Hillsborough Bay and volatile solids in South Tampa Bay.

The reason average background and plume transparency in Hillsborough Bay are not significantly different is because of (1) increased plume surface-water clarity due to turbidity barriers, and (2) the limited number of observations at background sites. The *P* level of 0.0219 (only slightly higher than the chosen significance level of 0.02) indicates that background and plume transparency may, with additional data, have shown a significant difference. Average background and plume concentrations of volatile solids in South Tampa Bay are the same, indicating that there is less organic material in the sediments of South Tampa Bay than in Hillsborough Bay.

Results comparing clarity constituents within turbidity plumes in South Tampa Bay and Hillsborough Bay are summarized in table 14. In general, background water in Hillsborough and South Tampa Bays are similar for all parameters except transparency. Transparency is about three times greater in South Tampa Bay indicating that transparency is highly sensitive to small changes in turbidity at low turbidity levels. Plumes generated in each of the bays, however, are dissimilar. High turbidity, high suspended solids, and low transparency in Hillsborough Bay plumes are attributed to the high percentage of fines within the dredge material and to weak tidal velocities with less capability for dilution. High volatile solids concentrations in Hillsborough Bay plumes are attributed to the presence of organic matter in the dredged sediment. The inferred high organic levels in the plumes are not reflected in ambient, background water.

Table 14 near here

Table 13.--Summary of statistical comparison of turbidity, suspended solids, volatile solids, and transparency between plume and background samples

Property	Background		Plume		Means significantly different?	*P* level
	N[1]	Mean	N[1]	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

[1] N - number of samples analyzed.

Table 14.--Summary of statistical comparisn of turbidity, suspended solids, volatile solids, and transparency between Hillsborough and South Tampa Bays

Property	South Tampa Bay		Hillsborough Bay		Means significantly different?	P level
	N[1]	Mean	N[1]	Mean		
Background						
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						
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

[1]N - number of samples analyzed.

Water-clarity data may indicate why photographs taken of plumes in Hillsborough Bay do not, in general, provide as great a contrast with adjacent background waters as do plumes in South Tampa Bay. The greater average background transparency in South Tampa Bay means that significantly more light can penetrate and be absorbed by the water than in Hillsborough Bay. The greater light absorption produces a darker appearing background against which even a relatively low concentration of fine, white, shell fragments create a striking contrast. Conversely, a larger concentration of darker, silty, bottom material in Hillsborough Bay must be discharged into less absorbtive, more reflective background waters to produce the same degree of contrast as in South Tampa Bay.

In spite of the significant differences between plume water-clarity levels in Hillsborough and South Tampa Bays (table 14), parameter relations in both subareas are very similar. Interrelations among turbidity, suspended solids, volatile solids, and transparency are given in figures 43, 44, and 45 for plume and background sites in South Tampa and Hillsborough Bays. Despite wide variability in types of dredged material, linear regression indicated a strong correlation (r=0.93) between turbidity and suspended solids. The reason for increased scatter below 10 NTU is probably related to the difficulty in measuring small differences in turbidity below 10 NTU and the sensitivity of low turbidity measurements to small changes in clay content (see Ritter and Brown, 1971). Volatile solids, a measure of suspended organic material, is also shown in figure 44 to be strongly correlated, by linear regression, with suspended solids (r=0.95).

Figs. 43-45 near here

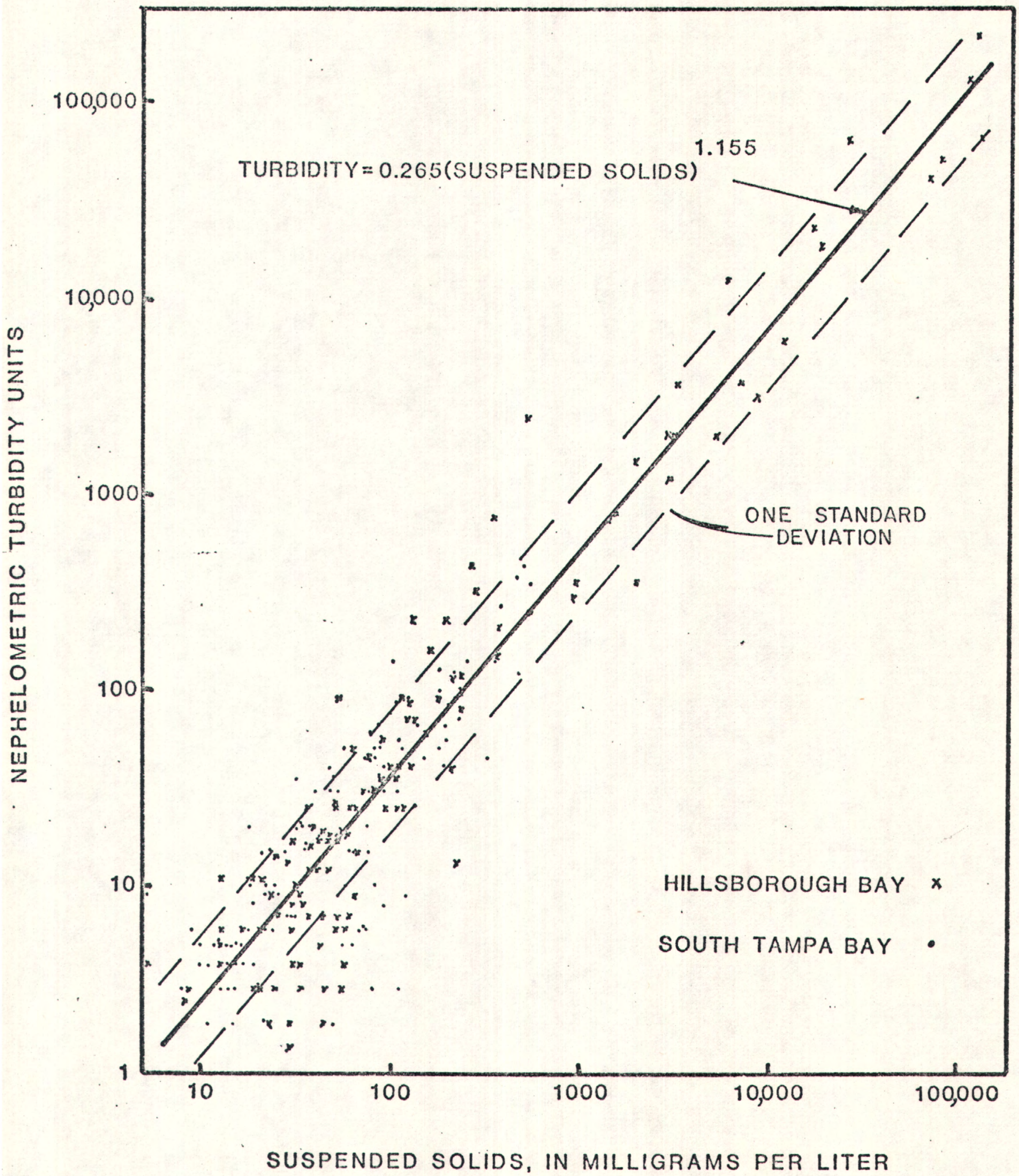


Figure 43.--Relation between suspended solids and turbidity.

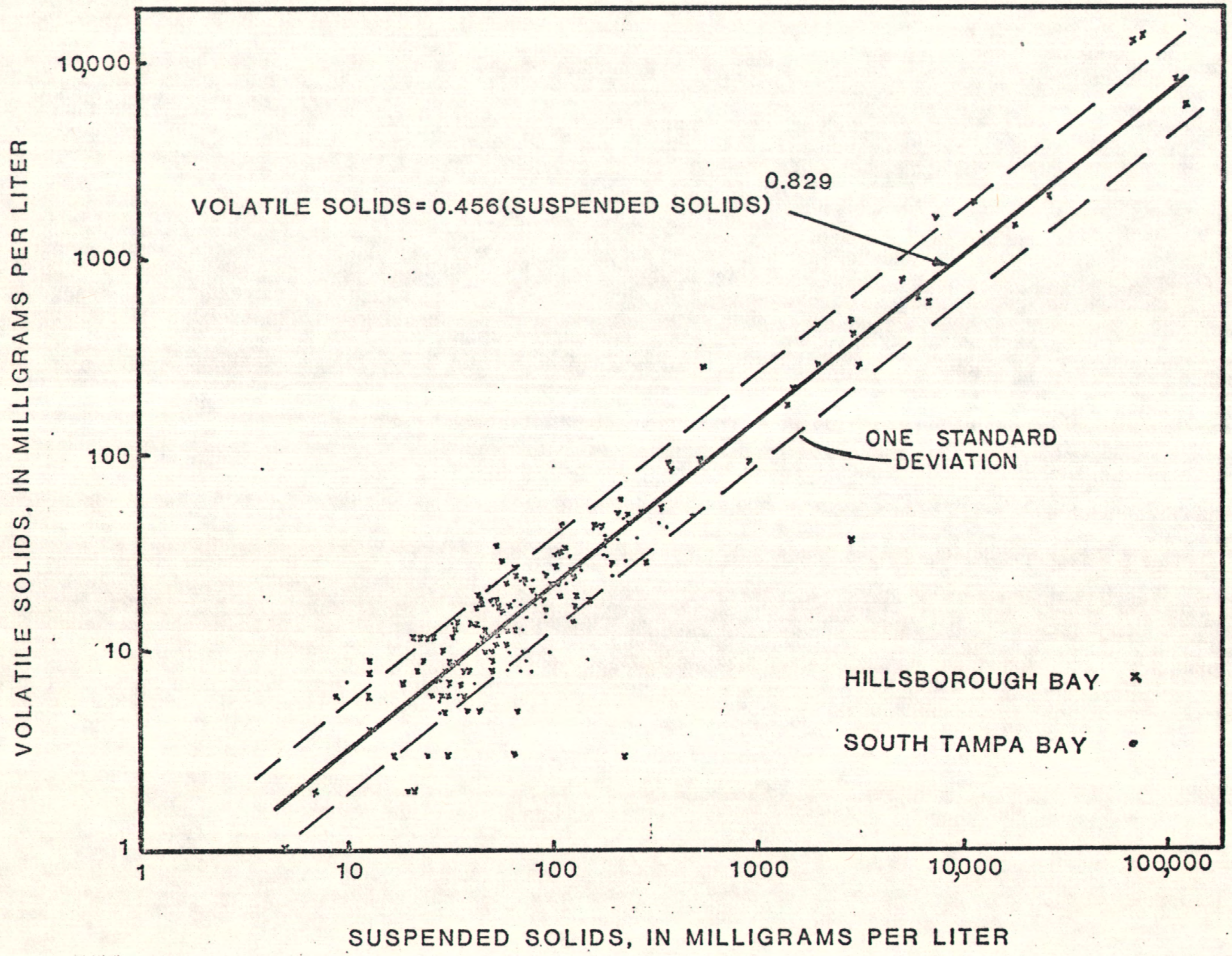


Figure 44.--Relation between suspended solids and volatile solids.

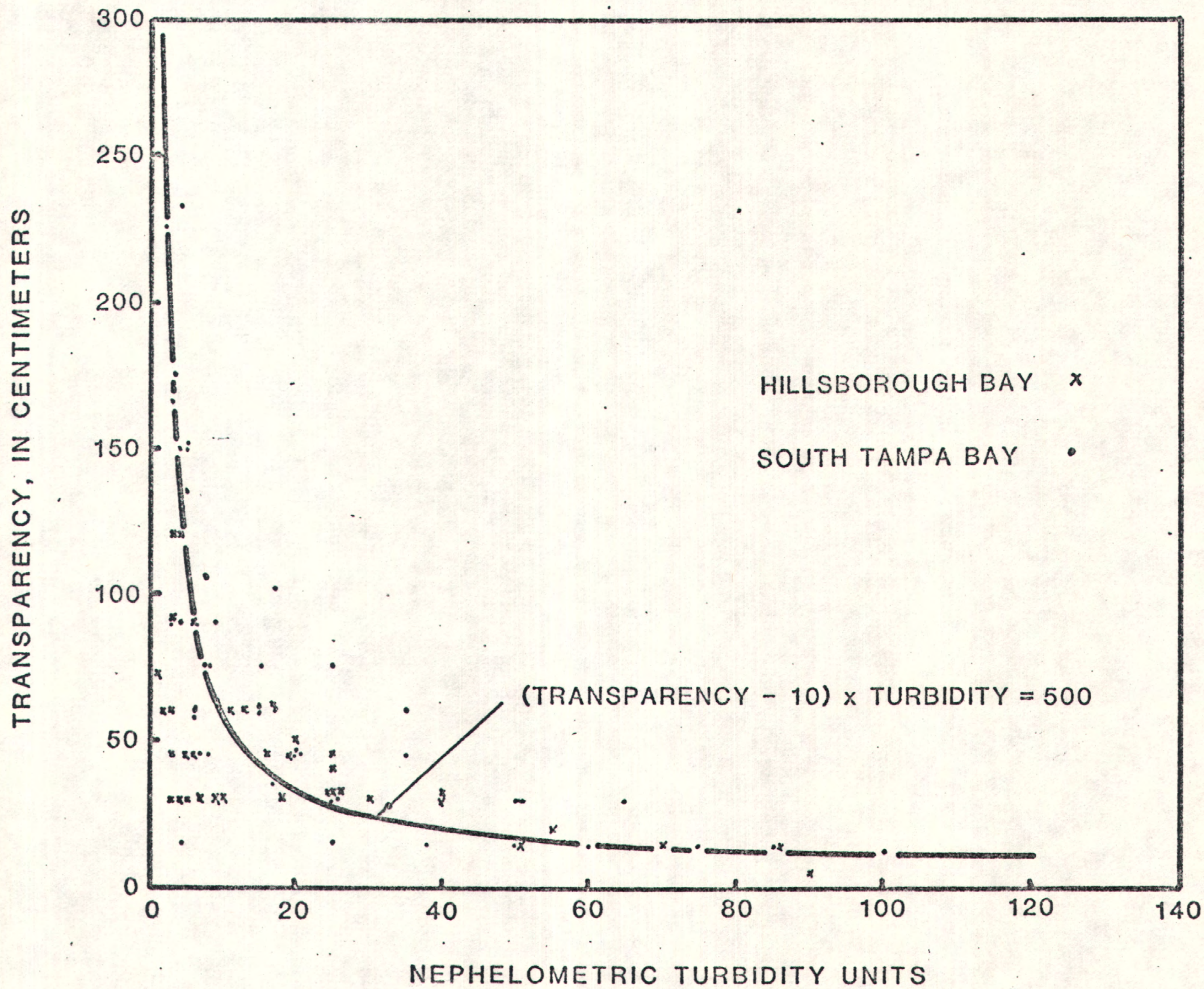


Figure 45.--Relation between turbidity and transparency.

The inverse relation between transparency and surface turbidity, two optical measures of water clarity, is shown in figure 45. High turbidity is associated with low light penetration and vice versa. The turbidity scale has been truncated and presented in arithmetic form to emphasize the hyperbolic relation between these two variables. Scatter of data is caused by (1) subjectivity of the transparency measurement, (2) comparison of point turbidity data with vertically integrated transparency data, and (3) possible lapse of several minutes between times of turbidity sample collection and transparency observation. Five apparent outlying points were not plotted on figure 45.

Nutrients

Nutrient determinations were made for filtered and unfiltered water samples from plume and background sites to determine whether plume water is enriched with dissolved or particulate nutrients. Results of comparisons between mean nutrient concentrations collected at background and plume sites are summarized in table 15. In no case is the concentration of any dissolved or total constituent for plume samples significantly different than concentration for corresponding background samples. The data indicate that dredge plumes in both Hillsborough and South Tampa Bays do not significantly increase dissolved or total nutrient concentration.

The average plume concentration for all phosphorous parameters measured in Hillsborough Bay is less than average background concentrations. Although not statistically significant, this indicates that phosphorus may be scavenged from the water by dredged sediment.

The differences between nutrient concentrations within turbidity plumes in Hillsborough Bay and South Tampa Bay and differences in average background nutrient concentrations between the bays are shown in table 16. Total and dissolved organic nitrogen in plumes in Hillsborough Bay are significantly higher than in South Tampa Bay, which supports the prior observation that sediments in Hillsborough Bay contain more organic material than sediments in South Tampa Bay (table 14). Background organic nitrogen was also higher in Hillsborough Bay than South Tampa Bay, but differences were not detected in background volatile solids between the two subareas. This indicates that organic nitrogen is either a more sensitive parameter for detecting organic material or that there is more nitrogen associated with organic material in Hillsborough Bay than South Tampa Bay. Higher dissolved nitrate levels were found for both plume and background samples in Hillsborough Bay (table 16).

Table 15.--Summary of statistical comparison of nutrient concentration between background and plume samples

Constituent	Background		Plume		Means significantly different?	P level
	N[1]	Mean	N[1]	Mean		
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

[1] N - number of samples analyzed.

Table 16.--Summary of statistical comparison of nutrient concentration between Hillsborough and South Tampa Bays

Constituent	South Tampa Bay		Hillsborough Bay		Means significantly different?	P level
	N[1]	Mean	N[1]	Mean		
Background						
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						
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

[1] N - number of samples analyzed.

All phosphorous concentrations in background and plume samples are significantly higher in Hillsborough Bay than in South Tampa Bay verifying previously published data (Goodwin and others, 1974 and 1975; Goetz and Goodwin, 1978; Wilkins, 1978).

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

Trace Metals and Arsenic

Water samples were analyzed for trace metals and arsenic to determine if significant amounts of these potentially harmful elements are introduced into the water column as a result of dredging operations. Tables 17 and 18 summarize the results of statistical analyses of the metal data. Arsenic, cadmium, chromium, and nickel were not analyzed in samples from sites in South Tampa Bay.

Tables 17 & 18 near here

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

Results of comparisons of mean values for dissolved and total metals between Hillsborough and South Tampa Bays are given in table 18 for background and plume sites. Differences in concentrations at background sites were not detected. The apparent higher concentration of total and dissolved lead in Hillsborough Bay needs 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. This result is not reflected in any of the other metal comparison tests, perhaps indicating greater test sensitivity in the "plume" data of table 18 due to the larger number of observations.

Table 17.--Summary of statistical comparison of trace metal concentration between background and plume samples

Constituent	Background N[1]	Background Mean	Plume N[1]	Plume Mean	Means significantly different?	P level
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

[1]N - number of samples analyzed.

Table 18.--Summary of statistical comparison of trace metal concentration between Hillsborough and South Tampa Bays

Constituent	South Tampa Bay		Hillsborough Bay		Means significantly different?	P level
	N[1]	Mean	N[1]	Mean		
Background						
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						
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

[1]N - number of samples analyzed.

Pesticides and Industrial Compounds

Samples were collected for analysis of pesticides and industrial compounds at 16 sites in Hillsborough and South Tampa Bays. Twelve samples were collected in turbidity plumes and four were collected at background sites. The samples were analyzed for aldrin, chlordane, DDD, DDE, DDT, dieldrin, endosulfan, endrin, heptachlor, heptachlor expoxide, lindane, toxaphene, 2,4-D, 2,4,5-T, silvex, polychlorinated biphenyls, and polychlorinated napthalenes. Only 6 of the 272 total determinations showed measurable amounts of these compounds. In each case, the samples were from Hillsborough Bay and contained low concentrations (0.01 to 0.05 ug/L) of the herbicide 2,4-D (table 19). The concentrations measured are close to the detection limits for analytical methods used.

The concentration of 2,4-D appears to bear little relationship 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, whereas the highest concentration of 2,4-D (0.05 ug/L) was associated with a turbidity of 7 NTU.

Samples collected in Hillsborough Bay on November 21, 1977, and January 5, 1978, did not contain any 2,4-D; samples collected on or after January 30, 1978, contained 0.01 to 0.05 ug/L of 2,4-D. The later samples, 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 application to land areas or water courses that drain into Hillsborough Bay.

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

Date	Time	Sampling depth (ft)	Sampling area	Turbidity (NTU)	Concentration of 2,4-D (ug/L)	Bay
2-17-77	1204	15	Plume	15	0	South Tampa Bay
2-17-77	1214	13	Background	4	0	
3-15-77	1101	12	Plume	3	0	South Tampa Bay
3-15-77	1116	16	Plume	4	0	
3-15-77	1141	19	Plume	20	0	
11-21-77	1111	8.5	Plume	35	0	Hillsborough Bay
11-21-77	1151	4.0	Plume	6,000	0	
1-5-78	1056	6.5	Plume	120	0	Hillsborough Bay
1-5-78	1106	4.0	Background	2	0	
1-5-78	1131	4.0	Plume	25	0	
1-30-78	1126	6.5	Plume	6	.02	Hillsborough Bay
1-30-78	1136	4.5	Background	1/ 4/6	.02	
1-30-78	1151	2.5	Plume	17	.01	
3-13-78	1056	22	Plume	7	.04	Hillsborough Bay
4-4-78	1001	5.0	Plume	7	.05	Hillsborough Bay
7-13-78	0906	5.5	Plume	1/ 10/210	.04	Hillsborough Bay

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

Summary of Water-Quality Results

Analysis of water-clarity data from both plume and background sites in Hillsborough and South Tampa Bays indicate the following:

1. Water is generally clearer at background sites than at sites within turbidity plumes. Use of turbidity barriers in Hillsborough Bay, however, produce surface plume clarity similar to surface background clarity as measured by Secchi disk transparency readings;
2. Background water in both bays have similar clarity characteristics. One exception is that background transparency in South Tampa Bay is about three times greater than for Hillsborough Bay, an indication that the 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 is limited because of low tidal velocities;
4. The relations between turbidity, suspended solids, volatile solids, and transparency are the same, indicating similar types of fine sediment in both bays.

Analysis of total and dissolved nutrient concentrations from background and plume sites in both Hillsborough and South Tampa Bays indicate the following:

1. Significant difference in concentration could not be detected between plume and background samples for any constituent in either bay;

2. Although not statistically significant, the concentration of phosphorus within plumes in Hillsborough Bay is less than background concentrations indicating the possibility of phosphorous scavenging by sediment particles within the plumes;

3. Concentrations of total and dissolved organic nitrogen, dissolved nitrate nitrogen, and all phosphorous parameters were higher in Hillsborough Bay background samples than South Tampa Bay background samples. The same constituents are more concentrated in Hillsborough Bay plume samples than in South Tampa Bay plume samples;

4. Nutrient concentrations within turbidity plumes in both South Tampa and Hillsborough Bays were about the same as concentrations in the water surrounding the plume. Effects of dredging on nutrient concentrations are not detectable.

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

1. Background and plume concentrations of any measured constituent were statistically the same in either Hillsborough or South Tampa Bay;

2. Background samples from both bays were statistically the same for all measured constituents:

3. Hillsborough Bay plume samples had higher concentrations of dissolved copper, lead, mercury, and total mercury than in South Tampa Bay plumes.

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

LONG-TERM TURBIDITY TRENDS

Water-quality analyses in this report have so far been limited to short-term (hours to days) impact that turbidity plumes have on clarity and chemical characteristics of receiving water. Potential long-term changes in water clarity due to dredging could also have important effects on the health and productivity of the Tampa Bay estuarine system.

Turbidity data collected in Hillsborough and South Tampa Bays from 1976 through mid-1980 by the Hillsborough County Environmental Protection Commission and approximate dredge-spoil production rates from 1977 through mid-1980 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 the mean, and the trend in minimum turbidity values for South Tampa Bay and Hillsborough Bay are shown in figures 46 and 47, respectively. Dredge-spoil production rates are also given. Turbidity in South Tampa Bay showed a repeating pattern with two periods of relatively low turbidity per year, a winter low occurred in December, January, or February and a summer low occurred between May and October. The minimum turbidities ranged from 1.6 to 3.4 NTU and showed a gently increasing trend throughout the dredging period of about 0.3 NTU per year. In May 1980, after dredging ceased, the minimum 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 (4.5 to 8.6 NTU). The highest mean turbidity level occurred in December 1978, at a time of relatively high dredge-spoil production, and in April 1980 during a period of no dredging activity. Turbidity maxima in figure 46 seem to be unaffected by dredging.

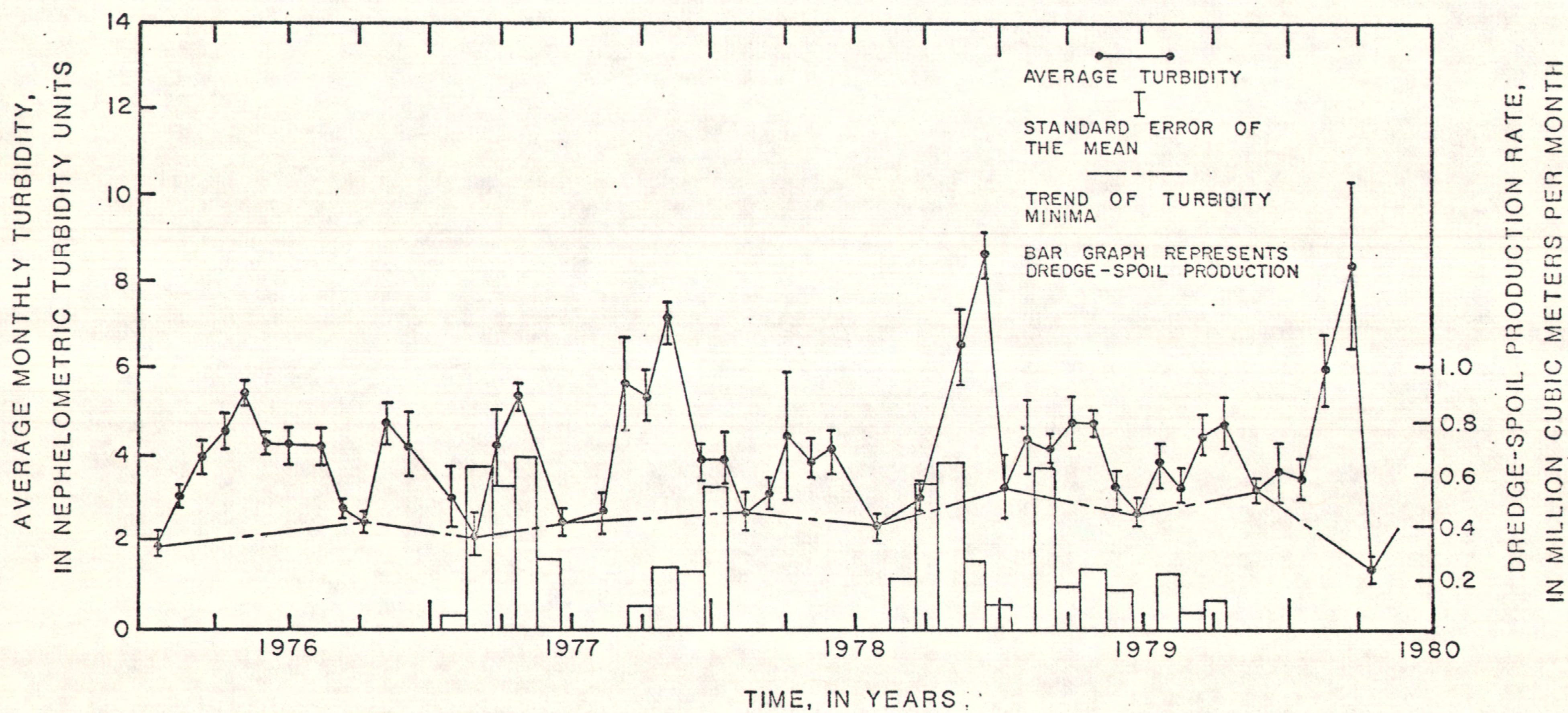


Figure 46.--Average monthly turbidity and monthly dredge-spoil production rate in South Tampa Bay.

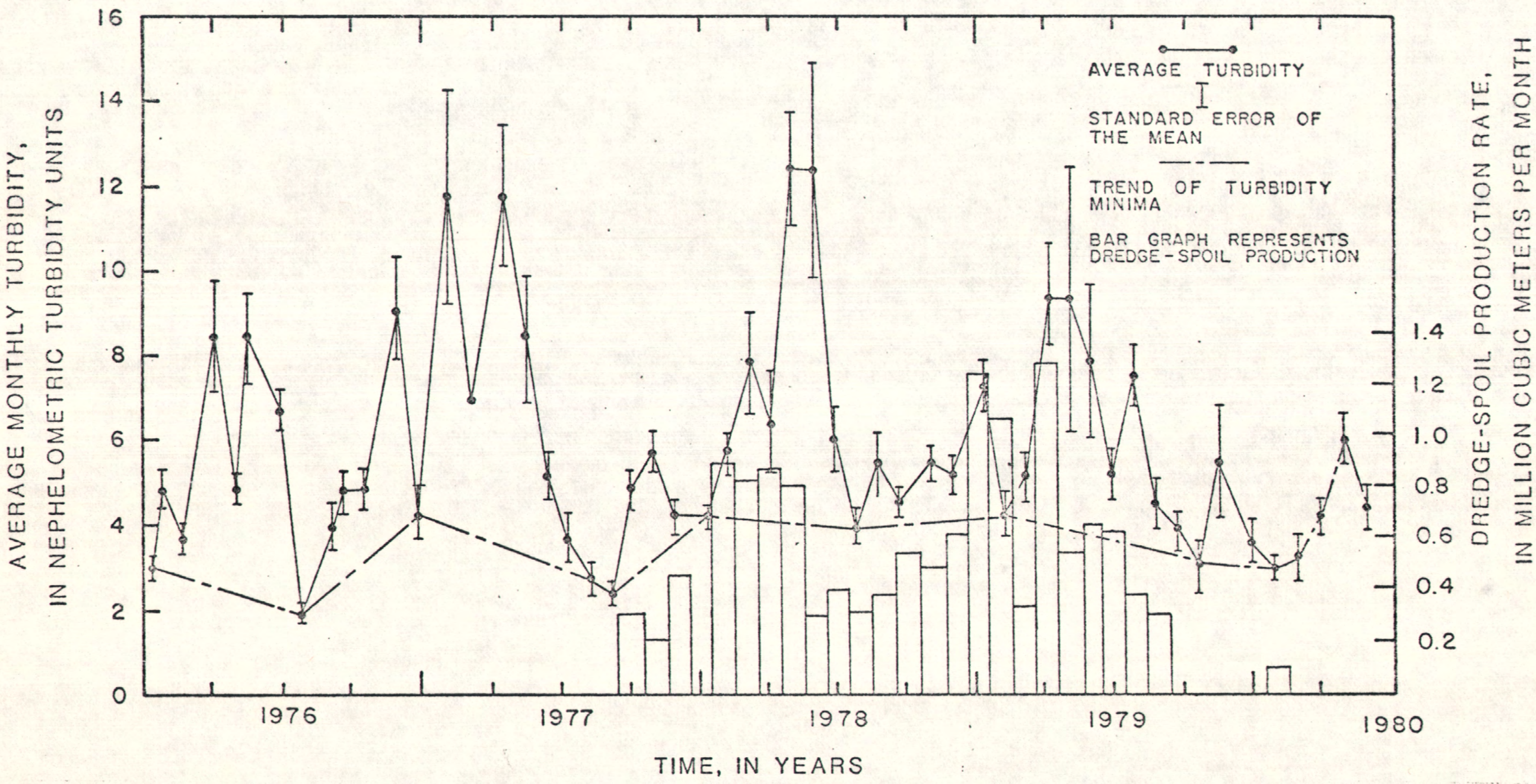


Figure 47.--Average monthly turbidity and monthly dredge-spoil production rate in Hillsborough Bay.

Turbidities in South Tampa Bay during periods of no dredging were, in most ways, about the same as during periods of high dredging activity. Data shown in figure 46 show that dredging may cause an increasing trend in seasonal turbidity minima with a rapid return to predredging levels after dredging ceases.

Average turbidity levels for Hillsborough Bay (fig. 47) show less consistency than for South Tampa Bay. With some generalization, 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 March to May. Data in figure 47 indicates that maximum average turbidities measured during dredging periods were not 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.

Comparison of turbidity and dredge-spoil production curves in figure 47 show some shape similarity, indicating that dredging may have affected turbidity levels in Hillsborough Bay. The fact that general seasonal turbidity variations were maintained during the period of dredging, however, indicates either that (1) the impact of dredging was insufficient to disrupt the seasonal pattern or (2) the dredge-spoil production rate coincidentally duplicated and was additive to the natural seasonal pattern.

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

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

SUMMARY AND CONCLUSIONS

Turbidity plumes in Tampa Bay are highly variable in appearance depending on sediment, dredge, disposal, containment, and tide conditions at the time of observation. In general, plumes in South Tampa Bay can be characterized as highly visible, elongated, and with low to moderate turbidity levels. Exceptions are that (1) plumes can be very compact during slack-tide periods and (2) beach nourishment plumes are not highly visible. Plumes in Hillsborough Bay can be generally characterized as faintly visible, diffuse, and with moderate to high turbidity levels. Exceptions are that (1) low turbidity levels are often found near the top of the water column and (2) plume visibility increases with incomplete closure of turbidity barriers.

In spite of relatively low silt and clay content in dredged material and high dilution rates due to fast flowing tidal currents, surface discharge to unconfined disposal areas in South Tampa Bay produced highly visible plumes. Conversely, plumes of low visibility were produced from material with relatively high silt and clay content discharged into slow moving tidal currents, having low dilution rates, behind turbidity barriers in Hillsborough Bay. The use of turbidity barriers in Hillsborough Bay was effective in limiting the visibility of turbidity plumes. The submerged, nonvisible part of plumes in Hillsborough Bay were significantly more turbid, however, than plumes in South Tampa Bay.

Considerable turbidity was found in secondary plumes that were generated in both Hillsborough and South Tampa Bays by resuspension of previously deposited dredged material. Secondary plumes were generated in South Tampa Bay as high velocity tidal currents eroded material from the disposal mounds created within submerged disposal areas. Turbulence from hopper-dredge maneuvering in South Tampa Bay and work boats operating in Hillsborough Bay produced secondary turbidity plumes of high visibility as bottom material was suspended in the water column.

Because of rapid flocculation of fine dredged material, turbidity plumes in Tampa Bay are less extensive than they could be. Flocculation is promoted by the electrolytic seawater solution and presence of montmorillonite clay minerals in dredged material.

During flood-tide conditions, a two-part or separated plume is formed from dredged material discharging west of the northern tip of Egmont Key. The plume narrows as incoming water accelerates past Egmont Key and widens again as the water decelerates after passing the constriction. The result is a plume that appears to have two separate parts.

Low silt and clay content of dredged material and high dilution rates due to strong tidal currents in South Tampa Bay produce plumes having less turbidity and greater clarity than plumes in Hillsborough Bay. Nutrient concentrations within turbidity plumes in both Hillsborough and South Tampa Bays cannot be distinguished at the 2 percent level of significance ($\alpha=0.02$) from nutrient levels in the ambient water in each bay. Data indicate that dredging does not increase nutrient levels in Tampa Bay waters.

Analysis of limited numbers of observations of 10 trace metals does not indicate a significant (α=0.02) difference between plume and background levels. There is an indication that dissolved copper, lead, mercury, and total mercury may be higher in Hillsborough Bay plumes than in plumes in South Tampa Bay. Of 262 analyses of 17 pesticide and industrial compounds sampled, all were below the detection limits except for 6 samples in Hillsborough Bay containing 2,4-D. A relation was not found between the 2,4-D samples and the dredging operation.

Long-term monthly average turbidity levels in South Tampa Bay showed little graphical correlation with dredge-spoil production rates. Two seasonal turbidity highs and lows per year were found with little apparent change during dredging and nondredging periods. An upward trend of turbidity minimum points of nearly 0.3 NTU per year was found during relatively continuous periods of dredging. After dredging ceased in South Tampa Bay, low seasonal turbidity levels rapidly reverted to predredging levels.

Long-term monthly average turbidity levels in Hillsborough Bay were graphically correlated with dredge-spoil production rates. Maximum turbidity levels reached during dredging periods were the same as maximum predredging turbidity levels. Minimum turbidity levels during dredging periods were greater than minimum predredging turbidity levels by about 2 NTU. After dredging, minimum turbidity levels in Hillsborough Bay decreased.

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