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U.S. DEPARTMENT OF COMMERCE
NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION
Environmental Research Laboratories

Suspended Particulate Matter in the New York Bight Apex: September-November 1973

DAVID E. DRAKE

BOULDER, COLO.
NOVEMBER 1974

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SUSPENDED PARTICULATE MATTER IN THE NEW YORK BIGHT APEX:

SEPTEMBER-NOVEMBER 1973

David E. Drake

ABSTRACT

The distribution of suspended particulate matter in the New York Bight apex was studied during the fall of 1973 as part of the Marine Ecosystems Analysis program of NOAA.

Five surveys from September through November revealed consistent suspended matter distributions that reflect the bight apex water circulation. Two major currents dominate during the fall season of limited river flow and gradually weakening water column stratification: (1) relatively fresh surface water, containing between 1 to 4 mg/l of suspended particles, flows from Hudson estuary and down the New Jersey coast within 5 to 10 km from shore; and (2) northward flow along Hudson shelf channel occurred during all surveys. Low concentrations of suspended matter and ashed-weight fractions dominated by diatoms indicate a central shelf origin for the shelf-channel current. Surface winds have a strong influence on the currents at all depths in the bight apex. During the fall season, winds are predominantly from western quadrants and tend to sweep through upwelling and northward flow along Hudson shelf channel. Current meter records appear to show that the shelf channel flow waxes and wanes in response to the strength and direction of surface winds.

Total suspended matter distributions and dispersion patterns of iron particles dumped at the acid-waste dumpsite support the existence of a clockwise gyre in the central portion of the area during the fall season; the shelf-channel current forms the western limb of this gyre. Dredge spoil and sewage sludge dumped near the head of the shelf channel settle within the shelf channel to form organic-rich mud lenses. However, some of this material is entrained by the northward valley current and transported from the shelf channel to the northeast over Cholera Bank. The bank crest does not accumulate fine sediment owing to relatively vigorous wave surge. However, as the turbid current turns south along the east side of Cholera Bank, fine-grained, organic-rich material begins to settle. The result is two disconnected lenses of organic-rich sediment on either side of the sand bank. Contaminated sediments are widely dispersed in the bight apex water column. However, major dispersion appears to be centered on the Hudson shelf channel with good evidence that material dumped at the valley head is transported both up and down the channel in substantial quantities.

One of our surveys coincided with a moderate storm which produced steep, 1.0- to 3.0-m seas. Resuspension of clay and silt-sized material occurred throughout the area, and, owing to the near absence of water column stratification, this sediment was rapidly mixed toward the sea surface. A minimum of 10^4 metric tons of sediment was entrained during this storm, and it is clear that such high energy events strongly influence the fate of natural and artificial sediments in the New York Bight.

1. INTRODUCTION

Five surveys of a standard station grid were completed in fall 1973 in the apex of the New York Bight (fig. 1). The surveys included a wide variety of observations designed to define physical and chemical water property distributions and controlling processes. Suspended particulate matter was among the properties investigated, and the results form the basis for this NOAA Report.

The work reported in this report is the beginning of a study of man's impact on the ecology of the continental shelf between Montauk Point, N.Y., and Cape May, N.J. Initial emphasis is being directed toward the shallow shelf off the Hudson estuary because this area annually receives approximately 4.6×10^6 tons of dredge spoils, sewage sludge, industrial wastes, and other waste products (Gross, 1972). Because of this dumping, sizable areas of the sea floor in the apex (principally near the sewage dumpsite) have been shown to be nearly devoid of marine life (Pearce, 1970). The degradation of the immediate coastal environment and the real possibility that the pollutants or their effects may spread to other areas emphasize the importance of gaining a complete understanding of the transport of both natural fine

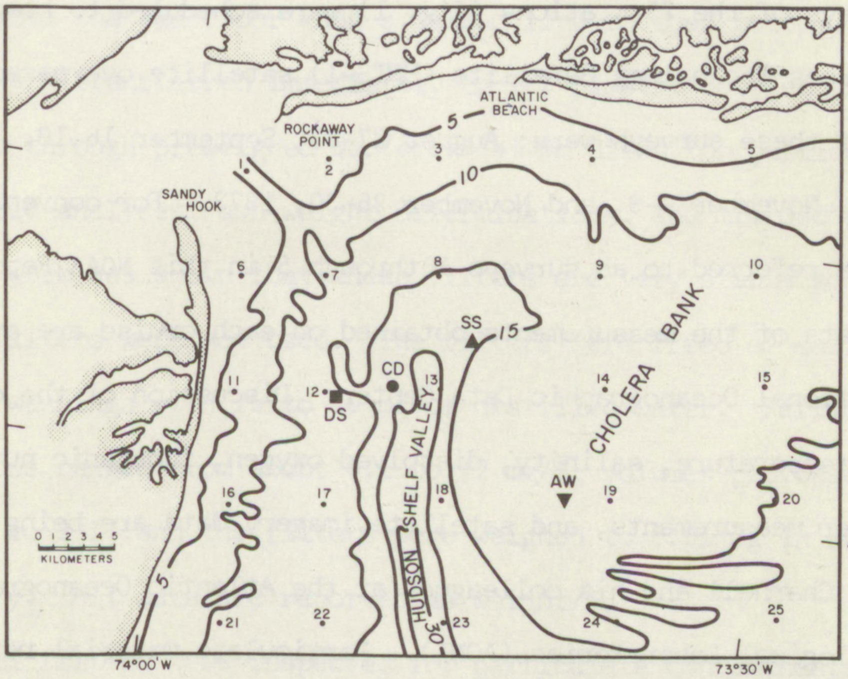


Figure 1. New York Bight apex. Stations are numbered solid circles (1-25). Major dumpsites are designated as follows: DS, dredge spoil; SS, sewage sludge; AW, acid waste; and CD, cellar dirt. Bathymetry is in fathoms.

sediments and artificial contaminants. The bulk of the demonstrably toxic pollutants (contained in dredge spoil and sewage sludge) can be expected to move predominantly as suspended load--either as discrete particles or adsorbed to the surfaces of other grains.

2. FIELD AND LABORATORY METHODS

Surveys of the 25 stations (fig. 1) were scheduled to bracket Earth Resources Technology Satellite (ERTS-1) satellite overpasses. The dates of these surveys were: August 27-31, September 16-19, October 1-4, November 4-9, and November 26-30, 1973. For convenience, they will be referred to as surveys 1 through 5 in this NOAA Report. Complete lists of the measurements obtained on each cruise are available from the National Oceanographic Data Center. Discussion of the distributions of temperature, salinity, dissolved oxygen, inorganic nutrients, current meter measurements, and satellite imagery data are being prepared by R. Charnell and his colleagues at the Atlantic Oceanographic and Meteorological Laboratories (AOML). Particulate material retained by glass-fiber filters has been analyzed for carbohydrate and protein content by P. Hatcher of AOML. In addition, Hatcher has studied these constituents along with the total organic carbon content of surficial bottom sediments. His work will be the subject of a separate NOAA Report.

Water samples for filtration through *Nuclepore* (0.45μ average pore diameter) and glass-fiber filters were obtained at the surface and at 10-m intervals down to approximately 2 m from the bottom using a submersible pumping system incorporated in an *Interocean* Conductivity-Salinity-Temperature-Depth unit. The pumping system was not used on the last survey (survey 5) because it was determined that samples were contaminated for metal analyses and the particulate matter was undergoing textural changes. The 10-l Niskin Polyvinyl Chloride water samplers were used on the last survey; one bottle was modified at close to 2 m above the sea floor when a leaded line touched bottom. Water samples were transferred immediately to 1-l plastic bottles and filtered by vacuum through preweighed *Nuclepore* 47-mm discs for particulate gravimetric analyses, ash-weight determinations, and microscope study. Previous work has shown that these filters are very stable so that control filters were not used. The filters were freed of salt by multiple washings with 25 to 50 ml of distilled water. Particle concentrations ranged from about 0.1 to 12 mg/l; volumes processed ranged from 0.3 to 2 l, and the filters were weighed to 0.01 mg in our shore laboratory. All data are reported as weight/l.

All filters were inspected for particulate contaminants with a petrographic microscope, but, owing to time limitations, only samples from the second and fifth surveys were studied for texture (samples *not* collected with the pump system). Temperature and salinity profiles through the fall season show the expected change from strong density stratification during early surveys to very weak stratification in late November. Vertical mixing in late November was accelerated by the passage of a storm front which produced 30-kt winds and steep 1.0- to 3.0-m seas from the south. All earlier surveys were blessed with relatively fair weather; thus, the late November data provide an opportunity to evaluate the effects of a moderate storm. Tentatively, we assume that suspended particle distributions during the second and fifth surveys are representative of late summer and early winter conditions, respectively.

Particles to 4 μm could be resolved with standard light microscopy; however, size measurement could be done with confidence only on grains > 10 μm. Intermediate diameters were measured and converted to equivalent spherical volumes for each Wentworth size-class. The accuracy of this method is low, but results should be internally consistent. Mineral grains were identified by their strong birefringence under polarized light; identification of mineral type was possible only in those few samples containing coarse silt and fine sand. Because biogenic particles are very difficult to size properly, only terrigenous material (birefringent) was studied for texture (see Bond and Meade, 1966). Future surveys will employ a Coulter Counter for size analyses.

The weight loss following ashing in air at 500°C was taken as a measure of total organic matter; the error involved in loss of water bound by clay minerals was neglected (Manheim *et al.*, 1970). The noncombustible ash is a mixture of inorganic and biogenic minerals (amorphous silica from plankton).

3. RESULTS

3.1 Suspended Sediment Distribution

Figures 2 through 4 present the areal distributions of total suspended particulate matter (SPM) at the sea surface, at 10 m, and at 20 m during fall 1973. Near-bottom concentrations determined with the bottom-tripping Niskin bottle during survey 5 are shown in figure 4d. Early results, using the pumping system near the sea floor, are questionable because of the steep vertical gradients in SPM and the lack of precise positioning of the pump head above the sediment surface. Benthic layer sampling can be meaningful only if samples are precisely located above the seabed by divers or bottom-tripping devices. SPM values are compiled, according to survey and depth, in the appendix; average concentrations (all surveys) are shown for each station and sampling level, and these "season averages" are plotted in figures 5a and 5b. The substantial increase in SPM at most stations during the last survey (which was affected by the storm) is particularly evident in the appendix.

Combustible and ash fractions of the suspended matter for the third survey and textural data for the second and fifth surveys are presented in figures 6, 7, and 8. Without chemical analyses, identification of most suspended pollutants is difficult or impossible. For example, even at stations within a few kilometers of designated sewage and dredge spoil sites, particles unquestionably derived from these sources cannot be separated with standard light microscopy. Inorganic and organic chemical investigations are in progress under the direction of

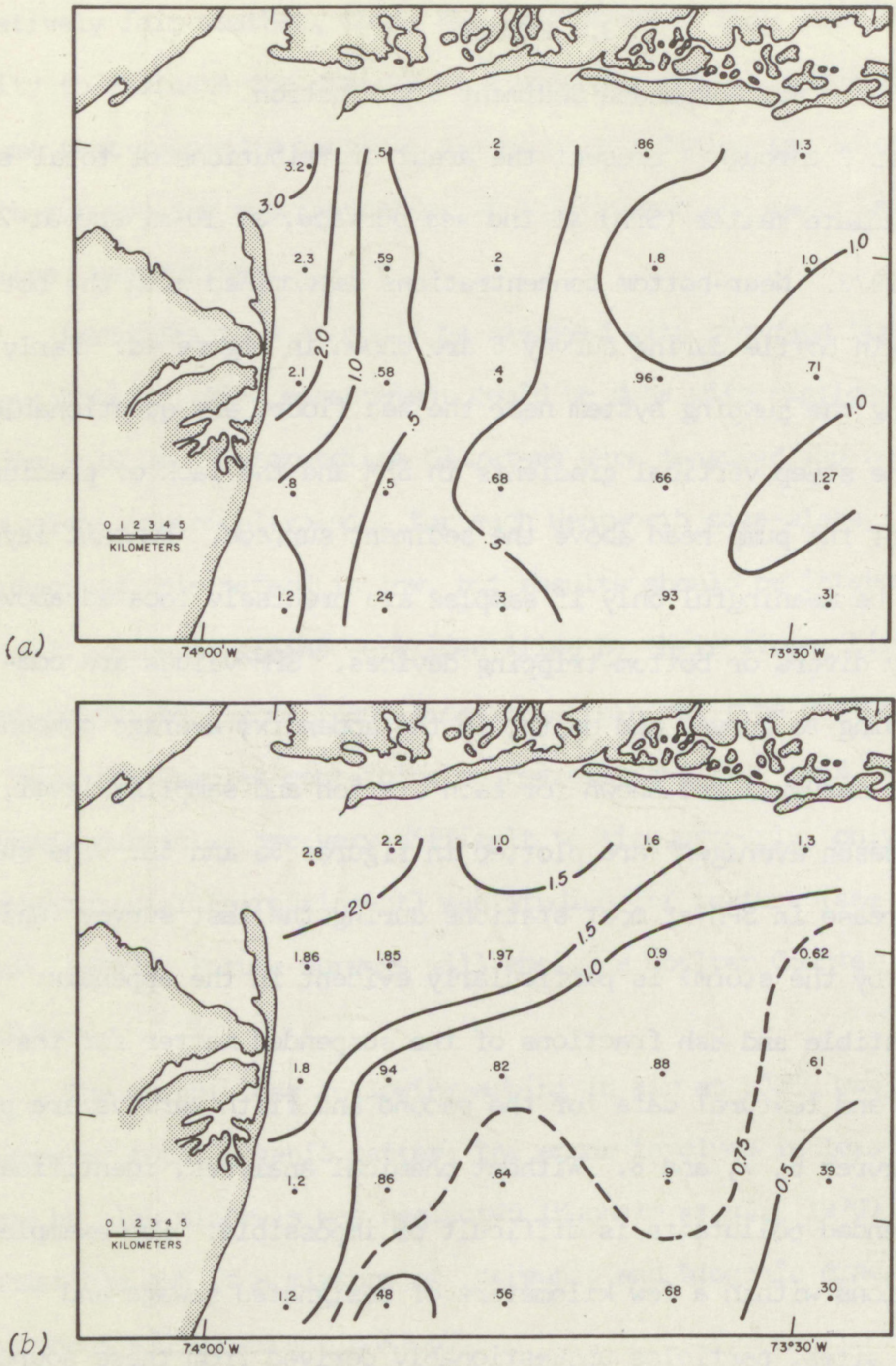


Figure 2. (a) Suspended particulate matter (mg/l) in the surface water, Sept. 16-19, 1973; and (b) suspended particulate matter (mg/l) in the surface water, Oct. 1-4, 1973.

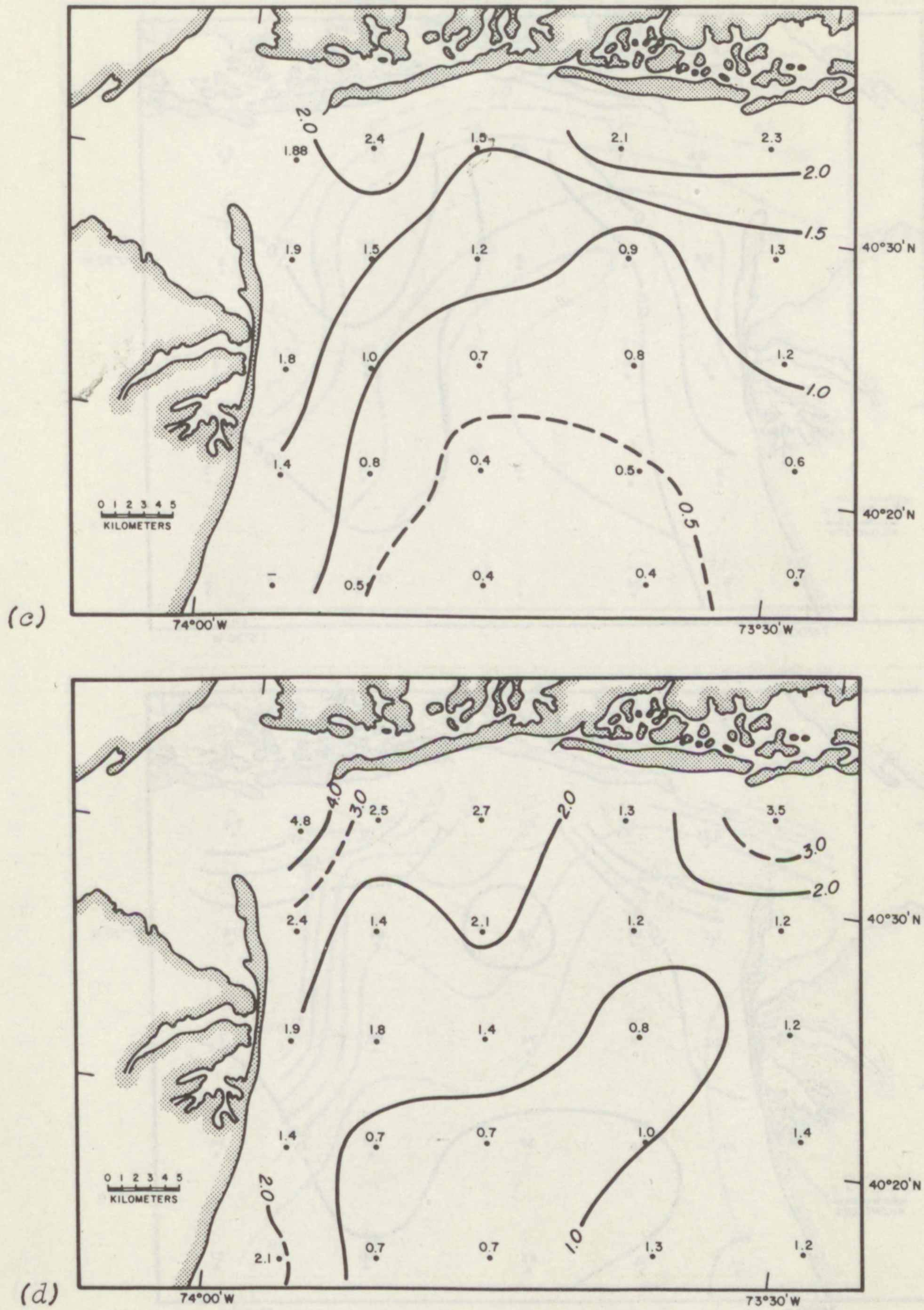


Figure 2. (c) Suspended particulate matter (mg/l) in the surface water, Nov. 5-9, 1973; and (d) suspended particulate matter (mg/l) in the surface water, Nov. 26-29, 1973.

(a)

(b)

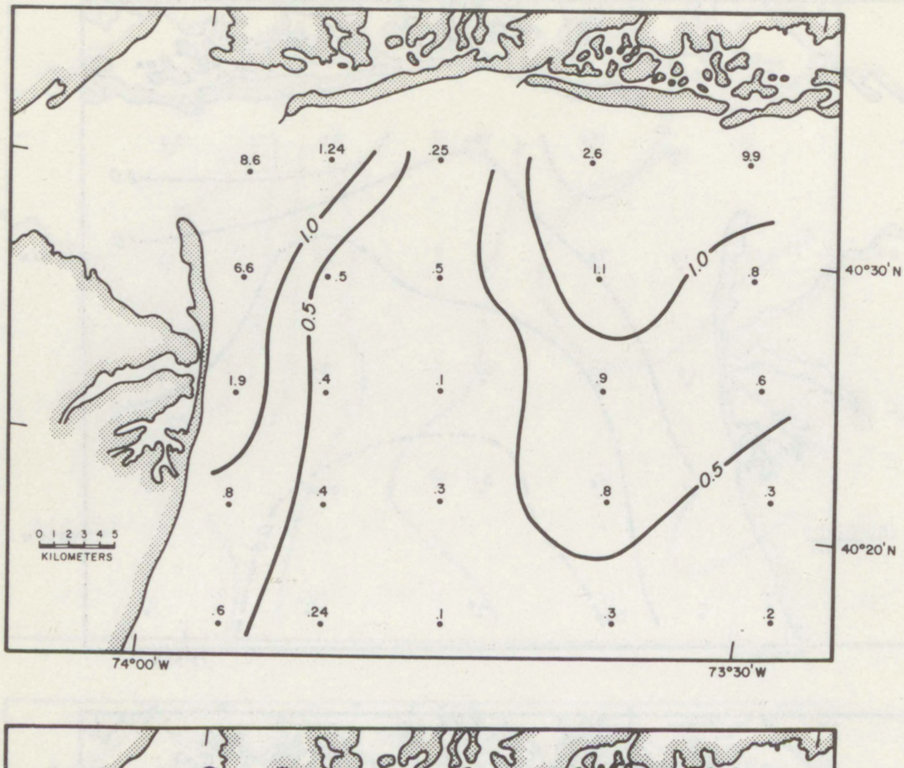


Figure 3. (a) Suspended particulate matter (mg/l) at a depth of 10 m, Sept. 16-19, 1973; and (b) suspended particulate matter (mg/l) at a depth of 10 m, Oct. 1-4, 1973.

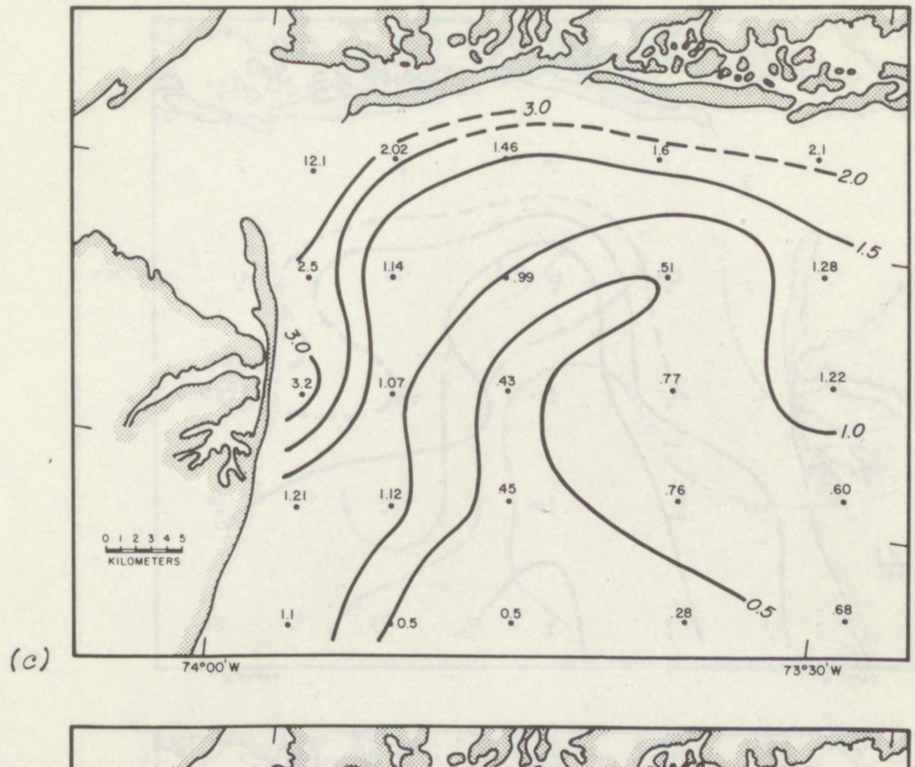
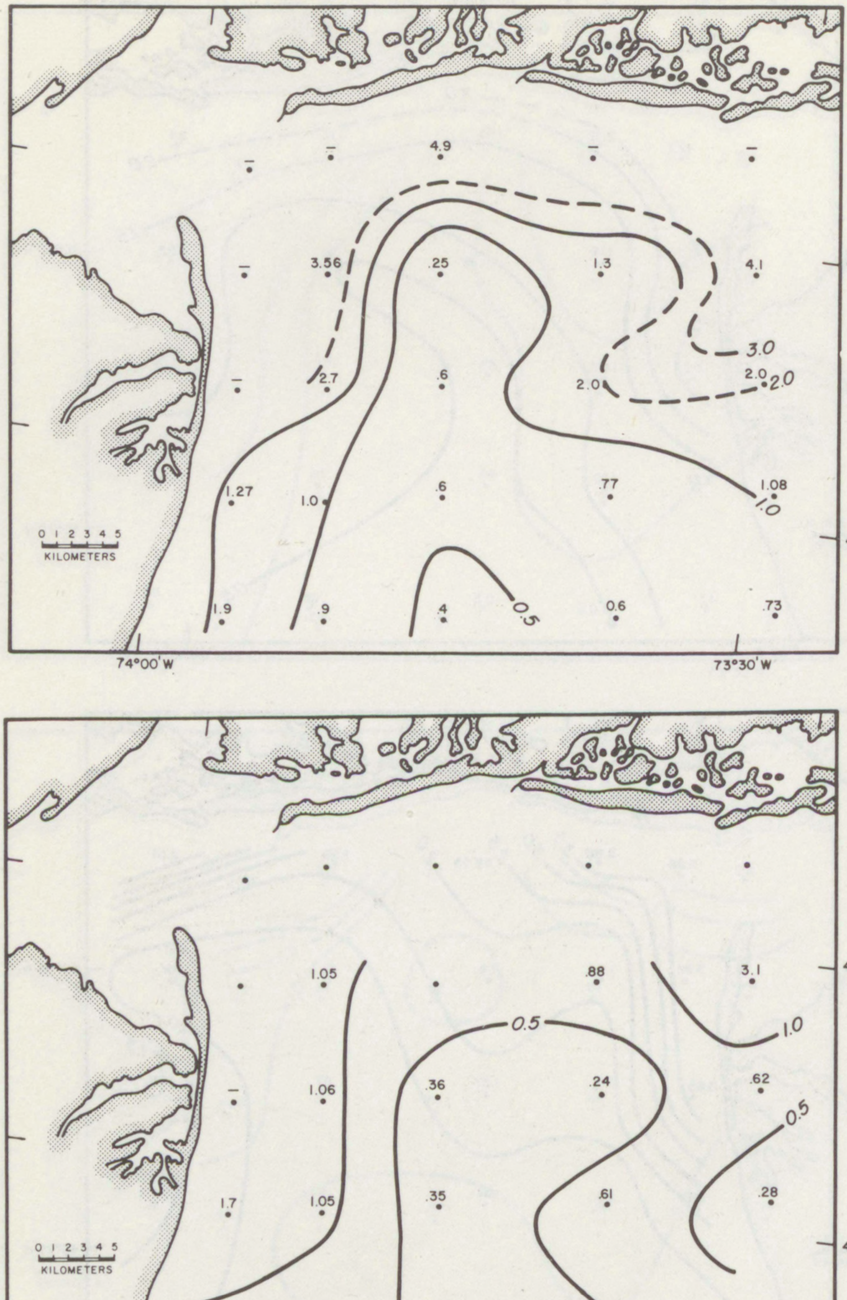


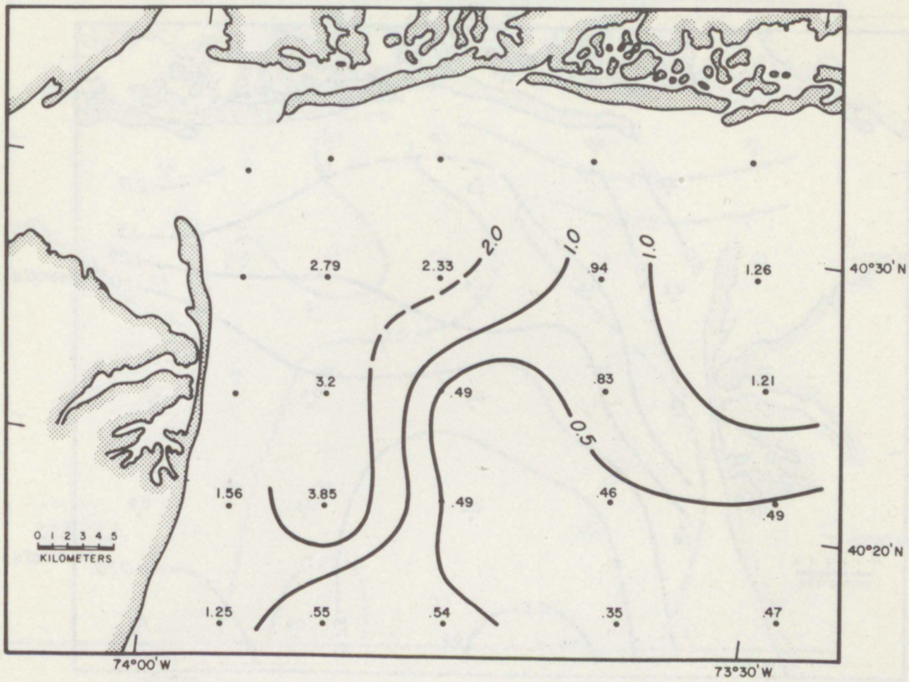
Figure 3. (c) Suspended particulate matter (mg/l) at a depth of 10 m, Nov. 5-9, 1973; and (d) suspended particulate matter (mg/l) at a depth of 10 m, Nov. 26-29, 1973.



(a)

(b)

Figure 4. (a) Suspended particulate matter (mg/l) at a depth of 20 m, Sept. 16-19, 1973; and (b) suspended particulate matter (mg/l) at a depth of 20 m, Oct. 1-4, 1973.



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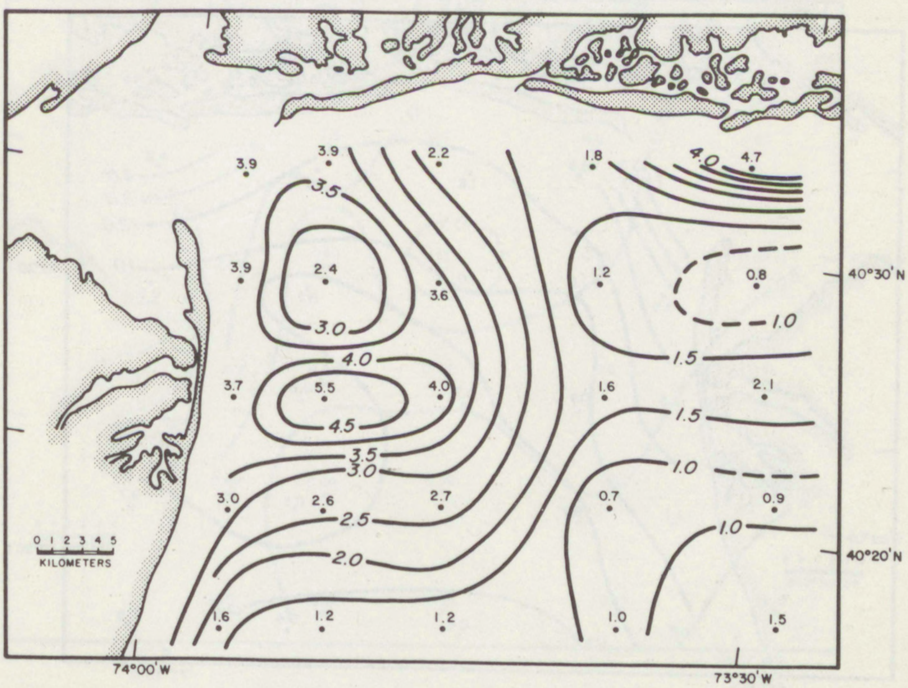


(d)

Figure 4. (c) Suspended particulate matter (mg/l) at a depth of 20 m, Nov. 5-9, 1973; and (d) suspended particulate matter (mg/l) 2 m over the sea floor, Nov. 26-29, 1973.

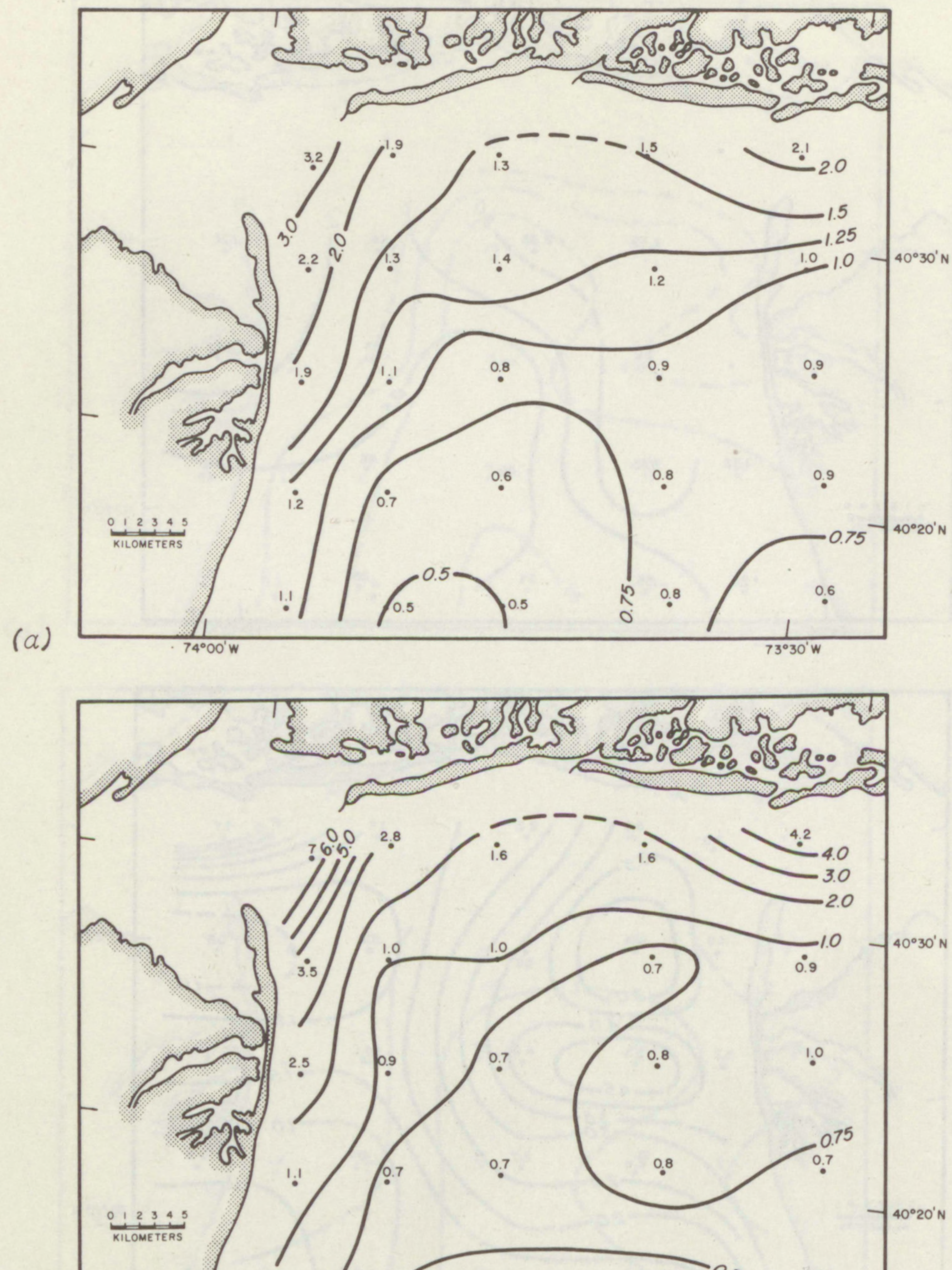
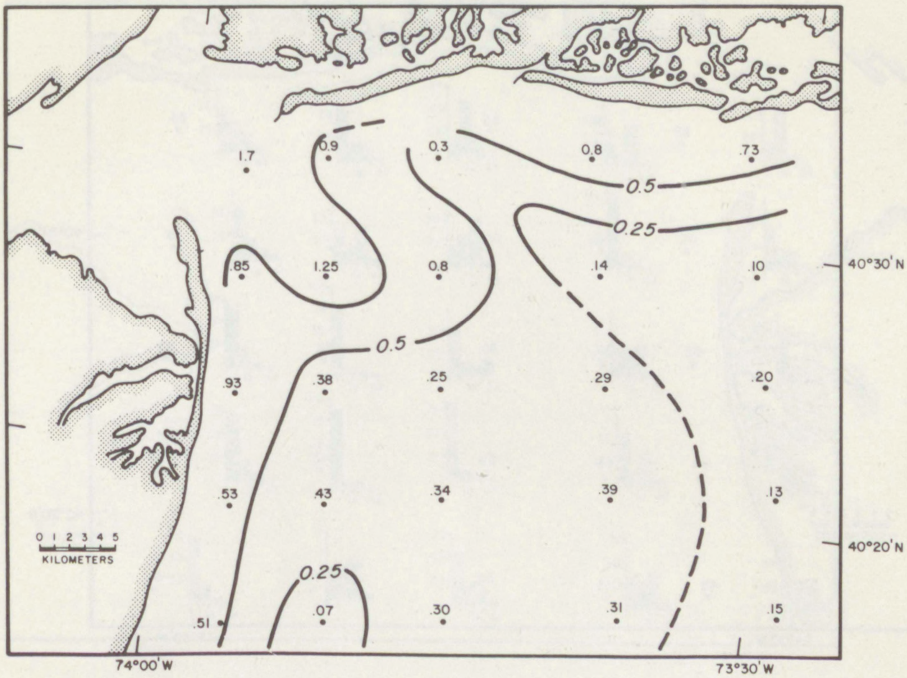
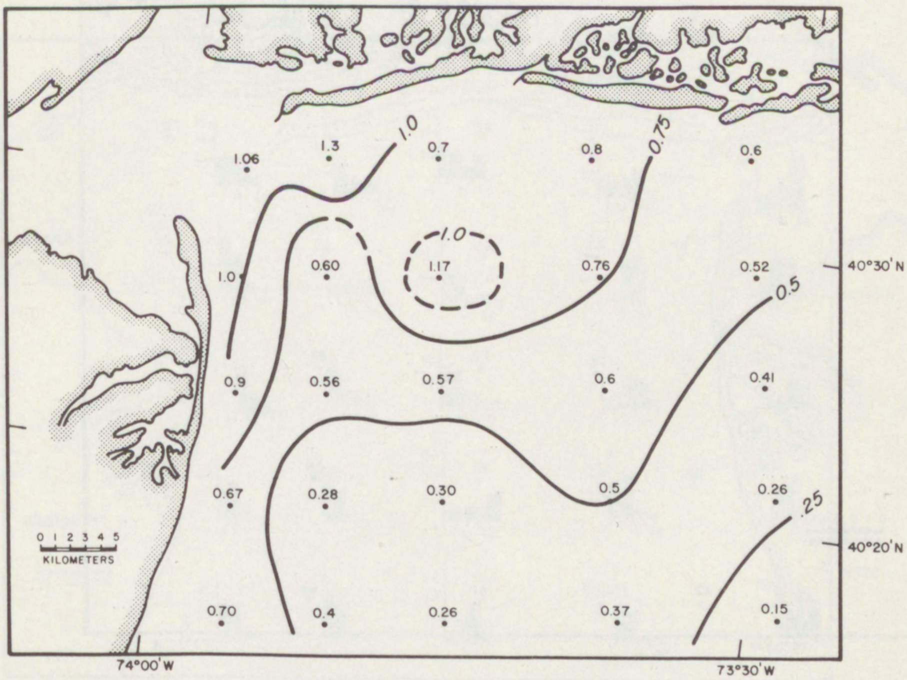


Figure 5. (a) Computed averages of suspended particulate matter (mg/l) in the surface water for all surveys; and (b) computed averages of suspended particulate matter (mg/l) at 10 m for all surveys.



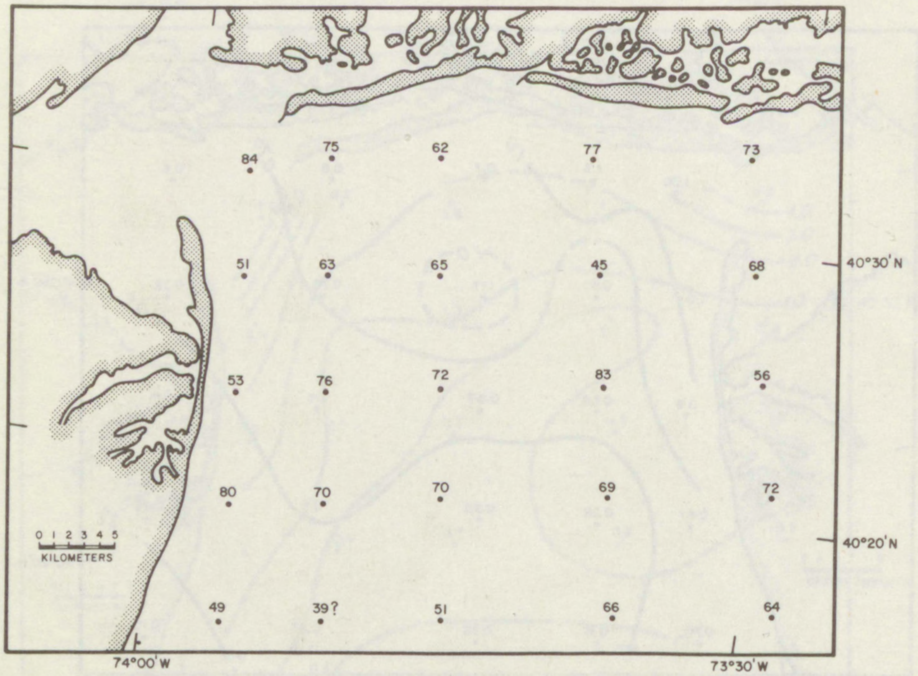
(a)



(b)

Figure 6. (a) Noncombustible fraction of suspended matter in surface waters during Oct. 1-4, 1973, in mg/l; and (b) combustible fraction of suspended matter in surface waters during Oct. 1-4, 1973, in mg/l.

(c)



(d)

Figure 6. (c) Noncombustible fraction of suspended matter in surface waters during Oct. 1-4, 1973, expressed as a percentage of the total suspended solids; and (d) noncombustible fraction of suspended matter near the sea floor during Oct. 1-4, 1973, as a percentage of the total suspended solids.

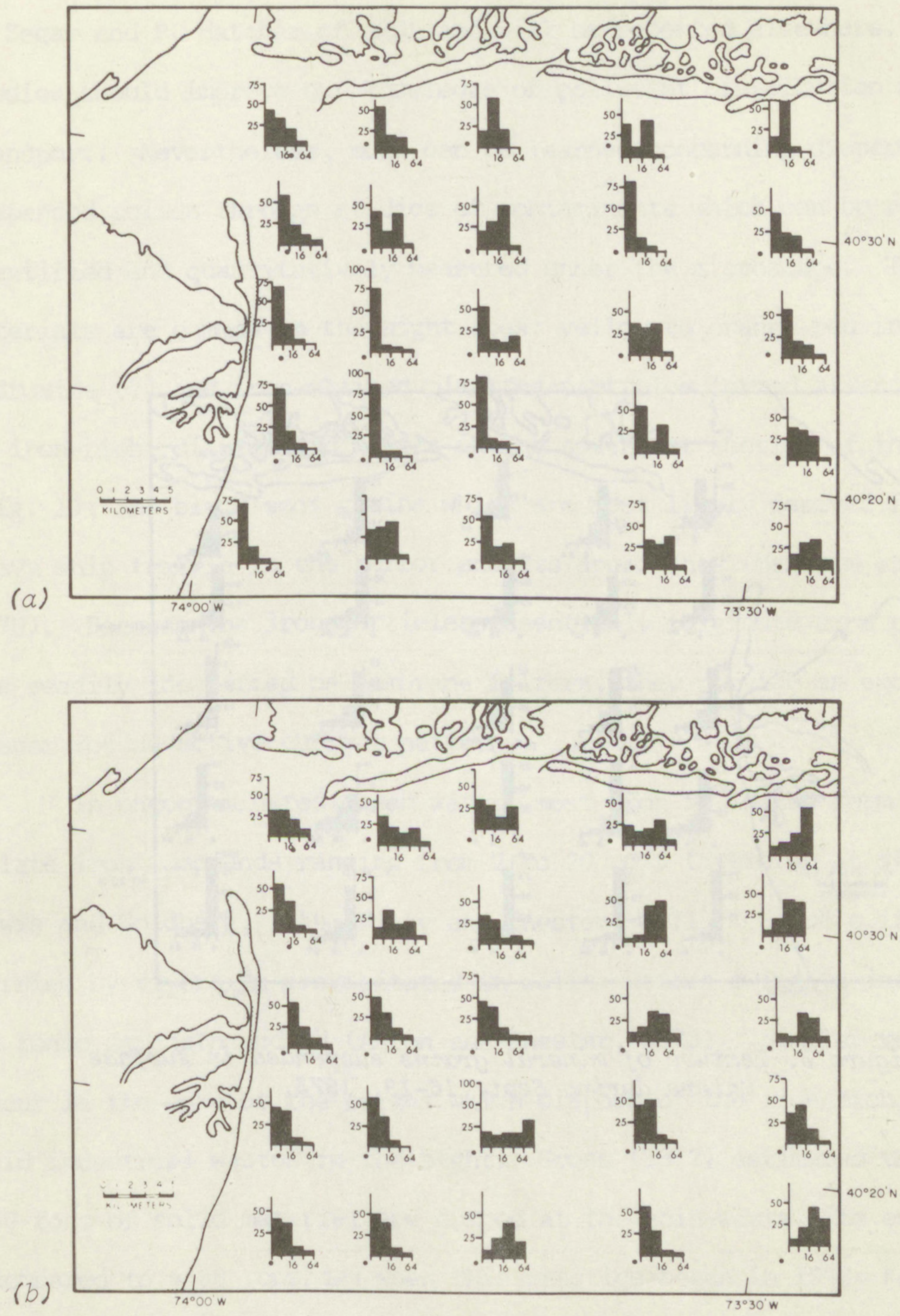


Figure 7. *(a) Size distributions of* *<u>mineral</u>* *grains suspended in surface waters during Nov. 26-29, 1973; and (b) size distributions of* *<u>mineral</u>* *grains suspended 2 m over the bottom during Nov. 26-29, 1973.*

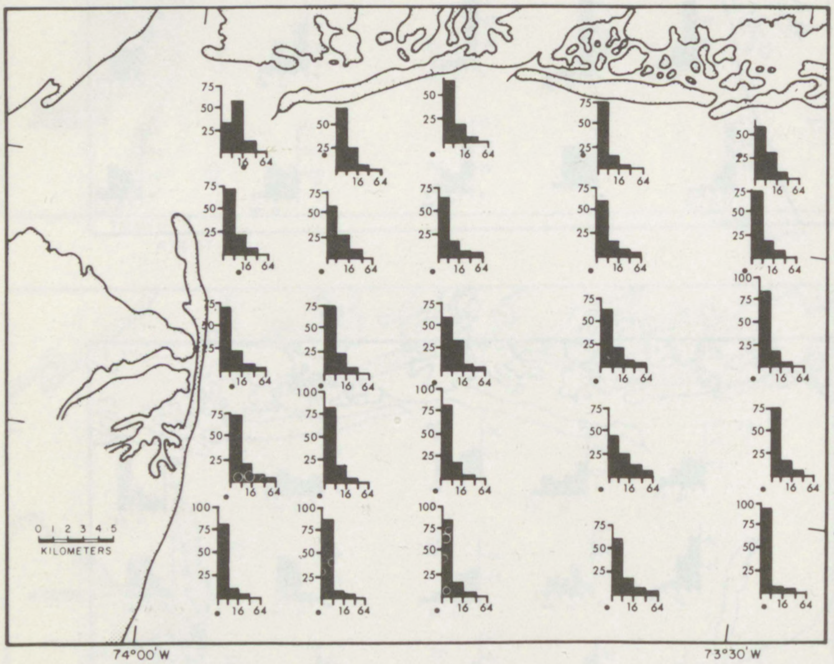


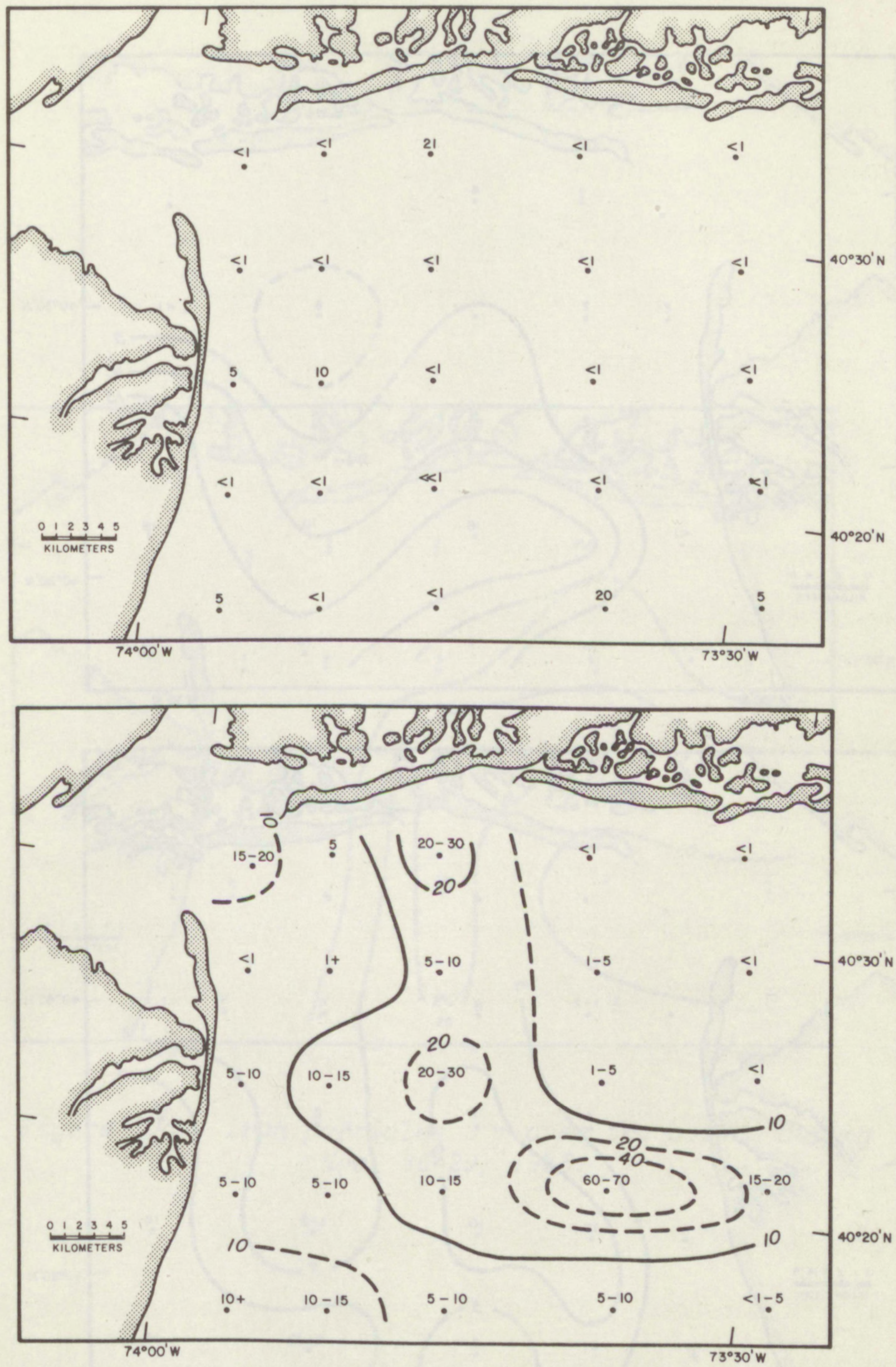
Figure 8. Texture of mineral grains suspended in surface waters during Sept. 16-19, 1973.

D. Segar and P. Hatcher of AOML and will be reported elsewhere. These studies should improve our knowledge of pollutant distribution and transport. Nevertheless, much can be learned concerning dispersal of suspended solids through studies of contaminants which can be readily identified and quantitatively measured under the microscope. Two such materials are common in the bight apex: yellow to orange-red iron hydroxide (?) and iron-stained plankton particles formed after dumping of iron-rich, dilute acid wastes in the southeast section of the area (fig. 1); and black soot grains which are most likely derived from the heavy ship traffic in the harbor and its approaches (Manheim *et al.*, 1970). Because the iron particles essentially originate at a point and are readily identified on membrane filters, they provide an excellent tracer for advective current patterns.

In uncontaminated ocean water, most iron is in the form of particulate iron compounds ranging from 2 to 20 μg/*l* (Sverdrup *et al.*, 1942; Lewis and Goldberg, 1954; Riley and Chester, 1971). Soluble iron carried by rivers is precipitated in saline waters owing to increases in ionic strength and pH (Aston and Chester, 1973). Similar reactions occur in the wake of the barges which dispose of the iron-rich, dilute acid industrial wastes in the bight. Gross (1972) estimated that about 800 tons of solid material are dumped at the acid-waste site every day (compared to ≈ 80 tons/day when this practice began in 1948; Ketchum *et al.*, 1951). Ketchum and his colleagues (1951) estimated the iron contribution from Hudson estuary as 40 to 50 tons/day; however, this estimate was made just after National Lead Company changed its dumpsite from the Raritan River (inside Hudson estuary) to the present offshore area. Consequently, it is likely that its data reflected the continuing "washing out" of sedimented iron from the estuary and river. During our field work, particulate iron particles, which were large enough to be counted under the microscope, averaged < 3/mm^2 of filter surface (3,000/l) near Hudson estuary. Thus, grain counts exceeding 3/mm^2 are considered to be indicative of material from the dumpsite. Generally, it is possible to determine the origin of iron particles using the grain-count distribution patterns.

The iron particles range in size from colloidal, yellow, filter coatings to sand-sized (> 62 μm) orange and red aggregates having the appearance of floccules of finer grains. X-ray diffractograms show no evidence for crystalline structure. Although this may result from the colloidal particle sizes and poor crystallinity, there is reason to believe that the orange and red grains are a mixture of hydrated iron oxide and iron-stained phytoplankton. In fact, the wide dispersal of this material in the bight supports the idea that some of it is low-density, easily transported plankton.

Figures 9 and 10 present the distribution of these particles derived from counts of the number of grains between 10 and 62 μm on 1 mm^2 of filter surface. In general, surface and mid-water samples near the acid-waste dumpsite contained a wide range of sizes from unresolvable colloidal material to medium silt. Concentrations near the bottom were typically higher (fig. 9 and 10) and coarser grained with some particles well into the very fine sand range. The trend toward coarser texture



(a) (b)

Figure 9. (a) Iron particles in surface waters during Oct. 1-4, 1973. Values are in number of grains (10 to 62 μm) counted in 1 mm^2 of filter surface. Refer to figure 1 for location of acid-iron dumpsite. (b) Iron particles near the bottom during Oct. 1-4, 1973. Values are in numbers of grains per mm^2 of filter surface.

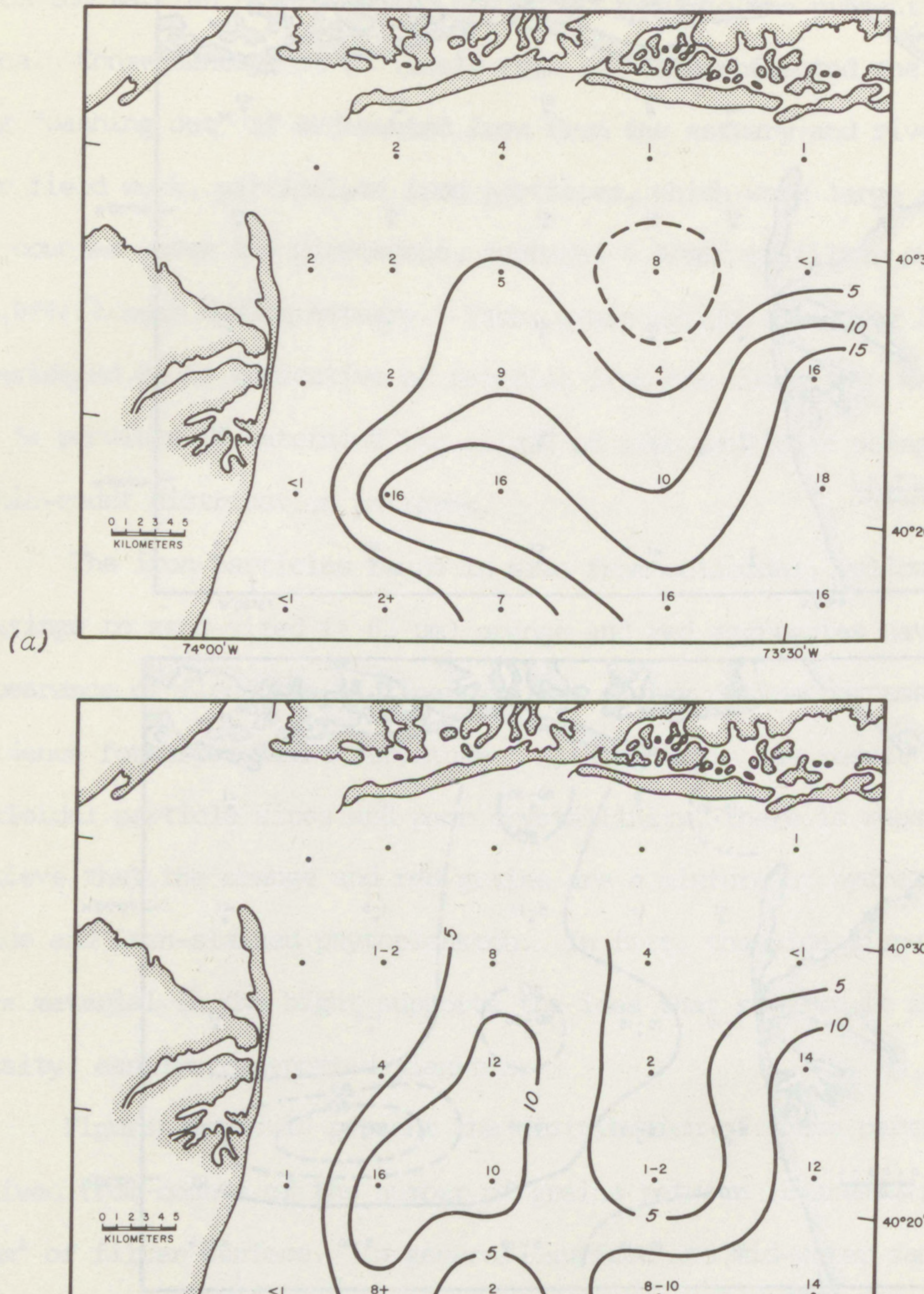


Figure 10. (a) Iron particles in surface waters during Nov. 26-29, 1973; and (b) iron particles at a depth of 10 m during Nov. 26-29, 1973.

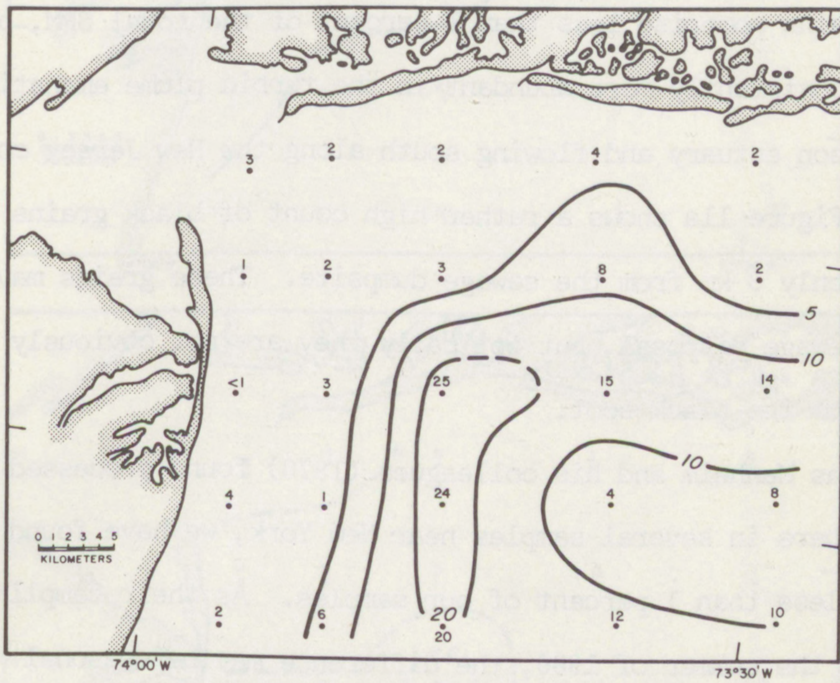


Figure 10c. Iron particles 2 m over the bottom during Nov. 26-29, 1973.

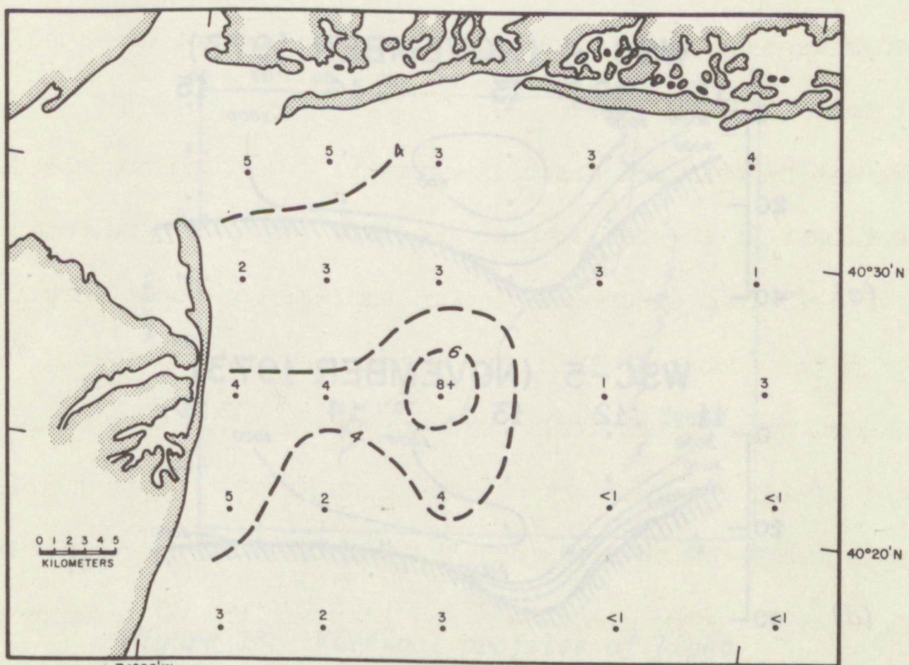
(and high grain counts) was particularly evident in near-bottom samples from the Hudson shelf channel in late November (stations 18 and 13; fig. 10).

Opaque, subspherical black grains and grain aggregates, ranging in size from fine silt to very fine sand are a common minor constituent of samples in the bight apex (Manheim *et al.*, 1970). In our samples, the black grains comprise less than 1 percent of the total SPM, but tend to be consistently more abundant in the turbid plume emanating from the Hudson estuary and flowing south along the New Jersey coast (fig. 11). Figure 11a shows a rather high count of black grains at station 13, only 3 km from the sewage dumpsite. These grains may be related to sewage disposal, but optically they are not obviously different from the black soot.

Whereas Manheim and his colleagues (1970) found processed cellulose fibers in several samples near New York, we have found this material in less than 1 percent of our samples. As their sampling was completed in the summer of 1966, the difference may be seasonal. However, it seems more likely that the few samples which they recovered coincidentally hit "patches" of heavily contaminated surface water.

Figure 12 presents representative examples of the vertical distribution of SPM throughout the fall season. The vertical profiles reflect the seasonal breakdown of temperature and salinity stratification. In early September, both temperature and salinity contribute to a stable stratification with a distinct, steep-gradient pycnocline between 15 and 25 m (fig. 13); the pycnocline tends to shoal toward

(a)



(b)

Figure 11. (a) Opaque black grains in surface waters during Nov. 26-29, 1973. Values are in number of grains per mm^2 of filter surface. (b) Opaque black grains 2 m over the bottom during Nov. 26-29, 1973. Values in no./mm^2 of filter.

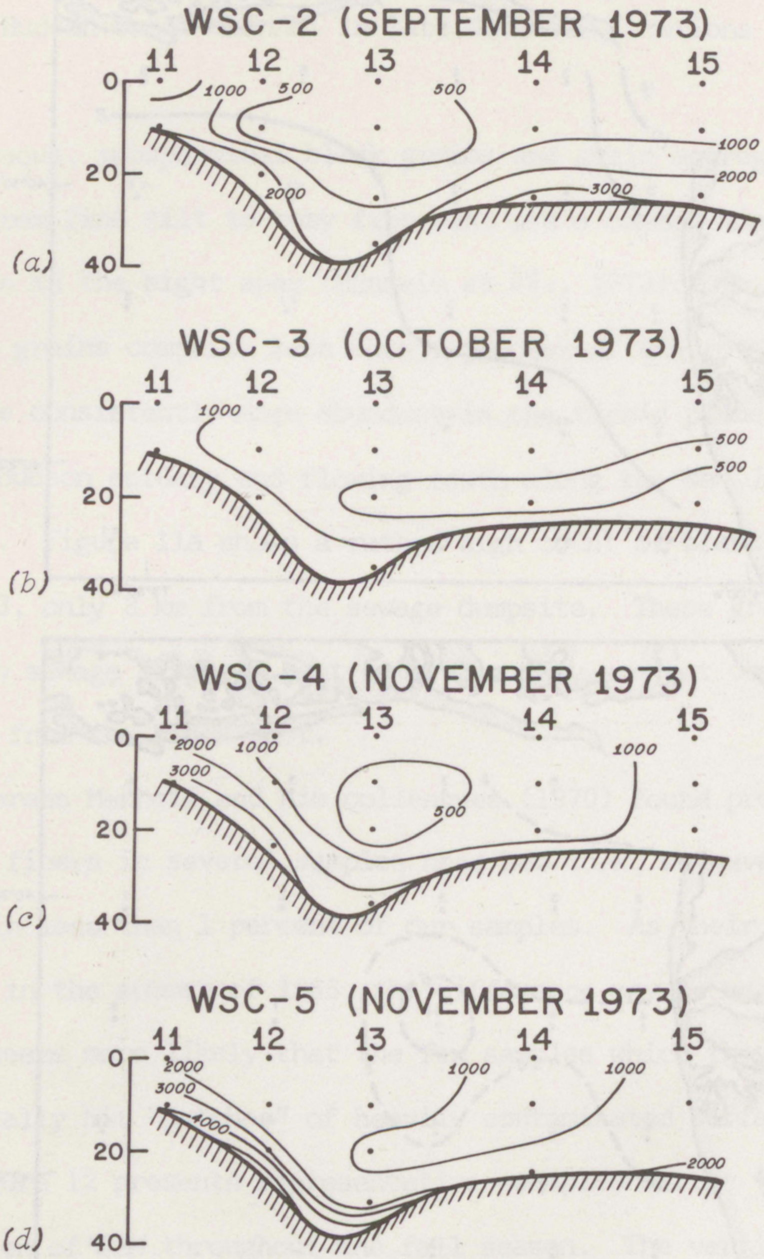


Figure 12. Cross sections of suspended particulate matter (in mg/l) through stations 11-15 for: (a) Sept. 16-19; (b) Oct. 1-4; (c) Nov. 5-9; and (d) Nov. 26-29, 1973. See figure 1 for station locations.

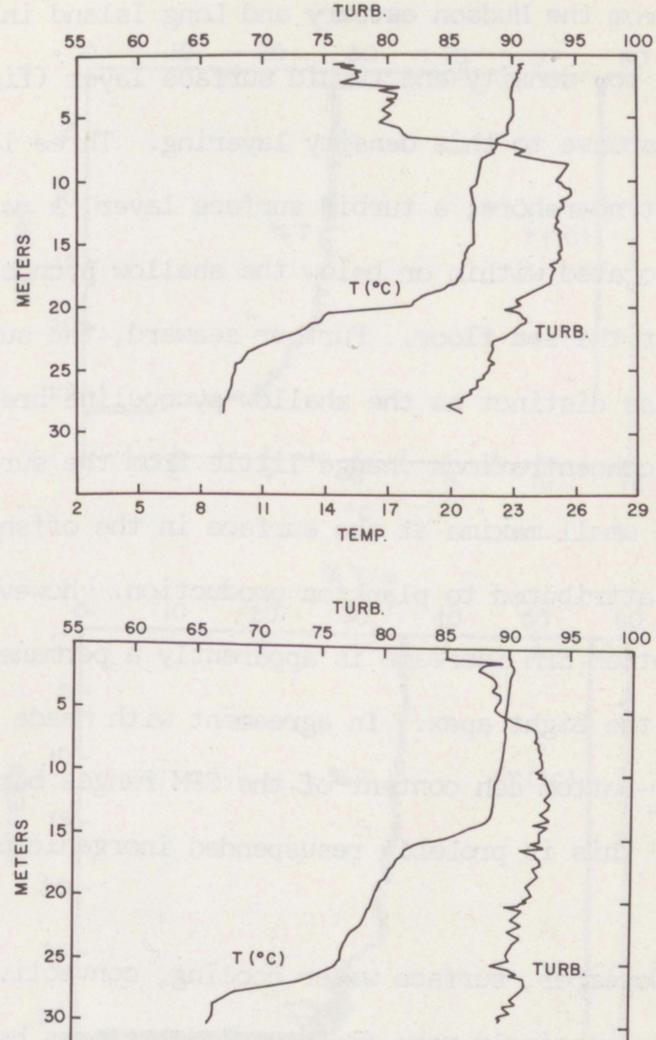


Figure 13. Vertical profiles of light beam transmission and temperature at stations 8 (upper plate) and 18 (lower plate) during Aug. 27-30, 1973.

shore, suggesting a slow upwelling of deeper shelf water. In nearshore areas (within 5 to 7 km of the coastline), flow of relatively low salinity water from the Hudson estuary and Long Island inlets produces a 5- to 10-m thick low density and turbid surface layer (fig. 12). SPM is stratified in response to this density layering. Three layers are typically present nearshore; a turbid surface layer, a *relatively* clear mid-water zone located within or below the shallow pycnocline, and a turbid layer near the sea floor. Further seaward, the surface turbid layer becomes less distinct as the shallow pycnocline breaks down. In such cases, SPM concentrations change little from the surface through mid-depths. The small maxima at the surface in the offshore parts of the area can be attributed to plankton production. However, the significant near-bottom SPM increase is apparently a permanent feature of all portions of the bight apex. In agreement with Meade *et al.* (in press), the near-bottom ash content of the SPM ranges between 40 and 84 percent; most of this is probably resuspended inorganic clay and silt (fig. 6).

By late November, surface water cooling, convective mixing, and the effects of increasingly more frequent local storms had produced a nearly homogenous surface layer ranging from 10 to 30 m in thickness (fig. 14). The vertical distribution of SPM reflected the weak stratification, with essentially uniform concentrations from the surface to the top of the near-bottom turbidity increase at many stations. The upper boundary of the bottom layer shows a striking correlation with the

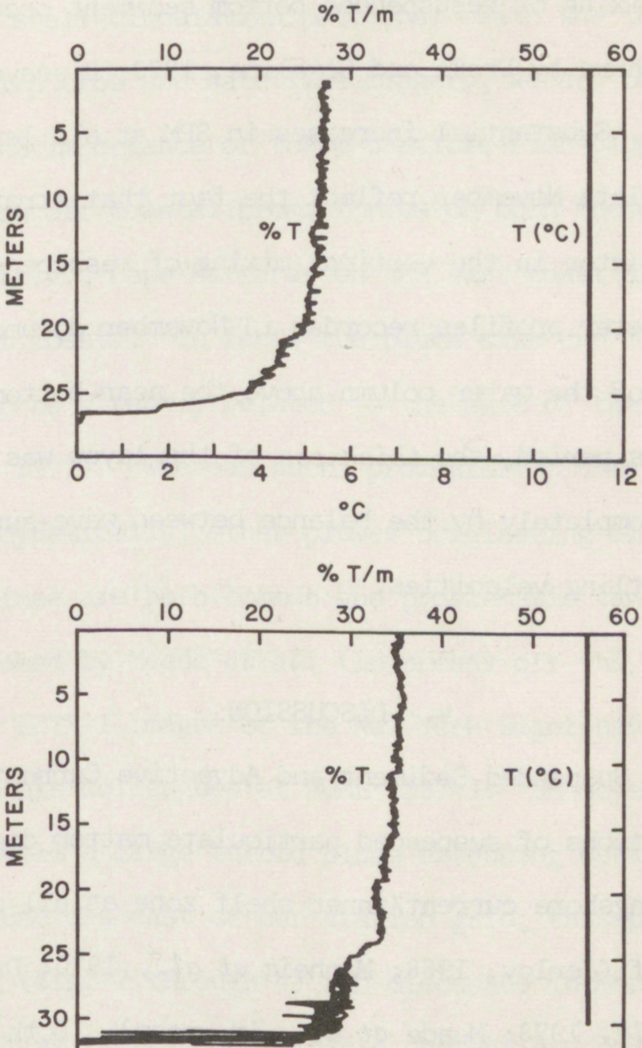


Figure 14. Vertical profiles of light beam transmission and temperature at stations 8 (upper plate) and 18 (lower plate) during Nov. 26-29, 1973.

position of the "main" pycnocline (fig. 12 through 14). The thickness of this particle-rich layer apparently is controlled by the ease with which vertical mixing of resuspended bottom sediment occurs (as has been found elsewhere by Drake and Gorsline, 1973; Biscaye and Eittreim, in preparation). Substantial increases in SPM at all levels of the water column in late November reflect the fact that stratification was not a limiting factor in the vertical mixing of resuspended bottom muds. Beam transmissometer profiles recorded in November document the well-mixed character of the water column above the near-bottom layer (fig. 14). During this period, the *thickness* of the layer was probably controlled almost completely by the balance between wave-surge turbulence and particle-settling velocities.

4. DISCUSSION

4.1 Suspended Sediment and Advective Currents

Concentrations of suspended particulate matter decrease rapidly away from the longshore current/inner shelf zone at all depths over the continental shelf (Jerlov, 1968; Manheim *et al.*, 1970; Drake *et al.*, 1972; Emery *et al.*, 1973; Meade *et al.*, in press). Both the inorganic and the organic fractions contribute to the decrease, but the decline in terrigenous detritus (derived from the rivers and coastal wetlands) is the major factor in this steep, seaward gradient. Additionally, currents tend to be coast-parallel within a few kilometers of shore (see McCave, 1972), and SPM moves seaward principally within rather widely spaced, cross-shelf advective plumes (Drake, 1972) or by diffusive mixing.

Advective mixing involving cross-shelf transport must produce measurable perturbations on the general seaward SPM gradient and thus aid in defining shelf-circulation patterns. With the increased availability of aerial photos and satellite imagery, we are becoming aware of the existence and importance of these particle-rich plumes. They appear to be very common off coastal promontories on both the Atlantic and Pacific coasts (e.g., Cape Hatteras on the east coast and Point Conception on the west coast). In fact, the plume size and its offshore extent appear to be directly related to the size of the coastal promontory (Drake, 1972). Whereas such "promontory plumes" are readily explained hydrodynamically, other plumes originating along essentially straight coastlines are both common and problematic (an example of this type has been found by Meade *et al.* (in press) off the central New Jersey coast). ERTS-1 images of the New York Bight have been studied by Charnell and his colleagues at AOML (1974). On several occasions, these images reveal a large turbid plume extending southward from the coast a few kilometers east of our station grid; this plume is detected in our SPM data (fig. 2 through 4) and discussed in more detail later. In these situations, suspended particle content and composition can be used effectively to determine the *pattern* of "relatively permanent" advective shelf currents even though the driving mechanisms may elude us (Jerlov, 1968; Drake, 1971). The areal distributions of SPM in the New York Bight apex illustrate this method (fig. 2 and 3).

The data at 10 m for the fall season show a persistent pattern characterized by the following:

(1) Surface waterflow out of Hudson estuary turns to the south and forms an easily distinguishable, turbid current along the New Jersey coast. If we use an SPM concentration of > 1.0 mg/l to mark arbitrarily the seaward limit of this current, it averaged 4 to 6 km in width.

(2) A sharp decline in SPM and a marked composition change occur in moving from the Hudson "plume" to the east. In fact, the lowest SPM concentrations in the area are commonly present over the north- to south-trending Hudson shelf channel (see fig. 2 through 5). Samples above the channel contain numerous diatoms which are common over the middle shelf, and Hatcher (personal communication, 1974) has found that these samples are rich in high protein phytoplankton. In addition, the water within the channel is often colder than water at the same depths elsewhere in the area. These data demonstrate a northward (upslope) flow of water from offshore along the Hudson shelf channel, although it is not yet certain to what degree this current is confined to the channel. When meteorological conditions are appropriate (strong westerly or northwesterly winds), this current reaches the sea surface and may extend north to within at least 5 km of Long Island (see fig. 2a).

Studies of the currents within submarine canyons on the Pacific coast of the United States have shown that they periodically reverse in response to tides and perhaps internal waves (Shepard and Marshall, 1969; 1973). Usually a net drift of the bottom water is superimposed on the oscillatory currents. In most canyons studied, the drift averages a few cm/s and is decidedly *down canyon*. The current oscillations occur with periods ranging from minutes to 6 to 8 hr, and speeds are typically between a few and 50 cm/s. Consequently, fine sediment maintained in suspension by the high speed events is slowly moved down canyon by the net drift (Drake and Gorsline, 1973). G.H. Keller and F.P. Shepard have recently collected long current recordings in Hudson Canyon seaward of the continental shelf break, and these show similar reversing flows. The calculations of net down-canyon drift are not yet available. Within the Hudson shelf channel (that portion of the system incising the shelf), J.W. Lavelle and G.H. Keller of AOML made one 11-day recording 1 m off the bottom at a depth of 62 m (≃ 6 km south of our study area). This record reveals that the shelf channel orientation controls the direction of near-bottom currents which are driven by both tides and surface winds. Extended periods of flow up or down the shelf channel were clearly related to wind direction and to the initiation of hydraulic currents. Up-channel flow occurred when surface winds swept water above the summer pycnocline seaward, whereas winds producing an onshore pile-up of water caused flow down the channel (Lavelle, personal communication, 1974). Both trace metal (Carmody *et al.*, 1973) and organic analyses (Hatcher, in preparation) show movement of contaminated sediment down Hudson shelf channel. On the other hand, suspended sediment data presented in this report reflect up-channel transport in the bight apex. Considerably more current measurements are needed to determine the degree to which surface winds and channel-currents are coupled, particularly, the seasonal variations in the system. Nevertheless, it is apparent that sediment dispersal along the channel both to the north and south is an ongoing process. Material dumped into this topographic low will be widely dispersed, and contaminants will be exported to areas far removed from the dumpsites.

(3) Figures 9 and 10 show that the Hudson shelf-channel current turns to the east-northeast following the configuration of the broad channel head. Eastward flow appears to occur subparallel to the shelf bottom contours between the depths of 10 and 20 m. The current, therefore, flows over the shoreward end of Cholera Bank. The fate of this flow is not clear. During all surveys, a particle-rich plume was present, trending south along the eastern margin of our area (fig. 2a, 4, and 5). As discussed earlier, this plume is easily recognized on ERTS-1 images and resembles an enormous rip current. This geometry suggests a southward deflection of the eastward current along the east flank of Cholera Bank.

The circulation system described above is completely supported by the dispersal pattern of iron hydroxide and iron-stained grains (fig. 9 and 10). In particular, data from the fifth survey suggest the degree to which the circulation is topographically controlled.

4.2 Suspended Sediment Textures

The size distribution of inorganic *mineral* grains in suspension was determined for the fifth survey and for the *surface* samples taken during the second survey (fig. 7). Inorganic minerals typically make up 25 to 50 percent (by volume) of the total suspended matter close to shore and near the bottom. In the seaward portions of the apex and within clear waters from the central shelf, the mineral content is from below 5 to 10 percent.

During the earlier of the two cruises, the suspended sediment was predominantly fine silt and clay with < 10 percent of the particles larger than 16 μm. The material counted as > 16 μm was, in nearly all cases, aggregates of many smaller grains bound together by amorphous organic matter. Although the microscope technique contributes to the apparent areal uniformity of the size distributions, it is clear that the texture of the mineral matter during September was similar at all stations. The predominance of < 8-μm material supports the suggestion that larger particles are either trapped inside the estuary or settle rapidly near the estuary mouth.

The November surface-water data show a significant coarsening of the suspended solids which we attribute to the addition of material from bottom resuspension. Nevertheless, most samples are predominantly composed of < 16-μm particles. Near the sea floor, the addition of mica, quartz, and grain aggregates in the silt-to-sand sizes was particularly evident over Cholera Bank and along the east wall of the Hudson shelf channel.

The sediment carried by the Hudson estuary plume along the New Jersey coast is texturally distinctive. Even the near-bottom suspensions are predominantly < 16 μm and generally become finer grained toward the south; this trend is well shown in the surface water samples (fig. 7). Except for samples near the sea floor, suspended particles larger than 16 μm are rarely single grains. Thus, the textural change which occurs as the Hudson plume moves southward is probably the result of the settling of large aggregates and agglomerates of organic and inorganic clay and very fine silt from the surface layer. These results are in agreement with the large body of data which show that Atlantic coastal plain estuaries are efficient sediment traps (see Meade, 1969; 1972). Salt balance considerations, direct current measurements, siltation studies, and bottom drifter surveys demonstrate landward flow of near-bottom, saline water into estuaries (Harrison *et al.*, 1967; Meade, 1969). Because reduced salinity surface water extends over the inner shelf, an "extended" estuarine-like circulation is typically developed within a few kilometers of estuary mouths (Gross *et al.*, 1969). Therefore, while estuary-mouth tidal currents are strong and mix coarse material into surface layers, this material settles back into the landward-flowing, saline bottom water within a few kilometers seaward of the estuary. Thus, only the finest sediment (< 8 μm) which moves with the surface water and escapes inclusion in grain aggregates can avoid transport into the estuaries along the coast.

Detailed investigation of the concentrations, composition, and settling rates of aggregates is planned. Our initial observations indicate that aggregates and fecal pellets are particularly abundant in the estuary mouth and along the transition zone between turbid coastal water and clearer open-shelf waters. Manheim *et al.* (1972) observed similar aggregate distributions in the Gulf of Mexico. Our future work will include Coulter Counter particle-size analyses. At the present time, we do not have sufficient data to draw firm conclusions regarding the regional patterns of suspensate texture.

4.3 Suspended Sediment Transport and Bottom Sediment Distribution

Recent research on shallow marine sedimentation has emphasized the difference between processes occurring during fair weather and storm conditions (Swift, 1970; Smith and Hopkins, 1972; Drake *et al.*, 1972; Rodolfo *et al.*, 1971; Sternberg and McManus, 1972). Undoubtedly, sedimentation at the shallow depths in the bight apex (mostly < 30 m) is very strongly influenced by winter storms. Owing to the weak density stratification in the winter, the transfer of wave- and wind-current energy to the bottom should be more efficient (Komar *et al.*, 1972), and, as shown by the SPM concentrations in late November, the vertical mixing of fine silt and clay sediment is relatively unimpeded. In an attempt to get some idea of how much fine sediment is entrained during storms, this author assumed that the data before our last survey are representative, "fair weather" data (September 16 through November 9). The assumptions involved are that contribution of "new" material from land and plankton production were constants. This is unlikely but our microscope analysis of the fall filters indicates that plankton standing crops in September and October were higher than those in November. Thus, the concentration differences (in terms of inorganic components) should, in fact, be greater, and we can take the computed "storm-entrained" amount as a minimal value. The November storm involved high velocity winds (20 to 30 kt), but no coastal precipitation; therefore, we will assume a constant discharge from the Hudson estuary. Using all data for surveys 2 through 5 (September 16 through November 29), the mean difference in SPM for the apex water volume between the early surveys and the fifth survey is approximately 0.5 mg/l. This omits the poorly known concentrations in the near-bottom zone (0 to 5 m above bottom) and, therefore, is a conservative estimate. The volume of the bight apex (fig. 1) included within our station grid is roughly 20 km^3 which yields a suspended solids "excess" of about 10,000 metric tons in late November, assuming a particle density of 2.0 g/cc. Some appreciation of the magnitude of this is gained if it is recalled that one barge load of sewage contains between 100 and 200 metric tons of solid material (on an average day, five barges dump sewage in the bight apex). The amount of material resuspended by more intense storms and longer period waves remains unknown, but it is obvious that winter storms must be of great importance in determining the ultimate fate of all particulate materials in the bight apex.

Although winter conditions accelerate sediment transport, our data suggest that under all conditions a near-bottom layer of particle-rich water is characteristic of the area (fig. 12 through 14). In the deep sea, this turbid layer has been termed the "nepheloid layer" (Eittreim *et al.*, 1969), and it appears to be a fundamental feature of vertical profiles of SPM over continental shelves (Spencer and Sachs, 1970; Drake, 1972; Buss and Rodolfo, 1972; Lisitsin, 1972). The particles in this zone are usually mostly noncombustible, and the terrigenous fraction is slightly-to-markedly coarser grained than near-surface material (fig. 7). SPM concentrations in the nepheloid layer in the bight apex were, with few exceptions, as high or higher than at any other level in the water column.

Observations of the Middle Atlantic Coastal Fisheries Center (1972) and ERTS-1 satellite imagery data (Charnell *et al.*, 1974) showed that surface turbidity increases resulting from sewage dumping and dredge spoiling may extend for several square kilometers to tens of kilometers around the dumpsites. Our data do not show any large increases in surface SPM near either site, but this probably is a function of our wide station spacing. In the future, we will conduct very detailed investigations of both dumping operations to determine: (1) the proportions of floating and rapidly settling materials; (2) the particle settling rates; and (3) the areal extent of impact. At the present time, we tentatively expect that most of the dumped material settles to the near-bottom zone within a few kilometers of each site. This does not mean that all, or even a large part, of a given barge load deposits on the bottom, but rather, it may be dispersed largely within the nepheloid layer. The distribution of suspended solids near the bottom in late November tends to support this conclusion (fig. 4d). Concentrations ranged from 0.91 to 5.5 mg/l, with most of the higher values (> 2 mg/l) present near the estuary and beneath the Hudson turbid plume. However, it is noteworthy that the highest concentrations beyond 5 km from shore were present near the dredge spoil and sewage sludge dumpsites. These highs are generally surrounded by a large area of turbid water containing more than 3.5 mg/*l* of SPM which apparently extends into the Hudson estuary. In addition, a band of relatively high particle concentrations was present trending eastward over Cholera Bank from the main sludge bed in agreement with the circulation pattern discussed earlier.

Charnell *et al.* (1972) have suggested that a part of the bottom water moving north along Hudson shelf channel continues into the estuary, whereas the data discussed here demonstrate transport out of the valley head to the east-northeast. These conclusions are not in conflict, but are a logical consequence of the "extended" shelf-estuarine circulation (Charnell *et al.*, 1972; Gross *et al.*, 1969; Harrison *et al.*, 1967) and the clockwise central-apex gyre (Charnell *et al.*, 1972; and this report).

The implications of what has been learned from our study of one season in the bight apex are:

(1) Future investigations of pollutant transport should focus on physical and chemical processes within 10 m of the sea floor.

(2) Iron particles formed following chemical waste disposal are an excellent current tracer. Dispersal of this material from the southeastern part of the area follows current patterns indicated by SPM distributions and is recently supported by direct current-meter measurements (Charnell, personal communication, 1974). Of particular significance is the wide dispersal of silt-sized iron particles found in the nepheloid layer in October 1973 (fig. 9). Although the method of

disposal of the iron-rich acid (pumping from a moving barge) undoubtedly contributes to this wide dispersal, it also is evident that no part of the bight apex which we have sampled is free of contamination.

(3) The dredge spoil and sewage dumpsites are located on either side of the Hudson shelf channel head, apparently within a current with a net northward flow during the fall season. As shown in figure 2a, this current at times can be traced as far north as 5 km from the Long Island coast where our stations start; it is probable that the current is closer to the shore than 5 km. However, this current appears more often to turn to the east as it flows out of the shelf channel. During November 1973, the pattern was especially well-defined by concentrations of silt and fine sand-sized iron particles (fig. 10). The distribution of "sewage-derived muds," determined from intensive sampling by the Middle Atlantic Coastal Fisheries Center (1972) and by Cok (unpublished data), strongly suggests that this material is being entrained by the shelf channel current and clockwise gyre (fig. 15). The distribution of organic matter in the bottom sediments reflects initial deposition of sewage and dredge spoil within the amphitheater of the shelf channel. It is noteworthy that Cok (unpublished data) found relatively clean sand immediately below the sewage dumpsite; black, cohesive muds are present several kilometers to the west of this site on the eastern slope of the shelf channel. The thickness of these black muds is thought to be less than 1.5 m, based on 3.5-KHz profiling and bottom sampling (Freeland, personal communication, 1974). Unless sewage barges have been consistently short-dumping, it is evident that this material is not accumu-

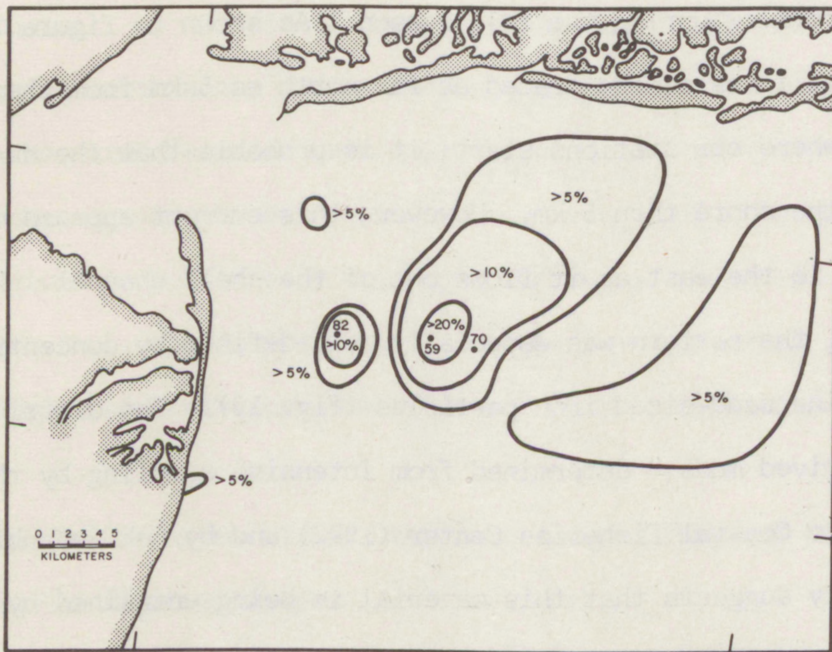


Figure 15. Total organic matter in surficial bottom sediments of New York Bight (after Middle Atlantic Coastal Fisheries Center, 1972). Recent work by Hatcher (AOML) has shown that high organic-carbon values extend south from the valley head following the course of Hudson shelf valley.

lating on Cholera Bank (beneath the designated dumpsite), but rather is being swept westward to form a thin but widespread lens of organic-rich sediment.

In addition to the channel-head deposit, a second lens of organic-rich silty sand is present on the eastern flank of Cholera Bank (fig. 15). The connection between this deposit and the primary deposit is not well defined, but evidence for a connection has been found in the ratio of carbohydrates to total organic carbon in bottom sediments over Cholera Bank (Hatcher, in preparation) and in our near-bottom SPM data (see fig. 4d and 10). Higher current energies along the crest of Cholera Bank are to be expected, and this is the simplest explanation for the lack of a mud deposit beneath the sewage dumpsite and a clear (textural) connection between the two areas of organic-rich material. Silt and clay entrained from the valley head deposits are moved north and east in the nepheloid layer by the clockwise gyre. These sediments are prevented from settling until the advective current has traversed the sand bank and begun to flow south-southeast into deeper water. The particulate load then settles in topographic lows which afford sufficient protection from wave surge and wind-related currents.

(4) Sediments entering the shelf channel also are actively carried to deeper water by downslope bottom currents caused by the pile-up of wind-driven surface water along the Long Island coast (Lavelle, personal communication, 1974) and tide-driven current reversals.

5. SUMMARY

Although the results presented in this report cover only a small portion of 1 year and many more analyses on these and other samples remain to be completed, it is possible to advance several important conclusions.

Northward flow and possible upwelling along the Hudson shelf channel are indicated by the persistence of relatively particle-free water within and above this topographic low. The "open shelf" water at times reaches close to the Long Island coast, but probably subsequently turns and flows eastward parallel to bottom contours between 10 and 20 m. A portion of this flow probably also moves directly into the Hudson estuary. Although supporting evidence is not strong, there is some justification for a southward turn of the current along the east flank of Cholera Bank to complete a clockwise gyre. Such an advective current geometry would seem to agree with the distribution of organic-rich (sewage?) muds on the bottom (Middle Atlantic Coastal Fisheries Center, 1972).

Major transport of fine particulate load along the New Jersey coast occurs within a surface layer of low salinity water contributed by the Hudson estuary. Textural analyses suggest that much of the coarser material (> 16 μm) and an indeterminate amount of aggregated, finer detritus in this current settle into the near-bottom zone close to the estuary mouth. Formation of organic aggregates containing significant amounts of inorganic mineral matter appears to occur near the mouth of the estuary.

In areas not influenced directly by the Hudson turbid plume, the bulk of the transport of detritus takes place in the nepheloid layer. The apparent permanence of this near-bottom, turbid "haze" indicates the importance of current activity and resuspension processes. Our data show that the seasonal breakdown of water column stratification and the passage of winter storms will lead to increased erosion of muds deposited during quieter periods and not yet appreciably compacted.

Iron hydroxide and iron-stained particles formed following acid waste disposal in the southeast corner of the area are spread widely by apex currents. If one allows that other waste materials can be dispersed as easily, the recent discoveries of "sewage sludge" deposits nearly 15 km northeast of the dumpsite and high concentrations of trace metals and organic matter nearly 30-km seaward in the shelf channel should be expected.

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APPENDIX. SUSPENDED SOLIDS DATA

Station	Sample depth(m)	Sept. 16-19 SPM	Sept. 16-19 % ash	Oct. 1-4 SPM	Oct. 1-4 % ash	Nov. 5-9 SPM	Nov. 26-29 SPM	Nov. 26-29 % ash	SPM averages	Bottom sediment	Station depth(m)
1	1	3.2		2.8	63	1.9	4.8		3.2	Clean, fine-med. sand	14
	10	8.6		2.8	84	12.1	3.9		7.0		
2	1	0.5		2.2	40	2.4	2.5		1.9	Clean, fine sand	12
	12	1.2		3.0	75	2.0	3.9		2.8		
3	1	0.2		1.0	33	1.5	2.7		1.3	Green, very fine sand	20
	10	0.25		0.64	62	1.5	2.2		1.6		
	18	4.9		0.7	--	4.8	2.2				
4	1	0.9		1.6	50	2.1	1.3		1.5	Clean, med. sand	18
	12	2.6		1.5	77	1.6	1.6		1.6		
5	1	1.3		1.3	56	2.3	3.5		2.1	Clean, fine-med. sand	16
	12	9.9		2.6	73	2.1	3.5		4.2		
6	1	2.3		1.9	45	1.9	2.4		2.2		11
	10	6.6		1.2	51	2.5	3.9		3.5		
7	1	0.6		1.9	68	1.5	1.4		1.3	Green-brown silt and sand	22
	10	0.5		0.9	46	1.1	1.6		1.0		
	20	3.6		1.1	63	2.8	2.4				
8	1	0.2		2.0	39	1.2	2.1		1.4	Silty, very fine sand	28
	10	0.5		0.4	26	1.0	1.9		1.0		
	20	0.3		---	--	---	3.2		---		
	25	11.6		2.2	64	2.3	3.6				
9	1	1.8		0.9	16	0.9	1.2		1.2	Clean, med.-coarse sand	25
	10	1.1		0.6	13	0.5	0.7		0.7		
	22	1.3		0.9	45	1.0	1.2				

Appendix. Suspended Solids Data (continued)

Station	Sample depth(m)	Sept. 16-19 SPM	Sept. 16-19 % ash	Oct. 1-4 SPM	Oct. 1-4 % ash	Nov. 5-9 SPM	Nov. 26-29 SPM	Nov. 26-29 % ash	SPM averages	Bottom sediment	Station depth(m)
10	1	1.0		0.6	16	1.3	1.2		1.0	Clean, fine sand	24
	10	0.8		0.7	35	1.3	0.7		0.9		
	20	4.1		3.1	68	1.3	0.8				
11	1	2.1		1.8	52	1.9	1.9		1.9	Fine-med. sand	12
	10	1.9		1.2	53	3.2	3.7		2.5		
12	1	0.6		0.9	39	1.0	1.8		1.1	Mottled red and green mud	22
	10	0.4		0.7	50	1.1	1.3		0.9		
	20	2.7		1.1	76	3.2	5.5				
13	1	0.4		0.8	30	0.7	1.4		0.8	Black mud and silty sand	37
	10	0.1		0.7	81	0.4	1.3		0.7		
	20	0.6		0.4	22	0.5	0.9				
	35	1.6		1.6	72	2.2	4.0				
14	1	1.0		0.9	32	0.8	0.8		0.9	Fine-med. sand	25
	10	0.9		0.7	38	0.8	0.6		0.8		
	20	2.0		0.2	83	0.8	---				
	24	3.0		---	--	---	1.6				
15	1	0.7		0.6	33	1.2	1.2		0.9	Clean, med. shelly sand	25
	10	0.6		0.5	--	1.2	1.8		1.0		
	20	2.0		0.6	56	1.2	2.1				
16	1	0.8		1.2	44	1.4	1.4		1.2	Coarse, shelly sand	22
	10	0.8		0.7	76	1.2	1.5		1.1		
	20	1.3		1.7	80	1.6	3.0				
17	1	0.5		0.9	50	0.9	0.7		0.7	Coarse, shelly sand	27
	10	0.4		0.5	65	1.1	0.7		0.7		
	25	1.0		1.0	70	3.9	2.6				

Appendix. Suspended Solids Data (continued)

Station	Sample depth(m)	Sept. 16-19 SPM	Sept. 16-19 % ash	Oct. 1-4 SPM	Oct. 1-4 % ash	Nov. 5-9 SPM	Nov. 26-29 SPM	Nov. 26-29 % ash	SPM averages	Bottom sediment	Station depth(m)
18	1	0.7		0.6	53	0.4	0.7		0.6	Yellow-orange fine sand	32
	10	0.3		0.4	8	0.5	0.8		0.7		
	20	0.6		0.4	57	0.5	0.8				
	30	3.1		0.4	70	0.6	2.7				
19	1	0.7		0.9	43	0.5	1.0		0.8	Med. clean sand	27
	10	0.8		0.7	18	0.8	0.7		0.8		
	20	0.8		0.6	69	0.5	0.8				
	25	2.2		---	--	---	0.7				
20	1	1.3		0.4	32	0.6	1.4		0.9	Med. coarse sand	29
	10	0.3		0.3	12	0.6	1.6		0.7		
	20	1.1		0.3	77	0.5	1.4				
	28	0.7		0.5	72	0.6	0.9				
21	1	1.2		1.2	43		2.1		1.1	Clean, med. sand	22
	10	0.6		1.1	45	1.1	0.9		0.9		
	20	1.9		1.0	49	1.2	1.6				
22	1	0.2		0.5	14	0.5	0.7		0.5	Coarse, shelly sand	27
	10	0.2		0.5	9	0.5	0.8		0.5		
	25	0.9		0.7	40	0.6	1.2				
23	1	0.3		0.5	54	0.4	0.7		0.5	Green, silty fine sand	52
	10	0.1		0.5	23	0.5	0.7		0.4		
	20	0.4		0.4	47	0.5	0.6		0.5		
	30	0.7		0.4	51	1.6	0.6				
	48	1.4		0.6	--	3.4	1.2				
24	1	0.9		0.7	45	0.4	1.3		0.8	Very fine sand	28
	10	0.3		0.5	22	0.3	0.7		0.4		
	20	0.6		---	--		0.9		0.75		
	25	1.1		0.5	66	0.4	1.0		0.75		

Appendix. Suspended Solids Data (continued)

Station	Sample depth(m)	Sept. 16-19 SPM	Sept. 16-19 % ash	Oct. 1-4 SPM	Oct. 1-4 % ash	Nov. 5-9 SPM	Nov. 26-29 SPM	Nov. 26-29 % ash	SPM averages	Bottom sediment	Station depth(m)
25	1	0.3		0.3	50	0.8	1.2		0.6	Clean, fine-med. sand	33
	10	0.2		0.3	15	0.7	1.3		0.6		
	20	0.7		---	--	0.5	1.2				
	30	0.8		0.5	64	0.5	1.5				

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