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Distribution of Suspended Particulate Matter, Patuxent River Estuary, Maryland

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DISTRIBUTION OF SUSPENDED PARTICULATE MATTER,

PATUXENT RIVER ESTUARY, MARYLAND

by

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ABSTRACT

DISTRIBUTION OF SUSPENDED PARTICULATE MATTER, PATUXENT RIVER ESTUARY, MARYLAND

Christopher W. Frye
Old Dominion University, 1988
Chairman: Dr. George F. Oertel

Physical processes which may affect estuarine circulation in a coastal plain estuary were monitored to determine their relative importance on temporal and spatial variability of the concentration, composition, and particle-size of suspended particulate matter (SPM) in Patuxent River estuary, MD, during 1985-86. Discharge rates from Patuxent River determined the character of fresh and estuarine water mixing, and magnitude of SPM concentration in the upper estuary. The mixing zone between fresh and estuarine water, defined as 0 - 1.5 °/oo, and turbidity maximum were geographically separated during most of the study period. This suggests that two-layer circulation may be less important than bottom sediment type, scouring ability of tidal currents, and seasonal increases in SPM concentrations related to pulses of freshwater runoff, in the formation of upper estuary turbidity patterns.

Wind direction and magnitude had little affect on SPM concentration for upper and lower estuary stations, but longitudinal variation in tidal current velocity was significantly correlated ($r^2 = 0.81$) with SPM concentration. Lower estuary SPM particle-size and composition, dominated by organic constituents 16.0 - 20.0 μm in diameter, were horizontally

limited by rapid salinity change and a large reduction in channel cross-sectional area landward of station 4. Upper estuary SPM was characterized by very-fine to fine-silt. However, large aggregates ranging between 25.0 - 32.0 μm in diameter were noted in the upper estuary in the summer, coincident with summer algal blooms.

TAKE ME TO THE RIVER
DROP ME IN THE WATER

-David Byrne-

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This study would not have been possible without the support provided by Benedict Estuarine Research Laboratory. Jim Sanders, Kevin Sellner, and Richard Vroom Lacouture were instrumental in providing equipment, shiptime, advice, and a bunk during the early developmental stages of this project. Sample collection was made possible with the assistance of the R/V Lark and the crew of the R/V Discovery.

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Finally, inevitable credit has to be given to my mother and father for their unfaltering encouragement and support. I know no better way of saying how I feel than "well thanks."

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1. INTRODUCTION

Statement of Problem

The Atlantic coastal plain estuaries of the United States have many similarities among their hydrodynamic processes and distributions of suspended matter. Pritchard (1955) used stratification and circulation to classify estuaries into four major groups; stratified, partially mixed, sectionally well mixed, and vertically well mixed. Estuaries of the Chesapeake Bay estuarine system are typically partially mixed. A net two-layer circulation pattern, associated with partially mixed estuaries, traps fine-grained suspended matter near the head of the estuary (Postma, 1967). The upper layer of estuarine water exhibits a net seaward flow, while the lower layer has a net landward flow. Suspended particles settling into the lower layer are transported upstream to the freshwater-estuarine interface. Following vertical ascent, particles repeat the process and ultimately form a turbidity maximum (Figure 1).

Postma (1967) proposed that the maximum concentration of suspended particulate matter within the "turbidity maximum" depends on several factors, most importantly, the amount of suspended matter in the river or sea. Intensity of the two-layer circulation pattern, or magnitude of the net velocity shear, and the settling velocity of available material were reported as secondary factors. However, Meade (1968) suggested that the maximum concentration of suspended particulate matter within the turbidity maximum was directly related to the intensity of the two-layer circulation pattern. The amount of material in the river and the intensity of the two-layer circulation pattern are related to the quantity of inflowing freshwater; therefore, it is difficult to determine which is more influential on the development of a turbidity maximum (Meade, 1968).

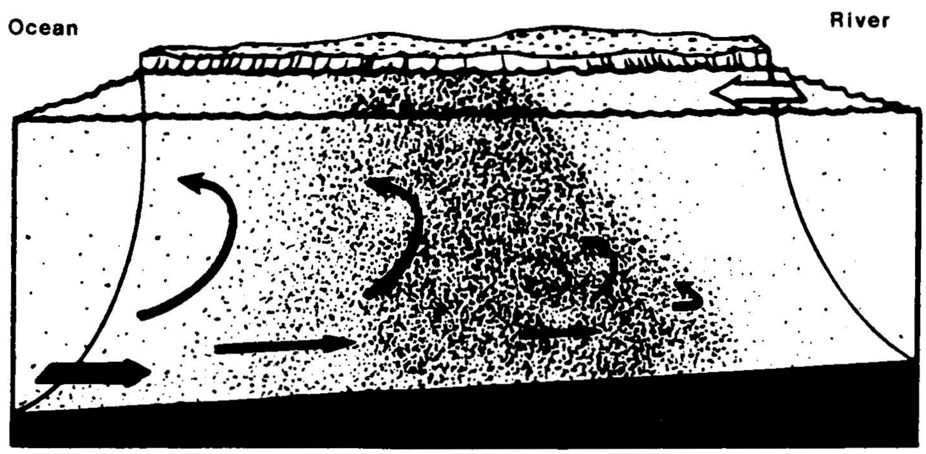


Figure 1: Coastal plain estuary circulation and suspended matter accumulation patterns (adapted from Pritchard, 1955).

Meade (1969) suggested that an optimal ratio between tidal input and river input (estuary number or N) may account for strongly developed two-layer circulation patterns. Officer (1976) developed an estuary circulation classification scheme based on the ratio of FI/TI or N, where TI is the volume of seawater entering the estuary between low and high tide, and FI equals the volume of freshwater entering the estuary over the same time span. A stratified estuary exists when N is of the order of 1, a partially mixed estuary when N is of the order of 0.1, and a vertically mixed estuary when N is of the order of 0.01. Typical estuary numbers for the James River and Patuxent River estuaries during low and high flow are 0.0002 to 0.08 (vertically to partially mixed), and 0.00001 to 0.05 (vertically mixed).

Factors causing variation in estuary numbers are river discharge, tidal range, spring-neap tidal cycles, and variable channel geomorphology. Although wind-induced waves result in resuspension and increased mixing, the estuary number is unaltered. Yet at shallow reaches of an estuary the two-layer circulation pattern may be eliminated.

The purpose of this study is to determine the effects of changing river flow, tidal parameters, winds, and channel configuration on the distribution of suspended particulate matter and the character of freshwater-estuarine mixing in Patuxent River estuary.

Description of Study Area

The Patuxent River, located entirely in Maryland, is a southeastern flowing tributary on the western shore of the Chesapeake Bay (Figure 2). During the Holocene, the Patuxent River estuary formed as part of the drowned ancestral Susquehanna River valley system. Total length of the river course is approximately 285 km; the lower 88 km is tidal. The drainage basin is approximately 2409 km^2 and is the largest drainage basin entirely within the state of Maryland (Roberts and Pierce, 1974). The Little Patuxent, Middle Patuxent, and Western Branch are the major tributaries entering the Patuxent River. Minor tributaries include Dorsey Run, Hammond Branch, and Collington Branch.

Approximately 12% of the upper drainage basin lies northwest of the fall line in the Piedmont physiographic province (Figure 2). This province is marked by a broad undulating surface with low knobs and ridges rising above the general level and with numerous relatively deep and narrow stream valleys. The Piedmont is composed of igneous and metamorphic rocks (Vokes, 1968). The southern 88% of the drainage basin is located in the Coastal Plain province (Figure 2). The coastal plain is characterized by low, rolling hills and is underlain by layers of unconsolidated sand, silt, clay, and gravel (Vokes, 1968).

This study was conducted in the area of the Patuxent River from Nottingham to Fishing Point, Maryland (76°42' - 76°25' E longitude and 38°43' - 38°19' N latitude). Based on changing physiography (NOAA, 1971), tidal ranges (NOAA, 1985), and surface salinity the study area is divided into three zones; freshwater, transition, and estuarine (Figure 3). Eight

FIGURE 2: Patuxent River drainage basin
and geological provinces.

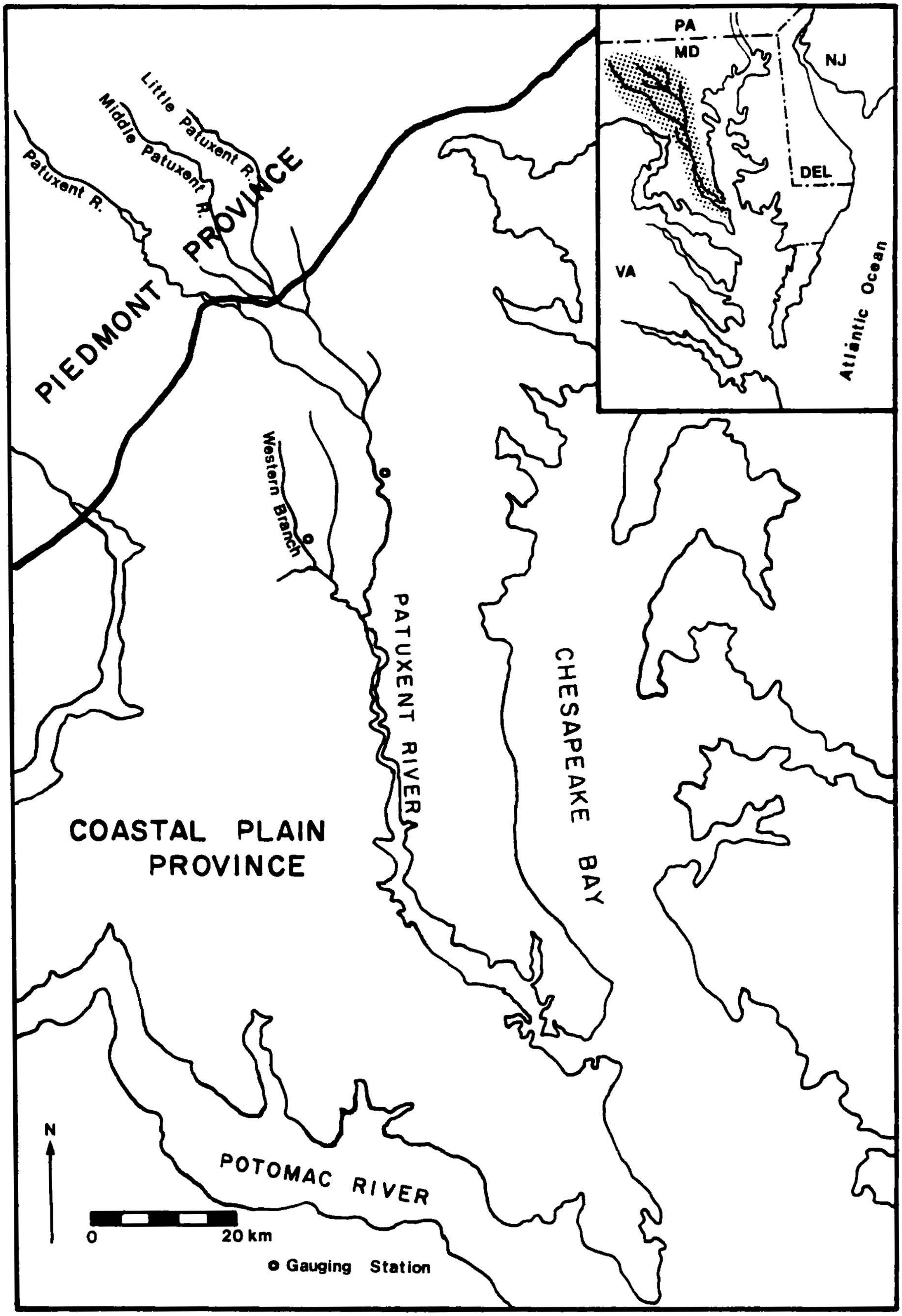
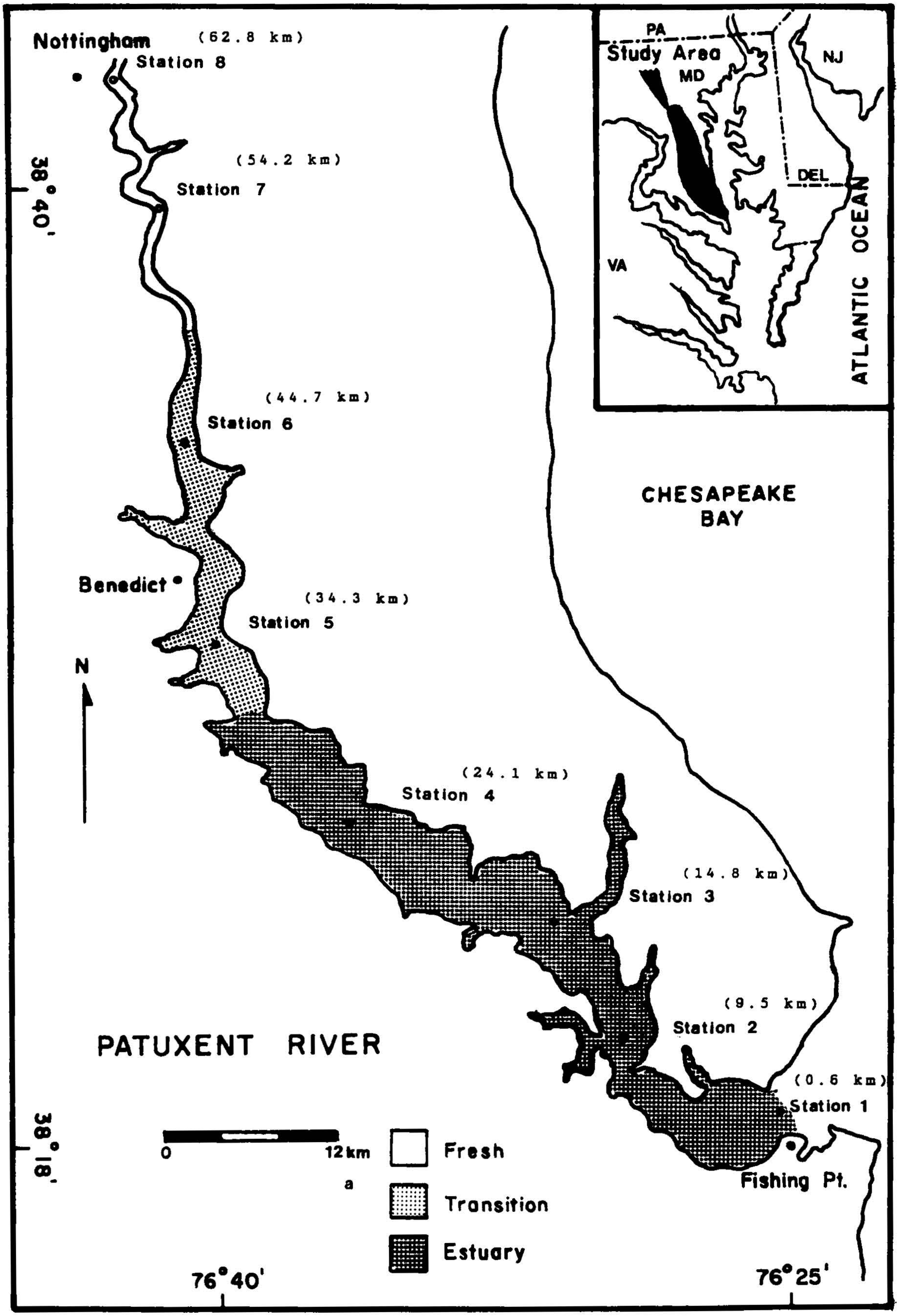

PA
MD
NJ
DEL
VA
Atlantic Ocean
Little Patuxent R.
Middle Patuxent R.
Patuxent R.
PIEDMONT PROVINCE
Western Branch
PATUXENT RIVER
CHESAPEAKE BAY
COASTAL PLAIN PROVINCE
POTOMAC RIVER
N
0
20 km
Gauging Station

FIGURE 3: Zonation of Patuxent River estuary
and station locations.


Nottingham
(62.8 km)
Station 8
(54.2 km)
Station 7
38°40'
(44.7 km)
Station 6
Benedict
(34.3 km)
Station 5
N
(24.1 km)
Station 4
(14.8 km)
Station 3
(9.5 km)
Station 2
(0.6 km)
Station 1
Fishing Pt.
PATUXENT RIVER
CHESAPEAKE BAY
38°18'
0
12 km
a
Fresh
Transition
Estuary
76°40'
76°25'
PA
Study Area
MD
NJ
DEL
VA
ATLANTIC OCEAN

stations previously established by the Office of Environmental Programs (OEP), MD (currently Maryland Department of the Environment), were monitored during the project. Depth (mean low water), location, and characteristic salinity of stations 1 - 8 are shown in Table 1.

Table 1: Station location, depth, and characteristic surface salinity for each station in the freshwater, transition, and estuarine zones of Patuxent River estuary, MD.

Zone	Station	Distance From Mouth (km)	Depth (m)	Salinity ($^{\circ}/_{oo}$) min	max	mean
Freshwater	8	62.8	11.1	0.0	0.6	0.1
	7	54.2	9.1	0.0	2.3	0.7
Transition	6	44.7	3.1	1.8	7.0	3.7
	5	34.3	11.1	8.1	14.5	10.2
Estuarine	4	24.1	12.9	9.9	15.7	12.1
	3	14.8	17.8	10.0	16,0	12.7
	2	9.5	23.1	10.0	16.0	13.0
	1	0.6	13.5	9.1	17.0	13.6

Hereafter, the interface between the freshwater and transition zones is referred to as the FW-T interface and defined as the approximate location where surface salinity is 1.5 $^{\circ}/_{oo}$. Also, the term "FW-T interface zone" refers to an area which brackets the FW-T interface in a landward and seaward direction.

Previous Studies

The origin, composition, transportation, and deposition of suspended particulate matter in the Chesapeake Bay and its tributaries have been studied extensively (Meade, 1968; Nichols, 1977; Schubel, 1968a, 1972; Schubel and Carter, 1976). Suspended particles have various origins: fluvial runoff, shore erosion, resuspension, primary production, and a marine source (Biggs, 1970; Burt, 1955; Schubel, 1968b). Each of the upper reaches of Chesapeake Bay and tributary estuaries have distinct areas with relatively high concentrations of suspended particulate matter at or near where freshwater first encounters marine water. The concentration of suspended particulate matter decreases in a landward and seaward direction from this mixing zone. Many biogeochemical interactions take place at turbidity maxima of river-estuarine systems, and although studied extensively, the formation of turbidity maxima is not completely understood.

Electrochemical flocculation (Ippen, 1966; Luneburg, 1939; Whitehouse et al., 1960) and deflocculation (Nelson, 1959) of river-borne sediment may be primary mechanisms by which turbidity maxima are formed in estuaries. Ippen (1966) stated that the phenomenon of flocculation has long been recognized as the cause for increased turbidity in the upper reaches of most estuaries.

Clay particles of colloidal and sub-colloidal dimensions have a negative charge balanced by a "double layer" of hydrated cations. Thickness of the double layer depends on various factors, one of which is the total ionic concentration of the surrounding liquid phase (Riley and Chester, 1971). Estuarine water has higher ionic concentrations relative to freshwater. As a result, particles transported from freshwater into estuarine water flocculate as thickness of the double layer decreases, and increased particle contact results.

Experimental data from particle settling rates have shown that suspended particles are flocculated mostly at a salinity between 0 - 3 ‰ (Gripenberg, 1934; Gibbs, 1983; Krone, 1962). However, Krone (1962) has shown that by increasing the concentration of suspended particulate matter, particle settling rates continue to increase in salinities greater than 3 ‰. In contrast, Whitehouse et al. (1960) showed that on pure clay minerals, particle settling rates were not affected by an increase in concentration of suspended sediment. These differences may be due to pure clay minerals which behave differently from suspensions containing other minerals and organic constituents.

Other researchers (Edgwald et al., 1974; Hahn and Stumm, 1970) found that clay minerals settled out of suspension at high rates upon entering saline water compared to settling rates in fresh. Consistent with the discussion above, clay mineral distribution patterns in the Pamlico River estuary were explained by variable flocculation characteristics and particle settling rates (Edgwald et al., 1974). However, flocculation, differential settling, and diagenesis of clay minerals are believed to have only minor influence on the distribution of clay minerals in James River estuary, Virginia. Feuillet (1976) determined that estuarine circulation was responsible for the clay mineral distribution by mixing of the upper James River clay suite and the lower Chesapeake Bay clay suite.

Nelson (1959) described two types of fine-grain fluvial particles entering the Rappahannock and York River estuaries, Virginia. He found that dispersed sedimentary particles were primarily transported in suspension, whereas flocculated and aggregated sedimentary particles were transported by saltation and temporary suspension. The high concentration of dispersed suspended particles at the head of the estuary was attributed to the deflocculation of aggregates. A downstream decrease in concentration of dispersed suspended particles was reported by Nelson (1959) to be the result of simple dilution by sea water.

Biological factors affecting suspended particulate matter at or near the FW-T interface include algae-clay aggregation (Avnimelech et al., 1982), algae aggregation (Sellner et al., 1987), and the mass mortality of freshwater phytoplankton populations (Filardo, 1983; Filardo and Dunstan, 1985; Morris et al., 1978). Avnimelech et al. (1982) described a process by which certain species of algae were removed from suspension due to their reactivity with clay particles and subsequent increased settling rates. Algae-clay aggregates formed when *Anabaena* sp., *Chlamydomonas* sp., and *Chlorella* sp. were mixed with bentonite clay in an electrolyte solution.

Aggregation of the cyanobacterium *Microcystis aeruginosa* occurred in the low salinity reaches of Potomac River estuary (Sellner et al., 1987). The authors speculated that agglomeration of *Microcystis* sp. accelerated their removal from the surface water phytoplankton assemblage due to increased particle settling rates. Others (Filardo and Dunstan, 1985; Morris et al., 1978) have speculated that freshwater phytoplankton may undergo mass mortality in low salinity estuarine waters, probably through osmotic stress acting on the phytoplankton populations.

Estuarine circulation is the major process controlling the distribution of suspended particulate matter in partially mixed estuaries (Kranck, 1979, 1981; Kuo et al., 1978; Meade, 1968, 1969; Nichols and Poor, 1967; Officer, 1980; Postma, 1967; Schubel, 1968a, 1971, 1972; Schubel and Carter, 1976, 1984; Schubel and Kennedy, 1984). A discussion of the physical hydrography of partially mixed estuaries provides some insight on several mechanisms which control their longitudinal distribution of suspended particulate matter. Pritchard (1952, 1955) was the first to provide a comprehensive descriptive and theoretical treatment of the characteristic circulation patterns in partially mixed estuaries. This concept was later expanded by Hansen and Rattray (1966) and Officer (1976).

Pritchard (1952) conducted a series of experiments to determine water velocities at several depths in the James River estuary, Virginia. His results depicted a net (i.e., time-averaged) seaward flow at the surface and a net landward flow near the bottom. This residual horizontal flow pattern is a result of density differences. Less dense freshwater flows seaward in the upper layer while denser sea water flows landward in the lower layer. A continuous upward flow of sea water maintains continuity. Landward of the upstream limit of sea water intrusion, the net movement is seaward at all depths. At some point near the upstream limit of sea water intrusion, opposing net flows meet and a zone of no net movement is formed.

A turbidity maximum is commonly found in the no net movement zone or "null zone". Particles moving seaward in the upper layer sink into the landward moving lower layer and are transported into the null zone. Particles repeat this cycle by being vertically mixed into the seaward moving upper layer, thus creating a "sediment trap".

The volume ratio of tidal inflow to river flow over a tidal cycle influences the maintenence of turbidity maxima (Pritchard, 1955). Changing river flow, spring-neap tidal cycles, and bathymetry can alter the tidal prism-river flow ratio. Increased river flow causes an increase in stratification which inhibits vertical mixing. Decreased river flow or an increase in the tidal prism causes increased mixing between the upper and lower layers, potentially eliminating the density differences and the residual flow pattern.

Kranck (1981) studied the turbidity maximum of Miramichi estuary, New Brunswick and concluded that its maintenance was dependent on estuarine circulation and flocculation. Fine-grain material, which would normally be transported seaward because its settling velocity was less than the vertical mixing velocity, was aggregated with numerous other constituents within the turbidity maximum zone and deposited. Flocculation varied directly with concentration of SPM. The flocs were reportedly 50 - 60 μm in diameter and were easily resuspended and broken by near-bottom shear forces. Therefore, the magnitude of the turbidity maximum increased because of increased particle settling and resuspension rates and the size range of the trapped particulate matter.

Kranck (1981) utilized the Niskin bottle and Coulter Counter during sampling and sizing procedures for her flocculation studies in a turbidity maximum. She reportedly measured floccules that were easily resuspended and broken-up by near-bottom shear forces. However, similiar forces associated with apertures of the Coulter Counter and Niskin Bottle have been shown to disturb the integrity of floccules (Gibbs, 1981, 1982). Gibbs (1982) reported breakage of floccules during water sampling by Niskin bottles and water pumps, and Coulter Counter size analysis methods. Flocs above 12 μm in diameter were disrupted during Coulter Counter size analysis when a 380 μm diameter aperture or orifice was used, approximately the same size orifice used during this study.

Schubel (1968b) identified and described a turbidity maximum in the upper reaches of Chesapeake Bay. He attributed its formation and maintenance to resuspension of bottom deposits by tidal currents and the trapping ability of the estuarine circulation pattern, dismissing flocculation as a possible explanation. The turbidity maximum selectively restricts the size range of particles retained in the circulation pattern on the basis of critical erosion velocities, and settling velocities that are less than mean vertical mixing velocities (approximately 10^{-3} cm/s). Nominal particle-size throughout the water column ranged from 1.1 μm at the surface to 12.2 μm near the bottom. The coarsest particles were found close to the bottom and associated with resuspended material. Suspended particulate matter near the bottom exhibited large fluctuations in concentration (15 - 280 mg/ℓ) due to resuspension, while concentrations in the upper layer remained constant (Schubel, 1972).

During periods of low and moderate river flow the turbidity maximum in the upper Chesapeake Bay migrated landward and seaward in response to tidal currents and increased river flow. High river flow in the spring eliminated the net two-layer flow pattern in the upper bay, and a sharp front separated low salinity water (≤ 1 °/oo) from estuarine water (Schubel, 1972; Schubel and Pritchard, 1986).

Some variations occur in the circulation patterns of upper Chesapeake Bay tributary estuaries due to their close proximity to the Susquehanna River, the major source of freshwater to Chesapeake Bay. A three-layer circulation pattern was identified in Patapsco River estuary (Cameron and Pritchard, 1963; Stroup et al., 1961). Freshwater inflow to Patapsco River estuary, or Baltimore Harbor, is approximately 1/315 of the total harbor volume. Schubel and Pritchard (1986) reported a 100 day flushing time based on the low river discharge and weak tidal currents. Stroup et al. (1961) proposed a 10 day flushing time based on observations of accumulated conservative components of certain wastes introduced into the harbor, suggesting that some other feature than tidal flushing must be renewing about 10% of the harbor volume each day (Stroup et al., 1961).

This feature, a three-layer circulation pattern, is driven by differences in the vertical salinity structure of Baltimore Harbor and the adjacent Chesapeake Bay. Surface water of the harbor is less saline (lighter) than surface water of the bay, while bottom water of the bay is more saline (heavier) than bottom water of the harbor. Therefore, bay water flows into the harbor on the surface and bottom, and intermediate salinity water of the harbor flows out at mid-depths. Intermediate salinity water is present due to tidal mixing in an embayment of restricted freshwater inflow (Cameron and Pritchard, 1963;

Stroup et al., 1961). An important feature contributing to the resulting circulation pattern is a navigational channel into the harbor, which is maintained at essentially the same depth as the adjacent bay.

In shallower estuaries, where depths are considerably less than the adjacent bay, another circulation pattern has been reported to occur (Schubel and Pritchard, 1986). Only in the upper narrow reaches of the estuary is the salinity pattern affected by freshwater runoff. The major factor controlling the exchange of water between the estuary and the adjacent bay is salinity difference. Since the channel depths are relatively low, only the upper layer of bay water interacts with surface and bottom water of the estuaries.

It has been shown that seasonal salinity variations in upper Chesapeake Bay estuaries lag salinity variations in upper Chesapeake Bay (Owen, 1969; Schubel and Pritchard, 1986). During low salinity periods (late winter and spring), salinity in the estuaries is higher than in the adjacent upper bay surface waters. Consequently, surface water of the bay flows into the estuary, and bottom water of the estuary flows into the bay. A reversal of this pattern is seen during high salinity periods (late spring, summer, and fall), as surface water of the estuary flows out and bay water flows in along the bottom (Schubel and Pritchard, 1986).

Owen (1969) characterized the Patuxent River estuary as a partially mixed estuary with a two-layer flow pattern. A 24-hour average of horizontal axial velocity components shows a net seaward flow in the surface layer and a net landward flow in the bottom layer (Owen, 1969). During low and moderate periods of river flow the FW-T interface (depicted as the 1 - 1.5 $^{o}/_{oo}$) was located in the upper most part of the study area, just upstream of Nottingham, Maryland. The interface moved seaward approximately 15 - 20 km during the spring runoff (Owen, 1969).

The variations between mean monthly salinity at the mouth of the Patuxent River estuary and the adjacent upper Chesapeake Bay were shown by Owen (Figure 9; 1969). During periods of low salinity (December to April), salinity was higher in the estuary than in the adjacent bay. At peak runoff for the Susquehanna River, generally March, the phase differences between Patuxent River estuary and upper bay salinity causes a change in the circulation pattern.

Because surface water of the bay is less saline than Patuxent River surface water and bottom water is more saline than Patuxent River bottom water, there is a net inflow of bay water into the Patuxent River at the surface and bottom. Surface bay water was found to penetrate as far landward as 25 km from the estuary mouth. Intermediate salinity water has a net outflow at mid-depths (Owen, 1969). Owen attributed the three-layer circulation pattern to phase differences between maximum flow conditions of the Susquehanna and Patuxent Rivers.

Roberts (1971) and Roberts and Pierce (1974, 1976) reported a zone of maximum turbidity in the Patuxent River estuary that was associated with the two-layer flow pattern and the FW-T interface. The turbidity maximum seasonally migrated a distance of approximately 20 km and concentrations of suspended particulate matter at mid-depth ranged from 50 - 100 mg/ℓ (Roberts and Pierce, 1976). The highest concentrations of suspended particulate matter were observed during summer months of low river discharge (OEP, 1984; Roberts and Pierce, 1976).

Roberts (1971) reported a secondary turbidity maximum located seaward of the primary turbidity maximum. The maximum was associated with a narrow area landward of where the estuary begins to widen and shoal. Constriction of the channel reportedly increased the velocity of landward flowing bottom currents, which increased resuspension and the concentration of suspended particulate matter. Although the Patuxent River estuary is ranked second in mean depth relative to the seven major tributaries entering Chesapeake Bay (Owen, 1969), some areas are still susceptible to resuspension of bottom deposits by wind waves. Roberts (1971) reported yet another turbidity maximum located in the wide and shallow upper reaches of Patuxent River estuary; Roberts speculated that this maximum was related to bottom material being resuspended by wind waves.

Areas of shoaling commonly occur near null zones (Meade, 1968, 1969; Roberts and Pierce, 1976). Dredging records of the Savannah and Delaware River estuaries show that most of the shoaling has occurred at the zone where net seaward and net landward bottom currents are equal (Meade, 1969). Roberts and Pierce (1976) reported two areas of net deposition for the Patuxent River estuary which were separated by the primary turbidity maximum in the upper reaches of the estuary. Suspended material transported downstream by stream flow was almost completely deposited upstream of the null zone. Seaward of the null zone, net deposition occurs where the estuary begins to widen and tidal current velocities lessen. The average annual rate of deposition for the upper estuary was reported as 3.7 cm, a fairly high rate when compared to estimates of 0.45 - 0.6 cm for the upper Chesapeake Bay

(Schubel, 1968a; Schubel and Hirschberg, 1977; Hirschberg and Schubel, 1979).

While the work of Owen (1969) and Roberts and Pierce (1976) generally described the circulation and turbidity of the Patuxent River estuary, it is not known how seasonal variations of river discharge and winds, spatial changes in channel geomorphology, and variability in the magnitude of tidal currents affect the concentration and distribution of suspended particulate matter. The effects of temporal and spatial variation in phytoplankton and microzooplankton must also be considered when analyzing the characteristics of suspended particulate matter.

This study was designed to determine the relative importance of these physical processes and characteristics on the concentration and distribution of suspended particulate matter in the Patuxent River estuary.

Objectives

The following objectives were established for this study.

1) locate and monitor the movement of the FW-T interface as it seasonally migrates in response to changing river discharge;
2) determine the longitudinal distribution of suspended particulate matter, inorganic and organic fractions over:
   a) the entire study area, and
   b) an area that brackets a migrating FW-T interface;
3) determine the longitudinal distribution of salinity over:
   a) the entire study area, and

b) an area that brackets a migrating FW-T interface;

4) determine whether any relationships exist between river discharge and the longitudinal distribution of salinity and suspended particulate matter;

5) determine whether any relationships exist between bathymetry, tidal currents, winds and the longitudinal distribution of suspended particulate matter;

6) determine whether separate particle-size populations exist:

   a) between the freshwater, transition, and estuarine zones, and

   b) horizontally and vertically over an area that brackets a migrating FW-T interface;

7) microscopically identify and quantify the dominant phytoplankton and microzooplankton species in suspension within the freshwater, transition, and estuarine zones;

8) microscopically identify and quantify the dominant inorganic particles suspended in an area that brackets a migrating FW-T interface.

2. MATERIALS AND METHODS

Study Plan

The goal of this study was to define the important factors controlling the temporal and spatial variability of salinity and turbidity within the Patuxent River estuary. Eight stations, covering a 60 km stretch from the estuary mouth to the upstream limit of sea water, were monitored for salinity and turbidity during a twelve month period (Figure 3). A denser spatial sampling scheme was developed for the upper portion of the estuary associated with the turbidity maximum. River discharge was collected daily (U.S. Geological Survey). Hourly measurements of wind direction and magnitude were collected by the Patuxent Naval Air Station. Tidal currents were measured by researchers at Benedict Estuarine Research Laboratory (BERL) (ANS, unpubl. data) during mid-summer 1980.

Linear regression, analysis of variance (ANOVA), and Student-Newman-Keuls statistical tests were used to analyze the relative importance of the above measured parameters in the distribution of salinity and suspended particulate matter in the Patuxent River estuary.

River Discharge

Owen (1969) indicated that the seasonal variation of freshwater runoff in the Patuxent River is a function of net precipitation less total evapotranspiration in the watershed, natural and man-derived storage, and the net precipitation less evaporation from the water surface. Owen (1969; Figures 3 and 5) depicted the mean monthly runoff (measured by stream gauges) and the adjusted mean monthly runoff for the Patuxent River and estuary during the period of 1952-1961. The adjusted mean monthly runoff was determined by the net precipitation less evaporation from the river and estuary surface, an additional drainage area not measured by the stream gauges. The adjusted runoff figure more accurately predicts the amount of freshwater entering the estuary downstream of the stream gage. A ratio between adjusted runoff and runoff for a nine year period was calculated as 2.14, and indicates a two-fold increase in the volume of freshwater entering the estuary relative to stream gage measurements.

Discharge into the Patuxent River estuary was determined from the U.S. Geological Survey Water-Data Report Maryland-Delaware (USDI, 1985, 1986). Two gauging stations were monitored, hydrologic unit 01594526 on Western Branch in Upper Marlboro, Md, and hydrologic unit 01594440 on Patuxent River near Bowie, Md (Figure 2). Changes in salinity throughout the estuary in response to pulses of freshwater were assumed to be no greater than five days. Mean daily discharge rates, averaged over a five day period immediately preceding the sampling day, are expressed as the mean monthly discharge rate (m^3/s). Each monthly discharge rate was multiplied by 2.14 (see above) to predict gross freshwater entering the estuary.

Winds

Climatic data were collected at the Patuxent Naval Air Station located near Lexington Park (Fishing Point), Md. Hourly measurements of wind direction (from) and speed (knots) were averaged over a four day period, beginning prior to and including the day of water sampling, to determine the dominant wind direction and speed. A four day average was used in the analysis since storm systems and associated winds are capable of dominating climatic conditions in a given region over several days.

The orientations of the estuarine, transition, and freshwater zones were determined from their trends relative to true north; 314°-134°, 0°-180°, and 0°-180° (NOAA, 1971). The cosine of the angle between zonal orientations and dominant wind direction during each sampling period was multiplied by the magnitude of the wind. Therefore, wind fetch is factored into the wind parameter used for the statistical analysis.

Tidal Currents

Researchers at BERL provided tidal current data taken during July 1980 (ANS, unpubl. data). Tidal currents were measured for a 24-hour period from each of the eight stations (Figure 3) at the surface, mid-depth, and above bottom using a Marsh-McBirney Current Meter Model 527. Three meters, mounted one above the other, simultaneously measured current direction (from) and speed (ft/s) at each depth. In accordance with suspended particulate matter sampling protocol, only surface current measurements were used in the tidal current analysis.

Field Sample Collection

Samples were collected monthly between July 1985 and June 1986, in order to obtain data during periods of varying river discharge and climatic conditions. Eight stations previously established by the Maryland Office of Environmental Programs (OEP) were sampled for salinity and suspended particulate matter (Figure 3). Tidal stage during sample collection took place close to predicted slack water in order to minimize tidally influenced variability in water column characteristics. One-liter surface water (approximately 0.5 m below the surface) samples were collected by an onboard pump for suspended particulate matter concentration determinations. Salinity was determined by a Hydrolab Model 8002 submersible probe (OEP). An additional 250 ml surface sample was collected from each station for suspended particle-size analysis.

Within 24 hours of the first collection, a second set of approximately 15 samples was collected from the upper estuary. Using an onboard pump, one-liter samples were collected from the surface, mid-depth, and one meter above bottom in a region upstream and downstream of the FW-T interface. Samples were initially collected from the FW-T interface as the tidal stage reached observed slack water. Immediately following interface sampling, two stations were sampled at approximately 3 km spacing further seaward and landward of the interface. The sampling scheme essentially allowed for simultaneous sample collection during observed slack water over a 15 km section of the estuary. Salinity was determined using a Beckman RS5-3 inductive salinometer (instrument provided by BERL).

Suspended Particulate Matter Concentrations

Suspended particulate matter (SPM) concentrations were determined by filtration and gravimetric analysis. Filters were prewashed with 100 ml of distilled water, ashed at 400°C for two hours, and weighed on a Mettler balance to 0.0001 grams. A known volume of sample water was then filtered through a Gelman A/E glass fiber filter. Proceeding sample filtration, the graduated cylinder used to measure the sample volume was rinsed with 50 ml of filtered distilled water for the removal of residue. A rinse of 150 ml of filtered distilled water was added for removal of sea salts. Filters were placed in a drying oven at 60°C for two hours. Upon removal from the oven, filters were allowed 20 minutes to equilibrate to room temperature and were weighed with an accuracy of 0.1 mg. Concentrations of suspended organic matter (SOM) and suspended inorganic matter (SIM) were determined by weight loss after ashing the filters in a muffle furnace for 2 hours at 400°C. Filters were again allowed 20 minutes to equilibrate to room temperature before being weighed.

Particle-Size Analysis

A Model TA II Coulter Counter was used for particle-size analysis. A single analysis was conducted to determine particle-size distribution for the suite of natural particles. Water samples were kept on ice prior to particle-size analysis. The particle-size distributions are believed to represent *in situ* size distributions; however, breakage of aggregated particles (inorganic) during similar sampling and sizing procedures has been documented by Gibbs (1981, 1982) and therefore must be considered.

The Coulter Counter utilizes an electrical field for the particle-size analysis. Two electrodes, one in the sample beaker and the other in the aperture tube, create an electrical field within the electrolyte. Particles are passed from the sample beaker through an orifice into the aperture tube, causing a change in the electrical field. The change produced is proportional to particle volume and the volume of electrolyte displaced. The displaced volume was assigned a radius equivalent to that of a spherical particle. A 400 μm aperture tube was used during the analysis permitting analysis of particles 6.4 - 161 μm in diameter.

After gentle agitation, a 5 - 15 ml aliquot of the suspended particle sample was diluted with a azide-free Isoton II electrolyte solution. The instrument was set to count 150,000 particles per analysis generating a size-distribution histogram of 16 different size classes with percent volume displaced in each size class. Primary and secondary size modes were identified from the size-frequency distributions.

Microscopic Analysis

A semi-quantitative microscopic analysis of suspended inorganic matter retained on the filters was conducted using a petrographic microscope. Two crossing transects, each approximately 35 mm in length, were analyzed from each filter. Particles counted were categorized as the following: present (10% or less), frequent (10 - 30%), and abundant (> 30%) relative to total particles counted. Concentrations (# of organisms/ℓ) and the identification of major phytoplankton and microzooplankton species were determined with a Leitz Diavert inverted microscope (Sellner and Brownlee, 1987). Utermohl (1931) inverted microscopic techniques were employed during plankton analysis.

Statistical Methods

An analysis of variance (ANOVA) procedure was used to test for significant differences in longitudinal variation of salinity and concentration of SPM. The ANOVA tested the equality between population means at stations 1 - 8 (n = 64) for the period October 1985 - June 1986. Rejection of the null hypothesis indicated that significant differences existed, but conclusions as to which means were different were lacking due to the limitations of the ANOVA test. However, the Student-Newman-Keuls (SNK) test, a multiple comparison test, allowed for determining which population means were different. Therefore, if the longitudinal distribution of salinity or SPM proved to be from more than one population (ANOVA) the spatial limits of that population could be determined through the SNK test.

Linear regressions of SPM and salinity versus river discharge were performed to determine how much of the temporal and spatial variability in SPM and salinity could be explained by river discharge. An ANOVA procedure tested the significance of each regression with the null hypothesis; H_o: B = 0, and the alternate hypothesis, H_a: B ≠ 0, where B = the slope of the regression line. H_o was tested by determining F from equation 1:

$$F = \text{regression MS}/\text{residual MS} \qquad (1)$$

where:

F = F distribution value

regression MS = linear regression mean square

residual MS = total mean square - linear regression mean square.

The critical value for the test was F (1), 1, (n-2). The percentage of total variation in the dependent variable (Y) that is accounted for by the fitted regression is termed the coefficient of determination or r^2. The coefficient of determination is a measurement of the strength of the straight-line relationship and is determined from equation 2:

$$r^2 = \text{regression SS}/\text{total SS} \qquad (2)$$

where:

r^2 = coefficient of determination

regression SS = linear regression sum of squares

total SS = total sum of squares.

Similar tests between station cross-sectional area, wind, and tidal current velocity versus SPM were performed.

The particle-size distributions of suspended particulate matter from stations 1 - 8 were tested to determine whether any significant differences existed between the particle-size populations. The use of a chi-square test enabled testing the null hypothesis, H_o: P1 = P2, that particle-size population 1 is equal to particle-size population 2.

3. RESULTS

River Discharge

Figure 4 shows seasonal variation of river discharge for the Patuxent River during the study period. The graph shows seasonal trends typical of mid-latitude rivers: high discharge in late winter and spring followed by low-to-moderate flow in summer and fall. Maximum discharge for the Patuxent River occurred during the month of February 1986 at a rate of 22.7 m^3/s. Minimum discharge occurred during September 1985 at a rate of 5.9 m^3/s. Overall, unusually low discharge rates dominated the Patuxent River basin as a result of reduced snow melt and precipitation during the late winter, spring, and summer of 1986. Record low flows were reported for many stream-gaging stations in the eastern United States during this same period (EOS, 1986).

Longitudinal Distribution of Surface Salinity

The temporal and spatial relationship between salinity and river discharge for the study area is shown in Table 2. There was no apparent relationship between salinity and river discharge measured from the same month for stations 1 - 4 (column A, Table 2); however, correlations became significant at stations 1 - 4 when a one month lag between

FIGURE 4: Mean monthly runoff (m^3/s) for Patuxent River, 1985-86.

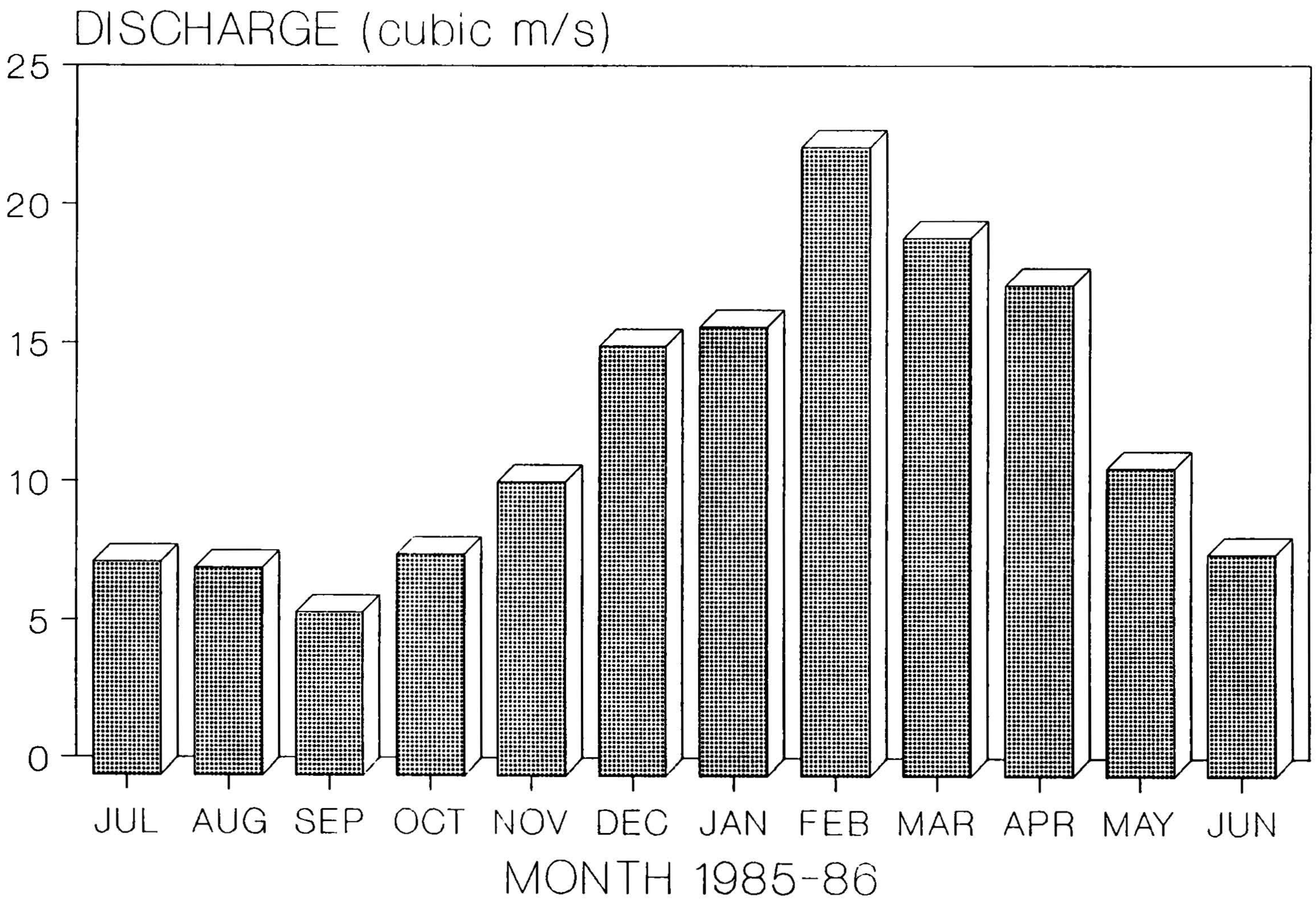

DISCHARGE (cubic m/s)
25
20
15
10
5
0
JUL
AUG
SEP
OCT
NOV
DEC
JAN
FEB
MAR
APR
MAY
JUN
MONTH 1985-86

Table 2. Linear regressions between monthly salinity observations (S) and mean monthly river discharge rates (D) at all stations. The linear equations, coefficients of determination (r^2), and F distribution values for regressions between data collected from the same month are shown (column A). The coefficients of determination (r^2) and F distribution values from regressions between river discharge and salinities one month later are shown in column B.

A

Station	Regressions	F	r^2
1	$S = -0.31D + 17.9$	4.8	0.44
2	$S = -0.23D + 16.6$	3.5	0.37
3	$S = -0.26D + 16.3$	4.0	0.41
4	$S = -0.29D + 15.9$	5.6	0.48
5	$S = -0.44D + 15.2$	11.1*	0.65
6	$S = -0.38D + 9.5$	30.2*	0.83
7	$S = -0.26D + 4.6$	11.7*	0.66
8	$S = -0.08D + 1.4$	6.3*	0.49

B

Station	Regressions	F	r^2
1	$S = -0.39D + 18.5$	38.4*	0.89
2	$S = -0.32D + 31.4$	45.7*	0.90
3	$S = -0.32D + 16.6$	44.5*	0.90
4	$S = -0.35D + 16.3$	69.5*	0.97
5	$S = -0.40D + 14.1$	14.6*	0.74
6	$S = -0.15D + 6.0$	2.4	0.33
7	$S = -0.10D + 2.0$	0.5	0.53
8	$S = -0.01D + 0.3$	0.1	0.01

* slope is significantly different from zero ($p < 0.05$)

discharge and salinity was considered (column B, Table 2). Approximately 89 - 97% ($0.89 < r^2 < 0.97$) of the variability in salinity at stations 1 - 4 was explained by the variability in river discharge when a one month lag was introduced. Conversely, a significant correlation between discharge and salinity within a month a stations 5 - 8 without the delay factor (0.49 < r^2 < 0.83; column A, Table 2); addition of the one month lag resulted in a non-significant relationship for stations 6 - 8.

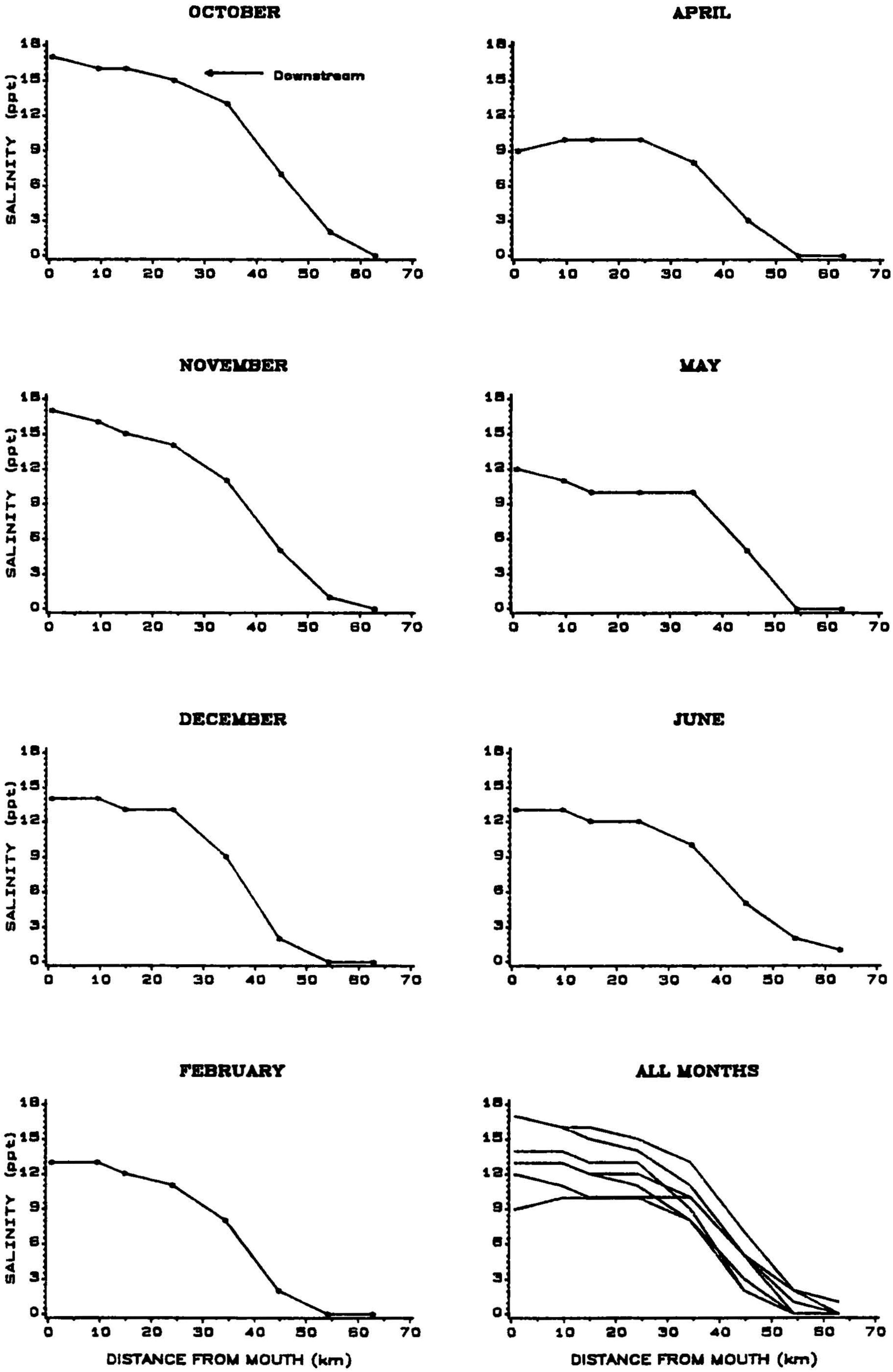
The salinity distribution from October 1985 to June 1986 is shown in Figure 5. The monthly plots of surface salinity from stations 1 - 8 consistently showed a landward decrease in salinity with three areas of distinctly different salinity. At stations 1 - 4 (estuarine zone) the salinity change was gradual, while between stations 4 - 7 (transition zone) salinity decreased rapidly. At stations 7 and 8 (freshwater zone) salinity changed gradually before encountering freshwater. Table 3 shows the results of the Student-Newman-Keuls test, i.e., where significant changes in the salinity gradients occurred.

Table 3. Results of the Student-Newman-Keuls test, which determined the location of the significant changes in salinity between stations 1 - 8, are shown below (n = 64). The bars which extend from one station (i) to another without interruption indicate there is no significant difference between mean salinity (xi) at those stations (p < 0.05).

Salinity station (i)	1	2	3	4	5	6	7	8
°/oo (xi)	14.1	13.8	13.1	12.6	10.5	4.9	1.4	0.4

Salinity was relatively uniform throughout the estuarine zone (0.1 °/oo/km) with initial significant changes occurring landward between stations 4 and 5 (Table 3). The rate of change for salinity within the transition zone (stations 5 and 6) was 0.4 °/oo/km, the highest rate of change for the study area. The freshwater zone exhibited a smaller rate of change in salinity (0.1 °/oo/km) and there

FIGURE 5: Monthly longitudinal plots of surface salinity (°/oo) for Patuxent River estuary, 1985-86.


OCTOBER
APRIL
NOVEMBER
MAY
DECEMBER
JUNE
FEBRUARY
ALL MONTHS
Downstream
SALINITY (ppt)
DISTANCE FROM MOUTH (km)
0
3
6
9
12
15
18
0
10
20
30
40
50
60
70

was no significant difference between salinities at stations 7 and 8 (Table 3). Salinity gradients measured during 1985-86 were very similar to gradients reported by Owen (1969) and OEP (1984).

Figure 5 depicts seasonal changes in surface salinity at each station and longitudinal displacement of the FW-T interface. Highest salinities were observed at stations 1 - 4 during October and November 1985, a period of increasing, but relatively low river discharge for the Patuxent River. Stations 1 - 4 had a salinity range of 17 - 14 °/oo, whereas stations 4 - 7 had a range of 15 - 1 °/oo. During this same period, salinity at stations 7 and 8 had a range of 2 - 0 °/oo. Excluded from Figure 4 is the salinity distribution during September 1985; maximum salinity values were measured during this period. Stations 7 and 8 had salinities of 6 - 2 °/oo, indicating a landward migration of the FW-T interface beyond the study area.

During December 1985, February and April 1986, salinity decreased at all stations concurrently with maximum rates of river discharge. Salinity measurements at stations 1 - 4 ranged from 14 - 9 °/oo, while ranges for stations 4 - 7 were 13 - 0 °/oo; freshwaters were found at stations 7 and 8. During periods of high river discharge the FW-T interface moved seaward approximately 10 - 15 km. The exact migration distance was unknown because the initial location of the interface was landward of the upper boundary of the study area.

During May and June 1986, river discharge decreased and salinity increased at all stations relative to measurements made during April 1986. A salinity range of 13 - 0 °/oo was noted for stations 1 - 4, and stations 4 - 7 had a surface salinity between 12 - 0 °/oo. Freshwater was encountered at stations 7 and 8 during the month of May 1986, but during June 1986 measurements revealed salinities greater than 1 °/oo. Between the sampling periods of May and June 1986, the FW-T interface migrated landward approximately 10 - 15 km above the study area, 9 km within the study area.

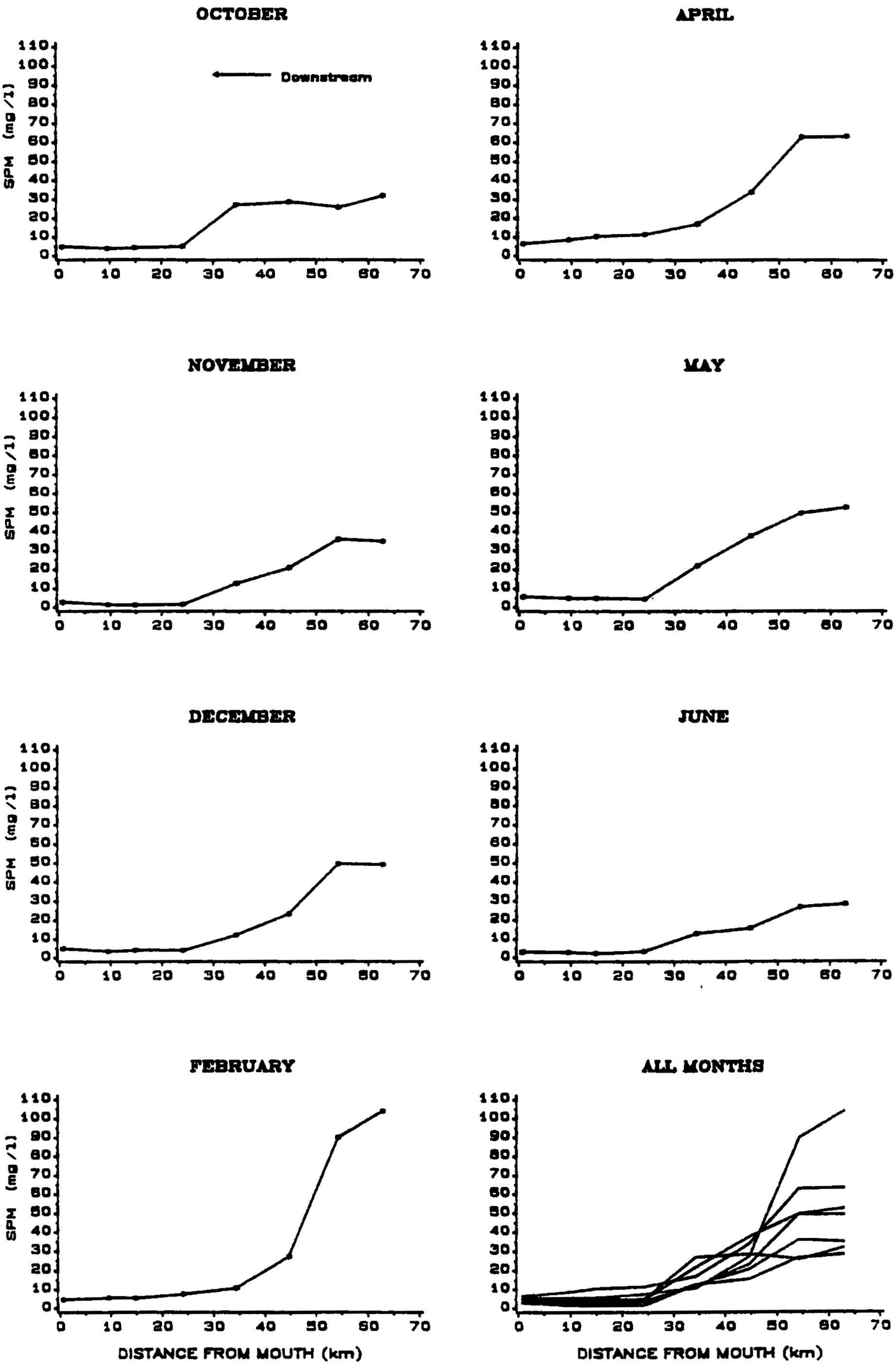
Longitudinal Distribution of Suspended Particulate Matter

The longitudinal distribution of suspended particulate matter (SPM) from October 1985 to June 1986 is shown in Figure 6. Concentration of SPM increased in a landward direction from the lower Patuxent during each month of the study period. The concentration of SPM in the estuarine zone remained below 12 mg/ℓ during the entire study period, and mean concentration of SPM from stations 1 - 4 ranged from 4.8 - 5.5 mg/ℓ. SPM concentrations significantly increased landward of station 4 throughout the transition zone. The mean concentration of SPM at station 5 was 16.5 mg/ℓ, but increased to 26.9 mg/ℓ at station 6. SPM showed little variability between stations 7 and 8 where mean concentrations ranged between 48.7 - 52.2 mg/ℓ. The highest concentration of SPM (104.3 mg/ℓ) was measured at station 8 during February 1986.

Rates of change for SPM in the estuarine, transition, and freshwater zones were 0.04 mg/ℓ/km, 2.1 mg/ℓ/km, and 0.2 mg/ℓ/km, respectively. However, there were no significant differences between SPM concentrations at stations 1 through 4, and stations 7 and 8 (Table 4). Significant changes in SPM concentrations were observed between stations 4 and 6, identifying the lower boundary of the transition zone.

The concentrations of suspended inorganic matter (SIM) and suspended organic matter (SOM) measured at stations 1 - 8 during the study period are listed in Appendix 1. Concentrations of SOM and SIM increased in a landward direction, and SNK test results reflected those of the SPM concentrations (Table 4). Although longitudinal distributions of SPM,

FIGURE 6: Monthly longitudinal plots of surface (0.5 m) suspended particulate matter (mg/ℓ) for Patuxent River estuary, 1985-86.


OCTOBER
APRIL
NOVEMBER
MAY
DECEMBER
JUNE
FEBRUARY
ALL MONTHS
Downstream
SPM (mg/l)
0
10
20
30
40
50
60
70
80
90
100
110
DISTANCE FROM MOUTH (km)

SOM, and SIM follow similar patterns, relative contributions of SIM and SOM were inversely related and a function of salinity. SOM comprised 50 - 80% of SPM in the estuarine region and decreased to 29%, on average, in the region of stations 4 and 5. By station 8, SOM made up only 12% of SPM.

Table 4. Results of the Student-Newman-Keuls test showing the location of significant differences ($p < 0.05$) between the concentrations of SPM, SIM, and SOM at stations 1 - 8 ($n = 56$). The bars which extend from one station (i) to another without interruption indicate less than significant differences between the mean concentrations (xi) for those stations.

SPM

station (i)	1	2	3	4	5	6	7	8
mg/ℓ (xi)	4.8	4.5	4.8	5.5	16.5	26.9	48.1	52.2

SIM

station (i)	1	2	3	4	5	6	7	8
mg/ℓ (xi)	2.4	1.8	2.2	2.3	11.8	20.6	39.6	43.1

SOM

station (i)	1	2	3	4	5	6	7	8
mg/ℓ (xi)	2.4	2.7	2.6	3.2	4.7	6.3	8.5	9.1

River Discharge and SPM

The volume of freshwater entering the Patuxent River estuary increased from October 1985 to February 1986 (Figure 5), and is concomitant with increased concentrations of SPM between stations 5 and 8 (Figure 6). From April to June 1986 (a period of decreasing river discharge) the concentration of SPM decreased at stations 5 through 8. The spatial and temporal relationship between SPM concentrations and river discharge is illustrated in Table 5. Stations 1 - 6 had less than significant correlations between river discharge and SPM concentrations (column A, Table 5). Station 5 was unusual because it exhibited a negative slope in the linear equation, which resulted from an uncommonly high concentration of SPM (27.2 mg/ℓ) measured during October 1985. At stations 7 and 8 the variability in SPM concentration was significantly correlated with river discharge ($r^2 > 0.90$).

SPM concentration at lower stations showed a one month response time to Patuxent River discharge. Between stations 1 - 6, all but station 5 had significant correlations between river discharge and SPM concentrations when a one month lag was included ($0.70 < r^2 < 0.92$). However, SPM concentrations at stations 7 and 8 were significantly correlated to river discharge within the same month, due to the proximity of these stations to the source of freshwater.

Table 5. Linear regressions between monthly river discharge (D) and concentrations of SPM at all stations. The linear equations, coefficients of determination (r^2), and F distribution values are shown in column A for regressions between data collected from the same month ($n = 7$). Column B shows coefficients of determination (r^2) and F distribution values for regressions between river discharge and the proceeding months concentrations of SPM ($n = 48$).

A

Station	Regressions	F	r^2
1	SPM = 0.10D + 3.5	1.3	0.20
2	SPM = 0.27D + 0.9	3.3	0.40
3	SPM = 0.31D + 4.2	2.7	0.35
4	SPM = 0.39D + 0.3	3.9	0.44
5	SPM = -0.53D + 23.6	1.5	0.23
6	SPM = 0.40D + 21.5	0.5	0.09
7	SPM = 3.90D + -3.6	70.4*	0.93
8	SPM = 3.69D + 0.5	44.9*	0.90

B

Station	Regressions	F	r^2
1	SPM = 0.23D + 1.1	16.0*	0.79
2	SPM = 0.45D + -1.7	43.9*	0.92
3	SPM = 0.54D + -2.9	23.3*	0.85
4	SPM = 0.57D + -2.6	13.4*	0.77
5	SPM = 0.48D + 8.0	2.7	0.40
6	SPM = 1.30D + 7.9	9.2*	0.70
7	SPM = 2.10D + 22.3	1.5	0.27
8	SPM = 2.30D + 20.0	1.8	0.31

* slope is significantly different from zero ($p < 0.05$)

Bathymetry and Tidal Currents

Figure 7 shows the cross-sectional area of the channel adjacent to stations 1 - 8. Stations 1 - 4 have the largest cross-sectional areas and exhibit a landward decrease of 422.0 m^2/km. The average percent change in cross-sectional area between adjacent stations (1 - 4) was less than 20%; however, there was a 62% decrease in cross-sectional area between stations 4 and 5 (Figure 8a). The gross decrease in cross-sectional area can be primarily attributed to decreasing width of the estuary. Cross-sectional area continued to decrease in a landward direction between stations 5 - 7 at 212.0 m^2/km with approximately a 60% reduction in cross-sectional area from station-to-station (Figure 8b). A 63% increase in cross-sectional area typifies the region from station 7 to 8, and was the only region that increased in area relative to the adjacent downstream station.

The magnitude of tidal current velocity increased in a landward direction within the study area (Figure 8b). Maximum tidal current velocity (surface) steadily increased from approximately 30 cm/s at the mouth of the estuary to a maximum of 70 cm/s at river km 55 (station 7). Decreased current velocities between stations 7 and 8 are possibly explained by increased cross-sectional area (Figure 8a and 8b). Crooks and O'brien (1967) reported maximum current velocities (100 cm/s) 70 km upstream of the estuary mouth. The landward increase in tidal current velocities is primarily due to the narrowing and shallowing of the estuary. An increase in tidal wave amplitude in a landward direction is observed in estuaries with convergent channel geometry and decreasing

FIGURE 7: Patuxent River estuary channel cross-sectional area (m^2) adjacent to stations 1 - 8.

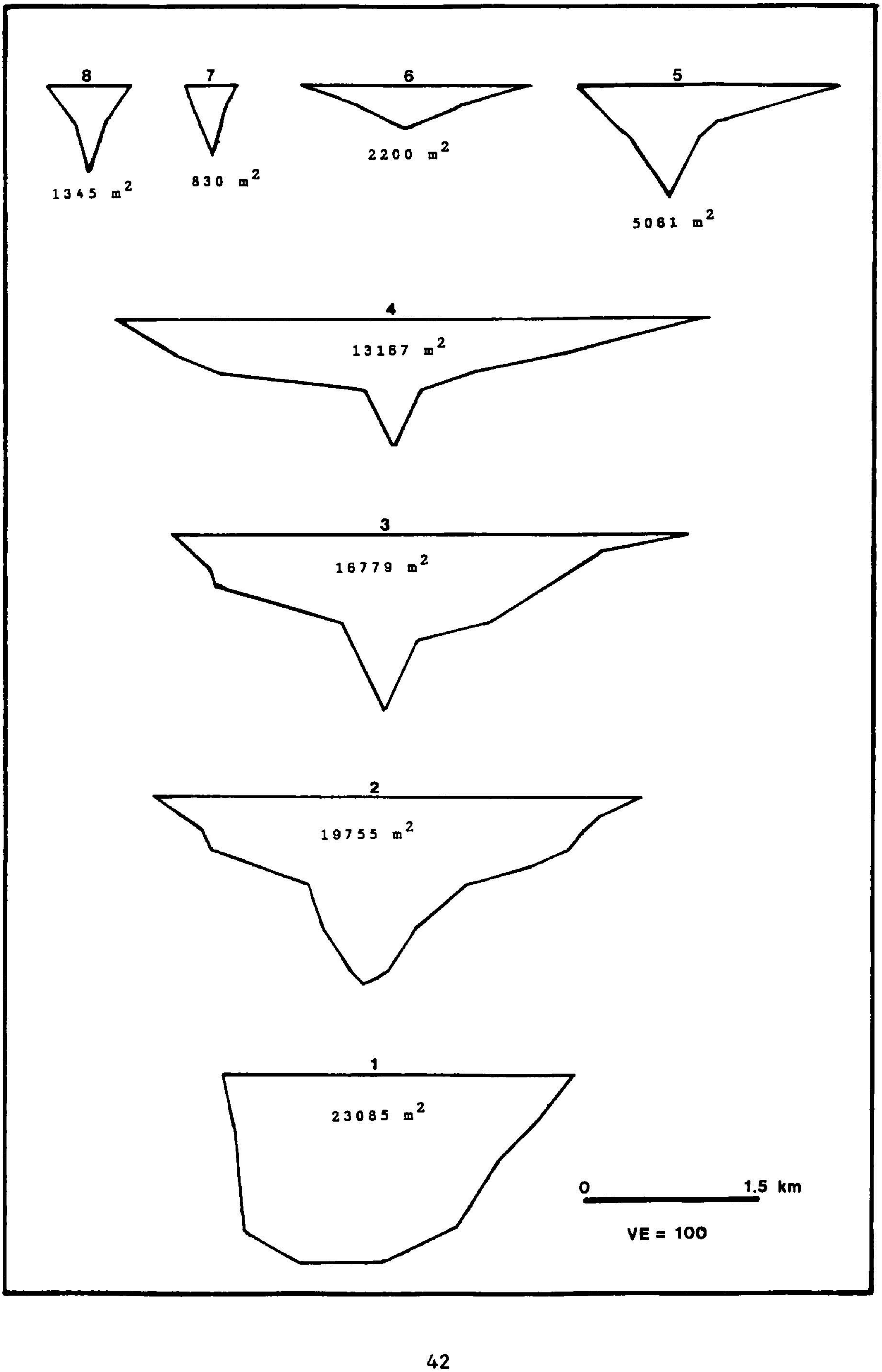
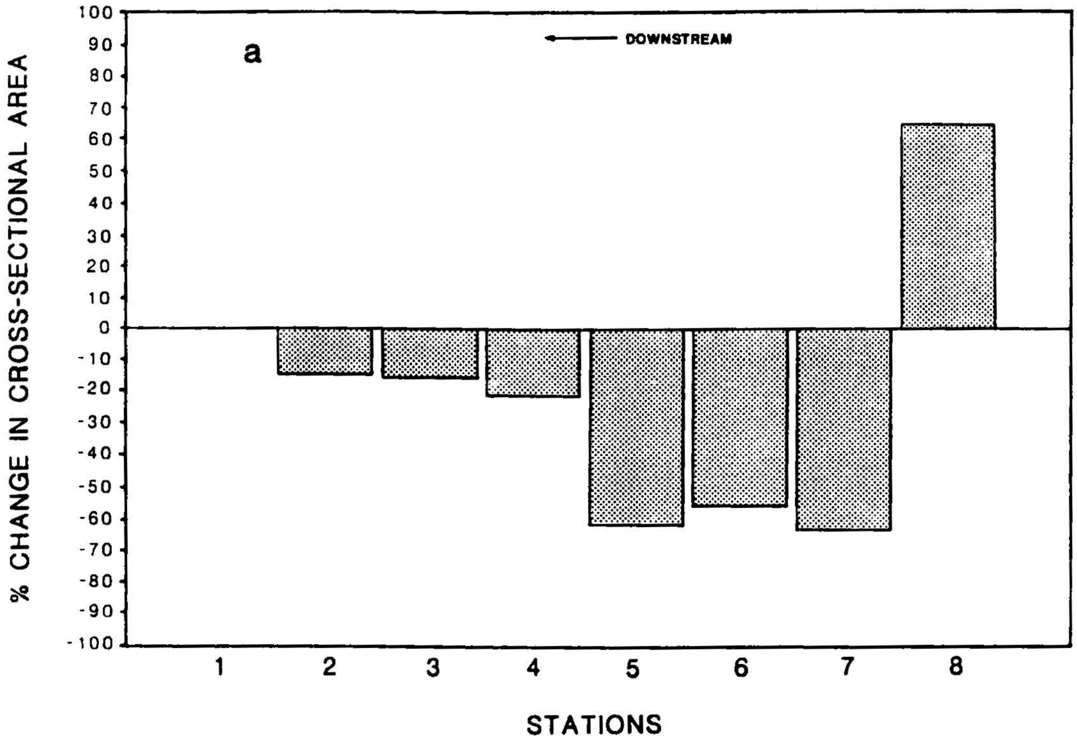
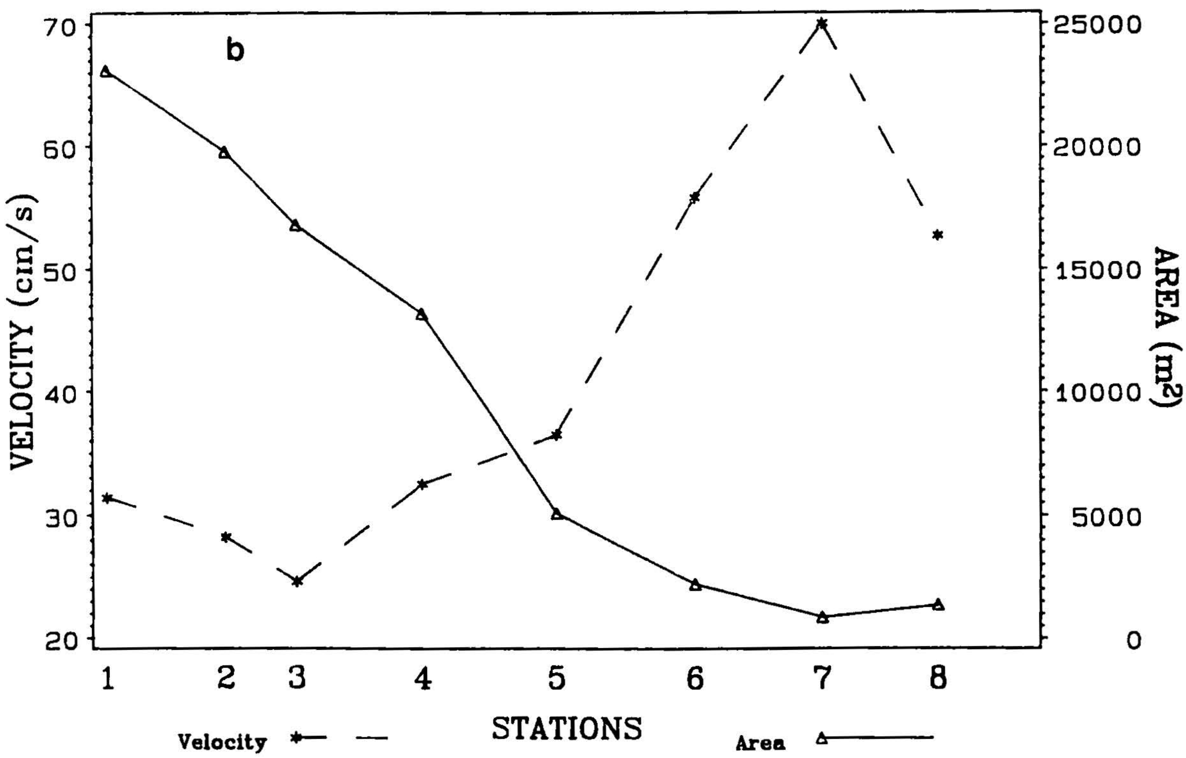

8
7
6
5
1345 m2
830 m2
2200 m2
5081 m2
4
13167 m2
3
16779 m2
2
19755 m2
1
23085 m2
0
1.5 km
VE = 100

FIGURE 8: Percent change in cross-sectional area between adjacent stations (a), and (b) cross-sectional area (m^2) versus tidal current velocity (cm/s; ANS, unpubl. data) for Patuxent River estuary.



a
DOWNSTREAM
% CHANGE IN CROSS-SECTIONAL AREA
100
90
80
70
60
50
40
30
20
10
0
-10
-20
-30
-40
-50
-60
-70
-80
-90
-100
1
2
3
4
5
6
7
8
STATIONS



b
VELOCITY (cm/s)
70
60
50
40
30
20
AREA (m^2)
25000
20000
15000
10000
5000
0
1
2
3
4
5
6
7
8
STATIONS
Velocity
Area

channel width and depth in a landward direction.

Over a few kilometers, location of initial significant changes in SPM, SIM, and SOM gradients are imprecise (Table 4). Initial significant changes in SPM concentrations, moving landward from the mouth, occurred in an area of dynamic channel configuration. At station 5 there was an abrupt change in cross-sectional area and the estuary was narrower and shallower relative to stations 1 - 4 (Figure 7). Correlation between cross-sectional area and tidal current velocity at stations 1 - 8 was significant, having an r^2 value of 0.71 (Table 6). Additionally, the concentration of SPM proved to be more strongly correlated with tidal current velocity ($r^2 = 0.81$) than with cross-sectional area ($r^2 = 0.73$).

Table 6. Linear regressions between cross-sectional areas (A), maximum observed tidal current velocities (Umax), and SPM concentrations measured at stations 1 - 8. The linear equation, coefficient of determination (r^2), and F distribution value is shown for each regression (n = 64).

Case	Regressions	F	r^2
Current Velocity versus Cross-sectional area	Umax = -0.002A + 62.1	14.1*	0.71
SPM versus Cross-sectional area	SPM = -0.002A + 41.1	15.9*	0.73
SPM versus Current Velocity	SPM = 1.1Umax + (-25.2)	26.0*	0.81

* slope is significantly different from zero ($p < 0.01$)

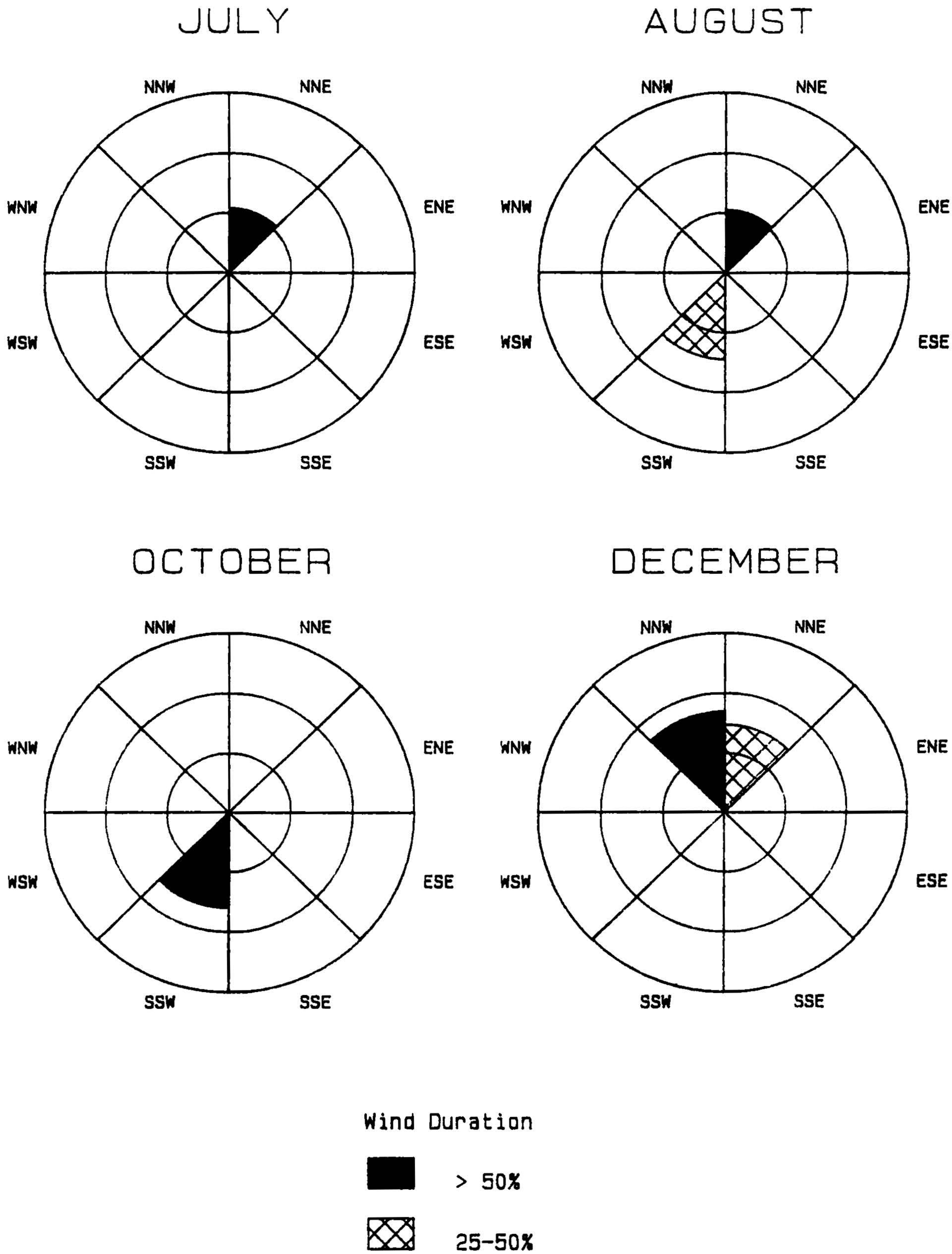
Winds

Previous studies suggest that wind generated waves are responsible for the resuspension of bottom material in shallow reaches of Patuxent River estuary (Roberts and Pierce, 1976), and sections of Chesapeake Bay (Schubel, 1972). Figures 9a and 9b show wind direction, magnitude, and duration over a four day period corresponding to each SPM sampling date. In general, wind speeds were negligible during the sampling periods (rarely exceeded 8 knots). During late summer and fall, winds were predominantly from the south, whereas winter and spring winds prevailed from the north-northwest. Highest wind speeds occurred during April 1986 at 12 knots, and persisted for approximately two days from the west-northwest (parallel to the estuarine zone).

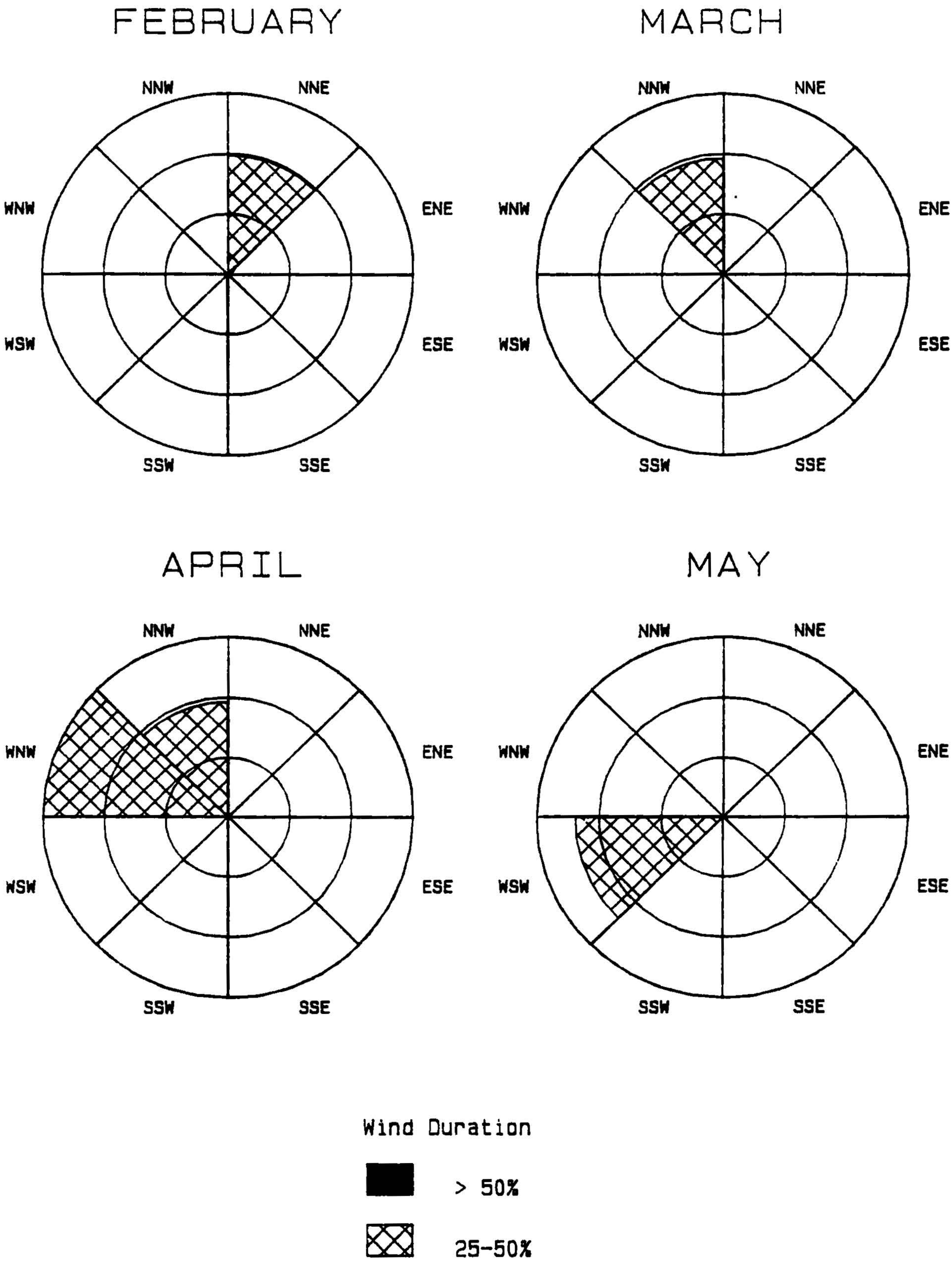
Linear regressions in Table 7 show the relationships between seasonal variations in SPM concentrations and wind for each station. The orientation of the zone in which stations are located and the predominant wind direction were factored into the regression analysis in order to account for wind fetch. At stations 2 and 3, wind and SPM concentrations were significantly correlated ($0.68 < r^2 < 0.70$).

Correlations between wind and SPM concentrations within the transition zone were not significant (Table 7). A negative slope between SPM concentration and wind was noted for Station 5 and may be the result of an unusually high SPM concentration (27.2 mg/ℓ) measured during October 1985. Station 6, the shallowest station (3 m),

FIGURE 9: Wind direction, magnitude, and duration during (a) July, August, October, and December 1985, and (b) February, March, April, and May 1986, Fishing Point, MD. Each wind rose is divided into 8 quadrants depicting a specified direction (from); magnitude is marked with concentric rings at 4 knots/ring. The legend shows duration as percent of the 4 day observation period.



JULY
NNW
NNE
WNW
ENE
WSW
ESE
SSW
SSE
AUGUST
NNW
NNE
WNW
ENE
WSW
ESE
SSW
SSE
OCTOBER
NNW
NNE
WNW
ENE
WSW
ESE
SSW
SSE
DECEMBER
NNW
NNE
WNW
ENE
WSW
ESE
SSW
SSE
Wind Duration
> 50%
25-50%


FEBRUARY
MARCH
APRIL
MAY
NNW
NNE
WNW
ENE
WSW
ESE
SSW
SSE
Wind Duration
> 50%
25-50%

was positioned within an area where Roberts and Pierce (1976) identified a secondary turbidity maximum and attributed its formation to resuspension of bottom material by wind waves. In the present study, no relationship was observed between wind and SPM concentration for the area. The freshwater zone (stations 7 and 8) also exhibited nonsignificant correlations between wind and SPM concentrations.

Table 7. Linear regressions between coded wind data (W) and SPM concentrations for stations 1 - 8. The linear equation, coefficient of determination (r^2), and F distribution value is shown for each regression ($n = 48$).

Location	Regression	F	r^2
Estuarine Zone			
Station 1	SPM = 0.22W + 4.0	3.4	0.46
Station 2	SPM = 0.51W + 2.4	8.8*	0.68
Station 3	SPM = 0.67W + 2.0	9.4*	0.70
Station 4	SPM = 0.64W + 3.0	4.3	0.52
Transition Zone			
Station 5	SPM = -0.86W + 21.1	0.2	0.05
Station 6	SPM = 0.29W + 26.3	0.0	0.00
Freshwater Zone			
Station 7	SPM = 8.20W + 9.0	1.9	0.32
Station 8	SPM = 14.50W + 3.0	2.5	0.38

* slope is significantly different from zero ($p < 0.05$)

Particle-Size and Composition

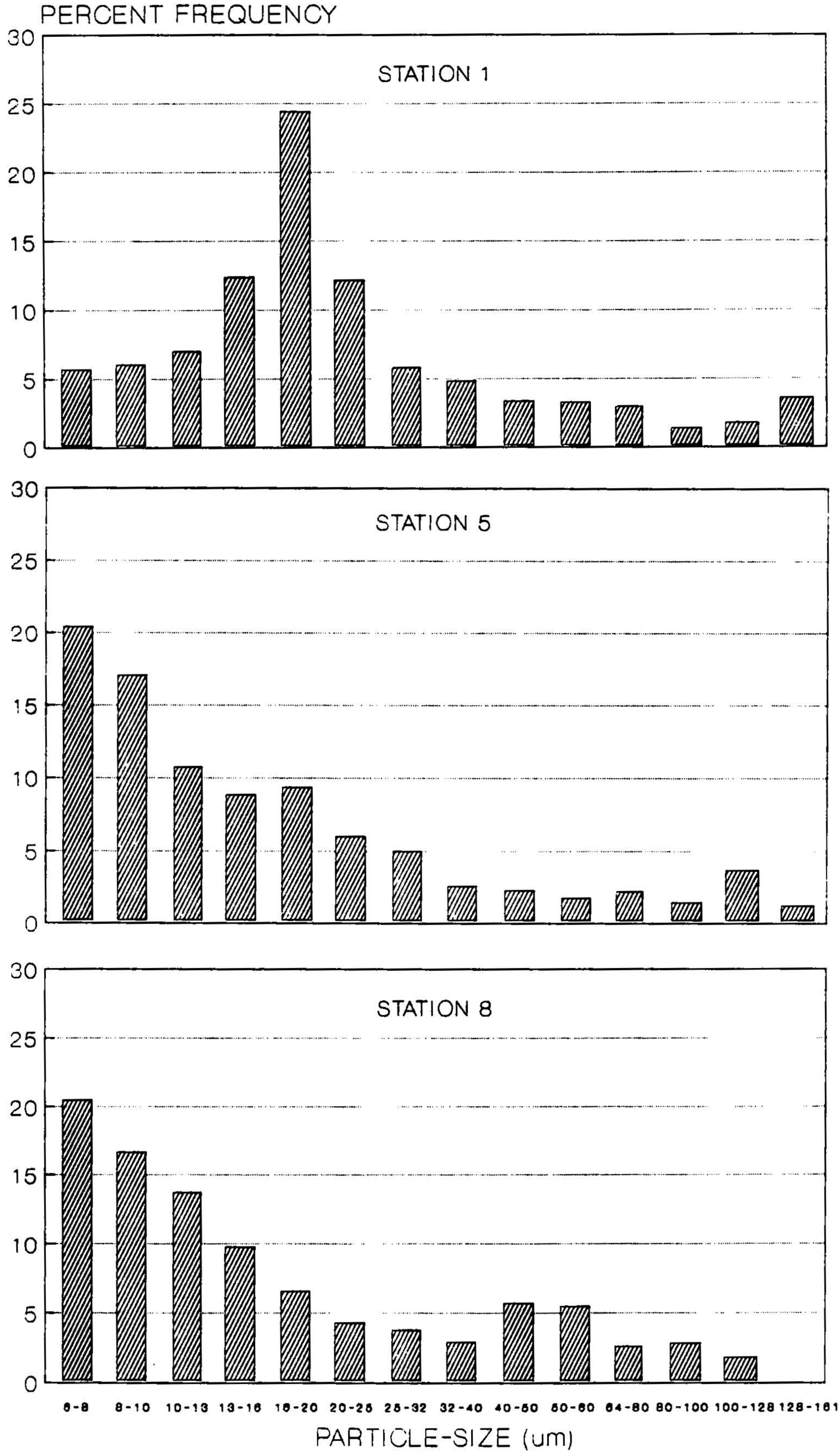
The particle-size distributions shown in Figures 10a and 10b are typical of the variability observed in the longitudinal distribution of particle-size, with two distinct populations along the axis of the estuary. During late fall, winter, and early spring, relatively large suspended particles (primary size mode of 10.0 - 20.0 μm in diameter) were consistently noted at stations 1 - 4 (Figure 10a, 10b); the largest particles (primary size mode 32.0 - 50.0 μm; see Appendix 2) were noted during November 1985.

Landward of station 4 the dominant particle-size decreased concurrently with increased concentration of SPM and larger contributions of SIM in the total suspended loads. The primary size mode of particles during low temperature months in the upper estuary (stations 5 - 8) was 6.0 - 8.0 μm in diameter (Figure 10a). A secondary size mode of approximately 40.0 - 60.0 μm in diameter was noted at stations 6, 7, and 8 during December 1985 (Figure 10a). The secondary size mode was evident in the upper estuary during much of the study, except during June 1986 when particles 25.0 - 32.0 μm in diameter dominated the particle-size distribution (Figure 10b). Particle-size at station 6 during April 1986, a period of intense winds, was dominated by particles 40.0 - 60.0 μm in diameter (Appendix 2).

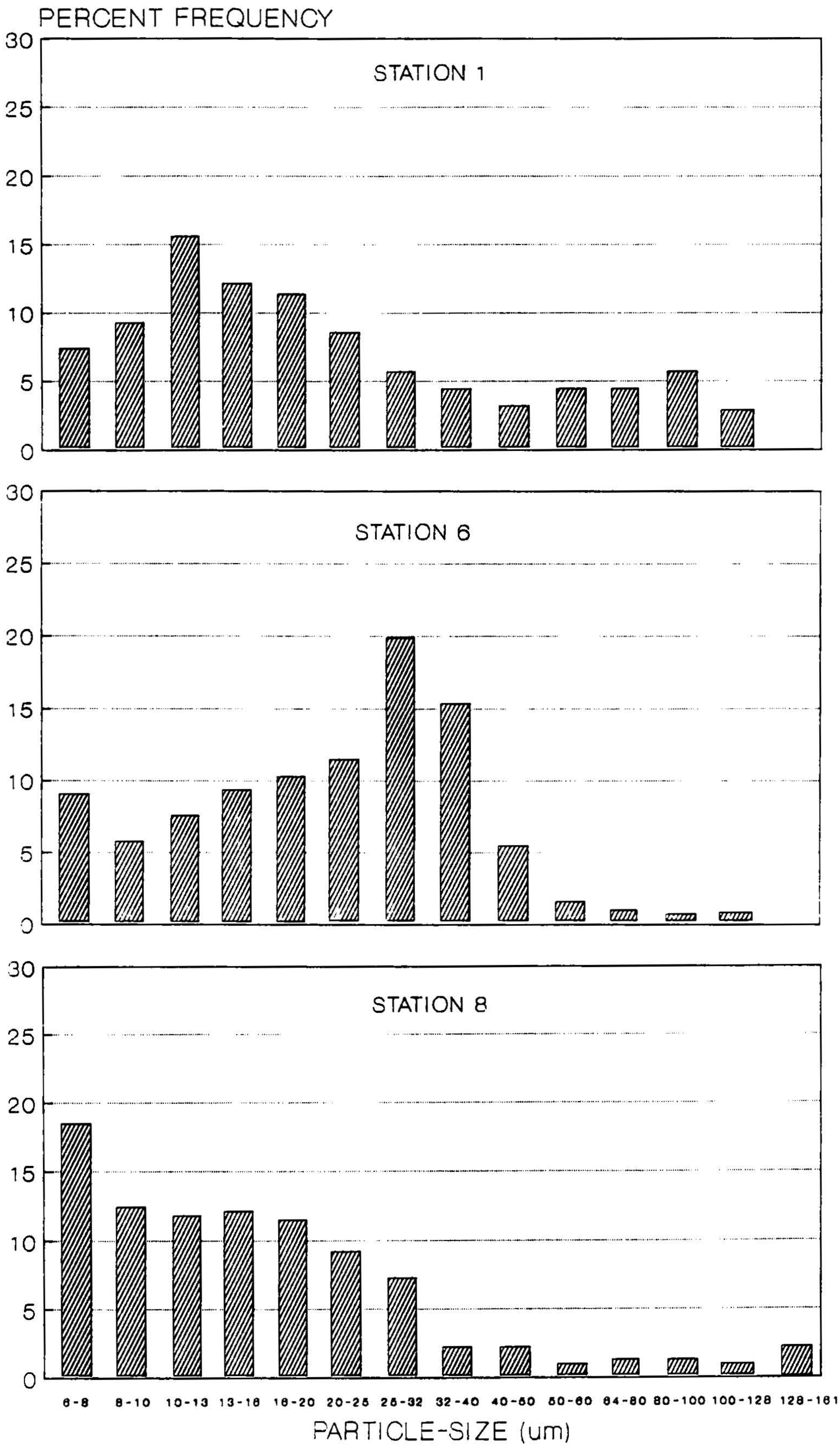
A boundary between stations 4 and 5 clearly separated particle-size populations of the upper (transition and freshwater zones) and lower (estuarine zone) estuary, except during December 1986. As noted previously (p. 37), large particles in the lower estuary were rich in

FIGURE 10: Longitudinal particle-size distributions for (a) stations 1, 5, and 8, December 1985, and (b) stations 1, 6, and 8, June 1986, Patuxent River estuary.

DECEMBER, 1985



JUNE, 1986


PERCENT FREQUENCY
30
25
20
15
10
5
0
STATION 1
STATION 6
STATION 8
6-8
8-10
10-13
13-16
16-20
20-25
25-32
32-40
40-50
50-60
64-80
80-100
100-128
128-161
PARTICLE-SIZE (um)

organic material. Microscopic analysis of suspended particulates indicated numerous centric diatoms and dinoflagellates with concentration (1.1×10^7 organisms/ℓ; Sellner and Brownlee, 1987) and size overlapping the primary size mode observed at stations 1 - 4. Although microzooplankton larger than 44 μm were noted and identified as rotifers and copepod nauplii, their concentrations were too low (282.2 organisms/ℓ) to significantly affect the particle size distribution in the SPM.

Inorganic material occurred as very-fine silt and fine-silt (Wentworth, 1922) and was the principal component of SPM in the upper estuary (stations 5 - 8). Particle-size distributions from the upper estuary (e.g. station 8, Figure 10a, 10b) were typically shifted towards the left (finer end), unimodal, and truncated. Truncation was caused by the lower resolution limit of the 400 μm aperture tube used with the coulter counter (6.4 μm), so that particles less than 6.4 μm in equivalent spherical diameter were not detected in the analysis.

Particle-size distributions along the estuary in summer and early fall (Figure 10b) were unlike those noted in cooler sampling periods. Particle-size distributions from stations 1 - 4 had a primary size mode of 10.0 - 13.0 μm, one size range lower than December 1985 observations. Microscopic analysis of lower estuary samples revealed unidentified blue-green algal spheres (1 - 3 μm), *Cryptomonas* sp. (cryptophyte), tintinnids, rotifers, and copepod nauplii. Algal spheres were present in high concentration, but these cells were too small to account for the primary size mode. *Cryptomonas* sp. has a diameter of approximately 10 μm, which is equivalent to the primary size mode measured at stations 1

- 4. Again, microzooplankton concentrations were too low to affect the primary size mode; however, the particle-size distribution did show a weak secondary size mode of 50.0 - 100.0 μm.

During the warmer sampling periods, primary size modes for stations 5 - 8 varied between 6.0 - 32.0 μm. Station 5 had a primary size mode of 13.0 - 16.0 μm, while station 6 showed the largest primary size mode of 25.0 - 32.0 μm. At stations 7 and 8 the primary size mode decreased to 6.0 - 8.0 μm. Microscopic analysis indicated high densities of *Microcystis* sp., *Leptocylindricus minimus*, *Merismopedia* sp., *Agmenellum* sp., *Cyclotella* sp. between stations 6 and 8. These organic particles, along with background inorganic particles (very-fine and fine-silt), had diameters equivalent to the primary size modes observed at stations 5, 7, and 8. However, there were no plankton identified that overlapped the 25.0 - 32.0 μm size mode measured at station 6.

Freshwater-Transition Interface Zone

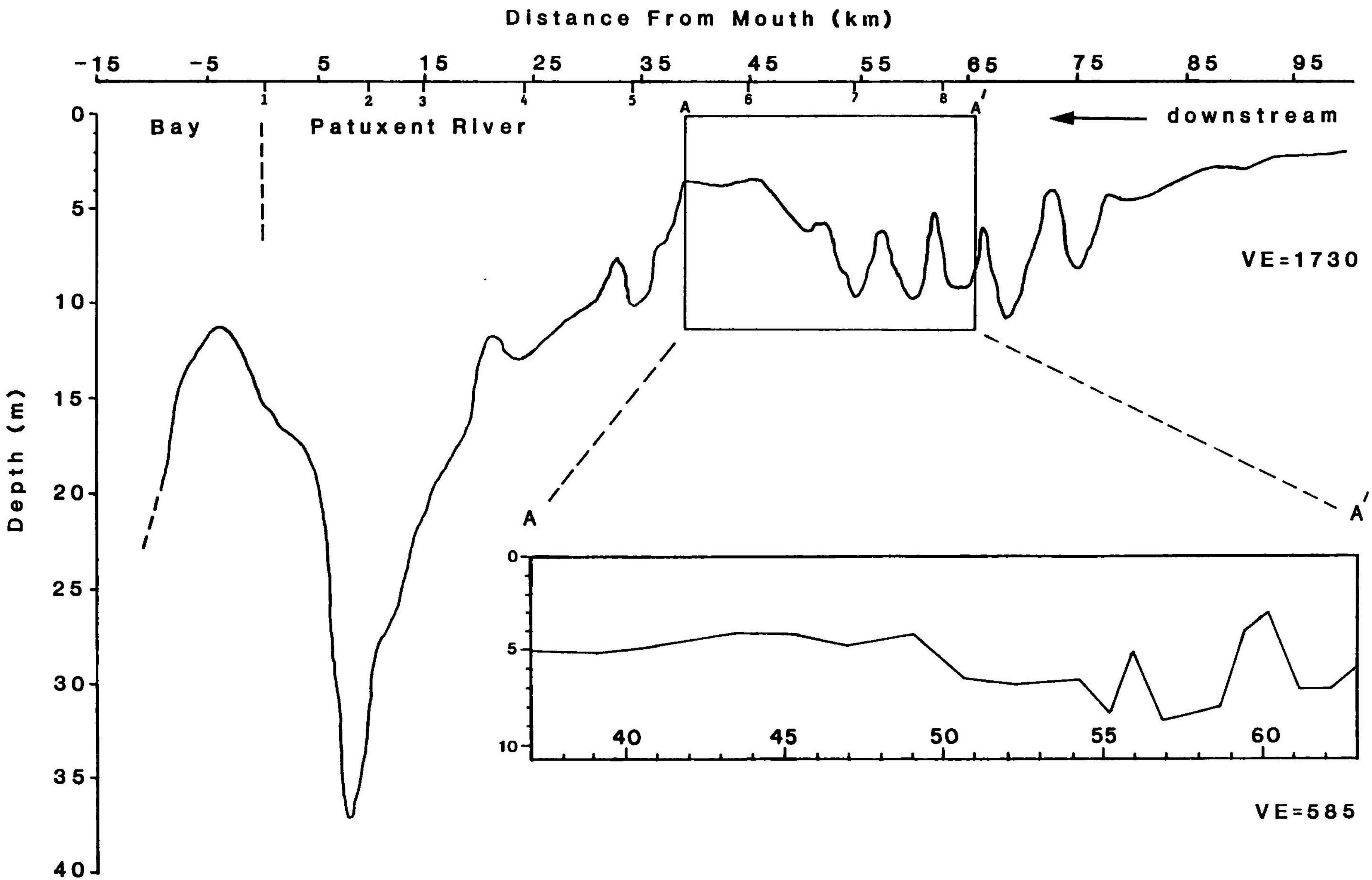
Suspended Particulate Matter Distribution

The lower or seaward portion of the Patuxent River (0 km to 30 km) is typified by depths exceeding 10 m (Figure 11). In the region 30 km above the mouth, depths were generally less than 10 m and bathymetry became quite variable. The area associated with the FW-T interface was located 37 - 63 km upstream, encompassing stations 6, 7, and 8, and is shown as an enlargement in Figure 11. The longitudinal migration of the FW-T interface was monitored and SPM concentrations were measured from July 1985 to May 1986; (Figures 12a, 12b, and 12c).

Average width and depth between 37 - 49 km from the mouth was approximately 1 km and 4 m, respectively. This broad and shallow section had little bathymetric irregularity and was typified by salinities greater than 1 ‰. Above 49 km from the estuary mouth, the estuary was narrow and bathymetry showed extensive variability. The average width was approximately 400 m and depths ranged from 3 - 9 m. Irregularity in bathymetry can be attributed to several severe meanders in the estuary channel located 55 km, 58 km, and 62 km from the estuary mouth. Maximum current velocities (70 cm/s; ANS, unpubl. data) were measured in this region along with typical salinities of 1 ‰ or less.

In July and August 1985 (Figure 12a), the FW-T interface was located approximately 60 km upstream of the estuary mouth. Maximum concentrations of SPM (50 - 60 mg/ℓ, respectively) were located in the FW-T interface 55 - 60 km above the mouth. In the region, concentrations of

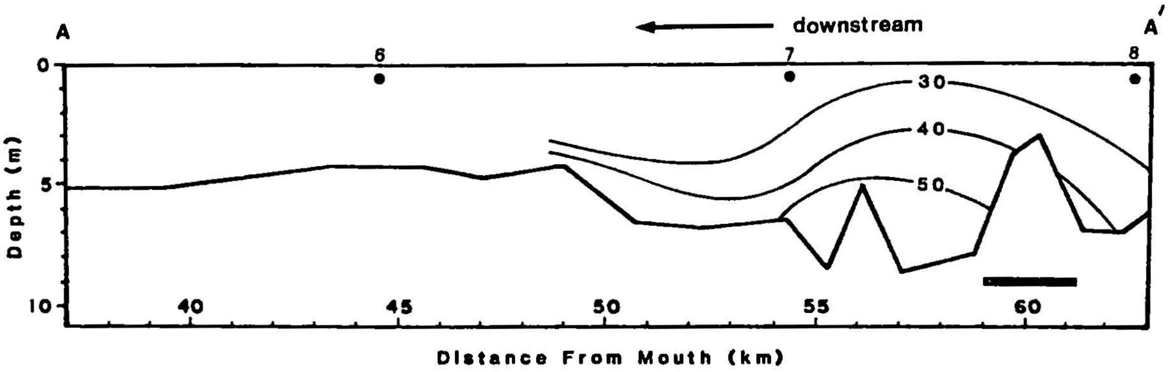
FIGURE 11: Longitudinal bottom profile of Patuxent River estuary at mean low water.



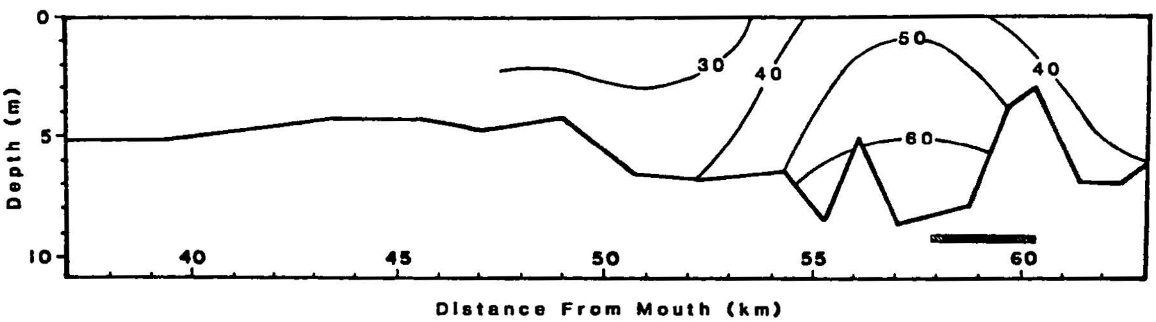
Distance From Mouth (km)
-15
-5
5
15
25
35
45
55
65
75
85
95
1
2
3
4
5
A
6
7
8
A'
Depth (m)
0
5
10
15
20
25
30
35
40
Bay
Patuxent River
downstream
VE=1730
A
A'
0
5
10
40
45
50
55
60
VE=585

FIGURE 12: Longitudinal profile of upper Patuxent River estuary depicting bathymetry and contours of suspended particulate matter (mg/ℓ) during: (a) July, August, and September 1985, (b) November, December 1985, and February 1986, and (c) March, April, and May 1986. The horizontal bar extending across each lower profile indicates the location of the 0.0 - 1.5 ‰ salinity range (left-hand side equals 1.5 ‰; far right-hand side equals 0.0 ‰).

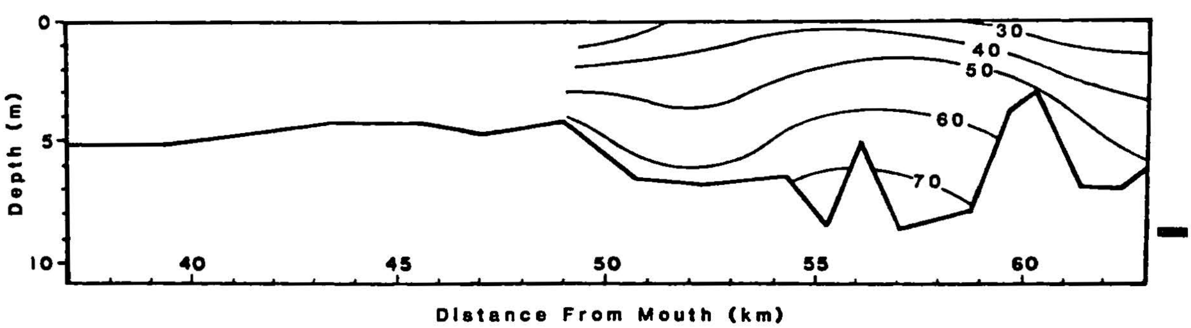
JULY 1985



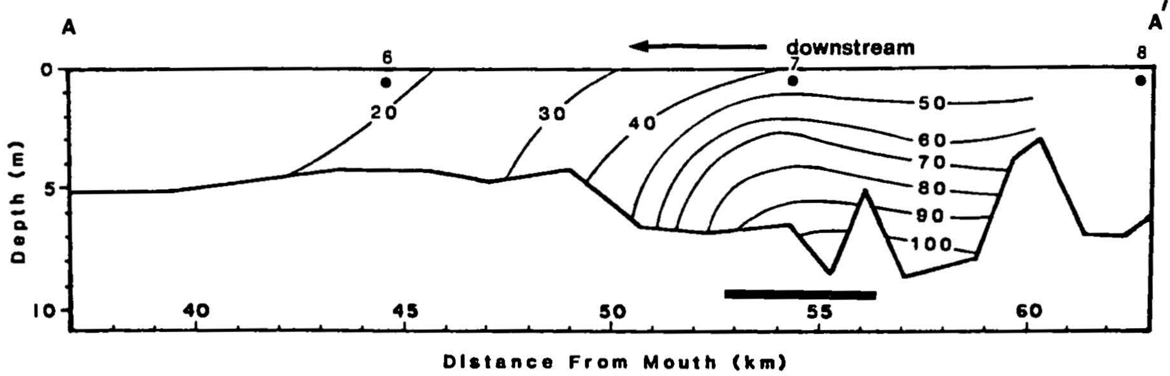
AUGUST 1985



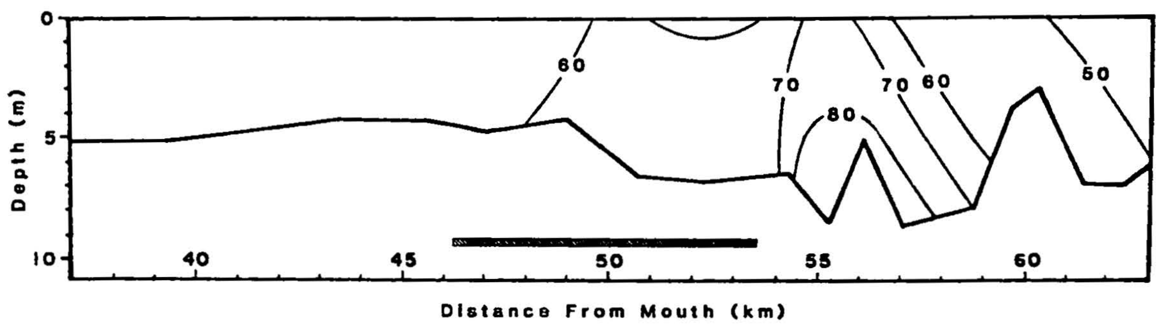
SEPTEMBER 1985



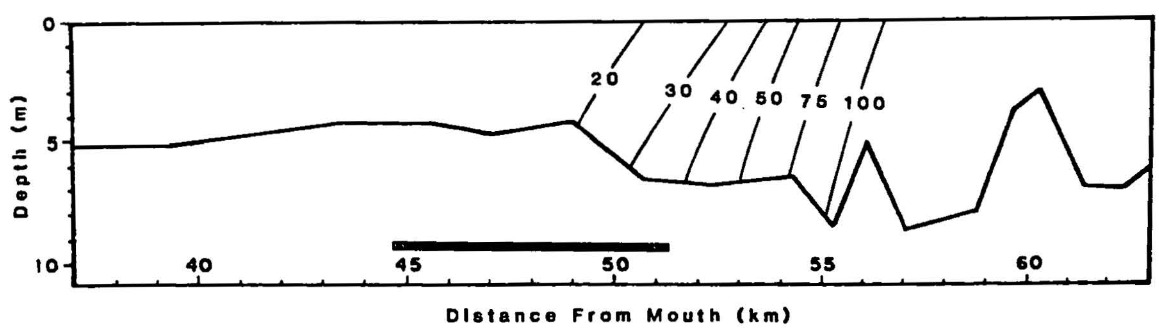
NOVEMBER 1985



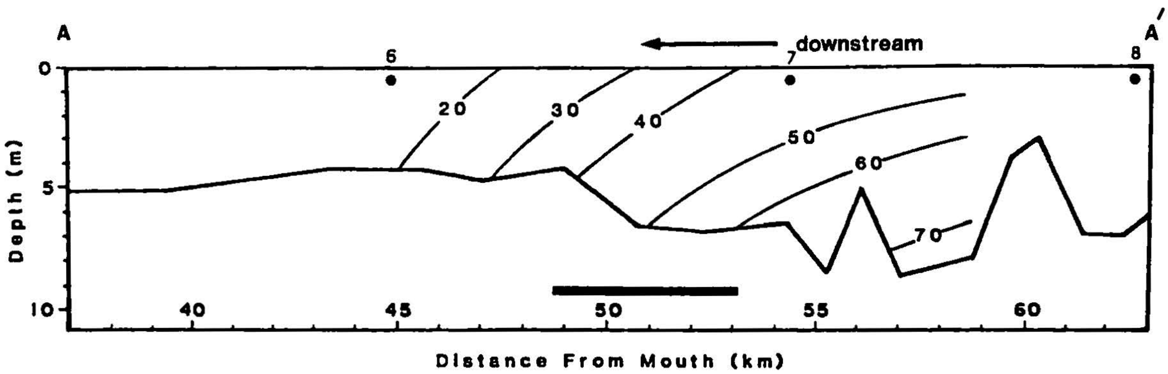
DECEMBER 1985



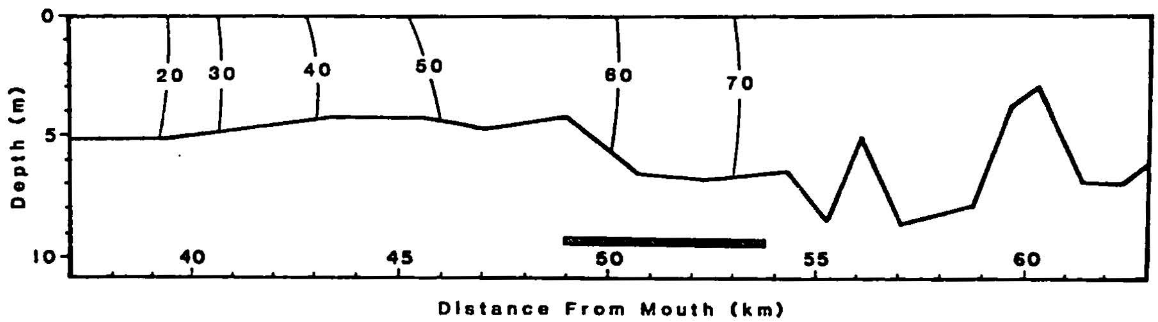
FEBRUARY 1986



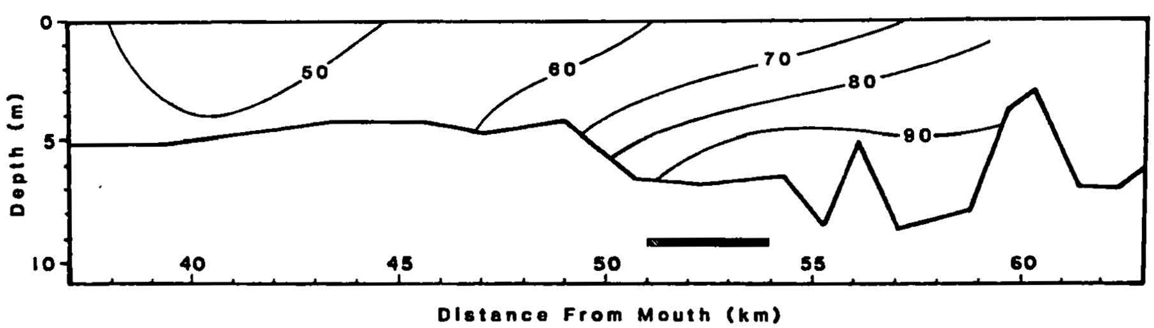
MARCH 1986



APRIL 1986



MAY 1986



SPM increased with depth; concentrations decreased in a landward and bayward direction.

The FW-T interface migrated landward of Nottingham (63 km above the mouth) during the month of September 1985 (Figure 12a). Landward migration of the FW-T interface corresponded with a minimum river discharge rate of 5.9 m^3/s. Maximum concentrations of SPM were measured between 55 - 60 km above the mouth, similar to July and August 1985, in a region downstream of the FW-T interface. Only a slight decline in SPM concentration was observed up or down estuary of the maximum.

During November 1985, the FW-T interface migrated bayward approximately 8 km to a location 55 km above the estuary mouth (Figure 12b). Downstream displacement of the FW-T interface occurred during a period of increased river discharge (Figure 5). The distance of migration is a rough approximation since the location of the FW-T interface during the previous month was landward of the study area. The maximum concentration of SPM exceeded 100 mg/ℓ and was located 55 - 60 km from the mouth. The concentration of SPM noticeably decreased bayward but remained high landward of the maximum.

In December 1985, the FW-T interface was located approximately 50 km from the estuary mouth, a 5 km bayward shift in position (Figure 12b). The maximum SPM concentration exceeded 80 mg/ℓ and was measured landward of the FW-T interface, 54 - 59 km from the mouth.

During February, March, and April 1986 the FW-T interface was located in the region 45 - 55 km from the estuary mouth (Figures 12b, 12c). The FW-T interface migrated a short distance bayward relative to its position during December 1985. Maximum concentrations of SPM (70 -

100 mg/ℓ) were observed between 55 - 60 km from the mouth. SPM concentrations never decreased landward of the FW-T interface during February and May and the upper estuary appeared vertically mixed. Increased turbidity during this period coincided with the highest discharge measured for the Patuxent River.

The FW-T interface was located approximately 57 km from the estuary mouth during May 1987 (Figure 12c), indicating a 7 - 10 km landward migration. Concentrations of SPM remained high in spite of low flow conditions with maximum concentrations exceeding 90 mg/ℓ. Elevated concentrations of SPM were associated with deeper sections of the upper estuary, 50 - 60 km from the mouth. Concentrations of SPM 37 - 49 km from the mouth were higher than at any other time during the study.

Particle-Size and Composition

Chi-square tests indicated that there were no significant ($p < 0.05$) horizontal or vertical differences between particle-size distributions of SPM in the FW-T interface zone. The primary size mode of SPM was 6.0 - 16.0 μm in diameter, corresponding to very-fine and fine-silts.

However, during July and August 1985, and June 1986, horizontal differences existed between particle-size populations within the FW-T interface zone. The freshwater portion of the interface zone was typified by particles with primary size modes equivalent to commonly observed modes during the entire study period (6.0 - 16.0 μm), but low salinity reaches had a much larger primary size mode (25.0 - 32.0 μm in diameter). This variation in particle-size may be the result of several mechanisms.

Microscopic analysis (Sellner and Brownlee, 1987) revealed high concentrations of the cyanobacterium *Microcystis aeruginosa*, commonly observed in massive blooms in upper Potomac River estuary during the summer. Sellner et al. (1987) described an aggregation process whereby *Microcystis* spp. formed large colonies after being exposed to daily salinity increases in the laboratory. These laboratory findings suggested that aggregation and prolonged exposure to osmotic stress can result in limited horizontal distribution of *Microcystis* spp. Sellner et al. speculated that colonies are removed from surface waters, bayward of the initial colonization region, due to increased particle settling rates accompanying decreasing photosynthetic ability and buoyancy regulation. Avnimelech et al. (1982) described a process where algal species aggregated with inorganic clay particles in low salinity solutions, increasing their settling rates due to increased size. The increased particle-size observed in the upper Patuxent River estuary may be an indicator of either of these processes.

Additional microscopic analysis identified several dominant inorganic particles with large diameters. Near-bottom samples commonly had abundant aggregates (30% or greater) that ranged from 30 - 80 μm in diameter. Composition of the aggregates remains undetermined but the average percentage of combustible material for the complete sample was 15%.

Aggregates were found at mid-depth and surface with similar frequency, but with smaller diameters (30 - 60 μm). Individual mineral grains, usually quartz, were also identified (10% or less) and were sometimes frequently observed (10 - 30%); diameters ranged between 30 -

60 μm. Bond and Meade (1966) reported that 2 - 11% of the SIM suspended in surface waters of Chesapeake Bay consisted of recognizable mineral grains.

4. DISCUSSION AND SUMMARY

During 1985-86 observations, maximum river discharge for the Patuxent River occurred in February 1986 (Figure 5). Strong correlations were noted between freshwater runoff and salinity and SPM concentration in the upper Patuxent River estuary (Tables 3 and 4, Columns A). However, for stations proximate to the estuary mouth, significant correlations were noted between SPM concentration and salinity and river discharge from the previous month (Tables 3 and 4, Columns B). These results indicate a lag in salinity and SPM concentration in the lower Patuxent River estuary to pulses of freshwater. Furthermore, increases in Patuxent River flow and turbidity in the upper estuary may have resulted from: (1) additional suspended material from upstream, and/or (2) net two-layer circulation increased trapping efficiency during high flow in the upper estuary.

The Patuxent River estuary can be divided into two segments based on salinity, SPM concentration, composition, and particle-size. Stations 1 - 4 are relatively uniform with respect to salinity and concentration of SPM. SPM at stations 1 - 4 is composed of large organic particles ranging from 10.0 - 50.0 μm in diameter, and the concentration of SPM and percentage of SOM in the lower estuary are similar to those reported by Schubel and Carter (1976) for the upper Chesapeake Bay adjacent to the Patuxent River estuary mouth: concentrations of SPM were less than

10 mg/ℓ and percentages of SOM ranged between 50 - 80% of SPM.

The lower estuary water mass has physical, biological, and geological characteristics of upper-to-mid Chesapeake Bay water. These characteristics changed significantly between stations 4 and 5, which is the approximate location, noted by Owen (1969), of the furthest landward intrusion of surface bay water during the spring. Furthermore, cross-sectional area of the estuary channel decreases by 62% between stations 4 and 5; bathymetry could be inhibiting net landward transport of lower estuary water.

Another possible explanation for the abrupt change in lower estuary SPM characteristics and salinity between stations 4 and 5 is a bayward limit of the effects of upper estuary processes. A significant correlation between salinity and freshwater runoff was noted for the region of stations 5 - 8 in the estuary; therefore, abrupt changes in salinity observed near stations 4 and 5 could be explained by rapid dilution of upper river freshwater by the larger volume of saline water in the rapidly widening estuary. Accordingly, fluctuations in discharge from the Patuxent River should cause the boundary between the upper and lower estuary water masses to deviate from its position. However, initial significant changes in salinity occurred between stations 4 and 5 during high and low periods of river discharge. It therefore appears discharge and bathymetry in the region of stations 4 - 5 may be the dominant factors influencing longitudinal variability in water mass characteristics.

A significant correlation between climatic conditions and SPM concentrations was noted for stations 2 and 3 (Table 7). Channel flanks in the lower estuary were typically broad and shallow, an area susceptible to bottom resuspension by wind generated waves. However, intensified wind conditions oriented parallel with the axis of the estuarine zone occurred during spring runoff. Therefore, it is difficult to attribute fluctuations in SPM concentration to increased fetch, resuspension by wind waves, and possible shore erosion during a period of known increased suspended load (spring runoff). Wind conditions during April 1986 did appear to affect particle-size at station 6, the shallowest of the eight stations.

Upper estuary SPM characteristics showed marked differences from those in the lower estuary. Particles in the upper estuary were smaller (6.0 - 8.0 μm) and predominantly composed of inorganic material relative to lower estuary particles. Additionally, there was extreme variability in SPM concentrations, minimum and maximum concentration measurements ranging from 11.0 - 104.3 mg/ℓ with an average approximating 45 mg/ℓ. Figure 6 clearly shows that the lowest SPM concentrations occurred during late summer and fall, while maximum SPM concentrations coincided with early and late spring.

Seasonal variability of SPM concentration patterns (turbidity maxima and turbidity fronts) at stations 7 and 8 can be explained by fluctuations in river discharge. Concentrations of SPM increased at stations 7 and 8 with increased river flow and suspended load. This function may suggest the two-layer circulation pattern became more effective in trapping SPM in this region at higher river flow. Additionally, increased river flow during the spring increases tidal flow velocities; therefore, increasing bottom shear stress and suspension of bottom material. The latter explanation is very possible since stations 7 and

8 were located in a narrow, deeply scoured, and swiftly flowing section of the upper estuary.

Turbidity contours of the upper estuary showed three separate configurations during the study period (Figure 12a-c). During July and August 1985, a "turbidity maximum" was present as concentrations of SPM decreased in both a landward and seaward direction. A "vertically stratified turbidity front" occurred during September, November, and December 1985, where concentrations of SPM increased landward and with depth, but decreased seaward. The frontal pattern was further altered during February, March, and April 1986 to a "vertically homogenous turbidity front," since concentrations of SPM showed little change landward and with depth. Similar fronts have been observed in the upper Chesapeake Bay during periods of high discharge in the Susquehanna River (Schubel and Pritchard, 1986). April 1986 was exceptionally well-mixed with respect to SPM concentration, and more than likely high SPM concentrations were the result of high winds (12 knots) and flow encountered during that sampling period.

Roberts and Pierce (1976) reported peak concentrations of SPM, relative to background concentrations upstream and downstream, 70 km above the mouth during low flow conditions. Intermediate concentrations of SPM were found 50 - 60 km upstream during average runoff, and minimum concentrations of SPM were located 45 km from the mouth during high runoff. The turbidity maximum reportedly migrated with the FW-T interface as it responded to changing conditions of freshwater runoff. However, the magnitude of turbidity in the upper estuary decreased with increasing runoff, a phenomenon unobserved during this study. In concurrence with Roberts and Pierce (1976), OEP (1984) depicted maximum concentrations of SPM during low flow conditions (summer) 45 - 65 km from the mouth. Intermediate and high flow conditions resulted in a seaward shift of the FW-T interface, but peak SPM concentrations remained between 45 - 65 km from the mouth. This type of response indicates bathymetry in this region may interact with flow to control turbidity patterns in the upper estuary.

Observations made during 1985-86 of SPM concentrations and salinity between 37 - 63 km from the estuary mouth showed the FW-T interface migrated between 48 - 63 km in response to changing river discharge conditions. The location of maximum concentrations of SPM did not correspond with the FW-T interface, but was stationary between 50 - 60 km above the mouth except during extreme flow conditions. SPM concentrations in February 1986 (high flow) were increasing up to station 8 and most likely peaked landward of station 8. During low and moderate river flow conditions, concentrations of SPM decreased bayward and landward of the upper estuary.

During periods of low to moderate river-discharge (July and August 1985; Figure 12a) the turbidity maximum remained stationary 53 - 63 km from the mouth, regardless of the location of the FW-T interface. The irregular bottom profile is related to the scour and fill of a meandering channel (Figure 11). Maximum tidal current velocities in the narrow, scoured, and meandering section of the upper estuary channel and high concentrations of SPM suggest the turbidity maximum is related to channel configuration, bottom sediment type, and scouring ability of tidal currents.

Lower Patuxent River estuary SPM particle-size and composition was dominated by organic constituents 10.0 - 20.0 μm in diameter. Numerous centric diatoms and dinoflagellates were identified from the microscopic analysis (Sellner and Brownlee, 1987) that overlapped the observed primary size mode. Particulate matter from the upper Patuxent River estuary had a primary size mode of 6.0 - 8.0 μm, similar to the particle diameters reported by Schubel (1971) in the Chesapeake Bay turbidity maximum. However, a secondary size mode (40.0 - 60.0 μm in diameter) was noted in the upper estuary stations during most of the study period. Inorganic particles identified as aggregates and mineral grains were found suspended in the water column throughout the twelve month study period. These particles had diameters overlapping the secondary size mode commonly observed at stations 6, 7, and 8, and the primary size mode at station 6 during April 1986.

Krank (1981) reported 50 - 60 μm floccules in the upper reaches of Miramachi estuary, Canada. Gibbs (1982) reported that floccules greater than 12 μm in diameter were disrupted during sampling and sizing procedures. The particles 40.0 - 60.0 μm in diameter noted in the upper Patuxent River estuary are probably unrelated to flocculation processes, and are better explained by the aggregates and mineral grains microscopically observed.

During two of the ten sampling periods, the primary size mode of SPM increased at station 6 (April 1986, 40.0 - 60.0 μm, Appendix 2; and June 1986, 25.0 - 32.0 μm, Figure 10b). Station 6 is the shallowest of the eight stations with an average depth less than 3 m, thus, resuspension of bottom material (aggregates and mineral grains) by tidal currents and wind waves could be the cause of the increased primary size mode. High wind conditions during April 1986 coincided with the larger particle-size observed during that month and although correlation between SPM concentration and wind was not significant for station 6, synergistic relations between wind and other factors might account for the observed spectra.

June 1986 climatic conditions were relatively calm but particle-size increased at station 6 to 25.0 - 32.0 μm. Phytoplankton and microzooplankton counts (Sellner and Brownlee, 1987) showed no overabundance of large organisms, but the blue-green algae *Microcystis aeruginosa* was found during both periods at high densities (6.4 - 14.0 x 10^7 cells/ℓ). It is possible that algal spheres agglomerate at low salinities forming larger colonies. Station 6 is located in a low salinity area which may be a critical zone for algal agglomeration, explaining the larger primary size mode observed only at station 6 during the summer and early fall. However, to date, *Microcystis* aggregates are not routinely observed in the Patuxent River estuary suggesting that resuspension of mineral grains and bottom materials is probably more likely.

The spatial and temporal variations in SPM characteristics of the Patuxent River estuary can be summarized as follows:

(1) Variability in river discharge causes changes in salinity and SPM within five days at the upper Patuxent River estuary (stations 5 - 8), while a one month lag in response was observed at the lower Patuxent River estuary (stations 1 - 4). However, sampling frequency limited the determination of actual response time; therefore, actual lag is 5 - 30 days.

(2) The 62% decrease in channel cross-sectional area between stations 4 and 5 illustrates the subdivision of the estuary into a narrow upper section and broad lower section. Significant changes in salinity, SPM concentration, and particle-size occur at the boundary between these sections.

(3) Organic particles between 10.0 - 25.0 μm were dominant in the lower estuary, while inorganic particles (6.0 - 10.0 μm) and seasonally occurring organic particles (20.0 - 32.0 μm) were noted in the upper Patuxent River estuary.

(4) A turbidity maximum and high velocity tidal currents were observed in the upper estuary during low flow conditions, indicating that bathymetry, tidal currents, and resuspension of bottom material is important in upper estuary turbidity patterns. However, a turbidity front persisted during high river flow that had higher SPM concentrations and a broader turbidity zone. High river flow may have geographically shifted a much stronger turbidity pattern from upstream into the present study area; therefore, overlapping with the bathymetrically controlled turbidity maximum and creating the more pronounced turbidity front.

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APPENDIX 1

SALINITY, CONCENTRATION OF SPM, SIM, AND SOM, AND SPM PRIMARY SIZE MODE

Station #	Date	Salinity (°/oo)	SPM	SOM (mg/ℓ)	SIM	SPM Size Mode (μm)
1	10/15/85	17.0	5.0	2.0	3.0	no data
2	"	16.0	3.8	1.6	2.2	"
3	"	16.0	4.4	1.8	2.6	"
4	"	15.7	5.2	2.4	2.8	"
5	"	14.5	27.2	6.2	21.0	"
6	"	7.0	28.7	9.4	19.3	"
7	"	2.3	25.7	6.7	19.0	"
8	"	0.0	32.1	4.8	27.3	"
1	11/18/85	17.0	3.0	2.2	0.8	no data
2	"	15.6	1.4	1.4	0.0	40.0 - 50.0
3	"	15.1	1.4	1.4	0.0	32.0 - 40.0
4	"	14.2	1.8	1.6	0.2	32.0 - 40.0
5	"	11.0	12.7	6.0	6.7	32.0 - 40.0
6	"	5.1	21.0	6.0	15.0	6.0 - 10.0
7	"	0.8	36.0	7.0	29.0	6.0 - 8.0
8	"	0.0	34.8	7.6	27.2	6.0 - 8.0
1	12/15/85	14.4	5.0	1.8	3.2	16.0 - 20.0
2	"	13.8	3.4	2.0	1.4	16.0 - 20.0
3	"	13.3	4.2	2.6	1.6	16.0 - 20.0
4	"	12.8	4.0	4.0	0.0	16.0 - 20.0
5	"	9.4	12.2	2.0	10.2	6.0 - 8.0
6	"	2.4	23.4	4.8	18.6	6.0 - 8.0
7	"	0.0	49.6	9.2	40.4	6.0 - 8.0
8	"	0.0	49.2	6.0	43.2	6.0 - 8.0

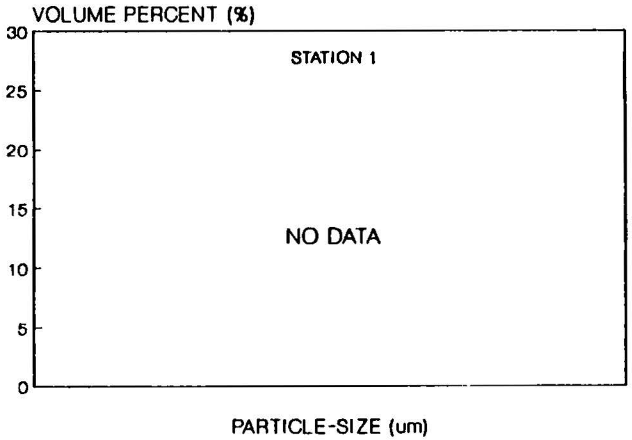
Station #	Date	Salinity (°/oo)	SPM	SOM (mg/ℓ)	SIM	SPM Size Mode (μm)
1	1/12/86	14.0	7.2	3.5	3.7	16.0 - 20.0
2	"	13.8	5.2	3.4	1.8	16.0 - 20.0
3	"	13.3	3.8	2.0	1.8	16.0 - 20.0
4	"	12.4	7.4	4.0	3.4	16.0 - 20.0
5	"	10.9	8.2	1.4	6.8	8.0 - 10.0
6	no data	-	-	-	-	-
7	no data	-	-	-	-	-
8	no data	-	-	-	-	-
1	2/10/86	13.0	4.8	2.3	2.5	16.0 - 20.0
2	"	12.5	5.8	3.0	2.8	20.0 - 25.0
3	"	12.1	5.6	3.0	2.6	16.0 - 20.0
4	"	10.5	7.8	4.0	3.8	25.0 - 32.0
5	"	8.2	11.0	4.4	6.6	8.0 - 25.0
6	"	1.8	27.4	4.0	23.4	6.0 - 8.0
7	"	0.0	90.0	10.8	79.2	6.0 - 8.0
8	"	0.0	108.0	14.6	93.4	6.0 - 8.0
1	4/9/86	9.1	6.6	3.4	3.2	20.0 - 25.0
2	"	10.0	8.8	3.8	5.0	16.0 - 25.0
3	"	10.0	10.6	4.6	6.0	16.0 - 20.0
4	"	9.9	11.7	4.7	7.0	16.0 - 20.0
5	"	8.1	17.2	3.6	13.6	6.0 - 8.0
6	"	2.7	34.0	5.5	28.5	80.0 - 100.0
7	"	0.0	63.0	9.5	53.5	6.0 - 8.0
8	"	0.0	63.5	10.0	53.5	8.0 - 10.0

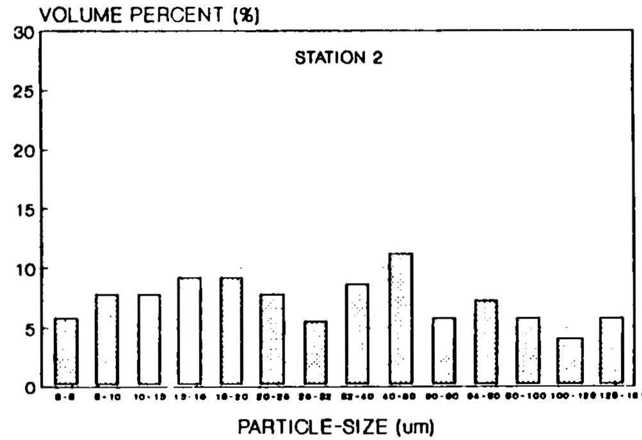
Station #	Date	Salinity (°/oo)	SPM	SOM (mg/ℓ)	SIM	SPM Size Mode (μm)
1	5/7/86	11.7	5.8	2.2	3.6	8.0 - 10.0
2	"	10.7	5.0	4.8	0.2	10.0 - 13.0
3	"	10.4	5.0	2.4	2.6	10.0 - 13.0
4	"	10.0	4.6	3.0	1.6	10.0 - 13.0
5	"	9.8	22.0	7.6	14.4	6.0 - 8.0
6	"	5.0	37.7	9.1	28.6	6.0 - 8.0
7	"	0.0	49.7	11.4	38.3	6.0 - 8.0
8	"	0.0	52.8	11.1	41.7	6.0 - 8.0
1	6/09/86	13.3	3.2	2.6	0.6	10.0 - 13.0
2	"	12.5	3.0	2.2	0.8	10.0 - 13.0
3	"	12.2	2.4	2.4	0.0	10.0 - 13.0
4	"	11.7	3.6	2.6	1.0	6.0 - 8.0
5	"	10.3	13.0	2.8	10.2	13.0 - 16.0
6	"	3.6	15.8	4.8	11.0	25.0 - 32.0
7	"	1.9	26.8	9.2	17.6	6.0 - 8.0
8	"	0.6	28.5	8.0	20.5	6.0 - 8.0

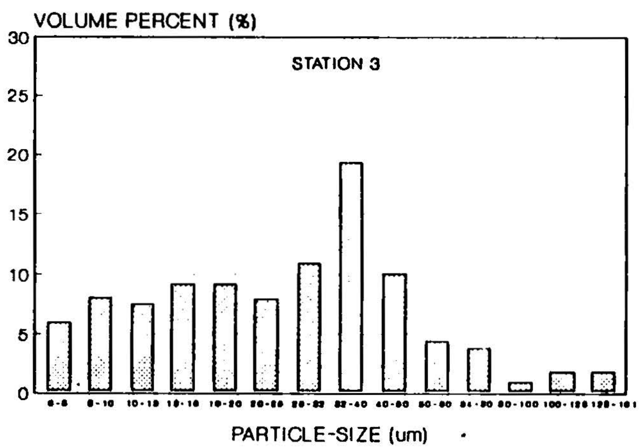
APPENDIX 2

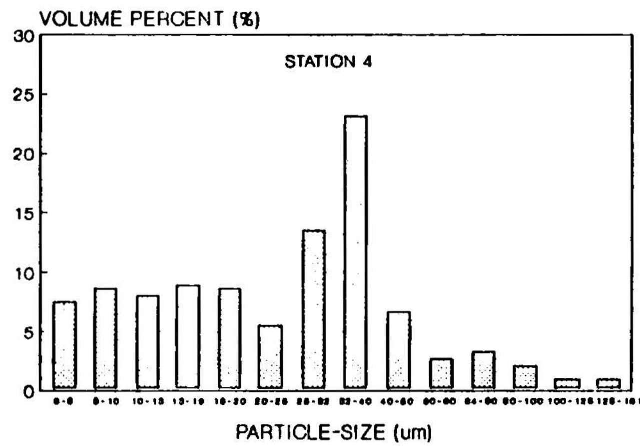
LONGITUDINAL PARTICLE-SIZE DISTRIBUTIONS

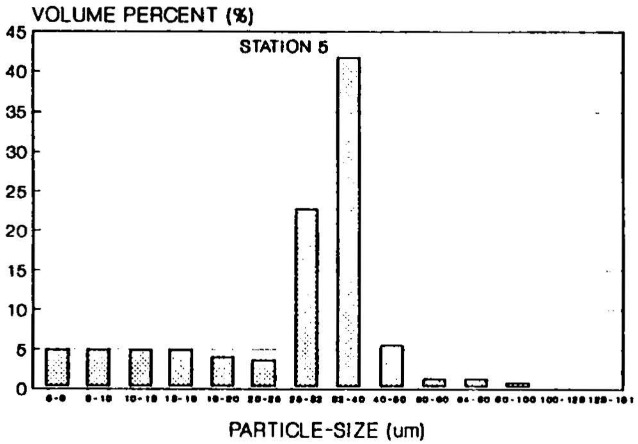
PARTICLE-SIZE DISTRIBUTION
NOVEMBER, 1985

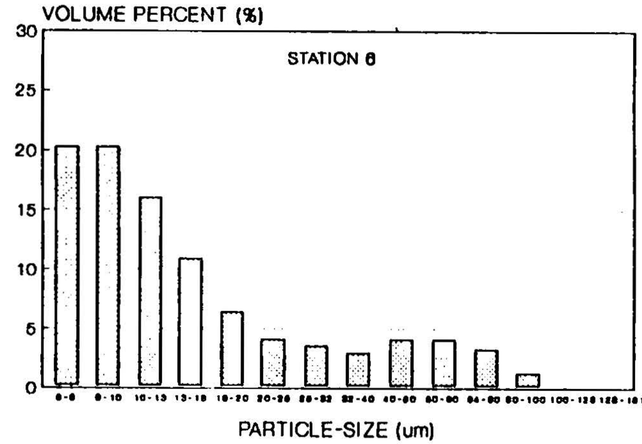


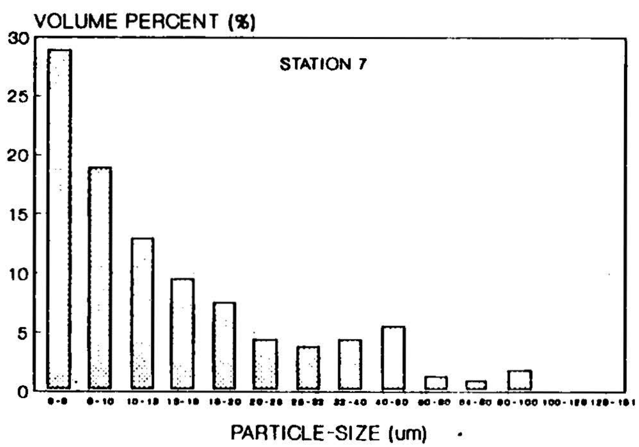


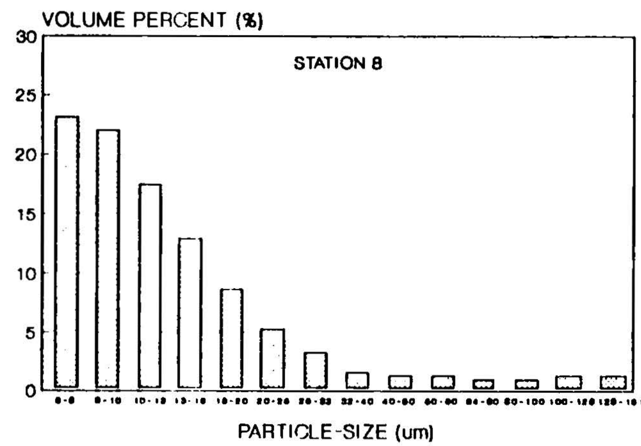




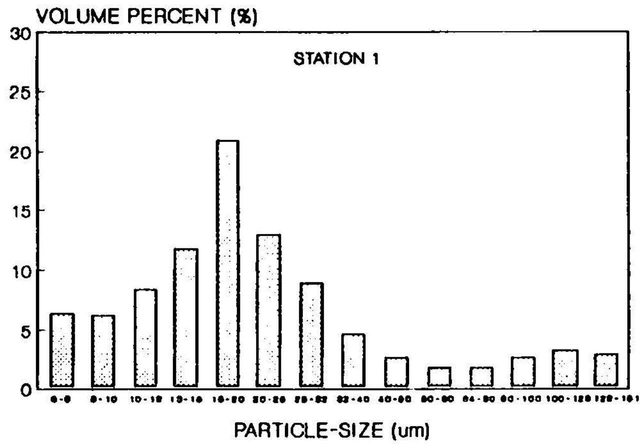

VOLUME PERCENT (%)
STATION 5
PARTICLE-SIZE (um)

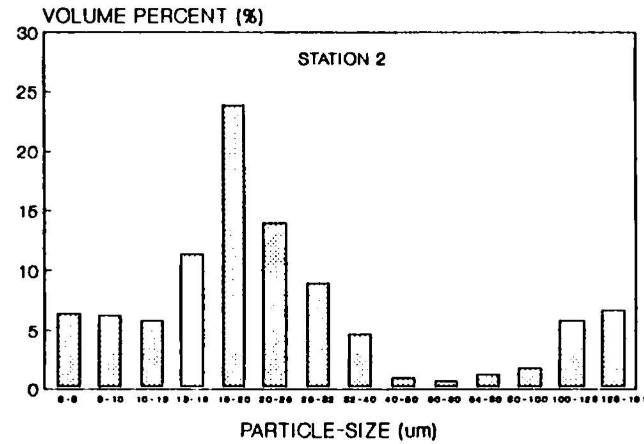

VOLUME PERCENT (%)
STATION 6
PARTICLE-SIZE (um)

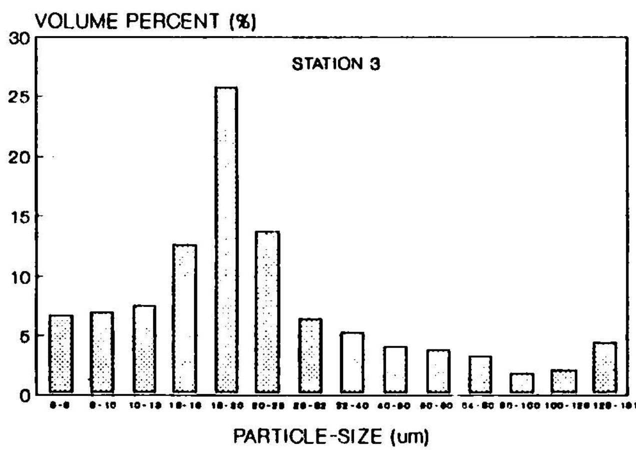

VOLUME PERCENT (%)
STATION 7
PARTICLE-SIZE (um)

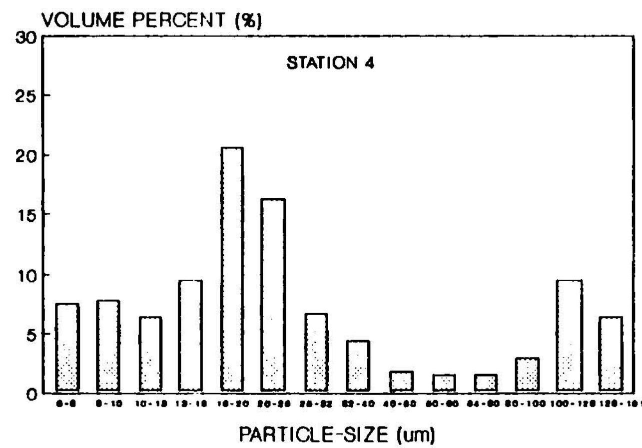

VOLUME PERCENT (%)
STATION 8
PARTICLE-SIZE (um)

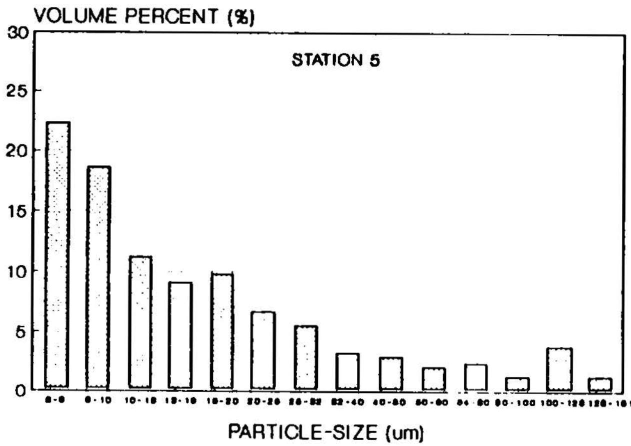
PARTICLE-SIZE DISTRIBUTION
DECEMBER, 1985







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5
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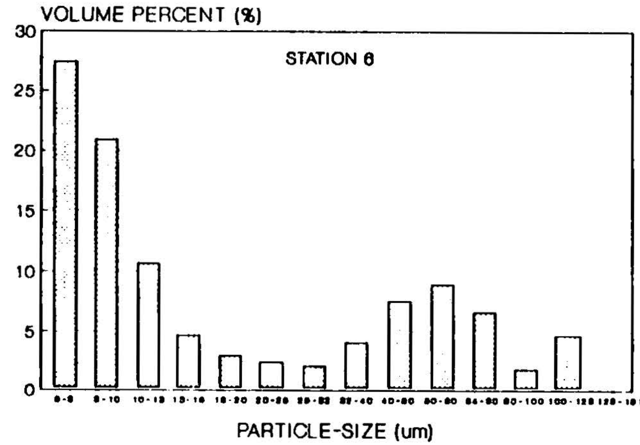
PARTICLE-SIZE (um)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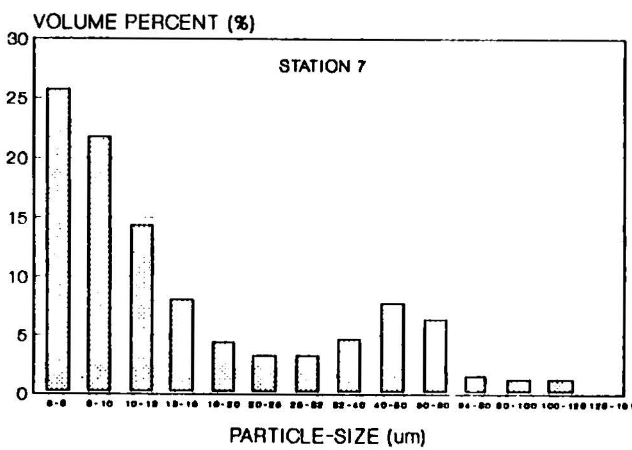
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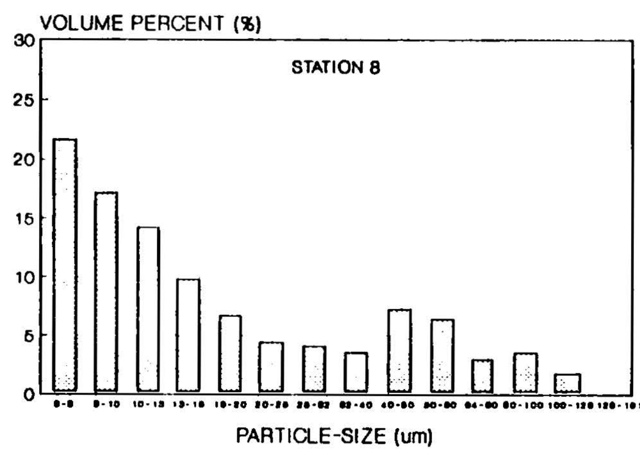
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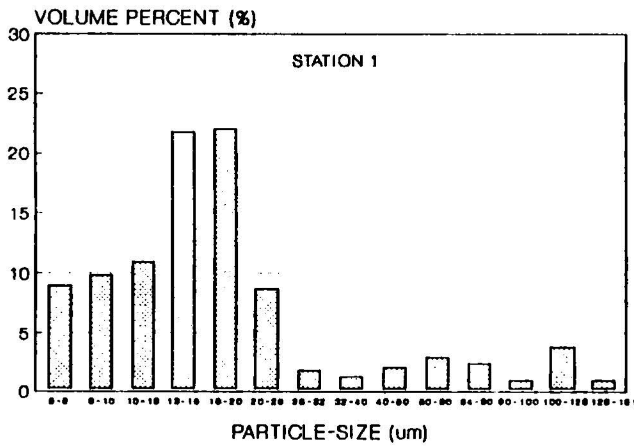
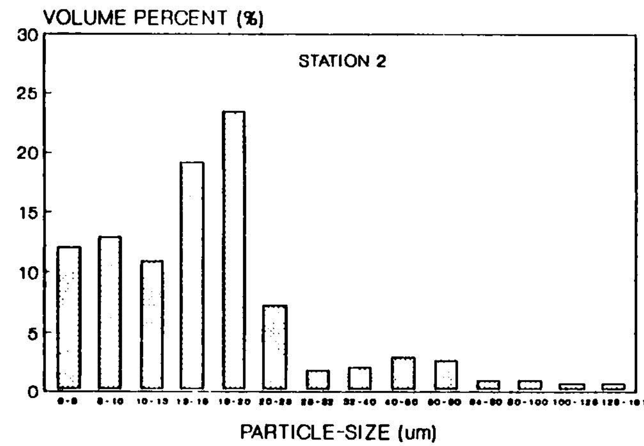
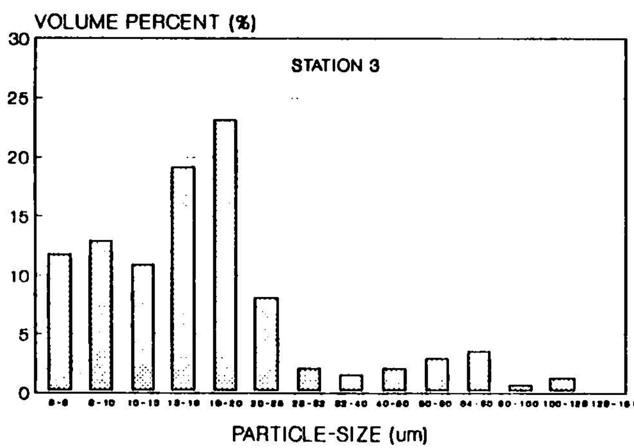
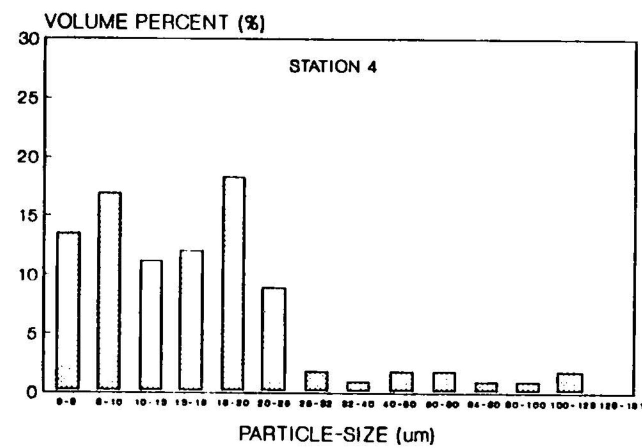
PARTICLE-SIZE (um)

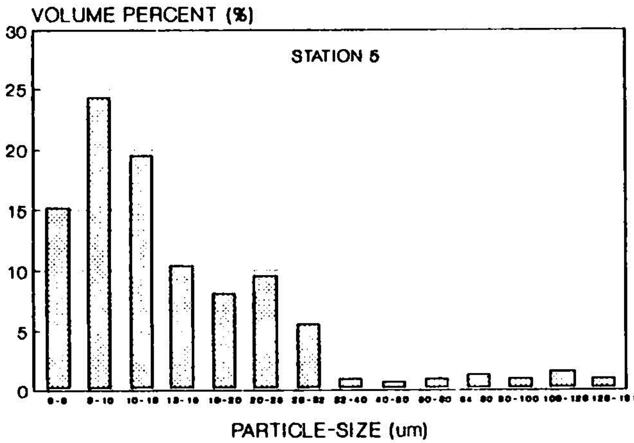
PARTICLE-SIZE DISTRIBUTION
JANUARY, 1986







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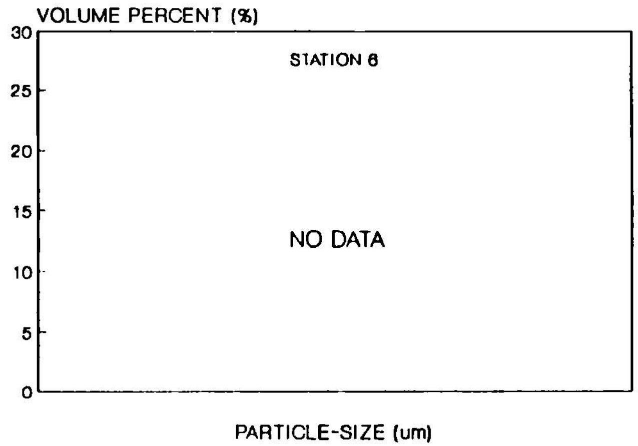
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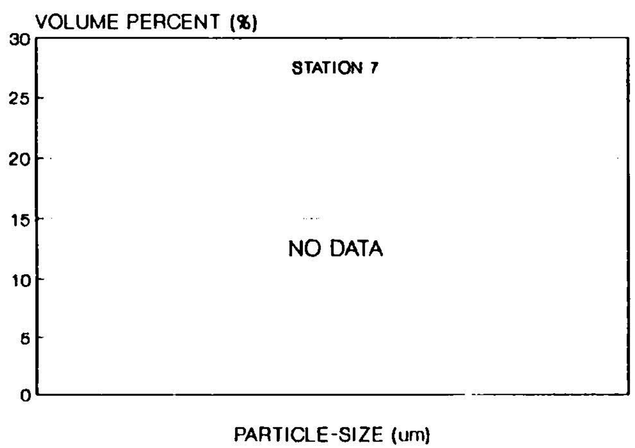
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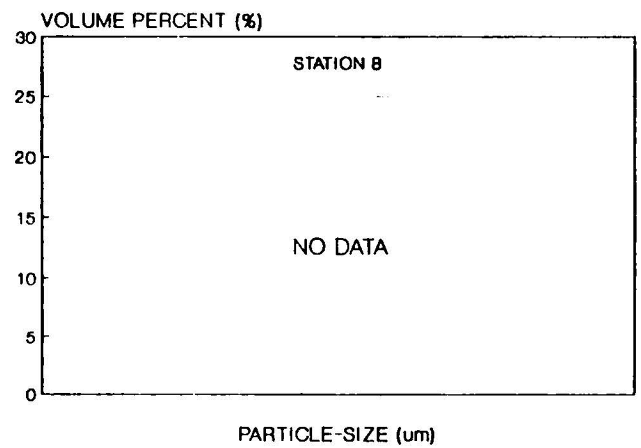
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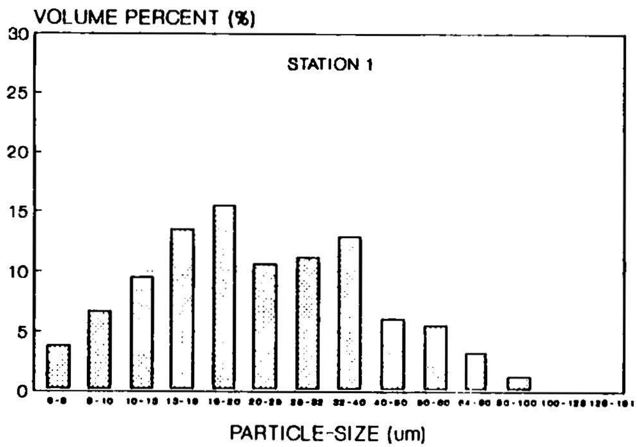
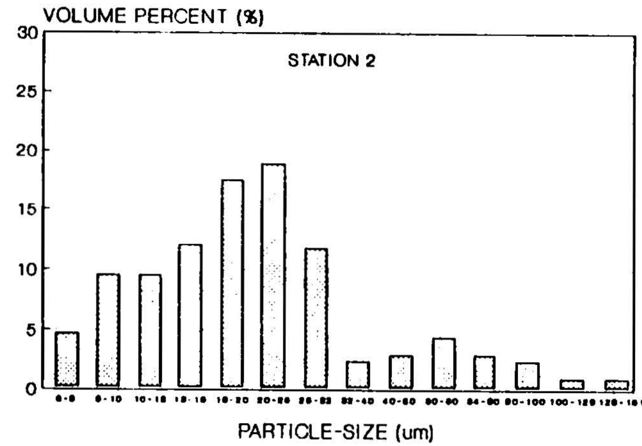
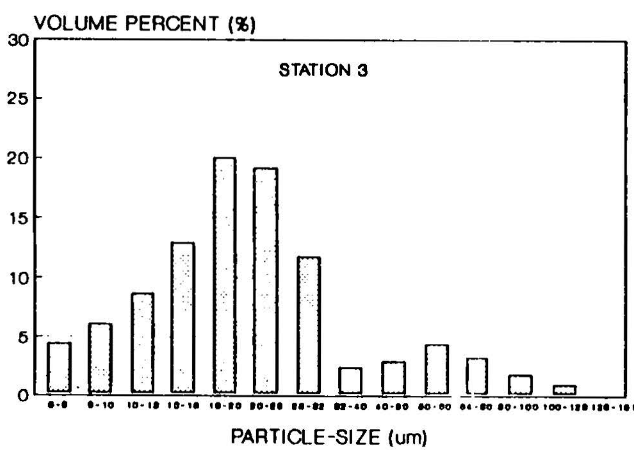
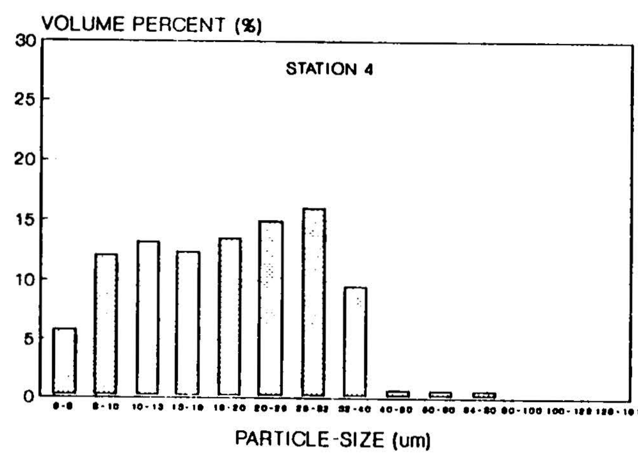
PARTICLE-SIZE (um)

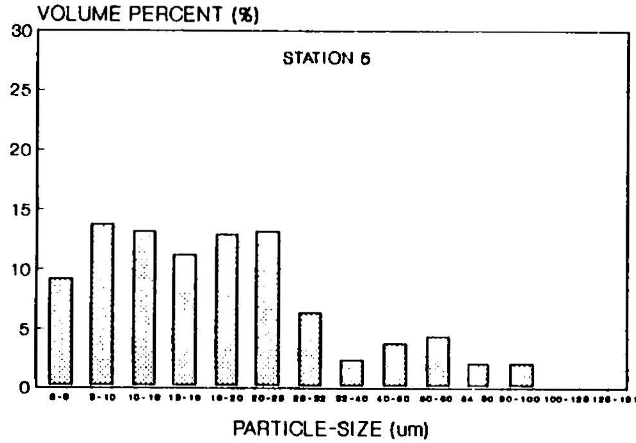
PARTICLE-SIZE DISTRIBUTION
FEBRUARY, 1986







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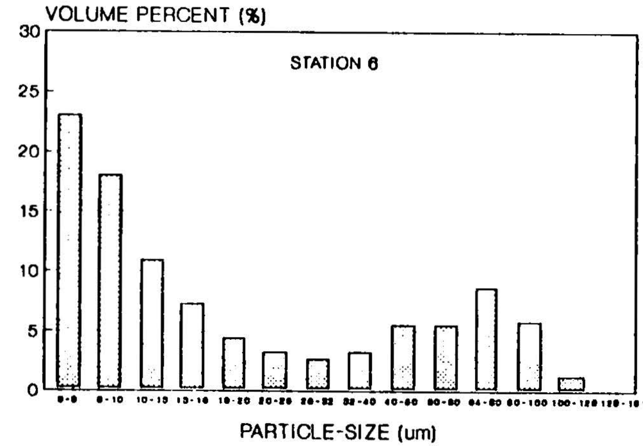
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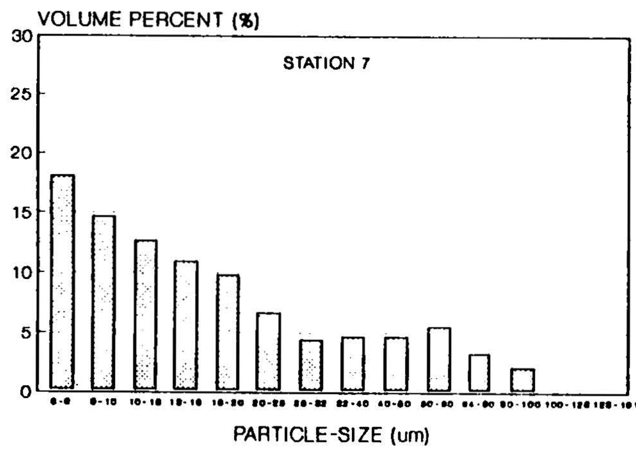
PARTICLE-SIZE (um)


VOLUME PERCENT (%)
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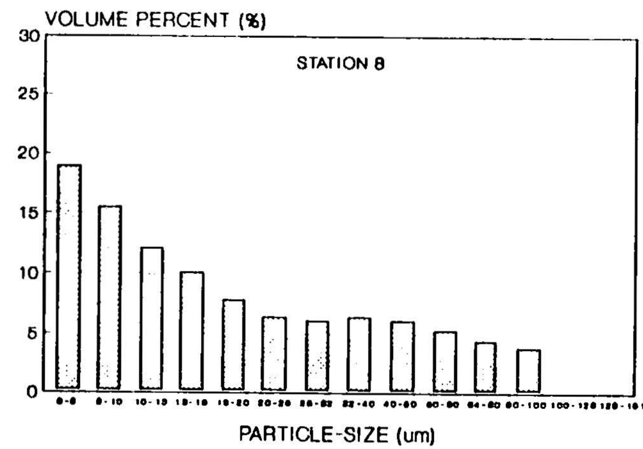
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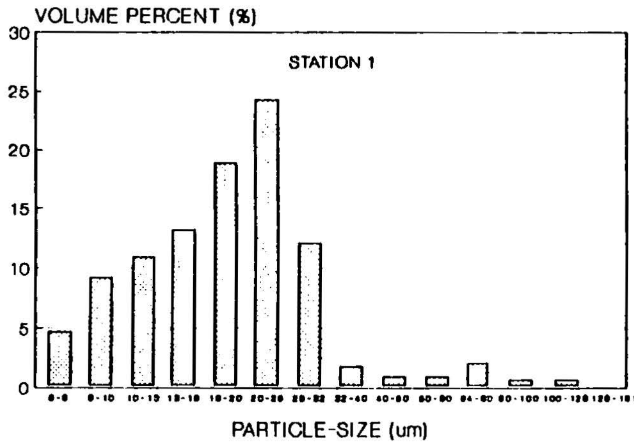
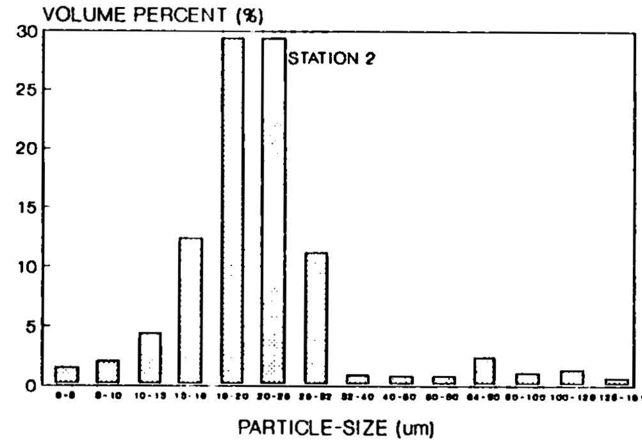
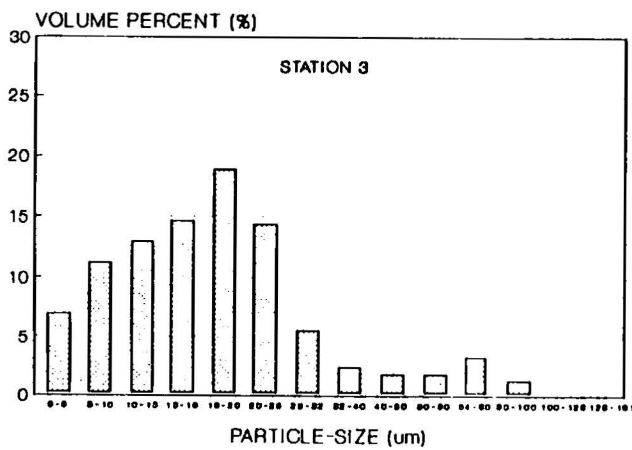
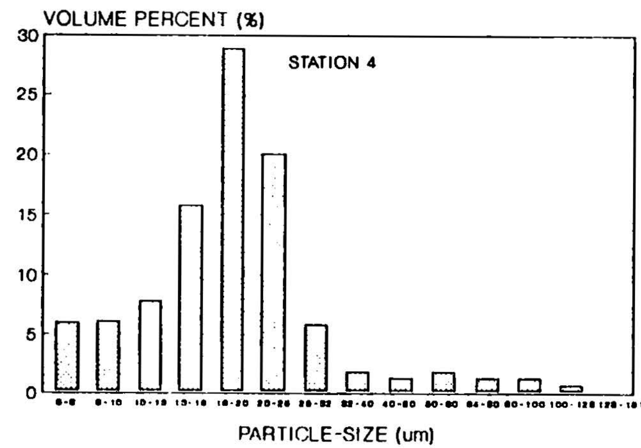
PARTICLE-SIZE (um)

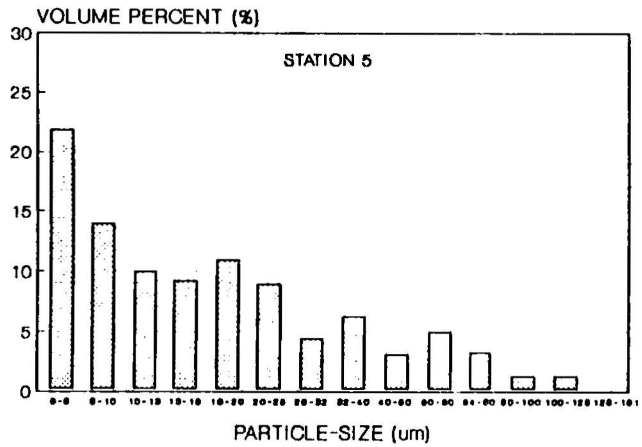
PARTICLE-SIZE DISTRIBUTION
APRIL, 1986

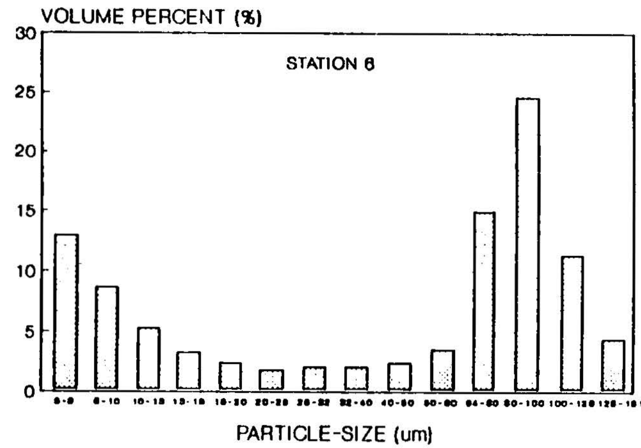









VOLUME PERCENT (%)
STATION 5
30
25
20
15
10
5
0
PARTICLE-SIZE (um)


VOLUME PERCENT (%)
STATION 6
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25
20
15
10
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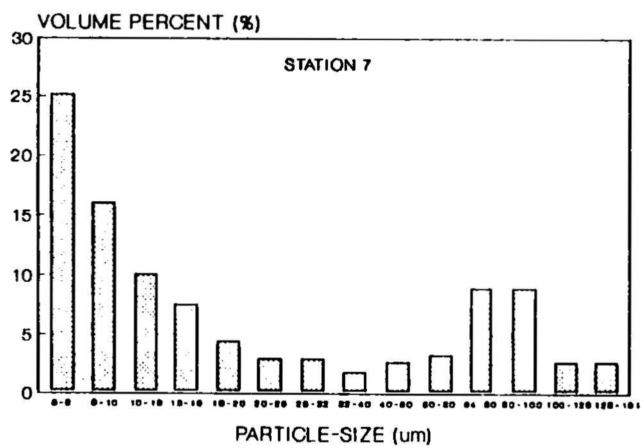
VOLUME PERCENT (%)
STATION 7
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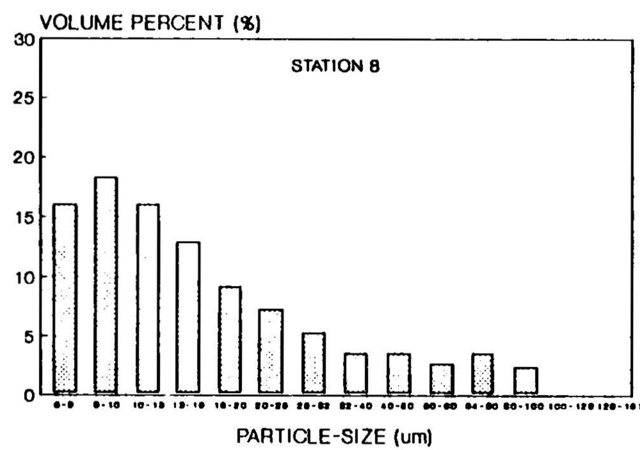
15
10
5
0
PARTICLE-SIZE (um)


VOLUME PERCENT (%)
STATION 8
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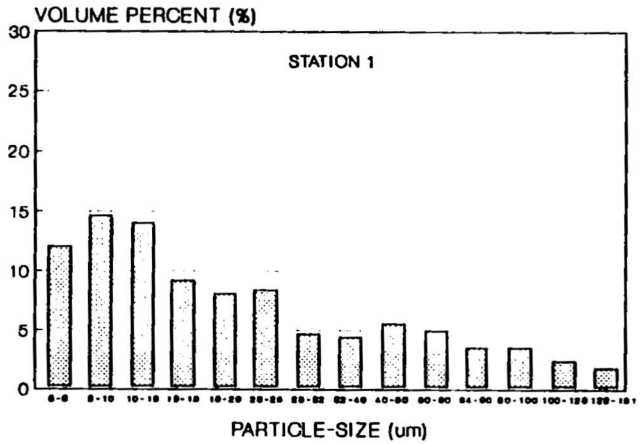
25
20
15
10
5
0
PARTICLE-SIZE (um)


VOLUME PERCENT (%)
STATION 1
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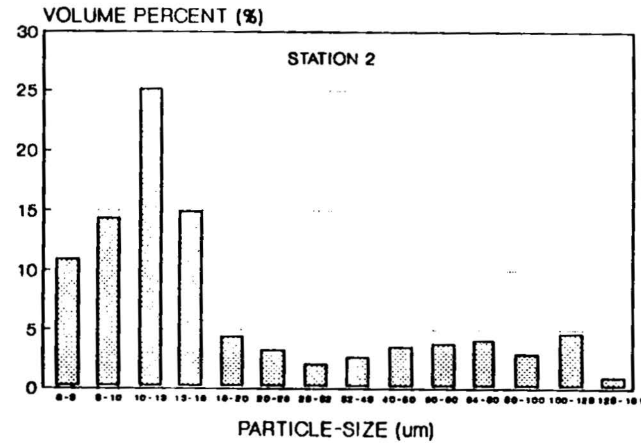
15
20
25
30
PARTICLE-SIZE (um)


VOLUME PERCENT (%)
STATION 2
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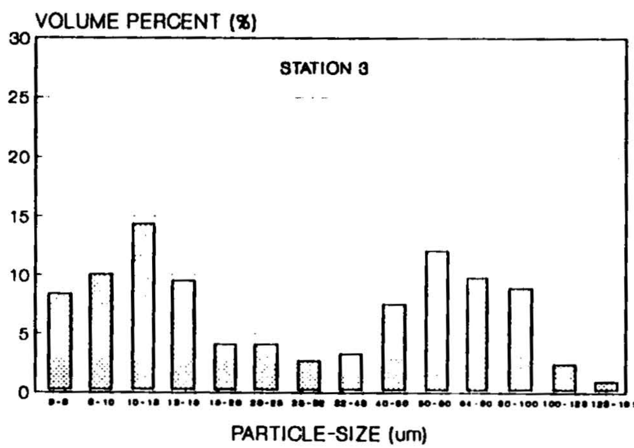
15
20
25
30
PARTICLE-SIZE (um)


VOLUME PERCENT (%)
STATION 3
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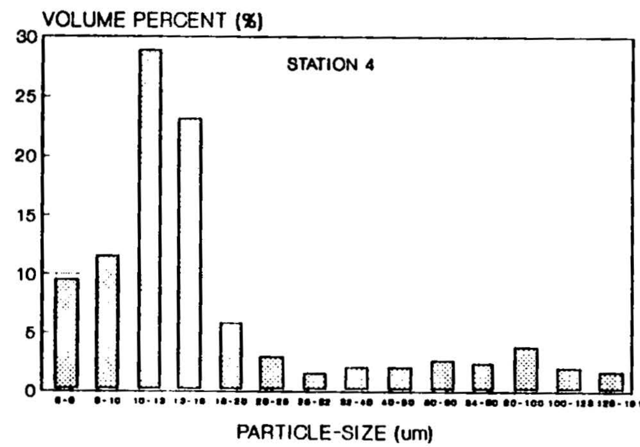
15
20
25
30
PARTICLE-SIZE (um)


VOLUME PERCENT (%)
STATION 4
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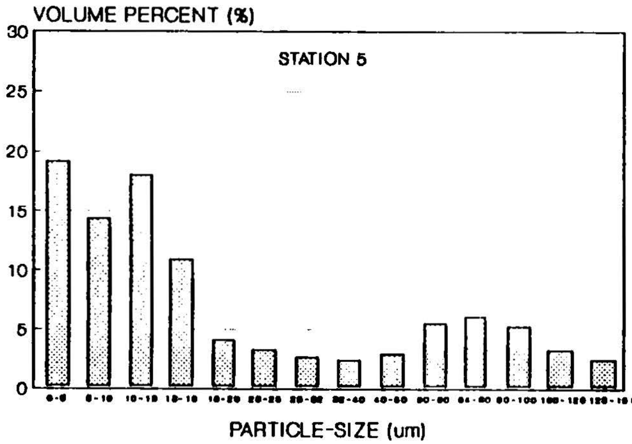
25
30
PARTICLE-SIZE (um)


VOLUME PERCENT (%)
STATION 5
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15
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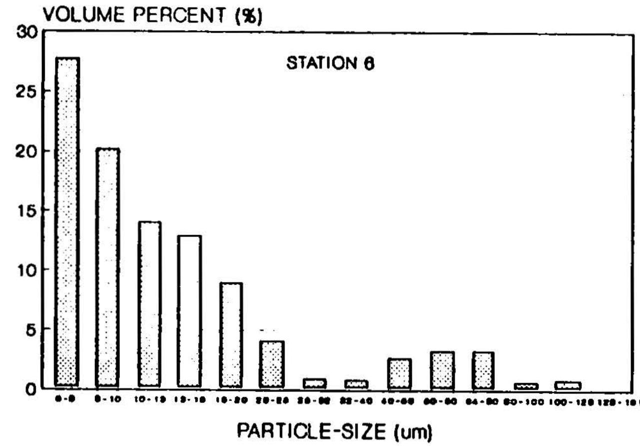
PARTICLE-SIZE (um)


VOLUME PERCENT (%)
STATION 6
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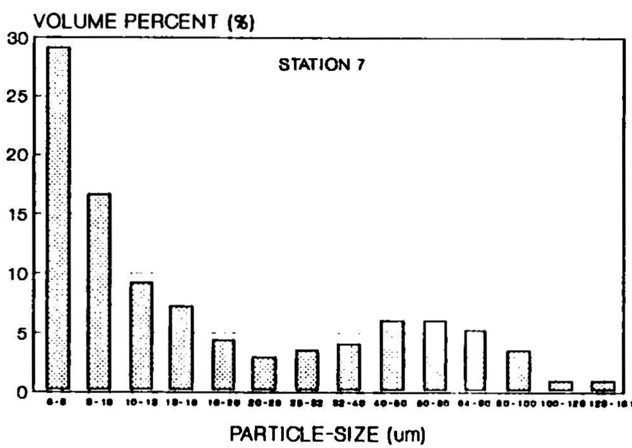
15
10
5
0
PARTICLE-SIZE (um)


VOLUME PERCENT (%)
STATION 7
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5
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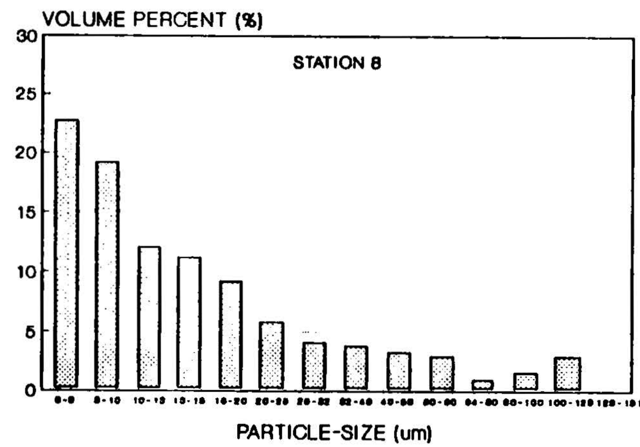
PARTICLE-SIZE (um)


VOLUME PERCENT (%)
STATION 8
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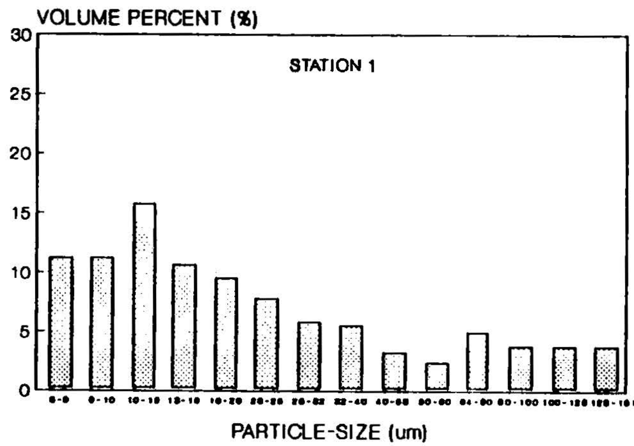
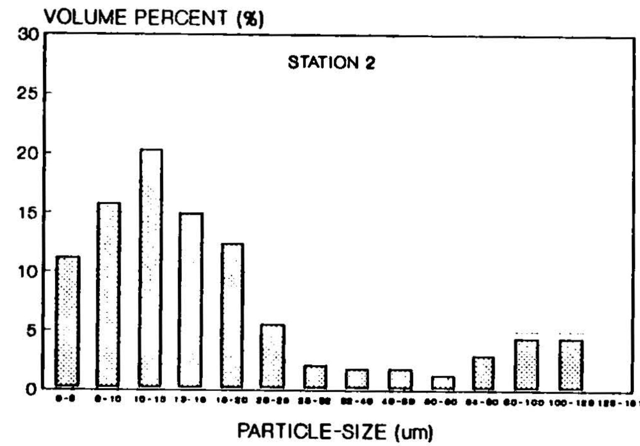
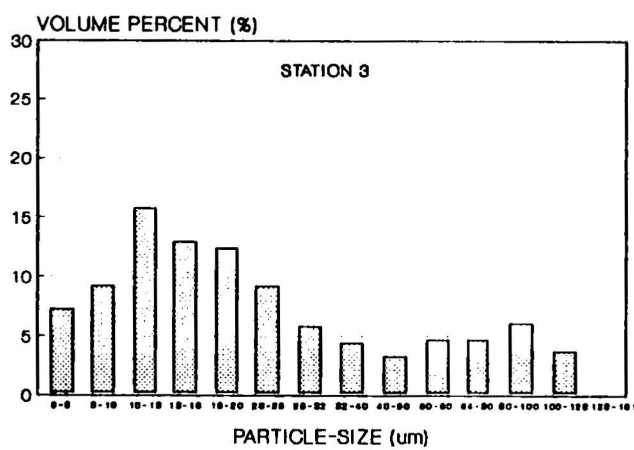
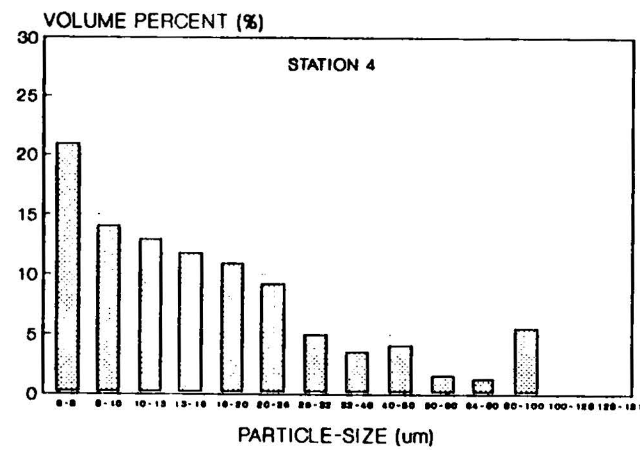
25
20
15
10
5
0
PARTICLE-SIZE (um)

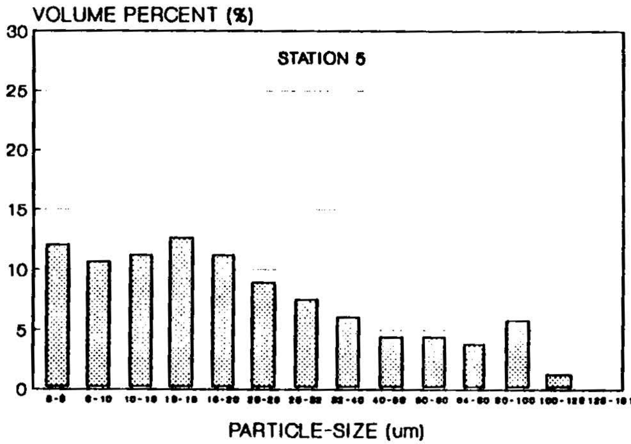
PARTICLE-SIZE DISTRIBUTION
JUNE, 1986

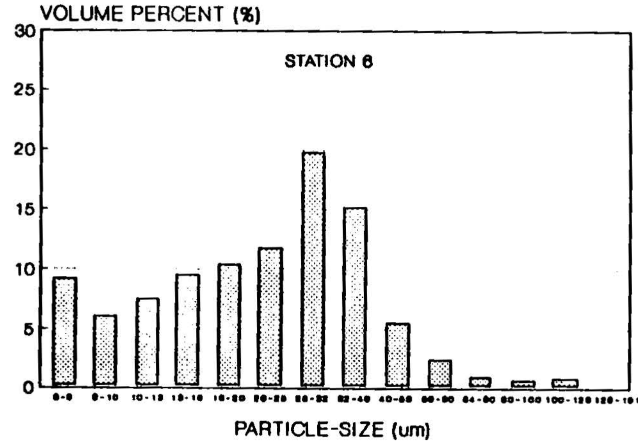


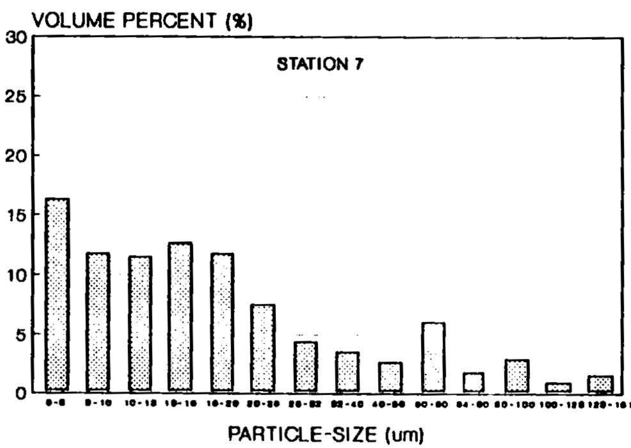


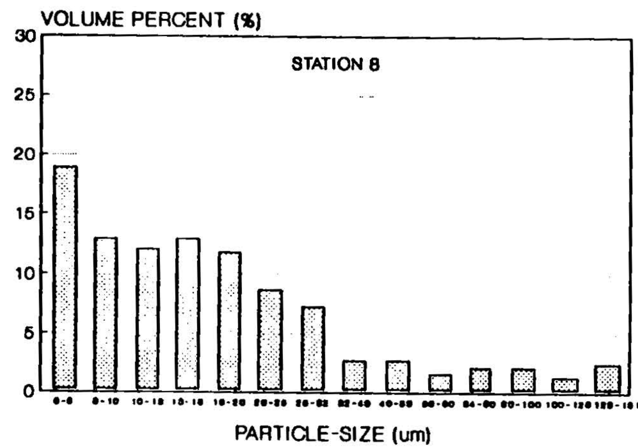





VOLUME PERCENT (%)
STATION 5
PARTICLE-SIZE (um)


VOLUME PERCENT (%)
STATION 6
PARTICLE-SIZE (um)


VOLUME PERCENT (%)
STATION 7
PARTICLE-SIZE (um)


VOLUME PERCENT (%)
STATION 8
PARTICLE-SIZE (um)