Bottom Sediments and Nutrients in the Tidal Potomac System, Maryland and Virginia

A Water-Quality Study of the Tidal Potomac River and Estuary

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Chapter F

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By JERRY L. GLENN

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A WATER-QUALITY STUDY OF THE TIDAL POTOMAC RIVER AND ESTUARY

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FOREWORD

Tidal rivers and estuaries are very important features of the Coastal Zone because of their immense biological productivity and their proximity to centers of commerce and population. Most of the shellfish and much of the local finfish consumed by man are harvested from estuaries and tidal rivers. Many of the world's largest shipping ports are located within estuaries. Many estuaries originate as river valleys drowned by rising sea level and are geologically ephemeral features, destined eventually to fill with sediments. Nutrients, heavy metals, and organic chemicals are often associated with the sediments trapped in estuaries. Part of the trapped nutrients may be recycled to the water column, exacerbating nutrient-enrichment problems caused by local sewage treatment plants, and promoting undesirable algae growth. The metals and organics may be concentrated in the food chain, further upsetting the ecology and threatening the shell and finfish harvests. Our knowledge of the processes governing these phenomena is limited and the measurements needed to improve our understanding are scarce.

In response to an increasing awareness of the importance and delicate ecological balance of tidal rivers and estuaries, the U.S. Geological Survey began a 5-year interdisciplinary study of the tidal Potomac River and Estuary in October of 1977. The study encompassed elements of both the Water Resources Division's ongoing Research and River Quality Assessment Programs. The Division has been conducting research on various elements of the hydrologic cycle since 1894 and began intense investigation of estuarine processes in San Francisco Bay in 1968. The River Quality Assessment program began in 1973 at the suggestion of the Advisory Committee on Water Data for Public Use which saw a special need to develop suitable information for river-basin planning and water-quality management. The Potomac assessment was the first to focus on a tidal river and estuary. In addition to conducting research into the processes governing water-quality conditions in tidal rivers and estuaries, the ultimate goals of the Potomac Estuary Study were to aid water-quality management decision-making for the Potomac, and to provide other groups with a rational and well-documented general approach for the study of tidal rivers and estuaries.

This interdisciplinary effort emphasized studies of the transport of the major nutrient species and of suspended sediment. The movement of these substances through five major reaches or control volumes of the tidal Potomac River and Estuary was determined during 1980 and 1981. This effort provided a framework on which to assemble a variety of investigations:

(1) The generation and deposition of sediments, nutrients, and trace metals from the Holocene to the present was determined by sampling surficial bottom sediments and analyzing their characteristics and distributions.

(2) Bottom-sediment geochemistry was studied and the effects of benthic exchange processes on water-column nutrient concentrations ascertained.

(3) Current-velocity and water-surface-elevation data were collected to calibrate and verify a series of one- and two-dimensional hydrodynamic flow and transport models.

(4) Measurements from typical urban and rural watersheds were extrapolated to provide estimates of the nonpoint sources of sediments, nutrients, and biochemical oxygen demand during 1980 and 1981.

(5) Intensive summertime studies were conducted to determine the effects of local sewage-treatment-plant effluents on dissolved-oxygen levels in the tidal Potomac River.

(6) Species, numbers, and net productivity of phytoplankton were determined to evaluate their effect on nutrients and dissolved oxygen.

(7) Wetland studies were conducted to determine the present-day distribution and abundance of submersed aquatic vegetation, and to ascertain the important water-quality and sediment parameters influencing this distribution.

(8) Repetitive samples were collected to document the distribution and abundance of the macrobenthic infaunal species of the tidal river and estuary and to determine the effects of changes in environmental conditions on this distribution and abundance.

The reports in this Water-Supply Paper series document the technical aspects of the above investigations. The series also contains an overall introduction to the study, an integrated technical summary of the results, and an executive summary which links the results with aspects of concern to water-quality managers.

Philip Cohen
Chief Hydrologist

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Potomac Study Coordinator

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[Plates are in pocket]

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METRIC CONVERSION FACTORS

For use of readers who prefer to use inch-pound units, conversion factors for terms used in this report are listed below:

Multiply	By	To obtain
square kilometer (km^2)	0.3861	square mile
kilometer (km)	0.6214	mile
meter (m)	3.281	foot
centimeter per second (cm/s)	0.03281	foot per second
cubic meter per second (m^3/s)	35.31	cubic foot per second
cubic decimeter (dm^3)	0.03531	cubic foot
millimeter (mm)	0.03937	inch
	0.003281	foot
megagram per year (Mg/yr)	1.102	short ton per year
kilogram per day (kg/d)	2.205	pound per day
milligram per kilogram (mg/kg)	$1.6x10^6$	ounce per pound
gram per kilogram (g/kg)	0.016	ounce per pound
micrometer (μm)	$3.281x10^{-6}$	foot
nautical mile (nmi)	0.8696	statute mile

The following abbreviations are used in this report: parts per thousand (‰)

A WATER-QUALITY STUDY OF THE TIDAL POTOMAC RIVER AND ESTUARY

Bottom Sediments and Nutrients in the Tidal Potomac System, Maryland and Virginia

By Jerry L. Glenn

Abstract

The characteristics and distributions of near-surface bottom sediments and of nutrients in the sediments provide information on modern sediment and nutrient sources, sedimentation environments, and geochemical reactions in the tidal Potomac system, Maryland and Virginia. This information is fundamental to an improved understanding of sedimentation and eutrophication problems in the tidal Potomac system.

The tidal Potomac system consists of 1,230 square kilometers of intertidal to subtidal Potomac mainstem and tributary streambed from the heads-of-tides to Chesapeake Bay. Tidal Potomac sediments are dominantly silt and clay except in local areas. An average sediment sample is about two-thirds silt and clay (fine) particles and one-third sand (coarse) particles. The mean of the median size of all samples is 6.60 phi, or 0.010 millimeters. Sorting generally is poor and the average sediment is skewed toward the fine tail of the size-distribution curve.

Mean particle-size measures have large standard deviations. Among geomorphic units, two distinctly different size populations are found; fine (median phi about 9), and poorly sorted (sorting about 3) sediments in the channel and the smooth flat, and coarse (median phi about 2), and well sorted (sorting about 1) sediments in the shoreline flat and the irregular slope. Among mainstem hydrologic divisions, an average sediment from the river and the estuary division is coarser and more variable than an average sediment from the transition division.

Substantial concentrations of total carbon, total nitrogen, and total phosphorus, and limited amounts of inorganic carbon, ammonia nitrogen and nitrite plus nitrate nitrogen occur in tidal Potomac sediments. An average tidal Potomac sediment sample weighing 1 kilogram contains about 21,000 milligrams of total carbon, 2,400 milligrams of total nitrogen, 1,200 milligrams of total phosphorus, 600 milligrams of inorganic carbon, 170 milligrams of ammonia nitrogen, and 2 milligrams of nitrite plus nitrate nitrogen. Total carbon, nitrogen, and phosphorus have an average ratio by weight of 18:2:1 and an average ratio by atoms of 94:8:1.

Nutrient concentrations and nutrient ratios have large ranges and standard deviations. Nutrient concentrations usually are closely related to particle size; large concentrations are characteristic of fine sediments in the channel and the smooth flat, and small concentrations are typical of coarse sediments in the shoreline flat and the irregular slope. Concentrations typically decrease from the river division to the estuary division.

Mainstem and tributaries show no statistically significant difference in mean particle-size measures or mean nutrient concentrations. Tributaries do not contribute large quantities of sediment with diverse texture or nutrient content to the Potomac mainstem. Particle-size measures and nutrient concentrations in the mainstem are significantly related to hydrologic divisions and geomorphic units; that is, particle size and nutrients vary significantly along and across the Potomac mainstem. Lateral variations in particle size and nutrient content are more pronounced and contribute more to significant relations than longitudinal variations contribute.

The mean values for the median particle size and for the percentage of sand indicate significant variations among hydrologic divisions for samples from a geomorphic unit, and among geomorphic units, for samples from a hydrologic division. Sediments of channels and smooth flats in the river division commonly are coarser than sediments of channels and smooth flats in the transition and the estuary divisions. Shoreline flats in the estuary division are coarser than shoreline flats in the river division. Shoreline flats and irregular slopes in each hydrologic division generally are significantly coarser than channels and smooth flats. Relations between particle-size measures and geomorphic units show progressively larger correlation coefficients from the river division to the estuary division.

Significant differences in mean values of total carbon and of total phosphorus show typical variations in nutrient concentrations of sediment samples from hydrologic divisions and geomorphic units. The river division channel and irregular slope contain greater carbon concentrations than the transition division and the estuary division channel and irregular slope contain. Phosphorus concentrations in the channel and the irregular slope in the transition division are relatively greater than phosphorus concentrations in the channel and irregular slope in the river division and significantly greater than phosphorus concentrations in the channel and irregular slope in the estuary division. For both carbon and phosphorus, the

channel and the smooth flat in each hydrologic division usually contain larger concentrations than the shoreline flat and the irregular slope.

The distribution of coarse sediments is indicative of sources of sediments in the tidal Potomac system. Variable coarse and fine sediments in channels near the heads-of-tides and the relative absence of shoreline flats indicative of a shore erosion source, identify variable river inflows as sediment sources. Extensive shoreline flats underlain by coarse sediments indicate that contributions from the shoreline source increase toward the Potomac mouth. Tributaries do not contribute coarse sediments to the Potomac mainstem.

Coarse sediments of irregular slopes occur in moderate to deep waters where modern currents are inadequate to transport sand and gravel. These sediments and the associated geomorphic features are "relict" from a pre-modern phase of Potomac River erosion and deposition. The present characteristics and the distribution of irregular slopes and relict sediments are indicative of modern sedimentation patterns. The increase in the relative extent of irregular slopes in a seaward direction in the Potomac mainstem is primarily an indication of rapid deposition and burial of relict sediments and features in the river and the transition divisions by modern sediments. The absence of irregular slopes and relict deposits in most tributaries is evidence for rapid deposition in the tributaries. Isolated occurrences of fine sediments on irregular slopes indicate that modern sediments are being deposited over relict sediments and geomorphic features in some locations.

Changes in sediment textures within the Potomac mainstem reflect the relative influences of contributions from the river and shoreline sources and (or) changing hydrologic conditions. Decreasing particle size in sediments of the channel and the smooth flat from the river division through the transition division is primarily an indication of decreased competence of currents and the development of a two-layer estuarine circulation pattern. In the estuary division, shoreline flats increase in extent, and nearby channel sediments are coarser and more variable than channel sediments in the transition division. Because nearby tributary and Chesapeake Bay sediments are uniformly fine grained, these changes indicate increased contributions from the shoreline source or from erosion of nearby relict deposits.

Large and variable nutrient concentrations and poor relations of concentrations to textures and to geomorphic units in the river division indicate nearby sources for most nutrients. Organic carbon to nitrogen ratios indicate that terrestrial organic matter from the Potomac River is the dominant source. Ratios do not vary significantly near sewage treatment plants or along the Potomac mainstem. Smaller ratios and larger and more variable nutrient concentrations in the estuary division may indicate a new source of organic matter, presumably in situ phytoplankton production. Changes in nutrient concentrations seaward from the river division are a complex function of physical, chemical, and biological processes. General seaward decreases in the concentrations of most nutrients occur because nutrients associated with particulate material are deposited, diluted, or dispersed with distance from sources in the river division, and some nutrients sorbed by sediments may be released to the water column. An increase in sediment phosphorus concentration from the river division to the transition division and a large decrease from the transition division to the estuary division probably indicates uptake of phosphorus by generally aerobic river and transition sediments and release in periodically anaerobic estuary sediments.

Nutrient concentrations are significantly related to particle size. Trends in nutrient concentrations among geomorphic units are primarily due to trends in particle size. Trends in nutrients along the Potomac mainstem mostly are independent of particle size and are due to changes in nutrient sources or to changes in hydrologic conditions that promote uptake or release of nutrients associated with sediments.

INTRODUCTION

Sedimentation and eutrophication are major problems in many tidal river and estuarine water bodies (National Research Council, 1977, p. 94–109; National Research Council, 1983, p. 7–8, p. 63–74). Particle size and nutrient content have been determined for samples of near-surface bottom sediments from the streambed of the tidal Potomac River, Maryland and Virginia, and from streambeds of selected tributaries of the tidal Potomac River. These determinations provide the foundation for an improved understanding of modern sediment and nutrient sources, sedimentation, and geochemical reactions in the tidal Potomac system.

Purpose and Scope

The purpose of this report is to present and to interpret data on the particle size and nutrient content of near-surface bottom sediments in the tidal Potomac system. The data were obtained as part of a U.S. Geological Survey study of sedimentation and eutrophication problems in the tidally influenced parts of the Potomac River and its tributaries. The Survey studies included research efforts to measure and to model sediment and nutrient inputs to the tidal Potomac system from multiple sources; this study uses characteristics and distributions of bottom sediments and sediment-borne nutrients to infer source changes, transport and deposition phenomena, and geochemical reactions involving sediments and nutrients after they reach the tidal Potomac system.

The scope of this report includes:

1. A review of information on sediment and nutrient sources to and transport processes in tidal river and estuarine waters in general and the Chesapeake and the Potomac systems in particular.
2. The presentation of data on particle size and nutrient content.
3. The determination of the statistical significance of particle size and nutrient differences among sediments from tributaries and the Potomac mainstem

and among sediments from hydrologic divisions and geomorphic units of the Potomac mainstem.

4. The establishment of relations between particle size and nutrients.
5. A discussion of causes of changes in sediment characteristics and nutrient concentrations in the tidal Potomac system.

The Tidal Potomac System

The Potomac River is the second largest tributary of Chesapeake Bay, the largest estuarine body of water in the United States (Lippson and others, 1979, p. 2). The tidal Potomac system extends seaward from the heads-of-tides for the Potomac River and for its tributaries to the Potomac River entrance (mouth) to Chesapeake Bay between Point Lookout, Maryland and Smith Point, Virginia (fig. 1). The system has a maximum length of about 100 nmi (nautical mile) measured along the thalweg from the head-of-tides in the area of Chain Bridge near Washington, D.C. to Chesapeake Bay (fig. 1). The width varies from a few hundred m at the head-of-tides to about 11,000 m near the Potomac mouth. The total surface area of tidal waters in the tidal Potomac system is about 1,230 km^2.

The tidal Potomac system is divided into mainstem and tributaries, longitudinal divisions, and lateral units. The Potomac mainstem consists of the Potomac River streambed from head-of-tides to the mouth and from shoreline to shoreline; the Potomac tributaries encompass all tributary streambeds from shoreline to shoreline landward to the head-of-tides from a line across the tributary mouth. Longitudinal divisions of the Potomac mainstem are based on hydrologic characteristics or on sample location in nautical miles relative to the Potomac River mouth. In the tributaries, hydrologic data were limited, and longitudinal divisions based on hydrologic characteristics were not made. Lateral units of the Potomac mainstem and of the tributaries are defined by geomorphic characteristics or by depth of water at each sample site.

Hydrologic Divisions

Three distinct hydrologic divisions of the Potomac mainstem are recognized: river, transition, and estuary (fig. 1). The river division (pl. 1) extends about 30 nmi seaward from the head-of-tides (about nmi 100) to near Quantico, Va. (about nmi 70, fig. 1). In this division, semidiurnal mean tide ranges are the highest observed in the tidal Potomac system, averaging about 0.9 m near Alexandria, Va. (fig. 1). River and tidal currents are variable spatially and temporally and are among the largest in the Potomac, typically in the 30-60 cm/s range (Lippson and others, 1979, p. 35). Waters in the river division commonly lack marine salts. Approximately 85 percent of the total mean yearly water discharge (U.S. Department of Interior, 1965-77) of about 400 m^3/s enters into the river division, and about 90 percent of the total drainage basin of 3,000 km^2 is inland of the seaward boundary of this division.

The river division varies from a few hundred m in width at Chain Bridge to 3,700 m at its widest cross section near the lower end. The widening occurs gradually along the length of the division. The average width is about 1,200 m and the average depth is about 5 m. The total surface area of tidal waters in the river division is about 90 km^2. The largest tributaries enter the river division through the Anacostia, Broad, Piscataway, Mattawoman, Occoquan, Gunston, Dogue, and Hunting Creek embayments (fig. 1).

The transition division (pl. 2) extends seaward from near Quantico, Va. to Morgantown, Md. (nmi 40, fig. 1) a distance of about 30 nmi along the thalweg of the Potomac. The mean tidal range in the transition division is much less than in the river division and is only about 0.3 m at a nodal point near Maryland Point (fig. 1). Tidal currents are low to moderate in the upper wide reach of the division, but may exceed 70 cm/s in the narrow lower reach (Lippson and others, 1979, p. 35). The transition from fresh to brackish water generally occurs in the transition division. Salinity varies from near zero $^{0}/_{00}$ at the head of the division to as much as 18 $^{0}/_{00}$ in the bottom waters at the lower end of the division during low river discharges in autumn. Although both vertical and lateral salinity gradients exist, they typically are not sharp or pronounced, and the tidal Potomac system is classified as a partially mixed estuarine system (Pritchard, 1967, p. 38; Lippson and others, 1979, p. 8).

The transition division includes a wide reach from about Quantico to Maryland Point and a narrow reach from Maryland Point to Morgantown. The average depth in the transition division is not appreciably different from the average depth in the river division, but the average width in the transition division is about three times greater. The transition division has a water-surface area of about 190 km^2. Tributary discharge to the transition division is low and tributary embayments are small. The larger embayments are at the mouths of Aquia Creek and Potomac Creek from the Virginia side in the upper, wide reach and at the mouths of Nanjemoy Creek and Port Tobacco River from the Maryland side in the lower, narrow reach (fig. 1).

The estuary division (pl. 3) extends 40 nmi from Morgantown, Md., to the mouth of the Potomac (nmi 0). Mean tidal range in the estuary division is about 0.4 m, slightly greater than the mean range in the transition division but substantially less than the mean range in the

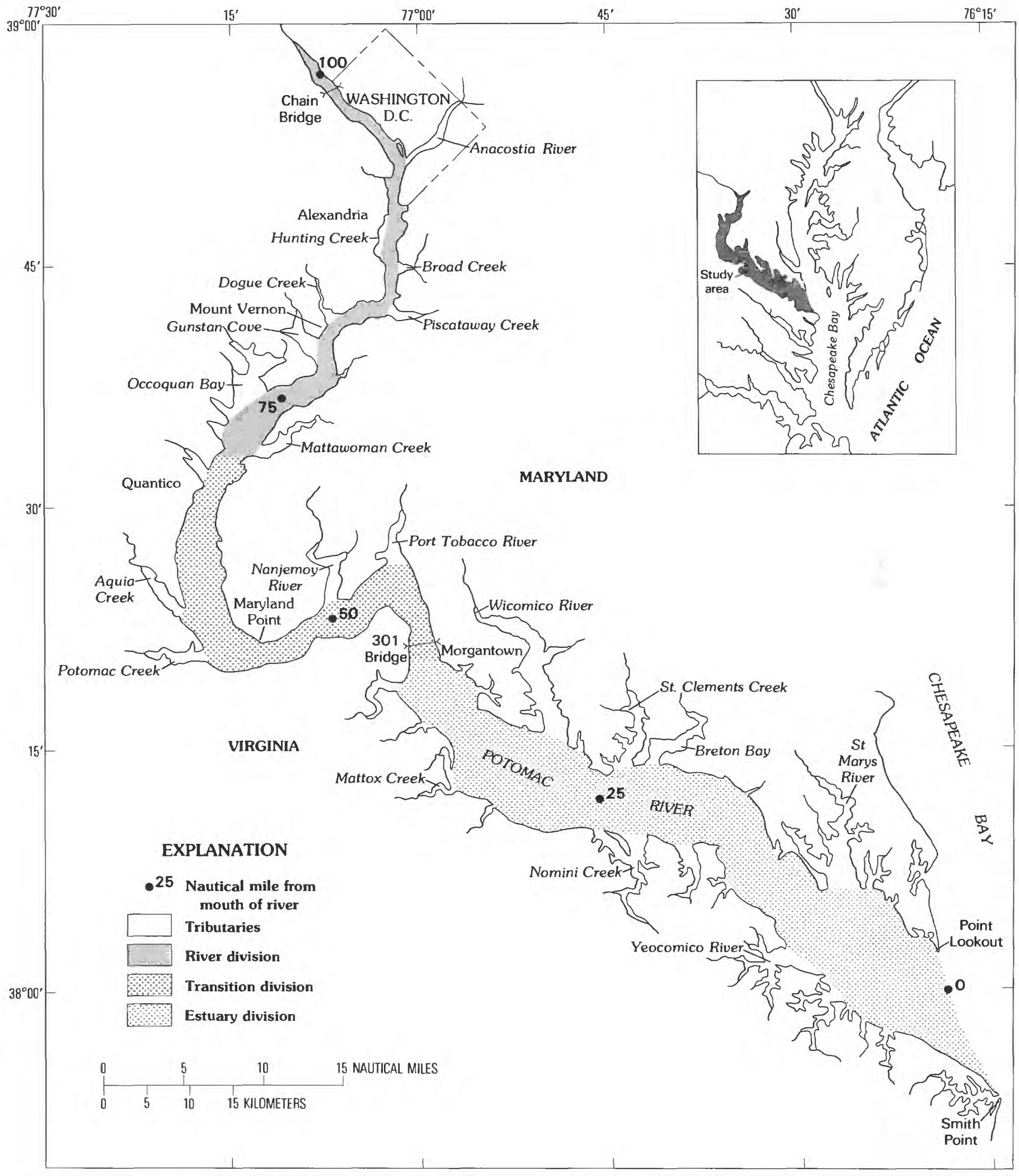


Figure 1. The tidal Potomac system.

river division. Calculated river and tidal currents are the smallest in the tidal Potomac system, rarely exceeding 20-40 cm/s (Lippson and others, 1979, p. 35). The estuary usually has brackish water from landward to seaward ends; freshwater occurs in the estuary only during or after major hurricanes. Salinity levels may be as large as 18-30 ‰ in bottom waters near Chesapeake Bay during periods of minimal freshwater inflow and as small as 5-18 ‰ in surface waters near Morgantown during periods of normal, maximum freshwater inflow. The surface area of tidal waters in the estuary is about 680 km^2, 2.4 times the combined water-surface areas in the transition and the river divisions.

The average depth in the estuary is about 7 m, and the average width is about 9,700 m. Immediately seaward of Morgantown, the estuary widens abruptly and maintains this width throughout much of its length. A slight narrowing near the middle of the estuary division separates wider upper and lower estuary reaches. Because of its width and exposure to prevailing winds, wave action is important in the estuary division. Several tributaries enter the estuary division, but the combined freshwater inflow from the tributaries is small. The major tributary embayments are at the mouths of the Wicomico River, the St. Clements Creek-Breton Bay, and the St. Marys River in Maryland and the Yeocomico River, Nomini Creek, and Mattox Creek in Virginia (fig. 1).

Samples grouped into the three hydrologic divisions are analyzed statistically in this report to describe longitudinal trends in mean particle-size measures and in mean nutrient concentrations along the Potomac mainstem. For additional perspective and detail on longitudinal trends, all samples from each of five 20 nmi-long divisions of the mainstem are grouped, and mean particle-size measures and mean nutrient concentrations are compared. The five nmi divisions are referred to as lower estuary, from nmi 0 to nmi 20, upper estuary, from nmi 20 to nmi 40, lower transition, from nmi 40 to nmi 60, upper transition-lower river, from nmi 60 to nmi 80, and upper river, from nmi 80 to nmi 100.

Geomorphic Units

Geomorphic units were identified from bathymetric profiles obtained during sampling efforts and from previously available bathymetric charts.[1] Four geomorphic units occur in varying proportions in the tidal Potomac system. The geomorphic units are called: shoreline flats, smooth flats, irregular slopes, and channels. Nine samples that could not be assigned to one of these units are listed as "other" and are not used in most analyses that follow. These nine samples are mostly from local areas extensively modified by dredging for sand and gravel, for moorage basins, or for other construction projects. Although geomorphic units have depth connotations, the depths will vary with location in the tidal Potomac system. For the Potomac mainstem, all samples from each geomorphic unit have mean depths as follows: shoreline flats, 1 m; smooth flats, 3 m; irregular slopes, 5 m; and channels, 10 m.

Shoreline flats are shallow-water environments bounded by beaches, cliffs, or marshes on the land side and commonly by a break in slope on the channel side. The flats show very little measurable local relief but usually slope steeply in the beach zone and gradually from the low waterline to a slope break on the channel side. Although they occur throughout the tidal Potomac system, shoreline flats are best developed in the estuary division and in lower parts of estuary tributaries where they may extend several hundred meters out from the present shoreline. In general, the flats are most extensive in the estuary where the shoreline is actively being eroded (Miller, 1986).

Depending on the local situation, any remaining geomorphic unit may occur adjacent to a shoreline flat. In places, deep waters impinge on the shoreline, and the channel-side break in slope leads to a channel unit; a more typical situation is for either a smooth flat or irregular slope or both to lie between a shoreline flat and the channel. Smooth flats are best developed in the river division and its tributaries and are nearly absent in the lower estuary and its tributaries. In general, they occur in progressively more shallow water as distance landward from the Potomac mouth increases. In the river division, some smooth flats are intertidal and are periodically exposed. An abrupt slope break typically separates a smooth flat from a steep slope leading to the adjacent channel bottom in the river division. In the wide part of the transition division and in the upper estuary, only a very gentle slope break may occur between smooth flats and adjacent channels or irregular slopes. Smooth flats commonly lack local relief other than that related to man's activities.

Irregular slopes are widespread in the estuary division, limited in extent in the transition division, and virtually absent in the river division. Their identifying characteristics are a gentle to steep channelward slope and (or) local relief features of irregular nature and extent. In the lower estuary, local relief features typically occur on moderately steep slopes leading from shoreline flats to an abrupt slope break on the channel-side margin; in the wide part of the transition division, the irregular relief features are on a more gently channelward sloping surface. The relief of the features decreases as the water deepens and the irregular slope merges into a smooth flat in the transition division or into a channel in the estuary

[1]Available from U.S. Department of Commerce, National Oceanic and Atmospheric Administration, National Ocean Survey. Chart numbers 12289, 12288, 12286 and 12233.

division. The local relief on an irregular slope is varied. In the upper estuary, isolated round to elongated ridges and mounds with 1-2 m of maximum relief are widespread, but irregular ridges several hundred m long with 6-9 m of relief also occur. In the lower estuary, low swales and ridges oriented both offshore and alongshore may be found. In the transition division, irregular slopes usually show only isolated small mounds and (or) depressions with less than 1 m of relief. In the lower narrow part of the transition division, however, several isolated irregular high relief ridges oriented parallel to flow directions are found and resemble those in the upper estuary. In the upper transition and the lower river, the local relief of irregular slopes more commonly has the form of long, low ridges and swales oriented parallel to the longitudinal axis of the channel. In some instances in the river division, the irregular relief appears to be due to dredging for sand and gravel.

The channel unit extends from the deepest part or thalweg of each cross section shoreward to slope breaks that mark the boundaries between the channel and adjacent units. For mapping purposes, the uppermost slope break was used to represent the channel boundary if two slope breaks occurred, one near the channel floor and one at some shallower depth. The boundaries and characteristics of channels change along the Potomac mainstem. In the upper river, from Chain Bridge to about the Anacostia River mouth, the channel bottom is extremely irregular as are the channel margins. At the scales of the available maps, only a channel unit can be differentiated in this reach. From the Anacostia River to near the lower boundary of the river division, the channel is sharply defined by steep regular slopes that lead upward to adjacent smooth flats; the channel bottom tends to be only slightly irregular and moderately flat, although deep holes may occur where the channel impinges against the shoreline. The channel in the upper wide parts of the transition division and of the estuary division generally has a flat floor and poorly defined boundary slopes. In most places, the only channel floor relief is artificial and is caused by dredging or by dragging anchors for navigational buoys or for various types of bottom trawls (Knebel and others, 1981, p. 585). In the lower part of the upper estuary, the channel thalweg may occupy a small subchannel that is displaced toward the Maryland side of the Potomac. In the lower estuary, this subchannel deep is represented by four semi- enclosed troughs or basins, but overall the channel floor and the sills separating basins exhibit very low relief. Channel margins in the estuary generally are sharply defined by a steep slope leading upward to the less steep slope of the irregular slope.

The relation between geomorphic units and sedimentologic units in the tidal Potomac system has been investigated by acoustic surface and subbottom profiling techniques (Knebel and others, 1981, p. 584-588). In the estuary, the channel and smooth flat are associated with the "modern estuarine mud" sedimentologic unit. Shoreline flats and irregular slopes are underlain by "upper Pleistocene and Holocene, estuarine and fluvial sandy and silty sediments" with only a veneer of modern sandy surface sediments derived from nearby shoreline erosion or from erosion of the underlying older deposits. In deeper waters, irregular slopes and sandy sediments appear to be relict features that are not in equilibrium with modern sedimentation conditions. In places, modern estuarine muds are being deposited over and around relict deposits and geomorphic features of the irregular slope, and in other places within the channel, erosion or nondeposition has occurred and older sandy sediments may be exposed (Knebel and others, 1981, p. 584).

Samples grouped by geomorphic units are used in this report to describe statistically lateral trends in mean particle-size measures and in mean nutrient concentrations in Potomac mainstem cross sections. For additional perspective and detail on lateral trends, samples also were grouped into nine depth units, based on 2-m depth intervals, and the significance of differences among units in mean particle-size measures and in mean nutrient concentrations was determined.

Field Methods

Reconnaissance samples for this study were collected in 1977. Preliminary results from these samples and observations during the reconnaissance effort suggested a sampling strategy based on possible relations of sediments and nutrients to longitudinal hydrologic divisions and to lateral geomorphic units. This strategy was applied during several sampling cruises in 1978, and was incorporated in the design of an acoustic survey in 1979 (Knebel and others, 1981). A few samples from previously unsampled parts of the upper tidal river and its tributaries were collected in 1981. In addition, some data from samples collected between 1978 and 1981 from the shoreline flats for a study of nearshore vegetation (Paschal and others, 1982, p. 127-131) and sediments are presented and are interpreted within the framework of this study.

All 1977 and 1981 samples and most 1978 samples were obtained with a trace-metal version of the US BM-54 sampler (U.S. Water Resources Council, 1966). The US BM-54 consists of a stainless-steel spring-loaded cup in a fish-shaped weight; the trace-metal version is coated with a special paint and is equipped with special gaskets to limit metal contamination. The sampler collects about 0.5 dm^3 (cubic decimeter) of sediment from the top 0-5 cm with each cast; multiple casts from an anchored vessel were made at locations where 0.5 dm^3 of sediment were inadequate for the number and kind of analyses desired. All 1977 samples were composites of four casts from each location as were most samples collected in 1978. The remaining 1978 samples, identified as benthos samples, were collected as part of a cooperative effort to examine sediments and benthic organisms. A hydraulic bucket sampler that obtains a volume of about 30 dm^3 from the sediment surface to about the 25-cm depth was used for these samples; a subsample of about 1 dm^3 volume was used for sediment analyses reported here. Statistical tests indicated no significant difference in mean particle-size measures and in mean carbon concentrations in US BM-54 and benthos samples collected from about the same location. The shoreline sediments were sampled by hand grabs in shallow water and by oyster tongs in deep water.

The majority of samples were collected along cross sections (plates 1-3) that extended from shoreline to shoreline at approximately right angles to the channel axis; a few samples were obtained at isolated locations or from geomorphic units not on cross sections. The cross sections extended up and across selected tributaries, including representative tributaries from each hydrologic division. The locations for cross sections were selected to encompass the tidal Potomac system at intervals determined in part by distance, in part by changes in geomorphic units noted on bathymetric charts, and in part by impressions on sediment variability gained by reconnaissance cruises and sampling efforts in 1977. The normal procedure at a cross section included a profiling run to determine the present bathymetric profile; this run was immediately followed by a return sampling run during which samples were taken from major geomorphic units identified on the profile. Positioning was accomplished by a combination of Radar and Loran, or by dead reckoning in some locations. The depth of water and changes in geomorphic features determined from the bathymetric profile obtained prior to the sampling run also were used to locate sampling positions.

Immediately after collection, samples from multiple casts were thoroughly mixed. The mixed sample was split into four quarters, each quarter was placed in a plastic sample bag, and the top of the bag was sealed. Quarters for detailed complete nutrient analyses were frozen within 15 minutes after collection and quartering and were kept frozen until laboratory analyses were begun; the quarter for particle-size analysis was stored unfrozen. Samples collected for combined sediment and benthic-organism studies were not frozen because only particle size and total carbon content were desired on these. Mixing and splitting of the benthos samples was done in the laboratory prior to analysis.

Laboratory Methods

All samples were analyzed in the U.S. Geological Survey water quality laboratory in Denver, Colo. The procedures for nutrient analyses are outlined in Skougstad and others (1979); procedures used in carbon analysis are presented in Wershaw and others (1983).

Particle size was determined by a combination of sieve analyses for gravel ($>2{,}000\ \mu m = < -1.0$ phi[2]) and sand ($<2{,}000\ \mu m > 62\ \mu m = > -1.0$ phi <4.0 phi) and hydrometer analyses for silt ($<62\ \mu m > 4\ \mu m = >4.0$ phi <8.0 phi) and clay ($<4\ \mu m = >8.0$ phi). All samples from brackish waters were pretreated to remove excess marine salts by dilution-decantion methods or by dilution and filter candle extraction of the salty water. Sodium hexametaphosphate and physical agitation by laboratory mixer were used to deflocculate and to disaggregate sediments immediately prior to analyses. For most samples, a complete particle-size distribution was defined by measurements at intervals of at least one phi (Krumbein, 1934); for some samples, only partial particle-size data (percentages of gravel, sand, silt and clay) were obtained.

Particle-size-distribution statistics of Inman (1952) were computed for all samples with complete particle-size-distribution data. A computer program (Hubbell and Glenn, 1973, p. 8) was used to define the necessary phi values at the 5, 16, 50, 84, and 95 percentiles of the particle-size-distribution curve. The program uses a linear interpolation to define values between measured points and a linear extrapolation from the nearest two points to determine values beyond measured points. For the Potomac samples, extrapolation often was necessary to define needed phi values at the fine-sediment end of the particle-size distribution. If the extrapolation indicated that 5 percent or more of sediment was finer than 14 phi, about 6.2×10^{-5} mm, phi was arbitrarily set at 14.00.

The analysis of sediment textures is based mostly on Inman statistics that generally did not require extrapolation to define end points. These statistics include: (1) Phi median diameter, a measure of central tendency equal to the phi value of the 50th percentile diameter of a cumulative frequency curve and an indication of the more abundant size (Inman, 1952, p. 133); (2) phi deviation, a measure of sorting equal to one-half the difference between phi values for the 84th and 16th percentile diameters; and (3) phi skewness, a measure of the skewness of the central 68 percent of the particle-size distribution and equal to one-half the sum of the phi values for the 84th and 16th percentile diameters minus the phi median diameter divided by the phi deviation. In addition, the percentage of sand, which could be determined without extrapolation or interpolation, is used to describe textural variations.

[2] phi $= -\log_2 D$ (Krumbein, 1934), where D is the particle diameter, in mm. Larger values of phi indicate smaller particle diameters, in mm.

SEDIMENTATION AND EUTROPHICATION

Sedimentation in tidal rivers and estuaries has resulted in (1) filling of channels and harbors and abandonment of port facilities or development of extensive dredging programs, (2) masking or burial of formerly productive shellfish beds and diminishing water column productivity, and (3) degrading of overall aesthetic qualities and loss of recreational value (National Research Council, 1977, p. 100; 1983, p. 63-64). In the tidal Potomac system, sediment deposition near the head-of-tides has resulted in abandonment of former ports on the Potomac River and on the Anacostia River near Washington, D.C. (fig. 1)(Gottschalk, 1945, p. 225-229; Williams, 1942, p. 6-11) and on many of the small tributaries of the tidal Potomac system (Gottshalk, 1945, p. 229-233; Froomer, 1980, p. 291-297). In addition, loss of shellfish, spawning, and nursery grounds (Palmer, 1975, p. 19-22; Dunnington, 1977, p. 27 and p. 40; Dunnington, 1980, p. 1-3) and extensive dredging (Hains, 1894; Gottschalk, 1945, p. 229-230; Palmer, 1975, p. 22) have resulted from sediment deposition in the Potomac mainstem between Washington, D.C. and the upper estuary.

Increased nutrient supply resulting from man's activities has resulted in "cultural eutrophication" in many urban tidal rivers and estuaries (National Research Council, 1977, p. 94). The effects of eutrophication include (1) excessive algal blooms and development of odoriferous floating algal mats, (2) low oxygen concentrations which limit fish and shellfish productivity and cause die off of desirable fish and shellfish stocks, and (3) development of nuisance accumulations of rooted plants that can clog waterways and harbors and can increase sedimentation rates (Champ, 1977, p. 37; Hobie and Copeland, 1977, p. 257). In the tidal Potomac system, eutrophication effects have been described by numerous authors, including Jaworski and others (1972, p. 254-255), Palmer (1975, p. 48-49), Jaworski (1977, p. 414-418), Young and others (1982, p. 10-14), and Macalaster and others (1982, p. 82-84).

Identification of sediment and nutrient sources and quantification of their contributions is an essential first step in understanding sedimentation and eutrophication problems. A basic understanding of hydrodynamic, geochemical, and biological processes within tidal rivers and estuaries also is necessary. In the following sections, the sources of sediments and nutrients to tidal rivers and estuaries in general and to the tidal Chesapeake and Potomac systems in particular will be described, and the general and specific processes that affect their distributions will be outlined. In addition, selected references on nutrients in bottom sediments of tidal rivers and estuaries are reviewed briefly.

Sediment Sources

The major sources of sediments to tidal river and estuary systems have been classified as external and internal by Rusnak (1967, p. 180-184). River inflows at the head-of-tides and tidal inflows through the mouth were identified as major external sources (Rusnak, 1967, p. 181), and biological activity and shoreline erosion were described as dominant internal sources. Schubel (1971, p. V-5) modified this classification to identify shoreline erosion as a separate source, called marginal, and discussed the available data on the relative importance of each source. River inflows were described (Schubel, 1971, p. V-7) as the source for the bulk of the sediment in the few tidal river and estuary systems that had been studied in detail.

Sources of suspended sediments supplied to Chesapeake Bay have been discussed by many authors including Biggs (1970), Schubel (1971a), and Schubel and Meade (1977). Chesapeake Bay is the tidal river and estuary system for the Susquehanna River and the immediate source of tidal inflow into the Potomac River. From studies of suspended sediments in northern Chesapeake Bay, Biggs (1970, p. 197) determined that the major sediment source changed from external (river inflow) near the Susquehanna River to marginal (shore erosion) and internal (primary production and skeletal material) north of the Potomac River mouth. Schubel and Meade (1977, p. 205-206) suggested that shore erosion was the dominant source of sediment in the middle and lower reaches of Chesapeake Bay, both north and south of the mouth of the Potomac River. Schubel and Carter (1976, p. 48-62) used a simple, single-segment model of the entire Bay to derive a budget for inorganic suspended sediment; in addition to Susquehanna River inflow and to sediment input from shore erosion, they identified the nearby Atlantic Ocean as the source for tidal inflow of suspended sediment into the lower Bay, and they suggested that tidal inflows carry sediments from the Bay into most major tributaries, including the Potomac River (Schubel and Carter, 1976, p. 59-60). Meade (1969, p. 232; Meade, 1972, p. 257-258) concluded that very little sediment from the larger Atlantic Coastal Plain rivers, such as the Susquehanna, reached the Atlantic Ocean, and that most sediments were trapped in the tidal rivers and estuaries or in the coastal marshes. Likewise, most sediments supplied to tributaries of the larger rivers, such as the Potomac River, never passed through the tributary and into the mainstem (Meade, 1982, p. 248).

Sediment sources in Chesapeake Bay also have been inferred from studies of bottom sediments. Ryan (1953), based on bottom topography and on characteristics of Chesapeake Bay bottom sediments, identified coarse, sandy sediments from shoreline erosion along the western and eastern Bay margins and fine to coarse sand from tidal inflow in the southern Bay (Ryan, 1953, p. 69); Susquehanna River inflow was established as the main source of silt and clay sediments in the Bay. Biggs attributed sandy bottom sediments in shallow waters in the middle part of the Bay to active erosion of the nearby western shoreline (Biggs, 1967, p. 243) and to wave-generated current action. Schubel and Carter (1976, p. 49) also attributed coarse, sandy sediments to shore erosion and fine, sandy sediments to tidal inflows; some coarse sand deposits were identified as relict, presumably indicating that they are a lag concentrate (Ryan, 1953, p. 42–43) that may not reflect modern transport conditions.

Two recent studies provide detailed information on bottom sediments in Chesapeake Bay (Byrne and others, 1982; Kerhin and others, 1982). These studies relied on extensive bottom-sediment characterizations in the Virginia and Maryland parts of the Bay and on comparison of time-separated bathymetric maps to identify sources and sinks of sediments. Byrne and others (1982, p. 72–83) noted that bottom sediments in the Virginia part of the Bay were sandier than previously reported, that grain-size gradients were very steep in cross sections, that coarser sediments usually occurred in shallow waters, and that finer sediments typically were found in deep channels or in sheltered waters of marginal embayments. From the distributions of sediment textures and of patterns of erosion and deposition, Byrne and others (1982, p. 107–136) concluded that the source of most fine sand in bottom sediments from deep waters of the Virginia part of the Bay was tidal inflow through the Bay mouth, whereas the source of most silt and clay in bottom sediments was inflow from the Maryland part of the Bay. Using a budget-type approach, Byrne and others (1982, p. 121–124) suggested that the large difference between measured bottom sediment accumulation and known or estimated sediment supply from all possible sources is lessened if the tributaries are sediment sources to Chesapeake Bay and if inflow through the Bay mouth is a stronger source than previously estimated.

Kerhin and others (1982, p. 52–55) determined that bottom sediments in the Maryland part of Chesapeake Bay were dominantly sand in shallow nearshore areas and silty clay in the deep channel. Some sands were identified as relict deposits, and some isolated pockets of sand and clay were attributed to nearby local sources, either shoreline erosion or subaqueous exposures of pre-Holocene deposits (Kerhin and others, 1982, p. 70). Overall, sediments in the Maryland part of the Bay were finer than those in the Virginia part (Kerhin and others, 1982, p. 54), and locally, within the Maryland part of the Bay, the sediments coarsen in a northward direction toward the mouth of the Susquehanna River (Kerhin and others, 1982, p. 67; p. 109–110).

Kerhin and others (1982, p. 119–124) reevaluated the available data on external and marginal sources of inorganic sediments supplied to the Maryland part of Chesapeake Bay, and provided new computations where additional data were available. The Susquehanna River and shoreline erosion were identified as the major sources of inorganic sediments; Kerhin and others, (1982, p. 120) concluded that available data for Bay tributaries were generally inconclusive as to whether the tributaries were sources or sinks for Chesapeake Bay sediments. The sediment contributed from the external and marginal sources was compared to the amounts deposited or eroded as determined from analysis of time-separated bathymetric maps of Chesapeake Bay. This comparison revealed that more sediments were deposited than were introduced into the Bay from external and marginal sources; selective Bay-floor erosion was necessary to supply additional sediments to depositional areas so that mass accumulation would not exceed mass supplied (Kerhin and others, 1982, p. 129). The amount supplied by both Bay-floor and external and marginal sources exceeded the amount deposited, indicating that an excess of sediment was available for export into the Virginia part of the Bay or into tributaries along the Maryland part of the Bay (Kerhin and others, 1982, p. 132).

Sources of sediments in the tidal Potomac system have been discussed recently by several authors, including Blanchard and Hahl (1986), Hickman (1984), Miller (1986), and Bennett (1983). The annual total load of suspended sediment for the Potomac River near the head-of-tides at Chain Bridge (fig. 1) was measured by Blanchard and Hahl (1986, table 12); the yearly sediment input varied from 2,400,000 to 359,000 Mg (megagram) and averaged about 1,400,000 Mg for the 3 water years (1979–81) during which measurements were made. Water discharges for the 3 years generally were characteristic of the 51-year average discharge, so the average sediment concentrations and loads may also be representative. Feltz and Herb (1978, p. 169) estimated that 1,340,000 Mg/yr of suspended sediment were transported by the Potomac River during the 12 years between 1964 and 1976 at a station 32 km upstream of the Chain Bridge station. Sediment inflow between Chain Bridge and the upstream station is minimal; thus, Blanchard and Hahl's (1986) measurements at Chain Bridge are fairly representative of a longer term average.

Hickman (1984, p. 56–62) used a combination of direct measurements and available data to determine that local tributaries and all nonpoint sources except shore erosion seaward of the head-of-tides for the tidal Potomac system contributed an average of 900,000 Mg/yr of sediment during the 1979–81 water years. The shore erosion contribution was determined by Miller (1986) from an analysis of time-separated shoreline surveys and aerial photographs. This contribution ranged from 375,000 to 565,000 Mg/yr for all sediment sizes (Miller, 1986, p. 35). Both Hickman (1984, p. 56–62) and Miller (1986,

p. 35–39) discussed the relative source strengths; sediment inflow from the Potomac River upstream the head-of-tides was identified as the dominant source although local tributaries and other nonpoint sources seaward of the head of tides were a close second. Shoreline erosion contributed about 6 to 9 percent of the total annual sediment input, although the relative importance of the shoreline contribution increased greatly toward the mouth of the tidal Potomac system (Miller, 1986, p. 37).

Bennett (1983, p. 217–227) used twice-weekly salt, suspended sediment and nutrient samples from six stations along the Potomac mainstem to calibrate a hybrid one-layer, two-layer box model of the tidal Potomac system and to compute monthly loads passing each station during the 1979–81 water years. These loads were used to produce individual water-year and 3-year summary budgets of transport through the three hydrologic divisions of the Potomac mainstem. For the 3-year study period, Chesapeake Bay was a small net source of sediment (about 1 percent of the total) to the tidal Potomac system. Bennett's computations indicated that the sediments in the Potomac mainstem are deposited mostly in the river and the estuary hydrologic divisions (Bennett, 1983, p. 225).

Sedimentation Processes

Once sediments enter tidal river and estuary systems, their distributions and characteristics depend on changes in local hydrologic, geomorphic and biologic conditions. The major hydrologic changes are related to tidal influences, to the presence of marine salts, and to increased wind effects (Postma, 1967). Tidal influences cause the water level to rise and fall and the currents to flow alternately landward (upstream or toward the head-of-tides) and seaward (downstream or toward the mouth). Rising and falling water levels promote deposition in intertidal environments (Postma, 1967, p. 177), and landward currents delay the transport of sediments through channels and thus facilitate sediment deposition in deep water environments. In the tidal Potomac River, landward currents are noted as far upstream as the central part of Washington, D.C. during low river discharges (Schaffranek, 1985); at high river discharges, or low tidal conditions, landward currents may only reach the southern boundary of Washington, D.C. (fig. 1).

Net nontidal currents and resuspension are major factors in the generation of the estuarine "turbidity maximum," or zone between the river and the estuary in which suspended-sediment concentrations are higher than in adjacent zones. The turbidity maximum usually is a zone of accelerated deposition of texturally uniform sediments in many estuaries (Postma, 1967, p. 173; Schubel, 1971, p. VI-11 and VIII-11). During the 1977 bottom sediment sampling cruise, the turbidity maximum in the Potomac mainstem extended from the the lower river to the upper estuary, and the suspended-sediment concentration was highest in the transition division near the landward limit of marine salts about 8 nmi upstream from Maryland Point (fig. 1). Additional data on turbidity, suspended-sediment and specific-conductance distributions in the tidal Potomac system for the 1979 through 1981 water years are included in reports by Blanchard and Hahl (1981), Blanchard and others (1982), and Blanchard and Coupe (1982). The 1979 through 1981 water-year data indicate that the turbidity maximum in the mainstem of the tidal Potomac system generally is centered in the Maryland Point area, although it migrates landward and seaward from this area as river discharges and tidal conditions change.

Marine salts combine with tidal influences to generate longitudinal or lateral estuarine circulation patterns (Pritchard, 1967) that promote landward transport and the trapping of sediments (Postma, 1967, p. 170–173) within the freshwater-saltwater transition zone of partially mixed tidal rivers and estuaries. The salts may promote flocculation of fine-grained sediments, and the flocs may settle into the lower part of the water column where they may be transported toward the head-of-tide with the net nontidal longitudinal flow of the more dense saltwater, or deposited on the streambed during slack water periods. Elliott (1976) reported that near-bottom net nontidal landward currents existed at Maryland Point during low flow conditions in the fall of 1973; although not directly observed, Elliott (1976) thought that net nontidal landward currents were possible up to 7 nmi landward from Maryland Point. During high flow conditions, net landward bottom currents were not observed inland of Morgantown (fig. 1) (Elliott, 1976).

Lateral circulation patterns are established when freshwater preferentially moves seaward along one side of a water body and saltwater moves landward along the other side (Pritchard, 1967, p. 39). Lateral circulation patterns in the tidal Potomac system are indicated by salinity data that show less saline water along the Virginia side than along the Maryland side (Lippson and others, 1979, p. 36–47). With varying morphologies, lateral circulation patterns may result in development of circulation cells in which sediments are trapped or deposited. The upper wide parts of the transition and estuary hydrologic divisions are possible locations for such circulation cells in the tidal Potomac system (pls. 2 and 3).

Increased wind effects and accompanying wave action are major factors in eroding sediments from supratidal shoreline deposits and in creating higher than normal tidal heights and currents (Miller, 1986; Elliott, 1982; Elliott, 1978; Elliott and Hendrix, 1976). Wind generated waves also resuspend bottom sediments from the shoal areas and assist in the transport of resuspended materials to nearby deep waters or to sheltered embayments. In the tidal Potomac system, wind effects increase in a seaward direction as the system widens and the flow direction changes from north-south to northwest-southeast (Miller, 1986).

Geomorphic changes in the tidal Potomac system are described in part in the sections dealing with hydrologic divisions and geomorphic units. Probably the most significant of the changes not described is the decrease in streambed slope at or near the head-of-tides. The slope decrease and the enlarging Potomac mainstem water body result in reduction of the river current velocity and in rapid deposition of river-borne sediments. As the velocity decreases, the competence of the river current decreases, with the result that sediment in transport and on the streambed typically becomes finer with distance seaward of the head-of-tides. Local constrictions and increases in slope along the Potomac mainstem occur in the Quantico area and between Maryland Point and Morgantown, Md. (fig. 1 and pl. 2). The net effect of these local geomorphic changes probably is to promote sediment deposition in the enlarged parts of the tidal Potomac system adjacent to the constrictions. Within the tide-effected tributaries of the tidal Potomac system, the slope decrease near the head-of-tide and the enlarging tributary water body also promote deposition. DeFries (1986) determined that only about 15 percent of the sediment supplied at the head-of-tide for the Port Tobacco River tributary (fig. 1 and pl. 2) reached the Potomac mainstem, and most tributary inputs determined by Hickman (1984) probably also are retained in the tributaries.

Tidal rivers and estuaries typically are highly productive environments that support large populations of planktonic and benthic organisms. These organisms are capable of forming aggregates of suspended and bottom sediments by a variety of processes (Schubel, 1971, p. X1–X29). The aggregates formed during these processes may be more readily deposited than the original sediment particles (Zabawa, 1978, p. 49–51). Benthic and some planktonic organisms filter vast quantities of water and create aggregates of the sediments in the water (Prokopovich, 1969, p. 894–895; Schubel, 1971, p. X24–X25). Cohen and others (1984, p. 178) indicated that Asiatic clams in a 6-km-long reach of the tidal Potomac River just seaward of Washington, D.C. were capable of filtering a volume of water equivalent to the entire volume in the reach in three to four days, a time about equal to the residence time of a water parcel in the reach during their study. Sediment particles also may be formed into aggregates that will settle more rapidly than the original particles by secretions from planktonic organisms. Large populations of benthic organisms rework bottom sediments; reworking can enhance the erodibility of bottom sediments if it results in deposits on the streambed or increased roughness of the streambed surface; alternatively, secretions by bottom dwelling organisms may aid formation of aggregates that may be more difficult to erode.

Nutrient Sources

Data on sources and supply rates of nutrients to tidal rivers and estuaries are even more limited than similar data for sediments. Ketchum (1967, p. 329–335) briefly described three sources of nutrient enrichment in estuaries: river inflow, local pollution, and tidal inflow. Champ (1977, p. 237–255) identified nitrogen, phosphorus, and organic carbon as the major components of nutrient loading in the nation's estuaries, and listed municipal sewage and industrial waste, urban runoff, and agricultural and forestry practices as the major nutrient sources. Hobbie and Copeland (1977, p. 257–274) and Aston (1980, p. 233–262) also described the sources of nutrients in tidal rivers and estuaries. Streams and rivers were identified as the major sources of nutrients; sewage and agricultural wastes were the sources of most nutrients in streams and rivers. Only small amounts of nutrients came from the ocean or from direct precipitation. Cutting of forests and growing urbanization were listed as major causes of increased nutrient loads related to man's activities.

Schubel (1972) presented an excellent summary of physical and chemical conditions of Chesapeake Bay and its tributaries, and discussed the relations of these conditions to eutrophication and sedimentation problems. Recent concerns about nutrient enrichment and resulting eutrophication have resulted in a synthesis of available data and in major new studies of nutrient sources and supply rates in Chesapeake Bay and in some bay tributaries (Macalaster and others, 1982). Summaries of results and management implications of results of the recent studies in Chesapeake Bay are contained in reports edited by Macalaster and others, 1983, and by Barker and others, 1983. Macalaster and others (1982, p. 45–102) gave an historical perspective of the development of eutrophication problems in Chesapeake Bay. Although considerable qualitative evidence exists of anthropogenic nutrient enrichment more than 100 years ago, data documenting sources, supply rates, and changes in Chesapeake Bay generally are available only for selected years since about 1950.

Five major sources of nutrients to Chesapeake Bay were identified and quantified by Macalaster and others (1982, p. 150–251); river sources (inland of the head of tides), point sources (seaward of the head of tides), atmospheric sources, bottom sources (sediments), and ocean sources. River sources were dominant, and point sources were the second largest contributors of the annual inputs of total nitrogen and total phosphorus.

Atmospheric and bottom sources made significant but minor contributions to the annual inputs of total nitrogen and of total phosphorus. The oceanic source was not well quantified but was indicated to be insignificant on a net basis. For the river-source nutrients, the nitrogen input was dominantly in solution, and the phosphorus input was primarily in suspension; the solution-suspension breakdown for most other sources was not reported. Seasonal variations in the loads from the various sources were substantial; the largest part of the annual total nitrogen load entered from river sources during the winter and spring, whereas much of the total phosphorus load came from river and bottom sources during spring and early summer (Macalaster and others, 1982, p. 236–237). The phosphorus input during summer was attributed to the development of anoxic conditions and subsequent phosphorus release from bottom sediments in deep waters of Chesapeake Bay. Macalaster and others, (1982, p. 237–238) constructed an annual budget from nitrogen and phosphorus input data for the various sources. The results from the budget indicated that all the nitrogen and phosphorus that entered the Chesapeake Bay stayed in the bay, mostly by permanent burial in the bottom sediments.

Nutrient enrichment and eutrophication have been recognized as serious problems for considerably more than 100 years in some tributaries of Chesapeake Bay, including the tidal Potomac system (Jaworski and others, 1972; Jaworski, 1977 and 1981; Macalaster and others, 1982; Bennett, 1983; Blanchard and Hahl, 1986; Hickman, 1984). Jaworski and others (1972, p. 254; Jaworski, 1977, p. 408 and 416) outlined trends in point source nutrient loads from wastewater treatment plants in the Washington, D.C. area and in resulting eutrophication effects. Between 1913 and 1970, total nitrogen loads from wastewater point sources increased steadily about 10-fold and total phosphorus loads about 22-fold; total carbon loads increased about 3-fold from 1913 to the late 1950's, when improved waste-treatment facilities reduced the carbon load to only about twice the 1913 level. The increase in point-source nutrient loads coincided with step-wise changes in dominant species, each species change indicating worsening eutrophication. Since 1970, total phosphorus loads from point sources have decreased about 75 percent because of advanced waste-treatment facilities, but total nitrogen loads have decreased only slightly (Jaworski, 1981, p. 90–91). For the 3-year period from October 1979 through September 1981, the average annual wastewater total phosphorus load was about 2,300 kg/d and total nitrogen load was about 26,000 kg/d (Hickman, 1984, p. 59), about 5- and 10-fold in excess of their 1913 levels, but not appreciably different from lower levels since 1970. Macalaster and others (1982, p. 207) estimated that the 1980 annual mean daily load from municipal wastewater and industrial point sources in the Washington, D.C. area was about 3,400 kg/d for total phosphorus and 27,000 kg/d for total nitrogen. An improvement in the scale of eutrophication effects from hyper-eutrophic to eutrophic (Jaworski, 1981, p. 97–104) was the apparent result of the changes in inputs from point sources.

No long-term data base for the input of nutrients from the Potomac River source is available, although Jaworski (1981, p. 88–90) presented mean daily loads for each month in 1966 and for 13 months beginning in February 1969 and ending in February 1970. These loads demonstrated considerable monthly and seasonal variability but were generally more variable during winter and spring months when river discharges were greater. Little difference in the loads between 1966 and 1969–70 was noted when water discharge differences were eliminated. Blanchard and Hahl (1986, table 9A–9D) reported monthly and water year nutrient loads from the Potomac River source for four water years starting in October 1978 and ending in September 1981. The average annual mean daily total phosphorus load was about 4,700 kg/d and the total nitrogen[3] load was about 61,600 kg/d. Macalaster and others, (1982, p. 176) also estimated annual mean daily nutrient loads for the 1979–81 water years. Their total phosphorus load was about 2,800 kg/d and their total nitrogen load was about 43,000 kg/d, somewhat less than the loads measured by Blanchard and Hahl (1986, Table 9B-9D) for the equivalent water years.

Rivers and streams tributary to and atmospheric inputs directly to the tidal Potomac system seaward of the head-of-tides at Chain Bridge also are potential sources of total phosphorus and of total nitrogen. Hickman (1984, p. 59) reported the magnitude of their contributions for the 1979–81 water years and compared these contributions to those from the Potomac River and from the metropolitan Washington, D.C. wastewater-treatment plants for the same time period. The Potomac River source was dominant for both nutrients, contributing 43 percent of the sum of all total phosphorus inputs and 57 percent of the sum of all total nitrogen inputs; the metropolitan treatment plants contributed about half as much total phosphorus (25 percent of the sum) and total nitrogen (26 percent of the sum) as the river source, and the local tributary sources contributed 32 percent of the total phosphorus inputs and 17 percent of the total nitrogen. The atmospheric source was less than 1 percent of the sum of the input for phosphorus and was only about 4 percent of the sum of the input for total nitrogen. The total daily load from all four sources was about 9,300 kg/d for total phosphorus and 98,000 kg/d for total nitrogen.

[3]Total nitrogen loads from Blanchard and Hahl were computed from data for total Kjeldahl nitrogen and for nitrite plus nitrate nitrogen. The loads should approximately equal the "total nitrogen loads" reported by Macalaster and others, 1982.

The exchange of nutrients between the tidal Potomac system and Chesapeake Bay, the "ocean source" so far as the Potomac is concerned, is poorly defined. Bennett (1983, p. 222-227) used preliminary data from Blanchard and Hahl (1986), Hickman (1984), and Miller (1986), and data from six stations along the tidal Potomac system to calibrate a hybrid, one-layer, two-layer kinematic transport model and to compute monthly nutrient loads and 1979-81 water-year nutrient budgets for the river, transition, and estuary divisions of the Potomac mainstem. These budgets indicated that Chesapeake Bay was a net sink for about 22 to 26 percent of the total phosphorus and total nitrogen supplied by the Potomac River source, by point sources in the Washington, D.C. area, and by local tributary and atmospheric nonpoint sources seaward of Chain Bridge. Although not specific as to process or reason, Bennett's budgets for each division suggested that more phosphorus and nitrogen were retained in the estuary division than in the river division or in the transition division. Presumably, much phosphorus and nitrogen retention within the hydrologic divisions reflects their accumulation in bottom sediments.

Nutrient Processes

Dilution, adsorption-desorption, coagulation and sedimentation have been identified as the major physical and chemical processes that change the concentrations of nutrients in tidal rivers and estuaries; biodeposition and nutrient uptake by photosynthetic organisms are major biological processes that remove or recycle nutrients within tidal river and estuary systems (Hobbie and Copeland, 1977, p. 260-262). Hobbie and others (1975, p. 287-302) suggested that sediments in the Pamlico estuary, North Carolina, were a trap for most phosphorus and nitrate nitrogen supplied by stream inflows. Peterson and others (1975, p. 153-187), Conomos and others (1979, p. 115-142), Arthur and Ball (1979, p. 143-174), and Peterson (1979, p. 175-194) also indicated the importance of sediments as a source or a sink for nutrients in the San Francisco Bay, California, estuarine system. Resuspension of bottom sediments has been identified as an important process in nutrient uptake and release from lake sediments (Ryding and Forsberg, 1977; Lam and Jaquet, 1976) and from estuarine sediments (Roman, 1978; Roman and Tenore, 1978).

Processes that affect the concentration and distribution of nutrients in the tidal Potomac system have been discussed by Jaworski and others (1972), Thomann and others (1974), Taft and Taylor (1976), McElroy and others (1978), and Peterson (1980). The important processes were those that resulted in uptake or release of nutrients by sediments and those that resulted in deposition of the sediments and sediment-borne nutrients. The tidal Potomac system exhibits the typical two-layer circulation pattern of partially mixed estuaries (Pritchard, 1967; Lippson and others, 1979, p. 8; Bennett, 1983, p. 219). This pattern enhances the retention of sediments and sediment-borne nutrients (Macalaster and others, 1982, p. 107; Peterson, 1979; Arthur and Ball, 1979). Bennett (1983, p. 225) concluded that all 8 million tons of sediment supplied to the tidal Potomac system from all sources during the 1979-81 water years was trapped in the system, as was nearly 75 percent of all the nutrients. Macalaster and others (1983, p. 39) estimated a sediment trapping efficiency of 95-100 percent for the tidal Potomac system based on the system capacity to inflow ratio.

Jaworski and others (1972, p. 250-254) described in general terms the nature and causes of changes in nutrient concentrations along the tidal Potomac system. Chemical transformations, biological uptake and subsequent deposition of organic detritus with bottom sediments, and dilution were identified as the causes of most changes in nitrogen. Phosphorus was shown to have a strong affinity for sediments in the river division, and phosphorus adsorption by sediments (Carpenter, Pritchard, and Whaley, 1969, p. 219-220) and subsequent sediment deposition were believed to be responsible for most changes. Callender (1982, p. 431-446) and Callender and Hammond (1982, p. 395-413) described and quantified the uptake of phosphorus by oxygenated sediments in the river division and the release of phosphorus in the periodically anoxic bottom sediments of the estuary division. Macalaster and others (1982, p. 141, p. 212-217), and Taft and Taylor (1976a, p. 80; 1976b, p. 71) described similar phosphorus reactions in Chesapeake Bay. Thomann and others (1974, p. 707, 714) modeled the behavior of phytoplankton and the effects of phytoplankton on nutrient distributions in the tidal Potomac River; their verification analyses indicated that both nitrogen and phosphorus were used and were removed by the phytoplankton from the water to the bottom sediments. Benthic organisms, such as the Asiatic clam that is abundant in the river division of the Potomac mainstem (Dresler and Cory, 1982; Cohen and others, 1984) also have been shown to use and to excrete large quantities of ammonium and phosphorus (Lauritsen and Mozley, 1983, p. 47-51). Resuspension of bottom sediments in a shallow-water area of the transition division recently has been shown to result in increased flux of nitrogen from the sediments to the water column (Simon, 1984).

Nutrients in Bottom Sediments

No detailed systematic studies of nutrient species, concentrations, and distributions in bottom sediments of tidal rivers and estuaries are available, but many reports contain data on carbon in a limited suite of samples from a range of tidal river and estuary environments. Carbon distributions in bottom sediments from marine and estuarine environments were reported by Trask (1932), who noted that fine sediments generally had larger concentrations of organic carbon than coarse sediments. Folger (1972) briefly summarized the available data on carbon in estuarine bottom sediments in 45 coastal environments (estuaries, lagoons, embayments, and deltas) of the United States, including Chesapeake Bay. Organic carbon concentrations in the sediments seldom exceeded 5 percent and generally were inversely related to particle size (Folger, 1972, p. 88–90). In addition to responding to the changes in settings that determine particle size, carbon concentrations were determined in part by the level of pollutants entering the coastal environment; carbon concentrations up to 15 percent were noted in bottom sediments from Boston and Charleston Harbors where sewage inflows were large (Folger, 1972).

Recent studies have stressed the use of stable carbon isotopes and of carbon to nitrogen ratios as indicators of sources of organic matter in tidal river and estuarine environments (Pocklington, 1976, p. 95; Tan and Strain, 1979). Terrestrial organic materials commonly have more negative stable carbon isotope ratios and higher carbon to nitrogen ratios than estuarine and marine organic materials. Spiker and Schemel (1979, p. 209) used stable carbon isotope data to determine the relative importance of riverine and marine sources of carbon in bottom sediments of San Francisco Bay. Riverine carbon from terrestrial plants dominated landward of the null zone turbidity maximum, and marine carbon from phytoplankton increased linearly with distance seaward of the null zone.

Kerhin and others (1982, p. 77–88) reported on the distribution of carbon in bottom sediments of the Maryland part of Chesapeake Bay. Organic carbon was identified as the dominant component of total carbon, and larger concentrations of carbon were associated with fine-grained sediments of deep waters or of sheltered shallow waters than with coarse-grained sediments in exposed shallow waters. Some unusually large carbon concentrations in the Maryland part of Chesapeake Bay were traced to the presence of coal from mining operations in the Susquehanna River drainage basin, to the shipment of coal from nearby ports, or to exposed relict sediments. The carbon content of the bottom sediments decreased progressively in a downbay direction from large concentrations (mean of 4.1 percent) near the mouth of the Susquehanna River to small concentrations (mean of 1.4 percent) in the segment north of the mouth of the Potomac River (Kerhin and others, 1982, p. 80). The correlation between particle size and carbon content was fairly strong throughout the Bay, but was stronger in groups of samples from downbay segments. Poor correlations existed in segments with large carbon concentrations near the mouth of the Susquehanna River.

The sources of organic matter and organic carbon in the Maryland part of Chesapeake Bay were discussed by Hunt (1966), Spiker and others (1982) and Kerhin and others (1982, p. 83–88). Based on stable carbon isotope data and on resistance to chemical degradation, resistant organic material with large ^{13}C ratios near the head of the Bay was attributed to input of terrestrial organic matter and coal from the nearby Susquehanna River. Smaller ^{13}C ratios in a downbay direction were interpreted as indicating the increased occurrence of organic materials (phytoplankton) from estuarine and marine sources. Near the mouth of the Potomac River, Kerhin and others (1982, p. 88) indicated that the marine source of carbon dominated over the terrestrial source, which was mostly identified as erosion of nearby shoreline deposits.

Byrne and others (1982, p. 98–107) reported the carbon content and distribution in sediments from the Virginia part of Chesapeake Bay from the Potomac River mouth south to the Bay mouth. Mean carbon concentrations in the Virginia part of the Bay were about 1.0 percent, slightly lower than mean values reported by Kerhin and others (1982) for the segment of the Bay immediately north of the Virginia part. Byrne and others (1982) noted strong correlations between organic carbon concentrations and percentage of clay, but generally poor correlations between water depth and various other sedimentological and chemical parameters. Local hydrologic, geomorphic, and bathymetric conditions were identified as the cause of most poor correlations. No attempt was made to identify sources of carbon in the sediments of the Virginia part of the Bay.

Published data relative to nutrient concentrations in tidal Potomac system bottom sediments are scarce. Jensen (1974, p. 67–79) reported data for volatile solids (an estimate of organic content) and for phosphorus for samples of fine-grained sediments from three cores taken from the transition division between Quantico and Maryland Point (fig. 1). Organic matter and phosphorus concentrations in near-surface sediments were about seven percent and 0.25 percent (dry weight), respectively. Mielke (1974) determined concentrations of carbon and of a group of trace metals for sediment samples from 42 cores collected in the river and the transition divisions and in adjacent tributaries between Chain Bridge and Maryland Point (fig. 1). Organic carbon ranged from 0.13 to 5.04 percent, and lowest values were found in the coarsest sediments (Mielke, 1974, p. 35). Both total and organic carbon decreased in a seaward direction, as did the mean grain size of the sediments. Sediments from locations near sewage treatment plants did not show elevated concentrations of carbon or other anthropogenic elements.

Callender (1982, p. 438–439) reported total sedimentary phosphorus concentrations in sediments from cores from six locations between Mount Vernon and Point Lookout (fig. 1). Concentrations in near-surface sediments ranged from 20 to 50 micromoles per gram. The largest total phosphorus concentrations in near-surface sediments were in cores from the transition division, and the smallest concentrations were in cores from the estuary division. Callender and Hammond (1982, p. 397) mentioned that sedimentary organic nitrogen concentrations were larger in the transition division than in the tidal river division, and that the resulting smaller carbon to nitrogen ratios indicated a local or phytoplankton source for the organic matter. Spiker and others (1982) indicated that algal production is the dominant source of organic carbon in the lower estuary of the Potomac mainstem, but Glenn and others (1982) reported that terrestrial sources were dominant in much of the tidal Potomac mainstem.

PRESENTATION OF DATA

Locations of bottom-sediment samples in the tidal Potomac system are shown on plates 1–3. Sample numbers generally increase in a seaward direction for samples from the Potomac mainstem and in a landward direction for samples from the Potomac tributaries. Numbers and types of analyses are summarized in table 1. The data base consists of 314 particle-size analyses, 227 complete and 87 partial, and 94–183 nutrient analyses, the exact number depending on nutrient species. An average of 73 percent of these analyses are for samples from the Potomac mainstem, and 27 percent are for samples from Potomac tributaries, roughly proportional to the relative water-surface areas in these divisions (table 2A). Within the Potomac mainstem, about one-third of the samples and analyses came from each of the three hydrologic divisions (table 1), although the estuary division alone contains 71 percent (table 2A) of the total water-surface area; greater variability of sediments and nutrients in the smaller river and transition divisions generally dictated this distribution. Within geomorphic units of the hydrologic divisions, the number and relative abundance of samples (table 1) vary approximately as the water-surface areas of the geomorphic units vary. The channel and smooth flat include 89 percent (table 2B) of the total water-surface area of the river division, and 83 to 90 percent of the analyses (table 1) from this division came from samples of these units; the channel and irregular slope contain 87 percent (table 2B) of the total water-surface area of the estuary division, and 71 to 86 percent of the analyses (table 1) from this division came from samples of these units.

The presentation that follows generally is organized around types of data and analyses. For each type, a general description of the data will be given, and the data from samples from the several parts of the tidal Potomac system will be compared. Statistical techniques will be used to test hypotheses about the significance of most comparisons.

Particle Size

Particle-size data for sediment samples from the tidal Potomac system are listed in table 3, and the distributions of one particle-size measure, the median, in samples from the Potomac mainstem and in samples from tributaries of the estuary division are shown in figures 2*A* and 2*B*. Tributaries of the river and transition divisions show essentially the same particle-size characteristics and distributions as tributaries of the estuary division show. The only exceptions are the two large tributaries of the river division, the Anacostia and the Occoquan, both of which show coarse sediments in channel deposits near the head-of-tides, much as the channel of the river division also shows coarse sediments in a few locations from the head-of-tides to Mount Vernon (table 3).

Particle-size data indicate that tidal Potomac sediments are quite variable in all measures of particle-size distribution, and the plots of the median show the nature of the variation for one measure among samples from hydrologic divisions and geomorphic units of the mainstem and geomorphic units of the tributaries. The median ranges from −2.13 phi (4.38 mm) in a sample from the irregular slope in the transition division to 10.32 phi (<0.0009 mm) in a sample from the channel in the estuary division (fig. 2*A*). Samples from tributaries of the estuary division generally show a similar upper limit for the median but not as small a lower limit as samples from the Potomac mainstem (fig. 2*B*). For all samples from the tributaries (table 3), most large and small values of the median are not appreciably different from most large and small values for samples from the Potomac mainstem. Trends in median with nmi are not readily apparent, but both the mainstem (fig. 2*A*) and the tributaries (fig. 2*B*) show similar trends in median among geomorphic units. These trends indicate that sediments from the channel and the smooth flat have finer particle sizes and higher values of the median particle size than sediments from the shoreline flat or the irregular slope.

Selected particle-size measures for samples from several parts of the tidal Potomac system are summarized in tables 4 and 5. Sediments in the tidal Potomac system are dominantly fine grained and average 36 percent clay, 27 percent silt, and 37 percent sand (table 4). The mean value for the median is 6.60 phi (0.010 mm), well into the silt range (Wentworth, 1922; Page, 1955). The average study-area sediment is poorly sorted and is skewed slightly toward the fines (table 4). The standard deviations for these means and averages are large, which indicates that the sediments are quite variable.

Means and standard deviations of particle-size measures for samples from mainstem and tributaries

Table 1. Distribution of samples and analyses

[Geomorphic units are: 0=shoreline flat; 1=smooth flat; 2=irregular slope; 3=channel; and 4= other; all=all units]

Type of analyses	Tidal Potomac system	NUMBER OF SAMPLES: Potomac mainstem hydrologic division — River, Geomorphic unit 0	1	2	3	4	All	Transition, Geomorphic unit 0	1	2	3	4	All	Estuary, Geomorphic unit 0	1	2	3	4	All	Potomac tributaries, Geomorphic unit 0	1	2	3	4	All
PARTICLE SIZE																									
Complete and partial	314	7	22	1	31	3	64	27	17	13	23	2	82	9	2	21	33	0	65	41	11	4	47	0	103
Complete	227	1	21	1	26	3	52	4	13	11	21	2	51	7	2	21	33	0	63	6	11	4	40	0	61
NUTRIENTS																									
Total carbon	183	1	14	1	30	5	51	3	13	11	16	2	45	4	2	12	21	0	39	5	10	2	31	0	48
Inorganic carbon	163	1	12	1	21	3	38	3	13	11	16	2	45	4	2	12	21	0	39	5	9	2	25	0	41
Organic carbon	163	1	12	1	21	3	38	3	13	11	16	2	45	4	2	12	21	0	39	5	9	2	25	0	41
Total phosphorus	114	0	9	1	26	4	40	2	4	5	9	2	22	4	2	6	9	0	21	3	9	0	19	0	31
Total nitrogen	114	0	9	1	26	4	40	2	4	5	9	2	22	4	2	6	9	0	21	3	9	0	19	0	31
Nitrite + nitrate nitrogen	94	0	7	1	17	2	27	2	4	5	9	2	22	4	2	6	9	0	21	3	8	0	13	0	24
Ammonia nitrogen	94	0	7	1	17	2	27	2	4	5	9	2	22	4	2	6	9	0	21	3	8	0	13	0	24

Table 2. Distribution of water-surface area in square kilometers

A. Tidal Potomac system, Potomac mainstem, Potomac tributaries, and mainstem hydrologic division

Tidal Potomac system	Potomac mainstem		Potomac tributaries		POTOMAC MAINSTEM HYDROLOGIC DIVISION: River		Transition		Estuary	
Area	Area	Percent	Area	Percent	Area	Percent	Area	Percent	Area	Percent
1,230	960	78	270	22	90	9	190	20	680	71

B. Mainstem geomorphic unit within each hydrologic division

Potomac mainstem hydrologic division	POTOMAC MAINSTEM GEOMORPHIC UNIT: Shoreline flat		Smooth flat		Irregular slope		Channel		Total area
	Area	Percent	Area	Percent	Area	Percent	Area	Percent	
River	4	4	50	56	6	7	30	33	90
Transition	10	5	70	37	40	21	70	37	190
Estuary	50	7	40	6	300	44	290	43	680

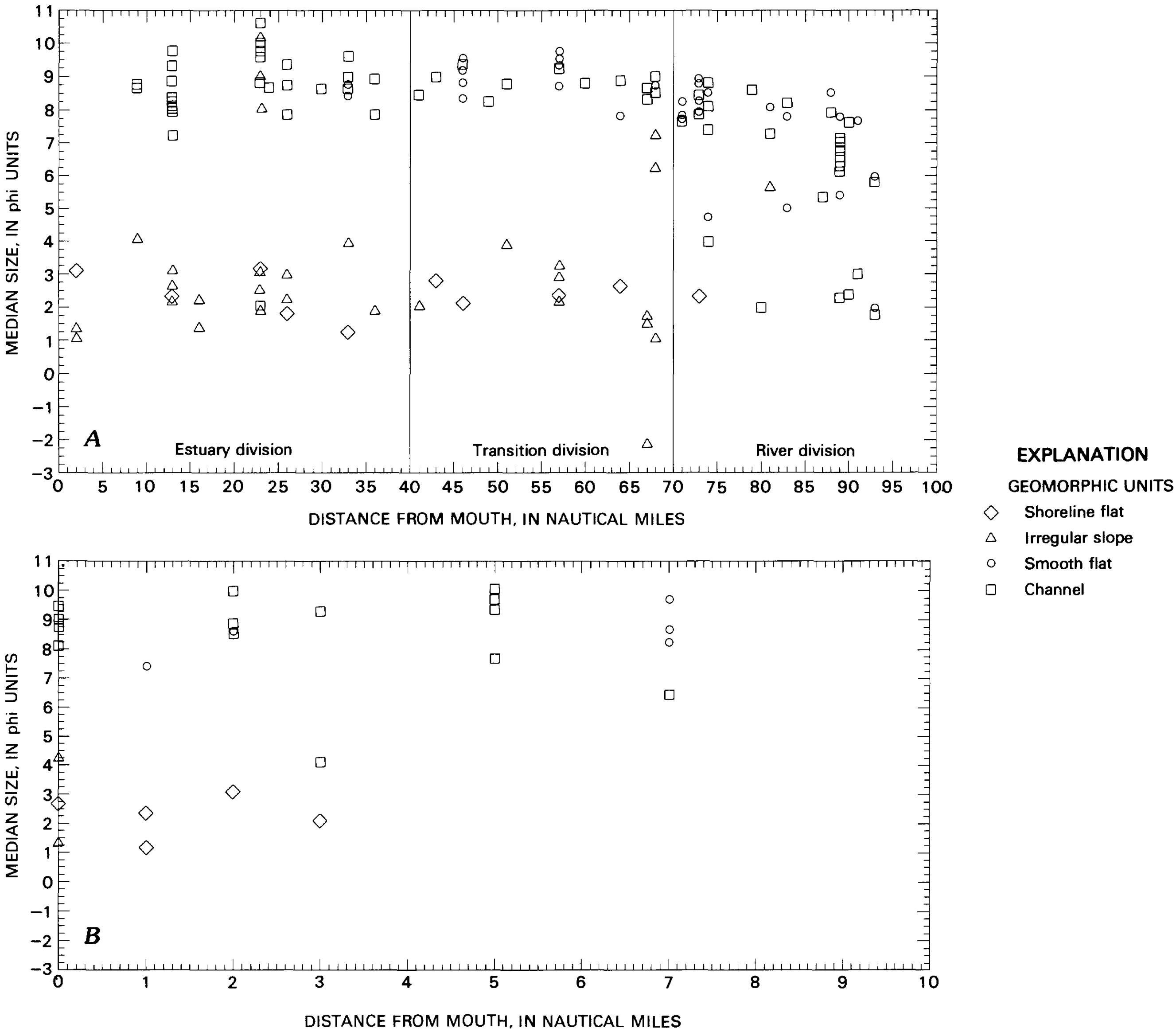


Figure 2. Variations in median particle size with nautical mile and geomorphic unit for samples from the *A*, Potomac mainstem. The reference lines at nautical mile 70 and nautical-mile 40 separate mainstem hydrologic divisions. *B*, Tributaries of the estuary division.

indicate very little difference between these parts of the tidal Potomac system (table 4). Mean values for skewness and for percentage of sand for all samples from hydrologic divisions of the Potomac mainstem show that sediments become more negatively skewed and contain more sand from the river division to the estuary division (table 4). These changes reflect the increase in water-surface area (table 2B) toward the Potomac mouth of shoreline flats and irregular slopes, geomorphic units generally characterized by coarse sediments (fig. 2*A*).

Sediments in geomorphic units show lateral trends in mean particle sizes. In the river hydrologic division, smooth flats and channels are widespread (table 2B), generally fine-grained geomorphic units from which numerous samples were collected (table 5, section A). These fine-grained units differ in the coarseness of sediments; smooth flats have higher mean values of the median size and lower mean values of sand than channels. Coarse sediments that are dominantly sand are found only in seven samples from the narrow shoreline flat that fringes the river division and in a few samples (table 3) from the channel between Mount Vernon (fig. 1) and the head of tides. The irregular slope in the river division is limited in extent, and the single sample from this unit is fine grained (table 3, sample number 76); an estimated 60 percent of the area of irregular slope in the river division is fine grained, and about 30 percent of the area of channel is coarse. In the transition division, smooth flats and channels are still dominant in areal extent, but both irregular slopes and shoreline flats are more common

Table 3. Particle-size data for near-surface samples of bottom sediments
[ND=Not determined]

Sample number	Hydrologic division	Nautical mile 1/	Nautical mile division 2/	Geomorphic unit	Water depth (meters)	Depth unit 3/	Particle-size data: Median	Sorting	Skewness	Percentage of: Gravel	Sand	Silt	Clay
1977 US BM-54 samples from the Potomac mainstem													
15	River	93	N5	Channel	3	D1	5.82	4.08	0.16	0	35	36	29
28	River	91	N5	Smooth flat	1	D0	7.65	2.83	.15	0	8	49	43
30	River	90	N5	Channel	8	D3	2.38	.75	.36	0	87	5	8
60	River	87	N5	Channel	8	D3	5.31	3.68	.13	0	39	36	25
77	River	80	N5	Channel	11	D5	1.96	5.38	.64	0	59	13	28
86	River	74	N4	Channel	13	D6	8.79	2.07	.06	0	2	34	64
125	Transition	68	N4	Channel	8	D3	8.97	2.58	.13	0	2	35	63
142	Transition	60	N3	Channel	8	D3	8.80	2.63	.33	0	2	39	59
162	Transition	57	N3	Channel	7	D3	9.35	2.45	.11	0	3	28	69
190	Transition	49	N3	Channel	11	D5	8.25	4.01	.44	0	3	46	51
225	Transition	43	N3	Shoreline flat	1	D0	2.82	3.14	.78	0	75	8	17
226	Transition	43	N3	Channel	13	D6	8.97	3.05	-.04	0	2	35	63
247	Estuary	33	N2	Channel	8	D3	9.61	1.85	-.01	0	1	18	81
274	Estuary	30	N2	Channel	8	D3	8.63	4.59	-.23	0	17	26	57
281	Estuary	24	N2	Channel	12	D5	8.67	5.87	-.09	0	32	14	54
301	Estuary	16	N1	Irregular slope	13	D6	1.37	.64	.41	0	93	2	5
302	Estuary	16	N1	Irregular slope	6	D2	2.22	1.46	-.21	6	92	2	0
321	Estuary	13	N1	Channel	25	D8	8.20	4.19	-.06	0	18	30	52
333	Estuary	9	N1	Channel	13	D6	8.76	4.23	.02	0	14	29	57
1977 US BM-54 samples from the Potomac tributaries													
17	4/	1	N1	Channel	7	D3	9.34	1.64	-.07	0	1	18	81
20	4/	1	N1	Channel	7	D3	8.93	2.32	-.09	0	4	29	67
251	4/	1	N1	Channel	8	D3	9.58	3.70	-.03	0	6	27	67
338	4/	0	N1	Irregular slope	10	D4	4.25	4.55	.72	0	49	21	30
1978 US BM-54 samples from the Potomac mainstem													
11	River	93	N5	Smooth flat	2	D0	5.93	2.61	.22	0	18	58	24
12	River	93	N5	Channel	6	D2	1.74	1.81	.19	0	85	7	8
13	River	93	N5	Smooth flat	2	D0	1.95	3.72	.78	0	75	8	17
27	River	91	N5	Channel	9	D4	3.00	1.35	.15	0	70	30	0
29	River	90	N5	Channel	9	D4	7.60	2.52	.11	0	3	55	42
38	River	89	N5	Channel	9	D4	7.00	3.54	.15	0	16	45	39
39	River	89	N5	Channel	8	D3	7.13	2.98	-.18	0	22	42	36
40	River	89	N5	Channel	8	D3	6.11	3.17	.26	0	20	52	28
41	River	89	N5	Channel	8	D3	6.30	3.01	.12	0	23	48	29
42	River	89	N5	Channel	8	D3	7.10	3.41	-.18	0	31	28	41
43	River	89	N5	Channel	8	D3	6.75	3.14	-.02	0	23	37	40
45	River	89	N5	Other	2	D0	3.88	4.84	.42	0	53	13	34
49	River	88	N5	Smooth flat	2	D0	8.50	2.50	-.21	0	4	36	60
50	River	88	N5	Channel	7	D3	7.90	1.98	.30	0	2	51	47
64	River	83	N5	Smooth flat	2	D0	5.00	3.08	.44	0	28	47	25
65	River	83	N5	Smooth flat	2	D0	7.78	2.85	.14	0	3	51	46
66	River	83	N5	Channel	21	D8	8.18	2.50	-.63	0	15	27	58
69	River	81	N5	Other	6	D2	8.47	1.94	-.21	0	2	36	62
74	River	81	N5	Smooth flat	4	D1	8.06	3.21	-.31	0	17	32	51
75	River	81	N5	Channel	8	D3	7.28	2.55	-.04	0	8	60	32
76	River	81	N5	Irregular slope	6	D2	5.62	2.72	.31	0	22	53	25
79	River	79	N4	Channel	12	D5	8.59	2.48	-.15	0	6	33	61
80	River	74	N4	Smooth flat	2	D0	4.73	1.39	.49	0	15	78	7
81	River	74	N4	Channel	4	D1	3.96	3.08	.63	0	51	23	26
82	River	74	N4	Smooth flat	4	D1	8.51	2.69	-.32	0	12	27	61

84	River	74	N4	Channel	8	D3	7.38	2.22	.08	0	9	54	37
85	River	74	N4	Channel	23	D8	8.10	2.32	-.11	0	4	44	52
87	River	73	N4	Smooth flat	3	D1	7.93	2.06	-.04	0	3	48	49
88	River	73	N4	Smooth flat	3	D1	8.29	1.78	-.18	0	2	40	58
103	River	71	N4	Smooth flat	2	D0	8.22	2.02	-.11	0	5	40	55
104	River	71	N4	Smooth flat	3	D1	7.83	2.26	.16	0	3	51	46
105	River	71	N4	Channel	7	D3	7.69	2.39	-.03	0	2	54	44
106	River	71	N4	Smooth flat	5	D2	7.72	2.25	.26	0	2	55	43
107	River	71	N4	Smooth flat	3	D1	8.28	2.15	.04	0	3	42	55
108	River	71	N4	Smooth flat	2	D0	8.24	1.81	-.25	0	6	37	57
126	Transition	67	N4	Other	9	D4	.16	8.97	.54	47	15	38	0
127	Transition	67	N4	Irregular slope	7	D3	1.73	4.11	.75	0	76	4	20
128	Transition	67	N4	Irregular slope	7	D3	1.51	3.79	.67	0	82	2	16
129	Transition	67	N4	Irregular slope	7	D3	-2.13	3.11	.46	61	28	2	9
130	Transition	67	N4	Channel	8	D3	8.32	2.11	.06	0	2	42	56
131	Transition	67	N4	Channel	8	D3	8.27	2.02	.08	0	1	44	55
132	Transition	67	N4	Channel	8	D3	8.65	1.81	-.07	0	1	34	65
133	Transition	67	N4	Channel	8	D3	8.58	1.67	-.10	0	1	34	65
134	Transition	67	N4	Channel	8	D3	8.33	1.85	-.12	0	1	41	58
136	Transition	64	N4	Shoreline flat	2	D0	2.63	.73	.20	0	95	5	0
137	Transition	64	N4	Irregular slope	3	D1	ND	ND	ND	0	61	13	26
138	Transition	64	N4	Smooth flat	4	D1	ND	ND	ND	0	6	45	49
139	Transition	64	N4	Smooth flat	5	D2	7.81	3.85	.61	0	6	52	42
140	Transition	64	N4	Channel	8	D3	8.88	2.19	-.13	0	12	20	68
143	Transition	57	N3	Shoreline flat	2	D0	2.34	.55	.46	0	93	7	0
144	Transition	57	N3	Smooth flat	3	D1	ND	ND	ND	0	1	43	56
145	Transition	57	N3	Smooth flat	6	D2	8.7	2.49	-.03	0	4	35	61
146	Transition	57	N3	Channel	8	D3	ND	ND	ND	0	2	45	53
147	Transition	57	N3	Smooth flat	5	D2	ND	ND	ND	0	4	44	52
148	Transition	57	N3	Shoreline flat	1	D0	ND	ND	ND	0	41	28	31
171	Transition	51	N3	Irregular slope	2	D0	3.88	5.09	.47	0	53	14	33
172	Transition	51	N3	Channel	14	D6	8.77	2.82	.19	0	2	39	59
173	Transition	51	N3	Irregular slope	3	D1	ND	ND	ND	0	11	33	56
174	Transition	51	N3	Channel	10	D4	ND	ND	ND	0	4	41	55
191	Transition	46	N3	Smooth flat	3	D1	8.82	2.74	-.16	0	10	26	64
192	Transition	46	N3	Channel	17	D8	8.80	1.52	-.10	0	5	23	72
193	Transition	46	N3	Shoreline flat	2	D0	ND	ND	ND	0	90	3	7
194	Transition	46	N3	Smooth flat	3	D1	8.36	3.26	-.12	0	8	37	55
196	Transition	46	N3	Shoreline flat	2	D0	ND	ND	ND	0	31	39	30
227	Transition	41	N3	Smooth flat	1	D0	ND	ND	ND	0	4	38	58
228	Transition	41	N3	Channel	11	D5	8.43	1.55	-.33	0	6	28	66
229	Transition	41	N3	Irregular slope	2	D0	2.04	3.21	-.75	34	64	2	0
230	Transition	41	N3	Other	11	D5	8.81	1.37	-.16	0	2	22	76
232	Estuary	36	N2	Channel	11	D5	8.94	1.36	-.14	0	5	16	79
233	Estuary	36	N2	Channel	9	D4	7.88	3.98	.10	0	13	38	49
234	Estuary	36	N2	Irregular slope	5	D2	1.91	.75	-.03	0	98	2	0
237	Estuary	33	N2	Shoreline flat	1	D0	1.29	.78	-.37	0	100	0	0
238	Estuary	33	N2	Smooth flat	3	D1	8.40	2.97	-.11	0	5	39	56
239	Estuary	33	N2	Smooth flat	6	D2	8.75	2.10	-.19	0	7	26	67
240	Estuary	33	N2	Irregular slope	7	D3	8.61	.74	-.09	0	4	14	82
241	Estuary	33	N2	Channel	9	D4	8.99	.96	.00	0	3	12	85
242	Estuary	33	N2	Channel	8	D3	8.68	2.74	-.40	0	8	26	66
243	Estuary	33	N2	Irregular slope	5	D2	3.98	5.43	.85	0	51	27	22
244	Estuary	33	N2	Shoreline flat	2	D0	1.22	1.47	.19	0	98	2	0
275	Estuary	26	N2	Shoreline flat	2	D0	1.84	.78	-.05	0	100	0	0
276	Estuary	26	N2	Channel	6	D2	8.76	3.09	-.26	0	10	27	63
277	Estuary	26	N2	Channel	8	D3	9.36	2.57	-.21	0	14	11	75
278	Estuary	26	N2	Channel	11	D5	7.87	5.10	.20	0	19	32	49
279	Estuary	26	N2	Irregular slope	7	D3	2.97	1.38	.34	0	81	5	14
280	Estuary	26	N2	Irregular slope	2	D0	2.26	.20	.00	0	100	0	0
282	Estuary	23	N2	Irregular slope	4	D1	3.18	.86	-.23	0	97	3	0
283	Estuary	23	N2	Irregular slope	6	D2	8.05	3.28	-.10	0	12	37	51
284	Estuary	23	N2	Channel	8	D3	10.62	6.03	-.44	0	25	12	63
285	Estuary	23	N2	Irregular slope	6	D2	1.93	.86	.05	0	100	0	0
286	Estuary	23	N2	Channel	8	D3	8.85	4.96	-.40	0	31	8	61
287	Estuary	23	N2	Irregular slope	8	D3	2.55	6.30	.77	0	72	5	23
288	Estuary	23	N2	Shoreline flat	2	D0	3.17	.94	-.32	0	99	1	0

Table 3. Particle-size data for near-surface samples of bottom sediments—Continued

Sample number	Hydrologic division	Nautical mile 1/	Nautical mile division 2/	Geomorphic unit	Water depth (meters)	Depth unit 3/	Particle-size data: Median	Sorting	Skewness	Percentage of: Gravel	Sand	Silt	Clay
1978 US BM-54 samples from the Potomac mainstem--continued													
303	Estuary	13	N1	Shoreline flat	2	D0	2.31	.43	-.03	0	100	0	0
304	Estuary	13	N1	Irregular slope	6	D2	2.68	3.67	.79	0	69	7	24
305	Estuary	13	N1	Channel	7	D3	8.38	3.04	-.29	0	13	30	57
306	Estuary	13	N1	Channel	11	D5	7.25	3.34	-.07	0	19	36	45
307	Estuary	13	N1	Channel	24	D8	7.97	3.97	-.11	0	19	31	50
308	Estuary	13	N1	Channel	24	D8	8.29	3.50	-.08	0	10	36	54
309	Estuary	13	N1	Channel	13	D6	7.17	3.12	-.04	0	17	42	41
310	Estuary	13	N1	Shoreline flat	2	D0	2.35	.55	.44	0	95	5	0
322	Estuary	9	N1	Irregular slope	4	D1	4.07	1.84	-.60	0	46	54	0
323	Estuary	9	N1	Channel	10	D4	8.65	2.85	-.17	0	12	27	61
334	Estuary	2	N1	Shoreline flat	2	D0	3.11	1.02	-.22	0	94	6	0
335	Estuary	2	N1	Irregular slope	10	D4	1.35	.49	.26	0	100	0	0
336	Estuary	2	N1	Channel	12	D5	8.20	2.91	-.03	0	9	38	53
337	Estuary	2	N1	Irregular slope	6	D2	1.06	.80	-.13	0	98	2	0
1978 US BM-54 samples from the Potomac tributaries													
16	4/	1	N1	Channel	7	D3	9.00	1.33	-.11	0	9	11	80
19	4/	1	N1	Channel	7	D3	2.72	1.43	-.02	0	82	18	0
26	4/	0	N1	Channel	3	D1	2.68	6.46	.75	0	67	16	17
51	4/	0	N1	Channel	2	D0	6.90	2.40	.10	0	10	59	31
52	4/	0	N1	Channel	3	D1	7.49	3.44	.57	0	2	69	29
53	4/	1	N1	Channel	5	D2	5.00	3.14	.28	0	40	36	24
62	4/	0	N1	Smooth flat	2	D0	7.22	2.94	.20	0	7	60	33
67	4/	0	N1	Smooth flat	2	D0	7.92	2.59	.18	0	6	45	49
68	4/	1	N1	Smooth flat	2	D0	6.75	2.48	.18	0	5	65	30
73	4/	0	N1	Smooth flat	4	D1	8.91	1.14	.05	0	2	18	80
91	4/	1	N1	Channel	3	D1	5.00	3.11	.43	0	31	45	24
92	4/	1	N1	Smooth flat	2	D0	2.67	1.76	.51	0	84	6	10
93	4/	2	N1	Channel	3	D1	1.29	.76	-.44	0	100	0	0
94	4/	3	N1	Channel	3	D1	.32	.58	.57	0	100	0	0
95	4/	3	N1	Channel	7	D3	.26	.39	.51	0	100	0	0
110	4/	1	N1	Channel	3	D1	7.66	5.06	-.11	0	28	26	46
111	4/	2	N1	Channel	7	D3	7.05	2.47	-.10	0	12	55	33
112	4/	2	N1	Smooth flat	1	D0	7.85	2.75	.18	0	7	47	46
149	4/	0	N1	Shoreline flat	2	D0	4.22	2.20	.94	0	5	77	18
150	4/	1	N1	Channel	2	D0	ND	ND	ND	0	4	36	60
151	4/	2	N1	Channel	2	D0	8.53	2.33	-.03	0	4	37	59
197	4/	1	N1	Channel	2	D0	ND	ND	ND	0	9	34	57
198	4/	2	N1	Channel	2	D0	ND	ND	ND	0	11	50	39
199	4/	2	N1	Channel	1	D0	3.82	3.37	.54	0	54	23	23
245	4/	0	N1	Channel	2	D0	8.12	4.38	.11	0	11	38	51
246	4/	1	N1	Smooth flat	2	D0	7.44	3.44	.15	0	10	46	44
252	4/	2	N1	Smooth flat	4	D1	8.60	3.06	-.14	0	6	35	59
253	4/	2	N1	Channel	11	D5	9.98	2.71	-.01	0	9	14	77
260	4/	5	N1	Channel	3	D1	9.37	2.43	-.03	0	9	19	72
261	4/	5	N1	Channel	2	D0	9.31	2.05	-.21	0	8	13	79
263	4/	7	N1	Smooth flat	1	D0	8.67	2.91	.14	0	9	33	58
264	4/	7	N1	Smooth flat	2	D0	8.24	4.23	-.24	0	31	16	53
289	4/	1	N1	Shoreline flat	2	D0	1.16	1.14	.07	0	98	2	0
290	4/	0	N1	Irregular slope	4	D1	1.34	1.28	.08	0	98	2	0
324	4/	0	N1	Channel	5	D2	8.73	3.81	.29	0	7	37	56
325	4/	1	N1	Shoreline flat	2	D0	2.35	2.40	-.68	25	70	0	5
326	4/	2	N1	Channel	3	D1	8.54	4.10	-.01	0	14	31	55
327	4/	0	N1	Channel	9	D4	8.04	2.84	.05	0	7	42	51

328	4/	2	N1	Channel	8	D3	8.31	3.63	-.14	0	15	31	54
329	4/	2	N1	Channel	8	D3	8.87	3.63	-.28	0	15	22	63
330	4/	2	N1	Shoreline flat	2	D0	3.09	.75	-.23	0	94	6	0
331	4/	5	N1	Channel	7	D3	7.68	3.14	.15	0	9	47	44
332	4/	7	N1	Channel	2	D0	6.46	4.40	.71	0	8	67	25
1978 benthos samples from the Potomac mainstem													
54	River	89	N5	Smooth flat	2	D0	7.78	3.44	-.07	0	15	39	46
55	River	89	N5	Smooth flat	2	D0	5.40	4.22	.39	3	38	29	30
56	River	89	N5	Channel	7	D3	2.28	.24	.00	0	99	1	0
57	River	89	N5	Channel	8	D3	6.54	3.96	.47	0	12	54	34
58	River	89	N5	Other	2	D0	4.19	2.27	.54	0	46	39	15
96	River	73	N4	Smooth flat	3	D1	8.80	1.88	.04	0	2	32	66
97	River	73	N4	Shoreline flat	2	D0	2.31	.42	.06	0	100	0	0
98	River	73	N4	Smooth flat	4	D1	8.46	1.98	.16	0	1	41	58
99	River	73	N4	Smooth flat	4	D1	8.90	1.97	.10	0	3	31	66
100	River	73	N4	Channel	8	D3	7.88	2.29	.14	0	2	50	48
101	River	73	N4	Channel	6	D2	8.43	2.34	.04	0	4	39	57
118	Transition	68	N4	Smooth flat	2	D0	8.77	2.62	.05	0	9	30	61
119	Transition	68	N4	Irregular slope	4	D1	6.22	4.60	.31	0	36	27	37
120	Transition	68	N4	Irregular slope	5	D2	7.22	8.07	-.41	30	8	19	43
121	Transition	68	N4	Irregular slope	4	D1	1.04	.85	-.11	0	99	1	0
122	Transition	68	N4	Channel	9	D4	8.53	1.32	-.09	0	2	31	67
123	Transition	68	N4	Channel	8	D3	8.79	2.39	-.08	0	1	35	64
124	Transition	68	N4	Channel	5	D2	8.84	2.48	-.06	0	5	31	64
153	Transition	57	N3	Irregular slope	3	D1	3.25	.86	.81	0	80	6	14
154	Transition	57	N3	Irregular slope	2	D0	2.90	.90	.04	0	94	6	0
155	Transition	57	N3	Smooth flat	4	D1	9.75	2.21	.03	0	5	17	78
156	Transition	57	N3	Irregular slope	4	D1	2.16	4.92	.74	0	67	1	32
157	Transition	57	N3	Smooth flat	5	D2	9.33	1.83	-.02	0	5	18	77
158	Transition	57	N3	Smooth flat	6	D2	9.53	3.03	.22	0	1	33	66
159	Transition	57	N3	Channel	6	D2	9.23	1.64	-.07	0	1	20	79
160	Transition	57	N3	Channel	6	D2	9.56	1.98	-.02	0	1	20	79
161	Transition	57	N3	Smooth flat	3	D1	9.37	2.10	-.08	0	3	21	76
200	Transition	46	N3	Shoreline flat	2	D0	2.12	.83	-.25	0	95	5	0
201	Transition	46	N3	Channel	20	D8	9.41	1.99	-.04	0	3	20	77
202	Transition	46	N3	Channel	7	D3	9.34	1.68	-.09	0	2	17	81
203	Transition	46	N3	Smooth flat	4	D1	9.19	1.20	.00	0	2	14	84
204	Transition	46	N3	Smooth flat	4	D1	9.52	2.06	-.05	0	2	20	78
205	Transition	46	N3	Smooth flat	3	D1	9.19	1.20	.00	0	1	15	84
206	Transition	46	N3	Smooth flat	4	D1	9.58	3.09	-.16	0	6	21	73
291	Estuary	23	N2	Irregular slope	5	D2	3.07	1.43	-.45	0	97	3	0
292	Estuary	23	N2	Irregular slope	6	D2	10.17	4.19	-.11	0	8	20	72
293	Estuary	23	N2	Irregular slope	8	D3	8.97	4.46	-.04	0	14	27	59
294	Estuary	23	N2	Channel	8	D3	9.99	2.91	-.03	0	2	22	76
295	Estuary	23	N2	Channel	8	D3	9.86	2.23	-.05	0	3	16	81
296	Estuary	23	N2	Channel	11	D5	2.04	6.23	.86	0	78	1	21
297	Estuary	23	N2	Channel	8	D3	9.78	4.52	-.07	0	13	22	65
298	Estuary	23	N2	Channel	9	D4	9.60	3.60	-.10	0	6	25	69
311	Estuary	13	N1	Irregular slope	5	D2	2.18	.84	-.23	0	100	0	0
312	Estuary	13	N1	Channel	9	D4	8.88	3.77	.02	0	8	33	59
313	Estuary	13	N1	Channel	10	D4	9.76	4.24	-.06	0	5	28	67
314	Estuary	13	N1	Channel	15	D7	9.74	2.93	-.08	0	6	20	74
315	Estuary	13	N1	Channel	16	D7	9.78	3.48	-.12	0	5	23	72
316	Estuary	13	N1	Channel	17	D8	8.85	5.77	-.11	0	27	17	56
317	Estuary	13	N1	Channel	18	D8	9.31	5.03	-.07	0	16	26	58
318	Estuary	13	N1	Channel	15	D7	8.08	3.81	-.19	0	24	25	51
319	Estuary	13	N1	Irregular slope	5	D2	3.13	.82	-.33	0	94	6	0
320	Estuary	13	N1	Irregular slope	5	D2	2.28	.88	-.21	0	97	3	0
1978 benthos samples from the Potomac tributaries													
59	4/	0	N1	Channel	4	D1	7.56	3.16	.41	0	3	51	46
152	4/	0	N1	Channel	2	D0	8.83	2.91	-.07	0	5	33	62
207	4/	0	N1	Channel	3	D1	9.49	2.58	-.10	0	3	23	74
208	4/	0	N1	Channel	3	D1	9.47	2.39	.00	0	4	23	73
209	4/	1	N1	Channel	3	D1	9.50	2.04	.00	0	2	21	77
248	4/	0	N1	Shoreline flat	3	D1	2.69	.72	.16	0	98	2	0

Table 3. Particle-size data for near-surface samples of bottom sediments—Continued

Sample number	Hydrologic division	Nautical mile 1/	Nautical mile division 2/	Geomorphic unit	Water depth (meters)	Depth unit 3/	Particle-size data: Median	Sorting	Skewness	Percentage of: Gravel	Sand	Silt	Clay
1978 benthos samples from the Potomac tributaries--continued													
249	4/	0	N1	Channel	6	D2	9.43	3.98	-.07	0	8	27	65
250	4/	0	N1	Channel	6	D2	8.98	4.81	.04	0	12	31	57
254	4/	3	N1	Channel	3	D1	4.13	2.49	.61	0	46	38	16
255	4/	3	N1	Channel	7	D3	9.29	2.62	-.06	0	4	26	70
256	4/	3	N1	Shoreline flat	3	D1	2.11	.66	.92	0	94	6	0
257	4/	5	N1	Channel	3	D1	9.68	3.98	-.10	0	9	23	68
258	4/	5	N1	Channel	4	D1	10.07	2.81	-.04	0	2	20	78
259	4/	5	N1	Channel	4	D1	10.32	3.87	-.07	0	8	18	74
262	4/	7	N1	Smooth flat	2	D0	9.70	4.11	.00	0	7	27	66
299	4/	0	N1	Irregular slope	6	D2	5.80	4.88	.47	0	32	27	41
300	4/	1	N1	Irregular slope	6	D2	3.94	4.99	.84	0	54	21	25
1981 US BM-54 samples from the Potomac mainstem													
1	River	97	N5	Channel	7	D3	ND	ND	ND	0	7	35	58
2	River	96	N5	Channel	7	D3	ND	ND	ND	0	14	56	30
5	River	95	N5	Channel	9	D4	ND	ND	ND	0	4	62	34
7	River	95	N5	Channel	7	D3	ND	ND	ND	0	9	62	29
9	River	94	N5	Channel	6	D2	ND	ND	ND	0	5	67	28
14	River	93	N5	Smooth flat	3	D1	ND	ND	ND	0	77	14	9
1981 US BM-54 samples from the Potomac tributaries													
18	4/	1	N1	Channel	7	D3	ND	ND	ND	0	2	60	38
21	4/	1	N1	Channel	7	D3	ND	ND	ND	0	2	25	73
22	4/	2	N1	Channel	6	D2	ND	ND	ND	0	1	41	58
25	4/	3	N1	Channel	2	D0	ND	ND	ND	0	60	29	11
1978 to 1981 shoreline samples from the Potomac mainstem													
32	River	89	N5	Shoreline flat	1	D0	ND	ND	ND	0	15	67	18
47	River	89	N5	Shoreline flat	1	DD	ND	ND	ND	0	42	58	0
61	River	87	N5	Shoreline flat	1	D0	ND	ND	ND	0	94	4	2
70	River	82	N5	Shoreline flat	1	D0	ND	ND	ND	0	60	40	0
71	River	82	N5	Shoreline flat	1	D0	ND	ND	ND	0	96	4	0
72	River	82	N5	Shoreline flat	1	D0	ND	ND	ND	0	81	14	5
135	Transition	67	N4	Shoreline flat	1	D0	ND	ND	ND	0	93	2	5
141	Transition	63	N4	Shoreline flat	1	D0	ND	ND	ND	0	84	11	5
163	Transition	52	N3	Shoreline flat	1	D0	ND	ND	ND	0	81	13	6
164	Transition	52	N3	Shoreline flat	1	D0	ND	ND	ND	0	89	9	2
165	Transition	52	N3	Shoreline flat	1	D0	ND	ND	ND	0	74	3	23
166	Transition	51	N3	Shoreline flat	1	D0	ND	ND	ND	1	73	14	12
167	Transition	51	N3	Shoreline flat	1	D0	ND	ND	ND	0	89	5	6
168	Transition	51	N3	Shoreline flat	1	D0	ND	ND	ND	0	74	18	8
169	Transition	51	N3	Shoreline flat	1	D0	ND	ND	ND	0	59	26	15
170	Transition	51	N3	Shoreline flat	1	D0	ND	ND	ND	0	40	35	25
175	Transition	50	N3	Shoreline flat	1	D0	ND	ND	ND	0	63	15	22
188	Transition	49	N3	Shoreline flat	1	D0	ND	ND	ND	0	95	0	5
189	Transition	49	N3	Shoreline flat	1	D0	ND	ND	ND	0	93	4	3
210	Transition	48	N3	Shoreline flat	1	D0	ND	ND	ND	0	88	10	2
211	Transition	48	N3	Shoreline flat	1	D0	ND	ND	ND	0	89	6	5
212	Transition	48	N3	Shoreline flat	1	D0	ND	ND	ND	0	93	2	5
213	Transition	47	N3	Shoreline flat	1	D0	ND	ND	ND	0	95	1	4
214	Transition	46	N3	Shoreline flat	1	D0	ND	ND	ND	0	92	2	6
215	Transition	45	N3	Shoreline flat	1	D0	ND	ND	ND	0	83	5	12
224	Transition	44	N3	Shoreline flat	1	D0	ND	ND	ND	0	75	15	10

235	Estuary	35	N2	Shoreline flat	1	D0	ND	ND	ND	0	94	4	2
236	Estuary	35	N2	Shoreline flat	1	D0	ND	ND	ND	0	74	16	10
1978 to 1981 shoreline samples from the Potomac tributaries													
102	4/	1	N1	Shoreline flat	1	D0	ND	ND	ND	1	65	23	11
113	4/	1	N1	Shoreline flat	1	D0	ND	ND	ND	0	98	2	0
114	4/	2	N1	Shoreline flat	1	D0	ND	ND	ND	0	86	9	5
115	4/	2	N1	Shoreline flat	1	D0	ND	ND	ND	0	11	89	0
116	4/	3	N1	Shoreline flat	1	D0	ND	ND	ND	0	92	8	0
117	4/	4	N1	Shoreline flat	1	D0	ND	ND	ND	14	73	7	6
176	4/	0	N1	Shoreline flat	1	D0	ND	ND	ND	0	10	61	29
177	4/	1	N1	Shoreline flat	1	D0	ND	ND	ND	0	70	20	10
178	4/	1	N1	Shoreline flat	1	D0	ND	ND	ND	0	19	53	28
179	4/	2	N1	Shoreline flat	1	D0	ND	ND	ND	0	92	3	5
180	4/	2	N1	Shoreline flat	1	D0	ND	ND	ND	0	21	49	30
181	4/	2	N1	Shoreline flat	1	D0	ND	ND	ND	0	81	12	7
182	4/	3	N1	Shoreline flat	1	D0	ND	ND	ND	0	19	42	39
183	4/	3	N1	Shoreline flat	1	D0	ND	ND	ND	0	38	62	0
184	4/	2	N1	Shoreline flat	1	D0	ND	ND	ND	0	27	42	31
185	4/	3	N1	Shoreline flat	1	D0	ND	ND	ND	0	81	14	5
186	4/	4	N1	Shoreline flat	1	D0	ND	ND	ND	0	16	52	32
187	4/	4	N1	Shoreline flat	1	D0	ND	ND	ND	0	49	35	16
216	4/	1	N1	Shoreline flat	1	D0	ND	ND	ND	0	64	36	0
217	4/	1	N1	Shoreline flat	1	D0	ND	ND	ND	0	74	14	12
218	4/	1	N1	Shoreline flat	1	D0	ND	ND	ND	0	95	2	3
219	4/	1	N1	Shoreline flat	1	D0	ND	ND	ND	1	90	3	6
220	4/	1	N1	Shoreline flat	1	D0	ND	ND	ND	0	55	37	8
221	4/	2	N1	Shoreline flat	1	D0	ND	ND	ND	0	78	12	10
222	4/	2	N1	Shoreline flat	1	D0	ND	ND	ND	0	93	1	6
223	4/	3	N1	Shoreline flat	1	D0	ND	ND	ND	0	20	54	26
265	4/	8	N1	Shoreline flat	1	D0	ND	ND	ND	0	62	21	17
266	4/	8	N1	Shoreline flat	1	D0	ND	ND	ND	0	45	39	16
267	4/	8	N1	Shoreline flat	1	D0	ND	ND	ND	0	51	28	21
268	4/	8	N1	Shoreline flat	1	D0	ND	ND	ND	0	39	32	29
269	4/	8	N1	Shoreline flat	1	D0	ND	ND	ND	0	78	7	15
270	4/	8	N1	Shoreline flat	1	D0	ND	ND	ND	0	75	17	8
271	4/	8	N1	Shoreline flat	1	D0	ND	ND	ND	0	79	15	6
272	4/	8	N1	Shoreline flat	1	D0	ND	ND	ND	0	67	25	8
273	4/	8	N1	Shoreline flat	1	D0	ND	ND	ND	0	83	11	6

1/ Sample location in nautical miles from the Potomac River mouth or from the tributary mouth.
2/ Nautical mile (nmi) division; N1 = 0 to 20 nmi; N2 = >20 to 40 nmi; N3 = >40 to 60 nmi; N4 = >60 to 80 nmi; N5 = >80 to 100 nmi.
3/ Depth unit; D0 = 0 to 2 m (meter); D1 = >2 to 4 m; D2 = >4 to 6 m; D3 = >6 to 8 m; D4 = >8 to 10 m; D5 = >10 to 12m; D6 = > 12 to 14 m; D7 = >14 to 16 m; D8 = >16 m.
4/ Not identified in Potomac tributaries.

Table 4. Mean and standard deviation of selected particle-size measures for samples from various parts of the tidal Potomac system.

[Std, standard deviation. See table 1 for numbers of analyses]

Particle-size measure	Tidal Potomac system		Potomac mainstem		Potomac tributaries		Potomac hydrologic division					
							River		Transition		Estuary	
	Mean	Std	Mean	Std	Mean	Std	Mean	Std	Mean	Std	Mean	Std
Median	6.60	2.95	6.55	2.96	6.73	2.92	6.53	2.15	6.90	3.25	6.28	3.29
Sorting	2.70	1.44	2.66	1.50	2.85	1.29	2.58	.98	2.60	1.62	2.78	1.74
Skewness	.07	.31	.05	.30	.14	.34	.11	.27	.09	.33	-.04	.30
Percentage of clay	36	26.8	38	26.9	33	26.4	35	20.0	39	28.7	38	30.4
Percentage of sand	37	36.4	36	37.1	38	34.9	27	30.1	37	38.5	44	39.9

Table 5. Summary statistics for selected particle-size measures in samples from geomorphic units

[ND=No data]

Geomorphic unit	Summary statistic	Particle-size measure			
		Median	Sorting	Skewness	Percentage of sand
	A. Samples from the Potomac River division				
Channel	Number of samples	26	26	26	31
	Mean	6.20	2.66	.10	25
	Range	7.05	5.14	1.27	97
	Standard deviation	2.23	1.06	.26	28
Smooth flat	Number of samples	21	21	21	22
	Mean	7.33	2.51	.09	15
	Range	6.95	2.83	1.10	76
	Standard deviation	1.74	.72	.28	22
Irregular slope	Number of samples	1	1	1	1
	Mean	5.62	2.72	.31	22
	Range	ND	ND	ND	ND
	Standard deviation	ND	ND	ND	ND
Shoreline flat	Number of samples	1	1	1	7
	Mean	2.31	.42	.06	70
	Range	ND	ND	ND	85
	Standard deviation	ND	ND	ND	32
	B. Samples from the Potomac transition division				
Channel	Number of samples	21	21	21	23
	Mean	8.81	2.18	.00	3
	Range	1.31	2.69	.77	11
	Standard deviation	.39	.62	.17	2
Smooth flat	Number of samples	13	13	13	17
	Mean	9.07	2.44	.02	5
	Range	1.94	2.65	.77	9
	Standard deviation	.56	.78	.20	3
Irregular slope	Number of samples	11	11	11	13
	Mean	2.71	3.59	.27	58
	Range	9.35	7.22	1.56	91
	Standard deviation	2.52	2.19	.52	30
Shoreline flat	Number of samples	4	4	4	27
	Mean	2.48	1.31	.30	79
	Range	.70	2.59	1.03	64
	Standard deviation	.31	1.22	.44	18

(table 2B). Coarse sandy sediments in the transition division are associated with both shoreline flats and irregular slopes; an estimated 40 percent of the area of irregular slope in the transition division has fine-grained surface sediments (table 3). Channels and smooth flats are fine grained and not appreciably different in mean particle-size measures (table 5, section B). In the estuary division, smooth flats are less common than in the river and the transition divisions, and irregular slopes and channels are dominant (table 2B). Summary particle-size measures among geomorphic units in the estuary division are basically the same as among units in the transition division; that is, the shoreline flats and irregular slopes are coarse whereas the smooth flats and channels are fine (table 5, section C). An estimated 40 percent of the area of irregular slope in the upper and middle part of the estuary division has fine-grained surface sediments. Shoreline flats in the estuary division are coarser and better sorted than the irregular slopes, but the fine-grained smooth flats and channels are basically similar in mean particle size.

Geomorphic units within Potomac tributaries generally show the same mean trends in particle size as geomorphic units in the nearby Potomac mainstem (table 5, section D). Sediments of the channel and the smooth flat are usually fine grained, and sediments of the irregular slope and the shoreline flat are coarse grained (fig. 2*B*). Longitudinal trends for samples from estuary-division tributaries are not evident (fig. 2*B*), but samples from some river-division tributaries coarsen toward the local head-of-tides (table 3).

Table 5. Summary statistics for selected particle-size measures in samples from geomorphic units—Continued

Geomorphic unit	Summary statistic	Particle-size measure			
		Median	Sorting	Skewness	Percentage of sand
	C. Samples from the Potomac estuary division				
Channel	Number of samples	33	33	33	33
	Mean	8.65	3.72	-.08	15
	Range	8.58	5.27	1.30	77
	Standard deviation	1.43	1.29	.22	14
Smooth flat	Number of samples	2	2	2	2
	Mean	8.57	2.53	-.15	6
	Range	.35	.87	.08	2
	Standard deviation	.25	.62	.06	1
Irregular slope	Number of samples	21	21	21	21
	Mean	3.71	1.97	.03	73
	Range	9.11	6.10	1.45	96
	Standard deviation	2.74	1.80	.40	35
Shoreline flat	Number of samples	7	7	7	9
	Mean	2.18	.85	-.05	95
	Range	1.95	1.04	.81	26
	Standard deviation	.79	.34	.29	8
	D. Samples from the Potomac tributaries				
Channel	Number of samples	40	40	40	47
	Mean	7.39	2.97	.10	20
	Range	10.06	6.07	1.19	99
	Standard deviation	2.78	1.23	.29	28
Smooth flat	Number of samples	11	11	11	11
	Mean	7.63	2.86	.10	16
	Range	7.03	3.09	.75	82
	Standard deviation	1.84	.91	.20	24
Irregular slope	Number of samples	4	4	4	4
	Mean	3.83	3.92	.53	58
	Range	4.46	3.71	.76	66
	Standard deviation	1.85	1.77	.34	28
Shoreline flat	Number of samples	6	6	6	41
	Mean	2.60	1.31	.20	62
	Range	3.06	1.74	1.62	93
	Standard deviation	1.02	.79	.64	29

A different perspective of the particle-size characteristics of surface sediments in the tidal Potomac is based on the larger data base (table 1) provided by determinations of gravel, sand, silt, and clay percentages and on the use of Shepard's (1954) sand-silt-clay classes. The boundaries for these classes and the positions within the classes of all samples except 11 samples with gravel-size clasts are shown in figure 3. The sediments show diverse sand-silt-clay relations, but two classes contain most samples (table 6). Thirty-two percent of all samples from the tidal Potomac are in the dominant single class, silty clay, and 52 percent of the samples are in the 4 classes containing less than 20 percent sand. The sand class includes 24 percent of all samples and is the second most common single class. Two greatly different size populations, a coarse (sand) group and a fine (silty clay) group, are present, and contain 56 percent of all tidal Potomac samples. Only 28 percent of the samples come from five classes intermediate between the coarse and fine groups.

No consistent differences between Potomac mainstem and tributary sediments are noted (table 6), which is consistent with the lack of an apparent difference based on means of particle size measures (table 4). Among mainstem hydrologic divisions, the percentage of samples in the sand class in the transition division and in the estuary division is about two times greater than the percentage in the river division. Many samples in the sand-silt-clay class and most samples in the clayey silt class are in the river division; in contrast, the river division does not have any of the clay-class samples that are common in the transition and the estuary divisions (table 6). These differences in relative abundances of size classes indicate that different sources of sediments or different sedimentation conditions exist among the hydrologic divisions. An analysis of data

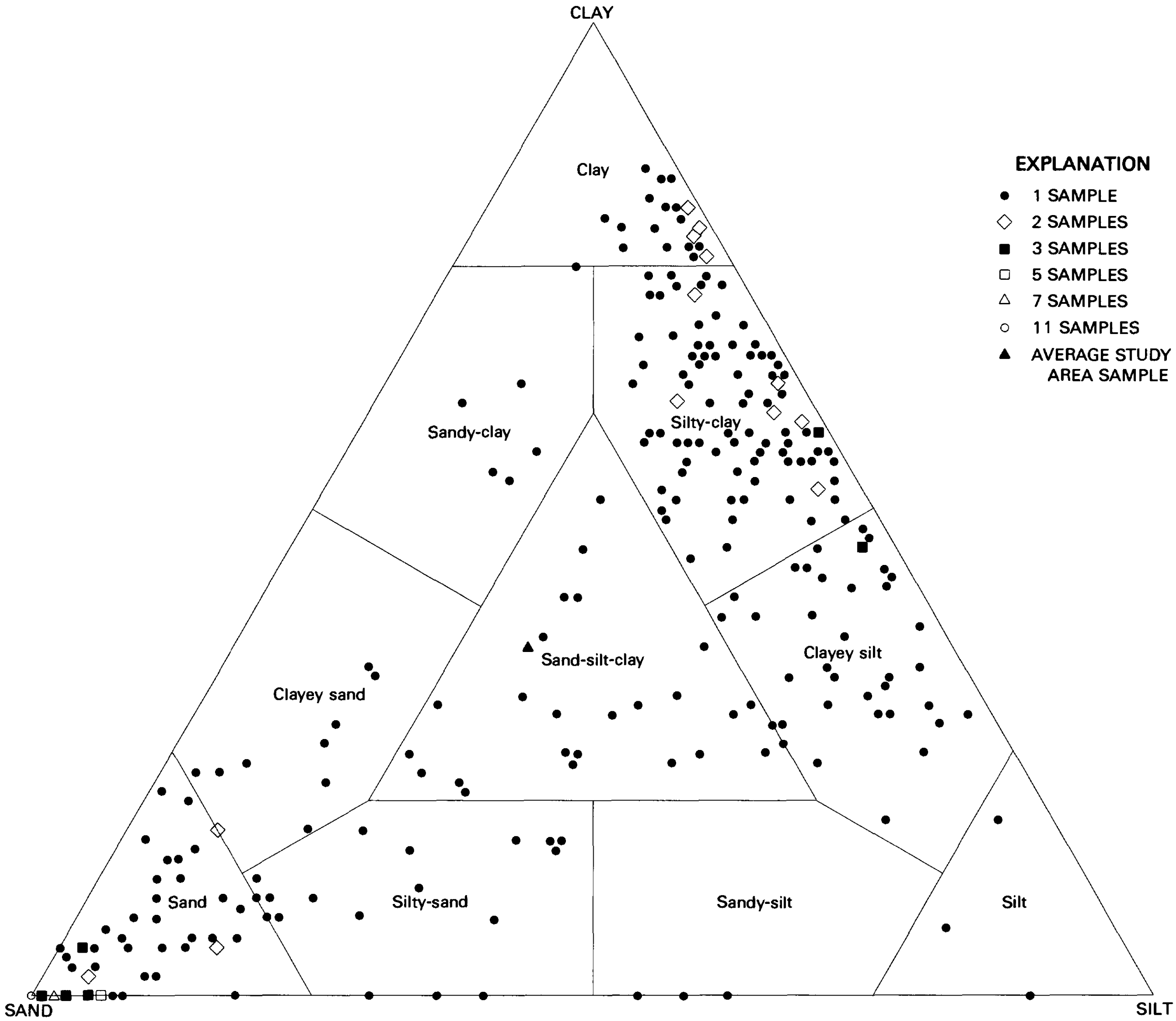


Figure 3. Diagram showing sand-silt-clay relations and Shepard's (1954) texture size classes for tidal Potomac sediments.

Table 6. Number and percentage of samples in Shepard's (1954) size classes

[No, number; Pct, percentage. Geomorphic units are: 0=shoreline flat; 1=smooth flat; 2=irregular slope; 3=channel; 4=other]

Size class	Tidal Potomac system		Potomac mainstem		Potomac tributaries		Potomac mainstem hydrologic division: River		Transition		Estuary		Potomac mainstem geomorphic unit: 0		1		2		3		4	
	No	Pct	No	Pct	No	Pct	No	Pct	No	Pct	No	Pct	No	Pct	No	Pct	No	Pct	No	Pct	No	Pct
Gravel 1/	11	4	7	3	4	4	1	2	5	6	1	2	1	2	1	2	4	11	0	0	1	20
Sand	77	24	54	26	23	22	9	14	24	30	21	32	31	73	2	5	12	49	4	5	0	0
Silty sand	16	5	6	3	10	10	2	5	2	2	1	2	4	9	0	0	0	0	1	1	1	20
Clayey sand	10	3	9	4	1	1	2	3	5	6	2	3	2	5	0	0	5	14	1	1	1	20
Sandy silt	3	1	2	1	1	1	1	2	0	0	1	2	1	2	0	0	1	3	0	0	0	0
Sandy clay	5	2	4	2	1	1	0	0	0	0	4	6	0	0	0	0	0	0	4	5	0	0
Sand-silt-clay	28	9	16	2	12	12	10	16	4	5	2	3	3	7	1	2	3	9	9	0	0	0
Silt	3	1	1	0	2	2	1	2	0	0	0	0	0	0	1	2	0	0	0	0	0	0
Clayey silt	35	11	19	9	16	16	17	26	1	1	1	2	1	2	6	15	0	0	12	14	0	0
Silty clay	101	32	75	35	26	24	20	30	30	37	25	37	0	0	24	59	4	11	46	53	1	20
Clay	25	8	18	9	7	7	0	0	11	13	7	11	0	0	6	15	1	3	10	11	1	20

1/ Gravel includes all samples with any sediment size in excess of 2,000 micrometers.

for geomorphic units without regard to hydrologic division shows that units 0 and 2 contain most samples from the sand class and units 1 and 3 contain most samples from classes dominated by clay- and silt-size particles (table 6). Differences among geomorphic units also indicate changes in sediment sources or in sedimentation conditions.

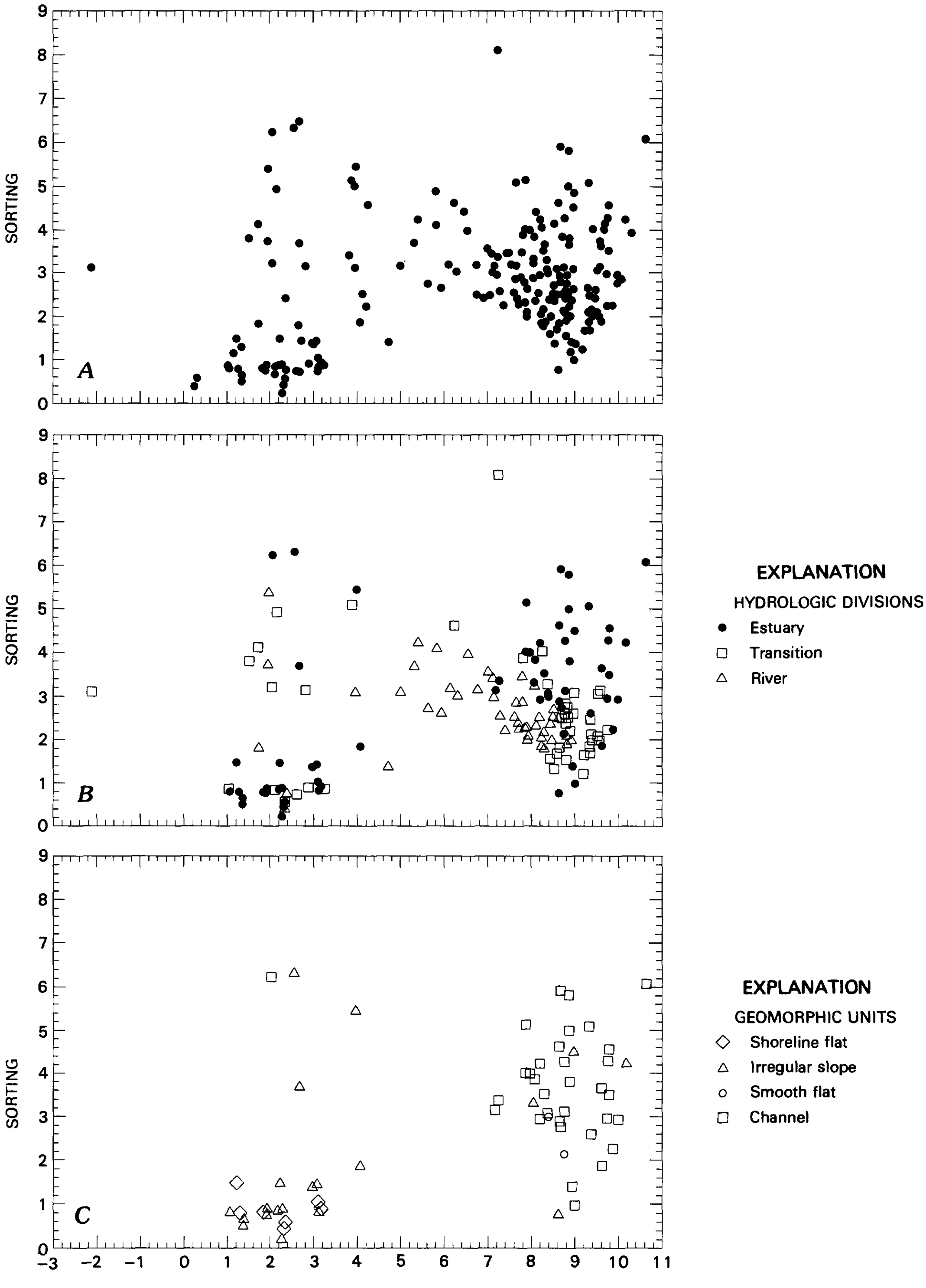
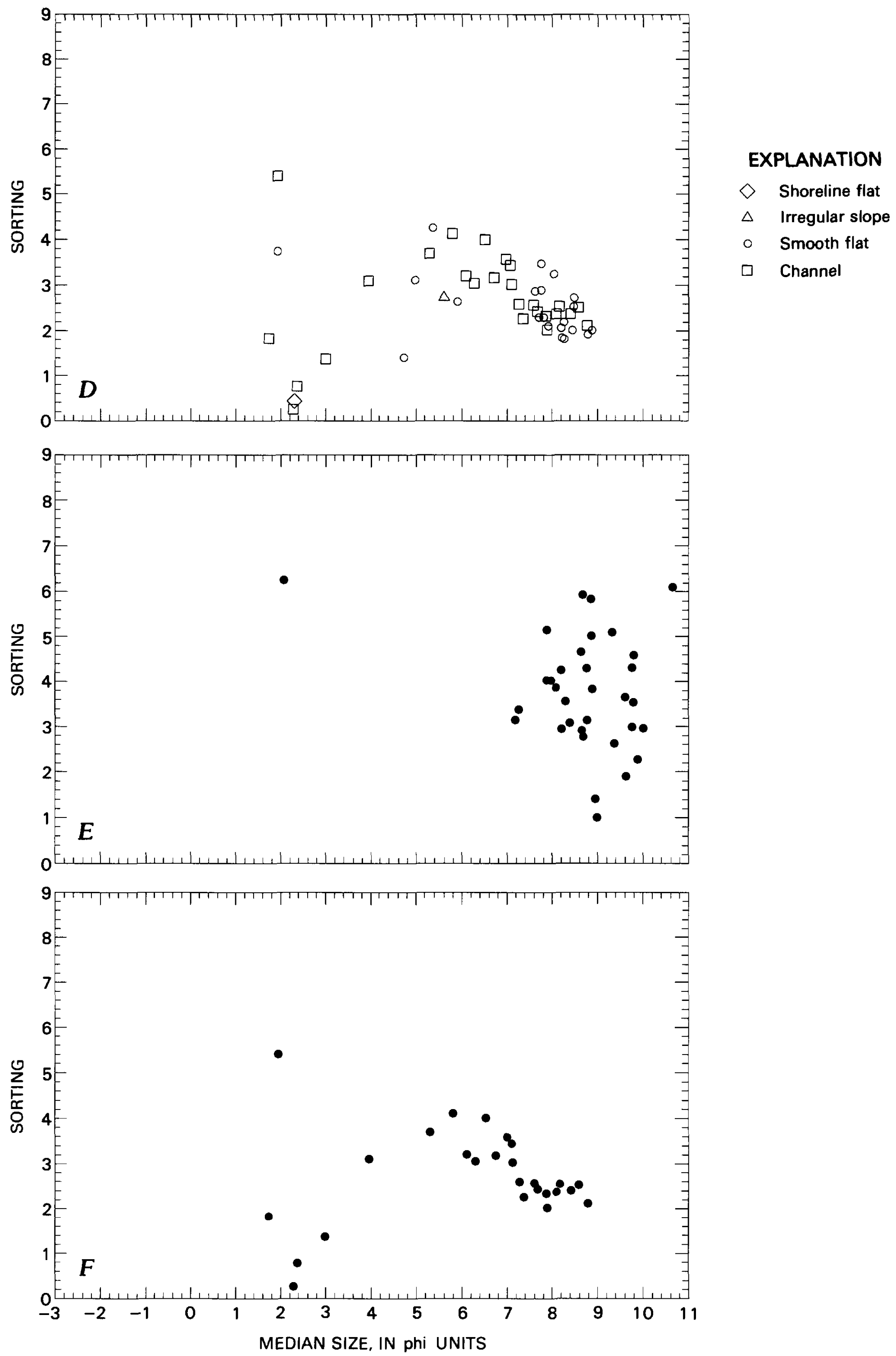


Figure 4 (above and facing page). Sorting versus median particle size for samples from the *A*, Tidal Potomac system; *B*, Potomac mainstem identified by hydrologic division; *C*, Potomac estuary division identified by geomorphic unit; *D*, Potomac river division identified by geomorphic unit; *E*, Channel of the Potomac estuary division; and *F*, Channel of the Potomac river division.

General characteristics of sediments and relations among sediment types and sample locations frequently are shown by plotting selected particle-size measures for individual samples against one another. These plots often reveal differences in particle-size distributions that relate to different sediment sources or sedimentation conditions. A series of plots of sorting versus median particle size for several groups of tidal Potomac samples are shown in figures 4*A*–4*F*. Two general clusters of samples appear in the plot showing all tidal Potomac data (fig. 4*A*); one cluster consists of fine-grained (median about 9) and poorly sorted (sorting about 3) sediments, and the second cluster is coarse (median about 2) and well sorted (sorting about 1) sediments. Scattered samples with poor



sorting and intermediate to coarse median sizes generally lie outside the boundaries of the major clusters.

Both the fine and the coarse clusters are a mix of samples from all three Potomac mainstem hydrologic divisions (fig. 4*B*). Within the fine cluster, samples from the estuary division generally are more poorly sorted than samples from the river or the transition divisions. Samples from the river and transition divisions comprise the majority of samples outside the cluster boundaries. Samples from the river division that are outside the cluster boundaries tend to form a secondary group with comparable sorting but coarser median sizes than most fine-grained samples from the transition or the estuary divisions (fig. 4*B*).

Identification of geomorphic units within hydrologic divisions shows additional particle-size characteristics of Potomac mainstem sediments. The range of characteristics is illustrated by plots for the estuary and the river divisions. Within the estuary division, the fine cluster consists dominantly of samples from the channel, whereas the coarse cluster is a mix of samples from the shoreline flat and the irregular slope (fig. 4*C*). Very few samples from the estuary division are outside of the cluster boundaries, and those that are mostly are poorly sorted, coarse-grained samples from the irregular slope. For the river division, samples from the channel and the smooth flat form the fine cluster, and samples from the channel are the dominant component in the poorly defined coarse cluster (fig. 4*D*). A mix of samples from the channel and the smooth flat comprise the numerous samples from the river division that extend beyond cluster boundaries and that indicate considerable variability of the river sediments and sedimentation environments. The limited extent (table 2B) of the shoreline flat and the irregular slope in the river division resulted in very few samples from these geomorphic units (table 1). In general, most samples from the shoreline flat would fall into the coarse cluster, and most samples from the irregular slope would be outside cluster boundaries.

The general nature of sediments within a geomorphic unit of a hydrologic division is indicated by sorting versus median plots for samples from the channel unit in the estuary division (fig. 4*E*) and in the river division (fig. 4*F*). Samples from the channel in the estuary division are characterized by a tight cluster with a narrow range of median diameters and a wide range in sorting. In contrast, samples from the channel in the river division show more scatter and have a wide range in median and a narrow range in sorting. Only 1 out of 33 samples from the channel in the estuary division was coarse grained (small median phi value), whereas 5 out of 31 samples from the channel in the river division were coarse grained.

Longitudinal trends in the Potomac mainstem are indicated by plots of mean values for selected particle-size measures versus location. The mean and standard deviation of the median size for all samples from the channel in each hydrologic division are plotted in figure 5*A*. This plot shows that coarser and more variable sediments occur in channels of the two end member divisions. A plot (fig. 5*B*) of the mean of the median size for all mainstem samples classified by geomorphic unit and by nmi division provides additional detail relative to trends in mean particle size in all geomorphic units in the Potomac mainstem; both channels (fig. 5*B*) and smooth flats become progressively finer (higher median) toward nmi 50, the mid-point for all samples from the 40 to 60 nmi division, from both landward (pronounced fining) and seaward (subtle change) directions. The 40–60 nmi division essentially includes the lower two-thirds of the transition division for which the previous plot (fig. 5*A*) has indicated that channel sediments are uniformly fine. Trends in mean values of median size for samples from the shoreline flat and the irregular slope (fig. 5*B*) are less obvious in part because of limited numbers of samples (see table 1). The available data indicate that the shoreline flats are finer in the upper river division than in the other nmi divisions but are uniformly coarse seaward of nmi 70 (fig. 5*B*); the irregular slopes, although typically coarse, are finer in the upper estuary (from nmi 20–40) and possibly in the upper river (nmi 80–100).

Lateral trends in the texture of tidal Potomac sediments are illustrated by relations between geomorphic units and particle-size measures or between water depths and particle size measures. The general nature of relations between geomorphic unit and median particle size is shown in figures 2*A* and 2*B* and is discussed briefly on pages 15, 17 and 25. The relation between geomorphic unit and the mean value of the median particle size in Potomac mainstem samples classified by nmi division is shown in figure 5*B*; in general, sediments associated with the shoreline and with shallow water near shore (shoreline flat) or with moderate-depth slopes that have considerable local relief (irregular slope) have coarser means of the median particle size than do sediments from deep water (channel) or from waters of intermediate depths (smooth flat).

Relations between water depth and median particle size of the sediments are generally poor for most major groups of samples from the tidal Potomac system. Samples from sediments in individual cross sections in the estuary division, however, frequently indicate that median particle size decreases with increasing water depth (fig. 6), but only rarely are similar relations observed in the transition division, and no similar relations are noted for samples from cross sections in the river division. Even in cross sections from the estuary division, the relation varies among the cross sections and is controlled by a cluster of coarse sediments from between the zero and eight m depths and a cluster of fine sediments from the

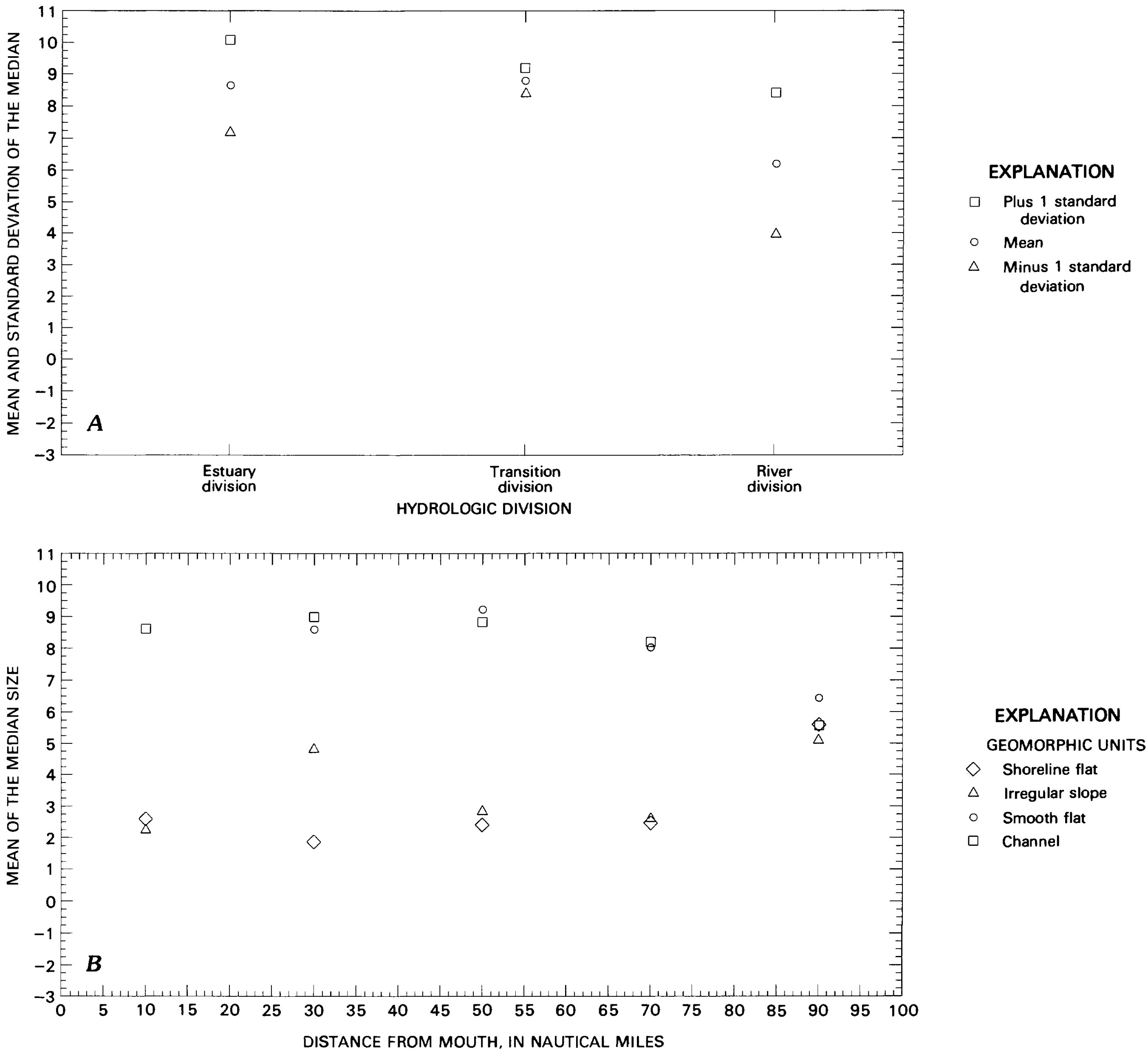


Figure 5. Variations in median particle size: *A*, Mean and standard deviation for samples from the channel unit in each hydrologic division; and *B*, Mean for samples from each geomorphic unit in each nautical-mile division.

eight to 17 m depths. The absence of samples from the estuary division with median diameters intermediate between those of the fine and coarse groups may indicate that an abrupt boundary separates major textural groups. At extreme depths in all divisions, sediments are fine grained but not appreciably finer than sediments from intermediate depths (fig. 6).

Statistical tests of the significance of many particle-size trends and relations described in the previous section are based on the TTEST procedure (Statistical Analysis System (SAS), 1982B, p. 217-221), the GLM (General Linear Model) procedure (SAS, 1982B, p. 140-199), or the REG (Regression) procedure (SAS, 1982B, p. 39-83) of the SAS software package. The TTEST computes the probability of greater absolute values for Students t (Freund and Littell, 1981, p. 1-3; Li, 1964, p. 100-107) under assumptions of equal and unequal variances; a high probability indicates that two means are not significantly different. The GLM procedure, which was used most often, uses regression or analysis of variance to test for the significance of relations for both balanced and unbalanced data. For the comparison of individual means (SAS, 1982B, p. 169-175), the TUKEY option (Kramer, 1956) was used with the GLM procedure to tell which means

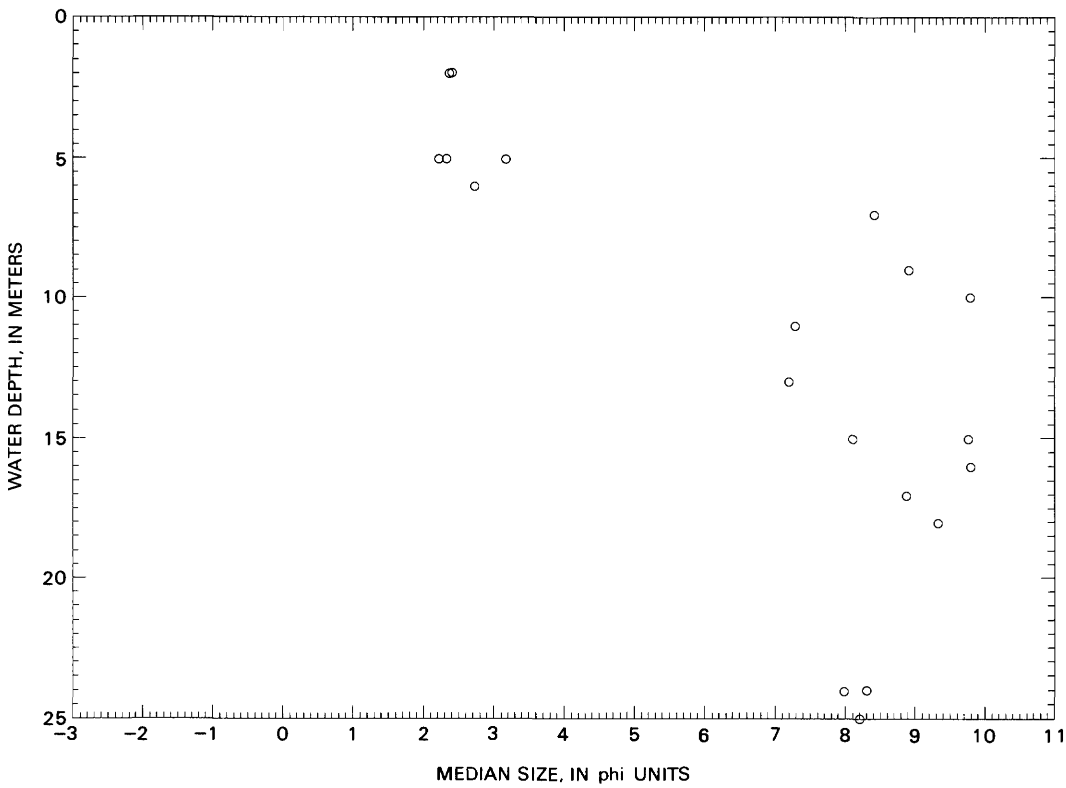


Figure 6. Variations in median particle size with water depth for sediment samples from nautical mile 13 in the estuary division.

differ from which other means. The general utility of this option for the comparison of means in unbalanced cases recently has been affirmed (Stoline, 1981, p. 134–140).

The statistical significance of differences between mean particle-size measures in samples from the Potomac mainstem and from the Potomac tributaries was established using the TTEST procedure. No statistically significant difference between mainstem and tributary samples was determined for any particle-size measure when means for all samples were compared (table 7), which confirms the observation made earlier of very little apparent textural difference between Potomac mainstem and tributary sediments (table 4). For most tributaries, the texture of samples from the channel and smooth flat near the tributary mouth is not significantly different from the texture of samples from the same geomorphic units in the nearby Potomac mainstem. The only exception to this is in the river division near the mouth of the Anacostia River, where both the mainstem and the tributary sediments are more variable than in other locations (table 3).

The GLM procedure was used to test the statistical significance of trends and variations in mean particle-size measures for samples assigned to longitudinal and lateral classes of the tidal Potomac system. The test procedure uses Fishers F (Freund and Littell, 1981, p. 1-3; Li, 1964, p. 118–132) to determine the significance of the overall relation between means of size measures and classes, the significance of specific relations between means of size measures and each class, and the presence or absence of significant interaction effects between classes. For the usual instance of significant interaction effects, these effects are considered in the TUKEY option tests for differences among individual means by comparing longitudinal (or lateral) class means separately for each lateral (or longitudinal) class.

The significance of relations between mean values of selected particle-size measures (dependent variables) and longitudinal and lateral classes (independent variables) of samples from the Potomac mainstem is shown in table 8. Median particle size (in phi) and percentages of sand and of clay are representative particle-size measures (dependent variables), and results are given for their relations to hydrologic and nautical-mile divisions combined with geomorphic and depth units. Relations between logarithmic transformations of clay percentages and independent variables also were determined; results (not shown) were the same as for untransformed percentages. The small probabilities of a greater F for the overall tests establish that mean values for all dependent variables are affected significantly by all combinations of longitudinal and lateral classes (table 8); that is, mean particle-size measures vary significantly in the Potomac mainstem

Table 7. Results of TTEST comparisons of selected particle-size measures for samples from different locations
[T=t statistic; SAS, 1982, p. 217-221]

Particle-size measure	Number of samples	Sample location	Mean	Standard deviation	Variances	Probability of greater absolute T
Median	61	Tributaries	6.73	2.924	Unequal	0.6780
	166	Mainstem	6.55	2.961	Equal	.6794
Sorting	61	Tributaries	2.85	1.286	Unequal	.3586
	166	Mainstem	2.66	1.497	Equal	.3913
Skewness	61	Tributaries	.14	.335	Unequal	.0711
	166	Mainstem	.05	.305	Equal	.0579
Percentage of sand	103	Tributaries	38	34.9	Unequal	.6917
	211	Mainstem	36	37.1	Equal	.6976
Percentage of clay	103	Tributaries	33	26.4	Unequal	.1469
	211	Mainstem	38	26.9	Equal	.1494

regardless of how longitudinal and lateral classes of samples are defined or combined. Coefficients of determination (R^2) for overall tests range from 0.378 to 0.743 and are highest for size measures versus nmi division and geomorphic unit (table 8). If depth is the independent variable, coefficients are always smaller than if geomorphic unit is the independent variable. The coefficients indicate that hydrologic divisions and geomorphic units ($R^2=0.657$) are better predictors of median size than hydrologic divisions and depth units ($R^2=0.378$), and possibly that nmi divisions and geomorphic units ($R^2=0.705$) are better predictors than hydrologic divisions and geomorphic units ($R^2=0.657$).

The probability of a greater F for relations of dependent variables and lateral classes is significant and is less than or equal to that for longitudinal classes (table 8), showing that lateral variability in size measures contributes more to significant overall relations than longitudinal variability in size measures contributes. The probability of a greater F for the median versus longitudinal variable (either hydrologic division or nautical-mile division) is greater than 0.0500 and is not significant in three of four relations (table 8), indicating also that the means are not dependent primarily on longitudinal variations. The only other longitudinal relation that is not significant is for the percentage of sand versus hydrologic division ($R^2=0.0709$); the percentage of clay and the logarithm of the percentage of clay plus 0.1 to avoid zero percentages are related significantly to longitudinal divisions.

Interaction between independent variables is present if the probability of a greater F for interaction is less than 0.0500; thirteen of the 14 relations in table 8 demonstrate significant interaction effects. The presence of interaction prevents a comparison of means for longitudinal variables averaged over all levels of lateral variables. If interaction is present, the significance of the trends and relations can be determined by coupling the GLM procedure, which computes the probability of a greater F for the relation between a dependent variable and an independent variable using only samples from a second independent variable, with the TUKEY option, which identifies significantly different means of the independent variable. These computations for selected relations from table 8 are shown in table 9. All computations are made as if interaction is present in all relations; thus, for the relation in which interaction is absent (table 8), the power of the tests is reduced somewhat.

Samples located in two of four geomorphic units show significantly different hydrologic division means of the median particle size (table 9, rows 1–4). Sediments of both channels (G3) and smooth flats (G1) differ among hydrologic divisions in means of the median size, but sediments of shoreline flats (G0) and irregular slopes (G2) do not differ. The coefficient of determination for the significantly different relations is small (table 9), which suggests that factors other than those accounted for by changing hydrologic conditions are important in the relations. Because the channel unit was present (table 2B) and was sampled (table 1) extensively throughout the Potomac mainstem, statistical tests for this unit give the best trend information. For channels, sediments from the transition (HT) and the estuary (HE) divisions are significantly finer than sediments from the river (HR) division. No significant difference can be detected between sediments from the channels in the transition and the estuary divisions, although the channel sediments from the transition division are relatively finer than the channel sediments from the estuary division (table 9).

A plot of the data used in the preceding analysis is shown in figure 7*A*. For shoreline flats, the means of the median size for sediment samples from each hydrologic division are essentially the same, and no significant differences can be detected (table 9; row 1) with the

Table 8. Statistical significance of longitudinal and lateral variations (independent variable) in particle size (dependent variable) in Potomac mainstem sediments

[F=F statistic; SAS, 1982, p. 114]

Dependent variable	Independent variables		Number of samples	Probability of a greater F				Coefficient of determination [1/] (R^2)
	Longitudinal division	Lateral unit		Overall	Longitudinal division	Lateral unit	Interaction	
Median	Hydrologic	Geomorphic	161	0.0001	0.8385	0.0001	0.1050	0.657
Percentage of sand	Hydrologic	Geomorphic	206	.0001	.0709	.0001	.0150	.685
Percentage of clay	Hydrologic	Geomorphic	206	.0001	.0088	.0001	.0211	.696
Median	Hydrologic	Depth	161	.0001	.0811	.0001	.0018	.378
Percentage of sand	Hydrologic	Depth	206	.0001	.0002	.0001	.0007	.493
Percentage of clay	Hydrologic	Depth	206	.0001	.0010	.0001	.0001	.528
Median	Nautical mile	Geomorphic	161	.0001	.3600	.0001	.0348	.705
Percentage of sand	Nautical mile	Geomorphic	206	.0001	.0209	.0001	.0009	.721
Percentage of clay	Nautical mile	Geomorphic	206	.0001	.0001	.0001	.0014	.743
Median	Nautical mile	Depth	161	.0001	.0118	.0001	.0034	.476
Percentage of sand	Nautical mile	Depth	206	.0001	.0010	.0001	.0059	.533
Percentage of clay	Nautical mile	Depth	206	.0001	.0001	.0001	.0001	.602

[1/] Applies to the overall relation between dependent and independent variables.

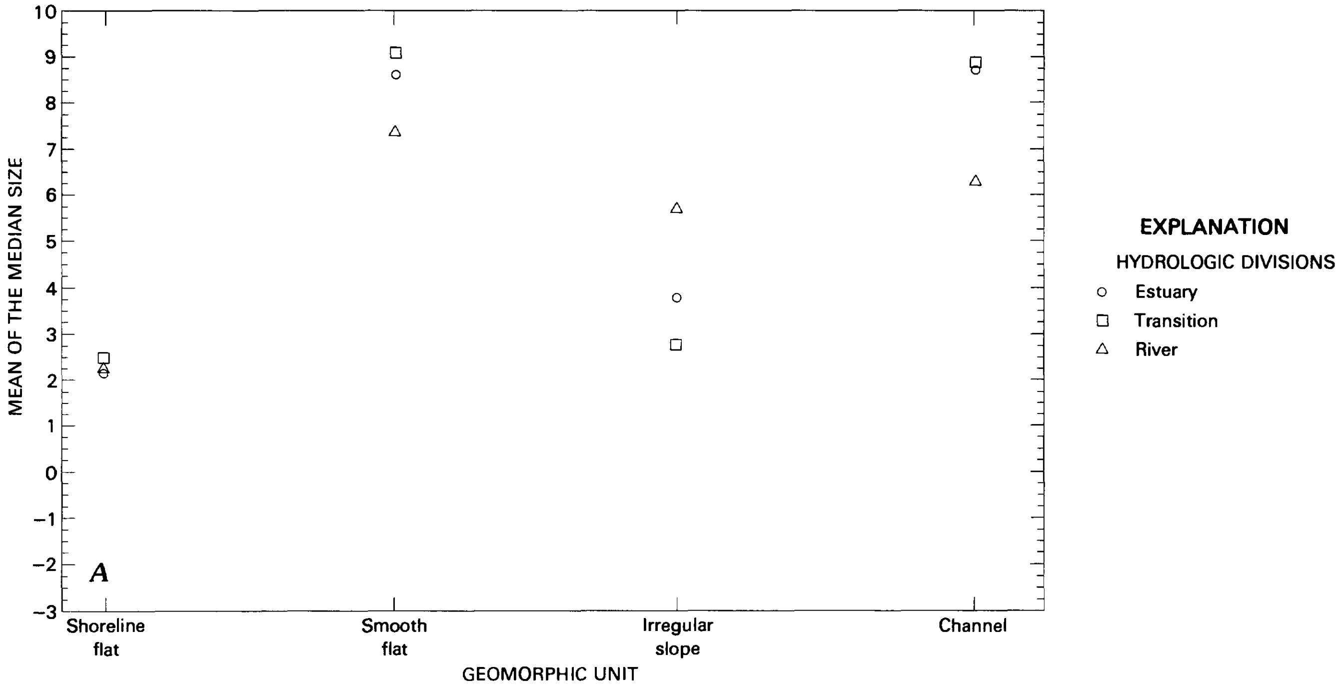
Table 9. Statistical significance of differences in individual means for selected relations from table 8 between particle-size measures (dependent variable) and longitudinal divisions and lateral units (independent variable)

[ND=No data; F=F statistic, SAS, 1982, p. 114]

Dependent variable	Independent variable 1/	Number of samples	Sample location 1/	Probability of greater F	Coefficient of determination (R^2)	Relative order of dependent variable means 1/	Significantly different means 2/
Median	H	12	G0	0.7869	0.052	HT>HR>HE	None
Median	H	36	G1	.0046	.279	HT>HE>HR	HT>HR
Median	H	33	G2	.4350	.054	HR>HE>HT	None
Median	H	80	G3	.0001	.365	HT>HE>HR	HT,HE>HR
Median	G	63	HE	.0001	.673	G3>G1>G2>G0	G3,G1>G2,G0
Median	G	49	HT	.0001	.852	G1>G3>G2>G0	G1,G3>G2,G0
Median	G	49	HR	.0495	.158	G1>G3>G2>G0	None
Percentage of sand	H	43	G0	.0386	.150	HE>HT>HR	HE>HR
Percentage of sand	H	41	G1	.1202	.106	HR>HE>HT	None
Percentage of sand	H	35	G2	.2119	.092	HE>HT>HR	None
Percentage of sand	H	87	G3	.0003	.177	HR>HE>HT	HR,HE>HT
Percentage of sand	G	65	HE	.0001	.693	G0>G2>G3>G1	G0,G2,>G3,G1
Percentage of sand	G	80	HT	.0001	.836	G0>G2>G1>G3	G0>G2,G1,G3; G2>G1,G3
Percentage of sand	G	61	HR	.0003	.286	G0>G3>G2>G1	G0>G3,G1
Median	N	28	D0	.0010	.540	N5>N4>N3>N1>N2	N5>N3,N2; N4>N2
Median	N	26	D1	.6121	.115	N3>N4>N5>N2>N1	None
Median	N	26	D2	.0002	.641	N3>N4>N2>N5>N1	N3,N4,N2>N1; N3>N5
Median	N	42	D3	.1572	.160	N3>N1>N2>N4>N5	None
Median	N	11	D4	.6513	.197	N2>N4>N1>N5	None
Median	N	10	D5	.3941	.502	N4>N3>N1>N2>N5	None
Median	N	6	D6	.5616	.319	N3>N4>N1	None
Median	N	3	D7	ND	ND	N1	ND
Median	N	9	D8	.4123	.410	N3>N1>N5>N4	None
Median	D	28	N1	.0008	.711	D7>D8>D3>D5>D4>D6>D1>D0>D2	D7,D8>D0,D2; D4>D2
Median	D	35	N2	.0031	.445	D4>D3>D5>D2>D1>D0	D4,D3>D0
Median	D	30	N3	.0001	.705	D2>D3>D8>D6>D5>D1>D0	D2,D3,D8,D6,D5,D1>D0
Median	D	40	N4	.8818	.084	D6>D5>D4,D8,D2>D1>D3>D0	None
Median	D	28	N5	.3031	.270	D8>D1>D0>D3>D4>D2>D5	None

1/ Symbols for variables and locations are: H = Hydrologic division; HT = Transition; HR = River; HE = Estuary.
G = Geomorphic unit; G0 = Shoreline flat; G1 = Smooth flat; G2 = Irregular slope; G3 = Channel.
N = Nautical mile (nmi) division; N1 = 0 to 20 nmi; N2 = >20 to 40 nmi; N3 = >40 to 60 nmi; N4 = >60 to 80 nmi; N5 = >80 to 100 nmi
D = Depth unit; D0 = 0 to 2 m (meters); D1 = >2 to 4 m; D2 = >4 to 6 m; D3 = >6 to 8 m; D4 = >8 to 10 m; D5 = >10 to 12 m; D6 = >12 to 14 m; D7 = >14 to 16 m; D8 = >16 m.

2/ Five percent significance level.



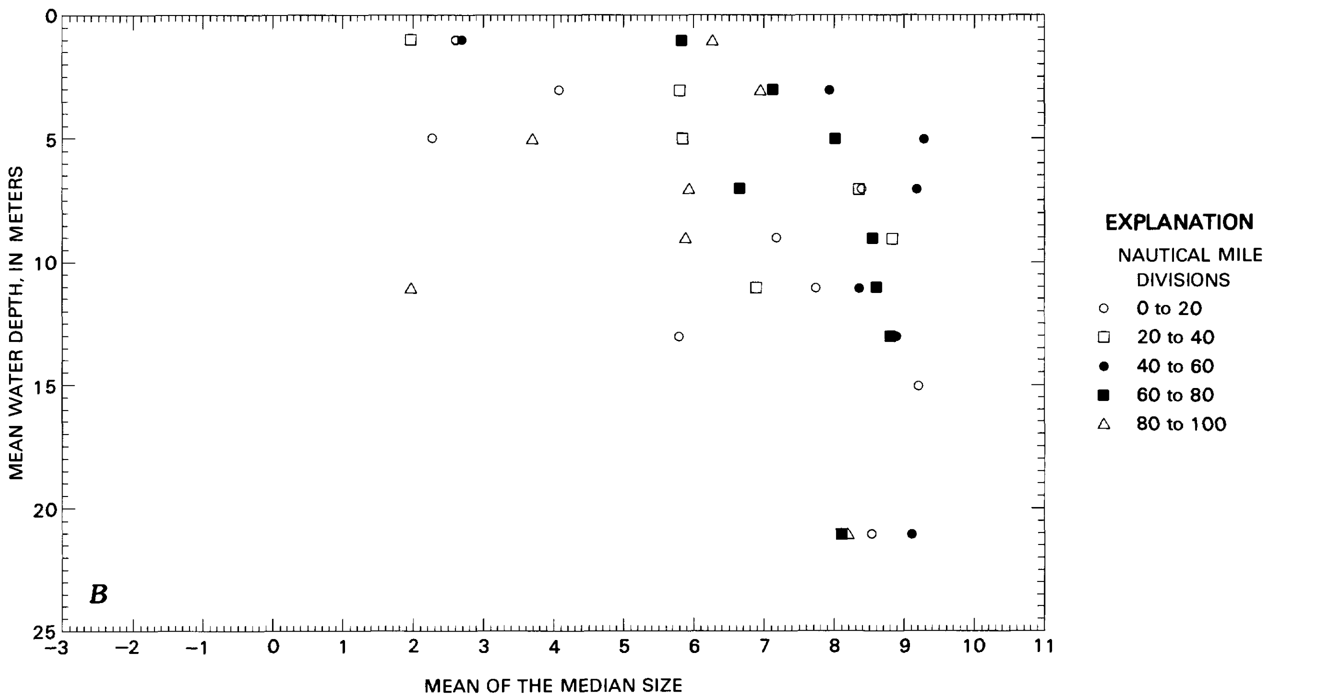


Figure 7. Variations in mean of the median particle size with *A*, Geomorphic unit and hydrologic division; and *B*, Depth unit and nautical-mile division.

number of samples available (table 5, sections A–C). Although the spread between the means for samples from smooth flats and channels is about the same as the spread for irregular slopes (fig. 7*A*), significant differences are identified for smooth flats and channels but not for irregular slopes. The lack of a significant difference for the irregular slope is probably due to the small area of this unit and to the single sample from this area in the river division.

Geomorphic units have significantly different mean values of the median sediment size in two of the three hydrologic divisions (table 9; rows 5–7). The mean of the median size does not vary significantly with geomorphic unit in the river division (HR, table 9) but, in both the estuary (HE) and the transition (HT) divisions, sediments of channels (G3) and smooth flats (G1) are significantly finer than sediments of shoreline flats (G0) and irregular slopes (G2). The same relative trends in means for sediments from the geomorphic units occur in all three hydrologic divisions (table 9), but significant trends are not identified in the river division either because of greater sediment variability or because too few samples were obtained (table 1) from sediments of geomorphic units of limited extent (G2 and G0) (table 2B). The coefficient of determination for the significant relations is higher for relations between median and geomorphic unit than for relations between median and hydrologic division, indicating that geomorphic units are better predictors of median size than hydrologic divisions are (table 9).

If the percentage of sand is the dependent variable in relations with hydrologic divisions (table 9; rows 8–11) or geomorphic units (table 9; rows 12–14), slightly different conclusions about significantly different longitudinal and lateral trends in particle-size measures result. Different conclusions may derive from the different numbers of samples involved (table 1), but more likely, they result from inherent differences in the dependent variables. For the relation between percentage of sand and hydrologic division, sediments from two geomorphic units, the shoreline flats (G0) and the channels (G3), show significantly different mean sand percentages. For sediments from shoreline flats, the estuary division has a significantly greater percentage of sand than the river division, but sediments in neither division are significantly different in sand content from those in the transition division (table 9). For sediments from channels, the river and the estuary divisions have significantly greater percentages of sand than the transition division, although the percentage of sand in sediments from the river and the estuary divisions is not significantly different. In general, an inverse relation exists between the percentage of sand and the median particle size (in phi) in Potomac mainstem samples; thus, for channels, both median and percentage of sand show compatible trends with hydrologic division (table 9).

Relations between percentage of sand and geomorphic unit are similar in significantly different means and in coefficients of determination to relations between median and geomorphic unit (table 9), as they should be if an inverse relation between dependent variables exists and if the variables are equally sensitive. For the estuary division, where the difference in number of samples is minimal, median and percentage of sand give exactly the same results. In both the transition and the river divisions, larger numbers of samples with determinations of sand percentages than with determinations of medians result in significantly different means in the river division and increased resolution for significantly different means in the transition division (table 9). In both divisions, the significant lateral distinctions are between greater percentages of sand in sediments from shoreline flats (G0) and irregular slopes (G2) than in sediments from smooth flats (G1) and channels (G3).

If hydrologic division and geomorphic unit are replaced by nmi division (N) as a longitudinal variable and depth unit (D) as a lateral variable, additional detail is provided on the nature and significance of longitudinal and lateral trends in sediment-particle size (fig. 7*B*). Median versus N relations (table 9; rows 15–23) show that significantly different means for the median size are confined to sediments from waters 6 m or less in depth (sample location D2, table 9). For the 0–2-m-depth unit (sample location D0, table 9; top row fig. 7B), means of the median size are largest and particle sizes are finest in higher number nmi divisions; that is, sediments from water 2 m or less in depth are significantly finer toward the landward end of the Potomac mainstem. For the greater than 4–6-m-depth unit (sample location D2, table 9; 3rd row, fig. 7*B*), significantly coarser sediments are found in both the most landward and the most seaward nmi divisions (N1, N5).

Significantly different means for the relation of median particle size to depth unit are limited to nmi divisions N1, N2, and N3, which include the lower three-fifths of the Potomac mainstem; that is, the mean of the median size varies significantly with depth only in the lower transition division and in the estuary division (table 9; rows 24–28). Even in these divisions, significant differences occur only between shallow-water depth units (D0 or D2) and deep-water depth units (D7 and D8 in N1, table 9) within each nmi division. The coefficient of determination for the significant median versus D relations is moderate to large (table 9) and is commonly larger than the coefficient for the significant median versus N relations. The larger coefficients indicate that depth unit, a lateral class, is a better predictor of median size than nmi division, a longitudinal class, just as geomorphic unit, also a lateral class, is a better predictor than hydrologic division, a longitudinal class.

Nutrients

Nutrient data for all samples of near-surface bottom sediments from the tidal Potomac are shown in table 10. The numbers and kinds of all analyses are indicated in table 1, and sample sites are located on plates 1–3. The emphasis in nutrient analyses was on determining the total amounts of carbon (as C), phosphorus (as P), and nitrogen (as N) associated with bulk samples of near-surface bottom sediments from the longitudinal divisions and lateral units of the tidal Potomac system (table 1). For carbon, additional analyses were made of inorganic carbon (as C), and organic carbon was computed by

Table 10. Nutrient concentrations for near-surface samples of bottom sediments

[Carbon concentrations in grams per kilogram; phosphorus and nitrogen concentrations in milligrams per kilogram. ND=Not determined]

Sample number	Hydrologic division	Nautical mile 1/	Nautical mile division 2/	Geomorphic unit	Water depth (meters)	Depth unit 3/	Nutrient concentration: Carbon Total	Carbon Inorganic	Carbon Organic	Phosphorus Total	Nitrogen Total	Nitrogen NO_2+NO_3	Nitrogen Ammonia
1978 US BM-54 samples from the Potomac mainstem													
11	River	93	N5	Smooth flat	2	D0	36.0	2.4	34.0	940	3950	0.0	220
12	River	93	N5	Channel	6	D2	6.4	0.4	6.0	360	900	0.0	24
27	River	91	N5	Channel	9	D4	5.0	0.3	4.7	610	2100	0.0	94
31	River	90	N5	Other	4	D1	36.0	1.5	35.0	1900	3450	0.0	678
33	River	89	N5	Channel	8	D3	46.0	1.2	45.0	1400	3000	2.2	450
34	River	89	N5	Channel	8	D3	35.0	1.0	34.0	1800	3100	0.0	490
35	River	89	N5	Channel	8	D3	36.0	1.0	35.0	1800	3600	0.0	490
36	River	89	N5	Channel	8	D3	35.0	0.9	34.0	1800	3100	2.6	400
37	River	89	N5	Channel	8	D3	36.0	1.1	35.0	1800	3000	0.0	380
38	River	89	N5	Channel	9	D4	34.0	1.9	32.0	2800	3350	0.0	235
39	River	89	N5	Channel	8	D3	43.0	1.4	42.0	780	2500	0.0	290
40	River	89	N5	Channel	8	D3	40.0	1.6	38.0	780	2200	0.0	310
41	River	89	N5	Channel	8	D3	43.0	1.2	42.0	210	2500	0.0	260
42	River	89	N5	Channel	8	D3	41.0	1.5	40.0	400	2400	4.6	270
43	River	89	N5	Channel	8	D3	38.0	1.5	37.0	880	2700	3.0	300
45	River	89	N5	Other	2	D0	18.0	0.9	17.0	2100	2250	0.0	73
49	River	88	N5	Smooth flat	2	D0	13.0	0.3	13.0	870	2450	0.0	60
64	River	83	N5	Smooth flat	2	D0	26.0	0.6	25.0	1800	2650	0.0	93
66	River	83	N5	Channel	21	D8	43.0	3.6	39.0	1000	3550	0.0	267
75	River	81	N5	Channel	8	D3	30.0	1.2	29.0	1600	3750	0.0	308
76	River	81	N5	Irregular slope	6	D2	31.0	1.1	30.0	150	3500	4.1	309
80	River	74	N4	Smooth flat	2	D0	16.0	0.1	16.0	360	2900	0.0	64
83	River	74	N4	Smooth flat	3	D1	29.0	1.2	28.0	410	3000	1.1	216
84	River	74	N4	Channel	8	D3	28.0	0.7	27.0	1500	3500	1.9	279
88	River	73	N4	Smooth flat	3	D1	24.0	0.3	24.0	110	2800	2.1	147
89	River	73	N4	Smooth flat	4	D1	25.0	0.4	25.0	1200	2900	1.1	200
105	River	71	N4	Channel	7	D3	29.0	0.7	28.0	1000	3400	0.0	283
126	Transition	67	N4	Other	9	D4	72.0	20.0	52.0	930	1500	2.6	56
127	Transition	67	N4	Irregular slope	7	D3	7.4	0.2	7.2	460	270	0.9	21
128	Transition	67	N4	Irregular slope	7	D3	6.5	0.0	6.5	370	550	0.0	22
129	Transition	67	N4	Irregular slope	7	D3	7.6	0.0	7.6	390	400	3.2	20
130	Transition	67	N4	Channel	8	D3	26.0	0.4	26.0	1200	2500	0.0	310
131	Transition	67	N4	Channel	8	D3	26.0	0.3	26.0	1500	2200	0.0	340
132	Transition	67	N4	Channel	8	D3	27.0	0.4	27.0	1500	2900	3.7	320
133	Transition	67	N4	Channel	8	D3	27.0	0.3	27.0	1600	2600	6.9	310
134	Transition	67	N4	Channel	8	D3	26.0	0.4	26.0	1600	2500	5.5	300
136	Transition	64	N4	Shoreline flat	2	D0	7.6	0.0	7.6	190	480	2.0	10
139	Transition	64	N4	Smooth flat	5	D2	25.0	0.2	25.0	1300	2400	0.0	150
140	Transition	64	N4	Channel	8	D3	27.0	0.3	27.0	1600	2700	3.2	200
143	Transition	57	N3	Shoreline flat	2	D0	14.0	1.3	13.0	300	530	7.6	10
145	Transition	57	N3	Smooth flat	6	D2	21.0	0.3	21.0	980	2300	3.3	90
171	Transition	51	N3	Irregular slope	2	D0	9.2	0.8	8.4	780	1100	0.0	30
172	Transition	51	N3	Channel	14	D6	24.0	0.3	24.0	1400	2600	0.0	150
191	Transition	46	N3	Smooth flat	3	D1	19.0	0.0	19.0	1000	2400	0.0	52
192	Transition	46	N3	Channel	17	D8	22.0	0.3	22.0	1400	3500	0.0	140
194	Transition	46	N3	Smooth flat	3	D1	26.0	1.1	25.0	880	3600	0.0	170
228	Transition	41	N3	Channel	11	D5	20.0	0.6	19.0	630	1900	0.0	63
229	Transition	41	N3	Irregular slope	2	D0	2.5	0.2	2.3	400	360	0.0	9.0
230	Transition	41	N3	Other	11	D5	21.0	0.2	21.0	1400	2300	0.0	70
238	Estuary	33	N2	Smooth flat	3	D1	20.0	0.4	20.0	690	2500	3.4	75
239	Estuary	33	N2	Smooth flat	6	D2	23.0	0.8	22.0	900	3000	6.2	110
241	Estuary	33	N2	Channel	9	D4	17.0	0.8	16.0	660	1800	3.7	660
244	Estuary	33	N2	Shoreline flat	2	D0	1.1	0.0	1.1	160	410	4.7	30
275	Estuary	26	N2	Shoreline flat	2	D0	0.5	0.2	0.3	490	160	1.1	10
277	Estuary	26	N2	Channel	8	D3	29.0	1.6	27.0	620	4100	4.8	150
280	Estuary	26	N2	Irregular slope	2	D0	0.5	0.1	0.4	55	170	1.3	13

282	Estuary	23	N2	Irregular slope	4	D1	1.8	0.1	1.7	320	106	1.2	25
284	Estuary	23	N2	Channel	8	D3	28.0	2.3	26.0	540	2500	2.6	61
285	Estuary	23	N2	Irregular slope	6	D2	1.7	0.4	1.3	110	200	1.3	13
286	Estuary	23	N2	Channel	8	D3	30.0	1.5	29.0	480	4100	2.3	200
303	Estuary	13	N1	Shoreline flat	2	D0	0.6	0.1	0.5	55	55	2.4	9.5
306	Estuary	13	N1	Channel	11	D5	29.0	0.6	28.0	470	3400	2.5	97
307	Estuary	13	N1	Channel	24	D8	35.0	0.8	34.0	600	3500	6.2	540
308	Estuary	13	N1	Channel	24	D8	33.0	1.5	32.0	780	3900	2.5	660
323	Estuary	9	N1	Channel	10	D4	23.0	0.6	22.0	390	3300	2.4	58
334	Estuary	2	N1	Shoreline flat	2	D0	0.5	0.1	0.4	90	350	1.2	2.4
335	Estuary	2	N1	Irregular slope	10	D4	1.8	0.2	1.6	80	580	1.2	4.8
336	Estuary	2	N1	Channel	12	D5	26.0	0.3	26.0	380	6200	2.6	4.3
337	Estuary	2	N1	Irregular slope	6	D2	1.4	0.3	1.1	50	170	1.1	8.0
339	Estuary	13	N1	Irregular slope	6	D2	2.0	1.3	0.7	120	44	2.2	14
				1978 US BM-54 samples from the Potomac tributaries									
16	4/	1	N1	Channel	7	D3	30.0	0.4	30.0	2400	2850	1.2	353
19	4/	1	N1	Channel	7	D3	30.0	0.5	30.0	2000	2800	0.0	300
26	4/	0	N1	Channel	3	D1	36.0	2.2	34.0	650	3350	6.5	314
51	4/	0	N1	Channel	2	D0	46.0	1.5	45.0	1400	3600	0.0	343
53	4/	1	N1	Channel	5	D2	34.0	0.9	33.0	7900	3950	0.0	191
62	4/	0	N1	Smooth flat	2	D0	22.0	0.5	22.0	1800	2700	0.0	130
68	4/	1	N1	Smooth flat	2	D0	23.0	0.2	23.0	2200	2700	0.0	135
73	4/	0	N1	Smooth flat	4	D1	28.0	0.4	28.0	2500	2400	0.0	172
78	4/	0	N1	Smooth flat	3	D1	25.0	0.4	25.0	950	2800	7.3	181
90	4/	0	N1	Smooth flat	3	D1	24.0	0.4	24.0	590	3050	0.0	117
109	4/	0	N1	Smooth flat	3	D1	25.0	0.3	25.0	160	3300	0.0	211
111	4/	2	N1	Channel	7	D3	34.0	0.2	34.0	250	2250	2.2	158
149	4/	0	N1	Shoreline flat	2	D0	6.2	2.6	3.6	450	800	1.5	33
151	4/	2	N1	Channel	2	D0	33.0	0.0	33.0	780	2900	0.0	170
199	4/	2	N1	Channel	1	D0	18.0	0.0	18.0	830	1200	0.0	31
246	4/	1	N1	Smooth flat	2	D0	40.0	0.2	40.0	1500	4400	4.8	100
253	4/	2	N1	Channel	11	D5	26.0	0.4	26.0	710	1700	5.1	190
260	4/	5	N1	Channel	3	D1	25.0	0.2	25.0	750	3100	7.9	97
263	4/	7	N1	Smooth flat	1	D0	27.0	0.3	27.0	750	3000	2.1	92
325	4/	1	N1	Shoreline flat	2	D0	3.4	1.9	1.5	130	76	2.2	9.2
326	4/	2	N1	Channel	3	D1	28.0	0.2	28.0	540	2900	2.3	79
329	4/	2	N1	Channel	8	D3	26.0	0.2	26.0	300	3500	2.0	37
330	4/	2	N1	Shoreline flat	2	D0	11.0	0.2	11.0	120	1100	1.3	17
332	4/	7	N1	Channel	2	D0	24.0	0.4	24.0	480	2100	3.1	40
				1978 benthos samples from the Potomac mainstem									
54	River	89	N5	Smooth flat	2	D0	16.0	0.3	16.0	ND	ND	ND	ND
55	River	89	N5	Smooth flat	2	D0	23.0	0.3	23.0	ND	ND	ND	ND
56	River	89	N5	Channel	7	D3	12.0	0.3	12.0	ND	ND	ND	ND
57	River	89	N5	Channel	8	D3	30.0	0.5	30.0	ND	ND	ND	ND
58	River	89	N5	Other	2	D0	14.0	1.1	13.0	ND	ND	ND	ND
96	River	73	N4	Smooth flat	3	D1	15.0	0.0	15.0	ND	ND	ND	ND
97	River	73	N4	Shoreline flat	2	D0	1.7	0.0	1.7	ND	ND	ND	ND
98	River	73	N4	Smooth flat	4	D1	14.0	0.2	14.0	ND	ND	ND	ND
99	River	73	N4	Smooth flat	4	D1	12.0	0.0	12.0	ND	ND	ND	ND
100	River	73	N4	Channel	8	D3	25.0	0.8	25.0	ND	ND	ND	ND
101	River	73	N4	Channel	6	D2	27.0	0.2	27.0	ND	ND	ND	ND
118	Transition	68	N4	Smooth flat	2	D0	23.0	0.3	23.0	ND	ND	ND	ND
119	Transition	68	N4	Irregular slope	4	D1	15.0	0.1	15.0	ND	ND	ND	ND
120	Transition	68	N4	Irregular slope	5	D2	17.0	1.3	16.0	ND	ND	ND	ND
121	Transition	68	N4	Irregular slope	4	D1	2.3	0.0	2.3	ND	ND	ND	ND
122	Transition	68	N4	Channel	9	D4	20.0	0.1	20.0	ND	ND	ND	ND
123	Transition	68	N4	Channel	8	D3	19.0	0.1	19.0	ND	ND	ND	ND
124	Transition	68	N4	Channel	5	D2	24.0	0.2	24.0	ND	ND	ND	ND
153	Transition	57	N3	Irregular slope	3	D1	2.2	0.0	2.2	ND	ND	ND	ND
154	Transition	57	N3	Irregular slope	2	D0	3.3	0.0	3.3	ND	ND	ND	ND
155	Transition	57	N3	Smooth flat	4	D1	19.0	0.0	19.0	ND	ND	ND	ND
156	Transition	57	N3	Irregular slope	4	D1	5.0	0.0	5.0	ND	ND	ND	ND
157	Transition	57	N3	Smooth flat	4	D2	14.0	0.0	14.0	ND	ND	ND	ND

Table 10. Nutrient concentrations for near-surface samples of bottom sediments—Continued

Sample number	Hydrologic division	Nautical mile 1/	Nautical mile division 2/	Geomorphic unit	Water depth (meters)	Depth unit 3/	Nutrient concentration: Carbon, Total	Carbon, Inorganic	Carbon, Organic	Phosphorus, Total	Nitrogen, Total	Nitrogen, NO_2+NO_3	Nitrogen, Ammonia
				1978 benthos samples from the Potomac mainstem--Continued									
158	Transition	57	N3	Smooth flat	6	D2	22.0	0.1	22.0	ND	ND	ND	ND
159	Transition	57	N3	Channel	6	D2	19.0	0.1	19.0	ND	ND	ND	ND
160	Transition	57	N3	Channel	6	D2	20.0	0.0	20.0	ND	ND	ND	ND
161	Transition	57	N3	Smooth flat	3	D1	20.0	0.0	20.0	ND	ND	ND	ND
200	Transition	46	N3	Shoreline flat	2	D0	2.5	0.0	2.5	ND	ND	ND	ND
201	Transition	46	N3	Channel	20	D8	23.0	0.3	23.0	ND	ND	ND	ND
202	Transition	46	N3	Channel	7	D3	16.0	0.0	16.0	ND	ND	ND	ND
203	Transition	46	N3	Smooth flat	4	D1	21.0	0.2	21.0	ND	ND	ND	ND
204	Transition	46	N3	Smooth flat	4	D1	15.0	0.1	15.0	ND	ND	ND	ND
205	Transition	46	N3	Smooth flat	3	D1	14.0	0.0	14.0	ND	ND	ND	ND
206	Transition	46	N3	Smooth flat	4	D1	16.0	1.2	15.0	ND	ND	ND	ND
291	Estuary	23	N2	Irregular slope	5	D2	3.3	0.2	3.1	ND	ND	ND	ND
292	Estuary	23	N2	Irregular slope	6	D2	15.0	0.0	15.0	ND	ND	ND	ND
293	Estuary	23	N2	Irregular slope	8	03	19.0	0.1	19.0	ND	ND	ND	ND
294	Estuary	23	N2	Channel	8	D3	23.0	1.2	22.0	ND	ND	ND	ND
295	Estuary	23	N2	Channel	8	D3	20.0	0.8	19.0	ND	ND	ND	ND
296	Estuary	23	N2	Channel	11	D5	7.6	2.5	5.1	ND	ND	ND	ND
297	Estuary	23	N2	Channel	8	D3	19.0	0.5	19.0	ND	ND	ND	ND
298	Estuary	23	N2	Channel	9	D4	22.0	0.0	22.0	ND	ND	ND	ND
311	Estuary	13	N1	Irregular slope	5	D2	1.3	0.5	0.8	ND	ND	ND	ND
312	Estuary	13	N1	Channel	9	D4	16.0	0.1	16.0	ND	ND	ND	ND
313	Estuary	13	N1	Channel	10	D4	16.0	0.2	16.0	ND	ND	ND	ND
314	Estuary	13	N1	Channel	15	D7	27.0	0.0	27.0	ND	ND	ND	ND
315	Estuary	13	N1	Channel	16	D7	22.0	0.3	22.0	ND	ND	ND	ND
316	Estuary	13	N1	Channel	17	D8	14.0	0.4	14.0	ND	ND	ND	ND
317	Estuary	13	N1	Channel	18	D8	25.0	0.2	25.0	ND	ND	ND	ND
318	Estuary	13	N1	Channel	15	D7	16.0	0.0	16.0	ND	ND	ND	ND
319	Estuary	13	N1	Irregular slope	5	D2	1.4	0.2	1.2	ND	ND	ND	ND
320	Estuary	13	N1	Irregular slope	5	D2	2.4	1.4	1.0	ND	ND	ND	ND
				1978 benthos samples from the Potomac mainstem									
59	4/	0	N1	Channel	4	D1	13.0	0.9	12.0	ND	ND	ND	ND
152	4/	0	N1	Channel	2	D0	23.0	0.0	23.0	ND	ND	ND	ND
207	4/	0	N1	Channel	3	D1	17.0	0.0	17.0	ND	ND	ND	ND
208	4/	0	N1	Channel	3	D1	16.0	0.0	16.0	ND	ND	ND	ND
209	4/	1	N1	Channel	3	D1	16.0	0.0	16.0	ND	ND	ND	ND
248	4/	0	N1	Shoreline flat	3	D1	1.5	0.0	1.5	ND	ND	ND	ND
249	4/	0	N1	Channel	6	D2	16.0	0.2	16.0	ND	ND	ND	ND
250	4/	0	N1	Channel	6	D2	14.0	0.1	14.0	ND	ND	ND	ND
254	4/	3	N1	Channel	3	D1	4.2	0.1	4.1	ND	ND	ND	ND
255	4/	3	N1	Channel	7	D3	21.0	0.0	21.0	ND	ND	ND	ND
256	4/	3	N1	Shoreline flat	3	D1	3.7	0.2	3.5	ND	ND	ND	ND
257	4/	5	N1	Channel	3	D1	16.0	0.1	16.0	ND	ND	ND	ND
258	4/	5	N1	Channel	4	D1	16.0	0.1	16.0	ND	ND	ND	ND
259	4/	5	N1	Channel	4	D1	22.0	0.4	22.0	ND	ND	ND	ND
262	4/	7	N1	Smooth flat	2	D0	22.0	0.2	22.0	ND	ND	ND	ND
299	4/	0	N1	Irregular slope	6	D2	10.0	0.4	10.0	ND	ND	ND	ND
300	4/	1	N1	Irregular slope	6	D2	7.7	0.1	7.6	ND	ND	ND	ND

					1981 US BM-54 samples from the Potomac mainstem								
1	River	97	N5	Channel	7	D3	32.0	ND	ND	1200	3400	ND	ND
2	River	96	N5	Channel	7	D3	41.0	ND	ND	1500	3700	ND	ND
3	River	96	N5	Channel	5	D2	34.0	ND	ND	1400	2600	ND	ND
4	River	95	N5	Channel	1	D0	34.0	ND	ND	1400	3400	ND	ND
5	River	95	N5	Channel	9	D4	36.0	ND	ND	1700	3600	ND	ND
6	River	95	N5	Smooth flat	1	D0	36.0	ND	ND	900	2600	ND	ND
7	River	95	N5	Channel	7	D3	36.0	ND	ND	1800	230	ND	ND
9	River	94	N5	Channel	6	D2	40.0	ND	ND	2200	3700	ND	ND
10	River	94	N5	Channel	2	D0	33.0	ND	ND	2700	2700	ND	ND
14	River	93	N5	Smooth flat	3	D1	7.3	ND	ND	430	0	ND	ND
32	River	90	N5	Other	3	D1	57.0	ND	ND	7700	7400	ND	ND
44	River	89	N5	Channel	8	D3	19.0	ND	ND	910	550	ND	ND
46	River	89	N5	Other	1	D0	4.0	ND	ND	530	0	ND	ND
					1981 US BM-54 samples from the Potomac tributaries								
8	4/	0	N1	Smooth flat	2	D0	29	ND	ND	1800	2600.	ND	ND
18	4/	1	N1	Channel	7	D3	28	ND	ND	4100	2500	ND	ND
21	4/	1	N1	Channel	7	D3	29	ND	ND	7700	2300	ND	ND
22	4/	2	N1	Channel	6	D2	27	ND	ND	1300	1900	ND	ND
23	4/	3	N1	Channel	5	D2	25	ND	ND	920	1600	ND	ND
24	4/	3	N1	Channel	3	D1	20	ND	ND	540	1100	ND	ND
25	4/	3	N1	Channel	2	D0	28	ND	ND	590	1300	ND	ND

1/ *Sample location in nautical miles from the Potomac River mouth or from the tributary mouth.*

2/ Nautical mile (nmi) division; N1 = 0 to 20 nmi; N2 = >20 to 40 nmi; N3 = >40 to 60 nmi; N4 = >60 to 80 nmi; N5 = >80 to 100 nmi.

3/ Depth unit; D0 = 0 to 2 m (meter); D1 = >2 to 4 m; D2 = >4 to 6 m; D3 = >6 to 8 m; D4 = >8 to 10 m; D5 = >10 to 12 m; D6 = > 12 to 14 m.

4/ Not identified in Potomac tributaries.

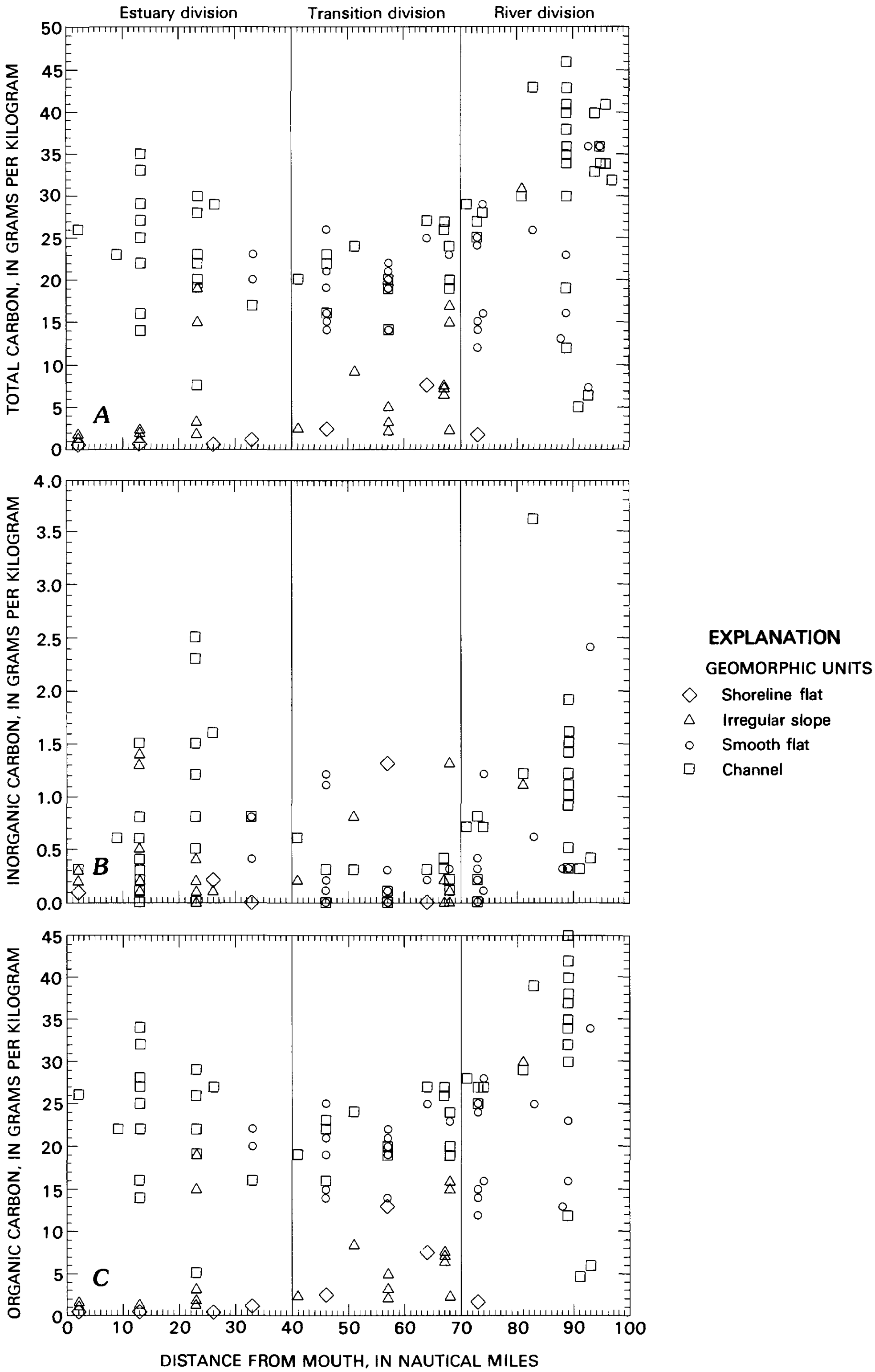
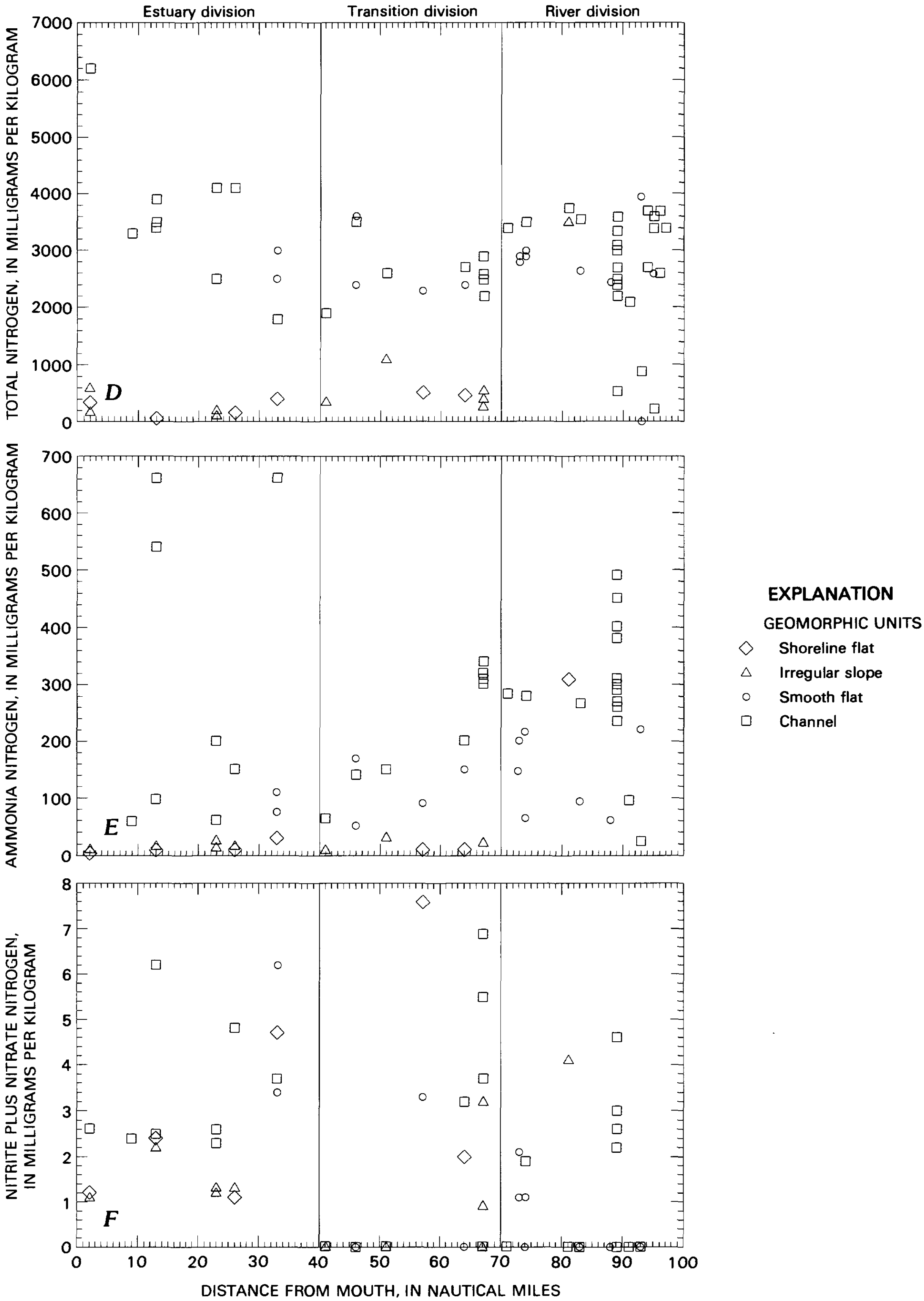


Figure 8 (above and facing page). Nutrient concentrations and distributions in Potomac mainstem sediments: *A*, Total carbon; *B*, Inorganic carbon; *C*, Organic carbon; *D*, Total nitrogen; *E*, Ammonia nitrogen; *F*, Nitrite plus nitrate nitrogen; and *G*, Total phosphorus.

difference (table 10). For nitrogen, additional analyses were made for two inorganic species, nitrite plus nitrate (as N) and ammonia (as N). Ammonia and nitrite+nitrate nitrogen were subtracted from total nitrogen when an estimate of organic nitrogen was desired.



Nutrient concentrations, distributions, and trends in sediment samples from the Potomac mainstem are shown in figures 8*A*–8*G*. Carbon is the dominant major nutrient in tidal Potomac sediments (table 10). The concentration of total carbon in mainstem sediments (fig. 8*A*) ranges from 0.5 to 46 g/kg. Inorganic carbon is a minor component of total carbon in most samples (fig. 8*B*), and organic carbon (fig. 8*C*) concentrations and distributions are similar to total carbon concentrations and distributions. Total nitrogen (fig. 8*D*) is the second most

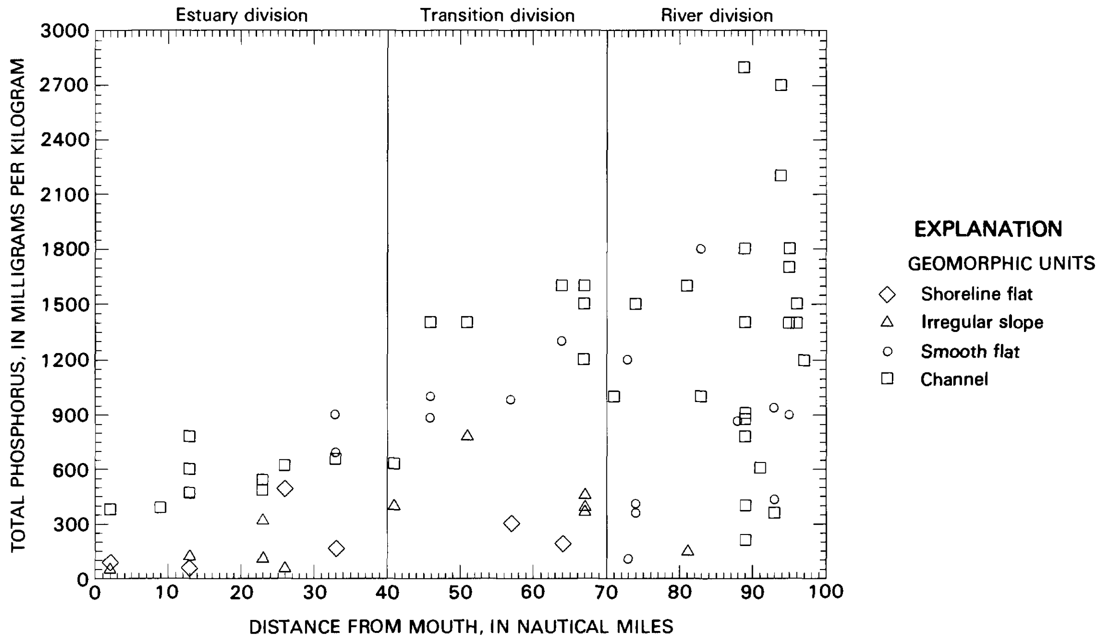


Figure 8. Nutrient concentrations and distributions—Continued.

abundant nutrient and is present in concentrations ranging from 0 to 6,200 mg/kg. Inorganic nitrogen is a minor component of total nitrogen, and organic nitrogen concentrations and distributions are similar to total nitrogen concentrations and distributions. Ammonia nitrogen (fig. 8*E*), the most abundant inorganic component of total nitrogen, ranges from 0 to about 700 mg/kg, and nitrite+nitrate nitrogen (fig. 8*F*) ranges from 0.0 to 7.6 mg/kg. Total phosphorus (fig. 8*G*) ranges from 50 to 2,800 mg/kg. Phosphorus data obtained using different sampling and analytical methods than used here, show a similar range for total phosphorus in Potomac near-surface sediments and indicate that about two-thirds of the total phosphorus is inorganic phosphorus (Goodwin and others, 1983).

Nutrients show different trends among Potomac mainstem hydrologic divisions but show similar trends among mainstem geomorphic units (figs. 8*A*–8*G*). Total carbon and total nitrogen concentrations generally are similar in distribution and are greater and more variable in the river and the estuary divisions than in the transition division. Total phosphorus concentration is high and variable in the river and the transition divisions, and low and less variable in the estuary division. Inorganic carbon concentrations follow total carbon concentrations, and ammonia nitrogen concentrations change in a somewhat similar fashion to total phosphorus concentrations. Nitrite plus nitrate nitrogen concentrations show no obvious longitudinal trend but tend to have greater minimum values in the estuary division than in the river and the transition divisions. Among geomorphic units, greater concentrations of all nutrients are found in the channel and the smooth flat than in the shoreline flat or the irregular slope (figs. 8*A*–8*G*).

The mean and standard deviation of nutrient concentrations in several groups of tidal Potomac sediments are summarized in table 11. An average sediment sample from the tidal Potomac system contains about 21 g/kg of total carbon, 2,400 mg/kg of total nitrogen, 1,200 mg/kg of total phosphorus, 600 mg/kg of inorganic carbon, 170 mg/kg of ammonia, and 2 mg/kg of nitrite plus nitrate. For all samples (table 1) from the tidal Potomac, the average ratio by weight of total carbon to total nitrogen to total phosphorus is about 18:2:1. The average total carbon to total nitrogen ratio (9:1) is not appreciably different from the ratio (ranges between 8:1 and 15:1 with a median between 10 and 12 to 1) for organic matter in surface soils (Buckman and Brady, 1960, p. 146–151). Inorganic carbon averages less than 3 percent of the total carbon, and inorganic species of nitrogen, dominated by ammonia, average about 7 percent of the total nitrogen. All nutrients have large standard deviations, indicating considerable variability in nutrient concentrations in tidal Potomac sediments.

Mean nutrient concentrations for all sediment samples from the Potomac mainstem are similar to mean nutrient concentrations for all sediment samples from the Potomac tributaries (table 11). Mean phosphorus concentrations in sediments from the tributaries are larger than in the sediments from the mainstem, although TTEST analyses do not establish any significant phosphorus-concentration differences either between all mainstem and all tributary samples or between only mainstem and tributary samples from the same geomorphic

Table 11. Mean and standard deviation of concentrations of nutrients in samples from various parts of the tidal Potomac system

[See table 1 for numbers of analyses. Carbon concentrations in grams per kilogram; phosphorus and nitrogen concentrations in milligrams per kilogram]

Nutrient	Tidal Potomac system		Potomac mainstem		Potomac tributaries		Potomac hydrologic division					
							River		Transition		Estuary	
	Mean	Std	Mean	Std	Mean	Std	Mean	Std	Mean	Std	Mean	Std
Total carbon	21.1	12.2	20.8	13.0	21.9	9.8	27.9	12.5	18.1	11.3	14.7	11.3
Inorganic carbon	.6	1.6	.7	1.9	.4	.6	.9	.7	.7	3.0	.6	.6
Organic carbon	19.5	11.3	19.1	11.6	20.8	10.4	25.9	11.3	17.6	9.4	14.2	11.2
Total phosphorus	1,155	1,303	1,019	982	1,519	1,891	1,368	1,233	991	486	383	270
Total nitrogen	2,371	1,334	2,344	1,449	2,446	978	2,810	1,267	1,890	1,058	1,930	1,860
Ammonia nitrogen	173	159.8	182	174.8	146	102.6	266	152.6	129	117.8	131	212.5
Nitrite + nitrate nitrogen	1.8	2.1	1.7	2.0	2.1	2.5	.8	1.4	1.8	2.4	2.7	1.6

unit. In Potomac mainstem hydrologic divisions, mean nutrient concentrations determined from analyses of all available samples show possible trends along the mainstem; total carbon and total phosphorus decrease steadily from the river division to the estuary division, nitrite plus nitrate nitrogen increases from the river division to the estuary division, and total and ammonia nitrogen decrease substantially between the river and the transition divisions.

Lateral trends in mean nutrient concentrations are indicated by summary data for all samples from geomorphic units in each hydrologic division (table 12, sections A–C) and in the tributaries (table 12, section D). In the river division, the channel and the smooth flat are widespread units (table 2B), and most nutrient analyses are on sediment samples from these units (table 12, section A); the channel has the largest mean concentrations (by a factor of about 1.6) for all nutrient species (table 12, section A), and is the preferred site for nutrient accumulations in the river division. In the transition division (table 12, section B), the difference between mean concentrations in the channel and the smooth flat has decreased substantially, and the smooth flat may have mean concentrations of some nutrients equal to or slightly greater than mean concentrations in the channel. Both the shoreline flat and the irregular slope are relatively more common in the transition division than in the river division (table 2B), and the number of samples from these geomorphic units is adequate to characterize their mean nutrient concentrations. Both units have small mean nutrient concentrations (table 12, section B) relative to concentrations in either the smooth flat or the channel; for total carbon, total phosphorus, and total nitrogen, mean concentrations in shoreline flats and irregular slopes are less than in smooth flats and channels by a factor that ranges from three to five. The channel and the smooth flat in the estuary (table 12, section C) continue to have the largest mean concentrations for most nutrients. Because of continued changes in the relative areas (table 2B) of the geomorphic units, only two samples from the upper estuary are from the smooth flat, and more samples are from the irregular slope and the shoreline flat. The irregular slope and the shoreline flat continue to exhibit small concentrations of most nutrients. Variations among hydrologic divisions in numbers of samples from geomorphic units with greatly different nutrient concentrations are undoubtedly important in differences in mean concentrations among hydrologic divisions.

Nutrient concentrations in geomorphic units (table 12, section D) from the tributaries generally follow the same pattern as those in the Potomac mainstem; large concentrations occur in the channel and the smooth flat, and small concentrations are found in the shoreline flat and in the irregular slope. If mean nutrient concentrations for all tidal Potomac samples from each geomorphic unit

Table 12. Summary statistics for nutrient concentrations in samples from each geomorphic unit

[Carbon concentrations in grams per kilogram; phosphorus and nitrogen concentrations in milligrams per kilogram. ND = Not determined]

Geomorphic unit	Summary statistic	Carbon Total	Carbon Inorganic	Carbon Organic	Phosphorus Total	Nitrogen Total	Nitrogen NO_2+NO_3	Nitrogen Ammonia
A. Samples from the Potomac River division								
Channel	Number of samples	30	21	21	26	26	17	17
	Mean	32.2	1.1	30.6	1,358.8	2,157.3	.8	301.8
	Range	41.0	3.4	40.3	2,590.0	3,520.0	4.6	466.0
	Standard deviation	10.2	.7	11.1	662.0	1,266.6	1.4	122.1
Smooth flat	Number of samples	14	12	12	9	9	7	7
	Mean	20.9	.5	20.4	780.0	747.8	.6	142.9
	Range	28.7	2.4	22.0	1,690.0	2,600.0	2.1	160.0
	Standard deviation	8.9	.7	7.0	518.4	726.2	.8	70.9
Irregular slope	Number of samples	1	1	1	1	1	1	1
	Mean	31.0	1.1	30.0	150.0	700.0	4.1	309.0
	Range	0	0	0	0	0	0	0
	Standard deviation	ND	ND	ND	ND	ND	ND	ND
Shoreline flat	Number of samples	1	1	1	0	0	0	0
	Mean	1.7	0	1.7	ND	ND	ND	ND
	Range	0	0	0	ND	ND	ND	ND
	Standard deviation	ND	ND	ND	ND	ND	ND	ND
B. Samples from the Potomac transition division								
Channel	Number of samples	16	16	16	9	9	9	9
	Mean	22.9	.3	22.8	1,381.1	2,600.0	2.1	237.0
	Range	11.0	.6	11.0	970.0	1,600.0	6.9	277.0
	Standard deviation	3.5	.2	3.6	310.2	444.4	2.7	100.5
Smooth flat	Number of samples	13	13	13	4	4	4	4
	Mean	19.6	.3	19.5	1,040.0	2,675.0	.8	115.5
	Range	12.0	1.2	11.0	420.0	1300.0	3.3	118.0
	Standard deviation	4.0	.4	3.9	181.1	618.5	1.6	54.3
Irregular slope	Number of samples	11	11	11	5	5	5	5
	Mean	7.1	.2	6.9	480.0	536.0	.8	20.4
	Range	14.8	1.3	13.8	410.0	830.0	3.2	21.0
	Standard deviation	5	.4	4.8	171.0	331.1	1.4	7.5
Shoreline flat	Number of samples	3	3	3	2	2	2	2
	Mean	8.0	.4	7.7	245.0	505.0	4.8	10.0
	Range	11.5	1.3	10.5	110.0	50.0	5.6	0
	Standard deviation	5.8	.8	5.3	77.8	35.4	4.0	0

C. Samples from the Potomac estuary division								
Channel	Number of samples	21	21	21	9	9	9	9
	Mean	22.7	.8	22.1	546.7	3,644.4	3.3	270.0
	Range	27.4	2.5	28.9	400.0	4,400.0	3.9	655.7
	Standard deviation	6.9	.7	6.8	131.4	1,220.8	1.4	270.5
Smooth flat	Number of samples	2	2	2	2	2	2	2
	Mean	21.5	.6	21.0	795.0	2,750.0	4.8	92.5
	Range	3.0	.4	2.0	210.0	500.0	2.8	35.0
	Standard deviation	2.1	.3	1.4	148.5	353.6	2.0	24.7
Irregular slope	Number of samples	12	12	12	6	6	6	6
	Mean	4.3	.4	3.9	122.5	211.7	1.4	13.0
	Range	18.5	1.4	18.6	270.0	536.0	1.1	20.2
	Standard deviation	6.0	.5	6.2	100.8	189.0	.4	6.9
Shoreline flat	Number of samples	4	4	4	4	4	4	4
	Mean	.7	.1	.6	198.7	243.7	2.3	13.0
	Range	.6	.2	.8	435.0	355.0	3.6	27.6
	Standard deviation	.3	.1	.4	199.0	164.9	1.7	11.9
D. Samples from the Potomac tributaries								
Channel	Number of samples	31	25	25	19	19	13	13
	Mean	23.9	.4	23.2	1,796.8	1,676.8	2.3	177.2
	Range	41.8	2.2	40.9	7,650.0	3,050.0	7.9	322.0
	Standard deviation	8.4	.5	9.0	2,303.7	972.9	2.7	118.6
Smooth flat	Number of samples	10	9	9	9	9	8	8
	Mean	26.5	.3	26.2	1,361.1	1,487.8	1.8	142.3
	Range	18.0	.3	18.0	2,340.0	3,920.0	7.3	119.0
	Standard deviation	5.3	.1	5.6	789.4	1,463.5	2.8	41.9
Irregular slope	Number of samples	2	2	2	0	0	0	0
	Mean	8.8	.2	8.8	ND	ND	ND	ND
	Range	2.3	.3	2.4	ND	ND	ND	ND
	Standard deviation	1.6	.2	1.7	ND	ND	ND	ND
Shoreline flat	Number of samples	5	5	5	3	3	3	3
	Mean	5.2	1.0	4.2	233.3	658.7	1.7	19.7
	Range	9.5	2.6	9.5	330.0	1,024.0	.9	23.8
	Standard deviation	3.7	1.2	3.9	187.7	526.4	.5	12.1

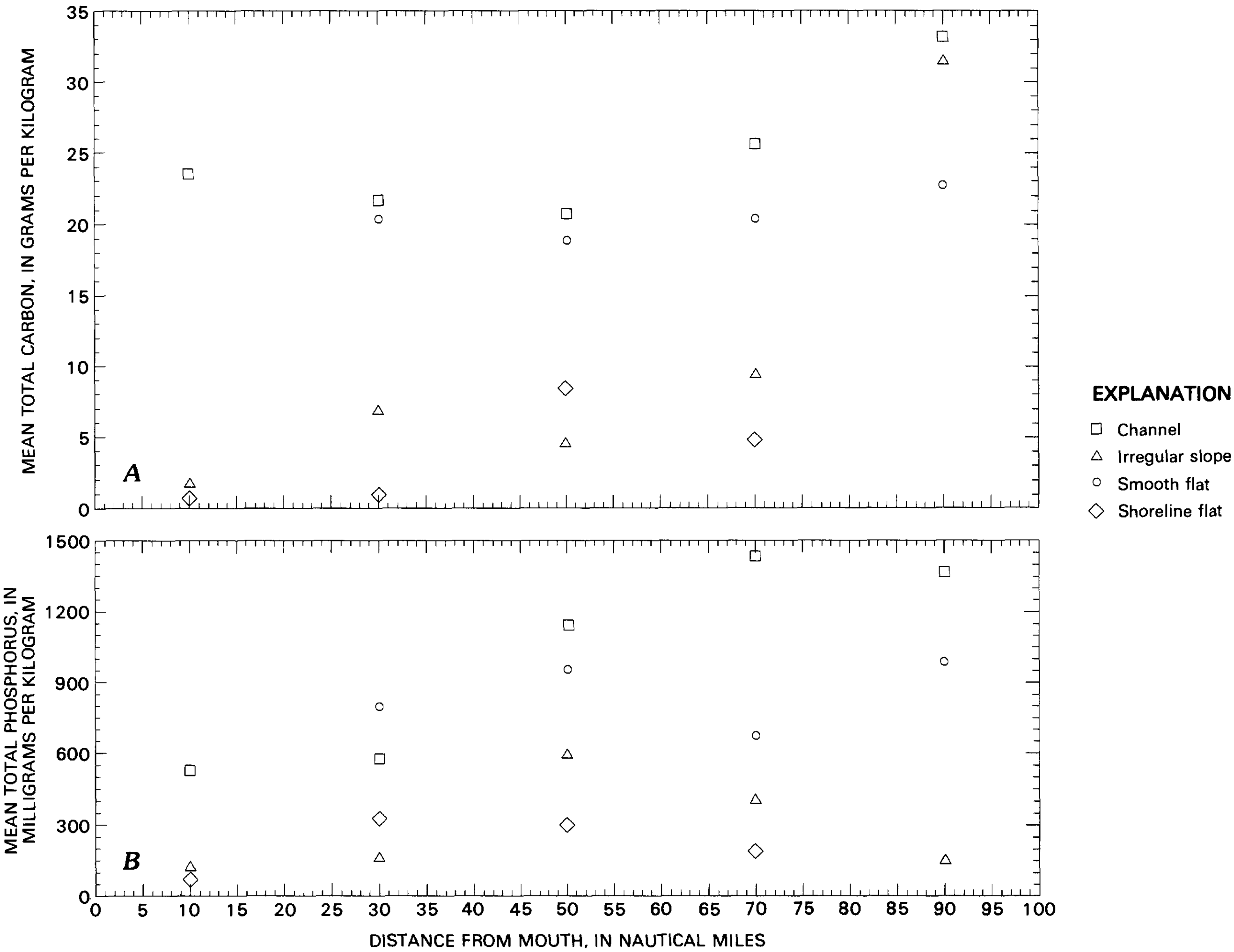


Figure 9. Variations in mean concentrations of selected nutrients in all samples from each geomorphic unit in each nautical-mile division: *A*, Total carbon; and *B*, Total phosphorus.

are computed, the relative order of concentrations in geomorphic units is channel > smooth flat > irregular slope > shoreline flat for five of six nutrients (organic carbon was excluded because it is computed by difference rather than determined directly). Relative to shoreline flats, the concentration ratios (by weight) of the four geomorphic units for total carbon, total phosphorus, and total nitrogen are about 7:5:2:1 for each nutrient; for inorganic carbon, the concentration ratio is about 4:2:2:1 and for ammonia, the ratio is about 18:10:3:1. Only nitrite plus nitrate, one of the more poorly defined and highly variable nutrient species, shows concentration ratios for the geomorphic units that deviate from the above order; that is, for nitrite plus nitrate, the shoreline flat has the largest mean concentrations followed by the channel, the irregular slope, and the smooth flat.

Trends along the Potomac mainstem in mean nutrient concentrations in sediments from each geomorphic unit are shown by plots of means for samples from the 5-nmi divisions. Unlike means for all samples from a division, means for geomorphic units are unaffected by differences in numbers of samples from units with greatly different concentrations. Means of total carbon and total phosphorus for all samples from each geomorphic unit in each nmi division are plotted at the mid points (10, 30, 50, 70, and 90) of the divisions in figures 9*A* and 9*B*. A plot of means for total nitrogen reveals essentially the same trends as the plot for total carbon reveals. For both total carbon and total phosphorus, the channel is represented by more samples in each division than are other geomorphic units, and trends among divisions in mean nutrient concentrations of channel sediments probably are more reliable. Low concentrations and few samples make the trends in means for the irregular slope or the shoreline flat particularly questionable.

Mean total carbon concentrations in sediments from the channel decrease sharply and steadily in a seaward direction between nmi divisions from the upper tidal Potomac (fig. 9*A*) and increase slightly in divisions from the middle part (nmi 50) to the mouth. For total phosphorus, the mean for sediments from the channel increases slightly between nmi divisions in the upper tidal Potomac and decreases from nmi 70 to the mouth. Most phosphorus decrease occurs between nmi 70 and the upper estuary; very little change occurs between the upper estuary and the lower estuary. Carbon trends in sediments from the smooth flat are basically the same as carbon trends in the channel (fig. 9*A*), but phosphorus means for sediments from smooth flats do not change appreciably between nmi divisions.

Lateral trends in nutrient concentrations have been described for sediment samples assigned to geomorphic units. If depth units replace geomorphic units as the lateral classification variable, increasing nutrient concentrations with increasing water depth are shown by some cross sections. Most cross sections with reasonably good relations are in the estuary division (fig. 10*A*), a few are in the transition division, but no cross sections with good relations are in the river division. Even in the estuary division, concentrations of some nutrients increase uniformly with increase in depth, but concentrations of other nutrients in the same cross section may only crudely increase with depth. Total carbon (fig. 10*A*), organic carbon, and ammonia nitrogen increase uniformly as depth increases for samples from the estuary, but inorganic carbon, total phosphorus, nitrite plus nitrate, and total nitrogen concentrations generally only crudely increase. Each cross section also seems to show slightly different concentration-depth relations, with the result that a plot including all data for the estuary division will show much scatter.

If mean concentrations of nutrients for all samples from a depth unit in each hydrologic division are computed, samples from shallow water usually have smaller mean concentrations than samples from deep water. Data for total carbon illustrate this point (fig. 10*B*). In addition, carbon data for samples from comparable depths typically show decreasing concentrations among hydrologic divisions toward the mouth of the Potomac (see data for depth = 0–2 m, >2–4 m, >4–6 m, and >8–10 m, fig. 10*B*). Samples from the >6–8 m depth are an exception to these patterns. Carbon seems to be preferentially concentrated in sediments of this depth unit throughout the Potomac mainstem, but particularly in the estuary division (fig. 10*B*).

Atomic ratios of organic carbon (C), organic nitrogen (N), and total phosphorus (P) for 94 samples of tidal Potomac sediments having carbon, nitrogen, phosphorus, nitrite + nitrate and ammonia data (table 1) are shown in table 13. These ratios are often used to infer sources of organic materials and geochemical reactions involving ratio components. The average C:N:P ratio is about 94:8:1, and the average C:N ratio is about 12. These ratios are typical of sediments in which the bulk of the organic material is allochthonous and terrestrial in origin (Giordani and Angiolini, 1983, p. 164; Muller, 1977, p. 765). The distribution of ratios in geomorphic units along the Potomac mainstem (table 13) indicates a substantial range in all ratios (fig. 11*A*, 11*B*, 11*C*). For ratios involving phosphorus (fig. 11*A*, 11*B*), the greatest range is in the river division and is mostly attributed to a sample from each geomorphic unit with a large ratio. Because C:N ratios (fig. 11*C*) and carbon and nitrogen concentrations (fig. 8*C*, 8*D*) for these samples are normal, anomalously low phosphorus concentrations cause the large C:P and N:P ratios. No explanation was apparent for low phosphorus concentrations. A few samples in each division have anomalously large C:N ratios (fig. 11*C*). The majority of these samples are from coarse-grained sediments on irregular slopes or shoreline flats that contain low concentrations of carbon (fig. 8*C*) and even lower concentrations of nitrogen (fig. 8*D*).

Clear differences in any ratio among geomorphic units or among hydrologic divisions generally are not apparent. Ratios of C:P and N:P in sediments from the estuary division indicate that sediments from channels (fig. 11*A* and 11*B*) have larger ratios than sediments from shoreline flats or irregular slopes. C:N ratios for sediments from the estuary division, however, do not show a similar separation among these geomorphic units (fig. 11*C*). Trends in ratios among sediments from the hydrologic divisions are not obvious except possibly for larger C:P and N:P ratios in sediments from channels of the estuary division than in sediments from channels of the river or the transition divisions. The C:N ratio is not obviously lower in the river division than in the other hydrologic divisions, as the ratio should be if sewage treatment plants are dominant sources of carbon and nitrogen (Jones and Jordan, 1979, p. 43; Gross, 1976), nor is the ratio obviously smaller in the transition and the estuary divisions, as it should be if large amounts of organic matter are produced by estuarine organisms (Pocklington, 1976, p. 95; Rashid and Reinson, 1979, p. 30).

The statistical significance of longitudinal and lateral trends in mean nutrient concentrations in tidal Potomac sediments also was determined using SAS programs. The nutrient data base is smaller than the particle-size data base (table 1), and statistical tests involving nutrients and large numbers of independent class variables, such as nmi division (five divisions) combined with depth unit (nine units) are limited in value. The statistical significance of trends and variations in mean nutrient concentrations for sediment samples assigned to hydrologic divisions and geomorphic units in the Potomac mainstem is shown in the first seven rows of table 14, and the significance of selected nutrient trends using depth units or nmi divisions in combination with hydrologic divisions or geomorphic units is shown in the last six rows.

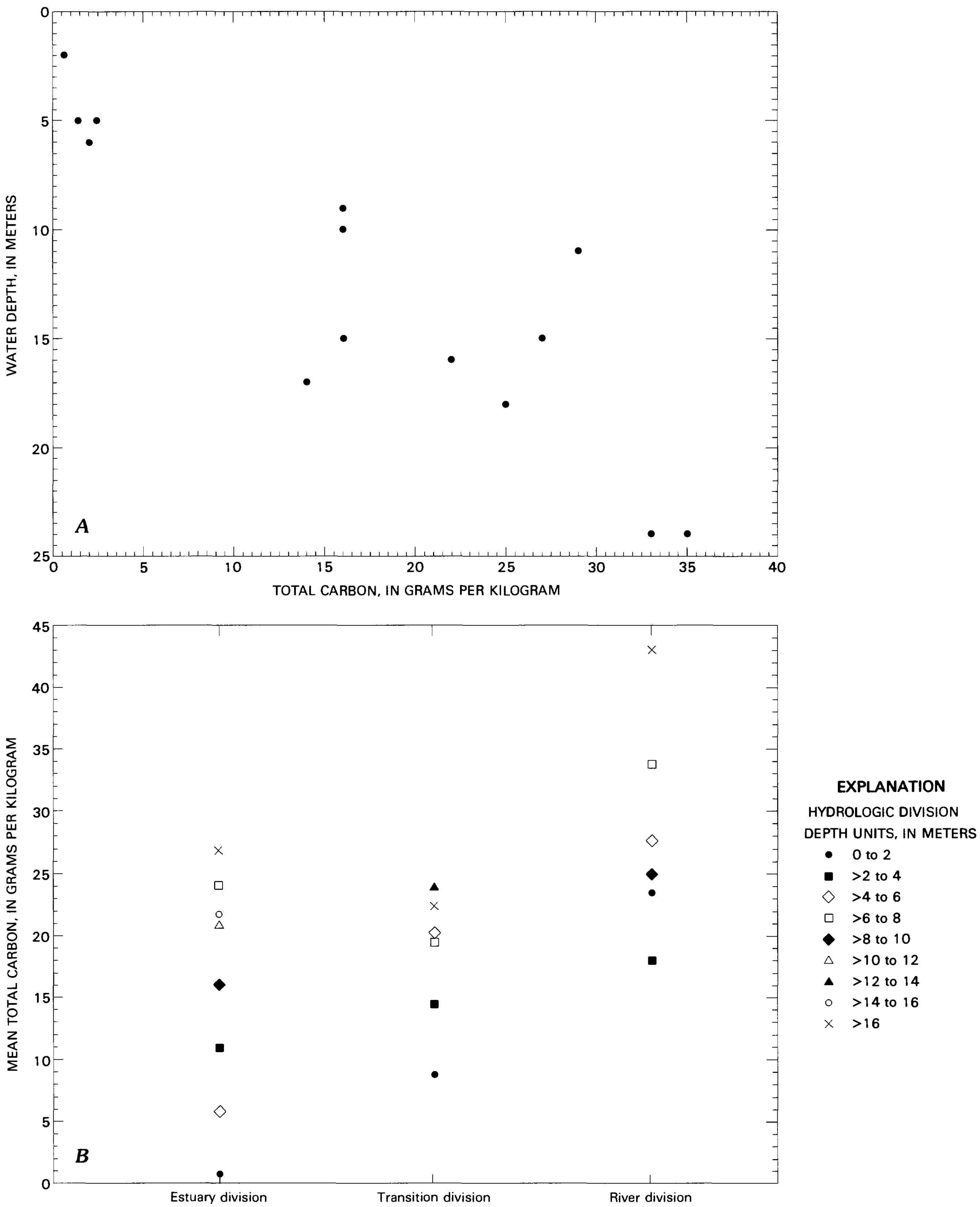


Figure 10. Variations in mean total carbon concentrations with water depth or depth units for samples from the *A*, Cross section near nautical mile 13 in the estuary division; and *B*, Potomac mainstem hydrologic divisions.

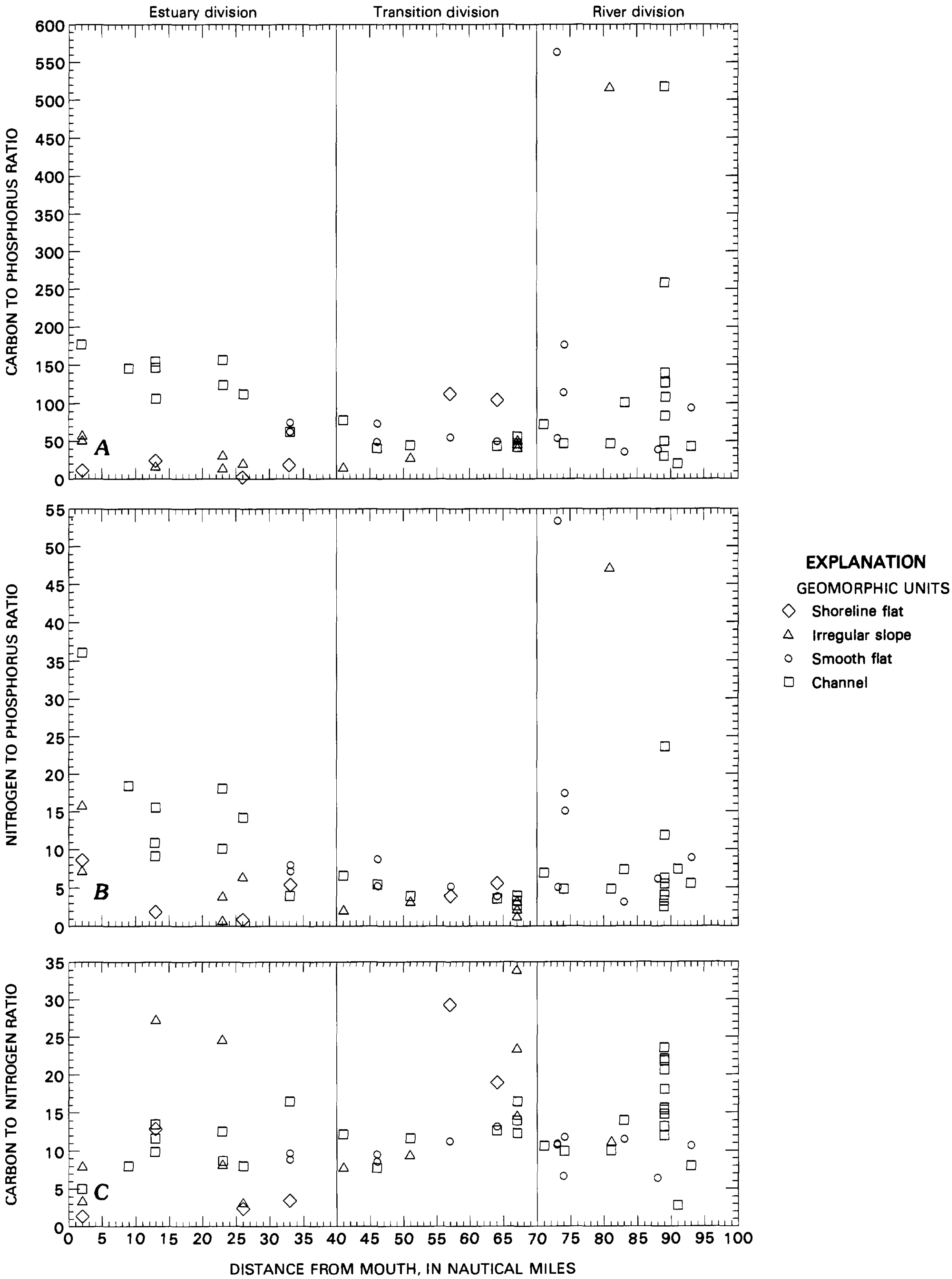


Figure 11. Variations in carbon, nitrogen, and phosphorus ratios for samples from the mainstem: *A*, Carbon:Phosphorus; *B*, Nitrogen:Phosphorus; and *C*, Carbon:Nitrogen.

Table 13. Nutrient ratios (atomic) for near-surface samples of bottom sediments

Sample number	Hydrologic division	Nautical mile 1/	Nautical mile division 2/	Geomorphic unit	Water depth (meters)	Depth unit 3/	Nutrient ratio C:P	Nutrient ratio N:P	Nutrient ratio C:N
A. 1978 US BM-54 samples from the Potomac mainstem									
11	River	93	N5	Smooth flat	2	D0	93	9	11
12	River	93	N5	Channel	6	D2	43	5	8
27	River	91	N5	Channel	9	D4	20	7	3
31	River	90	N5	Other	4	D1	48	3	15
33	River	89	N5	Channel	8	D3	83	4	21
34	River	89	N5	Channel	8	D3	49	3	15
35	River	89	N5	Channel	8	D3	50	4	13
36	River	89	N5	Channel	8	D3	49	3	15
37	River	89	N5	Channel	8	D3	50	3	16
38	River	89	N5	Channel	9	D4	30	2	12
39	River	89	N5	Channel	8	D3	139	6	22
40	River	89	N5	Channel	8	D3	126	5	23
41	River	89	N5	Channel	8	D3	517	24	22
42	River	89	N5	Channel	8	D3	258	12	22
43	River	89	N5	Channel	8	D3	109	6	18
45	River	89	N5	Other	2	D0	21	2	9
49	River	88	N5	Smooth flat	2	D0	39	6	6
64	River	83	N5	Smooth flat	2	D0	36	3	11
66	River	83	N5	Channel	21	D8	101	7	14
75	River	81	N5	Channel	8	D3	47	5	10
76	River	81	N5	Irregular slope	6	D2	517	47	11
80	River	74	N4	Smooth flat	2	D0	115	17	7
83	River	74	N4	Smooth flat	3	D1	176	15	12
84	River	74	N4	Channel	8	D3	47	5	10
88	River	73	N4	Smooth flat	3	D1	564	53	11
89	River	73	N4	Smooth flat	4	D1	54	5	11
105	River	71	N4	Channel	7	D3	72	7	10
126	Transition	67	N4	Other	9	D4	144	3	42
127	Transition	67	N4	Irregular slope	7	D3	40	1	34
128	Transition	67	N4	Irregular slope	7	D3	45	3	14
129	Transition	67	N4	Irregular slope	7	D3	50	2	23
130	Transition	67	N4	Channel	8	D3	56	4	14
131	Transition	67	N4	Channel	8	D3	45	3	16
132	Transition	67	N4	Channel	8	D3	47	4	12
133	Transition	67	N4	Channel	8	D3	44	3	14
134	Transition	67	N4	Channel	8	D3	42	3	14
136	Transition	64	N4	Shoreline flat	2	D0	103	5	19
139	Transition	64	N4	Smooth flat	5	D2	50	4	13
140	Transition	64	N4	Channel	8	D3	44	3	13
143	Transition	57	N3	Shoreline flat	2	D0	112	4	29
145	Transition	57	N3	Smooth flat	6	D2	55	5	11
171	Transition	51	N3	Irregular slope	2	D0	28	3	9
172	Transition	51	N3	Channel	14	D6	44	4	11
191	Transition	46	N3	Smooth flat	3	D1	49	5	9
192	Transition	46	N3	Channel	17	D8	41	5	8
194	Transition	46	N3	Smooth flat	3	D1	73	9	9
228	Transition	41	N3	Channel	11	D5	78	6	12
229	Transition	41	N3	Irregular slope	2	D0	15	2	8
230	Transition	41	N3	Other	11	D5	39	4	11

238	Estuary	33	N2	Smooth flat	3	D1	75	8	10
239	Estuary	33	N2	Smooth flat	6	D2	63	7	9
241	Estuary	33	N2	Channel	9	D4	63	4	16
244	Estuary	33	N2	Shoreline flat	2	D0	18	5	3
275	Estuary	26	N2	Shoreline flat	2	D0	2	1	2
277	Estuary	26	N2	Channel	8	D3	113	14	8
280	Estuary	26	N2	Irregular slope	2	D0	19	6	3
282	Estuary	23	N2	Irregular slope	4	D1	14	1	24
284	Estuary	23	N2	Channel	8	D3	124	10	12
285	Estuary	23	N2	Irregular slope	6	D2	31	4	8
286	Estuary	23	N2	Channel	8	D3	156	18	9
303	Estuary	13	N1	Shoreline flat	2	D0	23	2	13
306	Estuary	13	N1	Channel	11	D5	154	16	10
307	Estuary	13	N1	Channel	24	D8	146	11	13
308	Estuary	13	N1	Channel	24	D8	106	9	12
323	Estuary	9	N1	Channel	10	D4	146	18	8
334	Estuary	2	N1	Shoreline flat	2	D0	11	9	1
335	Estuary	2	N1	Irregular slope	10	D4	52	16	3
336	Estuary	2	N1	Channel	12	D5	177	36	5
337	Estuary	2	N1	Irregular slope	6	D2	57	7	8
339	Estuary	13	N1	Irregular slope	6	D2	15	1	27
B. 1978 US BM-54 samples from the Potomac tributaries									
16	4/	1	N1	Channel	7	D3	32	2	14
19	4/	1	N1	Channel	7	D3	39	3	14
26	4/	0	N1	Channel	3	D1	135	10	13
51	4/	0	N1	Channel	2	D0	83	5	16
53	4/	1	N1	Channel	5	D2	11	1	10
62	4/	0	N1	Smooth flat	2	D0	32	3	10
68	4/	1	N1	Smooth flat	2	D0	27	3	10
73	4/	0	N1	Smooth flat	4	D1	29	2	15
78	4/	0	N1	Smooth flat	3	D1	68	6	11
90	4/	0	N1	Smooth flat	3	D1	105	11	10
109	4/	0	N1	Smooth flat	3	D1	404	43	9
111	4/	2	N1	Channel	7	D3	351	19	19
149	4/	0	N1	Shoreline flat	2	D0	21	4	5
151	4/	2	N1	Channel	2	D0	109	8	14
199	4/	2	N1	Channel	1	D0	56	3	18
246	4/	1	N1	Smooth flat	2	D0	69	6	11
253	4/	2	N1	Channel	11	D5	95	5	20
260	4/	5	N1	Channel	3	D1	86	9	10
263	4/	7	N1	Smooth flat	1	D0	93	9	11
325	4/	1	N1	Shoreline flat	2	D0	30	1	26
326	4/	2	N1	Channel	3	D1	134	12	12
329	4/	2	N1	Channel	8	D3	224	26	9
330	4/	2	N1	Shoreline flat	2	D0	237	20	12
332	4/	7	N1	Channel	2	D0	129	10	14

1/ Sample location in nautical miles from the Potomac River mouth or from the tributary mouth.
2/ Nautical mile (nmi) division; N1 = 0 to 20 nmi; N2 = >20 to 40 nmi; N3 = >40 to 60 nmi; N4 = >60 to 80 nmi; N5 = >80 to 100 nmi.
3/ Depth unit; D0 = 0 to 2 m (meter); D1 = >2 to 4 m; D2 = >4 to 6 m; D3 = >6 to 8 m; D4 = >8 to 10 m; D5 = >10 to 12m; D6 = > 12 to 14 m; D7 = >14 to 16 m; D8 = >16 m.
4/ Not identified in Potomac tributaries.

Table 14. Statistical significance of longitudinal and lateral variations (independent variable) in concentrations of nutrients (dependent variable) in Potomac mainstem sediments

[F=F statistic; SAS, 1982, p. 114]

Dependent variable	Independent variables: Longitudinal division	Independent variables: Lateral unit	Number of samples	Probability of a greater F: Overall	Probability of a greater F: Longitudinal division	Probability of a greater F: Lateral unit	Probability of a greater F: Interaction	Coefficient of determination [1/] (R^2)
Total carbon	Hydrologic	Geomorphic	128	0.0001	0.0158	0.0001	0.0262	0.662
Inorganic carbon	Hydrologic	Geomorphic	117	.0004	.2447	.1271	.2364	.265
Organic carbon	Hydrologic	Geomorphic	117	.0001	.0163	.0001	.0407	.660
Total phosphorus	Hydrologic	Geomorphic	77	.0001	.0977	.0001	.1811	.538
Total nitrogen	Hydrologic	Geomorphic	77	.0001	.0359	.0001	.0033	.658
Nitrite + nitrate	Hydrologic	Geomorphic	66	.0015	.3864	.4055	.0102	.385
Ammonia	Hydrologic	Geomorphic	66	.0001	.0734	.0005	.6469	.481
Total carbon	Hydrologic	Depth	128	.0001	.0001	.0001	.0617	.572
Total phosphorus	Hydrologic	Depth	77	.0058	.0017	.4411	.4602	.444
Total nitrogen	Hydrologic	Depth	77	.0001	.0339	.0004	.0020	.553
Total carbon	Nautical mile	Geomorphic	128	.0001	.0003	.0001	.2454	.681
Total phosphorus	Nautical mile	Geomorphic	77	.0001	.3328	.0005	.6850	.551
Total nitrogen	Nautical mile	Geomorphic	77	.0001	.3043	.0001	.0454	.677

1/ Applies to overall relation between dependent and independent variables.

Significant overall longitudinal and lateral trends for all nutrients are established by probabilities of a greater F that generally are equal to 0.0001 and that never exceed 0.0058 (table 14). The coefficient of determination for overall relations ranges from a minimum of 0.265 to a maximum of 0.681. Coefficients less than about 0.5000 characterize longitudinal and lateral trends for inorganic carbon, nitrite plus nitrate nitrogen and ammonia nitrogen and coefficients of about 0.5000 or more distinguish trends for total carbon, total nitrogen and total phosphorus. Total carbon and total nitrogen show larger coefficients of determination for all relations than total phosphorus (table 14). Little change in coefficients results from substituting depth unit for geomorphic unit or nmi division for hydrologic division in the relations, although coefficients for depth relations are uniformly smaller and coefficients for nmi divisions are uniformly larger. The probability of a greater F is significant in 10 of 13 relations (table 14) involving nutrients and lateral units, but the same is true for only 7 of 13 relations between nutrients and longitudinal divisions. Lateral variability in nutrient concentrations thus apparently contributes more to significant overall relations than longitudinal variability contributes. This observation also is supported by generally smaller probabilities of a greater F for relations of nutrients to lateral units than for relations of nutrients to longitudinal divisions (table 14).

Significant interaction effects are identified in 6 of 13 relations shown in table 14. For consistency, interaction is considered to be present in all subsequent statistical analyses of nutrient concentrations versus hydrologic divisions or versus geomorphic units, just as it was in all relations of particle size versus longitudinal divisions or lateral units. The results of these analyses are shown in table 15. Because of limited nutrient data, only results from combinations of nutrients and hydrologic divisions or geomorphic units are shown, although tests involving nutrients and nmi divisions or depth units also were done.

Significant differences in mean nutrient concentrations among hydrologic divisions are detected for 10 of 24 combinations of nutrients and geomorphic units (table 15). Significant differences in organic carbon are not shown in table 15, but they follow the same pattern as differences in total carbon. For the significant relations, the coefficient of determination ranges from 0.224 to 0.994 (table 15) and is small for significant relations involving nutrients in sediments from the channel (G3 in table 15). The small coefficients for channel sediments indicate that factors other than those accounted for by changing hydrologic conditions influence concentrations of nutrients in channels.

The relative order of independent variable means and the significance of differences among these means combine to indicate different nutrient trends among hydrologic divisions (table 15, rows 1–24). For total carbon, both the irregular slope (G2, table 15) and the channel show the same relative order (river(HR)>transition(HT)>estuary(HE)) of mean nutrient concentrations in sediments from the three hydrologic divisions, and sediments from both the irregular slope and the channel have significantly greater total carbon concentrations in the river division than in either the transition or the estuary divisions. No significant difference among hydrologic divisions in total carbon concentration can be detected for samples from any geomorphic unit in the transition and the estuary divisions (table 15). For inorganic carbon, the relative order of independent variable means indicates that the transition division has smaller concentrations in three of four geomorphic units; significant differences among hydrologic divisions, however, are limited to data from the channel (G3, table 15), where both the river and the estuary divisions contain significantly higher concentrations than the transition division, but channels of the river and the estuary divisions are not significantly different from one another.

The relative order of hydrologic division means for concentrations of total phosphorus indicates that sediments in geomorphic units from the transition division always have higher concentrations than sediments in the same geomorphic units in other divisions; the relative order in those hydrologic divisions having significantly different means is transition(HT)>river(HR)>estuary(HE) (table 15). The significant differences for concentrations of total phosphorus, however, are between the transition and the estuary divisions for sediment samples from irregular slopes (G2, table 15) and between the transition and the river divisions and the estuary division for sediment samples from channels (G3, table 15).

Little consistency exists among relative orders of independent variable means for nitrogen species (table 15). In five of the nine comparisons involving sediments from all three hydrologic divisions (no sediments from shoreline flats (G0) in the river division were analyzed for nitrogen) the river division has greater concentrations of the nitrogen species. In the remaining four comparisons, the estuary division has greater concentrations. Only five of nine comparisons show significantly different concentrations of nitrogen species among the hydrologic divisions (table 15). For three comparisons, the concentrations in the river division are greater than the concentrations in the transition division or than the concentrations in the transition and the estuary divisions; for two comparisons, concentrations in the estuary division are greater than concentrations in the river division or than concentrations in the transition and the river divisions.

The relations between the mean concentrations of six nutrient species (relations for organic carbon are the same as relations for total carbon) and geomorphic units in each hydrologic division are shown in table 15, rows 25–42. For 10 of 18 relations, mean nutrient

Table 15. Statistical significance of differences in individual means for selected relations from table 14 between concentrations of nutrients (dependent variable) and longitudinal divisions and lateral units (independent variable)

[F=F statistic; SAS, 1982, p. 114]

Dependent variable	Independent variable 1/	Number of samples	Sample location 1/	Probability of greater F	Coefficient of determination (R^2)	Relative order of dependent variable means 1/	Significantly different 2/ means 1/
Total carbon	H	8	G0	0.1062	0.592	HT>HR>HE	None
Total carbon	H	29	G1	.8670	.011	HE>HR>HT	None
Total carbon	H	24	G2	.0006	.503	HR>HT>HE	HR>HT,HE
Total carbon	H	67	G3	.0001	.262	HR>HT>HE	HR>HT,HE
Inorganic carbon	H	8	G0	.6195	.174	HT>HE>HR	None
Inorganic carbon	H	27	G1	.4834	.059	HE>HR>HT	None
Inorganic carbon	H	24	G2	.1833	.149	HR>HE>HT	None
Inorganic carbon	H	58	G3	.0009	.224	HR>HE>HT	HR,HE>HT
Total phosphorus	H	6	G0	.7775	.022	HT>HE	None
Total phosphorus	H	15	G1	.6106	.079	HT>HE>HR	None
Total phosphorus	H	12	G2	.0055	.685	HT>HR>HE	HT>HE
Total phosphorus	H	44	G3	.0010	.288	HT>HR>HE	HT,HR>HE
Total nitrogen	H	6	G0	.1041	.524	HT>HE	None
Total nitrogen	H	15	G1	.9676	.005	HE>HT>HR	None
Total nitrogen	H	12	G2	.0001	.938	HR>HT>HE	HR>HT,HE
Total nitrogen	H	44	G3	.0425	.143	HE>HR>HT	None
Nitrite + nitrate	H	6	G0	.3132	.249	HT>HE	None
Nitrite + nitrate	H	13	G1	.0062	.638	HE>HT>HR	HE>HT,HR
Nitrite + nitrate	H	12	G2	.0393	.513	HR>HE>HT	HR>HT

Nitrite + nitrate	H	35	G3	.0096	.252	HE>HT>HR	HE>HR
Ammonia	H	6	G0	.7550	.027	HE>HT	None
Ammonia	H	13	G1	.5729	.105	HR>HT>HE	None
Ammonia	H	12	G2	.0001	.994	HR>HT>HE	HR>HT,HE
Ammonia	H	35	G3	.6436	.027	HR>HE>HT	None
Total carbon	G	39	HE	.0001	.724	G3>G1>G2>G0	G3,G1>G2,G0;
Total carbon	G	43	HT	.0001	.739	G3>G1>G0>G2	G3,G1>G0,G2;
Total carbon	G	46	HR	.0008	.324	G3>G2>G1>G0	G3>G1,G0;
Inorganic carbon	G	39	HE	.1616	.135	G3>G1>G2>G0	None
Inorganic carbon	G	43	HT	.8730	.018	G0>G1>G3>G2	None
Inorganic carbon	G	35	HR	.1055	.177	G2>G3>G1>G0	None
Total phosphorus	G	21	HE	.0001	.773	G1>G3>G0>G2	G1,G3>G0,G2
Total phosphorus	G	20	HT	.0001	.793	G3>G1>G2>G0	G3,G1>G0,G2
Total phosphorus	G	36	HR	.0238	.203	G3>G1>G2	None
Total nitrogen	G	21	HE	.0001	.822	G3>G1>G0>G2	G3,G1>G0,G2
Total nitrogen	G	20	HT	.0001	.863	G1>G3>G2>G0	G1,G3>G0,G2
Total nitrogen	G	36	HR	.6485	.026	G2>G3>G1	None
Nitrite + nitrate	G	21	HE	.0155	.449	G1>G3>G0>G2	G1>G2
Nitrite + nitrate	G	20	HT	.2275	.231	G0>G3>G1>G2	None
Nitrite + nitrate	G	25	HR	.0610	.225	G2>G3>G1	None
Ammonia	G	21	HE	.0568	.350	G3>G1>G0>G2	None
Ammonia	G	20	HT	.0003	.681	G3>G1>G2>G0	G3>G2,G0
Ammonia	G	25	HR	.0138	.323	G2>G3>G1	G3>G1

1/ Symbols for variables and locations are: H = Hydrologic division; HT = Transition; HR = River; HE = Estuary.
G = Geomorphic unit; G0 = Shoreline flat; G1 = Smooth flat; G2 = Irregular slope; G3 = Channel.
N = Nautical mile (nmi) division; N1 = 0 to 20 nmi; N2 = >20 to 40 nmi; N3 = >40 to 60 nmi; N4 = >60 to 80 nmi; N5 = >80 to 100 nmi.
D = Depth unit; D0 = 0 to 2 m (meters); D1 = >2 to 4 m; D2 = >4 to 6 m; D3 = >6 to 8 m; D4 = >8 to 10 m; D5 = >10 to 12 m; D6 = >12 to 14 m; D7 = >14 to 16 m; D8 = >16 m.

2/ Five percent significance level.

concentrations in sediments within a hydrologic division vary significantly among geomorphic units. Inorganic carbon is the only nutrient that doesn't vary significantly among geomorphic units in any hydrologic division, but nitrite plus nitrate only varies among geomorphic units in the estuary division. The coefficient of determination for most significant relations of nutrients to geomorphic units is generally greater than the coefficient for the relations of the same nutrients to hydrologic division (table 15), which indicates that nutrient trends and variations within the Potomac mainstem are determined more by lateral variations than by longitudinal variations. Comparisons among coefficients in the hydrologic divisions indicate that the river division has smaller coefficients and fewer significantly different relations than either the estuary or the transition divisions have. Some factor(s) other than those accounted for by different geomorphic units is important in determining nutrient concentrations in the river division. The relative order of independent variable means shows that channels (G3, table 15) and smooth flats (G1) form a group that usually has large concentrations of all nutrients, and irregular slopes (G2) and shoreline flats (G0) form a group that generally has small concentrations. Significantly different means commonly are determined only for comparisons of samples from geomorphic units with largest and smallest concentrations, and rarely are detected for comparisons of samples from the different geomorphic units within a high or a low group.

The statistical significance of trends and variations in mean nutrient ratios for sediments from hydrologic divisions and geomorphic units of the Potomac mainstem is shown in table 16. The overall relations among ratios and hydrologic divisions and geomorphic units were significant in all examples, although coefficients of determination were small. Unlike most other significant overall relations, longitudinal variations or trends among hydrologic divisions had smaller probabilities of a greater F than lateral variations or trends among geomorphic units. Interaction was significant for C:P and N:P ratios, but not for the C:N ratio; subsequent tests assume that interaction is present in all instances.

Significant differences in nutrient ratios among hydrologic divisions indicate differences in nutrient sources or in geochemical and biological reactions as hydrologic conditions change. The statistical significance of differences in mean ratios among hydrologic divisions for sediments from each geomorphic unit depend on the ratio and on the geomorphic unit (table 17). Ratios of C:P and N:P generally showed significant changes in two of four geomorphic units, and ratios of C:N varied in one of four units. Ratios for sediments from the channel probably indicate trends along the Potomac mainstem more completely than ratios for sediments from the other geomorphic units because of larger numbers of samples (G3, table 17). Both the C:P and the N:P ratios for sediments from channels show the same relative order of hydrologic division means, estuary(HE)>river(HR)>transition(HT), but the C:P means were not significantly different among the divisions and the N:P means were significantly different (larger) only in the estuary division (table 17). Sediments in channels of the river and the transition divisions had relatively larger mean C:N ratios than sediments in the channels of the estuary division, but the ratios were not significantly different (table 17).

Ratios of C:P in sediments from a hydrologic division generally indicate the same relative order for geomorphic-unit means as ratios of N:P in sediments from the same hydrologic division (table 17); ratios of C:N, however, show different relative orders. No consistent pattern in significantly different C:P or N:P means exists among geomorphic units in the hydrologic divisions. For C:P ratios, sediments of channels (G3) in the estuary division have significantly larger ratios than sediments of smooth flats (G1), irregular slopes (G2), or shoreline flats (G0). Channels in the estuary apparently are relatively depleted in phosphorus or enriched in carbon compared to other geomorphic units in the estuary division. In the transition and the river divisions, however, channels usually have relatively smaller C:P ratios than most other geomorphic units and significantly smaller ratios than at least one other geomorphic unit. In these divisions, sediments of channels are enriched in phosphorus relative to carbon. The C:N ratios show no significantly different geomorphic-unit means and little consistency among hydrologic divisions in the relative order of geomorphic unit means.

Relations Between Particle Size and Nutrients

The plot of median particle size versus nmi shows that Potomac mainstem sediments include a fine- and a coarse-grained component (fig. 2*A*), and plots of nutrient concentrations versus nmi indicate that Potomac mainstem sediments include a group with large concentrations and a group with small concentrations (fig. 8*A*–*G*). Inspection of data in tables 3 and 10 indicates the large nutrient concentrations generally occur in fine-grained sediments, and small nutrient concentrations in coarse-grained sediments. Other workers also have noted that particle size and nutrient concentrations are related (Trask, 1932; Folger, 1972; Byrne and others, 1982; Kerhin and others, 1982). The relation of particle size and nutrient concentration for sediments from the Potomac mainstem was examined by using only the samples for which both types of data are available (tables 3 and 10). Mean particle-size measures and mean nutrient concentrations in these samples are generally similar to those for all available samples from the Potomac mainstem (table 18), so results from these analyses should be representative.

Table 16. Statistical significance of longitudinal and lateral variations (independent variable) in ratios of nutrients (dependent variable) in Potomac mainstem sediments

[F=F statistic; SAS, 1982, p. 114]

Dependent variable	Independent variables: Longitudinal division	Independent variables: Lateral unit	Number of samples	Probability of a greater F: Overall	Probability of a greater F: Longitudinal division	Probability of a greater F: Lateral unit	Probability of a greater F: Interaction	Coefficient of determination 1/ (R^2)
C:P	Hydrologic	Geomorphic	66	0.0007	0.0001	0.0885	0.0005	0.404
N:P	Hydrologic	Geomorphic	66	.0001	.0001	.0285	.0001	.478
C:N	Hydrologic	Geomorphic	66	.0165	.0073	.4667	.0741	.309

1/ Applies to overall relation between dependent and independent variables.

Table 17. Statistical significance of variations in individual means for selected relations from table 16 between ratios of nutrients (dependent variable) and longitudinal divisions and lateral units (independent variable)

[F=F statistic; SAS, 1982, p. 114]

Dependent variable	Independent variable 1/	Number of samples	Sample location 1/	Probability of greater F	Coefficient of determination (R^2)	Relative order of dependent variable means 1/	Significantly different 2/ means 1/
C:P	H	6	G0	0.0002	0.975	HT>HE	HT>HE
C:P	H	13	G1	.5360	.117	HR>HE>HT	None
C:P	H	12	G2	.0001	.989	HR>HT>HE	HR>HT,HE
C:P	H	35	G3	.1313	.119	HE>HR>HT	None
N:P	H	6	G0	.8420	.011	HT>HE	None
N:P	H	13	G1	.4904	.133	HR>HE>HT	None
N:P	H	12	G2	.0001	.912	HR>HE>HT	HR>HE,HT
N:P	H	35	G3	.0005	.375	HE>HR>HT	HE>HR,HT
C:N	H	6	G0	.0199	.779	HT>HE	HT>HE
C:N	H	13	G1	.7528	.055	HT>HR>HE	None
C:N	H	12	G2	.6901	.079	HT>HE>HR	None
C:N	H	35	G3	.0684	.154	HR>HT>HE	None
C:P	G	21	HE	.0001	.828	G3>G1>G2>G0	G3>G1,G2,G0
C:P	G	20	HT	.0001	.765	G0>G1>G3>G2	G0>G1,G3,G2
C:P	G	25	HR	.0317	.269	G2>G1>G3	G2>G3
N:P	G	21	HE	.0483	.364	G3>G1>G2>G0	None
N:P	G	20	HT	.0123	.484	G1>G0>G3>G2	G1>G2
N:P	G	25	HR	.0015	.446	G2>G1>G3	G2>G1,G3
C:N	G	21	HE	.4126	.151	G2>G3>G1>G0	None
C:N	G	20	HT	.0625	.359	G0>G2>G3>G1	None
C:N	G	25	HR	.0940	.193	G3>G2>G1	None

1/ Symbols for variables and locations are: H = Hydrologic division; HT = Transition; HR = River; HE = Estuary.
G = Geomorphic unit; G0 = Shoreline flat; G1 = Smooth flat; G2 = Irregular slope; G3 = Channel.
N = Nautical mile (nmi) division; N1 = 0 to 20 nmi; N2 = >20 to 40 nmi; N3 = >40 to 6>80 to 100 nmi
D = Depth unit; D0 = 0 to 2 m (meters); D1 = >2 to 4 m; D2 = >4 to 6 m; D3 = >6 to 8 m;
D4 = >8 to 10 m; D5 = >10 to 12 m; D6 = >12 to 14 m; D7 = >14 to 16 m; D8 = >16 m.

2/ Five percent significance level.

Table 18. Mean and standard deviation of selected variables (particle-size measures or nutrient concentrations) for groups of samples from Potomac mainstem hydrologic divisions
[Std, standard deviation]

Variable	Sample group	River division			Transition division			Estuary division		
		Number of samples	Mean	Std	Number of samples	Mean	Std	Number of samples	Mean	Std
Median	1/	52	6.53	2.15	51	6.90	3.25	63	6.28	3.29
	2/	28	6.45	2.06	43	6.87	3.25	38	6.55	3.45
	3/	18	6.32	1.80	20	6.14	3.50	20	5.68	3.48
Percentage of sand	1/	64	27	30.1	82	37	38.5	65	44	39.9
	2/	34	24	28.3	43	25	35.0	38	43	42.0
	3/	24	22	23.0	20	28	34.9	20	52	43.6
Total carbon	1/	51	27.9	12.5	45	18.1	11.3	39	14.7	11.3
	4/	28	25.1	12.3	43	16.8	8.0	38	15.1	11.3
	5/	34	26.3	12.5	43	16.8	8.0	38	15.1	11.3
Total phosphorus	1/	40	1,368	1,233	22	991	486	21	383	270
	4/	18	897	682	20	974	502	20	396	270
	5/	24	1,040	699	20	974	502	20	396	270

1/ All samples with analysis of the indicated variable.
2/ Only samples with analyses of the indicated variable and of total carbon.
3/ Only samples with analyses of the indicated variable and of total phosphorus.
4/ Only samples with analyses of the indicated variable and of the median size.
5/ Only samples with analyses of the indicated variable and of the percentage of sand.

The general nature of relations between particle size and nutrient concentrations in Potomac mainstem sediments is illustrated by plots of median size versus total carbon (fig. 12*A*) and of median size versus total phosphorus (fig. 12*B*). Plots of total nitrogen and of other nutrient species versus median size are generally similar to the plot for total carbon. Total carbon and total phosphorus concentrations increase as the median size (in phi) increases and the sediments become finer. Considerable scatter exists in most median-nutrient relations, outlying points occur, and different nutrients show different relations to median size. Part of the scatter may be explained by changing median-nutrient relations among the three hydrologic divisions of the Potomac mainstem (fig. 13*A*–*F*). In the river division, relations of total carbon (fig. 13*A*) and total phosphorus (fig. 13*B*) to median size are poorly defined and are characterized by more scatter than are the same relations in the transition (figs. 13*C*, 13*D*) and the estuary (figs. 13*E*, 13*F*) divisions. In addition, concentrations of some nutrients, particularly at large values of median size, seem to be greater (see carbon, fig. 13*A* versus carbon, fig. 13*C*) or smaller (see phosphorus, fig. 13*D* versus phosphorus, fig. 13*F*) in some divisions than in others.

The statistical significance of relations between nutrients and particle-size measures was determined with the GLM procedure. The results for total carbon and total phosphorus versus median size are representative and are shown in table 19. Both total carbon and total phosphorus for samples from the Potomac mainstem show significant relations to median particle size (table 9, row 1 and row 5). The coefficients of determination for these relations are generally small and are smaller for the phosphorus-median relation than for the carbon-median relation. If only Potomac mainstem samples from the river division are used in the statistical analyses, the carbon to median relation is significant (probability = 0.0392) although the R^2 is low, and the phosphorus to median relation is not significant (table 19). Phosphorus concentrations in the river division apparently are determined largely by some factor(s) other than median particle size, and carbon concentrations are determined in part by some other factor(s). Significant relations of both carbon and phosphorus concentrations to median size are shown by Potomac mainstem samples from the transition and the estuary divisions (table 19); the factor(s) active in the river division is not dominant in the transition and the estuary divisions.

Different nutrients within a hydrologic division may show different relations to median particle size (fig. 13*A* and *B*), and the relations for a nutrient may change among hydrologic divisions (fig. 13*B*, *D*, and *F*). The river division seems to differ from other divisions in carbon-median relations, and the estuary division seems to differ from other divisions in phosphorus-median relations. The statistical significance of these differences can be determined by GLM procedures using analyses for heterogeneity of slopes (SAS, 1982B; Freund and Littell, 1981, p. 187–205).

Results from tests designed to determine whether concentrations of nutrients in a hydrologic division depend on median particle size and on nutrient species are given in table 20. Test results are given for only the three major nutrient species: total carbon, total phosphorus and total nitrogen. Tests using all seven nutrients give essentially the same results. The probability of a greater

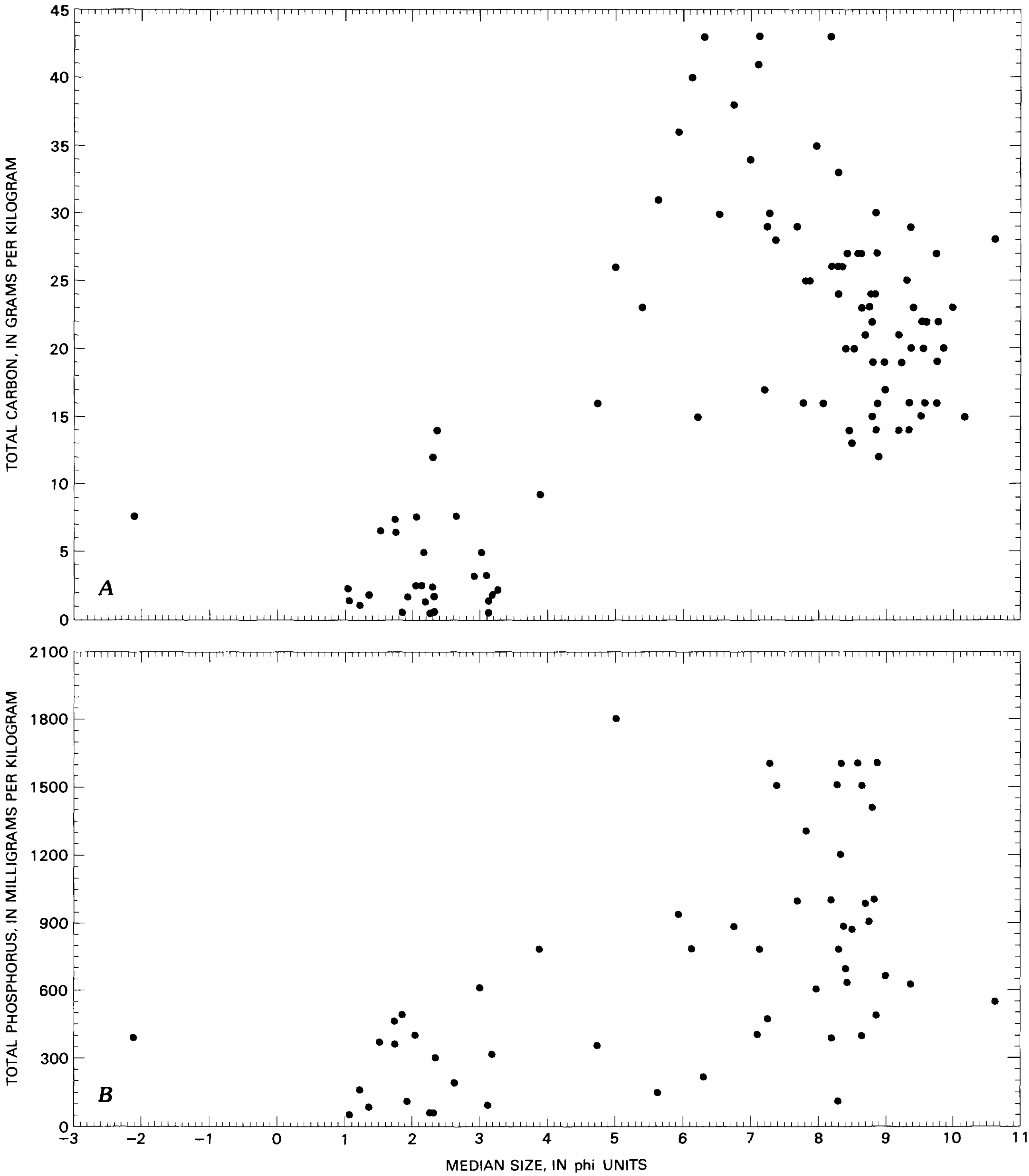


Figure 12. Relations between nutrient concentrations and median particle size in Potomac mainstem samples: *A*, total carbons. and *B*, Total phosphorus.

F for interaction is used to establish the significance of different regression relations (slopes) among nutrients and median size for samples from each hydrologic division (SAS, 1982B; Freund and Littell, 1981, p. 202). The interaction probability is significant in all tests, which indicates that at least one of the three nutrients shows a different slope in its nutrient concentration to particle size relation than the others show. Of the three major nutrients, total carbon and total nitrogen show visually similar slopes and the slope for total phosphorus probably

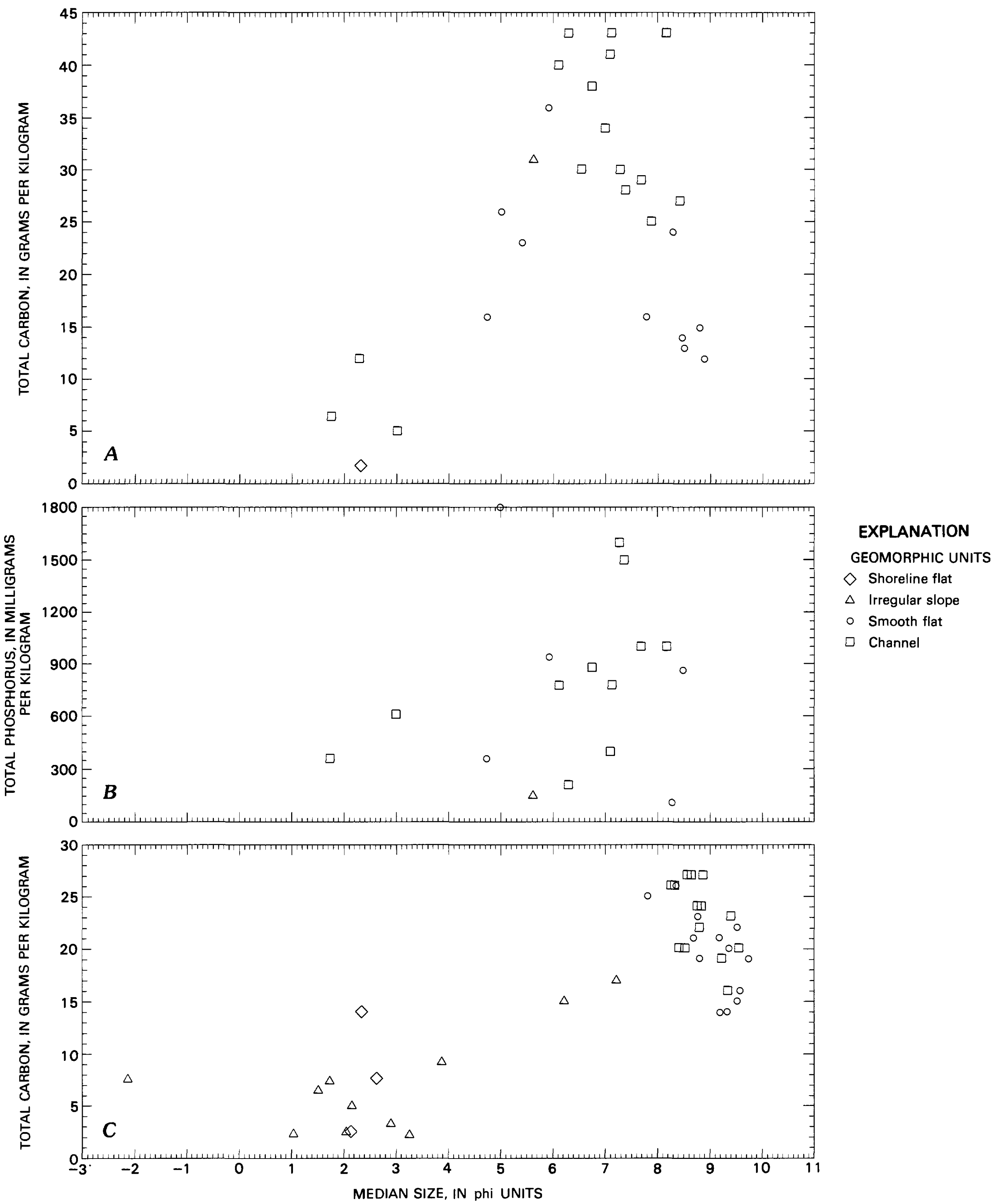
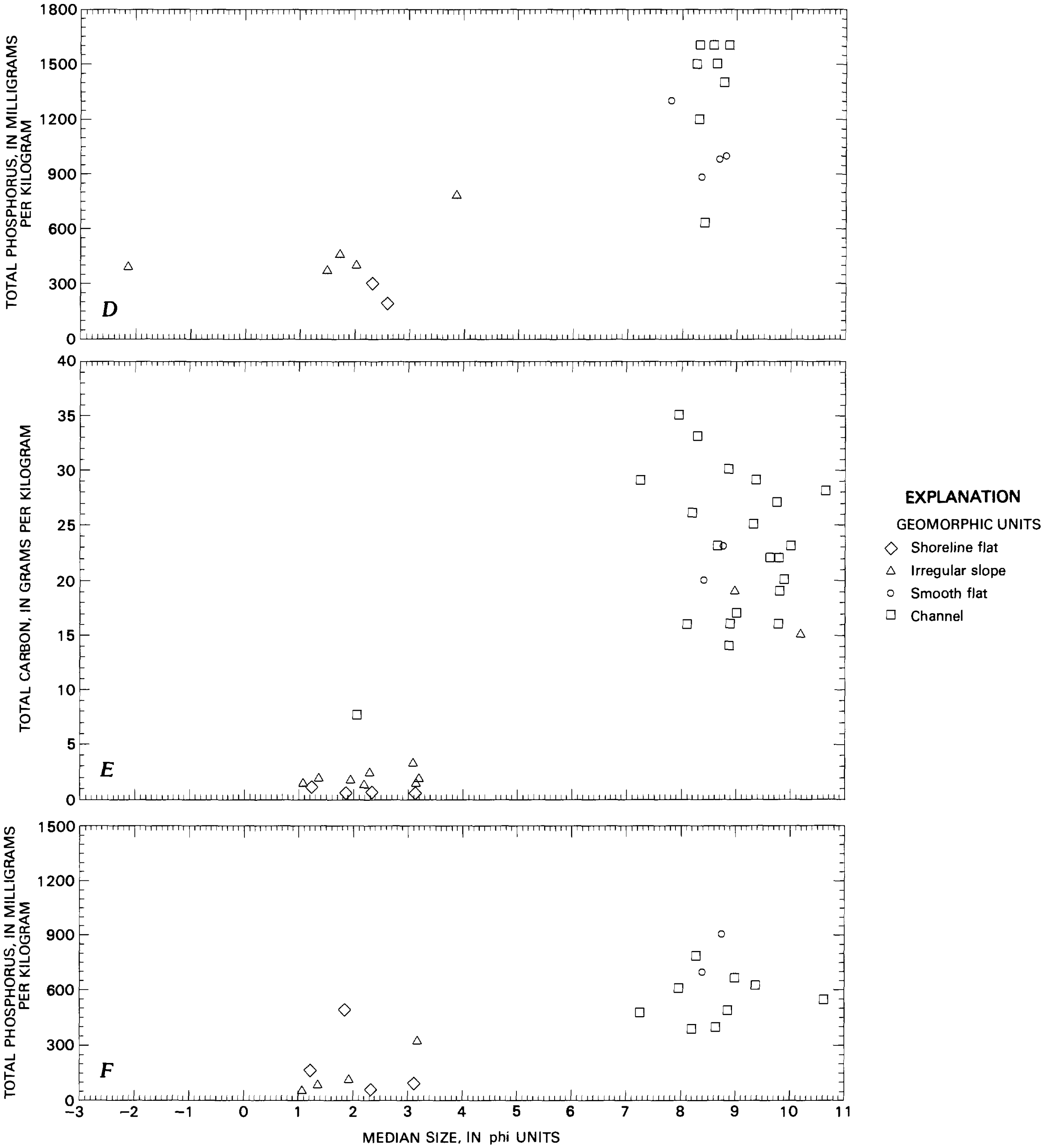


Figure 13 (above and facing page). Relations between nutrient concentrations and median size for samples from Potomac mainstem hydrologic divisions: *A*, Total carbon in the river division; *B*, Total phosphorus in the river division; *C*, Total carbon in the transition division; *D*, Total phosphorus in the transition division; *E*, Total carbon in the estuary division; and, *F*, Total phosphorus in the estuary division.



is different (compare carbon and phosphorus regression coefficients in table 19). The dominantly organic nutrients, carbon and nitrogen, apparently show one relation to particle size, and the mostly inorganic nutrient, phosphorus, shows a different relation.

Changing relations between nutrients and particle size among the three mainstem hydrologic divisions could indicate new sources of sediments and nutrients and (or) uptake and release of nutrients as the hydrologic environments change. The significance of changes is indicated by results in table 21 for both original and logarithmic transformations of concentrations of three nutrients: total carbon, total phosphorus, and total nitrogen. The regression relations in each hydrologic division for original concentrations of total carbon and total phosphorus are shown in table 19. The probability of a greater F for the interaction effect again establishes whether regression coefficients of the relations are significantly different in the three hydrologic divisions.

The three nutrients show different relations between concentrations and median size in the three hydrologic divisions (table 21). Original and transformed data for total nitrogen show significantly different relations to median in the three hydrologic divisions, original and transformed data for total phosphorus show no significant differences, and the significance of differences for total carbon depends on whether original or transformed data are used as input (table 21). Logarithmic transformations result in lower probabilities of a greater F, but the lower probability does not change the test results except for the total carbon to median relation. For this relation, original data indicate no significant differences in the relation among hydrologic divisions but transformed data indicate significant differences (table 21). The logarithmic transformation does result in generally smaller probabilities of a greater F for interaction and hydrologic division effects and in generally larger coefficients of determination for the overall relation (table 21).

Because nutrient concentrations are highly dependent on particle size, trends in nutrient concentrations along the Potomac mainstem (figs. 8*A*–*G*) were examined to see if factors other than particle-size differences are involved. Potomac mainstem samples were grouped into classes with a narrow range (10 percent clay; median = 2 phi) in selected particle-size measures so as to minimize the possible effects of particle-size changes. Nutrient concentrations in samples from each clay class and from each median phi class were plotted against the sample location in nautical miles from the Potomac mouth, and the plots were inspected for trends. Trends in total carbon, total nitrogen and total phosphorus in all mainstem samples whose median particle size is less than 2 μm (8 phi) are representative and are shown in figures 14*A*–*C*. All but two of these fine-grained sediment samples came from the channel or the smooth flat geomorphic units.

Total carbon (fig. 14*A*) and total nitrogen (fig. 14*B*) in texturally similar samples (mean and standard deviation of the median size is equal to 9.00±0.58 phi) from the Potomac mainstem generally show similar distributions; no well-defined longitudinal trends are evident, but sediments from the estuary and the river divisions are more variable than sediments from the transition division. Total phosphorus shows a fairly well defined

Table 19. Relations between concentrations of selected nutrients (dependent variable) and median particle size (independent variable) for samples from the Potomac mainstem and the mainstem hydrologic divisions

[F = F statistic; SAS, 1982, p. 114]

Variable: Dependent	Variable: Independent	Source of samples	Number of samples	Probability of greater F	Coefficient of determination (R^2)	Regression equation
Total carbon	Median	Potomac mainstem	109	0.0001	0.418	Total carbon = 2.7+2.4 (median)
Total carbon	Median	River division	28	.0392	.154	Total carbon = 9.9+2.3 (median)
Total carbon	Median	Transition division	43	.0001	.664	Total carbon = 3.2+2.0 (median)
Total carbon	Median	Estuary division	38	.0001	.745	Total carbon = -3.4+2.8 (median)
Total phosphorus	Median	Potomac mainstem	58	.0001	.269	Total phosphorus = 170+96 (median)
Total phosphorus	Median	River division	18	.3934	.046	Total phosphorus = 384+81 (median)
Total phosphorus	Median	Transition division	20	.0001	.677	Total phosphorus = 250+118 (median)
Total phosphorus	Median	Estuary division	20	.0001	.668	Total phosphorus = 36+63 (median)

Table 20. Statistical significance of regression relations between nutrient concentration, median particle size, and nutrient species for samples from each Potomac mainstem hydrologic division

[F=F statistic; SAS, 1982, p. 114]

Hydrologic division	Dependent variable	Independent variables		Number of samples	Probability of greater F				Coefficient of determination [1/] (R^2)
		Size	Species		Overall	Median	Nutrient	Interaction	
Estuary	Nutrient concentration	Median	Nutrient [2/]	78	.0001	.0001	.0001	.0001	.836
Transition	Nutrient concentration	Median	Nutrient [2/]	83	.0001	.0001	.0001	.0001	.930
River	Nutrient concentration	Median	Nutrient [2/]	64	.0001	.0573	.0001	.0167	.869

1/ Applies to the overall relation.
2/ Total carbon, total phosphorus and total nitrogen only.

Table 21. Statistical significance of differences in regression coefficient for relations of concentrations of selected nutrients (dependent variable) and the logarithm (log) of concentrations to median in different hydrologic divisions

[F=F statistic; SAS, 1982, p. 114]

Dependent variable	Independent variables		Number of samples	Probability of greater F				Coefficient of determination [1/] (R^2)
	Size	Longitudinal division		Overall	Median	Hydrologic division	Interaction	
Total carbon	Median	Hydrologic	109	0.0001	0.0001	0.0001	0.2462	0.58
Log total carbon	Median	Hydrologic	109	.0001	.0001	.0001	.0001	.76
Total phosphorus	Median	Hydrologic	58	.0001	.0001	.0005	.3918	.49
Log total phosphorus	Median	Hydrologic	58	.0001	.0001	.0001	.1986	.61
Total nitrogen	Median	Hydrologic	58	.0001	.0001	.0026	.0449	.73
Log total nitrogen	Median	Hydrologic	58	.0001	.0001	.0001	.0002	.84

1/ Applies to the overall relation.

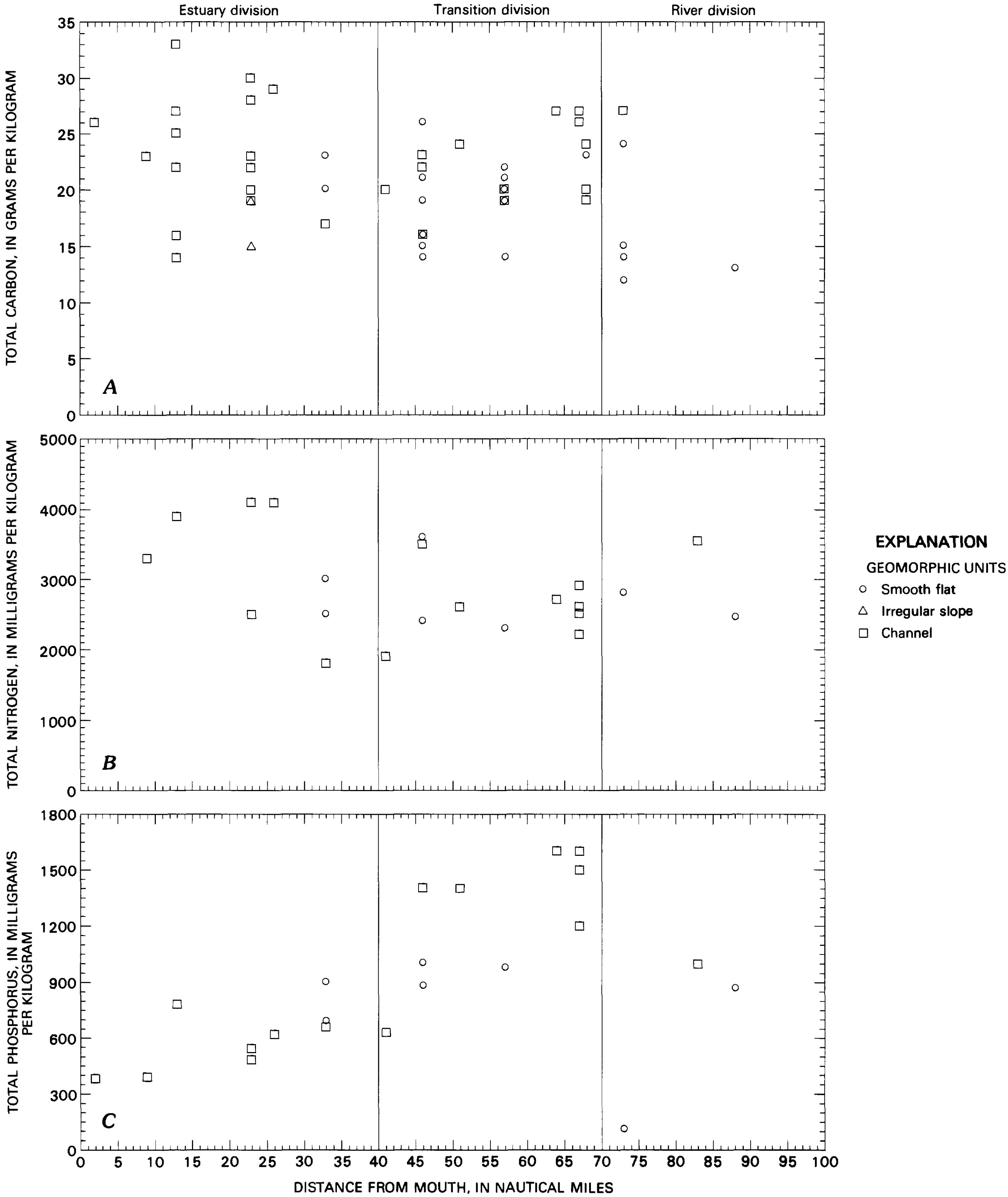


Figure 14. Trends in nutrient concentration with nautical mile from the Potomac mouth for samples whose median particle size is less than two μm: *A*, Total carbon; *B*, Total nitrogen; and *C*, Total phosphorus.

but sediments from the estuary and the river divisions are more variable than sediments from the transition division. Total phosphorus shows a fairly well defined decrease from the transition division to the estuary division and a less well defined increase from the river to the transition division (the phosphorus concentration in the sample from nmi 73 appears to be low by a factor of 10). Some factor(s) other than median particle size is evidently influencing phosphorus concentrations in the Potomac mainstem, but this factor is less effective in determining carbon and nitrogen concentrations.

DISCUSSION

Particle-size and nutrient data indicate several conclusions relative to the sources of sediments and nutrients and to the nature of sedimentation in the tidal Potomac system. Extensive areas of fine-grained sediments show that current velocities are generally small and unable to transport coarse sediments far from their immediate sources. Coarse sediments indicative of possible nearby sources are found in three general locations in the tidal Potomac system: channels near the heads-of-tides, shoreline flats that fringe most of the lower two-thirds of the study area, and irregular slopes.

Coarse sediments near the heads-of-tides establish river inflows as a sediment source, and coarse sediments on shoreline flats indicate shoreline erosion as a sediment source. Coarse sediments in the channel of the river division between Mount Vernon and the head of tides are supplied by Potomac River inflow because shoreline erosion is insignificant in the river division and local tributaries are separated from the mainstem by smooth flats composed of fine-grained sediments. Although the area of shoreline flats increases from the river division to the transition division, no change in the relative importance of shoreline erosion as a coarse sediment source can be detected in nearby channel and smooth-flat deposits, which are the finest and most uniform deposits in the Potomac mainstem. In the estuary division, channel deposits have greater percentages of sand and are more variable in texture than channel deposits of the transition division, although not as coarse and as variable as channel deposits of the river division. These characteristics indicate a new source for coarse sediments in channel deposits of the estuary division. Extensive shoreline erosion along the estuary (Miller, 1986, p. 36) or coarse deposits of irregular slopes are the most probable sources because sediments in tributaries of the estuary division and in nearby Chesapeake Bay are dominantly fine grained. Coarse-sediment distributions provide no evidence that sediments in the Potomac mainstem are derived from Chesapeake Bay or from mainstem tributaries.

Coarse sediments of irregular slopes occur in moderate to deep water locations where modern current velocities are too slow to transport sand and gravel; these sediments represent relict deposits whose origin predates the development of modern sedimentation conditions and whose source is Pleistocene and older deposits that underlie modern sediments throughout the tidal Potomac system (Knebel and others, 1981, p. 584). The textural similarity between coarse sediments of shoreline flats and of irregular slopes indicates that the sediments may have somewhat similar origins. In some cases, modern sediments from shoreline erosion are being transported offshore and into areas of irregular slopes. In other cases, the deposits being eroded along the modern shoreline also crop out beneath the irregular slopes and could have been eroded by near-shore processes when sea level was lower than present sea level. Shoreline flats probably were not able to form at the lower sea level because the rate of sea level rise then was larger than the current rate (Froomer, 1980); the sediments formed then, however, could be similar to those formed by modern processes.

The present distribution of irregular slopes in the tidal Potomac is mainly a function of modern sedimentation patterns. In the river division and in most tributaries, deposition is rapid (DeFries, 1986, p. 17; Brush and others, 1982, p. 213, 215–216; Glenn and Martin, 1983, p. 300; Bennett, 1983) and the irregular slopes are covered or are being covered by modern generally fine-grained sediments. Fine-grained sediments in samples from the irregular slope in the upper river and the upper estuary are from areas where modern fine sediments have been deposited, but the morphology of the underlying irregular slope is still apparent. Extensive areas of irregular slopes and of coarse-grained relict deposits exist in the estuary division, and the relative extent of irregular slopes increases markedly in a seaward direction along the Potomac mainstem. Deposition in much of the estuary division apparently is slow, either because the supply of fine sediments is minimal or the transport conditions are such that the fine sediments cannot be deposited.

Variations in the importance of inputs from the major sediment sources and changes in hydrologic conditions are major causes of most significant relations between particle-size measures and longitudinal divisions of the Potomac mainstem. Decreasing median diameters (see table 9) in sediments of the channel and the smooth flat between the river and the transition divisions indicate decreasing competence of river and tidal currents and decreasing ability to transport coarse sediments. The decrease in streambed slope at the head-of-tides, local geomorphic changes (widening) between Quantico and Maryland Point, and the tidal node near Maryland Point that results in low tide ranges are factors in the decreasing competence. Flocculation or agglomeration of fine sediments because of salinity and of many benthic organisms in the transition division also may be factors in this textural trend. The development of the two-layer estuarine circulation pattern and of the resulting turbidity maximum also promote sediment deposition in the transition division. The high uniformity of sediments in the transition division indicates the absence of nearby sediment sources and the development of a two-layer estuarine circulation pattern, which has been identified as producing uniform sediments in other estuarine systems (Postma, 1967; Schubel, 1971).

The fine sediments in the channel of the lower, narrow part of the transition division, in spite of large current velocities, indicate that coarse sediments from all sources are deposited before reaching this part of the Potomac mainstem. Although evidence for shoreline erosion increases between the river and the transition divisions, sediments from the shoreline source apparently are unimportant in nearby channel and smooth-flat deposits. In addition, there is no evidence that tributaries supply coarse or fine sediments to the Potomac mainstem. The sediments of mainstem and tributaries do not vary significantly in particle-size measures, deposition-rate data indicate rapid deposition in the tributaries (Brush and others, 1982; DeFries, 1986), and pollen data from one tributary in the transition division (DeFries, 1986) indicate the dominance of sediments from the Potomac River source at the tributary mouth.

Significantly smaller percentages of sand in sediments on shoreline flats (see table 9) of the river division and fine median diameters in sediments of the 0–2-m-depth unit in more landward nmi divisions appear to result mostly from changing hydrologic conditions. Miller (1986) noted no trends in sand-silt-clay percentages of eroding shoreline deposits that could result in textural differences in sediments of nearby shoreline flats. Wave action and shoreline erosion decrease as the Potomac mainstem narrows and curvature increases from the estuary to the river division; both changes decrease the fetch available for generation of waves, diminish the extent of shoreline erosion, and limit the resuspension and transport of bottom sediments.

Significant relations between particle-size measures and lateral units also are functions of changes in sources and sedimentation conditions. Shoreline flats in the transition and the estuary divisions are significantly coarser than channels and smooth flats because coarse sediments are available from the nearby shoreline source and wave action is effective in these divisions in removing fine sediments to deeper water where they are deposited with fine sediments from other sources. In the river division and in nmi divisions from the upper tidal Potomac, wave action is limited, shoreline erosion is minimal, and the Potomac River source supplies both fine and coarse sediments to channels. These factors combine to limit detection of significant differences (and to lower coefficients of determination) between geomorphic units in the river division.

Nutrient concentrations also provide information on nutrient and sediment sources, transport and deposition patterns, and geochemical reactions. Most nutrients show decreasing concentrations along the Potomac mainstem from the river to the estuary division. Large and variable concentrations in sediments of the river division are indicative of proximity to large and variable nutrient and sediment sources. Blanchard and Hahl (1986) and Hickman (1984) identified Potomac River inflows as the dominant source, followed by sewage treatment plants and inputs from local tributaries. Nutrient ratios indicate an allochthonous terrestrial source for most nutrients throughout the tidal Potomac; ratios in sediment do not differ near sewage treatment plant inflows, and changes in ratios provide little evidence that nutrients from autochthonous estuarine and marine sources (phytoplankton) are quantitatively important except possibly in the lower estuary. Nutrient concentrations in mainstem sediments are not signficantly different from those in tributary sediments; no evidence establishes tributary inflows along the tidal Potomac as sources for unusual concentrations of nutrients.

Lateral and longitudinal changes in nutrient concentrations along the Potomac mainstem are complex functions of source changes and of physical, chemical, and biological processes. Most nutrients show a strong affinity for finer sediments and significant relations to sediment particle size; thus, significant longitudinal and lateral trends in particle size typically are accompanied by significant relations of nutrient concentrations to longitudinal divisions and lateral units. Significantly larger mean nutrient concentrations in the channel and the smooth flat than in the shoreline flat and the irregular slope are primarily an indication of significantly finer sediments in the former and coarser sediments in the latter. Both source differences and sedimentation conditions are factors in particle-size differences among geomorphic units. Correlations between nutrient concentrations and particle size are poorer and fewer nutrients show significant relations in the river division than in the transition and the estuary divisions. This results because clear particle-size differences among geomorphic units in the river division have not developed, and nutrients from nearby sources in the river division have had little time to associate with finer sediments.

Significant relations of mean nutrient concentrations to longitudinal divisions are not so clearly dependent on particle size and nutrient relations. The channel and the smooth flat in the river division are coarser than the channel and the smooth flat in the transition and the estuary divisions, but carbon concentrations generally are smaller in the transition and estuary divisions, and phosphorus concentrations are much smaller in the estuary division than in the transition division although the mean particle sizes in the divisions are similar. In addition, texturally uniform samples from the mainstem hydrologic divisions commonly show the same longitudinal trends as all samples. For carbon, nearby sources and rapid deposition and burial in sediments of the river division explain significantly higher concentrations. Most of the carbon is deposited landward of the transition division, and high turbidity may limit the in situ production of carbon by phytoplankton in the transition division. In the estuary division, carbon concentrations are higher and more variable than in the transition division although lower and less variable than in the river division, which indicates that a new source of carbon exists. Although carbon to nitrogen ratios are not significantly different in the estuary division, they are relatively lower than in the river and transition divisions, which may indicate a phytoplankton source for carbon. For phosphorus, a buildup in both the river and transition divisions and a depletion in the estuary division may be necessary. Callender (1982, p. 436–437) indicated that phosphorus is readily sorbed by aerobic sediments in the river and the transition divisions and readily released from periodically anaerobic sediments in the estuary division; his data are generally consistent with data reported here, although it should be noted that the observed phosphorus decrease mostly occurs inland of the zone in the lower estuary known to become periodically anoxic (Seliger and others, 1985).

SUMMARY

Near-surface sediments from the tidal Potomac system are dominantly silt and clay except in local areas close to the heads-of-tides or to the shoreline. Moderately extensive areas of sandy and gravelly sediment occur mostly at intermediate water depths in the estuary and the transition divisions. The average sediment is about two-thirds silt and clay (fine) particles and one-third sand and gravel (coarse) particles. The average median particle size of all samples is 6.60 phi, or 0.010 mm, well in the very fine silt range. Sorting generally is poor, and the average sediment is skewed toward the fine tail of the size-distribution curve. Fifty-six percent of all tidal Potomac sediment samples come from two greatly different size classes; 32 percent of all sediment samples are fine grained and are classified as silty clay, and 24 percent are coarse grained and are classified as sand.

Patterns of particle-size distributions in sediments are determined by grouping data for samples from several parts of the tidal Potomac system; patterns are analyzed for statistical significance by standard tests. Potomac mainstem and tributary sediments are characterized by similar means and standard deviations for most particle-size measures; no significant differences between mean size measures for all sediment samples from the mainstem and mean size measures for all sediment samples from the tributaries were established. Potomac mainstem samples grouped by hydrologic division show longitudinal trends; mean percentages of sand increase and mean values of skewness decrease from the river division through the transition division to the estuary division.

Potomac mainstem samples grouped by geomorphic units show lateral trends in particle-size measures. Plots of median particle size versus sorting show particle-size differences between geomorphic units; a fine-grained and poorly sorted sediment group is dominantly from the channel and the smooth flat, and a coarse-grained and moderately well sorted sediment group is mostly from the shoreline flat and the irregular slope. Statistical tests establish significant mean particle-size differences between geomorphic units that are fine grained and units that are coarse grained, but generally not between geomorphic units within either the fine- or the coarse-grained group.

Additional detail of sediment particle-size distributions in the Potomac mainstem is provided by plotting mean particle-size measures for samples from each geomorphic unit versus nmi and versus water depth. Plots with nmi show longitudinal trends, whereas plots with water depth show lateral trends. Sediments of both channels and smooth flats progressively fine from landward and seaward directions into the 40–60 nmi division, the lower two-thirds of the transition division; shoreline flats show no change, and irregular slopes are finest in the 20–40 nmi division, the upper estuary, and in the 80–100 nmi division, the upper river.

Particle size generally decreases with increasing water depth but the relation varies for each cross section; relations show much scatter in the river division and less scatter in the estuary division. Below a depth of about 7 m, mean particle size is usually in the silt or clay range and is independent of further increases in depth.

Mean particle-size measures for sediment samples assigned to longitudinal divisions and lateral units of the Potomac mainstem vary significantly. Lateral trends in particle size explain more of the variation than longitudinal trends explain. Interaction effects prevent a simple comparison of overall means. The channel geomorphic unit is widespread and was sampled extensively in each mainstem hydrologic division. Sediments from the channel in the transition and the estuary divisions are significantly finer than sediments from the channel in the river division. Sediments from the shoreline flat and the irregular slope do not vary significantly among hydrologic divisions, but sediments from the smooth flat in the transition division are finer than in the river division. Sediments in geomorphic units within the estuary and the transition divisions show significantly different mean values of median particle size, but sediments in geomorphic units of the river division are not significantly

different. Sediments from the channel and smooth flat are significantly finer than sediments from the irregular slope or shoreline flat.

Particle size measures also are significantly related to longitudinal nmi divisions and lateral depth units. Significantly different means for median versus nmi division occur only for sediments from water less than 6 m deep. Significantly different means from the relation of median particle size to depth unit are limited to shallow water (depths less than 6 m) and to the three most seaward nmi divisions.

Tidal Potomac sediments contain substantial quantities of total carbon, total nitrogen, and total phosphorus, and limited amounts of inorganic carbon, nitrite plus nitrate nitrogen, and ammonia nitrogen. An average sample weighing 1 kg contains about 21 g of total carbon, 600 mg of inorganic carbon, 1,200 mg of total phosphorus, 2,400 mg of total nitrogen, 170 mg of ammonia nitrogen, and 2 mg of nitrite + nitrate nitrogen. The abundant nutrients have an average ratio by weight relative to phosphorus of 18:2:1 and an average atomic ratio of 94:8:1. Large standard deviations for mean concentrations of all nutrients indicate much nutrient variability within tidal Potomac sediments.

Patterns of nutrient concentrations in sediments are identified by comparing data for samples from several parts of the tidal Potomac system. Sediments from the Potomac mainstem have nutrient concentrations similar to those from the tributaries. Among mainstem hydrologic divisions, mean concentrations of total carbon and total phosphorus progressively decrease in a seaward direction, and mean concentrations of nitrite plus nitrate nitrogen increase. Total and ammonia nitrogen decrease sharply from the river division to the transition division, but remain unchanged from the transition division to the estuary division. Inorganic carbon appears to be less concentrated and less variable in the transition division than in the river and the estuary divisions. Within Potomac and tributary geomorphic units, the largest mean nutrient concentrations are in the sediments of the channel and the smooth flat, and the smallest mean concentrations are in the sediments of the irregular slope and the shoreline flat.

Channel sediments in the river division contain greater mean concentrations of total carbon than channel sediments in the transition and the estuary divisions contain. Inorganic carbon and nitrite plus nitrate nitrogen show little mean concentration difference among hydrologic divisions for samples from channels; total phosphorus and ammonia nitrogen, however, decrease between channels in the river and the estuary divisions. Sediments of smooth flats show no changes between divisions in mean concentrations of total carbon. Using nmi divisions instead of hydrologic divisions does not appreciably change carbon and phosphorus trends in sediments from channels, but does indicate that mean carbon increases in both landward and seaward directions from minimum values in the lower part of the transition division, and that mean phosphorus reaches maximum values in the lower part of the river division and the upper part of the transition division. Nutrient concentrations generally increase with water depth in cross sections from the estuary division but not in cross sections from the river division.

Statistical tests show that mean concentrations of all nutrients in the sediments are significantly related to longitudinal divisions and lateral units of the Potomac mainstem. Lateral variability in nutrient concentrations contributes more to significant overall relations than longitudinal variability contributes. Carbon is present in significantly greater mean concentrations in sediments of the channel and the irregular slope of the river division than in sediments of the channel and the irregular slope of the transition and the estuary divisions. Carbon in the shoreline flat and the smooth flat does not vary significantly among hydrologic divisions. Mean phosphorus concentrations are always relatively larger in all geomorphic units of the transition division than in geomorphic units of the river or the estuary divisions, but significant differences are limited to the irregular slope and the channel units. Nitrogen species show no consistent relative trends among hydrologic divisions, and significant trends are limited and are variable depending on both nitrogen species and geomorphic unit. All nutrient species except inorganic carbon show significant differences in mean concentrations among geomorphic units. The channel and the smooth flat typically have significantly larger mean concentrations of all nutrients than the shoreline flat and the irregular slope.

Nutrient ratios also are signficantly related to hydrologic divisions and geomorphic units. Unlike most other relations, trends in ratios among hydrologic divisions were larger contributors to significant overall relations than trends in ratios among geomorphic units. The relative order of mean ratios of C:P and N:P for sediments from channels was estuary division > transition division > river division; the ratio of N:P in the estuary division was significantly different (larger) than the ratios of N:P for other divisions. The mean C:N ratio did not vary significantly among most geomorphic units; the estuary has relatively smaller mean C:N ratios than the transition division in four of four comparisons and smaller ratios than both the transition and the river divisions in two of three comparisons. The C:N ratio changes although not statistically significant are compatable with an increase in contributions of organic matter from the marine and estuarine phytoplankton source.

Nutrient concentrations increase as the particle size of Potomac mainstem sediments decrease. The nutrient to particle-size relation varies with nutrient species and with hydrologic division. Total carbon and total phosphorus in the transition and the estuary divisions show significant linear relations to median particle size and large correlation coefficients, but carbon in the river division is marginally significantly related, and phosphorus is not related to median. Some factor(s) other than particle size affects carbon and phosphorus concentrations in the river division; variable inputs from nearby nutrient sources, the Potomac River and the Washington, D.C. area sewage treatment plants, probably are the main factor. As distance from these sources increases, more nutrients accumulate with finer sediments than with coarser sediments, and significant concentration-particle size relations result.

Total carbon, nitrogen and phosphorus concentrations within each hydrologic division are closely related to median size and to nutrient species; the coefficient of determination for these relations ranges from 0.85 to 0.94. Different nutrients within a hydrologic division show significantly different regression relations (slopes) to median size. The dominantly organic nutrients, total carbon and total nitrogen, show a similar relation, but the mostly inorganic total phosphorus shows a different relation. Between hydrologic divisions, only total nitrogen of the three major nutrients shows significantly different relations to median size.

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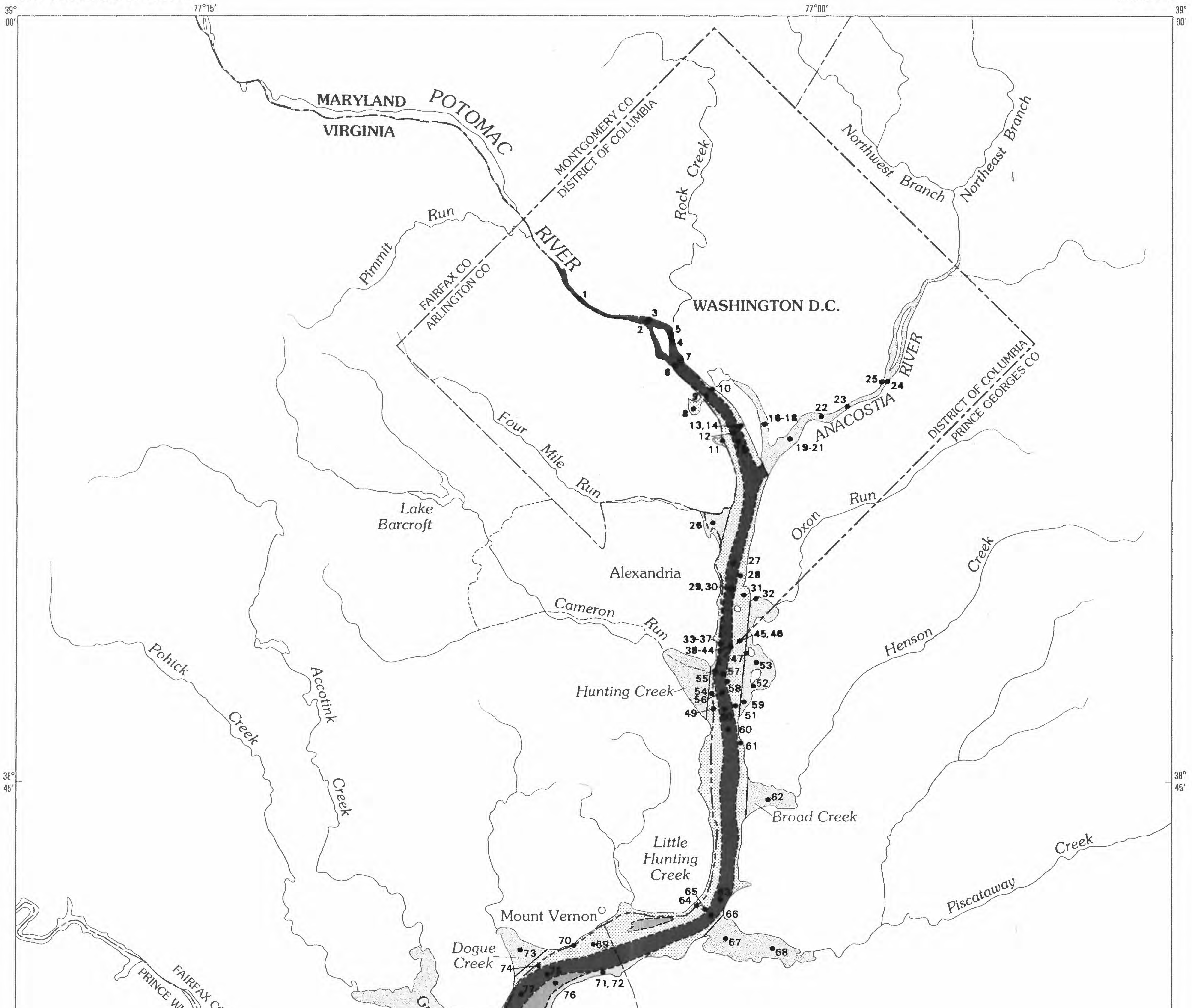
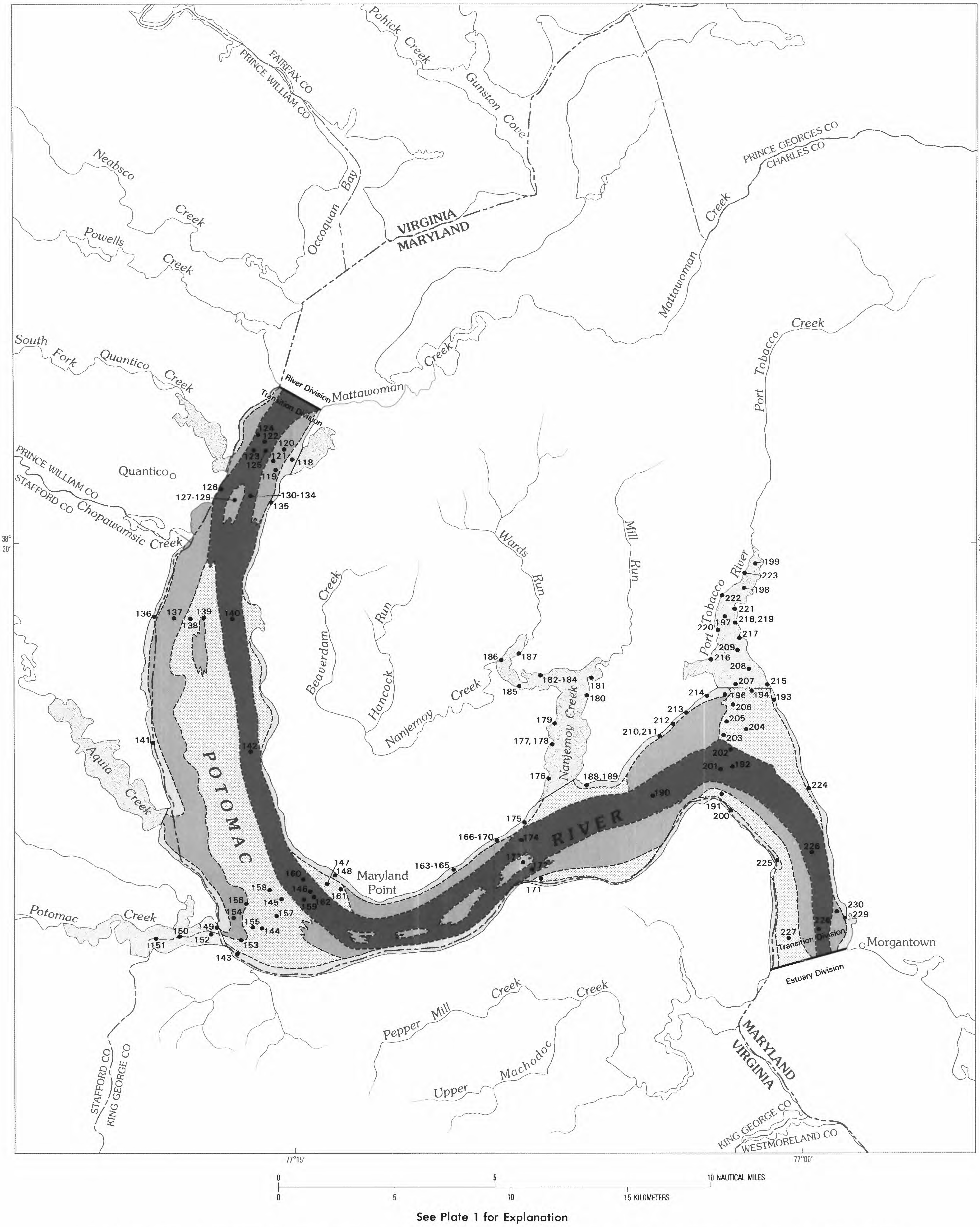
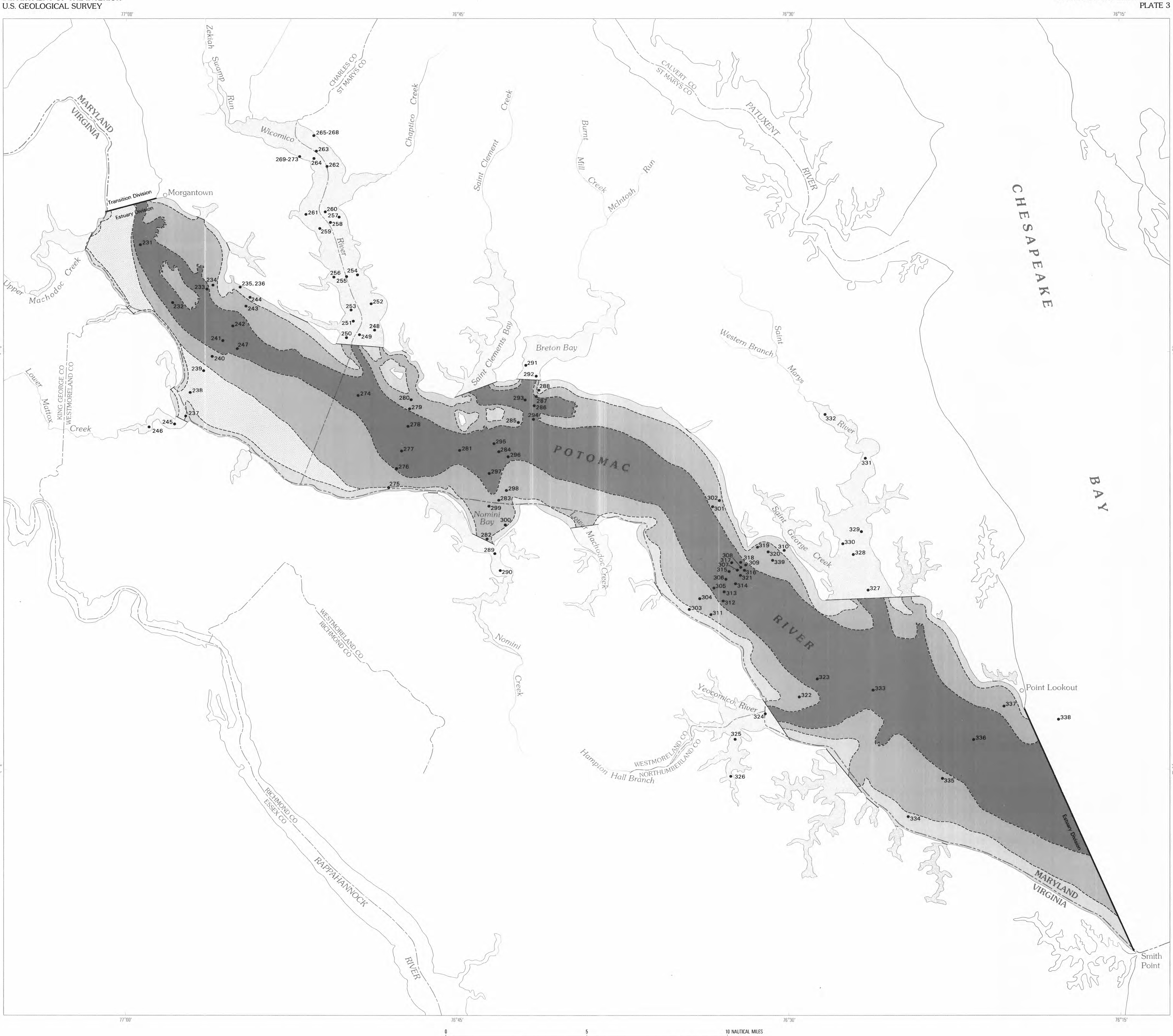


MAP SHOWING GEOMORPHIC UNITS AND SAMPLE LOCATIONS IN THE RIVER HYDROLOGIC DIVISION OF THE TIDAL POTOMAC SYSTEM, MARYLAND AND VIRGINIA



See Plate 1 for Explanation

MAP SHOWING GEOMORPHIC UNITS AND SAMPLE LOCATIONS IN THE TRANSITION HYDROLOGIC DIVISION OF THE TIDAL POTOMAC SYSTEM, MARYLAND AND VIRGINIA



See Plate 1 for Explanation

MAP SHOWING GEOMORPHIC UNITS AND SAMPLE LOCATIONS IN THE ESTUARY HYDROLOGIC DIVISION OF THE TIDAL POTOMAC SYSTEM, MARYLAND AND VIRGINIA