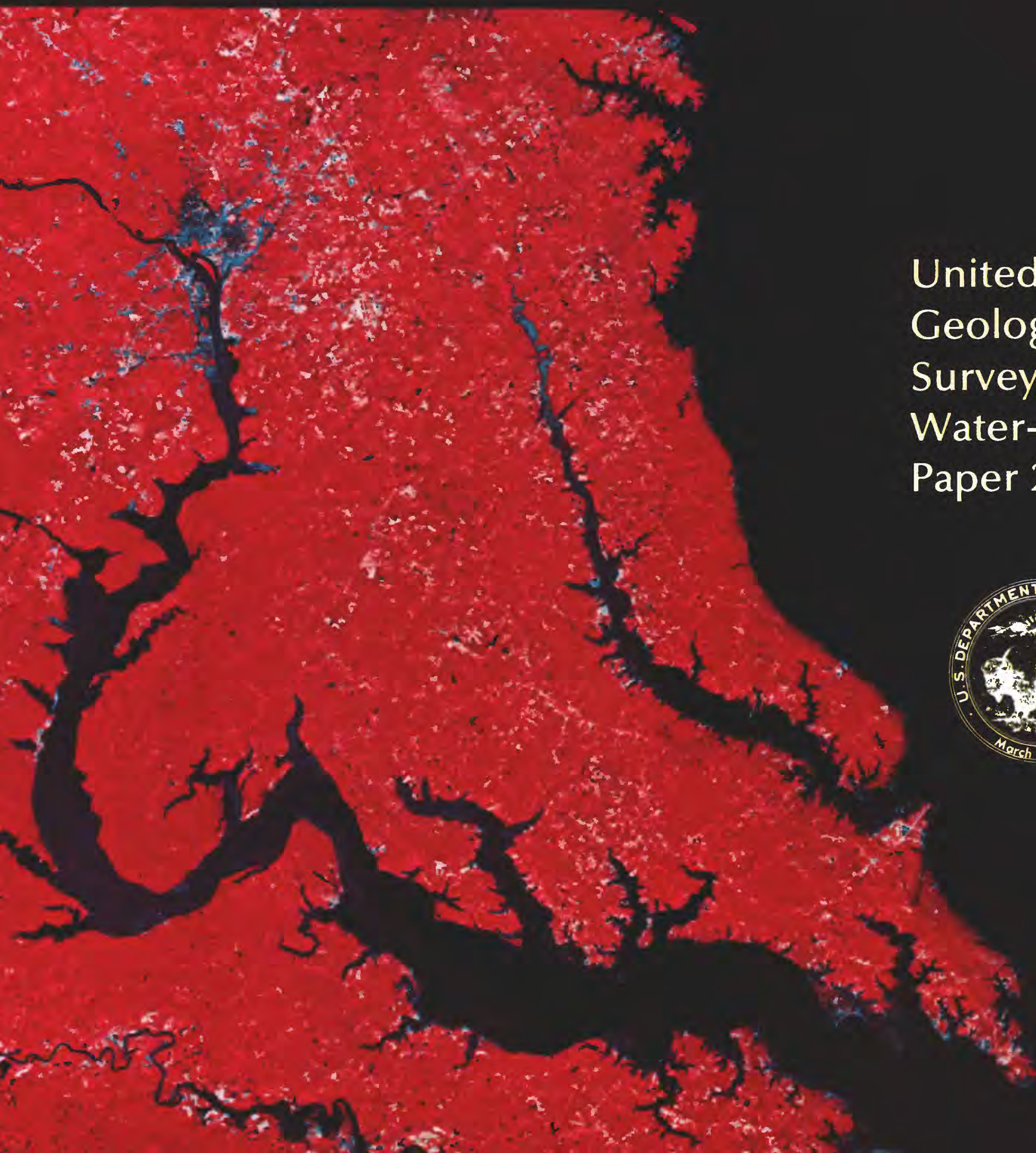
A WATER-QUALITY STUDY OF THE TIDAL POTOMAC RIVER AND ESTUARY—AN OVERVIEW



United States Geological Survey Water-Supply Paper 2233

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Edited by Edward Callender, Virginia Carter,
D. C. Hahl, Kerie Hitt, and Barbara I. Schultz

U.S. GEOLOGICAL SURVEY WATER-SUPPLY PAPER 2233

UNITED STATES DEPARTMENT OF THE INTERIOR
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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

James P. Bennett
Potomac Study Coordinator

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CONVERSION FACTORS

For use of readers who prefer to use metric (SI) units, conversion factors for terms used in this report are listed below:

Multiply	By	To obtain
	Length	
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
acre	4,047	square meter (m^2)
square inch ($in.^2$)	6.452	square centimeter (cm^2)
square foot (ft^2)	929.0	square centimeter (cm^2)
square foot (ft^2)	0.09294	square meter (m^2)
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
gallon (gal)	.003785	cubic meter (m^3)
million gallons (Mgal)	3,785	cubic meter (m^3)
cubic foot (ft^3)	0.02832	cubic meter (m^3)
	Flow	
foot per second (ft/s)	0.3048	meter per second (m/s)
foot per day (ft/d)	0.048	meter per day (m/d)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
mile per hour (mi/h)	1.609	kilometer per hour (km/h)
gallon per day (gal/d)	0.003785	cubic meter per day (m^3/d)
million gallons per day (Mgal/d)	0.04381	cubic meters per second (m^3/s)
	Mass	
ounce, avoirdupois (oz)	28.35	gram (g)
pound, avoirdupois (lb)	453.6	gram (g)
ton, short	0.9072	megagram (Mg)
	Temperature	
degree Fahrenheit (°F)	°C = 5/9 (°F - 32)	degree Celsius (°C)
	Specific conductance	
micromho per centimeter at 25° Celsius (μmhos/cm)		microsiemen per centimeter at 25° Celsius (μS/cm)

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

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Abstract

The U.S. Geological Survey began a 5-year interdisciplinary study of the tidal Potomac River and Estuary in October of 1977. The objectives of the study are: (1) to provide a basic understanding of physical, chemical, and biological processes; (2) to develop flow and transport models to predict the movement and fate of nutrients and algae; and (3) to develop efficient techniques for the study of tidal rivers and estuaries. The ultimate goal is to aid water-quality decisionmaking for the tidal Potomac River and Estuary.

The study is being conducted by scientists from many disciplines involved in 14 interrelated studies. These scientists are addressing five major problem areas: nutrient enrichment, algal blooms, dissolved oxygen, sedimentation, and effects of water quality on living resources. Preliminary results show that treatment of sewage has reduced the concentration load of organic carbon and phosphorus below that of the 1960's and 1970's, and changed the form of dissolved nitrogen in the tidal river. Concentrations of chlorophyll *a* during the study period were lower than those experienced during the massive algal blooms of the 1960's. Dissolved oxygen concentrations fluctuate in response to changes in algal populations, but remain above the Environmental Protection Agency limits during the summer low-flow period. Sedimentation rates have accelerated during the past 50-70 years due to urbanization and farming. Asian clams have recently invaded the tidal river; submersed aquatic vegetation has declined since the early 1900's, but conditions may now favor its return.

BACKGROUND OF THE STUDY

Our nation's estuaries are among the most biologically productive environments in the coastal zone, but their important characteristics are not well understood. In a geological sense, many estuaries are ephemeral features, river valleys drowned by rising sea levels and destined to fill with sediment. Estuaries are easily disturbed by nature and by man whose need for food, water, waste disposal, and industrial and agricultural production places ever-increasing stress on our coastal resources. Because estuaries are the meeting place of fresh and salt water, where the salinity and flow of water are influenced by constant changes in river inflow and tides, estuaries are complex physical, chemical, and biological environments. This complexity has made the study of estuaries and their associated tidal rivers very difficult; as a result the processes that take place within them are poorly understood. For example, nutrients, metals, and organic pollutants are often associated with or stored in sediments accumulating in a tidal river or estuary. The release of these substances to riverine or estuarine waters may affect the water quality and ecology as much as the materials dissolved in the inflowing water.

In response to public concern about the importance and delicate ecological balance of tidal rivers and estuaries, the U.S. Geological Survey (the Survey) began a 5-year interdisciplinary Potomac Estuary Study in October 1977. The study has focused on important water-quality considerations. The Potomac River, unlike many east coast tidal rivers and estuaries, is relatively free from pollution problems associated with manufacturing and chemical industries. The effects of processes such as sedimentation and nutrient enrichment can be studied in the tidal Potomac River and Estuary independent of complications from industrial pollution.

The general objectives of the U.S. Geological Survey Potomac Estuary Study are: (1) to provide a better understanding of basic physical, chemical, and biological mechanisms governing life cycles of phyto-

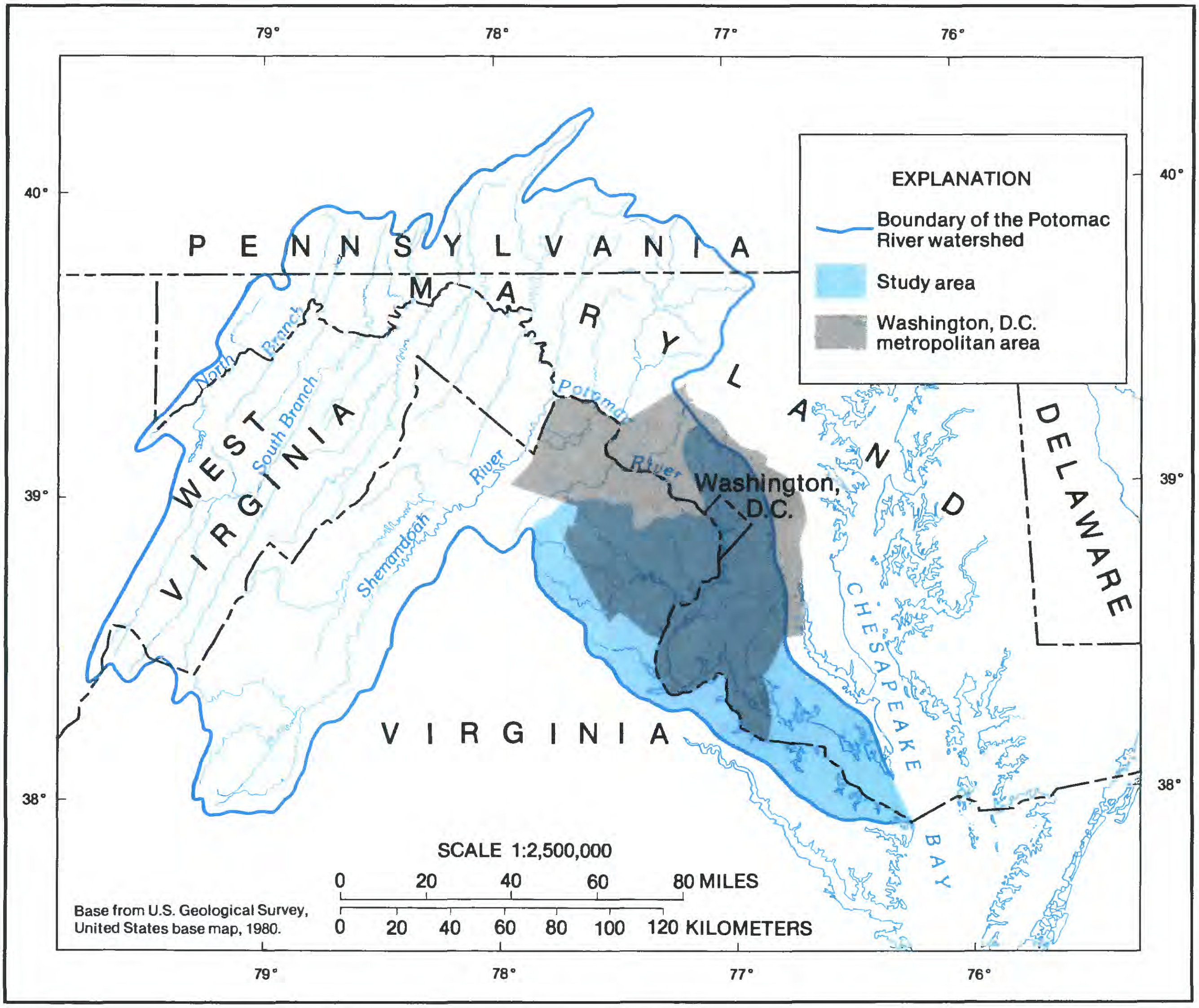


Figure 1. Potomac River drainage basin showing study area and the Washington, D.C., metropolitan area.

plankton, submersed vegetation, and bottom-dwelling animals in the tidal Potomac River and Estuary; (2) to develop, calibrate, and verify the mathematical flow and transport models necessary for predicting the movement and fate of sediments, nutrients, and algae; and (3) to develop, refine, and standardize efficient techniques for studying the water quality of the Potomac and other tidal rivers and estuaries in order that others may conduct their studies more efficiently. The ultimate goal of the study is to aid water-quality management decisionmaking for the Potomac, and to provide other groups with a rational and well-documented approach for the study of other tidal rivers and estuaries.

This report introduces the Potomac Estuary Study. It provides the background for the study, presents the major water-quality problems in the tidal river and estuary, discusses the overall approach to and the individual projects involved in the study, and presents some preliminary results. The report is intended to provide information to managers, planners, governmental officials, and members of the public concerned with water resources decisionmaking and the ultimate health of the tidal Potomac River and Estuary. The majority of the reports in this series will present the technical findings of the Potomac Estuary Study. There will be an integrated technical summary of the results, and a final report that will summarize the technical findings of the Study and will discuss how these results can relate to water-resources problems in the tidal Potomac River and Estuary.

STUDY AREA

The Potomac River is the second largest tributary to the Chesapeake Bay, extending about 400 miles from its source in the mountains of West Virginia to its junction with Chesapeake Bay at Point Lookout, Md. (fig. 1). The Potomac River basin is the second largest watershed in the Middle Atlantic States and has a drainage area of 14,670 square miles.

In much of the technical literature concerning the classification of estuaries, the term estuary refers to a body of water within which seawater is measurably diluted with fresh water (river water). Because the Potomac does not connect with the sea (Atlantic Ocean) but with Chesapeake Bay, fresh Potomac River water mixes with brackish Chesapeake Bay water in the **Potomac Estuary**. The reach of the Potomac River that contains only fresh water but is still influenced by tides is termed the **tidal Potomac River**. The upper part of the Potomac Estuary which experiences large changes in salt concentration is called the **transition zone** due to the fact that this zone links the riverine system with the estuarine system.

The **tidal Potomac River and Estuary** includes that part of the Potomac River which extends from Chesapeake Bay to Chain Bridge (fig. 2). The tidal river is less than half a mile wide at Washington, D.C.; the width increases gradually to 6 miles at the mouth of the estuary. The maximum depth is 107 feet at Mathias Point, Va., and the average depth is 19 feet. River flow fluctuates seasonally and from year to year. The 51-year average fresh-water inflow to the tidal river is 11,400 cubic feet per second (ft^3/s). The maximum and minimum flows on record are 484,000 ft^3/s in March 1936 and 121 ft^3/s in September 1966, respectively (U.S. Geological Survey, 1981: p. 329).

In this report, the tidal Potomac River and Estuary is subdivided into three reaches on the basis of salinity (fig. 2). The **tidal river** extends from Chain Bridge to Quantico, Va., and is characterized by fresh-water flows and riverine chemistry (fig. 3). This reach contains spawning and nursery areas for anadromous fish and is the zone affected by major municipal wastewater discharges. The average depth for this reach is 10 feet. The bottom topography is characterized by a long, narrow channel which ranges in depth from 21 to 70 feet and is bordered by shallow shelf areas. The **transition zone** of the estuary extends from Quantico, Va., to U.S. Highway 301 Bridge, Md., and represents a zone of mixing between fresh water of the Potomac River and salt water of the Chesapeake Bay (fig. 4). The transition zone is a region of comparatively high biological production and diversity characterized by the interaction of two opposing water masses (river and ocean). The average depth for this reach is 13 feet. Like the tidal river, the transition zone's bottom topography is characterized by a deep channel with an adjacent marginal slope that is bordered by a wide, shallow shelf. The channel ranges in depth from 20 feet to 107 feet. The remainder of the estuary (referred to as **estuary** for convenience in terminology), extending from the U.S. Highway 301 Bridge to the Chesapeake Bay, is characterized by salt water and marine life (fig. 5). The average depth for this reach is 22 feet. The bottom topography is dominated by a wide channel (1 to 3 miles) with gradually sloping, shallow flats near shore. The channel ranges in depth from 21 to 80 feet.

MAJOR WATER QUALITY PROBLEMS

The ultimate goal of the U.S. Geological Survey study is to aid water-quality management decisionmaking for the tidal Potomac River and Estuary, and to provide others with a well-documented approach for the study of other tidal rivers and estuaries. To achieve this goal, it is first necessary to develop a comprehensive data base for the tidal Potomac River and Estuary. In addition, after studying the interrelationships of the biological, physical, and chemical processes in the tidal river and estuary, it will be important to communicate our understanding of these processes to the water-quality manager. Five water-quality problems were identified as having significance to most water users in the lower Potomac River basin and as being important in other estuarine systems as well. These are discussed in detail below.

Nutrient Enrichment

The excessive discharge of dissolved nutrients (primarily organic carbon, phosphorus, and nitrogen) from sewage treatment plants and nonpoint sources (such as overland runoff) causes low concentrations of dissolved oxygen and blooms of blue-green algae in aquatic systems. Nutrient-laden particulate material in the sewage-treatment-plant and nonpoint-source discharges settles out of the water near the point at which the discharges enter the river. In the case of Washington's Blue Plains Sewage Treatment Plant (fig. 3) (the major point source discharge in the study area), most of the phosphorus and some nitrogen settle out immediately adjacent to the plant. High river flows resuspend and redistribute dissolved and particulate material downstream. Nutrients are also released to the water column by natural processes occurring in bottom

Figure 2. The tidal Potomac River and Estuary.

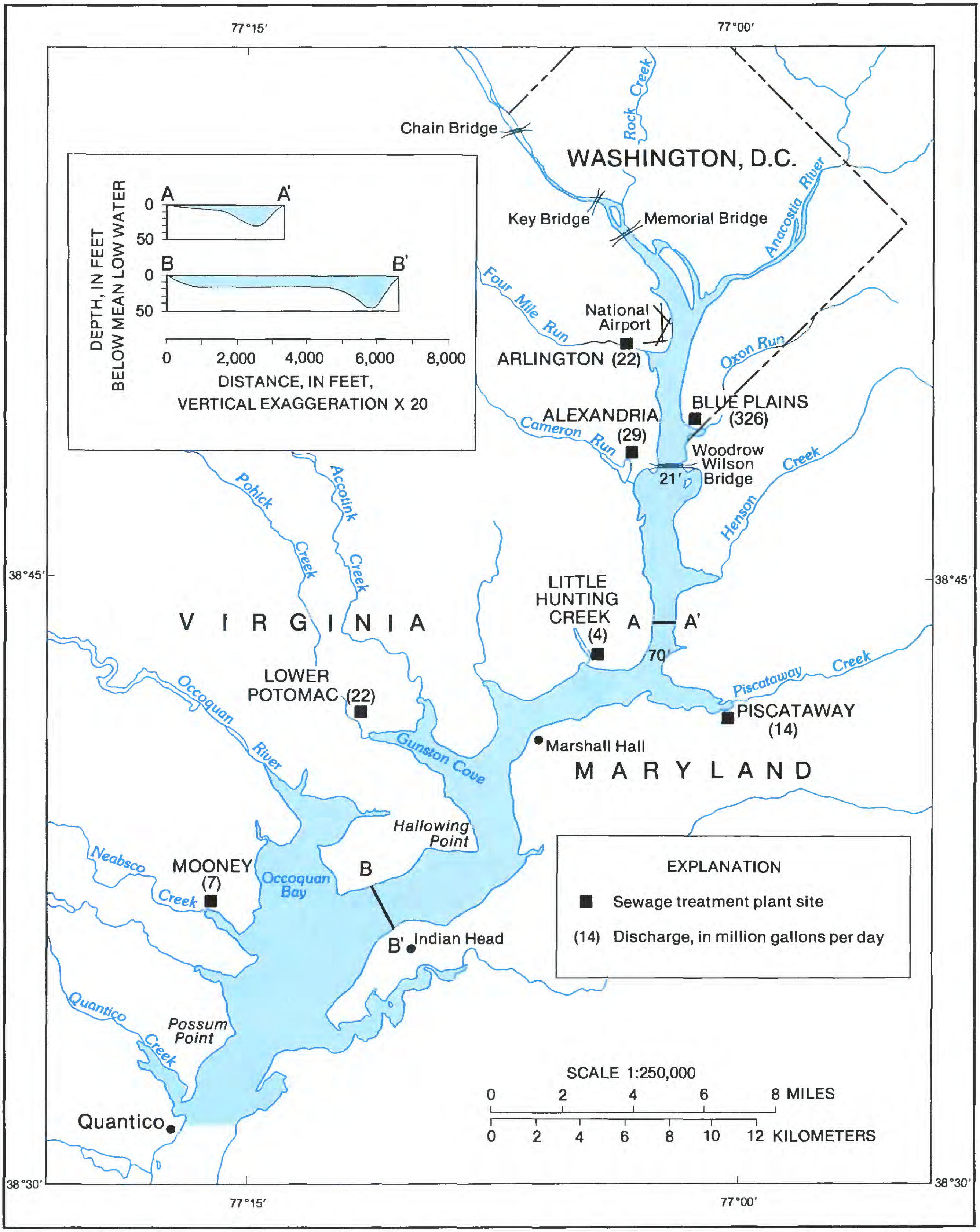


Figure 3. The tidal Potomac River, showing representative cross sections and the location of sewage treatment plants discharging in excess of 4 million gallons per day directly to tidal water in 1981.

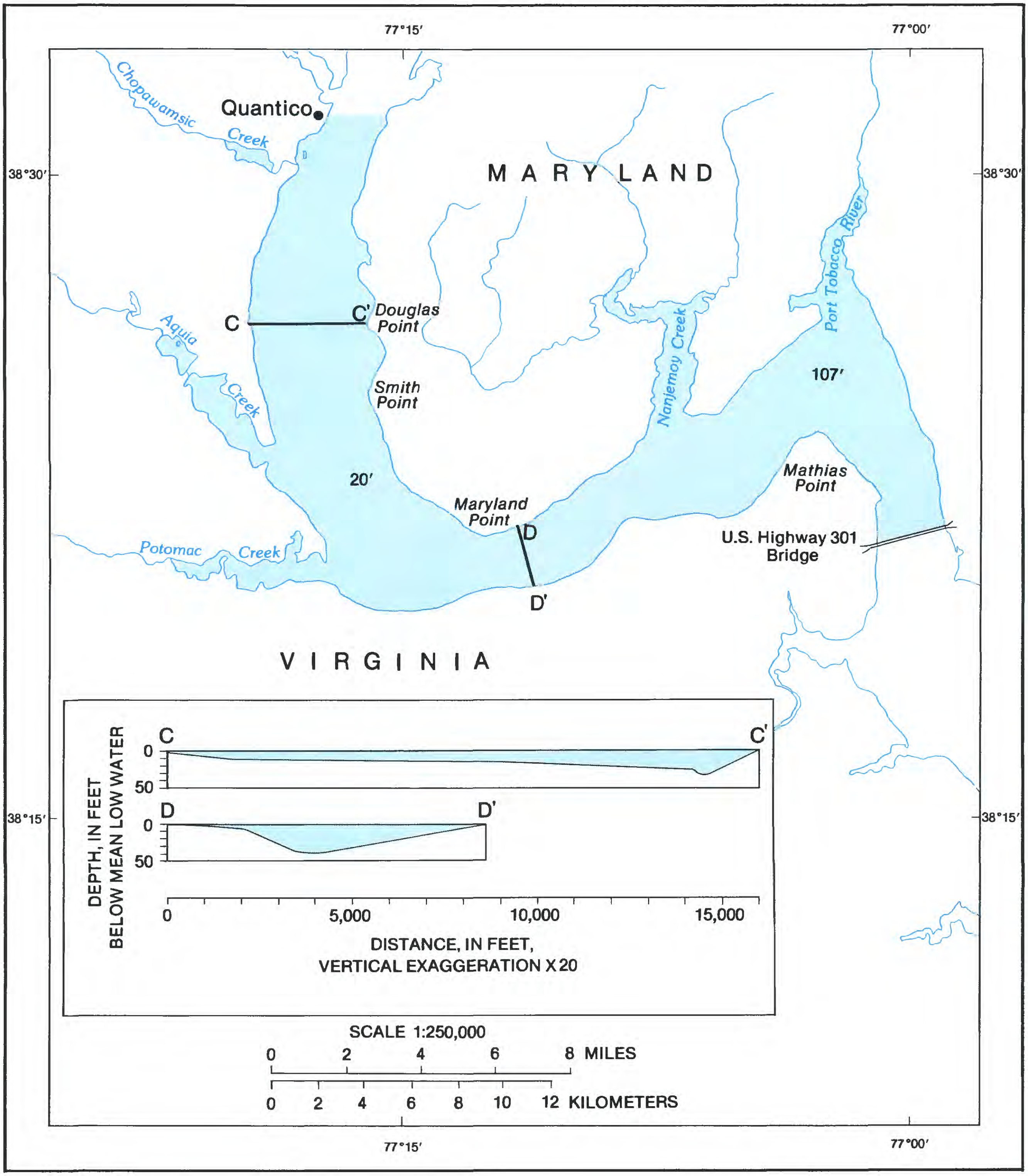


Figure 4. The transition zone, showing representative cross sections.

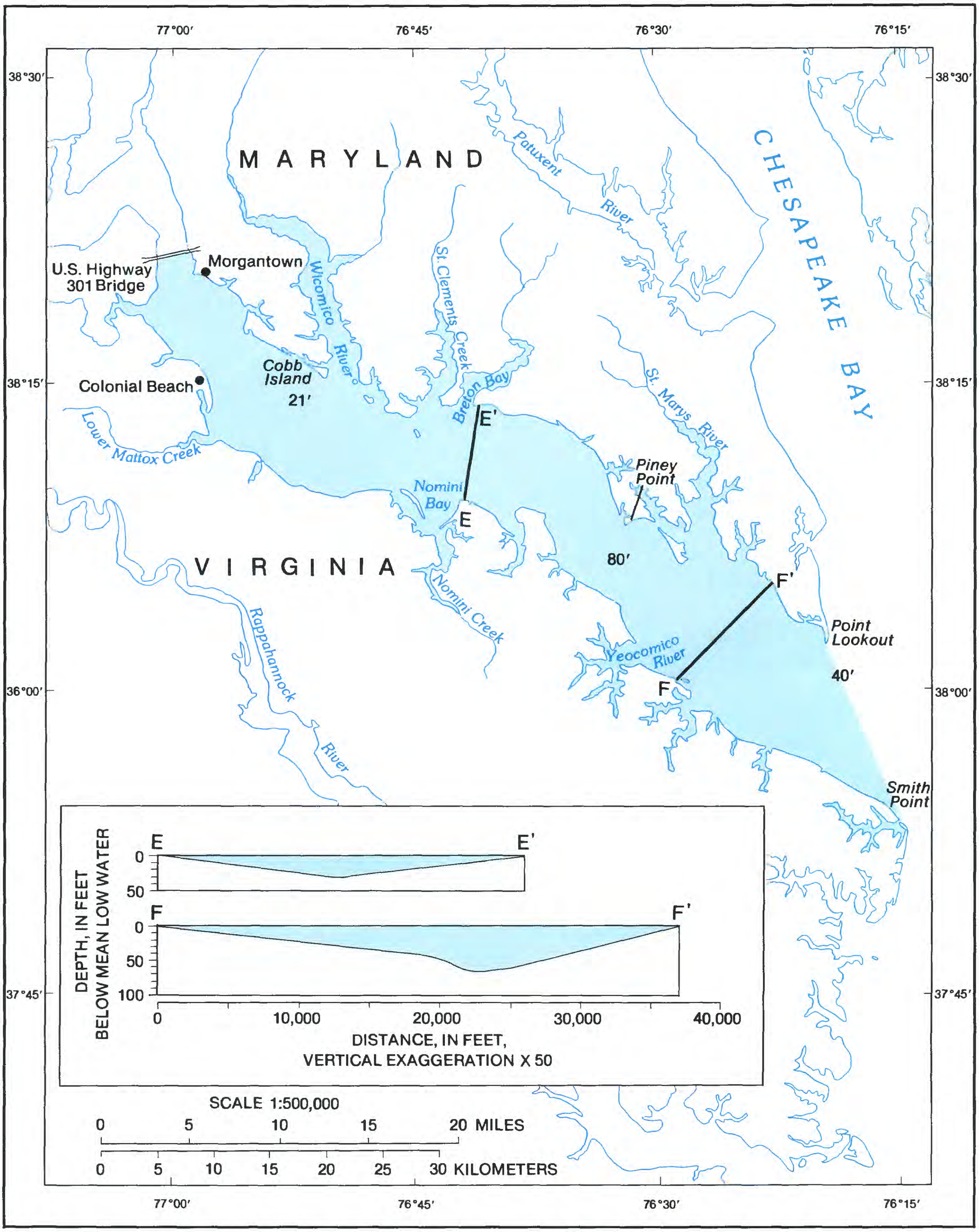


Figure 5. The estuary, showing representative cross sections.

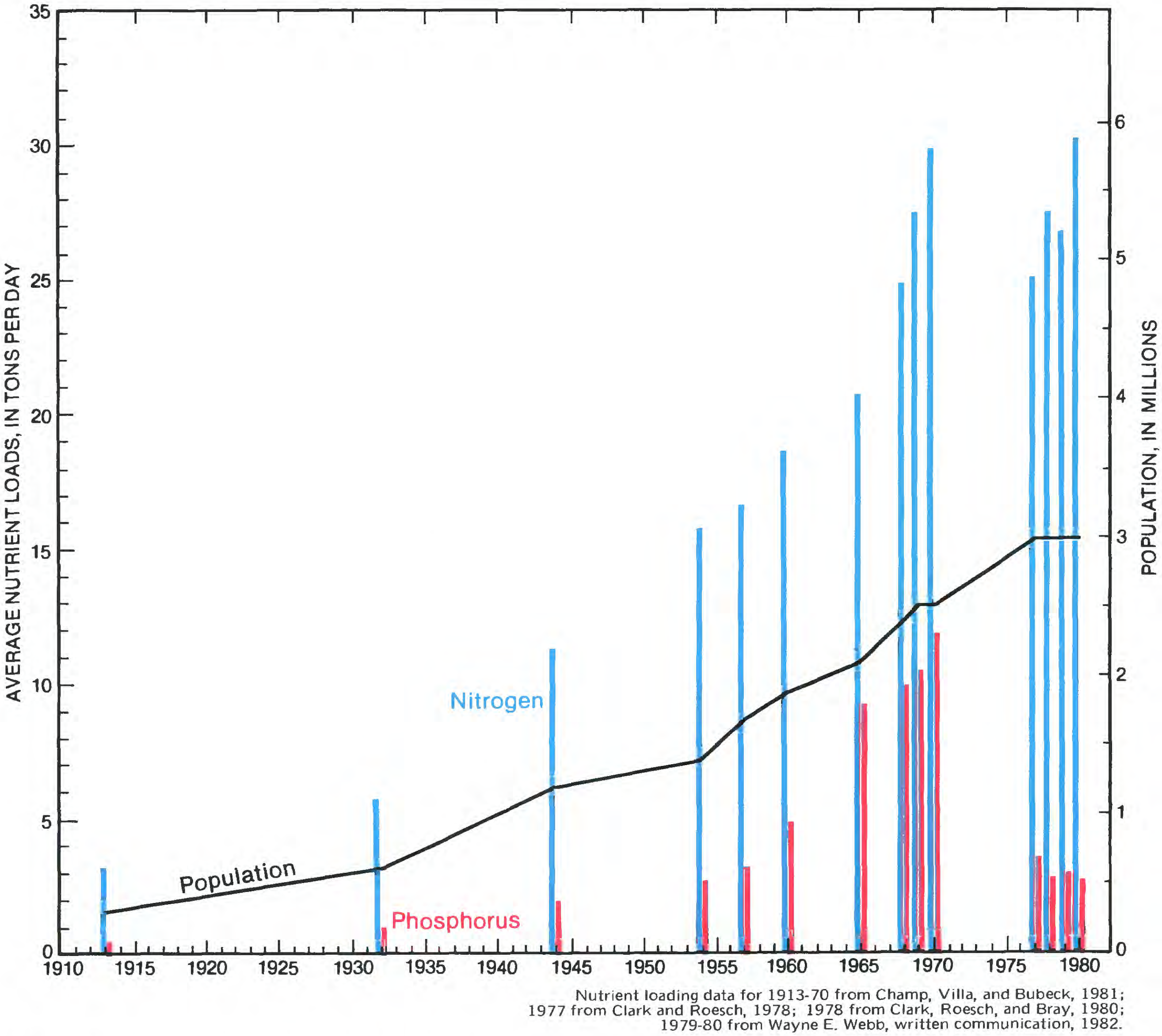


Figure 6. Nitrogen and phosphorus loadings from sewage, and population growth, in the Washington, D.C., metropolitan area, 1913-80.

sediments.

Organic carbon compounds are converted to carbon dioxide and water by bacterial processes that use oxygen. Sewage treatment plants are designed to reduce this oxygen demand; the organic carbon loads in their discharge are usually reported as BOD (biochemical oxygen demand). Nitrogen and phosphorus stimulate algal growth, which contributes dissolved oxygen to the river. However, dead algae are an additional source of organic carbon and thus increase oxygen demand.

In order to reduce nutrient loading in the tidal Potomac River, local officials have taken a series of steps to improve sewage treatment. Each step removes more of the nutrients, but with each step the cost of treatment increases. Until 1938, when the Blue Plains Sewage Treatment Plant began operation, the metropolitan Washington area (Government of the District of Columbia, 1974) discharged its untreated sewage into the Potomac River (fig. 6). In the 1940's and 1950's primary sewage treatment (settling) removed one-third of the organic carbon and some of the nitrogen and phosphorus. During 1944, when the population of the Washington metropolitan area was 1.2 million, sewage treatment plants discharged 11.4 tons per day of nitrogen and 2.0 tons of phosphorus per day

Figure 7. Color infrared aerial photograph of the tidal Potomac river near Gunston Cove, Va., (location shown in figure 3) showing a massive bloom of blue-green algae, (pink streaks), 1969.

into the tidal river. In 1959, Blue Plains, by far the largest sewage treatment plant in the Washington metropolitan area, converted to secondary sewage treatment to remove more carbon. In 1960, following this conversion, when the Washington area population was about 2 million, sewage treatment plants discharged 18.6 tons per day of nitrogen and 5.0 tons per day of phosphorus. In 1974, Blue Plains began tertiary treatment using chemical precipitation to remove phosphorus. Comprehensive surveys of nutrient loadings from all area sewage treatment plants, nonpoint sources, and the Potomac River at Chain Bridge were conducted from 1977 to 1980, when Washington's population was nearly 3 million. During 1977, sewage treatment plants discharged 25.0 tons per day of nitrogen and 3.6 tons per day of phosphorus into the tidal river. Nonpoint sources of nitrogen and phosphorus accounted for only 5.5 tons and 0.4 tons per day, respectively. The Potomac River upstream from the Washington metropolitan area contributed approximately 60.3 tons of nitrogen and 5.5 tons of phosphorus per day to the tidal river.

In 1980, Blue Plains began advanced wastewater treatment in which ammonia is converted to nitrate (nitrification) and additional phosphorus and carbon are removed. This reduces the amount of oxygen used in the river to oxidize ammonia to nitrate. Because it appears that algae prefer ammonia to nitrate as a source of nitrogen, it was predicted that this advanced treatment will raise dissolved oxygen levels and lower algae concentrations immediately below the sewage treatment plant. During 1980, 30.1 tons per day of nitrogen and 2.7 tons per day of phosphorus were discharged into the river. Sewage plants with advanced wastewater treatment added approximately one-third the quantity of nitrogen and one-half the quantity of phosphorus that the river itself contributed to the upper reach of the tidal Potomac River.

Algal Blooms

A significant water-quality problem that has had a profound effect on the use of the tidal river for recreation is nuisance blue-green algae. The presence of large numbers of blue-green algae (blooms) in natural waters indicates eutrophication caused by addition of nutrients. Blue-green algae can develop enough biomass in nutrient-enriched waters to cover the entire water surface with algal mats and to leave windrows of algae along the shoreline. The decomposition of dead algae creates an oxygen demand that reduces dissolved-oxygen concentrations. Many species of blue-greens excrete waste products that are toxic, distasteful, and foul smelling.

Blue-green algae have probably always been present in the tidal Potomac River. However, during the 1950's, 1960's, and early 1970's, the tidal river and transition zone were occasionally covered by massive blooms of blue-greens consisting mainly of the genus *Anacystis* (fig. 7) (Jaworski and others, 1971). Measurements of chlorophyll *a* (used to estimate algal biomass) made during the 1960's and 1970's indicated that these algal blooms were prevalent from May until November. The extent of the blooms increased between 1965 and 1970, and they were found as far downstream as the U.S. Highway 301 Bridge. In 1977, chlorophyll *a* levels were comparable to those measured in 1970 except in the vicinity of Douglas Point, Md., where they were significantly lower. Because of higher river flow during the summer of 1978, the chlorophyll *a* concentrations in the tidal river and transition zone were considerably lower than in 1977.

Dissolved Oxygen

In recent decades, the tidal Potomac River downstream of Washington has been unable to support healthy sport fish populations during the warm summer months because of low dissolved-oxygen concentrations. Dissolved oxygen is considered a primary indicator of the quality of natural water because most aquatic forms of life need oxygen to survive. Fishery biologists have determined that a minimum dissolved-oxygen concentration of 5 milligrams per liter (mg/L) (Welch, 1980) is necessary to maintain a healthy and diverse fish population. Factors that regulate dissolved oxygen in water are: (1) the amount of oxygen that enters the water from the atmosphere (aeration), (2) consumption of oxygen by oxidation of organic matter, and (3) production and consumption of oxygen by green plants (photosynthesis and respiration). The rate at which these natural processes function is specific to each aquatic environment.

Low concentrations of dissolved oxygen in the tidal river are caused by large amounts of waste material entering the system. During warm weather, low dissolved-oxygen concentrations (3 mg/L and lower) have occurred in the vicinity of the Woodrow Wilson Bridge, and have persisted down river to the vicinity of Marshall Hall, Md. (fig. 8). The severity of local declines in dissolved-oxygen concentration varies with the waste loading to the river and the river flow.

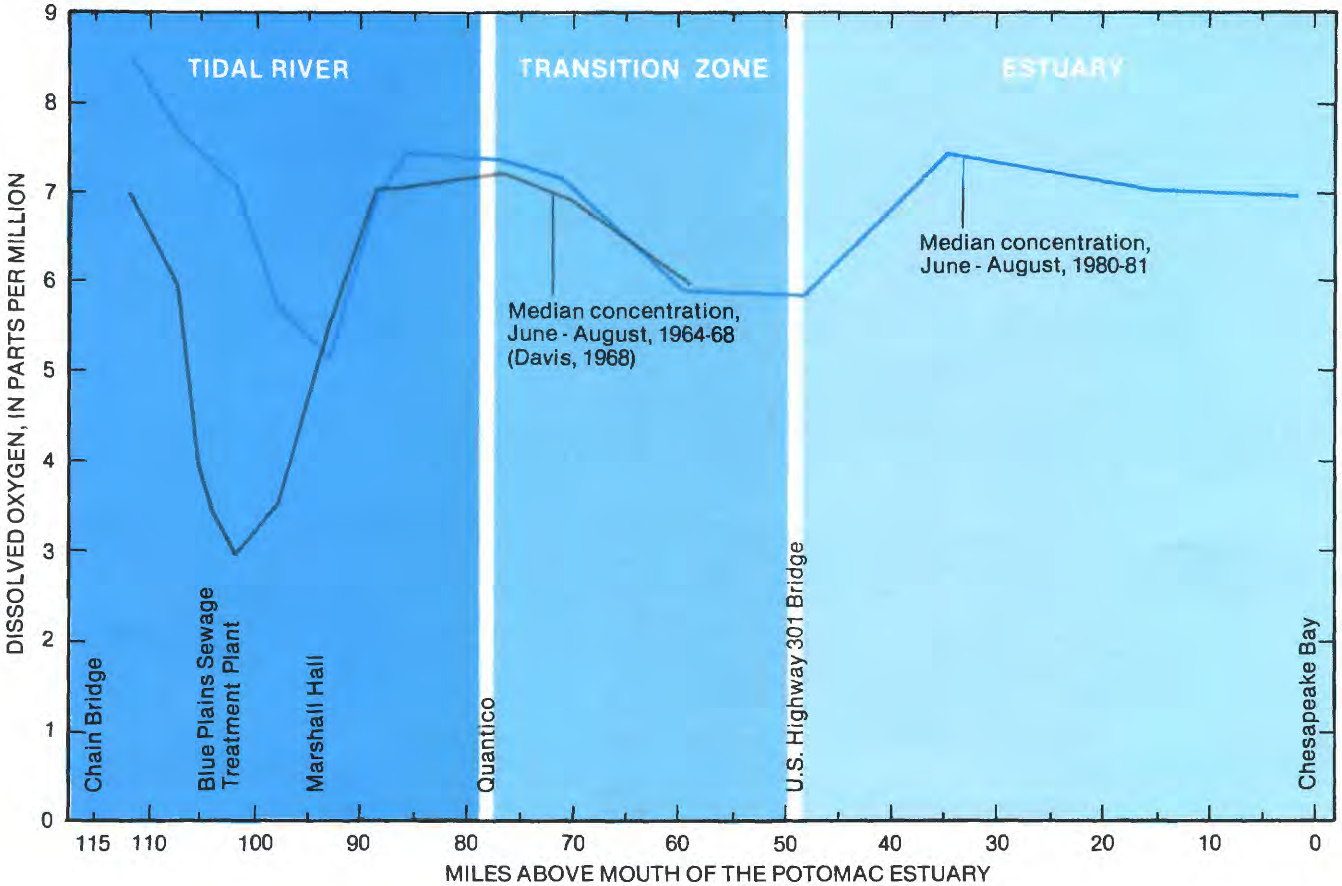


Figure 8. Distribution of dissolved oxygen in the tidal Potomac River and Estuary during summer.

Historical Sedimentation

Tidal rivers and estuaries are natural traps for sediment because the decrease in water velocity allows the sediment to settle to the bottom. Man's activities throughout the river drainage basin, as well as within the estuary itself, can greatly increase the rate of sediment infilling. Increased inputs of sediment can degrade a tidal river or estuary to the extent that its useful commercial, biological, and recreational lifetimes are reduced drastically.

Although the sediment deposited in a tidal river or estuary comes from several sources, including erosion of the shoreline and transport of sediment from the sea into the mouth of the estuary, the most important sources are the streams that carry sediment from upland areas. The sediment load is increased by man's activities, such as land clearing, farming, mining, and urbanization.

During colonial times, soil erosion was a major problem in the Chesapeake Bay area. Sedimentation, accelerated by farming and land clearing, resulted in much infilling of the tidal Potomac River and Estuary. Sediment carried by the streams and rivers filled navigation channels and harbors, impaired the productivity and drainage of bottomlands, and spoiled the environment for fish and oysters. A comparison of maps of the 1792 and 1947 shorelines of the tidal Potomac River shows that large areas near Washington have been filled with sediment (Schubel and Meade, 1977). In 1762, Georgetown (Washington, D.C.) was established as a site for ocean shipping trade, but by the 1830's Georgetown began to lose its importance as a port because the shipping channel was filling with sediment (Gottschalk, 1945). Other areas of the tidal Potomac River and Estuary have experienced much sedimentation.

The river has been gradually building up its bed in the area of Mount Vernon, Va., such that 4 feet of sediment accumulated in the channel from 1863 to 1904 in spite of periodic dredging (Gottschalk, 1945). Neabsco Creek, Va., and Quantico Creek, Va. (fig. 3), both

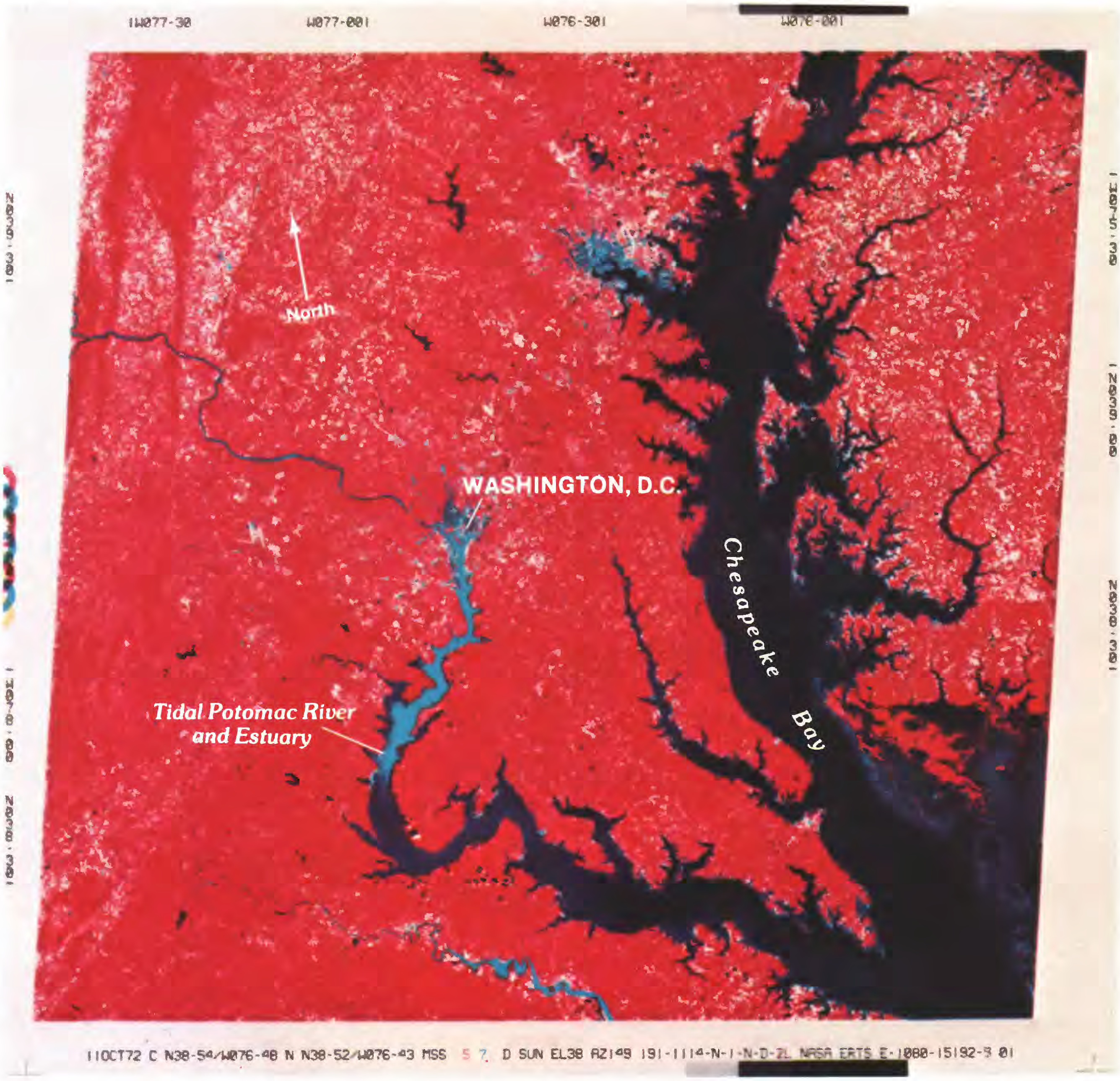


Figure 9. Landsat image (1080-15192) showing a flood-stage plume of suspended-sediment filling the tidal river, October 11, 1972. The greatest daily mean discharge for the flood was 78,000 cubic feet per second on October 8, 1972.

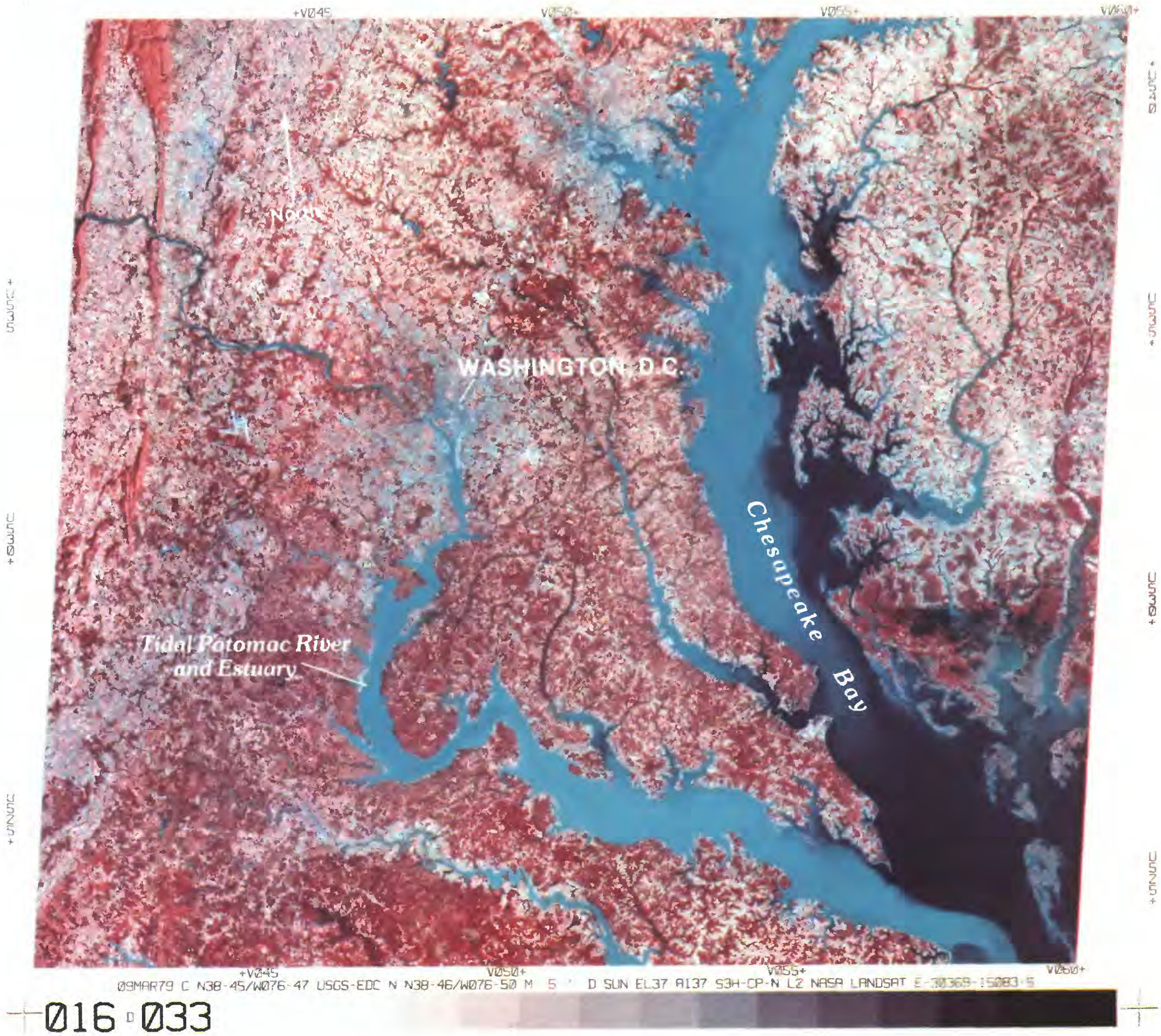


Figure 10. Landsat image (30369-15083) showing a flood-stage plume of suspended-sediment filling the tidal Potomac River and Estuary, March 9, 1979. The flood had two peak discharge periods. The daily mean discharges were 201,000 cubic feet per second on February 26 and 93,500 cubic feet per second on March 7, 1979.

housed shipbuilding and warehouse activities, but by 1790, the shipping harbors were filled with sediment (Gottschalk, 1945). Port Tobacco, Md. (fig. 2), 25 miles south of Washington, was once a flourishing seaport during colonial times. In the late 1790's the tidal creek extended past the town and was navigable for ships drawing 6 feet of water (Gottschalk, 1945). Presently (1982), the head of tidewater is more than a mile downstream from the site of the town.

Today, urbanization and farming in the tidal Potomac River basin are adding to the natural process of sedimentation. Land clearing for housing developments, road building, and so forth, has disturbed the soil and has left it exposed to wind and rain. Storm runoff from bare soil contains between 100 and 1,000 times more sediment than runoff from vegetated soil (Schubel and Meade, 1977). Landsat images taken following severe local (fig. 9) and widespread storms (fig. 10) show large amounts of suspended sediment in the tidal Potomac River and Estuary. The Survey recently estimated that the tidal Potomac River and Estuary receive about 250,000 tons of sediment annually from tributary streams other than the Potomac River (Feltz and Herb, 1978). More than twice as much additional sediment is transported into the tidal Potomac River and Estuary from all other upland sources draining into the Potomac River above Chain Bridge.

Besides the problems of closing ports and shoaling navigation channels, sedimentation has had an adverse effect on the oyster fishery. Old oyster grounds which extended from Maryland Point, Md., to Nanjemoy Creek, Md. (fig. 4), were actively harvested as recently as 50 years ago (Frey, 1946). Today these oyster bars are covered with sediment and no longer support the active culture and harvesting of oysters.

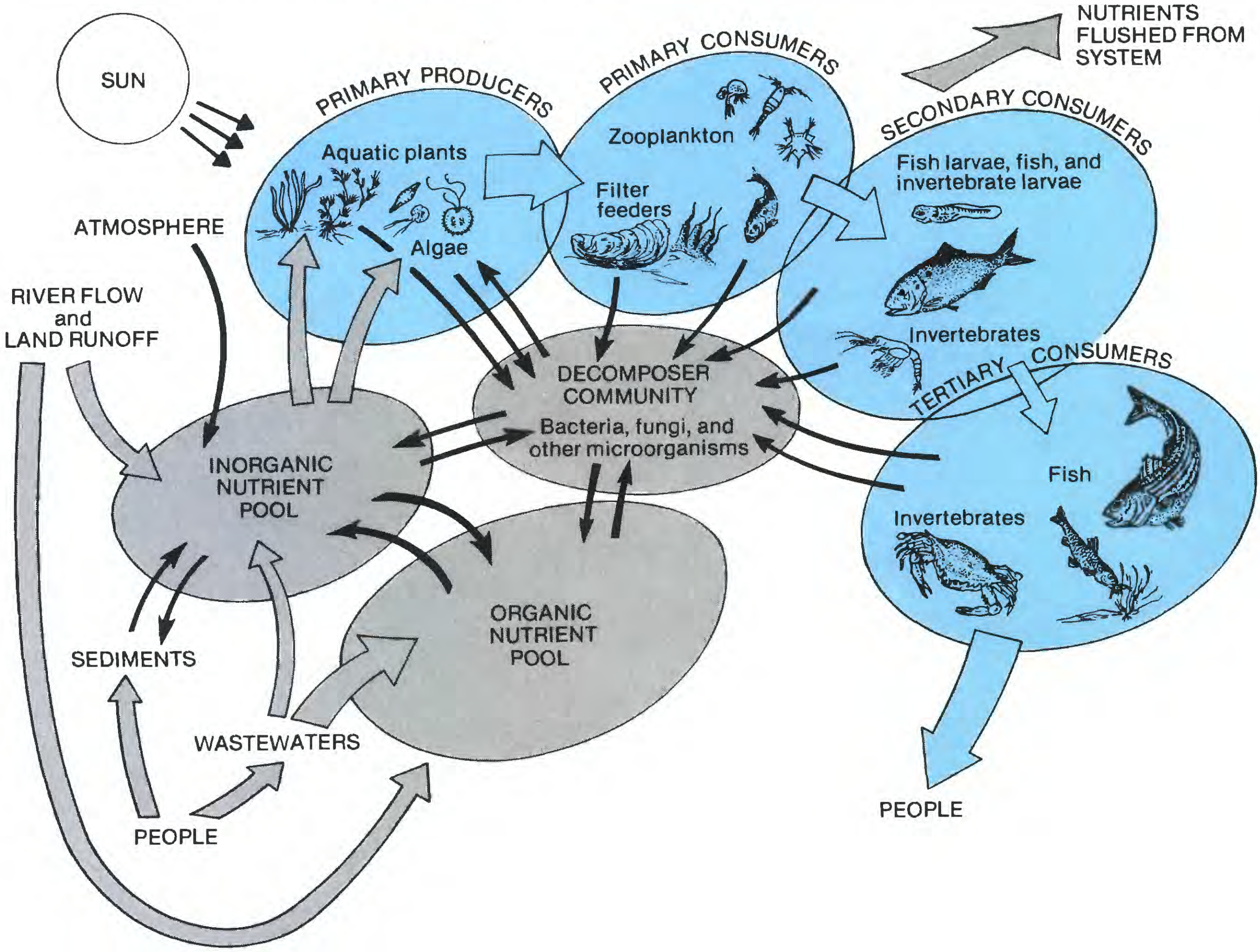


Figure 11. The aquatic food web. Modified from Lippson and others, 1979.

Effects of Water Quality on Living Resources

The complex environments of the tidal Potomac River and Estuary contain a variety of living resources that are ecological and commercial assets. The plants and animals require a delicate balance among the dynamic physical and chemical processes that alter their habitats and affect their distribution. As shown in figure 11, plants (algae, submersed aquatic plants, and emergent wetland plants) are critical links between the nutrients in the sediments and water column and the animals (invertebrates, fish, birds, reptiles, amphibians, and mammals). Shellfish and finfish are the living resources harvested by man (table 1); healthy, abundant populations usually occur in well-balanced and unpolluted ecosystems. More than 100 species of fish have been found in the tidal Potomac River and Estuary (Lippson and others, 1979).

Reproductive success of many fish species is strongly affected by variations in environmental conditions. Imbalances in the riverine ecosystems of the tidal Potomac River have led to algal blooms, low dissolved-oxygen concentrations, fish kills, changes in fish species, decrease in numbers of waterfowl, and decline in submersed plants during the last 30 to 50 years. For example, the American shad was the most valued fish in the Potomac in the 19th century, when 2.5 to 3 million pounds were landed annually. Population and catches have steadily declined since then, and between 1972 and 1976, approximately 200,000 pounds were harvested annually (table 1). Understanding the interrelationships among sedimentation, water quality, plants, and animals is essential to proper management of harvestable resources.

Table 1.-Average annual landings (in thousands of pounds) of eight dominant finfish species, other finfish, and three shellfish species in the Potomac Estuary main stem and tributaries; values are averaged over the periods indicated. From Lippson and others, "Environmental Atlas of the Potomac Estuary" (1979).

	Period 1964-67	Period 1972-76
Finfish		
Alewives	11,427	4,020
Catfish	389	112
American eel	324	541
Atlantic menhaden	6,365	10,112
American shad	378	205
Spot	446	162
Striped bass	1,313	1,148
White perch	274	107
Other finfish	543	3,686
Total Finfish	**21,458**	**20,093**
Shellfish		
Blue crabs	4,471	2,289
Soft-shell clams	2,048	4
Oysters	5,236	2,050
Total Shellfish	**11,755**	**4,343**
Total Finfish and Shellfish	33,213	24,436

RESEARCH STUDIES

Framework of the Potomac Estuary Study

The Potomac Estuary Study is conducted by scientists from many disciplines involved in 14 different but interrelated studies. Two major groups of research studies can be identified: River Quality Assessment and complementary studies. This River Quality Assessment, one of several that have been intended to develop suitable information for river-basin planning and water-quality management of the Nation's major rivers, is the first to focus on water-quality problems of a tidal river and estuary. The complementary studies were added in order to increase the scope of the overall study and to provide a more complete picture of processes and present conditions for use in making management decisions. The diagrams (fig. 12) presented on the following pages are designed to clarify the relationship between research studies and water-quality problems in the tidal Potomac River and Estuary. Titles of studies directed at specific water-quality problems are listed below the problem, and the arrows indicate the activities undertaken by each study. In all instances each study group uses data collected by other groups. Thus, each problem is documented with a broad data base and is addressed simultaneously from several points of view. Following this diagram are summaries of the individual research studies.

Hydrodynamics

To enhance our understanding of the physical, chemical, and biological processes in the tidal Potomac River and Estuary, we must know the quantity and direction of water movement (hydrodynamics). Flowing water transports dissolved and particulate constituents as well as living material through an estuary. Water movement also influences an estuary's mixing and flushing characteristics, important physical param-

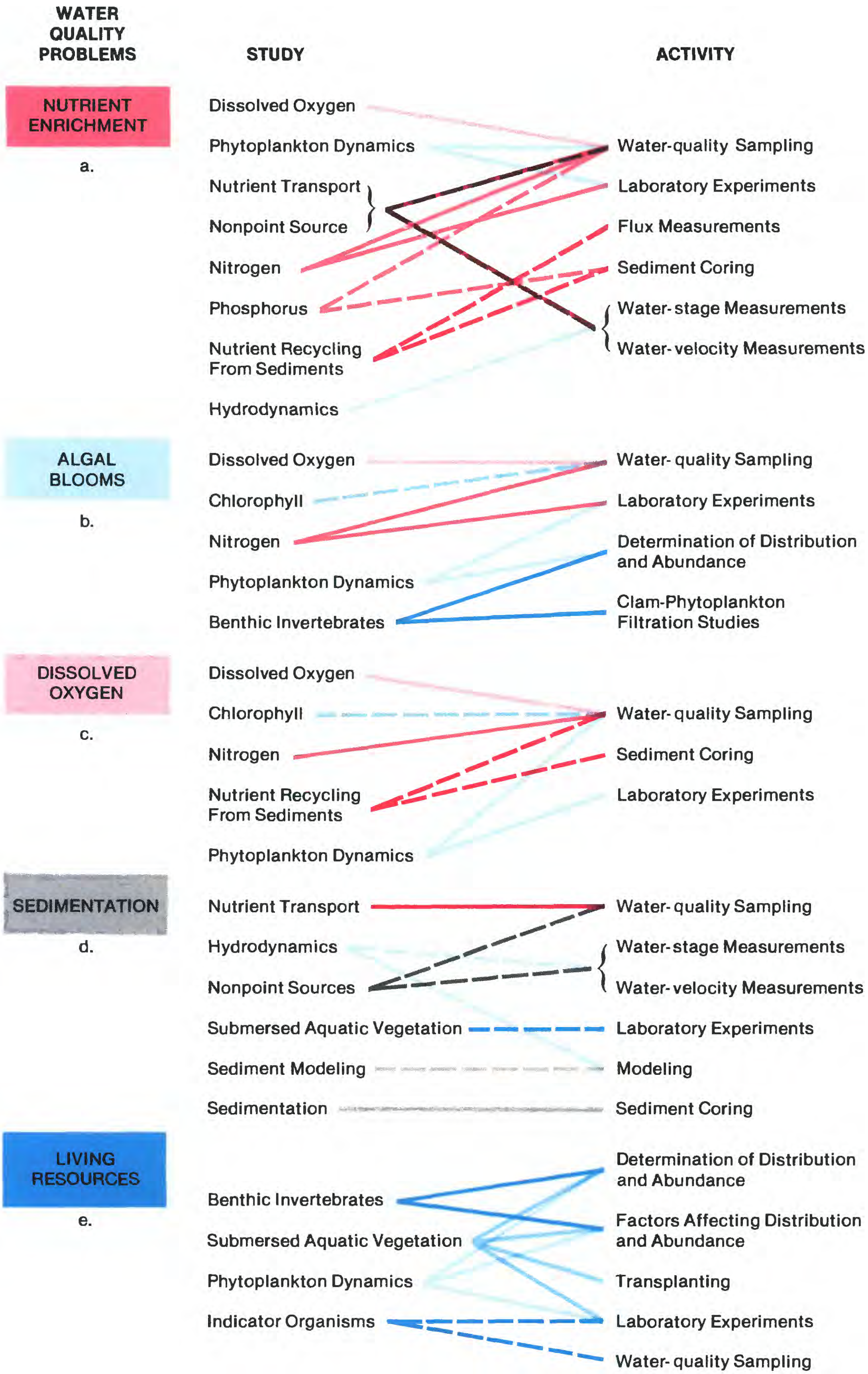


Figure 12. The relationship between Potomac Estuary research studies and field and laboratory activities.

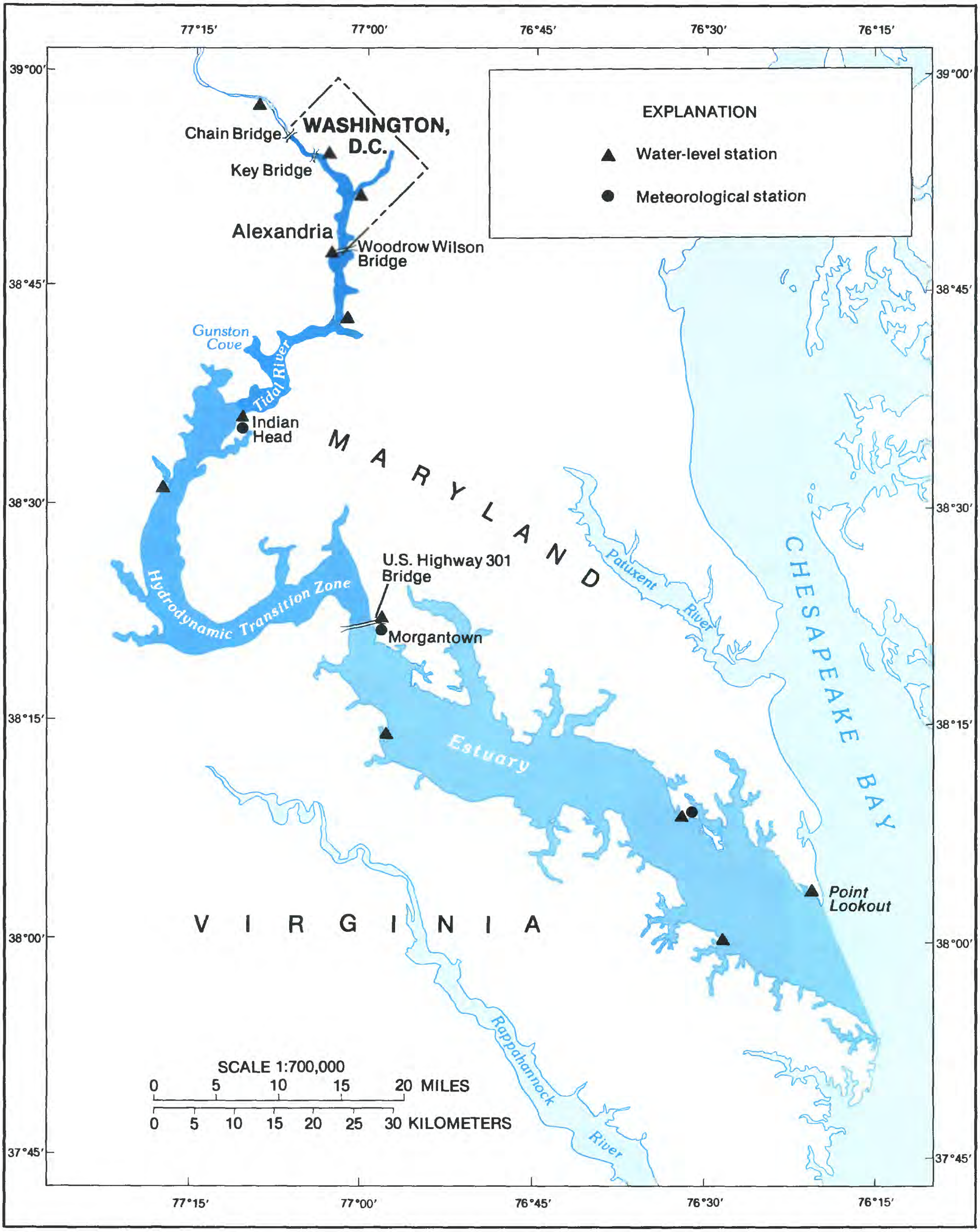


Figure 13. Locations of model reaches, gaging stations, and meteorological stations.

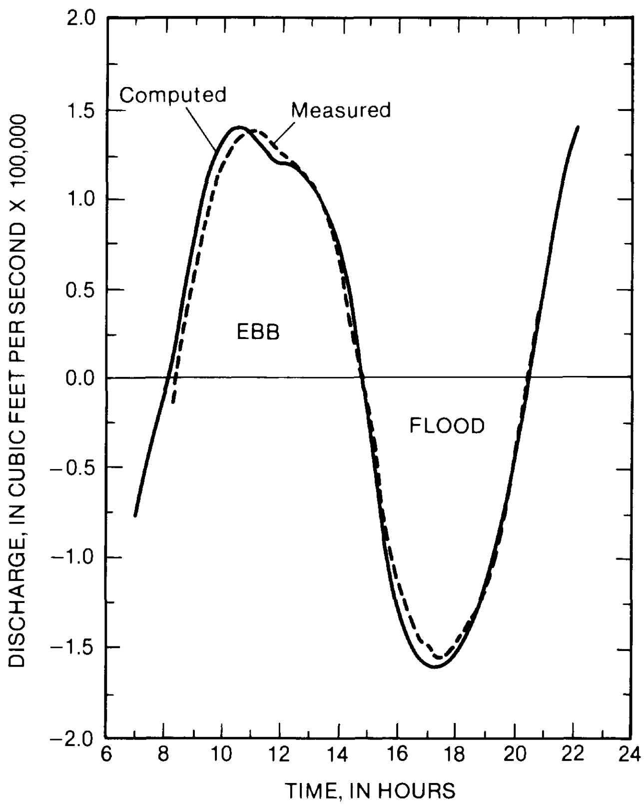


Figure 14. Comparison of measured and computed discharges for the branch network model segment, Gunston Cove, Virginia, to Indian Head, Maryland, March 6, 1981.

eters that affect water quality. However, the hydrodynamics of the tidal Potomac River and Estuary are difficult to measure and to analyze because the system is constantly changing in response to ebb and flood of the ocean tides, variations in fresh-water inflows, effects of winds and movement of weather fronts, and density differences between fresh water and sea water.

The Survey has implemented several computer transport simulation models that describe the flow and circulation patterns occurring throughout the tidal Potomac River and Estuary. A one-dimensional network flow model has been implemented to depict the tidal Potomac River from Chain Bridge, Washington to Indian Head, Md. Two-dimensional flow and transport models have been implemented to depict the downstream segment of the tidal river from Key Bridge, Washington to Indian Head, Md.; the hydrodynamic transition zone from Indian Head to Morgantown, Md.; and the estuary from Morgantown to Point Lookout, Md.

Data that scientists used to implement the models consist of depth soundings obtained from the National Ocean Survey (National Oceanic and Atmospheric Administration), water-level recordings obtained from a network of 12 tidal gaging stations (fig. 13), flow velocities obtained with current meters, and weather data (air temperature, air pressure, solar radiation, wind speed and wind direction) obtained from three automatic recording meteorological stations.

The patterns of flow vary throughout the tidal Potomac River and Estuary. Flow simulations using the one-dimensional model confirm the two distinct flow patterns exhibited within the tidal river. Unidirectional, pulsating, downstream flow occurs in the narrow channel upstream of Key Bridge, whereas bi-directional (successively upstream and downstream) flow occurs in the broader downstream channel. Flow in the transition zone is bi-directional with occasional vertical stratification in the lower portion of the segment. Flow in the estuarine segment is bi-directional but typical of a partly mixed type of estuary, that is, an estuary showing vertical stratification with a tendency for outflow in the surface layer and inflow near the bottom.

The one-dimensional model was used to compute time-varying discharges throughout the tidal river for June 3-4, 1981. Water-velocity measurements from current meters were used to compute discharges at Indian Head, Md., for the same time period. A comparison of model-computed and field-measured discharges at Indian Head, Md., is shown in figure 14. The difference between the computed and measured discharge hydrographs, as shown in the figure, is well within the limit of accuracy of the field measurements.

Output from the two-dimensional models covering the lower tidal river, the transition zone, and the estuary includes time-varying velocity-vector fields, as well as isolines of flow speed throughout each of these segments. This type of model output is illustrated for the lower tidal river (fig. 15).

Nutrient Transport

Nutrients, such as nitrogen, phosphorus, and silica, play an important role in the ecosystem of the tidal Potomac River and Estuary. The amount of nutrients in water affects its usefulness for municipal, industrial, and recreational purposes and influences the kinds and numbers of aquatic plants and animals present. When scientists measure the amount of nutrients moving through an estuarine system by sampling at representative stations, they can identify the relative importance of nutrient sources and determine reaches in which losses or gains in nutrients occur. Thus, measuring the concentration and quantity of nutrients that enter and are transported through the tidal Potomac River and Estuary is essential to understanding the entire ecosystem and aids in making management decisions such as whether to convert from secondary to tertiary waste treatment in sewage treatment plants.

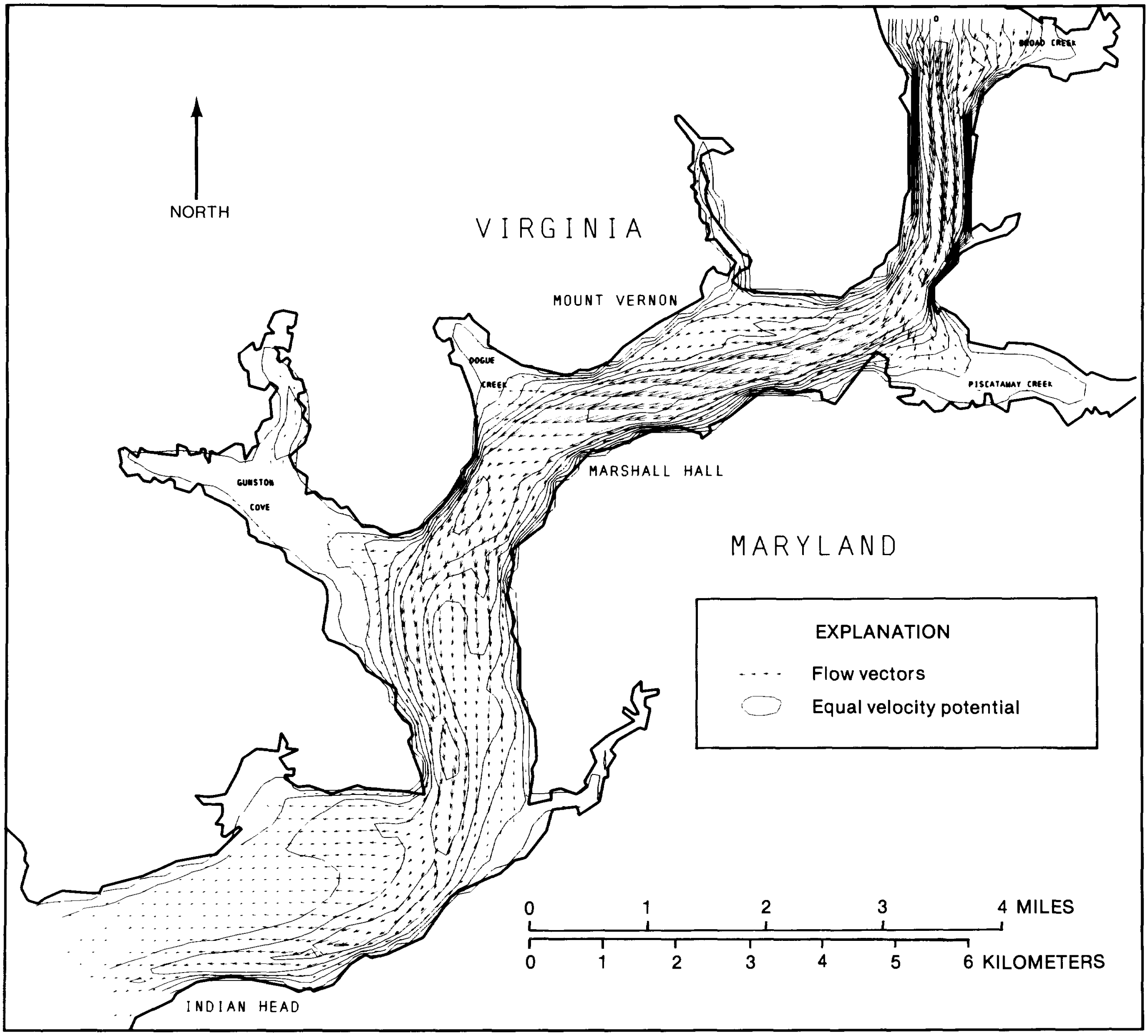


Figure 15. Flow vectors and lines of equal velocity potential generated by the two-dimensional model.

From October 1978 through September 1981, the U.S. Geological Survey conducted a water-quality sampling program from Chain Bridge, Md., to Point Lookout, Md. (fig. 16). The sampling program involved measuring the concentrations of nitrogen, phosphorus, and silica at five key stations (nutrient transport stations), which were sampled every week, and at 21 intervening stations (water-quality sampling stations), which were sampled every month. Data collected at the key stations were used to compute nutrient transport and the data collected at the intervening stations were used to show variations of nutrient concentrations in space and with time. The histograms (fig. 17) show the average specific conductance of the water and the average concentrations of nitrogen, phosphorus, and silica measured at the key sampling stations from October 1978 through September 1980.

Downstream changes in the concentration of nutrients are caused by many interrelated factors, some of which are point-source inflow, recycling from bottom sediments, consumption by algae, dilution, and salinity changes. A major increase in nutrient concentrations occurs at Alexandria, Va., where the effluent from the Blue Plains Sewage Treatment Plant enters the river. The concentrations of nitrogen, phosphorus, and silica are highest at this point. Nutrient concentrations are lower in the transition zone between Quantico, Va., and Morgantown, Md. In this reach the fresh-water, salt-water interface usually occurs, near which fresh-water organisms die off and salt-water

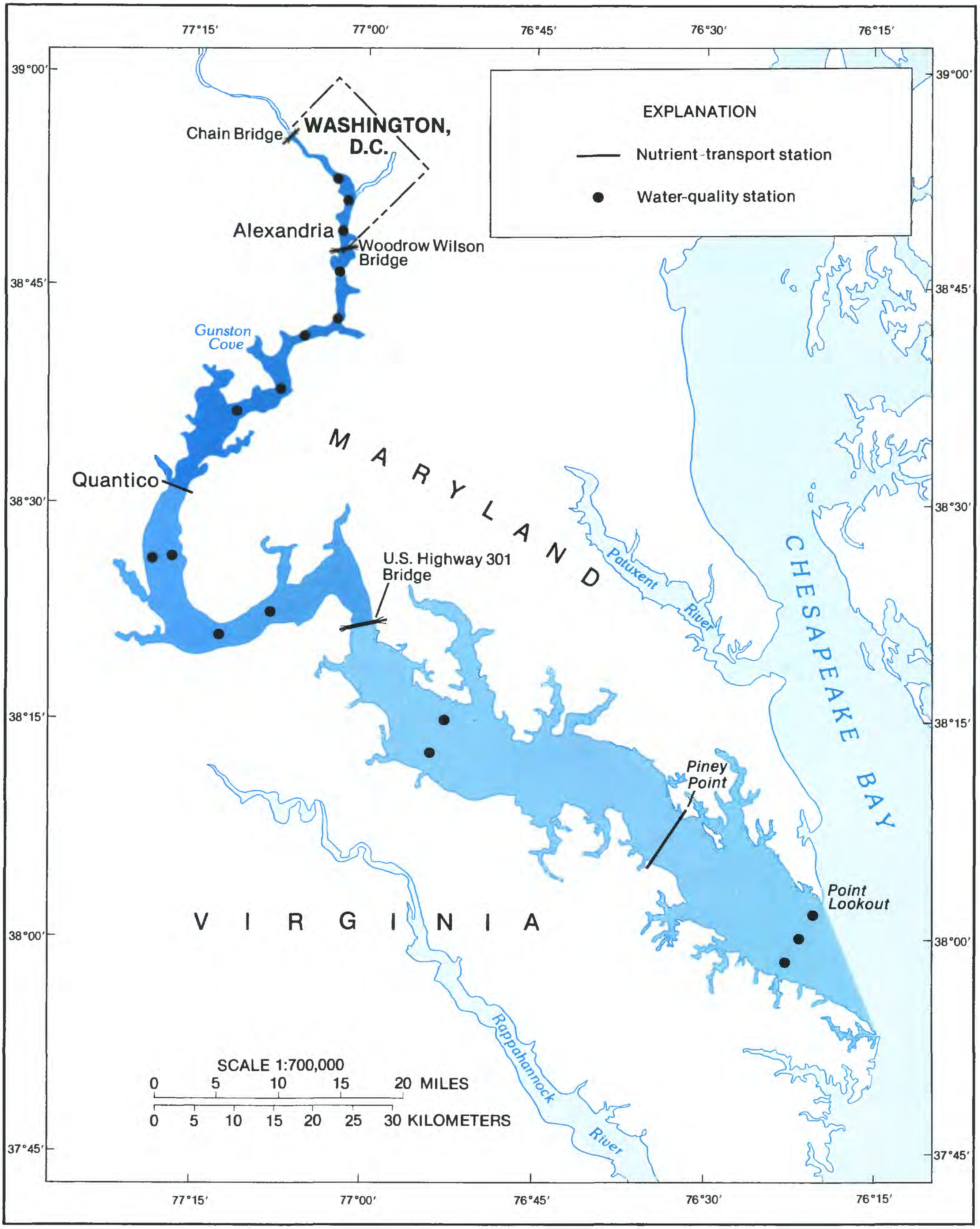


Figure 16. Location of nutrient transport and water quality sampling stations.

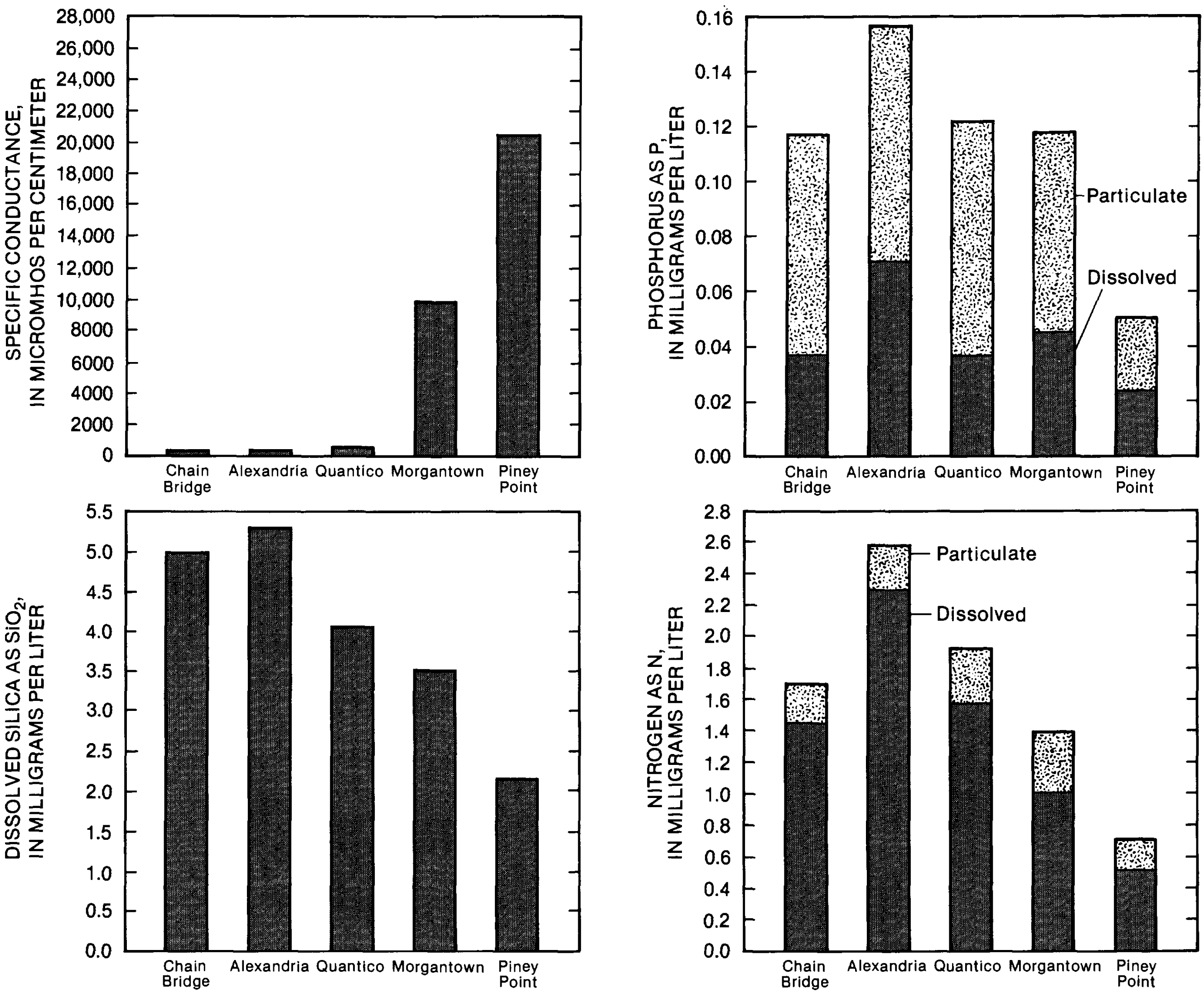


Figure 17. Average specific conductance and nutrient concentrations at key stations, 1979-80 water years.

organisms increase in number causing rapid changes in release and uptake of nutrients. Nutrient concentrations are also low in the saline part of the estuary where the diluting effect of Chesapeake Bay is apparent.

Dissolved Oxygen

When sewage is discharged into a river, dissolved oxygen is used up as bacteria decompose the organic material. In order to maintain a predetermined dissolved-oxygen concentration in a river or estuary, the States, with the approval of the U.S. Environmental Protection Agency (EPA), issue permits for the amount of BOD a sewage treatment plant can discharge. Determining the sources and relative amounts of BOD and the effect on dissolved oxygen in a river is not straightforward or easy because of the complex interaction among nutrients, phytoplankton growth and death, and other physical and chemical processes taking place. During the summer, longer days, warmer temperatures, and lower river flows combine to increase the impact of oxygen-demanding materials on dissolved oxygen. Generally, during periods of high flow or low temperatures, low concentrations of dissolved oxygen do not occur. In addition, as the total amount of sewage increases, the loads of nitrogen and phosphorus have an increasingly complex effect on dissolved oxygen in the river.

Treatment of sewage is expensive, and the cost effectiveness of such treatment is sometimes questionable because the cause-and-effect relationships between nutrients discharged and dissolved oxygen in the river are poorly understood. The removal of BOD associated with organic carbon is effective, beneficial, and economical. The cost of removing or changing the form of nitrogen or phosphorus discharged is much greater and the results are more uncertain. Also, the various sources and their relative concentrations of carbon, nitrogen, and phosphorus must be considered. Figure 18 shows that Potomac River water entering the tidal river at Chain Bridge contributes considerably more nitrogen and phosphorus than the discharge from the Blue Plains Sewage Treatment Plant, which receives three quarters of the sewage from the Washington metropolitan area. This fact suggests that removing more nitrogen and phosphorus from the sewage treatment plant discharge might not significantly reduce algae concentrations or change the dissolved oxygen concentrations.

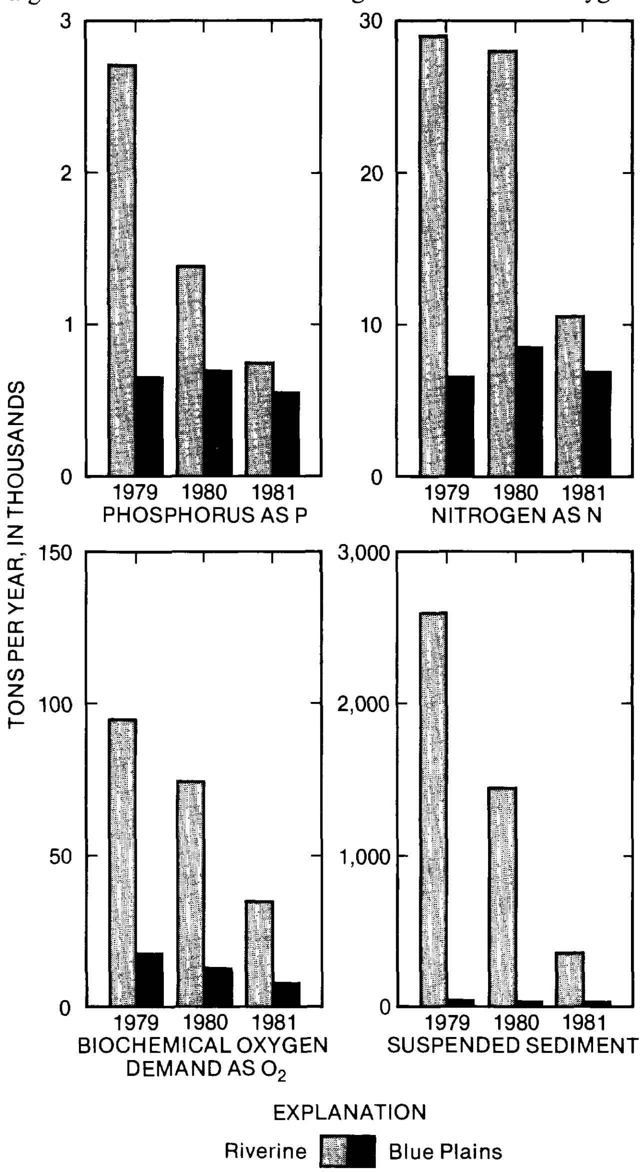


Figure 18. Comparisons of annual biochemical oxygen demands, nutrient, and suspended-sediment loads to the tidal river from Blue Plains Sewage Treatment Plant and from upstream of Chain Bridge for water years 1979 through 1981.

The U.S. Geological Survey is developing a predictive model for the tidal Potomac River relating dissolved oxygen to sewage and nonpoint source loads of BOD, nitrogen and phosphorus to enable water managers to examine various treatment alternatives for cost effectiveness. In order to make this model, the relationship of dissolved oxygen to the total riverine environment must be known. This requires measuring the inputs, outputs, and seasonal concentrations of nutrients; determining what processes control the dissolved oxygen; and determining how these processes are affected by physical, chemical, and biological factors. The data required to understand the processes and to predict dissolved oxygen concentrations include nutrient and BOD concentrations, light penetration, and attenuation, incident light, chlorophyll concentrations, pH, dissolved oxygen, temperature, specific conductance, water velocity, wind speed and direction, and wave height. These kinds of data were collected by the Survey during July, August, and September of 1980 and 1981. Morning and evening longitudinal studies were made to detect net changes in the parameters, and Lagrangian studies, involving 36-hour periods of observations in a single block of water, were conducted to observe processes in detail.

Figure 19 shows how dynamic the processes affecting dissolved oxygen can be. During a short but typical low-flow period in 1980, one-fourth of the dissolved oxygen in the system was lost every night and regained every day. Because large amounts of chlorophyll *a* also disappear at night and reappear each day, dissolved oxygen appears to be controlled by the photosynthetic activity of the algae during similar low-flow periods. Changes in sewage treatment plant effluent

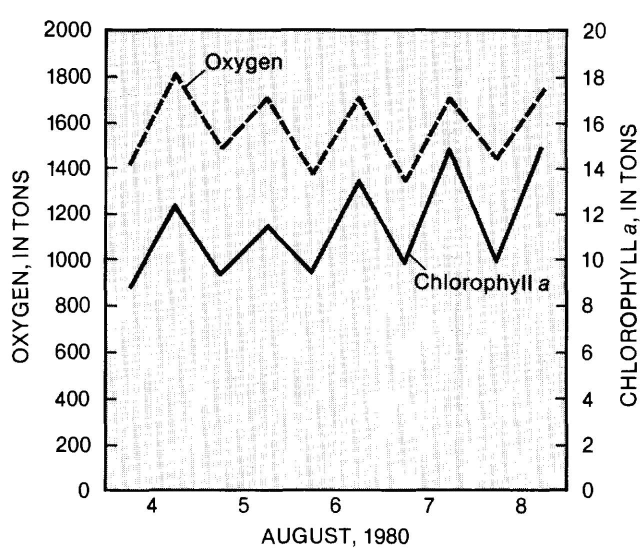


Figure 19. Chlorophyll and oxygen loads in the tidal Potomac River, August 4-8, 1980.

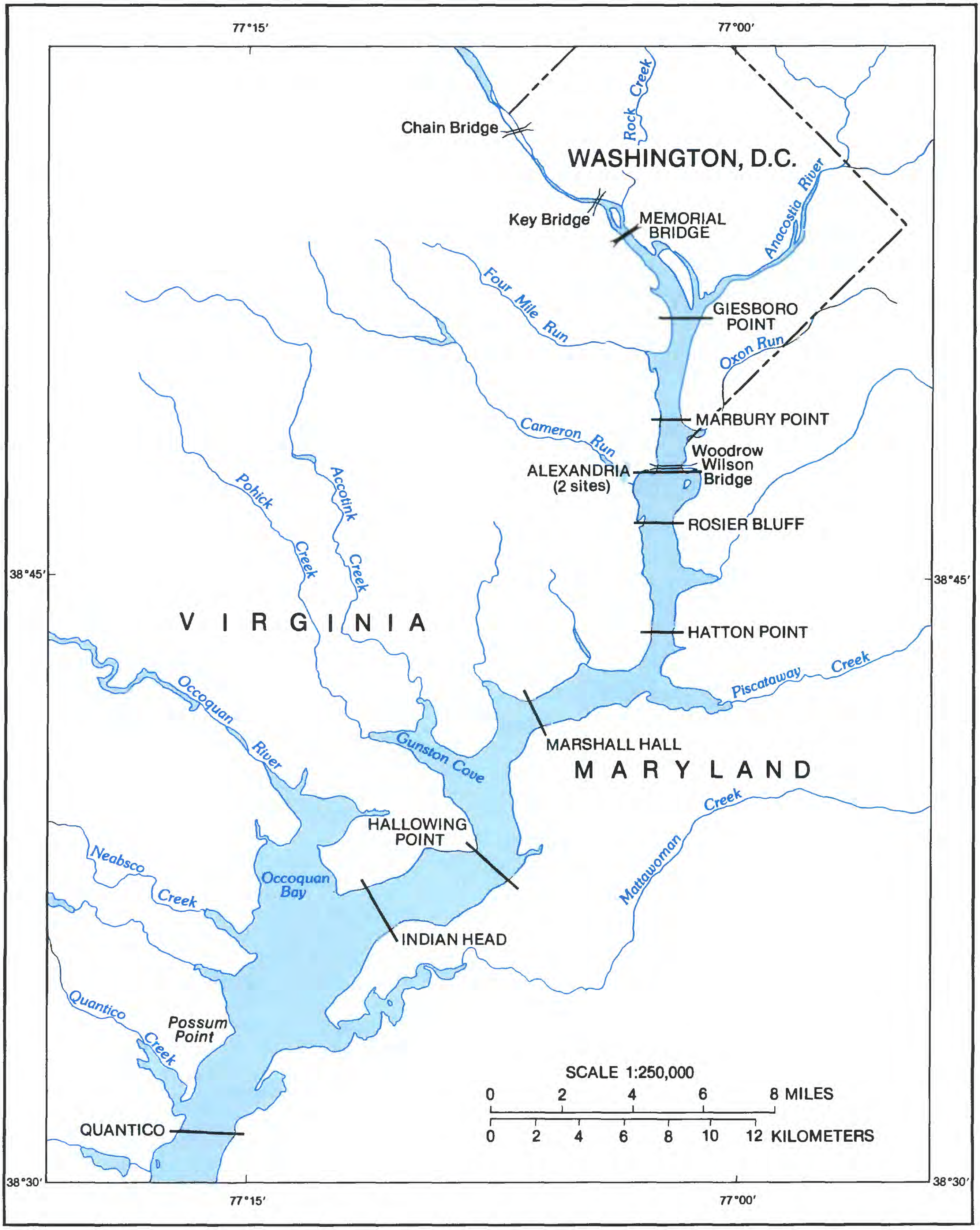


Figure 20. Location of nitrogen cycle sampling transects on the tidal Potomac River, 1980-81.

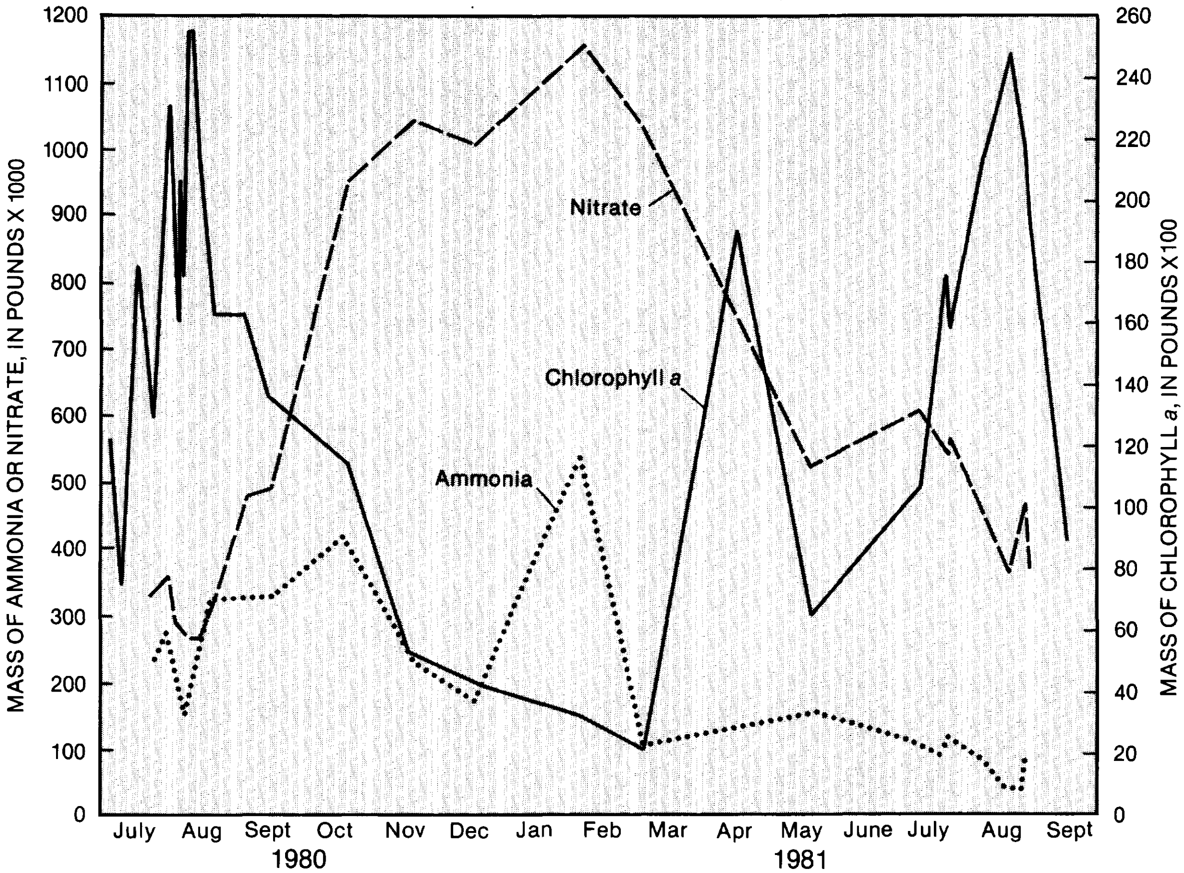


Figure 21. Mass of ammonia, nitrate, and chlorophyll *a* found in the tidal Potomac River, July 1980 to September 1981.

during these sensitive periods affect the algae and, thus, the dissolved-oxygen concentration in the river.

Nitrogen Dynamics in the Tidal River

In the tidal Potomac River, the concentrations of nitrogen species, including ammonia, nitrite, nitrate, and organic nitrogen, are greater than upstream river concentrations because of discharges from the Blue Plains Sewage Treatment Plant. Nitrification, the biological oxidation of ammonia to nitrite and the further oxidation of nitrite to nitrate, may significantly affect dissolved-oxygen concentrations in the tidal river. Additionally, high concentrations of ammonia, nitrate, or both, stimulate phytoplankton growth. The purpose of the Survey's nitrogen study was to determine the effect of reduced wastewater discharges of ammonia and increased discharges of nitrate on the processes involved in the riverine nitrogen cycle.

Regularly, during 1980 and 1981, the Survey determined the densities of ammonia-oxidizing bacteria (*Nitrosomonas*) and nitrite oxidizing bacteria (*Nitrobacter*), and the concentrations of ammonia, nitrite, nitrate, and organic nitrogen in the water column and surficial sediments at eleven transects along the tidal river (fig. 20). On the average, sediments had 1,000 times higher densities of nitrifying bacteria than the water column. From 1980 to 1981, the number of ammonia-oxidizers in the water column decreased while the number of nitrite-oxidizers increased. There was no apparent change with time in the numbers of nitrifying bacteria in the surficial sediments. Ammonia concentrations in river samples taken during the summer of 1981 were lower and nitrate concentrations were higher than concentrations in samples taken during the summer of 1980 (fig. 21).

The start of the nitrification reactors at Blue Plains Sewage Treatment Plant in the fall of 1980 appears to have had the expected effect of reducing the load of ammonia while increasing the load of nitrate (fig. 21). The reduced ammonia concentrations may have caused the thousand-fold decrease in ammonia-oxidizing bacteria in the water column. The simultaneous increase in nitrite-oxidizing bacteria may be due to an increased source of these bacteria from Blue Plains, where they are used in the nitrification reactors.

Because the number of nitrifying bacteria in the surficial sediments is much higher than in the water column and because the numbers in the sediment did not change with the reduced loading of ammonia from Blue Plains, most of the nitrification in the tidal river probably takes place in the sediments using ammonia generated in the sediments. Thus, the oxygen demand due to nitrification may not be eliminated by reducing the ammonia discharged from Blue Plains.

Although the total mass of nitrate increased in the tidal river after the nitrification reactors became operational in the fall of 1980, the total mass of chlorophyll *a* was approximately the same in the summers of 1980 and 1981. Thus, the reduction in ammonia loading to the river, although successful in reducing river concentrations of ammonia, may not have succeeded in reducing the quantity of phytoplankton in the river.

Phosphorus Dynamics in the Vicinity of the Blue Plains Sewage Treatment Plant

Because considerable quantities of untreated or partially-treated sewage containing carbon, nitrogen, and phosphorus are still being discharged into many of the Nation's lakes, rivers, and estuaries, scientists need to achieve a clearer understanding of nutrient behavior in sediment-water systems. They are particularly interested in phosphorus, because it is often the nutrient which limits algal growth, and also because it is less expensive to remove from sewage effluents than carbon and nitrogen. The Blue Plains Sewage Treatment Plant discharges an average of 4,400 pounds of phosphorus into the tidal Potomac River each day. During 1979 and 1980, the Survey sampled a 6-mile reach of the river near this plant in order to determine the major factors controlling the movement of phosphorus in the immediate vicinity of the sewage outfall. A map of the study area and the location of sampling sites is shown in figure 22.

In order to establish the flow pattern of the effluent and measure how long the effluent remains in the vicinity of the sewage-treatment-plant outfall before being flushed out, the Survey injected fluorescent-tracer dye through the outfall. Water samples were then collected over a series of several tidal cycles. These samples were analyzed for dye content and for dissolved and particulate phosphorus. The Survey also collected several cores to study chemical reactions between the bottom sediments and phosphorus in the overlying waters, and to estimate the amount of effluent-derived phosphorus retained in the sediments.

The dye studies show that the flow of effluent is largely confined to a restricted embayment on the eastern side of the river. As shown in figure 22, this embayment separates the effluent from the main channel of the river for more than 2 miles downriver from the outfall. Analyses of bottom sediments in the embayment revealed that about 10 percent of the phosphorus discharged from the outfall has been retained in this area; the remaining 90 percent has been flushed into the main channel of the river.

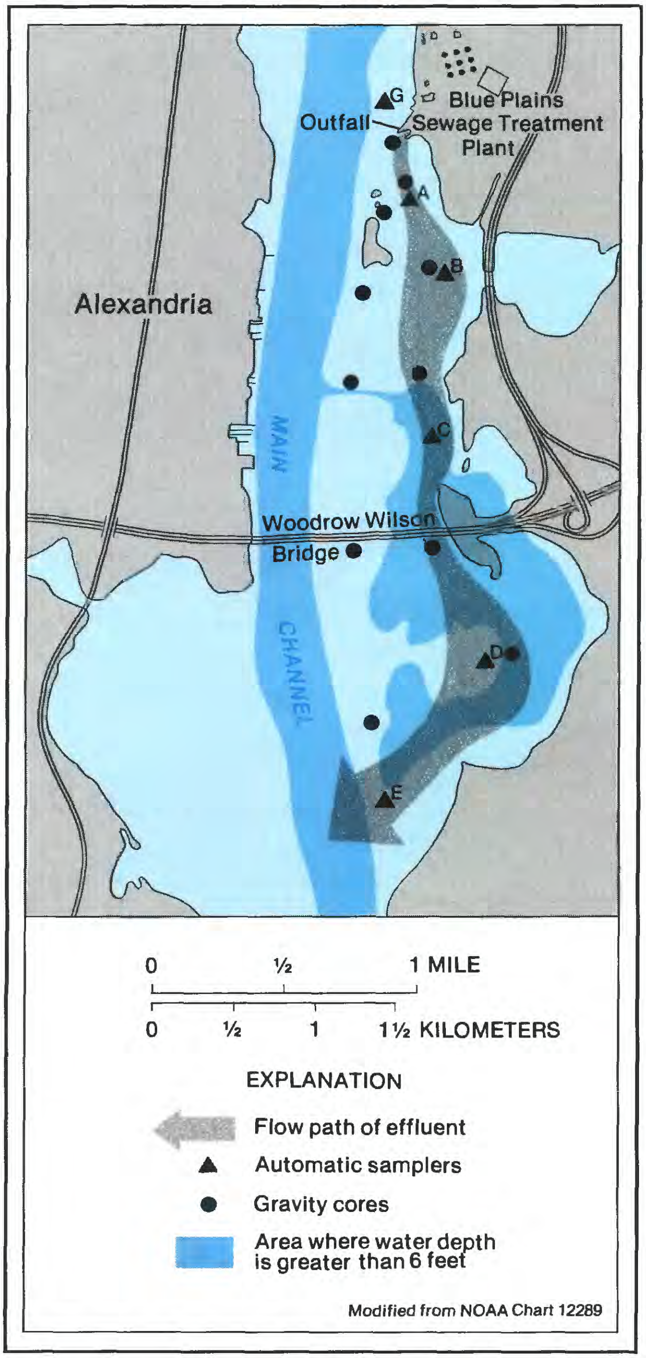


Figure 22. Location of phosphorus study area and sampling sites in the tidal Potomac River, 1980-81.

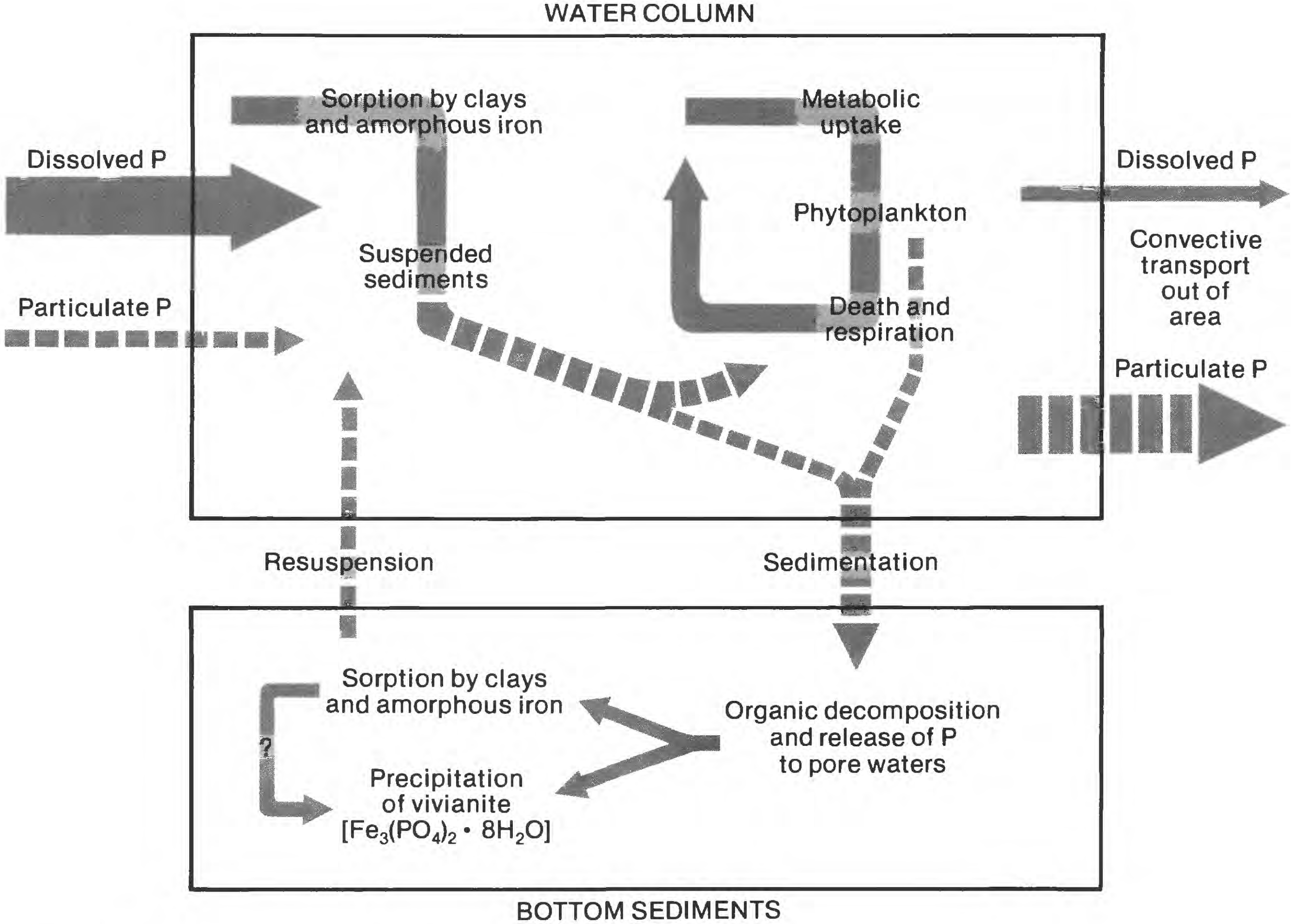


Figure 23. Major processes controlling phosphorus dynamics near a sewage outfall.

Several factors appear to be controlling the transport of phosphorus near the outfall. These factors are shown diagrammatically in figure 23. They include: 1) Sorption reactions between dissolved phosphorus and sediments. Much of the dissolved phosphorus discharged by the treatment plant is adsorbed quickly by amorphous iron compounds and clays in suspended and bottom sediments. Although most of the phosphorus in the effluent is in the dissolved form, the greater part of the phosphorus is transported from the area attached to suspended sediment. 2) Uptake and release of dissolved phosphorus by phytoplankton. Phytoplankton populations can utilize large quantities of dissolved phosphorus during growth. Although this removal may be extensive when large algal blooms form, most of the phosphorus is eventually returned to the water as the product of respiration and decay. 3) The deposition and (or) resuspension of sediments that have sorbed phosphorus. Suspended sediments will eventually settle out and become incorporated into bottom sediments. Most of the effluent-derived phosphorus retained in the bottom sediments accumulated in this way. Temporary increases in water velocity may resuspend bottom sediments, however, and return them to the water column. 4) Changes in circulation patterns due to variations in river discharge, tidal currents, wind direction, and wind velocity. Each one of these variables can affect the movement of sediments within the area. 5) Formation of phosphorus-containing minerals in bottom sediments. Sand-size grains of the iron-phosphate mineral vivianite have been found close to the outfall; however, they contain only a fraction of the phosphorus held by bottom sediments. These mineral grains are unlikely to be removed by resuspension because of their size.

Nonpoint Sources of Nutrients and Sediment

Sediment, phosphorus, nitrogen, and BOD in the streamflow leaving the tributary watersheds may have detrimental effects upon the water quality of the tidal Potomac River and Estuary. The substances carried in the streamflow come from four sources: the materials in the ground water that seep into the tribu-

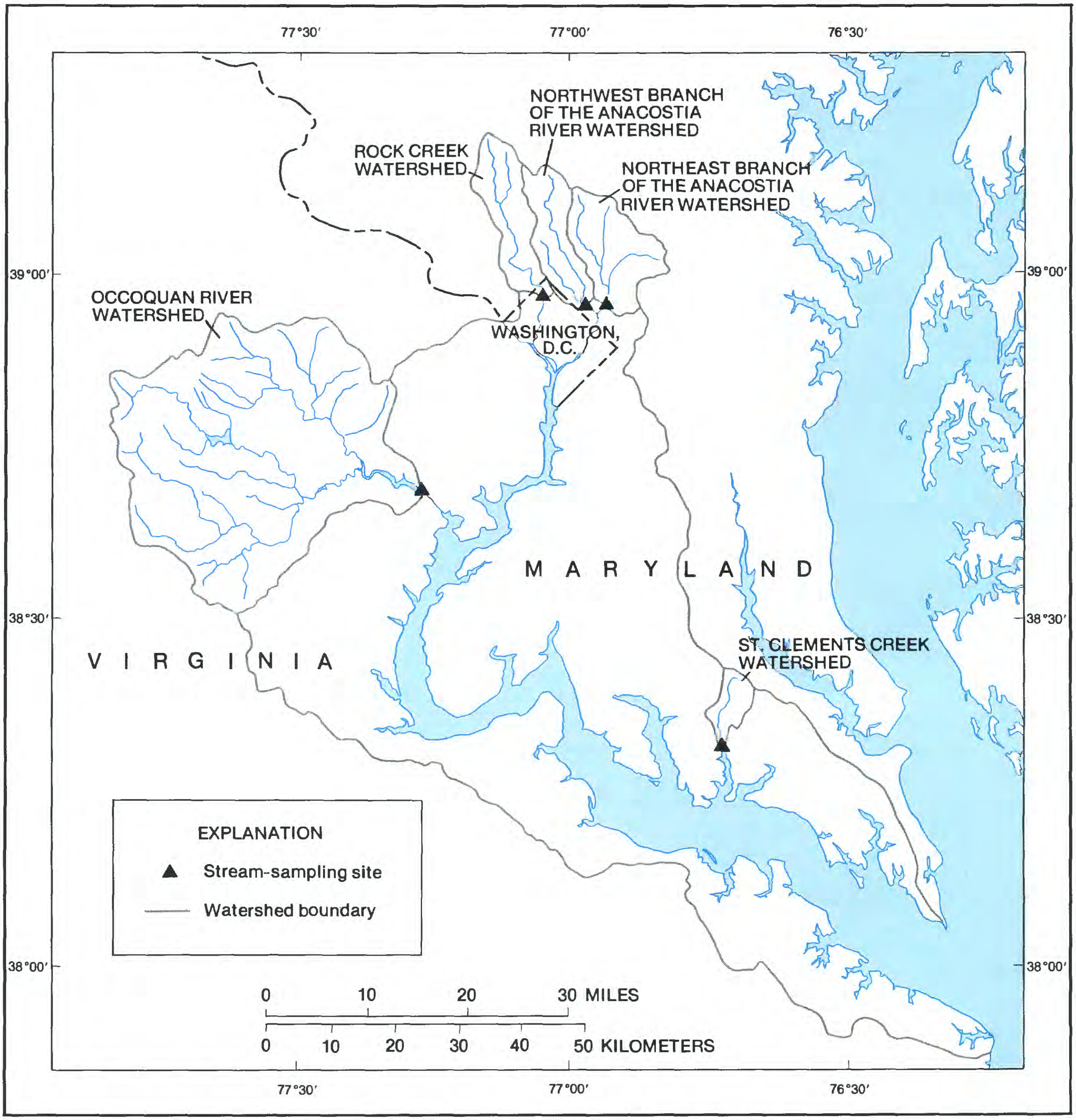


Figure 24. Locations of sampling sites, 1979-81 (triangles), with corresponding watershed boundaries.

tary stream channels, the materials that accumulate upon the surface of the land and are washed into the stream channels with the surface runoff, the materials in the rain, and the point sources discharging to the tributaries. The concentrations of these materials in the streamflow are generally much greater during storms than during nonstorm periods, and their short-term effects upon water quality are most noticeable during and following storms. Examples of such effects include the increase in turbidity during storms and the decrease in the concentration of dissolved oxygen following storms.

The U.S. Geological Survey determined the yield of sediment, phosphorus, nitrogen, and BOD for five selected watersheds (fig. 24) by sampling (fig. 25) the streamflow leaving these watersheds between 1979 and 1981. Preliminary analysis indicates that the average annual sediment yield for the urban watersheds (Rock Creek, and the Northeast and the Northwest Branches of the Anacostia River), 257 (tons/mi^2)/yr, is about

Figure 25. A standard suspended-sediment sampler used in the U.S. Geological Survey.

Figure 26. Photomicrograph (× 1200) of a diatom, *Diatoma vulgare*. *Diatoma* species are widely distributed in fresh-water environments and some species are marine. This collection was taken from the Potomac River at Quantico. (Photomicrograph by Vicki Stoelzel and Kim Boloukos).

one-quarter of the value calculated 20 years ago and close to the yield for the rural watershed (St. Clements Creek), 240 (tons/mi^2)/yr. The average annual yields of nitrogen and BOD for the urban watersheds are greater than the values for the rural watershed, and the average annual yield of phosphorus for the urban watersheds is less than the yield of the rural watershed.

Preliminary results show that the average annual loads of phosphorus, nitrogen, sediment, and BOD to the tidal Potomac River and Estuary from all tributary watersheds constitute a relatively small source compared to loads from sewage treatment plants and the Potomac River upstream of the study area. Loads from the tributary watersheds were calculated by applying the yields for the sampled urban watersheds to all the urban watersheds and the yields for the sampled rural watershed to all rural watersheds. The yields calculated for the Occoquan River watershed were applied to only the Occoquan River watershed. The average annual loads from all watersheds are 507,000 tons of sediment, 628 tons of phosphorus, 4,190 tons of nitrogen, and 21,000 tons of ultimate BOD. The average annual loads contributed by the Potomac River at Chain Bridge (Feltz and Herb, 1978; Sullivan and others, 1981), the Washington metropolitan area point-source discharges (Sullivan and others, 1981), and the District of Columbia combined sewer overflows (O'Brien and Gere Engineers, 1979) are available in the literature. If the loads from all the above sources are summed, the tributaries contributed from 7 to 30 percent of the totals.

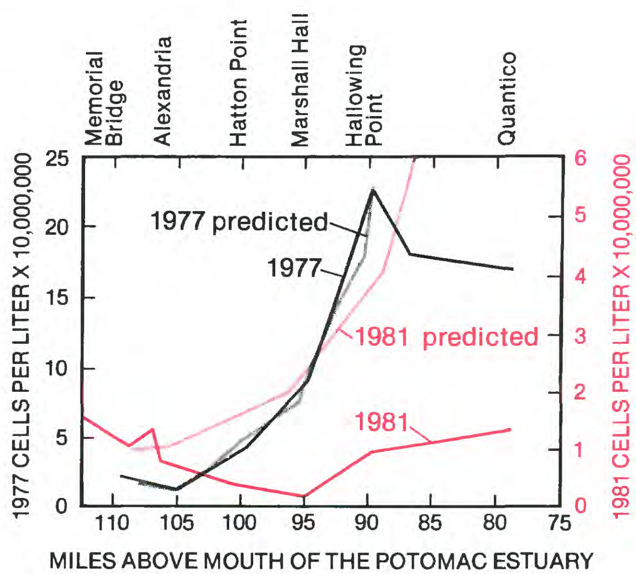


Figure 27. Comparison of predicted and measured phytoplankton abundance in the tidal Potomac River.

Phytoplankton Dynamics

Phytoplankton, the microscopic algae that are suspended in the tidal Potomac River and Estuary, both indicate and alter water quality. Diatoms (fig. 26) are one important group of algae. The U.S. Geological Survey investigated the effects of nutrients, light penetration, and aquatic animals on growth rate, oxygen production, distribution and transport of phytoplankton. In addition to understanding phytoplankton processes, the goal was to understand processes that control phytoplankton abundance in the tidal river.

Abiotic components of the tidal river and estuary such as light, nutrients, and discharge, as well as biotic components, regulate the rates of growth and disappearance of the phytoplankton in the the tidal Potomac River and Estuary. The Survey's phytoplankton computer model uses growth constants for the tidal Potomac River that were determined from laboratory experiments on the effects of nutrient enrichment, and from field measurements of photosynthesis. The growth constants reveal that in July, August, and September, phytoplankton have the potential to double their population every 3 to 4 days. River discharge was included in the model for abundance calculations because, if phytoplankton biomass is transported out of a river segment faster than it is transported in and grows, then the population will decrease in that segment.

Low flow, combined with high levels of sunlight and nutrients in the late summer, has resulted in high concentrations of phytoplankton in the tidal Potomac River from Washington to Quantico, Va., during the 1960's and 1970's (fig. 27). In the summers of 1980 and 1981, phytoplankton in the tidal river were much less abundant than in the 1960's and 1970's and less abundant than predicted by our model (fig. 27). A possible contributor to this decrease in phytoplankton abundance is the Asiatic clam, *Corbicula fluminea*, that invaded the tidal Potomac in 1975. By 1980, the clam's biomass had increased to such an extent that the clams could have filtered large quantities of phytoplankton from the reach between Alexandria, Va., and Hatton Point, Md.

When freshwater phytoplankton are transported to the transition zone, saltwater induces an osmotic stress and they die. Phytoplankton in the estuary are predominately brackish-water and marine species. Blooms of the dinoflagellate (flagellated brown algae) *Katodinium rotundatum* appeared in December and January 1980 and 1981 between Mathias Point, Md. and Cobb Island, Md. (fig. 5) and persisted until March. The number of phytoplankton in these blooms exceeded that found anywhere else in the river, even during the summer.

The phytoplankton in the estuary downstream from Piney Point resemble those found in Chesapeake Bay. During the winter and spring, when the estuary is well mixed from the top to bottom, diatoms such as *Rhizosolenia* dominate and bloom in late spring. As the estuary stratifies in early summer, the bottom waters become anoxic. Phytoplankton then are found only in the upper few meters of the water column.

Distribution of Chlorophyll *a*

Phytoplankton contain the chlorophyll *a* molecule, that fundamental unit capable of absorbing sunlight and using this energy to convert water and carbon dioxide into food and oxygen. This makes phytoplankton one of the important links between nutrients and animals in the aquatic food chain and a dominant influence on the amount of oxygen present in the water. The amount of chlorophyll *a* in a given volume of water is directly related to the amount of phytoplankton present. Because chlorophyll *a* can be extracted from the phytoplankton cell and analyzed quickly, easily, and economically, and because it does have a direct relationship to the phytoplankton population, measurements of chlorophyll *a* concentration can be used to study phytoplankton dynamics.

The U.S. Geological Survey collected and analyzed more than 15,000 chlorophyll *a* samples from 1979 to 1981. Patterns of planktonic chlorophyll *a* were examined from Chain Bridge, Washington to Pt. Lookout, Md., from bank to bank, and from the bottom of the water column to the top. Longitudinal and vertical distributions of chlorophyll *a* representative of winter and summer conditions during 1980 are shown in figures 28 and 29. High concentrations of chlorophyll *a* were not unique to the summer or to that reach of the river most closely associated with sewage discharge from the Washington metropolitan area. In fact, the greatest concentrations of chlorophyll *a* occurred during winter in a 15-mile reach of the river extending from the transition zone into the estuary (figs. 28 and 29). Fluctuations in the concentration of chlorophyll *a* are influenced by weather, river flow, nutrients, grazing by aquatic animals, salinity, and many other factors.

Chlorophyll *a* concentrations show a striking difference in vertical distribution patterns between summer and winter in the lower transition zone and estuary (figs. 28, 29). During winter, salinities, temperatures, and river flow created a very weak density gradient (fig. 30) that allowed water to circulate freely top to bottom. Chlorophyll *a* concentrations were uniform throughout the water column. In summer, the density gradient was strong thereby restricting water

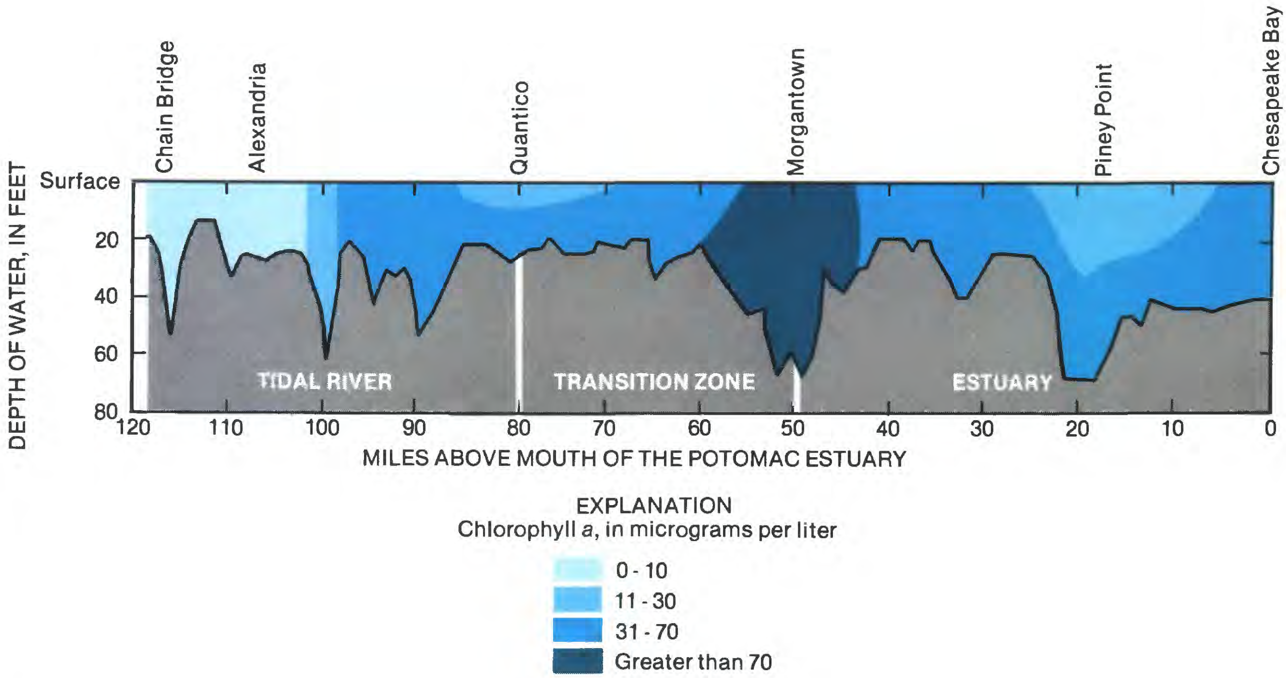


Figure 28. Longitudinal and vertical distribution of chlorophyll *a*, winter 1980 (based on February data).

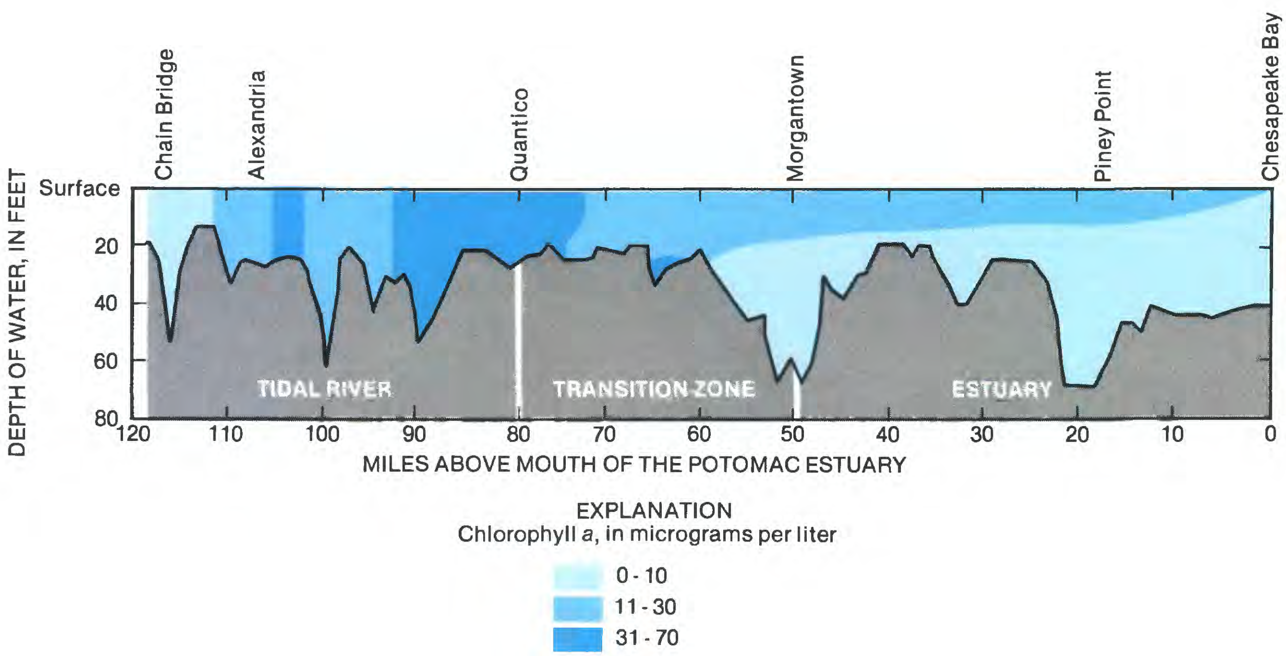


Figure 29. Longitudinal and vertical distribution of chlorophyll *a*, summer 1980 (based on July data).

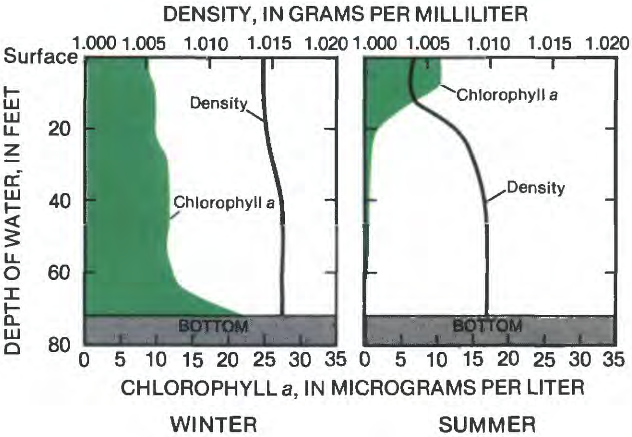


Figure 30. Vertical chlorophyll *a* distribution and density gradients in the lower estuary, summer and winter, 1980.

circulation and limiting chlorophyll *a* to the top part of the water column (fig. 30).

The weak density gradient in winter resulted in a greater volume of water available to contain viable chlorophyll *a*, and the mass of chlorophyll *a* was far greater in winter than in summer in the transition zone and estuary (fig. 31).

Indicator Organisms in the Tidal River

Scientists and engineers have used sanitary-quality-indicator organisms, such as total coliform bacteria, since the early 1900's to assess fecal contamination of natural waters. The organisms most commonly used include total coliform, fecal coliform, and fecal streptococci bacteria, which are present in much greater densities than any pathogens (disease-causing organisms) that might be present. The presence of indicator organisms shows that there is fecal contamination in the water, not that there are pathogens. However, the greater the fecal contamination, the greater the likelihood that pathogens are present. The recovery of pathogens from natural waters is an expensive and labor-intensive process; therefore, scientists and engineers rely on indicator organisms to provide a more rapid and inexpensive measure of the hygienic quality of water.

Increased recreational use, and potential use of the tidal river as a treated water source have focused

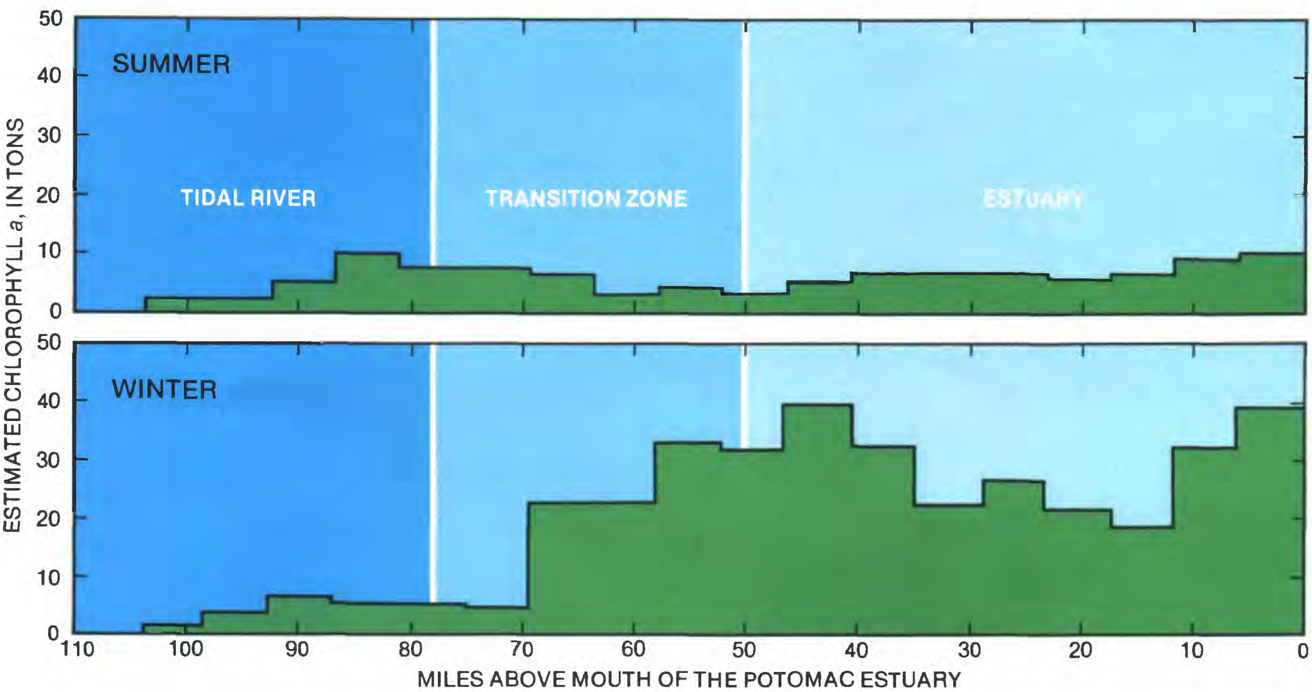


Figure 31. Tons of chlorophyll *a* present, winter and summer 1980 (based on February and July data).

attention on the sanitary quality of the tidal Potomac River. During 1980 and 1981, the U.S. Geological Survey conducted surveys along the tidal Potomac River to measure the densities of fecal coliforms and fecal streptococci at nine cross-sectional stations. To supplement these data, investigators also examined the effect of solar radiation, predation, temperature, and salinity on the survival of natural populations of indicator organisms and selected pathogens in the tidal Potomac River and Estuary.

Figure 32 shows the medians and ranges of fecal coliform densities observed in the tidal river during 1980 and 1981. These graphs show that the fecal coliform densities increase below Memorial Bridge as a result of sewage effluent entering the river from the Blue Plains Sewage Treatment Plant. The fecal coliform densities decrease from the maximum at Alexandria, Va., to Marshall Hall, Md. The fecal coliform densities from Marshall Hall to Hallowing Point, Md., appear to reflect background conditions for the tidal Potomac River.

Figure 33 shows the medians and ranges of fecal streptococci observed in the tidal river during 1980 and 1981. The fecal streptococci densities increase below Memorial Bridge, but not as much as the fecal coliform densities. Also, the fecal streptococci densities do not decrease in the same orderly fashion as the fecal coliform densities.

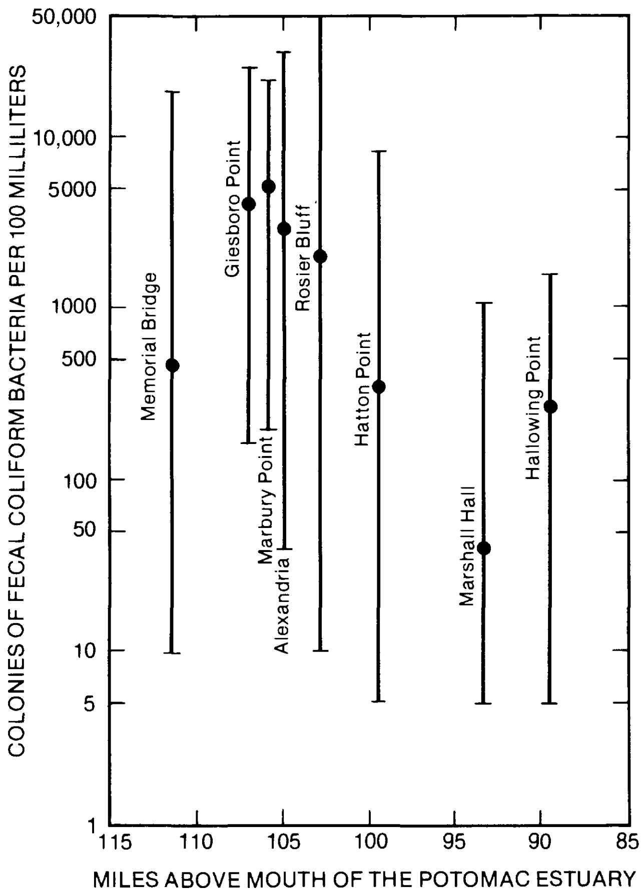


Figure 32. Medians and ranges of fecal coliform densities in the tidal Potomac River, 1980-81.

The investigation of the effect of solar radiation, predation, temperature, and salinity is providing data concerning the relative importance of these factors with respect to the survival of bacteria indicators and pathogens in the tidal Potomac River. These factors appear to interact with each other; no single factor controls the survival of indicator organisms throughout the year.

Submersed Aquatic Vegetation

In the tidal Potomac River and Estuary, submersed plants grow in beds along the shallow flats and margins of the main river and tributaries, or float on the water in masses moved by wind and tidal currents. These plants provide food and shelter for large numbers of insect larvae, mollusks, plankton, crustaceans, and other invertebrates that are food for fish, waterfowl, and larger invertebrates. Ducks, muskrats, snails, turtles, and fish feed on aquatic plant parts (seeds, leaves, stems, and tubers) and on attached epiphytes (plants that grow on other plants). Juvenile and adult fish, turtles, and larger invertebrates such as shrimp and crabs find shelter in the aquatic vegetation. The stems and leaves of submersed aquatic plants retard the river flow, and the roots stabilize the river bottom, thus slowing erosion and causing sediment to accumulate.

Populations of submersed aquatic vegetation in the Chesapeake Bay area have experienced a serious decline, which apparently began in the tidal Potomac River and Estuary in the 1930's. To characterize the changes in the Potomac's submersed aquatic plant communities, the U.S. Geological Survey launched a sampling program with the assistance of the U.S. Fish and Wildlife Service. Beginning in 1978, they sampled the number and kinds of submersed aquatic plants on shallow flats in the tidal Potomac River and Estuary and in selected tributaries on the Maryland and Virginia sides of the river. Vegetation and the associated substrate were sampled with oyster tongs (figs. 34 and 35). In addition, the Survey made many field observations of the distribution of the plants and the time of flowering and seed production.

Figure 36 shows the 1978-81 distribution of submersed aquatic plants in the tidal Potomac River and Estuary and tributary streams. Sixteen species of submersed aquatic plants (2 algae with stemlike and leaflike structures and 14 flowering plants) occurred in the study area; the greatest number of species were found in the transition zone of the main estuary and the

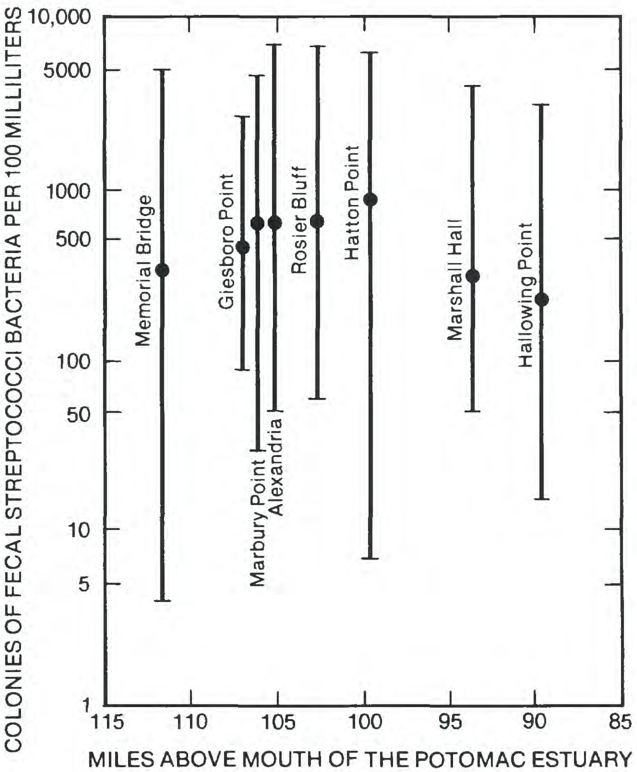


Figure 33. Medians and ranges of fecal streptococcus densities in the tidal Potomac River, 1980-81.

Figure 34. Sampling of submersed aquatic vegetation with oyster tongs. (Photograph by G.M. Haramis, U.S. Fish and Wildlife Service).

adjoining Wicomico River. The freshwater zone of the Potomac River and the estuary contained almost no submersed aquatic vegetation. Wildcelery, redheadgrass and widgeongrass were the most abundant species in the study area. Wildcelery was the only species found in the mainstem of the tidal river; small beds containing a total of four additional species were found in a tidal pond near National Airport, the upper end of Mattawoman Creek, and in tiny tributaries. The present distribution of submersed aquatic plants is unlike the historical distribution (fig. 37) in which perhaps as many as 10 fresh-water species occurred in the tidal Potomac River near Washington and eelgrass covered shallow flats in the Potomac Estuary downstream from the mouth of the Wicomico River. The reason for the unusual distribution of plants is not obvious; many factors, including excessive nutrient loading, high turbidity, storm damage, and grazing by predators may be involved (Carter and Haramis, 1980; Haramis and Carter, 1983).

Transplants and caging experiments show that submersed aquatic plants will survive in the fresh-water tidal river today (1981) if they are protected. The U.S. Geological Survey is doing further studies comparing light penetration, nutrient concentrations, epiphyte loadings, and sediment types with plant distribution to determine the relationships among these factors.

Figure 35. Researchers record abundance and distribution of each submersed plant species found in the river. (Photograph by G.M. Haramis, U.S. Fish and Wildlife Service).

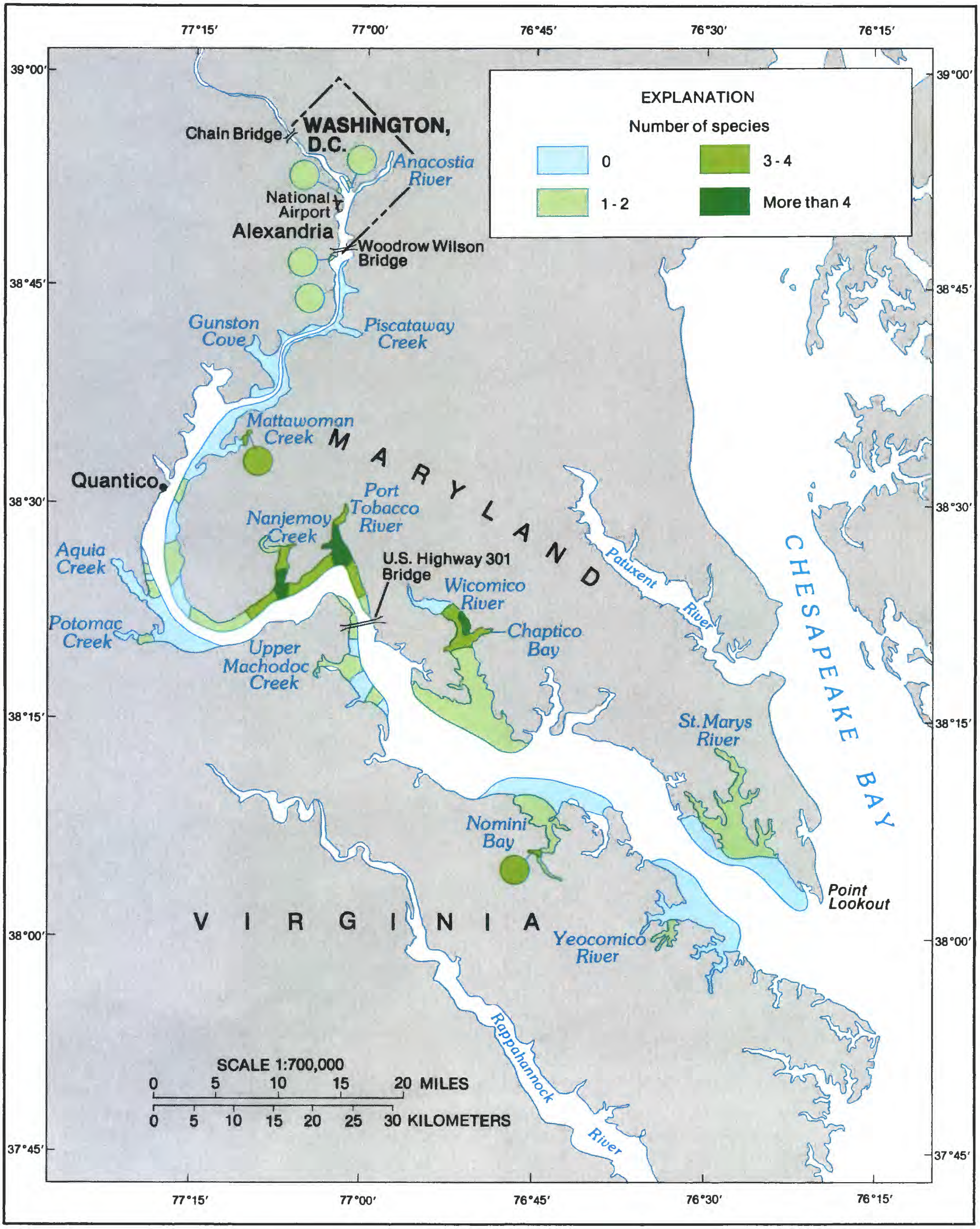


Figure 36. Present distribution of submersed aquatic plants, 1978-81.

Figure 37. Historical distribution of submersed aquatic plants in the tidal Potomac River.

Benthic Invertebrates

The aquatic plants and animals that live in the sediments and on the surfaces of submersed objects play an important role in both energy and material flows in the food web of the tidal Potomac River and Estuary. They are capable of filtering the water; feeding on deposited material; or cycling nutrients, trace elements, and dissolved gases between the sediments and the overlying water column as well as contributing to the deposition of river-bottom sediments.

Figure 38. Sediment grab sampler used to collect benthic invertebrates.

The U.S. Geological Survey conducted a 2-year sampling program to determine the numbers and kinds of benthic invertebrates living in the tidal Potomac River and Estuary (fig. 38). At seven selected locations, scientists laid out transects from bank to bank (fig. 39). Along these transects they took 3 to 10 samples so that both sides of the river or estuary as well as the channel were sampled. Only soft or sandy bed materials were sampled, thus excluding many of the invertebrates that are associated with oyster reefs and other hard substrates. After collecting and preserving all the invertebrates retained on a 0.5-mm mesh screen, biologists identified, counted, and weighed the animals collected at each station. Additional studies examined the distribution, abundance, and trace-metal content of clams living in the tidal river.

Nine phyla (major animal groups) and 123 species were identified. Three phyla, the mollusks (clams), annelids (segmented worms), and arthropods (crustaceans), accounted for 19, 39, and 28 percent, respectively, or a total of 86 percent, of the 123 species identified. The annelids, which are subdivided into the polychaetes (mostly saltwater worms) and the oligochaetes (mostly fresh-water worms) usually accounted for the largest percentage of individuals among all the

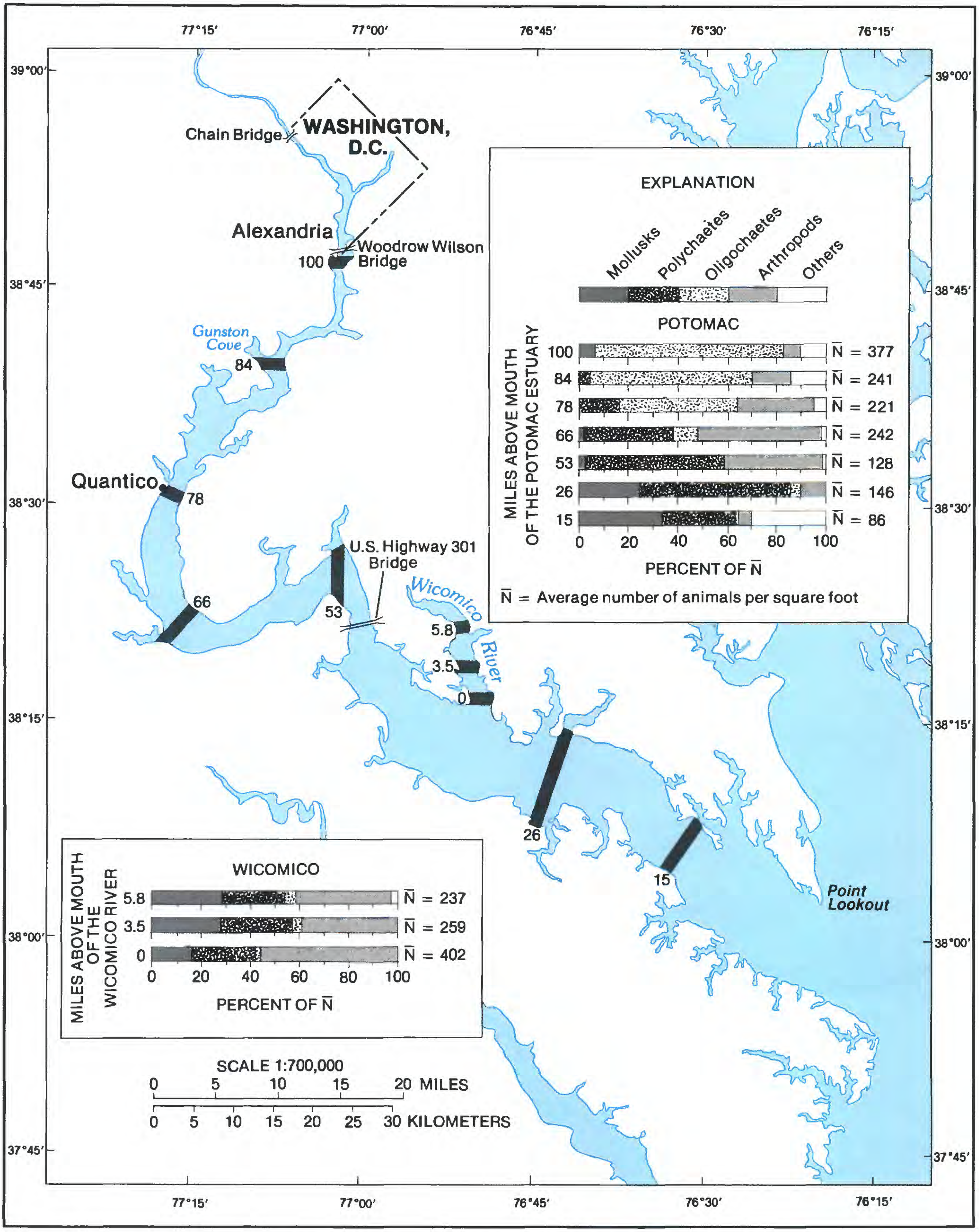


Figure 39. Location of benthic invertebrate sampling transects and abundance of principal animal groups.

Figure 40. Asiatic clams at a site typical of the tidal Potomac River

species found (fig. 39). The histograms (fig. 39) are based on animal collections totaled for the study period, autumn 1977 through summer 1979.

The initial discovery of the Asiatic clam, *Corbicula fluminea*, in the tidal Potomac River was a particularly interesting result of the benthic faunal studies (Dresler and Cory, 1980). A few specimens were collected at a single transect station during the autumn of 1977. From their size, number of annual growth rings, and the absence of dead clams, it was estimated these clams first invaded the tidal Potomac River in 1975. Special studies (1980-81) on the distribution and abundance of clams showed that since 1975 the Asiatic clam has proliferated to the extent that it may now occupy nearly every square foot of bottom in the tidal river (fig. 40).

The Asiatic clams affect the Potomac River's water quality in three ways. Their free-drifting larval stages act as a water contaminant because they have the ability to attach themselves to any hard substrate such as the inside of a water pipe. They have already clogged the water intake at a steam electric generating station in Alexandria, Va., placing a high financial burden on that facility to physically remove them. They have also altered the tidal-river benthos by greatly increasing the standing biomass (clams weigh more than worms), and changing the system from one that was principally a deposit-feeding community to a more dynamic, suspension, filter-feeding community. A third influence, and one that may be quite beneficial, is that, according to calculations based on their measured water-filtration rate and known densities, they are capable of filtering and clearing large volumes of water. It has been estimated that in the area of their highest density, clams filter the river water about three times before the water leaves the area. This may result in the removal of sediment and algae from a section of the river that was historically overburdened with these two constituents. Other Potomac studies have shown that low chlorophyll *a* concentrations and phytoplankton-cell counts appear to coincide with high clam densities during the summers of 1980 and 1981 (Cohen and others, 1982).

Sediment Modeling

Coastal-plain estuaries eventually fill with sediment until the main stream and its tributaries become an upland stream system. In the framework of geologic time, it is not a question of whether this will happen but rather of when it will happen. The tidal Potomac River and Estuary receive about 1.5 million tons of sediment each year, more than half of which comes from the Potomac River drainage. The remainder of the sediment comes from tributaries to the tidal river and estuary, from shoreline erosion, and from the Chesapeake Bay. The tidal Potomac River and Estuary form an efficient sediment trap.

If the total annual supply of sediment were spread uniformly over the entire bottom of the tidal river and estuary, a sediment blanket about one-twelfth of an inch thick would be formed. However, the sediment deposition is not distributed uniformly. In the tidal river and estuary, deposition is concentrated in the upper reaches, where the river slows down and loses its power to transport sediment, and also in the transition zone, where salt and fresh water first mix. The deposited sediment fills navigation channels, clogs marginal wetlands, and often harms shellfish and finfish. The transported sediment often contains appreciable quantities of nutrients, herbicides, pesticides, and heavy metals. Once deposited, nutrients, organic compounds, and heavy metals recycled from the sediments can fuel estuarine eutrophication or can concentrate in the food web, which may cause ecological damage and health problems.

An understanding of sediment transport and deposition in the tidal river and estuary is necessary to solve a variety of water-quality problems. One of the most effective methods for predicting the transport and deposition of sediments is to construct a mathematical model. The simplest and most effective mathematical models are "conservation of mass models." They are built by conceptually isolating short segments (fig. 41), or control volumes, of the tidal river and estuary, and writing a series of equations that keep track of the amount of sediment (and other substances) entering and leaving each segment. Another set of equations describes the processes occurring within each control volume, such as deposition of sediment or change in the form (dissolved to particulate) of nutrients.

The Survey developed a conservation of mass model that predicts the amount of sediment deposited in the tidal Potomac River and Estuary. The model (fig. 42) consists of a series of control volumes, introduces measured inputs, simulates the different processes that occur in each control volume, and predicts outputs. The model accounts for the fact that the main source of sediment is the upland Potomac River at Chain Bridge. It also accounts for sediment discharge from tributary streams and shore erosion. Furthermore, it simulates the persistent upstream circulation of salt water through the estuary and into the transition zone. The circulation is caused by the mixing of fresh and salt water and by tidal motion. Salt water brings sediment from Chesapeake Bay; therefore the model considers the concentration of sediment in the bay to get a complete picture of sediment transport in the tidal Potomac River and Estuary. Another process simulated by the model is the gravitational settling of suspended sediment.

Building the model was a multi-step process. First the appropriate equations were formulated and programed into a computer. Then, river discharge and the corresponding sediment concentration for a specific period were entered into the model. Finally, the remaining coefficients of the model were established by repetitively running the model on the computer and comparing predicted output concentrations with observed concentrations. The latter step, called calibration, fits the coefficients of a general model to the particular physical situation in the tidal Potomac River and Estuary. Comparison of model predictions and field observations showed acceptable agreement. Figure 43 compares sediment concentrations computed by the model and observed at the Wilson Bridge and Quantico, Va., transport stations for the months of January and February 1979.

Model simulation for the 1979 water year (Octo-

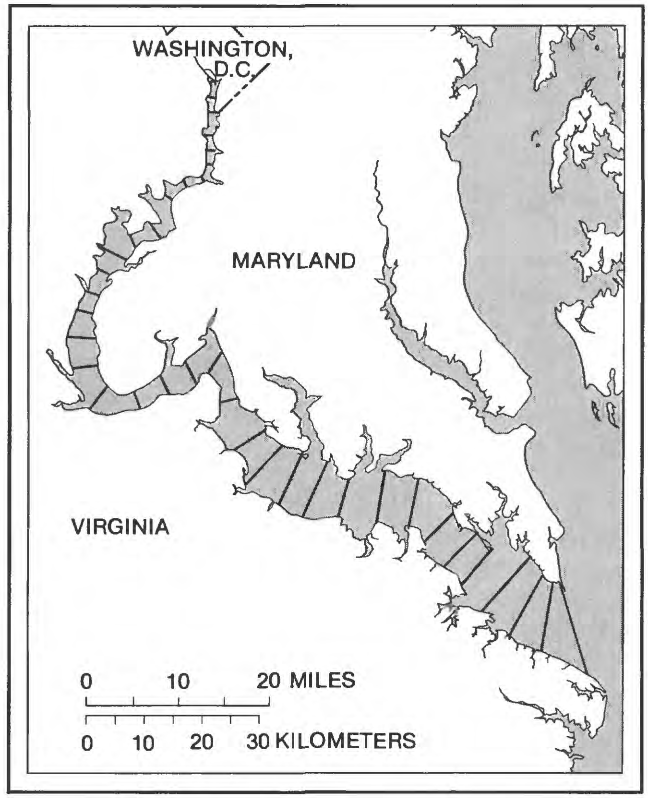


Figure 41. Location of model segments.

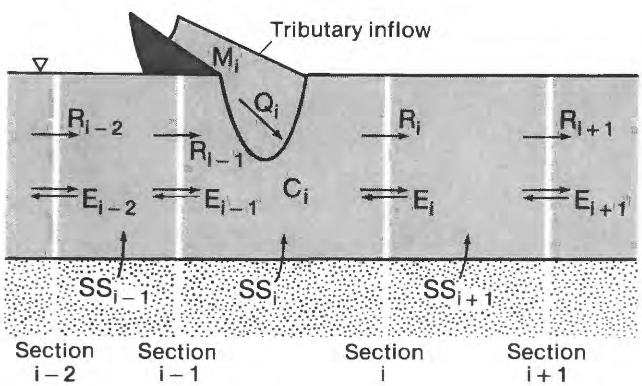


Figure 42. Diagrammatic cross section of a model control volume showing various inputs and outputs. Sediment concentration, C; river or advective flow, R; tributary discharge, Q; nonadvective exchange flow (a mixing parameter), E; concentration in tributary inflow, M; benthic source or sink, SS; and cross section number, i.

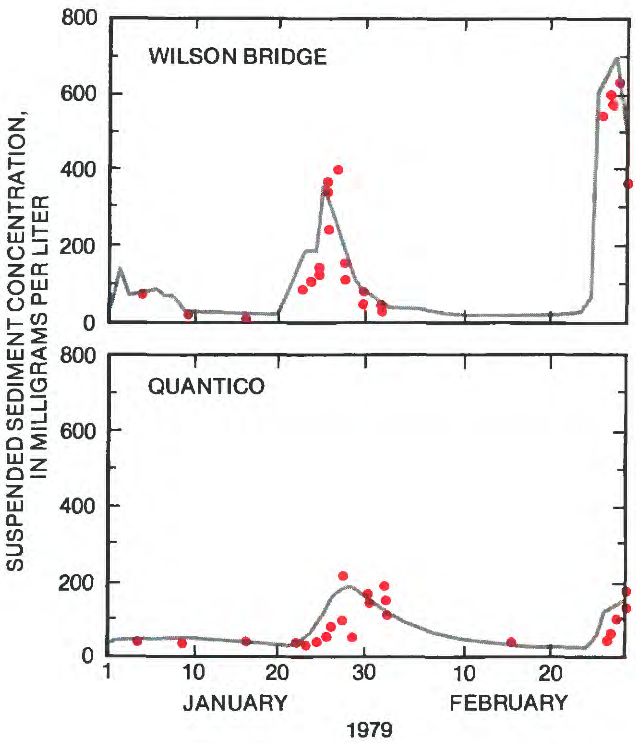


Figure 43. Comparison of observed (red dots) suspended-sediment concentrations with model output (black line).

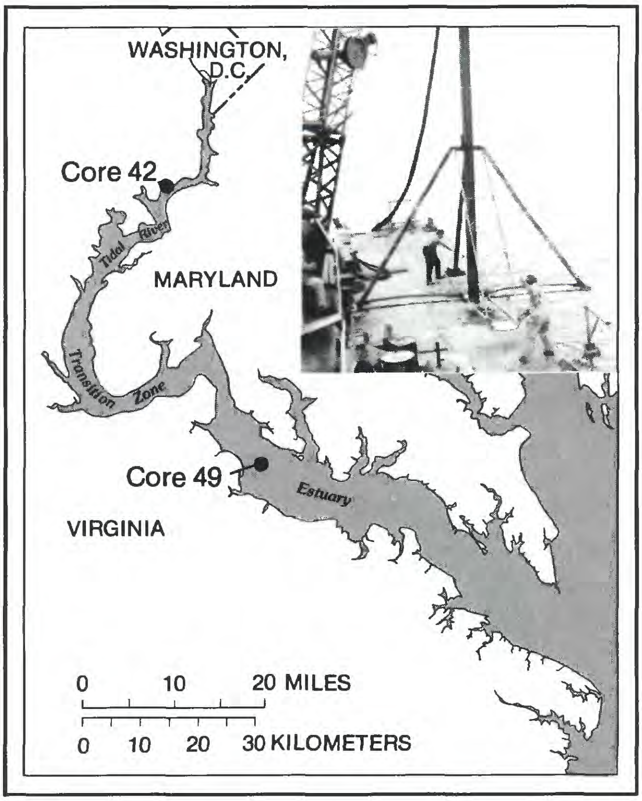


Figure 44. Location of deep-sediment core sites 42 and 49 and photograph of coring equipment (vibracorer).

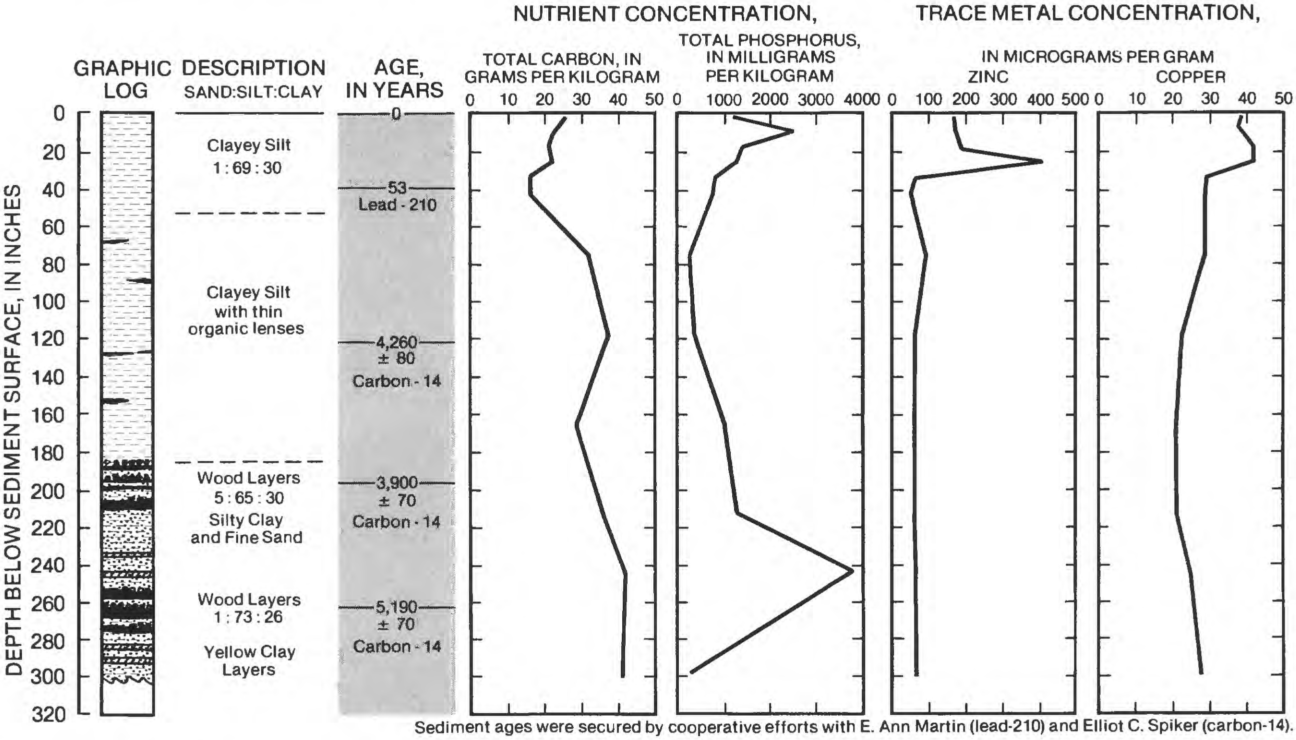
ber 1, 1978 to September 30, 1979) showed that sediment was not deposited uniformly in the tidal Potomac River and Estuary. The flow of the Potomac River at Chain Bridge near Washington was 42 percent above normal and the sediment load was 100 percent above normal. Of the sediment discharged into the tidal river at Chain Bridge, 12 percent was deposited between Chain Bridge and Wilson Bridge, 59 percent was deposited between Wilson Bridge and Quantico, Va., 4 percent was deposited between Quantico and U.S. Highway 301 Bridge, and 25 percent was discharged to the estuary below U.S. Highway 301 Bridge. This is equivalent to an average sediment deposition of about 1.5 inches per year in the segment from Chain Bridge to Quantico and 0.04 inch per year in the segment from Quantico to U.S. Highway 301 Bridge.

Sedimentation

Sediment deposits and sediment-borne nutrients and trace metals limit the use of tidal rivers and estuaries for commerce, recreation, and aquaculture. Sediments decrease channel depths and widths, and cover and destroy productive shellfish grounds. Nutrients can trigger undesirable eutrophic conditions and trace metals can concentrate in the food chain, causing ecological damage and danger to human consumers.

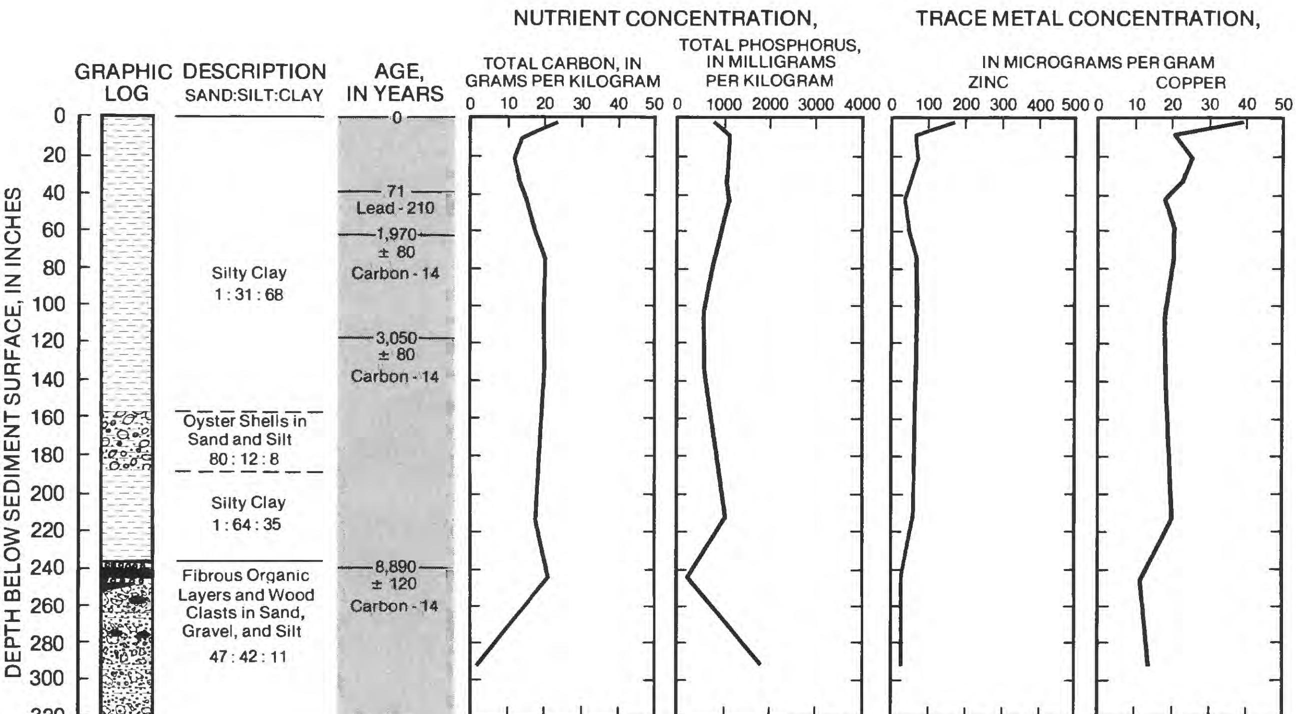
Sediments that contain elevated concentrations of nutrients and trace metals are accumulating rapidly in parts of the tidal Potomac River and Estuary and in parts of the adjacent marginal embayments. Sedimentation problems in the tidal Potomac River and Estuary are a consequence of essentially uncontrollable natural processes and potentially manageable anthropogenic influences. The problems began to develop naturally several thousand years ago when the current rise in sea level inundated the lower Potomac River valley. The rate of sedimentation accelerated locally when man began to clear adjacent forests for farms and cities and when agricultural, municipal, and industrial wastes began to enter the river and estuary system.

To characterize the sediments that are accumulating in the tidal Potomac River and Estuary, the U.S. Geological Survey determined the areal and stratigraphic distributions of sediment types and of the associated nutrients and trace metals. A combination of direct sampling (fig. 44) and remote sensing techniques was used to examine and compare sediments in different parts of the tidal Potomac River and Estuary. For clues to possible sources of sediment, the Survey



Sediment ages were secured by cooperative efforts with E. Ann Martin (lead-210) and Elliot C. Spiker (carbon-14).

Figure 45. Sediment characteristics and concentrations of sediment-borne contaminants (nutrients and heavy metals) at core site 42 in the tidal Potomac River.



Sediment ages were secured by cooperative efforts with E. Ann Martin (lead-210) and Elliot C. Spiker (carbon-14).

Figure 46. Sediment characteristics and concentrations of sediment-borne contaminants (nutrients and heavy metals) at core site 49 in the Potomac Estuary.

analyzed sediment samples for particle size, mineralogy, and nutrient and trace metal concentration. Scientists estimated sediment accumulation rates by radioactive dating techniques and by pollen distribution studies, and calculated amounts of sediment contributed by shoreline erosion from field mapping, monitoring, and sampling at selected sites and by studies of available aerial photographs and maps.

Selected characteristics of sediments and associated nutrients and trace metals at a tidal river and an estuarine location are shown in figures 45 and 46. Near-surface sediments in the tidal river are coarser than those in the estuary, but riverine sediments generally contain higher nutrient and trace-metal concentrations than estuarine sediments. These differences reflect changing sources, transport patterns, and geochemical reactions. Anthropogenic influences on trace metal and nutrient content are indicated by concentration increases at about the 3.2-foot depth. Sediment ages at various depths indicate that the near-surface sediment accumulation rate at the tidal river site, about three-quarters of an inch per year, is greater than the rate at the estuary site, a little more than one-half inch per year; based on these rates, anthropogenic increases in trace metals began 50 to 70 years ago. Radiocarbon dates suggest that sediment accumulation rates prior to this time were substantially lower than recent accumulation rates.

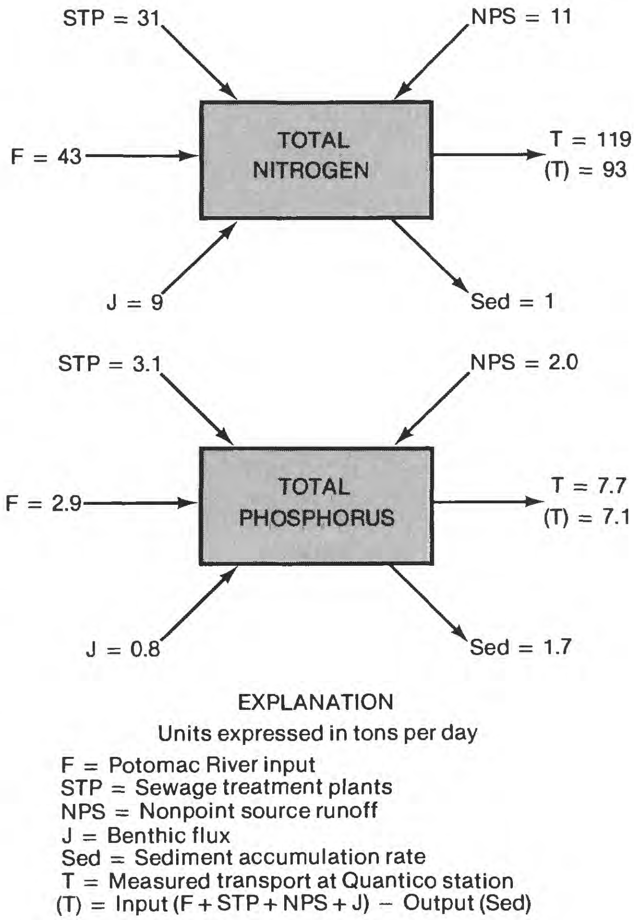


Figure 47. Input-output box model for total nitrogen and phosphorus in the tidal Potomac River for the summer of 1979.

Nutrient Recycling from Sediments

Nutrients enter the tidal Potomac River and Estuary from several sources (fig. 47): the river flow (F) at Chain Bridge, waste from sewage treatment plants (STP), nonpoint source runoff (NPS), and geochemical processes in the bottom sediments (J, SED). Although the inputs from point and nonpoint sources play a major role in the nutrient budgets of the tidal Potomac River, geochemical reactions that release nutrients from organic matter deposited on the bottom (benthic regeneration) may contribute significantly to nutrient budgets of the Potomac Estuary. The primary objective of this study is to quantify the effect that nutrient recycling from bottom sediments has upon nutrient budgets in the tidal Potomac River and Estuary.

During 1978 and 1979, the U.S. Geological Survey conducted an extensive sampling program to determine the levels of carbon, nitrogen, and phosphorus in bottom sediments and the potential for exchange (flux) of these nutrients between sediments and overlying waters. Sediment cores were taken from Alexandria, Va., to Point Lookout, Md., (fig. 2) and were processed aboard ship to separate the sediment pore waters from the sediment solids. In a shore-based laboratory, scientists analyzed the pore waters and sediments for a variety of chemical constituents. The Survey also used benthic flux chambers (fig. 48) to make field measurements of the exchange of nutrients from bottom sediment to overlying water. A benthic flux chamber works by enclosing sediment and overlying water in a plastic cyclinder where they are incubated for several hours. The change in nutrient concentrations in the trapped water is a measure of the exchange between the sediment and water.

The input-output models (fig. 47) show that, during the summer of 1979 in the tidal river, benthic regeneration of nitrogen (in the form of ammonia) and phosphorus (in the form of phosphate) was 25 percent of the total nitrogen and phosphorus inputs by Washington metropolitan area sewage treatment plants, and was as much as 10 percent of the total nutrient input.

SUMMARY

The U.S. Geological Survey began a 5-year interdisciplinary study of the tidal Potomac River and Estuary in October of 1977. The objectives of the study are to: (1) provide a basic understanding of physical, chemical, and biological processes; (2) to develop flow and transport models to predict the movement and fate of nutrients and algae; and (3) to develop efficient techniques for the study of tidal rivers and estuaries. The ultimate goal is to aid water-quality decisionmaking for the Potomac.

The study is being conducted by scientists from many disciplines involved in 14 different but interrelated studies. These include hydrodynamics, nutrient transport, dissolved oxygen, nitrogen dynamics in the tidal river, phosphorus dynamics in the vicinity of the Blue Plains Sewage Treatment Plant, nonpoint sources of nutrients and sediment, phytoplankton dynamics, distribution of chlorophyll *a*, indicator organisms in the tidal river, submersed aquatic vegetation, benthic invertebrates, sediment modeling, sedimentation, and nutrient recycling from sediments. These scientists are addressing five major problem areas -- nutrient enrichment, algal blooms, dissolved oxygen, sedimentation, and effects of water quality on living resources. The preliminary results of the Study are presented below.

The Potomac River above Chain Bridge is the largest single contributor of nitrogen and phosphorus to the tidal river. Changes in nutrient concentrations downriver from Chain Bridge are caused by point-source inflows, recycling from bottom sediments, growth and decay of algae, and mixing of fresh and salt water. During periods of high river flow, the Potomac River contributes considerably more nitrogen and phosphorus to the tidal river than do the metropolitan Washington sewage treatment plants. During periods of low river flow, the river upstream from Chain Bridge and sewage treatment plants contribute approximately equal quantities of nutrients.

Generally speaking, nutrient concentrations increase in the Alexandria, Va., area where the region's largest sewage treatment plant discharges its effluent. Nutrient concentrations decrease downriver of Alexandria. This is because of the removal of nutrients from the water column by biological and physical processes and because of the mixing of nutrient-rich river water with water of lower nutrient content from Chesapeake Bay.

Preliminary results of the nonpoint source study show that the average annual loads of nitrogen and phosphorus discharged to the tidal Potomac River and Estuary from all tributary watersheds downstream from Chain Bridge constitute a relatively small fraction of the loadings from sewage treatment plants and the Potomac River above the study area. During the summer of 1979, benthic regeneration of dissolved nitrogen and phosphorus from tidal-river sediments contributed an amount equal to 25 percent of the total nitrogen and phosphorus inputs by the metropolitan Washington sewage treatment plants.

The Blue Plains Sewage Treatment Plant effluent is confined primarily to a restricted embayment on the eastern side of the tidal Potomac River at Alexandria, Va. The start of advanced wastewater treatment at Blue Plains in the fall of 1980 appears to have had the expected effect of reducing the quantities of ammonia while increasing the nitrate concentrations in the tidal river. Approximately 10 percent of the phosphorus discharged at the Blue Plains Sewage Treatment Plant is deposited in bottom sediments adjacent to the outfall.

Generally, tidal-river sediments contain one thousand times more nitrifying bacteria than the overlying water column. Most of the nitrification in the tidal river probably occurs in the sediments using ammonia generated by bacterial degradation of sedimentary organic matter. The density of fecal coliform bacteria increases in the vicinity of the Blue Plains Sewage Treatment Plant, but then decreases to background levels at Marshall Hall, Md.

Dissolved oxygen in the tidal Potomac River appears to be controlled primarily by the photosynthetic activity of algae during times of low river flow. In the summers of 1980 and 1981, phytoplankton abundance in the tidal river was much lower than in the 1960's and 1970's. One possible cause of this decrease is the explosive growth of the Asiatic clam, *Corbicula fluminea*, which may have filtered large quantities of phytoplankton from the river between Alexandria, Va.,

Figure 48. Benthic flux chamber used to measure the exchange of nutrients between bottom sediment and overlying water.

and Hatton Point, Md.

In the Potomac Estuary, winter chlorophyll *a* concentrations are quite uniform throughout the water column while summer chlorophyll *a* concentrations are highest in the top part of the water column. The quantity of chlorophyll *a* present in the lower transition zone and estuary is considerably greater in the winter than in the summer.

Flow and transport simulation models have been implemented to describe the flow and circulation patterns throughout the tidal Potomac River and Estuary. When calibration is completed, the models will be used with a conservation of mass model to calculate the quantity of sediment and nutrients deposited in the tidal Potomac River and Estuary. The conservation of mass box model was used by itself to calculate the amount of water and suspended sediment that was transported through the study area. Model simulation for the period October 1978 to October 1979 showed that, of the suspended sediment discharged into the tidal river, 12 percent was deposited between Chain Bridge and Wilson Bridge, 59 percent was deposited between Wilson Bridge and Quantico, Va., 4 percent was deposited between Quantico, Va., and U.S. Highway 301 Bridge, Md., and 25 percent was discharged to the estuary.

The study of nonpoint sources determined that the present annual sediment yield from urban Washington watersheds is approximately one-quarter the yield determined 20 years ago by Survey scientists and is approximately the same as the yield of the rural St. Clements Creek watershed.

Tidal-river sediments are coarser than estuarine sediments, but riverine sediments generally contain greater concentrations of nutrients and trace-metals than estuarine sediments. Ages of bottom sediments indicate that the near-surface sediment accumulation rate is greater in the tidal river (approximately three-quarters of an inch per year) than in the estuary (approximately one-half inch per year).

The greatest number of species of submersed aquatic vegetation occurs in the transition zone of the Potomac Estuary. The tidal river and estuary contain almost no submersed aquatic vegetation.

Transplants and caging experiments show that submersed aquatic plants survive in the freshwater tidal river if they are protected. Clams, segmented worms, and crustaceans account for 86 percent of the benthic invertebrate fauna in the tidal river and estuary. Since 1975, the Asiatic clam, *Corbicula fluminea*, has proliferated to the extent that it may now occupy nearly every square foot of bottom in the tidal Potomac River.

GLOSSARY

Abiotic refers to the absence of life.

Algae are any of a group of chiefly aquatic nonvascular plants; most have chlorophyll.

Amorphous describes a mineral or other substance that lacks crystalline structure, or whose internal arrangement is so irregular that there is no characteristic external form.

Anadromous fish live in seawater, but move to fresh water to spawn.

Anoxic refers to inadequate oxygen.

Anthropogenic pertains to the influence of man's activities.

Benthic refers to material, especially sediment, at the bottom of an aquatic system.

Benthic organisms are organisms living in or on bottom substrates in aquatic systems.

Biochemical oxygen demand (BOD) is the weight of oxygen per volume of water that is required to bacterially or chemically oxidize all the compounds or elements in the water.

Biomass is the quantity of living matter.

Biotic has the characteristics of a plant or animal; related to living organisms.

Bottomlands refer to the floodplain of a river.

Chlorophyll is a group of green photosynthetic pigments that occur primarily in the chloroplasts of plant cells.

Chlorophyll *a* is the most important of the principal photosynthetic pigments, often used as a measure of plant biomass.

Coliform bacteria are bacteria that normally live in the intestines of man and animals.

Deposit feeders are infaunal organisms that meet their nutritional needs by either selectively or indiscriminately ingesting the sediments in which they live.

Dissolved oxygen (DO) is the oxygen that is dissolved in water.

Ecosystem is an interactive system which includes the organisms of a natural community together with their physical, chemical, and biological environment.

Ephemeral refers to temporary existence.

Eutrophication refers to a process in which the increase of mineral and organic nutrients within a water body results in depletion of dissolved oxygen, and produces an environment that favors plant over animal life.

Fecal refers to the waste material from the digestive system of animals.

Filter feeders are organisms that obtain food particles from the water column by filtering large quantities of water via a wide variety of mechanisms.

Fluorescent refers to the property of luminescence upon exposure to radiation of the proper wavelength.

Flushing characteristics are a measure of the displacement of water from a riverine or estuarine system as governed by the combined action of freshwater inflow and tidal exchange.

Flux is the movement of a mass of any constituent in a given period of time.

Flux chamber is the sampling equipment used to measure the flux of dissolved species into or out of the bottom sediment.

Food web refers to the complex interaction of food chains in a biological community including the processes of production, consumption, and decomposition.

Geochemical refers to the chemistry of earth materials such as water, soil, and rock.

Head of tidewater is the maximum upstream extent of tidal influence.

Infauna are animals that live in or burrow through bottom sediments.

Input-output model is a mathematical formulation that describes the mass transport of any constituent into or out of any section of a system.

Invertebrates are animals without backbones.

Isolines are lines depicted on a map connecting points having equal magnitude (flow speed, temperature, etc.) at a given time.

Lagrangian study consists of repeated measurements of biological, physical, and chemical parameters in a specific parcel of water as it moves in time.

Longitudinal study consists of a rapid succession of measurements of biological, physical, or chemical parameters at predetermined locations along the length of an aquatic system.

Mathematical model is a collection of mathematical expressions which describe a set of individual processes and their interactions in some real situation.

Mixing characteristics refer to the tendency for waters to blend; i.e., for dissolved or suspended matter to disperse into adjacent waters with movement and time.

Network model is a simulation model designed to reproduce the flow and transport occurring in a water body composed of interconnected channels and offering multiple flow paths.

Nitrification is the oxidation of ammonia to nitrite by *Nitrosomonas* bacteria and the further oxidation of nitrite to nitrate by *Nitrobacter* bacteria.

Nitrification reactor consists of tanks in which nitrification takes place.

Nonpoint source originates from more than one location.

Nutrient is a primary element necessary for the growth of living organisms, for example, carbon, nitrogen, phosphorus, and silicon.

One-dimensional model is a model defined along one space coordinate, for example, the thalweg of the channel in a river or estuary, wherein variables are averaged over the width and depth.

Osmotic is the tendency for diffusion through a membrane until there are equal concentrations of substances on both sides of the membrane.

Photosynthesis refers to the synthesis of organic compounds from water and carbon dioxide using light energy in the presence of chlorophyll.

Phytoplankton is a group of generally unicellular plants freely drifting in the water column.

Plankton is a group of general microscopic plants and animals passively floating or weakly swimming.

Primary waste-water treatment removes solid material by settling. This process removes 30 percent of the BOD.

Radioactivity is the phenomenon exhibited by certain chemical elements that spontaneously emit energy as a result of changes in the nuclei of atoms of those elements.

Radiocarbon dating determines the age of objects of plant or animal origin as determined by the measurement of the radioactivity of their carbon content.

Sanitary-quality-indicator organisms are bacteria or viruses associated with human or animal waste that can be easily identified. Some bacteria commonly used to indicate fecal contamination are total coliform, fecal coliform, and fecal streptococci.

Secondary waste-water treatment removes the oxygen-demanding material (BOD), mostly organic carbon compounds, by bacterial oxidation to carbon dioxide and water.

Sediment is particulate organic and inorganic matter that accumulates in a loose, unconsolidated form on the bottom of a body of water.

Sedimentation refers to infilling by sediment.

Simulation refes to the use of models either to imitate the observed behavior of a system in response to a particular known set of conditions or to predict the response of the system to changed conditions.

Sorption refers to the adherence of ions or molecules in a gas or a liquid to the surface of a solid with which they are in contact.

Spawning refers to the release of eggs and sperm or the release of brooded young.

Streptococci (fecal) bacteria are bacteria that normally live in the intestines of man and animals.

Substrate is bottom sediment.

Tertiary waste-water treatment is a process designed to remove or alter the form of nitrogen or phosphorus compounds from domestic sewage. When more than one of these processes is used, the treatment plant is called an advanced wastewater treatment plant.

Thalweg is an imaginary axis or line representing the course of the principal flow-conveying part of a channel (typically, the principal navigation channel).

Tidal river is the fresh water reach of a river under tidal influence and characterized by riverine chemistry.

Turbidity is a measure of the amount of suspended material in water.

Two-dimensional model is a model defined along two space coordinates, for example, the length and width of a segment of a river or estuary, wherein variables are averaged over the depth.

Velocity-vector field is an array of arrows depicting the magnitude and direction of flow at a given time throughout a given area.

Vivianite is the mineral: $Fe_3(PO_4)_2 \cdot 8H_2O$. It is colorless in the pure form, but turns green or blue when oxidized. It occurs as monoclinic crystals or fibrous masses in clays, peat, and bog iron.

Yield is the amount of a given substance leaving a square mile of watershed over a given period of time.

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* Many of the terms listed in the glossary were defined with the help of this reference.