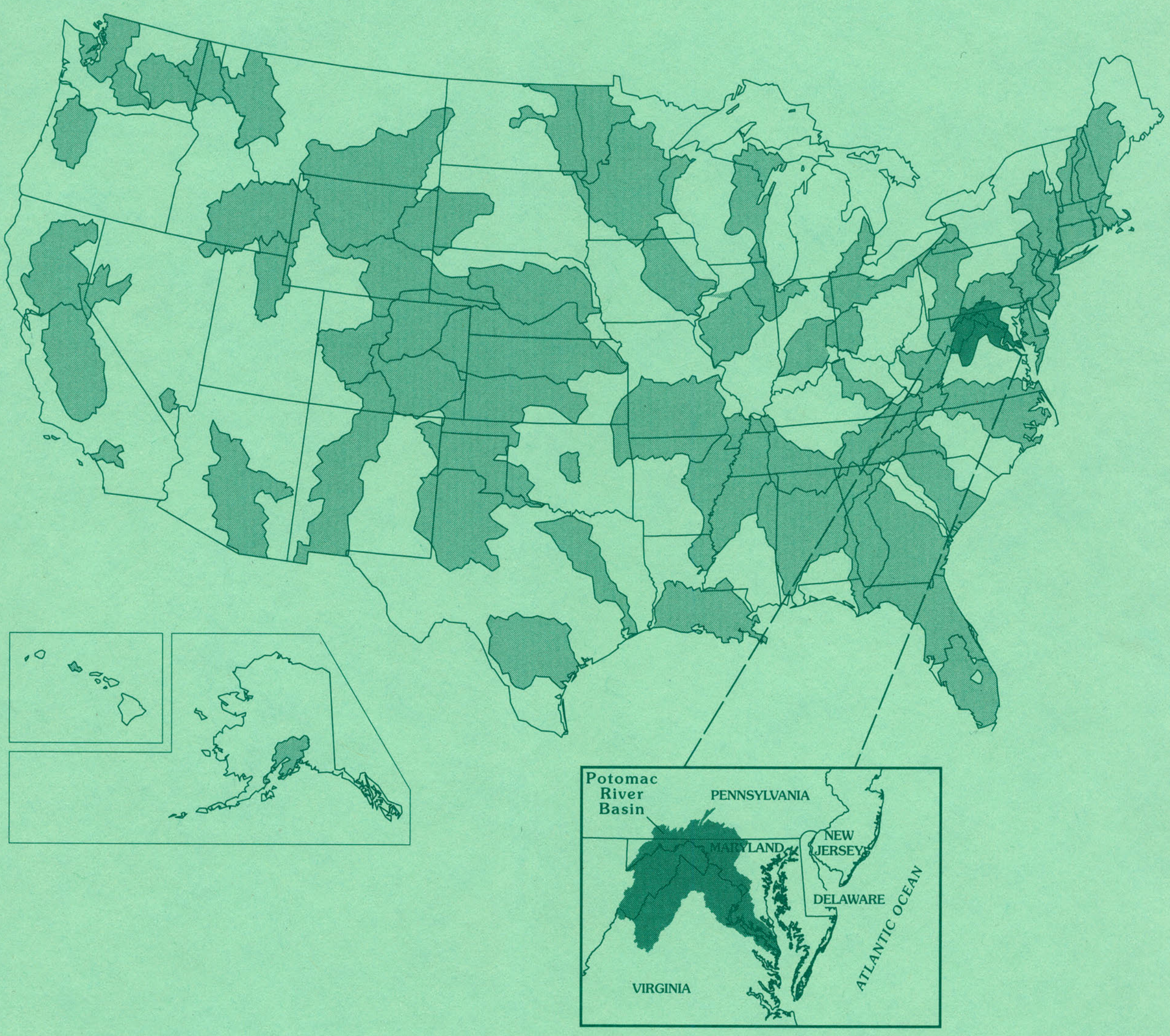
Water-Quality Assessment of the Potomac River Basin: Basin Description and Analysis of Available Nutrient Data, 1970–90



U.S. GEOLOGICAL SURVEY

Water-Resources Investigations Report 95–4221

NATIONAL WATER-QUALITY ASSESSMENT PROGRAM

Water-Quality Assessment of the Potomac River Basin: Basin Description and Analysis of Available Nutrient Data, 1970–90

By J.D. BLOMQUIST, G.T. FISHER, J.M. DENIS,
J.W. BRAKEBILL, and W.H. WERKHEISER

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BRUCE BABBITT, Secretary

U.S. GEOLOGICAL SURVEY

Gordon P. Eaton, Director

For additional information write to:

District Chief
U.S. Geological Survey
8600 LaSalle Rd, 206 Carroll Bldg.
Towson, MD 21286

Copies of this report can be purchased from:

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CONTENTS

FIGURES

FIGURES—Continued

FIGURES—Continued

TABLES

CONVERSION FACTORS, ABBREVIATIONS, AND VERTICAL DATUM

Multiply	By	To obtain
acre-foot (acre-ft)	1,233	cubic meter
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
foot (ft)	0.3048	meter
gallon (gal)	3.785	liter
gallon per minute (gal/min)	0.06308	liter per second
inch (in.)	25..4	millimeter
inch per year (in/yr)	25.4	millimeter per year
mile (mi)	1.609	kilometer
million gallons per day (Mgal/d)	0.04381	cubic meter per second
pound (lb)	0.4536	kilometer
pound per acre (lb/acre)	1.121	kilogram per hectare
pound per person per year [(lb/person)/yr]	453.6	gram per person per year
pound per square mile (lb/mi^2)	1.751	kilogram per square kilometer
square mile (mi^2)	2.590	square kilometer

Chemical concentration in water is expressed in milligrams per liter (mg/L).

Temperatures in degrees Fahrenheit (°F) and degrees Celsius (°C) can be converted using the following equations:

$$°F = 1.8\ (°C) + 32$$
$$°C = 5/9\ (°F - 32).$$

Sea level: In this report, "sea level" refers to the National Geodetic Vertical Datum of 1929—a geodetic datum derived from a general adjustment of the first-order level nets of the United States and Canada, formerly called Sea Level Datum of 1929.

Water year: The 12-month period, October 1 through September 30. The water year is designated by the calendar year in which it ends. Thus, the year ending September 30, 1990, is called the "1990 water year."

Water-Quality Assessment of the Potomac River Basin: Basin Description and Analysis of Available Nutrient Data, 1970–90

By J.D. Blomquist, G.T. Fisher, J.M. Denis, J.W. Brakebill, *and* W.H. Werkheiser

Abstract

The Potomac River Basin includes 14,670 square miles and has a complex environmental setting consisting of various combinations of natural and human factors that can affect water quality. The basin is divided into eight subunits on the basis of physiography and lithology for the purpose of water-quality assessment. The eight subunits are the Appalachian Plateau, Valley and Ridge, Great Valley Carbonate, Great Valley Noncarbonate, Blue Ridge, Piedmont, Triassic Lowlands, and Coastal Plain. Land use in the mid-1970's was 51 percent forest, 36 percent agricultural, and 8 percent urban. From 1970 to 1990, the population increased 43 percent to about 4.6 million people; two-thirds of this population resided in the Washington, D.C., area. About 97 percent of the freshwater used in the basin in 1990 was from surface-water sources.

In 1990, commercial fertilizer and animal manure comprised about 55 percent of the nitrogen input and 93 percent of the phosphorus input to the Potomac River Basin. Municipal and industrial wastewater discharges contributed about 12 percent of the nitrogen and 4 percent of the phosphorus inputs. Municipal wastewater discharges were largest downstream from Washington, D.C., where 88 percent of the nitrogen and 80 percent of the phosphorus discharges occurred. Atmospheric deposition contributed 32 percent of the nitrogen inputs. Fertilization rates are highest in the Monocacy River watershed with nutrient application rates of 15,300 lb/mi^2 (pounds per square mile) nitrogen and 4,490 lb/mi^2 phosphorus, and in the Conococheague Creek watershed with nearly 9,370 lb/mi^2 nitrogen and 2,940 lb/mi^2 phosphorus. The North Fork Shenandoah River has the highest manure production rate at 20,900 lb/mi^2 nitrogen and 4,660 lb/mi^2 phosphorus.

Dissolved-nitrate concentrations in ground water vary widely within the Potomac River Basin and range from less than 0.01 mg/L (milligram per liter) to 63 mg/L as nitrogen, with a median value of 1.8 mg/L. Dissolved-nitrate concentrations in the Appalachian Plateau, Valley and Ridge, and Coastal Plain subunits generally are low, with median concentrations of 0.10, 0.14, and 0.10 mg/L, respectively. Dissolved-nitrate concentrations in the Great Valley Carbonate subunit are generally higher (median 4.5 mg/L) than in other subunits and exhibit only small differences among land-use settings. Fourteen percent of the wells in carbonate rock have concentrations greater than or equal to the 10.0-mg/L Maximum Contaminant Level for drinking water established by the U.S. Environmental Protection Agency.

Nutrient-concentration data from 25 surface-water-quality monitoring sites indicate that nitrogen and phosphorus concentrations generally are lowest in the sparsely populated, forested watersheds of the Appalachian Plateau, Valley and Ridge, and Blue Ridge subunits and are highest in the agricultural watersheds of the Great Valley, Piedmont, and Triassic Lowlands subunits and

near urban centers where wastewater-treatment inputs are greater. Median concentrations of total nitrogen range from 0.42 to 3.9 mg/L at 22 sites, and median concentrations of dissolved nitrate range from 0.2 to 3.5 mg/L at 25 sites. Seasonal fluctuations of total-nitrogen and total-phosphorus concentrations in surface water are generally small at most sites. In agricultural and forest settings, nitrogen concentrations are highest during winter, and phosphorus concentrations are highest during summer. Where wastewater inputs are substantial, concentrations of nitrogen and phosphorus are higher during low streamflow conditions of the summer.

Few of the 25 monitoring sites on the Potomac River and its tributaries show strong long-term trends in total-nitrogen concentrations during 1970–90. Sites on Conococheague Creek and Seneca Creek both show an increase in nitrogen concentrations. Total-phosphorus and dissolved-orthophosphate concentrations appear to decline slightly at many of the monitoring sites.

The Potomac River near Washington, D.C., discharges a long-term average of 60 million pounds of nitrogen and 5.79 million pounds of phosphorus per year. The North Branch Potomac, South Branch Potomac, and Cacapon Rivers, draining three large forested watersheds, contribute only 17.5 percent of the dissolved nitrate and 7 percent of the phosphorus measured at Washington, D.C., and drain 25.9 percent of the basin. Greater nutrient loadings are generated from three predominantly agricultural watersheds—Conococheague Creek, Shenandoah River, and Monocacy River. Total nitrogen yields in these three tributaries range from 1,870 to 8,330 lb/mi^2, and dissolved nitrate yields range from 1,650 to 9,690 lb/mi^2, The smallest nitrogen yields occur in forest and urban watersheds where nitrogen inputs are predominantly from atmospheric sources. The largest nitrogen yields occur in Conococheague Creek, Antietam Creek, and Monocacy River, where agricultural land use is widespread and nitrogen inputs are dominated by commercial fertilizer and animal manure. The transport of phosphorus is also highly variable as total-phosphorus yields range from 68 to 654 lb/mi^2, whereas the phosphorus yield for the Potomac River Basin upstream from Washington, D.C., is 496 lb/mi^2. Ground-water discharge can contribute a substantial part of the total-nitrogen load to streams in agricultural watersheds underlain by carbonate rock. Base-flow nitrogen loads in Conococheague Creek and Antietam Creek contribute about 61 and 100 percent of measured nitrogen loads.

INTRODUCTION

This report describes the results of two components of the U.S. Geological Survey's (USGS) National Water-Quality Assessment (NAWQA) Program within the Potomac River Basin. First, major natural and human factors affecting water quality in the Potomac River Basin are described and used to subdivide the basin for the purpose of assessing water-quality conditions. The approach used for basin subdivision is consistent with the approach used by concurrent NAWQA studies in watersheds throughout the Nation (Hirsch and others, 1988). Second, information available from a variety of sources is used to describe water-quality conditions in the basin with respect to the nutrients nitrogen and phosphorus.

The basin description provides the essential background information for the analysis of nutrients in the basin and encompasses the conceptual framework used to design the multidisciplinary assessment of water-quality conditions. This description focuses on broad-scale natural conditions and human factors affecting water quality.

The analysis of available nutrient data will be used to help describe current water-quality conditions and to guide the NAWQA Program in the design of future studies of the Potomac River Basin. The major objectives of the analysis of available nutrient data are as follows:

(1) Document sources of nitrogen and phosphorus to the Potomac River Basin and describe the spatial distribution of sources in basin subunits and major watersheds.

(2) Document current monitoring programs and available nutrient-concentration data for ground water and surface water.

(3) Describe broad-scale geographic patterns of nutrient concentrations in ground water and surface

water and relate these patterns to sources and major controlling factors.

(4) Describe temporal patterns and long-term trends in nutrient concentrations in surface water.

(5) Describe the mass budget (loads) of nutrients in surface water and compare surface-water loads to estimates of nutrient inputs.

The National Water-Quality Assessment Program

The NAWQA Program began in 1986 with the appropriation of Congressional funds for the USGS to test and refine concepts for the design and conduct of the program (Hirsch and others, 1988). Seven pilot studies were started in 1986 and were mostly completed by 1991. Using lessons learned during the pilot studies and supported by recommendations by the National Academy of Science (National Academy of Science, 1990), the NAWQA Program began full-scale implementation in fiscal year 1991 (Leahy and others, 1990).

The goals of the NAWQA Program are to:

(1) Provide a nationally consistent description of current water-quality conditions for a large part of the Nation's water resources;

(2) Define long-term trends (or lack of trends) in water quality; and

(3) Identify, describe, and explain, to the extent possible, the major natural and human factors that affect observed water-quality conditions and trends.

It is anticipated that the data and findings of the NAWQA Program will provide a scientific basis for major national decisions that affect water-quality policy and regulation. It is important that such decisions be based on a sound understanding of the factors that affect water quality and that they be based on nationally consistent data and approaches. The NAWQA Program is designed to provide these requirements for informed decision making on a national level.

The NAWQA Program consists of two major components—national synthesis and study units (Leahy and Wilber, 1991). The national-synthesis component will address specific water-quality issues that are of common concern in most parts of the Nation. It is designed to address these issues through comparative studies among different hydrologic settings in the Nation, using data that are collected and analyzed in a consistent manner. The data needed for national-synthesis topics will be provided, in large part, by the other major component of the NAWQA Program—study units.

Sixty study units (major river basins and aquifer systems) have been identified for inclusion in the full-scale NAWQA Program (Leahy and others, 1990). The first 20 study units began operation in fiscal year 1991. A second group of 20 study units began in 1994, and a third group of 20 study units are planned to begin operation in 1997. Activity in each study unit is designed to be continual, with alternating periods of intensive investigation and low-level monitoring. Each study unit will address physical, chemical, and biological characteristics of surface-water and ground-water quality.

The Potomac River Basin study unit of the NAWQA Program is one of the 20 study units that began in fiscal year 1991 (Gerhart, 1991). It was selected to be studied in the first group of 20 study units because of its national prominence, its large population (mostly in the Washington, D.C., area), and its significance to the health of the Chesapeake Bay. The first intensive phase of the Potomac River Basin study unit is scheduled for completion in fiscal year 1997, at which time the study unit will enter its first low-level monitoring phase. In fiscal year 2002, the second intensive phase of the Potomac River Basin study unit is scheduled to begin.

Acknowledgments

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DESCRIPTION OF THE POTOMAC RIVER BASIN AND ITS SUBDIVISION FOR WATER-QUALITY-ASSESSMENT PURPOSES

The quality of water in the Potomac River Basin is affected by both natural and human factors. Natural factors that affect basin water quality include climate, physiography, geology, and hydrology. The natural water quality produced by these factors is then modified by human factors such as land use, population, water use, and wastewater discharges. Because of its large drainage area and diversity, the Potomac River Basin has a very complex environmental setting consisting of various combinations of these natural and human factors. Knowledge of the primary characteristics that comprise the environmental setting is necessary to understand basin water quality. The Potomac River Basin has been divided into eight subunits for the purpose of water-quality assessment. The following sections describe this subdivision and the important natural and human factors that affect water quality in the Potomac River Basin.

Location and Major Features

The Potomac River begins as a small spring in West Virginia and flows 383 mi to Point Lookout, Md., where it discharges into the Chesapeake Bay (fig. 1). Flow of the river increases downstream so that when it reaches the Chesapeake Bay, it constitutes about 15 percent of the estimated 49,300 Mgal/d total inflow to the Bay (J.F. Hornlein, U.S. Geological Survey, oral commun., 1991). In all, the Potomac River and its many tributaries drain 14,670 mi^2 in four States—Virginia (5,723 mi^2), Maryland (3,818 mi^2), West Virginia (3,490 mi^2), and Pennsylvania (1,570 mi^2)—and Washington, D.C. (69 mi^2).

Major tributaries to the Potomac River include the North Branch Potomac River, South Branch Potomac River, Cacapon River, Shenandoah River, Conococheague Creek, Monocacy River, and Occoquan River (fig. 1). The North Branch Potomac River drains the rugged northwestern part of the Potomac River Basin in Maryland, West Virginia, and Pennsylvania. The South Branch Potomac River and Cacapon River drain the mountainous West Virginia part of the basin. The Shenandoah River, the largest of the Potomac River's tributaries, drains the broad, relatively flat Shenandoah Valley in Virginia. Conococheague Creek and the Monocacy River drain the northern and northeastern parts of the basin in Maryland and Pennsylvania. The largest tributary in the eastern part of the basin is the Occoquan River in Virginia, which enters directly into the freshwater tidal Potomac River south of Washington, D.C.

The Potomac River is free flowing and contains freshwater upstream from Washington, D.C. At the northwestern boundary of Washington, D.C., as it flows onto the Atlantic Coastal Plain where it becomes tidal. The river contains freshwater and is tidal from Washington, D.C., to near Indian Head, Md., where the water becomes brackish (fig. 1). From Indian Head to Point Lookout, Md., the river water becomes progressively more salty as it approaches the Chesapeake Bay.

The major population center in the Potomac River Basin is Washington, D.C., and its suburbs, near the eastern boundary of the basin (fig. 1). Other major population centers include Cumberland, Hagerstown, Frederick, Rockville, and Waldorf in Maryland; Staunton, Waynesboro, Harrisonburg, Front Royal, Winchester, Leesburg, and Manassas in Virginia; Petersburg, Moorefield, and Martinsburg in West Virginia; and Chambersburg, Waynesboro, and Gettysburg in Pennsylvania.

Climate

The average annual temperature in the Potomac River Basin ranges from about 47 °F in the mountainous western part of the basin to just less than 58 °F in Washington, D.C. (U.S. Department of Commerce,

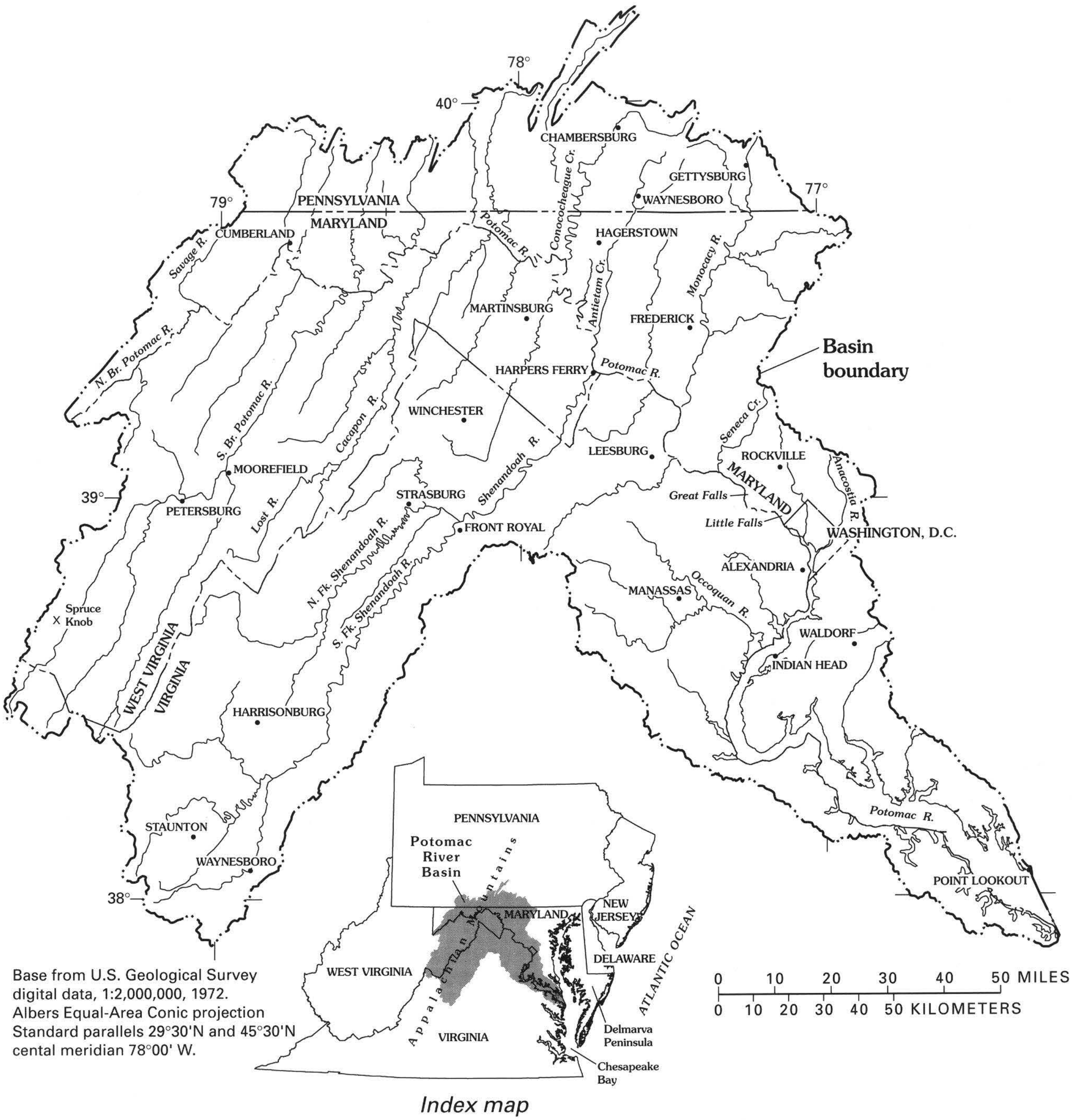


Figure 1. Location and major features of the Potomac River Basin.

1991a,b,c,d). Although temperatures are typically lower in the western part of the basin, throughout most of the rest of the basin average annual temperature ranges from about 51 to 55 °F, with no apparent areal pattern. Temperature varies considerably throughout the year. July tends to be the hottest month and January the coldest. The difference between the average monthly temperatures in July and January is about 45 °F, regardless of location in the basin.

The average annual precipitation in the basin ranges from about 32 in. in the South Branch Potomac River drainage to about 48 in. near the source of the Potomac River in the North Branch Potomac River drainage as shown in figure 2 (U.S. Department of Commerce, 1991a,b,c,d). Precipitation contours were drawn using data extending outside the Potomac basin boundary, with greater data density in areas with greater variability in precipitation amounts. In general,

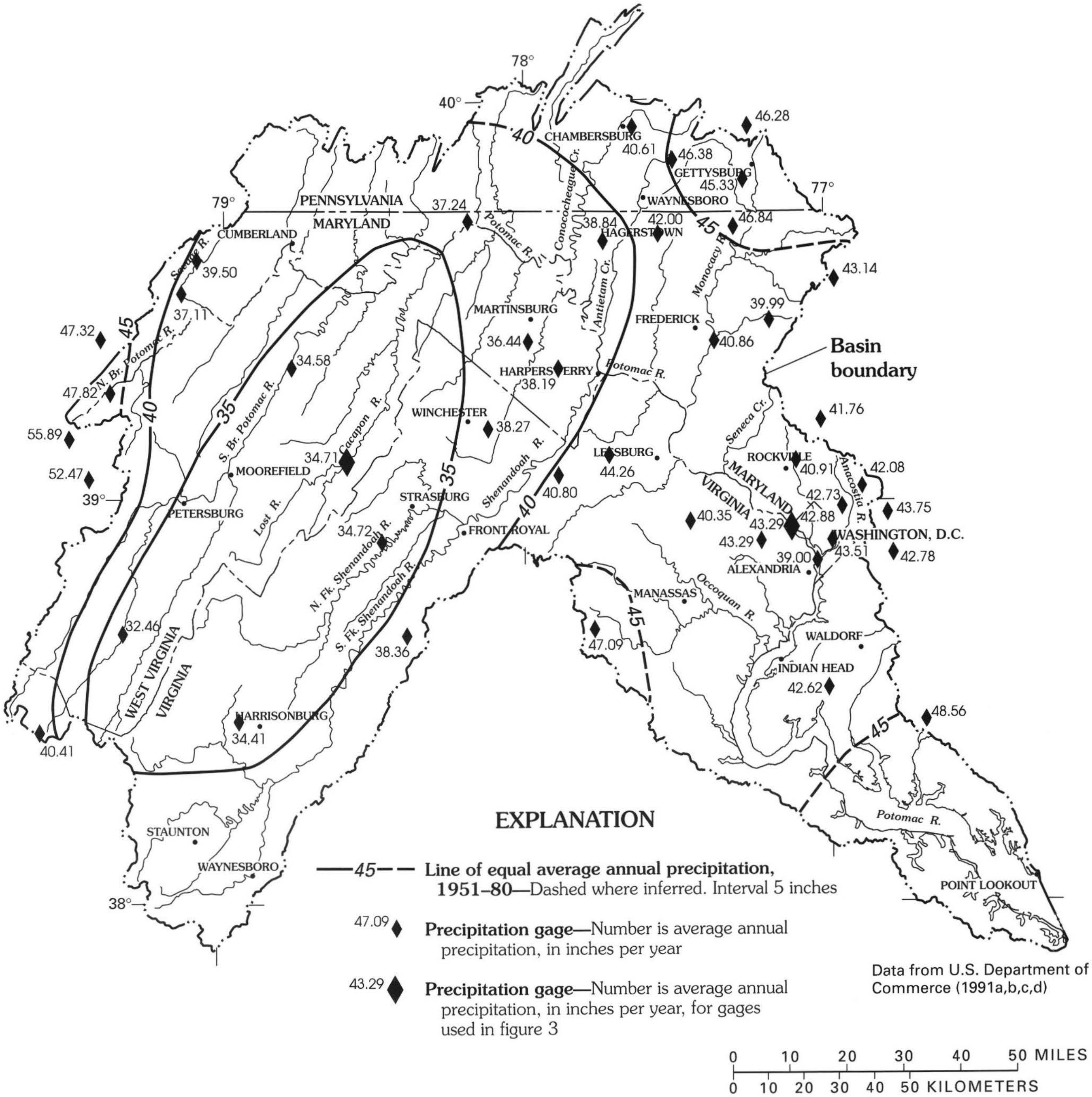


Figure 2. Average annual precipitation in the Potomac River Basin, 1951–80.

precipitation in the area of the South Branch Potomac and Shenandoah Rivers averages less than 40 in/yr, and precipitation in the rest of the Potomac River Basin averages more than 40 in/yr. The high western mountains of Maryland and West Virginia have the greatest variability in average annual precipitation, with amounts ranging from about 37 to 47 in. The rapid decrease in average annual precipitation from the high western mountains to the South Branch Potomac and Shenandoah River areas probably is caused by orographic effects of the western Appalachian Mountains. The eastern part of the basin is affected by coastal weather patterns and has average annual precipitation ranging from about 39 to 47 in.

Precipitation amounts vary seasonally as well as areally. Mean monthly precipitation is shown in figure 3 for two locations in the Potomac River Basin—one in the mountainous Cacapon River drainage of West Virginia, and one in the Washington, D.C., area, in northern Virginia (U.S. Department of

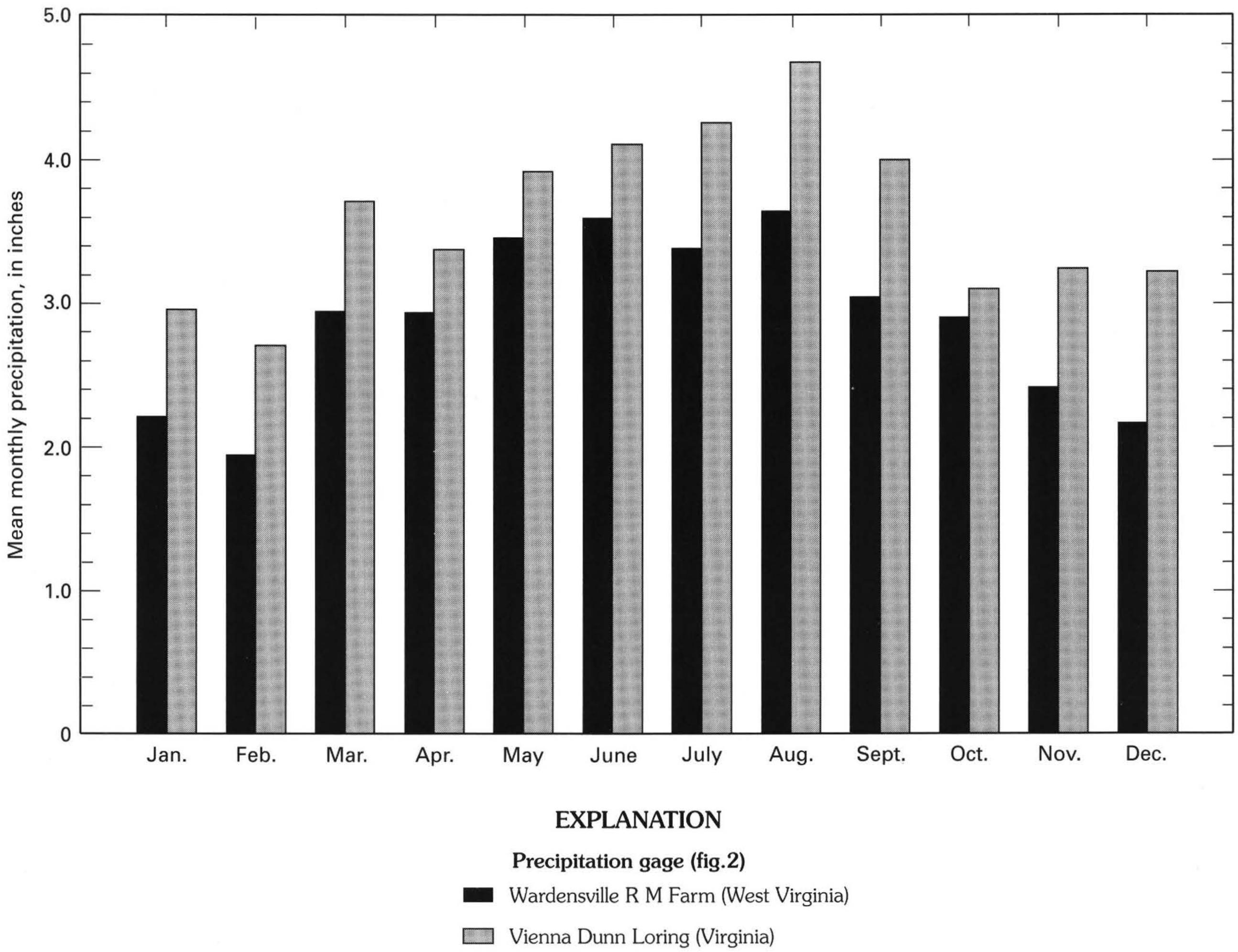


Figure 3. Mean monthly precipitation at two locations in the Potomac River Basin, 1951–80.

Commerce, 1991c,d). Although the total average annual precipitation at the two locations differs by about 9 in., the seasonal patterns are the same at both sites. In both locations, as well as in the rest of the Potomac River Basin, most precipitation occurs in the summer (June–August) and the least in the winter (December–February).

Physiography

The Potomac River Basin contains parts of seven physiographic provinces or subprovinces that extend from southwest to northeast along the Atlantic Coast of the United States (Fenneman and Johnson, 1946). The physiographic provinces include the Appalachian Plateau, Valley and Ridge, Blue Ridge, Piedmont, and Coastal Plain (fig. 4). The Valley and Ridge is the largest province in the basin and includes the Great Valley subprovince. The Piedmont is the second largest province and contains the Triassic Lowlands subprovince. The Valley and Ridge and Piedmont Provinces are treated as separate, distinct entities from their subprovinces because the subprovinces are topographically and geologically distinct. The varied topography of these seven provinces and subprovinces forms a complex landscape within the Potomac River Basin that includes steep mountains, rolling hills, broad valleys, and plains.

The Appalachian Plateau is the westernmost province and comprises about 4 percent of the basin in Maryland, Pennsylvania, and West Virginia. It is characterized by narrow valleys and steep, rugged ridges creating local topographic relief of 500 to 2,000 ft. The Appalachian Plateau contains the highest point in the basin, Spruce Knob, which rises to an altitude of 4,860 ft. The North Branch Potomac River drains the Appalachian Plateau, which is the only basin province where coal is found. The Appalachian Plateau is separated from the Valley and Ridge Province to the

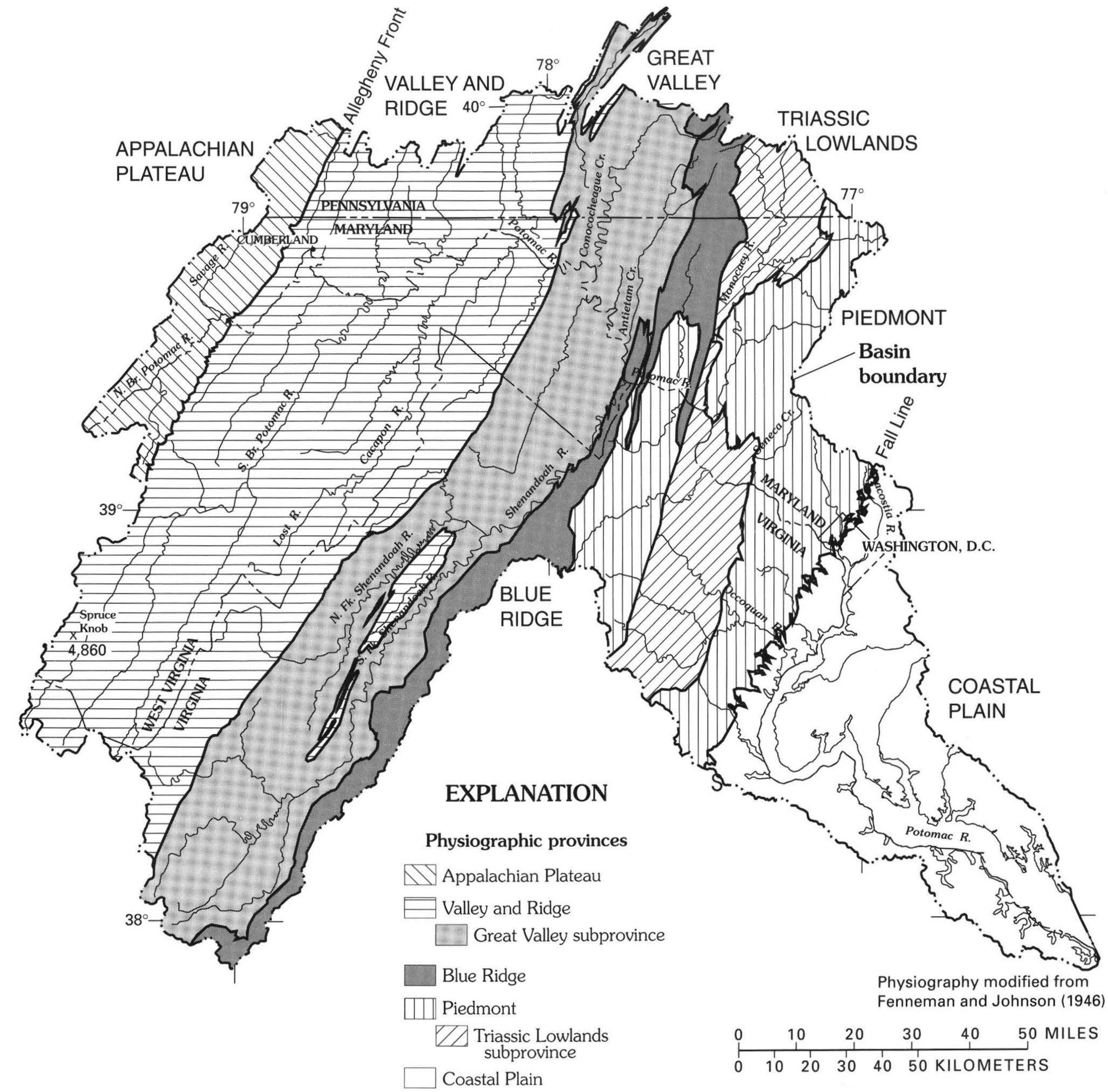


Figure 4. Physiographic provinces and subprovinces in the Potomac River Basin.

east by the Allegheny Front, a major escarpment with as much as 3,000 ft of local relief that trends northeast through the basin.

The Valley and Ridge Province is the most extensive province in the basin and occurs in Virginia, West Virginia, Maryland, and Pennsylvania (fig. 4). This province comprises 55 percent of the basin and 34 percent of the basin excluding the Great Valley subprovince. The rocks in this province have been intensely folded and faulted, producing long, narrow, northeast-trending structures. Subsequent erosion and weathering have resulted in the distinctive topographic grain of this province, with ridges capped by resistant sandstone and valleys underlain by less-resistant shale and carbonate rocks. Topographic relief in the Valley and Ridge Province is considerable, ranging to as much as 1,800 ft. The trend of the ridges substantially affects surface drainage in the basin, so that the principal tributary streams, the South Branch Potomac and Cacapon Rivers, flow northeast to the Potomac River.

The Great Valley is an important subprovince of the Valley and Ridge Province. It occupies the eastern part of the Valley and Ridge Province and is a broad valley, 15 to 20 mi wide, with minor relief over extensive areas (fig. 4). It covers 21 percent of the basin, and agricultural activities are the predominant land use. Shale and siltstone underlie the central part of the Great Valley and are bordered by areas underlain by carbonate rocks. The carbonate rocks that make this subprovince favorable for farming also are susceptible to dissolution, resulting in numerous caves and karstic features throughout most of the area. The Shenandoah River and Conococheague Creek are the major tributaries to the Potomac River that drain this subprovince.

Bordering the Great Valley on the east is the Blue Ridge Province (fig. 4). It covers 6 percent of the basin and consists of a mass of crystalline rocks that rises about 1,500 to 2,000 ft above the lowlands on either side. In Virginia, the Blue Ridge forms the southeastern boundary of the Potomac River Basin. In Maryland and Pennsylvania, it forms a major drainage divide within the basin, with all streamflow from west of the Blue Ridge flowing through the gap at Harpers Ferry, West Virginia. Because of relief and narrowness, most of the streams that drain the Blue Ridge are headwater tributaries of larger streams in the Great Valley or Piedmont.

The Piedmont Province lies to the east of the Blue Ridge and comprises about 12 percent of the basin in Virginia, Maryland, Pennsylvania, and Washington, D.C. (fig. 4). It is an area of gently rolling terrain with low to moderate relief. The eastern and western parts of the Piedmont are underlain by resistant crystalline rocks, whereas the central part, the Triassic Lowlands subprovince, 7 percent of the basin is underlain by less-resistant sedimentary rocks of primarily Triassic age. The Triassic Lowlands subprovince is generally flatter than the surrounding Piedmont. The principal tributary to the Potomac River in the Piedmont Province is the Monocacy River, which also drains agricultural lands in the Triassic Lowlands subprovince.

The Fall Line separates the Piedmont from the Coastal Plain Province to the east. At the Fall Line, the rolling hills of the Piedmont drop in elevation to meet the gently sloping Coastal Plain. Stream gradients abruptly steepen through the Fall Line as they enter the Coastal Plain. The Potomac River drops nearly 150 ft to near sea level as it flows through Great Falls and Little Falls near Washington, D.C. The Fall Line also marks the terminus of the upper Potomac River, which, at this point, drains about 11,670 mi^2 of the six provinces and subprovinces upstream. Smaller tributaries enter the tidal Potomac River after flowing from the Triassic Lowlands and Piedmont through the Fall Line onto the Coastal Plain.

The Coastal Plain Province is fundamentally different from the other physiographic provinces in that it is underlain by unconsolidated sediments that form a gentle seaward-sloping plain of low relief. Much of the population of the Potomac River Basin resides in this province, which covers about 15 percent of the basin in Virginia, Maryland, and Washington, D.C. (fig. 4). It is in this province that the Potomac River is tidally effected, eventually becoming a broad estuary before entering the Chesapeake Bay. The estuary is typically flanked by broad lowlands that mark the sinuous and deep course of an ancestral Potomac River Valley now filled by unconsolidated sediments.

Geology

The geology of the Potomac River Basin is complex and diverse, ranging from relatively undisturbed, unconsolidated sediments to intensely deformed crystalline rocks (Milici, 1963; Cardwell, 1968; Cleaves, 1968; Berg, 1980) (fig. 5). The most intensely deformed and the oldest rocks in the basin are crystalline rocks in the Piedmont and Blue Ridge Provinces. These rocks are primarily metamorphic and igneous rocks of Precambrian to Ordovician age that are deformed as a result of at least four episodes of increased tectonic activity. Predominant rock types are massive granite and layered gneiss, foliated phyllite and schist, quartzite, marble, and metadolomite. The folding and faulting associated with the tectonic stresses have produced structures too complex to show in figure 5. Instead, crystalline rocks are undifferentiated on the map.

Sedimentary rocks of Cambrian through Pennsylvanian age underlie the Valley and Ridge and Appalachian Plateau Provinces (fig. 5). The rocks of the Valley and Ridge have been deformed by folding and thrust faulting into a series of plunging folds that create the topographic grain of the province. Although folded and faulted, these rocks were farther away from the center of tectonic activity than the crystalline rocks of the Piedmont and Blue Ridge. Therefore, the rocks in the Valley and Ridge were not recrystallized during orogenic events. In the Valley and Ridge Province, the rocks can be broadly categorized into siliciclastic and carbonate types. Siliciclastic rocks are prevalent in the

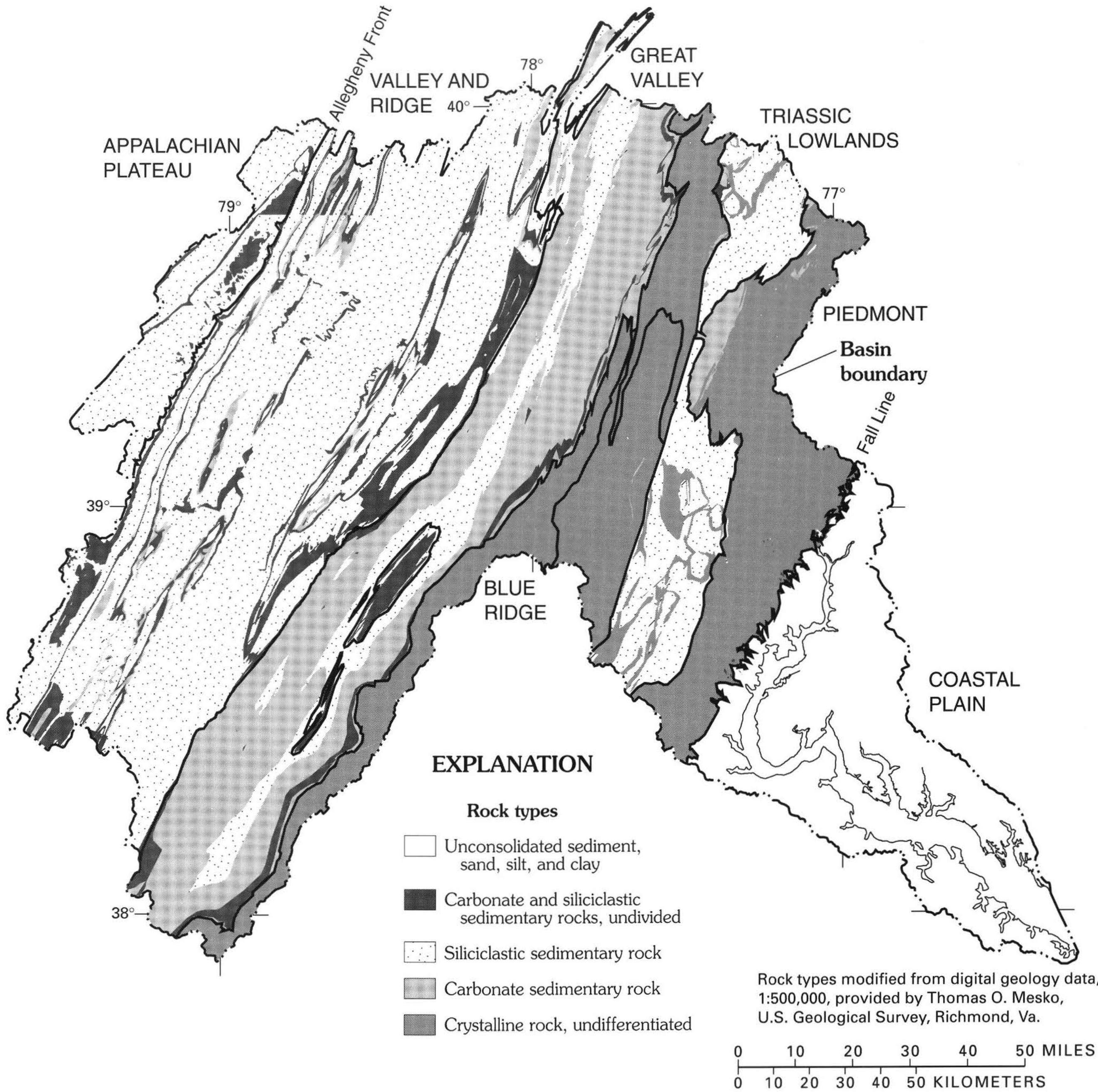


Figure 5. Generalized rock types in the Potomac River Basin.

Silurian, Devonian, Mississippian, and Pennsylvanian Systems, and carbonate rocks are prevalent in the Cambrian and Ordovician Systems. The largest extent of carbonate rocks is in the Great Valley subprovince where karstic features associated with dissolution of carbonate rocks are common. Rocks in the Appalachian Plateau Province are similar lithologically to the siliciclastic types in the Valley and Ridge with the exception that coal-bearing rocks are found in the Appalachian Plateau. Although major thrust faults occur at depth, rocks in the Appalachian Plateau Province are relatively flat-lying and less deformed than rocks in the Valley and Ridge.

The youngest consolidated rocks in the basin are found to the east of the Blue Ridge Province, in the part of the Piedmont Province underlain by sedimentary rocks (fig. 5). These rocks were formed during the Late Triassic and Early Jurassic by streams discharging sediment into down-faulted rift basins. In the Potomac River Basin, the faulted margin of these basins borders the Blue Ridge, and other faults are present throughout the sequence. The sedimentary sequence is interrupted locally by igneous intrusive and extrusive rocks.

The youngest geologic units in the basin are in the Coastal Plain Province (fig. 5). These units consist of unconsolidated sediment of Cretaceous through Holocene age that form a southeastward-thickening wedge of interbedded sand, silt, and clay.

Regolith, consisting of soil, terrace deposits, colluvium, residuum, tufa, travertine, alluvium, saprolite, and chemically and physically weathered rock, overlies most of the Potomac River Basin. The thickness of the regolith is variable, ranging from 0 to more than 150 ft over relatively short distances. In addition to areal variability, the character of the regolith may differ considerably over short vertical intervals.

Although the geology of the Potomac River Basin is very complex, the geologic units may be broadly categorized into four groups—unconsolidated sediment, carbonate sedimentary rocks, siliciclastic sedimentary rocks, and crystalline rocks (fig. 5). Unconsolidated sediments underlie about 15 percent of the basin, carbonate sedimentary rocks underlie about 17 percent, siliciclastic sedimentary rocks underlie about 42 percent, and crystalline rocks underlie about 19 percent of the basin. The remaining 7 percent consists of geologic units that contain significant proportions of both carbonate and siliciclastic sedimentary rocks.

Land Use and Population

Land-use patterns were fairly stable throughout the basin during 1970–85, with most of the development occurring in the Washington, D.C., area and it suburbs. In the mid-1970's, 51 percent of the land in the Potomac River Basin was in forest, 36 percent was used for agricultural activities, and 8 percent was urban (U.S. Geological Survey, 1979a,b,c,d; 1980a,b,c,d) (fig. 6). By 1985, 52 percent of the land in the basin was forested, 32 percent was used for agricultural activities, and 12 percent was urban (Camacho, 1989). Land-use data for the 1970's are from a digital geographic data base available for the entire United States. The 1985 land-use percentages were calculated using nondigital, county-based, land-use data, so the differences in land use from the mid-1970's to 1985 could reflect the different analysis techniques as well as changing land-use patterns. The data suggest a shift from agricultural land use to urban land use from the mid-1970's to 1985, with 4 percent of the basin that was agricultural land in the mid-1970's being converted to urban land use by 1985.

Mid-1970's land use differed considerably among physiographic provinces (table 1). Agriculture comprised 50 percent or more of the land use in the Great Valley, Piedmont, and Triassic Lowlands. Forests covered more than 75 percent of the land in the Appalachian Plateau, Valley and Ridge, and Blue Ridge. No individual land use comprised more than 40 percent of the land in the Coastal Plain, where the single largest land use was forest (38 percent), followed by water (23 percent), urban (19 percent), and agriculture (16 percent). Provinces having the most urban land use (19 percent) were the Piedmont and Coastal Plain. Less than 5 percent of land use was urban in the Appalachian Plateau, Valley and Ridge, and Blue Ridge Provinces.

The population of the Potomac River Basin increased from about 3.2 million people in 1970 to about 4.6 million people in 1990 (Carlton Haywood, Interstate Commission on the Potomac River Basin, written commun., 1995). Most of the 4.6 million people who lived in the Potomac River Basin in 1990 resided in the urban land-use settings (U.S. Department of Commerce, 1991e) (fig. 6). An estimated two-thirds of the basin's 1990 population lived in the Washington, D.C., metropolitan area. Population density exceeded 10,000 people per square mile in nearly all of Washington, D.C., and in nearby parts of Maryland and northern Virginia (K.J. Hitt, U.S. Geological Survey, written commun., 1992). Other population centers where 1990 population density exceeded 10,000 people per square mile included Cumberland, Hagerstown, Frederick, Rockville, and Waldorf, Md.; Harrisonburg, Leesburg, and Manassas, Va.; and Chambersburg, Pa. Because of the location of Washington, D.C., on their common boundary, the Piedmont and Coastal Plain were the most populous physiographic provinces in the Potomac River Basin in 1990, each having about 36 percent of the total basin population. The Great Valley and Triassic Lowlands subprovinces were next, with about 14 and 8 percent of the basin population, respectively. The Appalachian Plateau, Valley and Ridge, and Blue Ridge Provinces shared the remaining 6 percent of the 1990 population.

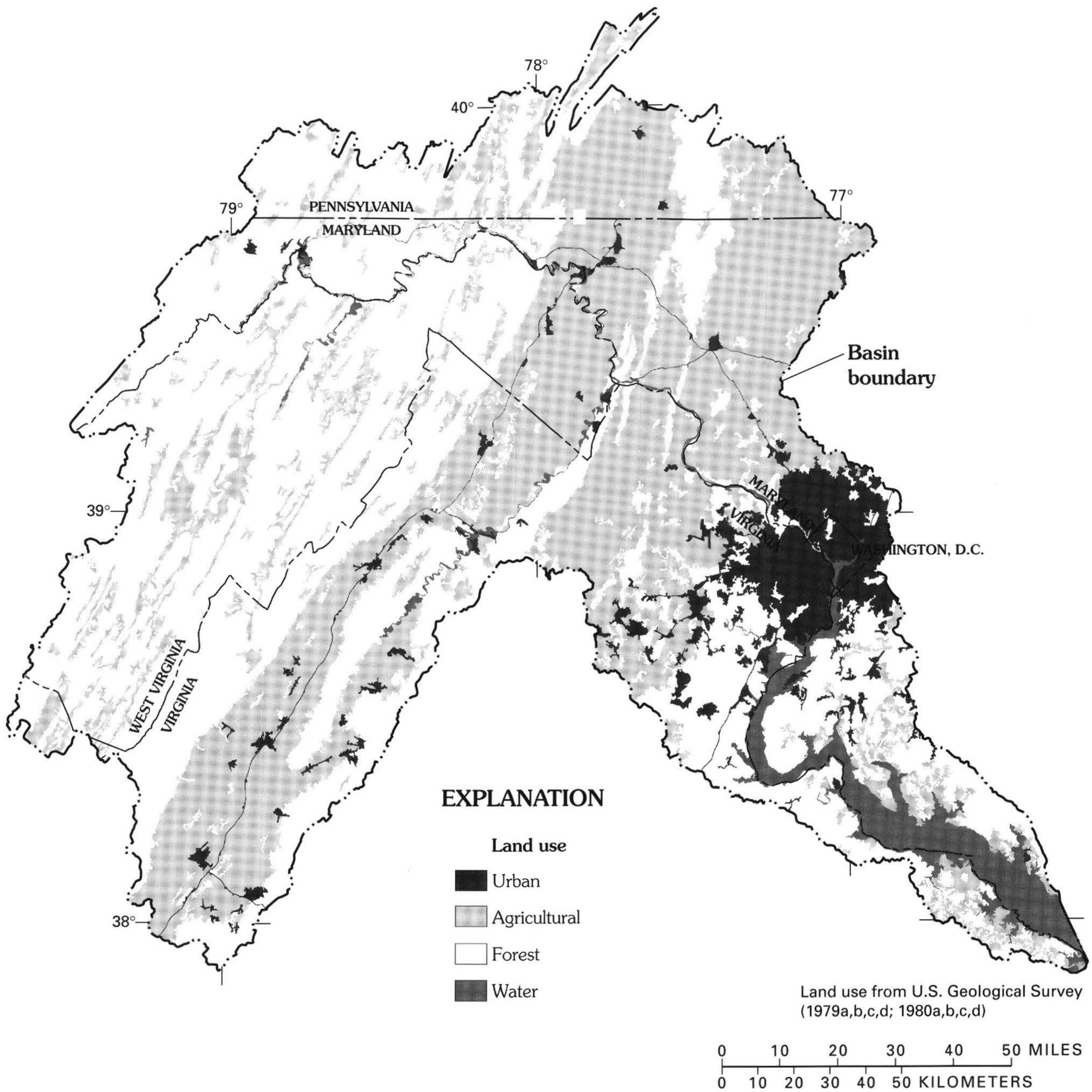


Figure 6. Generalized land use in the Potomac River Basin, mid-1970's.

Water Use and Wastewater Discharges

In 1990, about 6,374 Mgal/d of freshwater (about 85 percent of the average flow of the Potomac River at Washington, D.C.) was used for human-related activities in the Potomac River Basin. Most of the water used is returned to streams within the basin. The largest use of water, 86 percent of total use, was for power generation. Public water supply was the next largest use in the basin, accounting for about 10 percent of the total, followed by industrial, domestic, mining, agricultural, and commercial uses. (All data in this section are from H.A. Perlman (U.S. Geological Survey, written commun., 1993) and are for counties contained wholly or partially in the basin. Totals for water use in the basin may be slightly high because they include water use for those parts of counties that are outside the basin.)

If power-generation uses are ignored, the distribution of freshwater withdrawals in the Potomac River

Table 1. Potomac River Basin land use by physiographic province and subprovince, mid-1970's
[Data from U.S. Geological Survey, 1979a,b,c,d; 1980a,b,c,d]

Province or subprovince	Area (square miles)	Percentage of physiographic province or subprovince in each land use				
		Forest	Agricultural	Urban	Water	Other
Appalachian Plateau	660	82	13	1	0	4
Valley and Ridge	5,062	80	18	1	0	1
Great Valley	3,070	22	68	8	1	1
Blue Ridge	919	78	17	3	0	2
Piedmont	1,851	29	50	19	1	1
Triassic Lowlands	1,018	23	66	9	1	1
Coastal Plain	2,090	38	16	19	23	4
Potomac River Basin	**14,670**	**51**	**36**	**8**	**4**	**1**

Basin in 1990 (fig. 7) closely follows the distribution of population. The counties shown in figure 7 having the largest total freshwater withdrawals are Montgomery County in Maryland and Prince William County in Virginia, where the water supply for the Washington, D.C., metropolitan area is derived. Potomac River water was withdrawn in Montgomery County, Maryland, just upstream from Washington, D.C., at an average rate of about 387 Mgal/d in 1990, and the Occoquan River in Prince William County, Virginia, supplied about 58 Mgal/d to the Washington, D.C., metropolitan area in 1990. No major freshwater withdrawals were located in Washington, D.C., or in very populated Fairfax County, Virginia, as they were served by these Potomac River and Occoquan River withdrawals in neighboring counties.

Seven additional counties had total freshwater withdrawals exceeding 20 Mgal/d or more in 1990. These counties are located in parts of the Piedmont Province, and Triassic Lowlands and Great Valley subprovinces, as well as the northern part of the Valley and Ridge Province, where urban areas are served by public water supplies (fig. 7). Most of the counties with less than 5 Mgal/d of total freshwater use in 1990 are located in rural parts of the Valley and Ridge in West Virginia, the central part of the Great Valley, and the Coastal Plain Province in Virginia.

Although freshwater use for thermoelectric and hydroelectric power generation are not included in the county data shown in figure 7, they constitute an important water use at 14 locations in the Potomac River Basin (fig. 7). A total of about 2,130 Mgal/d of freshwater were withdrawn in 1990 for thermoelectric power generation at six locations throughout the basin. Only about 31 Mgal/d, or 1.5 percent, of this water were consumed. The rest was returned to surface water in the basin. Similarly, a total of about 3,377 Mgal/d of freshwater was used in 1990 for hydroelectric power generation at eight locations throughout the basin. All of this water was returned to streams in the basin.

About 6,170 of the 6,374 Mgal/d (97 percent) of total freshwater used in the Potomac River Basin in 1990 was from surface-water sources (fig. 8). Excluding the 5,508 Mgal/d of power-generation use, about 662 Mgal/d (76 percent) of freshwater withdrawals were from surface-water sources. Besides power-generation uses, which were essentially all from surface-water sources, public-supply withdrawals of freshwater were the next largest type of use in 1990, about 618 Mgal/d. About 93 percent of the public-supply withdrawals, or 577 Mgal/d, was from surface-water sources. Surface-water sources also supplied about 65 percent of the 86.3 Mgal/d used for industrial purposes and about 54 percent of the 34.5 Mgal/d used for livestock watering and irrigation in 1990.

Total ground-water withdrawals in the basin in 1990 were about 204 Mgal/d (fig. 8). Ground water supplied essentially all of the 58.3 Mgal/d withdrawn for domestic purposes, about 72 percent of the 17.4 Mgal/d used for commercial purposes, and about 87 percent of the 51.5 Mgal/d withdrawn for mining purposes.

Excluding freshwater withdrawals for power generation, about 64 percent, or 551 Mgal/d, of the freshwater withdrawn in 1990 was returned to surface water in the basin by wastewater-treatment facilities. The distribution and relative magnitude of the major discharges from wastewater-treatment facilities are shown in figure 9. The largest municipal discharge in

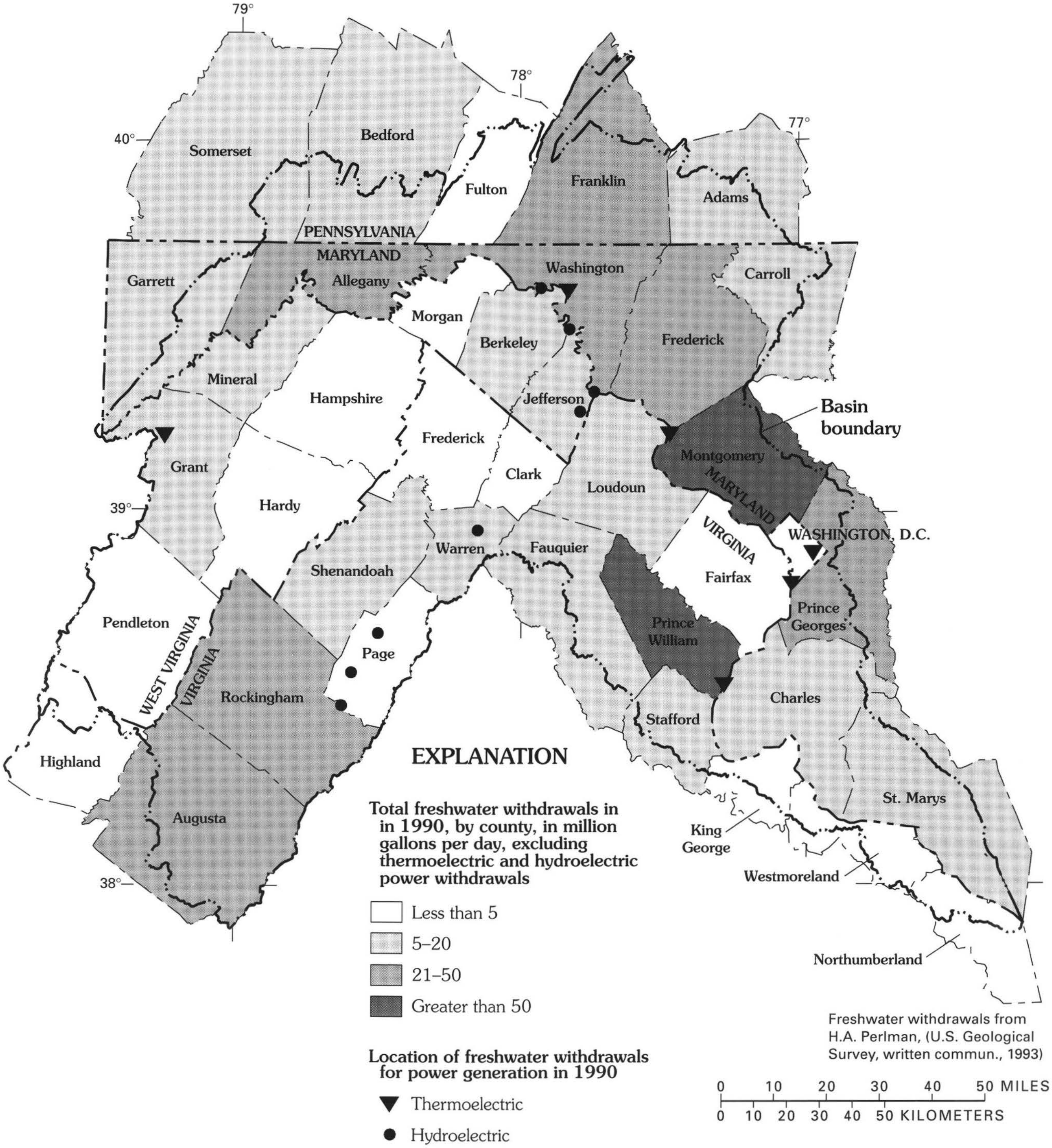


Figure 7. Generalized distribution of total freshwater withdrawals in the Potomac River Basin, 1990.

1990, about 317 Mgal/d, was into the tidal Potomac River from the Blue Plains Wastewater Treatment Plant downstream from Washington, D.C. Seven other municipal discharges of more than 10 Mgal/d were located in the Washington, D.C., metropolitan area. There were nine industrial discharges of more than 10 Mgal/d in 1990, with most of them located in the North Branch Potomac River area or the Great Valley subprovince. Two mining discharges of more than 10 Mgal/d were located in the Piedmont Province in 1990.

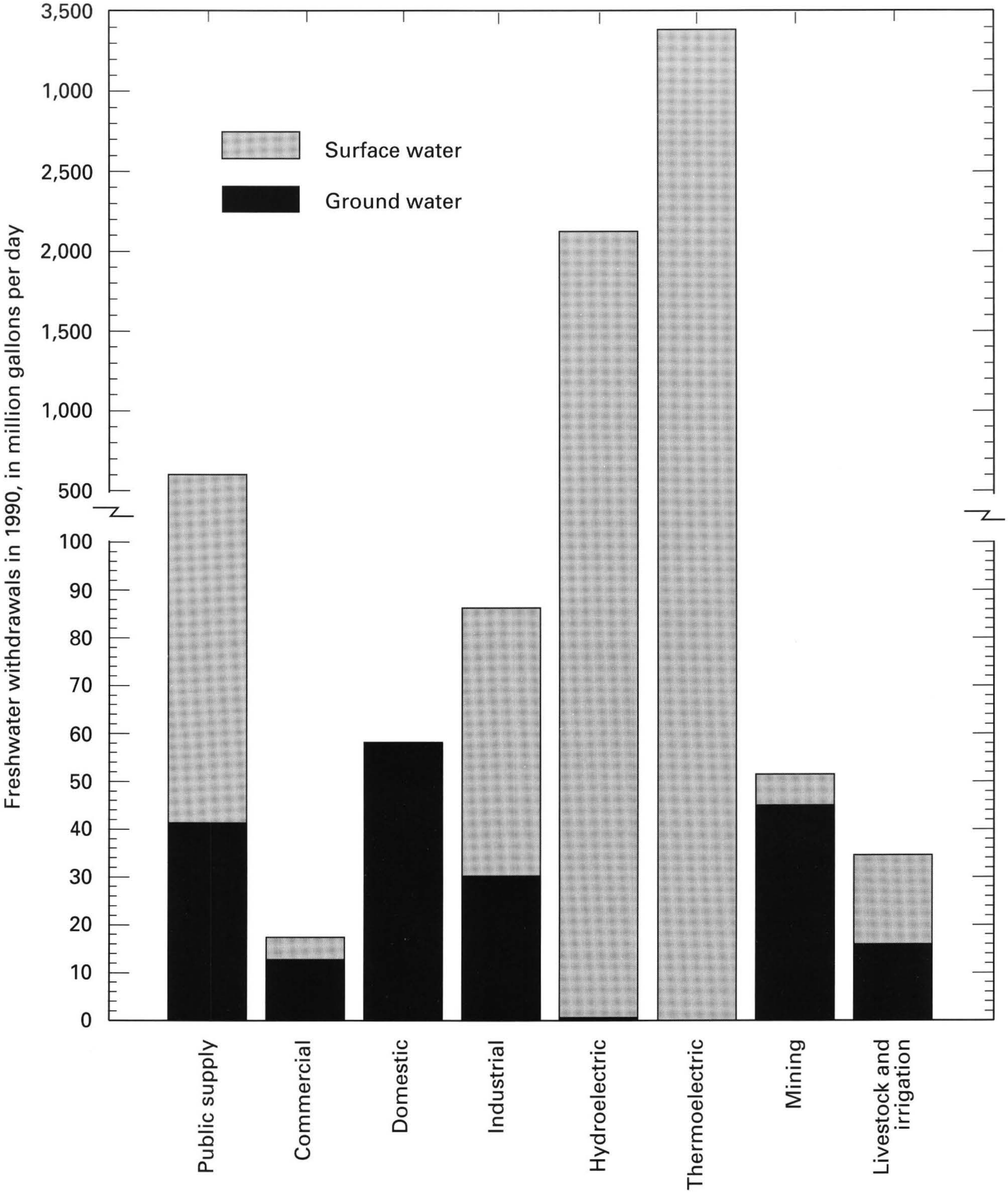


Figure 8. Surface-water and ground-water withdrawals of freshwater in the Potomac River Basin, 1990 (data from H.A. Perlman, U.S. Geological Survey, written commun., 1993).

Figure 9. Major wastewater discharges to streams in the Potomac River Basin, 1990.

Hydrology

Surface Water

The Potomac River Basin (fig. 1) includes six major tributaries—North Branch Potomac River, South Branch Potomac River, Cacapon River, Conococheague Creek, Shenandoah River, and Monocacy River. These six tributaries drain to the upper Potomac River upstream from the Fall Line. Selected streamflow characteristics for the upper Potomac River at Washington, D.C., and these six tributaries are shown in table 2. At the Fall Line, the Potomac River at Washington, D.C., maintains a mean annual streamflow of 11,771 ft^3/s. Additional tributaries drain directly to the tidal Potomac River and include the Anacostia and Occoquan Rivers. These smaller tributaries are important for water-quality and water-supply issues.

Streams upstream from the Fall Line generally have steeper gradients and flow more swiftly than streams downstream from the Fall Line. The mainstem Potomac River and major tributaries generally

Table 2. Streamflow characteristics of the Potomac River near Washington, D.C., and of six major tributaries

[mi^2, square miles; ft^3/s, cubic feet per second; in/yr, inches per year; $M_{7,20}$, 7-day minimum low-flow discharge, 20-year recurrence interval]

U.S. Geological Survey gaging station no. (fig. 10)	Station name	Drainage area (mi^2)	Period of record (water years)	Mean annual streamflow (ft^3/s)	Mean annual runoff (in/yr)	Low-flow discharge, $M_{7,20}$ (ft^3/s)	High-flow discharge (ft^3/s, 10-year recurrence interval)
[1]01603000	North Branch Potomac River near Cumberland, Md.	875	1929–90	1,276	19.82	112	37,100
01608500	South Branch Potomac River at Springfield, W. Va.	1,471	1928–90	1,310	12.1	62.1	56,600
01611500	Cacapon river near Great Cacapon, W. Va.	677	1922–90	586	11.76	34.7	36,000
01614500	Conococheague Creek near Fairview, Md.	494	1928–90	586	16.13	41	14,400
01636500	Shenandoah River at Millville, W. Va.	3,040	1928–90	2,697	12.05	330	82,000
01643000	Monocacy River near Frederick, Md.	817	1929–90	932	15.5	37	35,000
01646500	Potomac River near Washington, D.C.	11,560	1930–90	11,771	13.83	862	237,000

[1]Streamflow regulated since 1982.

have bedrock bottoms, with alluvial sediments in depositional areas. Stream-bottom materials range from bedrock to small cobbles and gravel in upstream areas, to eroded fine sediments in agricultural areas, to gravel, sand, and silt in Coastal Plain streams. Several streams, notably Conococheague Creek and the South Fork Shenandoah River, undergo considerable flood-plain meandering in their downstream reaches. Coastal Plain streams, downstream from the Fall Line, have shallow gradients and discharge to tidal creeks or wetlands, which have considerable effect on streamflow, stream morphology, and water quality.

Trainer and Watkins (1975) found that average base runoff from tributaries in the upper Potomac River Basin was approximately proportional to drainage area. The six major tributaries upstream from the Fall Line represent about 64 percent of the drainage area and contribute about 63 percent of the mean annual streamflow. At lower flows, however, Trainer and Watkins (1975) found that the areas underlain by carbonate rocks, which are mostly in the Great Valley subprovince, contribute a proportionately larger share of flow to the Potomac River at Washington, D.C. For example, the Shenandoah River contributes about 38 percent of the streamflow during low-flow conditions yet contains only 26 percent of the upper Potomac River Basin (Trainer and Watkins, 1975).

Figure 10 shows the distribution of mean annual runoff in the Potomac River Basin. The greatest runoff occurs in the Appalachian Plateau and westernmost parts of the Valley and Ridge Province. The least runoff occurs in the Shenandoah River part of the Great Valley. A comparison of the maps of mean annual runoff and average annual precipitation (fig. 2) reveals that patterns of runoff generally follow those of precipitation. However, the ratio of runoff to precipitation is somewhat higher in the Appalachian Plateau and westernmost parts of the Valley and Ridge Province, where steep slopes, shallow soils, and less-permeable bedrock contribute to the greater total runoff. About 50 percent of precipitation becomes surface runoff in these mountain areas. In the remainder of the Potomac River Basin, with generally flatter slopes, deeper soil profiles, and more fractured bedrock, karst terrain, or Coastal Plain deposits, about 35 percent of precipitation contributes to surface runoff.

Most streams in the Potomac River Basin generally have good year-round flow and infrequently experience very low or no flow. However, the Potomac River Basin has experienced notable hydrologic extremes. Floods of record for the Potomac River near Washington, D.C., include a maximum discharge of 484,000 ft^3/s in March 1936, resulting from intense rainfall and snowmelt, and 359,000 ft^3/s in June 1972, resulting from Hurricane Agnes. Although the peak discharge from Agnes was large, but not exceptional, on the main-stem Potomac River, this flood caused peaks of record on many tributaries downstream from Conococheague Creek (Bailey and others, 1975). Rains from Tropical Storm Juan in November 1985 produced catastrophic flooding in the South Branch Potomac River and parts of the Shenandoah River (Carpenter, 1990). The extreme low flow for the Potomac River at Washington, D.C., was only 601 ft^3/s on September 10, 1966, only about 5 percent of the mean annual streamflow.

Figure 11 shows mean annual and mean monthly streamflow for the Potomac River at Washington, D.C., for water years 1970–90. During this period, this gaging station had a mean annual streamflow of 11,600 ft^3/s, slightly less than the long-term mean. Maximum annual streamflows occurred in water years 1972 and 1984, and the minimum annual streamflow occurred in 1981. The last 10 years (1981–90) were the driest of the 21-year period as 7 out of 10 years were less than the annual mean. Streamflows for the Potomac River at Washington, D.C., show a strong seasonal pattern as mean monthly streamflows vary from less than 5,000 ft^3/s in August to more than 22,000 ft^3/s in April.

Streamflow regulation in the Potomac River Basin is minimal. Figure 12 shows the location of major surface-water impoundments in the Potomac River Basin. The four largest impoundments in the basin are Savage River Reservoir, William Jennings Randolph Lake on the North Branch Potomac River, Mt. Storm Lake on Stony River, and Occoquan Lake on Occoquan River. The Stony River dam provides cooling water for coal-generated electric power. William Jennings Randolph Lake provides flood control on the North Branch Potomac River in addition to other uses. William Jennings Randolph Lake and Savage River Reservoir combine to provide water-quality control in an area affected by acid-mine drainage, as well as low-flow augmentation on the North Branch Potomac River. Occoquan Lake on Occoquan River is a multiple-purpose reservoir that contains only Piedmont drainage but discharges to the Potomac River estuary downstream from Washington, D.C. There are a number of low-flow dams on the main-stem Potomac River

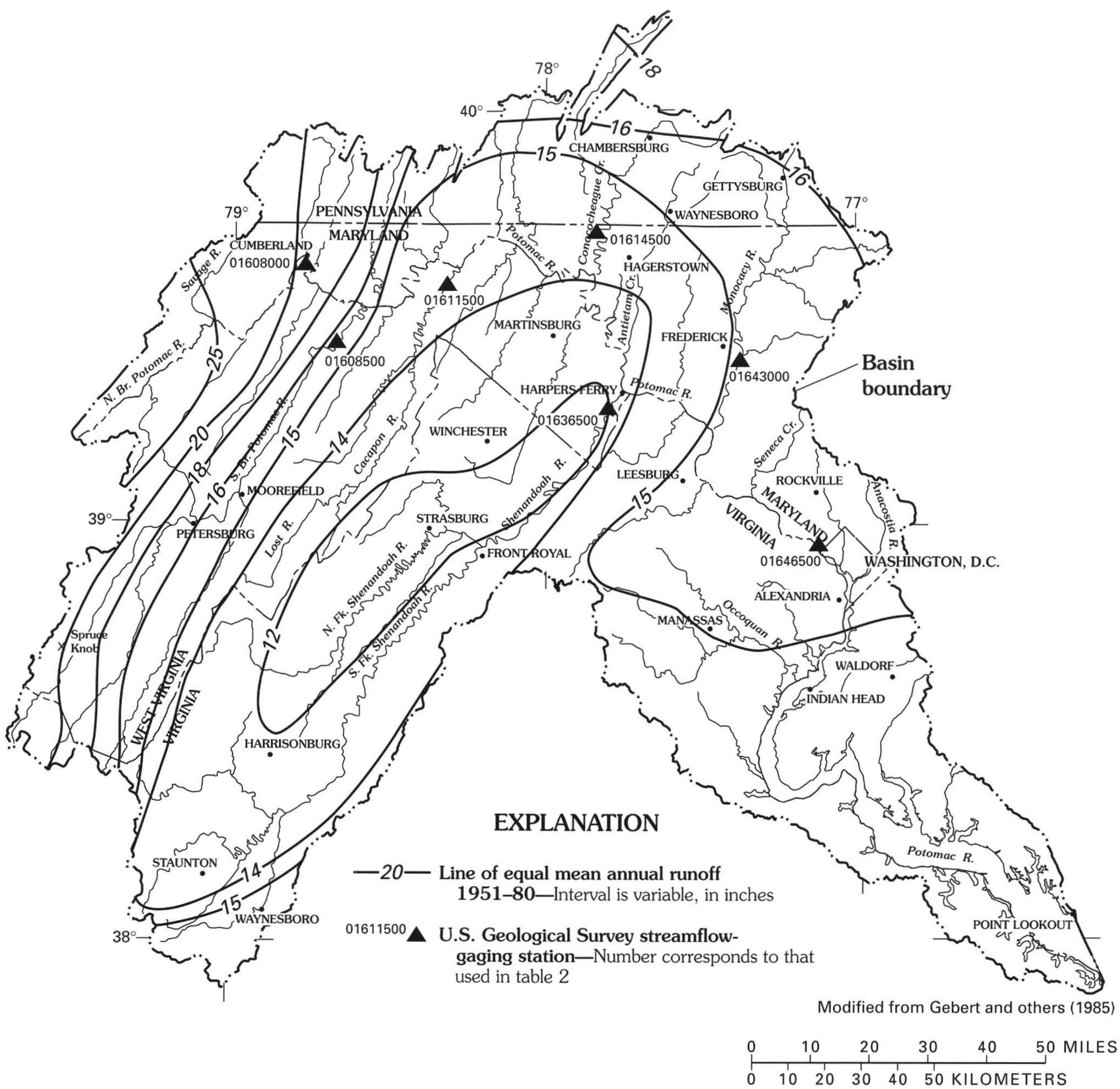


Figure 10. Mean annual surface-water runoff, 1951–80, and selected streamflow-gaging stations in the Potomac River Basin.

and on the Shenandoah River, but these have negligible effect on general streamflow characteristics.

Ground Water

Ground water in the Potomac River Basin is present in a variety of hydrogeologic settings, in both primary and secondary openings in the rock matrix and in local, intermediate, and regional flow systems. Principal factors affecting ground water are climate, aquifer and regolith characteristics, land use/land cover, water use, and topographic relief. The hydrogeologic setting that differs the most from the other settings in the basin is the Coastal Plain. Ground water in this setting resides in and moves through interstices between individual mineral grains, whereas ground water in the rest of the basin resides in and moves through fractures and other secondary openings in the rock matrix. The water-transmitting and water-storing properties of sediment in the Coastal Plain are determined by the environment in which the deposits were formed. Although these depositional environments varied greatly in space and time, the sediment

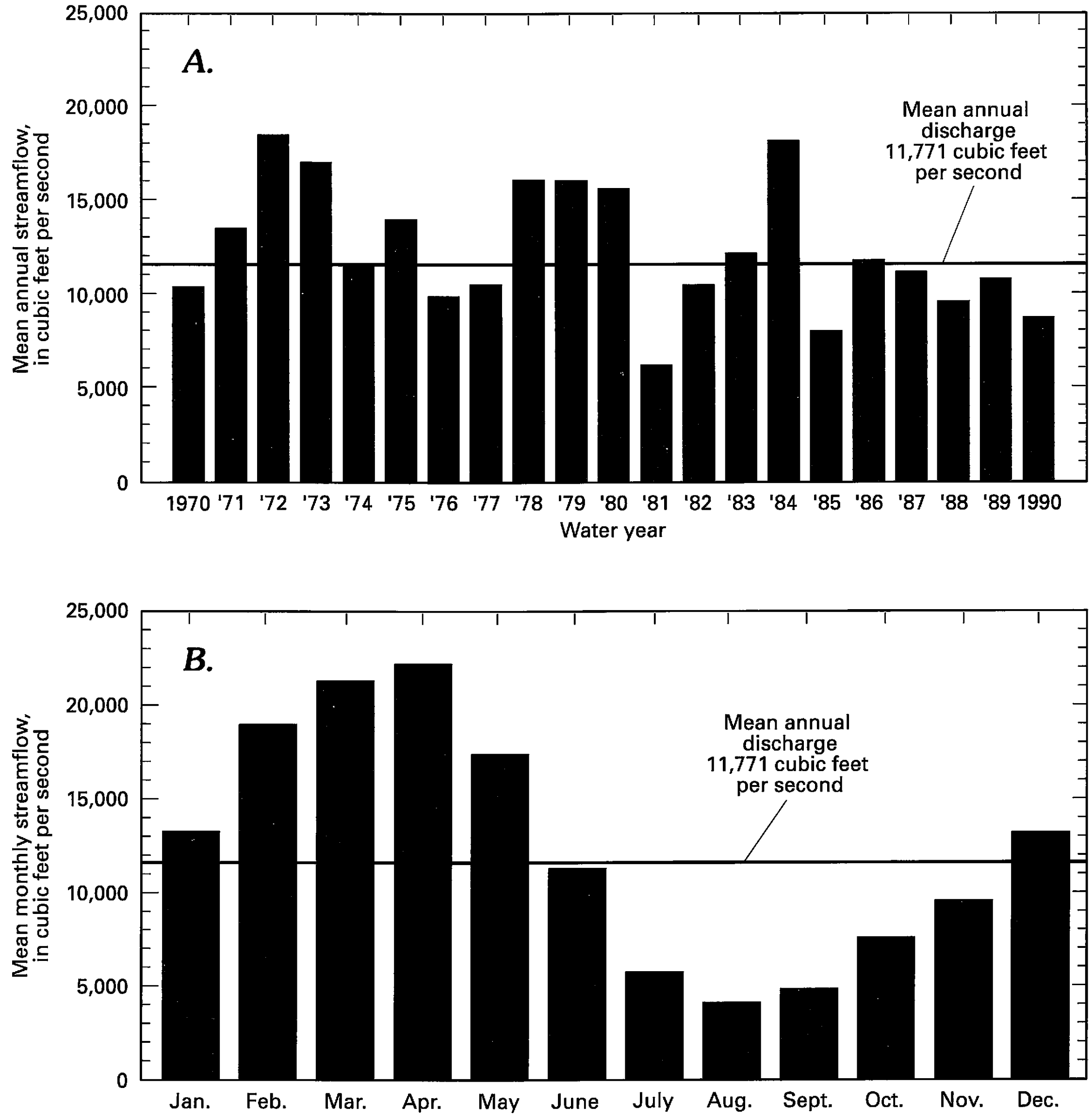


Figure 11. (*A*) Mean annual and (*B*) mean monthly streamflow in the Potomac River at Washington, D.C., 1970–90.

associated with them is conceptualized as a series of alternating aquifers and confining units. The uppermost sediment, which mantles the Coastal Plain, forms generally unconfined aquifers characterized by local ground-water flow systems and short flow paths. Regional confined aquifers subcrop beneath this surficial aquifer and are characterized by much longer flow paths. The Coastal Plain aquifers are capable of yielding large quantities of ground water, and many communities use ground water as their primary source of water.

The remainder of the basin may be divided into four hydrogeologic settings—Piedmont and Blue Ridge crystalline rocks, Piedmont sedimentary rocks, Valley and Ridge sedimentary rocks, and Appalachian Plateau sedimentary rocks. In all four settings water is stored primarily in and moves through secondary openings in consolidated rocks. Types of secondary openings that contain water include faults, joints, bedding-plane partings, stress-relief fractures, cleavage, and schistosity. In carbonate rocks, these openings may be enlarged further by dissolution of the rock matrix. In rocks that contain carbonate cementing material, the carbonate cement may be weathered away, resulting in intergranular porosity. The Appalachian Valleys-Piedmont Regional Aquifer-System Analysis Program (Swain and Holly, 1991) identified local and intermediate ground-water flow systems for

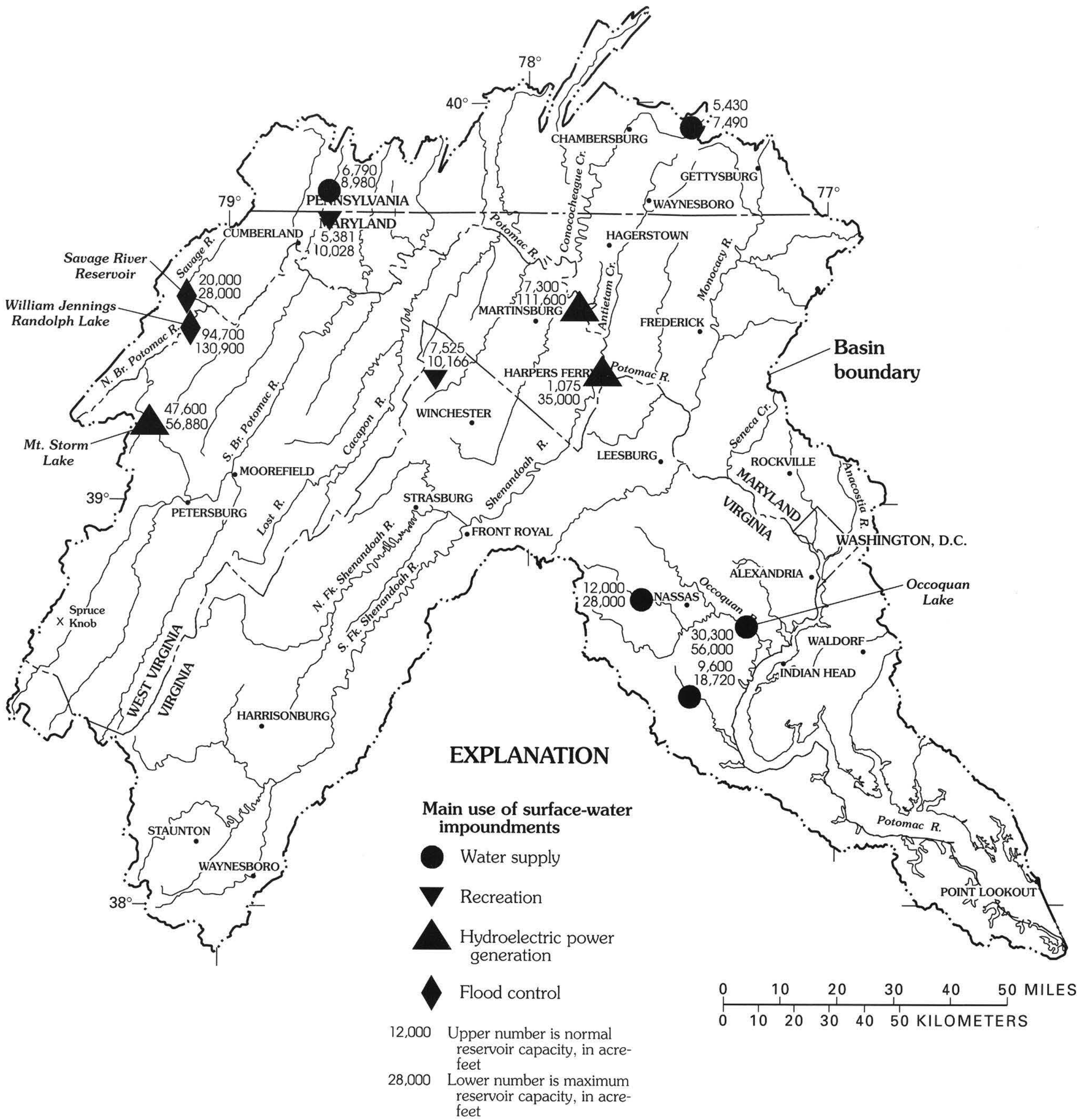


Figure 12. Location of major surface-water impoundments in the Potomac River Basin.

the Piedmont and Blue Ridge crystalline rocks, Piedmont sedimentary rocks, and the Valley and Ridge sedimentary rocks and described conceptual flow systems for each. The following section summarizes those flow systems.

In the Piedmont and Blue Ridge crystalline rock setting, well yields commonly range from 5 to 35 gal/min. The upper limit of well yields is relatively low compared with the sedimentary rock settings because secondary openings in crystalline rocks are not as likely to be enlarged by dissolution. Regolith, which may have a porosity several orders of magnitude greater than the underlying competent rock, is a critical component of the ground-water flow system because much of the ground water in this setting is stored in it. This stored water maintains base flow in streams during dry periods and is available to fractures in the underlying rocks to maintain water levels and ground-water flow in crystalline aquifers (Trainer and Watkins, 1975). Because of the small storage capacities of crystalline aquifers, regolith acts to sustain yields when recharge from precipitation is not adequate to meet demand in areas where wells yield moderate to large quantities of water. In areas with little or no overlying regolith, well yields can only be sustained if extensive fracture networks are present. Crystalline aquifers often are anisotropic because fractures, bedding-plane partings, and foliation tend to be preferentially aligned, creating heterogeneity in the permeability distribution of the rocks.

In the Piedmont sedimentary setting, ground water is stored and transmitted in both primary and secondary openings, with most water present in secondary openings. Well yields range from 5 to 1,500 gal/min, with the highest yields being from relatively deep wells that are located to obtain maximum quantities of water. Preferential ground-water flow along bedding strike is typical of these rocks and probably is caused by the fracturing characteristics of individual beds within the sedimentary sequence. Intrusive and extrusive igneous rocks within the sedimentary sequence yield little water and locally may impede ground-water flow.

In the Valley and Ridge, fracturing and dissolution have produced substantial secondary permeability in the upper 300 ft of rocks. Wells in this setting yield from 5 to 500 gal/min, with wells that encounter solution cavities having the greatest yield. Ground-water flow in the region is restricted by the parallel ridges common in this setting. The relation of streams to topography causes many adjacent, but hydraulically isolated, shallow flow systems. Ground water flows from ridge to adjacent valley until it either discharges to local streams or is intercepted and directed down-valley by a layer of rocks with well-developed secondary permeability. Such interception is probably common in the Great Valley subprovince where there are extensive carbonate aquifers.

The combination of geology and topography produces both local and regional ground-water flow systems in the Appalachian Plateau (Carswell and Bennett, 1963). Rock units in this setting are relatively flat-lying and consist of alternating beds of sandstone, shale, and coal. Topographically, the area is a relatively uniform upland that has been dissected by a network of stream valleys that act as local discharge areas for ground water. As ground water is recharged in the uplands and moves through the system, it tends to move vertically in fine-grained units and laterally towards valleys in coarse-grained units. As water moves progressively deeper in the system, lateral movement in the coarse-grained units may cause water to bypass local streams to discharge to larger, higher order streams. Past and present mining operations alter the ground-water flow system by dewatering sections of aquifers in the vicinity of mines and changing ground-water flow directions in parts of the aquifer not dewatered (Hobba and others, 1972; Duigon and Smigaj, 1985). Well yields in the Appalachian Plateau range from 2 to 250 gal/min.

Ground-Water/Surface-Water Interactions

Precipitation in the Potomac River Basin eventually becomes streamflow by overland runoff, which is controlled by surface and near-surface processes, and by base flow, which is controlled by subsurface processes. Overland runoff is delivered to streams over short time periods and may constitute the majority of streamflow during and shortly after storms. Base flow is delivered to streams by ground-water discharge through the streambed and maintains streamflow between storms. The time it takes for precipitation to flow through the ground-water system and become base flow may range from days to years, depending on conditions in the aquifer and the location of recharge. Ground-water discharge usually is highest in the spring, declines through the growing season, and is at a minimum in the fall.

In headwater areas, the ground-water flow system may not be able to maintain streamflow through extended dry periods, with the result that some headwater streams may cease flowing during the summer and fall. Even in higher order streams in the basin there may be reaches where the ground-water flow system ceases to contribute water to the streams. In these areas, hydraulic potential in the surface-water system is greater than that in the ground-water system, and water flows from the stream to the ground-water flow system. These losing stream reaches typically occur in areas underlain by carbonate rocks and at topographic and structural discontinuities. Perhaps the most dramatic example of this phenomenon is the Lost River, which loses its flow entirely to the subsurface and emerges again 2 mi downstream as the Cacapon River. Other examples occur along the western slopes of the Blue Ridge Province. As streams flow from the steep crystalline terrain of the Blue Ridge Province onto the flat carbonate rocks of the Great Valley subprovince, they lose large quantities of streamflow to the carbonate aquifers (Nutter, 1973).

Although losing reaches of streams are important locally, most of the streams in the Potomac River Basin are gaining streams in that they receive water from the ground-water flow system. Total streamflow and the relative proportions of overland runoff and base flow vary somewhat throughout the basin. In general, streams in the Appalachian Plateau and Valley and Ridge Provinces and in the part of the Piedmont Province underlain by crystalline rocks receive about one-half their flow from base flow, with overland runoff constituting the other half (Hobba and others, 1972; Duigon and Dine, 1987, 1991). In basins containing carbonate rocks and in basins with substantial regolith, base flow may constitute as much as 65 percent or more of the total streamflow (Nutter and Otton, 1969; Trombley and Zynjuk, 1985; Duigon and Dine, 1991). Total streamflow per unit area is highest in the Appalachian Plateau Province and lowest in the Valley and Ridge Province, reflecting precipitation patterns in the region (Hobba and others, 1972). In basins underlain almost entirely by carbonate rocks, such as in the Great Valley subprovince, and in basins in the Coastal Plain Province, streams derive more than 80 percent of their flow from base flow, reflecting the high storage capacity of these materials (Johnston, 1976; Becher and Taylor, 1982; Duigon and Dine, 1987). In contrast, base flow comprises only about 35 percent of total streamflow in the part of the Piedmont underlain by sedimentary rocks of Triassic and Jurassic age (Wood, 1980; Duigon and Dine, 1987).

Subunits for Water-Quality Assessment

Because of the diverse physical characteristics of the Potomac River Basin, it has been divided into eight subunits for the purposes of water-quality assessment. This subdivision was done using a hierachical process considering basin physiography and geology (fig. 13). Physical and geologic characteristics provide the primary factors affecting the hydrologic properties of the ground-water and surface-water systems and, thus, form the primary natural factors affecting water quality within the basin. Physiographic provinces and subprovinces are used as the primary units of the subdivision because of their structural effects on the hydrologic systems. Lithology is used as the secondary basis for subdivision due to its effects on ground-water flow and water quality. The eight subunits will be referred to throughout this report and will serve as the primary basis for areal comparisons of nutrient concentrations and loads in later sections. Additionally, these subunits will be used throughout the course of the NAWQA Program's assessment of water quality in the Potomac River Basin.

The Appalachian Plateau subunit, comprising 4 percent of the total area of the Potomac River Basin, is composed primarily of siliciclastic rocks, so it is considered to be one subunit.

The Valley and Ridge subunit is underlain by both siliciclastic and carbonate rocks and occupies 34 percent of the total basin area. Some of its carbonate rocks are interbedded with siliciclastic rocks, and some of its siliciclastic rocks are cemented by carbonate material. This interbedding is characteristic of the region. In these settings, ground water moves among beds of differing rock types, and surface water flows through both rock types. Thus, the Valley and Ridge subunit is not differentiated with respect to rock type. The Valley and Ridge subunit also includes an outlier, Massanutten Mountain, in the Great Valley subprovince, which is similar in topography and lithology to that of the Valley and Ridge.

The Great Valley subprovince is divided into a carbonate subunit (17 percent of the basin) and a noncarbonate subunit (5 percent of the basin) because carbonate regions have unique hydrologic properties and because the carbonate units are areally contiguous and extensive. The carbonate subunit is composed of limestone and dolomite of Cambrian and Ordovician age. An outlier of the Great Valley Carbonate subunit is in the Piedmont, in the vicinity of Frederick, Maryland. This small region is more similar to the Great Valley Carbonate subunit than the surrounding Piedmont. The Great Valley Noncarbonate subunit is underlain by shale of the Martinsburg Formation in the central part of the Great Valley subprovince.

The Blue Ridge subunit, comprising 6 percent of the basin, is formed by crystalline rocks. It is a separate subunit based on its high topographic position, which affects the ecological characteristics of the subunit.

The Piedmont subunit (12 percent of the basin) comprises the crystalline rock part of the Piedmont Province. As in the Blue Ridge subunit, the rocks underlying this subunit are crystalline. However, the rolling topography of this subunit provides a distinct hydrologic setting.

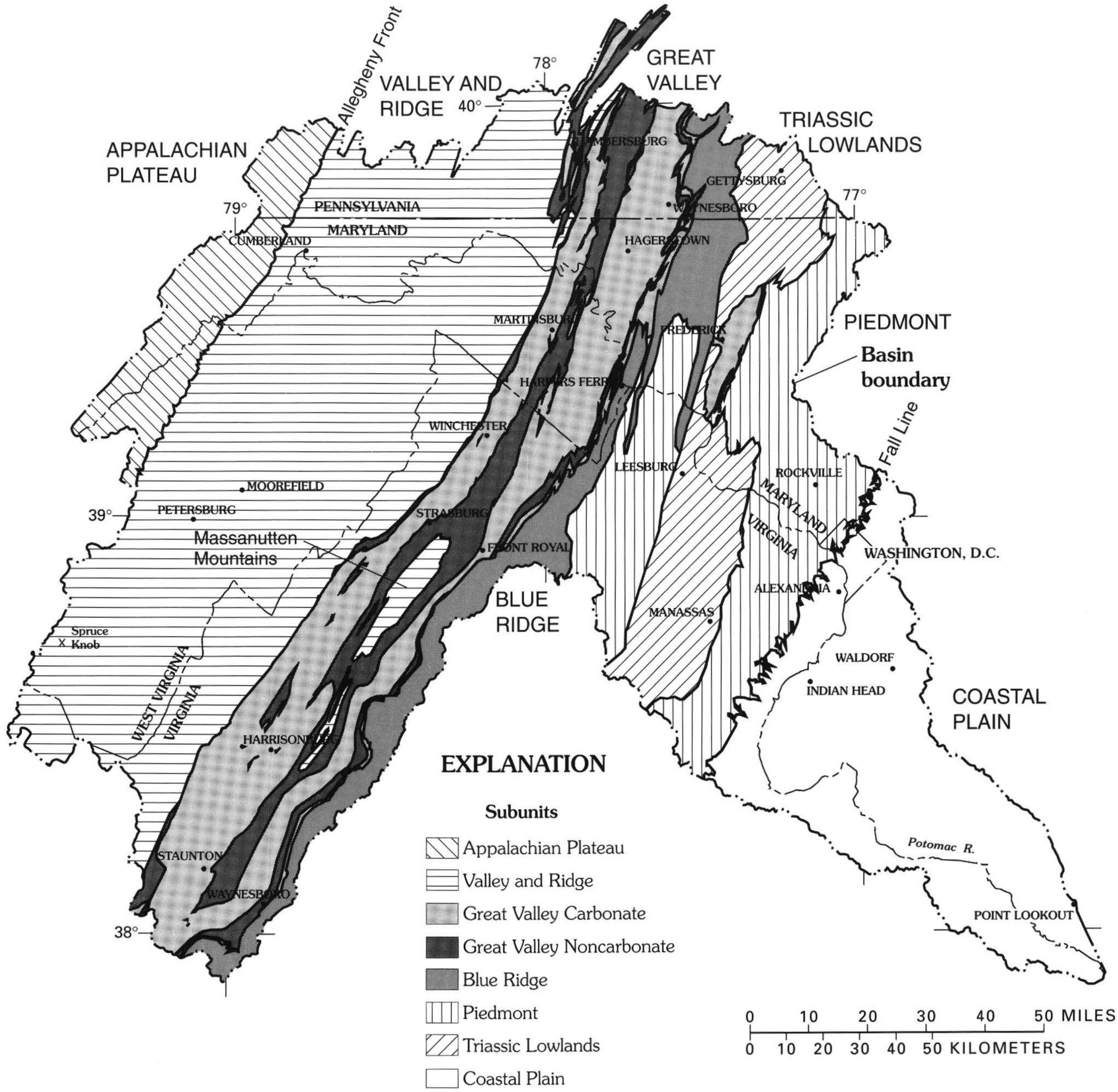


Figure 13. Division of the Potomac River Basin into subunits for the purpose of water-quality assessment.

The Triassic Lowlands subprovince is underlain by poorly indurated siliciclastic rocks and intrusive and extrusive igneous rocks. The igneous rocks are not used extensively for ground-water supply, and the effect of these rocks on surface-water chemistry probably is insignificant at the basin scale. Therefore, the Triassic Lowlands are considered to be one subunit (7 percent of the basin).

The Coastal Plain subunit (15 percent of the basin) is underlain by unconsolidated sediment. The hydrologic factors affecting ground-water and surface-water flow in this subunit are unique within the Potomac River Basin.

ANALYSIS OF AVAILABLE NUTRIENT DATA

Data on concentrations and sources of nitrogen and phosphorus in the Potomac River Basin have been compiled for this report from numerous references and data sources. The analysis of these data provides an understanding of the status of water quality in the basin with respect to these nutrients. Also, the compilation and analysis on the basin scale identify the data and information gaps that exist. The information included here will be used by the NAWQA Program in two ways—(1) to contribute to understanding conditions throughout the Nation and (2) to provide guidance for data collection and analysis in the study of the Potomac River Basin.

Nitrogen and phosphorus are two nutrients essential to the growth of plants and animals; however, high concentrations of these nutrients in ground water and surface water are of concern throughout the Potomac River Basin due to potential adverse effects on human health and aquatic life. Eutrophication caused by high nitrogen and phosphorus concentrations has been a problem in the tidal reaches of the Potomac River. The nitrogen and phosphorus causing this problem are delivered to the tidal Potomac from its network of tributaries that transects the eight diverse subunits of the Potomac River Basin. Sources of nitrogen and phosphorus differ across the basin, and available data are used to describe the spatial patterns in nutrient sources. These sources are used to explain and understand the patterns of nutrient concentrations found in ground water and surface water throughout the basin.

Methods

Estimates of Nutrient Inputs

Estimates of nitrogen and phosphorus inputs to the Potomac River Basin were made for point-source inputs to surface water from municipal and industrial discharges and for nonpoint-source inputs to the land surface from atmospheric deposition, commercial fertilizer, animal manure, and septic systems. Computer data bases with information on point-source discharges, population, land use, and agricultural practices were used with a geographic information system to make these estimates for the eight subunits of the Potomac River Basin and selected watersheds within the basin.

Information on municipal and industrial point-source inputs to streams was obtained from two national computerized data bases and from information provided by State and regional agencies. The computer data bases included the National Pollutant Discharge Elimination System/Permit Compliance System (NPDES/PCS) and the U.S. Environmental Protection Agency (USEPA) STORET data base. The PCS data retrieval included 271 facilities. Data on geographic locations were available for only 90 of the facilities. The STORET data retrieval included design flows and locations for 634 wastewater-treatment facilities, of which 70 also were included in the PCS data base. Only 242 municipal water-treatment facilities and 175 industrial facilities were included in the analysis of point sources. Facilities that contribute negligible amounts of nitrogen and phosphorus to effluent, such as powerplants and coal mines, were not included in the analysis. Discharges for the facilities in the PCS that could not be located are relatively minor and were not included in estimates of point-source loads. Lugbill (1990) was used to verify major point sources in the basin. Additional point-source information was provided by the Interstate Commission on the Potomac River Basin (ICPRB) (Carlton Haywood, Interstate Commission on the Potomac River Basin, written commun., 1994) and Maryland Department of the Environment (MDE) (Peter Legg, Maryland Department of the Environment, written commun., 1994).

Information on nutrient discharges was insufficient in any one data base to compute nutrient inputs for the entire basin. When actual concentrations and loads data in the PCS were insufficient, point-source inputs were determined by relating Standard Industrial Codes (SIC) to average concentrations of nitrogen and phosphorus in effluent. Lugbill (1990) compiled average concentrations of nutrients by SIC from previous work by the National Oceanic and Atmospheric Administration. Average concentrations for SIC's not included in Lugbill's tabulation were estimated by referring to similar industries. Total input was obtained by multiplying average concentrations and best estimates of facility flow rates. For 83 facilities, measured flows were available from the PCS and were used to estimate nutrient inputs. A comparison of these measured flows with design flows for the facilities showed that design flows are generally a good estimate of plant discharge, except for certain industries that are particularly susceptible to economic cycles, such as processing of primary metals. For 504 facilities, design flows were the best estimate available and were used to estimate nutrient loadings. No flow information was available for 56 facilities; flow rates for these facilities were considered to be minor and were assumed to be zero. The information provided by MDE and ICPRB was used to adjust concentration and flow data where computer data were missing, outdated, or unreasonable.

Nonpoint-source nutrient inputs to the land surface in the basin were computed and apportioned to basin subunits and selected watersheds using a geographic-information-system data base with the distribution of land use and population within subunit and basin boundaries. Land-use and land-cover data were obtained from the Geographic Information Retrieval and Analysis System (GIRAS) (Mitchell and others, 1977), which mapped land-use and land-cover data obtained from aerial photographs taken between 1972 and 1974. Although these data are not up to date, they do provide a good approximation of the general distribution of land use and land cover. The 1990 Census of Population and Housing (U.S. Department of Commerce, 1991e) and the 1987 Census of Agriculture (U.S. Department of Commerce, 1989) were used to identify areas of land-use and land-cover change.

The extent of orchard, forest, and water areas in the GIRAS data was assumed to be similar to 1990 conditions. It was also assumed that no net changes have occurred in the distribution of industrial land uses as these changes would have a relatively small effect on nonpoint-source inputs. Residential and commercial land uses were assumed to increase proportional to population but not to decrease in the case of population decrease. Other urban land uses were assumed to not change significantly over the time period considered.

Determining the distribution of agricultural lands used for crop and animal production, however, required a more complex approach. The 1987 Census of Agriculture (U.S. Department of Commerce, 1989) provided estimates of crop and pasture acreage and animal populations on a total county basis. GIRAS data were assumed to be representative of the areal distribution of cropland and pasture within counties, and it was assumed that crops, pasture, and animals were uniformly distributed within a county. Animal distributions were assumed to follow the distribution of cropland and pasture. Thus, the acreage of particular crops and the number of animals were based on actual 1987 census data, whereas the geographic distribution within counties and among subunits and selected watersheds was based on GIRAS mapping.

Inputs of nitrogen and phosphorus from application of commercial fertilizer to agricultural lands were estimated directly from county sales data, weighted by the percentage of a county's cropland in subunits and watersheds.

Nutrient inputs from manure were estimated by multiplying average concentrations for different animals by the number of animals from the 1987 Census of Agriculture. Nutrient concentrations in manure differ with different animals, as does mass production of nutrients. Animal manure may undergo several processes that may result in significant changes in nitrogen and phosphorus between the time it is excreted by animals and the time that it is applied to land surfaces. These processes are not addressed in this report but should be considered further in a more detailed analysis of nutrient cycling.

Nutrient inputs from septic systems were estimated using 1990 population data because the number and distribution of septic systems in the Potomac River Basin had not been mapped at the time of this analysis. The geographic distribution and number of people using septic systems were estimated by visually clustering 1990 census tracts around municipal centers and likely adjoining utility corridors. All population within these census-tract clusters was assumed to be serviced by municipal wastewater-treatment plants. Any other population was assumed to be on septic systems.

Reckhow and others (1980) compiled nutrient loadings for household wastewater discharged into septic tanks. In a review of seven studies, total nitrogen loadings ranged from 1.92 to 7.31 (lb/person)/yr, with a median value of 4.11 (lb/person)/yr. In eight studies, total phosphorus loadings ranged from 0.66 to 2.68 (lb/person)/yr, with a median of 1.33 (lb/person)/yr. To estimate septic inputs, these median values were multiplied by the population determined to be on septic systems.

Atmospheric inputs of nitrogen were estimated using data from the five USGS National Trends Network (NTN) monitoring sites located nearest to the Potomac River Basin. Total wetfall data available for water years 1980, 1985, and 1990 at these sites are tabulated below. Nitrogen deposition rates may differ significantly from year to year. The 1990 estimates used for estimation were the median of the three years at Parsons, West Virginia, and Leading Ridge, Pennsylvanian. The 1990 inputs were slightly higher than 1985 inputs at the three other sites. Also, the 1990 annual streamflow in Potomac River at Washington, D.C., was below average. Thus, precipitation and wet deposition in 1990 may be slightly less than the long-term average.

National Trends Network monitoring site	Nitrate and ammonia in wet deposition as nitrogen (pounds per acre)		
	1980	1985	1990
Parsons, W. Va.	7.05	2.16	3.35
Shenandoah National Park, Va.	---	2.83	3.36
Charlottesville, Va.	---	3.12	3.30
White Rock, Md.	---	3.23	3.24
Leading Ridge, Pa.	5.91	3.85	4.01

Dryfall loadings of nitrogen are difficult to determine, and there are little data available from monitoring programs. Estimates of nitrogen dryfall were made using a procedure suggested by Sisterson (1990) in which average ratios of dryfall to wetfall were determined for each State. These ratios were used to estimate a dryfall loading at each NTN site.

Adjustments were made to wetfall estimates because Sisterson (1990) found that wetfall in some areas exceeds that which would be indicated by interpolation from the NTN sites. In forested areas above about 2,600 ft in elevation in the eastern United States, Sisterson (1990) determined that direct contact with low clouds (fog) accounts for about three times as much deposition of nitrogen as monitored wetfall. In urban areas, the proximity of atmospheric-source generators, such as fossil-fuel powerplants, results in increases in loadings through wetfall and dryfall by factors of 1.75 and 5.0, respectively. In estimating total-nitrogen loadings from atmospheric deposition for areas in the Potomac River Basin, adjustments were made for both the extent of urban area and the area in forest above 2,600 ft in elevation. Urban areas were determined using the 1972–74 land-use and land-cover data, which were updated using 1990 Census of Population data (U.S. Department of Commerce, 1991e). Wetfall and dryfall nitrogen inputs were apportioned to subunits and watersheds by weighting data from the monitoring sites by the distance to a point in the center of the subunit or watershed segment. Adjustments were made on the basis of percentage of the area higher than 2,600 ft and the percentage of urban area.

Analysis of Nutrient Concentrations

Patterns in nutrient concentrations in the Potomac River Basin are presented in this report using graphical and statistical summaries of data compiled from the USGS WATer STOrage and REtrieval system (WATSTORE) and the U.S. Environmental Protection Agency STORET data system. Five forms of nitrogen and phosphorus are discussed, including total nitrogen, dissolved nitrate, dissolved ammonia, total phosphorus, and dissolved orthophosphate. Concentrations are in equivalent weights of nitrogen and phosphorus. The analysis of nutrient concentrations in ground water utilizes only data from the USGS WATSTORE system because well-depth and water-quality records were more complete. The analysis of concentrations in surface water relies on data from both WATSTORE and STORET data systems.

Twenty-five surface-water-quality monitoring sites are used to describe the spatial and temporal variability in nutrient concentrations throughout the basin. These sites were selected from a large number of sites that were located near continuous streamflow-monitoring stations and had a minimum of 50 samples. The 25 sites were chosen to represent a broad range of physiographic and land-use settings. At several sites both USGS and State monitoring programs are co-located, and the data from both programs are analyzed separately at these sites.

In general, sample collection at the State sites is done by collecting a single-vertical surface grab sample, whereas most samples collected by the USGS utilize depth- and width-integrated sampling methods using isokinetic sampling devices. Surface grab samples have been shown to underrepresent average instream concentrations of total nitrogen and total phosphorus because particulate matter is not evenly distributed throughout the water column. However, dissolved species of both nitrogen and phosphorus should be comparable from either sampling method (Martin and others, 1992).

The data-analysis procedures used in this report generally rely on graphical descriptions and robust statistical tests. Graphical analysis used in this report includes maps, histograms, X-Y plots, smoothed curves, and boxplots. Graphics are used to show the general pattern in the observed data and are not rigorous statistical tests. Nonparametric statistical tests are used to discern statistical significance in the observed patterns in order to minimize the need to satisfy distributional parameters of parametric tests. Estimates of nutrient loads, however, are determined using a fully parametric regression method. Therefore, data used for load estimation were screened rigorously before inclusion in this report.

The primary graphical method used to display patterns in the distribution of data is the boxplot. Boxplots used in this report display the 25th, 50th, and 75th percentiles as lines joined to form a box. Whiskers are drawn to the 10th and 90th percentiles. The size, shape, and central tendency of groups of data can be readily compared when plotted against the same vertical axis. Truncated boxplots, where whiskers are not shown, indicate clustering of values within the 25th to 75th percentile range. Also included in all boxplots is the number of data points used to construct the box and, where applicable, the number of censored values within the distribution. However, 20 percent of the distribution is not shown, and any outlier values, whether accurate or in error, are excluded.

A locally weighted sum of squares (LOWESS) is used to display the patterns of nutrient concentrations with respect to continuous variables. The LOWESS curve is used to show the relation of nutrient concentrations to well depth and streamflow. LOWESS is used to adjust concentrations for the effects of streamflow when presenting long-term trends in nutrient concentrations.

Streamflow values used throughout this report are mean daily discharge values as published in the annual data reports of the USGS. Mean daily discharge is used instead of instantaneous measurements because it is readily available for all stations, calculation of flow duration is simplified, and load-estimation programs use mean daily discharge values. Mean daily flow-duration percentages were determined for water years 1970 to 1990 and are used to graphically display the concentration-streamflow relation at many stations using a single coordinate system. Higher streamflow values correspond with lower frequency percentages, which indicate rarer events.

Annual loads of total nitrogen, dissolved nitrate, and total phosphorus were estimated where possible using the Minimum Variance Unbiased Estimator (MVUE) program as described in Cohn and others (1992). To achieve a linear model, both explanatory and response variables were transformed. The MVUE program estimates the log of load using the following variables: constant, log of discharge, log of discharge squared, time, time squared, sine of time, and cosine of time. In the load-estimation model, the discharge variables account for the effect of streamflow, the time and time squared variables account for the occurrence of trends, and the sine and cosine variables account for seasonal fluctuations in loads. All seven parameters were used for all estimates of load with no attempt to exclude parameters because of lack of significance. In most cases, probability values for discharge and time were less than 0.20 for the regression model. Using less significant parameters in the model, however, only serves to increase the error of the estimate and does not significantly affect the predicted load (T.A. Cohn, U.S. Geological Survey, oral commun., 1992). The MVUE program estimates daily loads on the basis of daily values of discharge data. Daily loads are summed to estimate monthly and annual estimates of load. Standard errors for daily load estimates are quite high; however, the cumulative error of monthly and annual estimates yields a fair degree of confidence in the estimated values. This report presents only estimates of annual loads. Average annual loads are calculated for the period of load estimation, which differs from site to site.

Prior to load estimation, all linear-regression models were first evaluated through independent model testing and development. Each observation used in all models was tested for measures of influence and leverage, as described in Helsel and Hirsch (1992). Insufficient data and outlier values proved to be the greatest obstacles to load estimation. Because of the distribution of samples with respect to time for all water-quality monitoring sites, a core period of water years, 1979–89, was chosen for load estimation. However, data were insufficient during this period for many sites, and they were dropped from the analysis. Loads were estimated at four additional sites for different periods. Outlier values were reviewed individually for reasonableness. Some values were obviously entered in error and could be excluded from the data set. Other values were not easily rejected, and where the model was still unstable and highly sensitive to these values, no load estimation was done.

Nutrient Sources

Estimates of nutrient sources to the entire Potomac River Basin in 1990 show the magnitude and relative importance of different sources to the basin. However, patterns in land use, land cover, and topography cause nutrient sources to differ among major subunits and watersheds in the basin. Nonpoint sources of nitrogen and phosphorus account for nutrients reaching the land surface with the potential to enter the ground-water system. Thus, patterns in nonpoint sources in subunits may be related to patterns in nutrient concentrations in ground water within basin subunits. Point-source nutrient inputs are discharged directly to surface water, and nutrient concentrations in surface water are dependent upon point and nonpoint sources of nutrients.

Basinwide Inputs

The occurrence of nutrients in surface and ground water throughout the Potomac River Basin can be attributed to several major sources, including atmospheric deposition, commercial fertilizer, animal manure, municipal and industrial wastewater discharges, and septic systems. Figure 14 shows the nitrogen and phosphorus inputs from major sources for 1990. Atmospheric deposition is not considered a significant source of phosphorus.

Nitrogen inputs in the Potomac River Basin in 1990 were dominated by atmospheric deposition, animal manure, and commercial fertilizer application. Agricultural inputs comprised about 55 percent of the nitrogen input, and atmospheric inputs contributed 32.1 percent. Municipal and industrial wastewater discharges contributed about 12 percent of the nitrogen inputs. This percentage is significant, however, because discharges are made directly to streams and rivers. Nitrogen inputs from other sources are distributed throughout the watershed and are subject to numerous processes affecting their potential for entering the ground-water or surface-water systems.

Phosphorus inputs were dominated by agricultural sources throughout the basin, with about 93 percent of the phosphorus inputs coming from commercial fertilizer and animal manure. Municipal and industrial discharges contributed only 3.8 percent of the phosphorus, and as with nitrogen, these inputs were made directly to surface-water bodies.

The major sources of nitrogen and phosphorus differ significantly in the watershed upstream and downstream from Washington, D.C. The watershed draining to the streamflow-gaging station on the Potomac River at Washington, D.C., located at the Fall Line, generally is referred to as the upper Potomac River Basin. In 1990, atmospheric and agricultural inputs were the largest sources of nitrogen to the entire basin and the primary inputs in the upper Potomac. Commercial fertilizer and animal manure inputs occurred mostly in

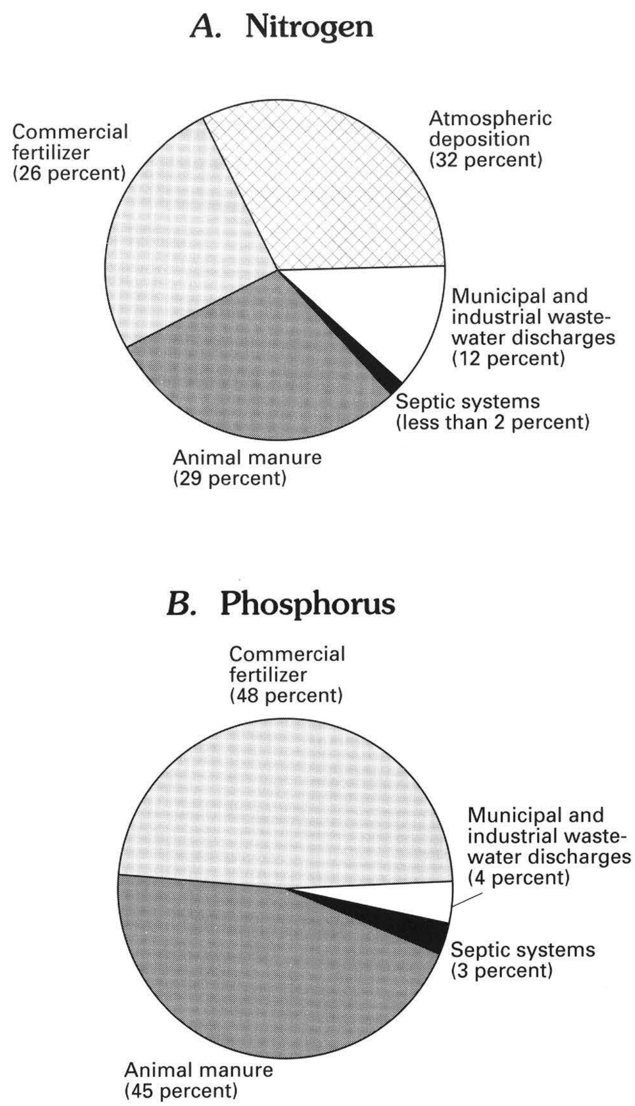


Figure 14. Major inputs of (*A*) nitrogen and (*B*) phosphorus to the Potomac River Basin, 1990.

the agricultural regions of the upper Potomac Basin. Municipal wastewater discharge was the largest nutrient source downstream from the Fall Line, and 88 percent of the basin discharges of nitrogen and 80 percent of the discharges of phosphorus occur downstream from Washington, D.C.

Several studies have estimated nutrient inputs to the Potomac River and Chesapeake Bay Basins. Smullen and others (1982) estimated point-source inputs of nitrogen from wastewater treatment and industrial processes. Lugbill (1990) prepared a comprehensive inventory of nutrient sources in the Potomac River Basin using published statistics. Fisher and Oppenheimer (1991) studied the relative contribution of atmospheric sources to nitrogen loadings to the

Chesapeake Bay. Their estimations of nitrogen loadings to the Chesapeake Bay for various sources have been simply multiplied by the percentage of the Bay basin that is included in the Potomac River Basin upstream from the Fall Line for comparison with this study. This approach probably overestimates nitrogen from municipal wastewater because most of the wastewater discharges in the Potomac River Basin occur downstream from the Fall Line. Jaworski and others (1992) expanded on both of the previous studies and prepared a nitrogen balance for the Potomac River Basin upstream from the Fall Line. The results of these investigations are compared with the results of this study in table 3.

Total nitrogen inputs estimated in this study are less than the total inputs from the three other comprehensive studies. Jaworski and others (1992) estimates for 1983–86 were highest and 15 percent higher than this study. There are notable differences among studies in the magnitudes of input from atmospheric deposition and manure in table 3. These studies compiled data from different sources and made different assumptions pertinent to their objectives. Although the studies used different approaches to estimating atmospheric deposition, the controlling factor for differences appears to be that nitrogen concentrations in wetfall were higher during the time periods used by earlier studies. Jaworski and others (1992) used estimates of raw manure inputs from Lugbill (1990), and Lugbill further reduced raw inputs to account for losses of nitrogen due to environmental factors. Manure-input estimates presented in this report are not reduced for losses, and atmospheric-deposition inputs are based on more recent data. All studies concluded that atmospheric deposition, commercial fertilizer, and animal manure account for most of the nitrogen input to the Potomac River Basin.

Distribution in Subunits

The magnitude and relative contributions of nitrogen and phosphorus sources differ considerably among the eight subunits of the Potomac River Basin. Estimated inputs of nitrogen and phosphorus to subunits are shown in tables 4 and 5. Within each subunit, nonpoint-source inputs are distributed in proportion to land use and account for about 88 percent of nitrogen input and 96 percent of phosphorus input to the entire basin. Figure 15 indicates the proportions and magnitudes of principal nonpoint-source nutrient inputs to the eight subunits in the Potomac River Basin. The largest nitrogen inputs occur in the Valley and Ridge and Great Valley Carbonate subunits. The largest phosphorus inputs occur in the Great Valley Carbonate subunit. The figure also shows that the proportional contribution by input sources differs considerably among subunits. With reference to tables 3 and 4 and

Table 3. Comparison of nitrogen input estimates to the Potomac River Basin upstream from Washington, D.C., from several studies

[--, inputs not estimated]

Source of inputs	Nitrogen input estimates by principal investigator and base year(s), in thousands of pounds				
	Smullen and others (1982)	Fisher and Oppenheimer (1991)	Lugbill (1990)	Jaworski and others (1992)	This study
	1980	1984	1986	1983–86	1990
Point sources:					
Sewage treatment	4,777	16,493	3,185	6,836	5,621
Industrial processes	1,911	*[1]	3,304	*[1]	1,590
Nonpoint sources:					
Atmospheric deposition	--	94,340	122,774	87,098	76,403
Commercial fertilizer	--	63,334	55,790	50,715	66,574
Animal manure	--	78,507	72,252	134,946	83,907
Septic systems	--	--	--	--	3,938
Total	--	252,674	257,305	279,595	238,033

[1]Sewage treatment and industrial processes were combined.

Table 4*A*. Estimated point-source inputs of nitrogen by subunits of the Potomac River Basin, 1990

[All point-source inputs are in thousands of pounds]

Subunit (fig. 13)	Point sources		
	Municipal sewage treatment	Industrial processes	Total
Appalachian Plateau	78	179	257
Valley and Ridge	854	82	936
Great Valley Carbonate	2,052	611	2,663
Great Valley Noncarbonate	1,259	703	1,962
Blue Ridge	62	0	62
Piedmont	2,120	118	2,238
Triassic Lowlands	1,731	9	1,740
Coastal Plain	25,687	355	26,042
Potomac River Basin, total	**33,843**	**2,057**	**35,900**

Table 4*B*. Estimated nonpoint-source inputs of nitrogen by subunits of the Potomac River Basin, 1990

[All nonpoiint-sources inputs are in thousands of pounds. Agricultural estimates are based on 1987 statistics (U.S. Department of Commerce, 1989)]

Subunit (fig. 13)	Area (square miles)	Nonpoint sources				
		Atmospheric deposition	Commercial fertilizer	Animal manure	Septic Systems	Total
Appalachian Plateau	660	7,403	895	799	68	9,165
Valley and Ridge	5,062	35,155	8,523	16,327	1,047	61,052
Great Valley Carbonate	2,220	11,327	25,139	43,232	1,516	81,214
Great Valley Noncarbonate	930	4,699	6,581	10,658	581	22,519
Blue Ridge	919	5,669	2,597	1,937	395	10,598
Piedmont	1,771	12,485	15,729	6,224	293	34,731
Triassic Lowlands	1,018	5,869	10,157	6,363	77	22,466
Coastal Plain	2,090	13,952	7,424	1,265	691	23,332
Potomac River Basin, total	**14,670**	**96,559**	**77,045**	**86,805**	**4,668**	**265,077**

figure 15, the distribution of nutrient sources and potential for water-quality effects from the principal input sources are discussed in the following paragraphs.

In the Potomac River Basin in 1990, 73 percent of the population resided in the Piedmont and Coastal Plain subunits. Municipal wastewater-treatment discharges in these subunits comprised 82 percent of the nitrogen and 49 percent of the phosphorus from wastewater in the Potomac River Basin. Because the largest treatment facilities are downstream from the Fall Line, most of the treated sewage discharges were directly to the tidal reach of the Potomac River in the Coastal Plain subunit. These treated discharges provided 11 percent of the total nitrogen input and 3 percent of the total phosphorus input to the Potomac River Basin. Wastewater discharges are particularly significant to the tidal Potomac River and estuary because they are mostly direct discharges to the estuary or tidal streams where the potential for eutrophic conditions to develop is high.

In most subunits, industrial discharges provide proportionally small inputs of nitrogen and phosphorus. Industrial inputs are largest in the two Great Valley subunits. Industrial discharges are small in the Blue Ridge and Triassic Lowlands subunits.

Nitrogen inputs from atmospheric deposition are distributed throughout the Potomac River Basin, with an estimated basinwide deposition rate of 6,582 lb/mi^2 for 1990. However, because of increased capture of fog droplets by trees at higher elevations, those areas with extensive forest cover account for much of the nitrogen input from atmospheric deposition. Atmospheric deposition rates are highest in the Appalachian

Figure 5*A*. Estimated point-source inputs of phosphorus by subunits of the Potomac River Basin, 1990

[All point-source inputs are in thousands of pounds]

Subunit (fig. 13)	Point sources		
	Municipal sewage treatment	Industrial processes	Total
Appalachian Plateau	19	54	73
Valley and Ridge	80	47	127
Great Valley Carbonate	292	189	481
Great Valley Noncarbonate	243	103	346
Blue Ridge	10	0	10
Piedmont	237	17	254
Triassic Lowlands	63	8	71
Coastal Plain	439	27	466
Potomac River Basin, total	**1,383**	**445**	**1,828**

Table 5*B*. Estimated nonpoint-source inputs of phosphorus by subunits of the Potomac River Basin, 1990

[All nonpoint-sources inputs are in thousands of pounds. Agricultural estimates are based on 1987 statistics (U.S. Department of Commerce, 1989)]

Subunit (fig. 13)	Area (square miles)	Nonpoint sources			
		Commercial fertilizer	Animal manure	Septic Systems	Total
Appalachian Plateau	660	276	221	22	519
Valley and Ridge	5,062	2,929	4,233	339	7,501
Great Valley Carbonate	2,220	7,775	10,531	490	18,796
Great Valley Noncarbonate	930	2,044	2,699	188	4,931
Blue Ridge	919	758	520	128	1,406
Piedmont	1,771	4,575	1,759	95	6,429
Triassic Lowlands	1,018	2,993	1,727	25	4,745
Coastal Plain	2,090	2,162	402	223	2,787
Potomac River Basin, total	**14,670**	**23,512**	**22,092**	**1,510**	**47,114**

Plateau at 11,217 lb/mi^2 because much of the forests are at elevations higher than 2,600 ft. Atmospheric inputs comprise 58 percent of the nonpoint sources of nitrogen to the Valley and Ridge subunit, although the average deposition rate is lower (6,904 lb/mi^2) as forest elevations are lower than in the Appalachian Plateau. The Piedmont subunit has the second highest deposition rate (7,050 lb/mi^2) due to the presence of larger urban areas. Atmospheric inputs of nonpoint-source nitrogen were also the predominant source of nitrogen in the Blue Ridge and Coastal Plain subunits.

Commercial fertilizer was an important source of nitrogen in subunits with extensive agriculture, including the Great Valley Carbonate, Great Valley Noncarbonate, Piedmont, Triassic Lowlands, and Coastal Plain subunits (fig. 15), and a major source of phosphorus in all subunits. Average basinwide fertilizer sales rates were 5,250 lb/mi^2 of nitrogen (table 4*B*) and 1,600 lb/mi^2 of phosphorus (table 5*B*). In the Appalachian Plateau, Blue Ridge, Piedmont, Triassic Lowlands, and Coastal Plain subunits, fertilizer contributed more than 50 percent of nonpoint-source phosphorus inputs as fewer nonagricultural sources of phosphorus exist. On a unit-area basis, however, those subunits with the highest nutrient-input rates from fertilizer were the Great Valley Carbonate, Triassic Lowlands, Piedmont, and Great Valley Noncarbonate, with average fertilizer sales rates of 11,300, 9,980, 8,880, and 7,080 lb/mi^2 of nitrogen and 3,500, 2,940, 2,580, and 2,200 lb/mi^2 of phosphorus, respectively.

Manure from animal-production activities was an important source of nitrogen and phosphorus in many subunits (fig. 15). Basinwide rates of manure input were 5,920 lb/mi^2 of nitrogen and 1,500 lb/mi^2 of

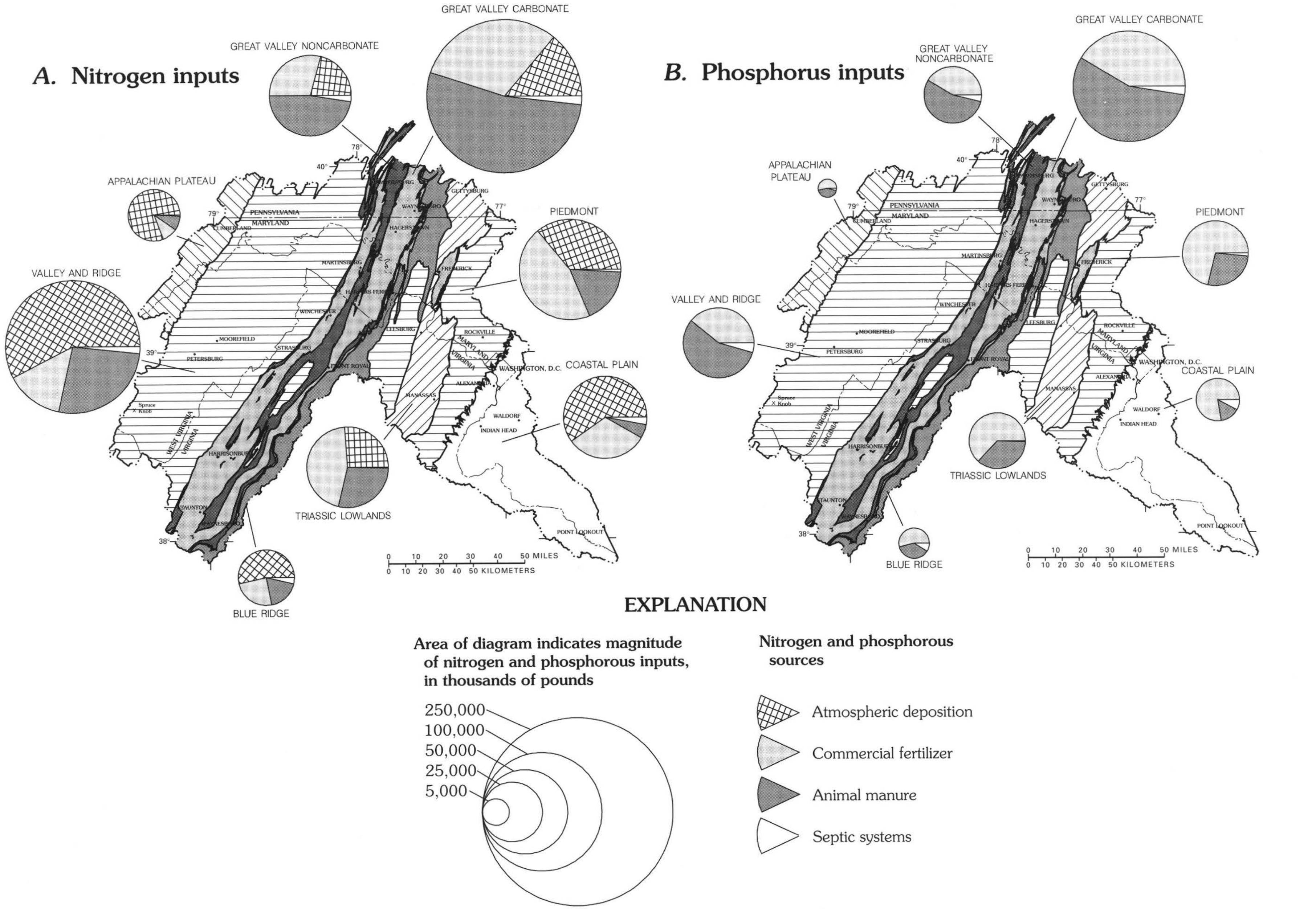


Figure 15. Distribution of (*A*) nitrogen and (*B*) phosphorus inputs from nonpoint sources to subunits of the Potomac River Basin, 1990.

phosphorus in 1990. Manure was the largest single source of nitrogen and phosphorus to the Great Valley subunits and contributed more than 50 percent of the phosphorus to the Valley and Ridge subunit. Manure inputs to the Great Valley Carbonate and Great Valley Noncarbonate subunits were highest, with average rates of inputs from manure of 19,500 and 11,500 lb/mi^2 of nitrogen and 4,740 and 2,900 lb/mi^2 of phosphorus, respectively.

Septic-system inputs of nutrients to the entire Potomac River Basin were estimated to be less than 2 percent for nitrogen and 4 percent for phosphorus. However, particular areas of concern include Coastal Plain and carbonate settings where pathways might occur for rapid transport of nutrients and associated septic contaminants to ground water. Much of the population in the Coastal Plain subunit is serviced by municipal wastewater treatment, so water-quality effects from septic systems, if any, probably are limited to rural areas with high water tables or near water bodies. The Great Valley Carbonate subunit contains a higher percentage of population relying on septic systems than other areas of the basin and has the highest input of nitrogen and phosphorus from septic systems. Another potential area of concern is the Valley and Ridge subunit where carbonate valleys and shallow soils increase the potential for ground-water contamination. In the Valley and Ridge subunit, septic inputs contribute 1,000,000 lb of nitrogen and 300,000 lb of phosphorus.

Distribution in Major Watersheds

The distribution of nitrogen and phosphorus inputs in major watersheds of the Potomac River Basin reflects the nutrient-input patterns of the eight major subunits. Basin characteristics of contributing watersheds are presented in table 6 for the 25 surface-water-quality monitoring sites used in this study. The location and watershed boundaries for these sites are shown in figure 16. Estimates of nitrogen and phosphorus inputs to these watersheds are presented in tables 7 and 8. The nitrogen and phosphorus inputs to these 25 watersheds are used to explain patterns in nutrient concentrations in surface water in later sections of this report. The magnitude and distribution of the principal sources of nitrogen and phosphorus to 10 major watersheds with drainage basins greater than 490 mi^2 are shown in figure 17. In figure 17, the cumulative effect of nutrient inputs to nested watersheds is apparent as total nutrient inputs increase downstream as drainage area increases. Watershed boundaries often transect several subunits; thus, the proportion of individual nutrient sources does not differ as widely as among subunits. The potential for water-quality effects from the principal nutrient sources is discussed in the following paragraphs.

In 1990, municipal wastewater discharges were a relatively small component of total nutrient inputs to the 10 major watersheds. As previously indicated, most of the nitrogen and phosphorus from municipal wastewater is discharged downstream from Washington, D.C. Upstream from Washington, D.C., municipal discharges accounted for 2.7 percent of the nitrogen and 1.9 percent of the phosphorus input (table 5*A*). Of the 10 sites in figure 17, the largest fraction of total nitrogen input from wastewater discharges was 3.5 percent at Monocacy River (site 19, table 7). Municipal discharges accounted for 3.2 percent of the phosphorus input to the North Branch Potomac River (site 2, table 8).

Nutrient inputs from industrial sources are small compared to most other sources; however, these inputs directly affect the surface-water system. The highest percentage of nitrogen inputs from industrial sources was to the North Branch Potomac (site 2, 1.6 percent) and Conococheague subbasins (site 7, 2.5 percent). Relatively high nitrogen inputs from industrial sources occurred in the South Fork Shenandoah (site 11), North Fork Shenandoah (site 14), Shenandoah (site 15), and Potomac River (sites 8 and 23) subbasins; however, the nitrogen input from industrial sources was less than 1 percent in these subbasins. Industrial inputs of phosphorus comprised 8.7 percent of total inputs to the North Branch Potomac River (site 2), the highest percentage for the 10 major watershed sites. Industrial inputs of phosphorus were also relatively high at sites 3, 8, 11, 14, 15, and 23; however, the maximum percentage of phosphorus inputs was 1.4 percent for these sites. Industrial sources generally contributed a smaller proportion of total nutrient inputs in the Shenandoah subbasins as inputs from other sources were larger.

All 10 major watersheds had significant inputs of nitrogen from atmospheric deposition. However, as discussed earlier, those areas with extensive forest cover at higher elevations account for much of the nitrogen inputs from atmospheric deposition. The Potomac River at Shepherdstown (site 8) accounted for about 44 percent of the nitrogen inputs from atmospheric deposition to the entire Potomac River Basin

Table 6. Summary of basin characteristics for selected surface-water-quality monitoring sites in the Potomac River Basin

[<, less than]

Site no.[1] (fig. 16)	Stream name and location	U.S. Geological Survey station identifier	Sampling agency(s)[2]	Drainage area (square miles)	Population (thousands)	Land use (percent)			Physiographic province or subprovince (fig. 4)
						Forest	Agriculture	Urban	
1	North Branch Potomac River at Kitzmiller, Md.	01595500	MD	225	4	80	13	<1	Appalachian Plateau
2	North Branch Potomac River near Cumberland, Md.	01603000	USGS	875	86	82	13	3	Appalachian Plateau
3	South Branch Potomac River at Springfield, W. Va.	01608500	WV	[3]1,470	29	78	22	<1	Valley and Ridge
4	Town Creek at Oldtown, Md.	01609000	MD	148	1.5	85	15	<1	Valley and Ridge
5	Lost River at McCauley, W. Va.	01610200	USGS	155	2.2	78	22	<1	Valley and Ridge
6	Cacapon River at Great Cacapon, W. Va.	01611500	WV	[3]677	11	82	18	<1	Valley and Ridge
7*A/B*	Conococheague Creek at Fairview, Md.	01614500	USGS/MD	[3]494	78	36	60	4	Great Valley
8*A/B*	Potomac River at Shepherdstown, W. Va.	01618000	USGS/MD	[3]5,936	424	69	28	2	Mixed
9*A/B*	Antietam Creek near Sharpsburg, Md.	01619500	USGS/MD	281	115	24	69	7	Great Valley
10	Christians Creek at Fishersville, Va.	01624800	VA	70	8.6	25	67	8	Great Valley
11*A/B*	South Fork Shenandoah River at Front Royal, Va.	01631000	USGS/VA	[3]1,642	188	51	40	8	Great Valley
12	North Fork Shenandoah River at Cootes Store, Va.	01632000	VA	213	2.7	88	10	2	Valley and Ridge
13	Smith Creek near New Market, Va.	01632900	VA	93	7.5	40	52	8	Great Valley
14*A/B*	North Fork Shenandoah River at Strasburg, Va.	01634000	USGS/VA	[3]768	48	54	40	6	Great Valley
15	Shenandoah River at Millville, W. Va.	01636500	USGS	[3]3,040	297	51	41	7	Great Valley
16	Catoctin Creek near Middletown, Md.	01637500	MD	67	8.3	38	61	1	Piedmont
17	Monocacy River at Bridgeport, Md.	01639000	USGS	173	29	20	78	2	Triassic Lowlands
18	Hunting Creek tributary near Foxville, Md.	01640970	USGS	4	[4]0	76	23	1	Blue Ridge
19	Monocacy River near Frederick, Va.	01643000	USGS	[3]817	181	23	73	3	Mixed
20	Goose Creek near Leesburg, Va.	01644000	VA	322	18	29	66	4	Triassic Lowlands
21*A/B*	Seneca Creek at Daowsonville, Md.	01645000	USGS/MONT	101	137	24	65	9	Piedmont
22	Difficult Run near Great Falls, Va.	01646000	VA	58	92	31	17	50	Piedmont
23	Potomac River at Washington, D.C.	01646500	USGS	11,670	1,655	55	40	4	Mixed
24	Cameron Run at Alexandria, Va.	01653000	VA	33.7	155	8	2	90	Piedmont
25	Bull Run near Manassas, Va.	01657000	VA	147	112	34	48	16	Piedmont

[1]Site identifier: A=U.S. Geological Survey sampling agency, B=non-U.S. Geological Survey sampling agency.

[2]Sampling agency codes: MD=Maryland Department of the Environment; MONT=Montgomery County government; USGS-U.S. Geological Survey; VA=Virginia Department of the Environmental Quality; WV=West Virginia Department of Natural Resources.

[3]Considered major watershed for purposes of this report (greater than 490 square miles).

[4]No census-tract centers located in the watershed.

Figure 16. Location and watershed boundaries for surface-water-quality monitoring sites used for analysis of nutrient data.

(96,559,000 lb). Atmospheric inputs were most important in the North Branch Potomac River watershed (site 2) with 79 percent of the total nitrogen input from atmospheric deposition.

As can be expected, the greatest inputs of nutrients from commercial fertilizer and animal manure occurred in watersheds with extensive agricultural land use. However, the proportion of fertilizer and manure inputs differed considerably among four agricultural watersheds, sites 7, 11, 14, and 19. Commercial fertilizer comprised 51 percent of the nitrogen and 63 percent of the phosphorus inputs to the Monocacy River watershed (site 19) and fertilization rates there were highest, with nitrogen and phosphorus applied at 15,300 and 4,490 lb/mi^2, respectively. In the Conococheague Creek watershed (site 7), fertilizer contributed 35 percent of the nitrogen and 47 percent of the phosphorus inputs, and application rates were somewhat lower at nearly 9,370 lb/mi^2 nitrogen and 2,940 lb/mi^2 phosphorus. In the North and South Fork Shenandoah Rivers (sites 14 and 11), fertilizer contributed about 17 percent of the nitrogen and about 27 percent of the phosphorus inputs, although the extent of agricultural land use is similar to the other basins.

Table 7. Estimated inputs of nitrogen to selected watersheds in the Potomac River Basin, 1990

[All numbers are in thousands of pounds. Agricultural estimates are based on 1987 statistics (U.S. Department of Commerce, 1989)]

		Point sources		Nonpoint sources				
Site no. (fig. 17)	**Stream name**	**Municipal sewage treatment**	**Industrial processes**	**Atmospheric deposition**	**Commercial fertilizer**	**Animal manure**	**Septic systems**	**Total**
1	North Branch Potomac River	14	18	3,425	272	322	20	4,071
2	North Branch Potomac River	130	203	9,970	1,135	999	104	12,541
3	South Branch Potomac River	61	57	14,848	2,131	7,404	204	24,705
4	Town Creek	49	0	757	261	176	10	1,253
5	Lost River	0	0	1,483	344	1,262	22	3,111
6	Cacapon River	6	0	4,374	1,156	2,525	44	8,105
7	Conococheague Creek	282	329	2,485	4,627	5,080	286	13,089
8	Potomac River	1,539	729	42,649	19,364	23,308	1,842	89,431
9	Antietam Creek	378	3	1,410	3,588	2,582	348	8,309
10	Christians Creek	46	0	366	573	1,020	46	2,051
11	South Fork Shenandoah River	1,258	394	12,079	8,640	25,941	654	48,966
12	North Fork Shenandoah River	0	0	1,877	354	1,729	27	3,987
13	Smith Creek	25	0	535	806	3,834	39	5,239
14	North Fork Shenandoah River	94	230	5,000	4,148	16,072	296	25,840
15	Shenandoah River	1,704	630	20,375	15,789	44,763	1,249	84,510
16	Catoctin Creek	39	0	296	1,066	474	42	1,917
17	Monocacy River	128	9	811	1,710	2,471	9	5,138
18	Hunting Creek tributary	0	0	19	26	11	0	56
19	Monocacy River	864	15	3,785	12,508	7,165	298	24,635
20	Goose Creek	25	0	1,643	2,109	1,462	76	5,315
21	Seneca Creek	272	0	539	1,621	201	0	2,633
22	Difficult Run	0	0	697	34	15	0	746
23	Potomac River	5,621	1,590	76,403	66,574	83,907	3,938	238,033
24	Cameron Run	0	0	584	0	0	0	584
25	Bull Run	159	0	975	512	290	0	1,936

Fertilizer application rates in these watersheds were much smaller at about 5,300 lb/mi^2 nitrogen and nearly 1,600 lb/mi^2 phosphorus.

Manure-production rates were quite different than fertilizer use as animal populations are largest in the southern part of the Great Valley subprovince. Of the four agricultural watersheds previously mentioned (sites 7, 11, 14, and 19), manure inputs were most intense in the North Fork Shenandoah River watershed (site 14), where manure contributed 62 percent of the nitrogen and 72 percent of the phosphorus input. The manure-production rate in this basin was 20,900 lb/mi^2 nitrogen and 4,660 lb/mi^2 phosphorus. In the South Fork Shenandoah River watershed (site 11), manure contributed 53 percent of the nitrogen and 67 percent of the phosphorus inputs. In the Conococheague Creek watershed (site 7), manure contributed 39 percent of the nitrogen and 47 percent of the phosphorus. Manure production and fertilizer applications were nearly equal in the Conococheague Creek watershed. Manure-production rates were lower in the Monocacy watershed (site 19) where manure inputs contributed 29 percent of the nitrogen and 33 percent of the phosphorus inputs.

Septic systems were a minor source of nitrogen and phosphorus in all 10 major watersheds. A

Table 8. Estimated inputs of phosphorus to selected watersheds in the Potomac River Basin, 1990
[All numbers are in thousands of pounds. Agricultural estimates are based on 1987 statistics (U.S. Department of Commerce, 1989)]

		Point sources		Nonpoint sources			
Site no. (fig. 17)	Stream name	Municipal sewage treatment	Industrial processes	Commercial fertilizer	Animal manure	Septic systems	Total
1	North Branch Potomac River	2	2	87	86	7	184
2	North Branch Potomac River	24	66	353	278	34	755
3	South Branch Potomac River	14	33	802	1,964	66	2,879
4	Town Creek	12	0	78	51	3	144
5	Lost River	0	0	131	287	7	425
6	Cacapon River	1	0	440	600	14	1,055
7	Conococheague Creek	71	0	1,451	1,466	92	3,080
8	Potomac River	251	150	6,453	6,397	595	13,846
9	Antietam Creek	62	7	1,063	745	113	1,990
10	Christians Creek	6	0	168	270	15	459
11	South Fork Shenandoah River	158	131	2,530	6,084	211	9,114
12	North Fork Shenandoah River	0	0	106	380	9	495
13	Smith Creek	3	0	236	842	13	1,094
14	North Fork Shenandoah River	10	52	1,216	3,578	96	4,952
15	Shenandoah River	212	187	4,729	10,406	404	15,938
16	Catoctin Creek	4	0	309	135	14	462
17	Monocacy River	6	8	530	635	3	1,182
18	Hunting Creek tributary	0	0	7	3	0	10
19	Monocacy River	131	13	3,671	1,930	96	5,841
20	Goose Creek	3	0	618	418	25	1,064
21	Seneca Creek	35	0	470	58	0	563
22	Difficult Run	0	0	10	4	0	14
23	Potomac River	792	403	20,459	21,223	1,273	44,150
24	Cameron Run	0	1	0	0	0	1
25	Bull Run	18	0	150	83	0	251

particular area of concern with septic systems is in watersheds underlain by carbonate rock, as represented by sites 7, 11, 14, and 15, where pathways occur for rapid transport of contaminants to ground water and to the surface-water system. These watersheds also have a high percentage of the population relying on septic systems. Conococheague Creek (site 7) had the highest number of septic systems per unit area of the 10 watersheds included in this analysis, and septic systems contributed about 2 percent of the nitrogen and 3 percent of the phosphorus inputs.

Nutrient Concentrations

Data Availability

Numerous water-quality-monitoring programs have been operated by governmental and educational institutions within the Potomac River Basin. Much of this information is available from the USGS WATSTORE and USEPA STORET computer systems. The nutrient-concentration data compiled for this report will be used for several purposes. First,

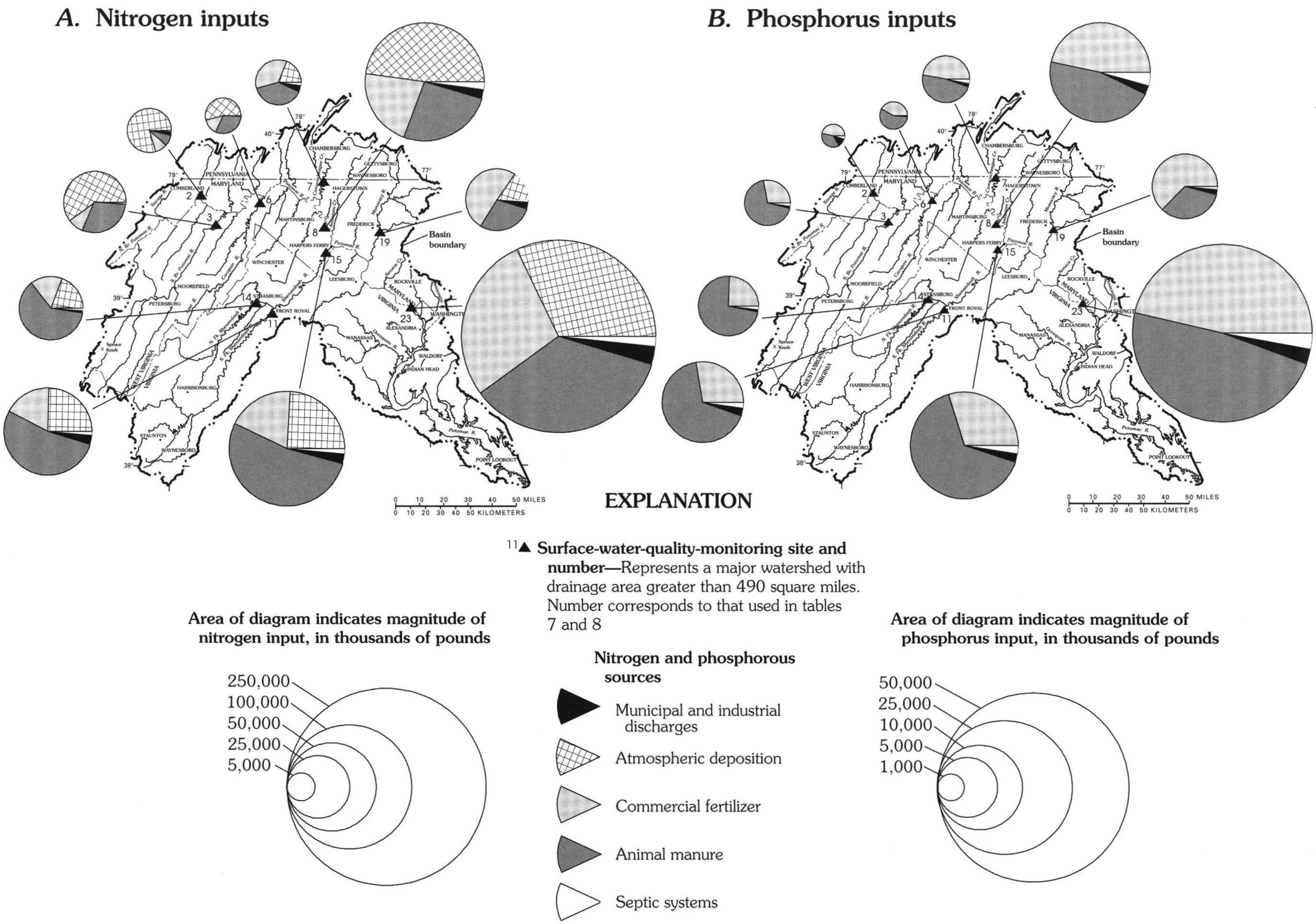


Figure 17. Distribution of (*A*) nitrogen and (*B*) phosphorus inputs to major watersheds of the Potomac River Basin, 1990.

some of the data will be used to assess water-quality conditions in the Potomac River Basin to guide data collection and analysis by the NAWQA Program. Second, other data may be used in conjunction with newly collected data to refine our understanding of the occurrence of nutrients in the basin. Using historical data sets to assess water-quality conditions, however, is difficult because of problems with data accessibility and data comparability. The data summarized in this report are limited to computerized data from WATSTORE and STORET for the period 1970–90. Data in these systems have been collected to meet the specific objectives of individual monitoring programs. These objectives include specific research or regulatory needs and may yield data that are inappropriate for broad-scale analysis of water-quality conditions. Also, many water-quality-monitoring networks use sampling and chemical-analysis methods that differ greatly, which could cause incomparability of nutrient-concentration data.

Many short- and long-term monitoring programs have operated within the Potomac River Basin during the past 100 years. The primary long-term, surface-water-quality and acid-precipitation monitoring networks of State, regional, and Federal agencies operating in the Potomac River Basin for 1970–90 are listed in table 9. These programs are identified and described in the Chesapeake Bay Basin Monitoring Program Atlas (Heasley and others, 1989). The primary Federal water-quality-monitoring program operating in the basin is the USGS National Stream-Quality Accounting Network (NASQAN), which has operated three long-term streamflow-gaging stations and water-quality monitoring sites on the Potomac River at Shepherdstown, W. Va., the Shenandoah River at Millville, W. Va., and the Potomac River at Washington, D.C.(sites 8, 15, and 23), since 1973. Sites 8 and 15 were discontinued by the NASQAN program in 1994. The Metropolitan Washington Council of Governments operated 50 sites within the basin in the vicinity of Washington, D.C., and coordinated the operation of 41 sites in the Anacostia River watershed. The number of surface-water-quality monitoring sites operated since 1973 by State programs differs from State to State—Maryland (52 sites), Pennsylvania (3 sites), Virginia (89 sites), West Virginia (5 sites), and the District of Columbia (76 sites). The data from these programs represent the data most suitable to the regional assessment of water-quality conditions in the Potomac River Basin because they cover the geographic extent of the basin and data have been collected over a range of seasonal and hydrologic conditions. Selected sites from these programs are used in this report to assess water-quality conditions.

Ground Water

Nutrient-concentration data are available for water samples from 1,158 wells in WATSTORE and 1,401 wells in STORET. The location of these wells is shown in figures 18 and 19. Many of the USGS-ground-water-quality monitoring sites were sampled as part of county ground-water-resource assessments of Carroll, Frederick, and Washington Counties, Maryland; Berkeley and Jefferson Counties, West Virginia; and Clarke and Prince William Counties, Virginia. Other samples were collected as part of both regional and site-specific monitoring, with particularly dense sampling distributions in the vicinity of Gettysburg, Pennsylvania, Indian Head, Maryland, and in the headwaters of the North Branch Potomac River. Few ground-water samples are available from WATSTORE for the Shenandoah Valley region of Virginia. A large number of ground-water samples from this region and the rest of the Virginia part of the basin were collected by the Virginia Department of Environmental Quality and are available from the STORET system.

The number of ground-water sites and nutrient samples available from the WATSTORE and STORET data bases is tabulated in tables 10 and 11 and indicates the nutrient analyses available for the eight subunits in the Potomac River Basin. The number of samples for individual nutrient constituents in each subunit greatly affects the ability to assess water-quality conditions within and among the subunits. Of the eight subunits, the Great Valley Carbonate has the largest number of wells with nutrient analyses in both data bases. The number of sampled wells in the WATSTORE data base ranges from 46 in the Appalachian Plateau subunit to 367 in the Great Valley Carbonate subunit. Dissolved-nitrate-concentration data are available for most of these wells. Dissolved-orthophosphate and ammonia concentrations, however, are present in a much smaller subset of wells. Thus, assessment of water-quality conditions for these constituents will not be as reliable as for nitrate. The number of wells with samples in STORET ranges from 2 in the Appalachian Plateau subunit to 762 in the Great Valley Carbonate subunit. Nearly all of the samples have concentration information for both dissolved

Table 9. Summary of selected surface-water-quality and acid-preciptitation monitoring programs collecting nutrient data in the Potomac River Basin, 1970–90

[Data obtained from Heasley and others (1989)]

Agencies and programs	First year of data collection	Number of sampling sites	Method of collection[1]	Frequency of samples collected
Federal				
U.S. Geological Survey, Water Resources Division				
National Stream-Quality Accounting Network	1973	3	a,c	Bimonthly
Regional				
Metropolitan Washington Council of Governments				
Potomac Regional Monitoring Program	1982	50	b,e	Monthly
Coordinated Anacostia Monitoring Program	1985	41	b,e	Monthly
State				
District of Columbia Department of Consumer and Regulatory Affairs, Environmental Control Division				
District of Columbia Water Quality Monitoring Program	1979	76	f	Monthly
Maryland Department of Environment, Water Management Administration				
Maryland Nontidal Tributary Water Quality Monitoring Program	1974	37	d	Monthly
Maryland Chesapeake Bay Water Quality Monitoring Program: Mainstem Chemical/Physical Component	1984	1	e	Monthly Nov.–Feb. Biweekly Mar.–Oct.
Maryland Chesapeake Bay Water Quality Monitoring Program: Tributary Chemical/Physical Component	1984	11	e	Monthly Nov.–Feb. Biweekly Mar.–Oct.
Maryland Chesapeake Bay Water Quality Monitoring Program: River Input Component	1984	1	a,g	1–4 times per month
Maryland Chesapeake Bay Water Quality Monitoring Program: Ecosystem Processes Component- Sediment Oxygen and Nutrient Exchange	1984	2	e	Quarterly
Maryland Department of Environment, Air Management Administration				
Maryland Acid Precipitation Monitoring Program	1984	1	h	Weekly
Pennsylvania Department of Environmental Resources, Bureau of Water Quality Management				
Pennsylvania Water Quality Network	1962	3	b,c	Monthly
Pennsylvania Atmospheric Deposition Monitoring Program	1981	1	h	Weekly
Virginia Department of Environmental Quality				
Virginia Ambient Water Quality Monitoring Program (program run by Virginia Northern Regional and Valley Regional Offices)	1968	57	d	Monthly
Virginia Northern Regional Ambient Water Quality Monitoring Network	1973	32	b	Monthly with some exceptions
Virginia Department of Air Pollution Control				
Virginia Acid Precipitation Network	1982	2	h	Weekly
West Virginia Department of Natural Resources				
West Virginia Ambient Water Quality Network	1960	5	c	Monthly

[1]Method of collection: a, cross-sectional and depth-integrated sample method; b, grab sample; c, composite laboratory samples with depth-integrated sample method; d, bucket sample method; e, water-column samples collected with submersible pump; f, 1.0-meter profile, April through October; g, flow-weighted, storm-sampling automatic sampler; h, wet/dry precipitation collector.

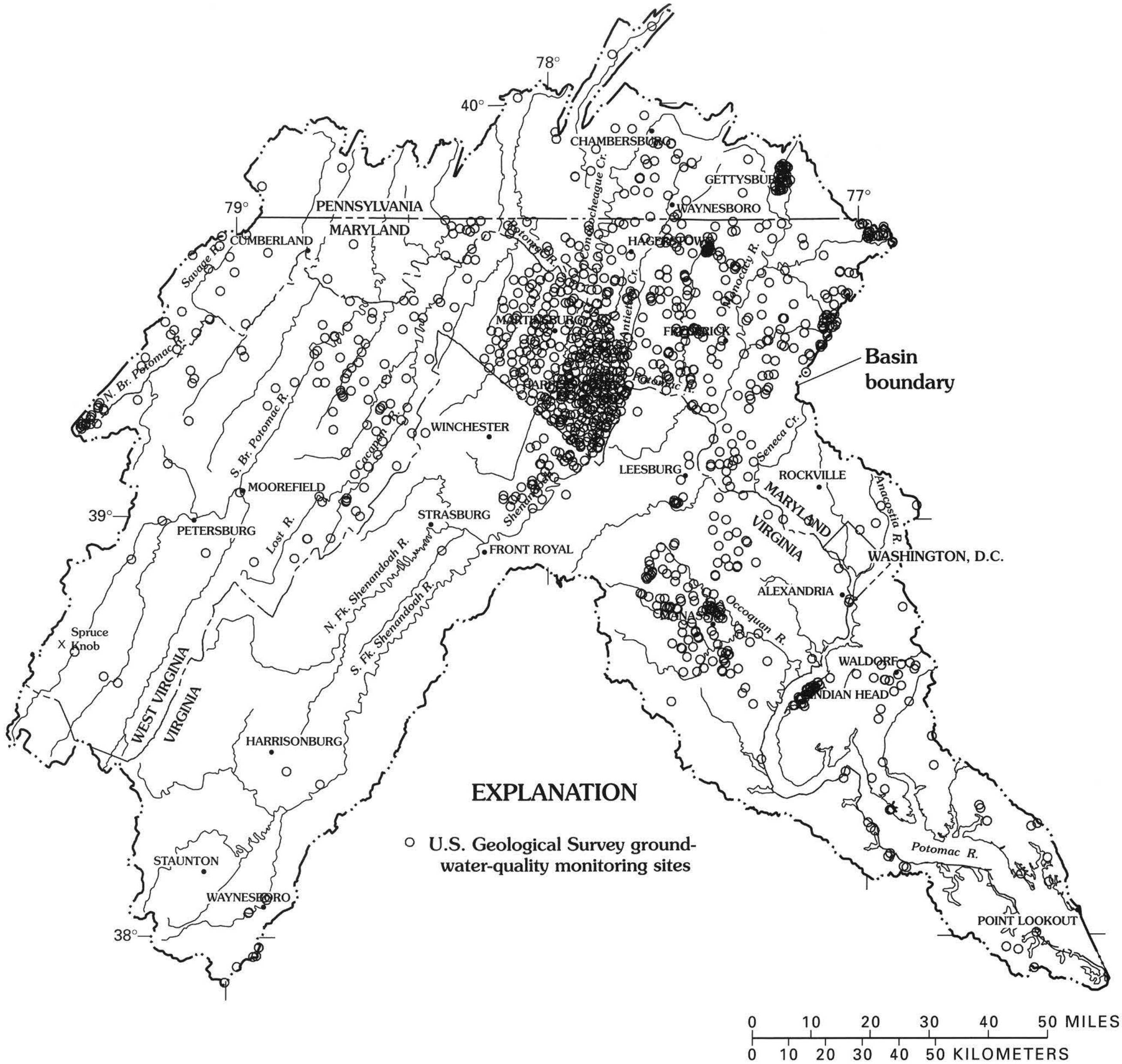


Figure 18. Location of ground-water wells with nutrient data in the U.S. Geological Survey's WATSTORE data base, 1970–90.

nitrate and dissolved orthophosphate, and none of the samples have dissolved-ammonia analyses.

Surface Water

Nutrient-concentration data for surface water are available for 456 sites in WATSTORE and 1,176 sites in STORET. Figures 20 and 21 show the distribution of surface-water-quality monitoring sites with nutrient data collected by USGS, other Federal programs, and States. Many samples are needed to perform a complete analysis of nutrient-concentration data in surface water because nutrient concentrations in surface water can vary greatly due to seasonal and streamflow conditions. Sites with more than 50 samples have been highlighted because these sites are usually long-term monitoring sites and are the best candidate sites for data analysis with respect to streamflow, seasonality, long-term trends, and nutrient loadings. The 456 USGS surface-water-quality monitoring sites are fairly evenly distributed throughout the basin, and 89 sites have more than 50 samples. Four areas have a dense coverage of sites, including the North Branch

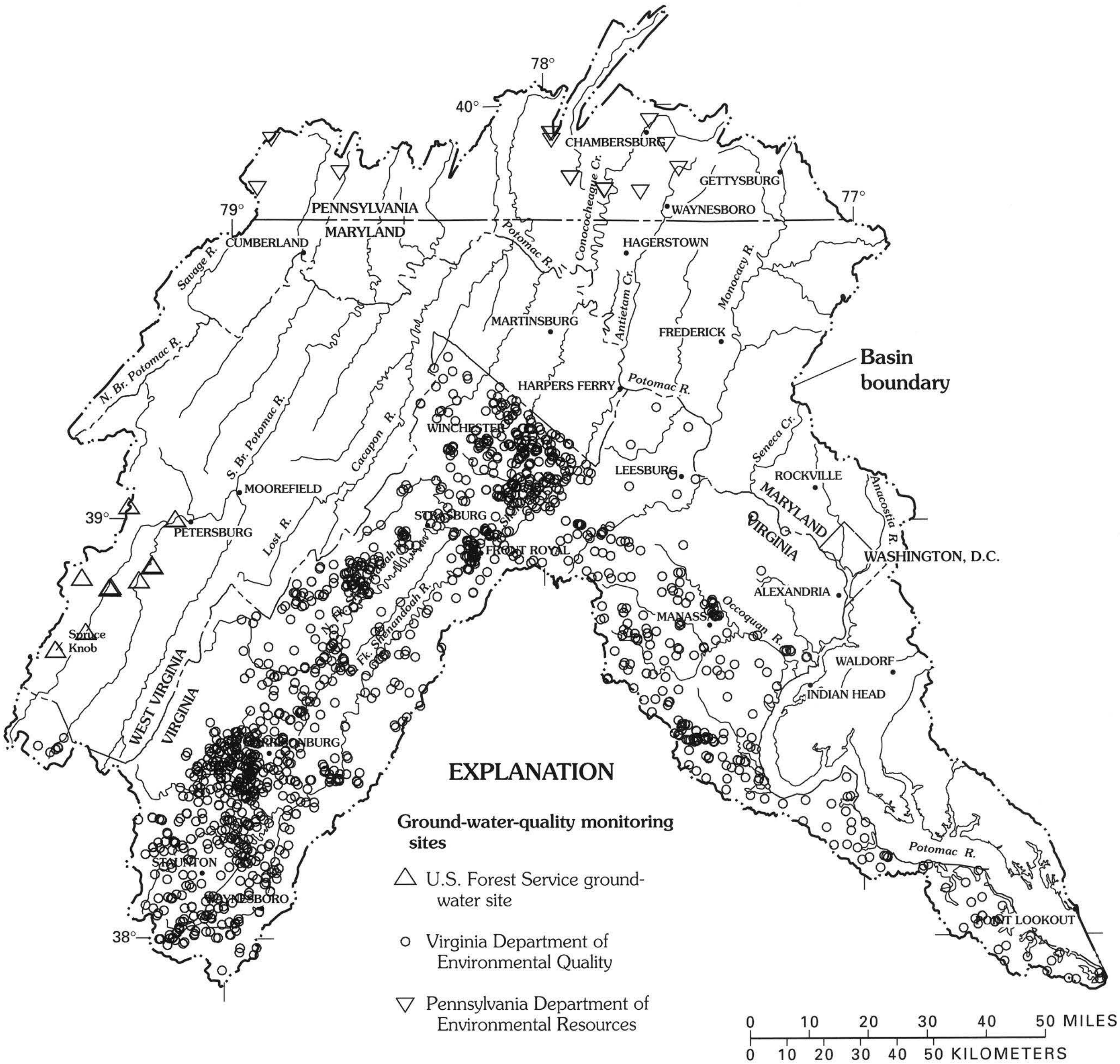


Figure 19. Location of ground-water wells with nutrient data in the U.S. Environmental Protection Agency's STORET data base, 1970–90.

Potomac River watershed, the Monocacy River watershed, the Blue Ridge subunit, and northern Virginia near Washington, D.C. Other Federal surface-water sites with nutrient data in the STORET data base are fairly evenly distributed throughout the basin. The USEPA maintains data from sites throughout the basin, with sites concentrated in the Potomac estuary. Few of these sites have more than 50 samples. The U.S. Forest Service maintains data in STORET from 13 sites in the southwestern corner of the South Branch Potomac River watershed. State and local monitoring sites are concentrated on major tributary systems, with large numbers of sites in Virginia, Washington, D.C., and Montgomery County, Maryland. West Virginia and Pennsylvania have comparatively few long-term monitoring sites.

A total of 31,567 surface-water samples are stored in WATSTORE, and 50,036 surface-water samples are stored in STORET (tables 12 and 13). The distribution of samples with respect to subunits reflects the areal distribution of samples shown in figures 20 and 21 and, as with the ground-water data, affects the ability

Table 10. Availability of ground-water nutrient-concentration data in the U.S. Geological Survey's WATSTORE data base, 1970–90

[Data compiled from the U.S. Geological Survey WATSTORE data base; --, no data available]

Subunits (fig. 13)	Number of wells	Number of samples	Number of nutrient analyses reported: Ammonia, dissolved	Nitrate, dissolved	Orthophosphate, dissolved
Appalachian Plateau	46	73	--	55	24
Valley and Ridge	154	202	39	114	53
Great Valley Carbonate	367	510	200	497	237
Great Valley Noncarbonate	71	83	39	83	46
Blue Ridge	95	286	21	267	200
Piedmont	152	179	19	166	38
Triassic Lowlands	182	290	111	233	79
Coastal Plain	91	223	1	84	18
Total	**1,158**	**1,846**	**430**	**1,499**	**695**

Table 11. Availability of ground-water nutrient-concentration data in the U.S. Environmental Protection Agency's STORET data base, 1970–90

[Data compiled from the U.S. Environmental Protection Agency STORET data base; --, no data available]

Subunits (fig. 13)	Number of wells	Number of samples	Number of nutrient analyses reported: Ammonia, dissolved	Nitrate, dissolved	Orthophosphate, dissolved
Appalachian Plateau	2	3	--	3	--
Valley and Ridge	113	211	--	210	150
Great Valley Carbonate	762	1,115	--	1,114	1,026
Great Valley Noncarbonate	205	257	--	256	231
Blue Ridge	51	56	--	56	49
Piedmont	112	175	--	161	145
Triassic Lowlands	69	188	--	106	103
Coastal Plain	87	135	--	125	88
Total	**1,401**	**2,140**	**--**	**2,031**	**1,792**

to compare conditions among subunits. In the WATSTORE system, the greatest number of samples are available for dissolved nitrate, with fewer samples available for ammonia, total nitrogen, dissolved orthophosphate, and total phosphorus. In the STORET system, dissolved-nitrate and total-phosphorus samples are most prevalent.

Concentrations in Ground Water

The analysis of nutrient concentrations in ground water for this study relies solely on data from the USGS WATSTORE data base because chemical analyses were generally complete, well characteristics were inventoried, and analytical quality assurance could be documented. Also, only one analysis per well, the most recent one, was used to assess concentrations in ground water. Potomac River Basin subunits and land-use designations were assigned to each ground-water monitoring well on the basis of its geographic location. The GIRAS land-use data from about 1972, as shown in figure 6, were used for this designation. Only wells in agricultural, urban, or forest areas were used to assess the relation between nutrient concentrations and land use.

Dissolved-nitrate concentrations in ground water vary widely within the Potomac River Basin, with much of the variability related to subunits and nutrient inputs from land-use practices. Dissolved-ammonia and dissolved-orthophosphate concentrations in ground water are generally near the analytical

Table 12. Availability of surface-water nutrient-concentration data in the U.S. Geological Survey's WATSTORE data base, 1970–90

[Data compiled from the U.S. Geological Survey WATSTORE data base]

Subunits (fig. 13)	Number of wells	Number of samples	Number of nutrient analyses reported: Nitrate, dissolved	Ammonia, dissolved	Nitrogen, total	Phosphorus, total	Orthophosphate, dissolved
Appalachian Plateau	93	2,713	303	56	61	109	65
Valley and Ridge	67	11,465	643	82	14	160	327
Great Valley Carbonate	60	5,132	1,922	966	1,291	1,588	883
Great Valley Noncarbonate	13	2,044	1,471	189	12	261	1,022
Blue Ridge	46	2,242	1,232	215	8	76	11
Piedmont	95	3,948	785	450	482	615	557
Triassic Lowlands	59	3,079	1,818	927	1,460	1,613	1,123
Coastal Plain	23	944	268	33	28	52	19
Total	**456**	**31,567**	**8,442**	**2,918**	**3,356**	**4,474**	**4,007**

Table 13. Availability of surface-water nutrient-concentration data in the U.S. Environmental Protection Agency's STORET data base, 1970–90

[Data compiled from the U.S. Environmental Protection Agency STORET data base]

Subunits (fig. 13)	Number of wells	Number of samples	Number of nutrient analyses reported: Nitrate, dissolved	Ammonia, dissolved	Nitrogen, total	Phosphorus, total	Orthophosphate, dissolved
Appalachian Plateau	24	1,161	1,091	312	643	1,123	446
Valley and Ridge	143	2,759	2,713	386	1,493	2,338	643
Great Valley Carbonate	161	6,376	6,302	164	5,920	6,249	2,413
Great Valley Noncarbonate	79	3,345	3,292	80	2,945	3,205	1,185
Blue Ridge	19	624	610	34	553	570	167
Piedmont	328	17,648	16,514	2,717	5,268	16,486	3,560
Triassic Lowlands	129	7,878	7,676	2,148	4,483	7,764	3,462
Coastal Plain	293	10,245	8,613	3,205	7,388	7,833	6,241
Total	**1,176**	**50,036**	**46,811**	**9,046**	**28,693**	**45,568**	**18,117**

detection level and show only slight spatial patterns throughout the basin.

Dissolved-nitrate concentrations in water from 1,049 wells in the Potomac River Basin range from less than 0.01 to 63 mg/L (milligrams per liter) and have a median value of 1.8 mg/L. The boxplots in figure 22 show the statistical distribution of dissolved nitrate in ground water for wells in the eight subunits. Nitrate concentrations are less than the laboratory detection level in water from 12 percent of the wells. Ground-water samples from all subunits display a wide range in dissolved-nitrate concentration. Concentrations are lowest in the aquifers of the Appalachian Plateau, Valley and Ridge, and Coastal Plain subunits, and highest in the Great Valley Carbonate subunit. Wells in the Great Valley Noncarbonate, Blue Ridge, Piedmont, and Triassic Lowlands subunits show similar median values and a wide range in nitrate concentrations. These patterns in concentration are consistent with nonpoint-source nitrogen inputs to the eight subunits and the hydrologic properties of the aquifer systems within these subunits.

Dissolved-nitrate concentrations in the Appalachian Plateau and the Valley and Ridge subunits are among the lowest in the basin, with median concentrations of 0.1 and 0.14 mg/L, respectively (fig. 22). These subunits are predominately covered by forest, and agriculture is generally limited to the flat, tillable areas in the narrow valleys. Thus, nitrogen sources in these subunits are fewer than in other subunits and are

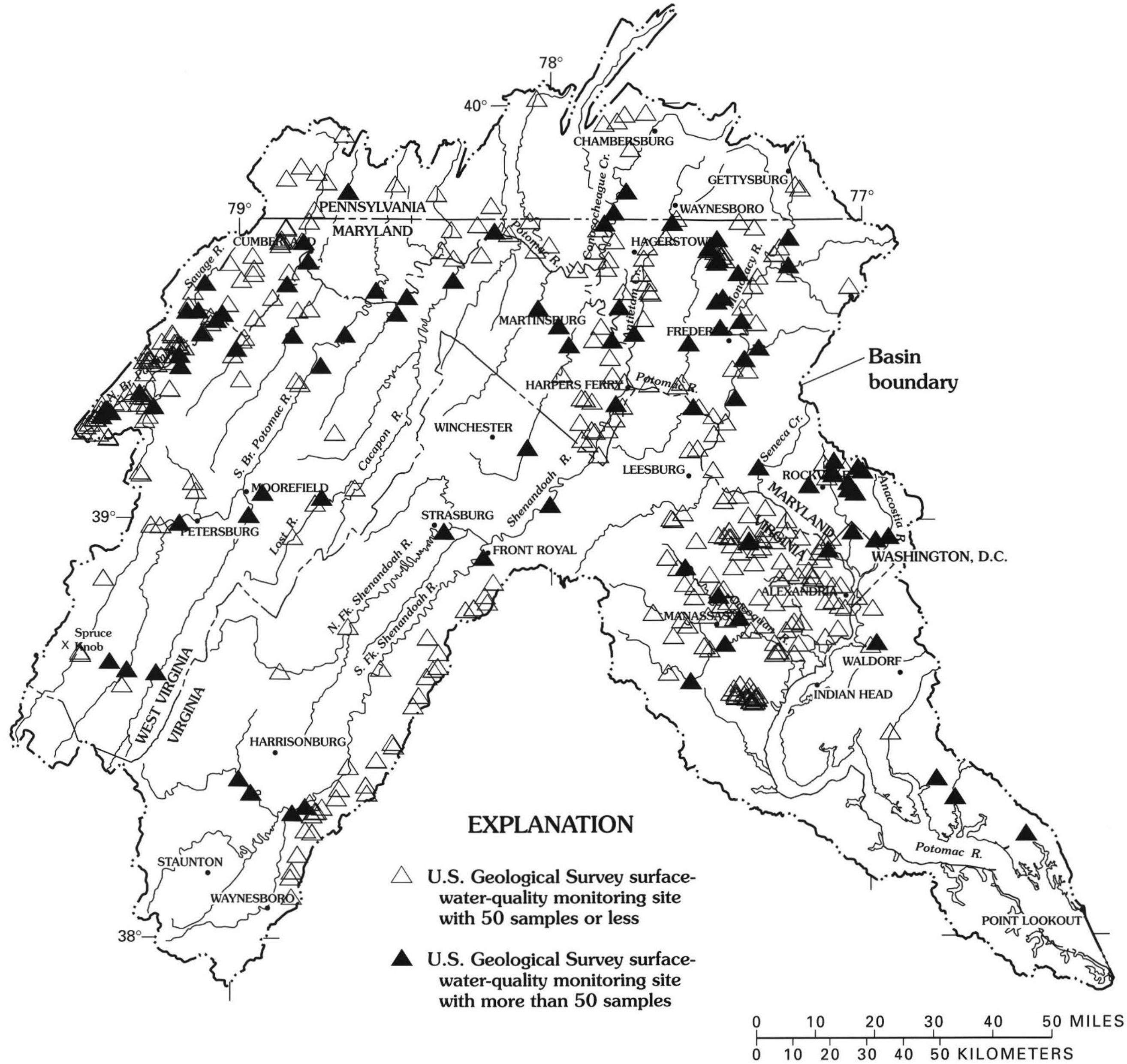


Figure 20. Location of surface-water-quality monitoring sites with nutrient data in the U.S. Geological Survey's WATSTORE data base, 1970–90.

dominated by atmospheric deposition in the forested highlands and agricultural inputs in the valleys. Eighty-six percent of the sampled wells in the Appalachian Plateau are located in forest settings. The median nitrate concentration (0.10 mg/L) in this subunit reflects relatively pristine conditions. In the Valley and Ridge subunit, the median nitrate concentration in ground water in agricultural settings (0.41 mg/L) is significantly higher (p=0.051) than in forest settings (0.11 mg/L) as shown in figure 23.

Dissolved-nitrate concentrations in ground water from the Great Valley Carbonate subunit are generally higher (median 4.5 mg/L) than in ground water from other subunits and exhibit relatively small differences among land-use settings (fig. 23). Nonpoint sources of nitrogen in the Great Valley Carbonate subunit are dominated by agricultural fertilizer and manure, with atmospheric deposition contributing only about 14 percent (table 4*B*). Fourteen percent of the wells in this subunit have concentrations greater than or equal

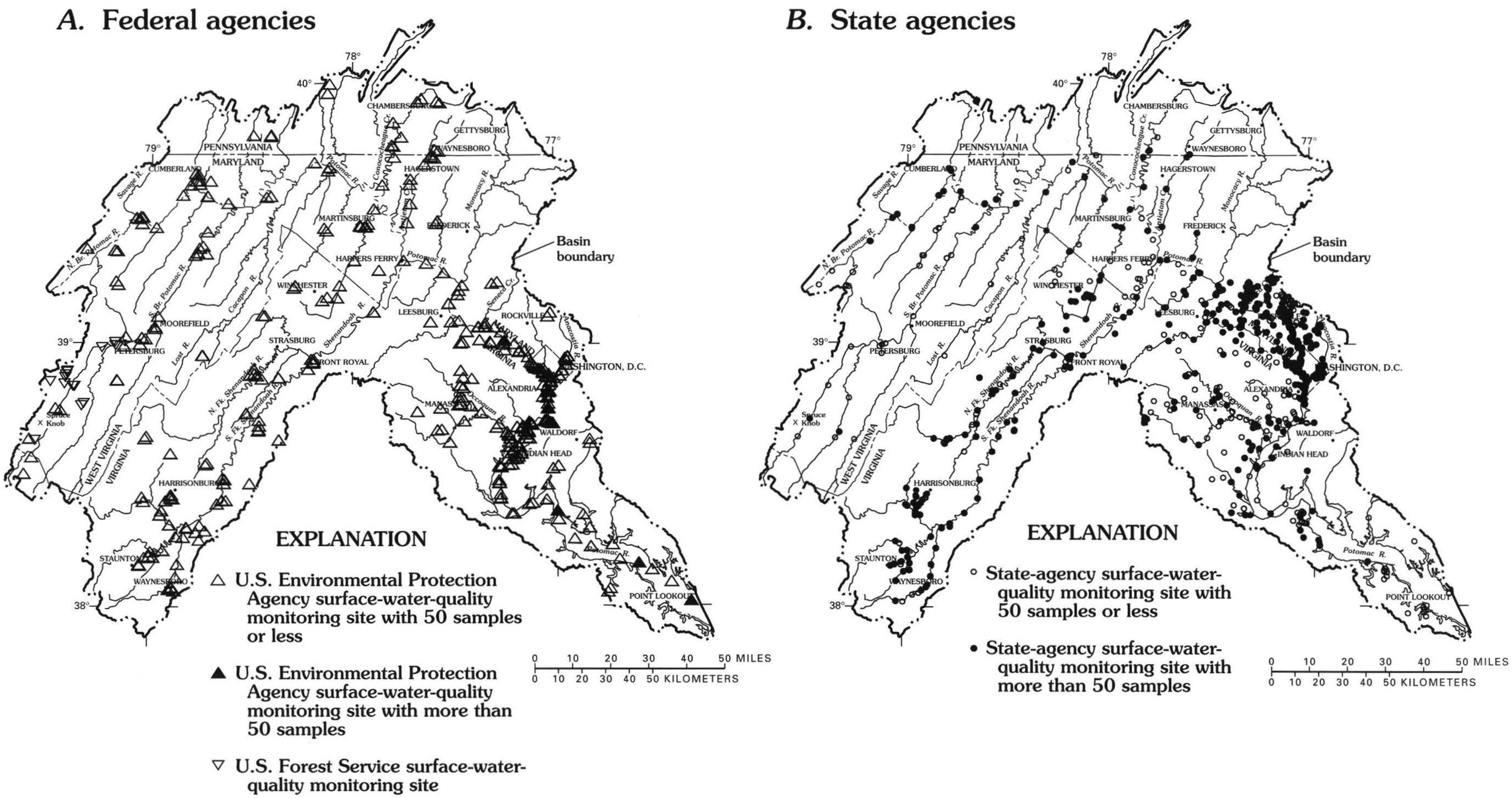


Figure 21. Location of surface-water-quality monitoring sites with nutrient data collected by (*A*) Federal and (*B*) State agencies in the U.S. Environmental Protection Agency's STORET data base, 1970–90.

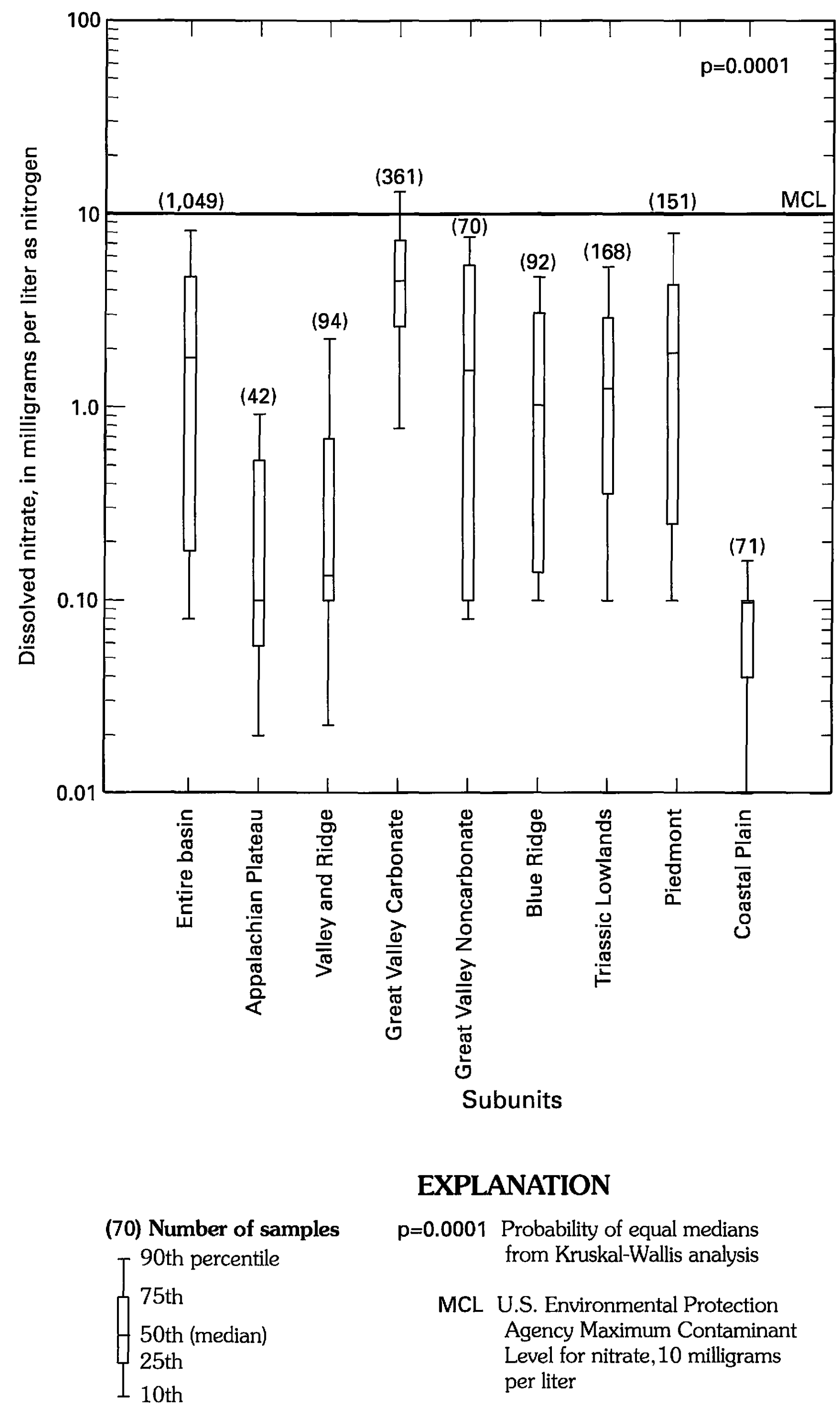


Figure 22. Dissolved-nitrate concentrations in ground-water samples from Potomac River Basin subunits, 1970–90.

to the 10-mg/L Maximum Contaminant Level (MCL) for drinking water established by the USEPA (U.S. Environmental Protection Agency, 1991) (fig. 22). The wells included in this analysis are located primarily in the northern extent of the subunit in West Virginia and Maryland and may be spatially biased. However, Goodell and LoCastro (1989) reported a higher median nitrate concentration of 8.4 mg/L in water from 290 wells in carbonate rock of Clarke and Frederick Counties, Virginia. Ground water in carbonate rock moves predominantly through solution channels, and water is quickly transmitted from the land surface to the water table. Thus, nitrogen-enriched water in this subunit is subjected to rela-

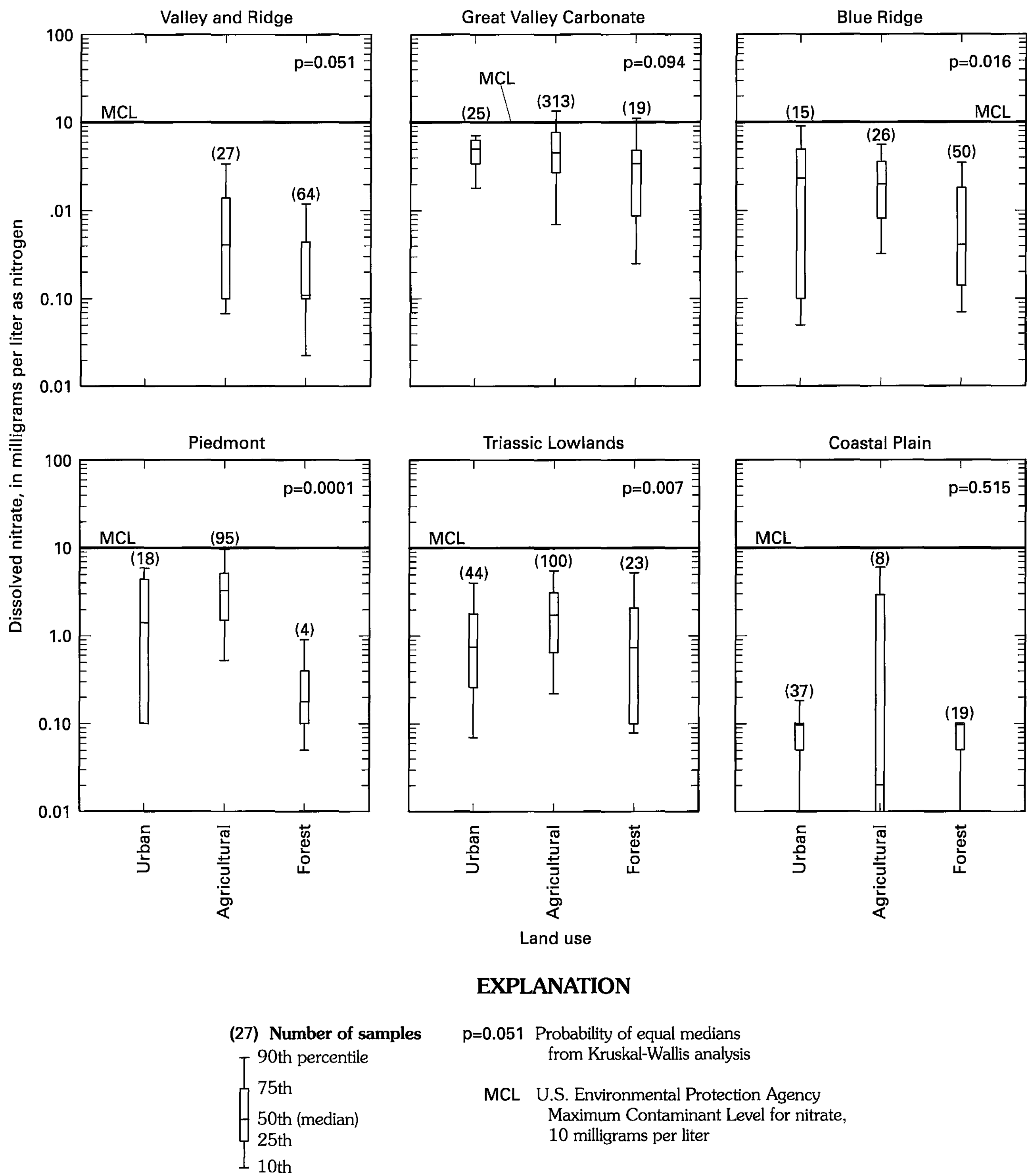


Figure 23. Dissolved-nitrate concentrations in ground-water samples from selected land-use settings in selected Potomac River Basin subunits, 1970–90.

tively short periods of time in the soil horizon, the most biologically active zone where nutrient uptake and cycling rates are highest. There appears to be only small differences (p=0.094) in nitrate concentration among land-use settings (fig. 23), and median concentrations are greater than 3.0 mg/L in urban, agricultural, and forest settings. The forests within the Great Valley Carbonate subunit tend to be smaller buffered zones within agricultural areas. Because of the nature of ground-water flow in carbonate aquifers, some ground water underlying much of the small forests is recharged through upgradient agricultural land.

Nitrate concentrations in ground water from the Great Valley Noncarbonate subunit are generally lower (median 1.6 mg/L) than from adjacent carbonate settings, although nitrogen inputs are similar. Goodell and LoCastro (1989) indicated that lower median nitrate concentrations in the noncarbonate region were the result of less agricultural land use. Land use and nitrogen inputs, however, are not significantly different between the two subunits. The differing hydrologic properties of the subunits probably best explain the observed differences in ground-water nitrate concentrations. The ground-water system in the noncarbonate subunit generally responds more slowly to recharge, and water travels through smaller secondary openings including fractures, joints, and bedding planes in these mostly shale aquifers. Thus, larger amounts of nitrogen may be exported from the land surface as runoff. Biogeochemical processes may also play an important role in reducing nitrate concentrations as ground-water movement is slower in noncarbonate rock than in the solution cavities of carbonate rock, allowing longer contact with aquifer minerals for weathering. Denitrification, the reduction of nitrate to nitrogen gas, is a biologically mediated process that occurs in anoxic ground water. Anoxic conditions favorable for nitrate reduction may be prevalent in the noncarbonate subunit because pyrite oxidation in saprolite and shale aquifers can remove oxygen from ground water (McFarland, 1989). Most sampled wells in the Great Valley Noncarbonate subunit are located in agricultural settings, and there are insufficient data in urban and forest settings to permit land-use comparisons.

Nitrate concentrations in ground water from crystalline rock of the Blue Ridge subunit are moderate in relation to the Potomac River Basin as a whole, with a median of 1.0 mg/L. Similar to the Valley and Ridge, the Blue Ridge is 78 percent forest (table 1), with agriculture confined to valleys and sidehills. Urban areas are interspersed, including local communities, the tourist industry, and some suburban communities. Nitrate-concentration data show significantly different median concentrations ($p=0.016$) for these land-use settings (fig. 23). Water from wells in forest settings has a median value (0.41 mg/L), which is much lower than in urban (2.3 mg/L) and agricultural (2.0 mg/L) settings. Nitrate concentrations in ground water from only 1 of the 92 wells in the Blue Ridge subunit exceeded the MCL.

Nitrate concentrations in ground-water samples from the Piedmont subunit vary greatly, with a range of less than 0.01 to 37 mg/L. The subunit-wide variability is largely related to differences in land use (fig. 23). Land use in the Piedmont varies spatially, with agriculture predominating in the northern and western parts and mixed agriculture, forest, and urban areas in the southeastern parts. Although only four samples were collected from forest settings, a Kruskal-Wallis analysis of nitrate concentrations by land use indicates that median concentrations in water from wells on agricultural land (3.3 mg/L) and in forests (0.18 mg/L) are significantly different ($p<0.0001$). Nitrate concentrations in urban settings, including northern Washington, D.C., and its suburbs, vary greatly and probably reflect residual nitrate concentrations characteristic of forest and agricultural land used for development in addition to urban nonpoint sources of nitrogen. None of the wells in forests or urban settings yielded water samples that exceeded the MCL; however, 14 percent of the agricultural wells had water samples that equaled or exceeded the 10-mg/L MCL for nitrate.

Nitrate concentrations in ground water from the Triassic Lowlands subunit (median 1.2 mg/L) are slightly lower than from the surrounding Piedmont, and differences between agricultural and forest settings are much less pronounced (fig. 23). However, median nitrate concentrations for water from wells in urban (0.75 mg/L) and forest (0.74 mg/L) settings are slightly lower than for wells on agricultural land (1.8 mg/L). Less than 4 percent of the wells have water with nitrate concentrations exceeding the MCL.

Dissolved-nitrate concentrations for wells in the Coastal Plain subunit are among the lowest of the basin subunits, with a median of 0.10 mg/L. Unlike other Potomac River Basin subunits, ground water in the Coastal Plain is withdrawn from confined and unconfined aquifers formed from fairly distinct unconsolidated layers of sand and gravel. Water in the unconfined aquifers generally is recharged locally, whereas water in deeper confined aquifers may originate at distant outcrops or through leakage from adjacent aquifers. The nitrate-concentration data used in this analysis are from samples from predominantly deeper wells in confined aquifers. Therefore, it is difficult to assess land-use effects from these data because water-quality characteristics of confined aquifers may

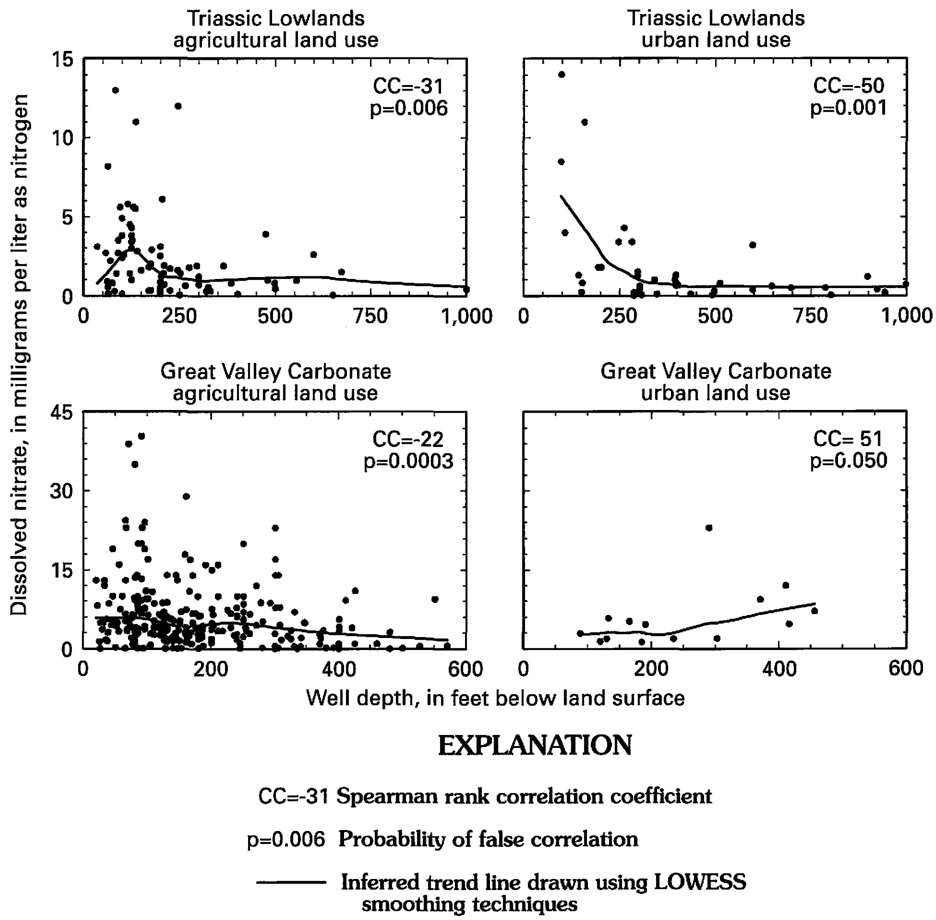


Figure 24. Relation of dissolved-nitrate concentration with well depth in selected land-use setting in selected Potomac River Basin subunits.

not be affected by the overlying land use. Median nitrate concentrations in water from all land-use settings are low, and water from agricultural wells shows the widest range of concentrations. Agricultural chemicals have been shown to have substantial effect on water quality in the surficial aquifers of the Coastal Plain of the Delmarva Peninsula of Maryland, Delaware, and Virginia (Hamilton and others, 1993). The hydrogeologic settings and agricultural practices of the Delmarva Peninsula are similar to the Coastal Plain subunit of the Potomac River Basin where the surficial aquifer may show similar degradation. Additional sampling from unconfined aquifers may be necessary to assess shallow ground-water quality on the Coastal Plain. None of the samples from Coastal Plain wells exceeded the 10-mg/L MCL for nitrate.

In the Potomac River Basin, nitrogen inputs have increased for hundreds of years since colonization; dissolved-nitrate concentrations in deeper, older ground water generally are expected to be less than in younger, more shallow ground water. A nonparametric Spearman rank correlation (Helsel and Hirsch, 1992) was used to compare dissolved-nitrate concentration with depth of wells in urban, agricultural, and forest, land uses of the eight subunits. The two variables were poorly correlated in 20 of the 24 possible cases. The poor correlation may be due to insufficient numbers of samples or to poor sample distributions with respect to well depth. Most ground-water wells in the study unit are constructed with a short surface casing and a long interval open to water-bearing fracture zones. Thus, well depth may not be directly related to the depth of the ground water sampled. In four cases, a significant concentration-depth relation was detected, and a smoothed estimate of these relations is shown in figure 24 using the LOWESS smoothing technique.

Within the agricultural setting of the Great Valley Carbonate subunit, nitrate concentrations decrease with depth; however, concentrations greater than the

10-mg/L MCL occur in wells deeper than 300 ft. In forest settings, nitrate concentrations increase slightly as wells deepen. It is possible that deeper wells in forest settings may intersect longer ground-water flow paths conveying water from agricultural settings where nitrogen inputs are high. In the Triassic Lowlands subunit, nitrate concentrations in water from both urban and agricultural wells decrease as wells deepen, and concentrations are less than 5.0 mg/L in water from wells deeper than 250 ft. Lower nitrate concentrations at depth in this subunit may be due to both the age of the ground water and biochemical denitrification under anoxic conditions in deeper ground water.

Dissolved-ammonia and dissolved-orthophosphate concentrations in ground water are generally less than or near the analytical reporting limits. Because of the high number of less-than values for ammonia and orthophosphate, only general observations of their spatial patterns in ground water can be made for the Potomac River Basin. Ammonia concentrations range from less than 0.01 to 7.7 mg/L in water from 345 wells. The median ammonia concentration is 0.02 mg/L, and 36 percent of the samples are less than the reporting limit for ammonia. Dissolved-orthophosphate concentrations range from less than 0.01 to 4.3 mg/L in water from 460 wells, and 56 percent are less than the reporting limit. Ammonia and orthophosphate are generally more chemically reactive than nitrate, and the low detection frequency is not surprising. Under most natural conditions, ammonia is biologically converted to more stable forms of nitrogen, and orthophosphate is used by plants and sorbs to soil and aquifer particles.

Concentrations in Surface Water

Patterns in nutrient concentrations in surface water of the Potomac River Basin are complex due to differences in physiography, hydrology, land use, and nutrient inputs. Because of this complexity, the analysis of nutrients in surface water focuses only on data from 25 surface-water-quality monitoring sites that encompass a wide range of conditions found within the basin, the same sites used to assess patterns in nutrient inputs (table 6, fig. 16). These 25 sites were selected from the sites with available concentration data in the WATSTORE and STORET data bases. The location of these sites is shown in figure 16, and a summary of land use and physiography of the contributing watersheds is shown in table 6 along with the name of the data-collecting agency. In this assessment of nutrient concentrations in surface water, the Great Valley is not subdivided into carbonate and noncarbonate subunits. The 25 sites drain relatively large watersheds, and where they intersect the Great Valley, the watersheds contain significant portions of both subunits. None of the sites used were within the Coastal Plain subunit. Six sites (7, 8, 9, 11, 14, and 21) (table 6) have data collected by both USGS and State or local programs. Because of differences in sampling and chemical-analysis methods, the data from these sites are interpreted separately, with USGS data designated as "A" and non-USGS data as "B". Most patterns in USGS and non-USGS data are similar, and differences are highlighted only where they exist.

Nutrient concentrations in surface water can respond dramatically to changing environmental conditions and show a wide range of spatial and temporal variability. Large-scale spatial patterns in nitrogen and phosphorus concentrations presented for the 25 sites are related to predominant physiographic and land-use settings. The temporal variability of nutrient concentrations is demonstrated for key sites and contrasted among different site types. Long-term trends in nutrient concentrations are inferred at key sites using existing concentration data in relation to known changes in land-use and management practices. The mass movement of nutrients in streams throughout the basin is evaluated by comparing calculated nutrient loads for selected tributaries and by comparing these loads with calculated inputs. Also, relative contributions of point-source inputs, base-flow nutrient loads, and average annual nutrient loads in selected streams are compared.

Spatial Variability

In surface water of the Potomac River Basin, nutrient concentrations mirror the spatial patterns in ground water with concentrations related to nutrient-input rates. The patterns in surface water are more complex, however, because larger streams drain multiple subunits and more diverse land uses. Also, point-source inputs of nutrients can have both localized and widespread effects on concentrations downstream. In general, nitrogen and phosphorus concentrations are lowest in the sparsely populated, forested regions of the Appalachian Plateau, Valley and Ridge, and Blue Ridge subunits and are highest in the agricultural region of the Great Valley, Piedmont, and Triassic

Lowlands, and near urban centers where wastewater-treatment inputs are greater.

Nitrogen concentrations differ greatly among streams in the basin. Median concentrations of total nitrogen range from 0.42 to 3.9 mg/L at 22 sites, and median dissolved nitrate ranges from 0.20 to 3.5 mg/L at 25 sites (fig. 25). The total-nitrogen analysis accounts for particulate and dissolved forms of nitrogen including nitrite, nitrate, ammonia, and organic nitrogen. The dissolved-nitrate analysis measures the species of nitrogen most predominant and available to affect aquatic life. Dissolved-nitrate concentrations are generally more temporally stable than total-nitrogen concentrations and are less affected by differences in sampling methods. Thus, dissolved-nitrate concentrations are often more suitable for site-to-site comparisons. Dissolved-ammonia concentrations are generally near the detection level, and no strong spatial patterns are evident as fewer sites have ammonia-concentration data. The statistical distribution of total-nitrogen and dissolved-nitrate concentrations has similar spatial patterns for both species. The sites are shown in downstream order in figure 25, and the sites are grouped according to the subunits in which the sites are located. Sites on larger rivers (sites 8, 15, 19, and 23) have watersheds that drain parts of several subunits. Site 12 is located in the Great Valley yet drains the Valley and Ridge subunit.

Median total-nitrogen and dissolved-nitrate concentrations are lowest at sites where nitrogen inputs are smaller and dominated by atmospheric deposition, including sites in the Appalachian Plateau, Valley and Ridge, and Blue Ridge subunits. These watersheds (sites 1–6, 12, and 18) drain predominantly forest land use and areas with less population density. Median dissolved-nitrate concentrations are lowest at sites 4 (0.3 mg/L), 5 (0.4 mg/L), and 6 (0.2 mg/L), reflecting conditions most unaffected by wastewater inputs or human land-use practices. Sites 1 and 2 on the North Branch Potomac River are affected by mining and industrial discharges and have slightly higher median nitrate concentrations of 0.56 and 0.53 mg/L, respectively. Nitrate concentrations at site 18 on Hunting Creek tributary in a forested part of the Blue Ridge subunit show a similar median of 0.58 mg/L. Sites 22 and 24, however, drain urbanized watersheds of Difficult Run and Cameron Run in Virginia, yet have nitrate concentrations similar to forest watersheds. Median nitrate concentrations at these sites of 0.70 and 0.50 mg/L also are dominated by atmospheric deposition as a nitrogen source in addition to urban nonpoint-source runoff.

Higher nitrogen concentrations occur in the largely agricultural watersheds of the Great Valley, Piedmont, and Triassic Lowlands; however, strong geographic patterns exist (fig. 25). In the Great Valley, there appears to be a difference in nitrogen concentration between northern and southern tributaries. Conococheague Creek (site 7) and Antietam Creek (site 9) have the highest median total-nitrogen concentrations of all sites at 3.1 and 3.9 mg/L, respectively, and drain the northern part of the Great Valley including parts of Pennsylvania and Maryland. Christians Creek and Smith Creek, sites 10 and 13, drain watersheds with a similar percentage of agriculture in the southern part of the Great Valley of Virginia and have lower median total-nitrogen concentrations of 2.1 and 2.3 mg/L. The remainder of the sites in the Great Valley encompass significant drainage from forests of the Valley and Ridge and Blue Ridge subunits and have median total-nitrogen and dissolved-nitrate concentrations slightly lower than the sites with a higher percentage of agricultural land use.

Monitoring sites in the agricultural areas of the Piedmont and Triassic Lowlands also have total-nitrogen and dissolved-nitrate concentrations greater than sites in forest settings. Median nitrogen concentrations in these areas differ greatly due to differences in land-use practices and point sources of nitrogen. The median dissolved-nitrate concentration of 1.3 mg/L in water from the Monocacy River at Bridgeport, Md. (site 17), is lower than in water from sites with similar agricultural intensity in the Great Valley. Downstream on the Monocacy River near Frederick, Md. (site 19), a higher median concentration of 2.1 mg/L is likely due to the effect of wastewater inputs, increased agricultural intensity, and drainage from both carbonate and crystalline rock. Nitrogen concentrations are similar at Seneca Creek (site 21), which drains a diverse watershed in the Piedmont including 65 percent agriculture, 24 percent forest, and 9 percent urban area, with significant nitrogen inputs from wastewater discharges in its headwaters. Other agricultural watersheds in the Piedmont and Triassic Lowlands, including Catoctin Creek (site 16) and Goose Creek (site 20), have water with lower median concentrations.

Few monitoring programs routinely sample for dissolved-ammonia concentrations; thus, there are insufficient data to assess spatial patterns. Eight sites

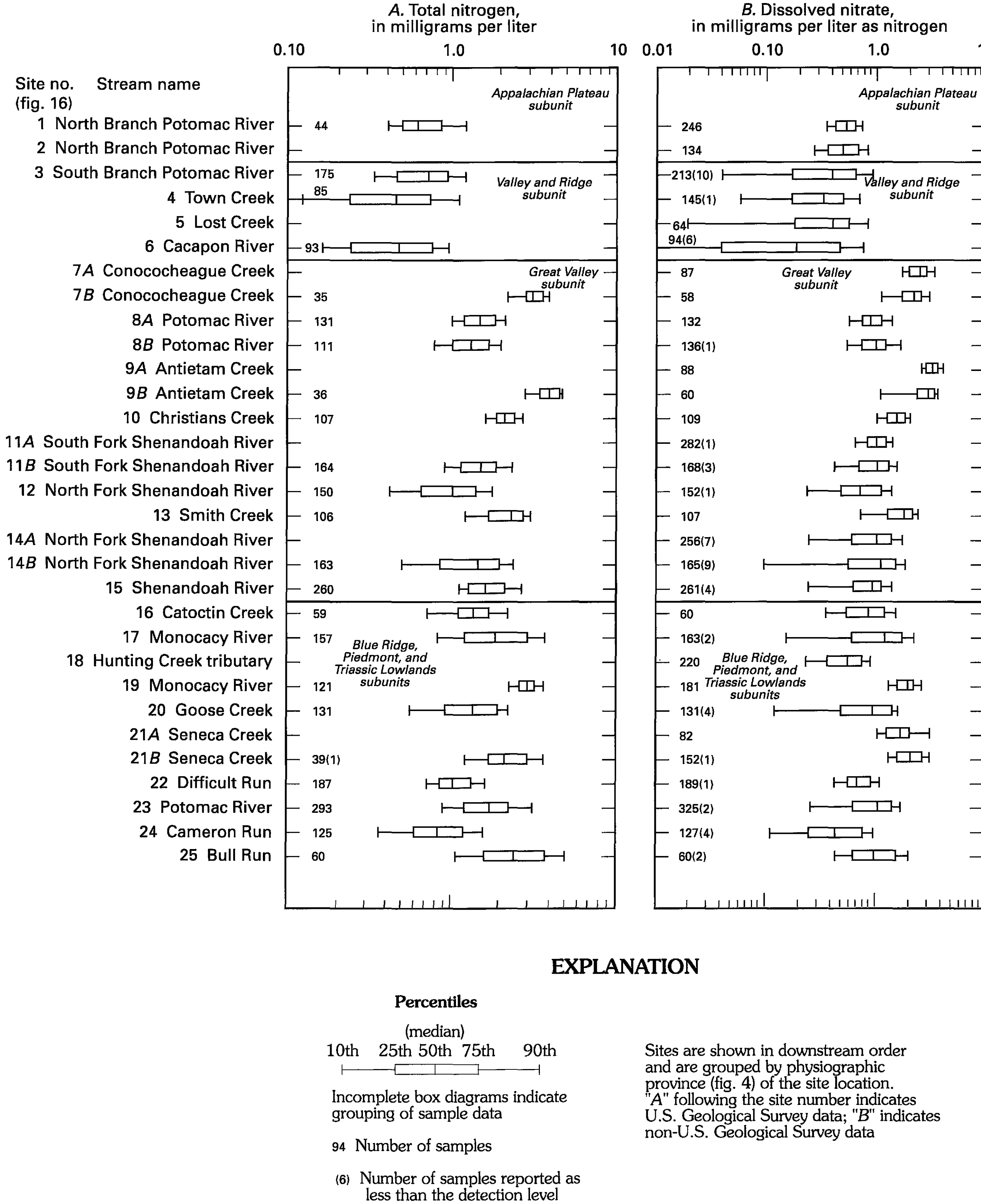


Figure 25. (*A*) Total-nitrogen and (*B*) dissolved-nitrate concentrations in water samples from selected surface-water-monitoring sites in the Potomac River Basin, 1970–90.

(1, 4, 9, 16, 18, 19, 22, and 24) had more than 10 samples with dissolved-ammonia analyses. Median ammonia concentrations at these sites range from 0.02 to 0.20 mg/L. Only two of these sites had median concentrations greater than 0.06 mg/L. The highest median concentration (0.20 mg/L) occurred in water from North Branch Potomac River at Kitzmiller, Md. (site 1). The elevated ammonia concentrations at this site may be due to acid-mine drainage, which occurs in many parts of this watershed. The river at this site lacks a healthy algal and macrophyte population, which in healthy streams would consume the available ammonia. The second highest ammonia concentration (0.11 mg/L) occurred in water from the Monocacy River at Bridgeport, Md. (site 17), which drains an agricultural part of the Triassic Lowlands subunit.

The spatial patterns in total-phosphorus and dissolved-orthophosphate concentrations are largely related to discharges from wastewater-treatment facilities and runoff from agricultural land. Figure 26 shows the distribution of total-phosphorus and dissolved-orthophosphate concentrations for samples from the 25 surface-water-quality monitoring sites. Lower concentrations occur for both measurements in the forest areas of the Appalachian Plateau, Valley and Ridge, and Blue Ridge, and higher concentrations occur in water from streams in the Great Valley, Piedmont, and Triassic Lowlands subunits. Total-phosphorus concentrations can increase substantially during high-flow conditions when phosphorus bound in soil and organic matter is transported. The median total-phosphorus concentration is highest in water from Antietam Creek (site 9) at 0.30 mg/L. In water from Christians Creek (site 10), Monocacy River (sites 17 and 19), and Bull Run (site 25), median total-phosphorus concentrations are about 0.20 mg/L. Total-phosphorus concentrations at Bull Run are strongly affected by upstream wastewater discharges; the sampling period at this site was prior to relocation of a municipal wastewater-treatment facility to a site farther downstream. Each of the other three sites encompasses significant agricultural drainage and also is affected by wastewater effluent. It is difficult to separate the effects of agriculture and wastewater at these sites. The lowest median total-phosphorus concentrations occur in water from sites 1 and 2 on the North Branch Potomac River and in water from sites 3, 4, and 6 in the Valley and Ridge subunit. In water from the North Branch, median concentrations increase from 0.04 mg/L at Kitzmiller (site 1) to 0.06 mg/L at Cumberland (site 2), Md. Presumably, industrial and municipal discharges near Cumberland cause this increase. Median total-phosphorus concentrations range from 0.04 to 0.16 mg/L in water from other sites in the Piedmont and Triassic Lowlands, including Goose Creek and Seneca Creek where phosphorus inputs to the watersheds are lower. Also, median total-phosphorus concentrations are low in water from the urban watersheds of Difficult Creek and Cameron Run because nonpoint-source inputs in urban areas are small.

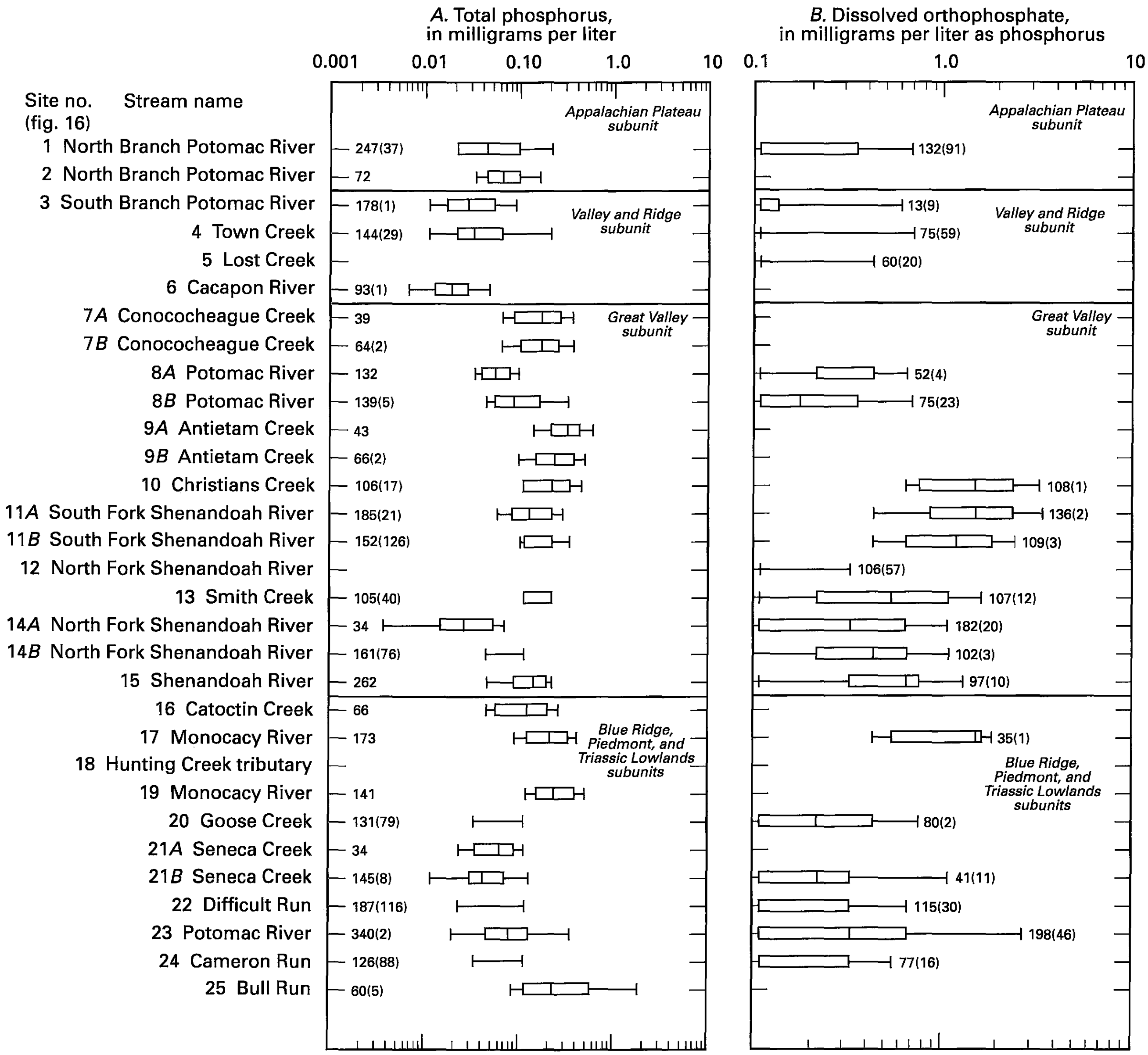
Median concentrations of dissolved orthophosphate are higher in streams draining agricultural watersheds than in those draining urban or forest watersheds. Dissolved-orthophosphate data are available for only 17 of the 25 sites, and concentrations frequently are reported as less than the analytical detection level of 0.01 mg/L (fig. 26). Median dissolved-orthophosphate concentrations range from 0.01 to 0.14 mg/L. Median concentrations were highest in water from Christians Creek (site 10), Shenandoah River (site 11), and Monocacy River (site 17). All three of these sites have substantial agricultural land use and wastewater phosphorus sources. Median concentrations in water from sites integrating large drainage areas (sites 8, 15, and 23) are moderate and appear to buffer the high-concentration agricultural water with more dilute water from forest watersheds.

Temporal Variability

Temporal variations in nitrogen and phosphorus concentrations in surface water are affected substantially by changes in streamflow conditions and seasonal cycles. In the streams of the Potomac River Basin, temporal patterns often differ from site to site, yet are similar within subunits and among land-use settings.

Streamflow Relations

Several different patterns in nitrogen concentration are evident in relation to streamflow conditions at the 25 monitoring sites and are shown for 8 key sites in figure 27. At all sites where both dissolved-nitrate and total-nitrogen concentration data exist, the concentration-streamflow relations are similar; however, total-nitrogen concentrations frequently are higher at higher streamflows. The relation between streamflow and concentration is inferred using the LOWESS smoothing technique in figures 27 and 28 using all available data for each site. High-streamflow conditions occur infrequently and are characterized by low



EXPLANATION

Percentiles

(median)
10th 25th 50th 75th 90th

Incomplete box diagrams indicate grouping of sample data

64 Number of samples

(2) Number of samples reported as less than the detection level

Sites are shown in downstream order and are grouped by physiographic province (fig. 4) of the site location. "*A*" following the site number indicates U.S. Geological Survey data; "*B*" indicates non-U.S. Geological Survey data

Figure 26. (*A*) Total-phosphorus and (*B*) dissolved-orthophosphate concentrations in water samples from selected surface-water-quality monitoring sites in the Potomac River Basin, 1970–90.

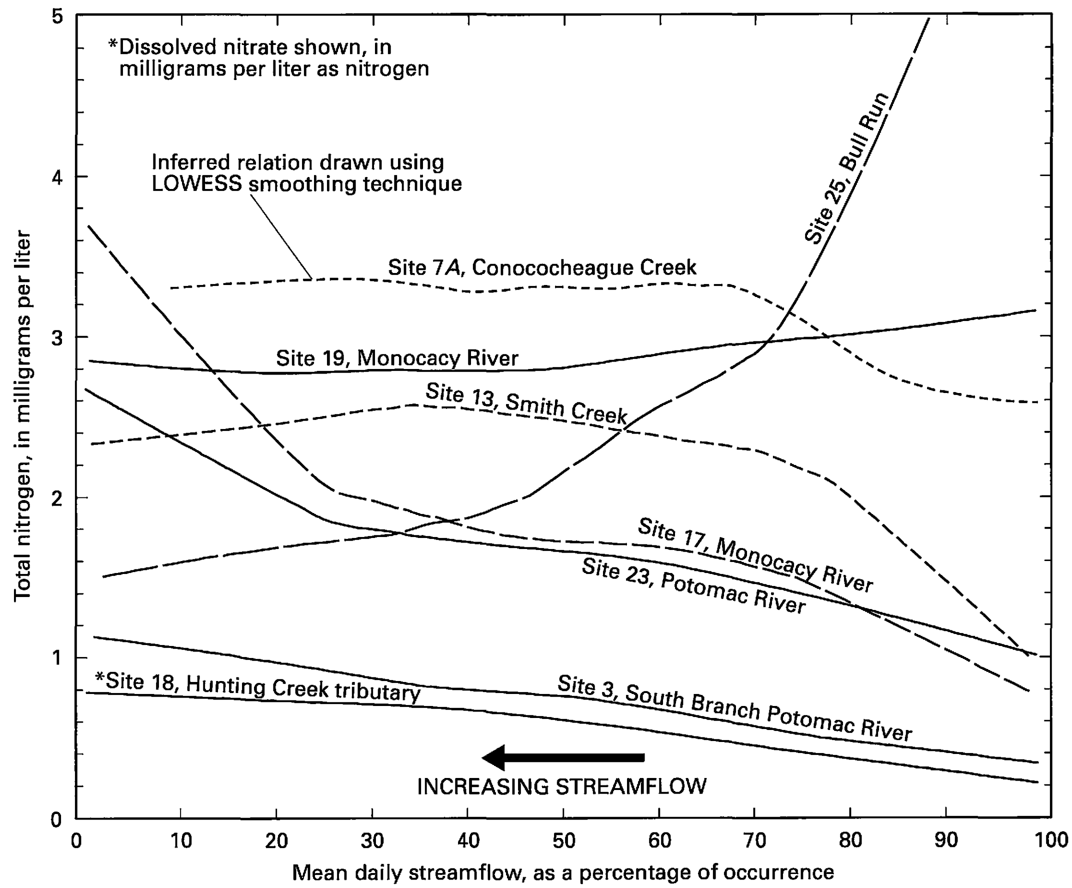


Figure 27. Relation of total-nitrogen concentrations to stream discharge at selected surface-water-quality monitoring sites in the Potomac River Basin. Location of sites is shown in figure 16.

percentages of occurrence. Thus, in figures 27 and 28, higher streamflows are drawn to the left and lower streamflows to the right side of the horizontal axis.

Streams draining forest watersheds show a characteristic relation of total-nitrogen concentration to streamflow. In water from forest watersheds, nitrogen concentrations usually are less than 1.0 mg/L and increase only slightly during higher flow conditions as shown for total nitrogen at site 3 and for dissolved nitrate at site 18 in figure 27.

Where total-nitrogen concentrations are maintained by wastewater-treatment-plant discharges, as at site 25, dilution causes a significant decrease in nitrogen concentration with increasing streamflow. Total-nitrogen concentrations in water from site 25 are greater than 3.0 mg/L during low-flow conditions and decline to less than 1.5 mg/L during high-flow conditions (fig. 27).

Streams draining agricultural watersheds often differ in their response to changing streamflow conditions due to differences in the hydrologic properties of the watersheds. Site 17 on the Monocacy River shows a concentration-streamflow relation typical of agricultural systems in the Triassic Lowlands subunit. During low-flow conditions, concentrations are low, near 1.0 mg/L, and increase dramatically during higher streamflows. The effect of storm runoff of fertilizers and animal manure from agricultural areas on total-nitrogen concentrations is substantial at this site.

Nitrogen concentrations in agricultural settings of the Great Valley subunits, however, show a very different relation. At sites 7 and 13, nitrogen concentrations increase only slightly with increased streamflow and maintain higher concentrations, 2.0 to 3.0 mg/L, throughout all but the lowest streamflow conditions. Ground-water discharge, which maintains base flow in these carbonate streams, maintains nitrogen concentrations that are higher than at most other sites. Also, storm runoff appears to have minimal effect on nitrogen concentration. In the Great Valley, where carbonate rock is predominant, much of the streamflow is generated through ground-water discharge, with a relatively small amount from overland and agricultural runoff. Extreme low-flow conditions in this region,

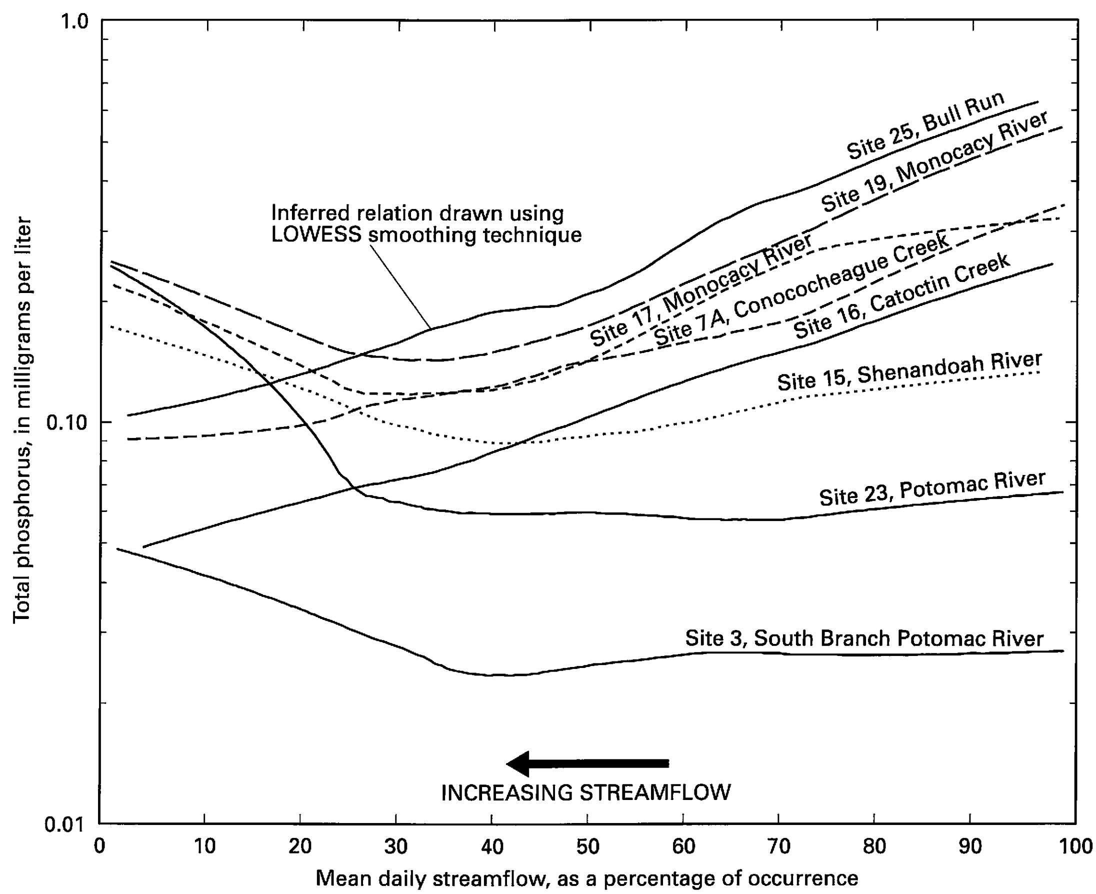


Figure 28. Relation of total-phosphorus concentrations to stream discharge at selected surface-water-quality monitoring sites in the Potomac River Basin. Location of sites shown in figure 16.

which usually occur during late summer, may allow in-stream biological processes to slightly reduce in-stream nitrogen concentrations.

Total-nitrogen concentrations in water from the Monocacy River near Frederick, Md. (site 19), appear stable with respect to streamflow. This relation, however, is likely the result of two distinct processes. During stable flow conditions, nitrogen concentrations represent the combined effect of ground-water discharge from agricultural areas and wastewater discharge from the City of Frederick, upstream of the monitoring site. As streamflow increases, nitrogen from wastewater discharges is probably diluted substantially, as at site 25, and agricultural runoff increases as seen at site 17. The combined effect of these processes likely gives the appearance of stable nitrogen concentrations.

Nitrogen concentrations in water from the Potomac River at Washington, D.C. (site 23), show the combined effect of all these patterns and resemble the runoff-generated model of nutrient concentrations and streamflow most closely. Because the patterns seen in contributing watersheds are diverse, it is apparent that the dynamics of nutrient concentrations at this site are far more complex than the simple relation shows. Each of the concentration-streamflow relations discussed previously is typical of large parts of the entire Potomac River watershed. Thus, concentrations at site 23 are a function of the streamflow relations in all physiographic and land-use settings. During low-flow conditions, concentrations of nitrogen are small because forests, where nitrate concentrations are small, cover 55 percent of the upper Potomac River Basin's land area. Also, biological uptake of nitrogen in the wide, shallow Potomac River is most significant during low-flow conditions. During higher flow conditions, however, nitrogen in agricultural runoff from the Great Valley, Piedmont, and Triassic Lowlands elevates concentrations significantly.

Total-phosphorus concentrations also differ greatly in response to streamflow in the basin, with the most significant differences in patterns occurring between forest watersheds and watersheds affected by agriculture and wastewater discharges. Because phosphorus is strongly sorbed to soil particles, concentrations are expected to increase with increasing streamflow and suspended-sediment load. This expected pattern occurs in the Potomac River at Washington, D.C. (site 23), where concentrations increase from about 0.07 to about 2.5 mg/L during high-streamflow conditions, which occur less than 30 percent of the time (fig. 28). Total-phosphorus concentrations in tributaries of the Potomac River, however, respond quite differently to changing streamflow conditions. Total-phosphorus concentrations in water from forest watersheds of the Appalachian Plateau and Valley and Ridge subunits are usually less than 0.05 mg/L and increase only slightly with increasing streamflow. These watersheds encompass a large part of the upper Potomac River Basin. An example of these sites in shown in figure 28 using data from the South Branch Potomac River (site 3). In watersheds affected by both agriculture and point-source discharges (sites 7*B*, 15, 16, 17, and 19), dilution appears to control phosphorus concentrations during stable streamflow conditions. At these sites, concentrations are typically greater than 0.10 mg/L during extreme low-flow conditions and decrease slightly with increasing streamflow (fig. 28). As streamflow increases to durations of less than 20 percent at sites 15, 17, and 19, total-phosphorus concentrations increase due to runoff from agricultural land. At Bull Run (site 25), total-phosphorus concentrations are contributed primarily from wastewater discharges and are diluted as streamflow increases.

Seasonal Patterns

Seasonal fluctuations of nitrogen concentrations in surface water are generally small at most sites in the Potomac River Basin. Seasonal fluctuations in nutrient concentrations are strongly related to seasonal fluctuations in streamflow conditions. Boxplots of seasonal nitrogen concentrations are shown in figure 29 for the same key sites shown in figure 27. Median nitrogen concentrations in water from forest watersheds, sites 3 and 18, are highest in the winter and lowest during the summer months, and overall variability is low. Total-nitrogen concentrations in agricultural settings, sites 7*B*, 13, and 17, also are highest in the winter months although fertilizer-application rates are highest in the spring and summer. Seasonal patterns at sites 19 and 25, which receive nitrogen from municipal wastewater discharges, are quite different. In water from the Monocacy River near Frederick (site 19), concentrations appear stable year-round. At Bull Run (site 25), where municipal discharges are the only major source of nitrogen, dilution causes lower nitrogen concentrations during the high flows of winter. Seasonal fluctuations in nitrogen concentration in water from the Potomac River at Washington, D.C. (site 23), primarily reflect the patterns seen for agricultural and forest settings, with higher concentrations occurring in winter and lower concentrations during summer.

Seasonal fluctuations of total-phosphorus concentrations are nearly opposite those of total-nitrogen concentrations (fig. 30). At nearly all sites, the highest total-phosphorus concentrations occur during the summer months when dilution is minimal. Seasonal patterns in water from the Potomac River at Washington, D.C. (site 23), however, are opposite of patterns in water from sites in the contributing watersheds and the overall variability is greater. The reason for the difference in seasonal patterns is unknown; however, the distribution of samples with respect to both streamflow and season may differ from the other monitoring sites. It is possible that larger numbers of high-flow and storm-runoff samples during winter months may cause higher median concentrations to occur at this site.

Long-Term Trends

Few of the 25 monitoring sites on the Potomac River and its tributaries show strong trends in total-nitrogen concentrations, although improvements in wastewater-treatment facilities and agricultural-management practices within the last 20 years would suggest that some decline should have occurred at many sites. However, population in the basin grew about 43 percent during 1970–90, which may affect concentrations due to increased wastewater effluent, septic systems, and other land-use changes. An inferred trend of flow-adjusted nitrogen concentrations is shown in figure 31 for selected sites with long-term data collection. To adjust for changes in streamflow, the residual of a LOWESS concentration-streamflow regression is subtracted from each measured concentration. Previous work by Trombley (1989) and Blomquist (1993) applied the nonparametric seasonal-Kendall trend test to similar data sets for several of the sites included in this report. The results of both studies are consistent with the visually inferred trends shown in this report. Trombley (1989) reported a trend at only one of 25 sites, a slight increase in total-nitrogen con-

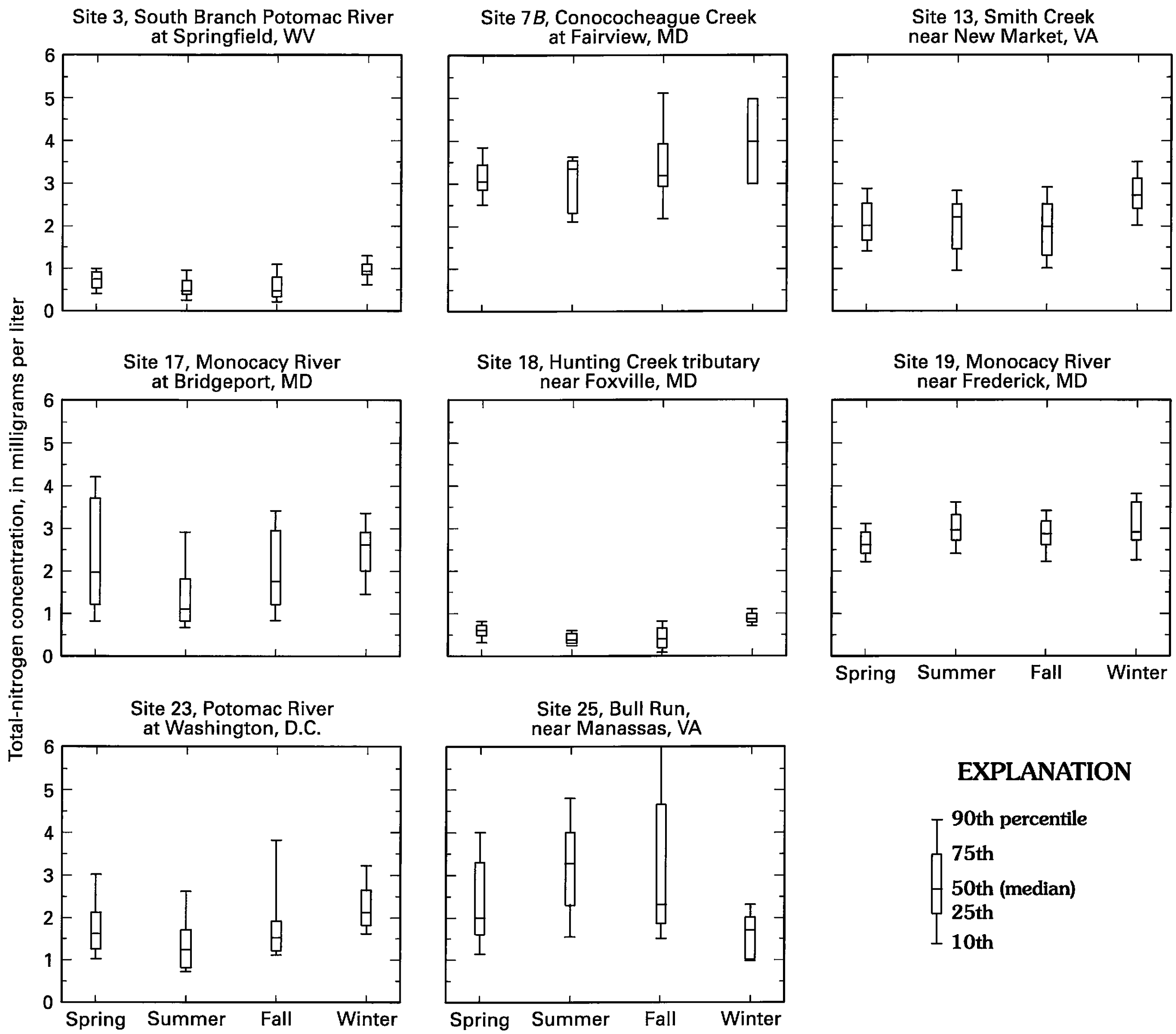


Figure 29. Seasonal total-nitrogen concentrations in water from selected surface-water-quality monitoring sites in the Potomac River Basin, 1970–90. Location of sites shown in figure 16.

centrations in water from the South Fork Shenandoah River (site 11). Flow-adjusted concentrations in figure 31, however, appear stable throughout the period at site 11. Blomquist (1993) reported no significant trend in total-nitrogen concentrations at sites 8, 15, and 23, the three long-term monitoring stations operated by the USGS NASQAN program.

None of the 25 monitoring sites with sufficient data to infer trends showed a large decline in total-nitrogen or dissolved-nitrate concentrations for 1970–90. Dissolved-nitrate concentrations increased at two sites during 1975–80. Site 7*A* on Conococheague Creek drains a watershed in the Great Valley where agricultural inputs of nitrogen predominate. Increasing nitrate concentrations in water from site 21 on Seneca Creek may result from increased wastewater discharge as the watershed has undergone urban development during this period. The Conococheague Creek watershed has experienced less development than Seneca Creek, and increasing nitrate concentrations may be related to changing agricultural practices. Specifically, increased fertilization and manure-application rates designed to increase crop yield can increase nitrogen concentrations in streams.

No agricultural watershed showed a declining trend for total nitrogen, dissolved nitrate, or dissolved ammonia in surface water. Agricultural nutrient best-management practices (BMP's) have been imple-

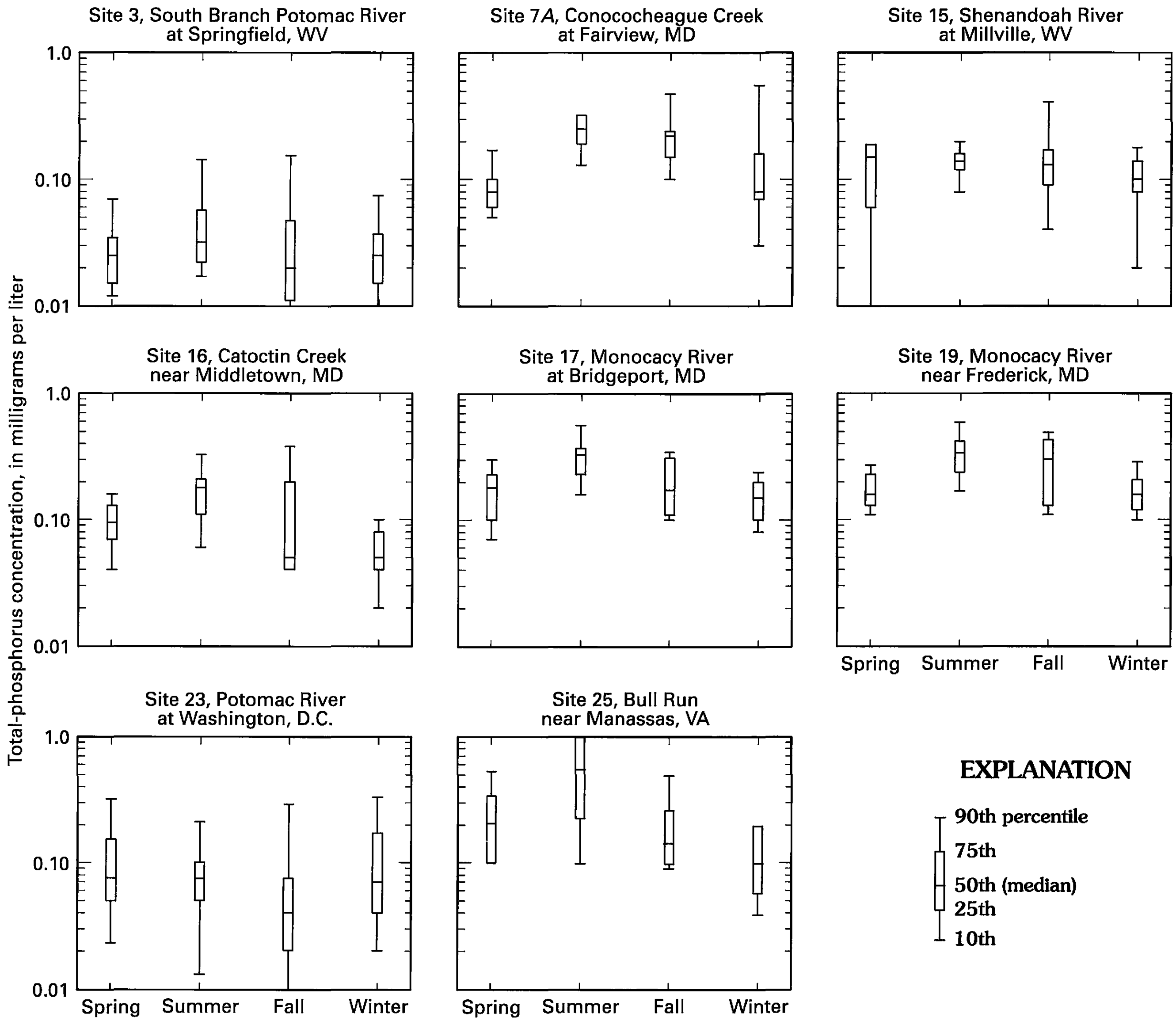
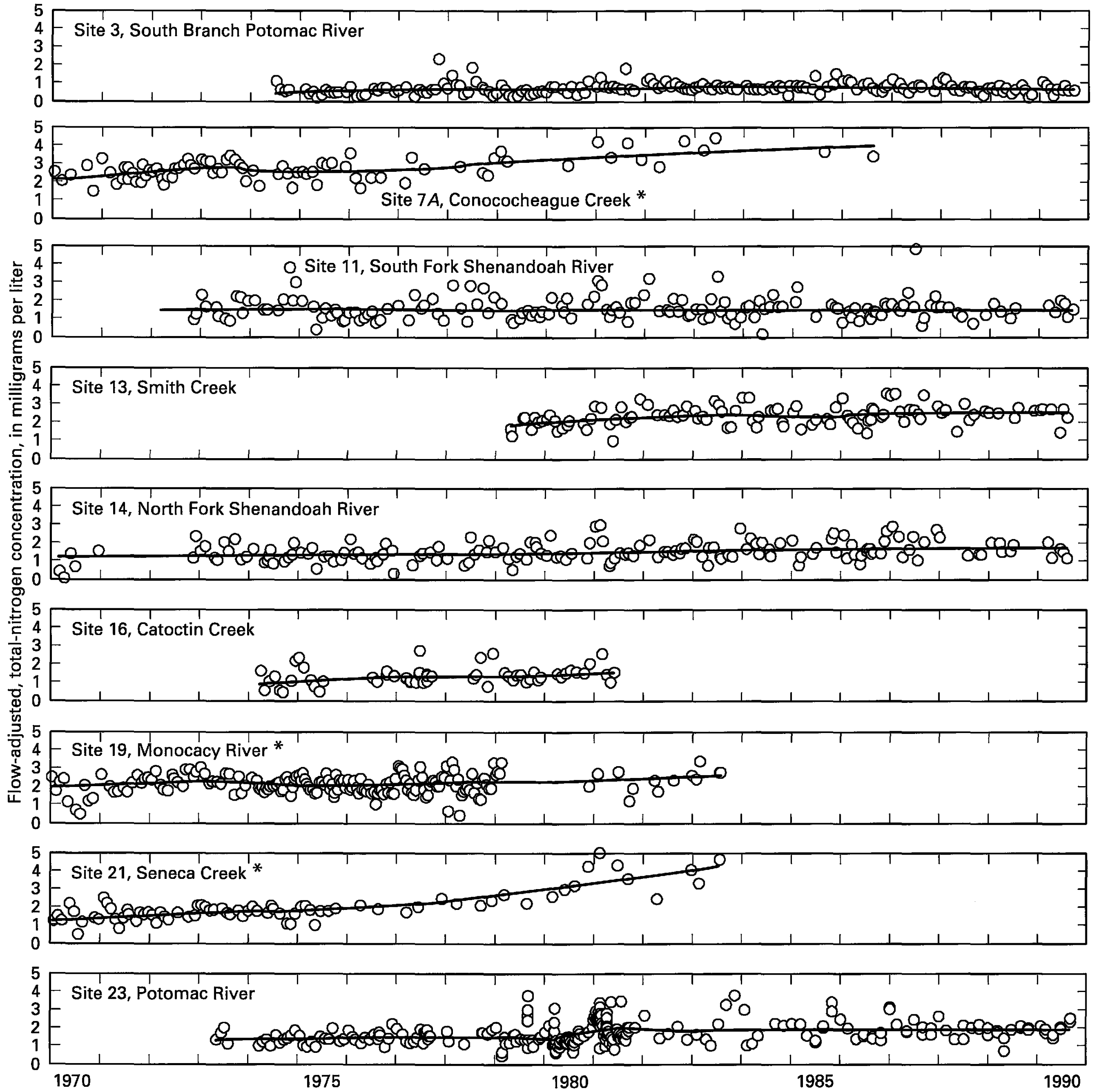


Figure 30. Seasonal total-phosphorus concentrations in water from selected surface-water-quality monitoring sites in the Potomac River Basin, 1970–90. Location of sites shown in figure 16.

mented at numerous farms throughout the Potomac River Basin through cooperative efforts of the Natural Resources Conservation Service, Agricultural Stabilization and Conservation Service, and State and county agricultural extension agents. These efforts typically are designed to minimize runoff of nitrogen, phosphorus, and sediment by use of conservation-tillage practices and improved manure-management procedures. In some cases, nitrogen concentrations may be changing but at an imperceptible rate as many monitoring programs may have insufficient numbers and types of samples to detect slight changes in nutrient concentrations. In settings such as the carbonate regions of the Great Valley subunit, chemical nitrogen reduction in ground water may be minimal, and BMP's may cause long-term increases in nitrate concentrations in ground water. This may result in a long-term increase in nitrate concentrations in surface water during base-flow conditions.

Total-phosphorus and dissolved-orthophosphate concentrations in surface water appear to decline in many watersheds for 1970–90 (fig. 32). The downward trend is most apparent at sites with wastewater discharged upstream. These declines are likely due to improvements in wastewater-treatment facilities, implementation of agricultural BMP's, and the ban of phosphate-based detergents first enacted by the State of Maryland in 1973 and later enacted in Pennsylvania



EXPLANATION

* Dissolved-nitrate concentration shown in milligrams per liter as nitrogen

Figure 31. Flow-adjusted, total-nitrogen concentrations through time in water from selected surface-water-quality monitoring sites, 1970–90. Location of sites shown in figure 16.

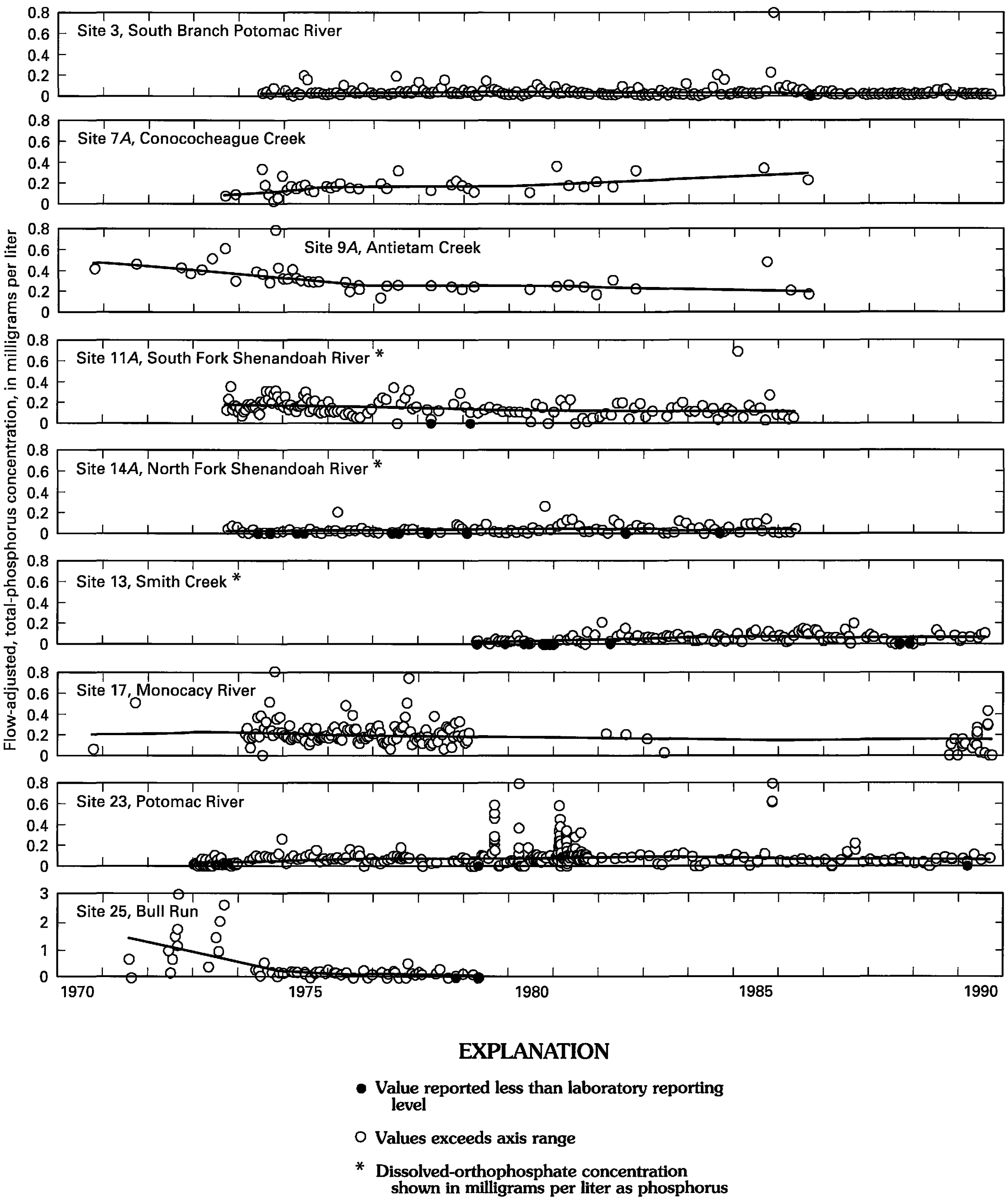


Figure 32. Flow-adjusted total-phosphorus concentrations through time in water from selected surface-water-quality monitoring sites, 1970–90. Location of sites shown in figure 16.

and Virginia. Because municipal effluent contributes a small part of the phosphorus in the rural areas upstream from Washington, D.C., no trend was apparent in water from the Potomac River (site 23). The trends detected in water from other sites are only slight because most of the sampling periods began in late 1973 following implementation of the phosphate-detergent ban. The greatest decline in total-phosphorus concentration occurs in water from Bull Run (site 25) where concentrations decline substantially between 1971 and 1974 as tertiary treatment was brought on-line at the municipal wastewater-treatment facility. Phosphorus concentrations in municipal wastewater have declined substantially due to the ban on phosphate detergents; however, most of the wastewater discharges are located downstream of the 25 monitoring sites.

Trombley (1989) reported downward trends in total-phosphorus concentrations in water from Antietam Creek (site 9*A*) and from the Potomac River at Point of Rocks, Md., downstream from its confluence with the Shenandoah River. Other slight downward trends are apparent in water from sites 11*A* and 17 (fig. 32) where agricultural practices and wastewater discharges are both significant sources of phosphorus. Trombley (1989) reported an upward trend in total-phosphorus concentrations in water from Conococheague Creek (site 7*A*) and the Potomac River Shepherdstown, W. Va. (site 8).

Nutrient Loads and Mass Budget

This report refines current knowledge of nutrient movement in the Potomac River Basin by estimating loads of dissolved nitrate, total nitrogen, and total phosphorus at 20 of the 25 surface-water-quality monitoring sites on the selected tributaries that are used in the preceding analyses of nutrient concentrations and nutrient inputs. Previous investigations of nutrient loadings of the Potomac River focus their analysis at the most downstream nontidal site, Potomac River at Washington, D.C. (site 23). Although load estimates at this site provide a good estimate of nutrients reaching the Potomac estuary and Chesapeake Bay from the upper Potomac River Basin, the relative contributions of major tributaries are not addressed, and processes affecting nutrient loads are often oversimplified. Long-term mean annual nutrient loads are presented for the 20 sites in table 14 along with the period of estimation and mean standard error of the model estimate. Annual loads are included in table 16 at the end of this report. Mean annual load estimates are used for site-to-site comparisons to avoid problems caused by comparing years of differing hydrologic conditions. Computation of nitrogen and phosphorus loads was attempted for dissolved nitrate, total nitrogen, and total phosphorus at all 25 sites. Loads are reported only for those sites and constituents that met data-quality controls.

Understanding the mass balance of nutrients in the Potomac River and its tributaries is essential when assessing relative effects of point sources, nonpoint sources, and land use within the watershed. It is particularly important to understand these relative effects within watersheds of the Potomac River Basin in order to appropriately manage the quality of surface water reaching the Potomac estuary and Chesapeake Bay. In addition to the estimates of nutrient sources presented earlier, several approaches to understanding the mass transport of nutrients in the Potomac River Basin are used here. Relative contributions of measured nutrient loads from the major watersheds draining large regions of diverse land use and physiography are compared. Nutrient loads per unit area (yields) are compared with major land-use patterns and source estimates within the watersheds. Also, data from selected watersheds are used to evaluate base-flow nutrient-load contributions and compare those loads with total loads and point-source loads.

Loads in Major Tributaries

The mass movement of nitrogen and phosphorus in surface water of the Potomac River Basin differs considerably among the major tributary systems. Nitrogen and phosphorus loads previously have been determined for the upper Potomac River Basin at Washington, D.C., by the USGS (L.D. Zynjuk, U.S. Geological Survey, written commun., 1994) as part of ongoing efforts by State and Federal agencies to monitor and control nutrient loads to the Potomac estuary and Chesapeake Bay. In November 1992, the USEPA's Chesapeake Bay Program set nutrient-load goals for all major tributaries of Chesapeake Bay to achieve a 40-percent reduction of nitrogen and phosphorus loads by the year 2000 (Alliance for the Chesapeake Bay, 1993). Targeted nutrient-load reductions for the Potomac River are 18.7 and 1.71 million lb of nitrogen and phosphorus, respectively. To date, however, the relative contributions of nutrients from major tributaries have only been estimated through estimates of input and runoff and have not been determined

Table 14. Estimated long-term mean annual loads of total nitrogen, dissolved nitrate, and total phosphorus at selected sites in the Potomac River Basin

[Loads and uncertainties reported in thousands of pounds per year; --, not calculated]

Site no.[1] (fig. 16)	Stream name	Period of record (water years)	Total nitrogen		Dissolved nitrate as nitrogen		Total phosphorus	
			Load	Standard error of estimate	Load	Standard error of estimate	Load	Standard error of estimate
1	North Branch Potomac River	1975–85	767	98.1	631	43	101.2	23.5
2	North Branch Potomac River	1973–83	--	--	2,580	276	190	33.8
3	South Branch Potomac River	1979–89	2,880	288	2,920	551	168	49.3
6	Cacapon River	1979–89	1,270	354	1,220	581	45.8	12.5
7*A*	Concocheague Creek	1979–86	--	--	4,640	387	243	76.6
8*A*	Potomac River	1979–89	24,100	1,650	14,000	803	1,420	216
8*B*	Potomac River	1979–87	20,000	2,020	--	--	2,440	705
9*A*	Antietam Creek	1979–86	--	--	2,720	224	--	--
10	Christians Creek	1979–89	346	49.8	255	36.2	30.1	8.98
11*B*	South Fork Shenandoah River	1979–89	--	--	3,900	452	654	220
12	North Fork Shenandoah River	1979–89	502	53.4	--	--	34.4	16
13	Smith Creek	1979–89	351	22.5	--	--	--	--
14*A*	North Fork Shenandoah River	1979–89	--	--	2,370	295	--	--
14*B*	North Fork Shenandoah River	1979–89	2,240	154	2,250	280	--	--
15	Shenandoah River	1979–89	--	--	9,050	1,290	1,030	176
17	Monocacy River	1979–89	--	--	824	224	45.4	8.47
18	Hunting Creek tributary	1982–89	--	--	9.62	1.06	--	--
19	Monocacy River	1973–83	6,800	399	4,660	255	535	66.1
20	Goose Creek	1979–87	1,430	154	1,220	199	75.3	16.6
21*B*	Seneca Creek	1979–89	--	--	500	45.1	19.1	7.45
22	Difficult River	1979–89	151	9.82	95.7	7.82	15.3	4.77
23	Potomac River	1979–89	60,000	3,230	38,500	3,940	5,780	1,330

[1]Site identifier: A, U.S. Geological Survey data; B, non-U.S. Geological Survey data.

using in-stream measurements. The load estimates presented here should prove useful as specific nutrient-reduction strategies are developed for the Potomac River Basin.

The Potomac River at Washington, D.C. (site 23), discharges a long-term average of 60 million lb of total nitrogen and 5.79 million lb of total phosphorus per year (table 14). Downstream from the Washington, D.C., site, an additional 28.7 million lb of total nitrogen and 0.63 million lb of total phosphorus are discharged to the estuary from municipal and industrial sources, and 1.94 million lb of total nitrogen are deposited directly into the estuary from atmospheric sources. Nitrogen and phosphorus loads from the many small tributaries draining the basin downstream of site 23 remain unquantified.

The amount of nitrogen transported differs greatly among major Potomac River tributaries. Average annual loads of dissolved nitrate and total nitrogen for two sites on the Potomac River and eight tributaries with drainage areas greater than about 500 mi^2 are compared in figure 33. Dissolved nitrate constitutes the major component of the nitrogen load, and dissolved-nitrate load estimates are available for all 10 sites. Total-nitrogen loads are not available for all sites because insufficient data were available or model assumptions could not be met. Because temporal variations in total-nitrogen concentrations are greater, standard errors of total-nitrogen loads usually are

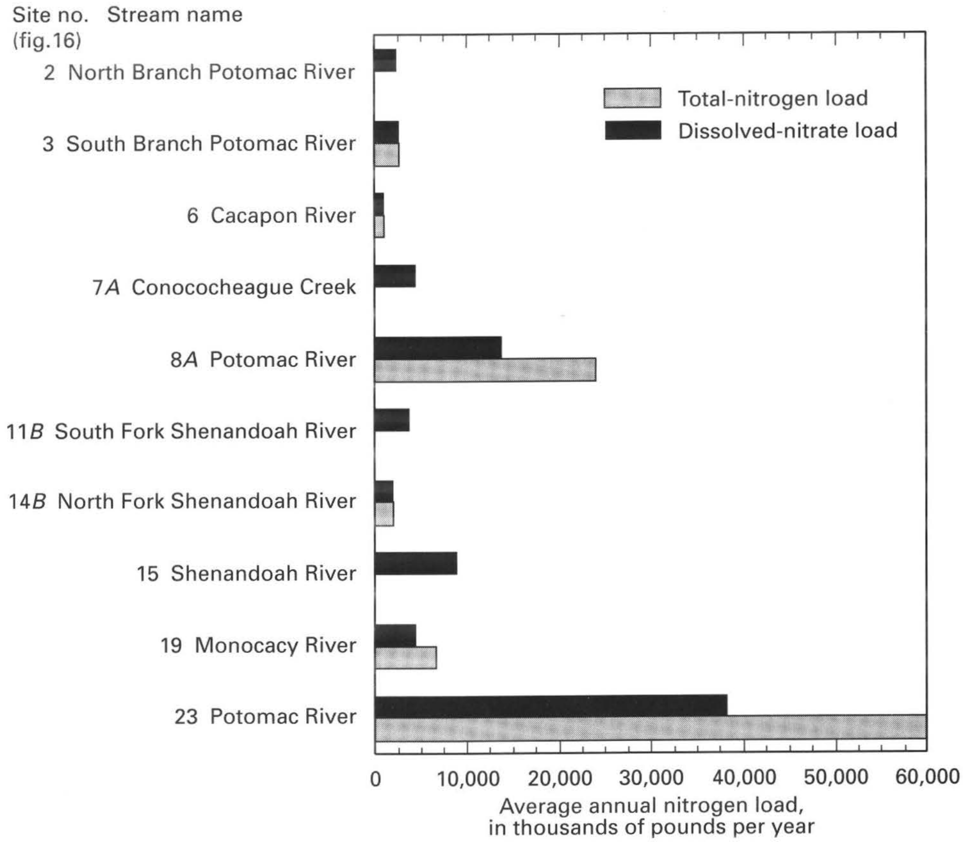


Figure 33. Estimated average annual total-nitrogen and dissolved-nitrate loads in the Potomac River and selected major tributaries.

greater than dissolved-nitrate loads; therefore, dissolved-nitrate loads are better suited for site-to-site comparison of loads. Dissolved-nitrate and total-nitrogen loads differ greatly at main-stem sites 8*A* and 23, with dissolved nitrate comprising 58 and 64 percent of the total load, respectively. At sites 3, 6, and 14, dissolved nitrate and total-nitrogen loads are nearly equal. In some cases the estimated dissolved-nitrate loads may exceed the estimated total-nitrogen loads. This is physically impossible; however, both estimates are within the standard errors of the load estimates. This indicates that dissolved-nitrate comprises nearly all the nitrogen load at these sites.

The average annual nitrogen load at main-stem Potomac River site 8*A* is the highest of the nine sites upstream of the Potomac River at Washington, D.C. The 14-million-lb dissolved-nitrate load and 24.2-million-lb total-nitrogen load at this site comprise 36 and 40 percent of the loads at site 23, and site 8*A* represents 51 percent of the watershed upstream of Washington, D.C. The Shenandoah River (site 15), Monocacy River (site 19), and Conococheague Creek (site 7*A*) are the three tributaries with the largest annual load of dissolved nitrogen as nitrate. These three watersheds have large agricultural regions, and each has an annual load greater than 4.5 million lb of dissolved nitrate. In the Shenandoah watershed, the South Fork Shenandoah River (site 11*B*) carries a larger annual dissolved-nitrate load than the North Fork Shenandoah River (site 14*A*) and contributes about 43 percent of the load to site 15 compared to 26 percent of the load at site 14*A*. Three major tributaries in the forest headwaters, North Branch Potomac River (site 2), South Branch Potomac River (site 3), and Cacapon River (site 6), contribute relatively small loads of dissolved nitrate to the Potomac River. These watersheds drain approximately 25.9 percent of the basin (table 6) yet contribute only 17.5 percent of the dissolved-nitrate load measured at Washington, D.C. (site 23).

Average annual total-phosphorus loads also differ among major tributaries to the Potomac River (fig. 34). Standard errors of the estimates of total-phosphorus loads are quite large relative to nitrogen loads and range from 12 to 49 percent. However, basinwide patterns in total-phosphorus loads are still

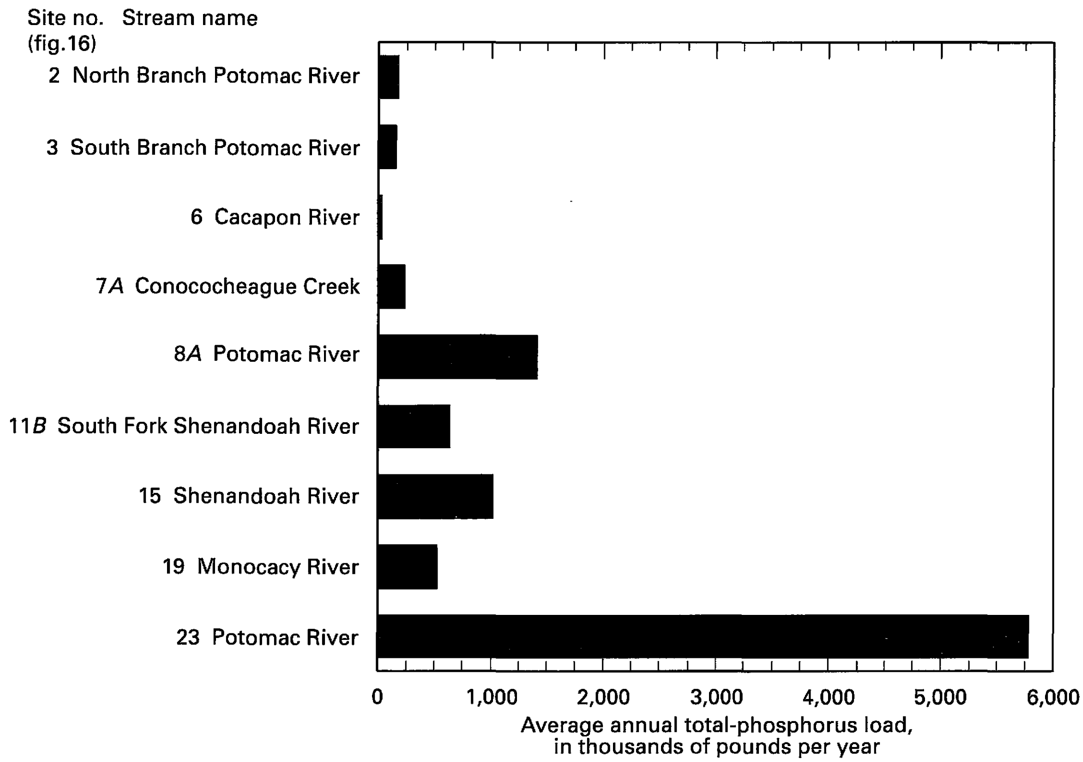


Figure 34. Estimated average annual total-phosphorus loads in the Potomac River and selected major tributaries.

discernible. Because phosphorus loads are most dependent upon high-flow conditions, more intense storm sampling is needed to improve these estimates. Potomac River at Washington, D.C. (site 23), has an average annual total-phosphorus load of 5.79 million lb. Potomac River (site 8*B*) carried 2.44 million lb of phosphorus—42 percent of the load at site 23. Three agricultural tributaries, South Fork Shenandoah River (site 11*B*), Shenandoah River (site 15), and Monocacy River (site 19), carried annual phosphorus loads greater than 0.5 million lb/yr. The three major forest tributaries (sites 2, 3, and 6) had phosphorus loads less than 0.2 million lb and contributed only 7 percent of the load measured at Potomac River at Washington, D.C. (site 23).

Mass Budget and Land Use

The balance of nutrient inputs and nutrient exports (loads) differs among the tributaries of the Potomac River Basin. These differences are primarily related to the land-use practices within the watersheds and resultant nutrient inputs. In general, larger nutrient yields (loads per unit area) correspond with larger nutrient inputs, and inputs of both nutrients are largest in watersheds dominated by agricultural land use.

The nutrient-input and nutrient-load data compiled for this report are used to show the general mass budget of nitrogen and phosphorus in the Potomac River Basin. Differences in nitrogen and phosphorus mass-budget characteristics occur in watersheds with similar land uses, and these differences appear to be related to hydrogeologic properties of the watersheds. Several recent studies have presented a watershed mass balance of nitrogen and phosphorus in the upper Potomac River Basin. Fisher and Oppenheimer (1991) used a nitrogen-flow model to assess the relative contributions of atmospheric deposition and other inputs to the Potomac River Basin. Lugbill (1990) presented and assessed relative contributions of numerous nutrient inputs to the Potomac River Basin. Jaworski and others (1992) builds upon these studies by simplifying the nitrogen-flow model and by balancing inputs with nitrogen and phosphorus loads measured for the Potomac River at Washington, D.C. These approaches account for the mass balance of nutrients in the upper Potomac River Basin; however, they certainly simplify the numerous and varied processes affecting the mass balance in major parts of the Potomac River watershed.

The following discussion attempts to refine the knowledge of the sources of nutrients to watersheds and the transport of nutrients in surface water. Mass budgets of nitrogen and phosphorus in major tributaries indicate large-scale differences in budgets throughout the basin. Mass budgets in smaller watersheds are indicative of common land-use practices and hydrogeologic settings that occur throughout the Potomac River Basin.

Nitrogen and phosphorus yields show substantial differences in nutrient transport throughout the Potomac River Basin. Dissolved-nitrate and total-nitrogen yields from the upper Potomac River (site 23) are 3,300 and 5,140 lb/mi^2, respectively. Dissolved-nitrate yields in contributing tributaries range from 1,650 to 9,690 lb/mi^2, and total-nitrogen yields range from 1,870 to 8,330 lb/mi^2. The geographic distribution of dissolved-nitrate and total-nitrogen yields is shown in figure 35. Both maps show similar patterns, although load data for both nitrogen species are unavailable at all sites. Dissolved-nitrate yields are smallest, less than 2,000 lb/mi^2, in three forest and sparsely populated watersheds, sites 3, 6, and 18, and one urban watershed, site 22. Dissolved-nitrate yields are slightly higher in watersheds draining the Appalachian Plateau, sites 1 and 2; the Shenandoah Valley, sites 10, 11, and 14; and the Piedmont in Virginia, site 20. Dissolved-nitrate yields are between 4,000 and 6,000 lb/mi^2 at sites 17, 19, and 21 in the Piedmont and Triassic Lowlands of Maryland and Pennsylvania. The largest dissolved-nitrate yields occur at Conococheague Creek (site 7) and Antietam Creek (site 9) in the northern part of the Great Valley in Maryland and Pennsylvania. Conococheague Creek and Antietam Creek deliver more than 9,000 lb/mi^2 of nitrate to the Potomac River, more than double the magnitude of sites 11 and 14, which drain similar settings of the South Fork and North Fork Shenandoah Rivers.

Total-nitrogen yields are available for fewer sites than dissolved nitrate; however, a similar geographic pattern occurs. In most cases, total-nitrogen yields are larger than dissolved-nitrate yields. The Monocacy River watershed (site 19) yields 8,210 lb/mi^2 of total nitrogen to the Potomac River, the largest total-nitrogen yield found in the basin.

The transport of phosphorus in tributaries is also highly variable as total-phosphorus yields range from 68 to 654 lb/mi^2. The total-phosphorus yield for the upper Potomac River Basin (site 23) is 496 lb/mi^2. Small phosphorus yields occur primarily in forest watersheds of the Valley and Ridge subunit, including sites 3, 6, and 12 (fig. 36). Seneca Creek (site 21) in the Piedmont subunit, however, also has a relatively small phosphorus yield at 189 lb/mi^2. Larger phosphorus yields occur in watersheds with greater agricultural intensity and higher inputs from wastewater-treatment facilities. The largest phosphorus yields occur at sites 1, 7, 10, and 19, but only Monocacy River (site 19) had a phosphorus yield (654 lb/mi^2) exceeding the downstream yield at site 23. The relatively large phosphorus yield of the North Branch Potomac River, site 1, may be related to several factors including the effects of acid-mine drainage, erosion from mining and silviculture, and wastewater discharges. Acid-mine drainage may limit in-stream algal uptake of phosphorus, and increased erosion causes elevated phosphorus concentrations as phosphate often is bound to suspended sediment. Agricultural runoff appears to be the primary source of phosphorus at other sites, although the combined effect of wastewater discharge also is important to total-phosphorus yield. Although wastewater discharges may be the primary cause of elevated phosphorus concentrations during stable streamflow, the total-phosphorus load from wastewater is small when compared to total-phosphorus loads in runoff during high-flow conditions.

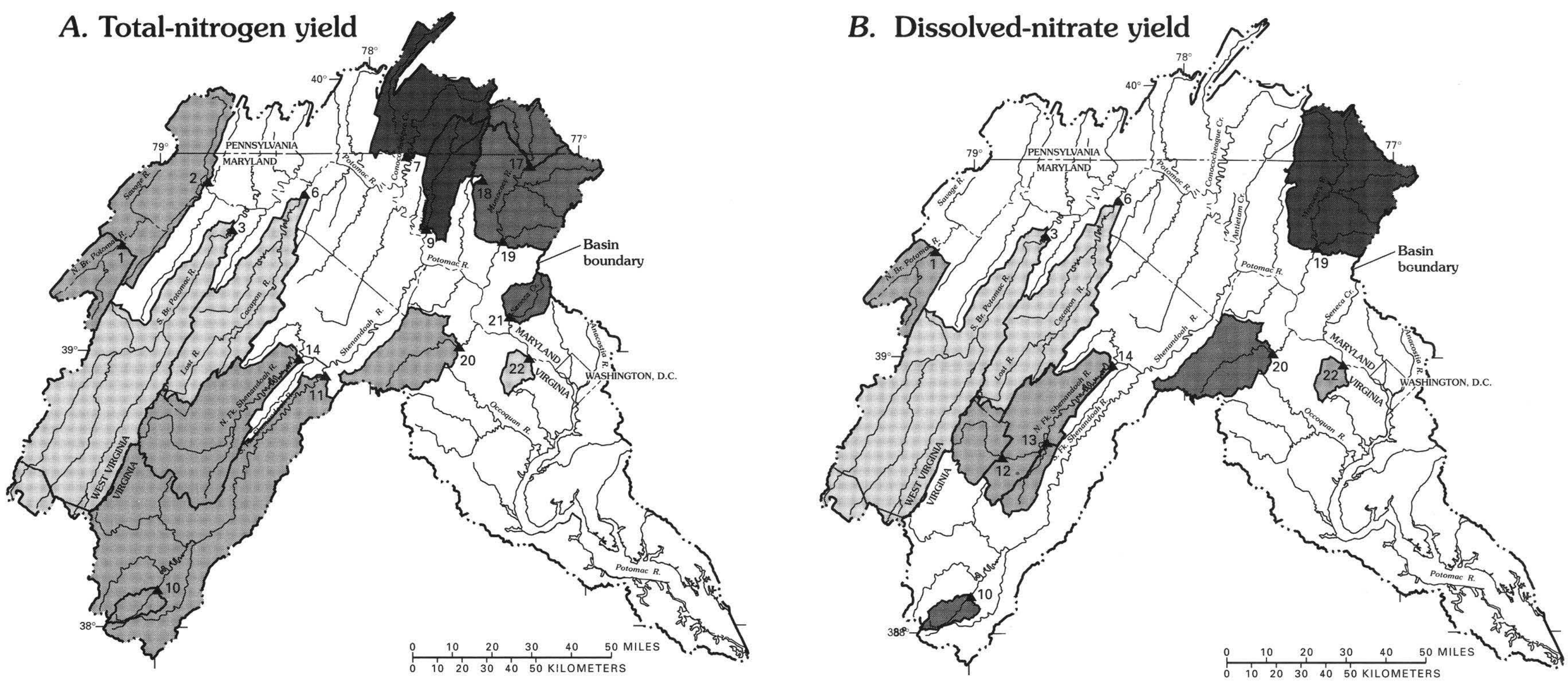
The balance of input and export of nitrogen in the Potomac River Basin is complex and, as indicated by the patterns seen in nutrient concentrations, strongly related to physiography and land-use patterns. A simple watershed nutrient budget essentially accounts for differences in estimates of nutrient input and measured estimates of nutrient loads at monitoring sites. A complete nutrient mass balance quantifies and accounts for major input, output, and storage-change terms for nitrogen and phosphorus within a watershed. Major inputs have been discussed previously. Major watershed output terms include:

(1) harvest of grains, lumber, and animal products,
(2) volatilization,
(3) denitrification,
(4) in-stream uptake and reduction of nutrients, and
(5) export through surface-water discharge.

Major storage-change terms include:

(1) biomass storage, and
(2) ground-water storage.

These mass-balance components are not quantified in this report; however, nitrogen and phosphorus export coefficients are calculated and indicate the percentage



EXPLANATION

Mean annual nitrogen yield for contributing drainage basins, in thousands of pounds per square miles

- Less than or equal to 2.0
- Greater than 2.0 to 4.0
- Greater than 4.0 to 6.0
- Greater than 6.0

—— **Drainage-basin boundary**

10▲ **Location of surface-water-quality monitoring site**—Number corresponds to that in table 16

Figure 35. Mean annual (*A*) total-nitrogen and (*B*) dissolved-nitrate yields for selected watersheds in the Potomac River Basin, 1970–90.

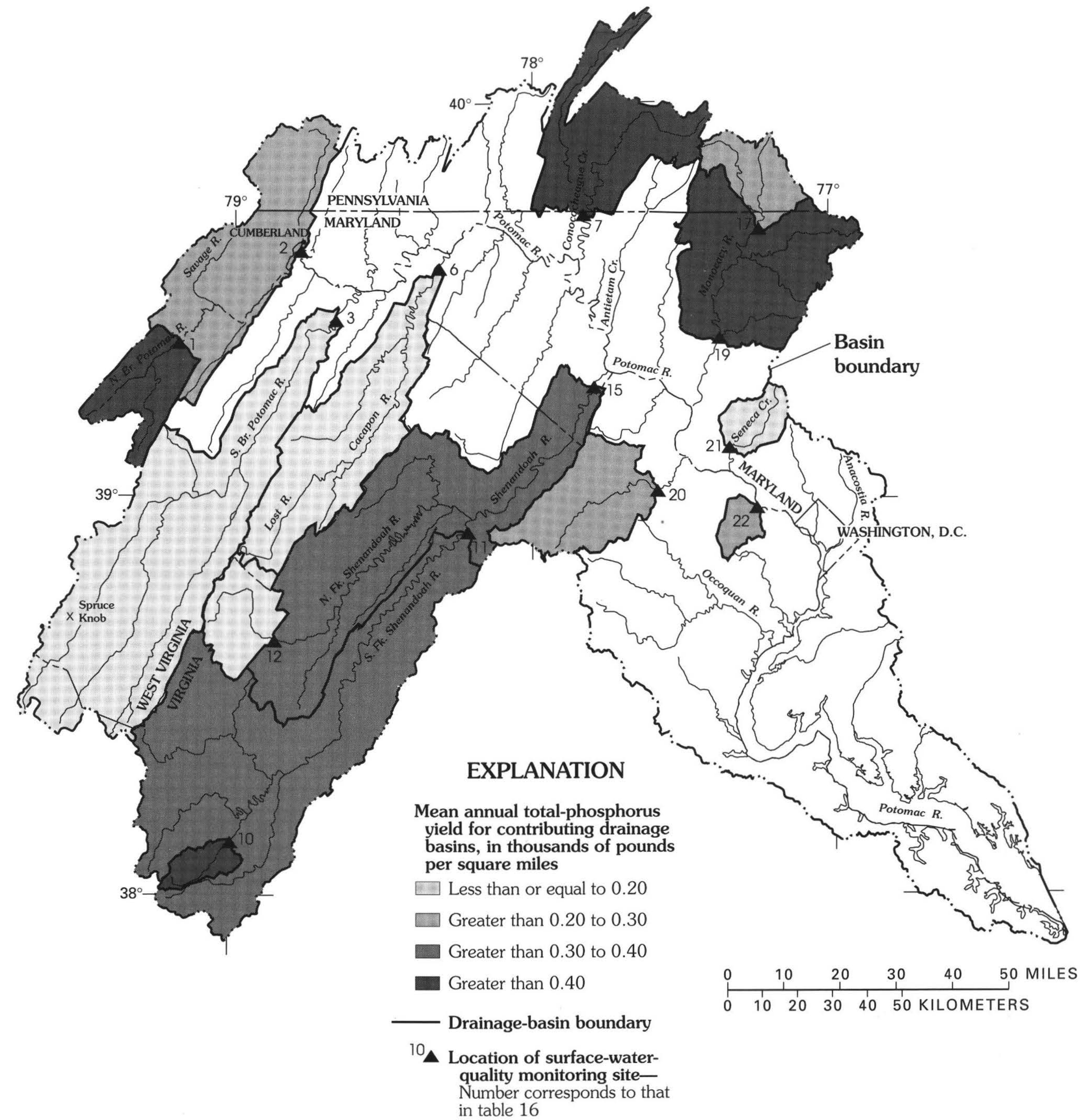


Figure 36. Mean annual total-phosphorus yield for selected watersheds in the Potomac River Basin, 1970–90.

of nutrient inputs that is transported in surface water. Major storage-change terms are assumed to be constant. Because the measured loads are a long-term, "approximately 10-year" average representing normal, wet, and dry climatic cycles, this is probably sufficient. Certainly these storage terms do change from year to year and over decades. The implications of the changes in these storage terms will be discussed later.

Nutrient retention and export in Potomac River tributaries are closely related to land-use practices and sources of nutrients and are affected further by hydrologic processes in the watersheds. Fisher and Oppenheimer's (1991) mass balance of the upper Potomac River Basin found that measured nitrogen and phosphorus exports agreed with predicted exports on the basis of a linear relation of inputs to retention.

However, they point out that there are "no data to determine the key factors regulating nutrient retention processes in the upper Potomac watershed." The nitrogen and phosphorus input and export rates presented here demonstrate the complexity of the input-export relation in tributaries to the Potomac River.

The relation of nitrogen yield to nitrogen input is shown in figure 37 for urban, agricultural, forest, and large watersheds with mixed land use. Simplified models suggest that a linear relation of input to export could be used for all watersheds. In general, yield increases as input increases. However, the proportion of nitrogen exported from these watersheds demonstrates considerable variability. The nutrient-export rate is the percentage of nutrient input to a watershed (tables 7 and 8) that is exported from the watershed as surface-water load (table 14). Nitrogen-export rates for the Potomac River and tributaries range from 7 to 35 percent.

In the Difficult Run (site 22) watershed, the one urban watershed with nutrient-load data, both inputs and yields are low. Inputs are dominated by atmospheric deposition, and 26 percent of the nitrogen is exported. Higher export rates may be expected in urban settings; however, land use in the Difficult Creek watershed is primarily suburban, with well-developed forest buffers.

Nitrogen inputs to agricultural watersheds are higher than the urban watershed and extremely variable, ranging from 16,600 to 56,400 lb/mi^2, and nitrogen-export rates range from 7 to 35 percent of the nitrogen input. Nitrogen-export rates are highest at sites 7, 9, and 19, on Conococheague Creek, Antietam Creek, and Monocacy River. Sites 7 and 9 drain intense agricultural areas in the Great Valley Carbonate subunit. Site 19 drains an agricultural watershed underlain by a combination of siliciclastic, crystalline, and carbonate rock. Fertilizer is the predominant nitrogen source in all three watersheds. Nitrogen-export rates are lowest at sites 13 and 14 in the southern Great Valley, where agricultural sources of nitrogen are dominated by manure.

Nitrogen inputs to forest watersheds (sites 3, 6, 12, and 18) are low, less than 19,000 lb/mi^2, and are dominated by atmospheric deposition. Nitrogen-export rates in most forest watersheds range from 11 to 13 percent. Nitrogen-export rates from the North Branch Potomac River (sites 1 and 2) are 15 to 20 percent higher. The lack of in-stream biological activity caused by acid-mine drainage in much of the watershed may inhibit biological uptake of nitrogen in this area. Site 8 on the Potomac River at Shepherdstown, W. Va., drains a large, primarily forest watershed; however, it is located downstream from the confluence with the highly agricultural watershed of Conococheague Creek and shows a higher export rate of total nitrogen—27 percent.

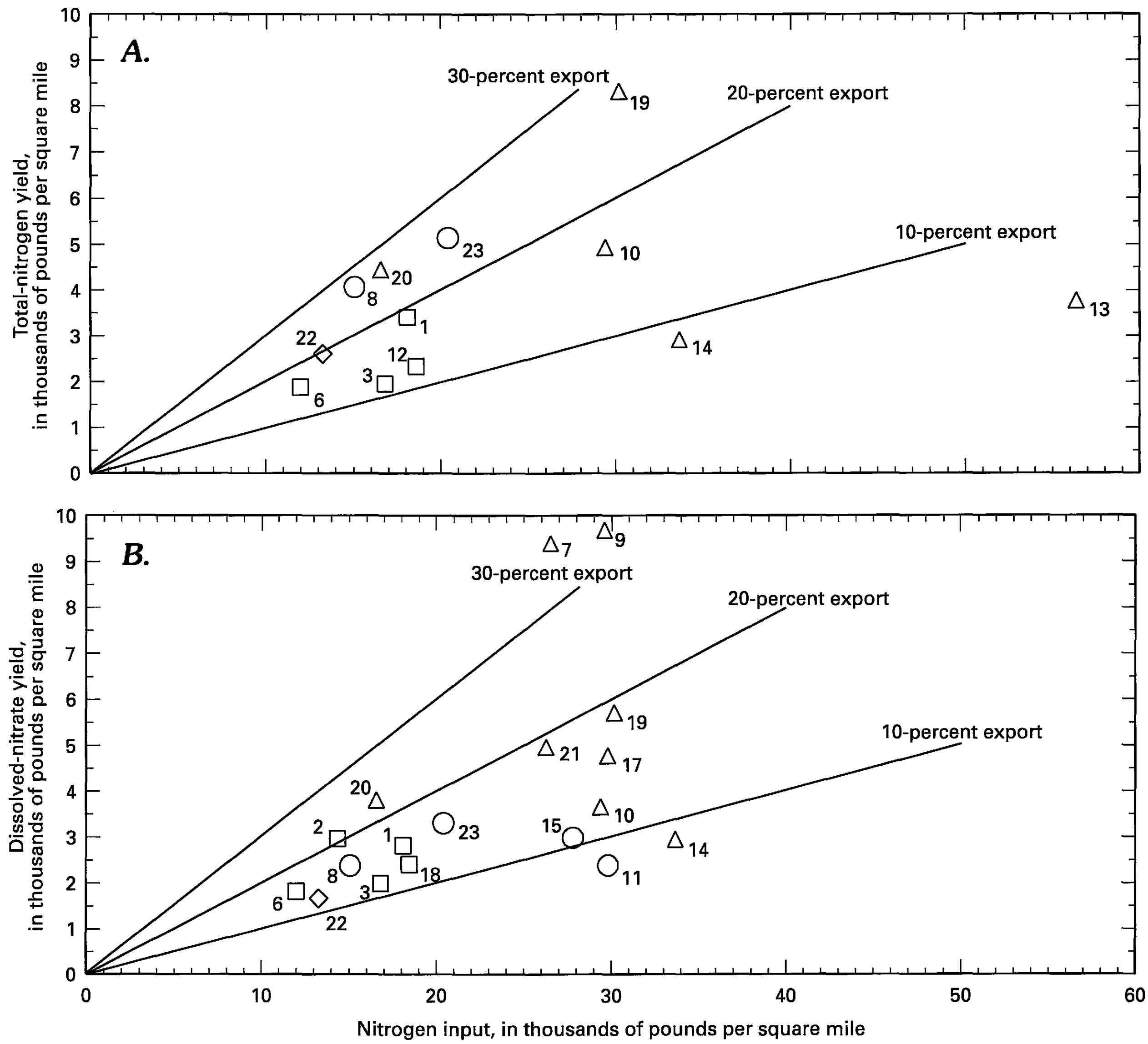
The mass budget of phosphorus in watersheds of the Potomac River Basin also differs considerably among watersheds due to land-use differences and phosphorus sources. Phosphorus inputs range from 600 to 11,900 lb/mi^2, and phosphorus yields range from 68 to 654 lb/mi^2. The relation of phosphorus yield to phosphorus input is shown in figure 38.

The one urban watershed, site 22, exported 26 percent of the phosphorus input; however, the input rate is lowest of all watersheds. Phosphorus-export rates in agricultural watersheds range from 3.4 to 9 percent, and both phosphorus inputs and exports are generally higher than in forest watersheds. Phosphorus-input rates are lowest in forest watersheds, generally less than 2,500 lb/mi^2, and export rates range from 4 to 9 percent. The highest export rates occur in the North Branch Potomac River (sites 1 and 2) and in Difficult Run (site 22). At site 1, 54 percent of the phosphorus is exported in surface water. As stated earlier, increased runoff from mined and forest areas may cause higher phosphorus loads, or acid-mine drainage may limit in-stream biological uptake and storage.

The phosphorus input/export relation in large tributaries with mixed land uses reflects a combination of agricultural and forest land uses. The input/export relation at site 8 on the Potomac River is graphically similar to the predominantly forest sites (fig. 38), and its watershed is 69 percent forest. The South Fork Shenandoah River (site 11) and Shenandoah River (site 15) are similar to agricultural watersheds. The Potomac River at site 23 exports 13 percent of the phosphorus input, and phosphorus exports range from 3.4 to 54 percent. The large standard errors associated with the phosphorus-load estimates probably prohibit an assessment of difference in phosphorus mass-budget characteristics beyond this level.

Base-Flow Nutrient Loads

Ground-water discharge can contribute large amounts of nitrogen to surface water in many tributaries of the Potomac River. It is clear from the analysis of nitrogen loads and mass budget that the processes affecting the transport of nitrogen in the Potomac



EXPLANATION

Land use

◇ Urban—Greater than 50 percent

△ Agricultural—Greater than 60 percent

□ Forest—Greater than 70 percent

○ Mixed—Large watershed (greater than 1,500 square miles)

3 **Monitoring site number**—Location of site given in figure 16

Figure 37. Relation of (*A*) total-nitrogen and (*B*) dissolved-nitrate yields to nitrogen-input rate and land use in the Potomac River Basin.

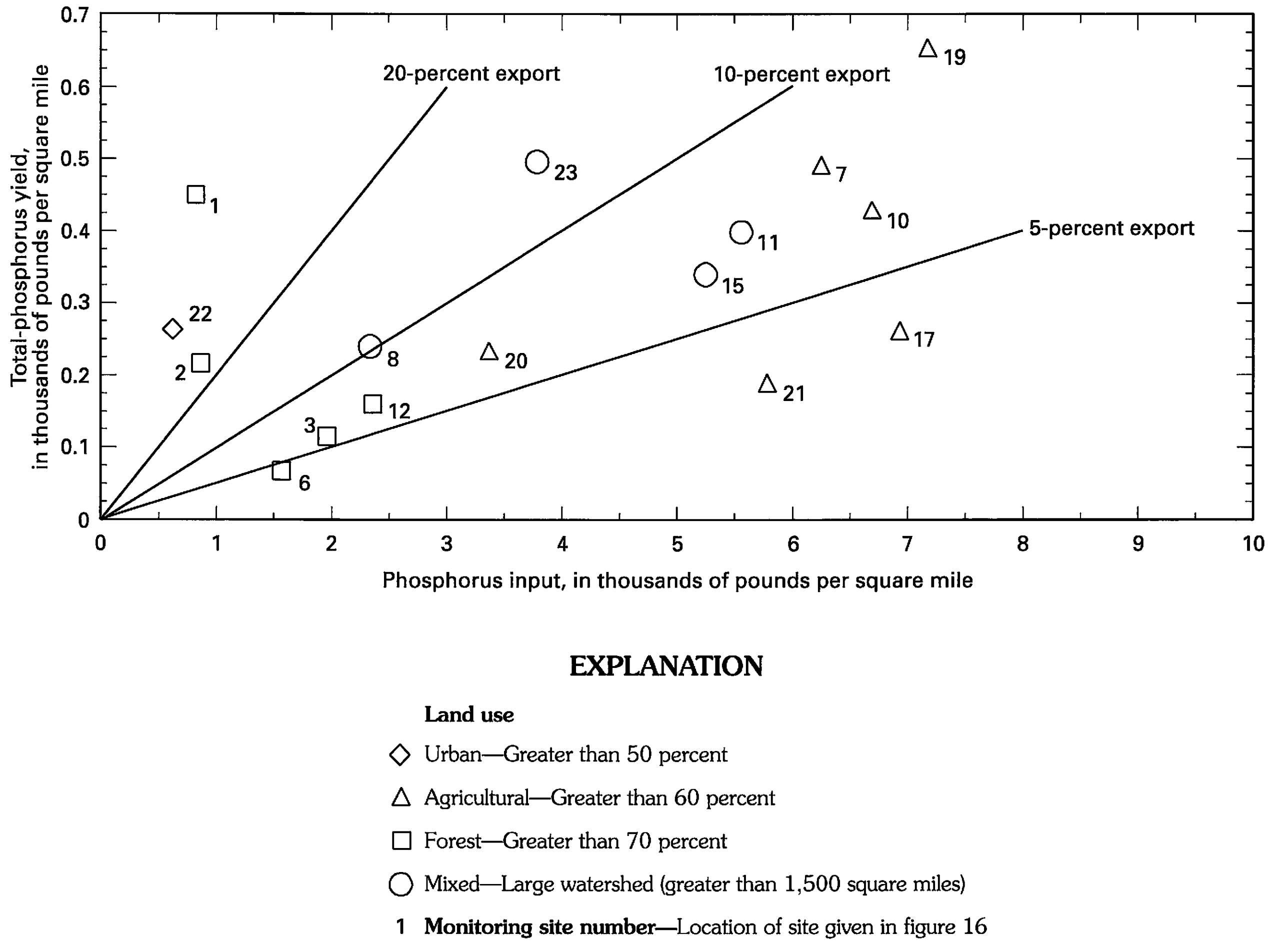


Figure 38. Relation of total-phosphorus yields to phosphorus-input rate and land use in the Potomac River Basin.

River Basin are complex, especially in agricultural watersheds. Ground-water discharge maintains streamflow during base-flow conditions. Thus, that part of the nutrient loads originating in ground water can be termed "base-flow loads." Nitrogen and phosphorus loads in surface water increase substantially during storms, and a large part of the nutrient load generated during storms often is attributed to overland runoff carrying nitrogen and phosphorus into streams from the land surface. In many settings, base-flow loads also increase during storms as ground-water discharge increases. Point-source loads are nearly constant throughout storms as wastewater-treatment facilities discharge nutrients into surface water at a nearly constant rate. Thus, during stable streamflow conditions, surface-water loads are maintained by base-flow and point-source loads. During storm-flow conditions, surface-water loads are caused by point-source, base-flow, and overland-runoff loads combined. An analysis of ground-water nutrient concentrations, streamflow data, and point-source inputs enables estimates of nutrient loads from base flow and point sources to be compared with total-nutrient loads in surface water for watersheds with sufficient ground-water data.

Ground-water discharge may contribute a substantial part of the estimated total-nitrogen load in many watersheds and may contribute a small part of the phosphorus load. Estimates of base-flow nitrogen loads can account for more than 100 percent of measured nitrogen loads in some watersheds. The actual load of nutrients discharged to surface water is expected to be greater than the nutrient load measured at downstream sites because in-stream processes, such as plant and algal uptake and denitrification, can remove nitrogen from the available fluvial system. At a minimum, though, the difference between in-stream nutrient load and base-flow loads originates from either overland runoff or point-source discharges. Base-flow loads are most important to nutrient loads in agricultural areas of the Potomac River Basin, particularly in those areas where concentrations of nitrogen in ground water are elevated due to agricultural land use and where base flow comprises a substantial part of annual streamflow.

Average annual ground-water nitrogen and phosphorus loads were estimated for eight watersheds where a sufficient number and geographic distribution of ground-water samples were available. Ground-water loads were approximated by using a median concentration of all ground-water samples within a watershed and by multiplying that concentration by that part of ground water in streamflow as determined by streamflow hydrograph-separation techniques (Pettyjohn and Henning, 1979; Sloto, 1988). This method of determining base-flow loads assumes that average nutrient concentrations in ground water in wells throughout the basin are the same as concentrations in ground water discharging to streams. The results of these calculations are tabulated in table 15. The contribution of ground water to annual streamflow ranges from 31.8 to 81.3 percent in the watersheds tested. The largest ground-water contributions occur in watersheds underlain by carbonate and crystalline rock. Smaller ground-water contributions occur in watersheds underlain by sedimentary rock of the Triassic Lowlands subunit, such as Monocacy River at Bridgeport (site 17) and Bull Run at Manassas (site 25).

Base-flow loads of nitrogen as nitrate can account for between 3 and 100 percent of the measured nitrogen load at six of the eight sites. Base-flow nitrogen loads in forest watersheds of the North Branch Potomac River (site 1) and Cacapon River (site 6) only contribute 11 and 3 percent of the measured loads. Base-flow loads in agricultural watersheds, however, contribute between 42 and 100 percent of measured loads. The highest percentage base-flow loads occur in Conococheague Creek (site 7) and Antietam Creek (site 9) (fig. 39). Both of these watersheds are largely cropland underlain by carbonate rock where nitrogen transport from surficial application down to the ground-water system can occur quickly. This effect is readily seen as elevated ground-water concentrations and high nitrogen loads in surface water. Base-flow loads in the Triassic Lowlands subunit (sites 17 and 19) are substantially lower (42 percent), primarily due to low infiltration rates and poor transmissivity of the siliciclastic rock. In all cases, ground-water contributions of phosphorus to surface-water loads are minimal. Point-source nitrogen loads are small in relation to total loads at the six sites with load estimates and are largest at sites 7, 9, and 19, where populations are higher.

Implementation of nutrient-management practices in watersheds with large percentages of nitrogen loads derived from base flow requires careful consideration and planning. Many agricultural BMP's are being implemented throughout the basin in an effort to minimize soil erosion and improve water quality by controlling surface runoff and decreasing nutrient contributions to surface water. These practices can be particularly effective at decreasing phosphorus loads to streams as phosphorus is bound to soil particles.

Table 15. Estimated base-flow loads of nitrogen and phosphorus for selected watersheds in the Potomac River Basin
[--, data unavailable]

		Ground-water discharge		Dissolved nitrate as nitrogen			Dissolved orthophosphate as phosphorus		
Site no. (fig. 16)	Stream name	Inches per year	Percent of total stream-flow	Number of ground-water samples	Median (milli-grams per liter)	Base-flow load (thou-sands of pounds per year)	Number of ground-water samples	Median (milli-grams per liter)	Base-flow load (thou-sands of pounds per year)
1	North Branch Potomac River	20.3	63.8	25	0.11	73	15	0	6.63
6	Cacapon River	6.3	51.9	16	.07	43.3	--	--	--
7	Conococheague Creek	12	63.6	24	3.3	2,830	17	.01	8.58
9	Antietam Creek	12.7	81.3	35	5.4	2,800	13	.01	5.19
16	Catoctin Creek	11	63.7	24	3.7	94	--	--	--
17	Monocacy River	6.64	39.2	35	2.1	346	--	--	--
19	Monocacy River	8.61	52.5	161	2.4	2,450	52	.02	20.4
25	Bull run	6.03	31.8	49	.3	8.6	27	.01	1.28

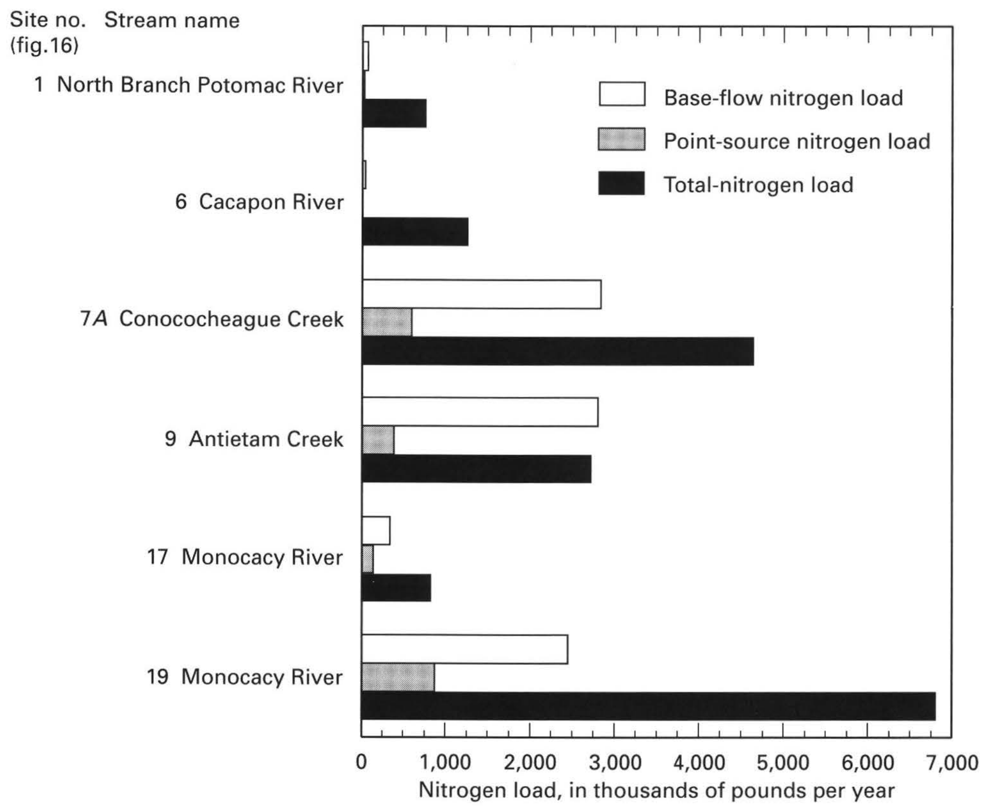


Figure 39. Estimated base-flow nitrogen loads, point-sources nitrogen loads, and total-nitrogen loads for selected watersheds in the Potomac River Basin.

Many of these practices, however, may increase nitrogen concentrations in ground water. Nitrogen loads in surface water may actually increase in areas where nitrogen is not chemically reduced in ground water as nitrogen-containing ground water eventually discharges to streams. Because most BMP's decrease the overland-runoff part of the nutrient loads, they will be most effective where overland runoff contributes a high percentage of the nitrogen load, such as in the Appalachian Plateau, Valley and Ridge, and Triassic Lowlands subunits. Also, these BMP's may be effective at decreasing in-stream nitrogen concentrations in areas where nitrogen is chemically reduced in ground water.

SUMMARY

The Potomac River Basin has a complex environmental setting consisting of various combinations of natural and human factors that can affect water quality in the basin. The 14,670-mi^2 watershed is divided into eight subunits on the basis of basin physiography and geology for the purpose of water-quality assessment. The Appalachian Plateau subunit comprises 4 percent of the basin and is composed primarily of siliciclastic rocks. The Valley and Ridge subunit (34 percent of the basin) is underlain by both siliciclastic and carbonate rocks. The Great Valley is divided into a carbonate subunit (17 percent of the basin) and a noncarbonate subunit (5 percent of the basin). The Blue Ridge subunit (6 percent of the basin) is formed by crystalline rocks. The Piedmont subunit (12 percent of the basin) is underlain by crystalline rocks. The Triassic Lowlands subunit (7 percent of the basin) is underlain by siliciclastic and igneous rocks; the Coastal Plain subunit (15 percent of the basin) by unconsolidated sediments.

Land use in the Potomac River Basin is diverse and generally coincides with physiographic boundaries. The population in the basin increased from about 3.2 million in 1970 to about 4.6 million in 1990, with most people residing in urban land-use settings in the Washington, D.C., area. In the mid-1970's, the basin was 51 percent forest, 36 percent agricultural, and 8 percent urban. By 1985, agricultural land use had decreased to 32 percent and urban land use had increased to 12 percent of the basin. Agriculture comprises 50 percent or more of the land use in the Great Valley Carbonate and Noncarbonate, Piedmont, and Triassic Lowlands subunits, and forests cover more than 75 percent of the land in the Appalachian Plateau, Valley and Ridge, and Blue Ridge subunits.

In 1990, about 6,374 Mgal/d of freshwater (about 85 percent of the average flow of the Potomac River at Washington, D.C.) was used for human-related activities. Surface-water withdrawals accounted for about 97 percent of total freshwater use and for about 93 percent of the public-supply withdrawals. Ground-water withdrawals were about 204 Mgal/d, with 58.3 Mgal/d withdrawn for domestic purposes.

Ground water in the Potomac River Basin is present in a variety of hydrogeologic settings, in both primary and secondary openings in the rock matrix, and in local, intermediate, and regional flow systems. In the Coastal Plain subunit, ground water resides in and moves through interstices between individual mineral grains. Ground water in the rest of the Potomac River Basin resides in and moves through fractures and other secondary openings in the rock matrix. In carbonate rocks, these fractures and openings may be enlarged further by dissolution of the rock matrix. Wells in Coastal Plain deposits, Piedmont sedimentary rocks, and Valley and Ridge sedimentary rocks generally provide the most ground water, whereas wells in the Piedmont and Blue Ridge crystalline rocks and Appalachian Plateau settings have smaller well yields.

Major tributaries to the Potomac River include North and South Branches Potomac River, Cacapon River, Conococheague Creek, Shenandoah River, Monocacy River, and Occoquan River. Total streamflow and the relative proportions of overland runoff and base flow differ throughout the basin. In general, streams in the Appalachian Plateau and Valley and Ridge subunits and that part of the Piedmont subunit underlain by crystalline rocks receive about one-half their flow from base flow. In basins containing carbonate rocks and in basins with substantial regolith, base flow may constitute as much as 65 percent or more of total streamflow. Total streamflow per unit area is highest in the Appalachian Plateau and lowest in the Valley and Ridge subunits, reflecting precipitation patterns in the basin. In watersheds underlain almost entirely by carbonate rocks and in the Coastal Plain, streams derive more than 80 percent of their flow from base flow, reflecting high storage capacity. In contrast, base flow comprises only about 35 percent of total streamflow in that part of the Piedmont underlain by sedimentary rocks of Triassic and Jurassic age.

Nitrogen inputs to the Potomac River Basin in 1990 were dominated by atmospheric deposition and agricultural sources, and phosphorus inputs were dominated by agricultural sources. Commercial fertilizer and animal manure comprised about 55 percent of the nitrogen input, and atmospheric deposition contributed about 32 percent. Municipal and industrial wastewater discharges contributed about 12 percent of the nitrogen inputs. Phosphorus inputs were dominated by agricultural sources throughout the basin, with about 93 percent of the phosphorus inputs coming from commercial fertilizer and animal manure. Municipal and industrial discharges contributed 4 percent of the phosphorus. Municipal wastewater discharge was the largest nutrient source downstream from the Fall Line, and 88 percent of the nitrogen and 80 percent of the phosphorus from wastewater were discharged downstream from Washington, D.C.

The magnitude and relative contributions of nitrogen and phosphorus sources differed considerably among the eight subunits in 1990. The largest nitrogen inputs occurred in the Valley and Ridge and Great Valley Carbonate subunits, and the largest phosphorus inputs occurred in the Great Valley Carbonate subunit. Average rates of nitrogen input from atmospheric deposition were highest in the Appalachian Plateau at 11,217 lb/mi^2 compared to the basinwide rate of 6,582 lb/mi^2. Commercial fertilizer was a significant source of nitrogen in intensely farmed subunits, including the Great Valley Carbonate, Great Valley Noncarbonate, Piedmont, Triassic Lowlands, and Coastal Plain subunits, and a major source of phosphorus in all eight subunits. Animal manure was the largest single source of nitrogen and phosphorus to both Great Valley subunits and contributed more than 50 percent of the phosphorus to the Valley and Ridge subunit. Septic-system inputs were estimated to be only about 2 to 4 percent of the total input.

Estimates of nitrogen and phosphorus inputs to 10 major watersheds (drainage basins greater than 490 mi^2) indicate that municipal wastewater discharges were a relatively small component of total nutrient inputs upstream from the Fall Line. Fertilization rates were highest in the Monocacy River watershed with nitrogen and phosphorus applied at 15,300 and 4,490 lb/mi^2, respectively, and in the Conococheague Creek watershed at nearly 9,370 lb/mi^2 nitrogen and 2,940 lb/mi^2 phosphorus.

The North Fork Shenandoah River had the highest manure production rate at 20,900 lb/mi² nitrogen and 4,660 lb/mi² phosphorus.

Numerous water-quality-monitoring programs have operated within the Potomac River Basin, with much of the resulting information available in the USGS WATSTORE and USEPA STORET computer systems. Nutrient-concentration data are available for water samples from 1,158 wells in WATSTORE and 1,401 wells in STORET. The number of surface-water-quality monitoring sites operated since 1973 by State programs differs from State to State—Maryland (52 sites), Pennsylvania (3 sites), Virginia (89 sites), West Virginia (5 sites), and the District of Columbia (76 sites). Nutrient-concentration data for surface water are available for 31,567 samples from 456 sites in WATSTORE and 50,036 samples from 1,176 sites in STORET. Some of these data are used in the analysis of nutrient-concentration data for this report. Subsets of these data may be used in other analyses of the Potomac River Basin.

Dissolved-nitrate concentrations in ground water vary widely within the Potomac River Basin, with much of the variability related to basin subunits and nutrient inputs from land-use practices. Dissolved-nitrate concentrations in water from 1,049 wells in the WATSTORE data base range from less than 0.01 to 63 mg/L as nitrogen and have a median value of 1.8 mg/L. Dissolved-nitrate concentrations in the Appalachian Plateau, Valley and Ridge, and Coastal Plain subunits generally are low, with median concentrations of 0.10, 0.14, and 0.10 mg/L, respectively. Dissolved-nitrate concentrations were higher in subunits with significant agricultural land use and were highest in the Great Valley Carbonate subunit (median 4.5 mg/L). Fourteen percent of the wells in the Great Valley Carbonate subunit have concentrations greater than or equal to the 10-mg/L MCL for drinking water established by the USEPA.

Nitrate concentrations in ground water varied due to surficial land use, and median concentrations were higher in agricultural settings in the Valley and Ridge, Blue Ridge, Piedmont, and Triassic Lowlands subunits. There were insufficient data to test for land-use effects in the Appalachian Plateau and Great Valley Noncarbonate subunits. In the Blue Ridge subunit, wells in forest settings had a median value (0.41 mg/L) much lower than in urban (2.3 mg/L) and agricultural (2.0 mg/L) settings. Nitrate concentrations in the Piedmont subunit range from less than 0.01 to 37 mg/L. Wells in Piedmont agricultural areas have a higher median concentration (3.3 mg/L) than wells in forest settings (0.18 mg/L). In the Triassic Lowlands, median nitrate concentrations in urban (0.75 mg/L) and forest (0.74 mg/L) settings are lower than for agricultural land (1.8 mg/L).

Nutrient-concentration data for 25 surface-water-quality monitoring sites in the Potomac River Basin show that spatial and temporal patterns in nutrient concentrations are complex. Variations in these patterns are due to differences in physiography, hydrology, land use, and nutrient inputs in the contributing watersheds. Nitrogen and phosphorus concentrations are lowest in the sparsely populated, forest watersheds of the Appalachian Plateau, Valley and Ridge, and Blue Ridge subunits and are highest in the agricultural watersheds of the Great Valley, Piedmont, and Triassic Lowlands subunits and near urban centers where wastewater-treatment inputs are greater. Median concentrations of total nitrogen range from 0.42 to 3.9 mg/L at 22 sites, and median concentrations of dissolved nitrate range from 0.20 to 3.5 mg/L at 25 sites. In the Great Valley, there appears to be a significant difference in nitrogen concentration between northern and southern tributaries. Conococheague Creek and Antietam Creek have the highest median total-nitrogen concentrations of 3.1 and 3.9 mg/L, respectively, and drain the northern part of the Great Valley including parts of Pennsylvania and Maryland. Christians Creek and Smith Creek drain agricultural watersheds in the southern part of the Great Valley of Virginia and have lower median total-nitrogen concentrations of 2.1 and 2.3 mg/L, respectively.

The spatial patterns in total-phosphorus and dissolved-orthophosphate concentrations are largely related to discharges from wastewater-treatment facilities and runoff from agricultural land. Lower concentrations occur in the forest watersheds of the Appalachian Plateau, Valley and Ridge, and Blue Ridge subunits, and higher concentrations occur in streams in the Great Valley, Piedmont, and Triassic Lowlands subunits. Median total-phosphorus concentrations are highest at Antietam Creek (0.30 mg/L), followed by Christians Creek, Monocacy River, and Bull Run. Total-phosphorus concentrations at Bull Run appear to be strongly affected by upstream wastewater discharges, and the other three sites encompass significant agricultural drainage in addition to wastewater discharges.

Temporal variations in nitrogen and phosphorus concentrations in surface water are affected substantially by changes in streamflow conditions and seasonal cycles that often differ from site to site. In forest watersheds, nitrogen concentrations are usually less than 1.0 mg/L and increase only slightly during higher flow conditions. Streams affected by wastewater-treatment-plant discharges show significant dilution of nitrogen and phosphorus concentrations as streamflow increases. Streams draining agricultural watersheds often differ in their response to changing streamflow conditions due to differences in hydrologic properties of the watersheds. Runoff-generated nitrogen concentrations occur in the Triassic Lowlands subunit at the Monocacy River near Bridgeport, Md. During low-flow conditions, concentrations are small, near 1.0 mg/L, and increase substantially during higher streamflows. In agricultural watersheds of the Great Valley subunit, nitrate concentrations increase only slightly with increased streamflow and maintain higher concentrations, 2.0 to 3.0 mg/L, throughout all but the lowest streamflow conditions. Nitrogen concentrations in water from the Potomac River at Washington, D.C., reflect runoff-generated nutrient concentrations; however, because the patterns of contributing watersheds are diverse, the relation of nitrogen concentration to streamflow at this site is complex.

Seasonal fluctuations of total-nitrogen and total-phosphorus concentrations in surface water are generally small at most sites. Median nitrogen concentrations in both agricultural and forest watersheds are highest in the winter and lowest during the summer, and overall variability is slight. Where municipal discharges are substantial, nitrogen concentrations are diluted by higher streamflow during winter months. At nearly all sites, the highest total-phosphorus concentrations occur during the summer months when dilution is minimal.

Few of the 25 surface-water-quality monitoring sites on the Potomac River and its tributaries show significant trends in total-nitrogen concentrations. Sites on Conococheague Creek and Seneca Creek both show a slight increase in nitrogen concentration during the sampling period, and no agricultural watershed shows a declining trend for nitrogen concentration. Total-phosphorus and dissolved-orthophosphate concentrations appear to decline slightly in many of the watersheds due to the ban of phosphate-based detergents first enacted by the State of Maryland in 1973 and later enacted in Pennsylvania and Virginia. The greatest decline in total-phosphorus concentration occurs at Bull Run where concentrations declined substantially between 1971 and 1974.

The Potomac River at Washington, D.C., discharges a long-term average of 60 million lb of total nitrogen and 5.79 million lb of total phosphorus per year. Downstream from the Washington, D.C., site, an additional 28.7 million lb of total nitrogen and 0.63 million lb of total phosphorus are discharged to the estuary from municipal and industrial sources, and 1.94 million lb of total nitrogen are deposited directly into the estuary from atmospheric sources. Three major tributaries, North Branch Potomac, South Branch Potomac, and Cacapon Rivers, contribute relatively small loads of dissolved nitrate to the Potomac River. These drain approximately 25.9 percent of the basin yet contribute only 17.5 percent of the dissolved-nitrate and 7 percent of the total-phosphorus loads measured at Washington, D.C. Much higher nutrient loadings are generated from three predominantly agricultural watersheds—Conococheague Creek, Shenandoah River, and Monocacy River.

Nitrogen and phosphorus yields (loads per unit area) show substantial differences in the amount of nutrient transport throughout the Potomac River Basin. These difference are primarily related to land-use practices within the watersheds and the magnitude of nutrient inputs. Dissolved-nitrate and total-nitrogen yields from the upper Potomac River at Washington, D.C., are 3,300 and 5,140 lb/mi^2, respectively. Dissolved-nitrate yields range from 1,650 to 9,690 lb/mi^2, and total-nitrogen yields in tributaries range from 1,870 to 8,330 lb/mi^2. The smallest dissolved-nitrate yields occur in one urban and three forest watersheds where nitrogen inputs are predominantly from atmospheric sources. The largest dissolved-nitrate yields occur at Conococheague Creek, Antietam Creek, and Monocacy River where agricultural land use is widespread and nitrogen inputs are dominated by commercial fertilizer and animal manure. The transport of phosphorus also differs greatly, as total-phosphorus yields range from 68 to 654 lb/mi^2, with the yield at the Washington, D.C., site being 496 lb/mi^2. Small phosphorus yields occur primarily in forest watersheds of the Valley and Ridge subunit. Larger phosphorus yields occur in watersheds with greater agricultural intensity and inputs from wastewater-treatment facilities.

The proportion of nitrogen inputs retained and exported from Potomac River watersheds differs considerably and is affected by hydrologic processes. Nitrogen inputs to forest watersheds are low, with 11 to 13 percent of the nitrogen being exported in surface water. Nitrogen inputs to agricultural watersheds are higher and more variable, with export rates ranging from 7 to 35 percent. Nitrogen-export rates are highest in Conococheague Creek, Antietam Creek, and Monocacy River where fertilizer is the predominant nitrogen source.

Ground-water discharge can contribute a substantial part of the total-nitrogen load to streams in many watersheds, particularly in those areas where concentrations of nitrogen in ground water are elevated due to agricultural land use. The contribution of ground water to annual streamflow ranges from 31.8 to 81.3 percent, and base-flow loads of nitrogen can account for between 3 and 100 percent of the measured nitrogen load. Base-flow nitrogen loads were largest in Conococheague Creek and Antietam Creek, two agricultural watersheds where base-flow loads contributed about 61 and 100 percent of measured nitrogen loads. Both of these watersheds are largely cropland underlain by carbonate rock where nitrogen transport from surficial application down to the ground-water system can occur quickly. Although land use is similar, base-flow loads in the Triassic Lowlands subunit at Monocacy River are smaller (42 percent), primarily due to low infiltration rates, poor transmissivity of the siliciclastic rocks, and lower nitrogen concentrations in ground water.

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Table 16. Estimated annual loads of total nitrogen, dissolved nitrate, and total phosphorus at selected surface-water-quality monitoring sites in the Potomac River Basin

[Loads and uncertainties reported in thousands of pounds per year; --, loads and uncertainties not estimated. Location of sites shown in figure 16]

Water year	Total nitrogen			Dissolved nitrate as nitrogen			Total phosphorus		
	Load	Standard error	Standard error of estimate	Load	Standard error	Standard error of estimate	Load	Standard error	Standard error of estimate
Site 1 North Branch Potomac River at Kitzmiller, Md.									
1979	1,357	260	269	717	45.2	56.6	107.4	19.6	28.9
1980	862	96.3	103	623	29.6	38.1	91	12.2	19.1
1981	575	40.9	48.2	534	24.3	32.2	76.3	8.98	14.1
1982	577	41.7	50	619	30.6	40.5	97.5	13	20.5
1983	452	33.1	39.9	498	22.7	31.4	76.2	9.33	16.4
1984	776	67.4	78.3	796	46.5	59.4	159.1	27.3	42.2
Mean	767	89.9	98.1	631	33.2	43	101.2	15.1	23.5
Site 2 North Branch Potomac River near Cumberland, Md.									
1973	--	--	--	2,590	194	230	174	33.4	34.6
1974	--	--	--	2,270	155	191	179	25.5	27.2
1975	--	--	--	3,000	234	272	218	27.8	30.2
1976	--	--	--	1,680	113	141	159	18.5	20.6
1977	--	--	--	2,320	179	219	187	23.6	26.5
1978	--	--	--	3,630	334	384	260	34.5	37.5
1979	--	--	--	3,940	411	476	249	33.6	36.2
1980	--	--	--	3,060	250	282	254	40.1	42.4
1981	--	--	--	1,870	183	206	152	31.4	32.6
1982	--	--	--	2,300	305	328	145	40.5	41.2
1983	--	--	--	1,750	298	312	108	42.3	42.7
Mean	--	--	--	2,580	241	276	190	31.9	33.8
Site 3 South Branch Potomac River at Springfield, W.Va.									
1979	3,390	288	318	3,580	549	656	244	41.2	48.9
1980	3,860	307	335	4,050	608	715	282	47.3	55.2
1981	1,560	86	106	1,550	185	256	92.3	10.8	14.5
1982	2,980	249	282	3,050	471	589	167	28.7	35.9
1983	3,020	242	274	3,180	477	595	154	25.4	31.4
1984	4,280	395	429	4,360	718	840	228	41.6	48
1985	2,700	175	206	2,780	362	471	119	15.5	20
1986	3,460	545	578	2,980	495	586	304	198	224
1987	2,720	242	272	2,790	452	546	114	23.8	29.6
1988	1,670	134	157	1,650	268	339	65.7	12.2	16
1989	2,030	193	209	2,100	407	466	83.1	16.4	18.4
Mean	2,880	260	288	2,920	454	551	168	41.9	49.3
Site 6 Cacapon River at Great Cacapon, W.Va.									
1979	1,700	512	534	972	441	484	61.1	16.8	17.5
1980	1,770	435	454	1,340	557	617	73.1	20.1	21
1981	693	100	114	772	257	323	35	6.33	7.1
1982	1,380	368	395	1,380	596	690	49.7	13	14
1983	1,600	419	447	1,900	847	964	58.4	15.8	16.8
1984	2,180	641	669	2,470	1,120	1,230	74.3	20.4	21.4
1985	685	99	118	903	267	347	28	4.36	5.06
1986	1,190	365	386	1,220	436	517	38.8	9.96	10.6
1987	1,210	321	343	1,260	519	600	37.4	9.4	10.1

Table 16. Estimated annual loads of total nitrogen, dissolved nitrate, and total phosphorus at selected surface-water-quality monitoring sites in the Potomac River Basin—Continued

Water year	Total nitrogen Load	Total nitrogen Standard error	Total nitrogen Standard error of estimate	Dissolved nitrate as nitrogen Load	Dissolved nitrate as nitrogen Standard error	Dissolved nitrate as nitrogen Standard error of estimate	Total phosphorus Load	Total phosphorus Standard error	Total phosphorus Standard error of estimate
Site 6 Cacapon River at Great Cacapon, W.Va.—Continued									
1988	874	252	272	707	292	344	26.6	7.33	7.93
1989	653	148	160	522	233	271	21.2	5.35	5.76
Mean	1,270	333	354	1,220	506	581	45.8	11.7	12.5
Site 7A[1] Conococheague Creek at Fairview, Md.									
1979	--	--	--	5,200	300	320	330	130	133
1980	--	--	--	5,020	282	296	231	50.5	51.4
1981	--	--	--	2,700	140	152	144	23.6	24.7
1982	--	--	--	3,810	228	237	166	24	24.6
1983	--	--	--	4,170	304	315	194	35.8	36.7
1984	--	--	--	7,790	743	758	482	221	227
1985	--	--	--	3,140	318	323	143	31.4	31.9
1986	--	--	--	5,300	685	693	252	82.5	83.7
Mean	--	--	--	4,640	375	387	243	74.8	76.6
Site 8A Potomac River at Shepherdstown, W.Va.									
1979	25,200	1,680	1,860	14,200	779	841	1,460	172	207
1980	25,800	1,100	1,250	15,600	600	670	1,310	83.5	99.3
1981	13,100	454	561	8,670	284	337	515	23.7	33
1982	22,200	1,090	1,248	13,200	585	656	1,120	81.2	101
1983	22,600	1,300	1,450	13,100	673	736	1,200	106	129
1984	38,800	2,670	2,920	20,600	1,200	1,280	2,760	331	394
1985	18,200	948	1,050	11,900	586	636	694	47.6	56.2
1986	33,000	2,540	2,910	16,800	962	1,050	4,050	783	1,030
1987	23,900	1,330	1,500	14,300	709	774	1,000	94.1	121
1988	20,500	1,340	1,480	12,300	699	750	881	98.4	119
1989	22,200	1,850	1,920	13,800	1,070	1,100	679	78.2	84.9
Mean	24,100	1,480	1,650	14,000	741	803	1,420	173	216
Site 8B Potomac River at Shepherdstown, W.Va.									
1979	23,700	2,480	2,670	--	--	--	2,350	584	678
1980	24,400	2,220	2,380	--	--	--	2,330	424	477
1981	11,200	767	879	--	--	--	1,050	133	168
1982	17,400	1,390	1,560	--	--	--	1,890	321	390
1983	16,600	1,330	1,500	--	--	--	2,060	378	462
1984	27,800	2,560	2,790	--	--	--	3,940	967	1,116
1985	14,700	889	1,050	--	--	--	1,500	181	229
1986	24,300	2,810	3,080	--	--	--	4,450	1,760	2,170
1987	19,900	2,100	2,250	--	--	--	2,400	551	651
Mean	20,000	1,840	2,020	--	--	--	2,440	589	705
Site 9A Antietam Creek near Sharpsburg, Md.									
1979	--	--	--	2,720	176	181	--	--	--
1980	--	--	--	2,940	176	181	--	--	--
1981	--	--	--	1,650	81.9	85.8	--	--	--
1982	--	--	--	2,380	141	146	--	--	--
1983	--	--	--	2,480	175	180	--	--	--

Table 16. Estimated annual loads of total nitrogen, dissolved nitrate, and total phosphorus at selected surface-water-quality monitoring sites in the Potomac River Basin—Continued

Water year	Total nitrogen			Dissolved nitrate as nitrogen			Total phosphorus		
	Load	Standard error	Standard error of estimate	Load	Standard error	Standard error of estimate	Load	Standard error	Standard error of estimate
Site 9*A* Antietam Creek near Sharpsburg, Md.—Continued									
1984	--	--	--	4,310	431	436	--	--	--
1985	--	--	--	2,320	221	224	--	--	--
1986	--	--	--	2,970	358	361	--	--	--
Mean	--	--	--	2,720	220	224	--	--	--
Site 10 Christians Creek at Fishersville, Va.									
1979	335	58.2	60.1	224	40.9	42.2	22.3	7.07	7.32
1980	379	37.8	39.3	285	33.4	34.7	24.6	4.3	4.49
1981	96.2	5.17	5.52	71.2	4.83	5.2	12.5	1.2	1.25
1982	253	19.8	21.8	186	14.9	16.4	23.5	3.48	3.9
1983	368	44.6	46.8	263	31	32.6	33.5	7.74	8.18
1984	572	81.5	83.7	410	61.9	63.6	50.3	13.6	14
1985	275	16.1	18.1	223	15.1	16.9	24.8	2.34	2.63
1986	435	97.9	102	304	57.6	60	51.2	28	29.4
1987	494	89.8	92.8	351	56.9	58.8	44.2	17.1	17.8
1988	184	10.7	11.3	161	12	12.7	16	1.6	1.67
1989	417	64.1	66.1	326	54.1	55.6	28.2	7.81	8.1
Mean	346	47.8	49.8	255	34.8	36.2	30.1	8.57	8.98
Site 11*B* South Fork Shenandoah River at Front Royal, Va.									
1979	--	--	--	4,740	488	545	804	160	176
1980	--	--	--	6,450	686	755	712	75.7	82.9
1981	--	--	--	1,620	131	156	271	18.9	20.9
1982	--	--	--	3,740	328	383	468	39.2	46.6
1983	--	--	--	4,450	428	486	611	73.3	81.9
1984	--	--	--	6,290	649	717	859	156	172
1985	--	--	--	3,260	268	318	335	21.2	25.2
1986	--	--	--	3,660	351	410	1,810	1,400	1,510
1987	--	--	--	3,600	386	428	673	190	213
1988	--	--	--	2,640	319	349	288	29.9	31.8
1989	--	--	--	2,480	409	428	363	55	58.4
Mean	--	--	--	3,900	404	452	654	202	220
Site 12 North Fork Shenandoah River at Cootes Store, Va.									
1979	579	53.2	59.9	--	--	--	35.4	12.4	13.8
1980	689	63.2	70	--	--	--	35.3	11.2	12.2
1981	145	8.9	11.6	--	--	--	6.42	1.38	1.66
1982	444	32.7	38.1	--	--	--	22.2	5.75	6.68
1983	486	40.5	46.5	--	--	--	27.8	8.42	9.49
1984	736	63.1	71	--	--	--	41.7	13.1	14.6
1985	335	19.7	24.6	--	--	--	14.9	2.87	3.53
1986	637	89.6	105	--	--	--	80.2	61	70.6
1987	633	58.2	65.3	--	--	--	49.7	17.2	19.9
1988	407	36.4	42	--	--	--	30.2	9.68	11.9
1989	435	50.4	53.8	--	--	--	34.7	11.4	12.2
Mean	502	46.9	53.4	--	--	--	34.4	14	16

Table 16. Estimated annual loads of total nitrogen, dissolved nitrate, and total phosphorus at selected surface-water-quality monitoring sites in the Potomac River Basin—Continued

Water year	Total nitrogen			Dissolved nitrate as nitrogen			Total phosphorus		
	Load	Standard error	Standard error of estimate	Load	Standard error	Standard error of estimate	Load	Standard error	Standard error of estimate
				Site 13 Smith Creek near New Market, Va.					
1979	393	33.1	34.1	--	--	--	--	--	--
1980	500	31.7	33.1	--	--	--	--	--	--
1981	108	4.64	5.17	--	--	--	--	--	--
1982	329	14.7	16.4	--	--	--	--	--	--
1983	438	23.2	25	--	--	--	--	--	--
1984	619	39.9	41.8	--	--	--	--	--	--
1985	234	10.1	11.5	--	--	--	--	--	--
1986	343	19.1	20.9	--	--	--	--	--	--
1987	375	21.5	23.2	--	--	--	--	--	--
1988	317	17.8	19.1	--	--	--	--	--	--
1989	208	16.9	17.7	--	--	--	--	--	--
Mean	351	21.1	22.5	--	--	--	--	--	--
				Site 14*A* North Fork Shenandoah River at Strasburg, Va.					
1979	--	--	--	3,190	244	294	--	--	--
1980	--	--	--	3,610	267	317	--	--	--
1981	--	--	--	607	35.8	54.5	--	--	--
1982	--	--	--	2,240	163	211	--	--	--
1983	--	--	--	2,600	220	268	--	--	--
1984	--	--	--	4,030	380	430	--	--	--
1985	--	--	--	1,480	143	172	--	--	--
1986	--	--	--	2,090	259	289	--	--	--
1987	--	--	--	2,690	427	454	--	--	--
1988	--	--	--	1,960	359	378	--	--	--
1989	--	--	--	1,570	366	379	--	--	--
Mean	--	--	--	2,370	260	295	--	--	--
				Site 14*B* North Fork Shenandoah River at Strasburg, Va.					
1979	3,040	178	198	3,000	293	335	--	--	--
1980	3,420	193	215	3,770	383	430	--	--	--
1981	740	34.6	43.5	654	57.4	79.1	--	--	--
1982	2,170	112	133	2,220	213	258	--	--	--
1983	2,420	140	162	2,350	236	281	--	--	--
1984	3,580	209	233	3,800	382	436	--	--	--
1985	1,470	71.3	87.3	1,570	148	186	--	--	--
1986	1,950	111	130	2,130	224	266	--	--	--
1987	2,440	165	183	2,310	274	311	--	--	--
1988	1,840	136	149	1,770	238	266	--	--	--
1989	1,590	154	164	1,220	214	230	--	--	--
Mean	2,240	137	154	2,250	242	280	--	--	--
				Site 15 Shenandoah River at Millville, W.Va.					
1979	--	--	--	13,100	1,400	1,810	1,530	128	193
1980	--	--	--	15,500	1,520	1,910	1,460	87.2	119
1981	--	--	--	2,210	173	243	306	13.4	17.6
1982	--	--	--	6,960	641	887	831	50.8	75.2

Table 16. Estimated annual loads of total nitrogen, dissolved nitrate, and total phosphorus at selected surface-water-quality monitoring sites in the Potomac River Basin—Continued

	Total nitrogen			Dissolved nitrate as nitrogen			Total phosphorus		
Water year	Load	Standard error	Standard error of estimate	Load	Standard error	Standard error of estimate	Load	Standard error	Standard error of estimate
Site 15 Shenandoah River at Millville, W.Va.—Continued									
1983	--	--	--	8,650	879	1,120	1,170	89.7	118
1984	--	--	--	14,700	1,680	2,030	1,770	158	216
1985	--	--	--	5,780	615	810	413	25.5	35.3
1986	--	--	--	9,540	1,160	1,570	2,390	525	929
1987	--	--	--	9,280	1,100	1,330	853	91.1	152
1988	--	--	--	7,130	983	1,130	323	28.9	34.9
1989	--	--	--	6,720	1,260	1,370	317	40.5	45.1
Mean	--	--	--	9,050	1,040	1,290	1,030	113	176
Site 17 Monocacy River at Bridgeport, Md.									
1979	--	--	--	1,120	252	282	93.9	16.4	18.7
1980	--	--	--	782	137	155	62.8	7.2	8.31
1981	--	--	--	432	94.2	118	30.3	3.58	4.36
1982	--	--	--	739	154	175	43.6	5.47	6.18
1983	--	--	--	852	199	217	49.3	7.88	8.65
1984	--	--	--	1,460	376	400	78.4	14.4	15.3
1985	--	--	--	526	119	138	27.3	4.28	4.83
1986	--	--	--	851	215	235	32.3	5.8	6.22
1987	--	--	--	892	237	255	31.4	6.32	6.69
1988	--	--	--	772	234	252	25.8	6.18	6.57
1989	--	--	--	641	232	241	24.1	7.11	7.38
Mean	--	--	--	824	204	224	45.4	7.69	8.47
Site 18 Hunting Creek tributary near Foxville, Md.									
1982	--	--	--	8.71	0.75	0.87	--	--	--
1983	--	--	--	11	.87	1.1	--	--	--
1984	--	--	--	17.7	1.77	2.02	--	--	--
1985	--	--	--	6.65	.44	.56	--	--	--
1986	--	--	--	9.48	.74	.88	--	--	--
1987	--	--	--	8.53	.76	.98	--	--	--
1988	--	--	--	7.35	.79	.97	--	--	--
1989	--	--	--	7.5	.97	1.06	--	--	--
Mean	--	--	--	9.62	.89	1.06	--	--	--
Site 19 Monocacy River near Frederick, Md.									
1973	7,620	483	494	5,900	198	237	580	49.8	53.3
1974	5,210	213	231	4,000	120	161	401	24.5	30.5
1975	8,880	419	481	5,860	218	284	1,100	152	214
1976	6,360	148	179	4,730	155	193	469	22.9	30.4
1977	6,090	217	269	4,080	146	201	597	57.1	90
1978	8,360	292	333	5,650	223	277	607	41.8	53.2
1979	9,290	418	466	5,930	270	328	742	69.7	88.2
1980	6,890	296	317	4,650	216	246	448	32.4	38.2
1981	3,610	219	231	2,430	132	153	230	19	21.4
1982	5,070	442	449	3,420	246	261	283	32.5	34
1983	7,450	923	935	4,590	440	460	423	69.9	73.6
Mean	6,800	370	399	4,660	215	255	535	52	66.1

Table 16. Estimated annual loads of total nitrogen, dissolved nitrate, and total phosphorus at selected surface-water-quality monitoring sites in the Potomac River Basin—Continued

Water year	Total nitrogen			Dissolved nitrate as nitrogen			Total phosphorus		
	Load	Standard error	Standard error of estimate	Load	Standard error	Standard error of estimate	Load	Standard error	Standard error of estimate
Site 20 Goose Creek near Leesburg, Va.									
1979	2,150	190	244	1,820	240	309	97.6	17.3	22.6
1980	1,670	118	140	1,410	147	176	84.4	13.4	16.7
1981	334	21.7	28.8	277	28.2	39.8	13.5	1.8	2.18
1982	1,130	80	105	972	105	141	56.8	8.31	11
1983	1,850	154	194	1,600	201	254	98	16.4	21
1984	2,840	249	294	2,440	322	383	168	28.3	33.6
1985	645	54.7	92	537	70	119	33.7	5.8	9.98
1986	1,030	98.8	112	879	127	146	56.2	10.6	12
1987	1,250	163	179	1,050	204	226	69.6	18.2	19.9
Mean	1,430	125	154	1,220	160	199	75.3	13.3	16.6
Site 21*B* Seneca Creek at Dawsonville, Md.									
1979	--	--	--	870	79.6	86.8	48.4	21.8	27.1
1980	--	--	--	730	57.7	62.7	23.4	7.79	11.5
1981	--	--	--	274	18.8	21.6	4.12	.5	.59
1982	--	--	--	377	27	31.2	7.59	1.16	1.71
1983	--	--	--	562	45	50.2	13	2.2	2.81
1984	--	--	--	749	62.8	67.8	17.9	2.93	3.51
1985	--	--	--	285	19.8	23.2	7.26	1.1	1.8
1986	--	--	--	247	17.2	19.4	5.45	.62	.73
1987	--	--	--	412	31.5	35.7	16.1	2.73	3.69
1988	--	--	--	507	43.3	47.8	30	7.6	10.5
1989	--	--	--	489	45.7	49.5	36.9	12.5	18
Mean	--	--	--	500	40.8	45.1	19.1	5.54	7.45
Site 22 Difficult Run near Great Falls, Va.									
1979	196	11	13.2	119	8.13	9.55	18	3.77	5.15
1980	193	10.8	13.3	117	7.6	8.84	24.7	7.38	11.5
1981	74.2	2.82	3.74	51.8	2.82	3.56	4.44	.55	.82
1982	104	4.39	5.88	68.8	3.99	5.04	7.99	1.15	1.89
1983	150	7	8.7	95.1	5.93	7.19	13	1.97	2.66
1984	236	12	14	143	9.7	11.2	24	3.82	4.94
1985	103	4.17	5.93	69.1	3.8	4.95	9.17	1.36	2.46
1986	90.2	3.52	4.47	63.7	3.62	4.48	6.19	.7	.91
1987	147	7.18	8.77	95.8	6.52	7.71	13.4	1.94	2.63
1988	161	9.49	11.4	103	8.28	9.5	17.1	3.34	4.92
1989	207	15.9	18.6	126	12.8	14	29.9	9.47	14.6
Mean	151	8.02	9.82	95.7	6.65	7.82	15.3	3.22	4.77
Site 23 Potomac River at Washington, D.C.									
1979	78,500	2,740	4,070	51,000	4,980	5,730	9,370	1,110	2,140
1980	75,600	2,500	3,230	51,400	3,690	4,330	7,220	612	923
1981	24,400	685	1,030	16,300	840	1,260	1,890	129	237
1982	49,600	1,460	2,170	32,100	2,140	2,780	4,750	352	690
1983	59,300	1,910	2,760	34,200	2,740	3,260	6,560	580	1,070
1984	102,000	3,750	5,150	59,100	5,600	6,310	12,600	1,470	2,650

Table 16. Estimated annual loads of total nitrogen, dissolved nitrate, and total phosphorus at selected surface-water-quality monitoring sites in the Potomac River Basin—Continued

Water year	Total nitrogen			Dissolved nitrate as nitrogen			Total phosphorus		
	Load	Standard error	Standard error of estimate	Load	Standard error	Standard error of estimate	Load	Standard error	Standard error of estimate
Site 23 Potomac River at Washington, D.C.—Continued									
1985	38,800	1,270	1,810	27,600	2,460	2,890	2,490	195	385
1986	72,400	3,430	5,140	43,400	4,200	4,930	10,300	2,070	4,670
1987	58,600	2,550	3,300	39,200	3,200	3,790	3,820	474	876
1988	49,000	2,530	3,120	33,900	2,990	3,490	2,690	387	636
1989	51,500	3,370	3,750	34,900	4,220	4,540	1,940	314	407
Mean	60,000	2,380	3,230	38,500	3,370	3,940	5,780	699	1,330

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