Loads of Suspended Sediment and Nutrients from Local Nonpoint Sources to the Tidal Potomac River and Estuary, Maryland and Virginia, 1979–81 Water Years

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

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By R. Edward Hickman

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FOREWORD

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

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

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

1. The generation and deposition of sediments, nutrients, and trace metals from the Holocene to the present was determined by sampling surficial bottom sediments and analyzing their characteristics and distributions.
2. Bottom-sediment geochemistry was studied and the effects of benthic exchange processes on water-column nutrient concentrations ascertained.
3. Current-velocity and water-surface-elevation data were collected to calibrate and verify a series of one- and two-dimensional hydrodynamic flow and transport models.
4. Measurements from typical urban and rural watersheds were extrapolated to provide estimates of the nonpoint sources of sediments, nutrients, and biochemical oxygen demand during 1980 and 1981.
5. Intensive summertime studies were conducted to determine the effects of local sewage-treatment-plant effluents on dissolved-oxygen levels in the tidal Potomac River.
6. Species, numbers, and net productivity of phytoplankton were determined to evaluate their effect on nutrients and dissolved oxygen.
7. Wetland studies were conducted to determine the present-day distribution and abundance of submersed aquatic vegetation, and to ascertain the important water-quality and sediment parameters influencing this distribution.
8. Repetitive samples were collected to document the distribution and abundance of the macrobenthic infaunal species of the tidal river and estuary and to determine the effects of changes in environmental conditions on this distribution and abundance.

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

Philip Cohen
Chief Hydrologist

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Loads of Suspended Sediment and Nutrients from Local Nonpoint Sources to the Tidal Potomac River and Estuary, Maryland and Virginia, 1979–81 Water Years

By R. Edward Hickman

Abstract

Loads of suspended sediment, phosphorus, nitrogen, biochemical oxygen demand, and dissolved silica discharged to the tidal Potomac River and Estuary during the 1979–81 water years from three local nonpoint sources have been calculated. The loads in rain falling directly upon the tidal water surface and from overflows of the combined sewer system of the District of Columbia were determined from available information. Loads of materials in the streamflow from local watersheds draining directly to the tidal Potomac River and Estuary downstream from Chain Bridge in Washington, D.C., were calculated from samples of streamflow leaving five monitored watersheds.

Average annual yields of substances leaving three urban watersheds (Rock Creek and the Northwest and Northeast Branches of the Anacostia River) and the rural Saint Clements Creek watershed were calculated either by developing relationships between concentration and streamflow or by using the mean of measured concentrations. Yields calculated for the 1979–81 water years are up to 2.3 times period-of-record yields because of greater than average streamflow and stormflow during this 3-year period.

Period-of-record yields of suspended sediment from the three urban watersheds and the Saint Clements Creek watershed do not agree with yields reported by other studies. The yields from the urban watersheds are 17 to 51 percent of yields calculated using sediment-concentration data collected during the 1960–62 water years. Previous studies suggest that this decrease is at least partly due to the imposition of effective sediment controls at construction sites and to the construction of two multipurpose reservoirs. The yield calculated for the rural Saint Clements Creek watershed is at least twice the yields calculated for other rural watersheds, a result that may be due to most of the samples of this stream being taken during the summer of the 1981 water year, a very dry period.

Loads discharged from all local tributary watersheds to the tidal Potomac River and Estuary during the 1979–81 water years were calculated by applying to the unsampled watersheds the yields determined for the monitored watersheds. The resulting loads are 2.7 million megagrams of suspended sediment, 3,100 megagrams of phosphorus, 14,000 megagrams of nitrogen, 74,000 megagrams of ultimate biochemical oxygen demand, and 68,000 megagrams of dissolved silica. The value for the load of sediment is probably an overestimate because the sediment yield calculated for the Saint Clements Creek watershed does not appear to be representative of rural watersheds.

Summed, the loads discharged from all local nonpoint sources (local tributary watersheds, rainfall, and combined sewer overflows) to the tidal Potomac River and Estuary during the 1979–81 water years are 2.7 million megagrams of suspended sediment, 3,300 megagrams of phosphorus, 18,000 megagrams of nitrogen, 78,000 megagrams of ultimate biochemical oxygen demand, and 69,000 megagrams of dissolved silica. These loads accounted for 17 to 38 percent of the loads discharged by major sources during this period.

INTRODUCTION

Background

The tidal Potomac River and Estuary has exhibited a number of water-quality problems over the last 200 years. Sediment has been deposited since colonial times in tidal embayments and in the reach near Washington, D.C. (fig. 1) (Gottschalk, 1945). The abundance and diversity of submersed aquatic vegetation have declined from levels noted in the early 1900's (Carter and Haramis, 1980). Algal blooms and low concentrations of dissolved oxygen have plagued the reach near the Washington metropolitan area, most notably during the 1960's (Lippson and others, 1979). However, reductions in the loads of nutrients and biochemical oxygen demand (BOD) from the area's wastewater-treatment plants during the 1970's have been accompanied by less severe algal blooms and greater concentrations of dissolved oxygen (Lippson and others, 1979; Champ and others, 1981).

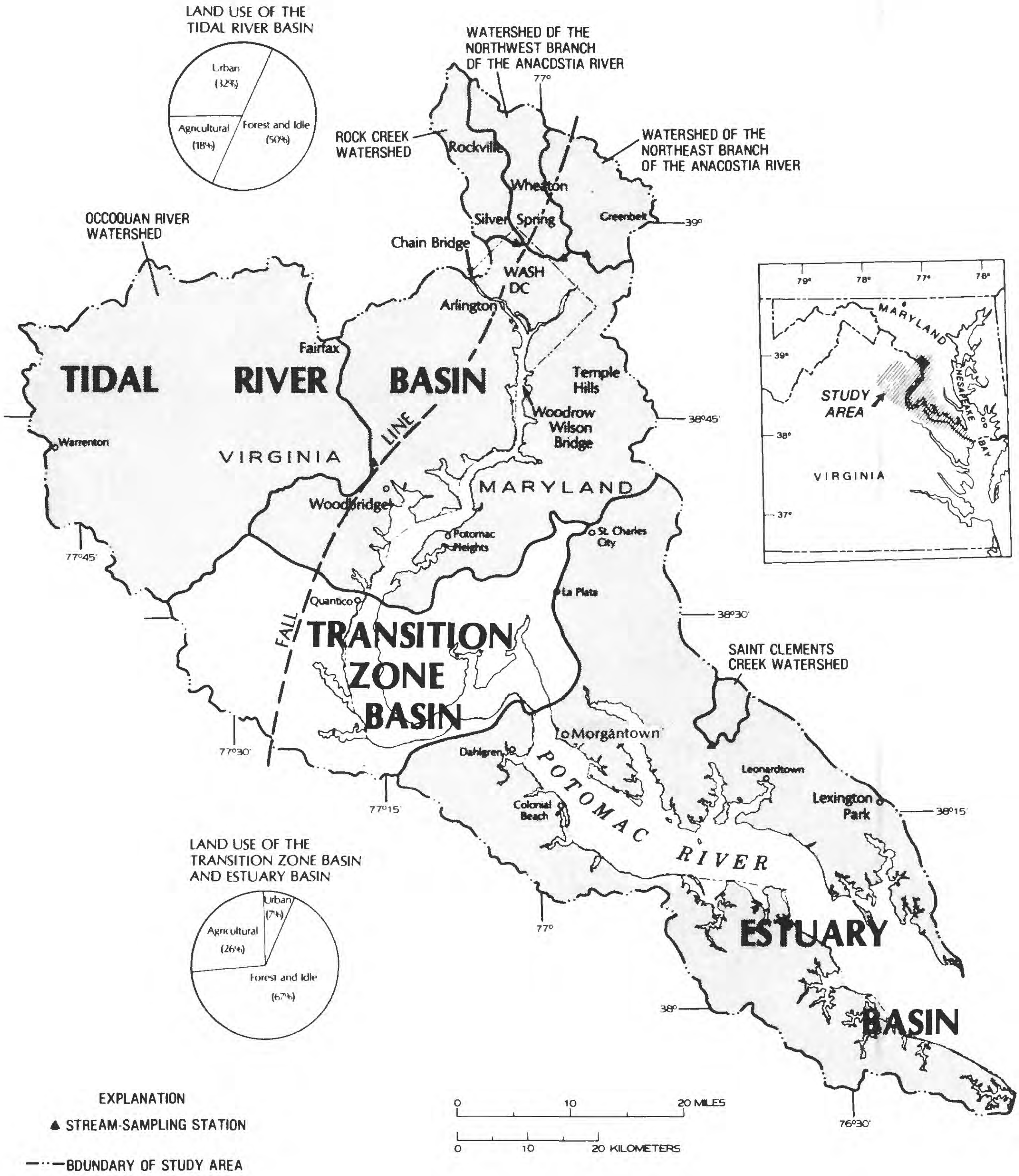

Figure 1. Local drainage basin for the tidal Potomac River and Estuary indicating general land-use characteristics, the Fall Line, and the instrumented watersheds.

Water-quality managers in the Washington metropolitan area are now considering the feasibility of reducing the loads of nutrients and BOD from nonpoint sources to achieve further improvements in the water quality of the tidal Potomac River and Estuary. Wastewater-treatment facilities, the largest point sources in the area, are currently being upgraded. According to recent estimates, the loads of phosphorus, nitrogen, and BOD contributed by these sources in 1983 would be less than or equal to loads in average annual storm runoff from the metropolitan area (Metropolitan Washington Council of Governments, written commun., 1980). As a result, the local planning agency, the Metropolitan Washington Council of Governments, is comparing the costs and effectiveness of nonpoint-source controls with point-source controls in order to guide implementation of controls to reduce the loads from all sources beyond 1983 (Sullivan and others, 1981).

Purpose and Scope

The purpose of this paper is to provide estimates of loads for selected materials that entered the tidal Potomac River and Estuary from local nonpoint sources during the 1979–81 water years (October 1978 to September 1981). These selected materials are sediment, phosphorus, nitrogen, biochemical oxygen demand, and dissolved silica. The three most important local nonpoint sources of these materials are considered to be (1) streamflow from the local watersheds discharging directly to the tidal river and estuary downstream from Chain Bridge (fig. 1), (2) overflows from the combined sewer system of the District of Columbia, and (3) rain falling directly upon the tidal water surface. The importance of these local nonpoint-source loads is assessed by comparing them with loads from other major sources.

The scope of this paper includes

1. Calculation of the loads in precipitation falling directly upon the tidal water surface during the 1979–81 water years by use of previously measured chemistry of precipitation.
2. Estimation of the average annual yields of constituents from five selected watersheds during the 1979–81 water years and the period of record for streamflow in these watersheds.
3. Estimation of the loads from all local tributary watersheds during the 1979–81 water years based on the yields calculated for these five watersheds.
4. Calculation of loads in the overflow of the combined sewer system of the District of Columbia during the 1979–81 water years from information supplied by O'Brien and Gere Engineers (Gregory J. Welter, written commun., 1981).
5. Comparison of loads from local nonpoint sources with loads from other major sources for the following reaches and time periods:
   a. The tidal Potomac River and Estuary during the 1979–81 water years.
   b. The tidal river by itself during the 1979–81 water years.
   c. The tidal river by itself during the summer months (July, August, and September) of the 1979–81 water years.

Description of Study Area

The tidal Potomac River and Estuary extends from Chain Bridge in Washington, D.C., to the Chesapeake Bay and is considered two reaches in this report (fig. 1). The tidal river (the freshwater zone) extends from Chain Bridge to Quantico, Va., and usually does not have salinities greater than 0.5 parts per thousand. The transition zone and estuary (considered one reach) extend from Quantico to the mouth. The transition zone (from Quantico to Morgantown, Md.) may consist of either freshwater, saline water, or a mixture, depending on the amounts of freshwater and saline water entering it from the tidal river and the estuary. The estuary lies between Morgantown and the mouth and contains saline water similar to that of Chesapeake Bay.

The local drainage area of the tidal Potomac River and Estuary is made up of tidal water and of land draining to the tidal river and estuary downstream from Chain Bridge. The tidal river basin, the local drainage area of the tidal river, is about equal in size to the combined local drainage area of the transition zone basin and the estuary basin (fig. 1, table 1). Tidal water makes up only 4 percent of the tidal river basin, but it constitutes 26 percent of the combined transition zone and estuary basin.

The local drainage area of the tidal river and estuary lies within two geomorphic provinces: the Piedmont province to the west of the Fall Line, and the Coastal Plain province to the east (fig. 1). About half the area of the watersheds draining to the tidal river is in each province, but almost all the area of the watersheds draining to the transition zone and estuary is in the Coastal Plain province.

Table 1. Local drainage areas of land and water surface for the tidal river and for the transition zone and estuary

Reach	Area, in square kilometers		
	Land	Tidal water[1]	Total[2]
Tidal river (from Chain Bridge, Washington, D.C., to Quantico, Va.).	3 693	151	3 844
Transition zone and estuary (from Quantico, Va., to the mouth).	3 086	1 100	4 186
Tidal Potomac River and Estuary	6 779	1 251	8 030

[1]Cronin, 1971.

[2]From planimetered 1:250,000-scale topographic maps.

Nearly one-third (32 percent) of the land in the tidal river basin is dedicated to urban uses, principally uses associated with the Washington metropolitan area (fig. 1). In contrast, the land draining to the transition zone and estuary is only 7 percent urban. The land-use data in figure 1 are estimated from available information (U.S. Department of the Army, 1973, as reported by Lippson and others, 1979; Mason, 1974; Michael Sullivan, Metropolitan Washington Council of Governments, written commun., 1979; Susan Alderman, Maryland Department of State Planning, written commun., 1980; Jack Hartigan, Northern Virginia Planning District Commission, written commun., 1980).

Streamflow leaving three urban watersheds and one rural watershed was sampled at active gaging stations (fig. 1). Rock Creek, the Northwest and Northeast Branches of the Anacostia River (hereafter referred to as the Northwest Branch and the Northeast Branch, respectively) flow into the tidal river (fig. 2) and drain watersheds consisting of more than 50 percent developed (urban) land (table 2). The Rock Creek watershed differs from the other two in that it contains two multipurpose reservoirs. Lakes Frank and Needwood (fig. 2) were built in the 1960's, in part for sediment control, and receive streamflow from about 40 percent of the Rock Creek watershed. The rural Saint Clements Creek watershed discharges to the estuary. The Saint Clements Creek watershed has land-use characteristics typical of the rest of the combined transition zone and estuary basin (fig. 2, table 2).

The Occoquan River was sampled at the Occoquan Dam, the point at which it leaves the Occoquan Reservoir (fig. 2). The watershed upstream from the reservoir is 11 percent urban and 89 percent agricultural, forested, and idle (fig. 1, table 2). The Occoquan Reservoir had a volume of 37 million cubic meters until 1980, when it was expanded to 42 million cubic meters. Approximately 2.6 cubic meters per second are withdrawn for water supply from this reservoir at the dam. Two other reservoirs (not shown), Lake Jackson (2.1 million cubic meters) and Lake Manassas (22 million cubic meters), are located upstream from the Occoquan Reservoir.

The combined sewer system of the District of Columbia serves an area of 51 square kilometers, about one-third of the District. This system was designed to carry both sanitary waste and storm runoff and to overflow during storms that produce more runoff than the system can carry. In addition to entering the tidal Potomac River directly, overflow enters the Anacostia River and Rock Creek downstream from the stations sampled in this report.

Methods of Sampling, Chemical Analysis, and Regression Analysis

Samples were collected by hand and with automated equipment. Samples were taken by hand at all five sampling stations using standard U.S. Geological Survey (USGS) techniques described in Guy and Norman (1970). In addition, samples were collected from the water-supply intake at the Occoquan Dam and from automated samplers set up on the other streams. Samples taken by hand using standard USGS techniques were used to verify that the samples taken from the water-supply intake and those taken by the automatic samplers were representative of the streamflow. Almost all samples were collected during stormflow.

Analyses for nutrients and suspended sediment in streamflow were conducted in USGS laboratories. Phosphorus, nitrogen, and dissolved silica analyses were done by the Central Laboratory in Atlanta, Ga., according to methods described by Skougstad and others (1979). The dissolved fraction of the nutrients is defined as that portion passing through a 0.45-micrometer membrane filter. Concentrations of total suspended sediment and of the sand, silt, and clay components of suspended sediment were determined at the sediment laboratory in Harrisburg, Pa., according to methods described by Guy (1969). Sand particles are 62 to 2,000 micrometers in size, silt particles are 4 to 62 micrometers, and clay particles are less than 4 micrometers. Analyses for BOD in streamflow were carried out by members of the USGS staff in Reston, Va. (Wayne Webb, oral commun., 1979–82). BOD samples were incubated for 20 days and the oxygen demand was monitored with electronic probes. The ultimate demand of each sample was determined with nonlinear least squares regression to fit demand values to an exponential curve. Unless stated otherwise, all values of BOD in this report are ultimate demand.

All regressions mentioned in this paper were carried out with the Statistical Analysis System (SAS Institute Inc.,

Table 2. Drainage areas and watershed land-use characteristics for water-quality sampling stations

[Land-use data for Rock Creek and the Anacostia River are from the Metropolitan Washington Council of Governments (Michael Sullivan, written commun., 1979), for the Saint Clements Creek watershed are from the Maryland Department of State Planning (Susan Alderman, written commun., 1980), and for the Occoquan River watershed are from Jack Hartigan, Northern Virginia Planning District Commission, written commun., 1980]

Station number	Station name	Watershed area (km^2)	Proportion of land use, in percentage: Urban	Agricultural	Forested and idle
01648000	Rock Creek at Sherrill Drive, Washington, D.C.	161	56	21	23
01651000	Northwest Branch of the Anacostia River near Hyattsville, Md.	128	62	5	33
01649500	Northeast Branch of the Anacostia River at Riverdale, Md.	189	51	4	45
01661050	Saint Clements Creek at Clements, Md.	47.9	2	36	62
01657667	Occoquan River below Occoquan Dam, near Occoquan, Va.	1 480	11	34	55

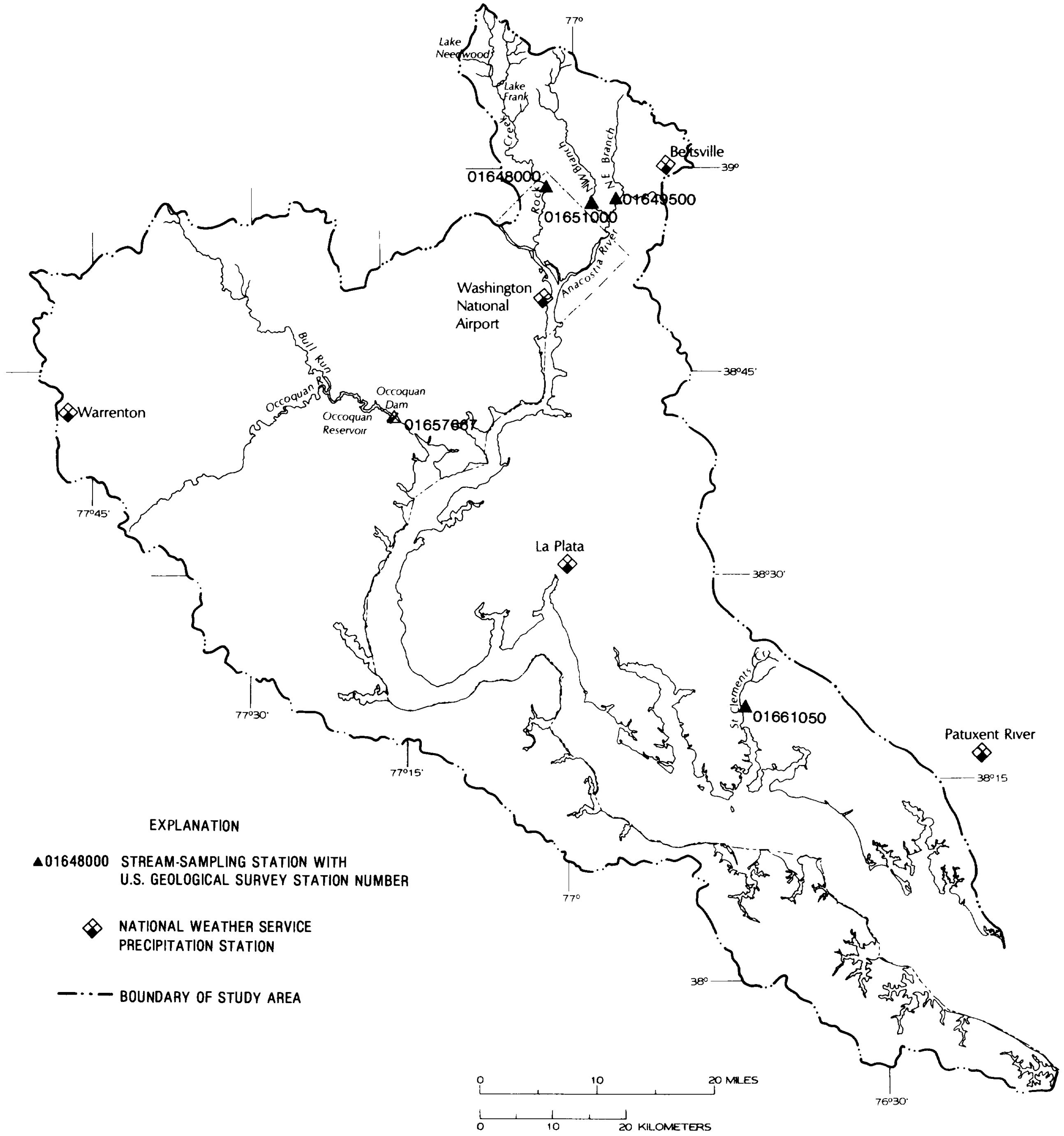

Figure 2. Locations of the stream-sampling stations, selected reservoirs, and selected National Weather Service precipitation stations.

1979), except the nonlinear regression used for ultimate BOD determination. Linear relationships developed by the simple least squares regression procedure are significant at the 0.05 level unless stated otherwise. Nonlinear relationships were developed using the nonlinear regression procedure. Values of standard deviation and level of significance were not available for the nonlinear relationships.

HYDROLOGY

Precipitation during the 1979–81 water years was nearly uniform over the study area (table 3). Mean annual precipitation at two National Weather Service precipitation stations during the 1979–81 water years are within 10 percent of values measured during the period 1941–70. Average monthly values of total precipitation in the study area

Table 3. Mean annual precipitation at selected National Weather Service stations during the 1979–81 water years and during the 1941–70 calendar years

[Precipitation is in millimeters; nd, not determined]

	1979-81 water years[1]	1941-70 calendar years[2]
Washington National Airport, Washington, D.C.	915	988
Beltsville, Md.	1 105	nd
Warrenton, Va.	1 137	nd
La Plata, Md.	1 085	1 058
Patuxent River, Md.	1 132	nd

1/From monthly National Weather Service reports for Maryland and Virginia.

2/U.S. Department of Commerce (1973a, 1973b).

during the 1979–81 water years were calculated by averaging precipitation measured at five National Weather Service stations (fig. 2) and are given in table 26 (tables 26–30 are at the end of the paper).

Mean annual runoff for the 1979–81 water years and for long-term conditions have been estimated for all the sampled watersheds. The long-term value for each of the streams except the Occoquan River is the average annual value of the data for the period of record, the length of time that flow of a particular stream has been measured. Table 4 shows that the four gaged streams have continuous streamflow records 13 to 52 years in length.

Streamflow of the Occoquan River at the Occoquan Dam was not recorded and had to be estimated from available information. Daily streamflow during the 1979–81 water years was calculated from the records of operation of the Occoquan Dam (see the section, "Loads of Suspended Sediment and Nutrients from the Occoquan River Watershed"). Annual streamflow calculated for the 1979 and 1980 water years is within 8 percent of the difference between the annual inflow to the Occoquan Reservoir and the annual water-supply withdrawal from the reservoir. The long-term average annual streamflow at the dam was calculated by subtracting the mean annual rate of withdrawal from the long-term mean annual inflow (Jack Hartigan, Northern Virginia Planning District Commission, written commun., 1981).

The average annual runoff leaving each of the sampled watersheds during the 1979–81 water years exceeds the respective value for long-term conditions (table 4). Values of runoff leaving the urban watersheds and the rural Saint Clements Creek watershed during the period of study differed from one another by 10 percent or less. Values for the Occoquan River watershed are less than those for the other watersheds and reflect withdrawal for water supply from the Occoquan Reservoir.

Table 4. Mean annual runoff for monitored watersheds during the 1979–81 water years and under long-term conditions

[Runoff is in millimeters; nd, not determined]

	1979-1981 water years[1]	Long-term conditions[1]	
	Mean annual runoff	Mean annual runoff	Period of record[2]
Rock Creek	462	345	1930-81
Northwest Branch	437	325	1939-81
Northeast Branch	460	402	1939-81
Saint Clements Creek	420	403	1969-81
Occoquan River	[3]317	[4]249	nd

1/Information for all streams other than the Occoquan River was taken from the streamflow records. The length of the period of record is not applicable to the Occoquan River.

2/Water years.

3/Calculated from the records of operation of the Occoquan Dam; see the section, "Loads of suspended sediment and nutrients from the Occoquan River Watershed."

4/Calculated by subtracting the average annual rate of water supply withdrawal for the period of study (56 mm) from the long-term average annual value of runoff (305 mm) entering the Occoquan Reservoir; the mean annual incoming runoff was obtained from the Northern Virginia Planning District Commission (Jack Hartigan, written commun., 1981).

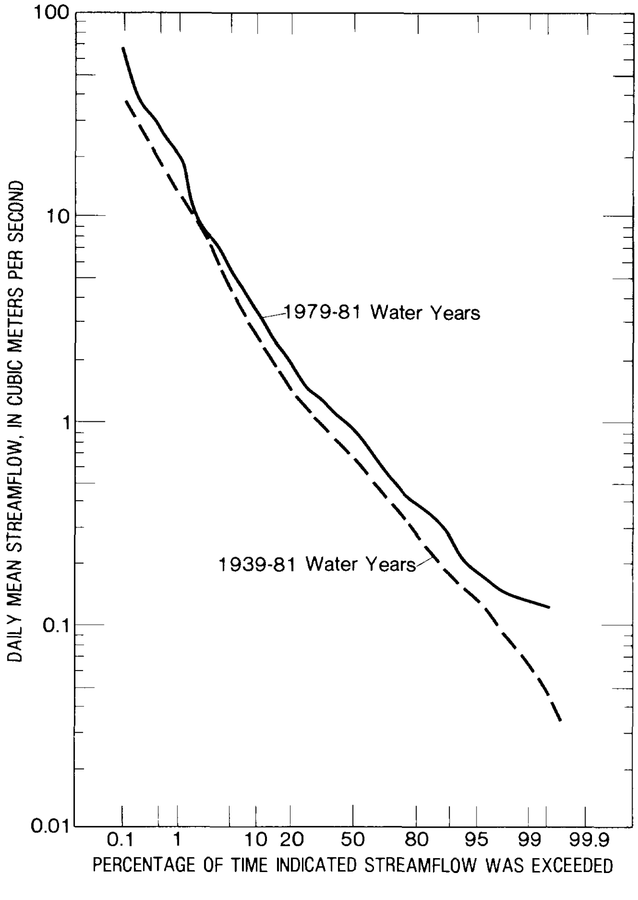

Figure 3. Flow-duration curves of the Northwest Branch for the 1939–81 and 1979–81 water years.

Stormflow of the urban streams and Saint Clements Creek during the 1979–81 water years was greater than stormflow estimated for the period of record. The leftmost portions of the flow-duration curves for the 1979–81 water years were greater than the corresponding portions of the curves for the respective period of record. The curves for the Northwest Branch are shown in figure 3 as an example. The greater stormflow during the period of study is partially due to the passage of tropical storm David through the study area in September 1979, when 120 to 200 millimeters of rain fell on the urban watersheds in 12 hours.

NUTRIENT LOADS IN RAIN

Results of chemical analyses for nutrients in precipitation (wet deposition) are given in table 5. Locations of referenced precipitation sites other than those for Pack (1980) are shown in figure 4. Although the sampling sites of Pack (1980) surround the study area, none are located in or adjacent to it. Concentrations of phosphorus, Kjeldahl nitrogen, and ammonia used to calculate loads in rain falling on the tidal river were different from those used to calculate loads in rain falling on the transition zone and estuary.

Table 5. Nutrient concentrations in rain falling in and adjacent to the study area

[Locations of numbered sites are shown in figure 4; concentrations are in milligrams per liter; phosphorus and nitrogen are given as P and N, respectively; nd, not determined; na, not applicable]

Area receiving sampled precipitation	Period	Source	Total phosphorus	Total Kjeldahl nitrogen	Total nitrate plus nitrite	Total ammonia	Dissolved silica
		Concentrations in the literature					
1 Occoquan River and Four Mile Run watersheds, Va.	June 1976-May 1977	Northern Virginia Planning District Commission (1978)[1]	0.14	2.0	0.45	0.53	nd
2 Rhode River watershed, Md.	1976	Miklas and others (1977)	.01	.24	[2].39	nd	nd
"	1977-1980	Correll and Ford[3] (1982)	nd	.58	.45	.22	nd
3 Kilmarnock, Va.	Feb. 1981 - Feb. 1982	Wade and Wong (1982)	.01	nd	.92	.30	[4]0.06
4 Soldiers Delight watershed, Md.	July 1969 - Feb. 1971	Cleaves and others (1974)	nd	nd	nd	nd	.09
4 Pond Branch watershed, Md.	Mar. 1966 - Mar. 1967	Bricker and others (1968)	nd	nd	nd	nd	0
Tidal Potomac River and Estuary	Aug. 1978 - June 1979	Pack (1980)	nd	nd	[5].3	nd	nd
		Concentrations estimated for this study					
Tidal river	1979-81 water years	na	0.14	2.0	0.50	0.53	0.05
Transition zone and estuary	"	na	.01	.24	.50	.24	.05

[1]Average of mean concentrations shown in table 20 of reference.

[2]Dissolved form.

[3]Concentrations are calculated from values of total precipitation (wet plus dry). Nitrate plus nitrite value is dissolved form.

[4]Concentration is for total (unfiltered) silica.

[5]Estimated from figure 2 of reference, nitrate nitrogen only.

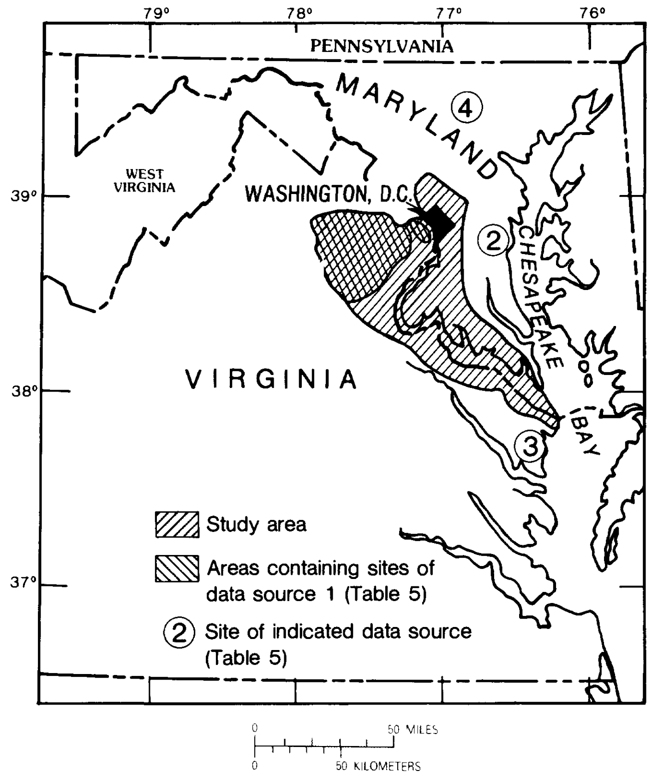

Figure 4. Sites of data sources for nutrients in precipitation.

Concentrations of phosphorus, Kjeldahl nitrogen, and ammonia in the rain falling on the tidal river are the mean of concentrations of samples collected at nine sites in and adjacent to the Washington metropolitan area during the period 1976–77 (Northern Virginia Planning District Commission, 1978). These sites were in areas showing all types of land use; five were in the Occoquan River watershed and four were in the Four Mile Run watershed near the center of the metropolitan area (fig. 4). There were no obvious relationships between concentration and distance from the center of the Washington metropolitan area (Randall and others, 1978).

The concentrations of phosphorus, Kjeldahl nitrogen, and ammonia in the rain falling on the transition zone and estuary were estimated from samples collected at two rural sites outside the study area: one in the Rhode River watershed, Maryland (site 2 in fig. 4), and the other at Kilmarnock, Va. (site 3). Miklas and others (1977) reported the concentrations of these nutrients in rain falling on the rural Rhode River watershed during 1976. Concentrations of total Kjeldahl nitrogen, dissolved ammonia, and dissolved nitrate plus nitrite were derived from samples of total (both wet and dry) deposition at this site during 1977–80 (Correll and Ford, 1982). Mean concentrations of phosphorus and ammonia in rainfall at Kilmarnock, Va., during 1981–82 were calculated using the data in Wade and Wong (1982).

One value of nitrate plus nitrite (0.50 milligram per liter as N) and one value of dissolved silica (0.05 milligram per liter) were used for both the tidal river and the transition zone and estuary. Except for Kilmarnock, Va., all concentrations of nitrate plus nitrite are within the range 0.3 to 0.5 milligram per liter as N, even the concentration derived for the study area from the results of Pack (1980). Pack developed a map of mean nitrate concentrations in rain falling on the Northeastern United States from data resulting from two precipitation water-quality monitoring programs. The value for dissolved silica is based on the sampling of rain at three rural sites (sites 2 and 4 in fig. 4).

Loads to the tidal river and estuary from rainfall (table 6) were calculated using the values of precipitation in table 26. The loads of phosphorus and Kjeldahl nitrogen to the tidal river are greater than the loads to the transition zone and estuary because the concentrations of phosphorus and Kjeldahl nitrogen reported by the Northern Virginia Planning District Commission (1978) for the Washington metropolitan area are an order of magnitude greater than concentrations measured in the Rhode River watershed or at Kilmarnock, Va. The lack of any apparent relationship between either phosphorus or Kjeldahl nitrogen and the distance from the center of the Washington metropolitan area (Randall and others, 1978) may indicate either that the area of high phosphorus and Kjeldahl nitrogen concentrations extends beyond the locations sampled by Randall and others, or that the high concentrations noted by Randall and others are due to the use of techniques different from those used in other precipitation water-quality studies. The use of different assumptions concerning the extent of the area over which the Northern Virginia Planning District Commission data are representative could produce significantly different values for phosphorus and Kjeldahl nitrogen loads.

LOADS OF SUSPENDED SEDIMENT AND NUTRIENTS FROM THE ROCK CREEK, NORTHWEST BRANCH, NORTHEAST BRANCH, AND SAINT CLEMENTS CREEK WATERSHEDS

The suspended sediment and nutrient loads of Rock Creek, Northwest Branch, Northeast Branch, and Saint Clements Creek come from a variety of sources: precipitation, ground water, storm seepage, soil, and materials other than soil washing off the land surface. Storm seepage is the component of stormflow that enters the ground, flows through the soil for a distance, and then emerges from the soil to become runoff. There are no large point-source discharges within these four watersheds.

Linear and nonlinear regression was used to develop relationships between suspended-sediment concentrations and flow, between nutrient concentrations and flow, and between nutrient concentrations and suspended-sediment concentrations (table 27). Mean concentrations were employed in cases in which no significant relationships exist.

Table 6. Loads of phosphorus, nitrogen, and dissolved silica in rain falling on the water surface of the tidal river and transition-estuary zones during the 1979–81 water years

[Loads are in megagrams; phosphorus and nitrogen are given as P and N, respectively]

	Total phosphorus	Total nitrogen[1/]	Total Kjeldahl nitrogen	Total nitrate plus nitrite	Total ammonia	Dissolved silica
Tidal river	68	1 220	974	244	258	24
Transition zone and estuary	35	2 620	851	1 770	851	177
Tidal river and estuary	103	3 840	1 820	2 010	1 110	200
Mean annual loads to the tidal river and estuary	34	1 280	607	670	370	67

1/Calculated by summing values for Kjeldahl nitrogen and nitrate plus nitrite. Values are rounded.

Average annual yields of suspended sediment and nutrients (presented in this section) were calculated with the relationships developed above. Yields for the 1979–81 water years were determined from the mean daily streamflow during this period. Yields for the period of record were calculated using the flow-duration-curve method (Miller, 1951). The periods of record (13–52 years) are listed in table 4. The yields for the 1979–81 water years are all greater than for the period of record because the streamflow and the stormflow for the 1979–81 water years were greater than for the period of record.

Suspended Sediment

Sediment, made up predominantly of soil particles, is transported in streams through two processes: the suspended load carried in the water column is made up of the finer particles, and the bedload is made up of the heavier particles, which slide, skip, and roll along the bottom of the stream. Wark and Keller (1963) estimated that the bedload leaving selected streams throughout the Potomac River basin was about 10 percent of the suspended load. Only the suspended loads are considered in this report, and unless stated otherwise, the term "sediment" refers only to suspended sediment.

Relationships between sediment concentration and streamflow were developed for each stream (table 27). The following nonlinear equation was fit to the data for each urban stream and produced relationships such as in figure 5, having r^2 values of 0.97 or greater, where r is the correlation coefficient:

$$\log (SED) = A \times (1 - (B \times Q)^C), \qquad (1)$$

where

log = base 10 logarithm;
SED = sediment concentration, in milligrams per liter;
Q = streamflow, in cubic meters per second; and,
A, B, and C are constants.

A linear logarithmic equation was fit to the data for Saint Clements Creek because these data do not exhibit the same curvilinear pattern as the data for the urban streams:

$$\log (SED) = A + (B \times \log (Q)). \qquad (2)$$

The resulting relationship for Saint Clements Creek (fig. 6) has an r^2 value of 0.61.

The sediment yield calculated for the Saint Clements Creek watershed for either the 1979–81 water years or the period of record is within the range of the yields of the urban watersheds (table 7). The Rock Creek watershed shows the smallest yield of the three urban watersheds.

Table 8 shows mean annual yields of sediment from the urban watersheds calculated with streamflow data through the 1981 water year and sediment concentrations measured during the 1979–81 water years (col. 1) to be only 11 to 29 percent of the yields calculated by Wark and Keller (1963) from sediment concentrations measured during the 1960–62 water years (col. 4). Although Wark and Keller published only yields of total sediment (bedload plus suspended load), a review of their unpublished notes allowed

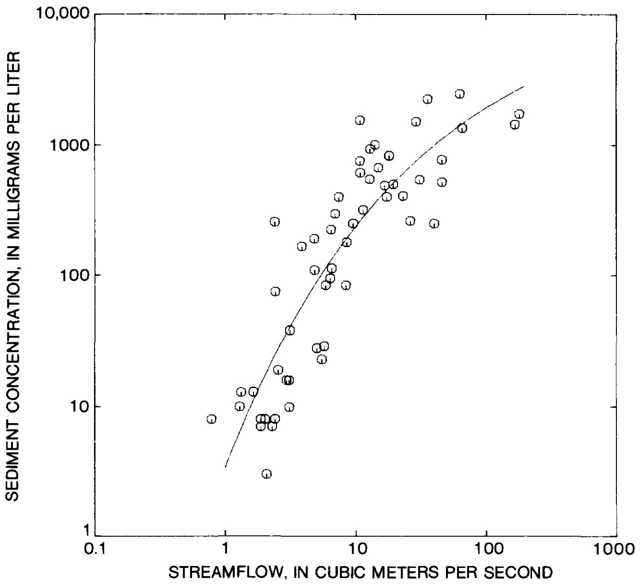

Figure 5. Sediment concentration versus streamflow for the Northeast Branch, 1979–81 water years.

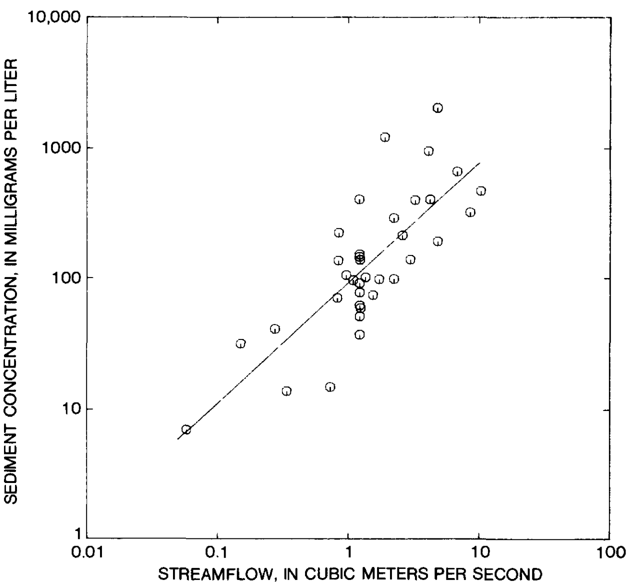

Figure 6. Sediment concentration versus streamflow for Saint Clements Creek, 1979–81 water years.

determination of their yields of suspended sediment, which were calculated by developing linear relationships between the logarithms of instantaneous sediment load and steamflow and then using the flow-duration-curve method and streamflow data up through the 1957 water year. The significant differences between the two sets of values reflect not only changes in the quantities of sediment leaving these watersheds, but also differences between the methods used by Wark and Keller and those used in this study.

A comparison of the methods used by Wark and Keller (1963) and those used in this study was accomplished by calculating yields of sediment from the method used in this study and the sediment concentration and streamflow data used by Wark and Keller (col. 3, table 8). The resulting values are only half of the yields calculated by Wark and Keller (col. 4) and indicate significant differences between the two methods. A review of their unpublished notes shows that two of their procedures resulted in overestimation of yields. First, their use of a linear relationship between the logarithm of instantaneous sediment load and the logarithm of streamflow inherently assumed a linear relationship between the logarithm of sediment concentration and the log-

Table 7. Mean annual yields of sediment, sand, silt, and clay from the urban and Saint Clements Creek watersheds for the period of record and the 1979–81 water years

[Yields are in megagrams per square kilometer per year except as indicated; nd, not determined]

Watershed	Period of record: Sediment yield	1979-81 water years: Sediment yield	Proportion of sand, silt, and clay, in percentage: Sand	Silt	Clay
Rock Creek	57	120	24	40	36
Northwest Branch	97	220	42	32	26
Northeast Branch	91	140	17	35	48
Saint Clements Creek	72	160	nd	nd	nd

Table 8. Comparison of mean annual yields of sediment calculated for the urban watersheds from sediment concentrations measured during the 1979–81 water years with yields calculated from concentrations measured during the 1960–62 water years

[Yields are in megagrams per square kilometer per year]

Watershed	Calculated with streamflow data through the 1981 water year		Calculated with 1960-62 water year sediment concentrations and with streamflow data through the 1957 water year	
	with 1979-81 water year sediment concentrations (1)	with 1960-62 water year sediment concentrations (2)	By author (3)	Wark and Keller 1/ (1963) (4)
Rock Creek	57	340	2/270	510
Northwest Branch	97	390	280	540
Northeast Branch	91	180	160	310

1/Suspended sediment only; calculated from unpublished notes. Stream data for the Northwest Branch and the Northeast Branch are through the 1957 water year, and for Rock Creek are through the 1958 water year.

2/Calculated with streamflow data through the 1958 water year.

arithm of streamflow. However, their data (except those for the Northeast Branch, which exhibit much scatter) show the same curvilinear pattern as the samples collected during the 1979–81 water years (as in fig. 5). Second, Wark and Keller did not adequately define the flow-duration curves from the record of streamflow. For each of the three streams, the portions of the curves dealing with peak stormflow—that is, the leftmost portion of the curves in figure 3—were estimated by extending the flow-duration curve at lower values of streamflow.

The sediment yields calculated for the urban watersheds with streamflow data up through the 1981 water year (col. 2, table 8) are greater than the yields calculated with streamflow data only up through the 1957 water year (col. 3) because the stormflows recorded during the 1979–81 water years are greater than predicted from the streamflow data through the 1957 water year. Both sets of yields were determined with the sediment-streamflow relationships developed from the sediment concentrations observed during 1960–62 water years.

Yields calculated for the urban watersheds with streamflow up through the 1981 water year and sediment-streamflow relationships developed from sediment concentrations observed during the 1979–81 water years (col. 1, table 8) are only 17 to 51 percent of the corresponding yields calculated with sediment-streamflow relationships developed from sediment concentrations measured during the 1960–62 water years (col. 2). Two phenomena account for at least part of this decrease in sediment yield from the urban watersheds: the imposition of effective sediment controls at construction sites, and the construction of Lakes Frank and Needwood. Yorke and Herb (1978) measured the sediment and streamflow leaving the headwaters of the Northwest Branch during 1962–74 and attribute the decrease in the amount of sediment leaving during 1962–74 to the imposition of effective sediment controls at construction sites. Herb (1980) measured the amounts of sediment entering and leaving Lake Frank during 1968–74 and determined that this reservoir trapped 96 percent of the sediment entering it during this period. Calculations with the method described by Brune (1953) indicate that Lake Needwood traps about the same percentage of incoming sediment. Brune developed a relationship between reservoir trap efficiency and the ratio of reservoir capacity to streamflow entering the reservoir.

Sand made up 17 to 42 percent, silt, 32 to 40 percent, and clay, 26 to 48 percent of the sediment that left the urban watersheds during the 1979–81 water years (table 7). These values were calculated by developing linear relationships between the concentration of sediment and the concentration of particles in each size class (table 27). The relationships have r^2 values 0.42 to 0.98, the relationship for clay in the Northwest Branch being significant at the 0.08 level. The relationships for the Northwest Branch are given in figure 7 as examples.

The period-of-record sediment yield from Saint Clements Creek is at least twice the yields that have been determined for other rural watersheds in this area (table 9). This discrepancy probably is due, in part, to two factors. First, most of the samples of this stream were taken during

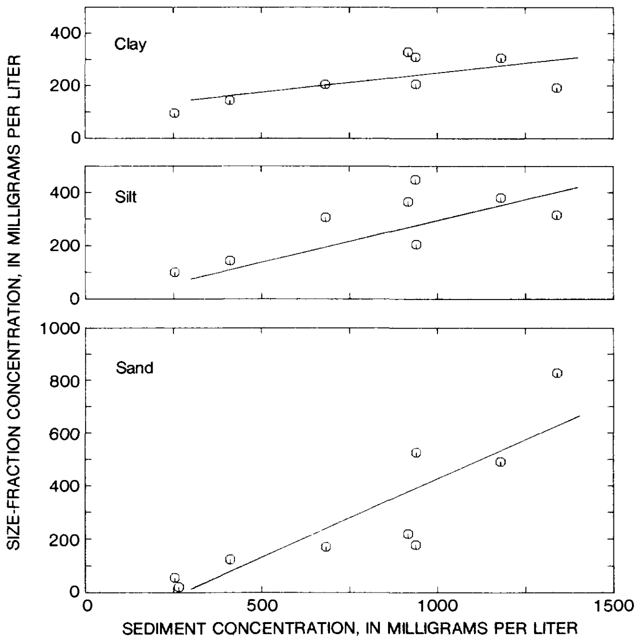

Figure 7. Concentrations of sand, silt, and clay versus sediment concentration for the Northwest Branch, 1979–81 water years.

the 1981 water year, a period during which Saint Clements Creek had a streamflow only 40 percent of the long-term annual average. Miller's (1951) use of the flow-duration-curve method and sediment concentrations observed during the dryer than average years led to overestimation of the measured 19-year yield by as much as 268 percent. These overpredictions resulted from the stormflow during a period of less than average streamflow containing greater sediment concentrations than stormflow during times of average streamflow. Second, most samples were taken during the summer months. Sediment concentrations in stormflow in this area are greater during summer months than during winter months (Guy, 1964).

Table 9. Comparison of the yield of sediment for the period of record from the Saint Clements Creek watershed with yields calculated for other rural watersheds

[Yields are in megagrams per square kilometer per year]

Watershed	Sediment yield	Period
Saint Clements Creek, Md.	72	1969-81 water years[1]
Rhode River, Md.	[2]11-31	1974-76
Mattawoman Creek, Md.	[3]9	[3]1951-58

[1]Period of record.

[2]The range of yields of three small watersheds tributary to the Rhode River.

[3]Suspended-sediment yield from unpublished notes of Wark and Keller (1963).

The calculated sediment yield for Saint Clements Creek for the 1979–81 water years (160 megagrams per square kilometer per year) is more than twice the yield from the Occoquan River watershed draining to the Occoquan Reservoir during the 1979 and 1980 calendar years (63 megagrams per square kilometer per year). The latter value, calculated from the data in table 19, does not reflect the entire period of study and therefore is an underestimate.

Phosphorus

Concentrations of total phosphorus in Rock Creek, the Northwest and Northeast Branches, and Saint Clements Creek increase with increasing sediment concentration and indicate that phosphorus occurring in soil is an important source within all four watersheds. Linear relationships between phosphorus concentration and sediment concentration have r^2 values 0.50 to 0.79 (table 27). As an example, figure 8 shows the observed data and the relationship for the Northeast Branch.

The relationships between sediment concentration and the ratio of dissolved phosphorus to total phosphorus also indicate that soil is an important source of phosphorus. Dissolved phosphorus as a proportion of total phosphorus decreases exponentially with increasing sediment concentration because the amount of large particles in suspension increases with increasing sediment concentration. Phosphorus generally is not believed to be associated with the larger

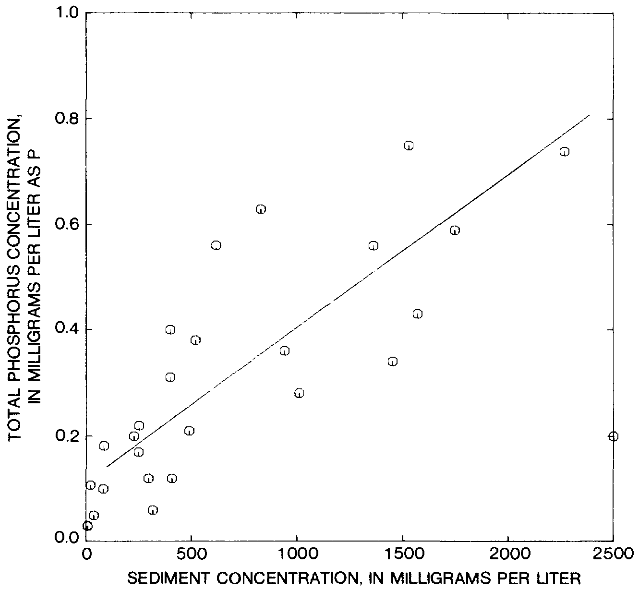

Figure 8. Total phosphorus concentration versus sediment concentration for the Northeast Branch, 1979–81 water years.

particles. The concentration of dissolved phosphorus was simulated with the following nonlinear equation:

$$(DP/TP)=(A\times[\exp\ (B\times SED)])+C, \qquad (3)$$

where

DP = dissolved phosphorus, in milligrams per liter as P;
TP = total phosphorus, in milligrams per liter as P;
SED = sediment concentration, in milligrams per liter;
exp = exponent to base e; and
A, B, and C are constants.

The resulting equations (table 27) have r^2 values 0.69 to 0.99. As an example, figure 9 shows the observed data and the relationship for the Northwest Branch.

The yield of total phosphorus from the Saint Clements Creek watershed during the 1979–81 water years was twice as great as the yields from the urban watersheds (table 10). About one-quarter (25 to 28 percent) of the phosphorus that left the urban watersheds was in the dissolved form. The corresponding value for the Saint Clements Creek watershed was 10 percent.

In general, period-of-record yields of total phosphorus calculated for the urban watersheds agree rather well with long-term average yields calculated by the Metropolitan Washington Council of Governments (Michael Sullivan, written commun., 1979) but less well with the results of a study of Rock Creek by CH2M Hill (1979) (table 11). The Metropolitan Washington Council of Governments calculated average annual yields using an unverified rainfall/runoff model that had been calibrated with rates of pollutant buildup on and washoff from the surface of the land. These rates of buildup and washoff were determined from the monitoring of several small watersheds of uniform land use (Northern Virginia Planning District Commission, 1978). CH2M Hill (1979) used a hydrologic water-quality model and water-quality samples to estimate the yield of orthophosphate phosphorus from nonpoint sources in the Rock Creek watershed upstream from the Maryland-District of Columbia line from March 1978 to February 1979. CH2M Hill assumed that orthophosphate phosphorus (not measured) made up one-third of the measured concentrations of total phosphorus. The yield of total phosphorus calculated

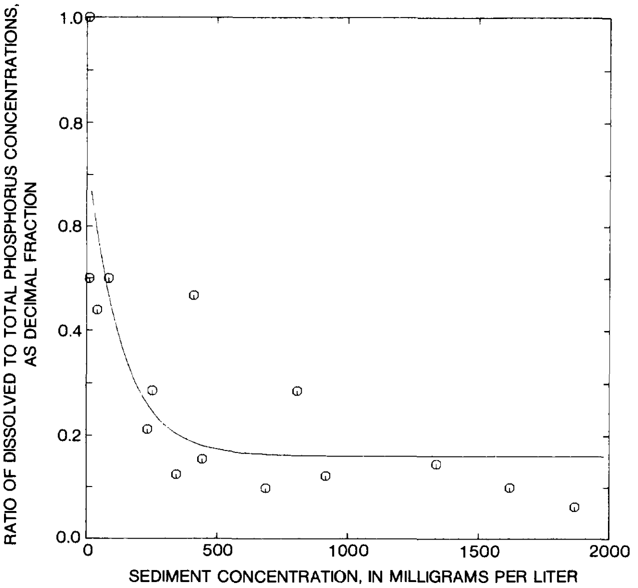

Figure 9. Ratio of phosphorus concentrations versus sediment concentration for the Northwest Branch, 1979–81 water years.

Table 10. Mean annual yields of phosphorus from the urban and Saint Clements Creek watersheds

[Yields are in megagrams per square kilometer per year as P, except as indicated]

Watershed	Period of record: Total phosphorus	1979-81 water years: Total phosphorus	1979-81 water years: Dissolved phosphorus	1979-81 water years: Ratio of dissolved phosphorus to total phosphorus, in percentage
Rock Creek	0.047	0.078	0.022	28
Northwest Branch	.062	.121	.030	25
Northeast Branch	.072	.094	.026	28
Saint Clements Creek	.109	.221	.022	10

Table 11. Comparison of yields of total phosphorus for the period of record with yields calculated by other studies

[Yields are in megagrams per square kilometer per year as P; nd, not determined]

Urban Watersheds			
Watershed	Period of record (from table 10)	Metropolitan Washington Council of Governments[1]	CH2M Hill (1979)
Rock Creek	0.047	0.093	[2]0.061
Northwest Branch	.062	.080 (Northwest and Northeast Branches)	nd
Northeast Branch	.072		nd

Rural Watersheds			
Watershed	Period of record (from table 10)	Northern Virginia Planning District Commission[3]	Smithsonian Institution (1977)
Saint Clements Creek	0.109	nd	nd
Occoquan River	nd	0.049	nd
Rhode River, Md.	nd	nd	0.091

[1]Michael Sullivan, written commun., 1979.
[2]Orthophosphate phosphorus, only.
[3]Jack Hartigan, written commun., 1982.

with the methods of CH2M Hill would probably be three times the yield of orthophosphate phosphorus and two to three times all other listed yields of total phosphorus from the urban watersheds.

Table 11 shows the yield of total phosphorus from the Saint Clements Creek watershed under period-of-record streamflow conditions to be close to the yield calculated for the rural Rhode River watershed during 1976 (Smithsonian Institution, 1977) but twice the long-term average annual yield calculated for the watershed draining to the Occoquan Reservoir (Jack Hartigan, Northern Virginia Planning District Commission, written commun., 1982). The value for the Rhode River watershed is based on the sampling of runoff from subbasins during 1976. The yield for the watershed draining to the Occoquan Reservoir was calculated with a hydrologic-water-quality model (Hydrocomp, Inc., 1978) that had been calibrated and verified with water-quality data.

Nitrogen

Concentrations of total Kjeldahl nitrogen and total ammonia in Rock Creek, the Northwest and Northeast Branches, and Saint Clements Creek increase with increasing sediment concentration. Most of the observed concentrations of each substance show a linear relationship with sediment concentration and indicate that Kjeldahl nitrogen and ammonia present in soil are important sources in each of the four watersheds. A few concentrations significantly greater than the others (as in fig. 10) may indicate sources other than soil.

Linear relationships between total Kjeldahl nitrogen and sediment and between total ammonia and sediment have r^2 values of 0.08 to 0.72 (table 27). The relationship for total Kjeldahl nitrogen in the Northeast Branch has a level of significance of 0.11, and the relationship for total ammonia in Rock Creek has a level of significance of 0.10. The lowest r^2 values and levels of significance are due to a few observations of relatively great concentration (as in fig. 10).

Two methods were used to determine the dissolved portions of the total Kjeldahl nitrogen and total ammonia (table 27). The dissolved portion of the total Kjeldahl nitrogen in Saint Clements Creek was simulated by fitting the following nonlinear equation to the data:

$$(DKN/TKN)=(A\times\exp(B\times SED))+C, \quad (4)$$

where

TKN=total Kjeldahl nitrogen, in milligrams per liter as N; and,

DKN=dissolved Kjeldahl nitrogen, in milligrams per liter as N.

The r^2 value for this relationship is 0.99. The dissolved portion of total ammonia in Saint Clements Creek has been simulated by fitting a linear relationship between the ratio of dissolved-to-total ammonia concentrations to sediment concentration (r^2=0.86; level of significance=0.08). The ratios of the dissolved-to-total concentrations of neither Kjeldahl nitrogen nor ammonia showed a significant relationship to sediment for the urban streams. For each site the mean of all measured values was calculated.

For the 1979–81 water years, the Northeast and Northwest Branch watersheds showed the greatest yields of total Kjeldahl nitrogen and Saint Clements Creek showed the greatest yield of total ammonia (table 12). The dissolved forms accounted for 51 to 63 percent of the yields of total Kjeldahl nitrogen and 64 to 72 percent of the yields of total ammonia.

All the nitrate plus nitrite was considered to be in the dissolved form because dissolved concentrations showed no difference from total concentrations. Values of dissolved nitrate plus nitrite were used in place of missing values of total nitrate plus nitrite in the determination of yields.

Only the data for Rock Creek showed significant relationships between the concentrations of total nitrate plus nitrite and streamflow (table 27). Concentrations in Rock Creek decreased with increasing streamflow and were simulated with a linear relationship between concentration and the logarithm of streamflow (fig. 11) having an r^2 value of 0.36.

Available water-quality data for Montgomery County, Md. (the county containing most of the Rock Creek watershed), indicate that the pattern of decreasing concentrations of nitrate plus nitrite with increasing streamflow in Rock Creek (fig. 11) is due to the presence of relatively high

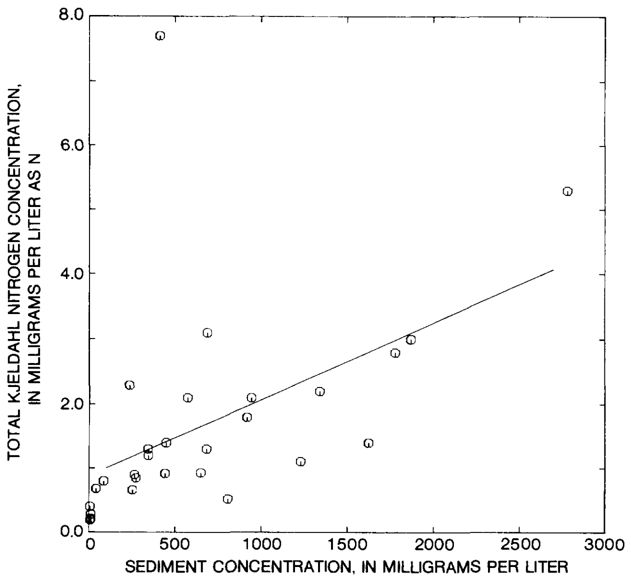

Figure 10. Total Kjeldahl nitrogen concentration versus sediment concentration for the Northwest Branch, 1979–81 water years.

Table 12. Mean annual yields of Kjeldahl nitrogen and ammonia from the urban and Saint Clements Creek watersheds

[Yields are in megagrams per square kilometer per year as N, except as indicated]

	Kjeldahl nitrogen				Ammonia			
	Period of record	1979-81 water years			Period of record	1979-81 water years		
Watershed	Total Kjeldahl nitrogen	Total Kjeldahl nitrogen	Dissolved Kjeldahl nitrogen	Ratio of dissolved Kjeldahl nitrogen to total Kjeldahl nitrogen, in percentage	Total ammonia	Total ammonia	Dissolved ammonia	Ratio of dissolved ammonia to total ammonia, in percentage
Rock Creek	0.30	0.43	0.24	55	0.030	0.041	0.028	68
Northwest Branch	.40	.65	.41	63	.023	.050	.032	64
Northeast Branch	.58	.69	.37	54	.058	.072	.052	72
Saint Clements Creek	.38	.50	.25	51	.085	.112	.074	66

concentrations of nitrate in the ground water. Under low-flow conditions, most streamflow originates as ground water. Water samples taken since 1946 from 48 percent of the wells in Montgomery County have shown concentrations of nitrate greater than 1.3 milligrams per liter as N (Woll, 1978), the low-flow concentration of nitrate plus nitrite in Rock Creek as estimated from figure 11. The nitrate in ground water also influences low-flow concentrations of nitrate plus nitrite in streams throughout the Rock Creek and Anacostia River watersheds within Montgomery County. Low-flow concentrations of nitrate or nitrate plus nitrite at selected sites average 0.9 to 3.0 milligrams per liter as N (CH2M Hill, 1977, 1982).

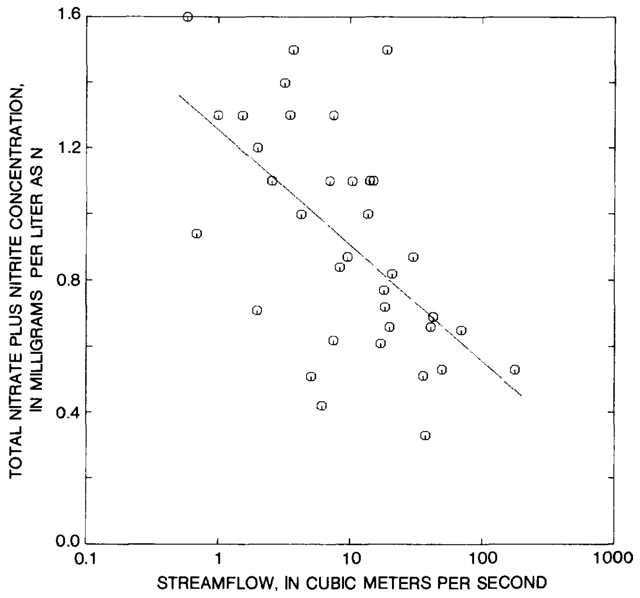

Figure 11. Total nitrate plus nitrite concentration versus streamflow for Rock Creek, 1979–81 water years.

The yields of nitrate plus nitrite are greater for the urban watersheds than for Saint Clements Creek (table 13). The yields for the Northwest Branch, Northeast Branch, and Saint Clements Creek watersheds were calculated with the mean of measured concentrations.

The period-of-record yield for the Rock Creek watershed, 0.38 megagrams per square kilometer per year as N, is 33 percent less than the yield of nitrate calculated by CH2M Hill (1979), 0.57 megagrams per square kilometer per year. Most of the nitrate plus nitrite in streamflow is generally considered to be in the form of nitrate.

Yields of total nitrogen (all species), calculated by summing the values of Kjeldahl nitrogen and nitrate plus nitrite, are greater for the urban watersheds than for the Saint Clements Creek watershed (table 13). During the 1979–81 water years, the dissolved form accounted for 63 to 79 percent of the yields of total nitrogen from the four watersheds. The period-of-record yields of total nitrogen are in good agreement with yields calculated by other studies (table 14).

Ultimate BOD

Yields of BOD from the Rock Creek, Northeast Branch, Northwest Branch, and Saint Clements Creek

Table 13. Mean annual yields of total nitrate plus nitrite and total nitrogen from the urban and Saint Clements Creek watersheds

[Yields are in megagrams per square kilometer per year as N, except as indicated]

Watershed	Total nitrate plus nitrite: Period of record	Total nitrate plus nitrite: 1979-81 water years	Total nitrogen[1]: Period of record	Total nitrogen[1], 1979-81 water years: Total nitrogen	Total nitrogen[1], 1979-81 water years: Dissolved nitrogen	Total nitrogen[1], 1979-81 water years: Ratio of dissolved nitrogen to total nitrogen, in percentage
Rock Creek	0.38	0.48	0.68	0.91	0.72	79
Northwest Branch	.24	.33	.64	.98	.74	76
Northeast Branch	.29	.34	.87	1.03	.71	69
Saint Clements Creek	.17	.18	.55	.68	.43	63

1/All species.

watersheds were calculated by developing a mean stormflow concentration and a mean nonstormflow concentration for each watershed (table 27). Mean BOD concentrations for nonstorm periods, calculated by averaging all measured BOD concentrations of samples having sediment concentrations of less than 10 milligrams per liter, are all about 5 milligrams per liter. The stormflow concentrations were estimated by averaging all BOD concentrations of samples having sediment concentrations of greater than or equal to 10 milligrams per liter. Mean stormflow BOD concentrations for the urban streams (16 to 21 milligrams per liter) are greater than the mean stormflow concentration for Saint Clements Creek (11 milligrams per liter).

Table 14. Comparison of yields of total nitrogen[1] for the period of record with yields calculated by other studies

[Yields are in megagrams per square kilometer per year as N; nd, not determined]

Urban Watersheds		
Watershed	Period of record (from table 13)	Metropolitan Washington Council of Governments[2]
Rock Creek	0.68	0.78
Northwest Branch	.64	.73 (Northwest and Northeast Branches)
Northeast Branch	.87	

Rural Watersheds			
Watershed	Period of record (from table 13)	Northern Virginia Planning District Commission[3]	Smithsonian Institution (1977)
Saint Clements Creek	0.55	nd	nd
Occoquan River	nd	0.49	nd
Rhode River, Md.	nd	nd	0.38

1/All species.

2/Michael Sullivan, written commun., 1979.

3/Jack Hartigan, written commun., 1982.

The record of streamflow for both the period of record and the period of study was divided into stormflow and nonstormflow in order to calculate yields of BOD. Stormflow during the 1979–81 water years was separated from nonstormflow by examining the record of daily streamflow. The proportions of period-of-record mean annual flow made up by stormflow and nonstormflow were assumed to be equal to the proportions calculated for the 1974 water year from an examination of the record of daily streamflow. The 1974 water year was selected as representative of period-of-record stream conditions in order to avoid an examination of the daily stream values throughout the period of record for each site. The mean annual flow and flow-duration curve for the 1974 water year approximate the respective values for the period of record.

Yields from the urban watersheds are greater than the yield from the rural Saint Clements watershed (table 15). The period-of-record yields from the urban watersheds agree with yields calculated by other recent studies, but the value for the Saint Clements Creek watershed is about 50 percent greater than the long-term average estimated for the rural land draining to the Occoquan Reservoir (table 16).

Dissolved Silica

Relationships between the concentration of dissolved silica and the logarithm of streamflow were found for Rock

Table 15. Mean annual yields of ultimate BOD and dissolved silica from the urban and Saint Clements Creek watersheds

[Yields are in megagrams per square kilometer per year]

Watershed	Ultimate BOD		Dissolved silica	
	Period of record	1979-81 water years	Period of record	1979-81 water years
Rock Creek	3.7	5.1	3.4	4.2
Northwest Branch	4.1	6.7	2.5	3.1
Northeast Branch	4.5	6.0	2.5	2.7
Saint Clements Creek	2.9	3.3	3.4	3.6

Creek, the Northeast Branch, and the Northwest Branch but not for Saint Clements Creek. The linear relationships for the urban streams (table 27) have r^2 values 0.65 to 0.78 and show decreasing concentrations with increasing streamflow (as in fig. 12). Concentrations at low flow reflect concentrations in the ground water and are less than or equal to concentrations reported by Woll (1978) for wells in this area. Concentrations at high flows never decrease to the levels in the rainfall (table 5), and this indicates that the silica comes from other than ground water or rainfall, possibly from the dissolution of soil. Kennedy (1971) notes that storm seepage in the Mattole River basin contains greater dissolved silica concentrations than do surface or groundwater runoff and attributes these high storm-seepage concentrations to the dissolution of soil.

Table 16. Comparison of yields of ultimate BOD for the period of record with yields calculated by other studies

[Yields are in megagrams per square kilometer per year; nd, not determined]

Urban Watersheds			
Watershed	Period of record (from table 15)	Metropolitan Washington Council of Governments[1]	CH2M Hill (1979)
Rock Creek	3.7	4.0	[2]3.6
Northwest Branch	4.1	4.0 (Northwest and Northeast Branches)	nd
Northeast Branch	4.5		nd

Rural Watersheds		
Watershed	Period of record (from table 15)	Northern Virginia Planning District Commission [3]
Saint Clements Creek	2.9	nd
Occoquan River	nd	1.8

[1]Michael Sullivan, written commun., 1979.

[2]Five-day demand has been converted to ultimate demand by assuming an exertion rate of 0.1 per day (base e).

[3]Jack Hartigan, written commun., 1982.

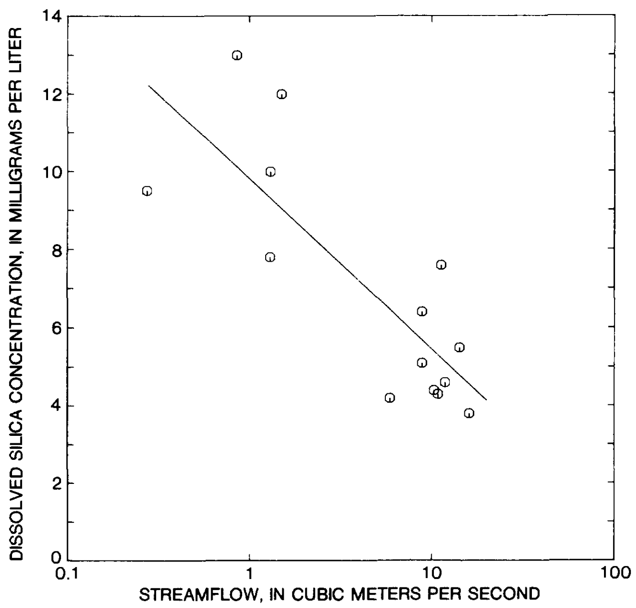

Figure 12. Dissolved silica concentration versus streamflow for the Northwest Branch, 1979–81 water years.

Yields of dissolved silica from Saint Clements Creek (calculated with the mean of all measured concentrations) are within the range of yields calculated for the urban watersheds (table 15). Although the mean concentration for Saint Clements Creek is based on only five samples, the annual yield from the Saint Clements Creek watershed during the 1979 water year is within 10 percent of the yield calculated for the Occoquan River watershed (adjusted for water-supply withdrawal) during the same period. The period-of-record yields from all four watersheds are within the range of yields of other watersheds having the same annual runoff (Davis, 1964).

LOADS OF SUSPENDED SEDIMENT AND NUTRIENTS FROM THE OCCOQUAN RIVER WATERSHED

Daily streamflow leaving the Occoquan River watershed was estimated from the records of operation of the Occoquan Dam (Fairfax County Water Authority, written commun., 1979–82). Streamflow over the dam crest was estimated from daily observations of the elevation of the water level in the reservoir and the following formula for flow over a broad-crested weir:

$$Q = C \times L \times H^{3/2}, \tag{5}$$

where

Q = streamflow over the weir, in cubic meters per second;

C = constant, = 1.77 if H is less than or equal to 0.15 meters, or = 1.88 if H is greater than 0.15 meters;

L = length of the weir crest, = 158 meters; and,

H = height of the water surface above the weir crest, in meters.

Flow passing through the two turbine generators at the dam was determined from their estimated capacity (7.9 cubic meters per second, total) and times of operation.

Streamflow leaving the Occoquan Reservoir during each of the 1979 and 1980 water years calculated in this manner is within 8 percent of values calculated from the record of streamflow entering the reservoir and the record of water-supply withdrawals (table 17). Rainfall directly onto and evaporation directly from the reservoir surface were not included in these calculations because their effect on the reservoir's water budget is small. Complete records of incoming streamflow were not available for the 1981 water year.

Loads of sediment, phosphorus, nitrogen, BOD, and dissolved silica leaving the Occoquan River watershed during the 1979–81 water years (table 18) were calculated with one of two different methods to estimate the concentrations of materials in the water passing the Occoquan Dam. Either the mean of the observed concentrations was used, or relationships were developed between concentration and the values of turbidity of the water supply in the intake located at the dam. In the latter case, the record of daily average turbidity was used to generate the daily average concentrations. The results of sampling for ammonia, nitrate plus nitrite, and suspended sediment done during 1979 by the Occoquan Watershed Monitoring Laboratory (Thomas Grizzard, written commun., 1980) were added to data collected by the USGS.

Relationships with turbidity were determined for suspended sediment, total phosphorus, total Kjeldahl nitrogen, ultimate BOD, and dissolved silica (table 28). Linear relationships, developed for all constituents except sediment, had r^2 values 0.40 to 0.83 (see fig. 13 for example). Dissolved silica was the only substance that showed decreasing concentration with turbidity. A nonlinear relationship (r^2=0.81) was developed between suspended-sediment concentration and turbidity.

Table 18. Loads of selected constituents leaving the Occoquan River watershed during the 1979–81 water years

[Loads are in megagrams, except as indicated; phosphorus and nitrogen are given as P and N, respectively; nd, not determined]

	Total load	Dissolved load	Ratio of dissolved load to total load, in percentage
Sediment	61 700	nd	nd
Phosphorus	125	58.0	46
Nitrogen[1]	2 150	1 940	90
Kjeldahl nitrogen	1 150	944	82
Ammonia	309	204	66
Nitrate plus nitrite	998	998	100
Ultimate BOD	9 860	nd	nd
Dissolved silica	nd	13 000	nd

[1] Calculated by summing the loads of Kjeldahl nitrogen and nitrate plus nitrite. Values of load are rounded.

Table 17. Comparison of two methods of estimating annual runoff of the Occoquan River at the Occoquan Dam during the 1979–80 water years

[Streamflow is in millimeters as runoff from the Occoquan River watershed, except as noted; streamflow entering the Occoquan Reservoir was measured at gage 016576700 on the Occoquan River near Manassas, Va., and at gage 01657415 on Bull Run near Clifton, Va.]

	Water year	
	1979	1980
Streamflow entering the Occoquan Reservoir	589	449
Water-supply withdrawal	56	56
Streamflow of the Occoquan River passing the Occoquan Dam:		
1) incoming streamflow minus the water-supply withdrawal	533	393
2) estimated from the records of the operation of the Occoquan Dam	560	360
Difference, in percent	[1]5	[2]-8

[1] ((560-533)/533)x100=5

[2] ((360-393)/393)x100=-8

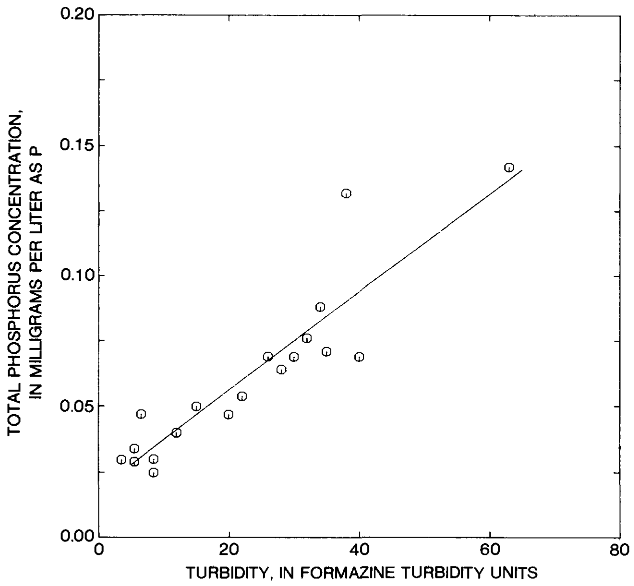

Figure 13. Total phosphorus concentration versus turbidity for the Occoquan River, 1979–81 water years.

The dissolved portions of phosphorus and of Kjeldahl nitrogen were determined by developing linear relationships between the dissolved and the total (unfiltered) forms (r^2 value for phosphorus=0.82; r^2 value for Kjeldahl nitrogen=0.85). The dissolved forms accounted for 46 and 82 percent of the loads of phosphorus and Kjeldahl nitrogen, respectively, that left the watershed during the 1979–81 water years (table 18).

The mean concentrations of total and dissolved ammonia nitrogen and total nitrate plus nitrite nitrogen were used to estimate loads leaving the reservoir. All the nitrate plus nitrite nitrogen was assumed to be in the dissolved form. The dissolved portion of total ammonia was set at 66 percent, which is the same as the dissolved portion of the total ammonia load estimated to have left the Saint Clements Creek watershed during the period of study.

The loads estimated to have left the Occoquan Reservoir during the 1979 and 1980 calendar years were compared with the loads entering as a check of the methods (table 19). All loads leaving are close to or less than the loads entering during the respective periods (Occoquan Watershed Monitoring Laboratory, 1980, 1981). The retention of particulate material in the reservoir would account for the loads leaving being less than the loads entering. Annual sediment-trap efficiencies of the reservoir (calculated from data in table 19) show mixed agreement with values calculated by the method described by Brune (1953):

	Sediment trap efficiency (percentage of incoming load trapped)	
	Calculated from table 19	With the method of Brune
1979	69	75
1980	96	80

LOADS OF SUSPENDED SEDIMENT AND NUTRIENTS FROM THE COMBINED SEWER SYSTEM OF THE DISTRICT OF COLUMBIA

The volume of overflow from the combined sewer system of the District of Columbia during the 1979–81 water years was taken from work by O'Brien and Gere Engineers (1979). Daily overflow during the 1979 and 1980 water years was obtained from O'Brien and Gere Engineers (Gregory Welter, written commun., 1981). Daily overflow for the 1981 water year was calculated with the record of daily precipitation at Washington National Airport and a linear relationship between daily overflow during the 1980

Table 19. Comparison of the loads of selected constituents entering and leaving the Occoquan Reservoir in streamflow during the 1979 and 1980 calendar years

[Loads are in megagrams, except as indicated; phosphorus and nitrogen are given as P and N, respectively]

	1979			1980		
	Loads entering[1]	Loads leaving	Proportion of loads leaving to loads entering, in percentage	Loads entering[1]	Loads leaving	Proportion of loads leaving to loads entering, in percentage
Sediment	181 000	55 700	31	101 000	4 420	4
Total phosphorus	230	108	47	90.9	15.1	17
Total nitrogen	2 130	1 690	79	1 100	387	35
Total Kjeldahl nitrogen	1 240	938	76	508	180	35
Total ammonia	216	232	107	70.9	64.1	90
Total nitrate plus nitrite	893	748	84	588	207	35

1/From the Occoquan Watershed Monitoring Laboratory (1980, 1981).

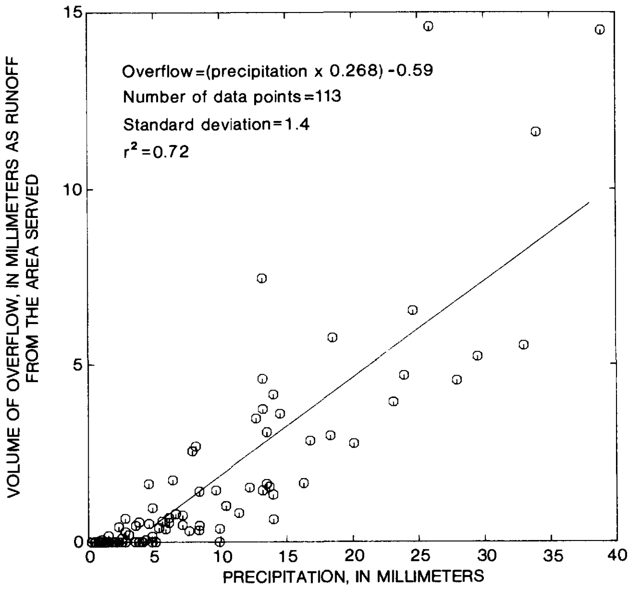

Figure 14. Daily overflow from the combined sewer system of the District of Columbia versus daily precipitation at Washington National Airport, 1980 water year.

water year and the corresponding daily precipitation at Washington National Airport (fig. 14). The data for the 1979 water year were not included in the regression because changes in the operation of the system during the 1979 water year reduced the volume of overflow produced by a given amount of rain (Gregory J. Welter, O'Brien and Gere Engineers, oral commun., 1982). The volume of overflow during the period of study, calculated by summing daily values, was 45 million cubic meters.

Table 20. Loads of selected constituents in the overflow of the combined sewer system of the District of Columbia during the 1979–81 water years

[Loads are in megagrams, except as indicated; phosphorus and nitrogen are given as P and N, respectively; nd, not determined]

	Total Load	Dissolved Load	Proportion of dissolved load to total load, in percentage
Sediment	10 400	nd	nd
Phosphorus	96.1	53.0	55
Nitrogen	240	194	81
Kjeldahl nitrogen	198	176	89
Ammonia	95.7	72.5	76
Nitrate plus nitrite	41.7	18.3	44
Ultimate BOD	3 940	nd	nd
Dissolved silica	nd	440	nd

Loads of sediment, phosphorus, nitrogen, BOD, and dissolved silica in the overflow from the combined sewer system during the 1979–81 water years (table 20) were calculated with the mean of observed concentrations (table 21). The concentration of suspended sediment is the mean of concentrations of settleable solids observed in the discharge from two points of overflow during a 6-month period (Roy F. Weston, Inc., 1970). Concentrations of 5-day BOD, phosphorus, and the nitrogen species are the mean concentrations observed in the overflow at nine sites from November 1978 through June 1980 (G.J. Welter, O'Brien and Gere Engineers, written commun., 1981, and oral commun., 1983). The value of BOD was converted to ultimate demand by assuming an exertion rate of 0.1 per day (base e). The concentration of dissolved silica in the overflow is equal to the mean of concentrations observed in the outfall of the Blue Plains wastewater-treatment plant (Blanchard and others, 1982).

COMPARISON OF LOCAL NONPOINT-SOURCE LOADS AND OTHER MAJOR SOURCES

The loads discharged from the local watersheds tributary to the tidal Potomac River and Estuary were calculated by adopting the yields calculated for the Northwest Branch and Northeast Branch watersheds as representative of the urban watersheds and the yields calculated for the Saint

Table 21. Mean concentrations of selected constituents in the overflow of the combined sewer system of the District of Columbia during the 1979–81 water years

[Concentrations are in milligrams per liter, except as indicated; phosphorus and nitrogen are given as P and N, respectively; nd, not determined]

	Total	Dissolved	Ratio of dissolved concentration to total concentration, in percentage
Sediment	1/229	nd	nd
Phosphorus	2/2.12	2/1.17	55
Nitrogen3/	5.28	4.28	81
Kjeldahl nitrogen	2/4.36	2/3.88	89
Ammonia	2/2.11	2/1.60	76
Nitrate plus nitrite	2/0.92	2/0.40	44
Ultimate BOD	2/87	nd	nd
Dissolved silica	nd	4/9.7	nd

1/Value is for settleable solids, only (Roy F. Weston, 1970).

2/From O'Brien and Gere Engineers (Gregory J. Welter, written commun., 1981; and Gregory J. Welter, oral commun., 1983); phosphorus includes only orthophosphates and polyphosphates as defined by method 223B in American Public Health Association, 1971; 5-day BOD value converted to ultimate demand by assuming an exertion rate of 0.1 per day (base e).

3/Calculated by summing values for Kjeldahl nitrogen and nitrate plus nitrite.

4/Mean of observed concentrations of the Blue Plains wastewater treatment plant; calculated from data in Blanchard and others (1982).

Clements Creek watershed as representative of the rural watersheds. Comparisons between the period-of-record yields for these three watersheds and the yields reported by other studies indicate that this is a reasonable assumption except for the sediment yield for the Saint Clements Creek watershed. Watersheds consisting of more than 30-percent urban land were considered urban, and all others were considered rural. These definitions indicated that urban watersheds account for 40 percent of the land draining of the tidal river and estuary, and rural watersheds account for 60 percent.

The resulting loads from all local watersheds to the tidal Potomac River and Estuary during the 1979–81 water years are 2.7 million megagrams of sediment, 3,100 megagrams of phosphorus, 14,000 megagrams of nitrogen, 74,000 megagrams of ultimate BOD, and 68,000 megagrams of dissolved silica. Yields from the Northeast Branch and Northwest Branch watersheds were averaged and applied to all urban watersheds except the Rock Creek watershed and the area served by the combined sewer system of the District of Columbia. Yields from the Saint Clements Creek watershed were applied to all rural watersheds except for the Occoquan River watershed. The loads from Rock Creek and Occoquan River watersheds were added separately because of the respective influences of Lakes Frank and Needwood and the Occoquan Reservoir.

The loads of sediment discharged to the tidal river and estuary (2.7 million megagrams) and to the tidal river (1.2 million megagrams) are probably overestimates because the period-of-record sediment yield calculated for the Saint Clements Creek is at least twice yields of sediment calculated for other rural watersheds. Alternative values of sediment loads discharged during the 1979–81 water years to the tidal river and estuary (1.7 million megagrams) and to the tidal river (1.0 million megagrams) were calculated by adopting a yield of 80 megagrams per square kilometer per year (half the 1979–81 water year yield calculated for the Saint Clements Creek watershed) for the rural watersheds. These alternate sediment loads discharged to the tidal river and estuary are, respectively, 63 percent and 83 percent of the loads determined with the yield calculated for the Saint Clements Creek watershed as representative of rural watersheds.

The three local nonpoint sources together contributed 2.7 million megagrams of sediment, 3,300 megagrams of phosphorus, 18,000 megagrams of nitrogen, 78,000 megagrams of ultimate BOD, and 69,000 megagrams of dissolved silica to the tidal river and estuary during the 1979–81 water years (table 22). Tributary streamflow, by far the largest of the three sources, contributed at least 94 percent of the load of each measured substance except nitrogen. Rain falling on the surface of the tidal river and estuary contributed 21 percent of the nitrogen. Monthly loads from all local nonpoint sources to the tidal river and estuary and to the tidal river are given in tables 29 and 30, respectively.

Table 22. Loads from local nonpoint sources discharging to the tidal Potomac River and Estuary during the 1979–81 water years

[Phosphorus and nitrogen are given as P and N, respectively; nd, not determined]

Local nonpoint sources	Sediment	Phosphorus	Nitrogen	Ultimate BOD	Dissolved silica
		Loads, in megagrams			
Streamflow from local tributaries	2.7×10^6	3 100	14 000	74 000	68 000
Overflows from the combined sewer system of the District of Columbia	1.0×10^4	96	240	3 900	440
Rain falling upon the tidal water surface	nd	100	3 800	nd	200
Totals (rounded)	2.7×10^6	3 300	18 000	78 000	69 000
	Proportion of loads from each local nonpoint source, in percentage				
Streamflow from local tributaries	100	94	78	95	99
Overflows from the combined sewer system of the District of Columbia	<1	3	1	5	1
Rain falling upon the tidal water surface	nd	3	21	nd	<1

Summing the monthly loads from local nonpoint sources to the tidal river and estuary required three assumptions: (1) all the nitrate plus nitrite in the overflows of the combined sewer was in the dissolved form; (2) all the phosphorus in the rainfall was in the dissolved form; and (3) all the nitrogen in the rainfall was in the dissolved form. The first two assumptions were not critical because the loads of nitrate plus nitrite in the overflows and of phosphorus in the rainfall are less than 5 percent of the respective loads from all the nonpoint sources. However, the third assumption was more important because rainfall contributed 21 percent of the nitrogen load from the nonpoint sources. Half of the load of total nitrogen was in the readily soluble form of nitrate plus nitrite, and so the uncertainty was associated with the solubility of the Kjeldahl nitrogen.

The largest monthly local nonpoint-source loads occurred during months having the greatest stormflow, and stormflow was generally greatest in months during which large, intense rainstorms occurred. The importance of the loads discharged during such storms is illustrated by comparing the local nonpoint-source loads that occurred during September 1979 (when tropical storm David passed through the area) with the loads calculated for the 1979–81 water years. Although September 1979 accounted for only 3 percent of the 1979–81 water years, the loads during this month made up the following proportions of the local nonpoint-source loads during the 1979–81 water years: 37 percent of the sediment, 31 percent of the phosphorus, and 8–13 percent of the nitrogen, ultimate BOD, and dissolved silica.

Loads from other major sources of sediment, phosphorus, nitrogen, BOD, and dissolved silica were considered to assess the importance of loads from local nonpoint sources. Loads discharged during the 1979–81 water years to the tidal river and estuary from the Potomac River at Chain Bridge (Daniel Hahl, U.S. Geological Survey, written commun., 1982), from the metropolitan Washington wastewater-treatment plants (Wayne Webb, U.S. Geological Survey, written commun., 1982), shore erosion (silt plus clay, only; current conditions excluding the bulkheaded areas; Andrew Miller, oral commun., 1982), as well as from local nonpoint sources, are given in table 23. Similar loads entering only the tidal river during the 1979–81 water years (table 24) and during the summer months (July, August, and September) of the 1979–81 water years (table 25) also have been calculated.

Local nonpoint sources contributed 17 to 38 percent of the loads to the tidal river and estuary during the 1979–81 water years (table 23). The Potomac River at Chain Bridge, the largest source, contributed 43 percent of the phosphorus and more than half of all other materials. Local nonpoint sources supplied a smaller percentage of the loads that entered the tidal river during the 1979–81 water years (10 to 23 percent) than they did of the loads that entered the entire tidal river and estuary during this period (table 24).

During the summer months, local nonpoint sources contributed 15 to 49 percent of the total loads that entered the tidal river (table 25). These percentages are greater than

Table 23. Major source loads of sediment, phosphorus, nitrogen, ultimate BOD, and dissolved silica to the tidal Potomac River and Estuary during the 1979–81 water years

[Phosphorus and nitrogen are given as P and N, respectively; nd, not determined]

Major sources	Sediment	Phosphorus	Nitrogen	Ultimate BOD	Dissolved silica
		Loads, in megagrams			
Potomac River at Chain Bridge	4.0×10^6	4 400	61 000	190 000	190 000
Metropolitan Washington wastewater treatment plants	3.0×10^4	2 500	28 000	43 000	19 000
Shore erosion	4.5×10^5	nd	nd	nd	nd
Local nonpoint sources	2.7×10^6	3 300	18 000	78 000	69 000
Totals (rounded)	7.2×10^6	10 000	110 000	310 000	280 000
		Proportion of loads for each major source, in percentage			
Potomac River at Chain Bridge	56	43	57	61	68
Metropolitan Washington wastewater treatment plants	<1	25	26	14	7
Shore erosion	6	nd	nd	nd	nd
Local nonpoint sources	38	32	17	25	25

Table 24. Major source loads of sediment, phosphorus, nitrogen, ultimate BOD, and dissolved silica to the tidal Potomac River during the 1979–81 water years

[Phosphorus and nitrogen are given as P and N, respectively; nd, not determined]

Major sources	Sediment	Phosphorus	Nitrogen	Ultimate BOD	Dissolved silica
		Loads, in megagrams			
Potomac River at Chain Bridge	4.0×10^6	4 400	61 000	190 000	190 000
Metropolitan Washington wastewater treatment plants	3.0×10^4	2 500	28 000	43 000	19 000
Shore erosion	5.0×10^4	nd	nd	nd	nd
Local nonpoint sources	1.2×10^6	1 200	10 000	47 000	34 000
Totals (rounded)	5.3×10^6	8 100	99 000	280 000	243 000
		Proportion of loads for each major source, in percentage			
Potomac River at Chain Bridge	76	54	62	68	78
Metropolitan Washington wastewater treatment plants	<1	31	28	15	8
Shore erosion	1	nd	nd	nd	nd
Local nonpoint sources	23	15	10	17	14

Table 25. Major source loads of sediment, phosphorus, nitrogen, ultimate BOD, and dissolved silica to the tidal Potomac River during July, August, and September of the 1979–81 water years

[Phosphorus and nitrogen are given as P and N, respectively; nd; not determined]

Major sources	Sediment	Phosphorus	Nitrogen	Ultimate BOD	Dissolved silica
		Loads, in megagrams			
Potomac River at Chain Bridge	480 000	610	5 700	25 000	19 000
Metropolitan Washington wastewater treatment plants	5 400	530	7 100	9 100	4 800
Shore erosion[1/]	12 000	nd	nd	nd	nd
Local nonpoint sources	480 000	420	2 200	10 900	6 000
Total (rounded)	980 000	1 600	15 000	45 000	30 000
		Proportion of loads for each major source, in percentage			
Potomac River at Chain Bridge	49	39	38	56	64
Metropolitan Washington wastewater treatment plants	1	34	47	20	16
Shore erosion	1	nd	nd	nd	nd
Local nonpoint sources	49	27	15	24	20

1/Calculated by assuming that annual rate of shore erosion is constant over the year.

the corresponding percentages for the 1979–81 water years (10 to 23 percent).

The summer period as defined does not represent normal summer conditions of loads to the tidal river because tropical storm David in September 1979 produced unusually high summer loads from local nonpoint sources and from the Potomac River at Chain Bridge. During this month, local nonpoint sources discharged the following proportions of summer-month loads from local nonpoint sources: 88 percent of the sediment, 74 percent of the phosphorus, and 45–55 percent of the nitrogen, ultimate BOD, and dissolved silica. The loads from the Potomac River at Chain Bridge discharged during September 1979 constituted nearly the same respective proportions of its summer-month loads.

The proportions of major source loads contributed by local nonpoint sources to the tidal river during the summer were calculated excluding the loads during September 1979 in order to better describe mean summer conditions. The resulting proportions calculated when September 1979 is excluded, shown below, are less than or equal to the respective proportions calculated with the September 1979 loads. The porportion of phosphorus shows the biggest decrease, and the proportions of dissolved silica and sediment show little or no decrease.

Local nonpoint-source loads as proportions of major source loads to the tidal Potomac River during July, August, and September of the 1979-81 water years, in percentage

	Sediment	Phosphorus (as P)	Nitrogen (as N)	Ultimate BOD	Dissolved silica
including September 1979	49	27	15	24	20
excluding September 1979	46	15	10	20	20

SUMMARY AND CONCLUSIONS

Rain falling on the water surface of the tidal Potomac River and Estuary during the 1979–81 water years contained 100 megagrams of phosphorus, 3,800 megagrams of nitrogen, and 200 megagrams of dissolved silica. These values were calculated with the means of concentrations in the rain falling at several sites measured by other researchers. The mean concentrations of phosphorus and Kjeldahl nitrogen measured in the rain falling in and around the Washington metropolitan area are an order of magnitude greater than concentrations measured at two other rural sites. The average annual value of precipitation during this period was near the long-term average.

Average annual yields of selected constituents in the streamflow leaving three urban watersheds (Rock Creek, the Northwest Branch, and the Northeast Branch) and one rural watershed (Saint Clements Creek) were determined from samples taken during the 1979–81 water years. Yields during this period were calculated with the record of streamflow and either the mean of observed concentrations or relationships developed between concentration and streamflow. Period-of-record yields were calculated by the flow-duration-curve method and with streamflow data for the period of record, which, depending on the stream, ranged from 13 to 52 years. The yields for the 1979–81 water years are up to 2.3 times the period-of-record yields and reflect greater streamflow and stormflow during the 1979–81 water years than during the period of record. Except for suspended sediment, the period-of-record yields generally agree with yields that have been calculated by other studies.

The period-of-record yield of sediment from the rural Saint Clements Creek watershed, 72 megagrams per square kilometer per year, is within the range of yields exhibited by the urban watersheds, 57 to 97 megagrams per square kilometer per year, and at least twice the yields estimated for other rural watersheds in other studies. The yield calculated for Saint Clements Creek is probably an overestimate of the actual yield of sediment from this watershed, in part because most of the samples of this stream were taken during the 1981 water year, a very dry period.

Period-of-record yields of sediment calculated for the Rock Creek, Northwest Branch, and Northeast Branch watersheds are 17 to 51 percent of the yields calculated from sediment concentrations measured 20 years ago. This decrease is due partially to the imposition of effective sediment controls at construction sites in the urban area and to the construction of Lakes Frank and Needwood in the Rock Creek watershed. The data and methods used by Wark and Keller (1963) to calculate sediment yields from concentrations measured 20 years ago were reviewed, and their values of sediment yield from these three watersheds were found to be overestimates.

The period-of-record yield of total phosphorus from the Saint Clements Creek watershed, 0.109 megagrams per square kilometer per year as P, is greater than the yields calculated for the urban watersheds, 0.047 to 0.072 megagrams per squre kilometer per year as P; the yields of other nutrients from the Saint Clements Creek watershed are less than or within the range of the corresponding yields for the urban watersheds. The period-of-record yields for the Saint Clements Creek watershed and the urban watersheds are, respectively, 0.55 and 0.64 to 0.87 megagrams per square kilometer per year of nitrogen (as N), 2.9 and 3.7 to 4.5 megagrams per square kilometer per year of ultimate BOD, and 3.4 and 2.5 to 3.4 megagrams per square kilometer per year of dissolved silica. Concentrations of total phosphorus, total ammonia, and total Kjeldahl nitrogen in the urban streams and Saint Clements Creek increase with increasing sediment concentration and indicate that soil is an important source of all three nutrients. The importance of soil as a source of phosphorus is also indicated by the decreasing ratio of dissolved-to-total phosphorus with increasing suspended-sediment concentration. Decreasing concentrations with increasing streamflow noted for total nitrate plus nitrite in Rock Creek and dissolved silica in all three urban streams indicate that ground water is an important source of these two nutrients in the indicated watersheds.

During the 1979–81 water years, 62,000 megagrams of sediment, 120 megagrams of phosphorus, 2,200 megagrams of nitrogen, 9,900 megagrams of BOD, and 13,000 megagrams of dissolved silica left in the Occoquan River watershed and entered the tidal river and estuary. Streamflow was estimated from the record of operation of the Occoquan Dam, and concentrations were either calculated from the record of turbidity of the water-supply intake at the dam or set equal to the mean of observed concentrations.

The following loads of nutrients and sediment from the local tributary watersheds discharged to the tidal Potomac River and Estuary during the 1979–81 water years were calculated by applying yields determined for the monitored watersheds to the watersheds not sampled: 2.7 million megagrams of sediment, 3,100 megagrams of phosphorus, 14,000 megagrams of nitrogen, 74,000 megagrams of BOD, and 68,000 megagrams of dissolved silica. The sediment load is probably an overestimate because the period-of-record yield from the Saint Clements Creek watershed is greater than yields that have been estimated for other rural watersheds.

During the 1979–81 water years the overflows of the combined sewer system of the District of Columbia discharged 10,000 megagrams of sediment, 96 megagrams of phosphorus, 240 megagrams of nitrogen, 3,900 megagrams of BOD, and 440 megagrams of dissolved silica to the tidal river and estuary. These values were calculated with the volumes of daily overflow calculated by O'Brien and Gere Engineers (Greg Welter, written commun., 1981) and the mean of concentrations observed by O'Brien and Gere Engineers (Greg Welter, written commun., 1981, and oral commun., 1983), Roy F. Weston, Inc. (1970), and the mean of dissolved silica concentrations in the outfall of Blue Plains wastewater-treatment plant (Blanchard and others, 1982).

During the 1979–81 water years, the three local nonpoint sources (streamflow leaving the local tributary watersheds, overflows of the combined sewer system of the Distric of Columbia, and rain falling directly upon the tidal water surface) together contributed 2.7 million megagrams of sediment, 3,300 megagrams of phosphorus, 18,000 megagrams of nitrogen, 78,000 megagrams of BOD, and 69,000 megagrams of dissolved silica. Tributary discharge, by far the largest nonpoint source, contributed 78 percent of the nitrogen and more than 90 percent of the loads of the other materials.

Large portions of the local nonpoint-source loads were discharged during September 1979, when tropical storm David passed through the area. The loads during this month made up 37 percent of the sediment load, 31 percent of the phosphorus load, and 8–13 percent of the nitrogen, ultimate BOD, and dissolved silica loads discharged from local nonpoint sources during the 1979–81 water years.

Loads from local nonpoint sources discharged to the tidal Potomac River and Estuary during the 1979–81 water years provided 17 to 38 percent of the loads entering from major sources. The other major sources considered in this comparison were the Potomac River at Chain Bridge, shore erosion, and the Washington metropolitan area wastewater-treatment plants. If only the tidal river is considered, these values dropped to 10 to 23 percent of the total loads.

During the summer months (July, August, and September) of the 1979–81 water years, local nonpoint sources contributed 15 to 49 percent of the nutrient and sediment loads discharged by the major sources. The loads contributed by the local nonpoint sources during the summer months were greater than the corresponding values for the entire period of study because the tributaries discharged a greater portion of their annual loads during the summer than did the Potomac River at Chain Bridge.

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TABLES 26–30

Table 26. Mean monthly precipitation estimated for the local drainage area of the tidal Potomac River and Estuary during the 1979–81 water years

[Precipitation is in millimeters; data are averages of precipitation measured at National Weather Service precipitation stations in Washington, D.C. (Washington National Airport), Beltsville, Md., Warrenton, Va., La Plata, Md., and Patuxent River, Md.]

	Water Year		
	1979	1980	1981
October	24	139	93
November	70	82	81
December	102	31	17
January	181	81	10
February	147	29	96
March	75	141	31
April	68	102	76
May	106	87	107
June	102	39	94
July	116	115	135
August	194	51	90
September	195	48	70
Annual	1 380	945	900

Table 27. List of relationships used to predict sediment and nutrient concentrations in Rock Creek, Northwest Branch, Northeast Branch, and Saint Clements Creek during the 1979–81 water years

[All linear regressions are significant at the 0.05 level, except as indicated; nd, not determined; *Q* is streamflow in cubic meters per second and concentrations are in milligrams per liter; *SED* is suspended sediment concentration; *TP* is total phosphorus concentration as P; *DP* is dissolved phosphorus concentration as P; *TKN* is total Kjeldahl nitrogen concentration as N; *DKN* is dissolved Kjeldahl nitrogen concentration as N; *TNH3* is total ammonia concentration as N; *DNH3* is dissolved ammonia concentration as N; *TN023* is total nitrate plus nitrite concentration as N; *UBOD* is ultimate BOD concentration; *DSI02* is dissolved silica concentration; log is logarithm; exp is exponent; *r* is correlation coefficient]

Substance	Stream	Relationship	Number of observations	r^2 value	Standard deviation
Sediment	Rock Creek	$\log(SED) = 4.33 \times (1. -(2.14 \times Q)^{-0.275})$	61	1/0.97	nd
	Northwest Branch	$\log(SED) = 11.30 \times (1. -(6.53 \times Q)^{-0.644})$ maximum concentration set to 2000 mg/L; 2 observations not considered in regression	56	1/.99	nd
	Northeast Branch	$\log(SED) = 4.18 \times (1. -(1.56 \times Q)^{-0.306})$	57	1/.97	nd
	Saint Clements Creek	log(*SED*) = 1.97 + (0.920 x log(*Q*))	36	1/.61	0.34
Sand	Rock Creek	Sand = − 91 + (*SED* x 0.403)	21	.77	145
	Northwest Branch	Sand = − 165 + (*SED* x 0.592)	9	.75	143
	Northeast Branch	Sand = − 23 + (*SED* x 0.219)	12	.85	37
Silt	Rock Creek	Silt = − 1 + (*SED* x 0.420)	18	.87	111
	Northwest Branch	Silt = 82 + (*SED* x 0.242)	8	.53	91
	Northeast Branch	Silt = − 61 + (*SED* x 0.469)	11	.98	28
Clay	Rock Creek	Clay = 76 + (*SED* x 0.186)	18	.77	70
	Northwest Branch	Clay = 100 + (*SED* x 0.149) Level of significance = 0.08	8	.42	70
	Northeast Branch	Clay = 78 + (*SED* x 0.317)	11	.93	36
Total phosphorus	Rock Creek	*TP* = 0.078 + (*SED* x 0.000354) 1 observation not included in regression	28	0.50	0.20
	Northwest Branch	*TP* = 0.076 + (*SED* x 0.000394)	26	.79	.11
	Northeast Branch	*TP* = 0.114 + (*SED* x 0.000291) 1 observation not included in regression	26	.69	.13
	Saint Clements Creek	*TP* = 0.052 + (*SED* x 0.00123)	28	.69	.38
Dissolved phosphorus	Rock Creek	*DP/TP* = (0.53 x exp(*SED* x (−0.0659))) + 0.24	26	.69	nd
	Northwest Branch	*DP/TP* = (0.59 x exp(*SED* x (−0.00761))) + 0.16	15	.87	nd
	Northeast Branch	*DP/TP* = (0.42 x exp(*SED* x (−0.00602))) + 0.14 1 observation not included in regression	13	.91	nd
	Saint Clements Creek	*DP/TP* = (0.45 x exp(*SED* x (−0.0109))) + 0.06	5	.99	nd
Total Kjeldahl nitrogen	Rock Creek	*TKN* = 0.69 + (*SED* x 0.000971)	32	0.54	0.50
	Northwest Branch	*TKN* = 0.89 + (*SED* x 0.00118)	28	.25	1.43
	Northeast Branch	*TKN* = 1.28 + (*SED* x 0.000704) Level of significance = 0.11	32	.08	1.60
	Saint Clements Creek	*TKN* = 0.80 + (*SED* x 0.000979)	17	.63	.39

Table 27. List of relationships used to predict sediment and nutrient concentrations in Rock Creek, Northwest Branch, Northeast Branch, and Saint Clements Creek during the 1979–81 water years—Continued

Substance	Stream	Relationship	Number of observations	r^2 value	Standard deviation
Dissolved Kjeldahl nitrogen	Rock Creek	*DKN/TKN* = 0.55	24	nd	nd
	Northwest Branch	*DKN/TKN* = 0.63	15	nd	nd
	Northeast Branch	*DKN/TKN* = 0.54	15	nd	nd
	Saint Clements Creek	*DKN/TKN* = (0.36 x exp(*SED* x (-0.0132))) + 0.43	5	.99	nd
Total ammonia	Rock Creek	*TNH3* = 0.078 + (*SED* x 0.0000409) Level of significance = 0.10	22	.13	.08
	Northwest Branch	*TNH3* = 0.007 + (*SED* x 0.000212)	21	.72	.09
	Northeast Branch	*TNH3* = 0.118 + (*SED* x 0.000122)	21	.47	.09
	Saint Clements Creek	*TNH3* = 0.134 + (*SED* x 0.000443)	16	.50	.11
Dissolved ammonia	Rock Creek	*DNH3/TNH3* = 0.68	10	nd	nd
	Northwest Branch	*DNH3/TNH3* = 0.64	7	nd	nd
	Northeast Branch	*DNH3/TNH3* = 0.72	4	nd	nd
	Saint Clements Creek	*DNH3/TNH3* = 1.0 -(*SED* x (-0.00137)) Minimum value of *DNH3/TNH3* set to 0.45; level of significance = 0.08	4	.86	0.14
Total nitrate plus nitrite	Rock Creek	*TNO23* = 1.26 - (log(*Q*)x 0.350)	36	.36	.27
	Northwest Branch	*TNO23* = 0.75	31	nd	nd
	Northeast Branch	*TNO23* = 0.73	32	nd	nd
	Saint Clements Creek	*TNO23* = 0.43	18	nd	nd
Ultimate BOD	Rock Creek	*UBOD* = 5.4 for nonstorm periods = 16 for storms	48	nd	nd
	Northwest Branch	*UBOD* = 4.5 for nonstorm periods = 21 for storms	31	nd	nd
	Northeast Branch	*UBOD* = 4.6 for nonstorm periods = 18 for storms	38	nd	nd
	Saint Clements Creek	*UBOD* = 4.5 for nonstorm periods = 11 for storms	16	nd	nd
Dissolved silica	Rock Creek	*DSIO2* = 12.2 - (log(*Q*) x 4.88) Minimum concentration set to 2.0	29	0.78	1.50
	Northwest Branch	*DSIO2* = 9.8 - (log(*Q*) x 4.35) Minimum concentration set to 3.0	14	.65	1.88
	Northeast Branch	*DSIO2* = 8.3 - (log(*Q*) x 3.08) Minimum concentration set to 2.0	18	.72	.89
	Saint Clements Creek	*DSIO2* = 8.7	5	nd	nd

1/Logarithmic correlation coefficient squared.

Table 28. List of relationships used to predict sediment and nutrient concentrations in the Occoquan River during the 1979–81 water years

[All linear regressions are significant at the 0.05 level, except as indicated; nd, not determined; *TURB* is turbidity in formazine turbidity units (FTU); concentrations are in milligrams per liter; *SED* is suspended-sediment concentration; *TP* is total phosphorus concentration as P; *DP* is dissolved phosphorus concentration as P; *TKN* is total Kjeldahl nitrogen concentration as N; *DKN* is dissolved Kjeldahl nitrogen concentration as N; *TNH3* is total ammonia concentration as N; *DNH3* is dissolved ammonia concentration as N; *TN023* is total nitrate plus nitrite concentration as N; *UBOD* is ultimate BOD concentration; *DSI02* is dissolved silica concentration; exp is exponent; *r* is correlation coefficient]

Substance	Relationship	Number of observations	r^2 value	Standard deviation
Sediment	*SED* = (33.0 x exp(*TURB* x 0.0181)) - 31.8 includes only those observations with values of turbidity greater than 5 FTU	71	0.81	nd
Total phosphorus	*TP* = 0.0186 + (*TURB* x 0.00188)	19	.83	.01
Dissolved phosphorus	*DP* = -0.00409 + (*TP* x 0.512)	19	.82	.01
Total Kjeldahl nitrogen	*TKN* = 0.440 + (*TURB* x 0.0101)	19	.40	.20
Dissolved Kjeldahl nitrogen	*DKN* = -0.203 + (*TKN* x 0.846)	13	.85	.09
Total ammonia	*TNH3* = 0.22	69	nd	nd
Dissolved ammonia	*DNH3* = 0.14	nd	nd	nd
Total nitrate plus nitrite	*TNO23* = 0.71	84	nd	nd
Ultimate BOD	*UBOD* = 4.58 + (*TURB* x 0.0652)	25	0.44	1.19
Dissolved silica	*DSIO2* = 11.5 - (*TURB* x 0.0603)	19	.70	.64

Table 29. Monthly loads to the tidal Potomac River and Estuary from local nonpoint sources during the 1979–81 water years

[Runoff is in millimeters over the local watersheds, loads are in megagrams, and phosphorus and nitrogen are given as P and N, respectively]

YEAR	MONTH	RUNOFF	SEDIMENT	TOTAL PHOSPHORUS	DISSOLVED PHOSPHORUS	TOTAL KJELDAHL NITROGEN	DISSOLVED KJELDAHL NITROGEN	TOTAL NITRATE PLUS NITRITE	TOTAL AMMONIA	DISSOLVED AMMONIA	ULTIMATE BOD	DISSOLVED SILICA
78	10	5.	612.	5.	3.	49.	39.	37.	14.	13.	293.	343.
78	11	11.	2908.	13.	7.	114.	88.	86.	37.	35.	782.	670.
78	12	28.	18557.	36.	13.	247.	171.	169.	69.	63.	1977.	1618.
79	1	96.	170922.	176.	41.	867.	566.	502.	207.	160.	7376.	5055.
79	2	114.	756898.	887.	82.	1535.	845.	514.	399.	231.	8360.	5956.
79	3	72.	48904.	82.	23.	501.	321.	329.	118.	95.	3582.	4240.
79	4	42.	17875.	40.	14.	290.	193.	201.	72.	61.	2216.	2491.
79	5	31.	19672.	40.	14.	263.	181.	182.	76.	67.	1868.	1822.
79	6	35.	41108.	47.	16.	316.	220.	209.	80.	69.	2520.	1918.
79	7	28.	46581.	75.	14.	284.	183.	170.	88.	70.	2069.	1653.
79	8	50.	79688.	116.	24.	479.	311.	302.	149.	120.	3598.	2892.
79	9	114.	980325.	1018.	93.	1758.	964.	555.	404.	250.	8765.	5787.
79	10	87.	128910.	150.	33.	728.	473.	434.	176.	133.	5481.	4776.
79	11	53.	56731.	87.	16.	395.	229.	234.	99.	77.	2868.	3109.
79	12	37.	23958.	44.	10.	245.	143.	145.	55.	46.	1573.	2248.
80	1	54.	44211.	71.	17.	387.	241.	247.	97.	79.	2374.	3182.
80	2	28.	10725.	24.	9.	184.	116.	117.	40.	36.	1033.	1706.
80	3	62.	63213.	82.	21.	492.	317.	328.	127.	106.	3710.	3557.
80	4	50.	30999.	52.	16.	367.	238.	257.	94.	81.	2612.	2973.
80	5	33.	17271.	31.	11.	257.	175.	186.	65.	58.	1792.	1944.
80	6	11.	2951.	10.	5.	96.	70.	70.	24.	22.	633.	676.
80	7	11.	5176.	15.	9.	145.	114.	119.	51.	49.	908.	589.
80	8	4.	572.	4.	3.	54.	44.	49.	20.	20.	258.	227.
80	9	2.	299.	4.	3.	42.	37.	39.	19.	19.	165.	118.
80	10	8.	4541.	11.	6.	107.	86.	88.	40.	39.	590.	446.
80	11	12.	3818.	13.	6.	122.	94.	95.	40.	38.	776.	679.
80	12	8.	853.	6.	2.	58.	42.	40.	13.	12.	305.	484.
81	1	7.	635.	4.	2.	48.	34.	32.	10.	9.	245.	424.
81	2	19.	11047.	22.	10.	185.	132.	133.	53.	50.	1436.	1097.
81	3	13.	3080.	11.	5.	98.	69.	67.	24.	22.	656.	795.
81	4	20.	8129.	21.	9.	170.	119.	118.	47.	45.	1104.	1208.
81	5	25.	13316.	28.	11.	218.	153.	159.	64.	59.	1686.	1456.
81	6	25.	27240.	45.	9.	222.	143.	144.	66.	56.	1689.	1455.
81	7	7.	4318.	13.	9.	129.	111.	116.	55.	53.	655.	396.
81	8	3.	4731.	8.	5.	82.	70.	75.	35.	34.	367.	191.
81	9	5.	2250.	7.	4.	75.	62.	70.	30.	29.	400.	335.
TOTALS FOR THE WATER YEARS												
79		627.	2184049.	2534.	343.	6704.	4081.	3257.	1713.	1235.	43904.	34446.
80		432.	385016.	575.	153.	3392.	2196.	2228.	867.	724.	23907.	25105.
81		152.	83956.	189.	78.	1515.	1114.	1136.	477.	445.	9909.	8967.
TOTALS FOR THE 1979-81 WATER YEAR PERIOD												
		1210.	2653021.	3297.	574.	11611.	7391.	6621.	3056.	2405.	77720.	68518.
AVERAGE ANNUAL LOADS FOR THE 1979-81 WATER YEAR PERIOD												
		403.	884340.	1099.	191.	3870.	2464.	2207.	1019.	802.	25907.	22839.

Table 30. Monthly loads to the tidal Potomac River from local nonpoint sources during the 1979–81 water years

[Runoff is in millimeters over the local watersheds, loads are in megagrams, and phosphorus and nitrogen are given as P and N, respectively]

YEAR	MONTH	RUNOFF	SEDIMENT	TOTAL PHOSPHORUS	DISSOLVED PHOSPHORUS	TOTAL KJELDAHL NITROGEN	DISSOLVED KJELDAHL NITROGEN	TOTAL NITRATE PLUS NITRITE	TOTAL AMMONIA	DISSOLVED AMMONIA	ULTIMATE BOD	DISSOLVED SILICA
78	10	5.	339.	4.	2.	28.	20.	15.	5.	4.	197.	174.
78	11	9.	1546.	8.	5.	61.	46.	29.	12.	11.	492.	299.
78	12	25.	10291.	19.	9.	134.	95.	72.	26.	21.	1228.	768.
79	1	113.	121090.	101.	31.	582.	404.	302.	106.	76.	5173.	2995.
79	2	106.	250724.	243.	40.	699.	452.	271.	138.	86.	4974.	2659.
79	3	77.	23379.	39.	15.	292.	205.	200.	60.	43.	2323.	2450.
79	4	41.	7292.	19.	9.	158.	112.	109.	32.	24.	1343.	1361.
79	5	28.	8987.	20.	9.	139.	99.	78.	28.	23.	1133.	887.
79	6	42.	33562.	32.	12.	214.	150.	116.	38.	29.	1845.	1172.
79	7	19.	12098.	24.	8.	123.	86.	54.	26.	21.	1007.	589.
79	8	41.	29950.	43.	14.	231.	163.	116.	50.	39.	1974.	1275.
79	9	113.	421997.	311.	45.	874.	544.	295.	157.	102.	5455.	2685.
79	10	98.	78772.	75.	23.	459.	323.	260.	86.	61.	3734.	2782.
79	11	39.	16707.	26.	7.	163.	103.	97.	31.	23.	1277.	1242.
79	12	25.	5404.	12.	4.	91.	57.	60.	17.	13.	583.	859.
80	1	47.	16098.	26.	9.	188.	128.	121.	38.	28.	1516.	1533.
80	2	21.	2719.	8.	4.	77.	51.	51.	13.	11.	451.	704.
80	3	63.	37256.	39.	13.	280.	190.	170.	53.	40.	2346.	1926.
80	4	50.	15490.	24.	9.	201.	137.	134.	39.	30.	1649.	1624.
80	5	35.	11080.	17.	7.	151.	103.	97.	26.	21.	1223.	1100.
80	6	12.	1973.	7.	4.	58.	40.	35.	9.	7.	444.	381.
80	7	15.	4598.	12.	7.	100.	75.	49.	18.	16.	779.	434.
80	8	6.	554.	4.	3.	38.	29.	20.	6.	6.	243.	193.
80	9	3.	290.	4.	2.	28.	23.	12.	6.	6.	157.	103.
80	10	7.	3404.	7.	4.	61.	48.	26.	12.	11.	384.	222.
80	11	10.	2003.	7.	4.	66.	50.	32.	12.	11.	465.	314.
80	12	6.	260.	3.	2.	29.	20.	17.	4.	3.	153.	222.
81	1	6.	166.	2.	1.	24.	16.	15.	3.	3.	112.	196.
81	2	18.	6741.	12.	6.	103.	73.	52.	17.	15.	874.	512.
81	3	11.	1004.	5.	3.	48.	34.	29.	8.	7.	317.	362.
81	4	14.	2304.	9.	5.	77.	55.	41.	14.	12.	533.	475.
81	5	22.	5653.	13.	7.	114.	81.	64.	21.	18.	934.	708.
81	6	17.	7542.	14.	5.	95.	66.	48.	18.	15.	720.	546.
81	7	9.	4099.	10.	6.	83.	68.	36.	17.	16.	509.	278.
81	8	6.	4728.	7.	4.	58.	46.	25.	11.	10.	363.	179.
81	9	9.	2167.	6.	3.	53.	41.	29.	11.	9.	356.	293.
TOTALS FOR THE WATER YEARS												
79		619.	921256.	863.	198.	3535.	2376.	1657.	677.	480.	27135.	17312.
80		414.	190940.	254.	92.	1834.	1258.	1107.	343.	262.	14402.	12884.
81		135.	40072.	97.	50.	811.	597.	413.	149.	130.	5781.	4307.
TOTALS FOR THE 1979-81 WATER YEAR PERIOD												
		1168.	1152267.	1213.	341.	6180.	4231.	3177.	1169.	872.	47318.	34503.
AVERAGE ANNUAL LOADS FOR THE 1979-81 WATER YEAR PERIOD												
		389.	384089.	404.	114.	2060.	1410.	1059.	390.	291.	15773.	11501.

METRIC CONVERSION FACTORS

For use of readers who prefer to use inch-pound units, conversion factors for the International System of Units (SI) used in this report are listed below:

Multiply SI unit	by	To obtain inch-pound unit
	Length	
millimeter (mm)	0.03937	inch
	0.003281	foot
meter (m)	3.281	foot
kilometer (km)	0.6214	mile
	Area	
square kilometer (km^2)	0.3861	square mile
	Volume	
cubic meter (m^3)	264.2	U.S. gallon
	35.31	cubic foot
	Flow	
cubic meter per second (m^3/s)	35.31	cubic foot per second
	Weight	
gram (gm)	2.205×10^{-3}	pound
kilogram (kg)	2.205	pound
megagram (Mg)	1.102	short ton (1000 pounds)
	Yield	
megagram per square kilometer per year [(Mg/km^2)/a]	2.854	short ton per square mile per year

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