Transport of Dissolved and Suspended Material by the Potomac River at Chain Bridge, at Washington, D.C., Water Years 1978–81

A Water Quality Study of the Tidal Potomac River and Estuary

United States Geological Survey Water-Supply Paper 2234–B

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By S. F. Blanchard and D. C. Hahl

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FOREWORD

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

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

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

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

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

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

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

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

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

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

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

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

Philip Cohen
Chief Hydrologist

James P. Bennett
Potomac Study Coordinator

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CONVERSION FACTORS

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

Multiply	By	To obtain
	Length	
meter (m)	39.372	inch (in)
meter (m)	3.281	feet (ft)
kilometer (km)	0.6214	statute mile (mi)
	0.5396	nautical mile (nt mi)
	Volume	
liter (L)	.2642	U.S. gallon (gal)
cubic meters (m^3)	35.314	cubic feet (ft^3)
	Flow	
cubic meters per second (m^3/s)	35.314	cubic feet per second (ft^3)
	Mass	
metric ton (t)	1.1025	ton
kilogram (kg)	2.205	pound (lb)

Transport of Dissolved and Suspended Material by the Potomac River at Chain Bridge, at Washington, D. C., Water Years 1978-81

By S. F. Blanchard and D. C. Hahl

ABSTRACT

The measuring station Potomac River at Chain Bridge at Washington, D.C., is located at the upstream end of the tidal Potomac River. Water-quality data were collected intensively at this site from December 1977 through September 1981 as part of a study of the tidal Potomac River and Estuary. Analysis of water-discharge data from the long-term gage at Little Falls, just up stream from Chain Bridge, shows that streamflow for the 1979-81 water years had characteristics similar to the 51-year average discharge (1931-81). Loads were computed for various forms of phosphorus and nitrogen, major cations and anions, silica, biochemical oxygen demand, chlorophyll *a* and pheophytin, and suspended sediment.

Load duration curves for the 1979-81 water years show that 50 percent of the time, water passing Chain Bridge carried at least 28 metric tons per day of total nitrogen, 1.0 metric tons per day of total phosphorus, 70 metric tons per day of silica, and 270 metric tons per day of suspended sediment. No consistent seasonal change in constituent concentrations was observed; however, a seasonal trend in loads due to seasonal changes in runoff was noted. Some storm runoff events transported as much dissolved and suspended material as is transported during an entire low-flow year.

INTRODUCTION

Background

The non-Federal Advisory Committee on Water Data for Public Use recommended that the U.S. Geological Survey conduct a pilot interdisciplinary estuarine study patterned after the successful U.S. Geological Survey RQA (river quality assessment) study of the Willamette River (Rickert and Hines, 1975). The U.S. Geological Survey responded to the committee's recommendation by starting in August 1977 an estuarine RQA; that is, the PES (Potomac Estuary Study) was initiated to investigate physical, chemical, and biological conditions in the tidal Potomac River and Estuary located in Washington, D.C., Maryland, and Virginia (fig. 1). The chemical and hydrodynamic phenomena that existed in tidal rivers and estuaries prompted the U.S. Geological Survey to augment the RQA study group with chemical, geochemical, geological, biological, and hydrodynamic research teams. The RQA data collection on the tidal Potomac River and Estuary was completed in September 1981. Four hydrologic data reports (Smith and Herndon, 1979, 1980a, 1980b, 1980c) contain data for longitudinal surveys of the tidal river and estuary conducted between August 1977 and September 1978; one hydrologic data report (Blanchard, 1983) contains data at Chain Bridge; three hydrologic data reports (Blanchard and Hahl, 1981; Blanchard, Coupe, and Woodward 1982; and Blanchard and Coupe, 1982) cover periodic and synoptic data collection at approximately 23 stations for the period October 1978 through September 1981.

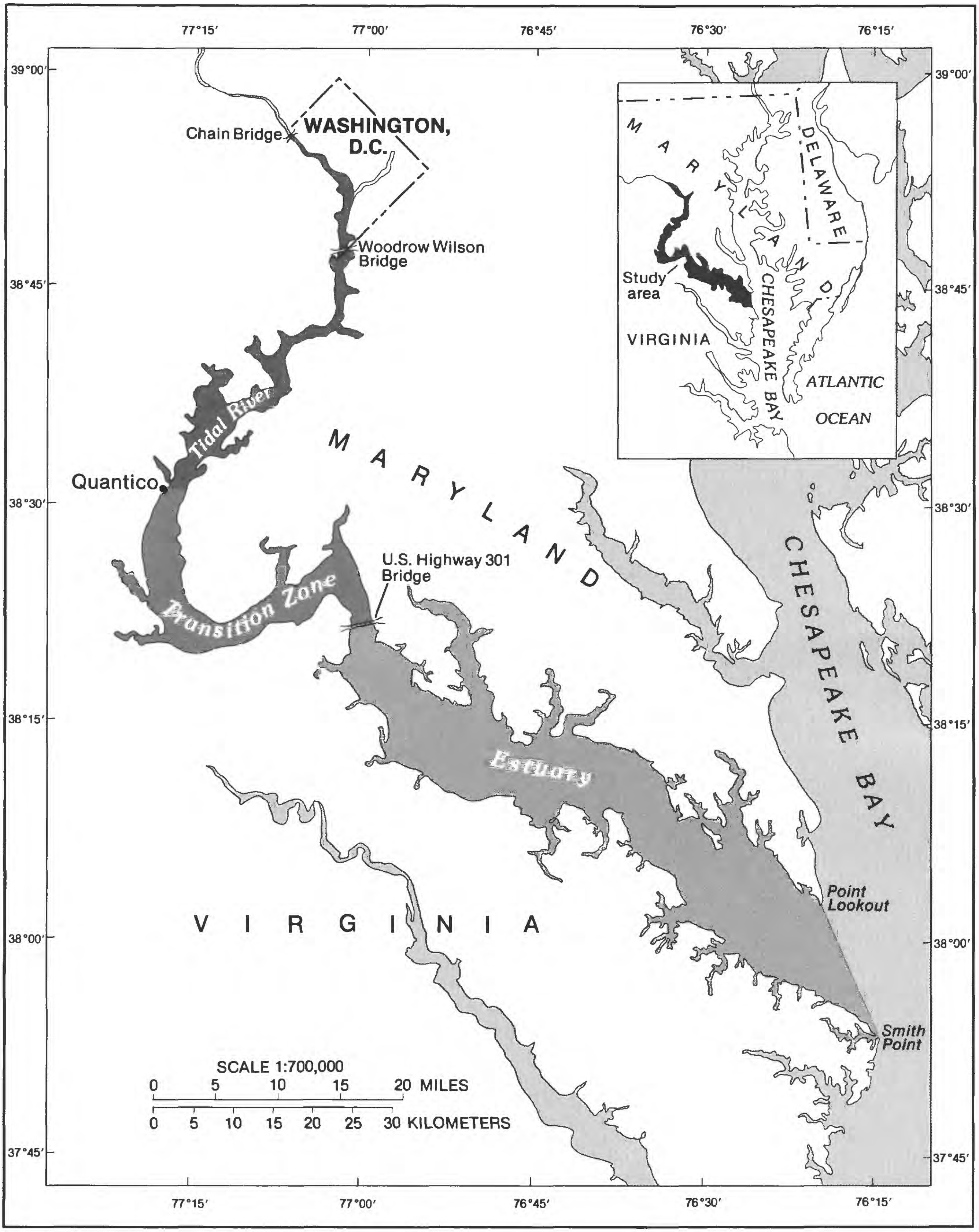

Figure 1. The tidal Potomac River and Estuary.

Purpose and Scope

This report presents information on the discharge of dissolved and suspended material entering the tidal Potomac River from the river basin above Chain Bridge at Washington, D.C., for the 1978-81 water years. Discharges were computed for the various forms of phosphorus and nitrogen, major cations and anions, silica, BOD (biochemical oxygen demand), chlorophyll *a* and pheophytin, and suspended sediment. The results cited in this report will be incorporated with concurrent studies of the dynamics of material transported through the tidal river and estuary.

CHARACTERISTICS OF THE POTOMAC RIVER AT THE MEASURING STATIONS

Streamflow Station and Flow Characteristics

The streamflow station, Potomac River near Washington, D.C., is located (fig. 2) at Little Falls Dam on the Potomac River, 1.9 km (kilomers) upstream from Chain Bridge and has been active since March 1930 (U.S. Geological Survey, 1982). The drainage area upstream of the gaging station is 29,940 km^2 (square kilometers). For the 51-year (1931-81) period of record the maximum discharge is 13,700 m^3/s (cubic meters per second) (Mar. 19, 1936), the minimum discharge is 3.43 m^3/s (Sept. 9, 1966) and the average annual discharge is 322.8 m^3/s.

Figure 3 shows that peak discharges are most likely to occur during February through June; (71 percent of historical peak flows occurred during these months). The relationship of annual peak discharges during the data-collection period to those of the 51-year period of record is shown in table 1. The flood that occurred during the Potomac Estuary study in 1979 was the seventh largest recorded flood; the larger floods are shown in order of their magnitude. A flood probability analysis (fig. 4), using the log Pearson Type III distribution, shows that the recurrence interval for the mean daily discharge of this flood is nine years.

Streamflow during the 3 years of intensive sampling (1979-81 water years) varied considerably as shown by tables 2 and 3. The mean discharge for the 1979 and 1980 water years was similar but each had different high- and low-flow characteristics. (High- and low-flow periods were considered as those periods of time for which the flow was 50 percent greater than or less than the 51-year average annual discharge.) For example, for low flow, the 1979 water year had the 30th lowest flow for 30 consecutive days and 1980 water year had the 50th. For high flow the 1979 water year had the third highest flow for 30 consecutive days and the 1980 water year had the 15th. The range in flow characteristics for all three water years varied from the sixth highest one day mean flow in 1979 to the 25th lowest one day mean flow in 1981, and from the fourth highest 183 consecutive day mean flow in 1979 to the ninth lowest 183 consecutive day mean flow in 1981. The streamflow, depicted as flow-duration curves in figure 5, also shows that the 1979-81 water years represented a wide range of hydrologic conditions.

The streamflows during these 3 years, when combined, generate a flow-duration curve similar to the flow-duration curve for the long-term period. Flow-duration curves for the 3-year intensive sampling period and for the 9 years during which at least periodic water-quality data are available are superimposed on the flow-duration curve for the 51 years of record (1931-81) in figure 6. The three curves show the same characteristics for 95 percent of the time.

From tables 1, 2 and 3, and the flow-duration curves it seems that the water-quality data for the Potomac Estuary Study was collected under nearly the entire range of conditions from high- to low-flow periods. Average concentrations of water-quality data for the study period could be representative of long-term streamflow conditions.

Water-Quality Station and Sample Collection

Water-quality data were collected (fig. 2) from March 1973 to March 1978 at Potomac River at Great Falls, which is 14 km upstream from Little Falls Dam (U.S. Geological Survey, 1978). In 1978 the water-quality sampling station was moved to Chain Bridge at Washington, D.C. In March 1978 a water-quality monitor was also installed at the station. In addition to the water-quality data collected by the Potomac Estuary Study from December 1977 to September 1981, water-quality data were collected at Chain Bridge as part of other programs. These data were used to supplement analysis of the Potomac Estuary Study data (U.S. Geological Survey, 1979, 1980, 1981, 1982).

The Chain Bridge station is 1.9 km downstream from Little Falls Dam and is in a narrow (fig. 7), boulder strewn channel (fig. 8) containing many rock outcrops. The result is that water passing through the channel, even at low flow, is very turbulent as shown by the three large eddies in figure 8 and the rippled water surface in figure 9. Note in figure 10 that the flood shown has not reached the top of the river bank at this site. Water velocities in the largest floods exceed 4.5 m/s (meters per second). In fact, even during low flow

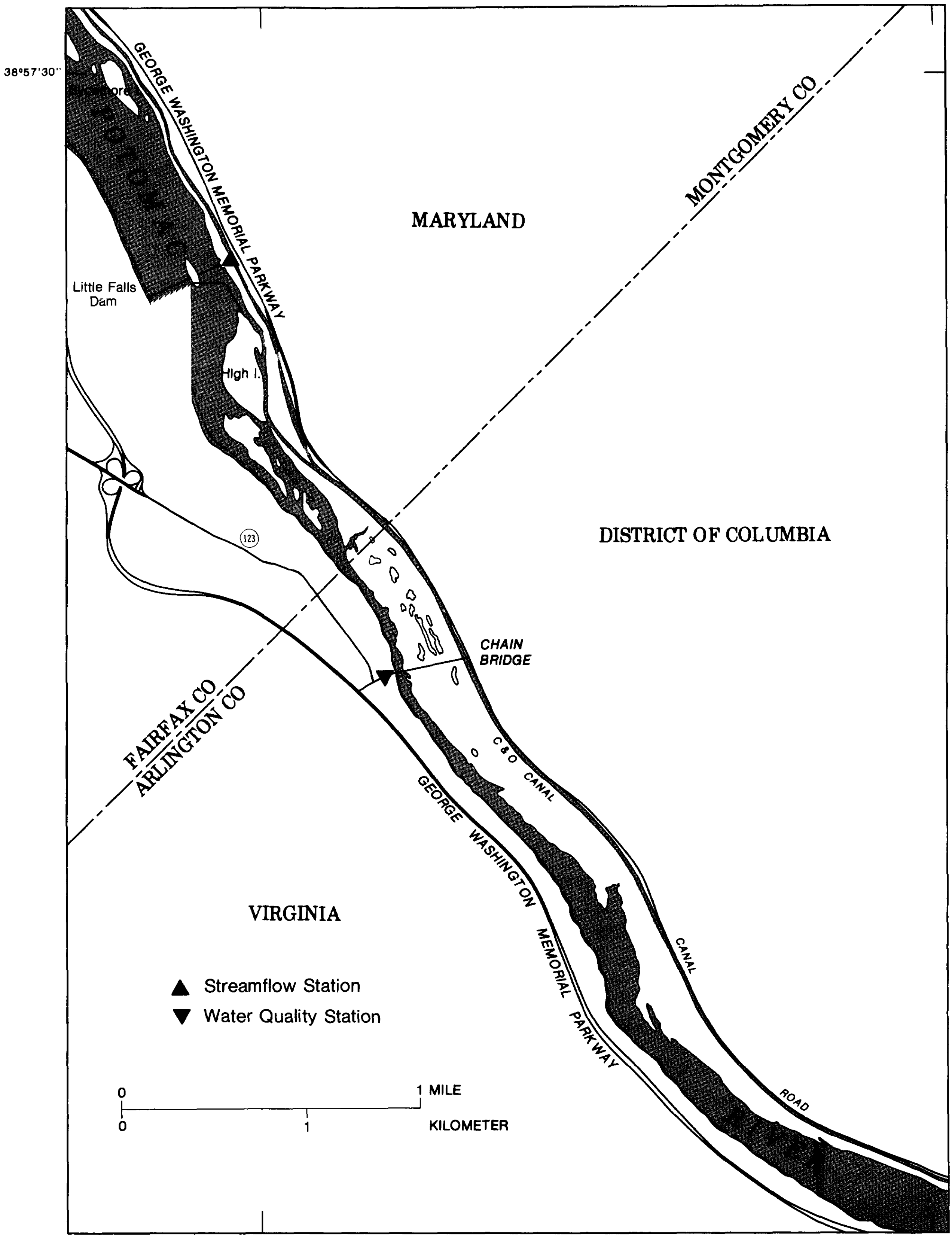

Figure 2. Location of stations: Potomac River near Washington, D.C., and Potomac River at Chain Bridge at Washington, D.C.

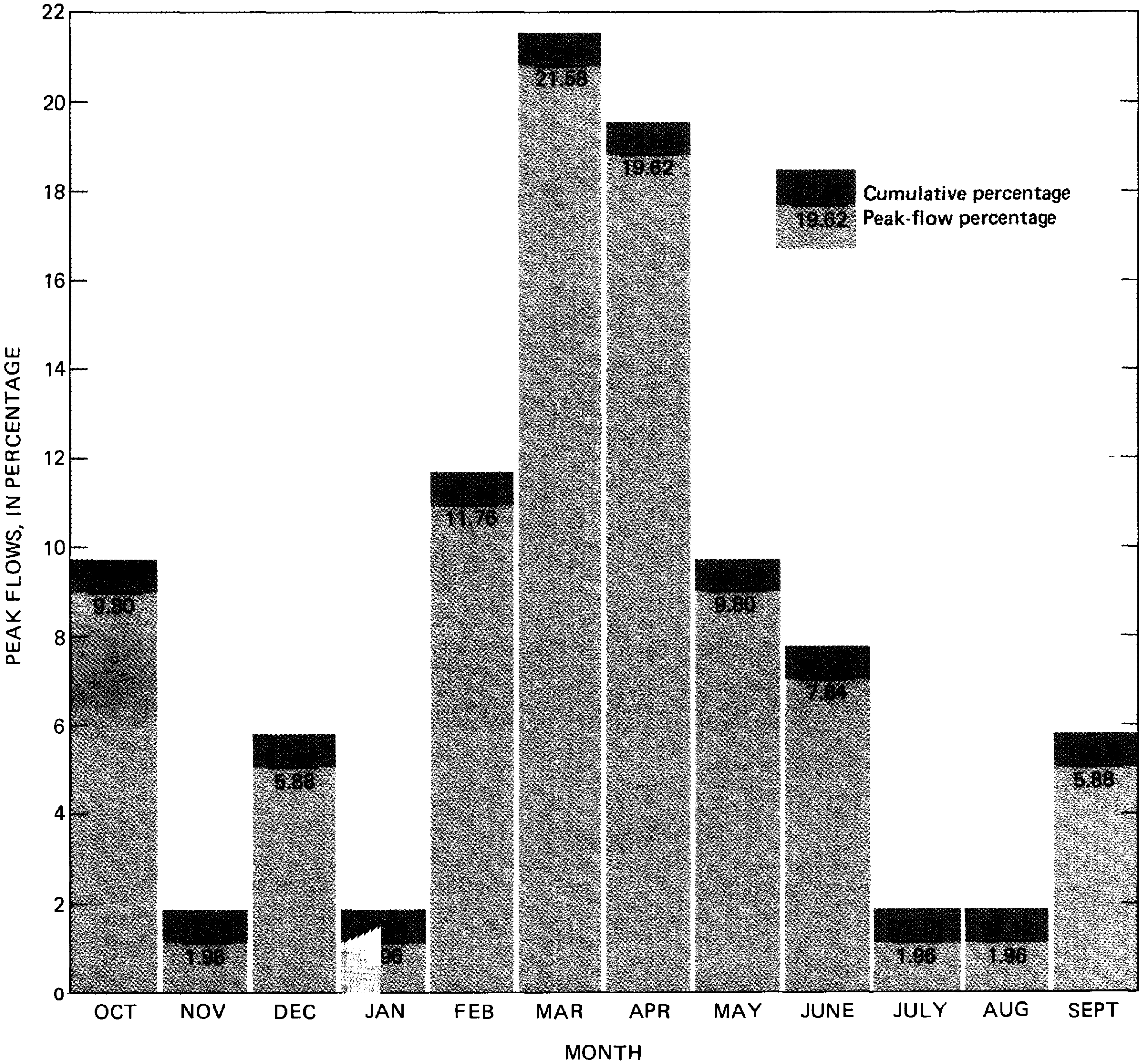

Figure 3. Percentage of peak flows that occurred in each month, 1931–81.

Table 1. The magnitude of floods on the Potomac River near Washington, D.C.

Water years	Daily mean discharge (m^3/s)	Instantaneous peak discharge (m^3/s)
1931-81	323	13,700
1936	438	13,700
1943	453	12,700
1972	526	10,200
1937	431	9,830
1955	364	6,120
1977	301	5,890
1978	458	4,330
1979	452	5,830
1980	441	2,310
1981	179	1,530

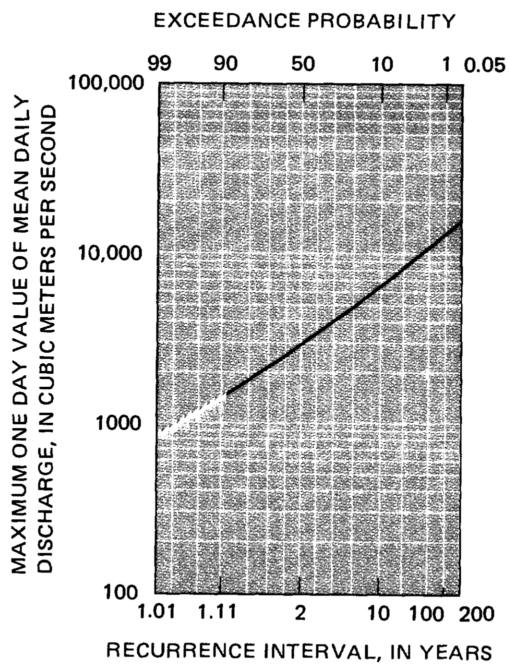

Figure 4. Frequency curve for maximum annual 1-day mean flow for period 1931–81.

the velocities are so fast that it is difficult to submerse a sampler more than 2 or 3 meters.

Comparison of suspended sediment analyses of the few samples (table 4) collected simultaneously from the water-quality monitor intake line and from the channel under the bridge showed very little difference. The average difference in concentration between the two sampling sites for samples with concentrations less than 65 mg/L (milligrams per liter) was 4 mg/L, and for samples with concentrations greater than 400 mg/L was 40 mg/L. Suspended sediment concentrations (table 5) were determined across the width of the river during flood stage on February 27, 1979. The standard deviation among sample concentrations was 15 mg/L or about 3 percent. The suspended sediment analyses, coupled with visible turbulence and water velocities, lead to the conclusion that the water passing Chain Bridge was well mixed for most sizes of transported material and that samples from a single point in the main channel are representative of discharge weighted samples. Therefore, most samples collected during the study were taken from the water-quality monitor intake line.

The water-quality sample collection frequency was biased toward periods of maximum transport of dissolved and suspended material. That is, the sampling frequency was increased to three or four times a day on very large floods and decreased to weekly during periods of low flow. For a more complete description of the methods of sample collection, shipment, and analysis used, refer to the four annual hydrologic data reports Blanchard and Hahl (1981), Blanchard and others (1982), Blanchard and Coupe (1982), and Blanchard (1983).

METHOD OF LOAD COMPUTATION

Only 30 km^2 of additional drainage area exists between the streamflow station at Little Falls and the water-quality station at Chain Bridge. No significant flow enters via the intervening drainage area. Chain Bridge is the upper limit of tidal influence. Therefore, the Little Falls water-discharge data were used with the Chain Bridge water-quality data to compute loads entering the tidal river.

Cations and Anions

Concentration Estimation Techniques

The water sampling program for cations and anions was intermittent. Specific conductance, however, was monitored continuously. Therefore, daily

Table 2. Lowest mean discharge and ranking for a given number of consecutive days for the year ending March 31, 1931–81 water years

	Number of consecutive days									
	1 day		7 days		30 days		90 days		183 days	
Year	Discharge (m^3/s)	Ranking	Discharge (m^3/s)	Ranking	Discharge (m^3/s)	Ranking	Discharge (m^3/s)	Ranking	Discharge (m^3/s)	Ranking
1931	12.68	4	14.12	3	15.96	2	17.18	1	24.34	1
1932	21.37	10	23.38	10	25.53	8	37.92	7	86.60	13
1933	16.56	5	17.12	4	24.42	6	40.75	10	159.61	37
1934	52.07	39	64.24	41	71.60	38	92.82	34	144.33	33
1935	33.68	25	37.64	27	48.39	28	82.35	33	129.90	29
1936	46.41	35	50.37	36	55.75	33	124.24	41	145.46	34
1937	34.53	27	36.22	25	46.98	24	70.18	26	97.07	21
1938	56.88	41	68.77	45	89.14	45	164.14	45	322.62	48
1939	35.94	29	41.03	29	46.98	25	61.13	22	107.54	25
1940	30.00	19	34.81	21	56.32	34	93.96	35	101.60	23
1941	60.00	43	70.75	47	97.63	47	187.91	47	217.91	44
1942	18.17	7	20.72	7	22.84	4	35.37	5	63.11	5
1943	65.09	49	70.75	48	110.65	49	215.36	51	280.45	47
1944	24.17	14	27.96	15	30.85	12	46.13	13	71.03	9
1945	24.17	15	26.01	14	30.00	11	49.24	14	87.73	15
1946	62.83	48	78.96	49	91.41	46	198.67	50	245.64	46
1947	28.30	17	31.13	17	47.83	27	79.24	31	91.13	18
1948	30.56	20	32.26	19	39.62	18	72.16	27	111.50	26
1949	61.41	47	65.66	43	82.35	43	128.76	43	186.21	41
1950	59.15	42	61.13	40	73.58	39	120.84	39	182.25	40
1951	44.43	34	48.96	35	61.69	37	108.11	37	199.23	43
1952	34.81	28	37.64	26	41.60	22	55.75	19	99.05	22
1953	49.81	38	52.92	38	56.88	35	101.03	36	154.23	35
1954	31.13	21	31.70	18	33.39	14	43.02	11	67.07	7
1955	24.90	16	29.15	16	35.66	15	53.20	17	121.97	27
1956	37.36	31	43.58	32	61.69	36	79.24	32	188.76	42
1957	60.56	44	65.37	42	77.54	41	124.24	40	166.69	38
1958	23.43	13	24.71	12	27.82	9	38.77	8	71.03	8
1959	36.51	30	39.05	28	49.52	29	57.17	20	90.28	16
1960	20.49	9	22.13	9	36.22	16	53.49	18	95.94	20
1961	31.13	22	44.15	33	49.52	30	57.73	21	82.64	11
1962	40.75	32	43.02	31	46.98	26	65.66	24	90.56	17
1963	29.71	18	32.83	20	38.77	17	44.43	12	86.60	14
1964	19.98	8	21.45	8	23.72	5	30.85	3	59.15	4
1965	10.58	2	12.42	2	18.90	3	37.36	6	53.20	3
1966	12.28	3	19.92	6	24.51	7	33.68	4	34.24	2
1967	3.42	1	5.12	1	12.51	1	20.32	2	92.54	19
1968	46.98	36	51.79	37	79.52	42	117.44	38	135.27	30
1969	22.67	12	25.19	13	32.83	13	50.66	15	86.03	12
1970	16.92	6	19.41	5	40.19	20	77.82	30	107.26	24
1971	33.11	24	35.37	22	41.03	21	63.39	23	140.93	31
1972	52.35	40	60.28	39	84.90	44	136.69	44	234.32	45
1973	61.41	45	67.35	44	74.99	40	174.04	46	418.84	51
1974	61.41	46	69.62	46	108.11	48	124.80	42	168.10	39
1975	41.60	33	42.17	30	54.90	32	72.16	28	123.10	28
1976	86.03	50	97.07	50	126.22	50	188.19	48	353.75	49
1977	31.70	23	35.66	23	44.71	23	77.26	29	144.05	32
1978	22.53	11	23.91	11	28.87	10	40.47	9	63.96	6
1979	46.98	37	48.11	34	51.22	31	65.94	25	154.23	36
1980	88.30	51	101.03	51	137.25	51	192.44	49	382.05	50
1981	33.96	26	35.94	24	39.90	19	52.92	16	73.30	10

Table 3. Highest mean discharge and ranking for a given number of consecutive days for the year ending September 30, 1931–81 water years

	Number of consecutive days									
	1 day		7 days		30 days		90 days		183 days	
Year	Discharge (m^3/s)	Ranking	Discharge (m^3/s)	Ranking	Discharge (m^3/s)	Ranking	Discharge (m^3/s)	Ranking	Discharge (m^3/s)	Ranking
1931	1021.63	50	769.76	47	475.44	46	365.07	45	256.11	47
1932	1782.90	10	2244.19	15	806.55	33	599.96	30	401.86	38
1933	594.30	19	2176.27	16	1103.70	13	806.55	10	591.47	12
1934	1335.76	48	749.95	48	447.14	47	311.30	49	234.61	50
1935	566.00	20	1593.29	29	806.55	34	707.50	20	549.02	17
1936	735.80	1	2122.50	1	2368.71	1	1208.41	1	783.91	1
1937	283.00	4	1047.10	4	1236.71	9	764.10	14	682.03	6
1938	2122.50	9	2264.00	14	1055.59	18	517.89	37	404.69	37
1939	650.90	18	2026.28	18	1064.08	17	724.48	18	478.27	22
1940	2807.36	28	1765.92	23	919.75	27	631.09	26	458.46	26
1941	1952.70	42	1075.40	44	611.28	43	379.22	44	359.41	43
1942	849.00	14	1613.10	28	673.54	40	498.08	39	370.73	42
1943	198.10	2	1528.20	3	1378.21	6	798.06	11	682.03	7
1944	2074.39	41	1233.88	40	908.43	29	645.24	25	410.35	36
1945	849.00	15	1672.53	25	854.66	31	495.25	40	376.39	41
1946	1664.04	45	998.99	45	588.64	44	449.97	42	427.33	33
1947	1154.64	49	724.48	49	399.03	50	305.64	50	268.57	45
1948	2592.28	30	1327.27	36	764.10	36	608.45	28	416.01	35
1949	481.10	21	1290.48	37	982.01	22	820.70	8	597.13	11
1950	2105.52	40	1245.20	39	707.50	38	515.06	38	438.65	29
1951	735.80	17	2351.73	10	1001.82	21	761.27	15	679.20	8
1952	1301.80	11	2648.88	6	1157.47	10	840.51	6	662.22	9
1953	820.70	16	1652.72	26	950.88	25	747.12	16	636.75	10
1954	254.7	26	1214.07	41	566.00	45	350.92	46	240.55	49
1955	198.10	5	2326.26	11	922.58	26	551.85	35	447.14	28
1956	1845.16	44	1086.72	43	769.72	35	580.15	31	396.20	39
1957	1949.87	43	1276.33	38	653.73	41	557.51	34	418.84	34
1958	2303.62	35	1559.33	30	1041.44	19	823.53	7	580.15	13
1959	1347.08	47	713.16	50	418.84	49	342.43	48	252.72	48
1960	452.80	22	2394.18	9	1132.0	12	721.65	19	534.87	19
1961	283.00	24	2266.83	13	1267.84	8	982.01	2	577.32	15
1962	396.20	23	1927.23	19	1389.53	5	815.04	9	523.55	20
1963	254.70	25	1915.91	20	1335.76	7	616.94	27	387.71	40
1964	2583.79	31	1808.37	21	888.62	30	648.07	23	472.61	25
1965	2620.58	29	1451.79	33	840.51	32	648.07	24	435.82	30
1966	2193.25	38	1160.30	42	625.43	42	444.31	43	260.64	46
1967	1103.70	13	2119.67	17	1066.91	16	602.79	29	430.16	31
1968	2133.82	39	1412.17	35	761.27	37	529.21	36	455.63	27
1969	823.53	51	554.68	51	285.83	51	209.70	51	174.33	51
1970	2425.31	34	1448.96	34	979.18	23	682.03	21	475.44	23
1971	2532.85	32	1780.07	22	1137.66	11	747.12	17	580.15	14
1972	962.20	3	1754.60	2	1579.14	2	976.35	3	783.91	2
1973	2215.89	36	1465.94	32	1035.78	20	789.57	12	724.48	3
1974	0.00	27	1644.23	27	970.69	24	580.15	32	503.74	21
1975	2433.80	8	2504.55	7	911.26	28	670.71	22	546.19	18
1976	2479.08	33	1516.88	31	693.35	39	492.42	41	427.33	32
1977	2660.20	7	2413.99	8	1078.23	14	566.00	33	472.61	24
1978	1132.00	12	2306.45	12	1415.0	4	868.81	5	699.01	5
1979	28.30	6	566.00	5	1564.99	3	950.88	4	704.67	4
1980	2207.40	37	1681.02	24	1066.91	15	766.93	13	571.66	16
1981	1511.22	46	922.58	46	435.82	48	345.26	47	285.83	44

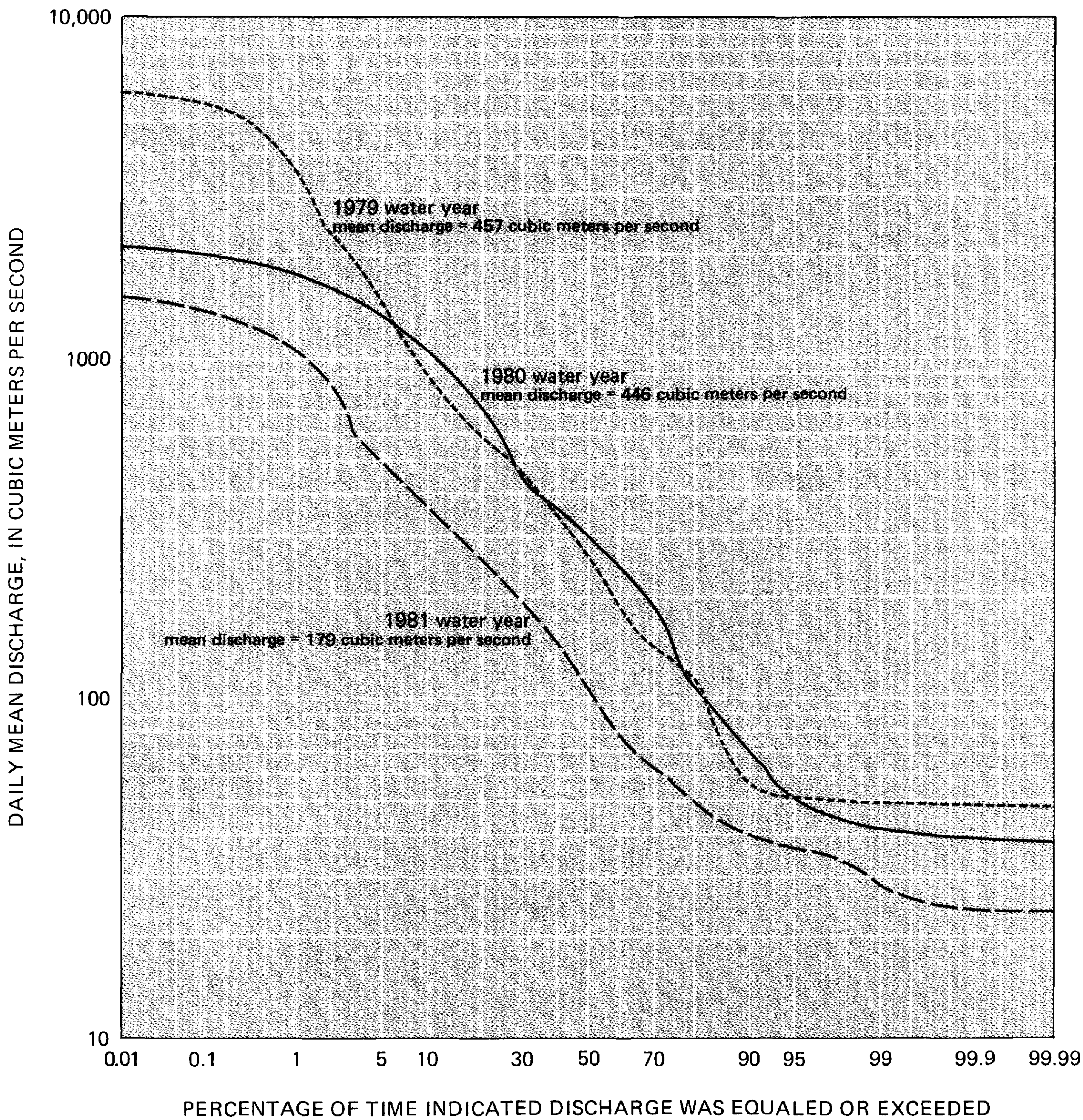

Figure 5. Flow-duration curves for the 1979, 1980, and 1981 water years.

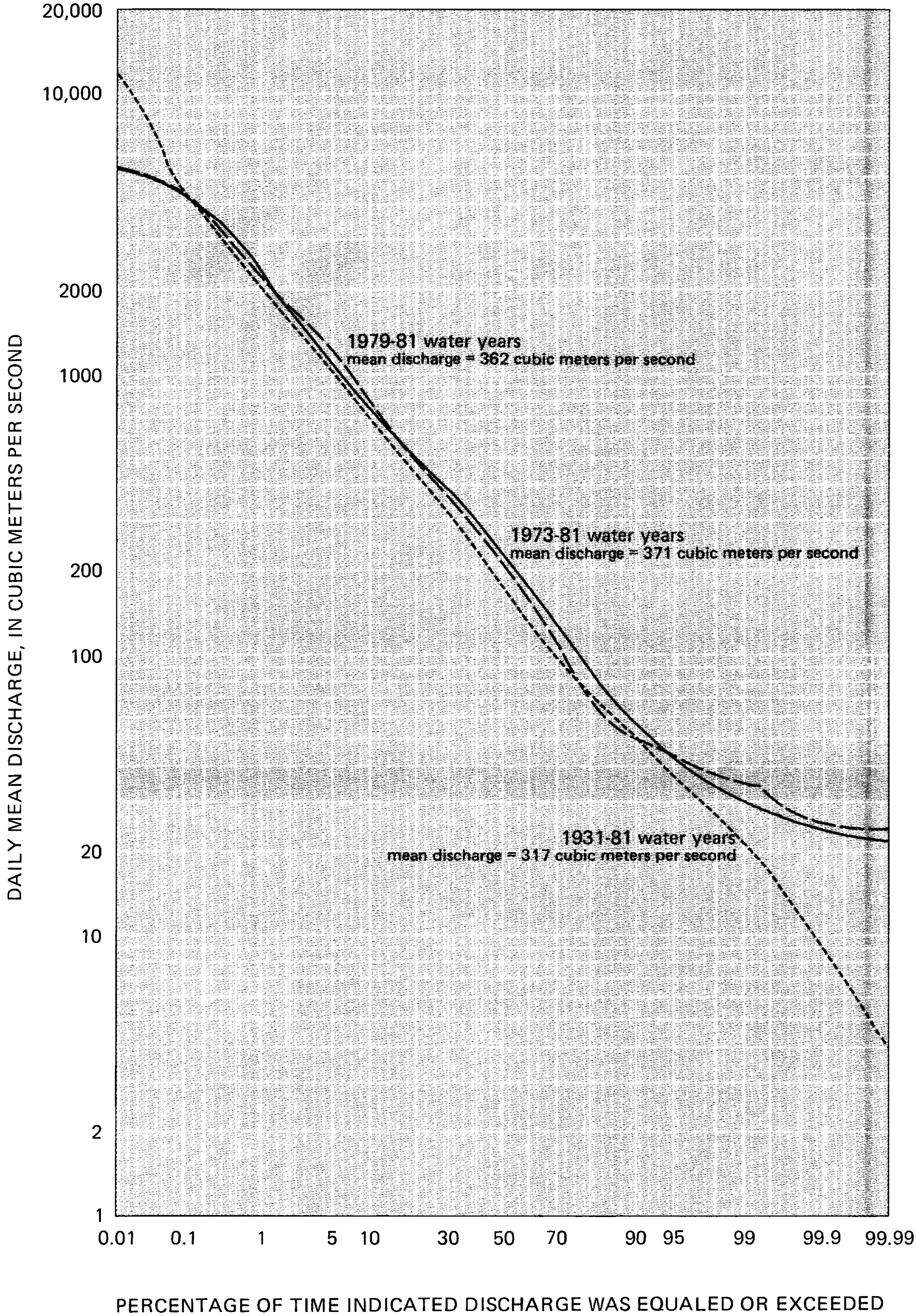

Figure 6. Flow-duration curves for the period 1979–81, compared to historical data.

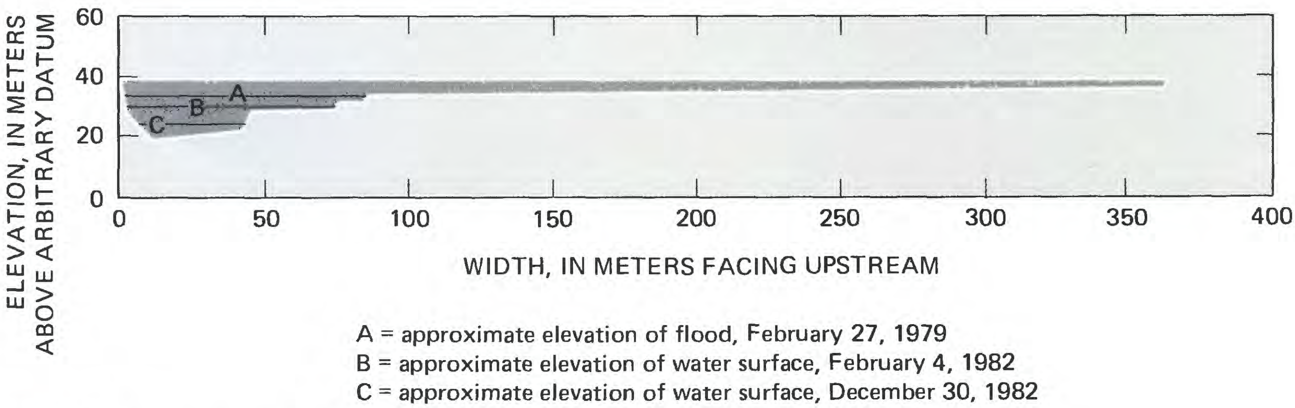

Figure 7. Cross section of the Potomac River at Chain Bridge at Washington, D.C.

Figure 8. The Potomac River at Chain Bridge at Washington, D.C. View upstream on December 30, 1981.

Figure 9. The Potomac River at Chain Bridge at Washington, D.C. View upstream on December 30, 1982, at 1300 hours; discharge 195 cubic meters per second.

Figure 10. The Potomac River at Chain Bridge at Washington, D.C. View upstream on February 4, 1982, at 1640 hours; discharge 1,296 cubic meters per second.

Table 4. Comparison of suspended-sediment samples from the river channel and from the water-quality monitor intake line

	River channel		Monitor intake	
Date	Time (hours)	Concentration (milligrams per liter)	Time (hours)	Concentration (milligrams per liter)
6-30-78	1333	14	1340	16
7-03-78	1415	34	1424	39
7-07-78	1032	458	1023	406
1-15-79	1040	13	1105	11
1-18-79	1015	13	1035	19
1-22-79	0850	305	0851	311
1-26-79	1401	419	1400	474
1-29-79	1230	61	1230	55
1-31-79	0845	28	0845	29

Table 5. Variation of suspended-sediment concentrations with distance from right bank

Time (hours)	Distance from right bank (meters)	Suspended sediment concentration (milligrams per liter)	Time (hours)	Distance from right bank (meters)	Suspended sediment concentration (milligrams per liter)
1400	69	464	1700	174	442
1500	84	458	1745	210	481
1530	113	448	1800	225	453
1600	128	452	1830	259	443
1700	158	433	1915	274	434

mean concentrations of the major cations and anions were determined by linear regression with specific conductance. A multiple regression analysis was not required because the ratio between constituent concentrations and specific conductance is constant over the range of recorded specific conductance. Good correlations were developed for all the major anions and for all the major cations, except potassium, which was not sensitive to changes in specific conductance. The concentration of potassium is less than 5 mg/L or less than 2 percent of the total concentration of dissolved constituents; therefore a relatively large change in the concentration of potassium ion results in almost no change in specific conductance. The coefficient of determination for potassium was low (r^2 of 0.22), and the correlation was not used. The correlations developed for Potomac Estuary Study agree very well with those developed for the Potomac River at Chain Bridge by Lang (1982, p. 17) for another study. The Potomac Estuary Study relationships, described by the equations in table 6, were used with the continuous record of specific conductance data obtained from the monitor at Chain Bridge to derive daily mean concentrations of selected dissolved constituents.

Estimates of specific conductance were made for periods of missing record based on instantanteous specific conductance data obtained from water-quality samples.

Computed Loads

Daily loads of cations and anions were computed by the following equation:

$$L = k\,C\,Q$$

where: L = constituent load, in metric tons per day

Table 6. Linear regression equations for concentration estimation of the major cations and anions

(C_i = concentration in milligrams per liter; SC = daily mean specific conductance in micromhos; N = number of data pairs used to determine regression.)

Dissolved ion	Regression equation	Coefficient of determination (r^2)	N
Chloride	$C_i = (0.0579 \times SC) - 3.4380$	0.84	74
Sulfate	$C_i = (0.1884 \times SC) - 13.575$	.94	74
Calcium	$C_i = (0.0923 \times SC) + 5.3497$	.89	74
Magnesium	$C_i = (0.0285 \times SC) - 0.76510$	.91	74
Sodium	$C_i = (0.0674 \times SC) - 7.1691$	.93	74
Bicarbonate	$C_i = (0.3288 \times SC) - 0.05682$	.90	55
Total dissolved solids	$C_i = (0.5962 \times SC) - 4.4959$	.95	40

(also represents constituent discharge); k = unit conversion factor, 0.0864; C = daily mean concentration, in milligrams per liter; Q = daily mean water discharge, in cubic meters per second.

The monthly loads are the sum of the daily values. Loads of major cations and anions for water years 1979–81 are shown in tables 7a, 7b, and 7c.

Evaluation of Computed Loads

The precision of the cation and anion loads can be tested by calculating the cation-anion balance for each month. Hem (1970) states that if a water sample were analyzed in the laboratory, "the sum of the cations in milliequivalents per liter (meq/L) should equal the sum of the anions," and "the difference between the sums will generally not exceed 1 or 2 percent" unless "the total equivalents of anions and cations is less than about 5 meq/L," then "larger percentage errors are sometimes unavoidable." Of the 36 months for which data were computed, 31 had a cation-anion difference of three percent or less. The other 5 months each had meq/L values of 5 or less. Accordingly, if the major cations and anions computed for the study period had been determined in the laboratory the values would be acceptable.

The results of another test that was performed on the cation and anion daily loads are presented in table 8. For this test the regression equations were used to estimate constituent concentrations for times when laboratory analyses were available. Estimated values were plotted versus the corresponding laboratory concentrations for the 1979-1981 water years. A linear regression line was then calculated for each constituent and the slope of each line was determined. These slopes are about equal to 1.00 therefore the linear regression equation used to determine the daily cation and anion concentrations produce results that are comparable to the laboratory results.

The cation-anion balance test and the results of the linear regression equations indicate that the computed values closely represent actual values and accurately represent missing data.

Nutrient Species, Chlorophyll, and Biochemical Oxygen Demand

Concentration Estimation Techniques

Attempts to obtain daily concentrations for the nutrients, chlorophyll, and BOD by linear correlation with discharge were unsuccessful. The inconsistent relationships with discharge led to the testing of multiple regression equations involving SS (suspended sediment), pH (hydrogen ion concentration), T (temperature), DO (dissolved oxygen), and SC (specific conductance) to estimate daily mean concentrations for phosphorus, nitrogen, silica, chlorophyll, and oxygen demanding materials (BOD).

Nutrient data were analysed by a regression technique developed by James H. Goodnight (Helwig and Council, 1979) called MAXR (Maximum R^2 Improvement Technique). The MAXR method is better than the stepwise regression method because it does not settle on the initial model for the entire series of regressions. Instead, this method selects the best model for each step by comparing all r^2 values each time a variable is entered. In other words, a variable with a

Table 7a. Monthly loads of major cations and anions, Potomac River at Chain Bridge at Washington, D.C., 1979 water year

		Dissolved calcium			Dissolved magnesium			Dissolved sodium			Dissolved bicarbonate		
Month	Average discharge (m^3/s)	Average concentration (mg/L)	Total load (metric tons × 10^{-3})	Discharge (metric tons per day)	Average concentration (mg/L)	Total load (metric tons × 10^{-3})	Discharge (metric tons per day)	Average concentration (mg/L)	Total load (metric tons × 10^{-3})	Discharge (metric tons per day)	Average concentration (mg/L)	Total load (metric tons × 10^{-3})	Discharge (metric tons per day)
October	53.77	50	7.2	232	13	1.9	60	26	3.8	121	160	23	743
November	61.40	53	8.4	281	14	2.2	74	27	4.3	143	168	27	890
December	299.3	31	24.8	801	7.1	5.7	183	11	8.8	284	90	72	2,325
January	866.9	22	51.0	1,646	4.3	10.0	322	4.8	11.1	359	59	137	4,414
February	854.4	34	70.2	2,507	8.2	16.9	605	12	24.8	885	100	206	7,374
March	1,073	30	86.1	2,778	7.0	20.1	648	11	31.6	1,019	89	256	8,242
April	520.5	26	35.0	1,168	5.5	7.4	247	7.9	10.6	355	73	98	3,279
May	478.0	26	33.3	1,073	5.8	7.4	239	8.3	10.6	342	75	96	3,094
June	399.3	25	25.9	862	5.4	5.6	186	7.5	7.7	258	72	74	2,481
July	154.3	34	14.0	453	8.2	3.4	109	14	5.8	186	103	43	1,372
August	153.9	34	14.0	452	7.9	3.3	105	17	7.0	226	100	41	1,328
September	605.2	24	37.6	1,254	5.0	7.8	261	6.4	10.0	334	66	103	3,447
1979 water year	457.4	28	407.5	---	6.3	91.0		9.4	135.5	---	82	1,176	---

	Dissolved sulfate			Dissolved chloride			Total dissolved solids		
Month	Average concentration (mg/L)	Total load (metric tons × 10^{-3})	Discharge (metric tons per day)	Average concentration (mg/L)	Total load (metric tons × 10^{-3})	Discharge (metric tons per day)	Average concentration (mg/L)	Total load (metric tons × 10^{-3})	Discharge (metric tons per day)
October	78	11	362	25	3.6	116	286	41	1,327
November	83	13	440	26	4.1	138	300	48	1,590
December	38	30	982	12	9.6	310	159	127	4,107
January	20	46	1,496	6.9	16.0	516	102	237	7,632
February	46	95	3,392	12	24.8	885	183	378	13,495
March	38	109	3,519	12	34.4	1,111	157	451	14,540
April	28	38	1,259	9.5	12.8	427	129	174	5,795
May	30	38	1,238	9.9	12.6	408	132	169	5,446
June	27	28	930	9.2	9.5	317	125	129	4,308
July	46	19	613	15	6.2	200	183	76	2,437
August	44	18	584	14	5.8	186	178	73	2,364
September	24	38	1,254	8.2	12.8	428	116	182	6,059
1979 water year	34	48	---	11	152.2	---	145	2,084	---

Table 7b. Monthly loads of major cations and anions, Potomac River at Chain Bridge at Washington, D.C., 1980 water year

		Dissolved calcium			Dissolved magnesium			Dissolved sodium			Dissolved bicarbonate		
Month	Average discharge (m^3/s)	Average concentration (mg/L)	Total load (metric tons × 10^{-3})	Discharge (metric tons per day)	Average concentration (mg/L)	Total load (metric tons × 10^{-3})	Discharge (metric tons per day)	Average concentration (mg/L)	Total load (metric tons × 10^{-3})	Discharge (metric tons per day)	Average concentration (mg/L)	Total load (metric tons × 10^{-3})	Discharge (metric tons per day)
October	955.5	23	58.8	1,897	4.8	11.9	396	6.0	15.3	495	64	164	5,278
November	516.8	43	57.5	1,918	7.3	9.8	326	12	16.0	535	93	124	4,148
December	372.7	28	27.9	901	6.2	6.2	199	9.2	9.2	296	80	80	2,573
January	520.2	25	34.8	1,122	5.4	7.5	242	7.3	10.2	328	71	99	3,188
February	227.8	30	17.1	590	6.8	3.9	134	11	6.3	216	87	50	1,711
March	660.7	23	40.7	1,312	4.6	8.1	262	5.5	9.7	314	62	110	3,535
April	876.7	20	45.4	1,513	3.7	8.4	280	3.5	8.0	265	52	118	3,935
May	716.5	25	47.9	1,546	5.2	10.0	322	7.0	13.4	433	69	132	4,267
June	224.0	31	18.0	599	7.1	4.1	137	11	6.4	213	92	53	1,779
July	121.1	36	11.7	376	8.6	2.8	90	15	4.9	157	108	35	1,129
August	96.26	38	9.8	316	9.4	2.4	78	17	4.4	141	117	30	972
September	47.1	40	4.9	163	9.9	1.2	40	18	2.2	73	123	15	500
1980 water year	446.0	27	374.5	---	5.4	76.3	---	7.5	106.0	---	72	1,010	---

	Dissolved sulfate			Dissolved chloride			Total dissolved solids		
Month	Average concentration (mg/L)	Total load (metric tons × 10^{-3})	Discharge (metric tons per day)	Average concentration (mg/L)	Total load (metric tons × 10^{-3})	Discharge (metric tons per day)	Average concentration (mg/L)	Total load (metric tons × 10^{-3})	Discharge (metric tons per day)
October	23	58.8	1,897	7.9	20.2	651	112	286	9,236
November	41	54.9	1,829	13	17.4	580	160	214	7,137
December	32	31.9	1,029	11	10.1	323	141	141	4,536
January	27	37.6	1,212	9.0	12.5	404	124	173	5,567
February	36	20.5	708	12	6.8	236	153	87	3,008
March	22	38.9	1,255	7.4	13.1	422	107	189	6,102
April	16	36.3	1,211	5.7	12.9	431	90	204	6,811
May	26	49.8	1,608	8.7	16.7	538	121	232	7,483
June	38	22.0	735	12	7.0	232	160	93	3,093
July	48	15.6	502	16	5.2	167	191	62	1,996
August	53	13.6	440	17	4.4	141	207	53	1,720
September	57	7.0	232	18	2.2	73	218	27	886
1980 water year	27	386.9	---	9.1	128.5	---	125	1,761	---

Table 7c. Monthly loads of major cations and anions, Potomac River at Chain Bridge at Washington, D.C., 1981 water year

Month	Average discharge (m³/s)	Dissolved calcium			Dissolved magnesium			Dissolved sodium			Dissolved bicarbonate		
		Average concentration (mg/L)	Total load (metric tons × 10⁻³)	Discharge (metric tons per day)	Average concentration (mg/L)	Total load (metric tons × 10⁻³)	Discharge (metric tons per day)	Average concentration (mg/L)	Total load (metric tons × 10⁻³)	Discharge (metric tons per day)	Average concentration (mg/L)	Total load (metric tons × 10⁻³)	Discharge (metric tons per day)
October	48.14	46	5.9	191	12	1.6	50	23	3.0	96	146	19	607
November	105.1	42	11.4	381	11	3.0	100	20	5.4	181	132	36	1,197
December	100.6	36	9.7	313	8 6	2.3	75	15	4.0	130	108	29	938
January	50.24	47	6.3	204	12	1.6	52	24	3.2	104	149	20	646
February	387.1	29	27.1	969	6.4	6 0	214	9.8	9.2	327	83	78	2,773
March	213.7	29	16.6	535	6.5	3 7	120	10	5.7	184	84	48	1,549
April	375.5	25	24.3	810	5.4	5 2	175	7.5	7.3	243	71	69	2,301
May	292.0	27	21.1	680	6.0	4.7	151	9.0	7.0	227	78	61	1,966
June	364.8	26	24.6	819	5.5	5.2	173	7.7	7.3	242	73	69	2,298
July	129.5	33	11.4	369	7 9	2.6	88	13	4.5	145	99	34	1,107
August	53.10	29	4.1	133	6.6	.9	30	10	1.4	46	85	12	390
September	74.45	44	8 5	283	11	2.1	71	21	4.0	135	139	27	893
1981 water year	179.4	30	171.0	---	6.8	38.9	---	11	62 0	---	88	502	---

Month	Dissolved sulfate			Dissolved chloride			Total dissolved solids		
	Average concentration (mg/L)	Total load (metric tons × 10⁻³)	Discharge (metric tons per day)	Average concentration (mg/L)	Total load (metric tons × 10⁻³)	Discharge (metric tons per day)	Average concentration (mg/L)	Total load (metric tons × 10⁻³)	Discharge (metric tons per day)
October	70	9.0	291	22	2.8	91	261	34	1,084
November	62	16.9	562	20	5.4	181	234	64	2,123
December	48	12.9	417	16	4.3	139	191	51	1,658
January	72	9.7	312	23	3.1	100	266	36	1,153
February	34	31.8	1,136	11	10.3	368	146	136	4,878
March	34	19.4	627	11	6.3	203	147	84	2,711
April	26	25.3	843	9.2	8 9	298	125	121	4,051
May	32	25.0	806	10	7.8	252	137	107	3,453
June	28	26.5	882	9.4	8.9	296	127	120	3,999
July	43	14.9	481	14	4.8	156	176	61	1,967
August	35	5.0	160	12	1.7	55	150	21	687
September	65	12 7	424	21	4.0	135	248	48	1,594
1981 water year	37	209.1	---	12	68 3	---	155	883	---

high r^2 value when only pairs of values are being considered may be dropped if its presence in the regression is detrimental to subsequent r^2 values when more than two variables are being considered. This method developes a model for which r^2 is maximized.

The results from the MAXR analyses when applied to phosphorus, nitrogen, silica, chlorophyll, and BOD data did not yield any relationships that could be used to determine daily concentrations for the 3-year period. Correlations were not improved by selecting data by season or by grouping data by magnitude of discharge. The only regression of significance was that for total phosphorus for the 1979 water year, r^2 of 0.86.

As a result of the failure of the multiple regression techniques daily concentrations for phosphorus and nitrogen species, silica, chlorophyll, pheophytin, and ultimate and carbonaceous BOD were interpolated between sampling dates by using the constituent concentration, the rate of change in the hydrograph, and changes in other constituents as guides. This manual technique is known as the hydrograph method of computing loads (Porterfield, 1972). When rapid changes in constituent concentration occurred during a single day, such as those shown for phosphorus on February 26, 1979 (fig. 11), that day was subdivided and the observed concentrations for that day were weighted by the discharge that occurred during the subdivision to arrive at a daily mean concentration.

Computed Loads

Daily loads of nutrients, chlorophyll, and BOD were computed by the following equation:

$$L = k C Q$$

Table 8. Slope of line for plots of known versus computed concentrations of the major cations and anions

Dissolved ion	Slope of line for plot of known verses computed concentrations
Chloride	0.99
Sulfate	0.99
Calcium	1.09
Magnesium	1.01
Sodium	1.01
Bicarbonate	1.00
Total dissolved solids	1.00

where: L = constituent load, in metric tons per day (also represents constituent discharge); k = unit conversion factor, 0.0864; C = daily mean concentration, in milligrams per liter; Q = daily mean water discharge, in cubic meters per second.

The monthly loads are the sum of the daily values. Loads for nitrogen, phosphorus, and silica for water years 1978–81 are shown in tables 9a, 9b, 9c, and 9d and the loads for chlorophyll *a*, pheophytin, and uninhibited ultimate and ultimate carbonaceous BOD for water years 1979–81 are shown in tables 10a, 10b, and 10c.

Evaluation of Computed Loads

Procedures are not available for testing the accuracy of the nutrient loads obtained by the hydrograph method. The multiple regression equation for total phosphorus (r^2 of 0.86) for the 1979 water year was used to calculate loads that could be compared to the hydrograph-method loads for that year. The annual load of total phosphorus from the equation was 5 percent higher than the annual load determined by the hydrograph method. The method used in this report to obtain total phosphorus loads therefore yields results similar in magnitude to results from the regression

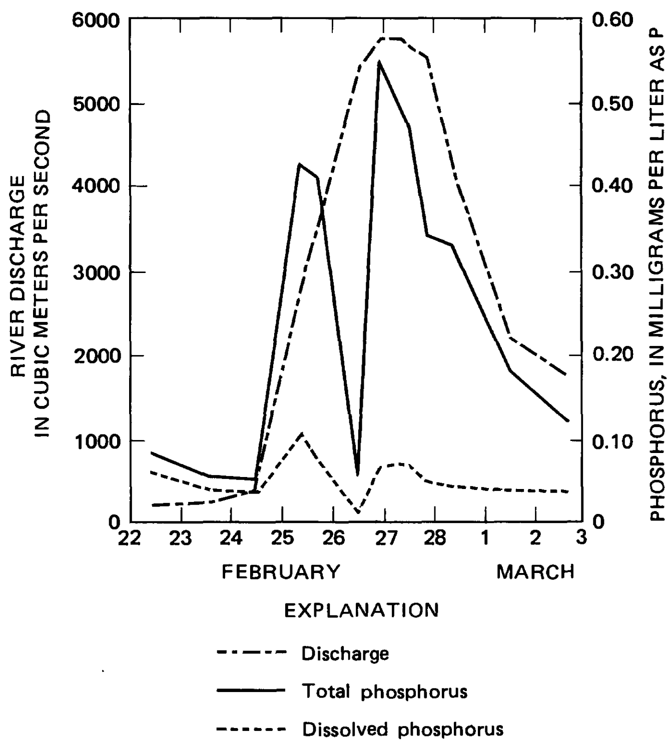

Figure 11. Variation in concentration of total and dissolved phosphorus as functions of discharge and time, February–March, 1979.

Table 9a. Monthly loads of selected nutrients, Potomac River at Chain Bridge at Washington, D.C., 1978 water year

		Phosphorus						Nitrogen					
		Total			Dissolved			Total Kjeldhal			Dissolved Kjeldhal		
Month	Average discharge (m³/s)	Average concentration (mg/L)	Total load (metric tons × 10^{-3})	Discharge (metric tons per day)	Average concentration (mg/L)	Total load (metric tons × 10^{-3})	Discharge (metric tons per day)	Average concentration (mg/L)	Total load (metric tons × 10^{-3})	Discharge (metric tons per day)	Average concentration (mg/L)	Total load (metric tons × 10^{-3})	Discharge (metric tons per day)
October	68.60	0.075	14	0.45	0.016	3	0.10	0.64	118	3.8	0.36	67	2.2
November	408.1	.188	200	6.5	.21	48	1.6	.87	926	29.9	.52	553	17.8
December	617.5	.175	291	9.4	.061	102	3.3	.81	1,348	43.5	.50	832	26.8
January	691.4	.239	445	14.4	.067	125	4.0	.96	1,789	57.7	.39	727	23.4
February	306.2	.047	35	1.1	.034	25	.81	.27	201	6.5	.24	178	5.7
March	1,212	.236	771	24.9	.039	127	4.1	1.2	3,919	126	.68	2,221	71.7
April	456.8	.043	51	1.7	.018	22	.71	.35	417	13.4	.26	310	10.0
May	870.5	.174	408	13.2	.027	63	2.0	.73	1,712	55.2	.35	821	26.5
June	180.8	.049	23	.74	.013	6	.19	.57	268	8.7	.32	151	4.9
July	246.0	.154	102	3.3	.033	22	.71	.79	524	16.9	.44	292	9.4
August	306.5	.138	114	3.7	.063	52	1.7	.80	661	21.3	.45	372	12.0
September	94.72	.060	15	.46	.020	5	.16	.62	153	4.9	.35	86	2.8
1978 water year	457.9	.170	2,469	---	.041	600	---	.83	12,036	---	.45	6,610	---

	Nitrogen						Silica		
	Dissolved ammonia			Dissolved $NO_2 + NO_3$			Dissolved		
Month	Average concentration (mg/L)	Total load (metric tons × 10^{-3})	Discharge (metric tons per day)	Average concentration (mg/L)	Total load (metric tons × 10^{-3})	Discharge (metric tons per day)	Average concentration (mg/L)	Total load (metric tons × 10^{-3})	Discharge (metric tons per day)
October	---	---	---	.94	174	5.6	0.8	149	4.8
November	---	---	---	.85	905	29.2	6.0	6,385	206
December	---	---	---	1.2	1,997	64.4	7.9	13,146	424
January	---	---	---	1.5	2,794	90.1	5.7	10,620	343
February	---	---	---	1.9	1,416	45.7	6.8	5,068	163
March	---	---	---	1.3	4,245	137	5.6	18,290	590
April	---	---	---	1.2	1,430	46.1	4.3	5,122	165
May	---	---	---	.94	2,205	71.1	5.7	13,371	431
June	---	---	---	.64	302	9.7	2.3	1,084	35.0
July	---	---	---	1.2	796	25.7	5.4	3,580	115
August	---	---	---	.80	661	21.3	5.9	4,873	157
September	---	---	---	.52	128	4.1	2.8	691	22.3
1978 water year	---	---	---	1.2	17,053	---	5.7	82,379	---

Table 9b. Monthly loads of selected nutrients, Potomac River at Chain Bridge at Washington, D.C., 1979 water year

Month	Average discharge (m^3/s)	Phosphorus, Total: Average concentration (mg/L)	Phosphorus, Total: Total load (metric tons × 10^{-3})	Phosphorus, Total: Discharge (metric tons per day)	Phosphorus, Dissolved: Average concentration (mg/L)	Phosphorus, Dissolved: Total load (metric tons × 10^{-3})	Phosphorus, Dissolved: Discharge (metric tons per day)
October	53.77	0.041	6	0 19	0.010	1	0.05
November	61.40	.060	10	.31	.020	3	.11
December	299.3	.15	120	3 9	.070	56	1.8
January	866.9	.25	580	19	.051	118	3.8
February	854.4	.28	578	21	.050	103	3.7
March	1,073	.11	316	10	.030	86	2.8
April	520.5	.070	93	2.2	.020	27	.90
May	478.0	.10	128	4.1	.031	40	1.3
June	399.3	.13	134	4.5	.060	62	2.1
July	154.3	.061	25	.81	.020	8	.27
August	153.9	.11	45	1.5	.040	16	.53
September	605.2	.28	439	15	.071	111	3.7
1979 water year	457.4	0.17	2,474	---	0.044	631	---

Month	Nitrogen, Total Kjeldhal: Average concentration (mg/L)	Nitrogen, Total Kjeldhal: Total load (metric tons × 10^{-3})	Nitrogen, Total Kjeldhal: Discharge (metric tons per day)	Nitrogen, Dissolved Kjeldhal: Average concentration (mg/L)	Nitrogen, Dissolved Kjeldhal: Total load (metric tons × 10^{-3})	Nitrogen, Dissolved Kjeldhal: Discharge (metric tons per day)
October	0.57	82	2.6	0.43	62	2.0
November	.50	79	2.6	26	41	1.4
December	.66	529	17	.64	513	17
January	.93	2,157	70	.25	580	19
February	1.2	2,478	88	.57	1,177	42
March	.50	1,435	46	.13	373	12
April	.29	391	13	.14	189	6.3
May	.71	908	29	.34	435	14
June	.72	744	25	.53	548	18
July	.57	236	7.6	.39	161	5.2
August	.78	321	10	.64	264	8.5
September	.81	1,269	42	.48	752	25
1979 water year	0.74	10,629	---	0 35	5,095	---

Month	Nitrogen, Dissolved ammonia: Average concentration (mg/L)	Nitrogen, Dissolved ammonia: Total load (metric tons × 10^{-3})	Nitrogen, Dissolved ammonia: Discharge (metric tons per day)	Nitrogen, Dissolved $NO_2 + NO_3$: Average concentration (mg/L)	Nitrogen, Dissolved $NO_2 + NO_3$: Total load (metric tons × 10^{-3})	Nitrogen, Dissolved $NO_2 + NO_3$: Discharge (metric tons per day)	Silica, Dissolved: Average concentration (mg/L)	Silica, Dissolved: Total load (metric tons × 10^{-3})	Silica, Dissolved: Discharge (metric tons per day)
October	---	---	---	0.68	98	3.2	1.0	144	4.6
November	---	---	---	.69	110	3.7	.8	127	4.2
December	---	---	---	1.2	961	31	4.6	3,684	119
January	---	---	---	1.1	2,551	82	4.6	10,669	344
February	---	---	---	1.0	2,065	74	5.1	10,530	376
March	---	---	---	1.2	3,445	111	6.5	18,661	602
April	---	---	---	1.1	1,482	49	5.3	7,143	238
May	---	---	---	86	1,110	35	4.8	6,139	198
June	---	---	---	1.3	1,344	45	6.9	7,134	238
July	---	---	---	.66	273	8.8	2.2	909	29
August	---	---	---	.65	286	8.6	4.0	1,647	53
September	---	---	---	1.1	1,724	57	6.6	10,342	345
1979 water year	---	---	---	1.1	15,421	---	5.4	77,129	---

Table 9c. Monthly loads of selected nutrients, Potomac River at Chain Bridge at Washington, D.C., 1980 water year

		Phosphorus						Nitrogen					
		Total			Dissolved			Total Kjeldhal			Dissolved Kjeldhal		
Month	Average discharge (m^3/s)	Average concentration (mg/L)	Total load (metric tons × 10^{-3})	Discharge (metric tons per day)	Average concentration (mg/L)	Total load (metric tons × 10^{-3})	Discharge (metric tons per day)	Average concentration (mg/L)	Total load (metric tons × 10^{-3})	Discharge (metric tons per day)	Average concentration (mg/L)	Total load (metric tons × 10^{-3})	Discharge (metric tons per day)
October	955.5	0.13	332	11	0.060	153	4.9	0.84	2,147	69	0.32	818	26
November	516.8	.067	90	3.0	.024	32	1.1	.47	629	21	.39	522	17
December	372.7	.038	39	1.2	.023	23	74	.37	368	12	33	328	11
January	520.2	.062	86	2.8	.036	50	1.6	.56	779	25	.35	487	16
February	227.8	.038	22	.75	.025	14	.49	.32	182	6.3	.31	177	6 1
March	660.7	.12	212	6.8	.036	64	2.1	.58	1,025	33	.32	566	18
April	876.8	.11	250	8.3	.033	75	2.5	.50	1,135	38	.26	590	20
May	716.5	.087	167	5.4	.032	61	2.0	.63	1,208	40	.30	575	19
June	224.0	.075	43	1.4	.033	19	.64	.39	226	7.5	.30	174	5.8
July	121.1	.066	21	.69	016	5	.17	.52	168	5.4	.35	113	3 7
August	96.26	.066	17	.55	.033	8	.27	.36	93	3.0	.22	57	1 8
September	47.10	.060	7	.24	.037	5	.15	.49	60	2.0	26	32	1.1
1980 water year	446.0	0.092	1,286	---	0.036	509	---	0.57	8,020	---	0.31	4,439	---

	Nitrogen						Silica		
	Dissolved ammonia			Dissolved $NO_2 + NO_3$			Dissolved		
Month	Average concentration (mg/L)	Total load (metric tons × 10^{-3})	Discharge (metric tons per day)	Average concentration (mg/L)	Total load (metric tons × 10^{-3})	Discharge (metric tons per day)	Average concentration (mg/L)	Total load (metric tons × 10^{-3})	Discharge (metric tons per day)
October	0.015	38	1.2	1.4	3,579	115	8.2	20,963	676
November	.026	35	1.2	1 1	1,472	49	5.4	7,226	241
December	.014	14	.45	1.3	1,294	42	4.6	4,578	148
January	.032	45	1.4	1.3	1,809	58	6.2	8,629	278
February	.023	13	.45	1.6	912	31	4.0	2,281	79
March	.034	60	1.9	1.3	2,298	74	5.2	9,192	297
April	.051	116	3.9	1 3	2,951	98	6.7	15,211	507
May	.026	50	1.6	1.1	2,109	68	6.1	11,694	377
June	.064	37	1.2	.88	510	17	3.2	1,856	62
July	.035	11	.37	.57	185	6.0	4.6	1,490	48
August	.051	13	.42	.54	139	4.5	6.0	1,545	50
September	.049	6	.20	.57	70	2.3	4.9	598	20
1980 water year	0.031	438	---	1 2	17,328	---	6.0	85,263	---

Table 9d. Monthly loads of selected nutrients, Potomac River at Chain Bridge at Washington, D.C., 1981 water year

Month	Average discharge (m^3/s)	Phosphorus: Total: Average concentration (mg/L)	Total load (metric tons × 10^{-3})	Discharge (metric tons per day)	Phosphorus: Dissolved: Average concentration (mg/L)	Total load (metric tons × 10^{-3})	Discharge (metric tons per day)	Nitrogen: Total Kjeldhal: Average concentration (mg/L)	Total load (metric tons × 10^{-3})	Discharge (metric tons per day)	Nitrogen: Dissolved Kjeldhal: Average concentration (mg/L)	Total load (metric tons × 10^{-3})	Discharge (metric tons per day)
October	48 14	0.056	7	0.23	0.032	4	0.13	0 34	44	1.4	0.29	37	1.2
November	105.1	.13	35	1.2	064	17	.58	49	133	4.4	29	79	2.6
December	100.6	.045	12	.39	.033	9	.29	35	94	3 0	.31	83	2 7
January	50.24	061	8	.26	.051	7	.22	34	46	1.5	.26	35	1.1
February	387.1	.26	243	8.7	.071	66	2 4	1 1	1,029	37	.57	533	19
March	213.7	.056	32	1.0	.036	21	.66	.35	200	6 5	.23	132	4.2
April	375.5	.12	117	3 9	.028	27	.91	67	651	22	.19	185	6.2
May	292.0	.089	70	2.2	.031	24	78	.60	469	15	.43	336	11
June	364.8	.12	113	3.8	.051	48	1.6	.61	576	19	49	463	15
July	129 5	.069	24	.77	.026	9	.29	.66	229	7.4	42	146	4.7
August	53.10	.079	11	.36	.019	3	.09	71	101	3.3	.49	70	2.2
September	74.45	088	17	.57	.064	12	.41	.57	110	3 7	.37	71	2 4
1981 water year	179.4	0 12	689	---	0 044	247	---	0.65	3,682	---	0.38	2,136	---

Month	Nitrogen: Dissolved ammonia: Average concentration (mg/L)	Total load (metric tons × 10^{-3})	Discharge (metric tons per day)	Nitrogen: Dissolved $NO_2 + NO_3$: Average concentration (mg/L)	Total load (metric tons × 10^{-3})	Discharge (metric tons per day)	Silica: Dissolved: Average concentration (mg/L)	Total load (metric tons × 10^{-3})	Discharge (metric tons per day)
October	0.035	4	0.15	0.59	76	2.5	1.5	193	6.2
November	.047	13	.43	.97	264	8.8	2 2	599	20
December	.042	11	.36	1 3	350	11	1.9	511	16
January	014	2	.06	1 6	215	6.9	.1	13	.43
February	13	122	4.3	1.6	1,497	53	5.2	4,864	174
March	040	23	.74	1.7	972	31	3.6	2,058	66
April	.091	88	2 9	.82	797	27	5.2	5,056	169
May	.079	62	2 0	.86	672	22	4.6	3,594	116
June	.073	69	2.3	.47	444	15	7.1	6,706	224
July	.015	5	.17	.77	267	8.6	4.5	1,559	50
August	.044	6	.20	.21	30	.96	2.4	341	11
September	.050	10	.32	95	183	6.1	4.3	829	28
1981 water year	0.073	415	---	1.0	5,767	---	4.6	26,323	---

Table 10a. Monthly loads of chlorophyll *a*, pheophytin, and biochemical oxygen demand, Potomac River at Chain Bridge at Washington, D.C., 1979 water year

		Chlorophyll *a*			Pheophytin		
Month	Average discharge (m^3/s)	Average concentration (mg/L)	Total load (metric tons × 10^{-3})	Discharge (metric tons per day)	Average concentration (mg/L)	Total load (metric tons × 10^{-3})	Discharge (metric tons per day)
October	53 77	---	---	---	---	---	---
November	61 40	---	---	---	---	---	---
December	299 3	---	---	---	---	---	---
January	866 9	---	---	---	---	---	---
February	854 4	---	---	---	---	---	---
March	1.073	---	---	---	---	---	---
April	520.5	---	---	---	---	---	---
May	478.0	13	17	0.55	7.3	9.2	.30
June	399.3	7.8	8.1	.27	3.2	3.4	.11
July	154.3	39	16	.040	17	7.1	.23
August	153.9	24	9.7	.027	16	6.4	.21
September	605.2	5.4	8.5	.005	7.6	12	.40
1979 water year	457.4	---	---	---	---	---	---

	Biochemical oxygen demand, ultimate					
	Carbonaceous			Uninhibited		
Month	Average concentration (mg/L)	Total load (metric tons × 10^{-3})	Discharge (metric tons per day)	Average concentration (mg/L)	Total load (metric tons × 10^{-3})	Discharge (metric tons per day)
October	4.8	692	22	5.7	817	26
November	4.6	728	24	5.4	854	28
December	5 2	4.183	135	5.5	4.413	142
January	6.5	14.971	483	8.2	19.040	614
February	5.9	12.249	437	8.5	17.542	626
March	2.7	7.817	252	3.7	10.615	342
April	2.8	3.748	125	3.7	4.983	166
May	3.8	4.909	158	5.0	6.496	210
June	3.3	3.410	114	5.2	5.395	180
July	4.8	1.980	64	7.4	3.047	98
August	4.4	1.793	58	7.3	2.997	97
September	5.4	8.467	282	7.4	11.611	387
1979 water year	4.5	64.947	---	6.1	87.810	---

Table 10b. Monthly loads of chlorophyll *a*, pheophytin, and biochemical oxygen demand, Potomac River at Chain Bridge at Washington, D.C., 1980 water year

		Chlorophyll *a*			Pheophytin		
Month	Average discharge (m^3/s)	Average concentration (mg/L)	Total load (metric tons × 10^{-3})	Discharge (metric tons per day)	Average concentration (mg/L)	Total load (metric tons × 10^{-3})	Discharge (metric tons per day)
October	955.5	2	6.2	0.20	3	7.7	0.25
November	516.8	19	25	.83	9	12	.39
December	327.7	12	11	.34	5	4.8	.15
January	520.2	19	26	.84	8	11	.37
February	227.8	11	6.0	.21	3	1.6	.06
March	660.7	32	56	1.8	14	26	.82
April	876.8	12	26	.88	10	23	.76
May	716.5	11	21	.67	8	15	.49
June	224.0	39	23	.76	13	7.8	.26
July	121.1	26	8.4	.27	23	7.6	.24
August	96.26	5	1.1	.04	8	2.3	.07
September	47.10	2	.2	.01	56	.4	.02
1980 water year	446 0	15	209.9	---	8	119.2	---

	Biochemical oxygen demand, ultimate					
	Carbonaceous			Uninhibited		
Month	Average concentration (mg/L)	Total load (metric tons × 10^{-3})	Discharge (metric tons per day)	Average concentration (mg/L)	Total load (metric tons × 10^{-3})	Discharge (metric tons per day)
October	4.0	10,264	331	5.4	13,750	444
November	3.0	4,032	134	3.8	5,148	172
December	3.5	3,093	100	4.1	3,609	116
January	3.8	5,316	171	4.4	6,192	200
February	2.4	1,366	47	3.5	1,991	69
March	3.7	6,518	210	5.0	8,816	284
April	2.6	5,842	195	3.6	8,232	274
May	2.7	5,214	168	4.7	8,926	288
June	5.1	2,929	98	7.4	4,275	142
July	5.8	1,876	61	8.1	2,631	85
August	3.9	995	32	5.3	1,363	44
September	2.3	280	9	3.5	421	14
1980 water year	3.4	47,725	---	4.6	65,354	---

Table 10c. Monthly loads of chlorphyll *a*, pheophytin, and biochemical oxygen demand, Potomac River at Chain Bridge at Washington, D.C., 1981 water year

Month	Average discharge (m^3/s)	Chlorophyll *a* Average concentration (mg/L)	Chlorophyll *a* Total load (metric tons × 10^{-3})	Chlorophyll *a* Discharge (metric tons per day)	Pheophytin Average concentration (mg/L)	Pheophytin Total load (metric tons × 10^{-3})	Pheophytin Discharge (metric tons per day)
October	48.14	5	0.5	0.02	5	0.5	0.02
November	105.1	18	4.9	16	6	1.4	.05
December	100.6	3	.8	.03	2	.7	.02
January	50.24	2	.2	.01	1	.1	.00
February	387.1	33	30	1.1	16	15	.54
March	213 7	6	3.8	.12	4	2.1	.07
April	375.5	43	41	1.4	21	21	.68
May	292 0	37	29	.93	12	9.2	.30
June	364.8	10	9 0	.30	10	9.8	.33
July	129.5	18	6.1	20	14	4.8	.16
August	53.10	50	7 1	.23	22	3.1	.10
September	74.45	3	5	.02	5	.9	.03
1981 water year	179.4	23	132 9	---	12	68.6	---

Biochemical oxygen demand, ultimate

Month	Carbonaceous Average concentration (mg/L)	Carbonaceous Total load (metric tons × 10^{-3})	Carbonaceous Discharge (metric tons per day)	Uninhibited Average concentration (mg/L)	Uninhibited Total load (metric tons × 10^{-3})	Uninhibited Discharge (metric tons per day)
October	3 0	381	12	4.1	529	17
November	4.0	1,097	46	5.1	1,389	37
December	2.9	770	25	3.7	1,008	32
January	3.1	420	14	4.0	532	17
February	6.6	6,151	220	9.0	8,423	301
March	2.6	1,502	48	3.5	2,016	65
April	5.0	4,819	212	6.5	6,349	161
May	3 8	2,984	96	6.6	5,121	165
June	2 7	2,572	86	4.0	3,798	127
July	3 4	1,167	38	4.6	1,581	51
August	5 8	828	27	6.9	979	32
September	2.8	540	18	4.1	795	26
1981 water year	4.1	23,231	---	5.8	32,520	---

equation. Comparison of the annual loads of total and dissolved phosphorus, dissolved ammonia, and dissolved nitrate plus nitrite presented in this report with those reported by Lang (1982) also show good agreement. Loads for the other constituents probably are equally as good.

Suspended Sediment

Suspended sediment has a consistent relationship with water discharge over a wide range of discharges. Suspended sediment loads were previously reported in inch-pound units by the U.S. Geological Survey (1979, 1980, 1981, 1982). For this report, the monthly-mean suspended-sediment loads were converted to metric tons (t) and corresponding suspended-sediment concentrations were computed by dividing the monthly mean loads by kQ (where Q is the monthly mean water discharge, in m^3/s) and rounding the concentrations to the nearest milligram per liter. Loads for suspended sediment are shown in table 11.

DISCUSSION

Frequency Analysis of Concentrations and Loads

Frequency analyses were made of the daily concentrations and loads of nutrients, chlorophyll, and sediment. The results of these analyses are plotted as concentration- and load-duration curves in figures 12 and 13. The concentration-duration curves, shown in figure 12, give the percentage of time a particular level of concentration prevailed or was exceeded during the study period. Fifty percent of the time during the 1979-1981 water years the daily mean constituent concentrations were greater than or equal to the following magnitudes, in milligrams per liter:

total phosphorus as P	≥	0.07
dissolved phosphorus as P	≥	.03
dissolved nitrate plus nitrite as N	≥	1.0
dissolved ammonia as N	≥	.03
dissolved silica	≥	4.5
chlorophyll *a*	≥	.007
BOD ultimate uninhibited	≥	4.3
BOD ultimate carbonaceous	≥	3.2
suspended sediment	≥	15

The load-duration curves, shown in figure 13, indicate the percentage of time during the study for which a designated minimum load of material was being transported. For example, 50 percent of the time during the 1979-1981 water years the daily mean constituent discharges were greater than or equal to the following magnitudes, in metric tons per day:

total phosphorus as P	≥	1.0
dissolved phosphorus as P	≥	.5
dissolved nitrogen as N	≥	28
dissolved nitrate plus nitrite as N	≥	20
dissolved ammonia as N	≥	.4
dissolved silica	≥	70
chlorophyll *a*	≥	.17
BOD ultimate uninhibited	≥	81
BOD ultimate carbonaceous	≥	61
suspended sediment	≥	270

Seasonal Variations in Concentrations and Loads

Examination of the data in tables 7, 9, 10, and 11 shows that in general the monthly mean concentrations change with season. For the most part the changes are neither consistent from year to year for the same constituent nor consistent between pairs of constituents. However, the summary in table 12 indicates relatively small changes in the annual-average concentrations of each constituent for the water years 1979-81.

The consistency in annual-average concentrations is emphasized by the annual loads shown in table 12. During the 1979 and 1980 water years the high flow runoff patterns were quite different (table 3 and fig. 5), yet the total volume of flow and the total loads are similar. During the 1981 water year streamflow was much below that for the proceeding two years, yet the average concentrations of nutrients remained nearly the same. Of course, the loads were much less. Therefore, the variable annual load entering the tidal Potomac River is due mostly to changes in discharge rather than changes in the annual-average concentrations of nutrients.

This pattern also holds for the major cations and anions. Comparison of annual mean concentrations of cations and anions (table 7) for 1979-81 shows little change, but, the change in loads is large.

In conclusion, there is very little consistant seasonal change in constituent concentrations. The seasonal trend in loads, however, exists as a direct function of changes in runoff. Edwards (1973) also came to the same conclusion for several rivers in Norfolk, Great Britain.

Table 11. Monthly loads of suspended sediment, Potomac River at Chain Bridge at Washington, D.C., 1978–81 water years

	1978 water year				1979 water year			
		Suspended sediment				Suspended sediment		
Month	Average discharge (m^3/s)	Average concentration (mg/L)	Total load (metric tons)	Discharge (metric tons per day)	Average discharge (m^3/s)	Average concentration (mg/L)	Total load (metric tons)	Discharge (metric tons per day)
October	68.60	8	1,479	47.7	53.77	14	1,973	64
November	403.1	153	162,830	5,253	61.40	12	1,840	62
December	617.5	121	201,350	6,495	299.3	63	50,572	1,631
January	691.4	217	404,310	1,034	866.9	254	588,165	18,973
February	306.2	12	8,945	286	854.4	351	725,306	25,904
March	1,212	250	816,523	26,339	1,073	106	303,743	9,798
April	456.8	26	30,970	999	520.5	61	82,058	2,735
May	870.5	145	340,140	10,972	478.0	61	78,413	2,529
June	180.8	16	7,544	243	399.3	103	106,317	3,544
July	246.0	121	80,210	2,587	154.3	20	8,156	263
August	306.5	110	90,850	2,931	153.9	46	18,829	607
September	94.72	23	5,681	174	605.2	275	430,177	14,339
	457.9	148	2,150,840	---	457.4	163	2,395,549	---

	1980 water year				1981 water year			
		Suspended sediment				Suspended sediment		
Month	Average discharge (m^3/s)	Average concentration (mg/L)	Total load (metric tons)	Discharge (metric tons per day)	Average discharge (m^3/s)	Average concentration (mg/L)	Total load (metric tons)	Discharge (metric tons per day)
October	955.5	161	411,933	13,288	48.14	6	815	26
November	516.8	83	110,907	3,697	105.1	24	6,546	218
December	327.7	29	29,629	956	100.6	8	2,069	67
January	520.2	32	43,916	1,417	50.24	4	595	19
February	227.8	18	10,053	347	387.1	165	154,435	5,516
March	660.7	109	192,341	6,205	213.7	15	8,351	269
April	876.8	98	222,382	7,413	375.5	125	121,639	4,055
May	716.5	124	238,057	7,679	292.0	26	16,781	541
June	224.0	25	14,378	479	364.8	37	35,391	1,180
July	121.1	23	7,590	245	129.5	21	7,118	230
August	96.26	17	4,256	137	53.10	18	2,462	79
September	47.10	6	673.6	22.5	74.45	17	3,172	106
	446.0	91	1,286,116	---	179.4	64	359,374	---

Storm Runoff

Storm runoff from the Potomac River basin above Chain Bridge contributes large amounts of constituents to the tidal Potomac River. Water discharges and loads of selected constituents for five of the largest storms that occurred during the study period are shown in table 13. The storm-runoff period was considered as that period of time for which the flow exceeded the long-term average flow. The three largest storms of the 1979 water year (table 14) transported 40 to 70 percent of the 1979 annual load (table 12) of nutrients and carbonaceous oxygen demanding material and 77 percent of the 1979 annual suspended sediment load (percent ages are shown in parentheses in table 14). Runoff from the same three storms transported as much as 40 to 55 percent of the nutrients, 80 percent of the carbonaceous oxygen demanding material, 122 percent of the total phosphorus, and 143 percent of the suspended sediment loads was transported during the entire 1980 water year. The loads carried by the largest runoff

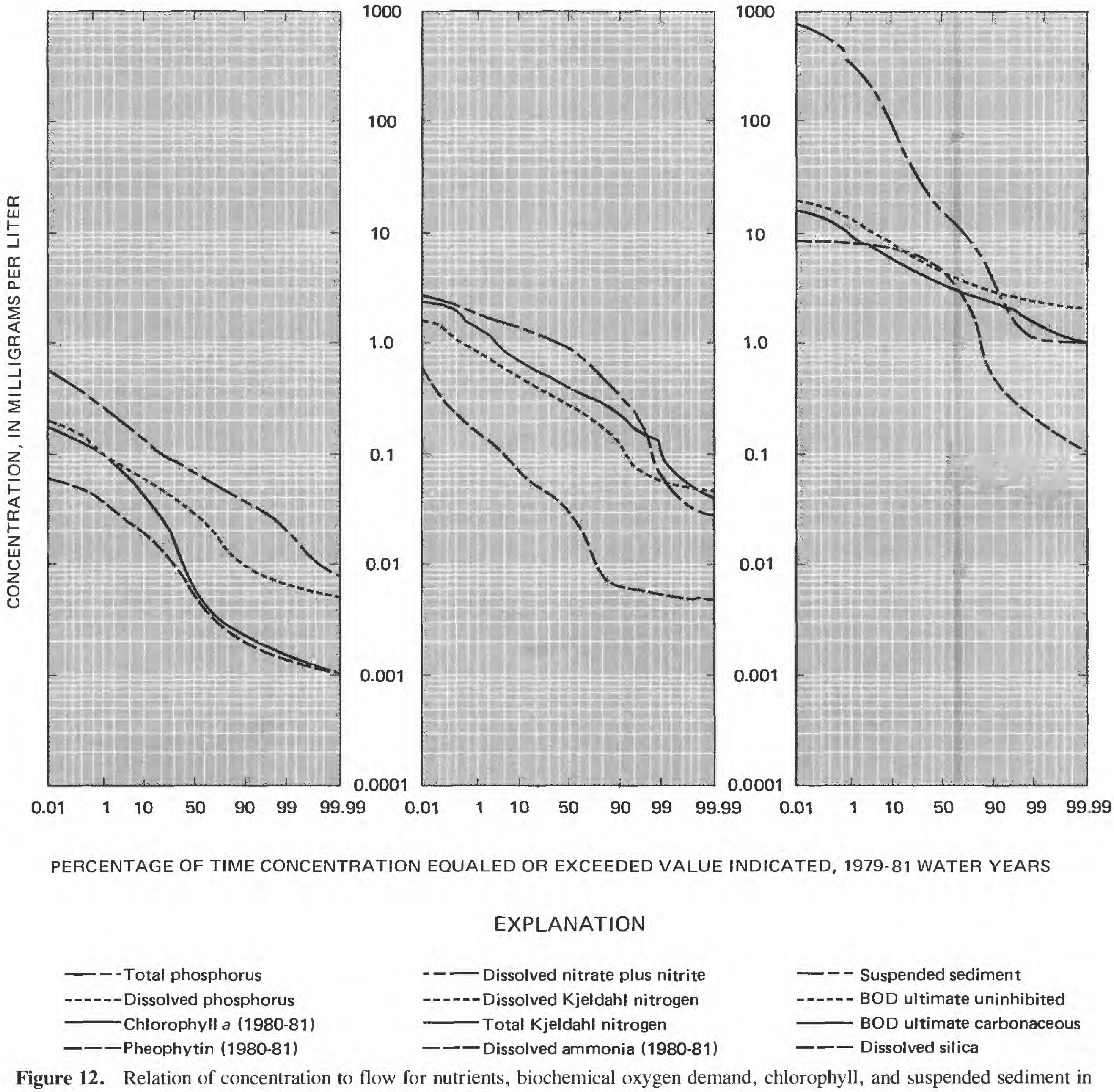

Figure 12. Relation of concentration to flow for nutrients, biochemical oxygen demand, chlorophyll, and suspended sediment in the Potomac River at Chain Bridge at Washington, D.C., water years 1979–81.

period during the study, February 24 to March 23, 1979, a 28-day period, made up about 30 percent of the annual nutrient and BOD loads and about 40 percent of the annual suspended sediment load for 1979. Loads transported during the 28-day runoff period, compared to those transported during the 1981 water year, carried an amount equivalent of 60 to 80 percent of the annual load of most of the nutrients and BOD, 116 percent of the annual load of total phosphorus, and 284 percent of the annual load of the suspended sediment for that entire water year. The data are summarized in table 14.

In summary, some storm runoff events yield as much dissolved and suspended material as is transported during entire low-flow years. A good example is the comparison of loads from the February 24-March 23, 1979 storm runoff event (28 days) with loads for the entire 1981 water year. Storm runoff in some years transports one-third to two-thirds of the annual loads of constituents. Even though the average discharges for 1979 and 1980 were about equal, the storm runoff characteristics were different and the 1980 loads of suspended material were less than those for 1979.

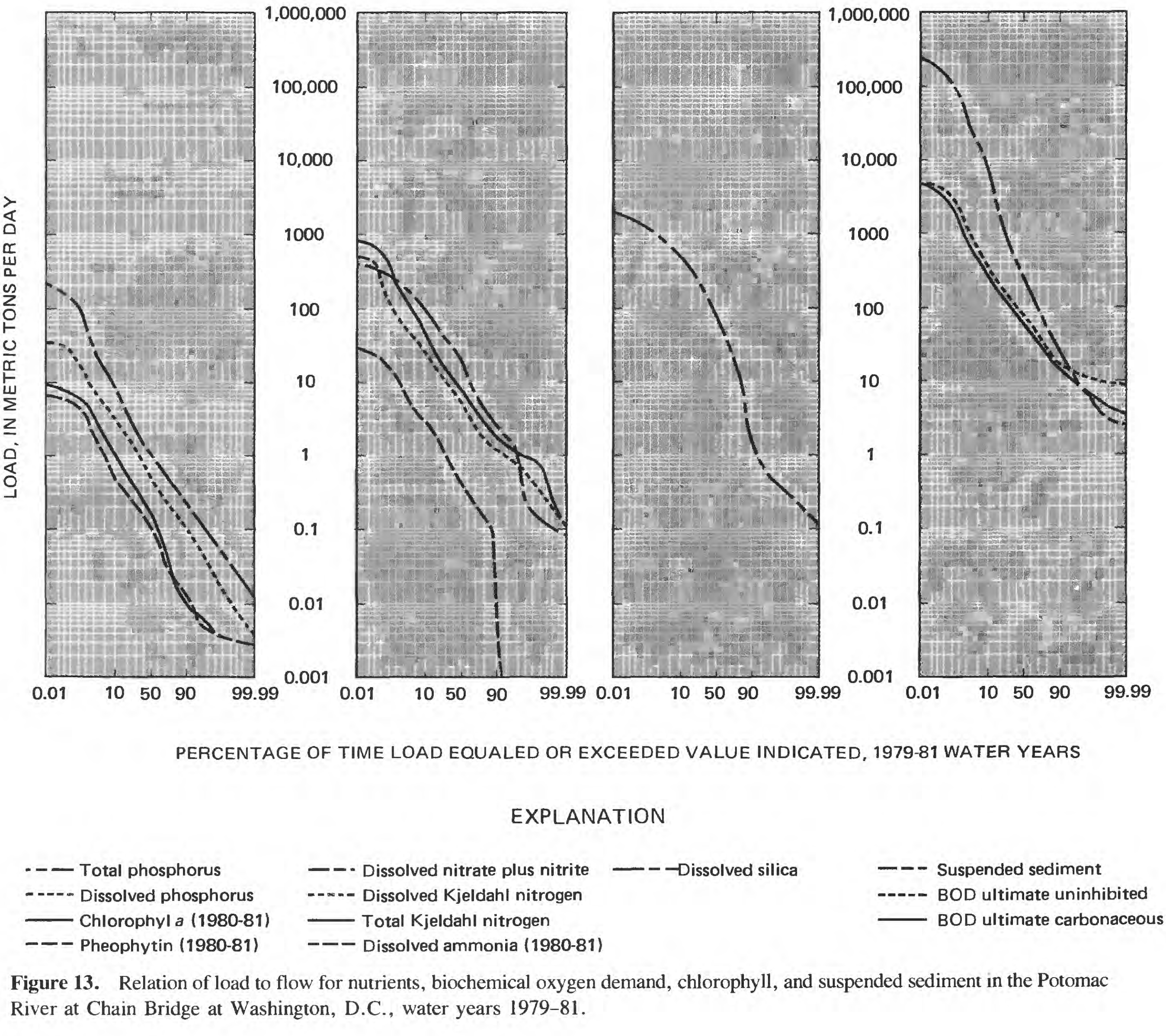

Figure 13. Relation of load to flow for nutrients, biochemical oxygen demand, chlorophyll, and suspended sediment in the Potomac River at Chain Bridge at Washington, D.C., water years 1979–81.

Examination of Selected Water-Quality Constituents

No satisfactory predictive relationships were developed for the nutrient species, for chlorophyll, for BOD or for suspended sediment. There are several good correlations between these constituents and the agents affecting their change. These correlations are not useful for accurate predictions because the response of the constituent to a specific change is not always of the same magnitude. For example, a peak discharge of 1400 m^3/s could result in several different concentrations for a given constituent. The peak discharge could be from a long duration-low intensity storm, from a short duration-high intensity storm, from snow melt, or from a rainfall event in just one watershed of the drainage basin. In each case, the resultant concentration would probably be different. The effects of biological removal, the interval between flow events, and hyteresis also increase this variability. Figure 14 shows the variation in concentration of four constituents to a rainfall event. Hendrickson and Krieger (1960) show the same type of cyclic response for several cations and anions. Figure 14C shows that even though there are several possible concentrations for a low river discharge, suspended sediment tends to increase with increasing discharge. It is this type of positive correlation that will be discussed below.

Phosphorus

Phosphorus in natural waters appears as phosphate anions, complexes with metal ions, and colloidal particulate material (Hem, 1970). One would expect, therefore, that the best correlations with phosphorus would involve suspended sediment, river discharge, and

Table 12. Summary of annual-average concentrations and annual total loads for the Potomac River at Chain Bridge at Washington, D.C., 1979–81 water years

Characteristic	Concentration (mg/L)			Load (metric tons)		
	1979	1980	1981	1979	1980	1981
Mean discharge (m^3/s)	457	446	179	457	446	179
Total phosphorus as P	0.17	0.09	0.12	2,470	1,290	690
Dissolved phosphorus as P	.04	.04	.04	630	510	250
Total nitrogen as N	1.8	1.8	1.7	26,000	25,300	9,450
Dissolved nitrogen as N	1.5	1.5	1.4	20,500	21,800	7,900
Dissolved nitrate + nitrite as N	1.1	1.2	1.0	15,400	17,300	5,770
Dissolved ammonia as N	-	.03	.07	-	440	420
BOD ultimate uninhibited	6.1	4.6	5.8	87,800	65,400	32,500
BOD ultimate carbonaceous	4.5	3.4	4.1	64,900	47,700	23,200
Chlorophyll *a* (μg/L)	-	15	23	-	210	133
Dissolved silica as SiO_2	5.4	6.0	4.6	77,100	85,300	26,300
Suspended sediment	166	91	64	2,400,000	1,290,000	359,000
Dissolved calcium as Ca	28	27	30	407,000	374,000	171,000
Dissolved sodium as Na	9.4	7.5	11	135,000	106,000	62,000
Dissolved bicarbonate as H_2CO_3	82	72	88	1,180,000	1,010,000	502,000
Dissolved sulfate as SO_4	34	27	37	483,000	387,000	209,000
Dissolved chloride as Cl	11	8.5	12	152,000	119,000	68,300
Total dissolved solids	145	125	155	2,080,000	1,760,000	883,000
Dissolved magnesium as Mg	6.3	5.4	6.8	91,000	76,000	38,900

Table 13. Comparison of nutrient, suspended sediment, and biochemical oxygen demand loads for the Potomac River at Chain Bridge at Washington, D.C., for selected storms

Characteristic	Date of storm		
	January 21– February 4, 1979	February 24– March 23, 1979	September 6–13, 1979
Peak daily mean discharge (m^3/s)	2,917	5,692	2,379
Total discharge (m^3/s-day)	17,700	44,800	9,000
Total phosphorus as P	450	800	330
Dissolved phosphorus as P	59	160	63
Total nitrogen as N	3,210	7,670	1,640
Dissolved nitrogen as N	1,180	5,620	1,250
Dissolved nitrate + nitrite as N	1,490	4,290	830
BOD ultimate uninhibited	16,560	26,760	8,680
Bod ultimate carbonaceous	12,760	19,150	6,430
Dissolved ammonia as N	---	---	---
Dissolved silica as SiO_2	5,870	22,220	5,500
Suspended sediment	486,200	1,018,000	336,900

Characteristic	Date of storm	
	October 1–27, 1979	April 26– May 16, 1979
Peak daily mean discharge (m^3/s)	2,209	1,929
Total discharge (m^3/s-day)	28,300	14,500
Total phosphorus as P	334	73
Dissolved phosphorus as P	150	40
Total nitrogen as N	5,500	2,310
Dissolved nitrogen as N	4,180	1,870
Dissolved nitrate + nitrite as N	3,430	1,500
BOD ultimate uninhibited	14,750	5,050
BOD ultimate carbonaceous	10,990	3,190
Dissolved ammonia as N	34	27
Dissolved silica as SiO_2	20,350	8,230
Suspended sediment	410,600	139,300

metal ions. The data from this study support that hypothesis. In general, the best relationships involve total phosphorus and not dissolved phosphorus. Those relationships significant at the 99 percent level and their corresponding r^2 value are listed in table 15. Monthly mean values of phosphorus were also regressed against monthly means of the various constituents in order to eliminate some of the variations.

The best relationships for total phosphorus are with suspended sediment, iron, and aluminum. The reason for this is that on the average, approximately 55 percent of the total phosphorus is composed of suspended phosphorus. According to particle-size data presented by Blanchard and Hahl (1981), more than half the suspended sediment is composed of clay minerals, which have a high aluminum content. Iron is abundant in rocks and soils and is probably a major component in the rest of the suspended sediment. Lang (1982) also showed a correlation between aluminum, iron and suspended sediment at Chain Bridge. Figure 15 shows graphically the relationship between total phosphorus, suspended iron and suspended aluminum for a storm runoff event in March 1980.

Dissolved phosphorus concentrations correlated well with the same constituents as did total phosphorus, except for pH and DO, which correlated only with dissolved phosphorus. Indirectly, the correlation with DO might be related to biological activity and the uptake of dissolved phosphorus. Similarly, the correlation with pH is probably related to the effects that pH has on the solubility of aluminum and iron and their ability to form complexes with dissolved phosphorus. In support of the DO hypothesis, the percent of dissolved phosphorus is lowest, 35 percent,

Table 14. Comparison of selected constituent loads for the three largest storms of the 1979 water year combined, and the largest storm of the 1979 water year to the annual loads of the 1979–81 water years

Characteristic	Three largest storms, 1979 water year	1979 water year annual load	1980 water year annual load
Total discharge (m^3/s-day)	71,500	167,000 (43)	163,300 (44)
Total phosphorus as P	1,580	2,470 (64)	1,290 (122)
Dissolved phosphorus as P	282	630 (45)	510 (55)
Total nitrogen as N	12,520	26,000 (48)	25,300 (49)
Dissolved nitrogen as N	8,680	20,500 (42)	21,800 (40)
BOD ultimate carbonaceous	38,340	64,900 (59)	47,700 (80)
Dissolved silica as SiO_2	33,590	77,100 (44)	85,300 (39)
Suspended sediment	1,841,100	2,400,000 (77)	1,290,000 (143)

Characteristic	Largest storm during study period (1978-81 water years)	1979 water year annual load	1981 water year annual load
Total discharge (m^3/s-day)	44,800	167,000 (27)	65,505 (68)
Total phosphorus as P	800	2,470 (32)	690 (116)
Dissolved phosphorus as P	160	630 (25)	250 (64)
Total nitrogen as N	7,670	26,000 (30)	9,450 (81)
Dissolved nitrogen as N	5,620	20,500 (27)	7,900 (71)
BOD ultimate carbonaceous	19,150	64,900 (30)	23,200 (83)
Dissolved silica as SiO_2	22,220	77,100 (29)	26,300 (84)
Suspended sediment	1,018,000	2,400,000 (42)	359,000 (284)

during the biological growth period of summer and highest, 65 percent, during the biological dormant period of winter.

Dissolved and total phosphorus concentrations at Chain Bridge ranged from 0.00 to 0.20 mg/L and 0.00 to 0.68 mg/L, respectively. Hem (1970) attributes the low concentrations of phosphorus in natural waters to "utilization of phosphorus by aquatic vegetation" and "the absorbtion of phosphate ions by metal oxides, expecially ferric hydroxides".

Nitrogen

Dissolved nitrate plus nitrite is the predominant species of nitrogen at Chain Bridge (fig. 16). It accounts for approximately 75 percent of the total nitrogen concentration and 63 percent of the total nitrogen load. Approximately 80 percent of the nitrogen is dissolved and 20 percent is suspended. Because most nitrogen is dissolved, its concentration correlates very poorly with suspended sediment and river discharge; those correlations that are significant (at the 99 percent

Table 15. Coefficient of determination (r^2) for total and dissolved phosphorus

Characteristic	Total phosphorus r^2	Dissolved phosphorus r^2
River discharge	.14	--
Suspended sediment	.56	.20
River discharge and suspended sediment	.67	
* pH and DO	--	.41
Suspended iron	.79	--
Total iron	--	.33
Total aluminum	--	--
Suspended aluminum	.75	--

*Indicates monthly mean values used in regression.

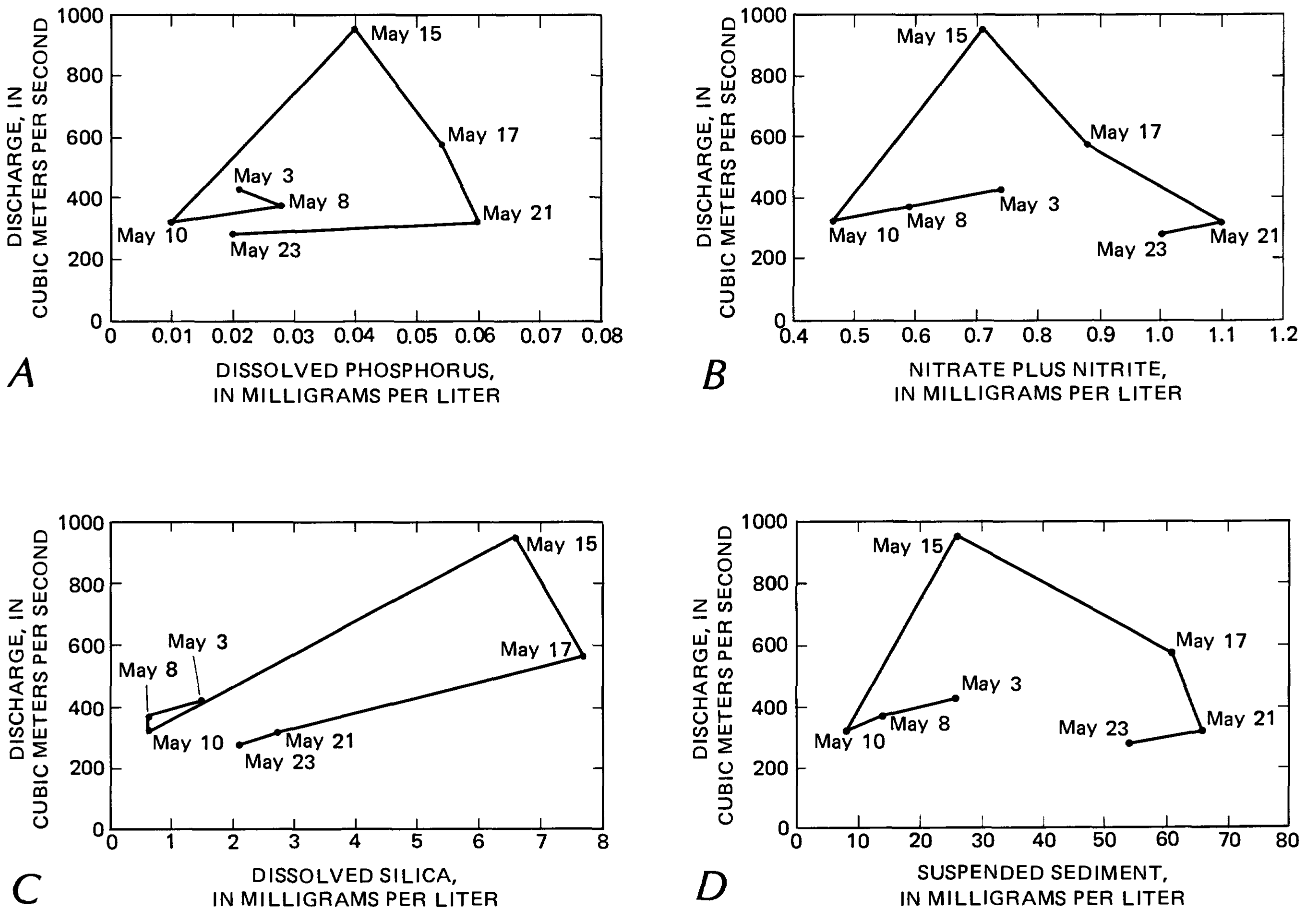

Figure 14. Variation in concentration of dissolved phosphorus, dissolved nitrate plus nitrite, dissolved silica, and suspended sediment.

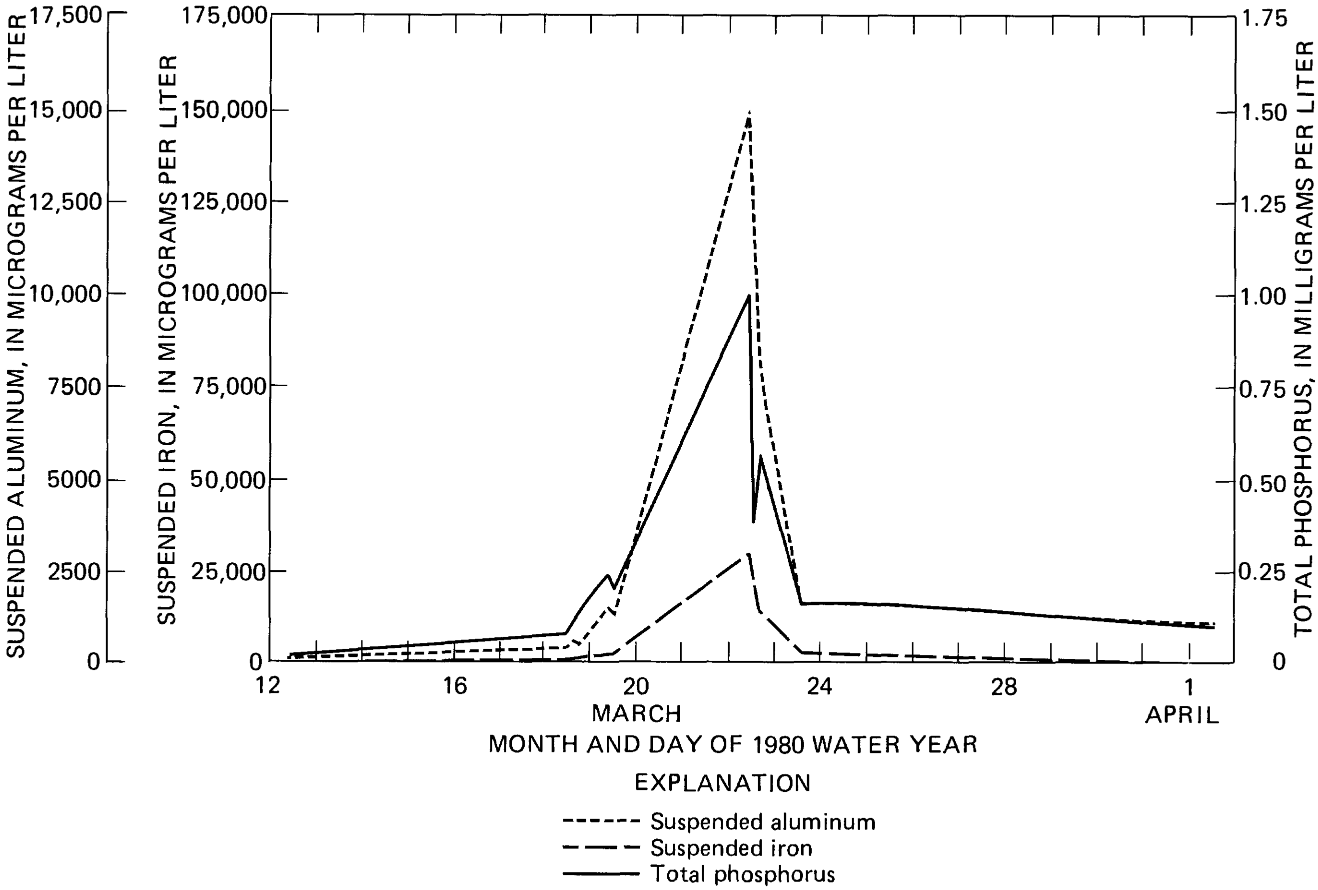

Figure 15. Variation of suspended aluminum, suspended iron, and total phosphorus concentrations, March 12–31, 1980.

level) are listed in table 16.

Total Kjeldhal nitrogen at Chain Bridge is approximately 50 percent suspended; hence the correlation with suspended sediment. Dissolved nitrate plus nitrite is inversely correlated to temperature and specific conductance. Increases in specific conductance and temperature generally occur during the growing season indicating that the correlation is indirectly related to biological activity. Figure 17 supports this hypothesis by showing how increases in chlorophyll *a* correspond to decreases in nitrate plus nitrite and vice versa. Johnson and others (1969) also concluded that summer biological activity reduced nitrate concentrations for streams in the Hubbard Brook watershed.

Silica

Dissolved silica concentrations in natural waters should range between 6 mg/L, the solubility of quartz reported by Morey and others (1962) and 120 mg/L, the solubility of amorphous silica reported by Siever (1962). Silica concentrations can be substantially depleted through biological activity. Edwards (1973) reported that at times as much as 90 percent of the dissolved silica supplied to the river Yare was removed by diatoms. Thus, the effective range of dissolved silica is 0.0 mg/L to 120 mg/L. At Chain Bridge, the discharge-weighted mean concentration for the water years 1978 to 1981 was 5.6 mg/L, the maximum was 8.6 mg/L, and the minimum was 0.0 mg/L.

Edwards (1973), Kennedy (1971), and Davis (1964) determined that dissolved silica was uncorrelated with discharge. For the Potomac River at Chain Bridge however, there is a significant correlation between river discharge and dissolved silica concentration at the 99 percent level. Using daily values, the correlation explained little of the variation in concentration but for mean monthly values approximately half the variation was explained. Figures 18a, 18b, and 18c show dissolved silica, river discharge, and chlorophyll *a* for 3 water years, 1979 to 1981. These graphs show that generally, dissolved silica increases with discharge. There are three exceptions to this relationship. First, for the January and February 1979 runoff events there is a decrease in concentration corresponding to, or just preceeding the peak discharge. This decrease could be the result of an initial snow melt for both runoff events;

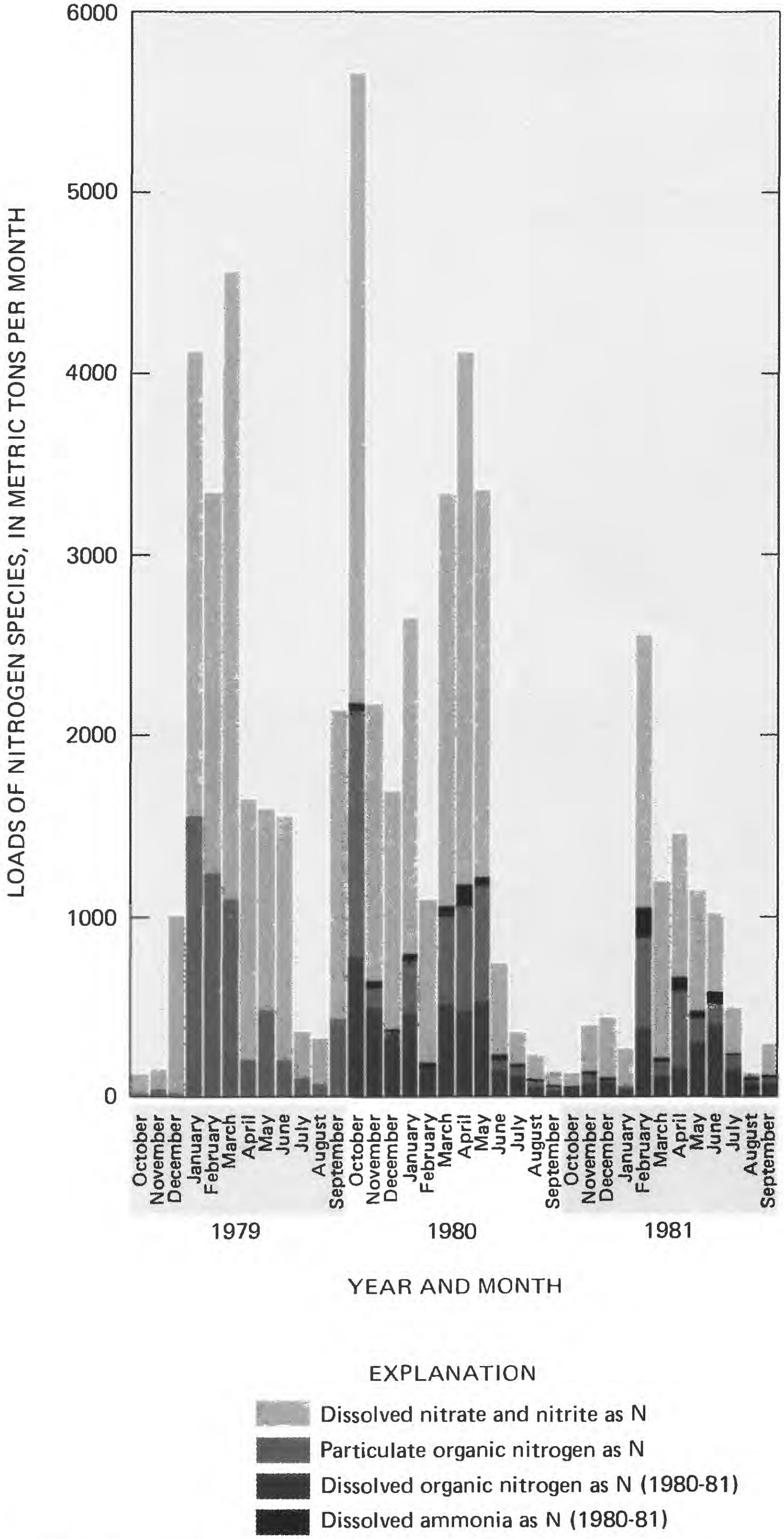

Figure 16. Nitrogen species loads, water years 1979–81.

Table 16. Coefficient of determination (r^2) for total and dissolved Kjeldhal nitrogen, dissolved nitrate plus nitrite, and dissolved ammonia

Characteristic	Total Kjeldhal nitrogen r^2	Dissolved Kjedhal nitrogen r^2	Dissolved nitrate plus nitrite r^2	Dissolved ammonia r^2
Suspended sediment	50.8	9.0	--	--
Temperature	--	--	30.8	--
Chlorophyll *a*	--	--	5.1	--
* Temperature	--	--	64.0	--
* Temperature and specific conductance	--	--	74.0	--

*Indicates monthly mean values used in regression.

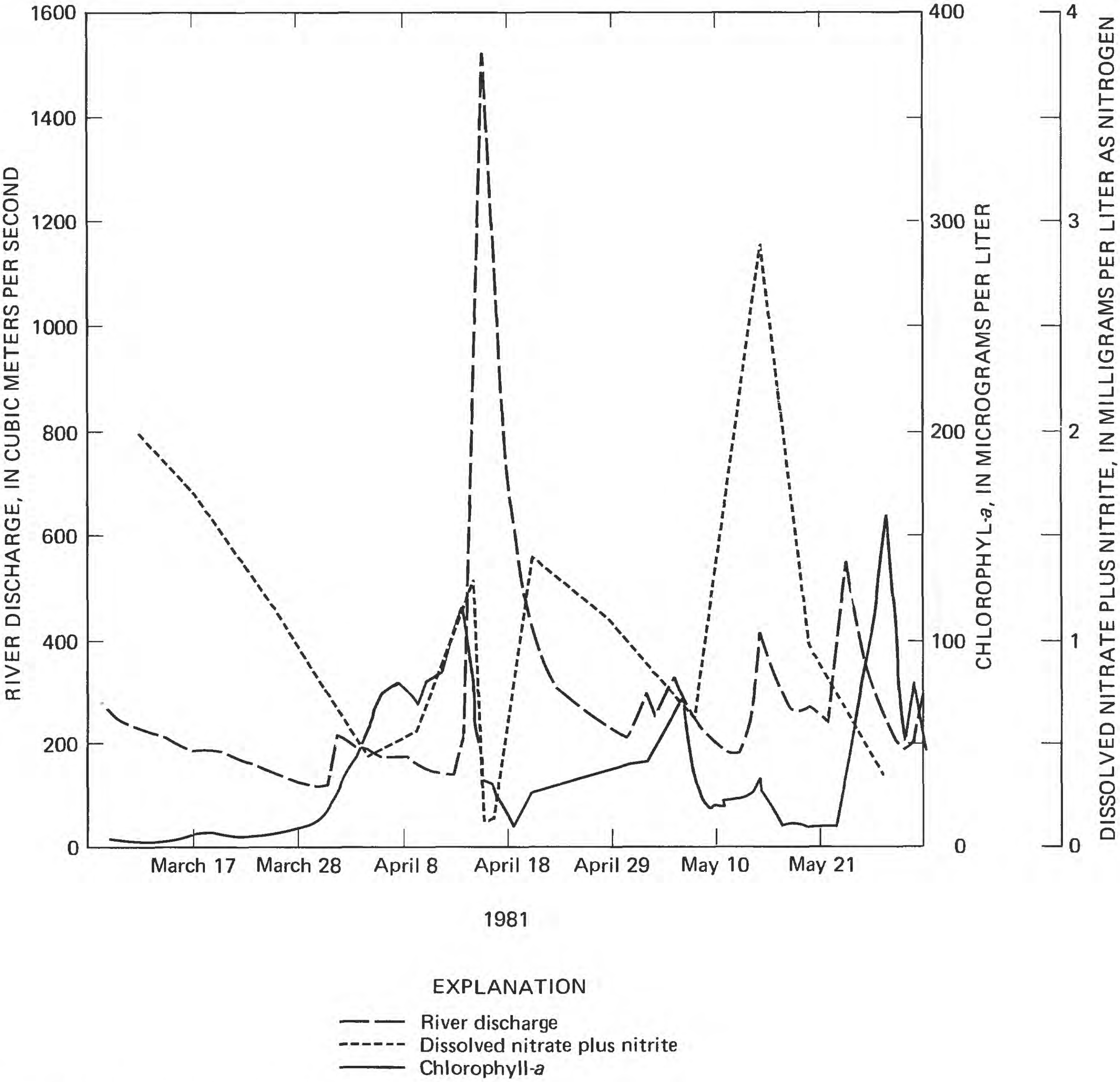

Figure 17A. River discharge, dissolved nitrate plus nitrite, and chlorophyll *a* concentration, February–May, 1981.

thus runoff would be low in dissolved silica and would also cause a decrease in dissolved silica concentration until the snow melt was completed.

The second exception to the river discharge and dissolved silica relationship is caused by biological activity. This effect is strongest during low flow periods and weakest during high flow periods. For example, figure 18b shows that for the peak discharges, dissolved silica concentrations increased even if chlorophyll *a* levels increased. But during low flow periods, such as July, August, and September 1981, the biological removal was dominant over slight increases in river discharge.

The third variation on the river discharge and dissolved silica relationship is due to the effects of ground water discharge. The dissolved silica concentration in the local aquifiers (approximately 20 mg/L) is considerably higher than the river concentration. During the low-flow period of July, August, and September 1980, the increase in dissolved silica is due to the increased ground water fraction of the total river discharge. In contrast, during the July, August, and September 1981 low flow period, the dissolved silica concentration began to increase due to ground water inflow. However, because biological activity is greater, indicated by increased chlorophyll concentrations, the

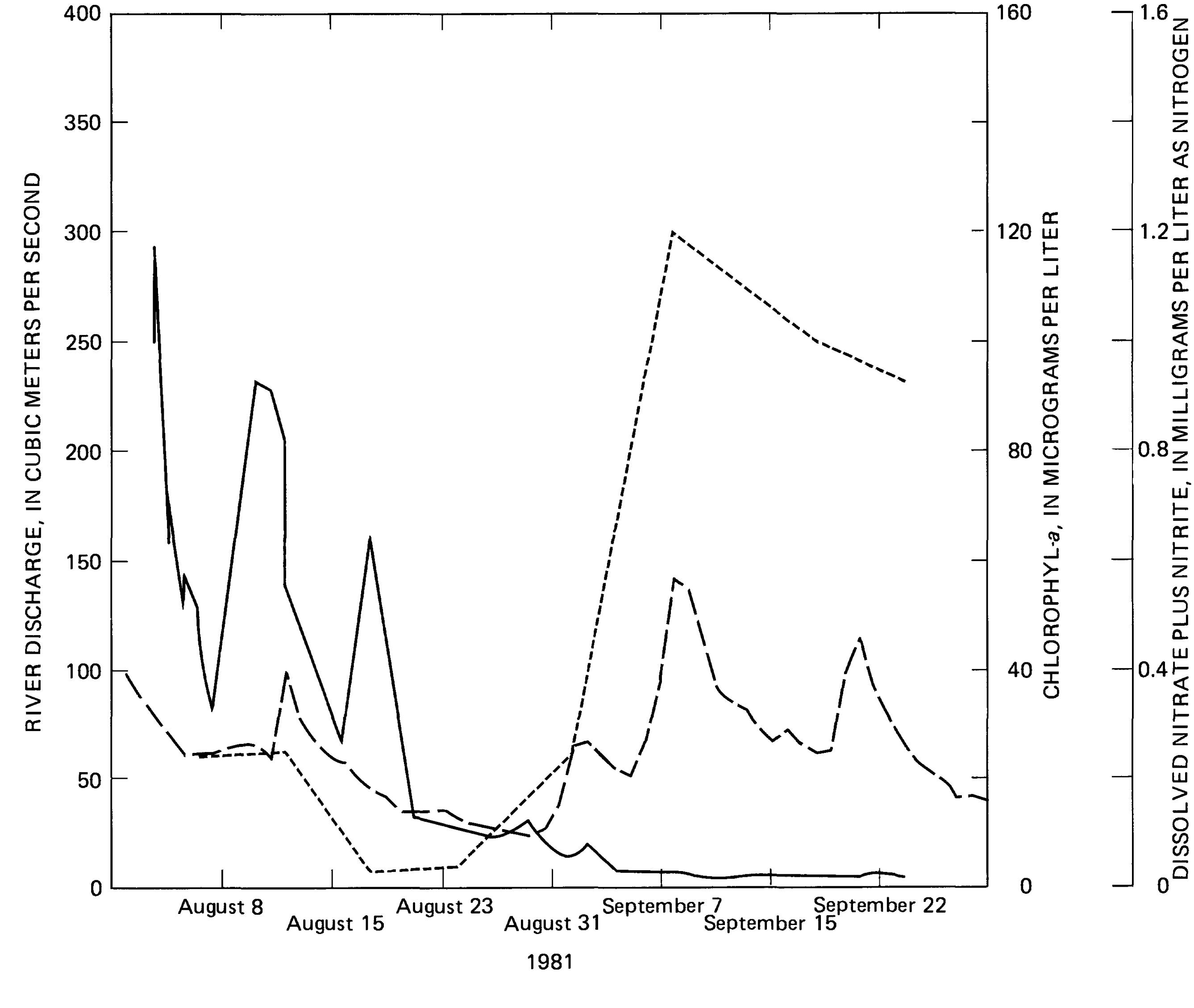

Figure 17B. River discharge, dissolved nitrate plus nitrite, and chlorophyll *a* concentration, August–September, 1981.

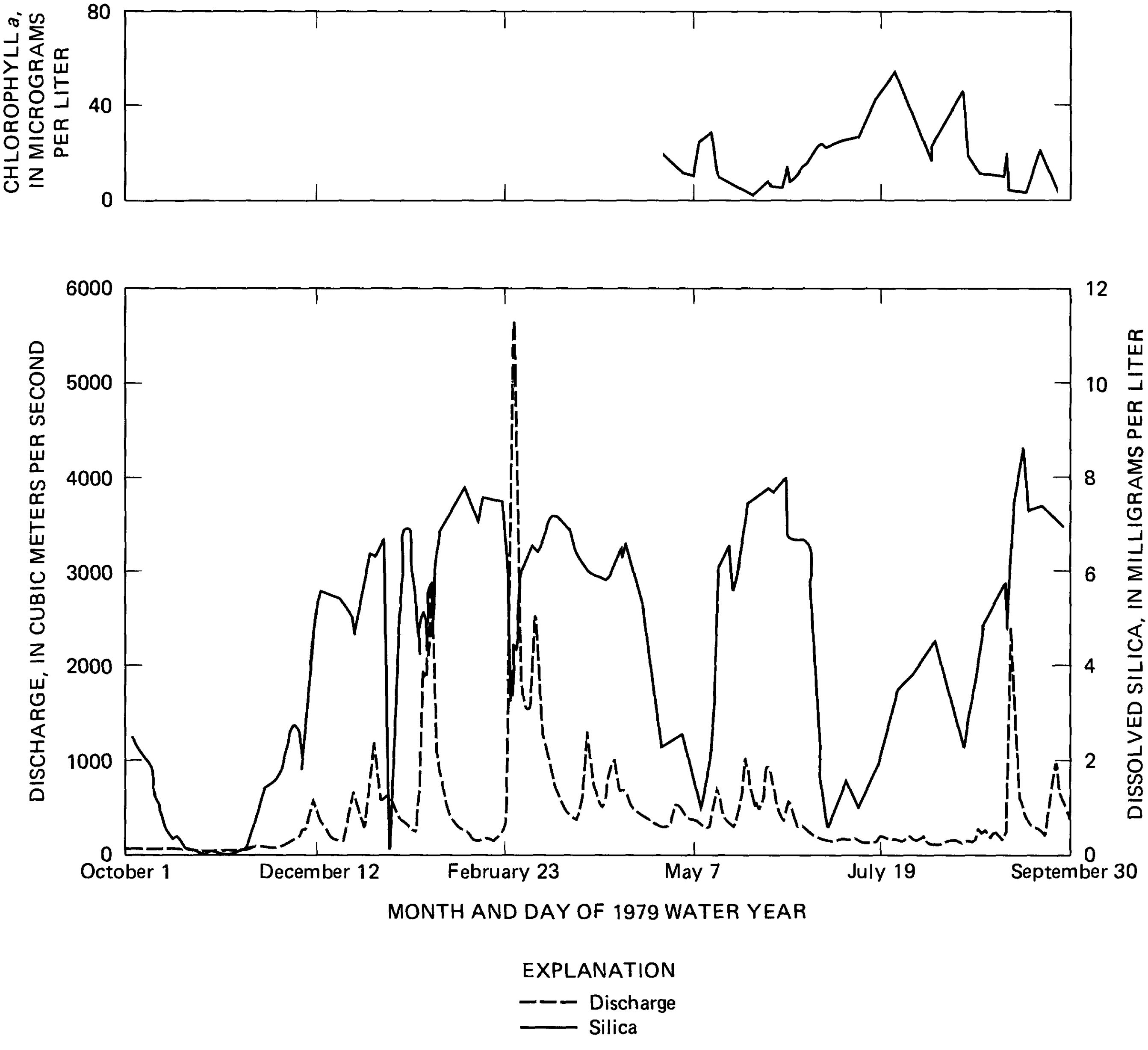

Figure 18A. River discharge, dissolved silica concentration, and chlorophyll *a* concentration, 1979 water year.

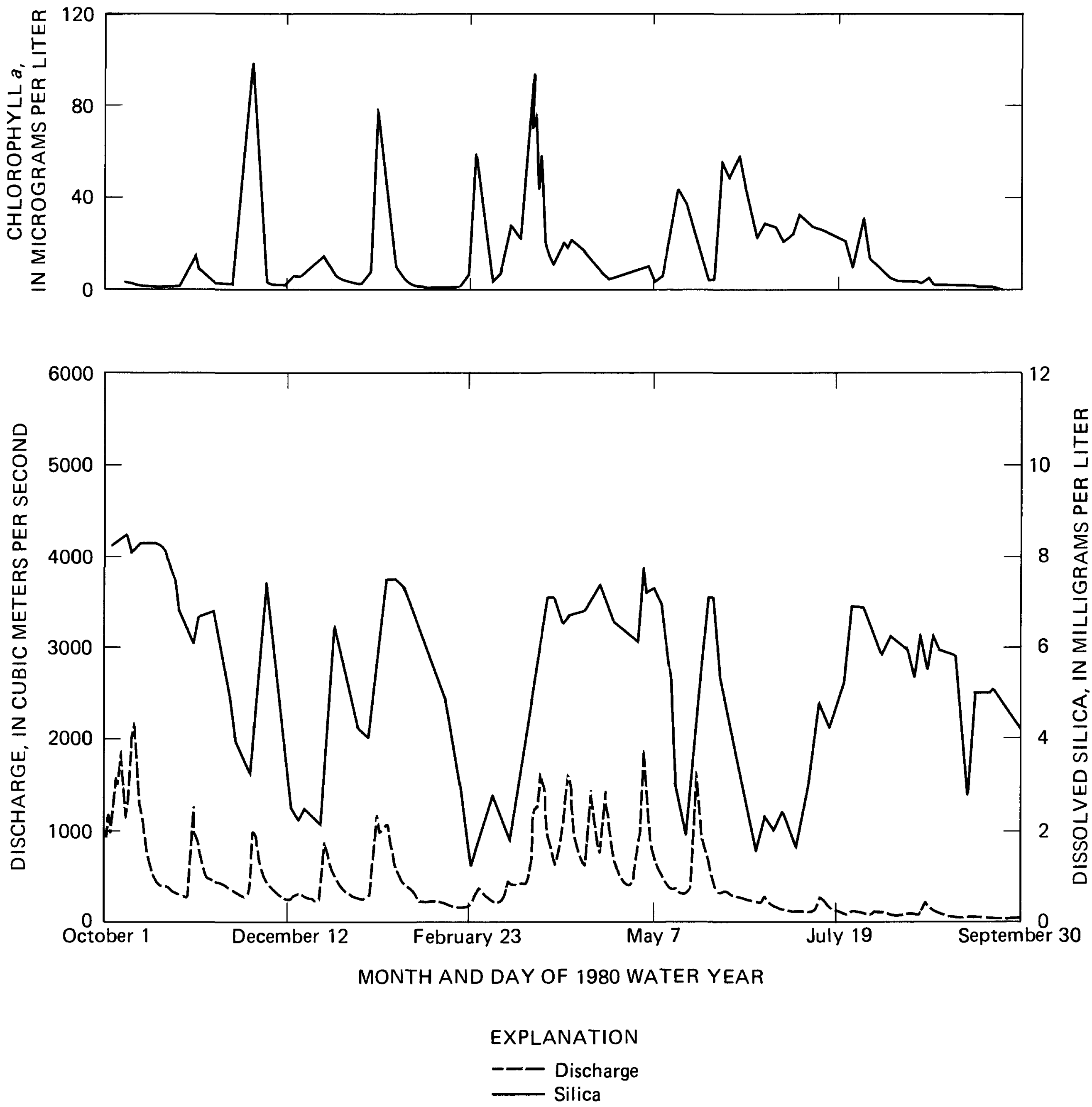

Figure 18B. River discharge, dissolved silica concentration, and chlorophyll *a* concentration, 1980 water year.

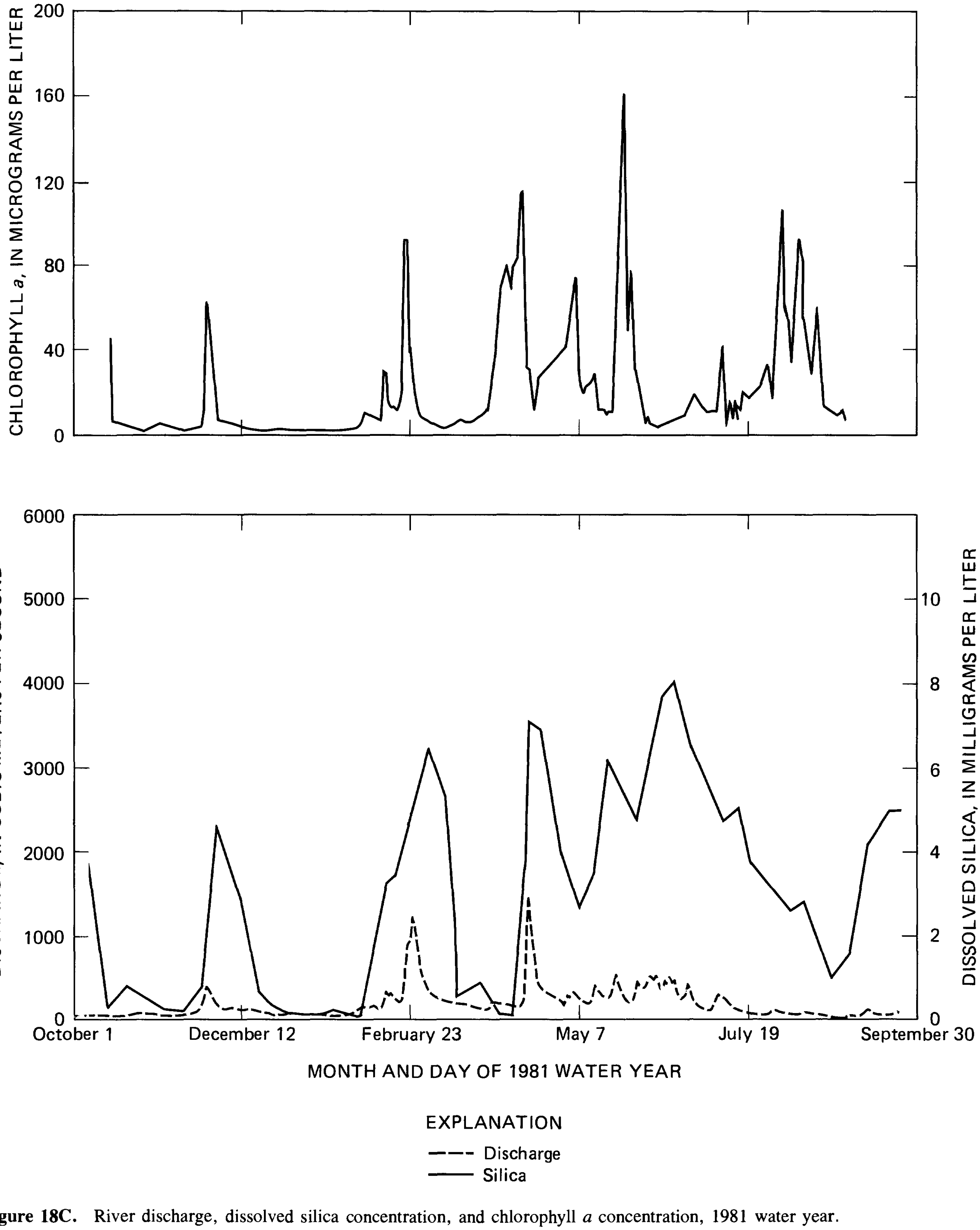

Figure 18C. River discharge, dissolved silica concentration, and chlorophyll *a* concentration, 1981 water year.

increase in dissolved silica is negated. This increase in dissolved silica due to groundwater corresponds to the typical biological growth season and therefore is usually negated.

Suspended Sediment

Suspended sediment at Chain Bridge correlates well with river discharge. For the water years 1979 to 1981, the best relationship with river discharge produced an r^2 of 0.55. The data were separated into three categories based on rising river discharge, falling river discharge, and steady river discharge (daily change in river discharge less than 6 m^3/s). Sediment was regressed against river discharge in each category producing the following results: rising river discharge, r^2 of 0.47; falling river discharge, r^2 of 0.65, steady river discharge, r^2 of 0.29.

Suspended sediment concentrations are primarily affected by the previous river discharge conditions and the time of year. For example, of the three largest storm runoff events of 1979, the largest, by a factor of two, had the lowest peak sediment concentration; this storm occurred in February 1979. In January 1979, the second largest storm occurred transporting all the readily available sediments and leaving little time for additional sediments to accumulate before the February storm. The January storm had a higher peak sediment concentration even though it had half as high a peak river discharge. The highest suspended sediment concentration, however, occurred in September 1979. This storm runoff event was preceeded by a 3 month low-flow period allowing sufficient time for sediment to accumulate in the river channel. The January and February storms were during the winter when the ground was covered with snow and frozen. Therefore, even though their respective peak discharges were higher than the September storm, the rain and runoff had less potential for sediment transport.

The steady low-flow is similarly affected. The lowest sediment concentrations in 1979 occurred after the January and February storms. During these two storms the readily available sediments were flushed from the river channel. Little sediment was available following these storms for transport and what there was, probably accumulated in the river channel. This is why for a given steady low flow discharge, the sediment concentration before these two storms was higher than after them.

Historical Extension of the Data

The equations for determining daily cation and anion concentrations (eq. 1) can be used with historical and future conductivity data to estimate concentrations at the the 95 percent confidence level (α = 0.05). (See section Evaluation of Computed Results for Cations and Anions.)

The similiarity of the 1979-81 flow duration curves to the 1973-81 and to the 1931-81 curves (figure 6) suggests that the nutrient concentrations in streamflow at Chain Bridge would have occurred during the two periods and would have frequencies similar to those shown in figure 12, assuming 1979-81 basin-wide conditions of water use, waste treatment, and land use had existed during the earlier periods. The concentration- and load-duration curves shown in figures 12 and 13 may be used to estimate water-quality conditions only if the 1979-81 basin-wide use and return flow conditions prevailed during the period in question and only if the flow-duration curve for the period in question matches the curve for the study period. Because runoff during the 1979-1981 water years was similar to 95 percent of historical runoff and because the concentrations of constituents remained fairly consistent over the 3-year period 1979-81, it is postulated that future nutrient concentrations entering the tidal river probably will remain similar to the annual-average concentrations shown in table 12 unless significant changes take place in the river basin. The loads, on the other hand, will be subject to the variations in runoff but probably will follow the pattern described in the section on storm runoff.

SUMMARY AND CONCLUSION

The Potomac River at Chain Bridge at Washington, D.C. is located at the head of the tidal Potomac River and Estuary. Water-resources data were collected intensively at this site from December 1977 through September 1981. Based on these and other available data, the following is a summary of observations and conclusions.

1. Water discharge for the three years of study represents the characteristics of the 51-year (1931-81) average discharge 95 percent of the time.

2. Statistical and comparative tests show that the computed monthly and annual loads shown in this report reliably represent the laboratory data.

3. The concentration-duration curves show that 50 percent of the time water passing Chain Bridge contained at least 0.07 mg/L total phosphorus as P, 0.03 mg/L dissolved phosphorus as P, 1.0 mg/L dissolved nitrate plus nitrite as N, 0.03 mg/L dissolved ammonia as N, 4.5 mg/L dissolved silica as SiO_2, 0.007 mg/L chlorophyll *a*, 4.3 mg/L ultimate BOD, 3.2

mg/L carbonaceous BOD, and 15 mg/L suspended sediment.

4. The load duration curves show that, for 50 percent of the time, water passing Chain Bridge transported at least 1.0 t/d (metric tons per day) total phosphorus as P, 0.5 t/d dissolved phosphorus as P, 28 t/d total nitrogen as N, 20 t/d dissolved nitrate plus nitrite as N, 0.4 t/d dissolved ammonia as N, 70 t/d silica as SiO_2, 0.17 t/d chlorophyll *a*, 81 t/d ultimate BOD, 61 t/d carbonaceous BOD, and 270 t/d of suspended sediment.

5. Constituent concentrations show little consistent seasonal change; however, there is a seasonal trend in loads directly due to seasonal changes in runoff. The high flow seasons, winter and spring (January to June), generally produce the largest loads.

6. The annual mean discharges for the 1979 and 1980 water years were similar, 459 m^3/s and 448 m^3/s respectively, but the discharge characteristics were different for each year; 1979 had higher peak discharges. The differences in discharge characteristics are reflected in smaller loads of suspended materials in 1980.

7. The annual mean water discharge for 1981 (179 m^3/s) was less than half the annual mean discharge for 1979 (459 m^3/s) and 1980 (448 m^3/s); the amounts of suspended sediment and nutrients transported in 1981 were also less than half those transported in 1979 and 1980.

8. Some storm events yield almost as much dissolved material and more suspended material than is transported during an entire low-flow year. The storm runoff for 28 days (Febuary 24 to March 23) of 1979 transported about 30 percent of the annual nutrient load and 40 percent of the annual suspended sediment load for that year.

9. Constituents generally respond to storm events in a cyclical manner.

10. Total phosphorus is positively correlated with suspended sediment, iron, and aluminum.

11. Dissolved nitrate plus nitrite accounts for approximately 75 percent of the total nitrogen concentration and 63 percent of the total nitrogen load for the 1979 to 1981 water years.

12. Dissolved silica is primarily affected by discharge, biological activity, and groundwater inflow.

13. The 1979-81 concentration- and load-duration curves may be used to estimate water quality conditions for other periods only if the flow-duration curve for the period in question matches the curve for the 3 years and if 1979-81 basin-wide water use and return flow prevailed during the period in question.

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